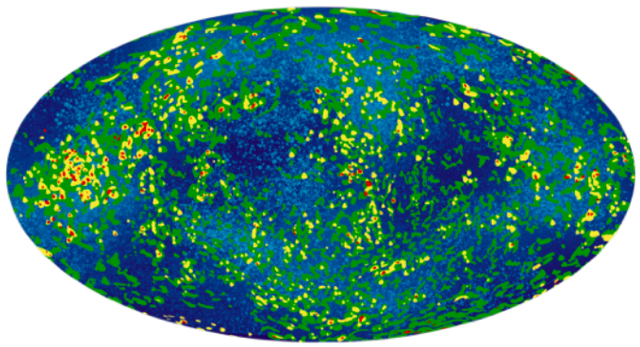
Dark Matter and Axion searches

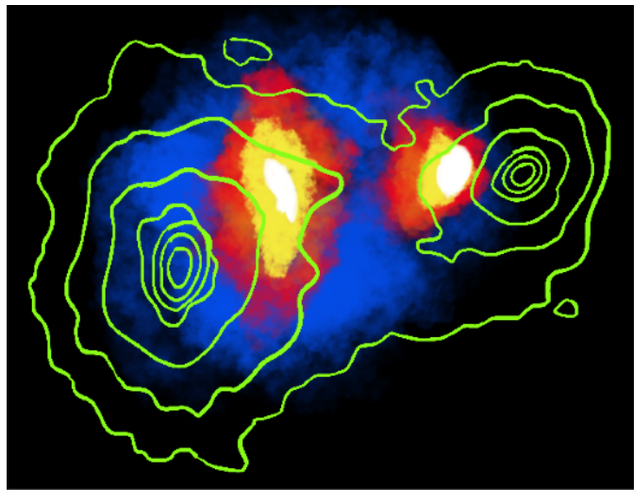
Clara Murgui (CERN)

EPS-HEP conference — July 9th 2025 — Marseille

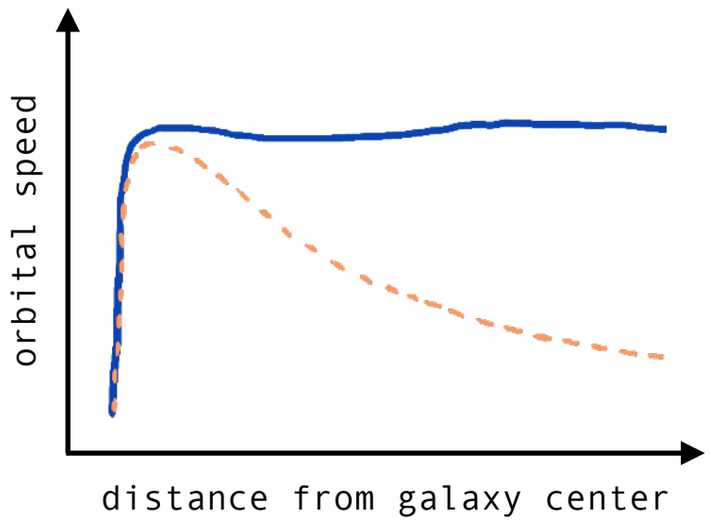
Echoes of the Unseen



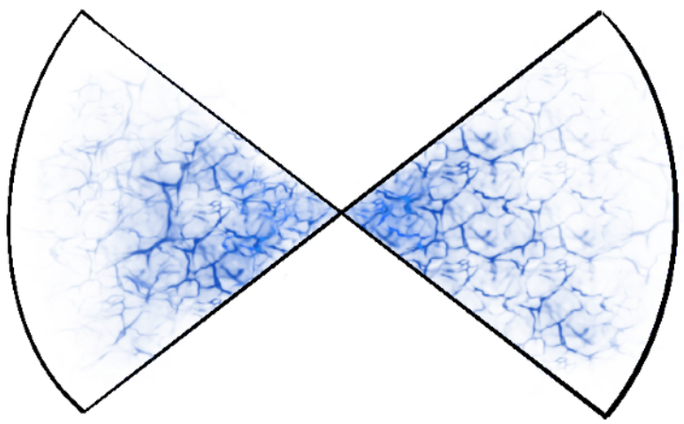
Observed DM density
@ CMB



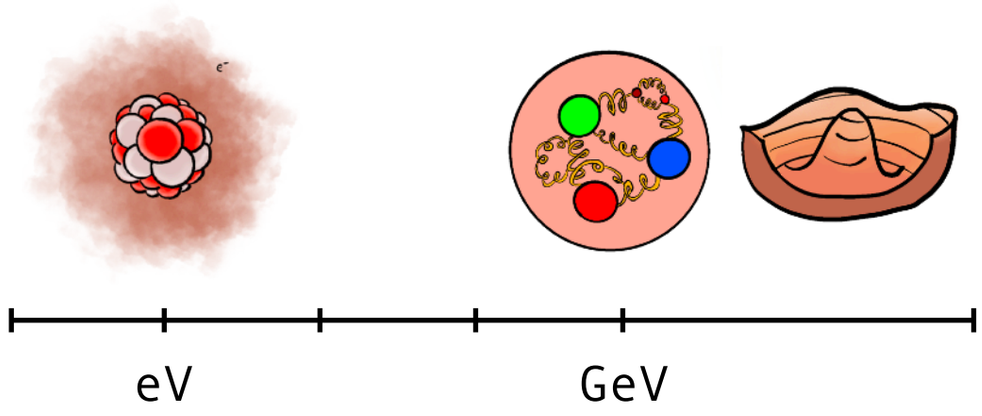
Gravitational lensing
(e.g. Bullet cluster)

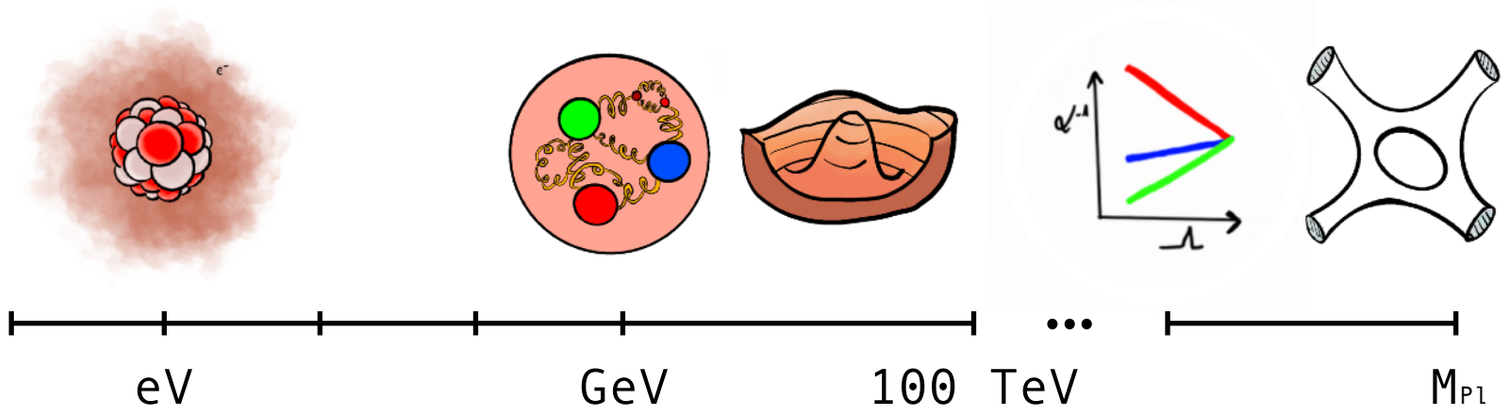


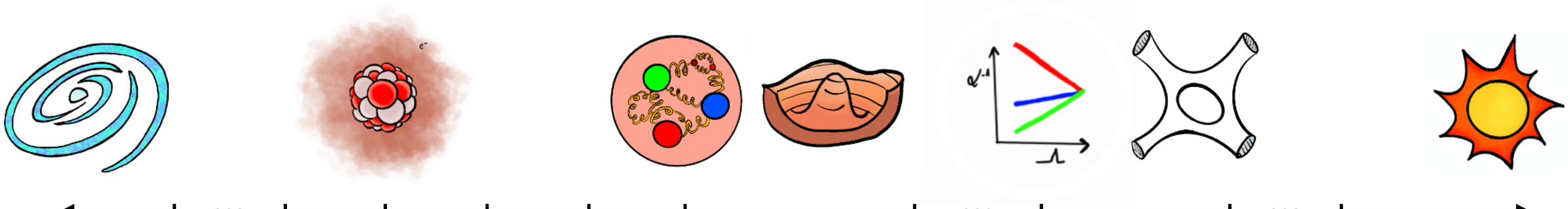
Galaxy rotation curves

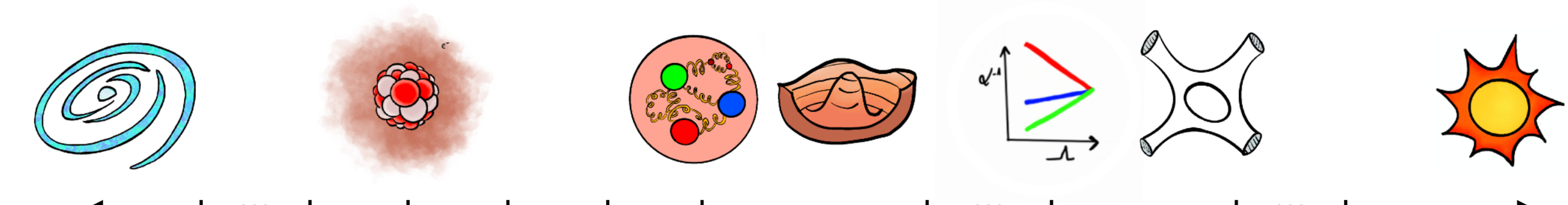


LSS formation

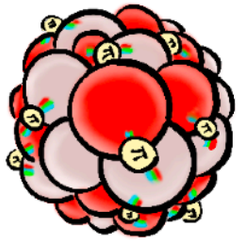

eV
GeV


eV
GeV
100 TeV
M_{Pl}

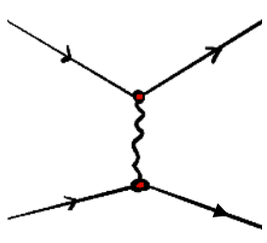

10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_\odot$



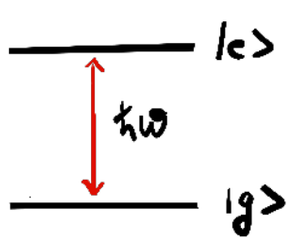
Spans over many branches…
…all over the world



nuclear physics

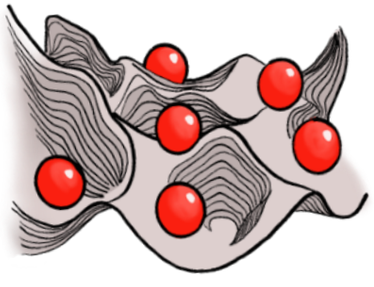


particle physics

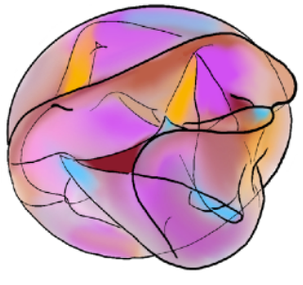


quantum optics, AMO

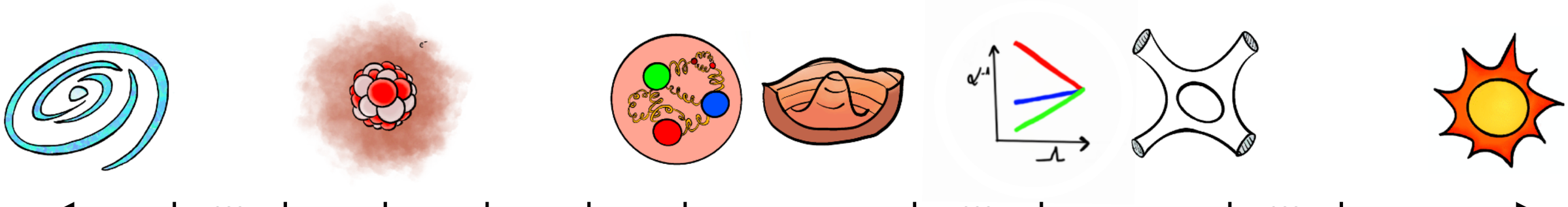
astroparticles cosmology



condensed matter



string theory



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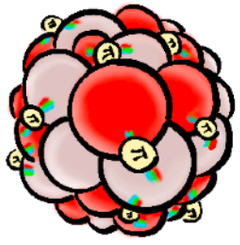

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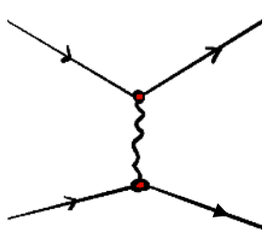

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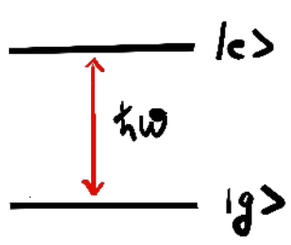

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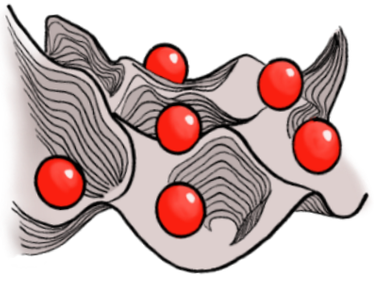

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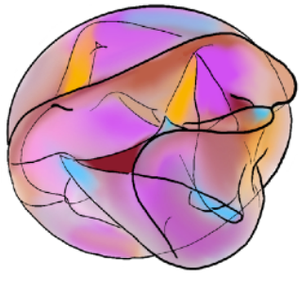


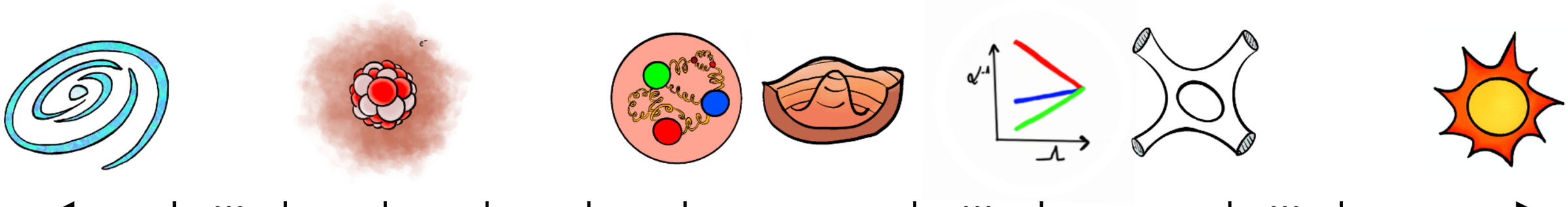
string theory

DISCLAIMER

Due to space-time constrains, many interesting material will be left uncovered :(

Please check out the following recent reviews:

[Cirelli, Strumia, Zupan,'24]
[Cong et al., '24]
[Zurek, '24]
[Chou et al, '23]
[Hütten, Kerszberg, '22]



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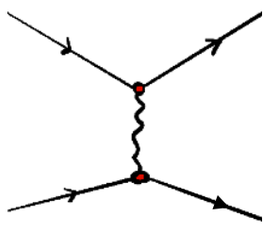
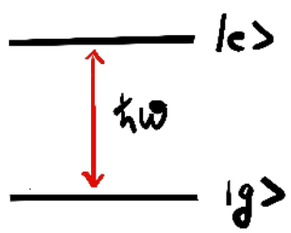


particle physics



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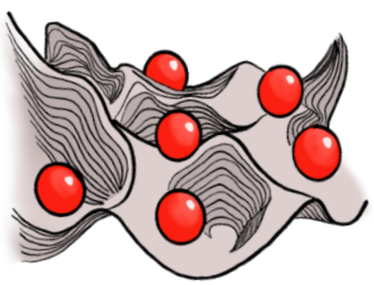

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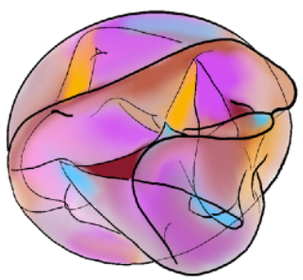
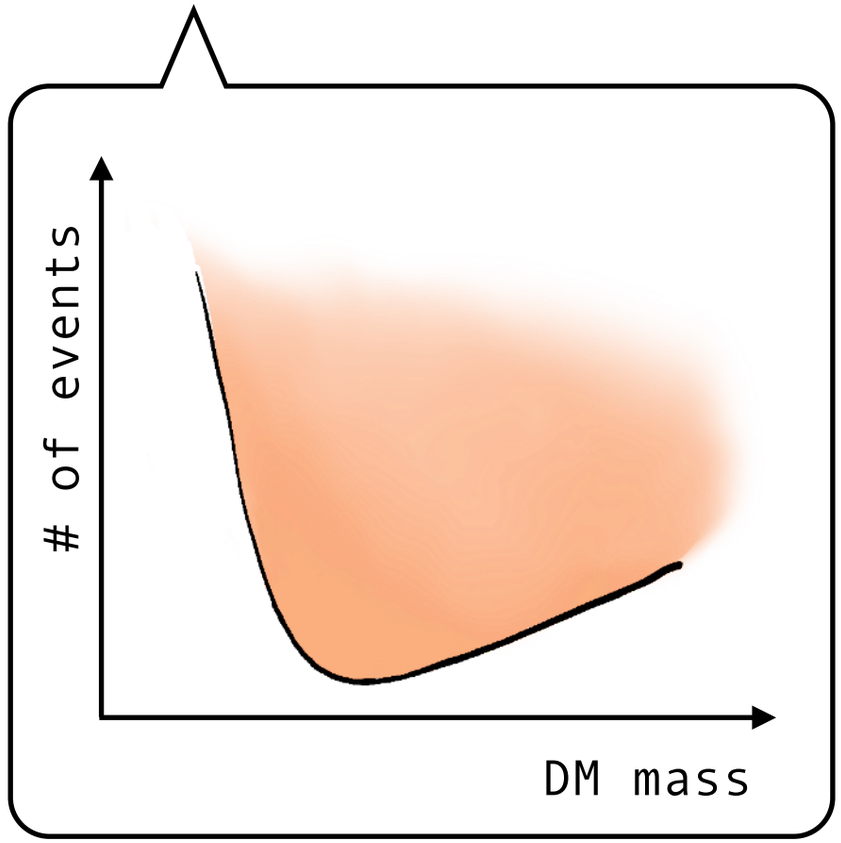
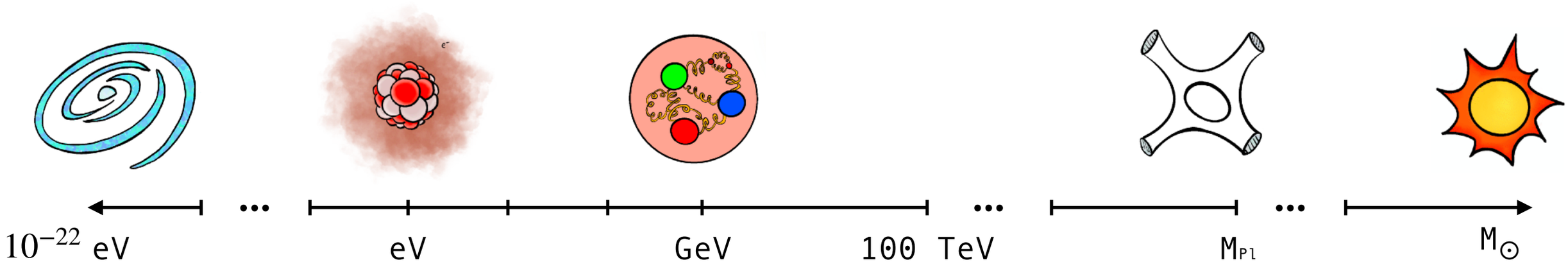


string theory




10^{-22} eV
eV
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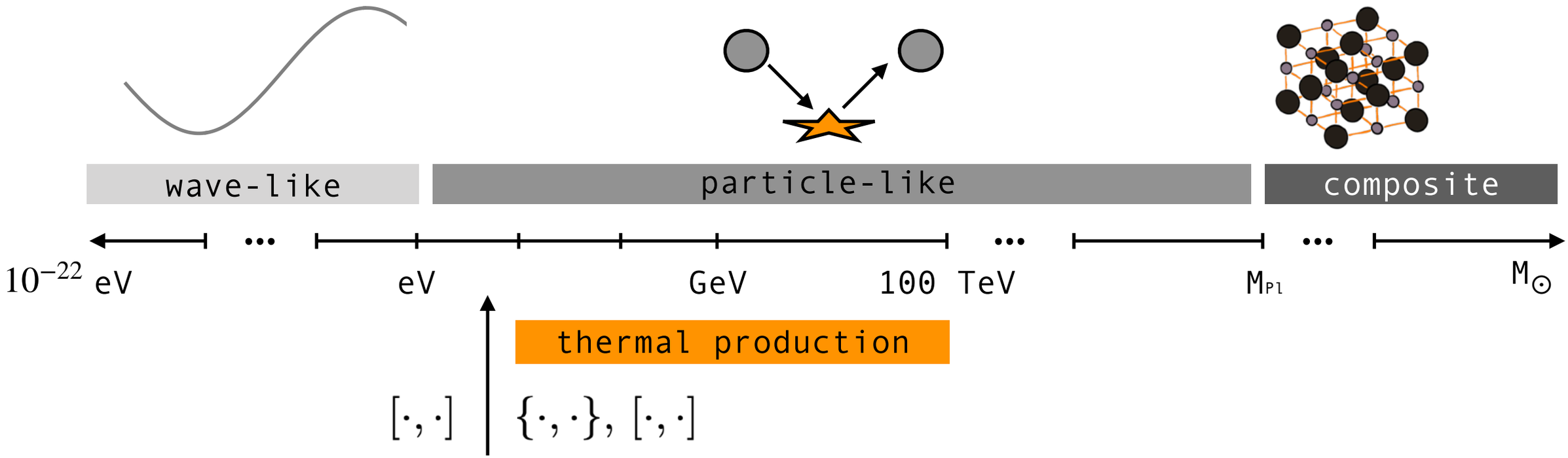
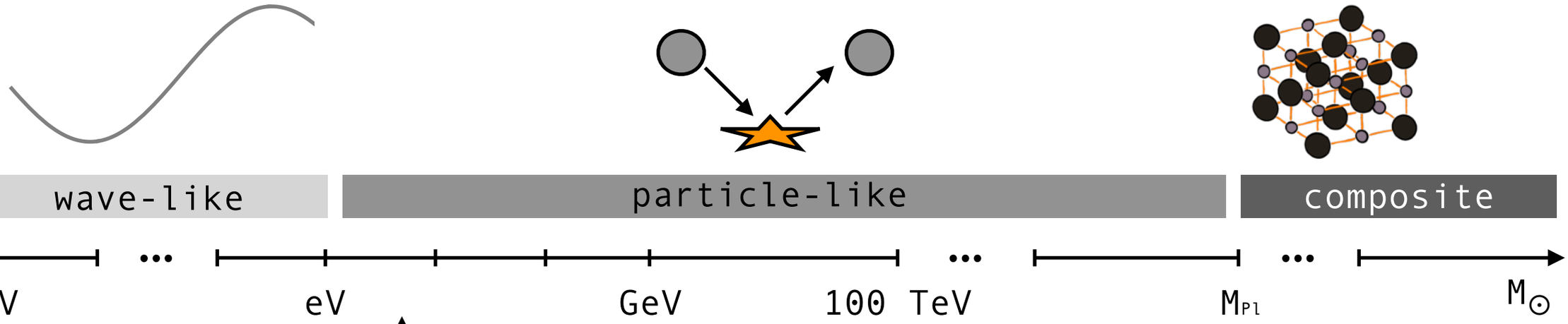
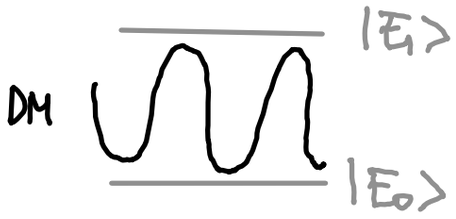
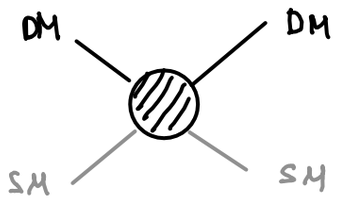


[see talk by Laura Lopez]

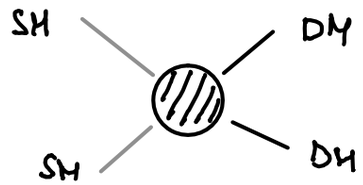




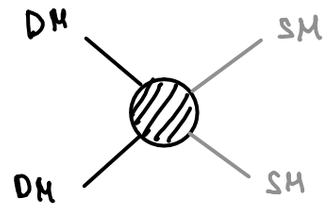
quantum sensors, etc.



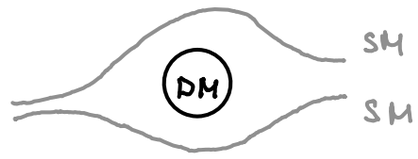
direct detection



collider Searches



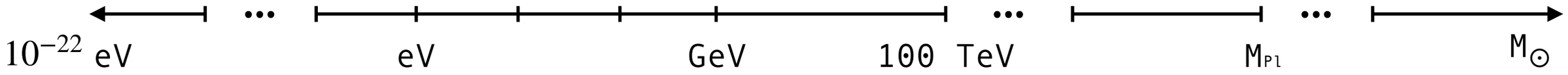
indirect detection



lensing, etc.

Where do we expect it?

Having a goal



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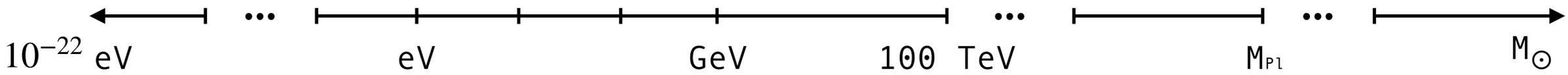
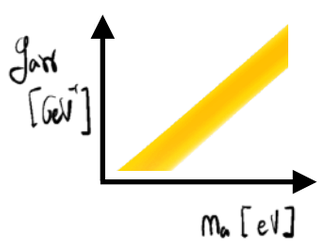
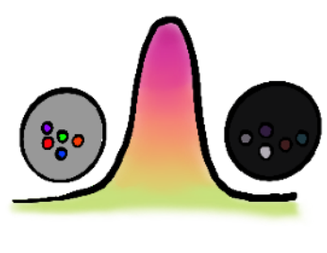
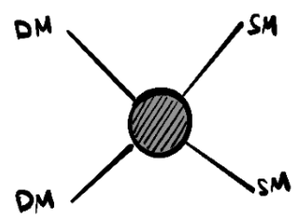




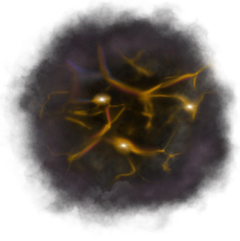
axions



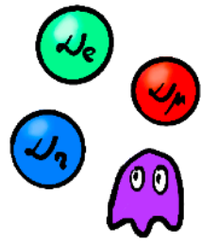
hidden sector



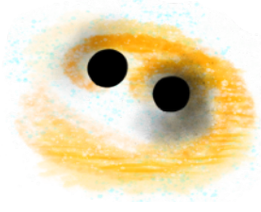
WIMPs



fuzzy DM



sterile Neutrinos



PBHs

[see talk by Laura Lopez]

Where do we expect it?

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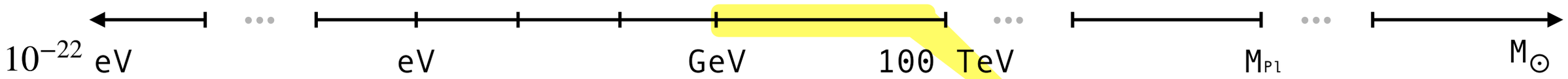
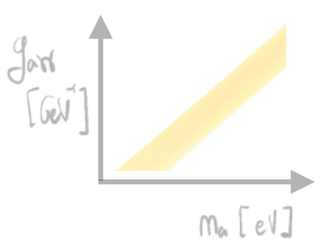
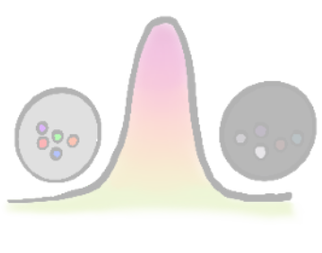
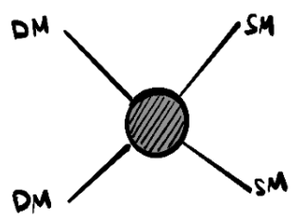




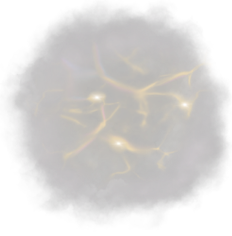
axions



hidden sector



WIMPs



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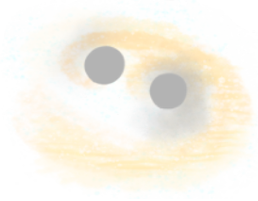

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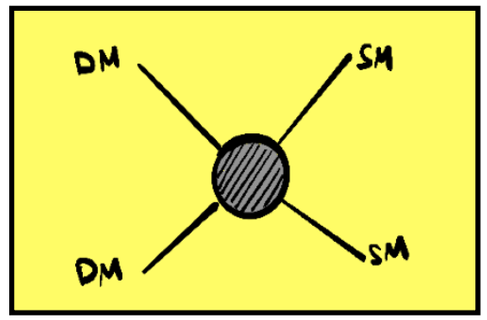
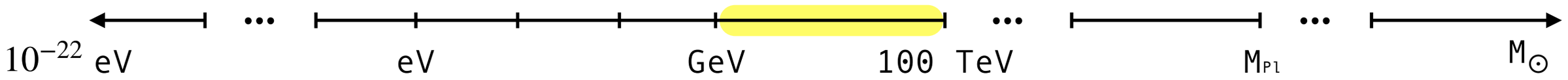
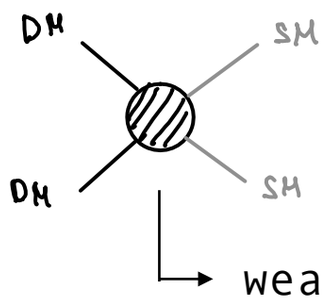


Lee-Weinberg bound
[Lee, Weinberg,77]

Unitary bound
[Griest, Kamionkowski,90]



WIMP miracle

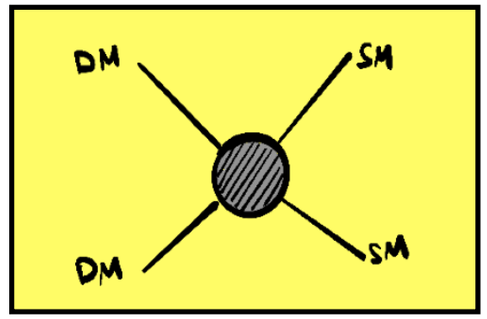


$$\langle \sigma v \rangle \sim \frac{G_F^2}{8\pi} m_{\rm DM}^2 \frac{c}{3}$$

$$\Omega_{\rm DM} \sim 0.1 \times \left(\frac{3 \times 10^{-26}\ {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \right)$$

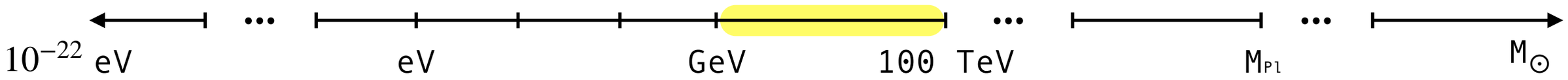
if $m_{\rm DM} \sim \Lambda_{\rm EW}$

WIMPs

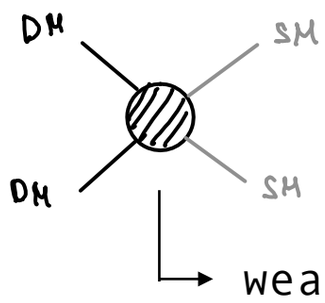


Lee-Weinberg bound [Lee, Weinberg,77]

Unitary bound [Griest, Kamionkowski,90]



WIMP miracle



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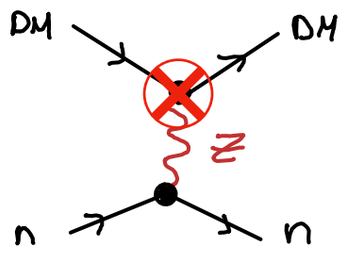
if $m_{\rm DM} \sim \Lambda_{\rm EW}$

e.g. neutralino (SUSY) [Goldberg.'83] [Ellis et al.,'84]

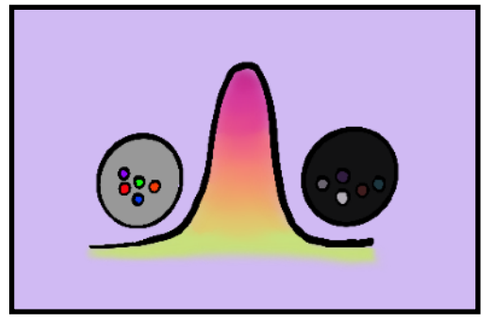
$$\text{DM} = \alpha(\text{bino}) + \beta(\text{wino}) + \gamma(\text{higgsinos})$$



e.g. minimal DM [Cirelli et al.'06]

DM ~ (1,5,0) $m_{\rm DM}$ ~ 9.4 TeV [Cirelli, Strumia, '09]

Hidden sector

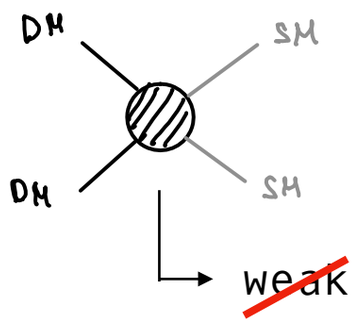


Lee-Weinberg bound
[Lee, Weinberg,77]

$\langle \sigma v \rangle \sim G_F^2 m_\chi^2$

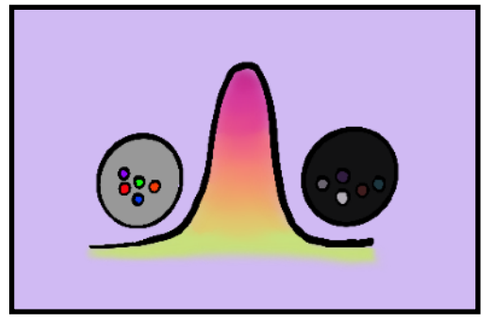
10^{-22} eV ••• eV GeV 100 TeV ••• M_{Pl} ••• $M_\odot$

WIMPless DM [Feng, Kumar, 08]



weak $\mathcal{G}_{\rm SM} \otimes {\rm U}(1)_X$

Hidden sector



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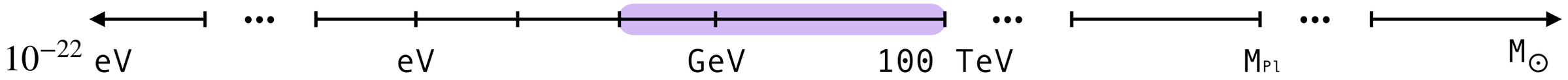
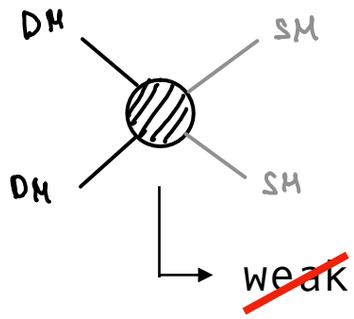


WIMPless DM [Feng, Kumar, 08]



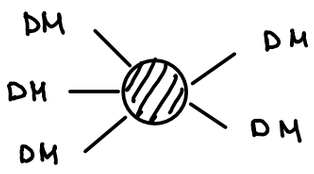
weak $\mathcal{G}_{\rm SM} \otimes \mathrm{U}(1)_X$

e.g. accidental symmetries

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\ell_L\ell_L HH + \frac{1}{\Lambda}Q_L Q_L Q_L \ell_L + \cdots$$

$\mathrm{U}(1)_B, \mathrm{U}(1)_L$ [Fileviez, Wise, 10]

e.g. SIMP miracle [Hochberg, et al. 14]



$\rightarrow m_\chi \sim 100$ MeV

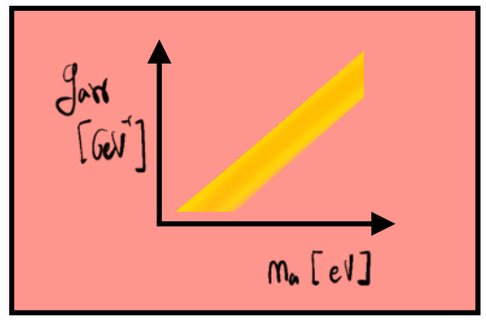
strongly coupled $\mathrm{SU}(N)_D$
Wess-Zumino-Witten term
thermal bridge $T_D \leftrightarrow T_{\rm SM}$

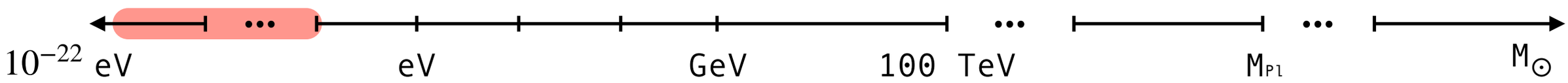
e.g. asymmetric DM [Kaplan, Luty, Zurek, 09]

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} = \frac{m_{\rm DM} Y_{\rm DM}}{m_p Y_B} \sim 5 \quad \rightarrow m_{\rm DM} \sim m_p = \mathcal{O}(\mathrm{GeV})$$

efficient depletion
simplified models

Axions



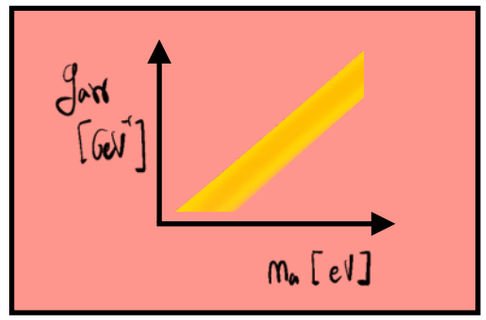


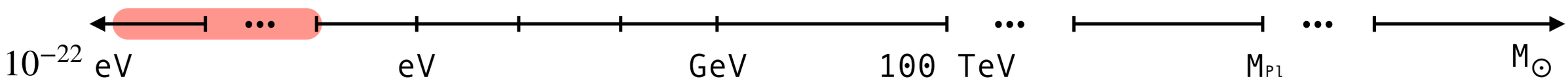
The strong CP problem

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

$$\bar{\theta} = \theta + \arg\{\det[M_d M_u]\}$$

Axions





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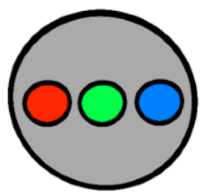
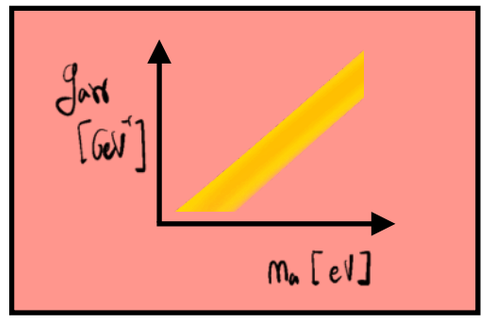
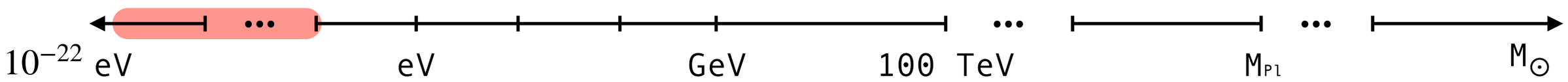


$$\bar{\theta} = \theta + \arg\{\det[M_d M_u]\} < 10^{-10}$$

[Abel et al. 20]

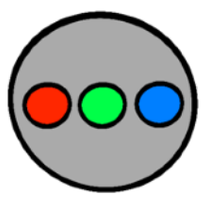
Axions





The strong CP problem

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{a(x)}{f_a}\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$



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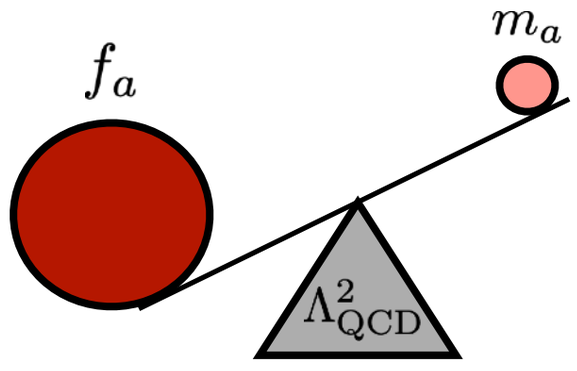
[Abel et al. 20]

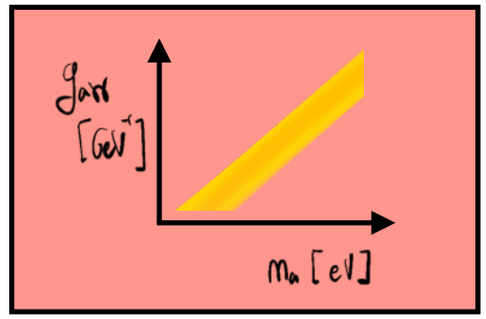


[Peccei, Quinn,'77]
[Weinberg,'78]
[Wilczek,'78]

$$V(a) = \Lambda^4_{\rm QCD}\left[1 - \cos\left(\frac{a}{f_a}\right)\right] \quad \longrightarrow \quad m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$

Anomalous global symetry

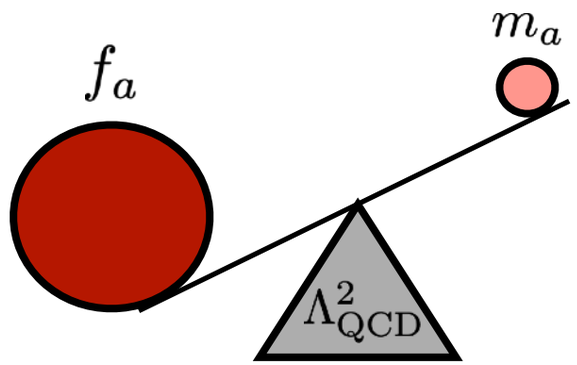
Axions



Interactions with the SM

$$-\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma}\, a\, F\tilde{F} + \frac{1}{4} g_{aGG}\, a\, G\tilde{G} + \frac{1}{2} g_{af} (\partial_\mu a) \bar{f} \gamma^\mu \gamma_5 f$$

$$g_{a\mathrm{SM}} \propto \frac{1}{f_a}$$



[Peccei, Quinn,'77]
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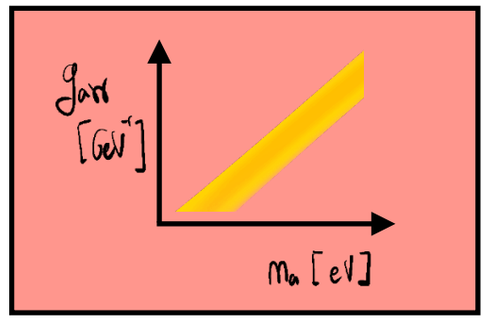
$$V(a) = \Lambda^4_{\mathrm{QCD}} \left[1 - \cos\left(\frac{a}{f_a}\right)\right] \quad \longrightarrow \quad m_a \sim \frac{\Lambda^2_{\mathrm{QCD}}}{f_a}$$

Anomalous global symetry

Axions



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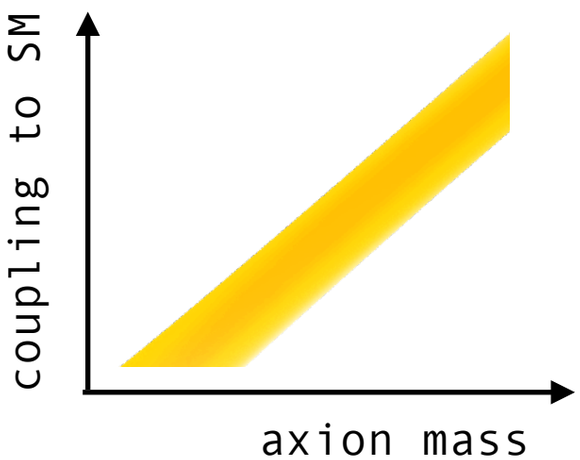

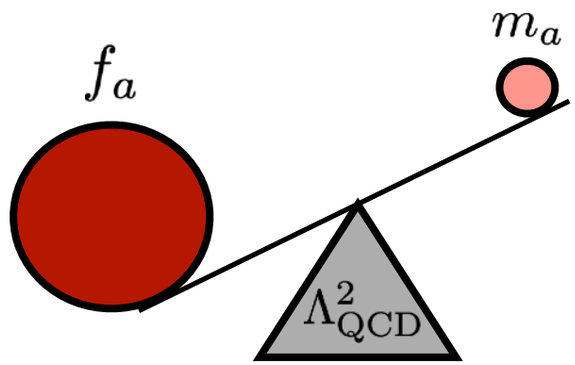

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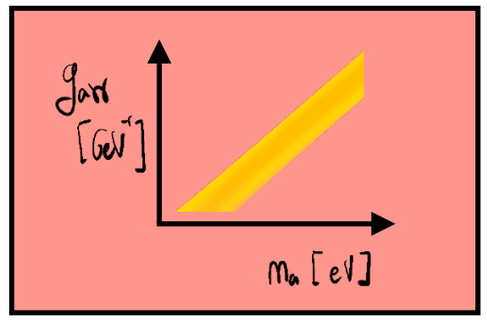

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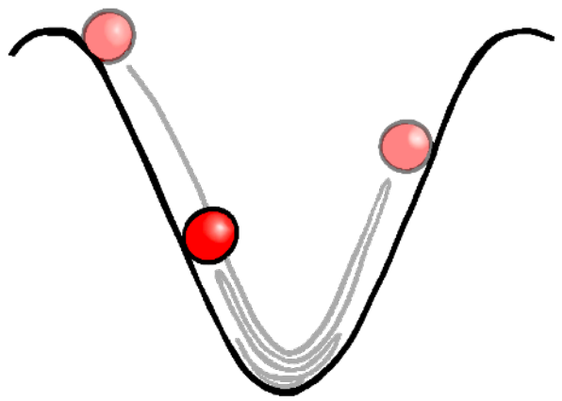
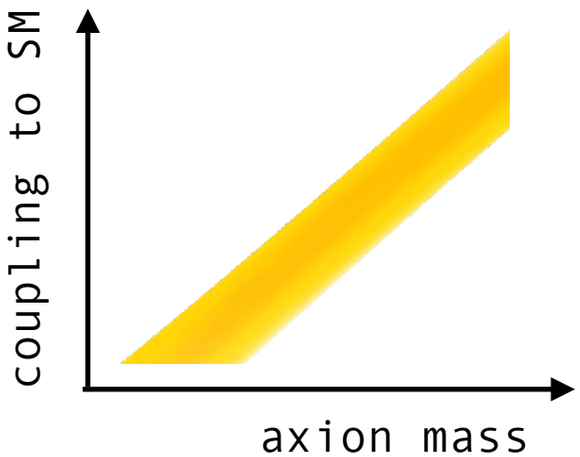
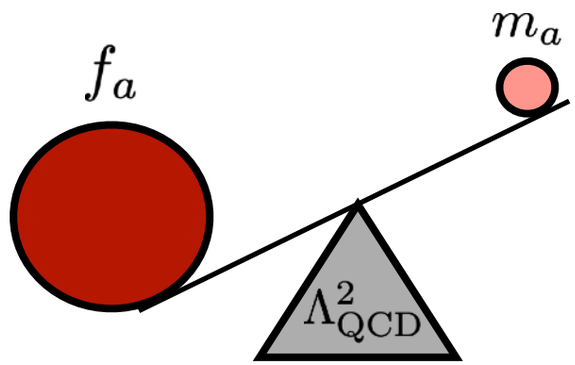


[Preskill, Wise, Wilczek, 83]
[Abott, Sikivie, 83]
[Dine, Fischler, 83]





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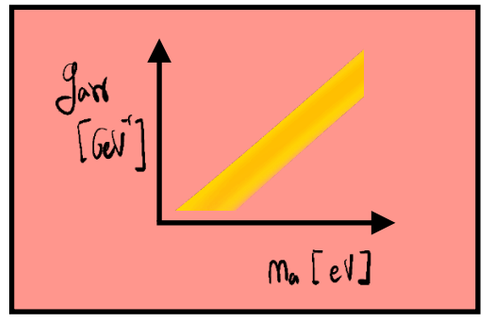
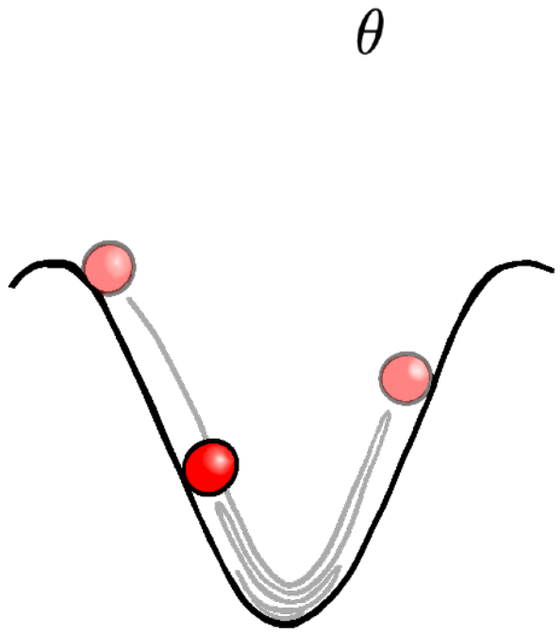
Good dark matter candidate

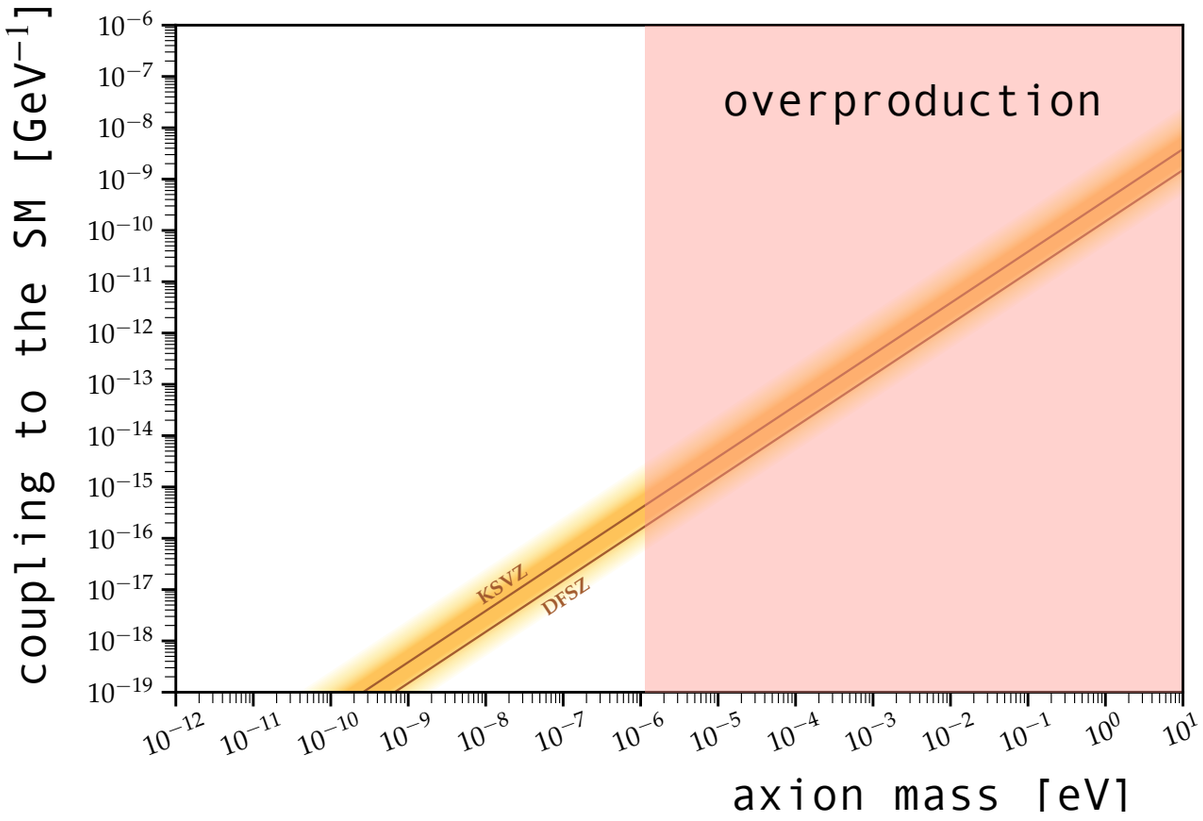
Anomalous global symetry

Axions



Inflation: “pre”



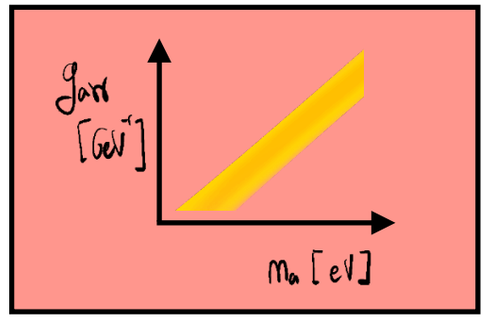


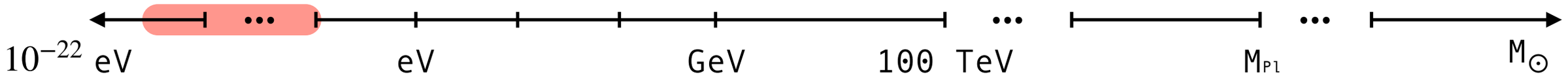
$$\Omega_a h^2 \sim 0.12\,\theta^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\sim 1} \quad \text{(around } \mu\text{eV)}$$

$$V(a) = \chi(T)\left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

Good dark matter candidate

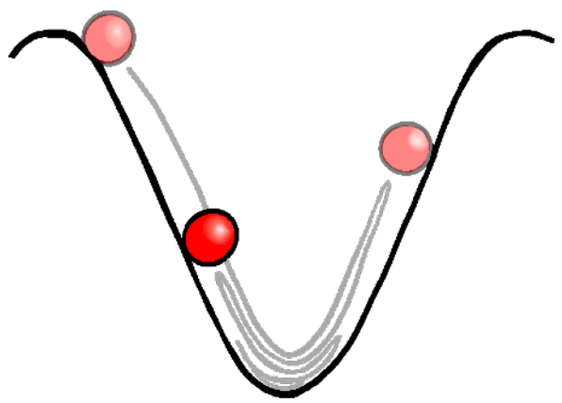
Axions





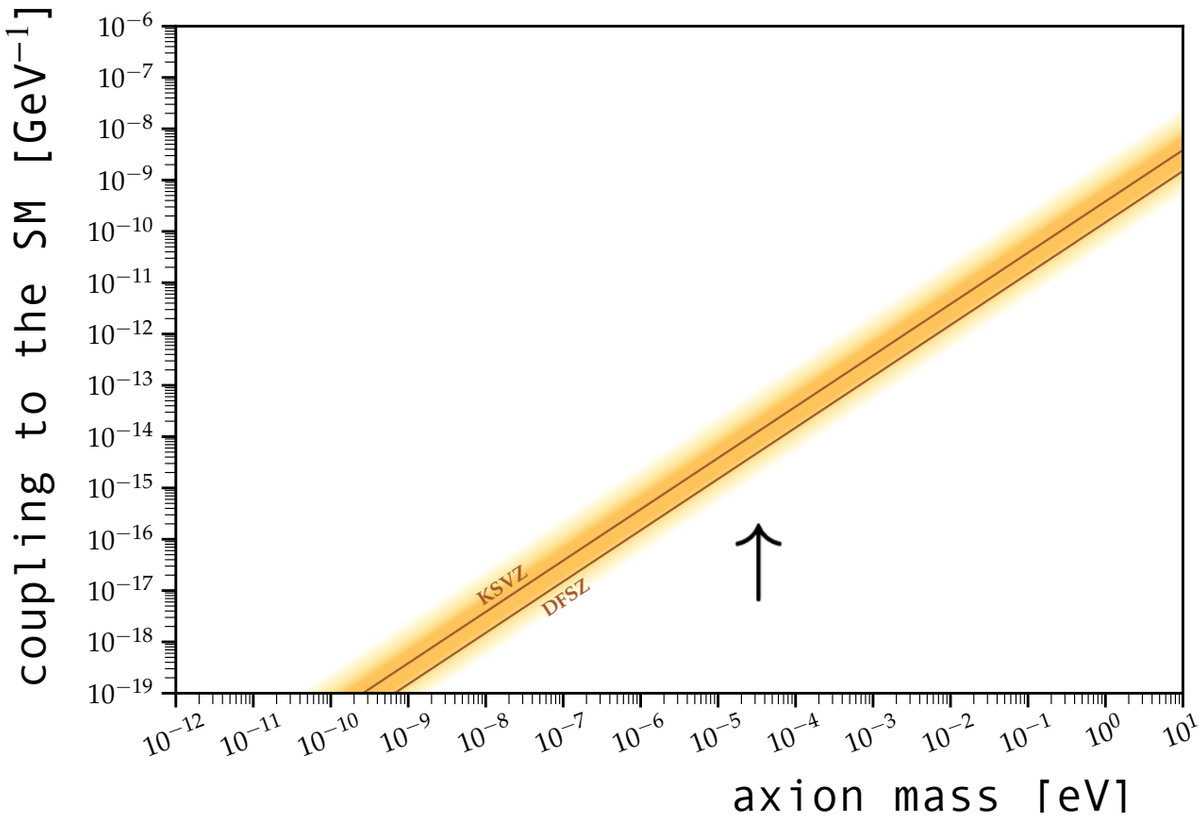
Inflation: “pre” vs “post”

$\theta \qquad \langle\theta^2\rangle = \frac{\pi^2}{3}$



$\Omega_a h^2 \sim 0.12\,\theta^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\sim 1}$ (around μeV)

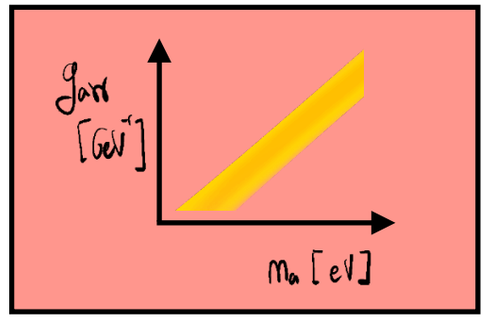
Good dark matter candidate



$V(a) = \chi(T)\left[1 - \cos\left(\frac{a}{f_a}\right)\right]$ [Benabou et al.,’25]

$\Omega_a h^2 = 0.12 \;\Rightarrow\; m_a \sim 45 - 65\,\mu\mathrm{eV}$

Axions



Inflation: “pre” vs “post”

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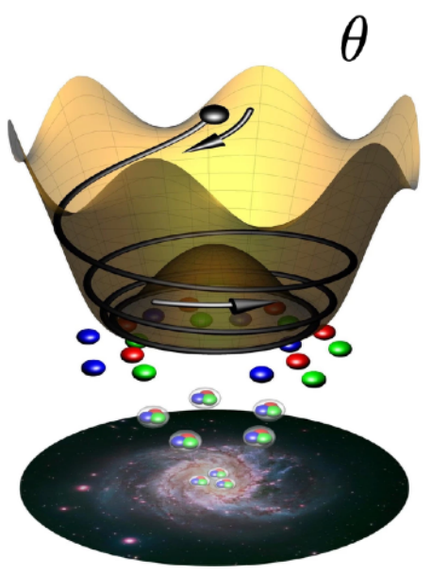
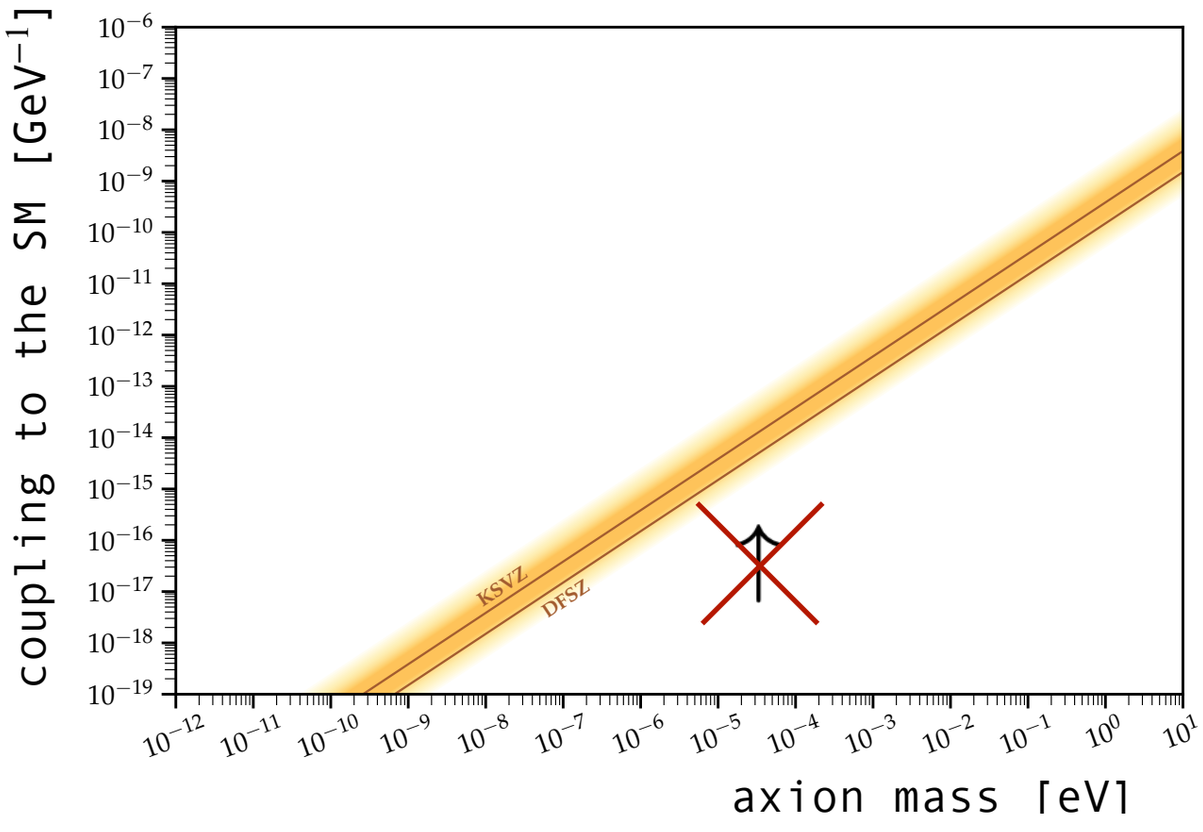


[Co, Hall, Harigaya, 22]

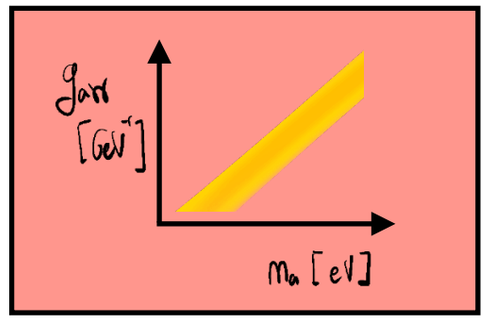


$$\Omega_a h^2 \sim 0.12\,\theta^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\sim 1} \text{(around } \mu\text{eV)} \qquad V(a) = \chi(T)\left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

Good dark matter candidate [Gouttenoire, Servant, Simekachom, 22] [Fasiello et al. 25]
(signatures) (lattice simulation)

Axions

-like particles (ALPs)



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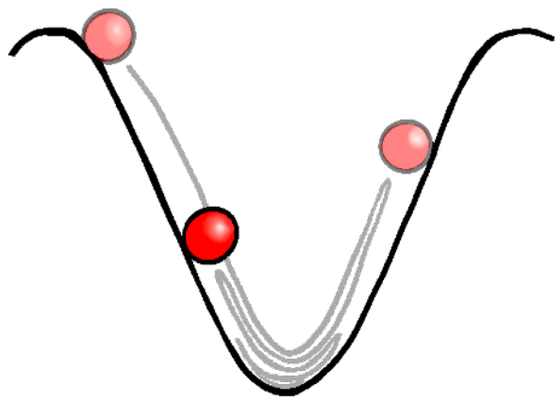

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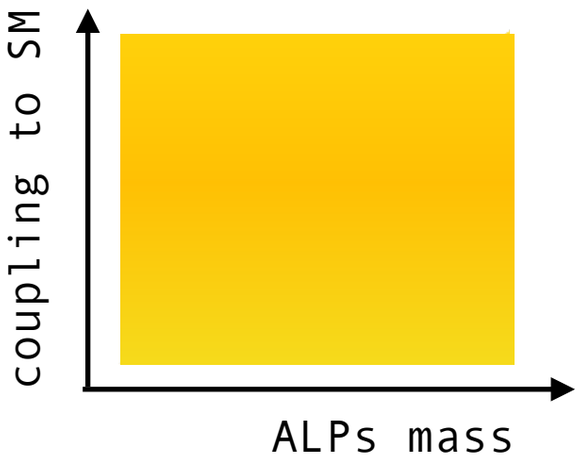

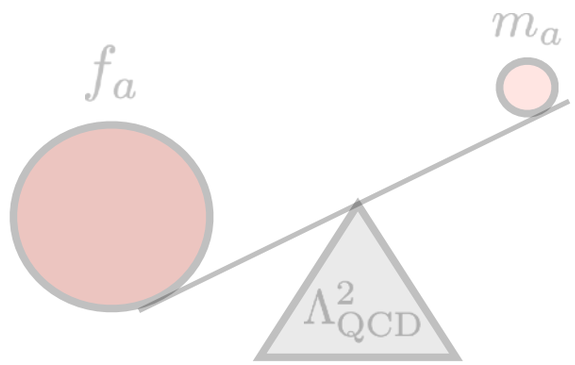

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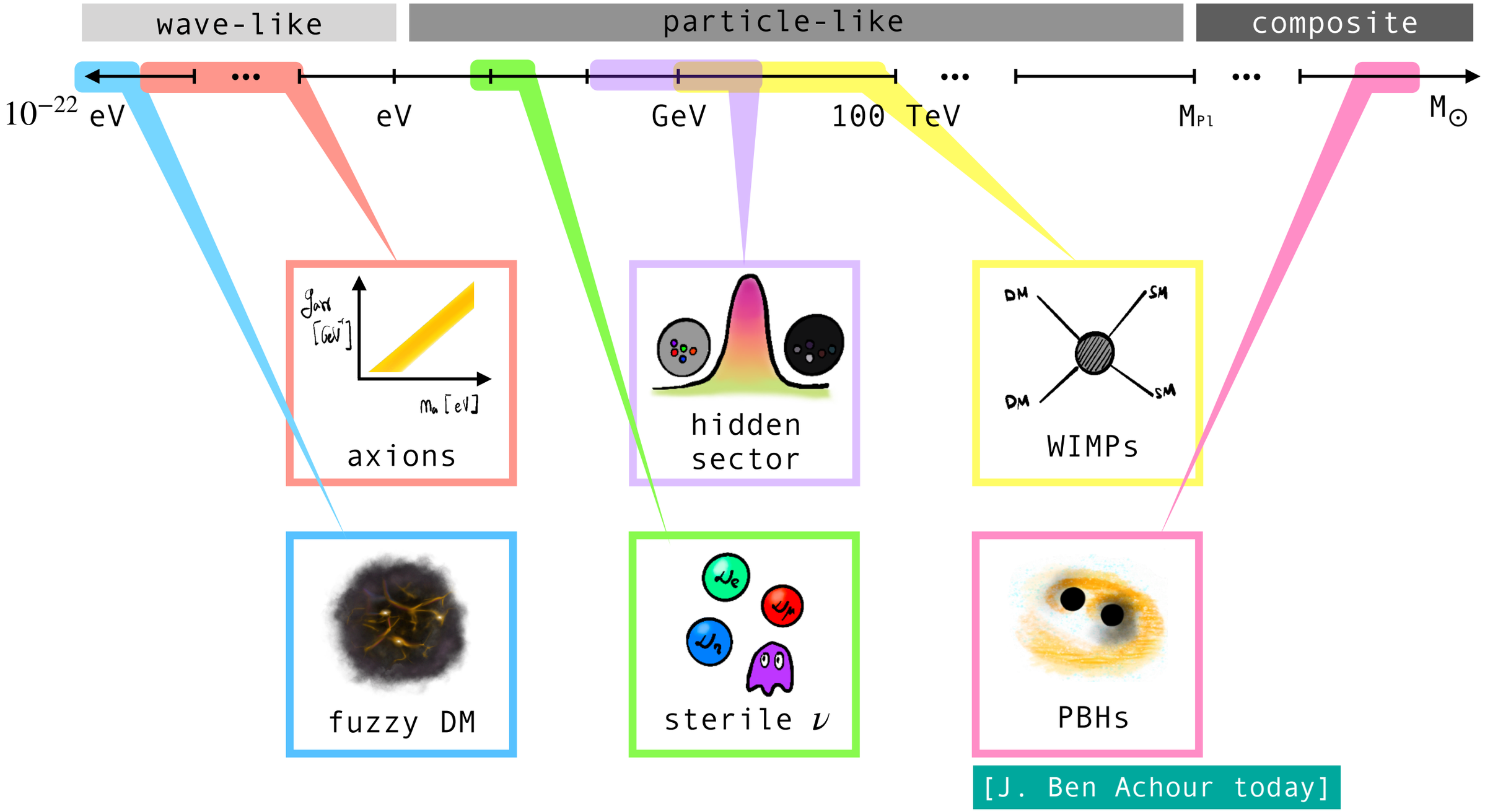
Good dark matter candidate

~~Anomalous global symetry~~

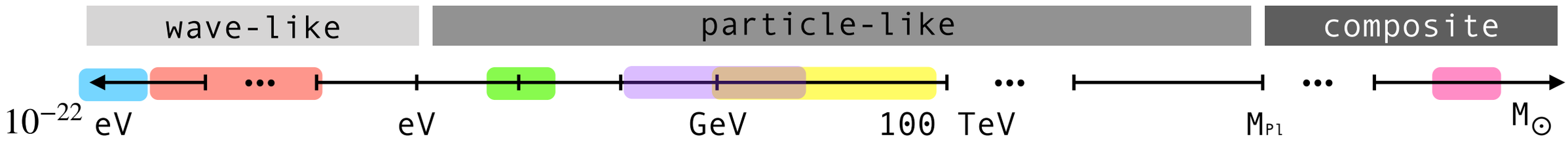
Where do we expect it?

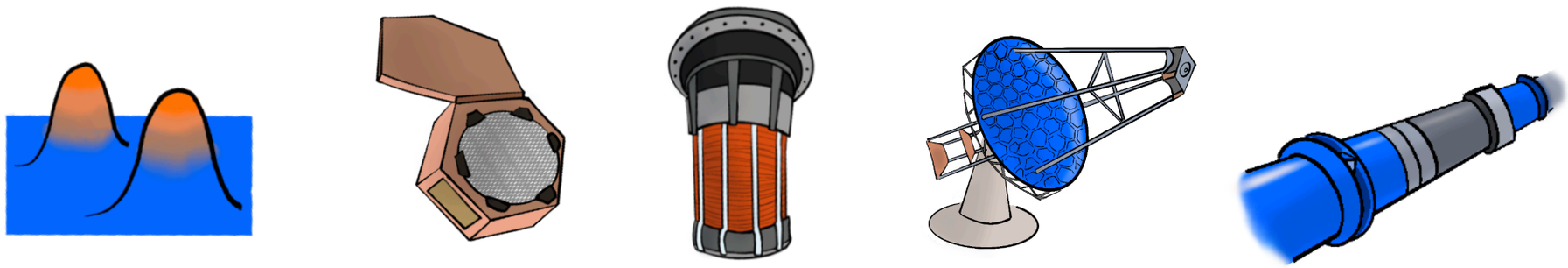
Having a goal



[J. Ben Achour today]

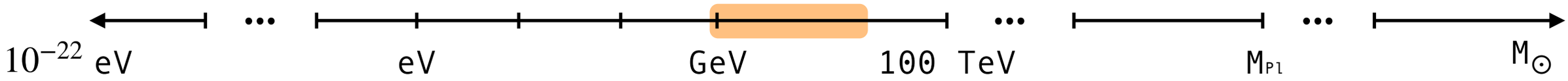
Experimental tools

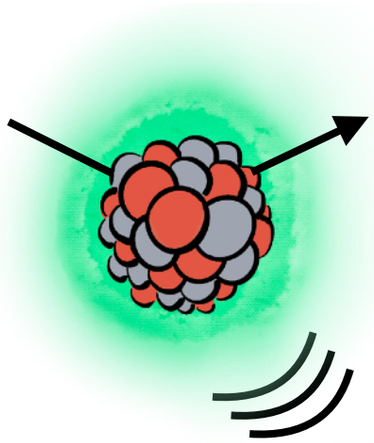




Size

Direct detection





Nuclear recoil
PTM exp.

54 Xe Xenon 131.29	18 Ar Argon 39.9	32 Ge Germanium 72.630

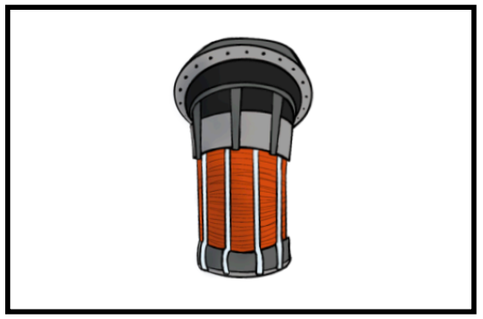
...

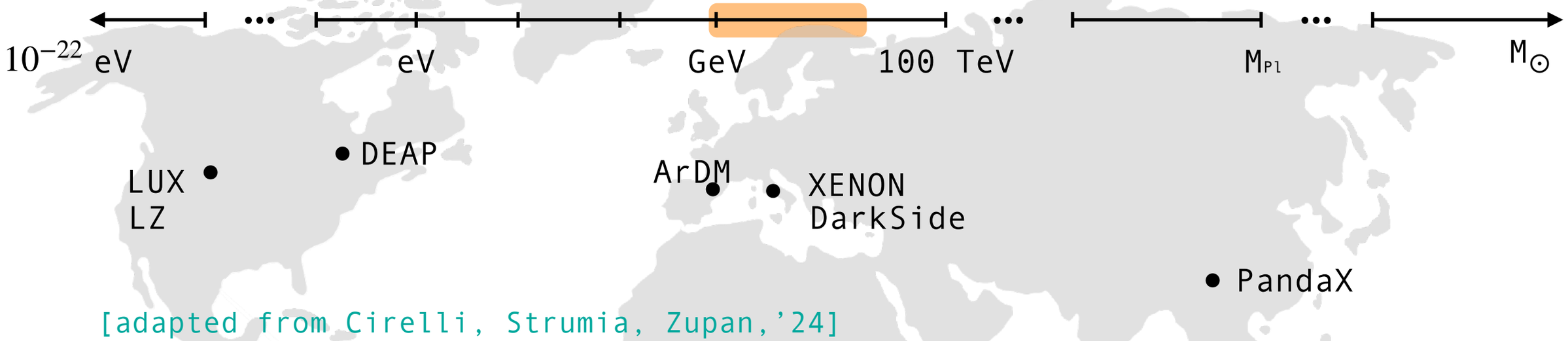
~keV energy resolution

LZ, PandaX, XENON, DarkSide, DEAP…

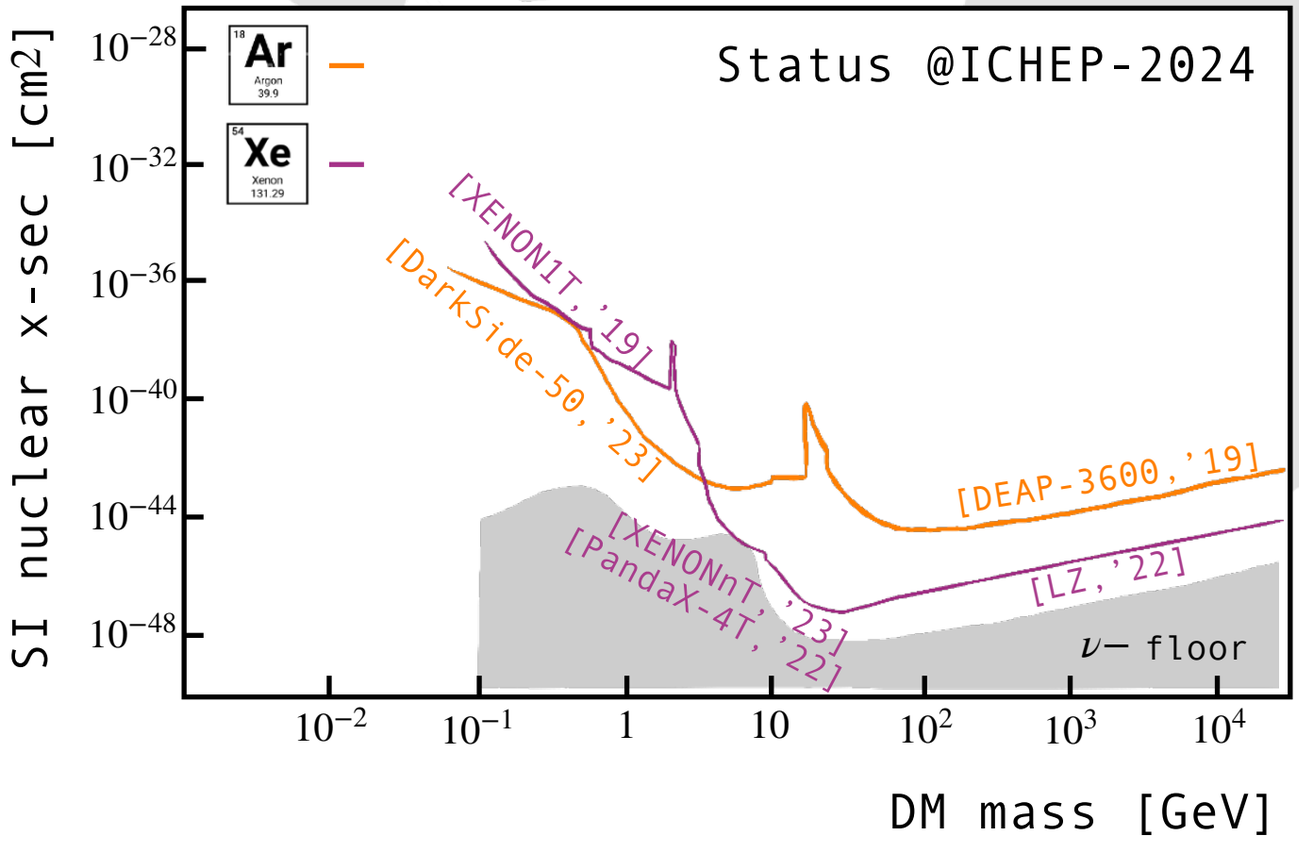
Direct detection

nuclear recoil



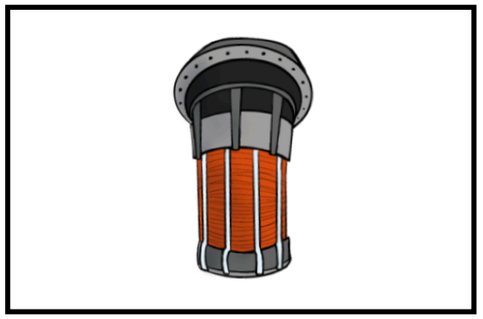


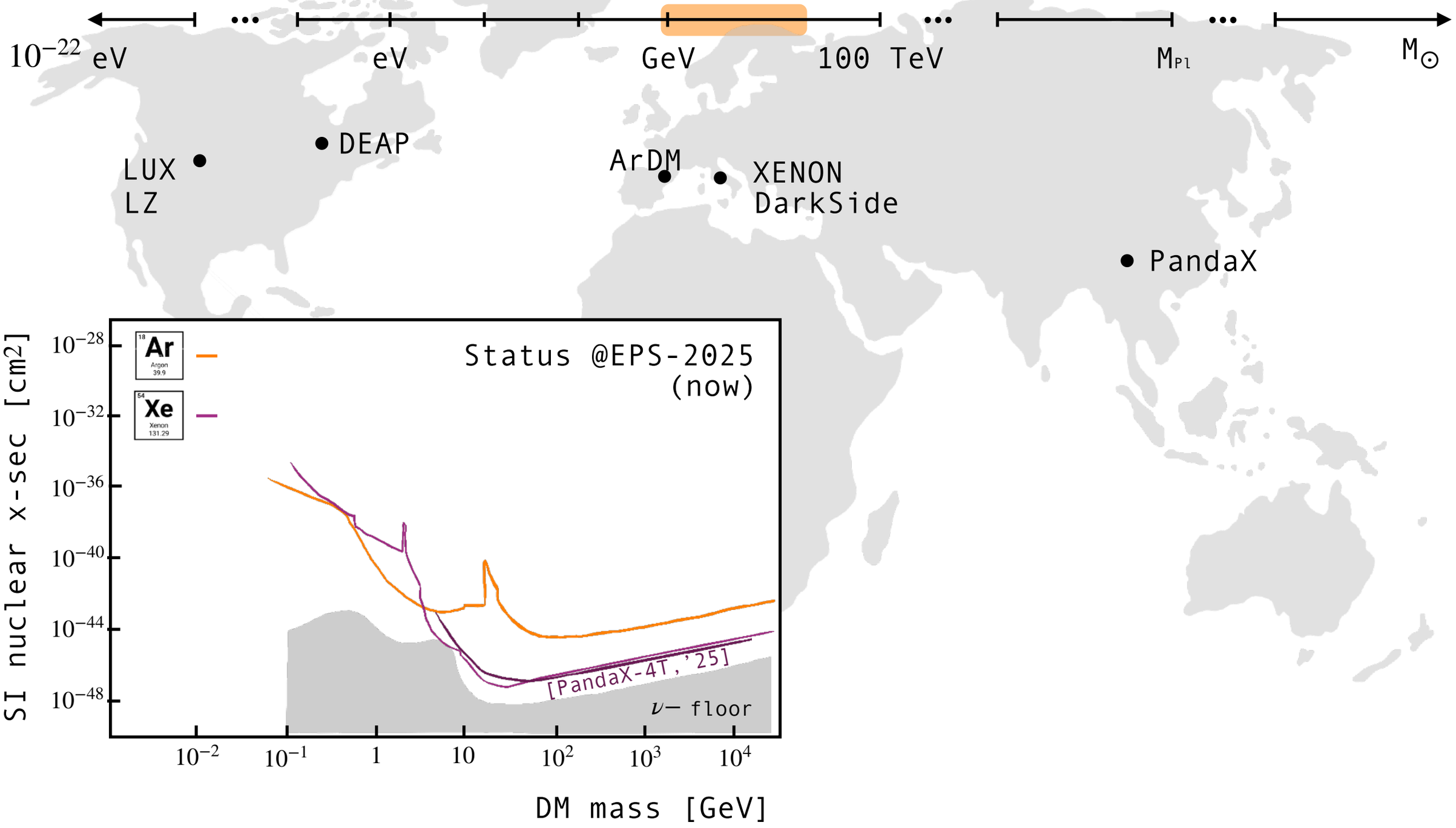
[adapted from Cirelli, Strumia, Zupan,'24]



Direct detection

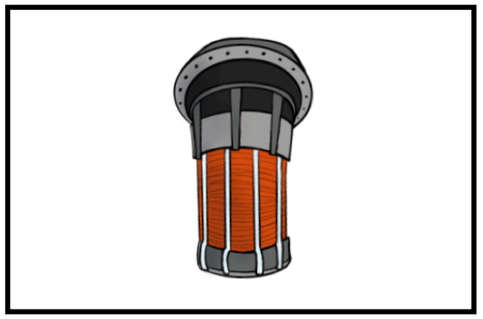
nuclear recoil

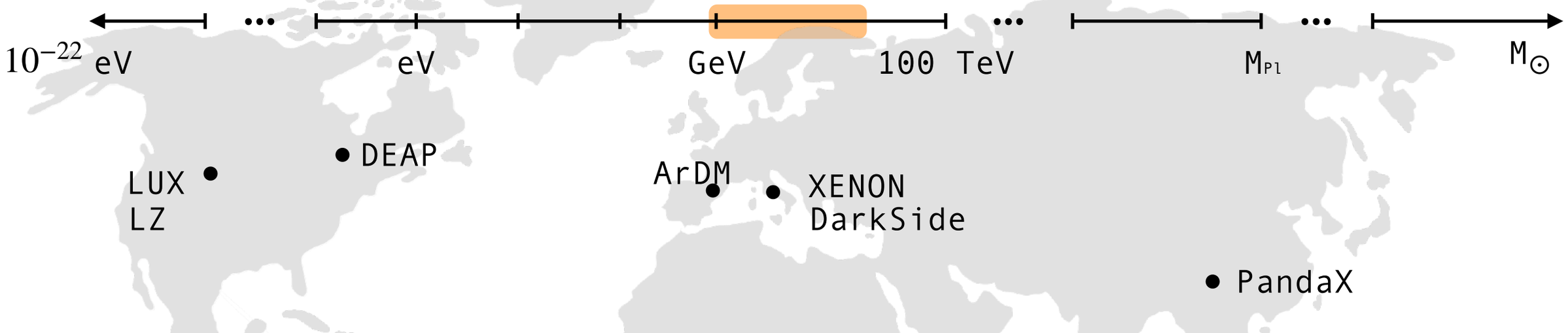


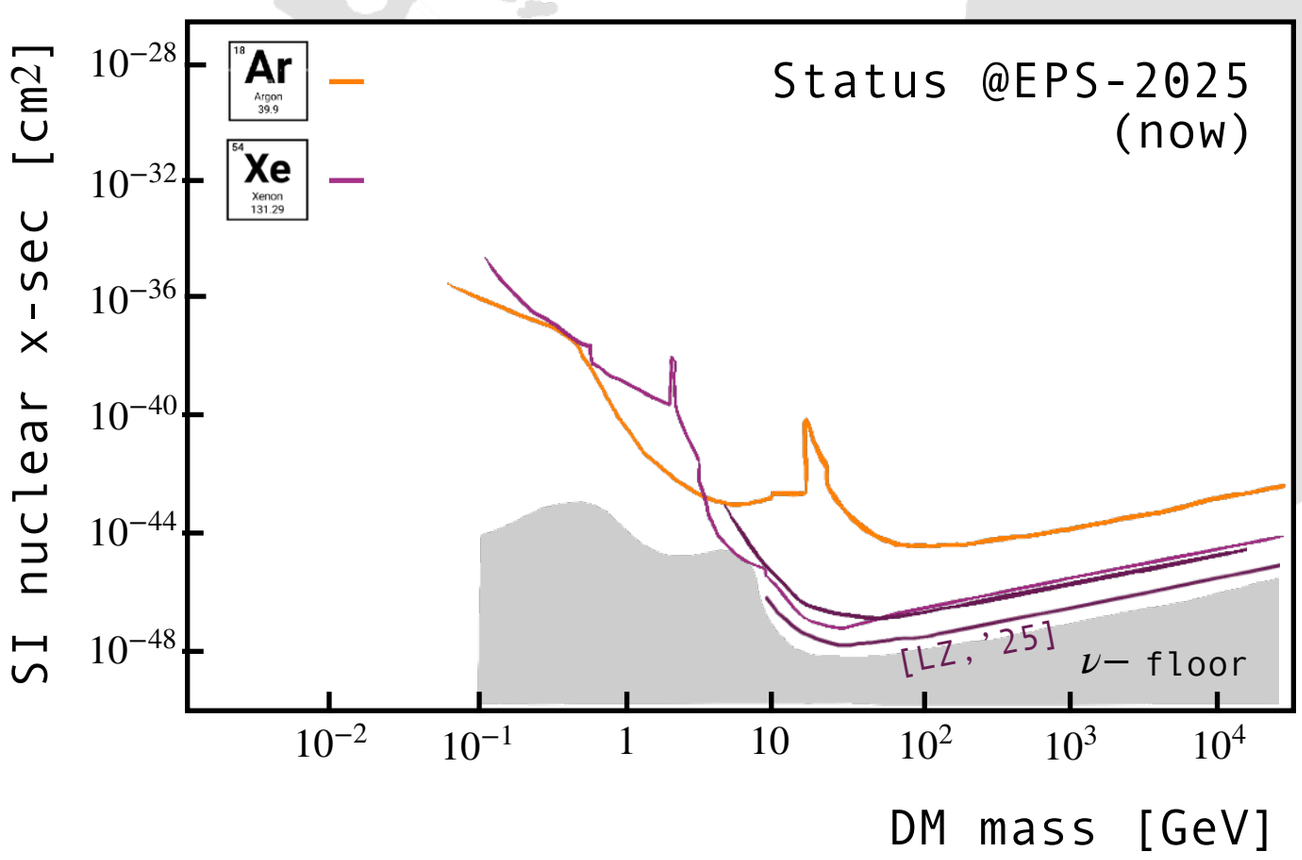


Direct detection

nuclear recoil





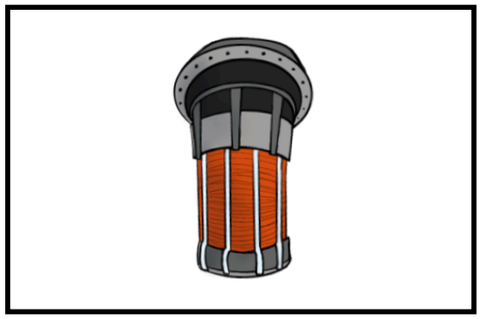


[Y. Xu on Monday]

[A. Cottle on Tuesday]

Direct detection

nuclear recoil



10^{-22} eV ··· eV — GeV — 100 TeV ··· M_{Pl} ··· $M_\odot$

LUX
LZ

DEAP
ARGO

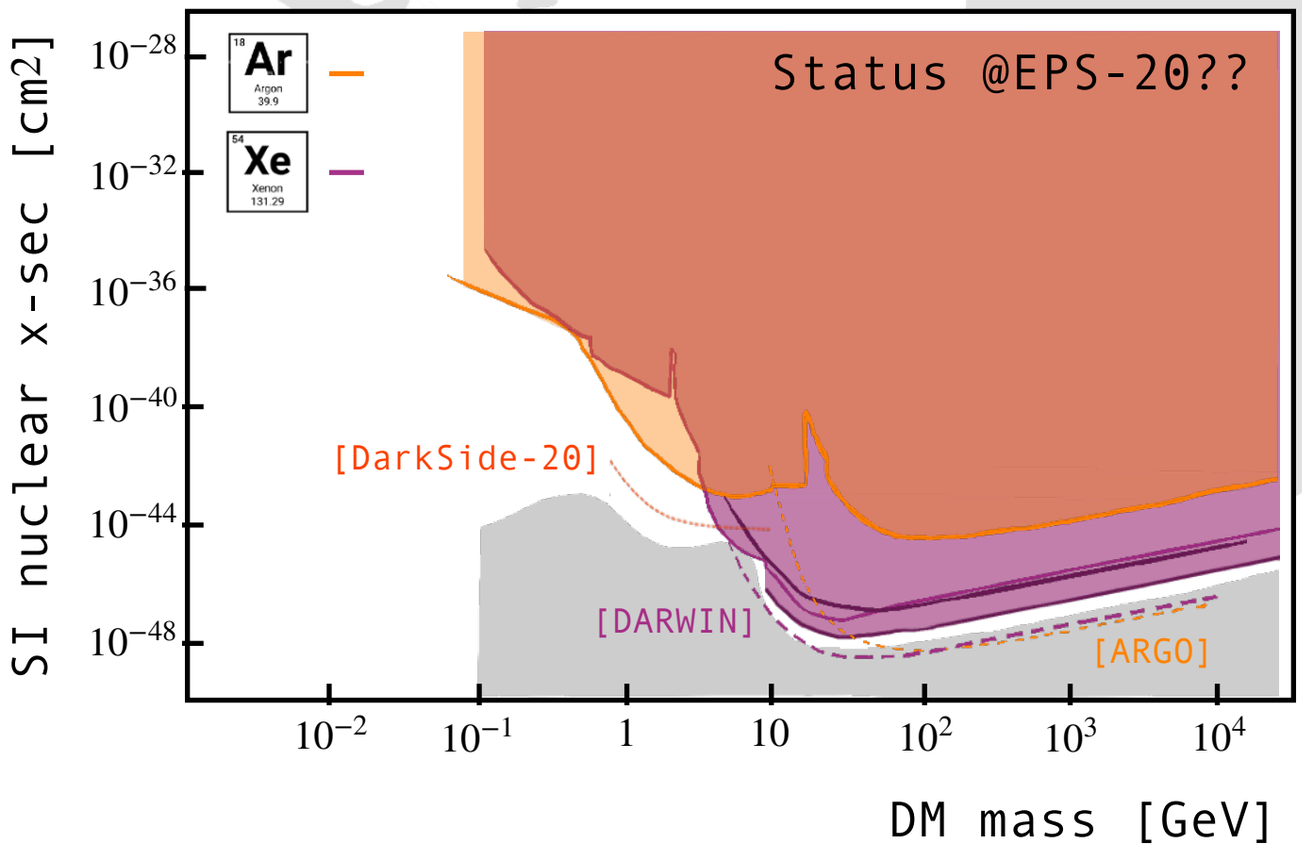
ArDM

XENON
DarkSide-20K

[P. Kunze, Z. Balmforth, on Monday]

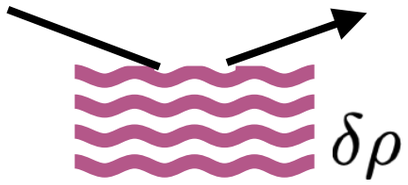
PandaX

DARWIN (XLZD)



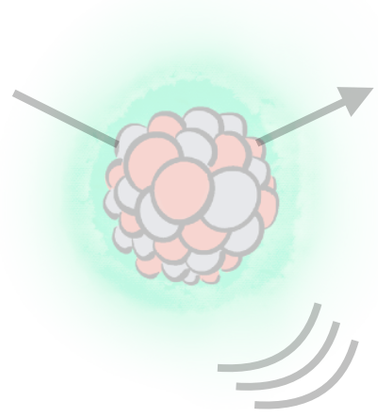
Direct detection

10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$



Collective excitations

~meV energy resolution



Nuclear recoil
PTM exp.

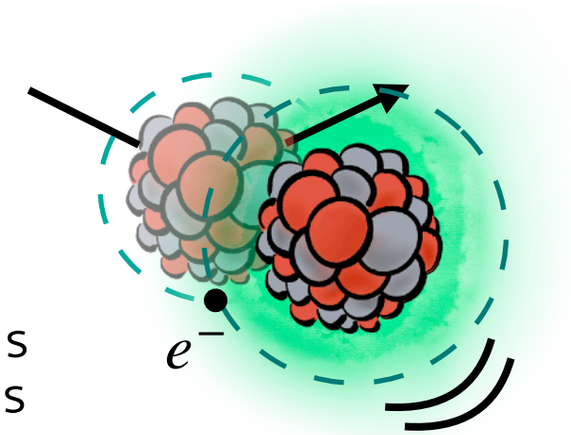
...

~keV energy resolution

LZ, PandaX, XENON, DarkSide, DEAP…

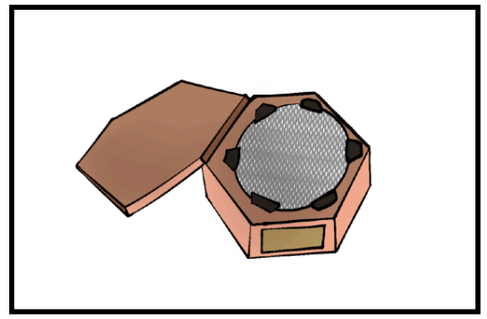
~eV energy resolution

Migdal Effects
Semiconductors



Direct detection

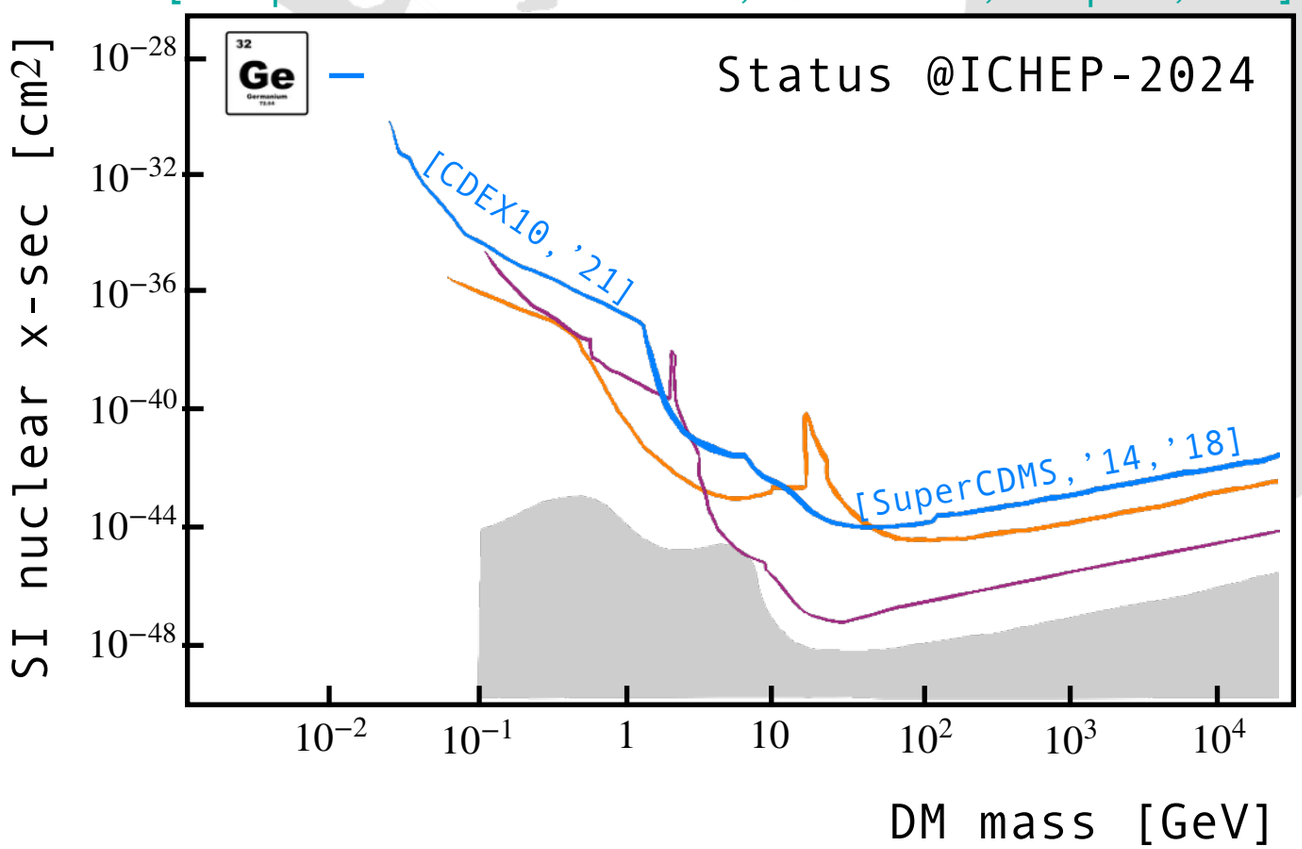
light dark matter



10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$

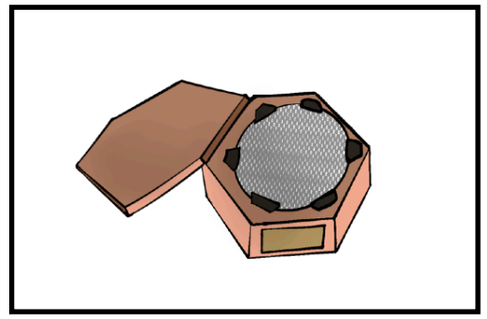
CDMS
DEAP
ARGO
SuperCDMS
LUX
LZ
EDELWEISS
ArDM
XENON
DarkSide-20K
PandaX
CDEX
DARWIN (XLZD)

[adapted from Cirelli, Strumia, Zupan,'24]



Direct detection

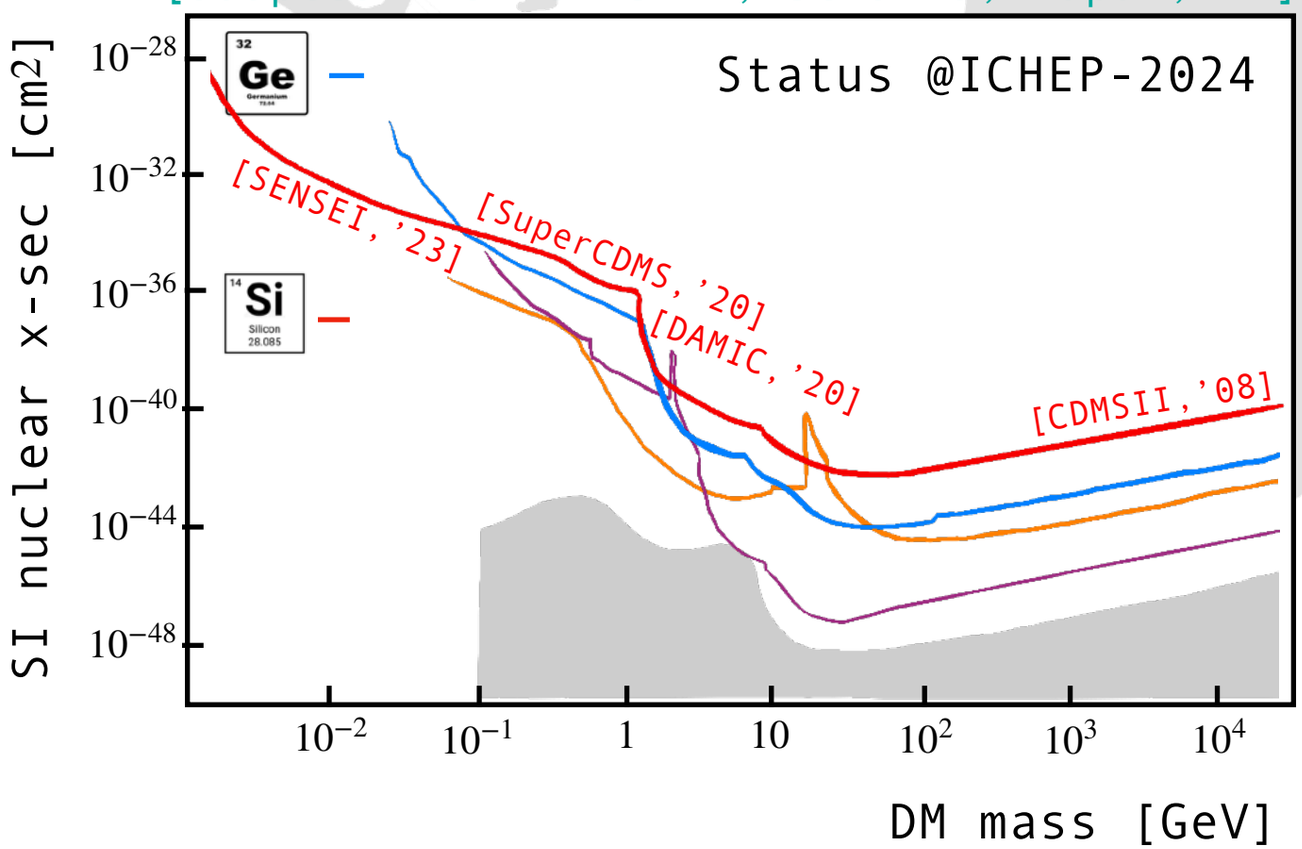
light dark matter



10^{-22} eV ··· eV — GeV — 100 TeV ··· M_{Pl} ··· $M_\odot$

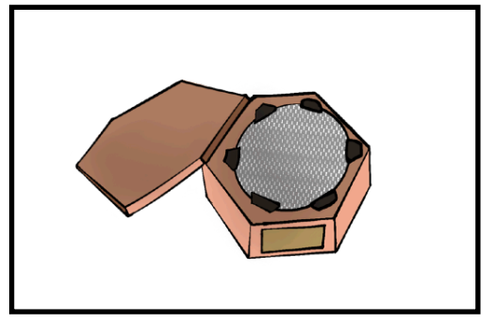
CDMS
DEAP
ARGO
SuperCDMS
SENSEI
DAMIC
LUX
LZ
EDELWEISS
ArDM
XENON
DarkSide-20K
PandaX
CDEX
DARWIN (XLZD)

[adapted from Cirelli, Strumia, Zupan,'24]



Direct detection

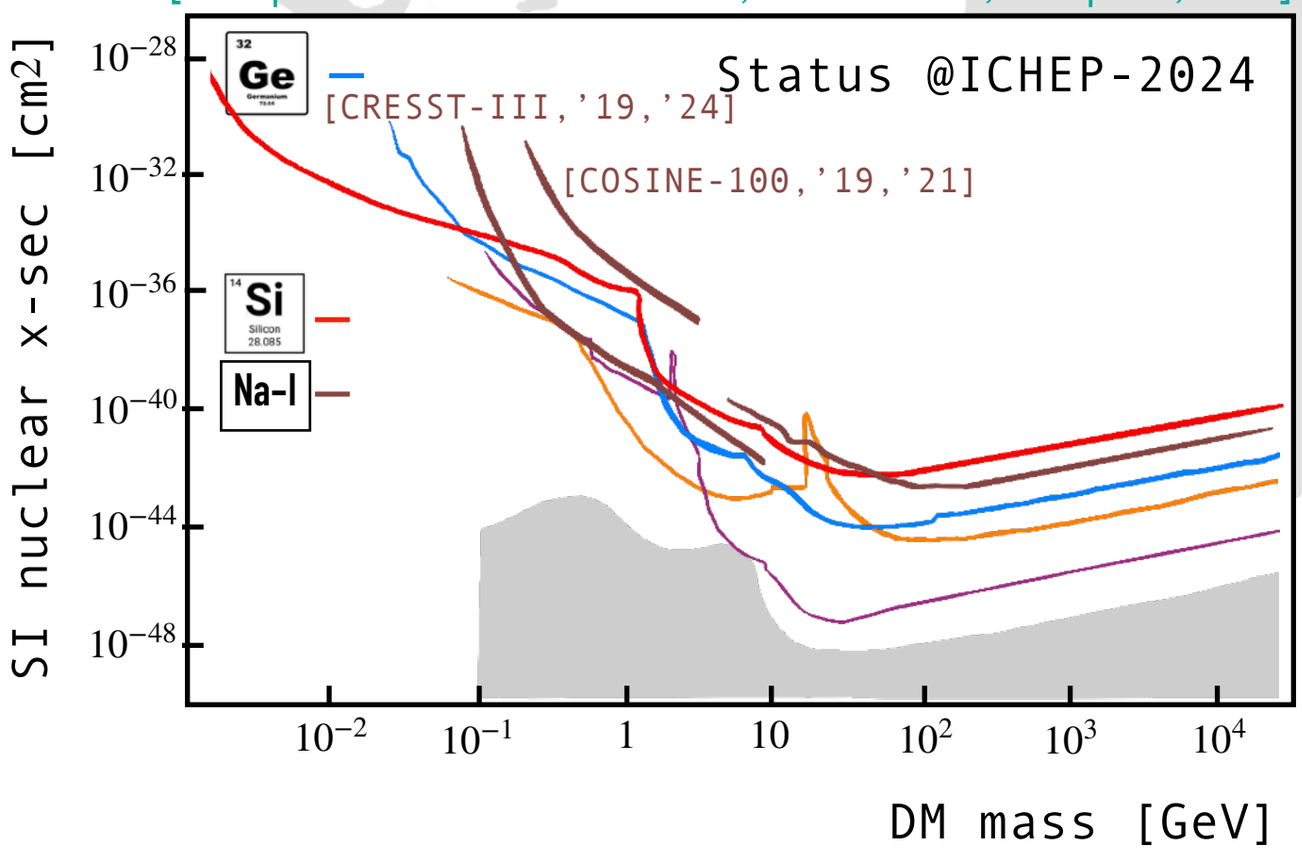
light dark matter



10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$

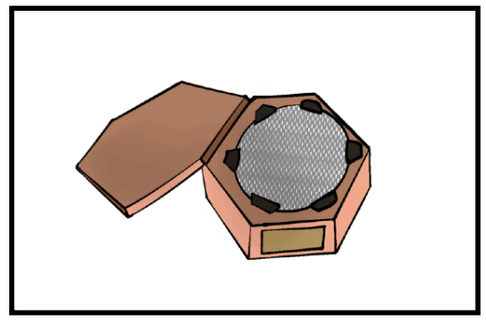
CDMS
DEAP
ARGO
SuperCDMS
SENSEI
DAMIC
LUX
LZ
NEWS-G
[P. Knights tomorrow]
ANAIS
EDELWEISS
ArDM
XENON
DarkSide-20K
CRESST
DAMA/LIBRA
COSINE
PandaX
COSINUS
CDEX
DARWIN (XLZD)

[adapted from Cirelli, Strumia, Zupan,'24]



Direct detection

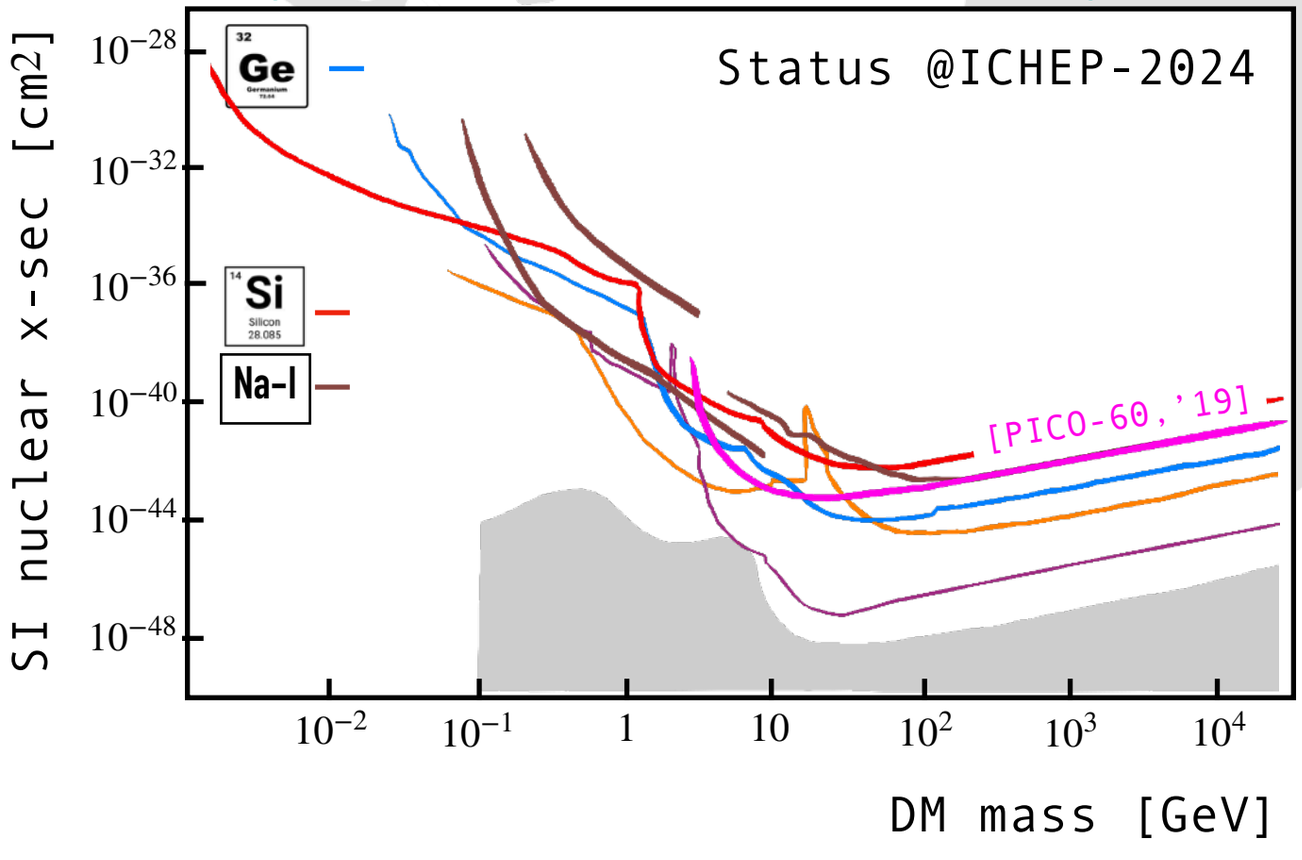
light dark matter



10^{-22} eV ··· eV ··· GeV ··· 100 TeV ··· M_{Pl} ··· $M_\odot$

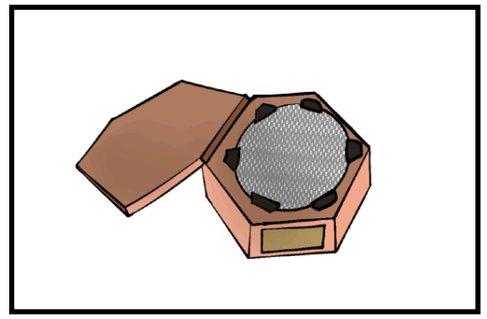
CDMS
DEAP
ARGO
SuperCDMS
SENSEI
DAMIC
Pico
LUX
LZ
NEWS-G
ANAIS
EDELWEISS
ArDM
XENON
DarkSide-20K
CRESST
DAMA/LIBRA
COSINUS
COSINE
PandaX
CDEX
DARWIN (XLZD)

[adapted from Cirelli, Strumia, Zupan,'24]



Direct detection

light dark matter



10^{-22} eV ... eV ... GeV ... 100 TeV ... M_{Pl} ... $M_\odot$

CDMS
DEAP
ARGO
SuperCDMS
SENSEI
DAMIC
Pico

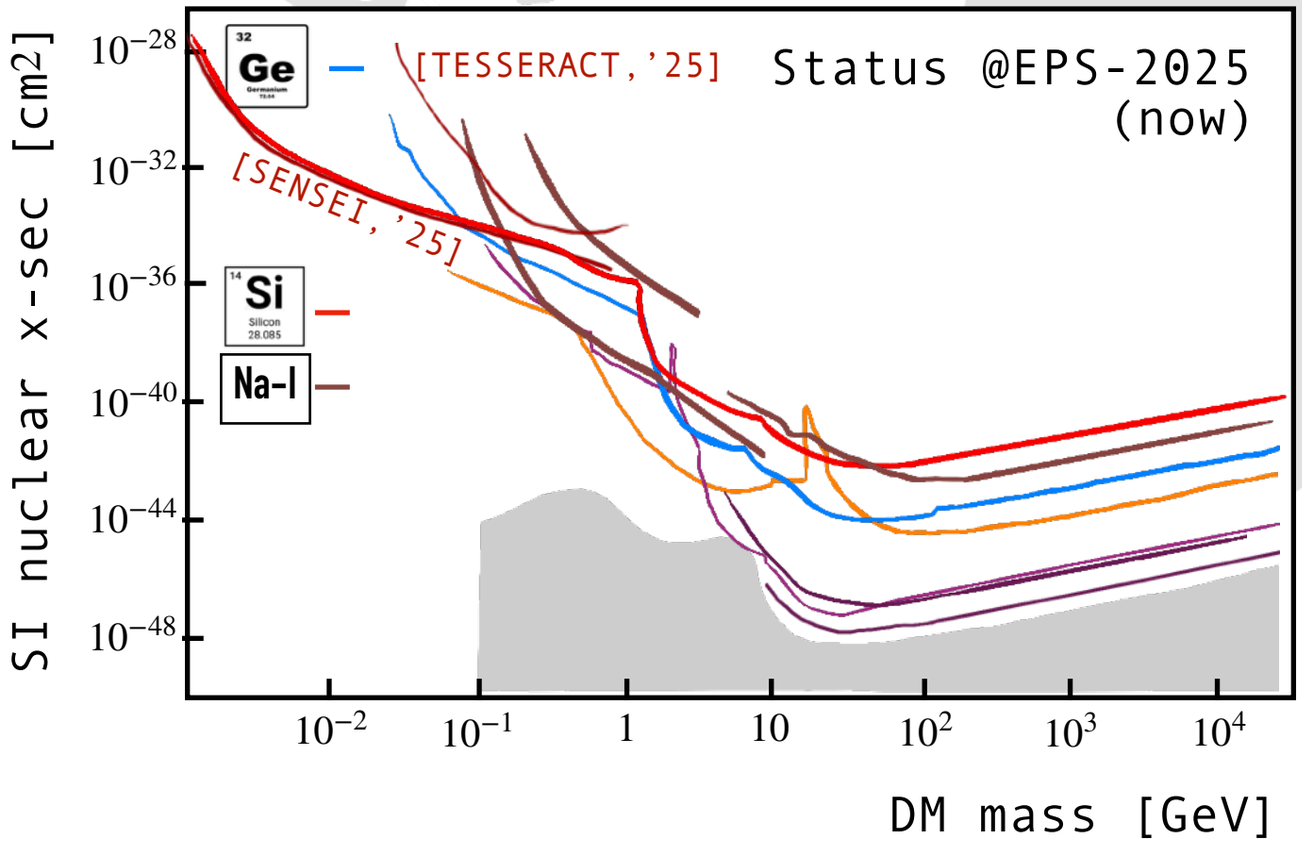
LUX
LZ
TESSERACT

NEWS-G
ANAIS
EDELWEISS
ArDM
XENON
DarkSide-20K
CRESST
DAMA/LIBRA
COSINUS

COSINE

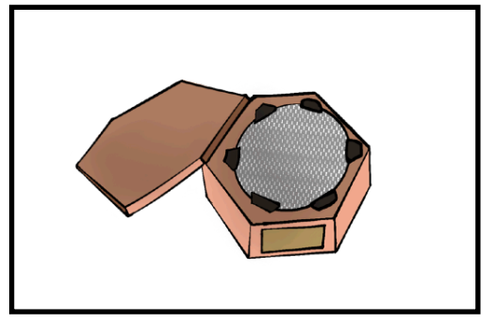
PandaX
CDEX

DARWIN (XLZD)



Direct detection

light dark matter



10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$

CDMS
OSCURA
DEAP
ARGO
SuperCDMS
SENSEI
DAMIC
Pico

LUX
LZ
TESSERACT

NEWS-G
ANAIS
EDELWEISS
ArDM
EURECA
XENON
DarkSide-20K
CRESST
DAMA/LIBRA
COSINUS

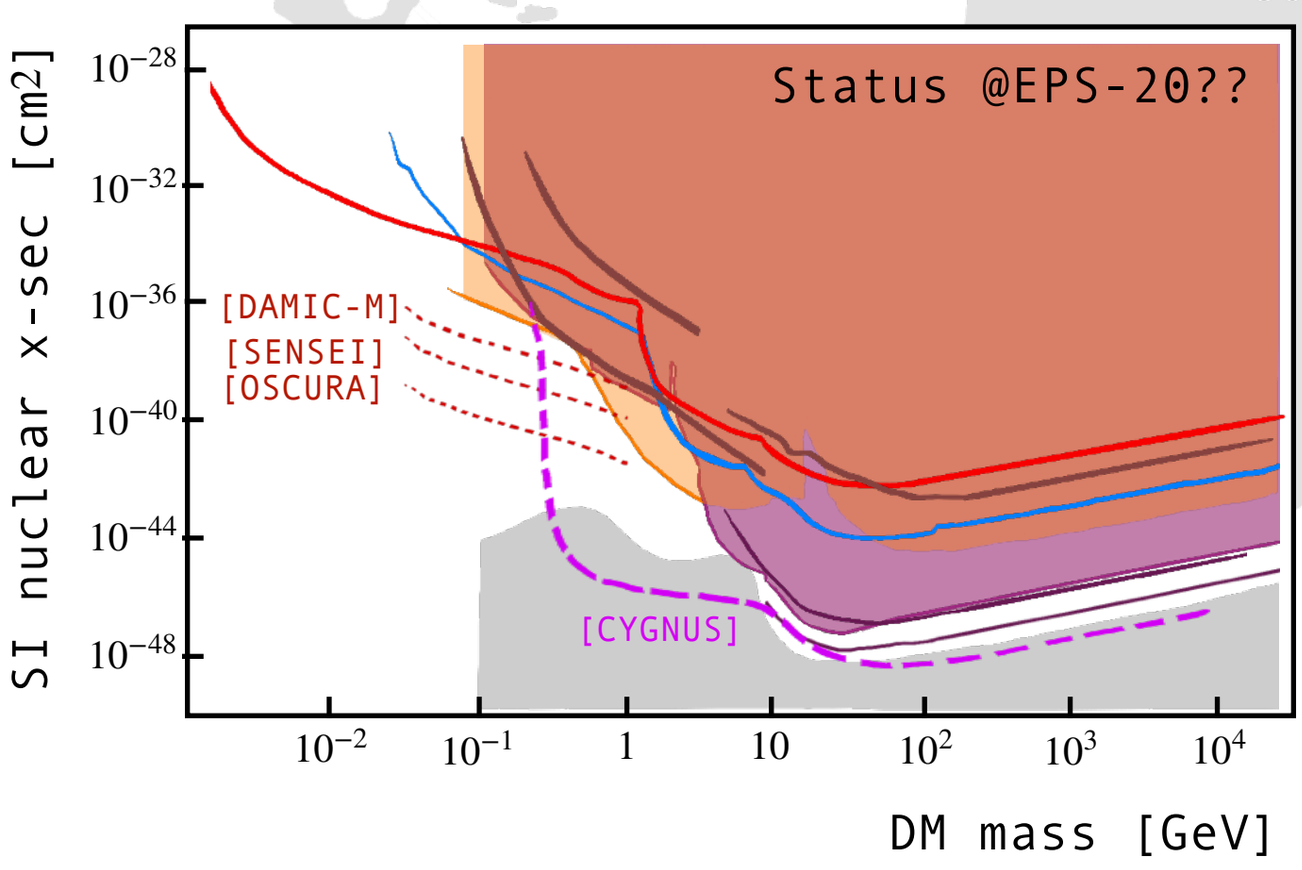
COSINE

PandaX
CDEX

CYGNO
[D. Fiorina tomorrow]

[K. Rule tomorrow]
SABRE

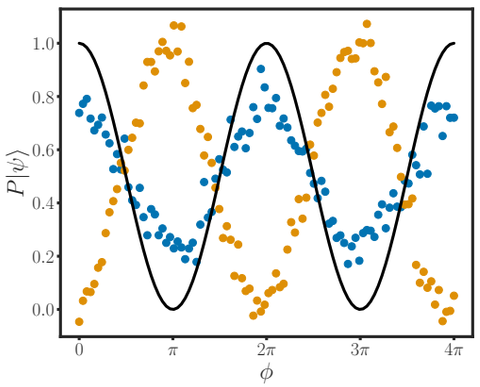
CYGNUS
DARWIN (XLZD)



Direct detection

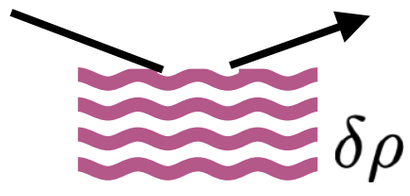
Accelerated DM [L. Maneti on Tue]

10^{-22} eV ••• eV GeV 100 TeV ••• M_{Pl} ••• $M_\odot$



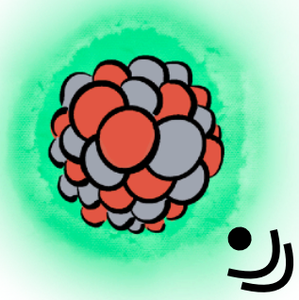
Atom interferometers

nearly thresholdless



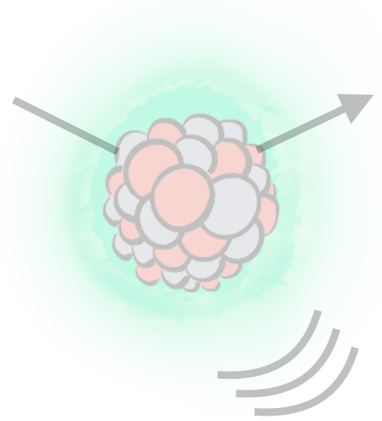
Collective excitations

~meV energy resolution



~eV energy resolution

Electron recoils
Migdal Effects
Semiconductors



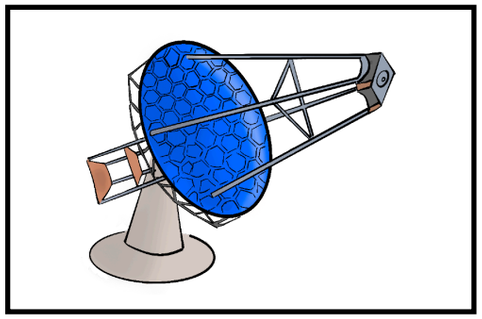
Nuclear recoil
PTM exp.

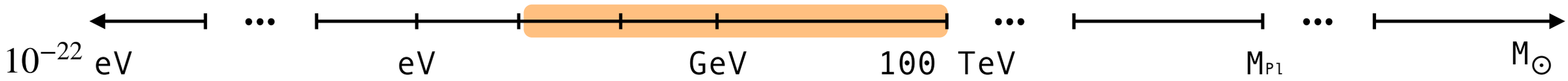
...

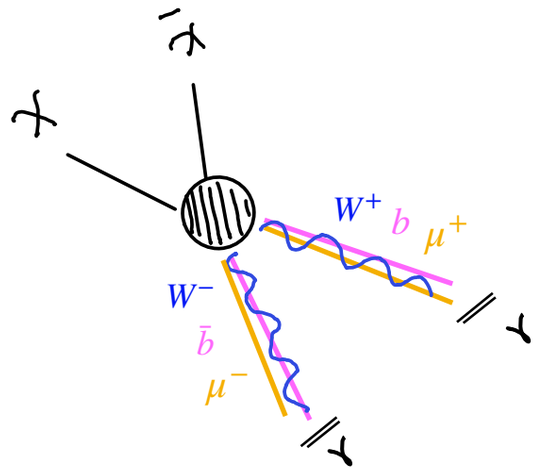
~keV energy resolution

LZ, PandaX, XENON, DarkSide, DEAP…

Indirect detection



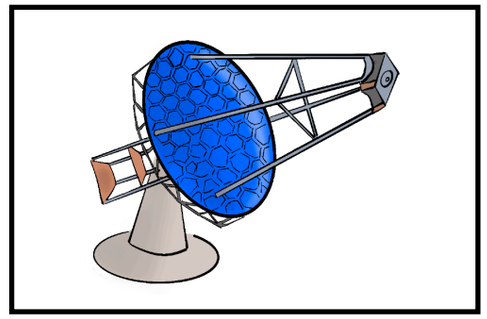


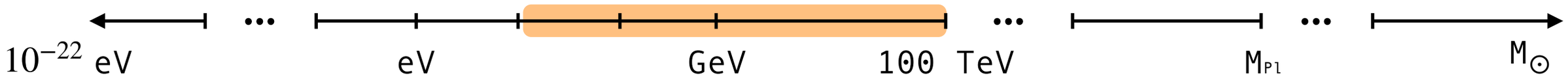


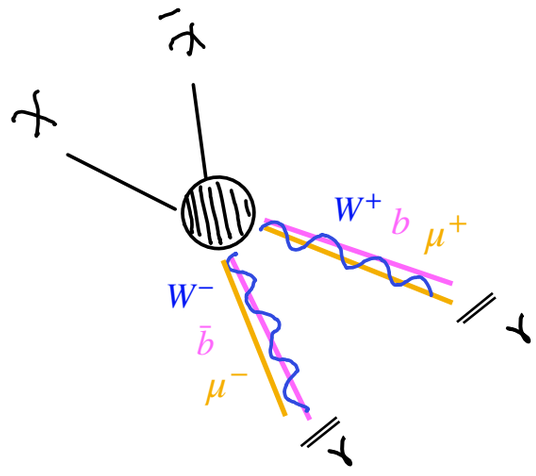
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \text{(geo factor)}\, P(E) \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

[F. Bradascio on Mon]

Indirect detection

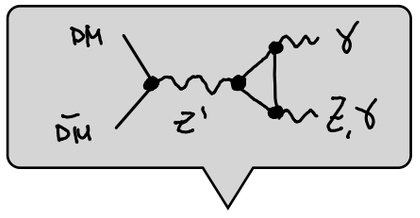




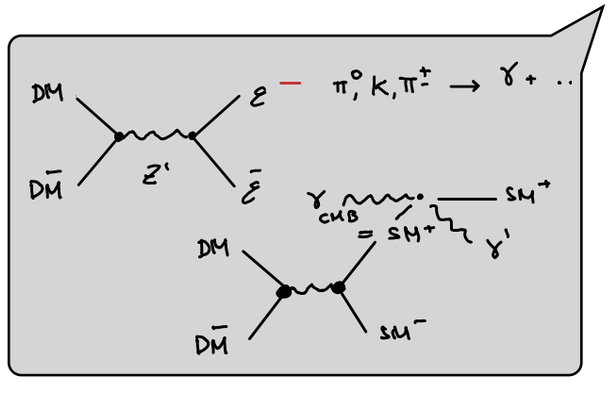


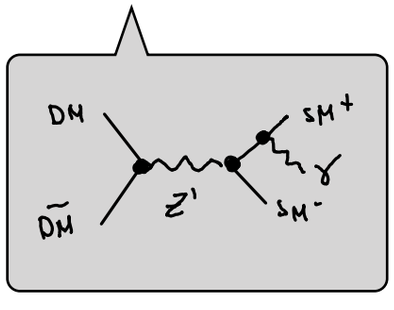
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \text{(geo factor)}\, P(E) \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

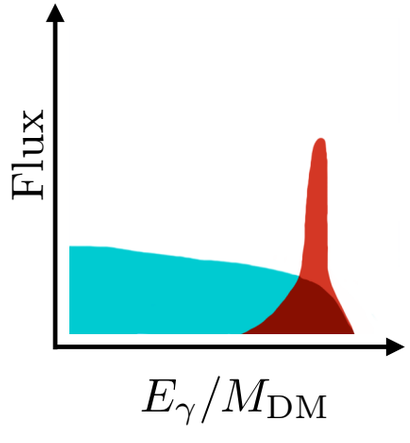
[F. Bradascio on Mon]



$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E} = \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\gamma\gamma} + \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\text{sec}} + \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\text{FSR}}$$

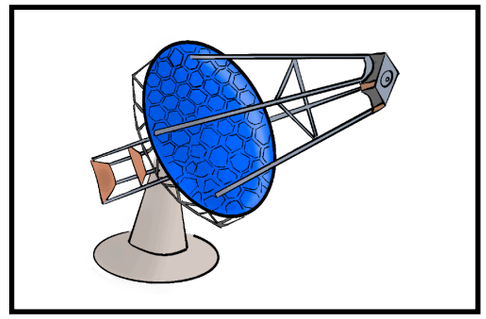


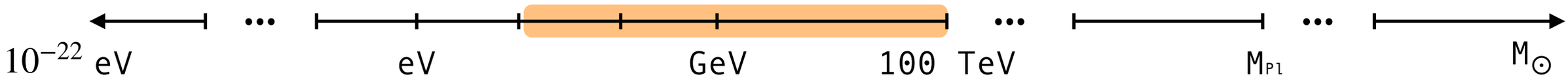


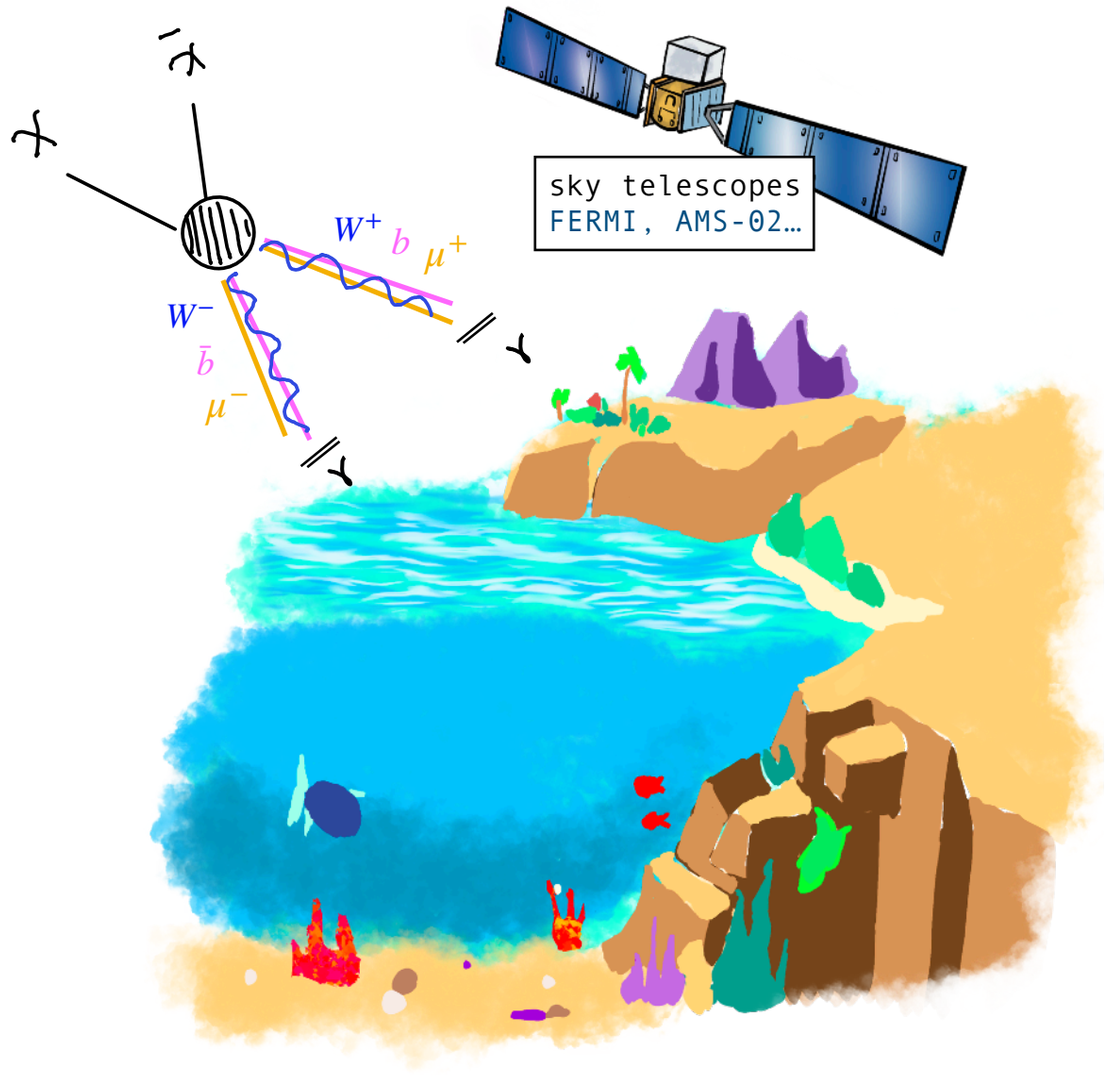


SM background under control!

Indirect detection

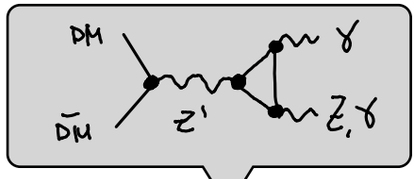




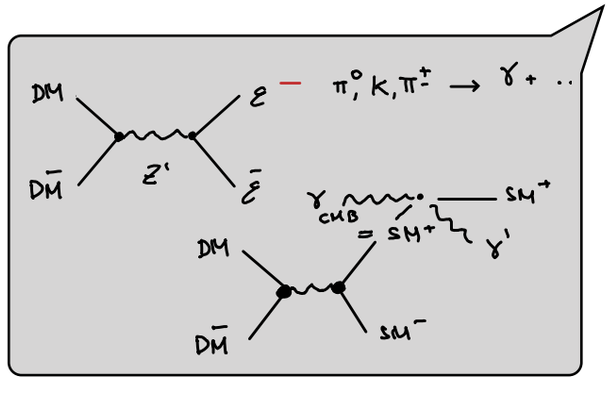


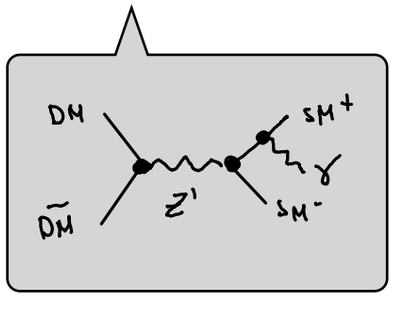
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \text{(geo factor)}\, P(E) \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

[F. Bradascio on Mon]

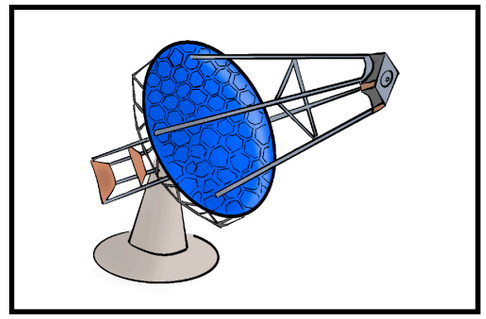


$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E} = \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\gamma\gamma} + \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{sec}} + \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{FSR}}$$

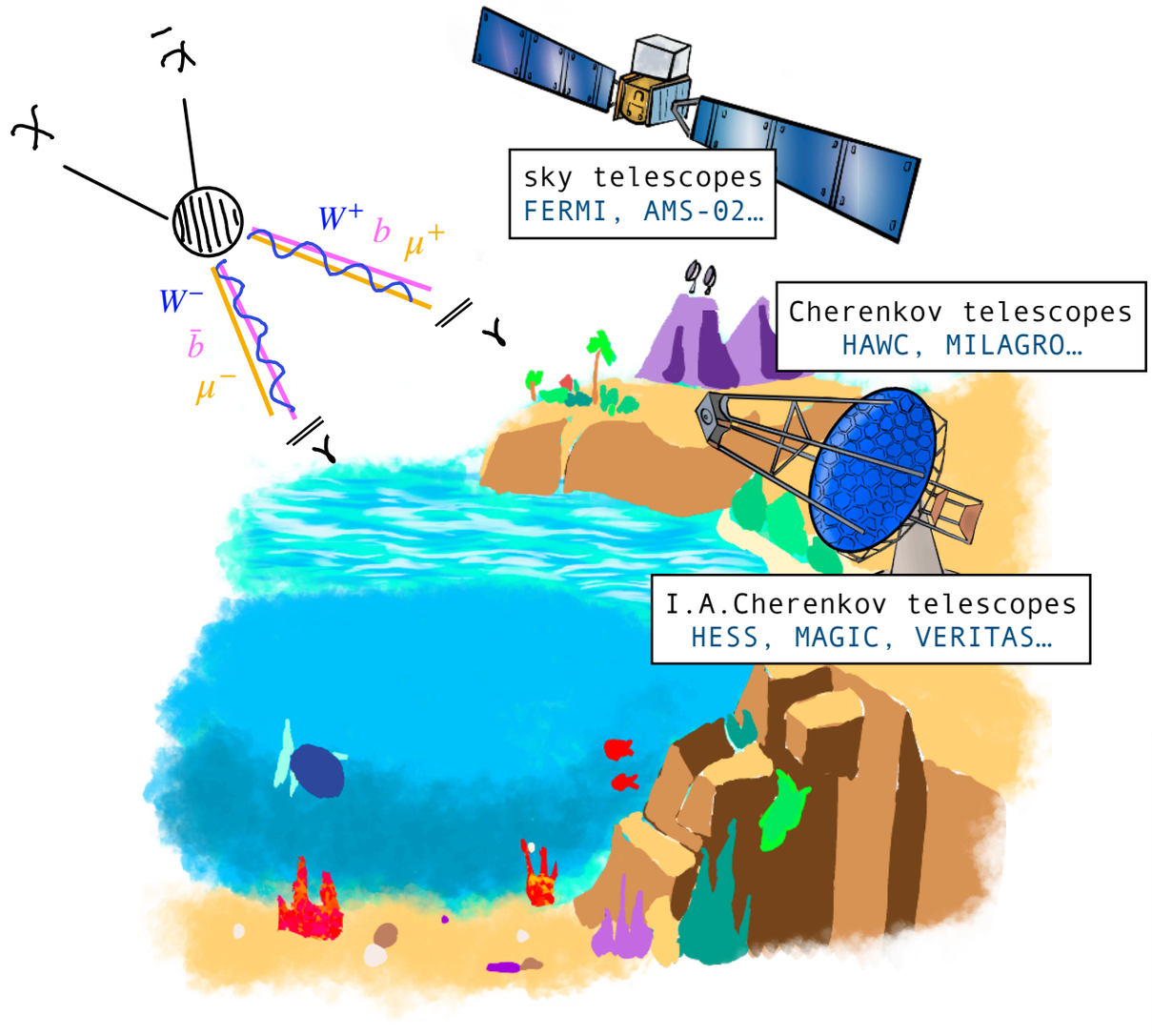




Indirect detection

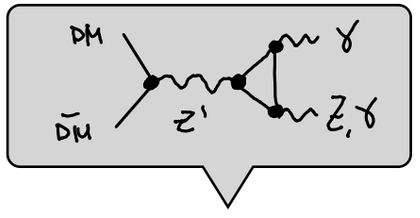


10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$

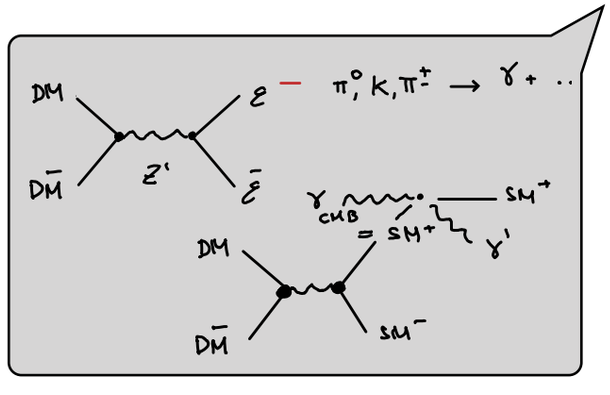


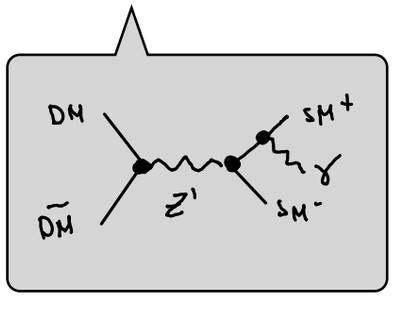
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \text{(geo factor)}\, P(E) \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

[F. Bradascio on Mon]

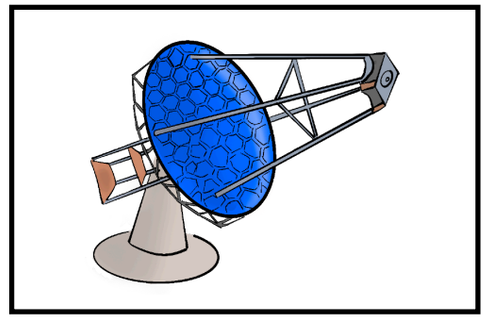


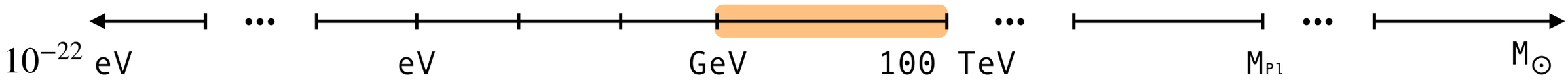
$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E} = \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\gamma\gamma} + \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{sec}} + \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{FSR}}$$



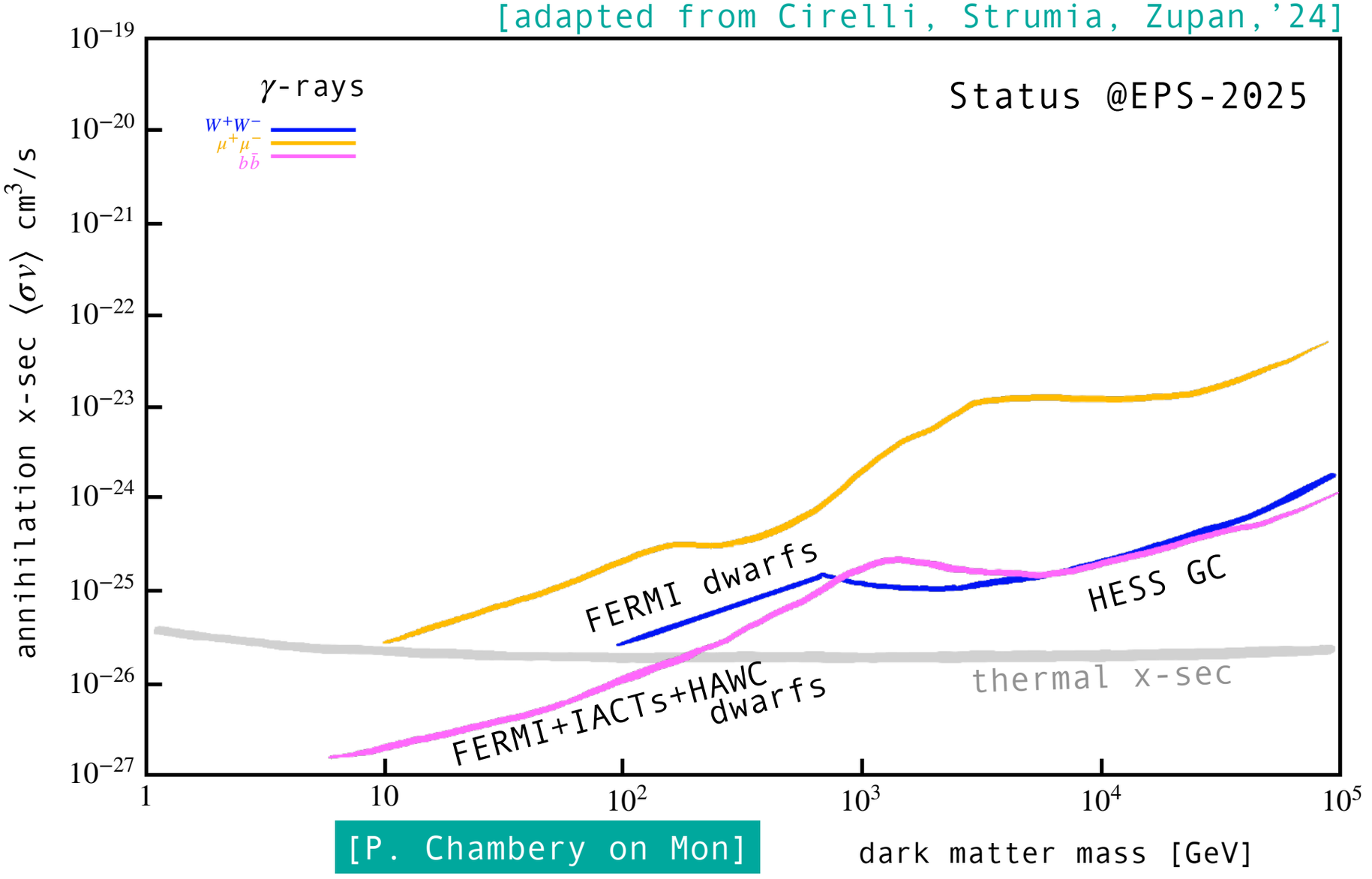


Indirect detection



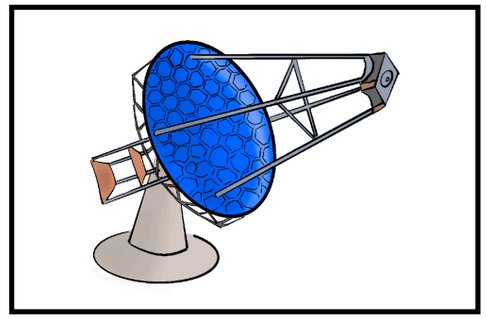


[adapted from Cirelli, Strumia, Zupan,'24]

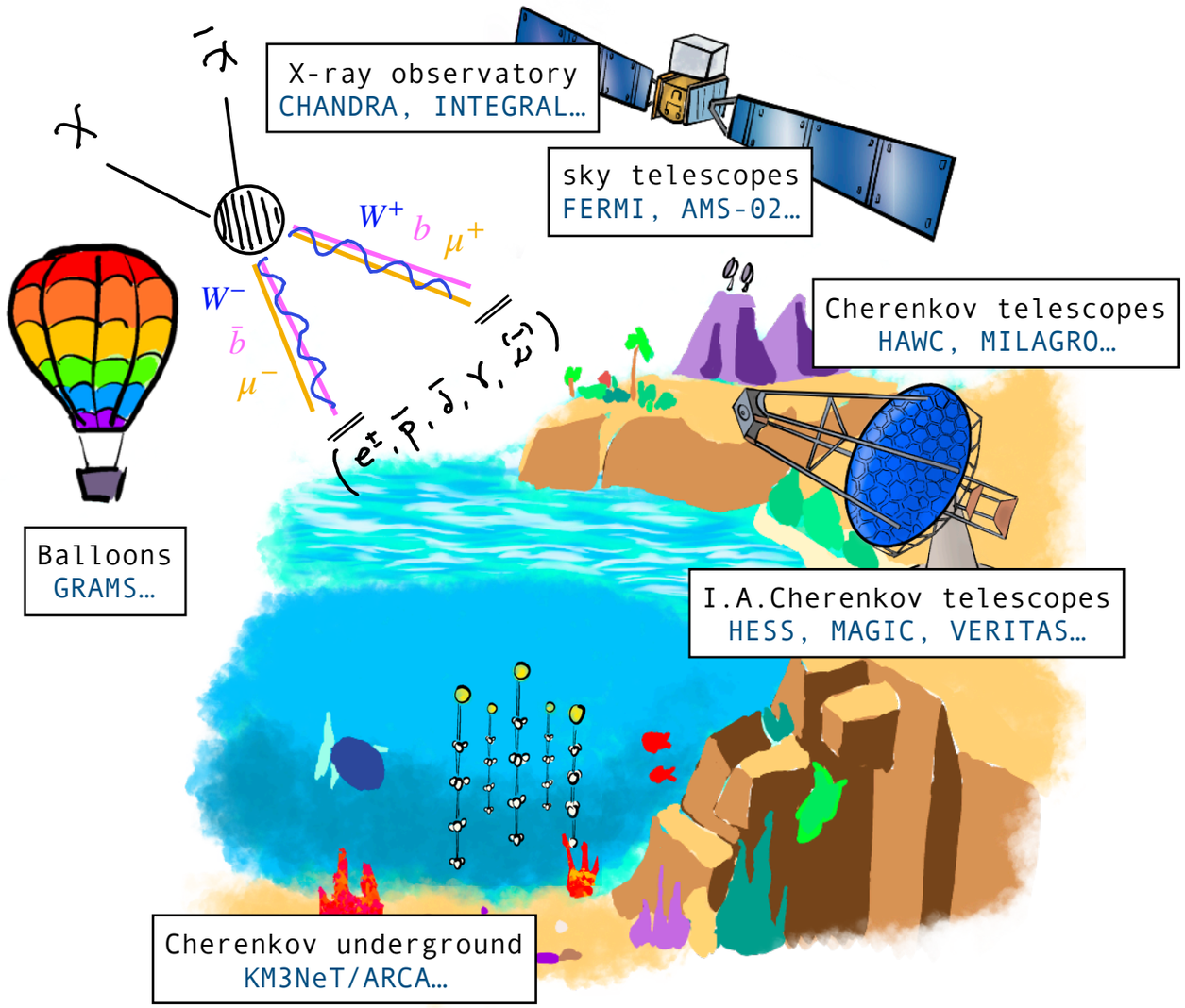


[P. Chambery on Mon]

Indirect detection



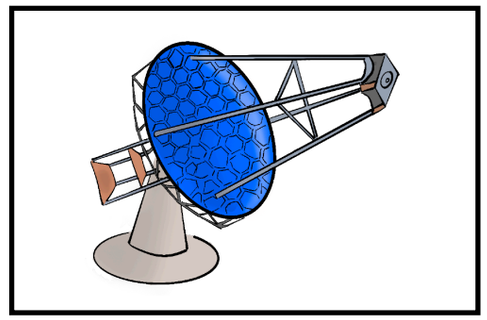
10^{-22} eV ••• eV GeV 100 TeV ••• M_{Pl} ••• $M_\odot$

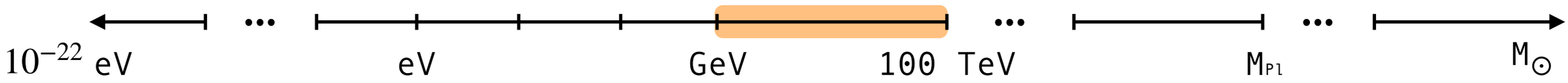


$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \text{(geo factor)}\, P(E) \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_{\mathrm{obj}}}{\mathrm{d}E}$$

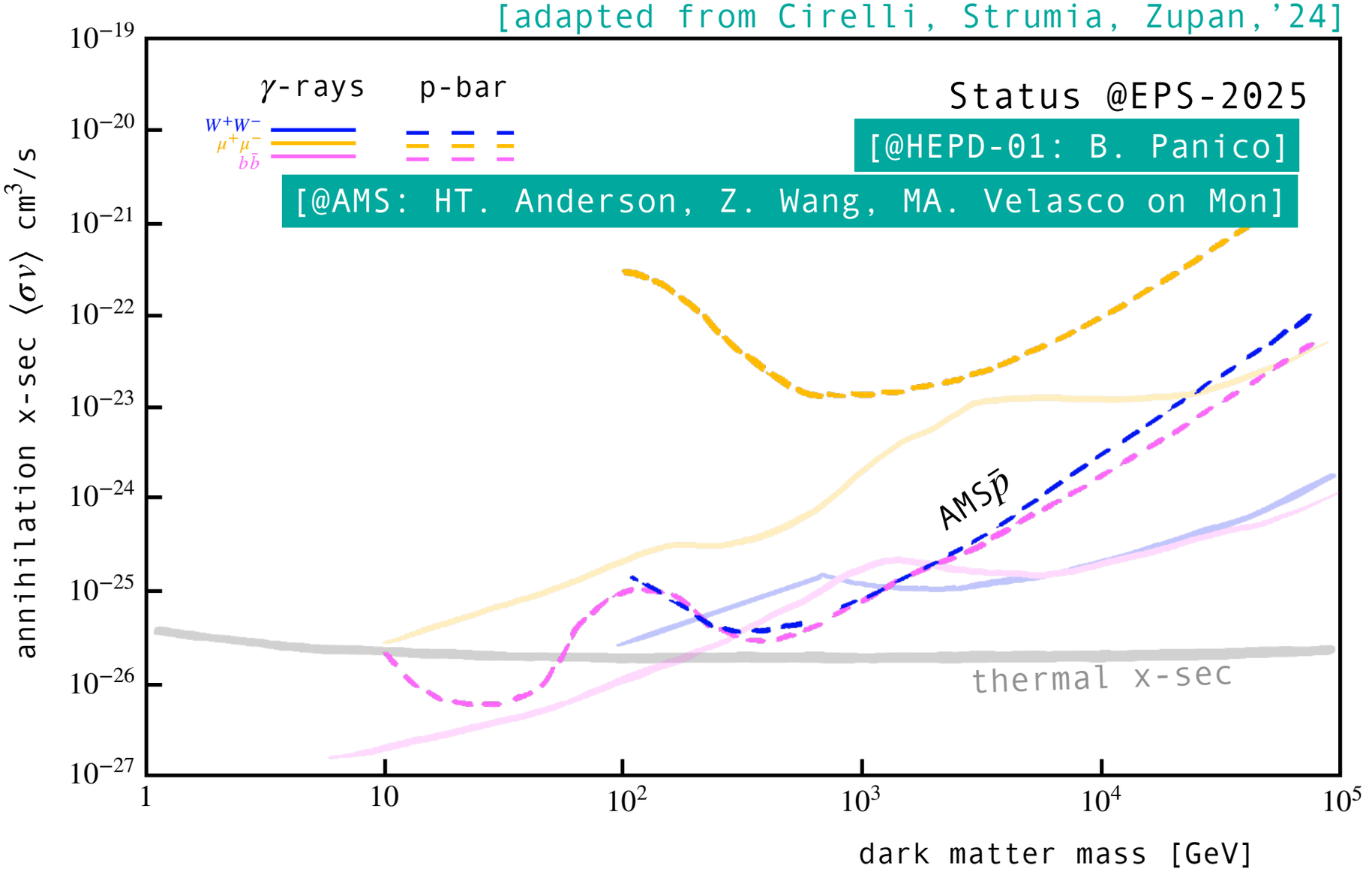
[A. Romanov on Mon]

Indirect detection

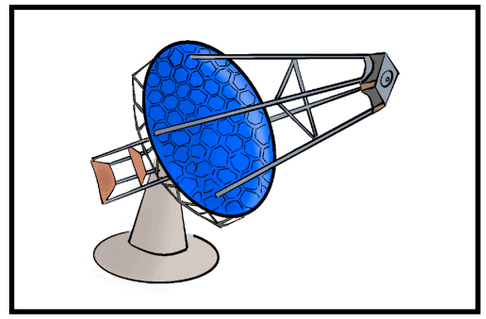


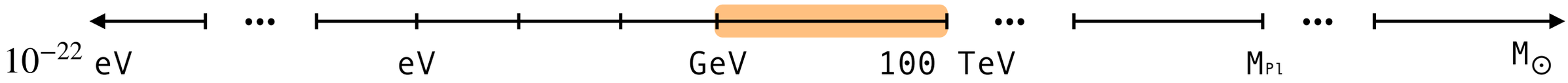


[adapted from Cirelli, Strumia, Zupan,'24]

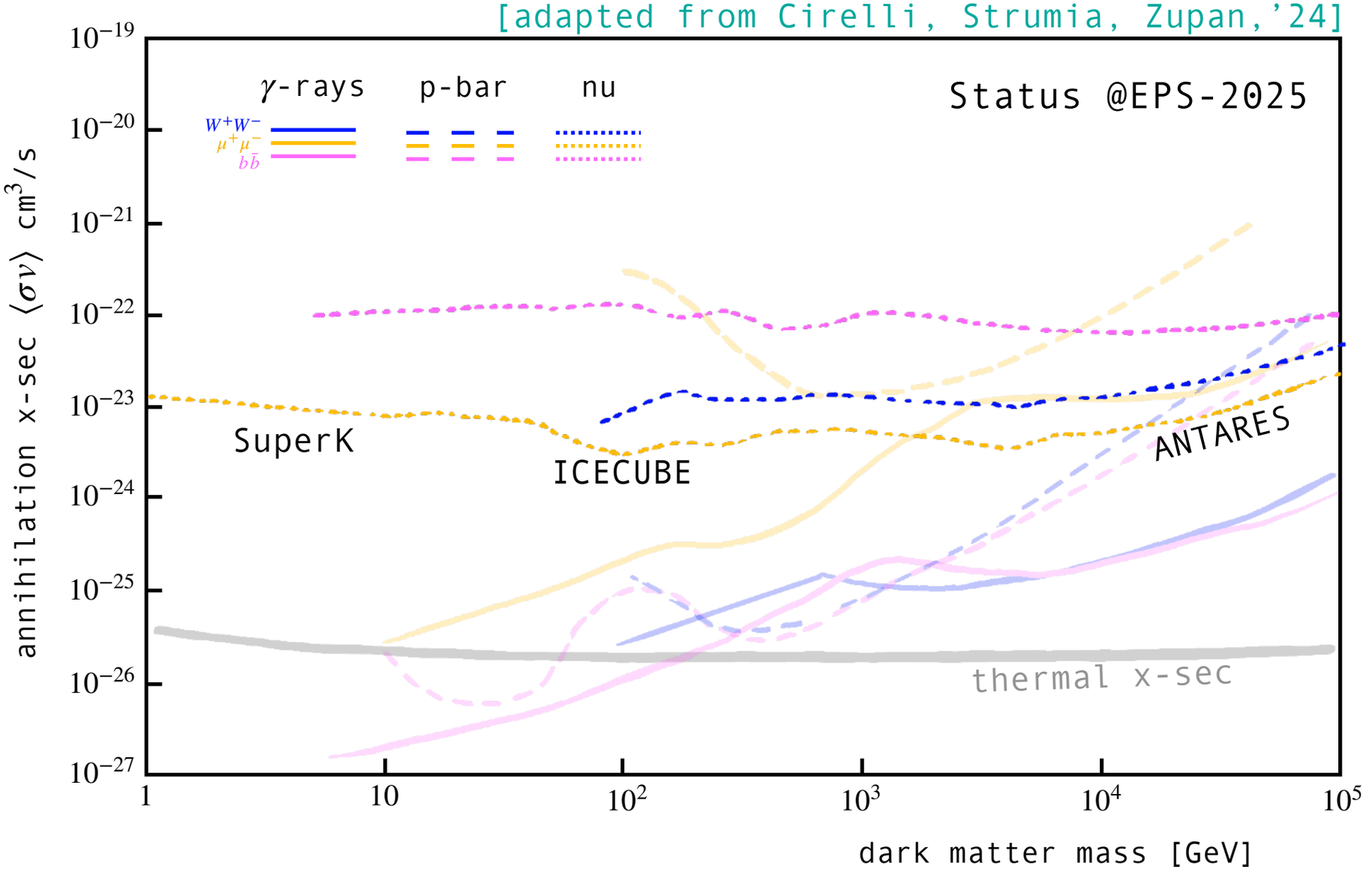


Indirect detection

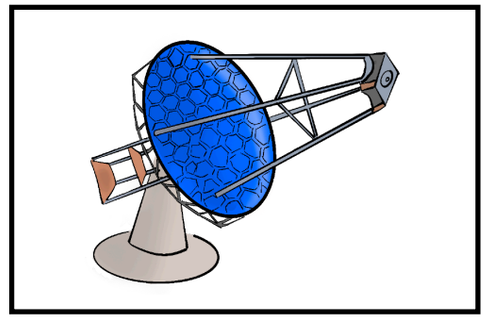


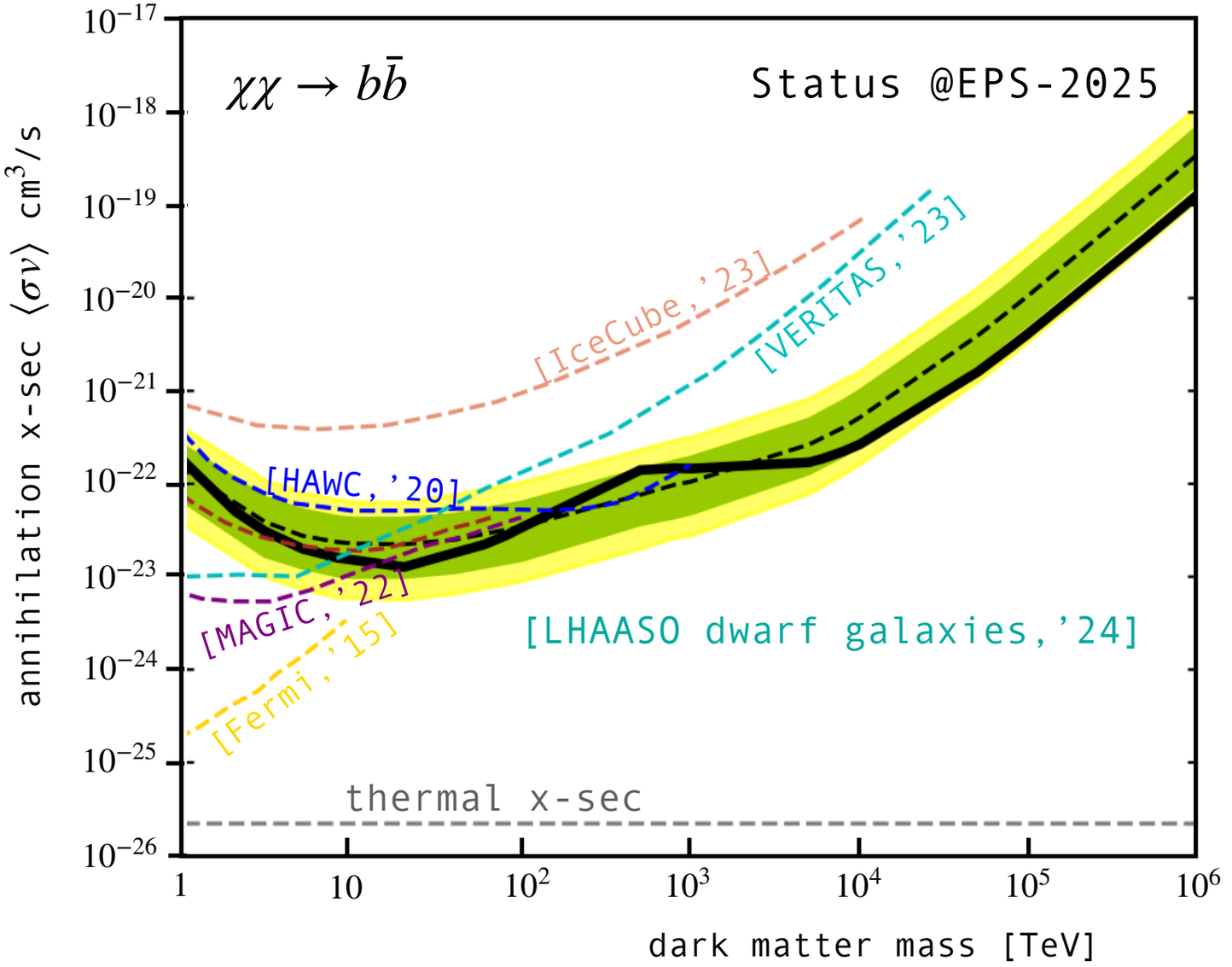


[adapted from Cirelli, Strumia, Zupan,'24]



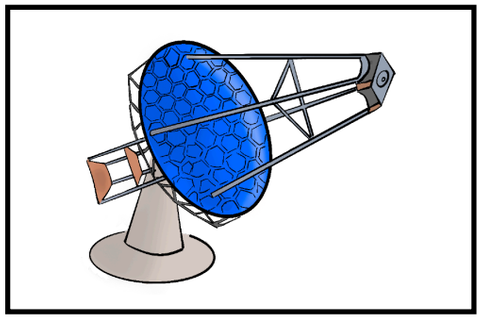
Indirect detection



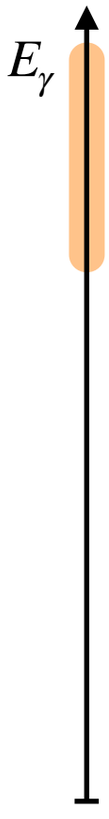


Indirect detection

γ-line



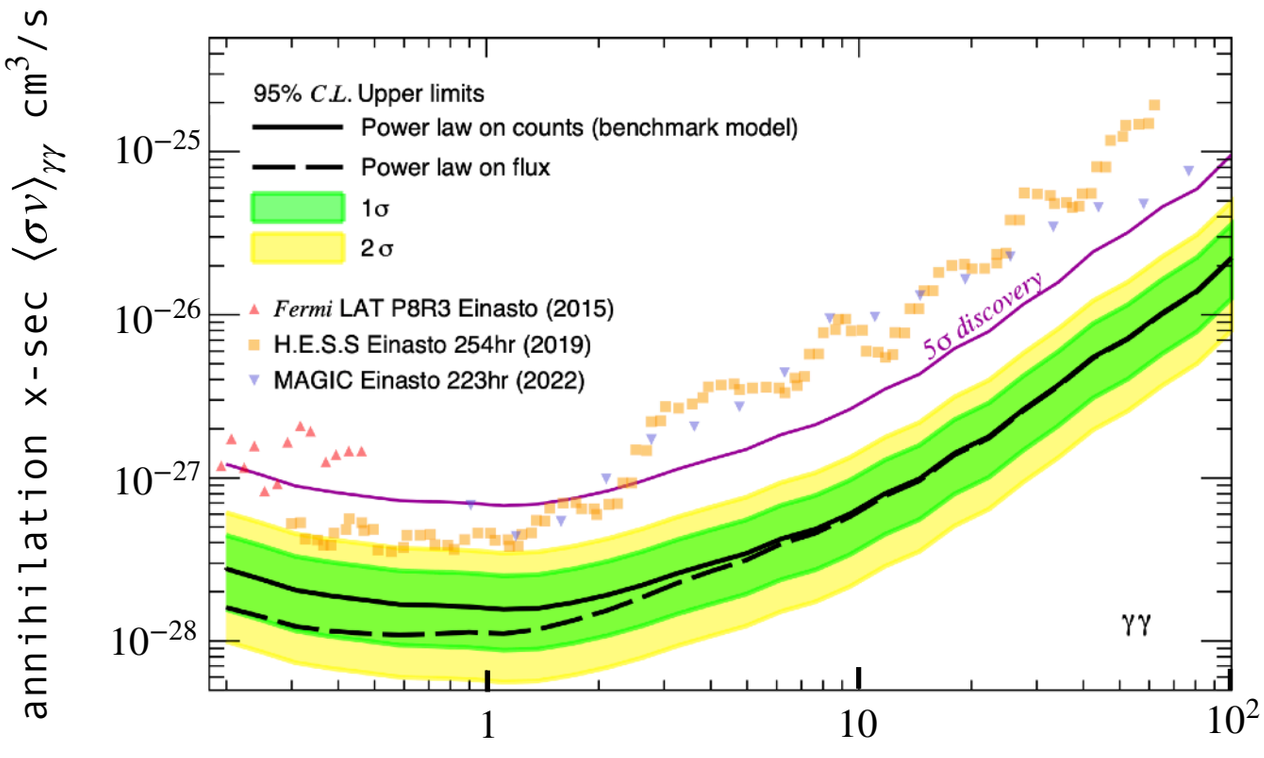
[Bringmann, Sæther Hatlen, Zaharijas et al, '24]



Pair-production

$$\gamma + Z \to e^+ + e^- + Z$$

$E_\gamma > 2m_e \sim$ 100 MeV

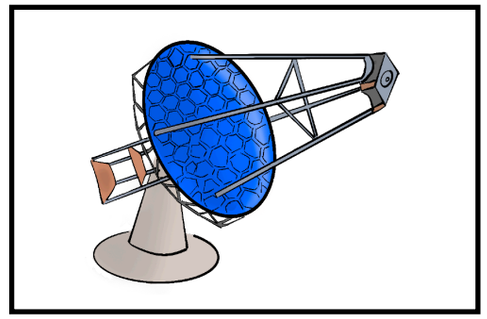


Higher energies (>EeV) @ Pierre Auger Observatory

[N. Gonzalez, B. Cermáková on Mon]

Indirect detection

γ-line



10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$

E_γ

the MeV GAP

Pair-production

$\gamma + Z \to e^+ + e^- + Z$

$E_\gamma > 2m_e \sim 100$ MeV

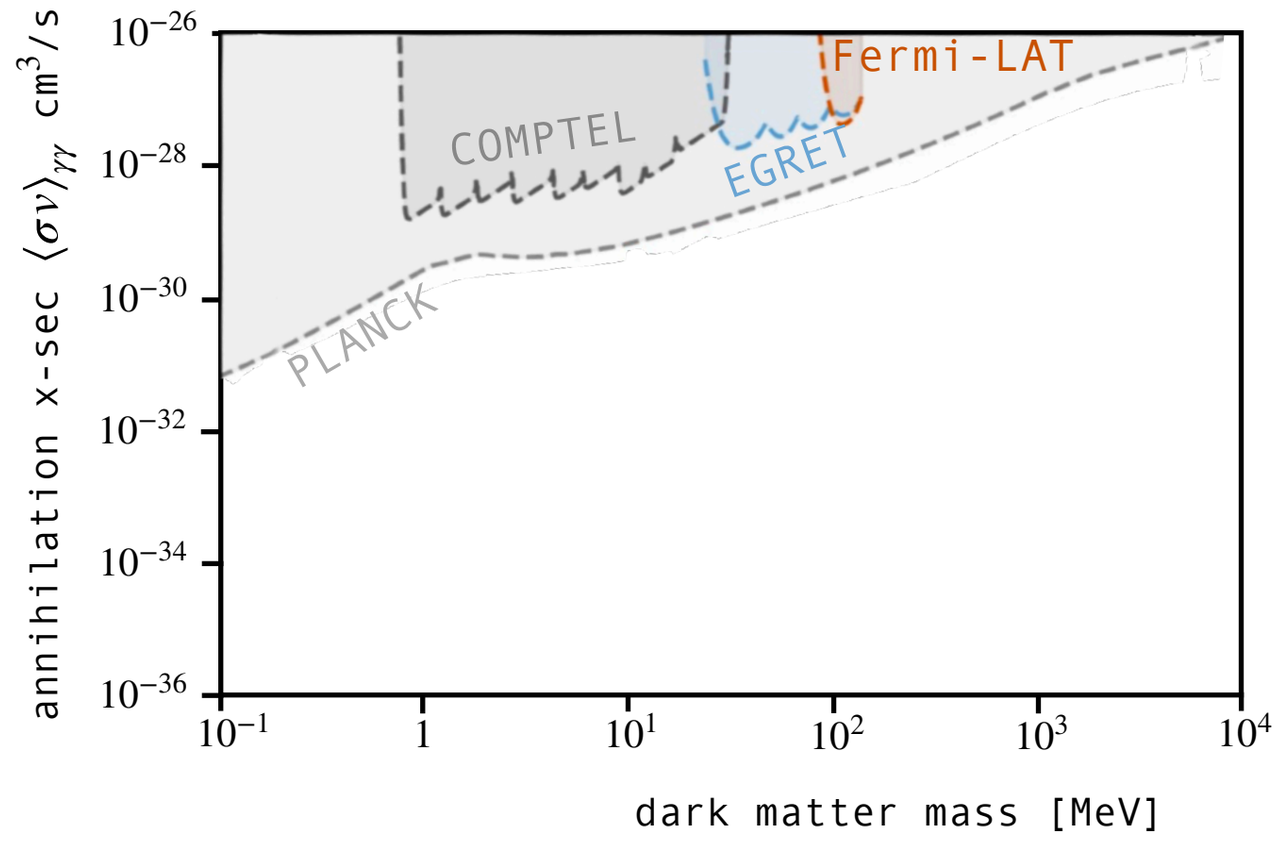
Compton scattering

$\gamma + e \to \gamma' + e'$

Photoelectric effect

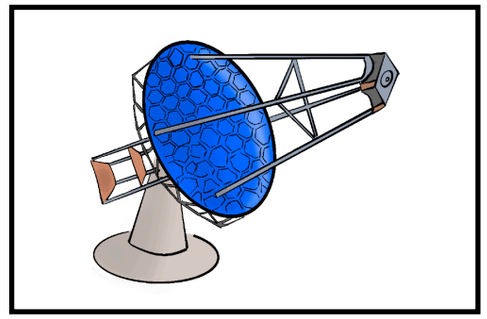
$\gamma + A \to A^+ + e^-$

30-100 keV (depending on Z)



Indirect detection

γ-line



10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$

E_γ

the MeV GAP

Pair-production

$$\gamma + Z \to e^+ + e^- + Z$$

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Compton scattering

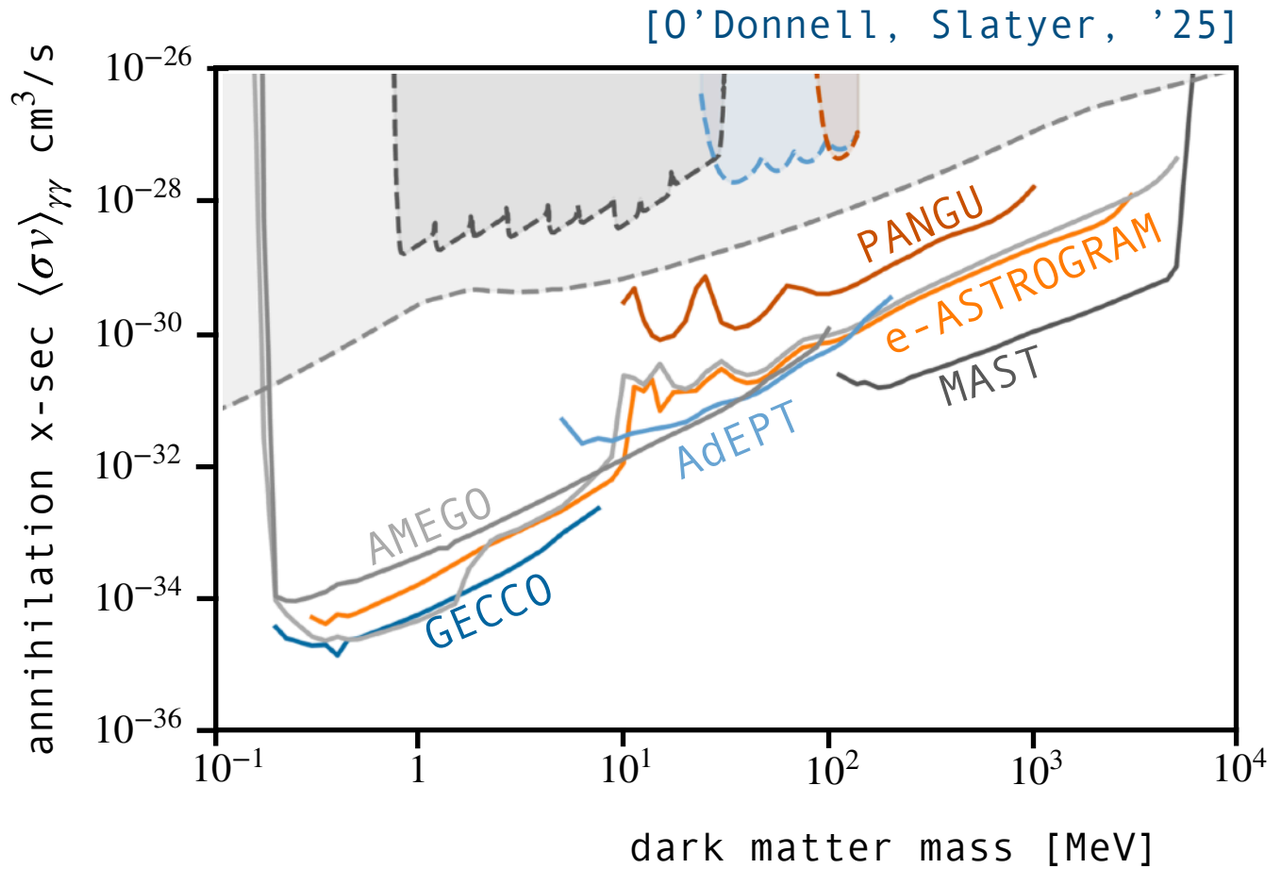
$$\gamma + e \to \gamma' + e'$$

Photoelectric effect

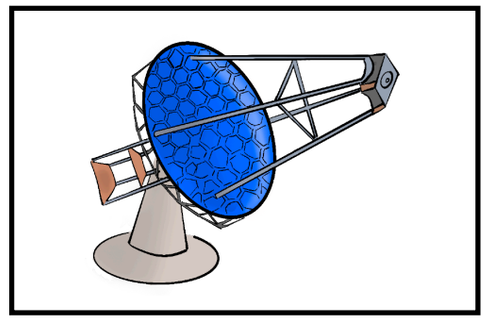
$$\gamma + A \to A^+ + e^-$$

30-100 keV (depending on Z)

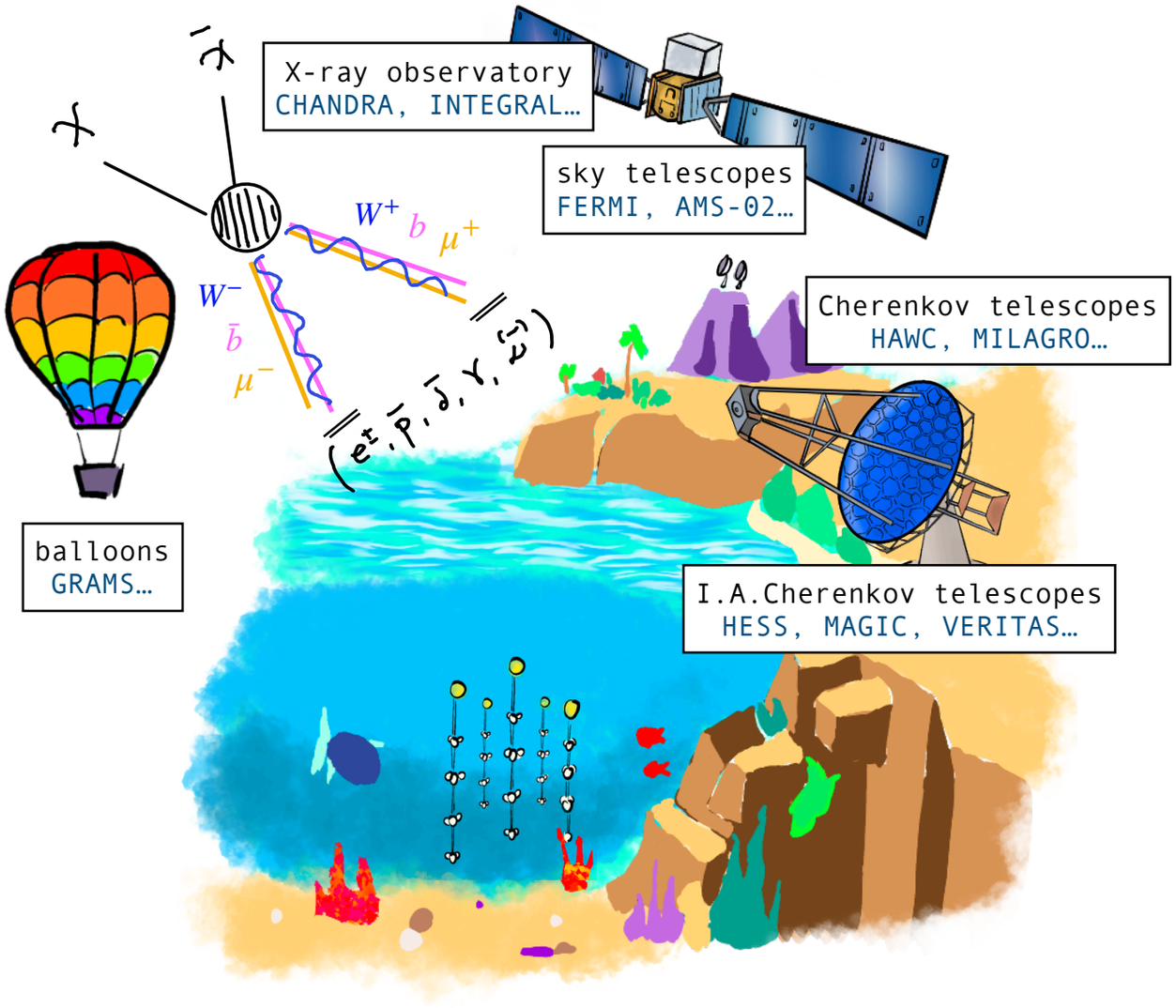
[O'Donnell, Slatyer, '25]

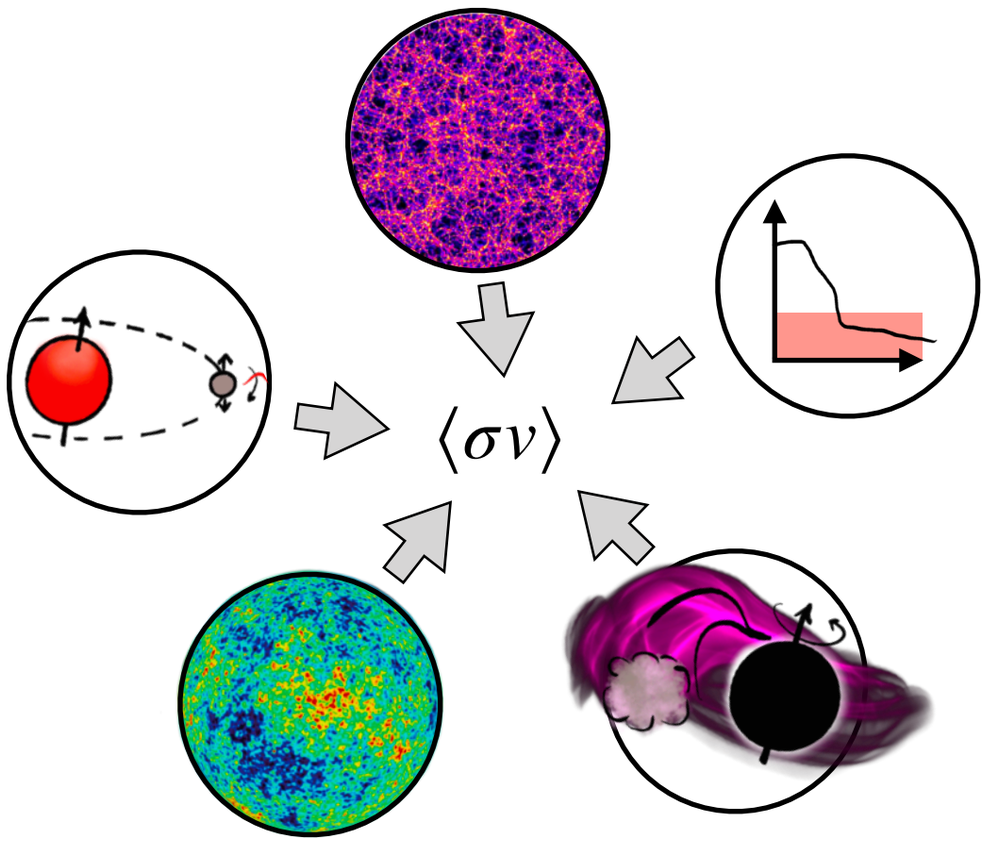


Indirect detection

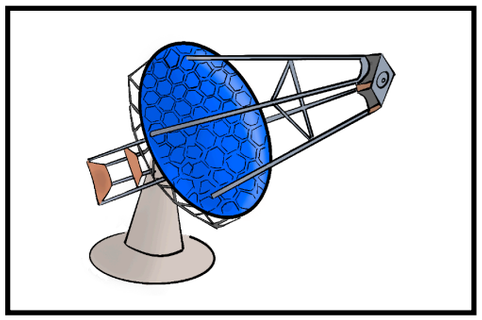


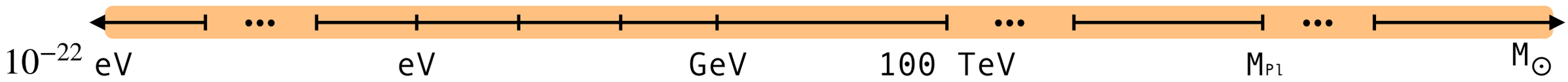
10^{-22} eV ••• eV — GeV — 100 TeV ••• M_{Pl} ••• $M_\odot$





Indirect detection





X & γ rays

Radio lines

CMB SD

X-ray lines

X rays

γ rays

CRs, ν

CMB SD

Radio rays

X & γ rays

CRs

CMB SD

Superradiance

GW EMRI dephasing

PBH mergers & SGWB

GW NS mergers

NS heating

Structure formation

Microlensing

[EUCAPT,'21]

[NuStars: D. Vatsyayan]

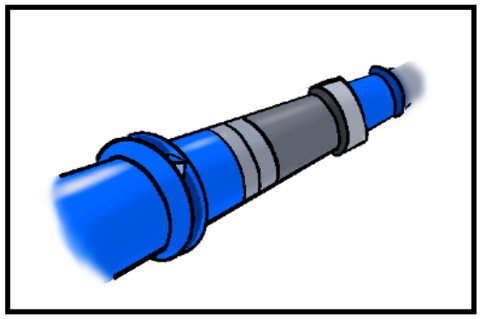
[EUCLID: EJ. Gonzalez, WD. Doumerg on Tue, S. Escoffier on Fri]

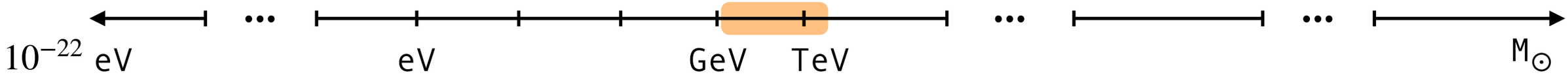
[Vera Rubin observatory: B. Sanchez on Tue]

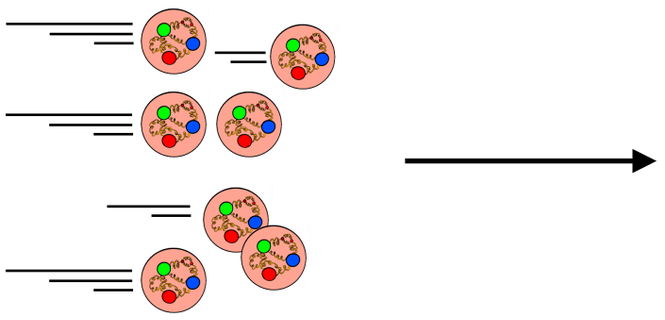
[ACT: A. La Posta on Fri]

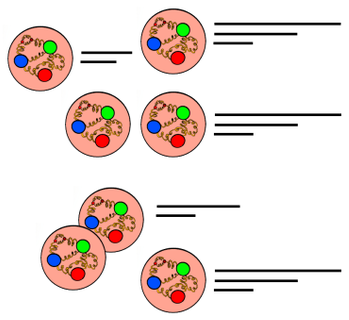
[R. Galazo today]

Collider searches

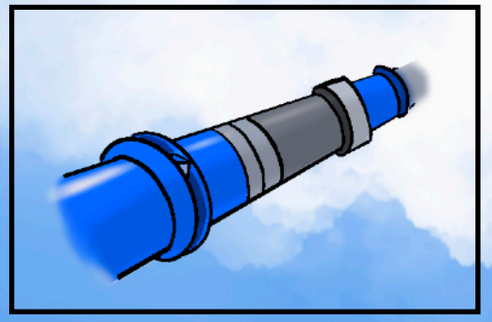






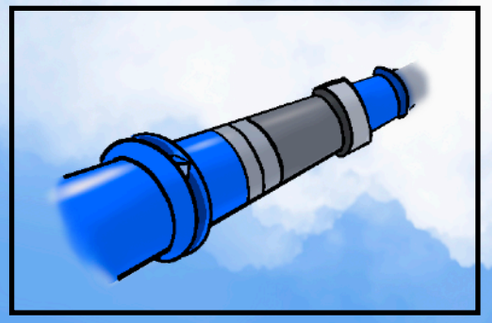


Collider searches



10^{-22} eV ••• eV GeV TeV ••• ••• $M_\odot$

Collider searches



10^{-22} eV ••• eV GeV TeV ••• ••• $M_\odot$

ELSA

[L. Salutari today]

BELLE-II

[L. Salutari today]

BESIII

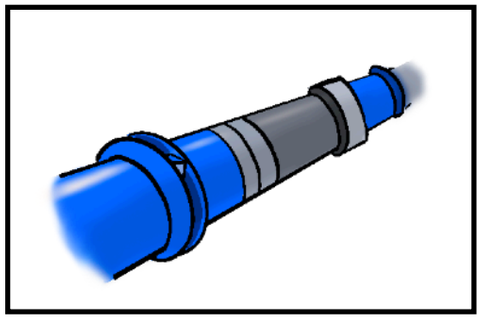
[Z. Li today]

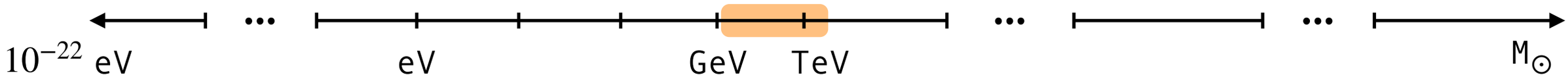
BaBar

[X. Ai on Fri]

Collider searches

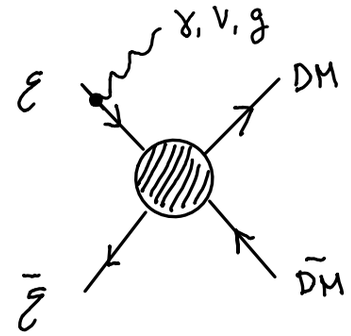
EFTs





Mono-object + missing energy

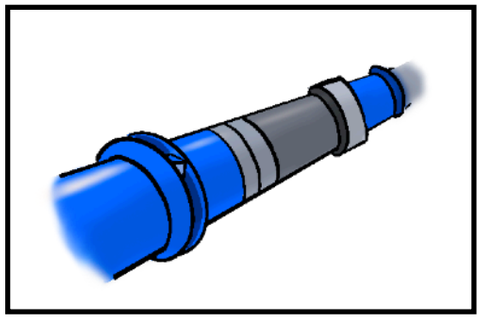
$pp \to DM\ \overline{DM}$ + something (jet, Z, Higgs…)

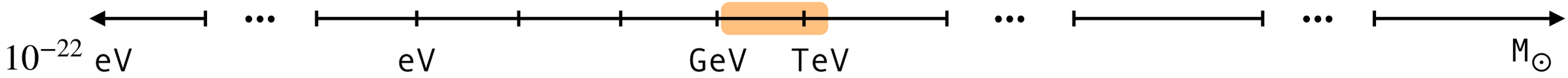


$\Lambda_{NP} \gg \sqrt{s}$

Collider searches

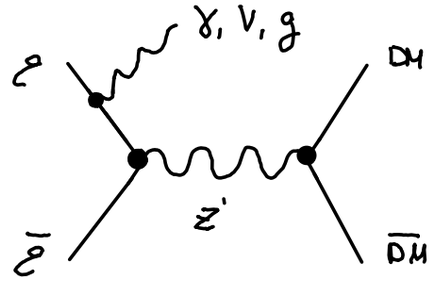
Theories





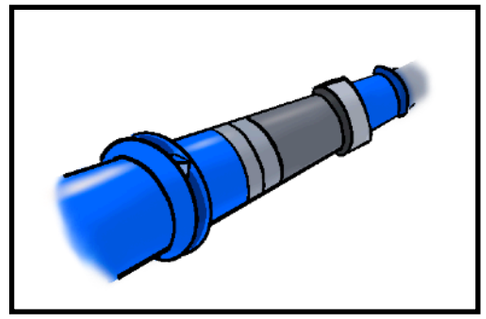
Mono-object + missing energy

pp → Mediator* → DM $\overline{\text{DM}}$ + something



Collider searches

Theories



10^{-22} eV ••• eV GeV TeV ••• ••• •••

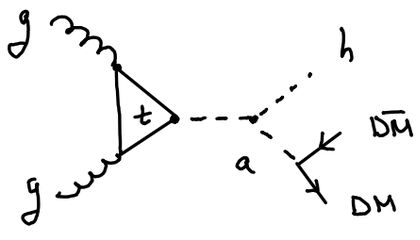
Mono-object + missing energy

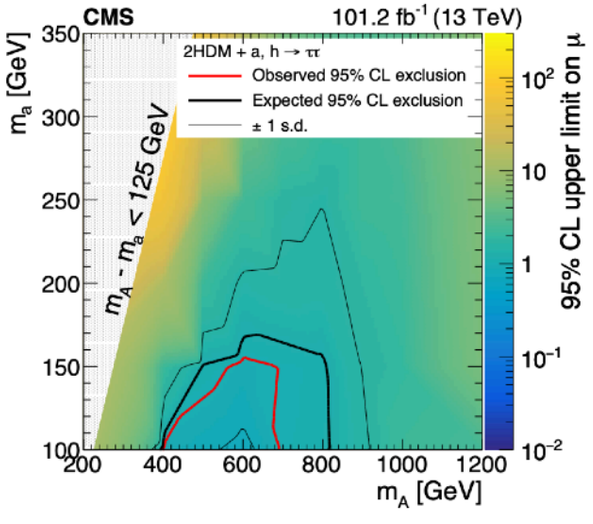
pp → Mediator* → DM $\overline{\text{DM}}$ + something

Particular UV completion

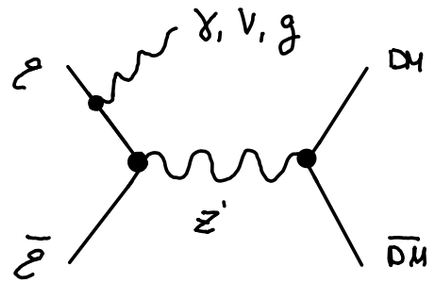
e.g. SUSY, nu-MSM, 2HDM+a…

[CMS, June '25]





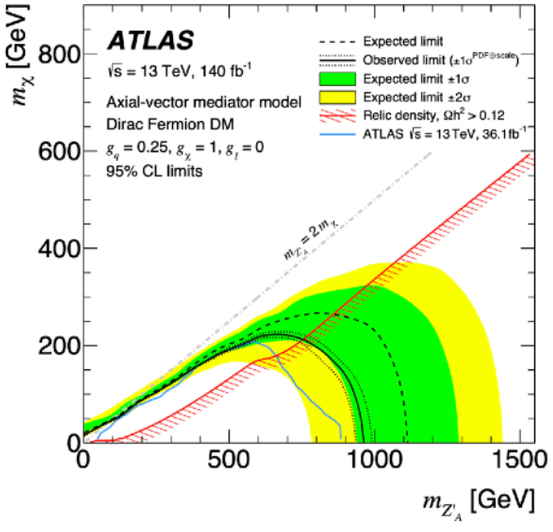
[S. Singh Chauhan, J. Lahiri on Wed]



Simplified models

e.g.(pseudo)scalar, (axial)vector

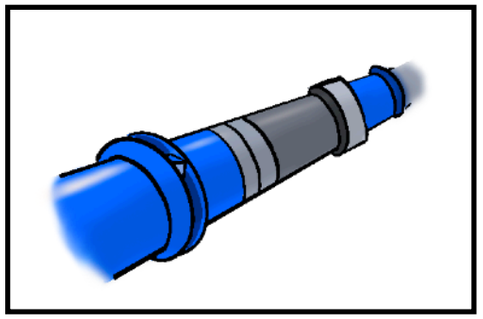
[ATLAS, Dec '24]

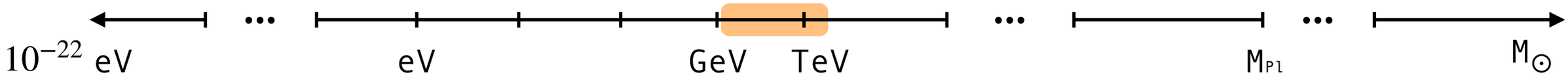


[S. Sekmen, EL. Woodwark, P. Scholer on Mon]

Collider searches

Theories



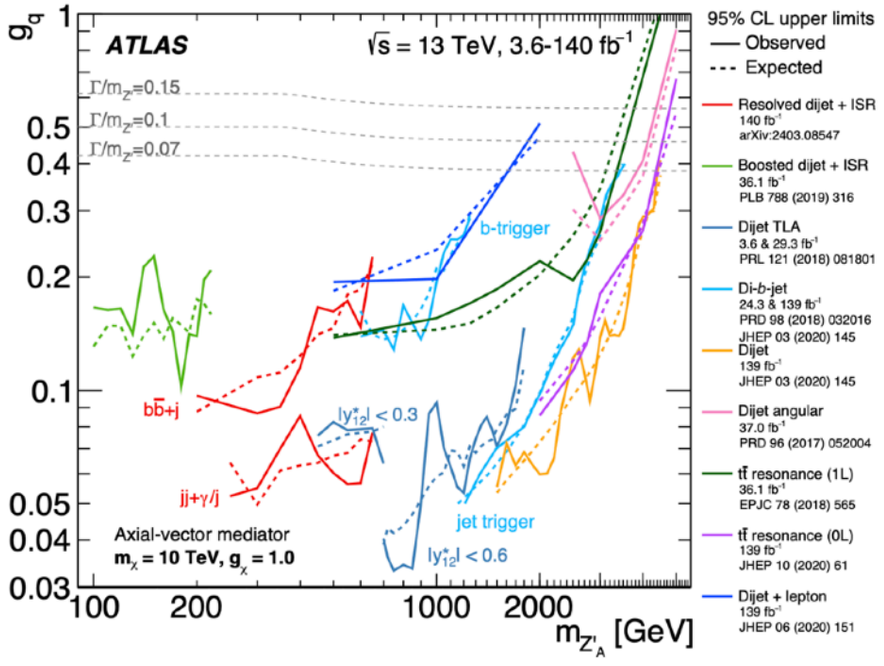


Mono-object + missing energy
Dijet resonances
Higgs invisible decay

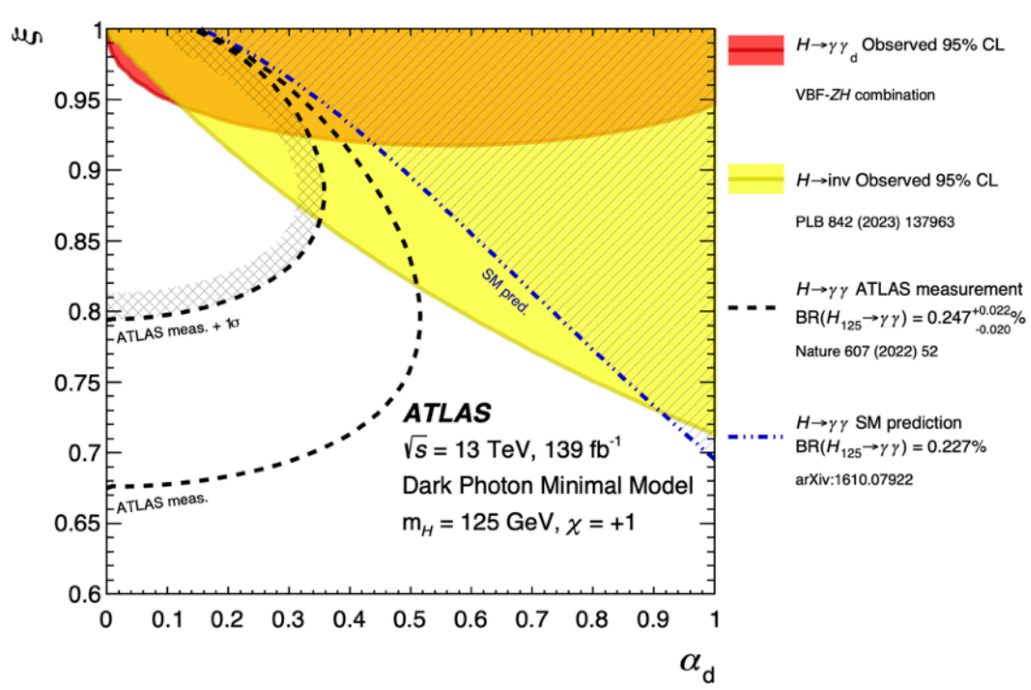
Dark photons
Dark Higgs
Dark showers

Heavy flavour + DM
ALPS
…

[ATLAS, Nov 2024]

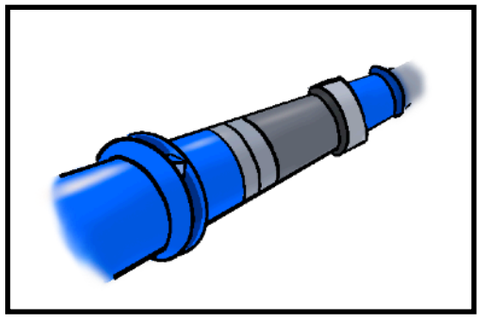


[@LHCb: L.Fantini today]

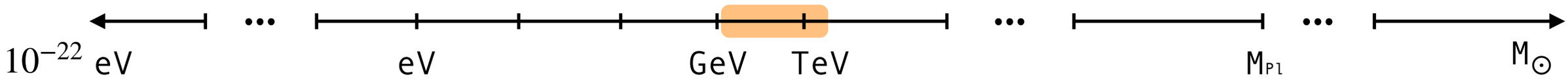


Collider searches

Projections



[A. Maloizel on Mon]

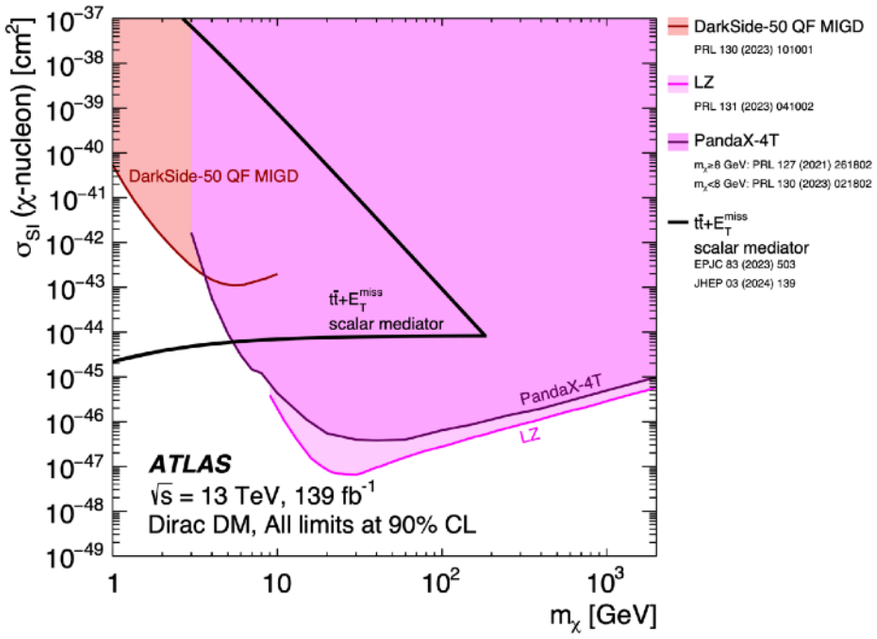


Mono-object + missing energy
Dijet resonances
Higgs invisible decay

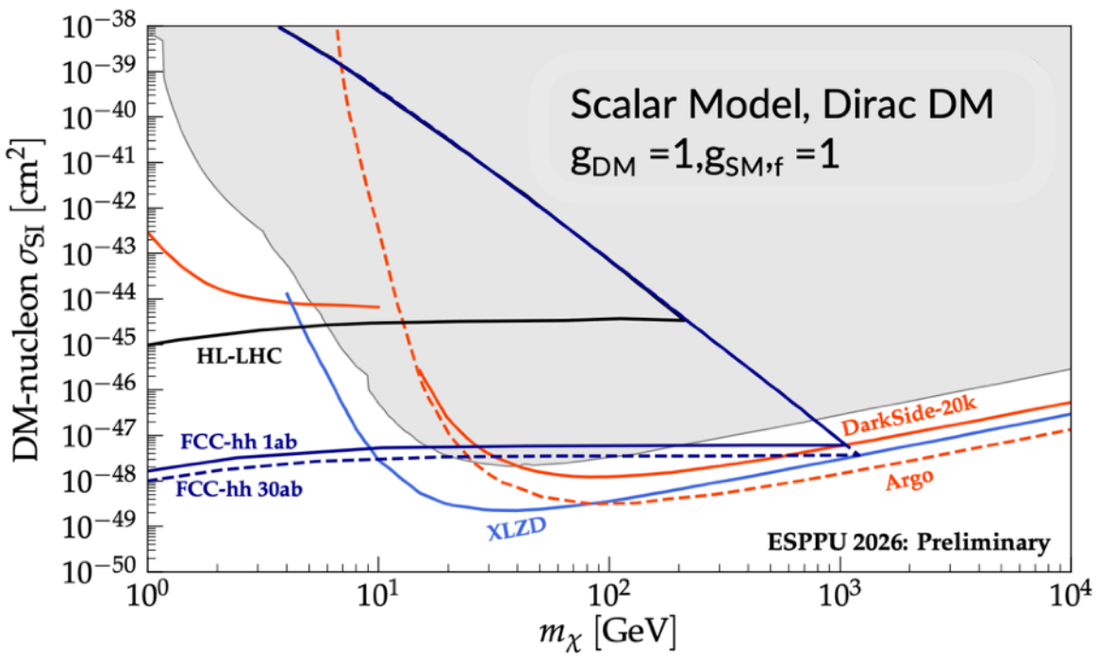
Dark photons
Dark Higgs
Dark showers

Heavy flavour + DM
ALPS
…

[ATLAS, Nov 2024]

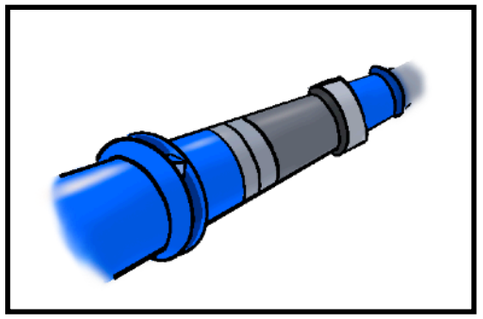


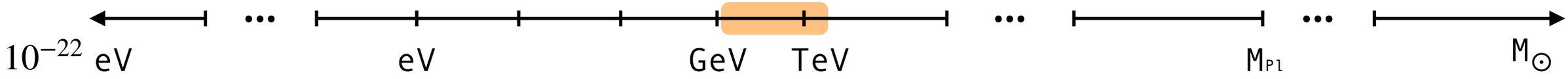
[European Strategy symposium, '25]



[@LHCb: J. Hui Zhuo on Mon, L. Fantini, S. Libralon on Wed]

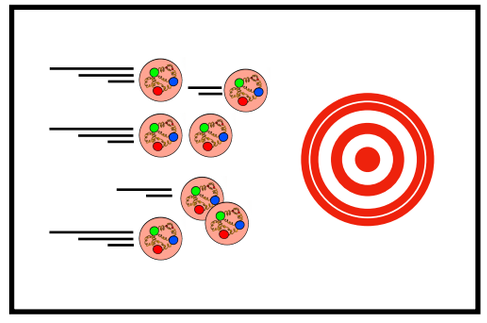
Collider searches

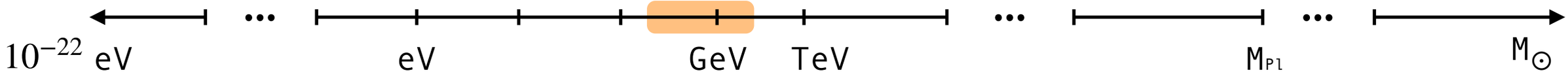


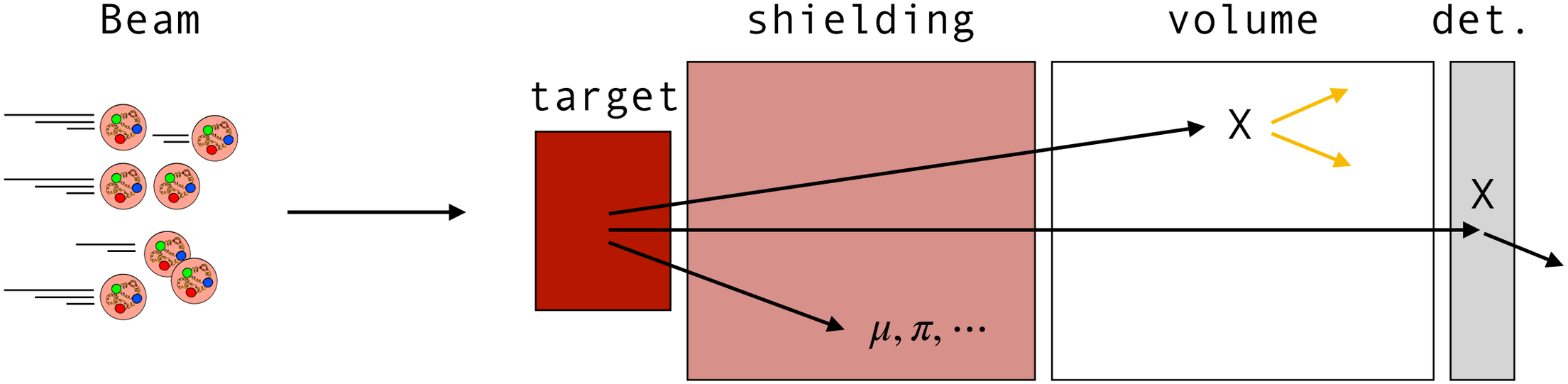


Energy frontier

Accelerator-based probes

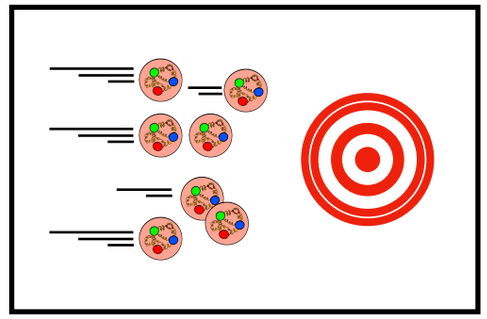


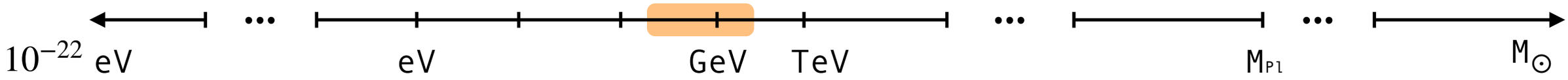




INTENSITY frontier

Accelerator-based probes





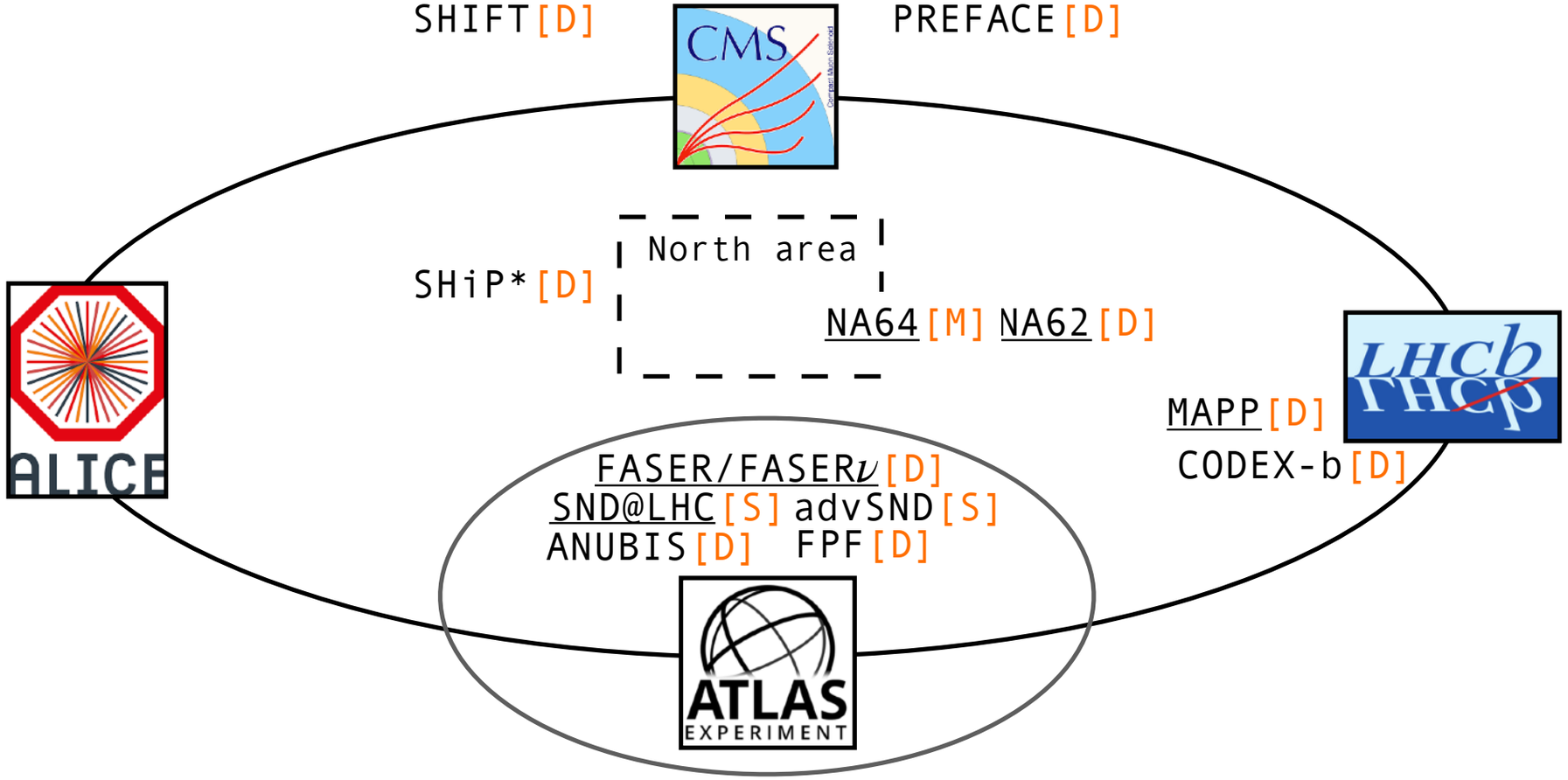
e.g. those @ CERN

STATUS

running
proposed
approved*

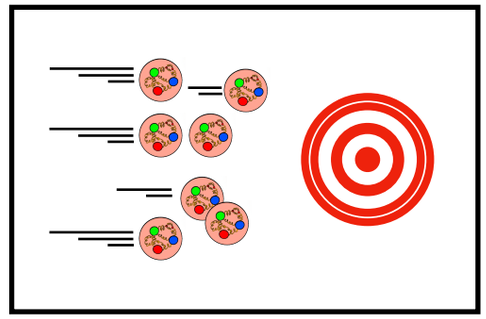
SIGNATURE

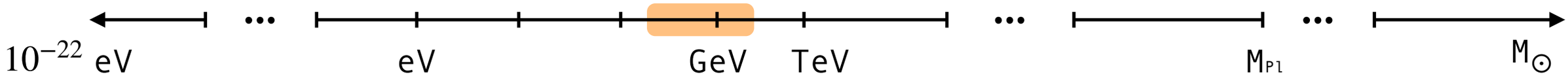
scatterings [S]
decays [D]
missing Energy [M]



[see M. Ovchynnikov @ European Strategy '25]

Accelerator-based probes





e.g. those @ CERN

STATUS
running
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SIGNATURE
scatterings [S]
decays [D]
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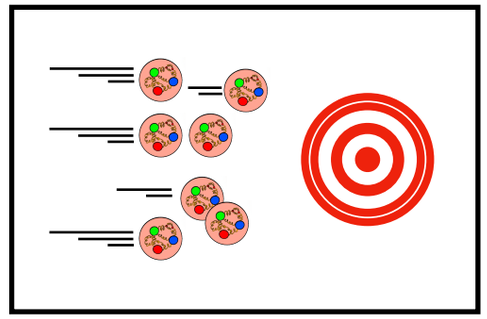
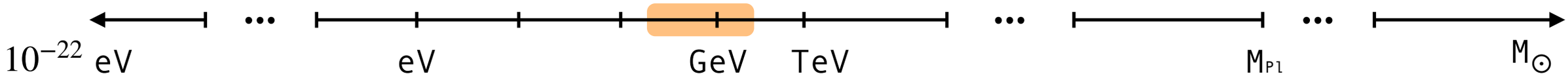
[see M. Ovchynnikov @ European Strategy '25]

MATHULSA[D]
SHIFT[D]
[JS. Tafoya on Fri]
MilliQan[S] FORMOSA[S]
PREFACE[D]
[M. Ovchynnikov today]
SHiP*[D]
North area
[V. Duk, I. Rosa on Mon]
NA64[M] NA62[D]
MAPP[D]
CODEX-b[D]
[X. Ai on Fri]
FASER/FASERν[D]
SND@LHC[S] advSND[S]
ANUBIS[D] FPF[D]
[V. Gligorov today]
[ANUBIS: T. Reymermier on Mon]
[N. Hemme today]

Accelerator-based probes

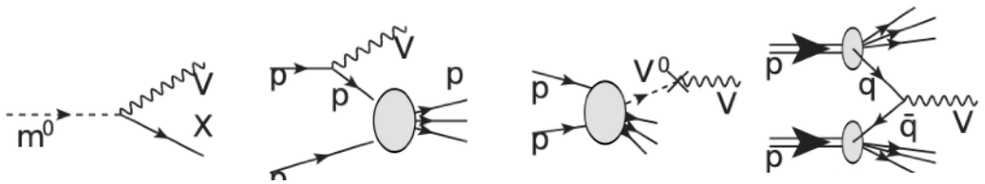


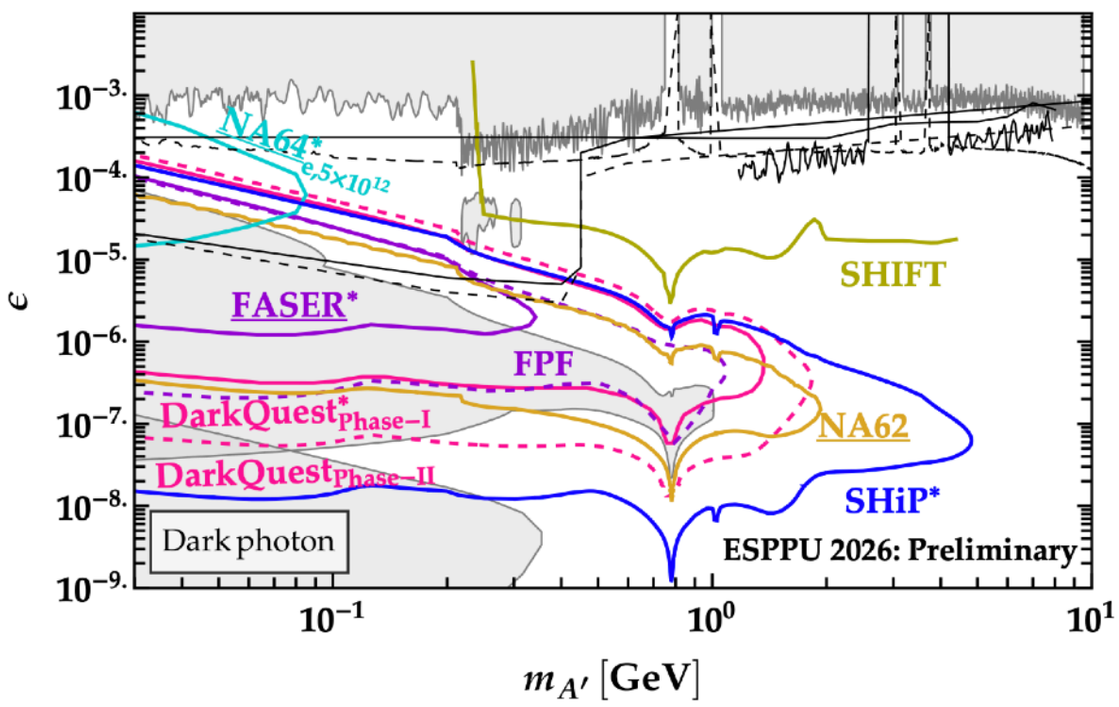


Dark photon

$$\mathcal{L} = \frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu}$$

e.g.[Kyselov, Ovchynnikov,'24]





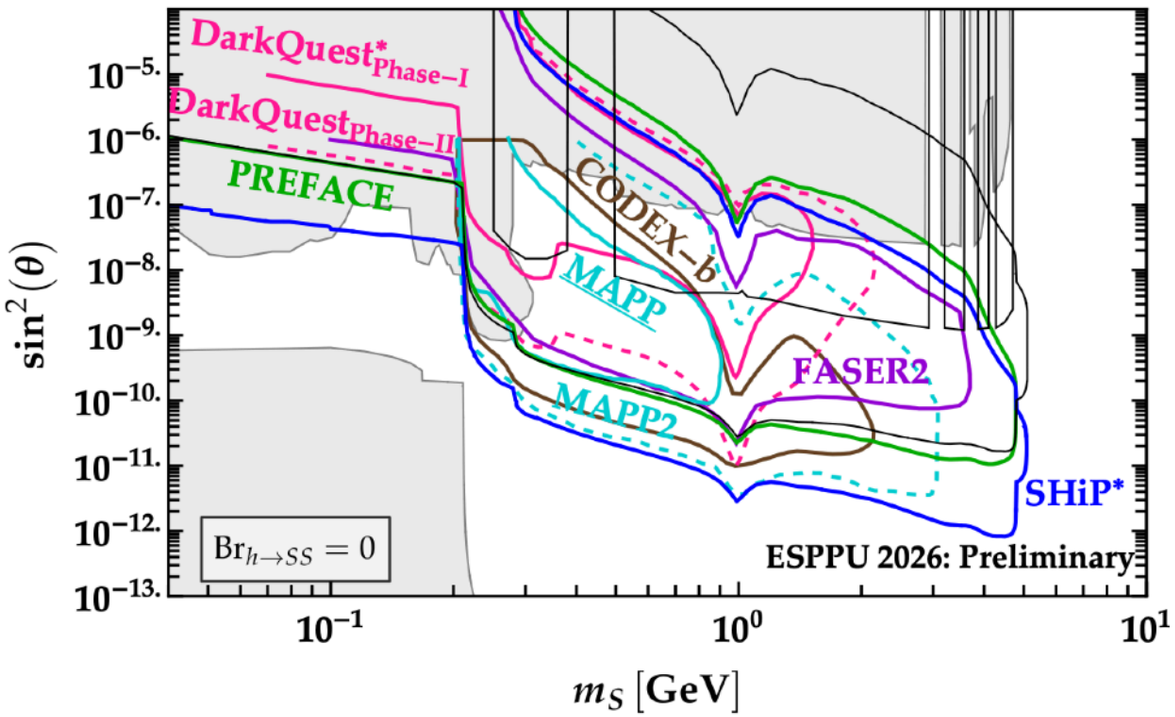
Singlet scalar

$$\mathcal{L} = c_g \frac{\alpha_s}{12\pi v_H} \phi G^a_{\mu\nu} G^{a\mu\nu} - \sum_f c_f \frac{m_f}{v_H} \bar{f} f \phi$$

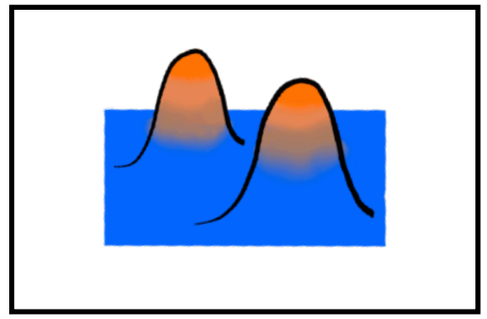
e.g. [Baclkstone et al.,'24]

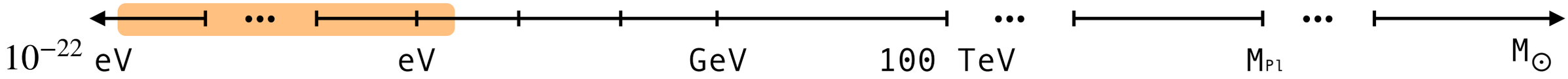
$$c_f = c_g = \sin\theta_h$$

[European Strategy Symposium '25]



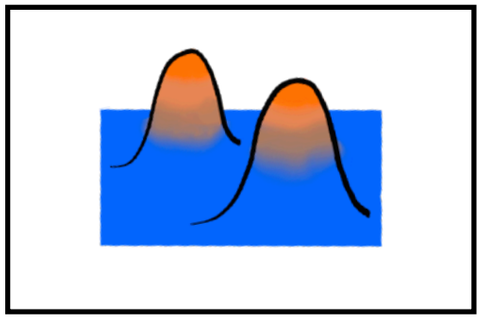
Quantum sensors

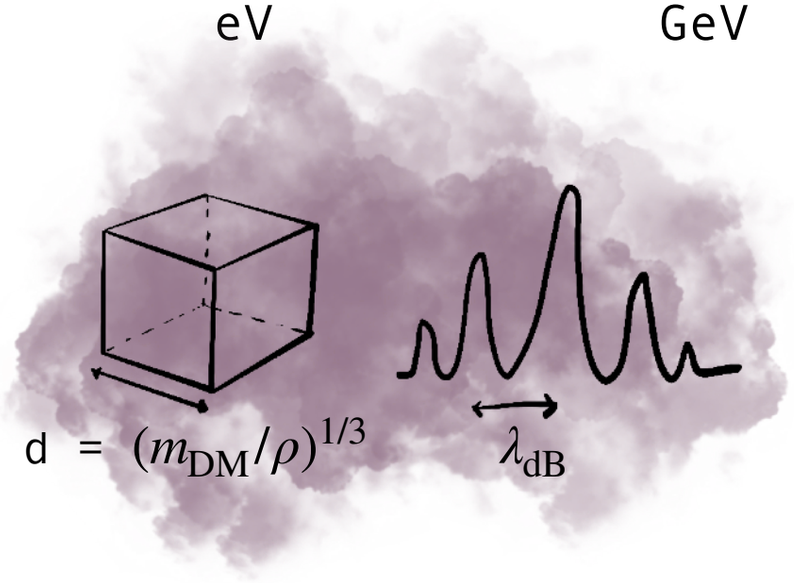




scalar $\quad \mathcal{L} \supset g_{\phi\gamma}\ \phi\ FF + g_{\phi G}\ \phi\ GG - g_f\ \phi\ \bar{f}f + \text{h.c.}$

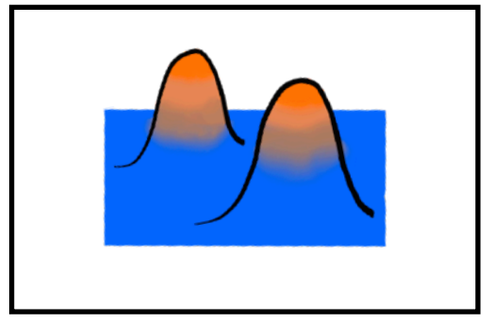
Quantum sensors

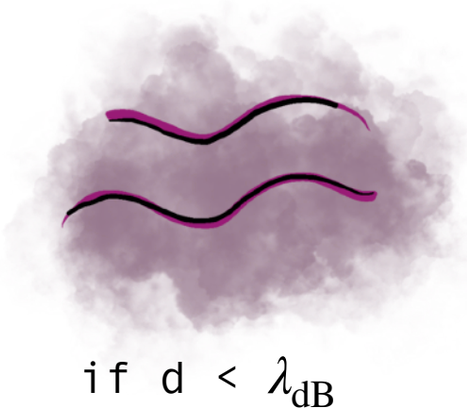




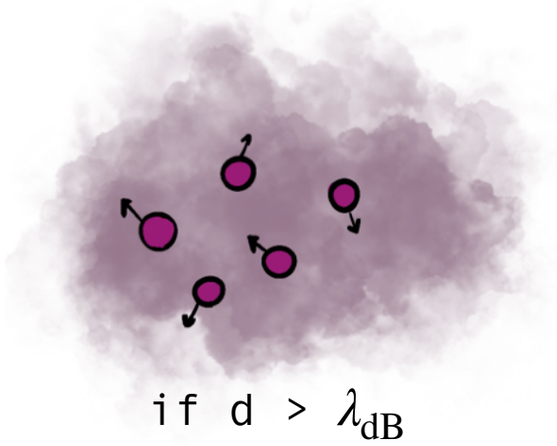
scalar $\quad \mathcal{L} \supset g_{\phi\gamma}\ \phi\ FF + g_{\phi G}\ \phi\ GG - g_f\ \phi\ \bar{f}f + \text{h.c.}$

Quantum sensors





if d < $\lambda_{\rm dB}$

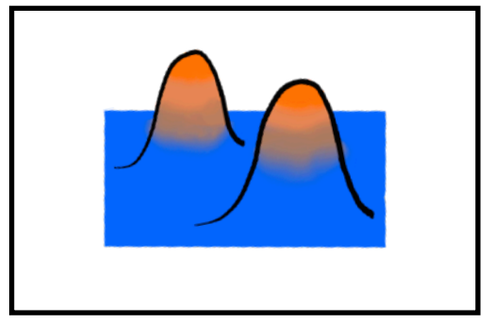


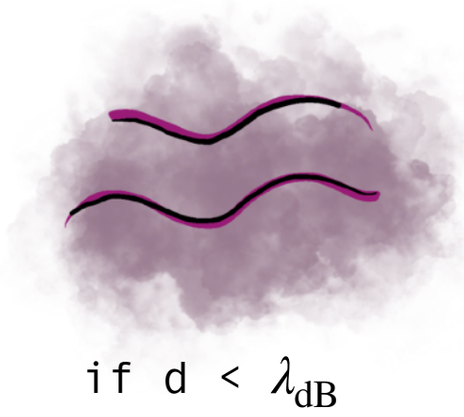
if d > $\lambda_{\rm dB}$

scalar $\quad \mathcal{L} \supset g_{\phi\gamma}\langle\phi\rangle FF + g_{\phi G}\langle\phi\rangle GG - g_f\langle\phi\rangle \bar{f} f + \text{h.c.}$

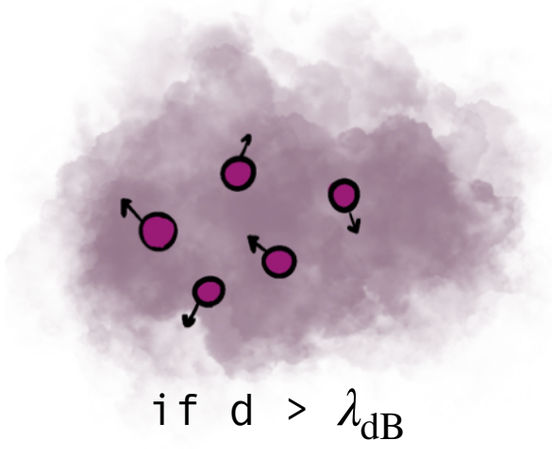
$$\longrightarrow \quad C_{\rm SM}(t) = C_{\rm SM} + \#\langle\phi\rangle$$

Quantum sensors



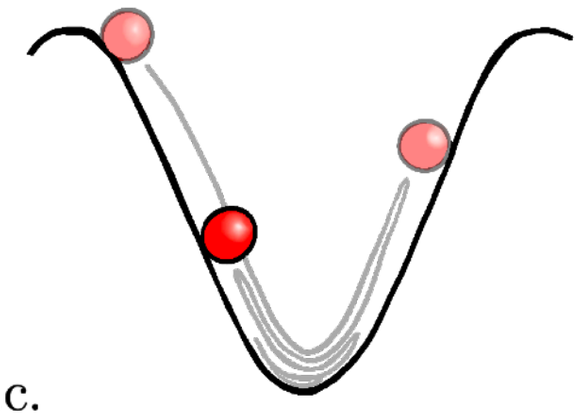


if d < $\lambda_{\rm dB}$



if d > $\lambda_{\rm dB}$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + m_\phi^2\phi^2$$



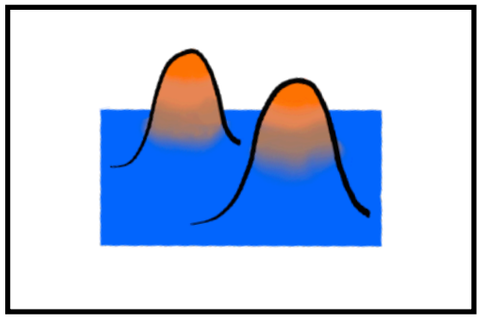
scalar $\quad \mathcal{L} \supset g_{\phi\gamma}\langle\phi\rangle FF + g_{\phi G}\langle\phi\rangle GG - g_f\langle\phi\rangle\bar{f}f + \text{h.c.}$

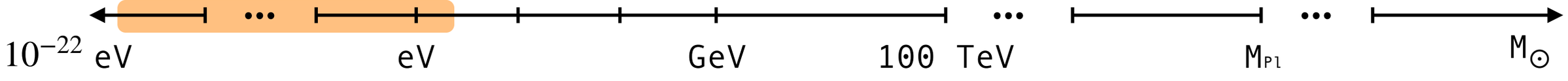
$$\longrightarrow \; C_{\rm SM}(t) = C_{\rm SM} + \#\phi_0\cos(m_\phi t)$$

$C_{\rm SM}(t)$ enter in atomic energy splittings! ⇨ precision physics @ low energies

Quantum sensors

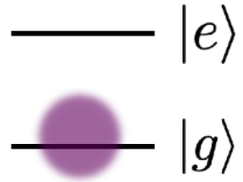
accelerometers





e.g. atomic clocks

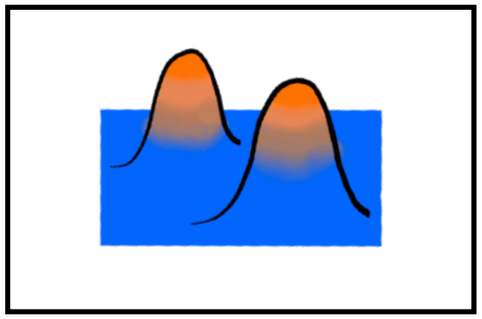
$\Delta E = f[C_{\rm SM}(t)]$



$|g\rangle$ state preparation

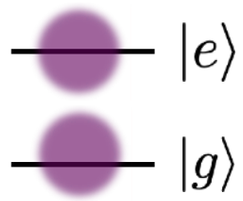
Quantum sensors

accelerometers



e.g. atomic clocks

$$\Delta E = f[C_{\rm SM}(t)]$$



$|g\rangle$ state preparation

$\downarrow$

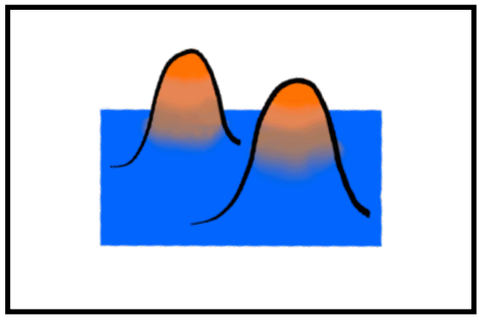
$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$

$\downarrow$ let system evolve

$\frac{1}{\sqrt{2}}(|g\rangle + e^{i\Delta E t}|e\rangle)$

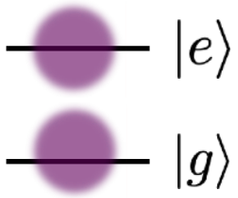
Quantum sensors

accelerometers



e.g. atomic clocks

$$\Delta E = f[C_{\rm SM}(t)]$$



$|g\rangle$ state preparation

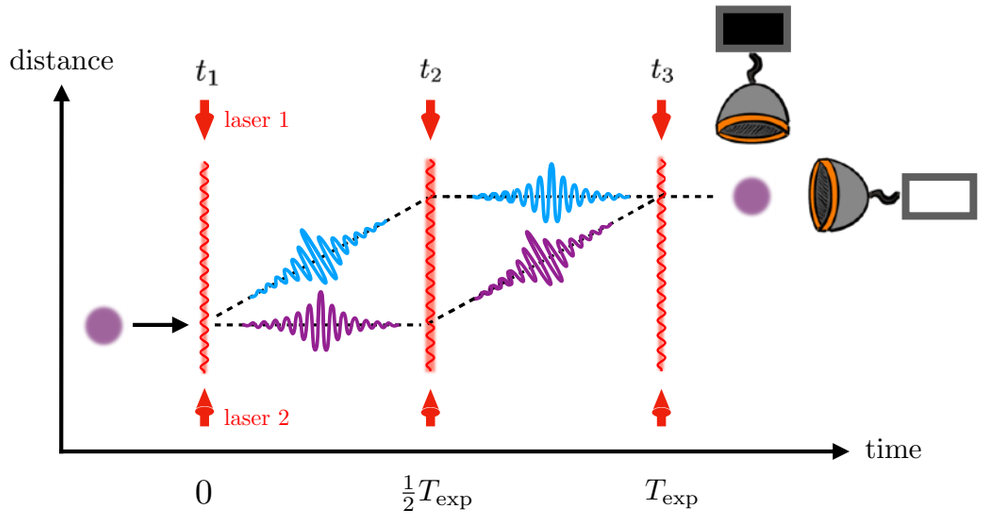
$\downarrow$

$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$

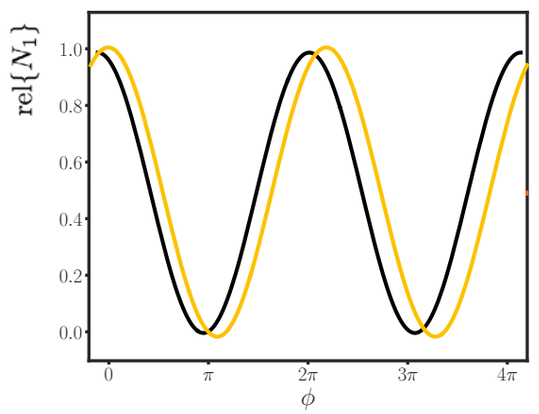
$\downarrow$ let system evolve

$\frac{1}{\sqrt{2}}(|g\rangle + e^{i\Delta E t}|e\rangle)$

atom interferometers

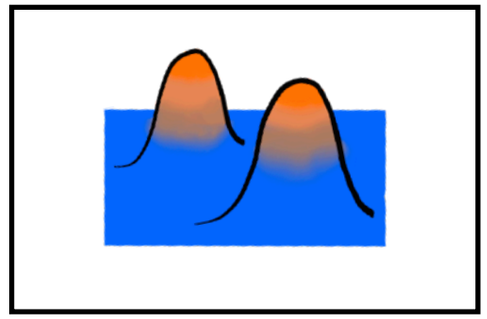


$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & e^{i(\phi+\Delta\phi)} \\ e^{-i(\phi+\Delta\phi)} & 1 \end{pmatrix}$$



Quantum sensors

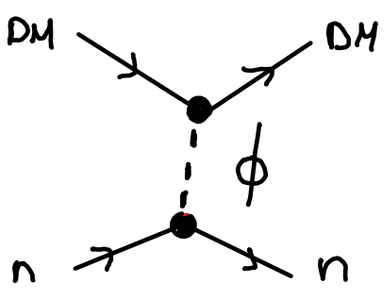
accelerometers



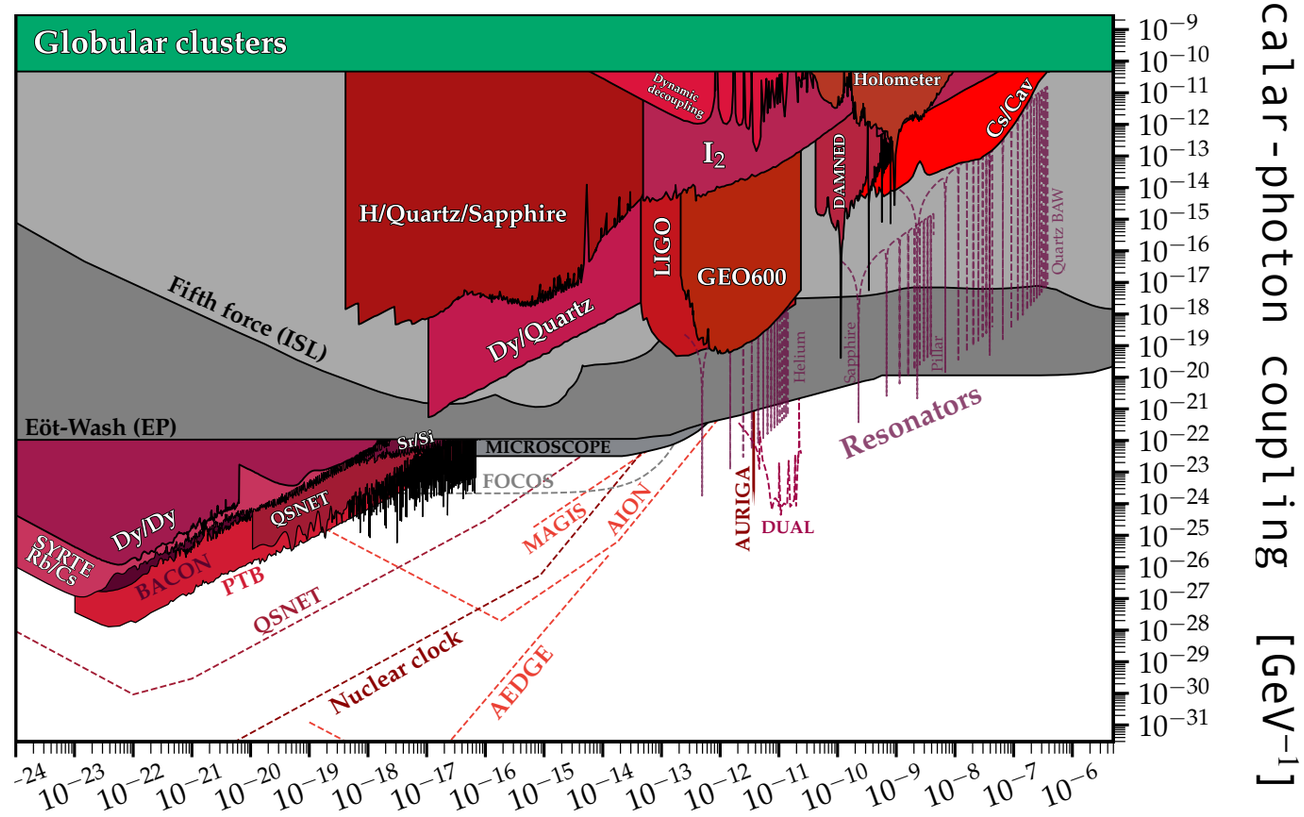
Atom gradiometers can be sensitive to pure gravitational interactions [Badurina et al.,'25]

scalar $\quad \mathcal{L} \supset g_{\phi\gamma}\langle\phi\rangle FF + g_{\phi G}\langle\phi\rangle GG - g_f\langle\phi\rangle \bar{f}f + \text{h.c.}$

5th force searches

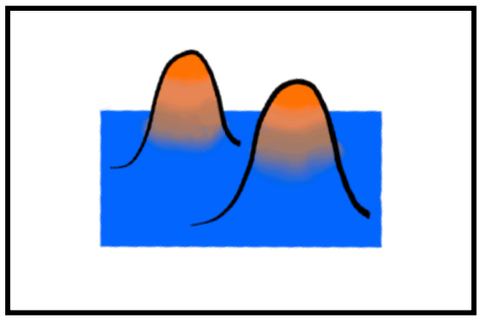


$$\Rightarrow V(r) = -\frac{y_n^2}{4\pi}\frac{1}{r}e^{-m_\phi r}$$



[C. O'Hare]

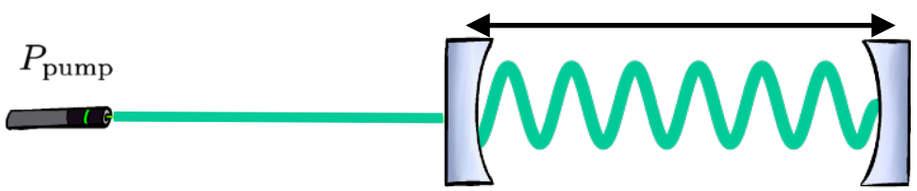
Quantum sensors



vector $\quad \mathcal{L} \supset \mathcal{Q}_A A'_\mu \bar{f}\gamma^\mu f + \kappa\, F'_{\mu\nu}F^{\mu\nu} + d\, F'_{\mu\nu}\bar{f}\sigma^{\mu\nu} f$

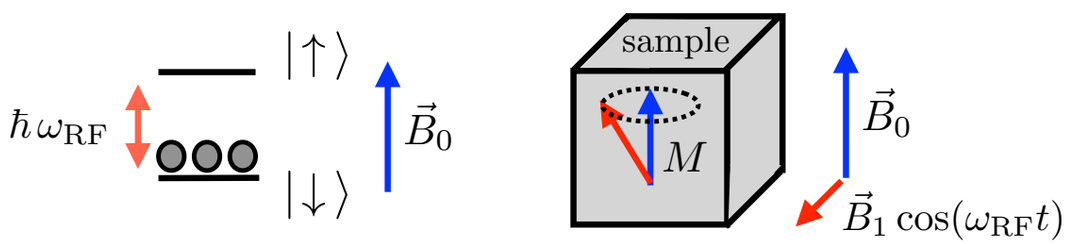
EM detectors

e.g. optical cavities, acoustic resonators…



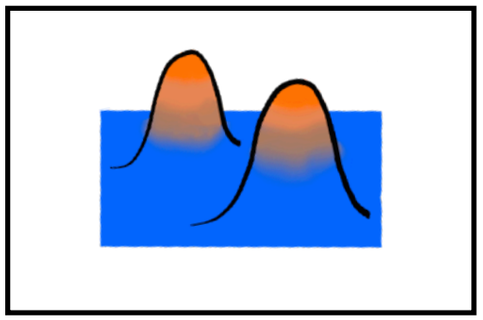
Spin, Dipole-M detectors

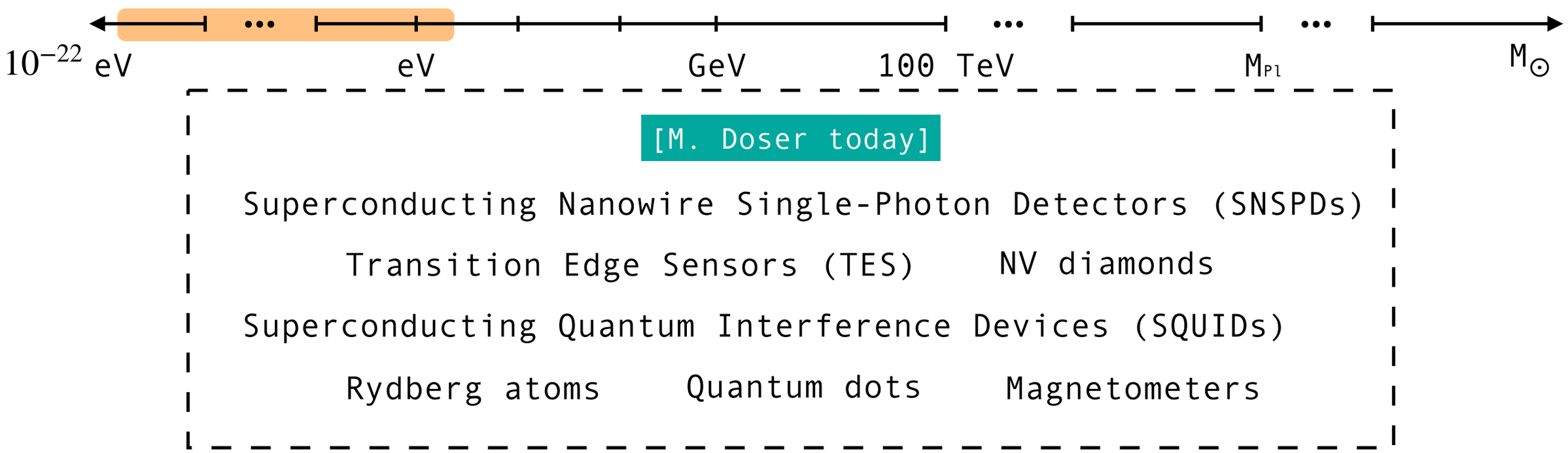
e.g. co-magnetometers, NMR…



Axial-vector $\quad \mathcal{L} \supset \mathcal{Q}_A A'_\mu \bar{f}\gamma^\mu\gamma_5 f$

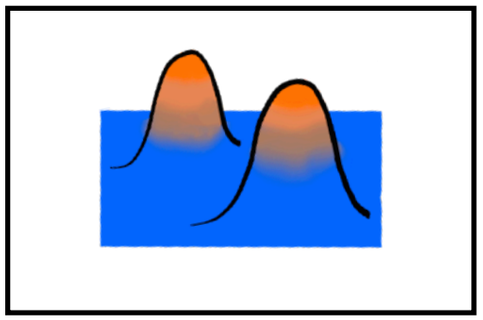
Quantum sensors





Quantum properties!

Quantum sensors



10^{-22} eV — eV — GeV — 100 TeV — M_{Pl} — $M_\odot$

[M. Doser today]

Superconducting Nanowire Single-Photon Detectors (SNSPDs)

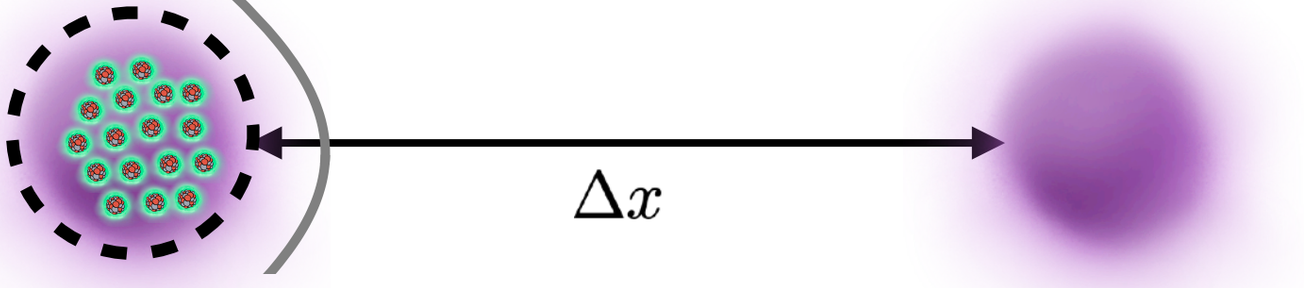
Transition Edge Sensors (TES) NV diamonds

Superconducting Quantum Interference Devices (SQUIDs)

Rydberg atoms Quantum dots Magnetometers

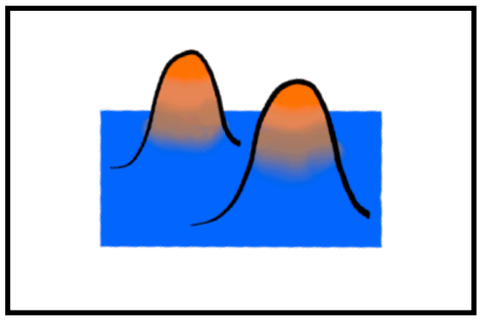
Quantum properties!

Coherence & Decoherence



[Riedel,'13][Du et al'22][Badurina, CM, Plestid,'24][Arvanitaki, Dimopoulos, Galanis,'24]

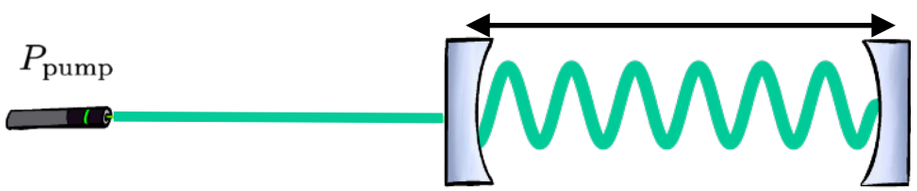
Quantum sensors



vector $\quad \mathcal{L} \supset \mathcal{Q}_A A'_\mu \bar{f}\gamma^\mu f + \kappa\, F'_{\mu\nu}F^{\mu\nu} + d\, F'_{\mu\nu}\bar{f}\sigma^{\mu\nu} f$

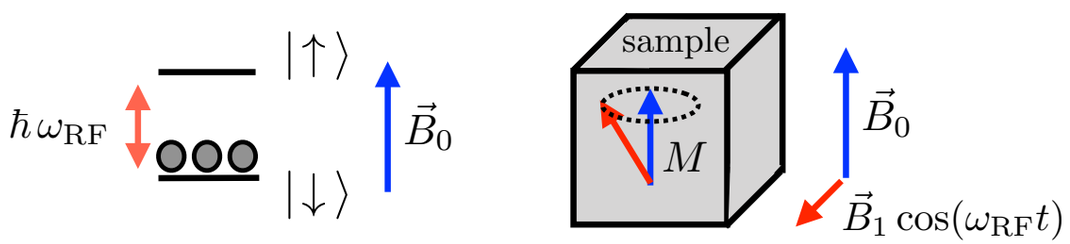
EM detectors

e.g. optical cavities, acoustic resonators…



Spin, Dipole-M detectors

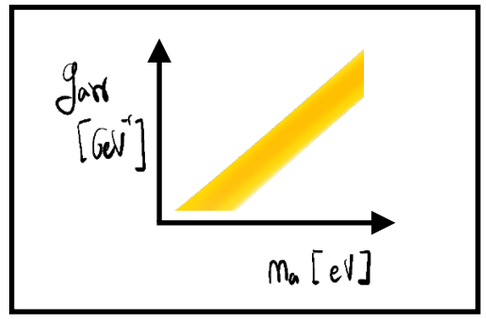
e.g. co-magnetometers, NMR…



Axial-vector $\quad \mathcal{L} \supset \mathcal{Q}_A A'_\mu \bar{f}\gamma^\mu\gamma_5 f$

pseudoscalars $\quad$ … next slide!

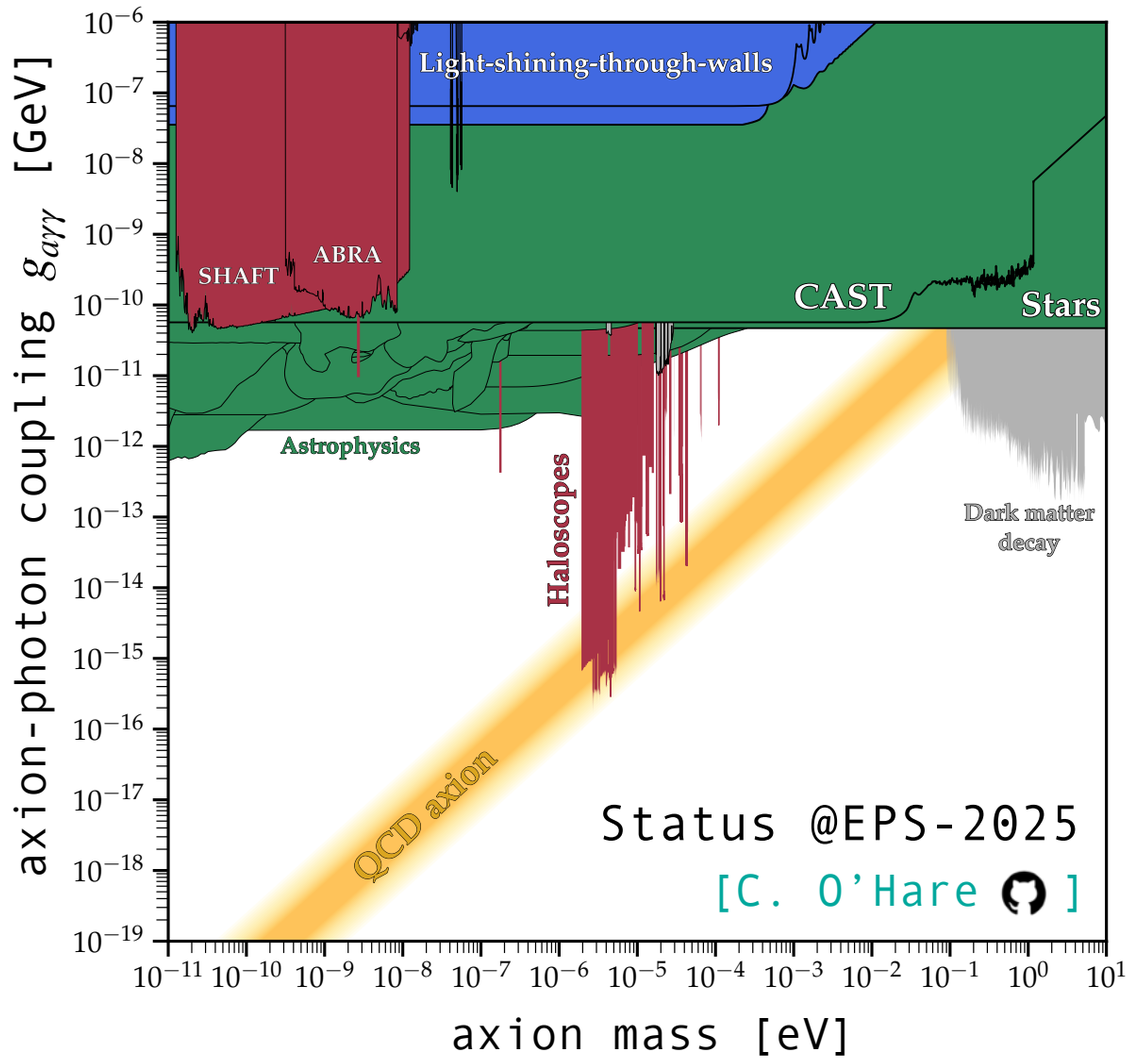
Axion searches



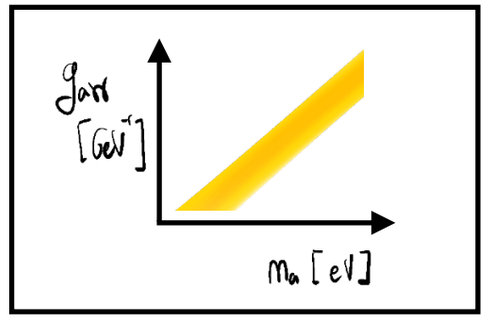
pseudo-scalar $-\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} + \frac{1}{4} g_{aN\gamma}\, a\, \bar{n}\sigma_{\mu\nu} n F^{\mu\nu} - g_{aNN}(\partial_\mu a)\bar{n}\gamma^\mu\gamma_5 n$

10^{-22} eV — eV — GeV — 100 TeV — M_{Pl} — $M_\odot$

Haloscopes (e.g. ADMX, ABRA…)



Axion searches



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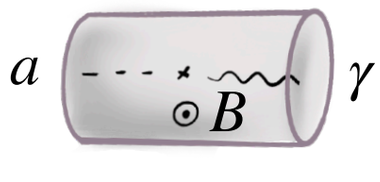
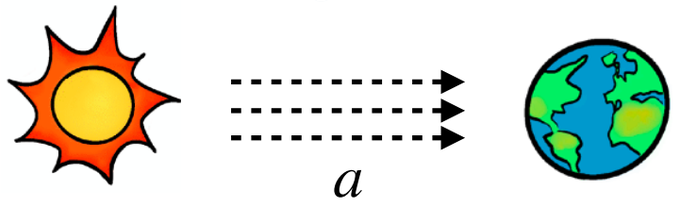
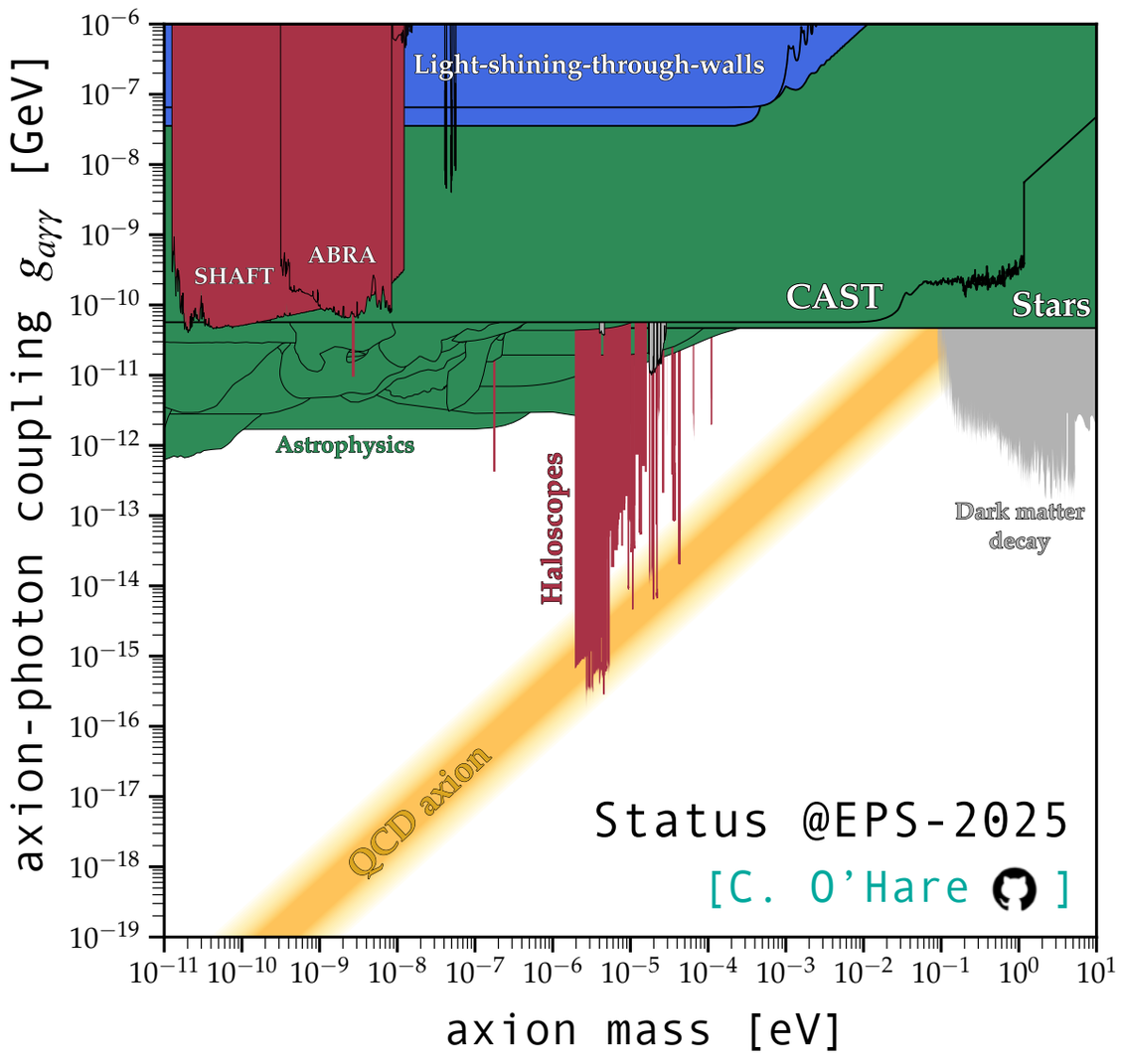
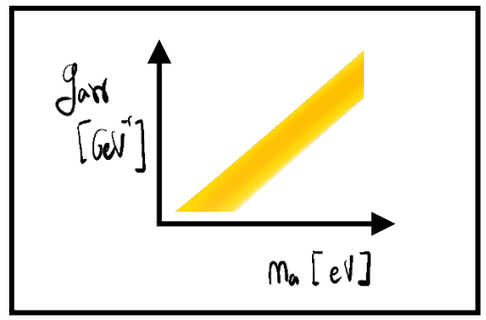


Helioscopes (e.g. CAST, IAXO)





Axion searches



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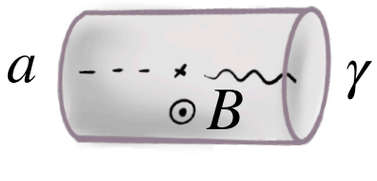

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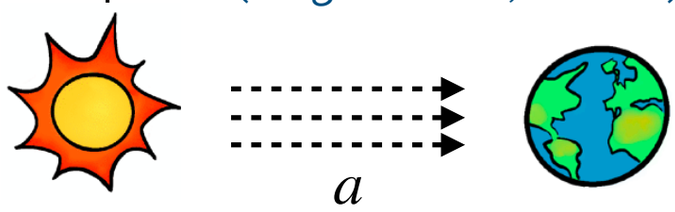
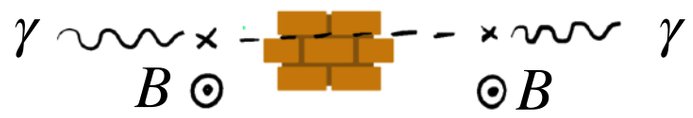
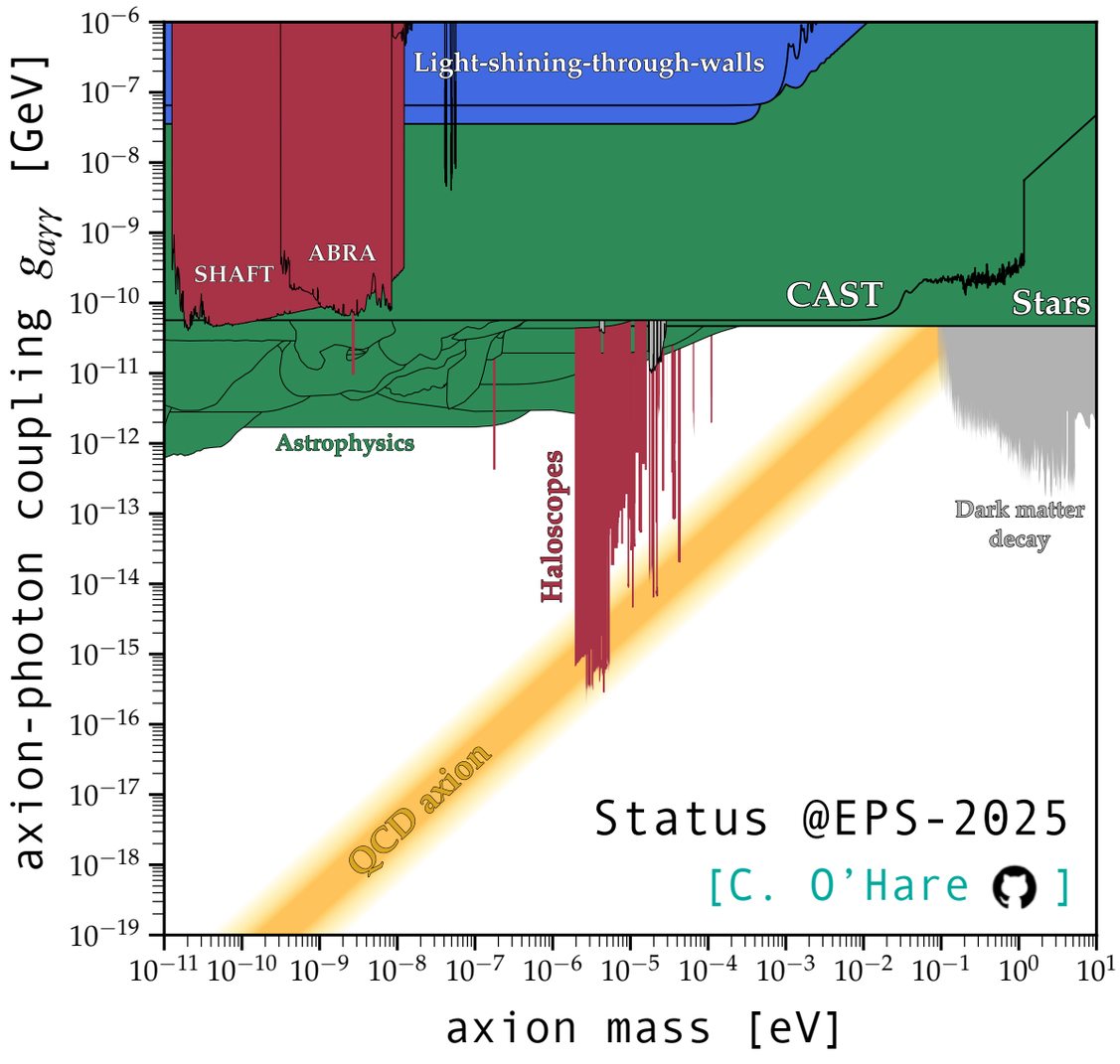


Light-shining-through-walls
(e.g. ALPS-II) [JA Rubiera Gimeno today]



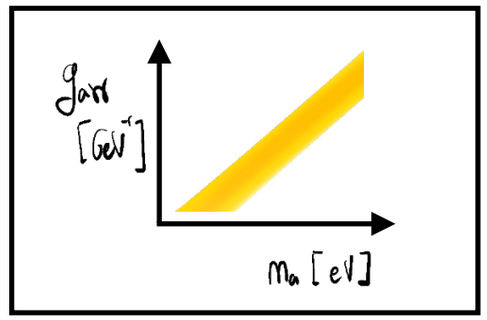
Astrophysics (e.g. SN1987A, FermiLAT…)

Colliders (e.g. LHC),
beam bump (e.g. NA62, SHiP…)



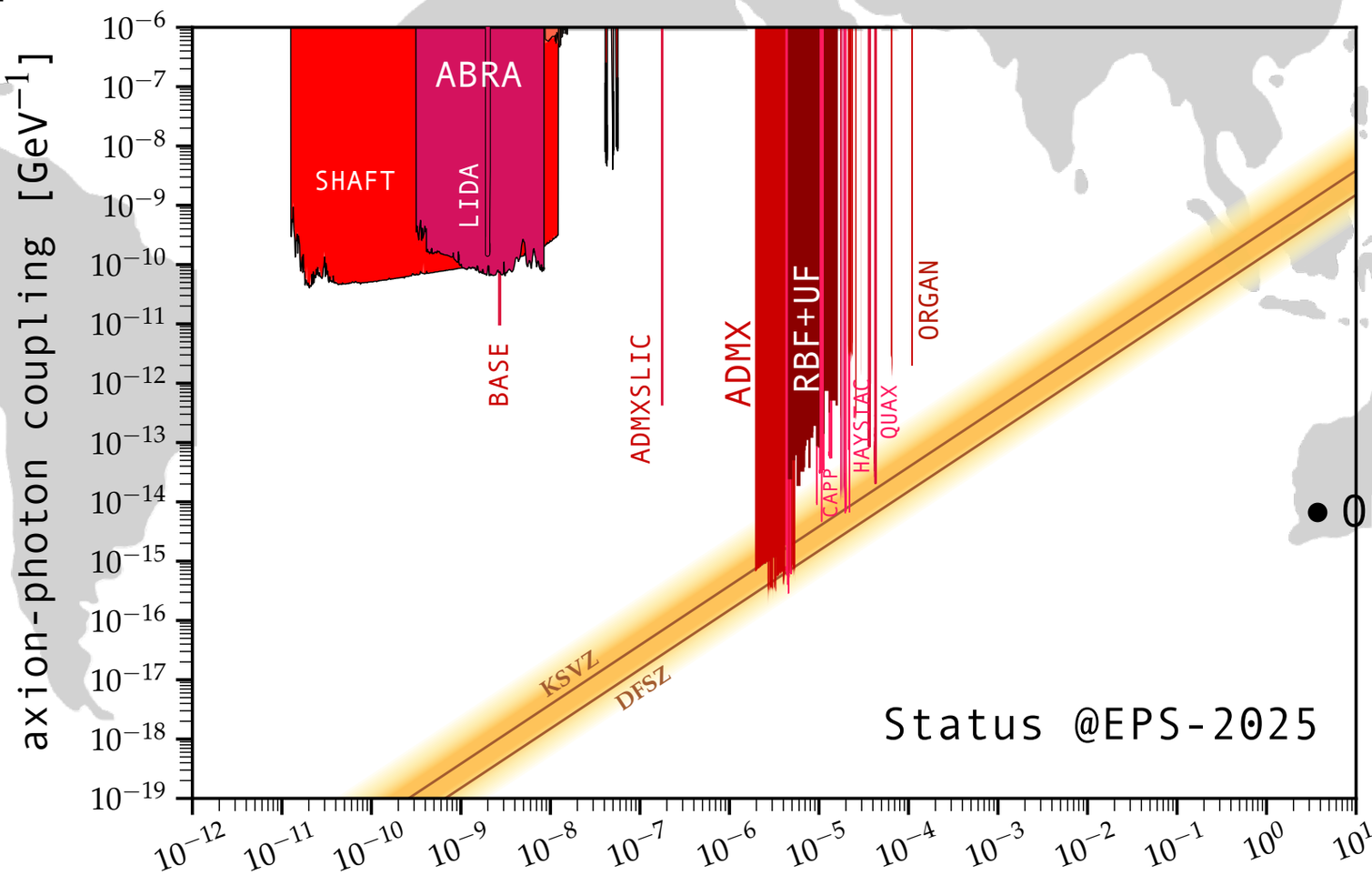
Axion searches

haloscopes



10^{-22} eV — eV — GeV — 100 TeV — M_{Pl} — $M_\odot$

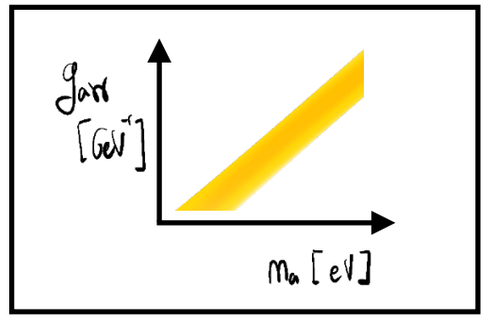
- ADMX
- RBF
- HAYSTAC
- ABRA
- UF
- LIDA
- BASE
- GrAHal
- QUAX
- [A Talarmin on Monday]
- CAPP
- ORGAN



[C. O'Hare]

Axion searches

haloscopes



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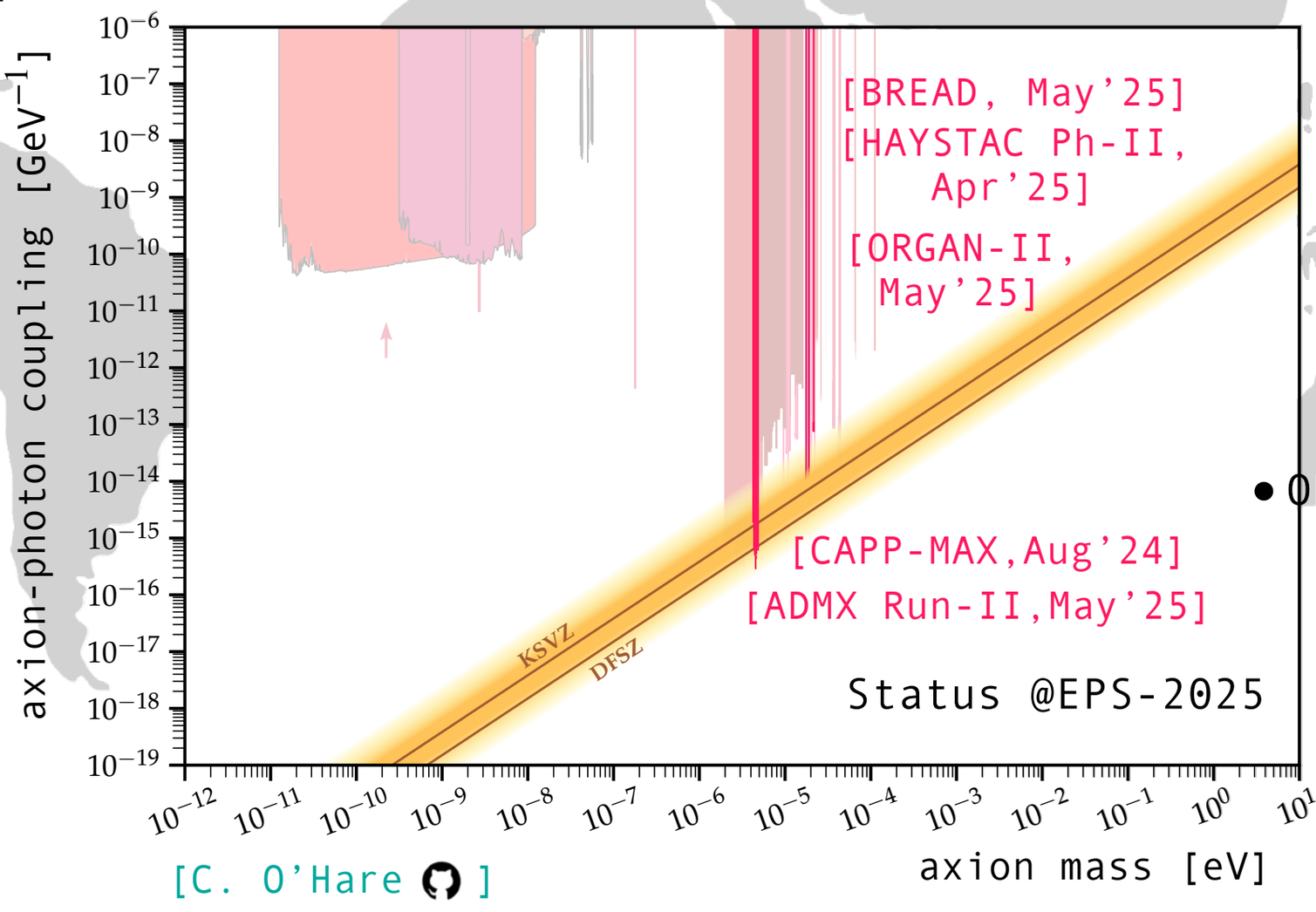
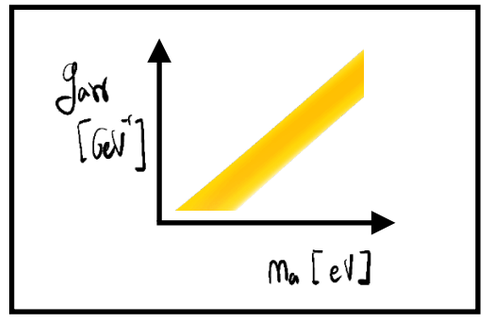


[C. O'Hare]

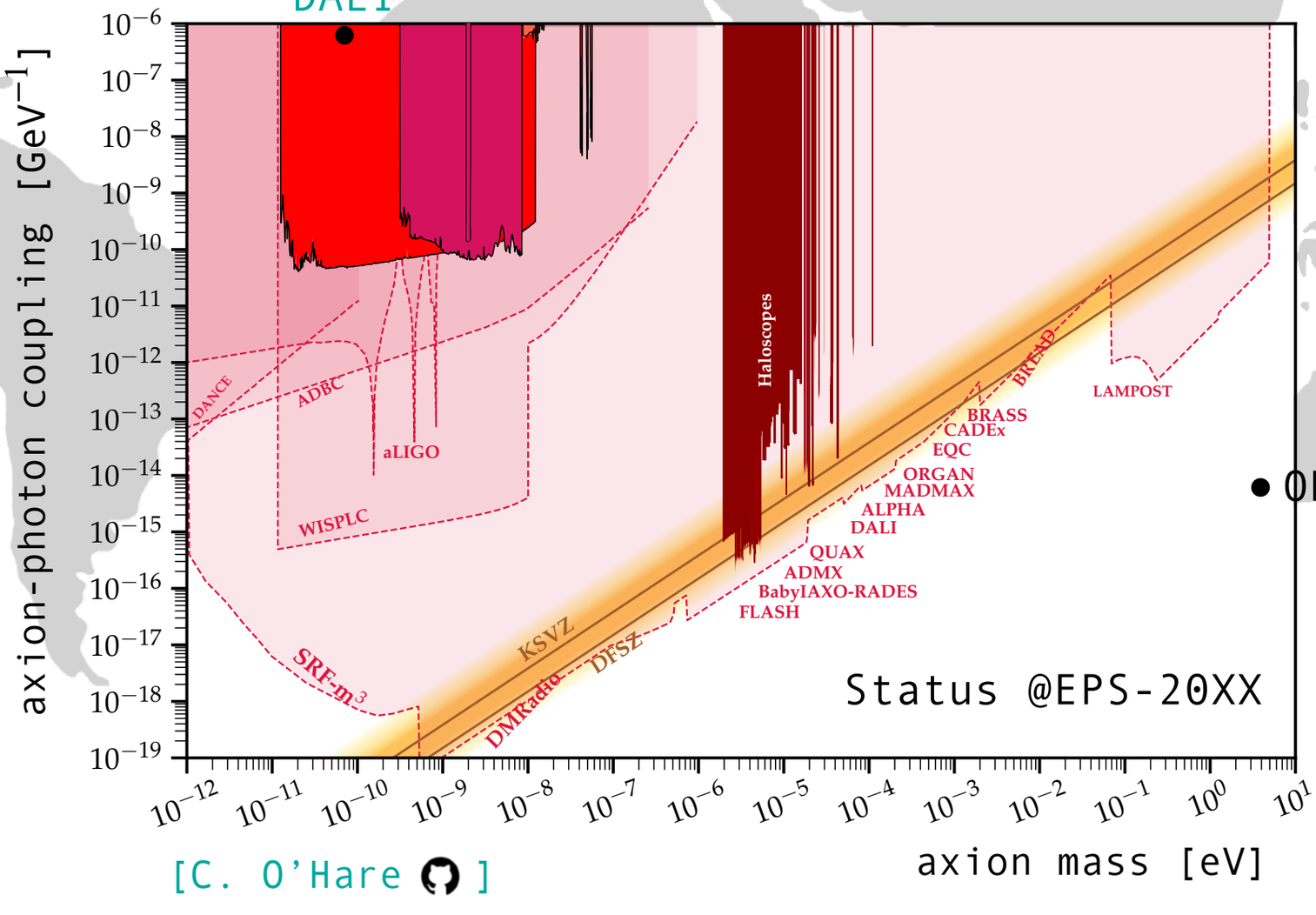
Axion searches

haloscopes



10^{-22} eV ••• eV ••• GeV ••• 100 TeV ••• M_{Pl} ••• $M_\odot$

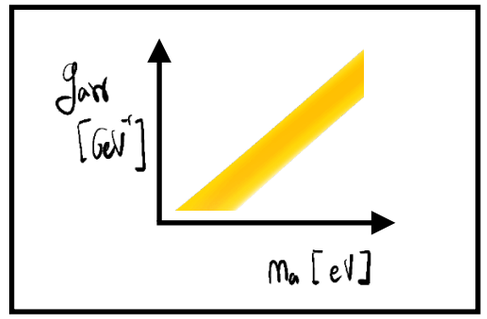
ADMX
BREAD
RBF
LAMPOST
HAYSTAC
ABRA
DMRadio
UF
ADBC
DALI
LIDA
BRASS
WISPLC
MADMAX
BabyIAXO
BASE
[F. Hubaut on Monday]
CADEx
FLASH
RADES
CAPP
DANCE
ORGAN

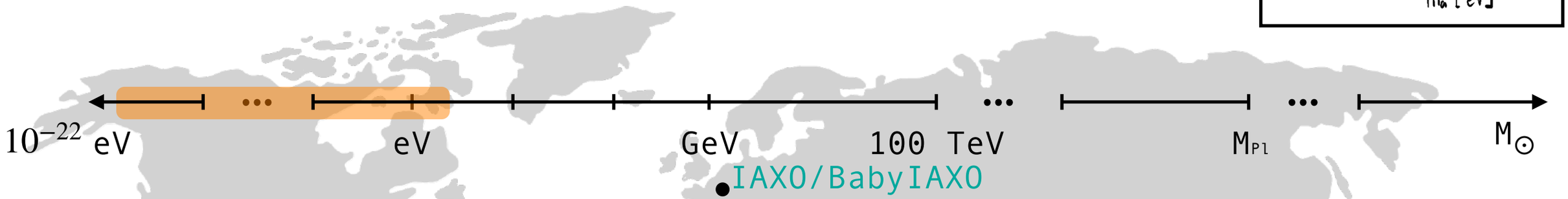


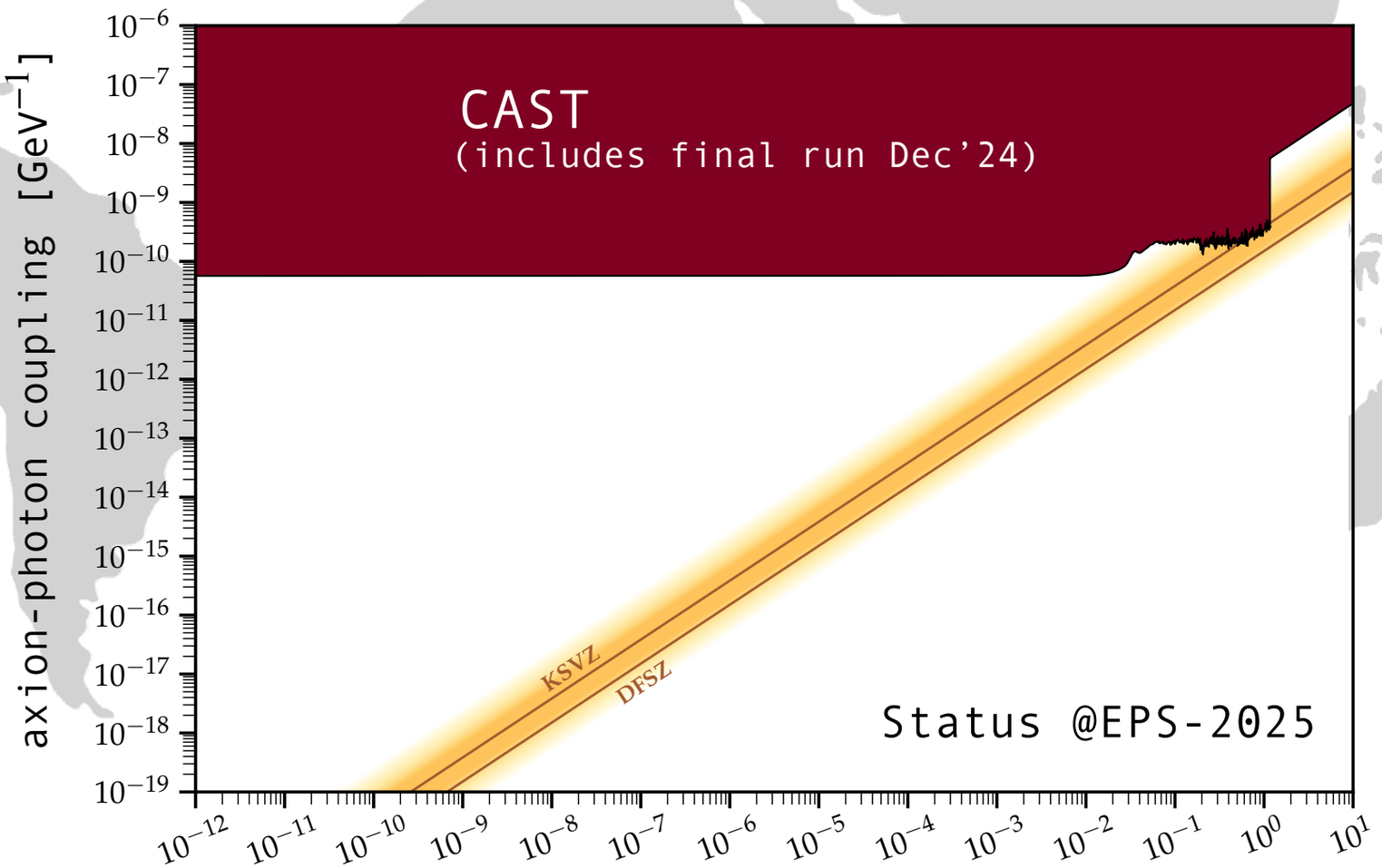
[C. O'Hare]

Axion searches

helioscopes



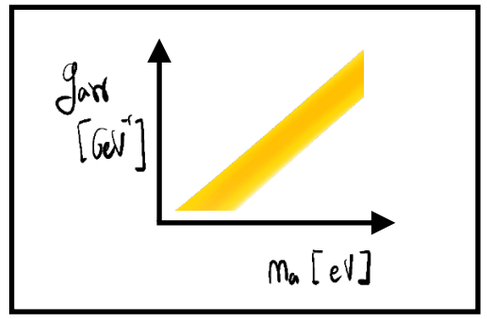


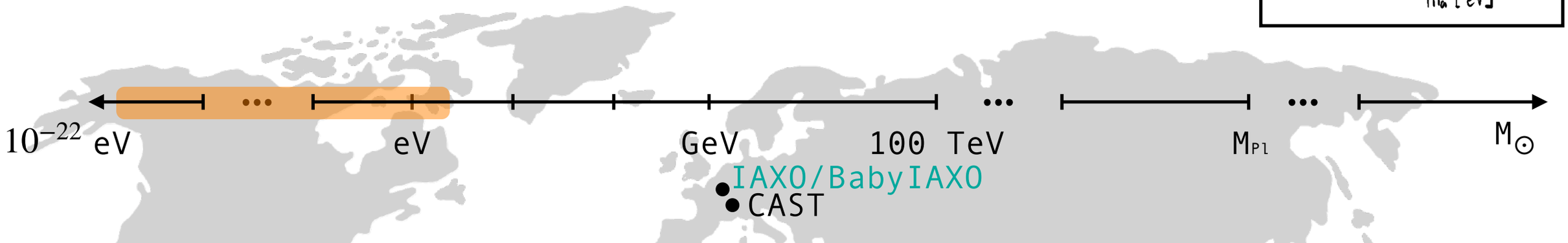


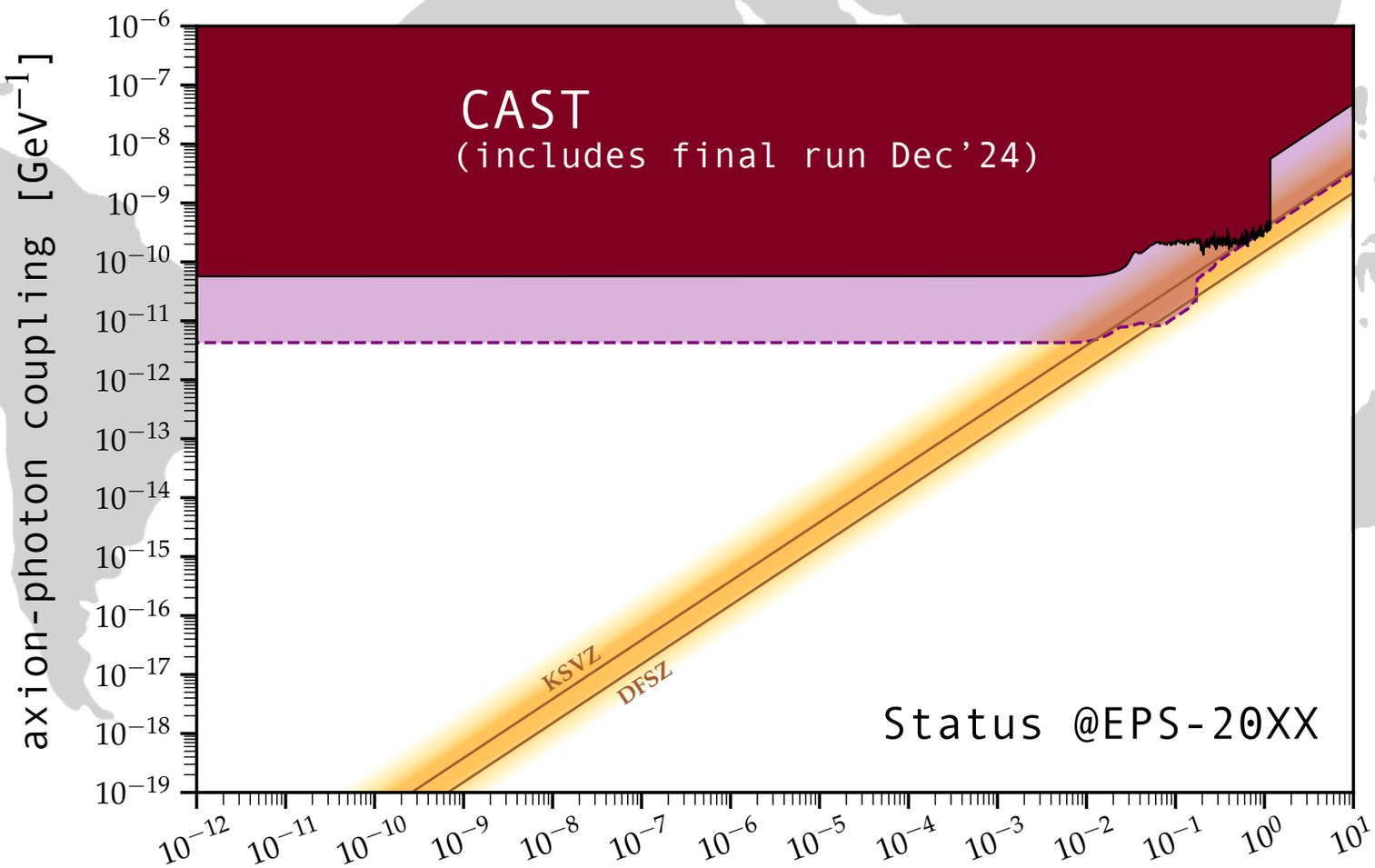
[C. O'Hare]

Axion searches

helioscopes



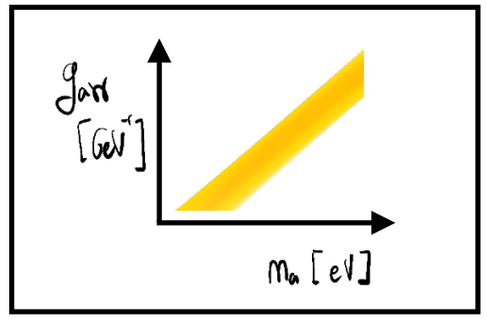


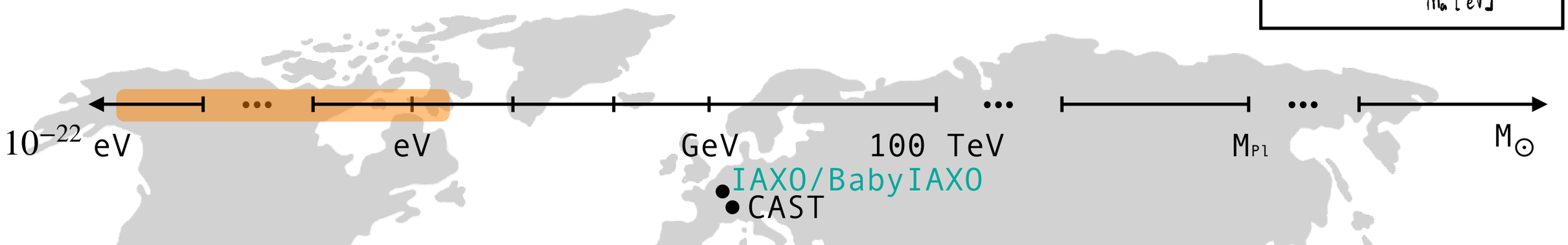


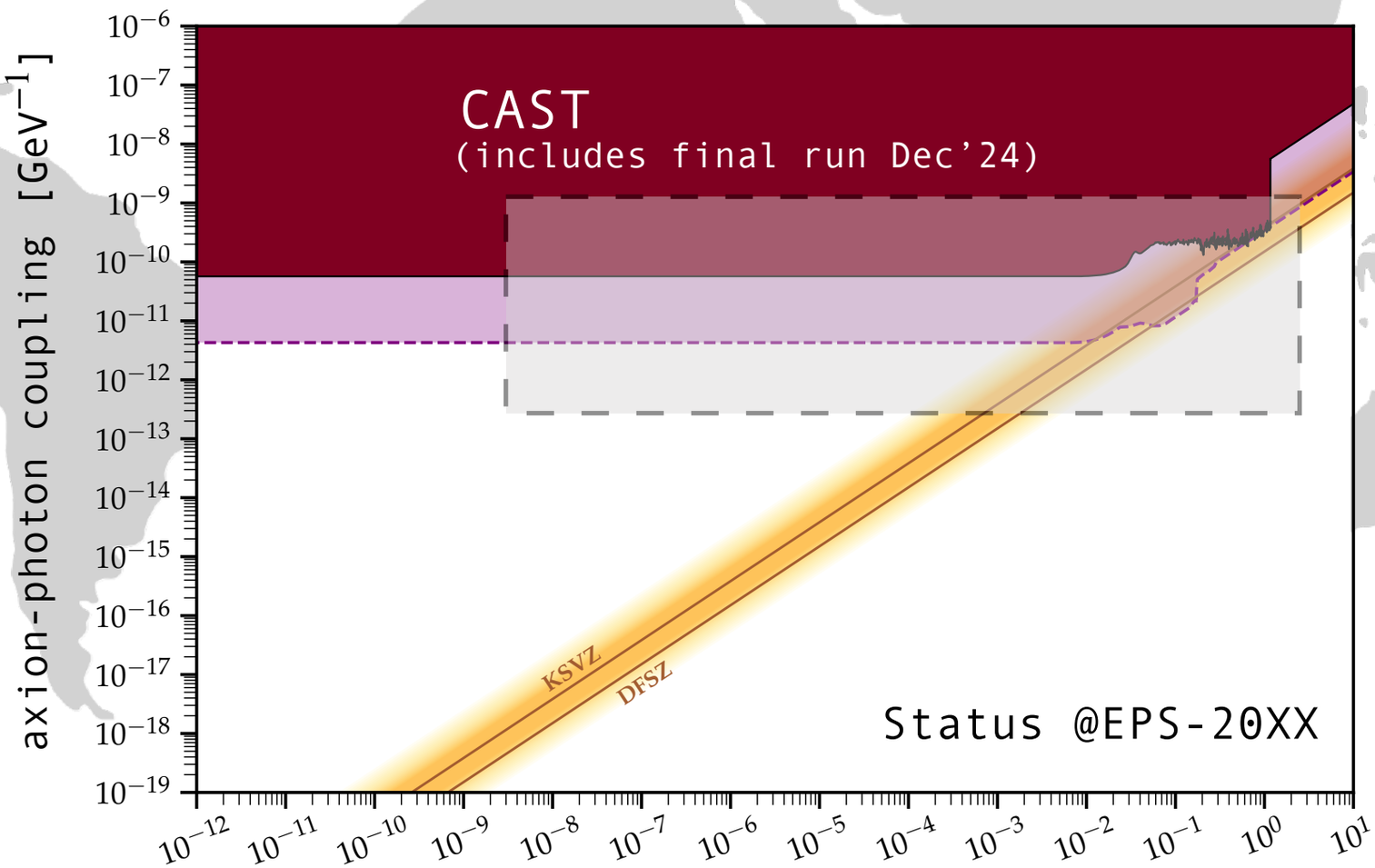
[C. O'Hare]

Axion searches

helioscopes



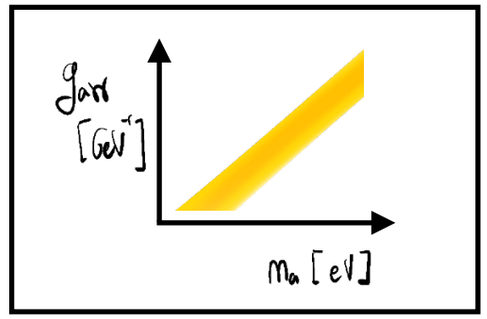




[C. O'Hare]

Axion searches

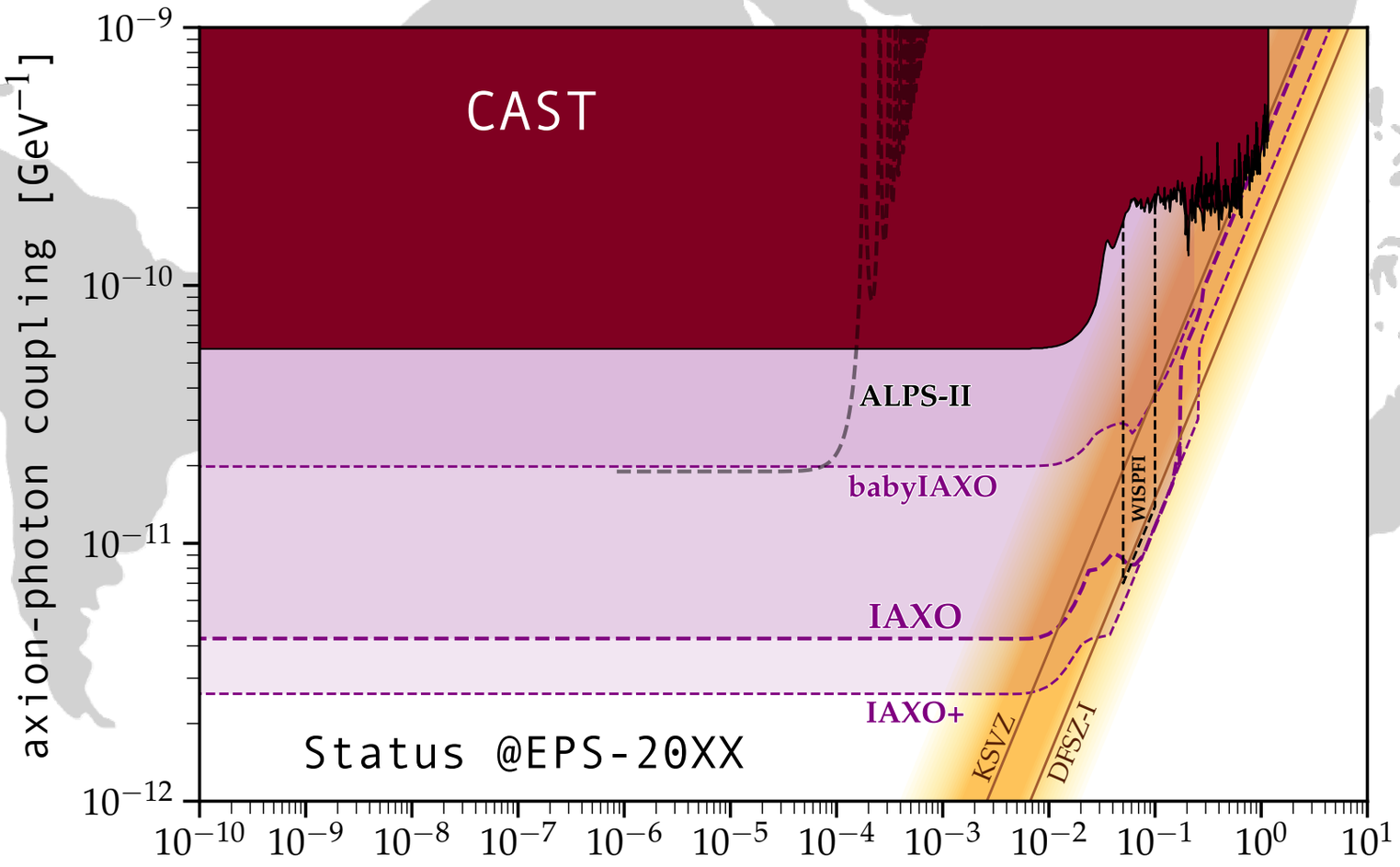
helioscopes



10^{-22} eV — eV — GeV — 100 TeV — M_{Pl} — $M_\odot$

IAXO/BabyIAXO

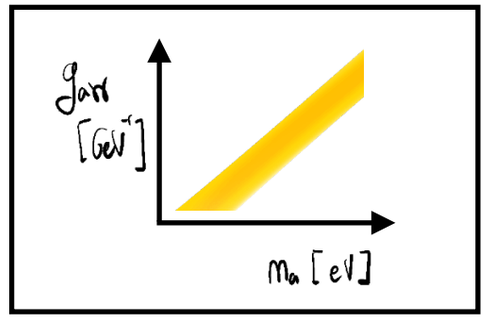
CAST

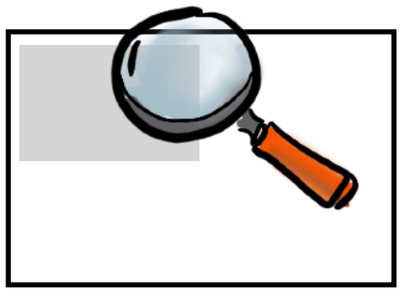


[C. O'Hare]

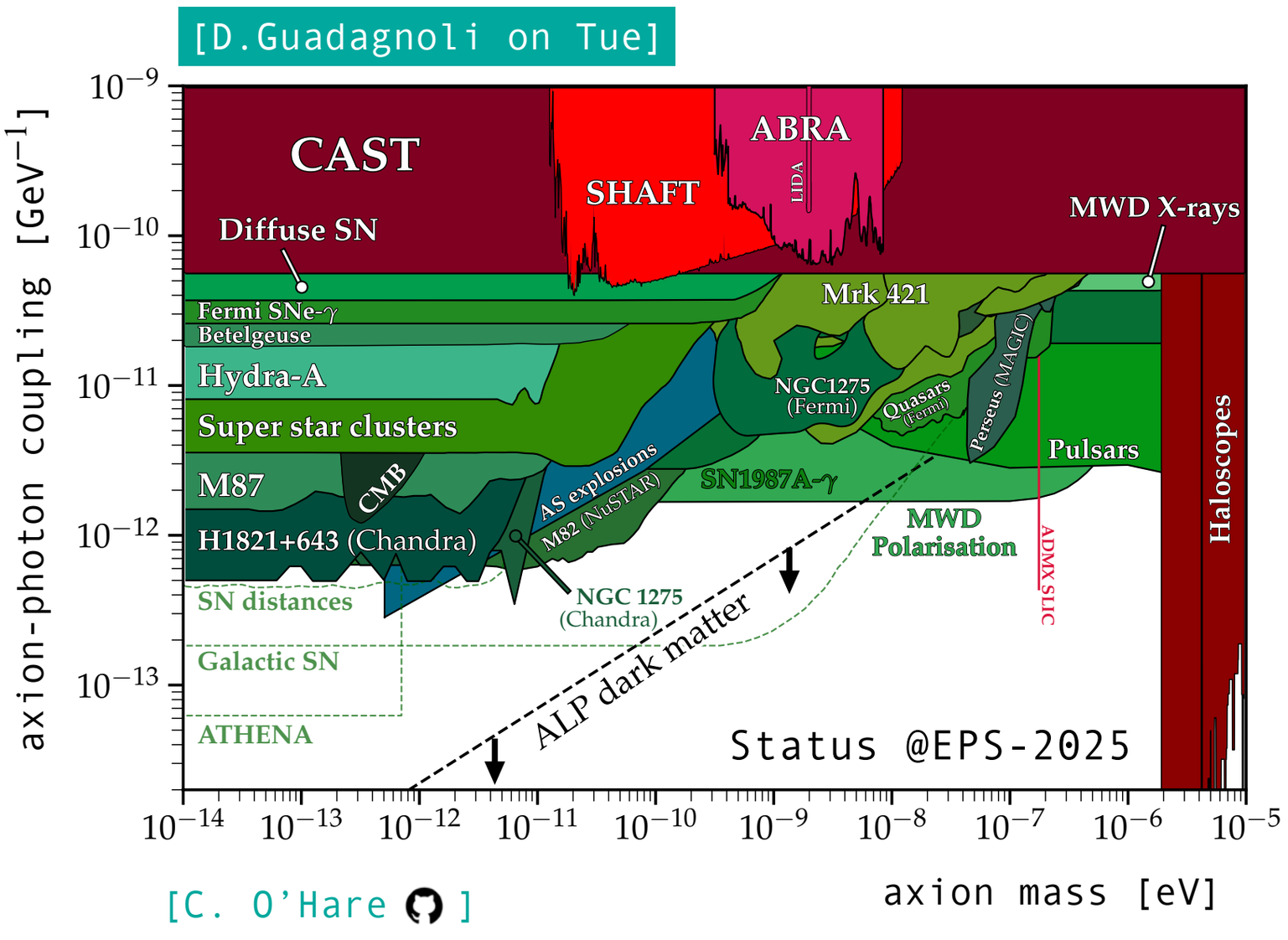
Axion searches

astrophysics





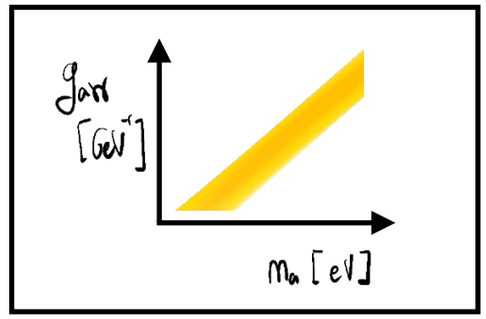
[D.Guadagnoli on Tue]

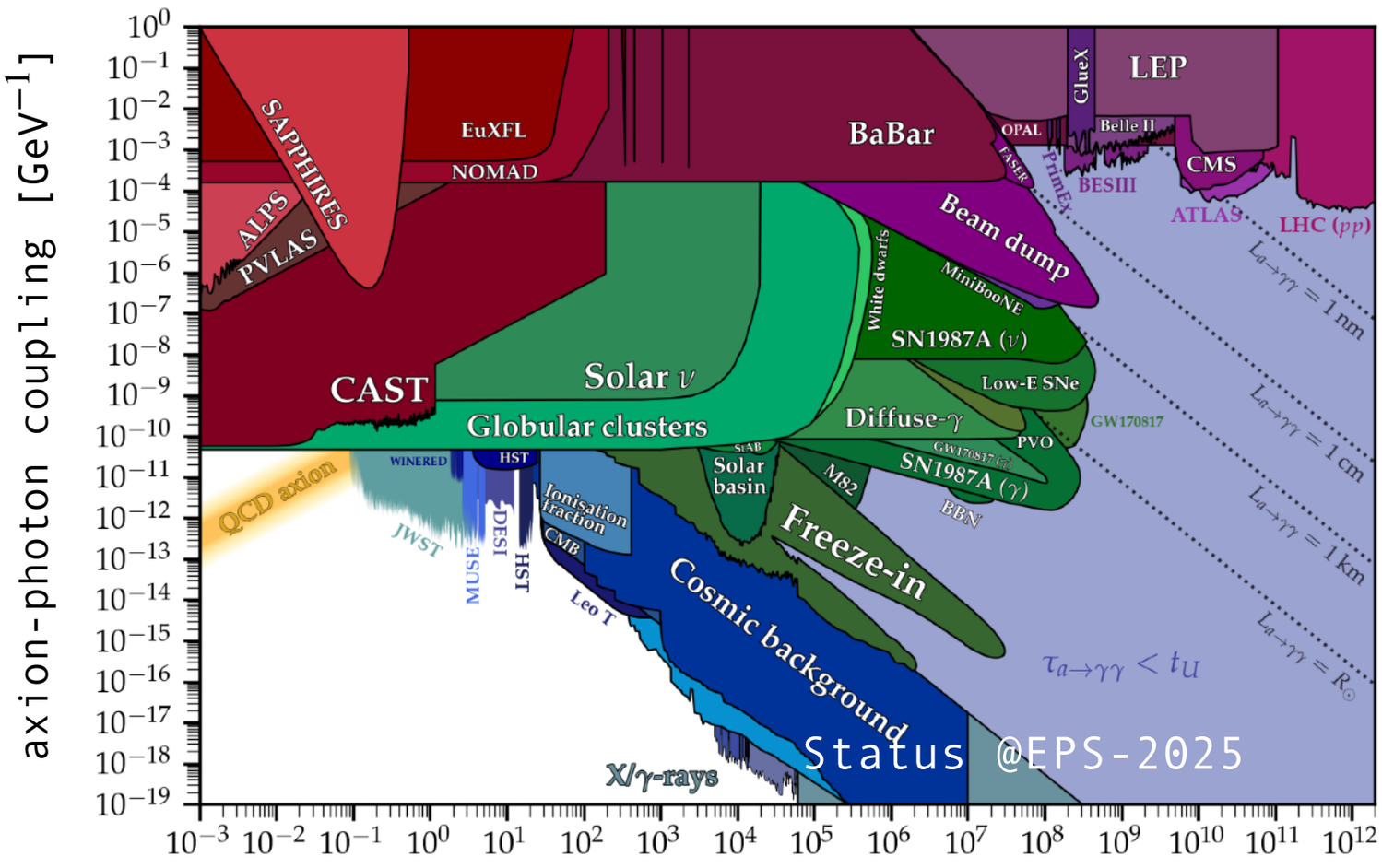


[C. O'Hare]

Axion searches

colliders / beam dump

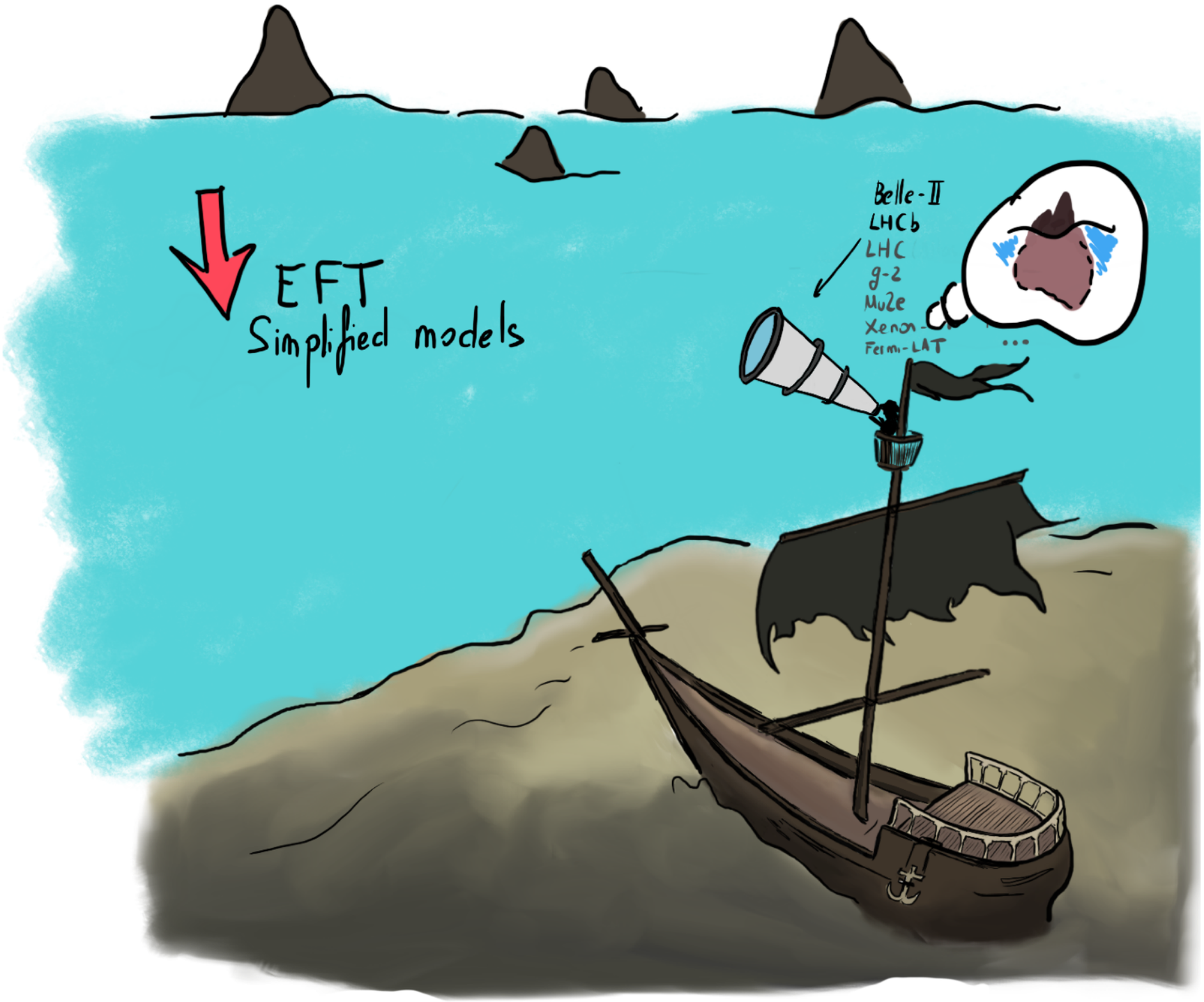




[C. O'Hare]

What if?

Something is found tomorrow



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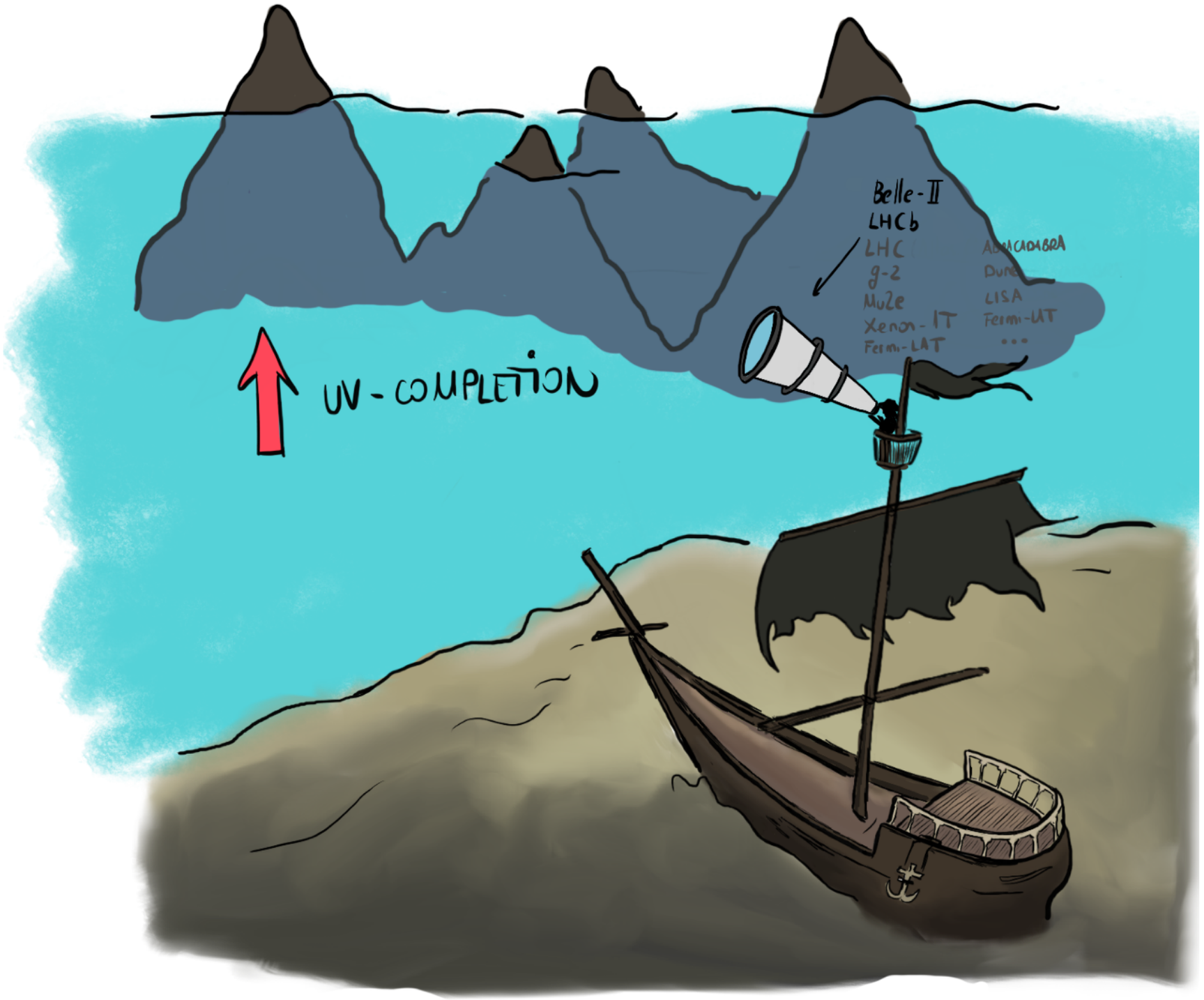

Conclusions

Top-bottom: Having a goal

Energy(GeV)

Well motivated benchmarks are being (and will be) tested!

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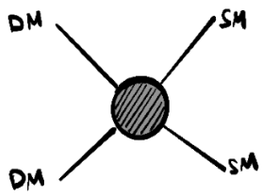

WIMP dark matter cornered by DD & ID searches.

e.g. neutralino (SUSY) [Rodd, Safdi, Xu, '24]

$$\text{DM} = \alpha(\text{bino}) + \beta(\text{wino}) + \gamma(\text{higgsinos})$$

Conclusions

Top-bottom: Having a goal

Energy(GeV)

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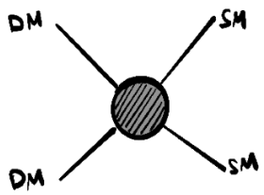

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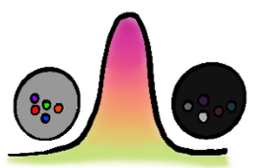

SubGeV DM is not longer an untouched frontier. Although still largely unconstrained, promising low energy threshold detectors are being explored.

Conclusions

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Energy(GeV)

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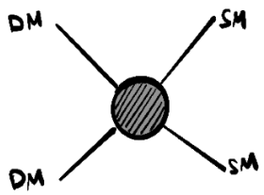

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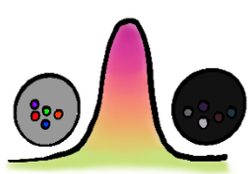

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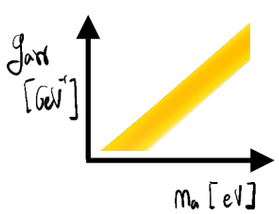
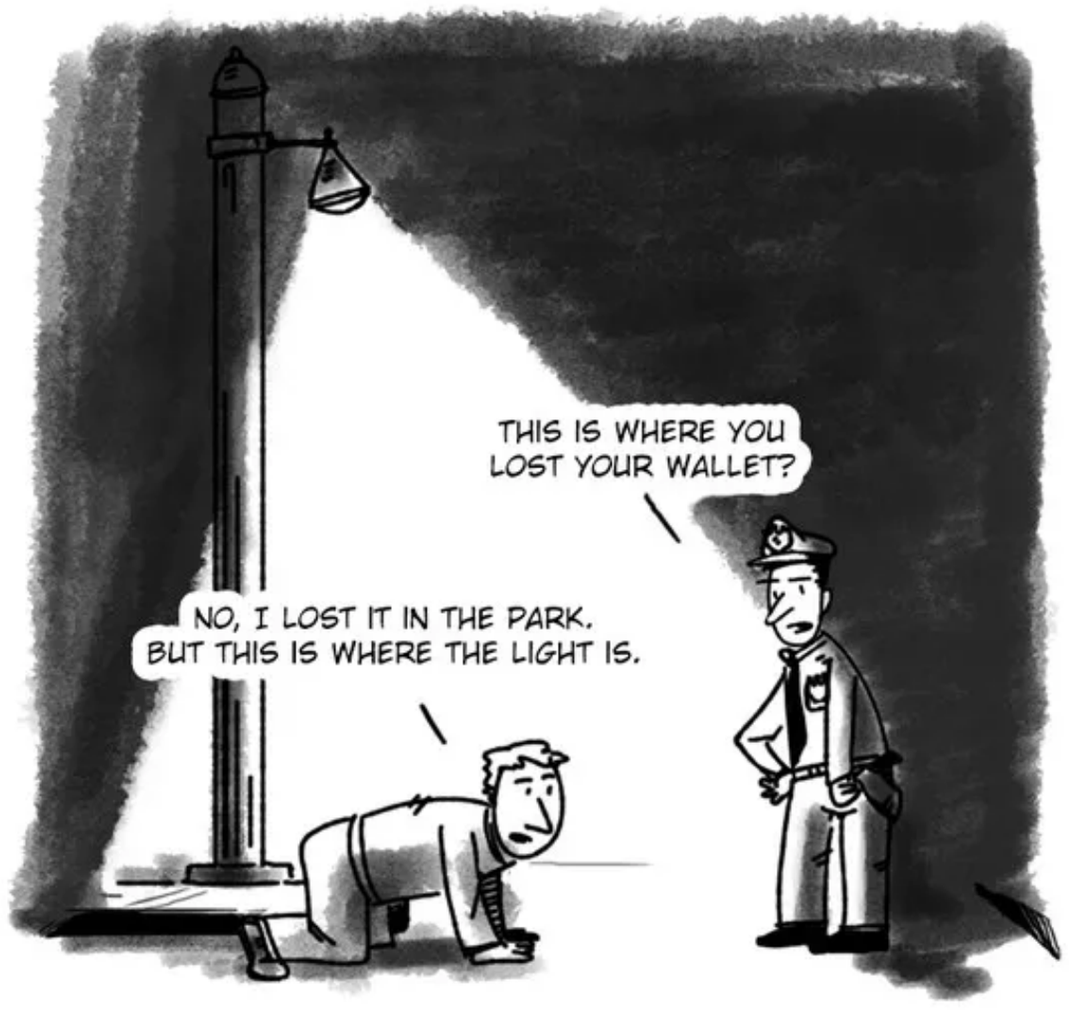


The QCD axion starts being challenged! We will know if it is our dark matter candidate within a decade scale (although non-standard cosmologies may still survive).

Conclusions

Bottom-up: Being open

Energy(GeV)



Conclusions

Bottom-up: Being open

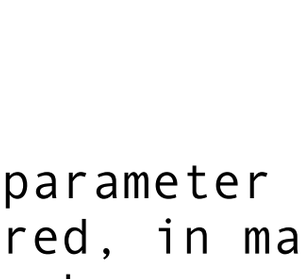
Energy(GeV)

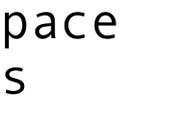
Lots of new parameter space will be covered, in mass range and reach.

DIALOG between communities is crucial.

Watch out for parasitic searches!

Balance according to constraints…





“Searching means: having a goal. But finding means: being free, being open, having no goal. You, oh venerable one, are perhaps indeed a searcher, because, striving for your goal, there are many things you don’t see, which are directly in front of your eyes.”

— Siddhartha, by Hermann Hesse.