14 June 2021
LPNHE

Dark Matter candidates circa 2021:
the WIMPs and beyond the WIMPs

Marco Cirelli
(CNRS LPTHE Jussieu Paris)

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Dark Matter candidates circa 2021:
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Candidates

The Dark Matter theory space:

Candidates

The Dark Matter theory space:

SuSy DM

Non SuSy DM

Candidates

The Dark Matter theory space:

SuSy DM

Non SuSy DM

?

Candidates

A matter of perspective:

SuSy neutralino

other exotic candi-dates

Candidates

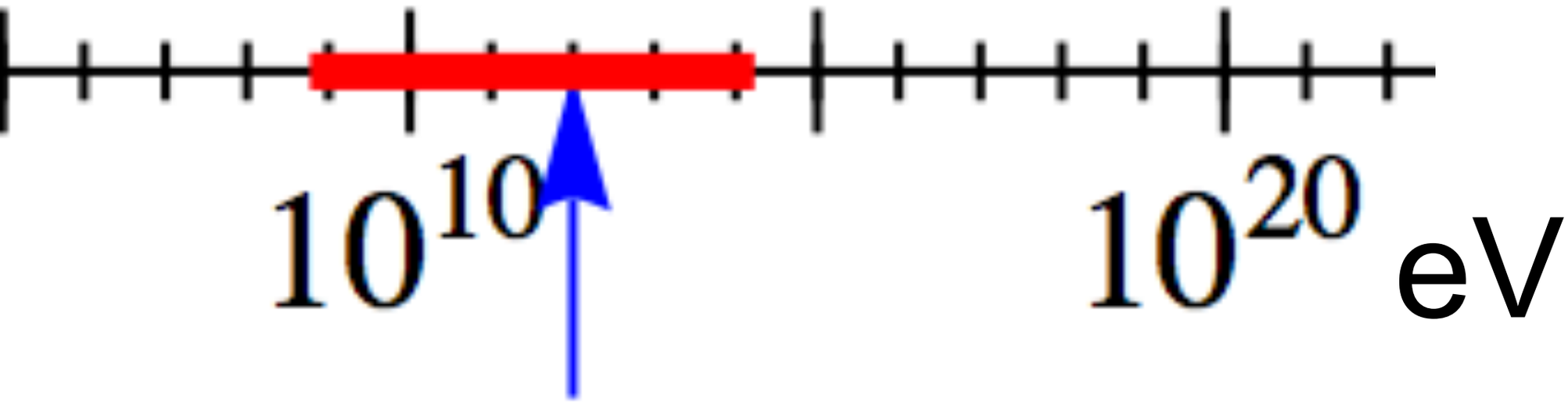
graviballs DM
Large Nightmare DM
omeopathic DM
Ballistic DM
Spectato DM
Undulating DM
Zombie DM
Puffy DM
Fuzzy DM
Cannibal DM
Minimal DM
Impede DM
Little Higgs DM
Fluffy DM
Asym-metric DM
Anapole DM
Axino
dipolar DM
SIMPs
ELDER DM
self-destructing DM
SuSy neutralin
foamy DM
Techi-baryon
Rayleig DM
eXciting
Inflatable DM
Dichromatic DM
WIMPzillas
Vector DM
STUMP DM
charming DM
Pandemic DM
Leptobary DM
Relentless DM
Sterile Neutrino
Luminous DM
Geometric DM
Elko DM
Gravitino
quark uggets
MeV DM
Q-balls
Fluorescent DM
dark photon
Imperfect
Higgs ploding
Mimetic DM

Candidates

A matter of perspective: plausible mass ranges

thermal

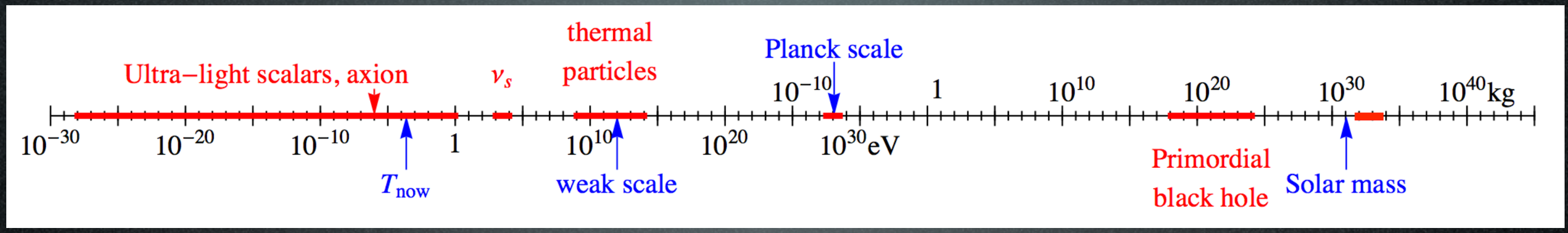
particles



weak scale (1 TeV)

Candidates

A matter of perspective: plausible mass ranges

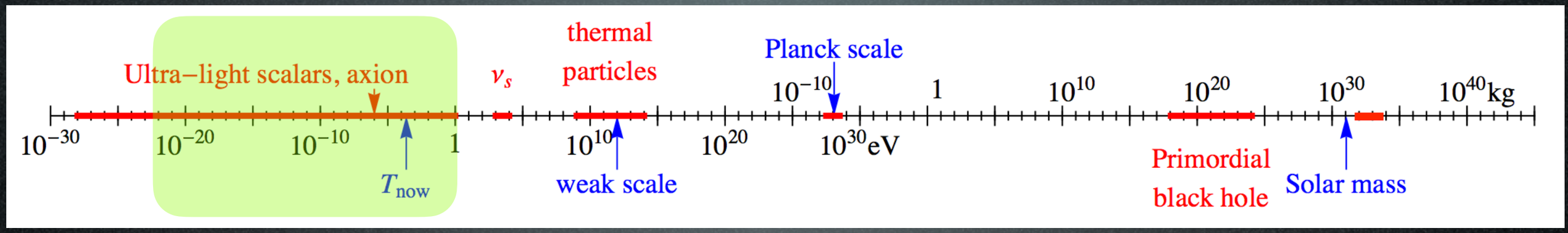


90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges

field



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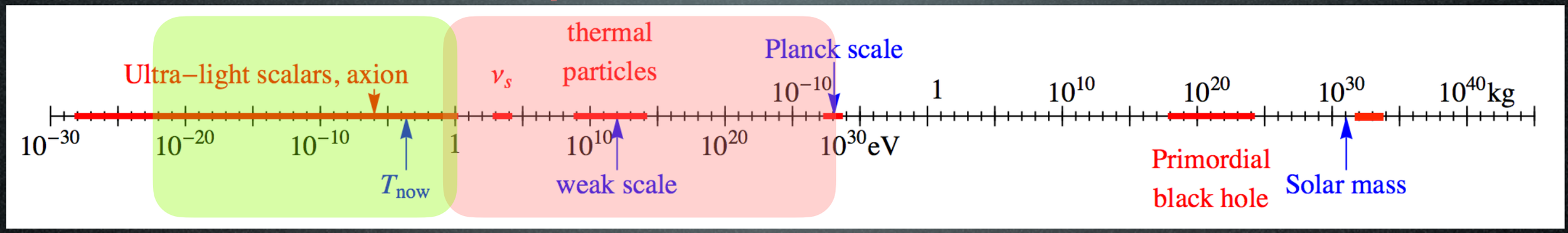
Candidates

A matter of perspective: plausible mass ranges

field particle



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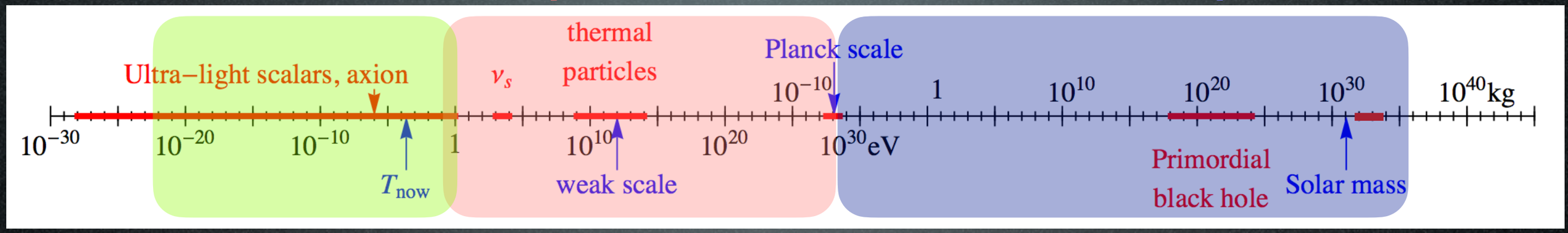
Candidates

A matter of perspective: plausible mass ranges

field particle macroscopic



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Candidates

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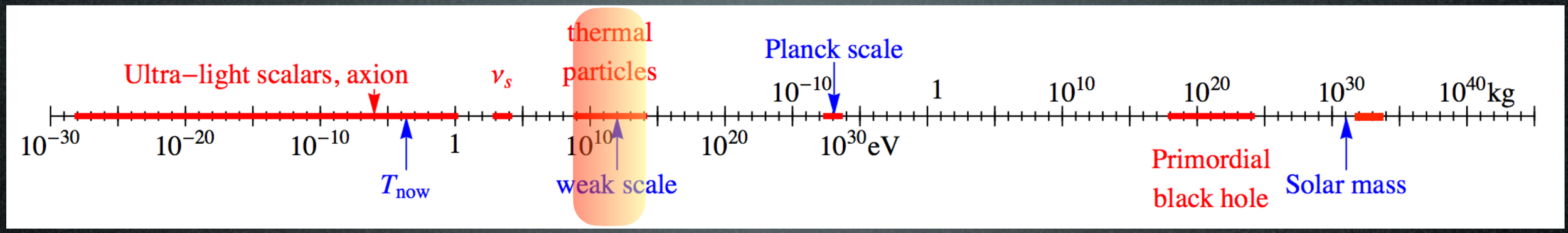

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Candidates

WIMPs

Candidates

new physics at the TeV scale

thermal freeze-out

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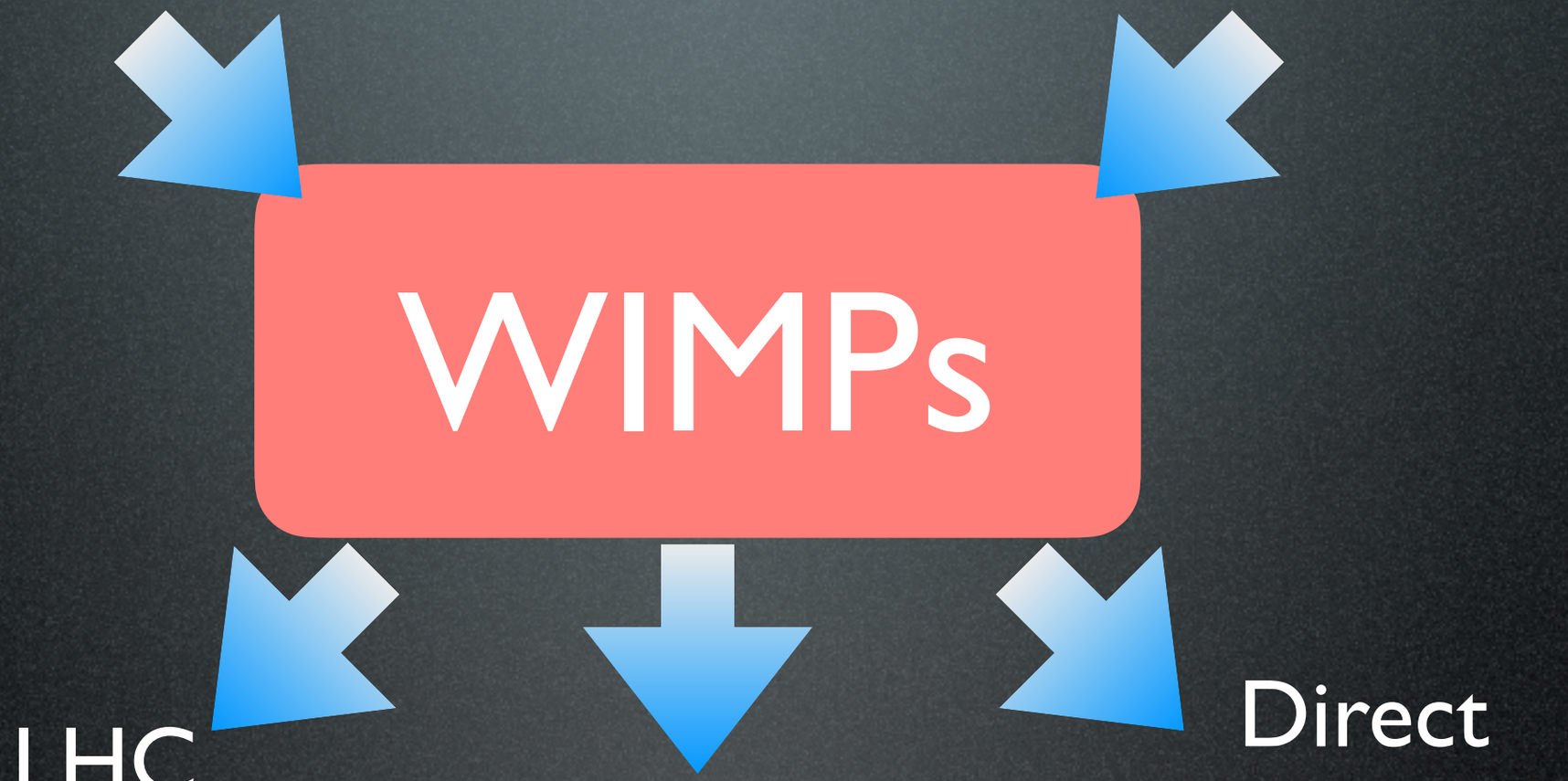


LHC

Indirect Detection

Direct Detection

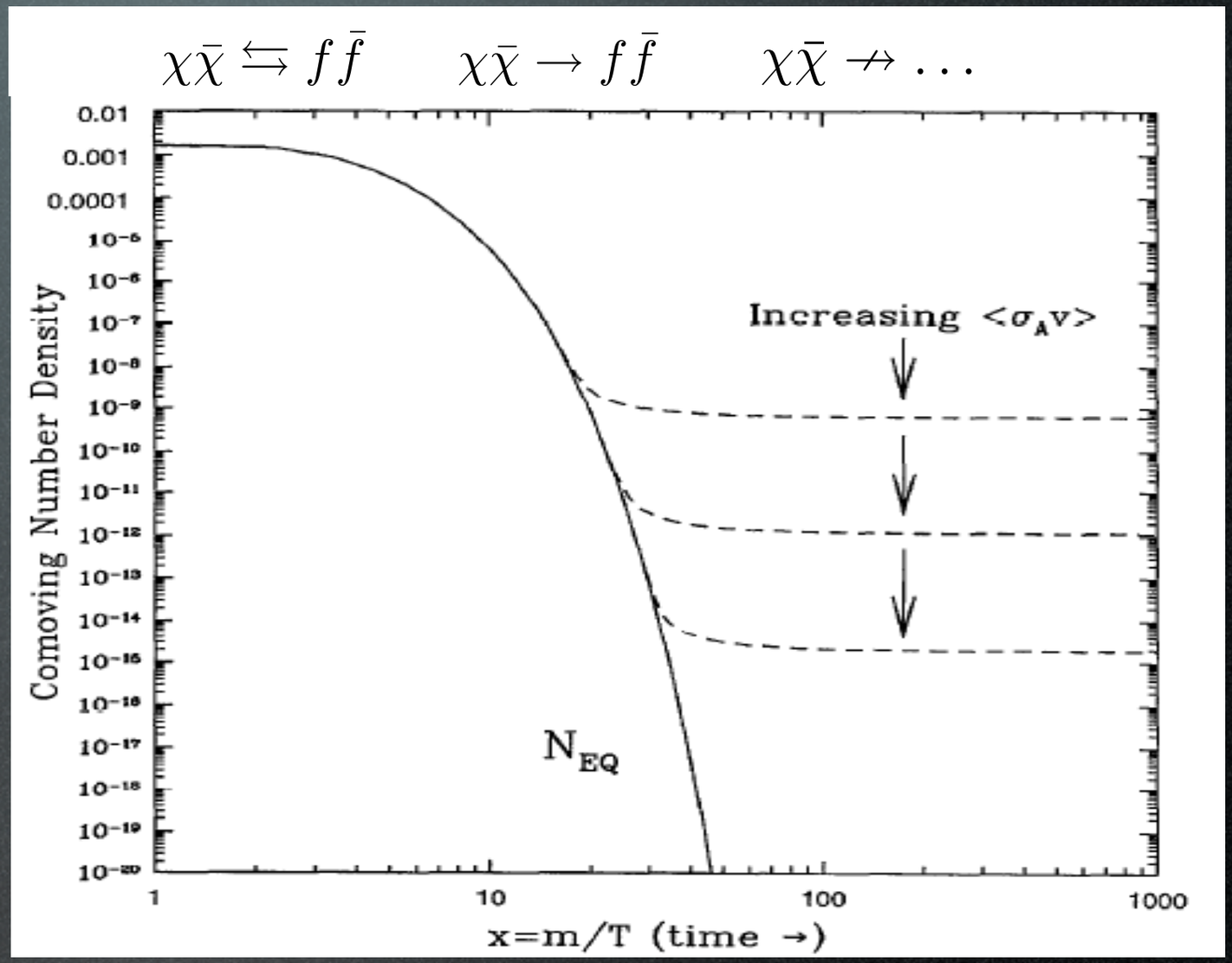
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}}v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}}v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

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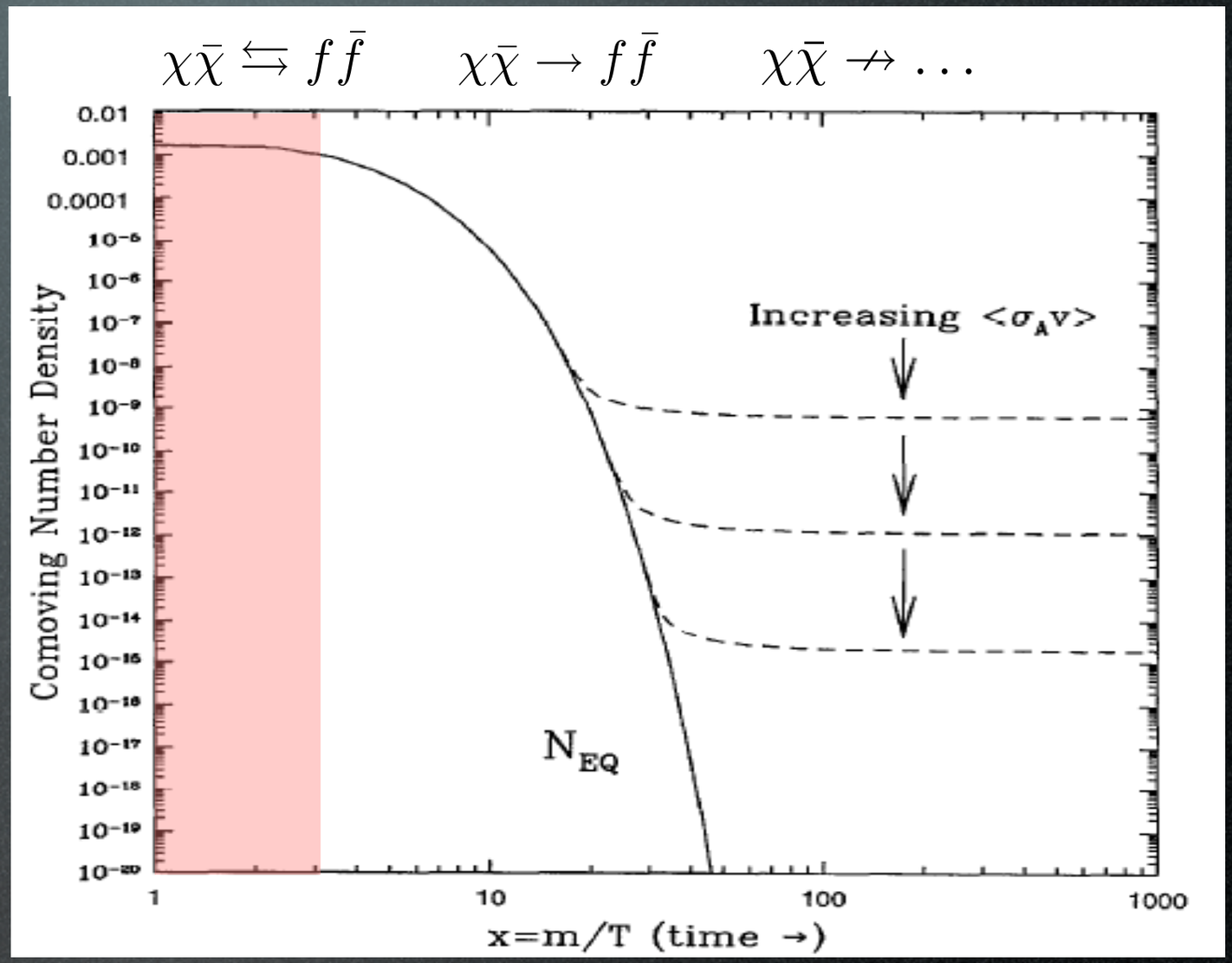

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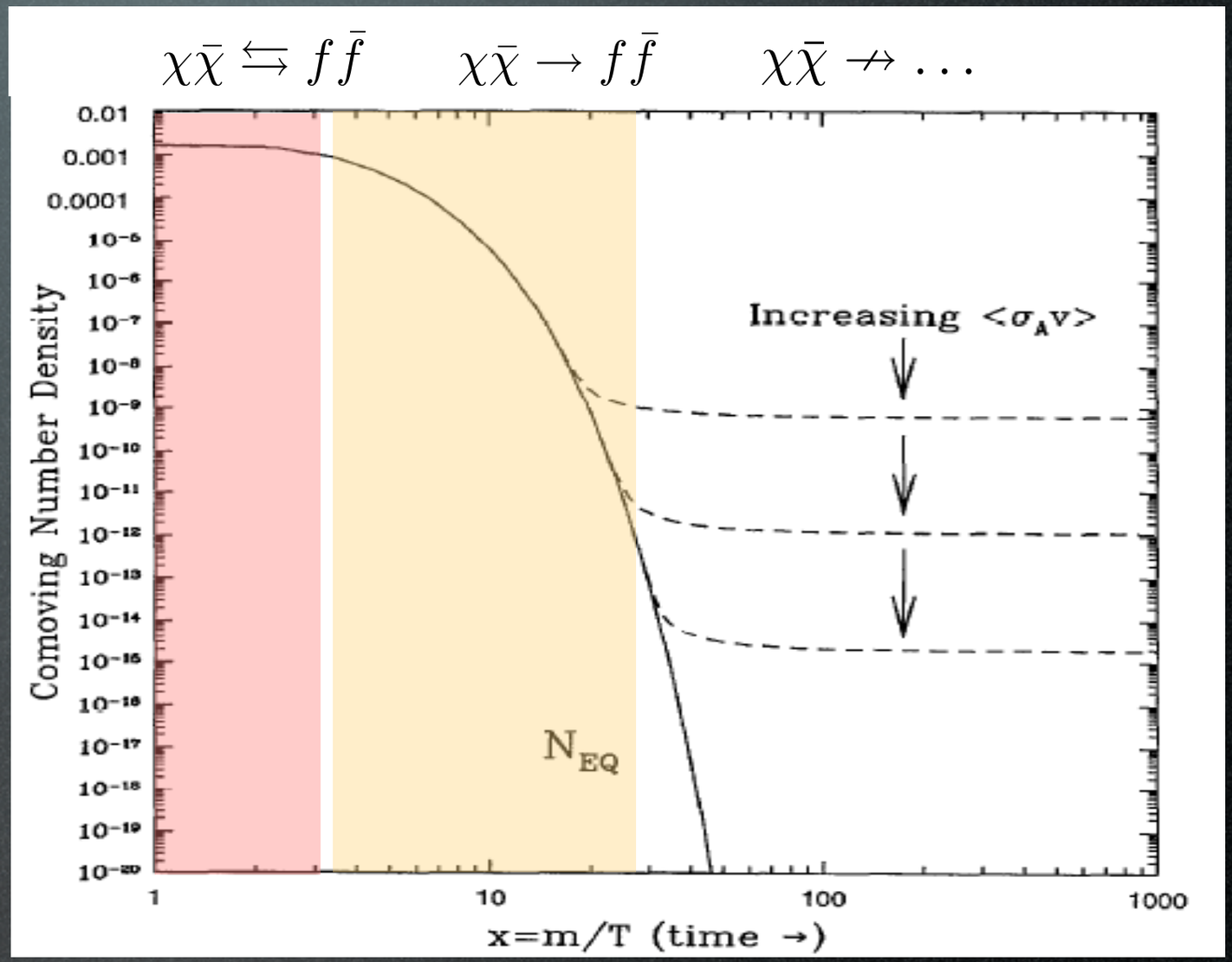

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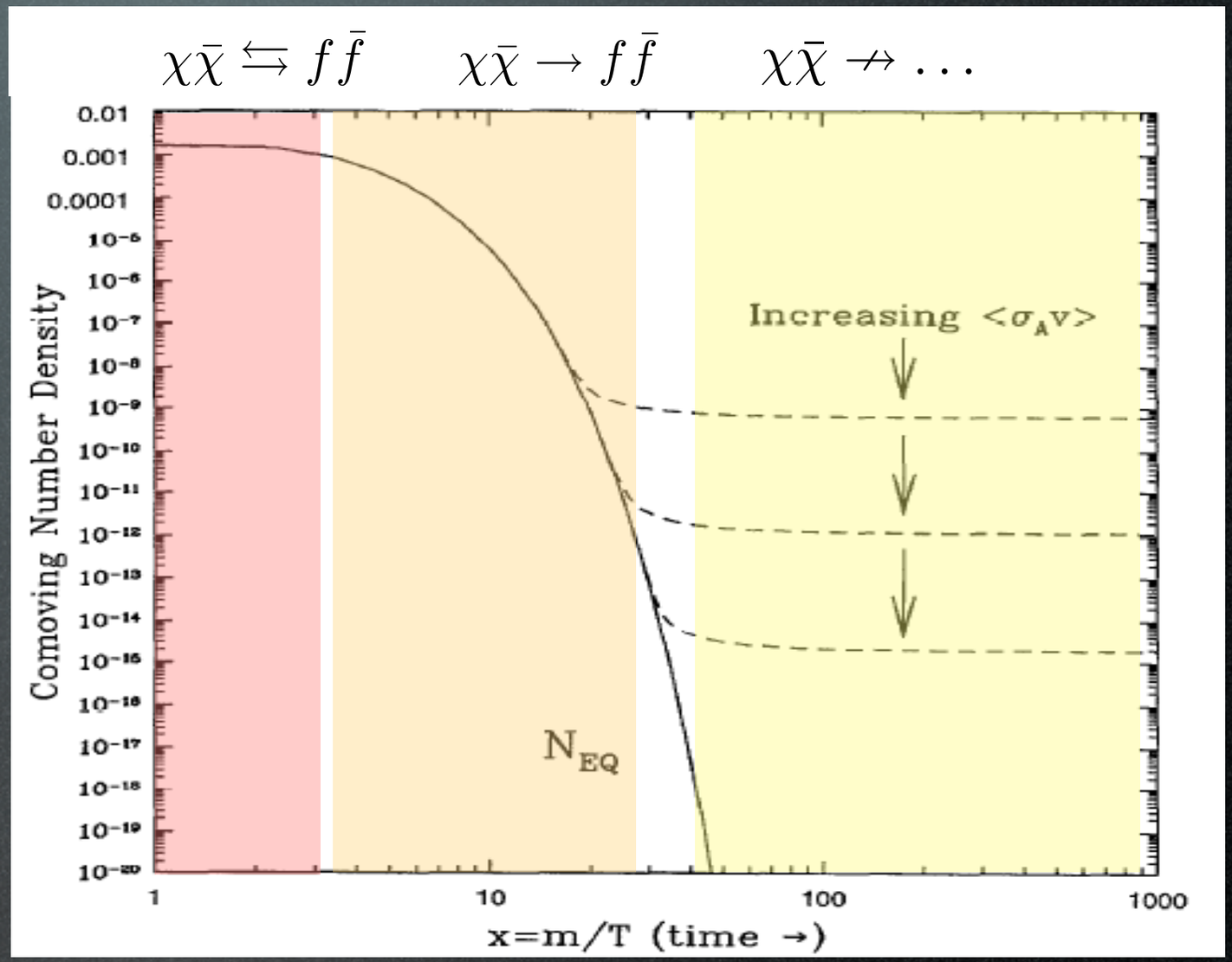

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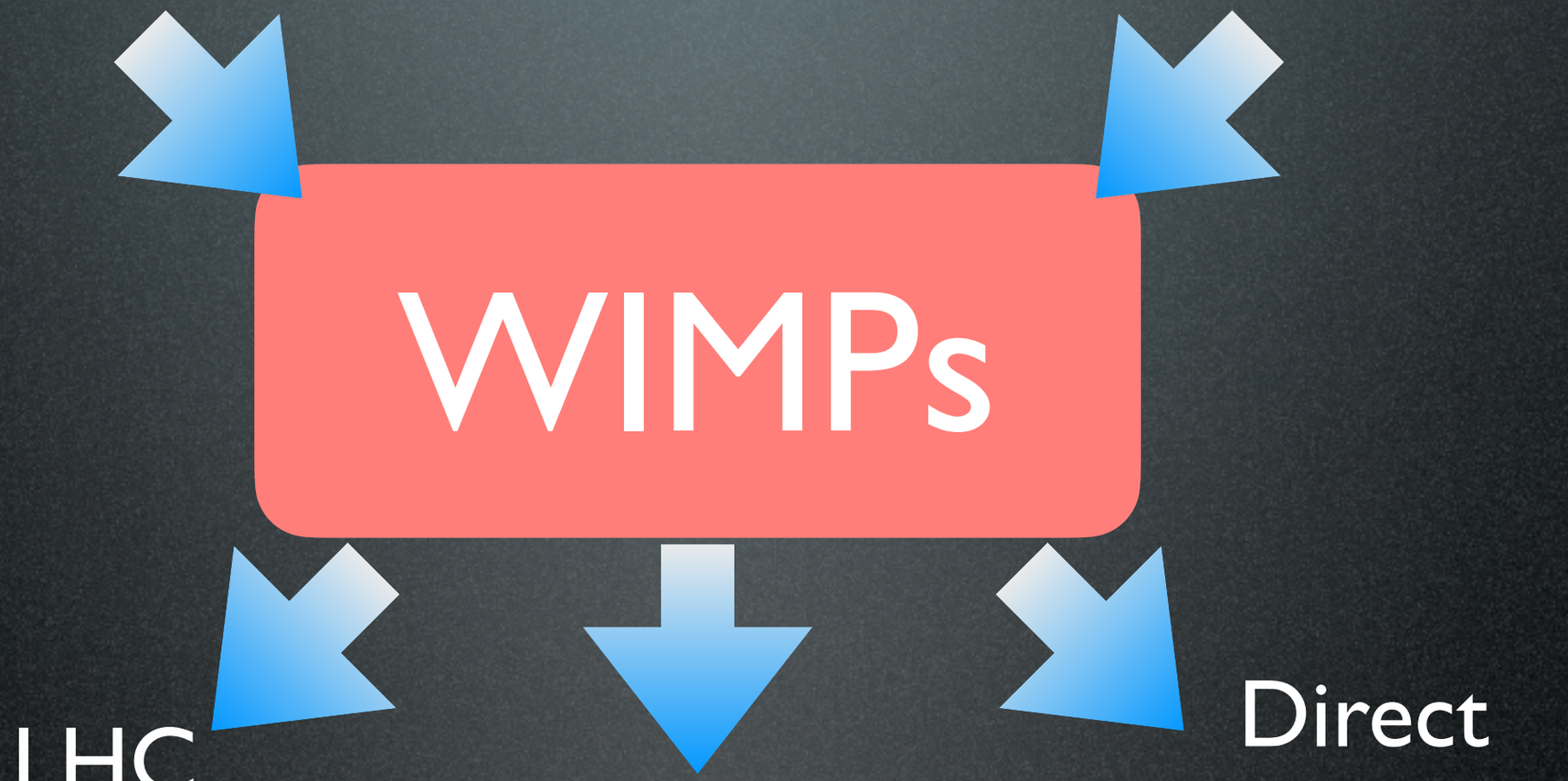
Candidates

new physics at the TeV scale

thermal freeze-out

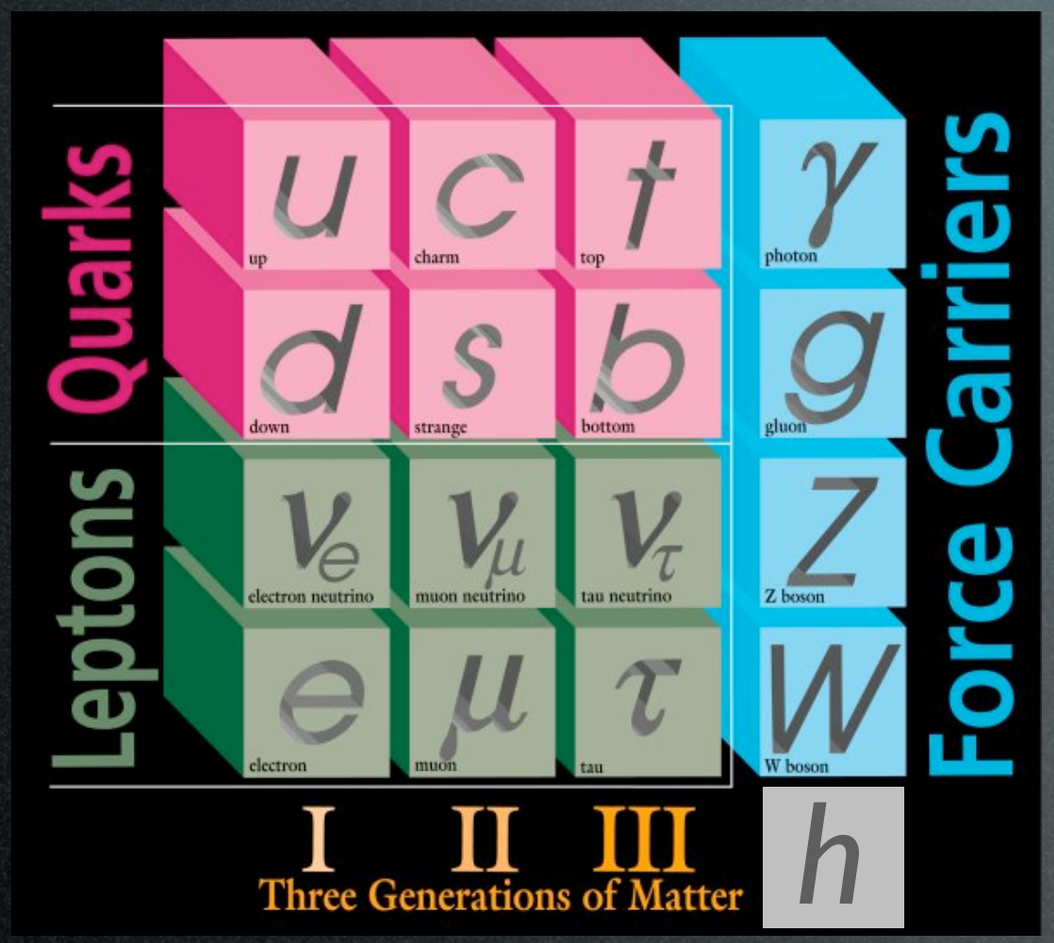


LHC

Indirect Detection

Direct Detection

SuSy DM in 2 minutes



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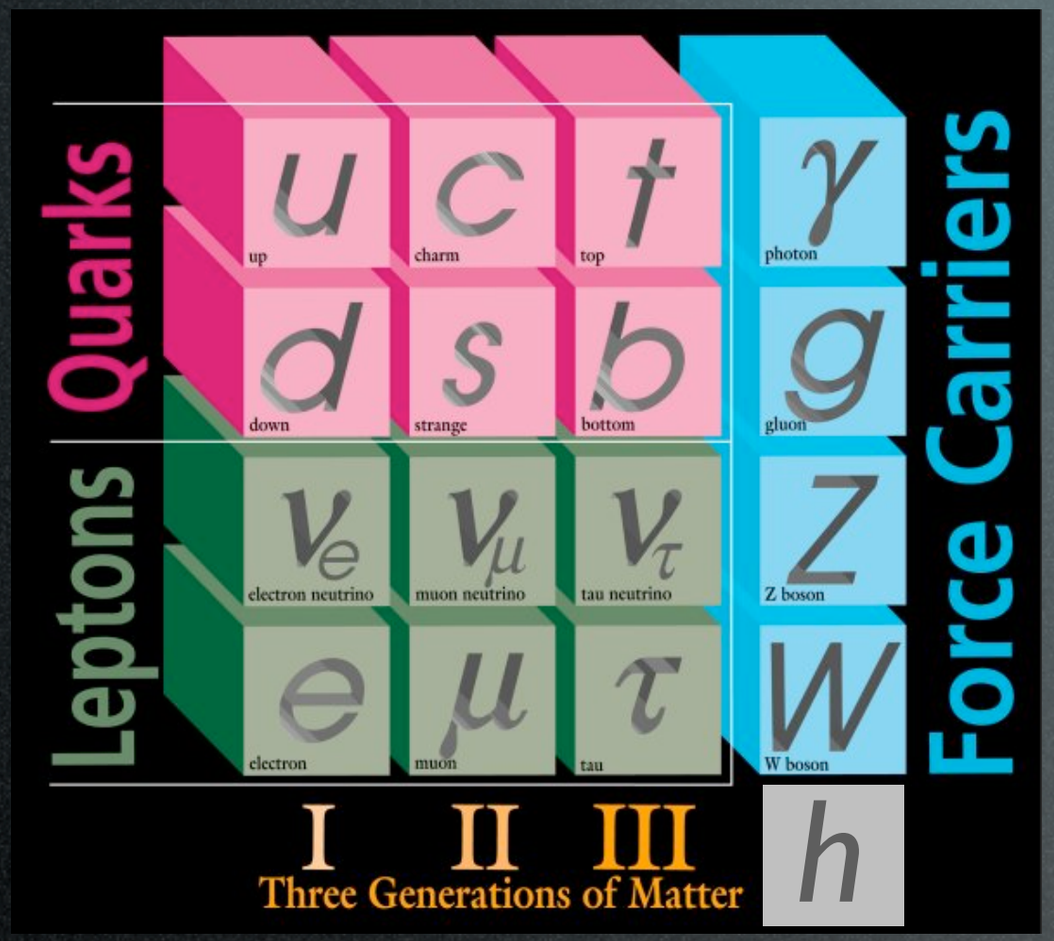
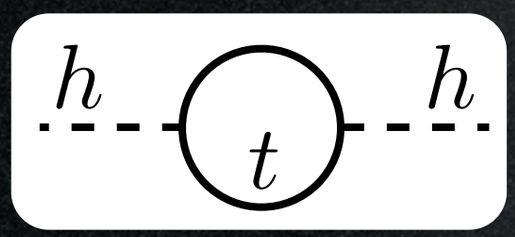
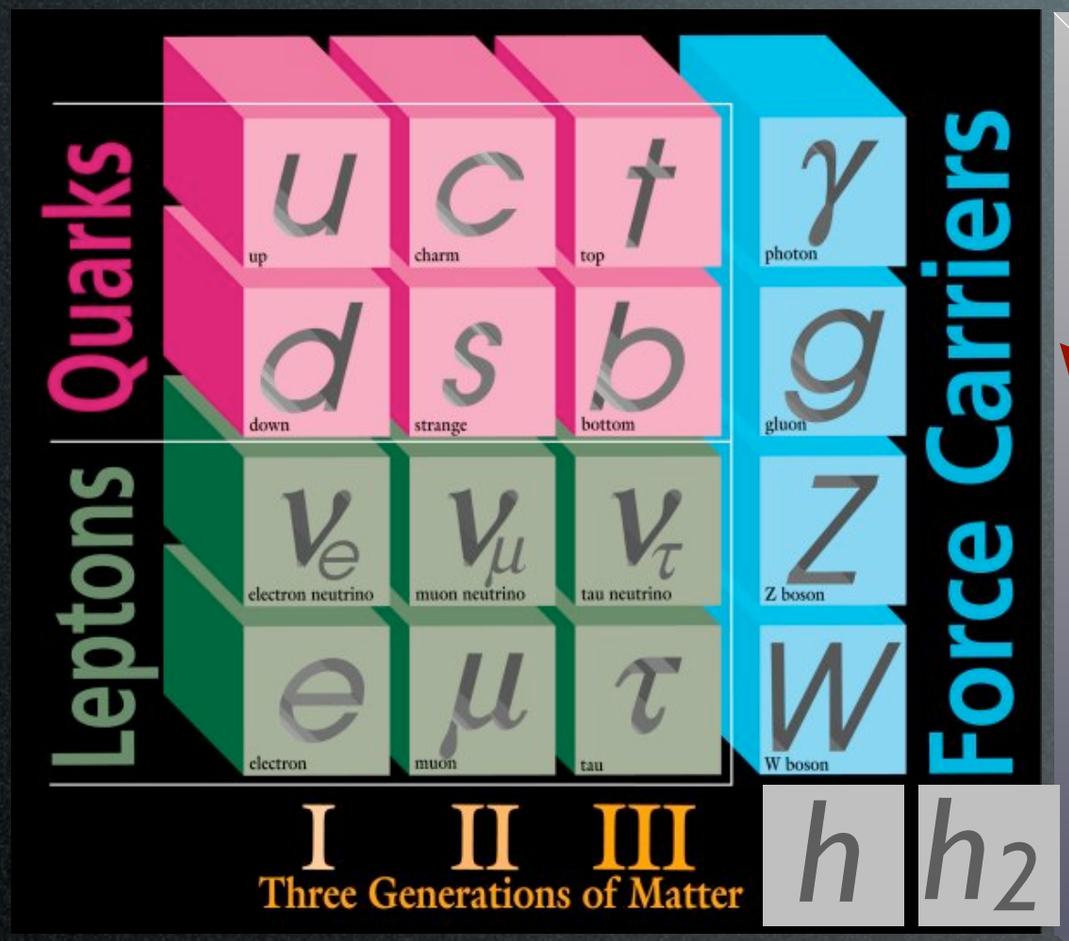


$$m_{\rm h} \simeq 125 \text{ GeV}$$

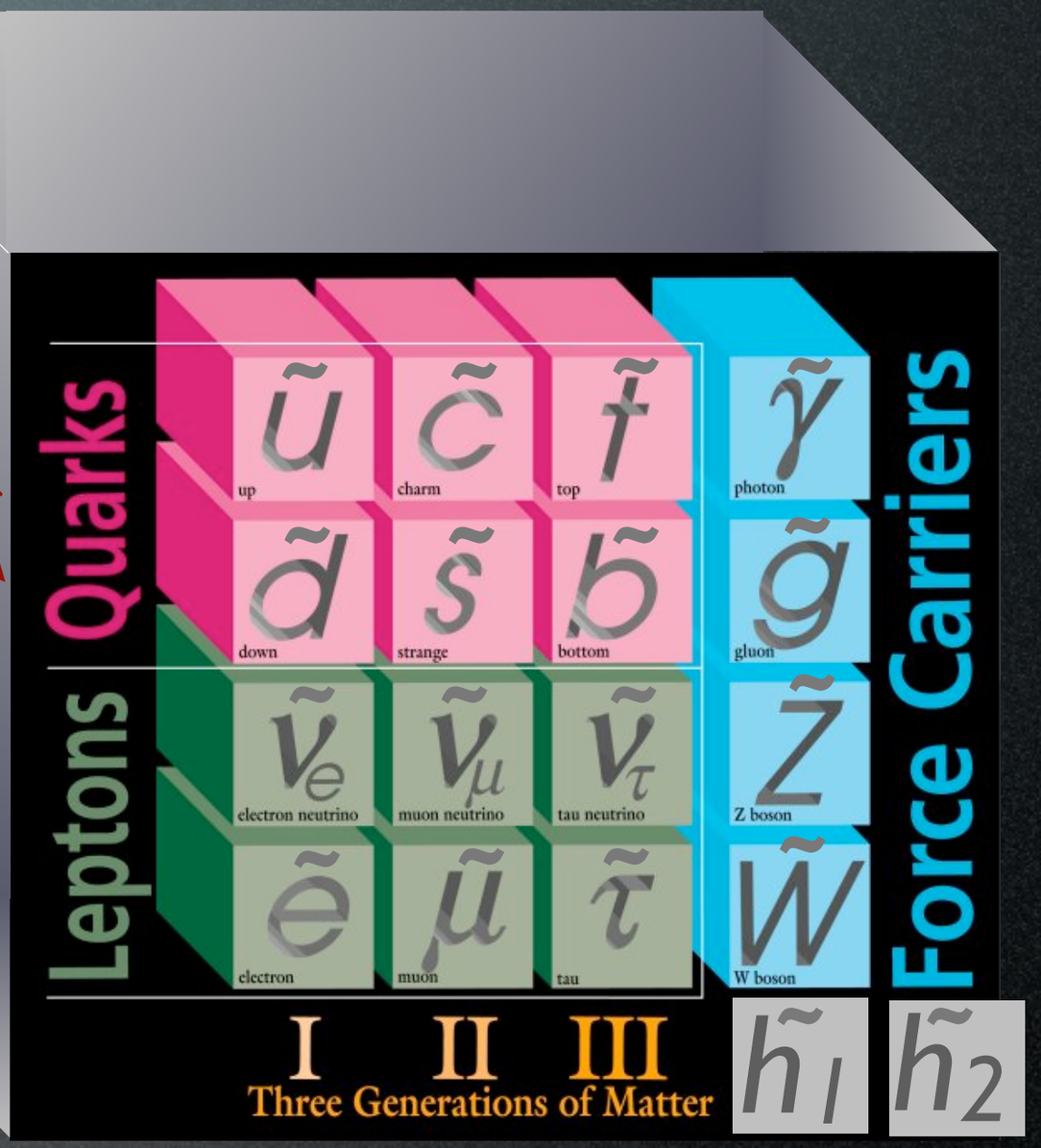


$$\Delta m_{\rm h} \propto 10^{19} \text{ GeV}$$

SuSy DM in 2 minutes



200 GeV



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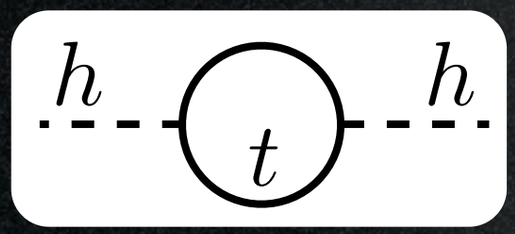

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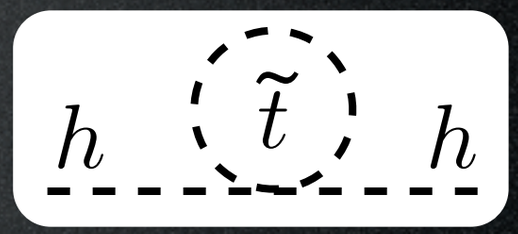
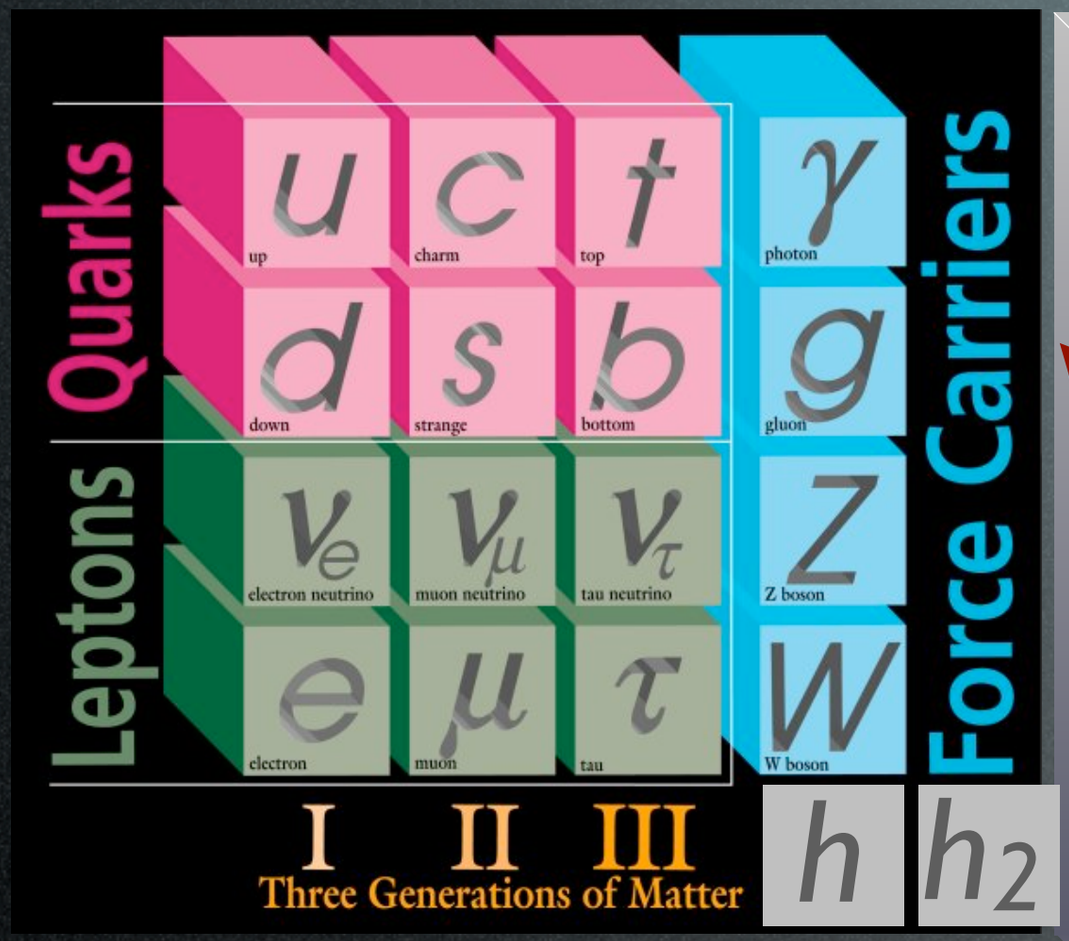


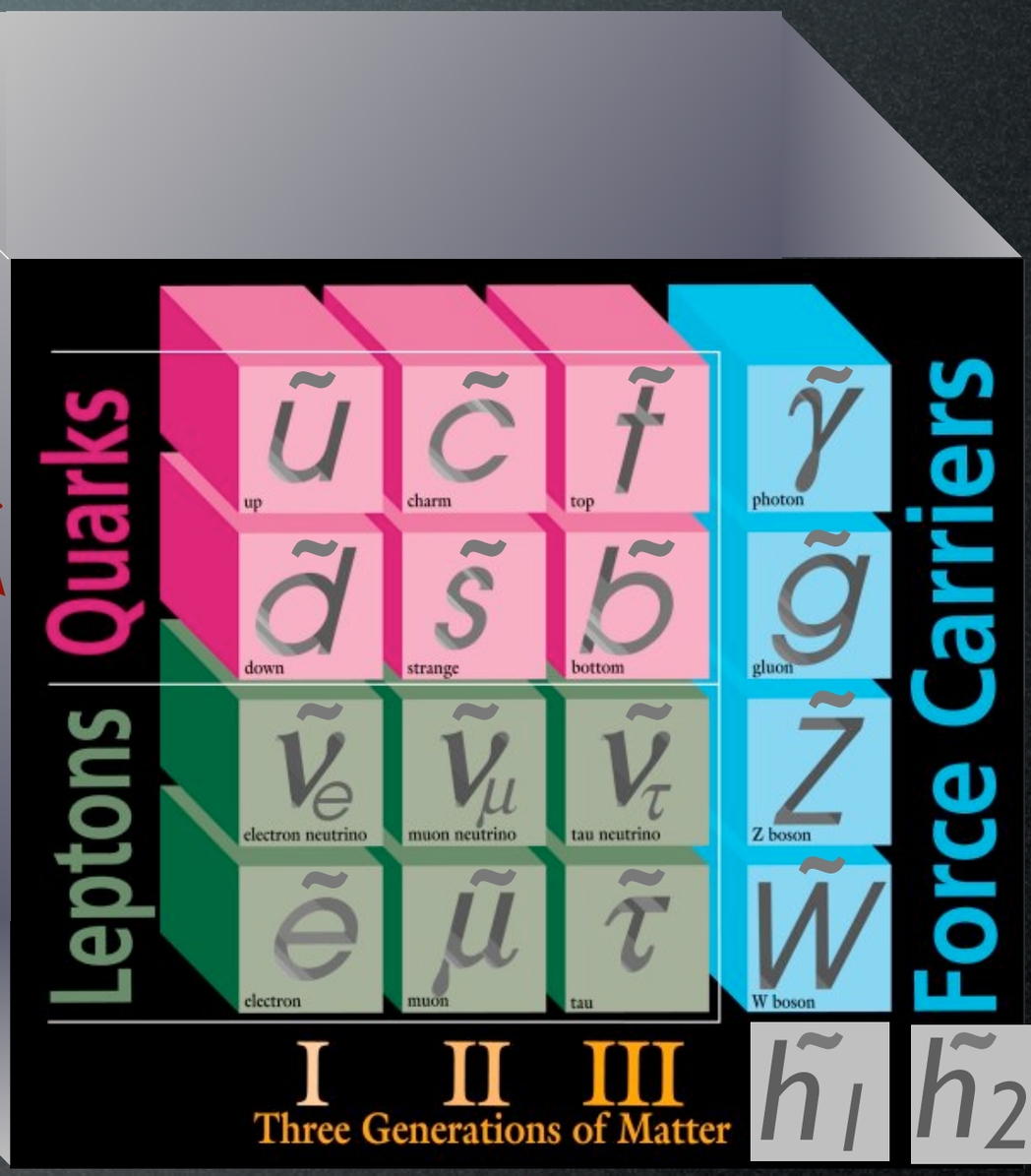
$\Delta m_{\rm h} \propto -10^{19}$ GeV

SuSy DM in 2 minutes

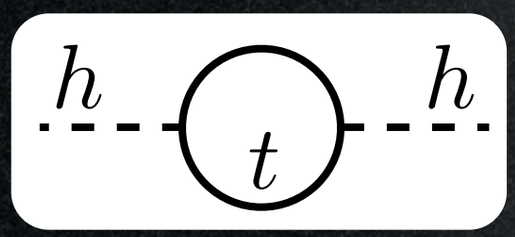


$R = +1$

200 GeV

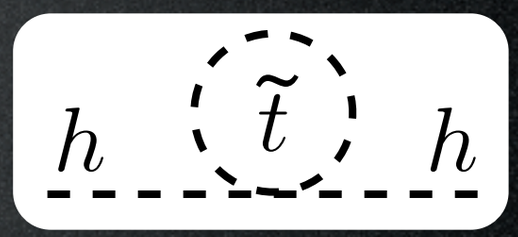


$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$



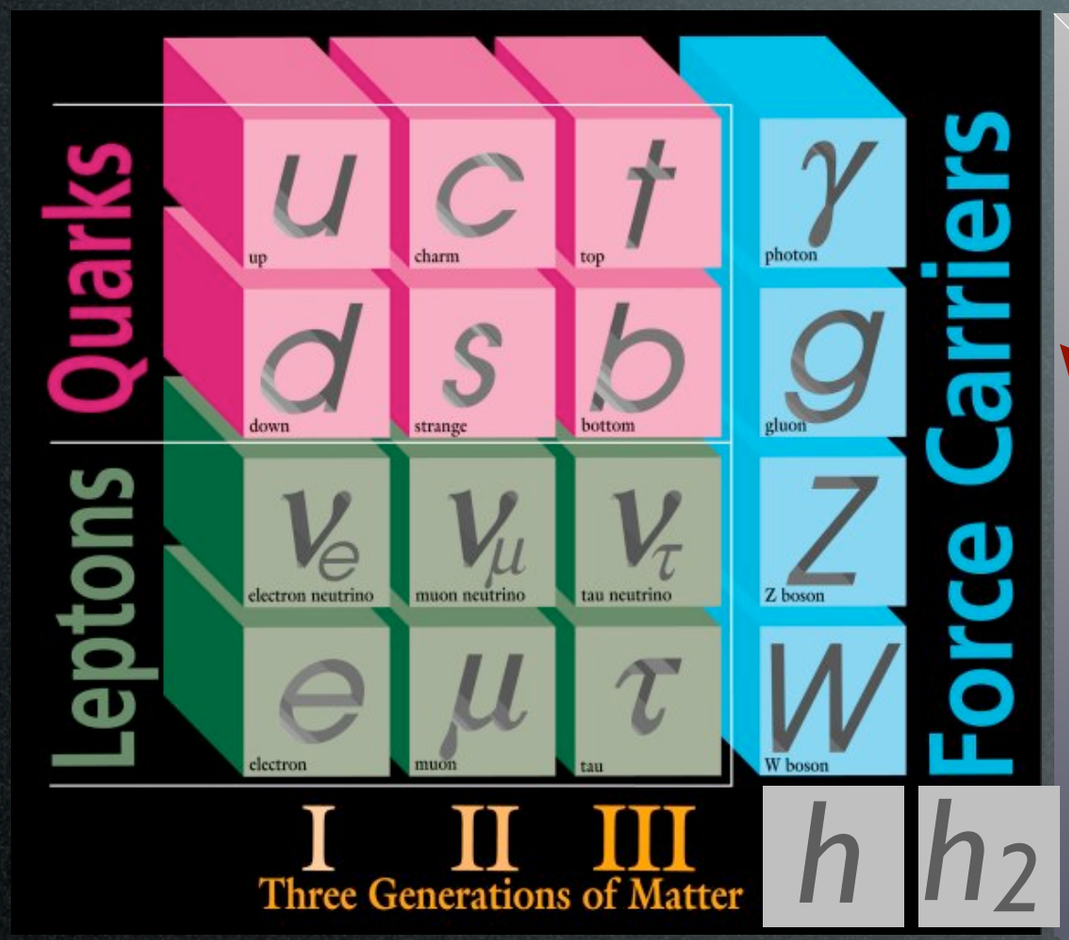
$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$

$R = -1$



$\Delta m_{\mathrm{h}} \propto -10^{19}\ \mathrm{GeV}$

SuSy DM in 2 minutes



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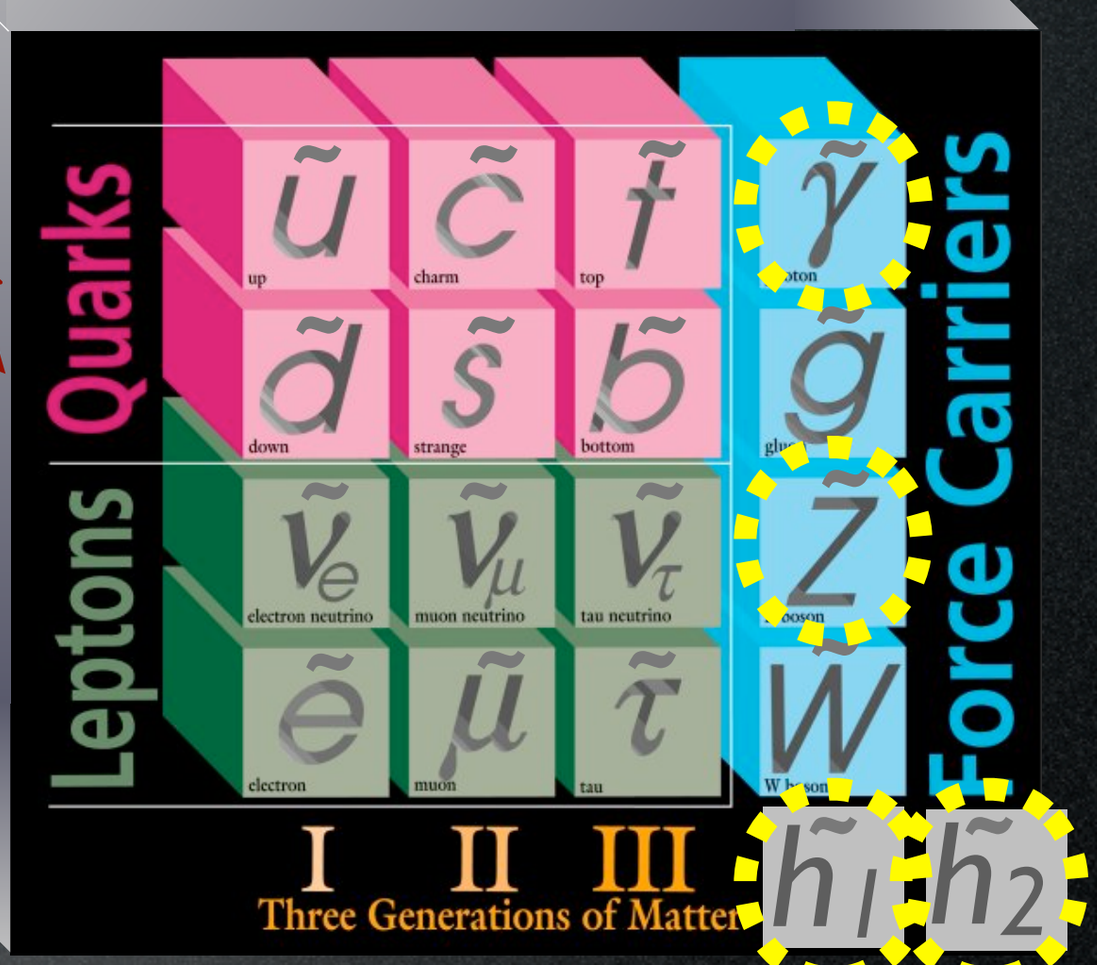
200 GeV



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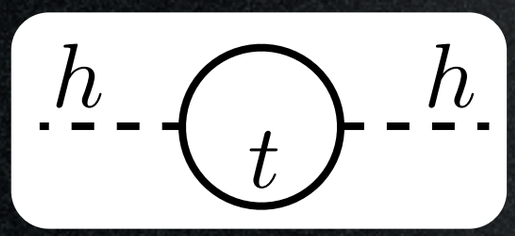

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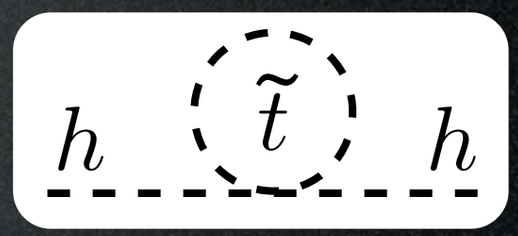

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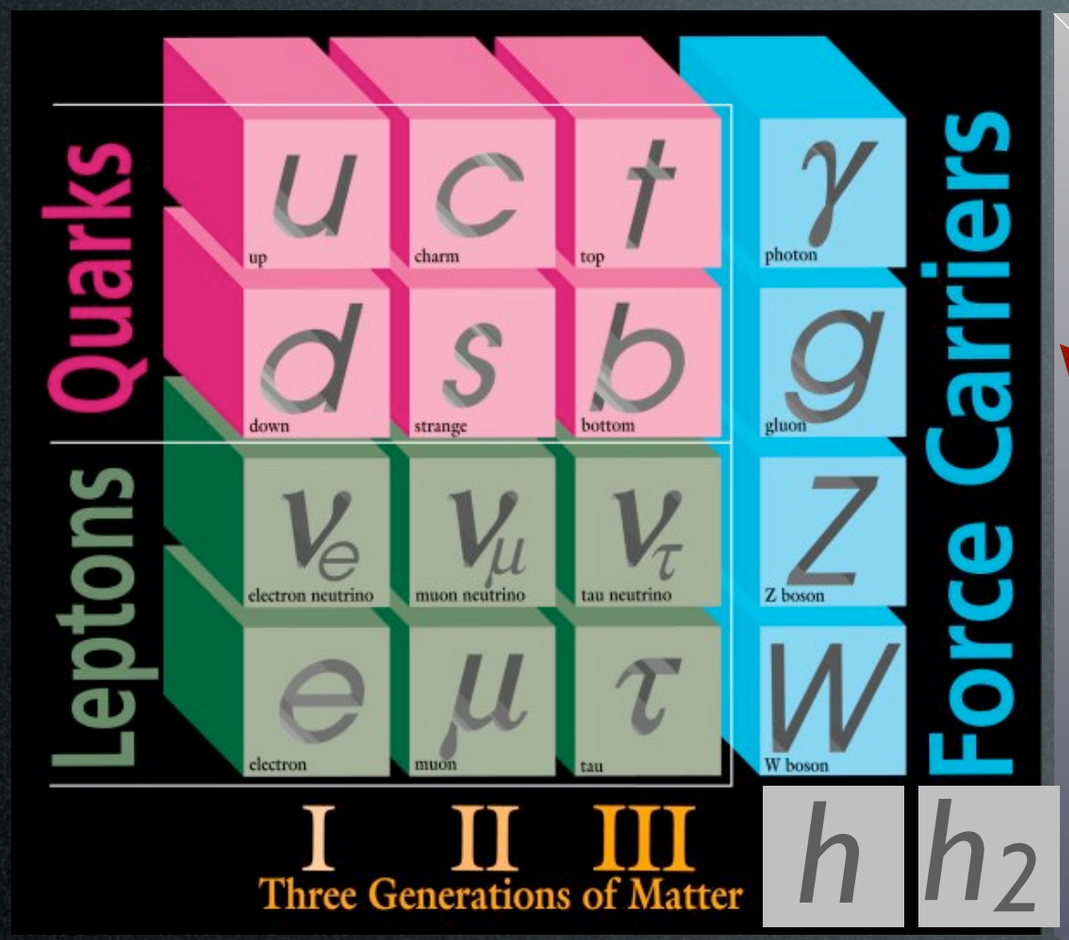

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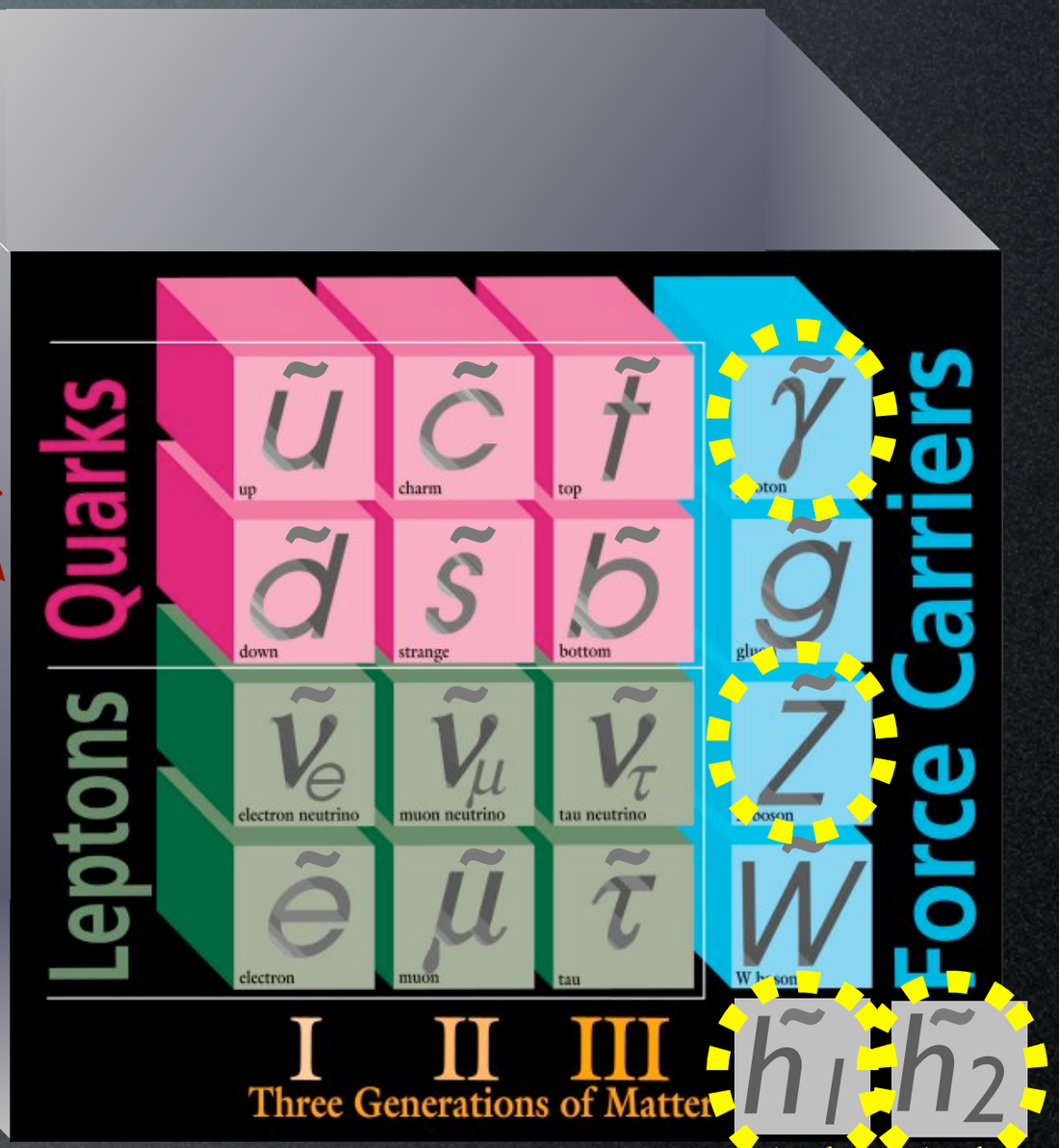

$R = +1$

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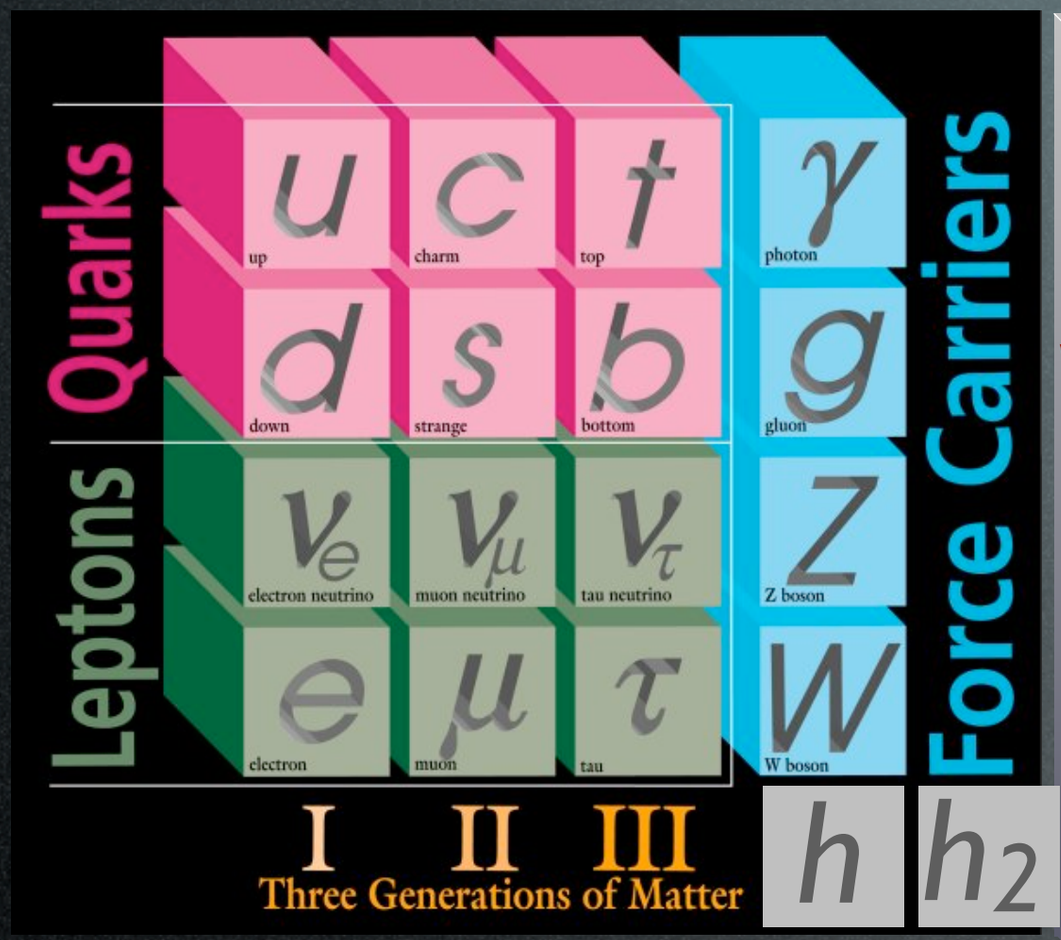

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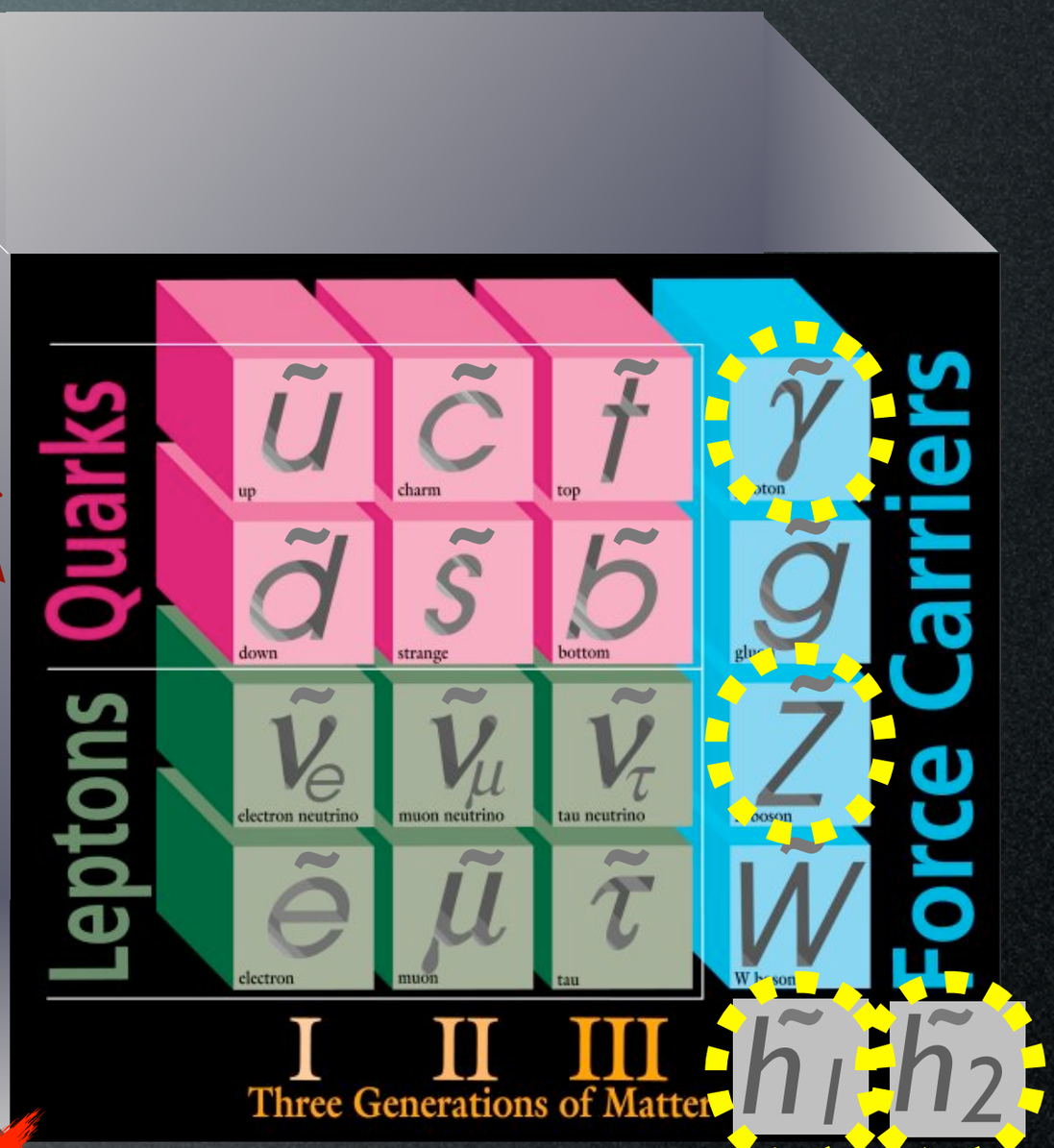


$R = +1$

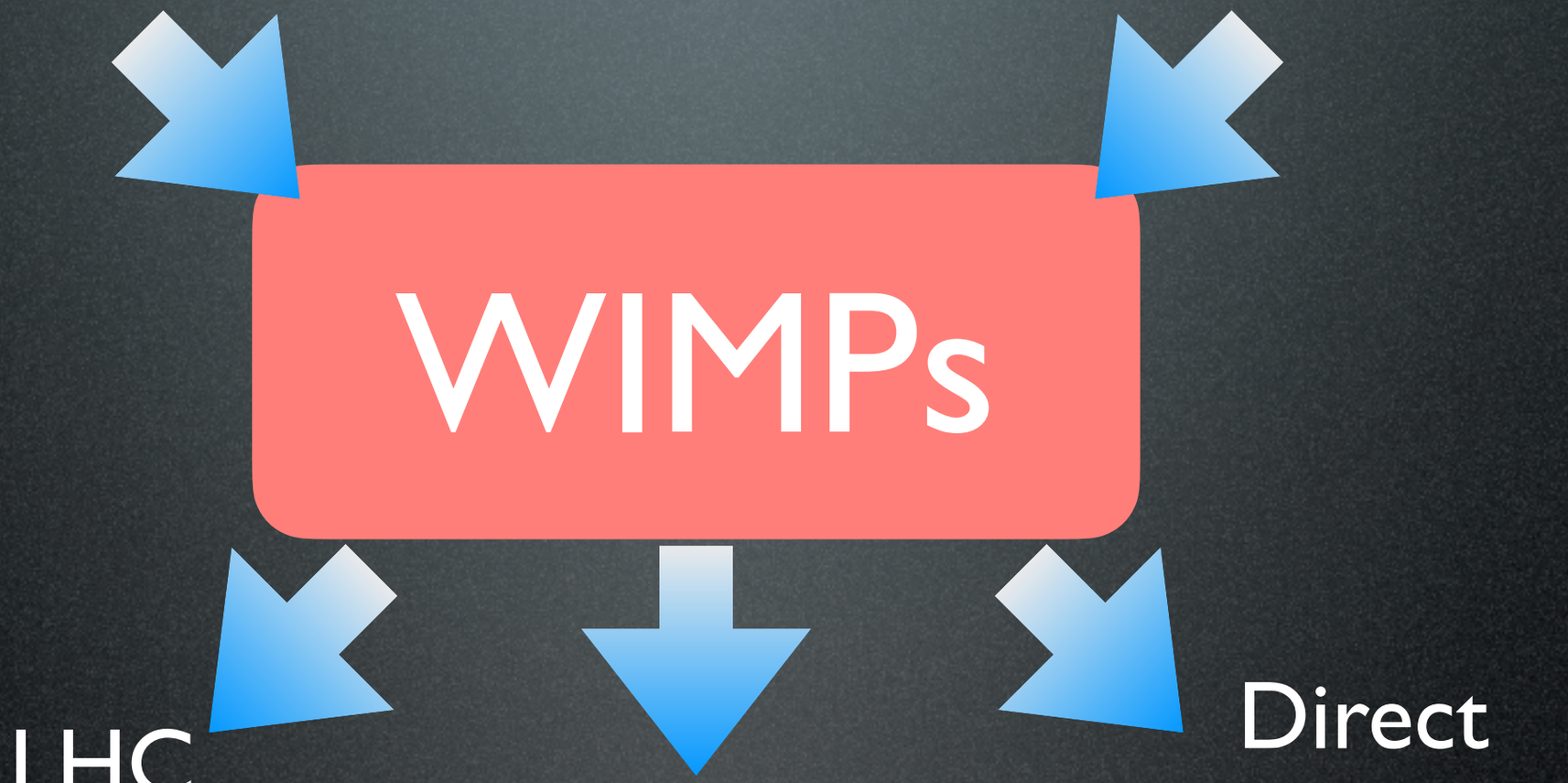
$R = -1$

prevent
proton decay

Candidates

new physics at the TeV scale

thermal freeze-out



1.
2.

Candidates

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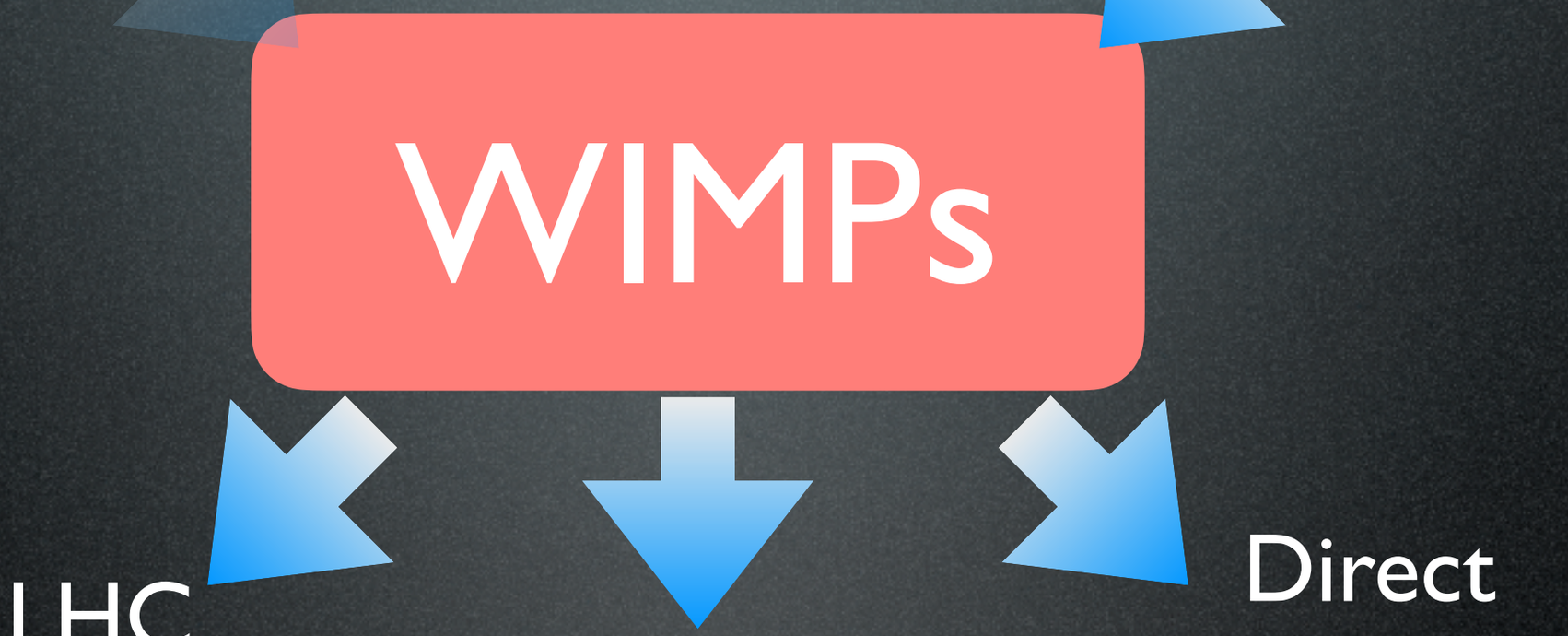


1. even without a larger framework, WIMPs are still appealing
2.

Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

LHC

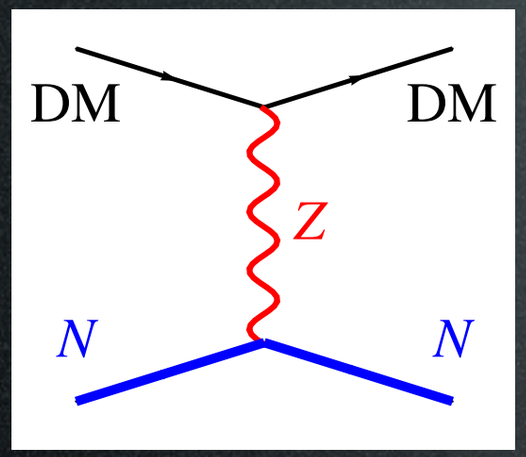
Indirect Detection

Direct Detection

1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary

WIMP DD: 'theory'

SM weak scale SI interactions

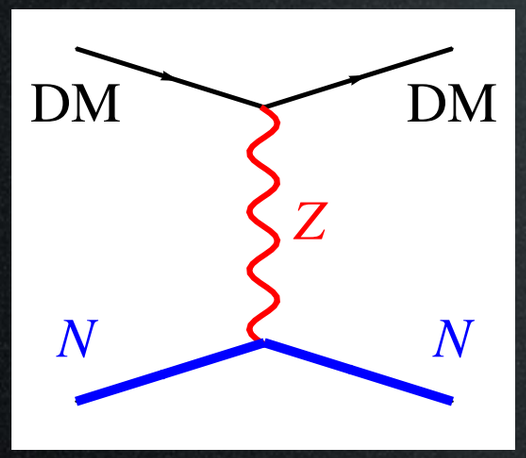


tree level, vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^2}{M_Z^4}$$

WIMP DD: 'theory'

SM weak scale SI interactions



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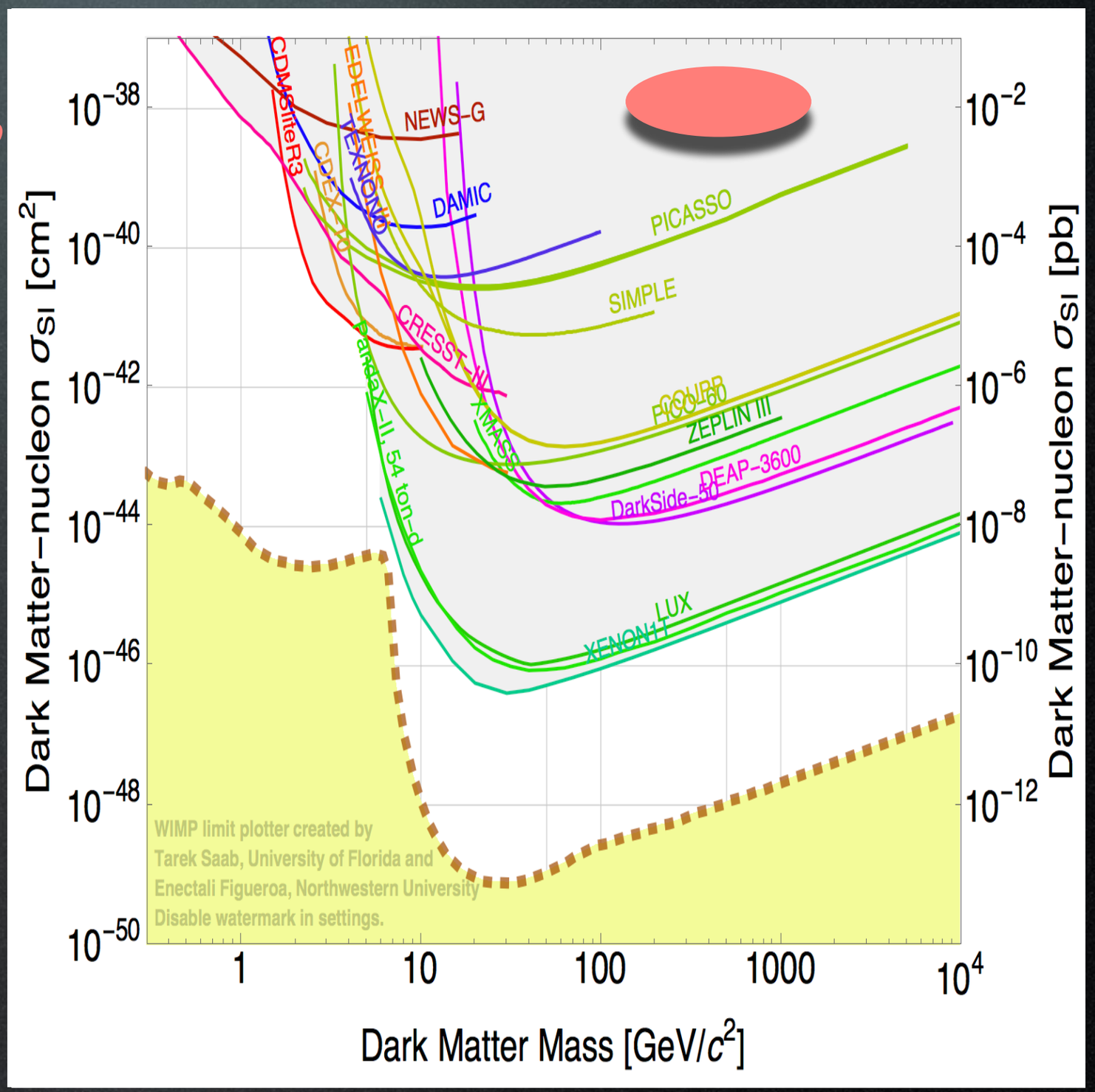

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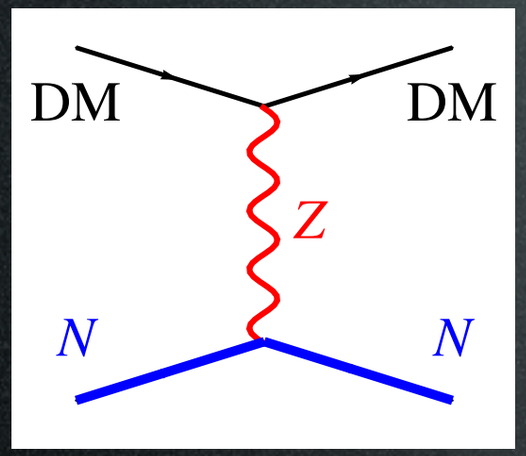

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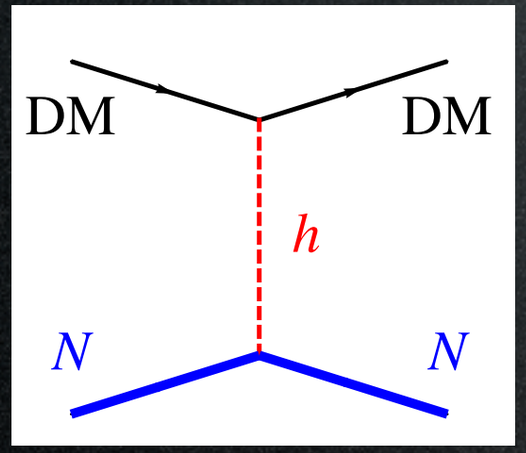

tree level, scalar

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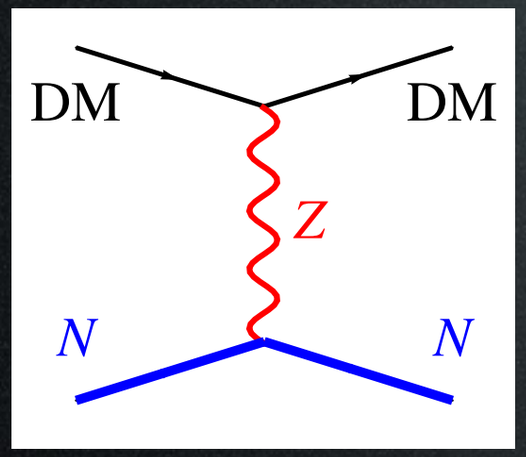
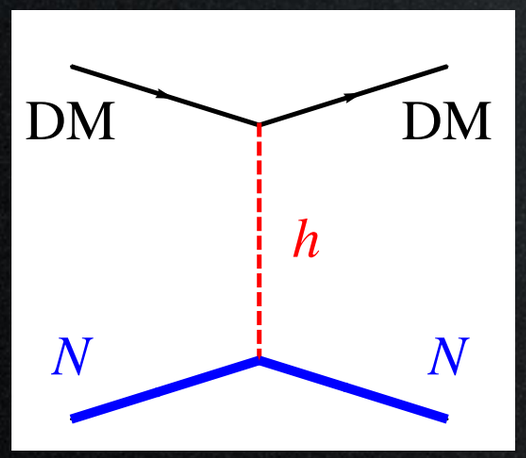
SM weak scale SI interactions



tree level, vector



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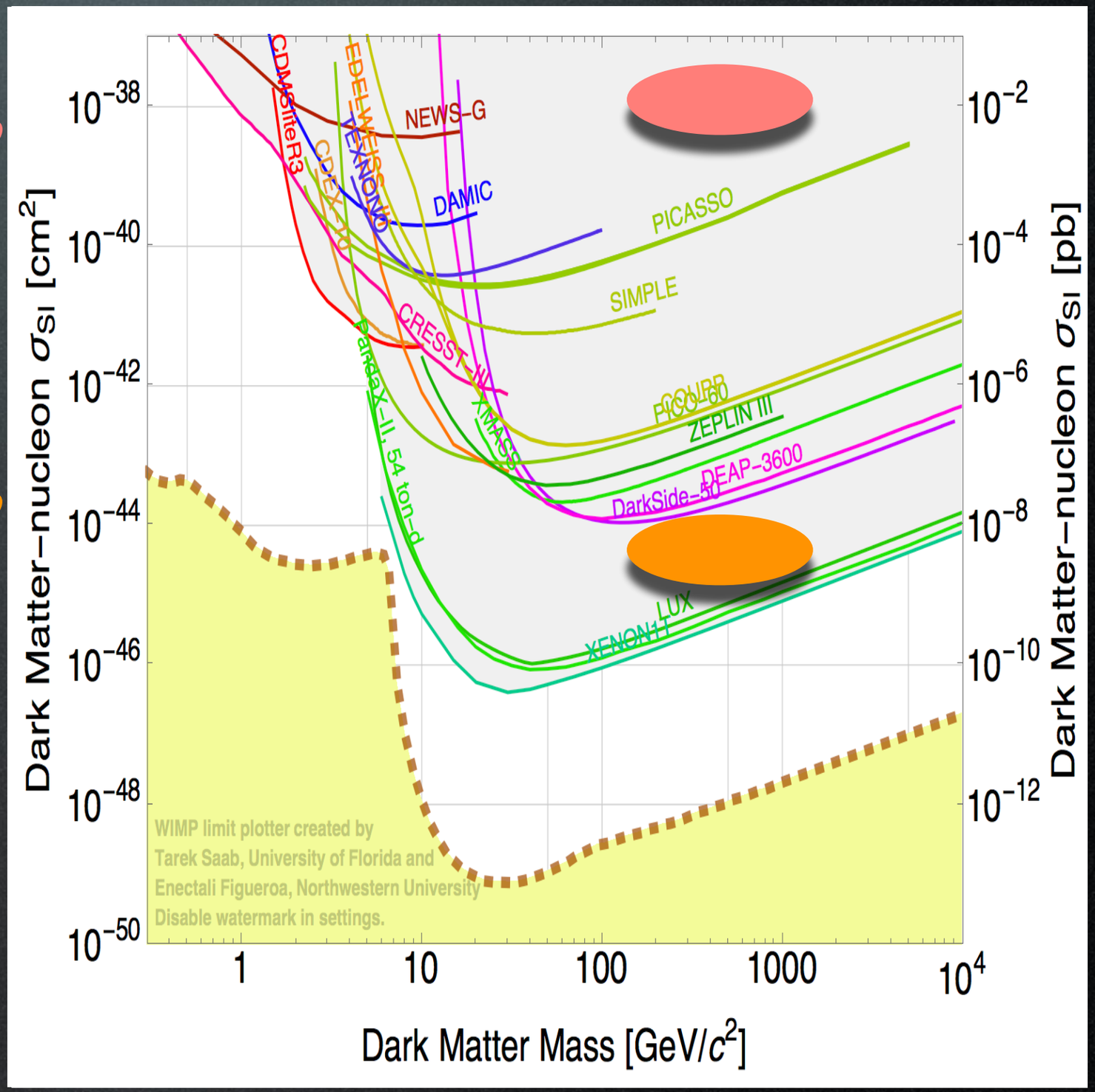

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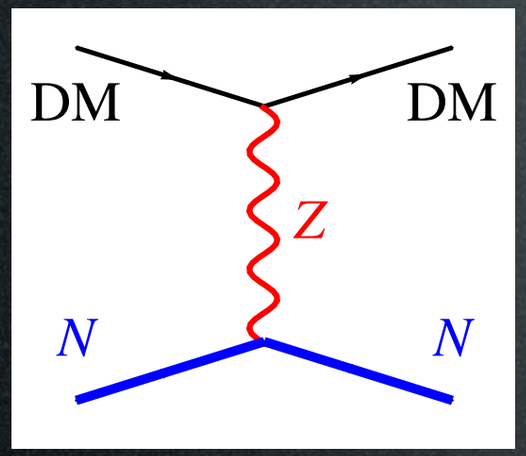

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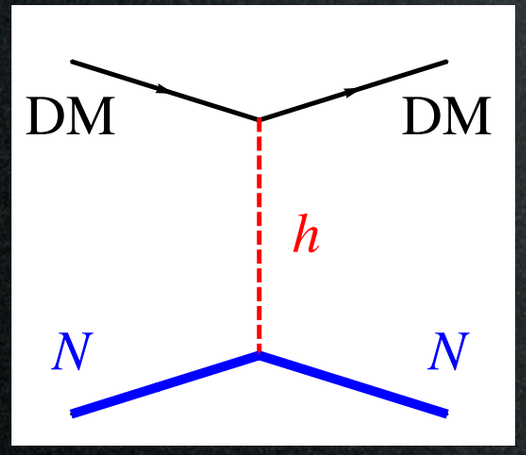

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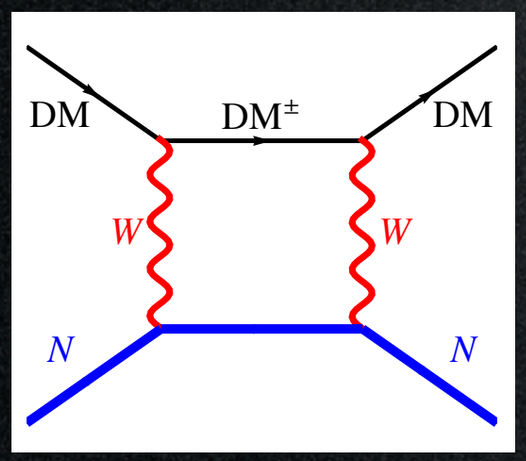
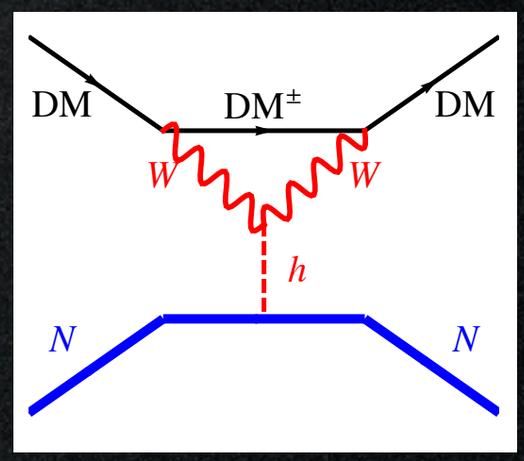


one loop

$$\sigma_{\rm SI} \sim \frac{\alpha^4 \ m_N^4}{M_W^6}$$



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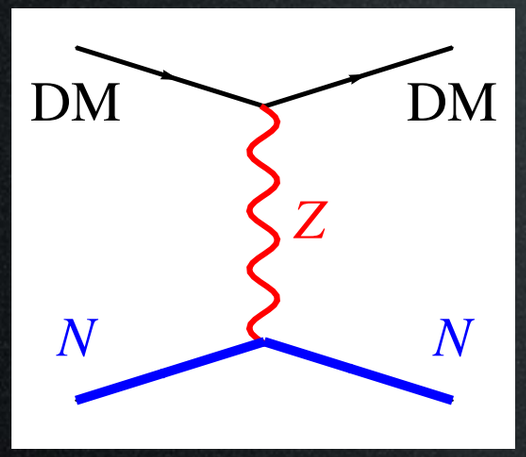
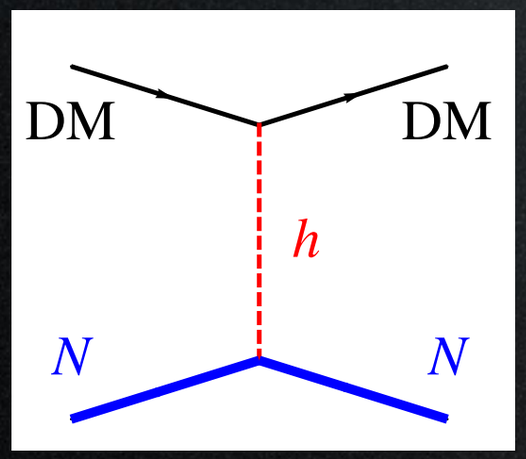
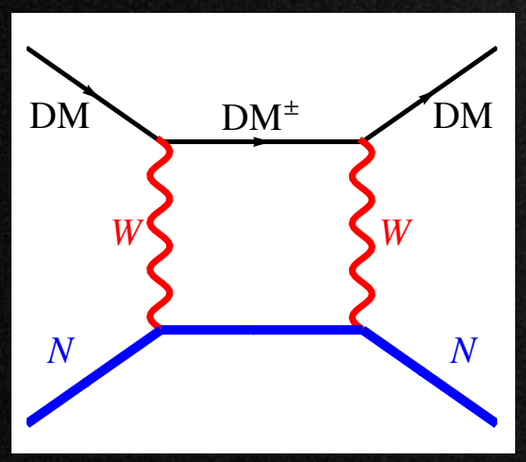


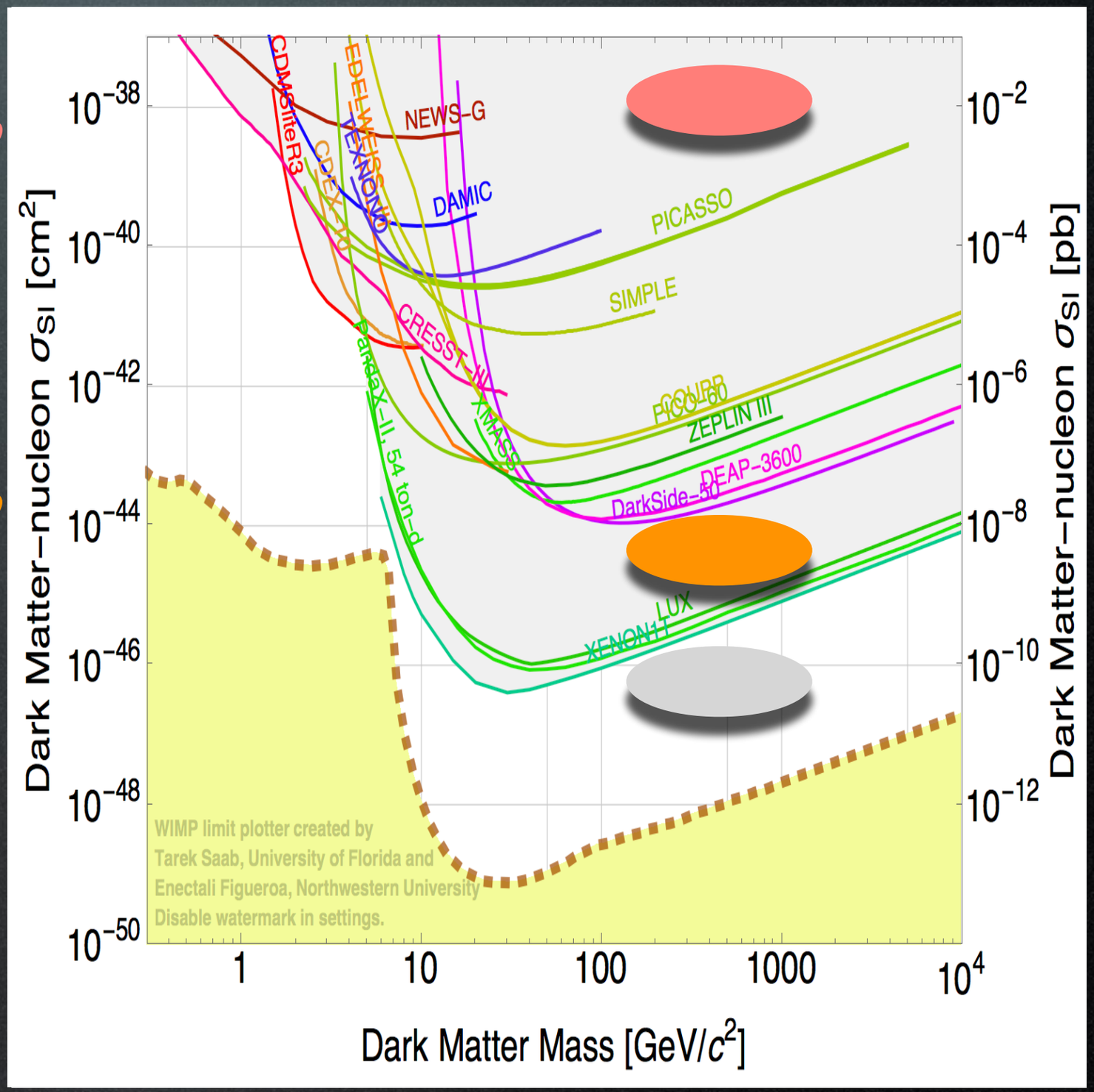
tree level, vector



tree level, scalar

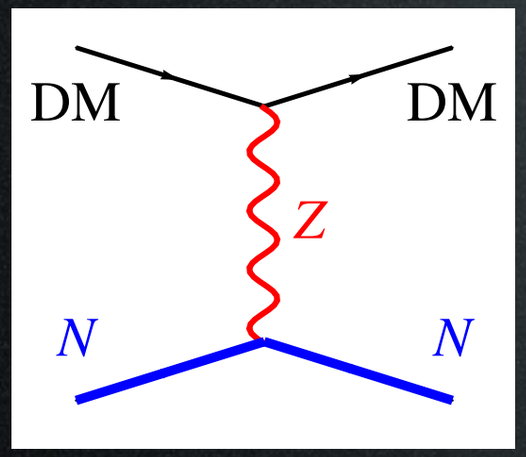


one loop



WIMP DD: 'theory'

SM weak scale SI interactions



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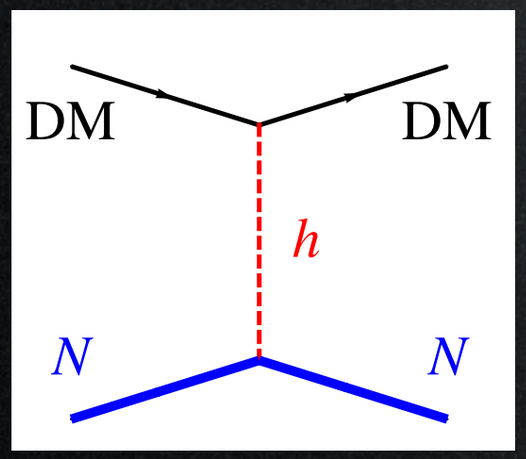

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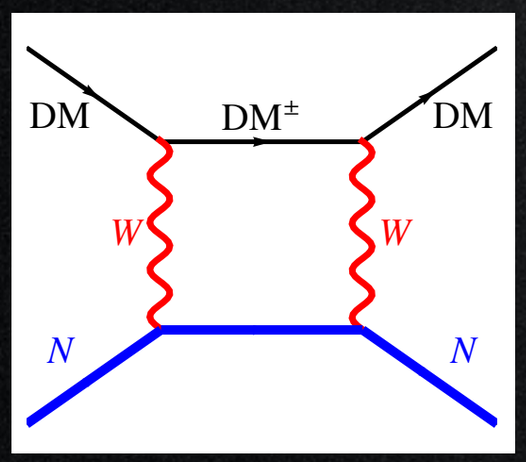

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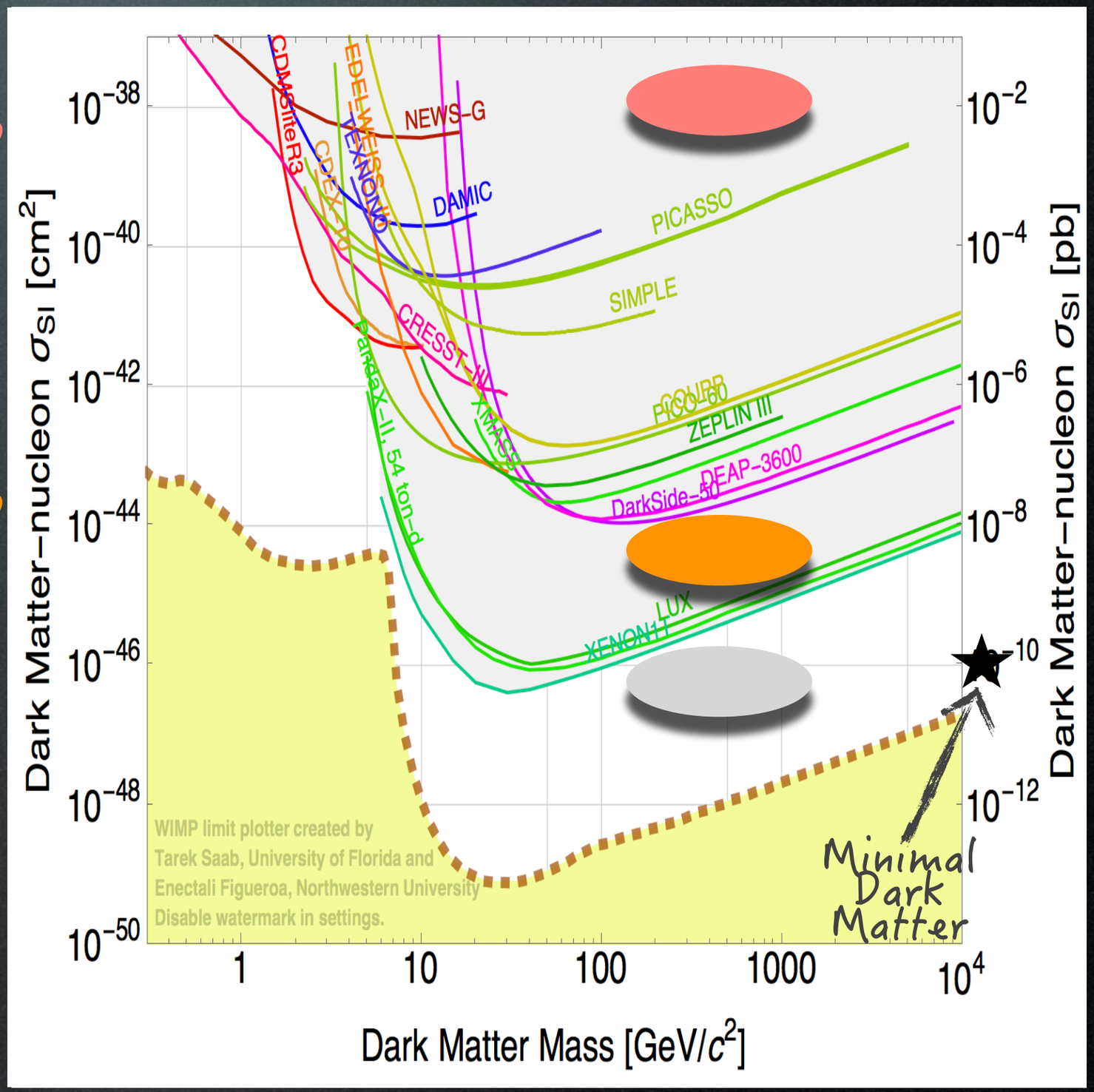

Cirelli, Fornengo, Strumia hep-ph/0512090

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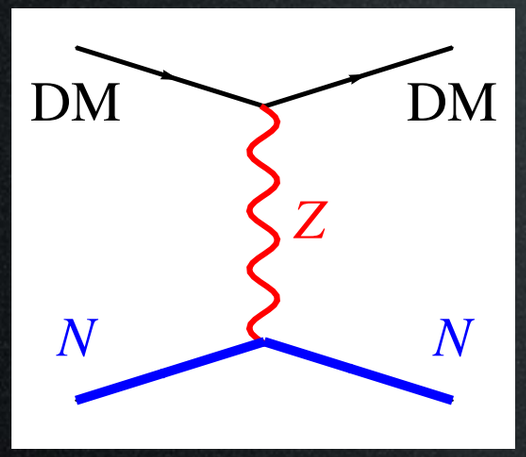

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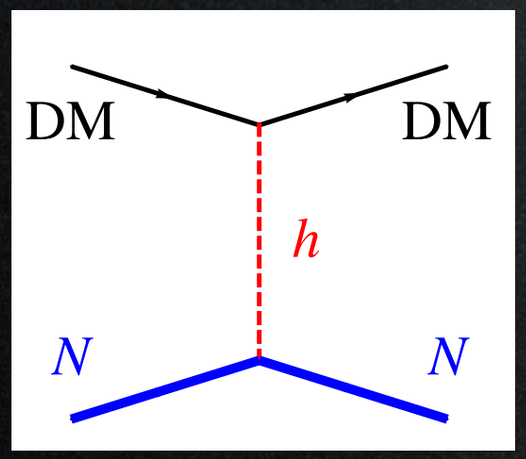

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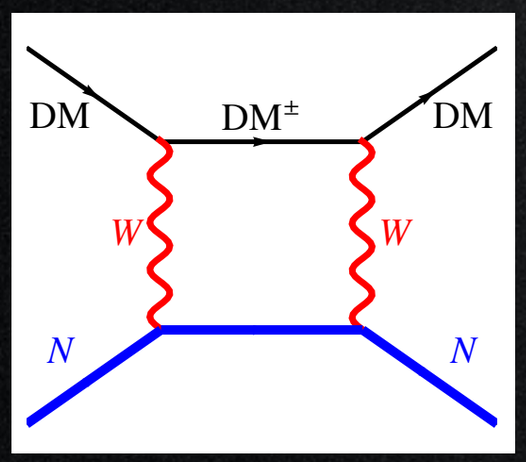

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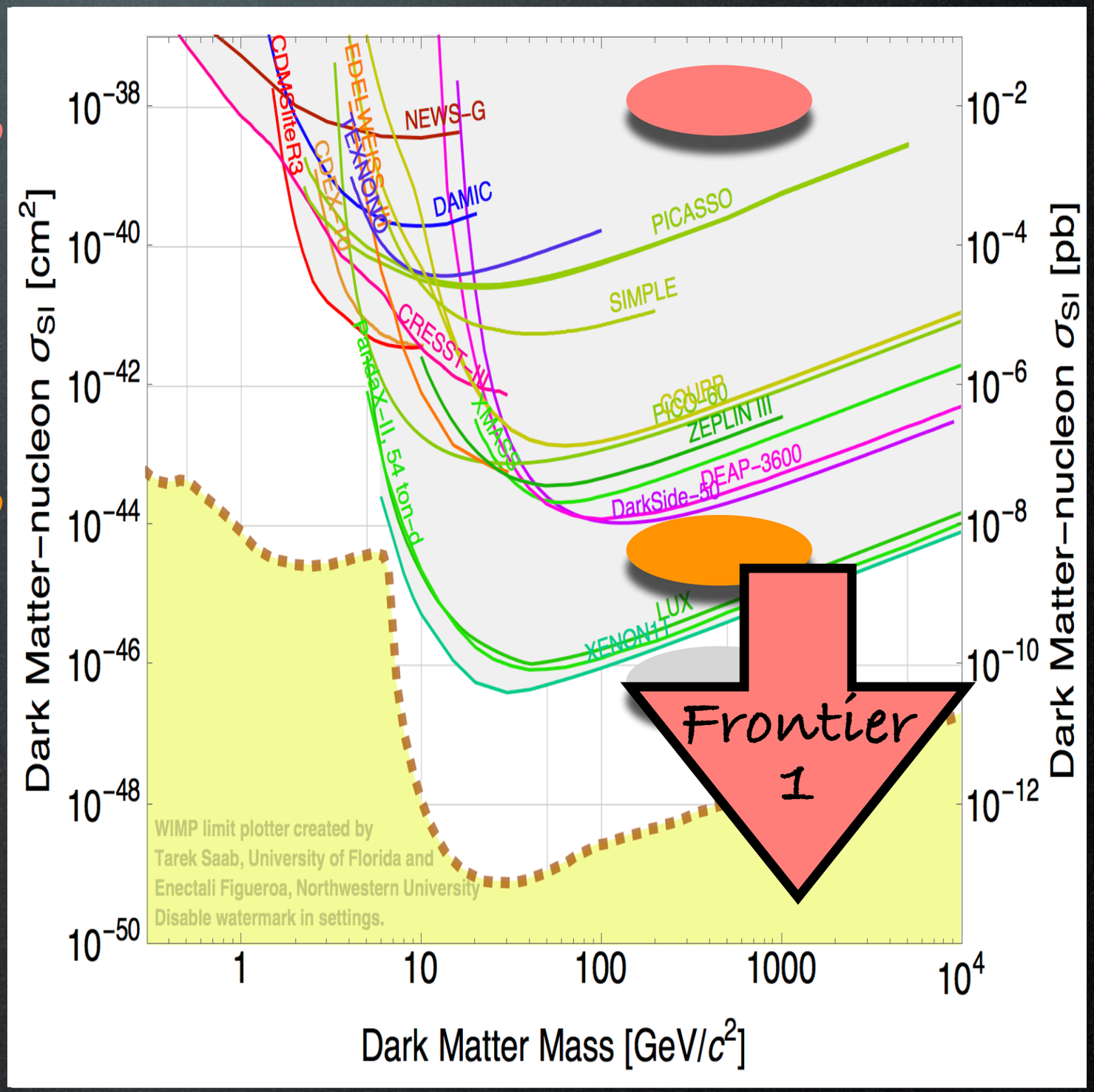

Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

LHC

Indirect Detection

Direct Detection

1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary

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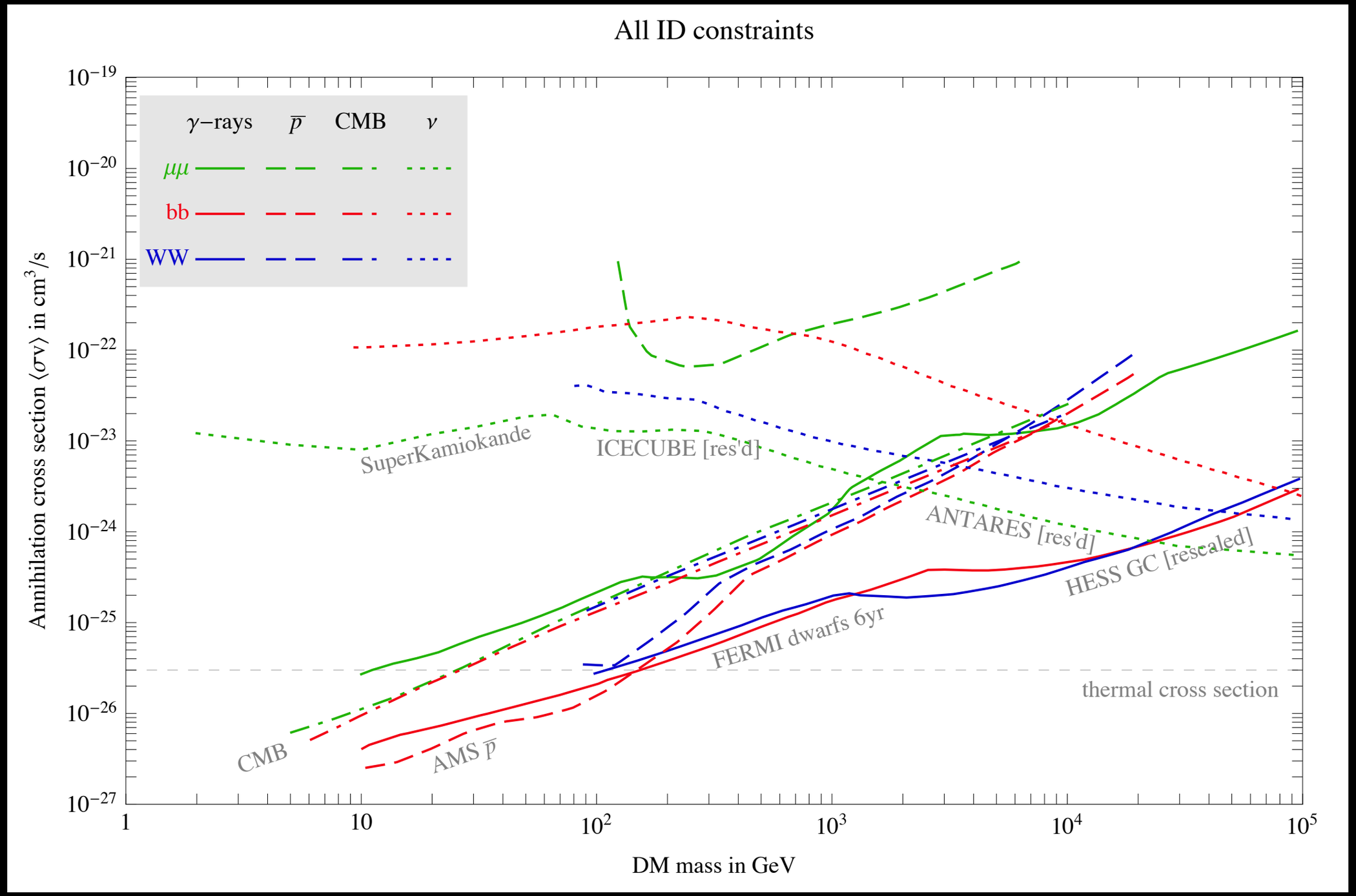
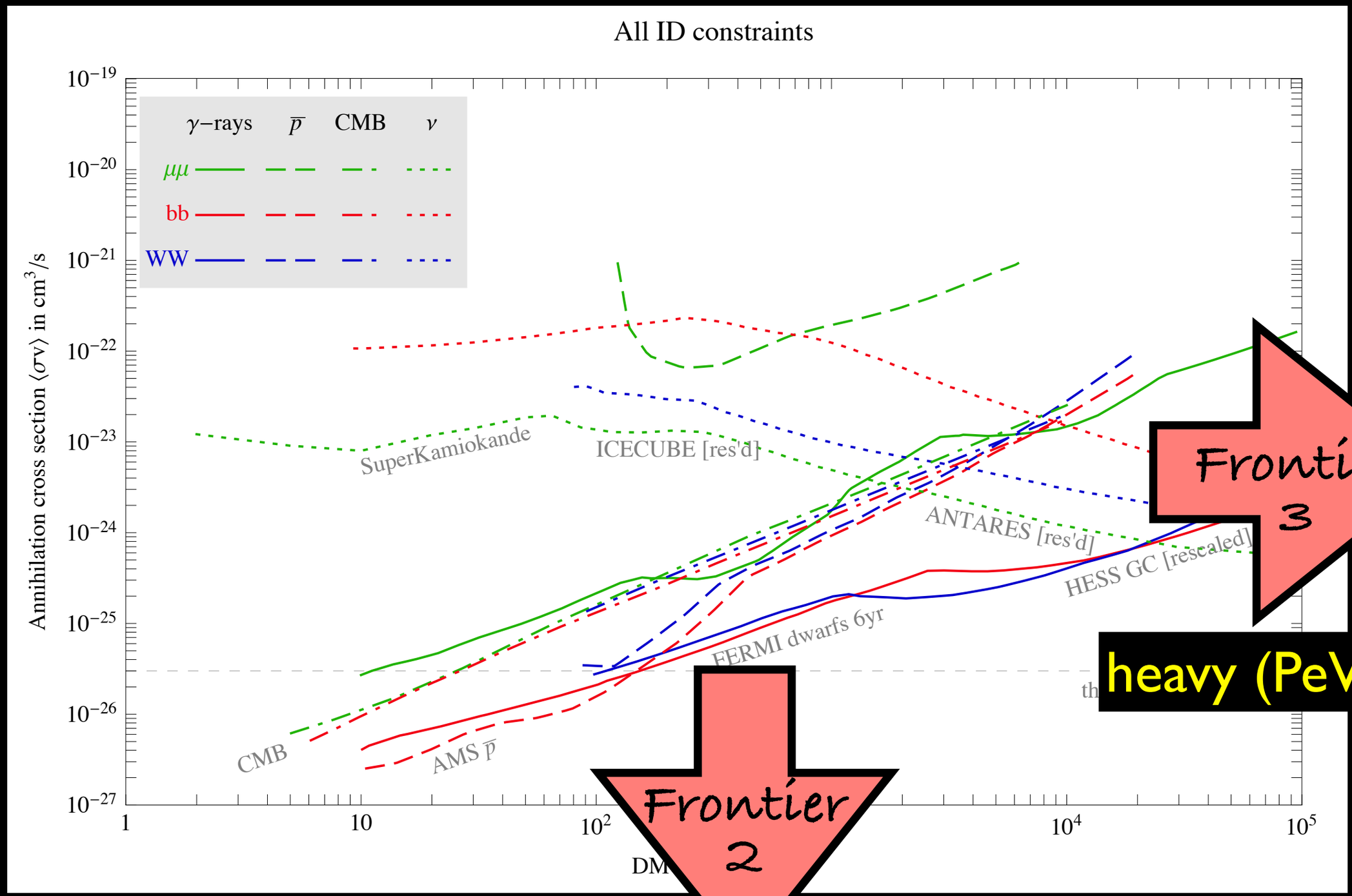


M. Cirelli, A. Strumia, J. Zupan to appear

Indirect Detection



WIMPs & very weakly coupled DM

Indirect Detection

Frontier 3:
heavy (PeV) DM

Indirect Detection

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- 'Pure WIMP' models foresee multi-TeV DM
  models with only DM beyond SM,
  no other ingredients

Indirect Detection

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heavy (PeV) DM

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Indirect Detection

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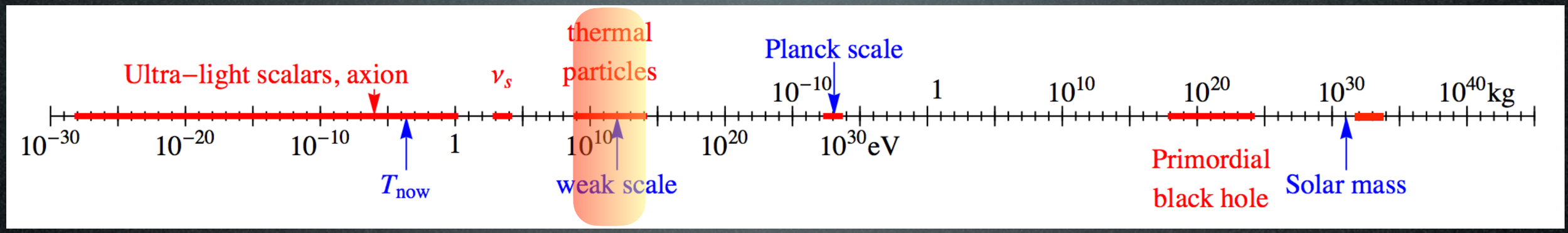
- Unitarity bound (~300 TeV) can be overcome

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

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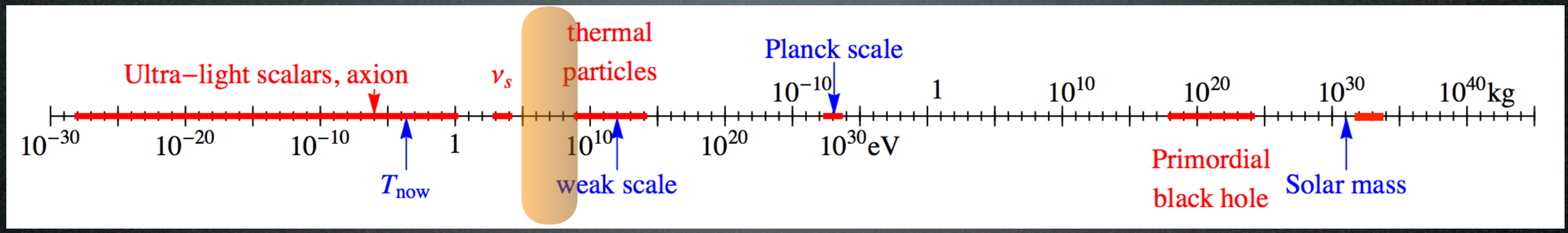

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Sub-GeV DM?

Candidates

theory?

production?

Collider Searches?

Indirect Detection?

Direct Detection?

Theory

Sub-GeV DM

- WIMPless Dark Matter

  Feng & Kumar 0803.4196

  a.k.a. hidden sector DM

  ~secluded DM

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  $$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\rm TeV^2}$$

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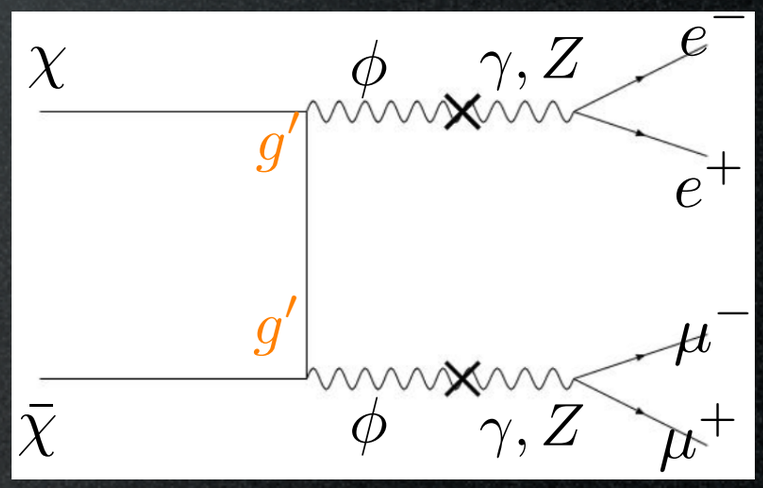
if g_x is small,
m 'naturally' small
(but nothing points to a precise value)



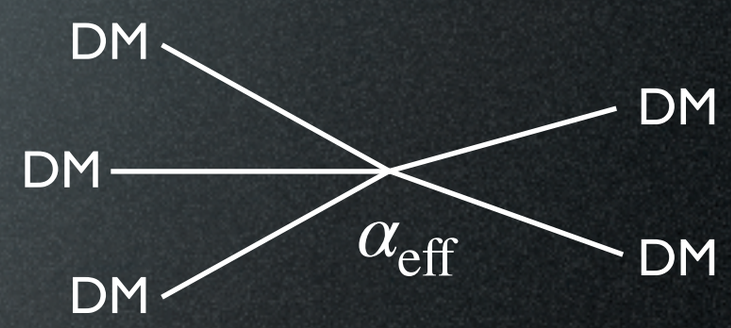
Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

- ‘SIMP miracle’:

  scalar DM with relic abundance set by 3 -> 2 processes



  points to $$m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100\ {\rm MeV}$$

  Hochberg et al 1402.5143

‘naturally realized’ in a dark-QCD-like setup

$$\alpha_{\rm eff} = \mathcal{O}(1) \quad \text{i.e.} \quad g_x \sim 4\pi$$

Theory

Sub-GeV DM

- 'MeV (scalar) DM' (for the Integral 511 KeV excess?)

Boehm & Fayet hep-ph/0305261

> In conclusion, scalar Dark Matter particles can be significantly lighter than a few GeV's (thus evading the generalisation of the Lee-Weinberg limit for weakly-interacting neutral fermions) if they are coupled to a new (light) gauge boson or to new heavy fermions F (through non chiral couplings and poten-

Theory

Sub-GeV DM

- ‘simplified (light) DM models’ Knapen, Lin, Zurek 1709.07882

Theory

Sub-GeV DM

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scalar DM and
hadrophilic
scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n\phi\bar{n}n,$$

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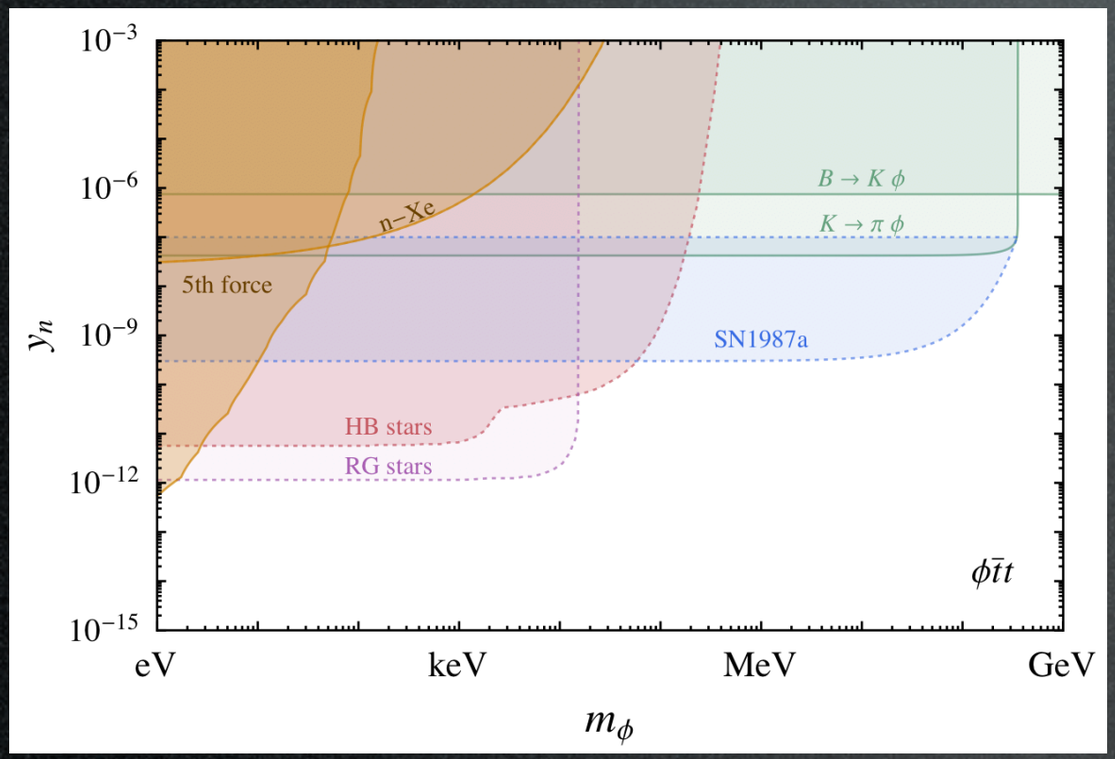

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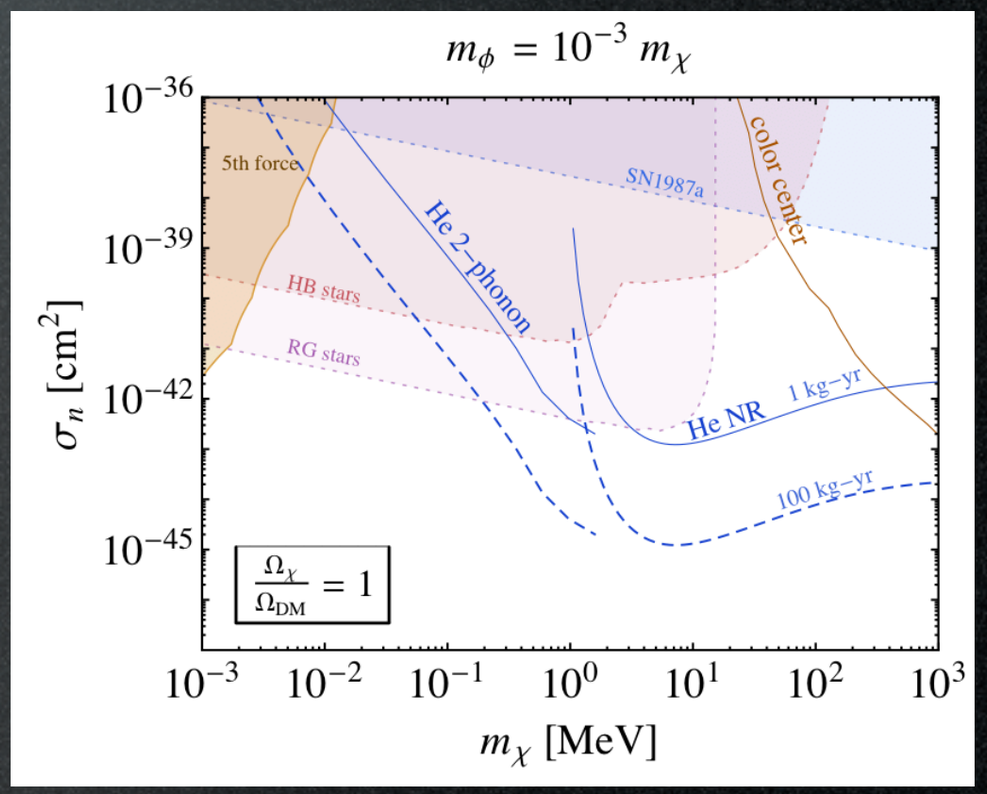

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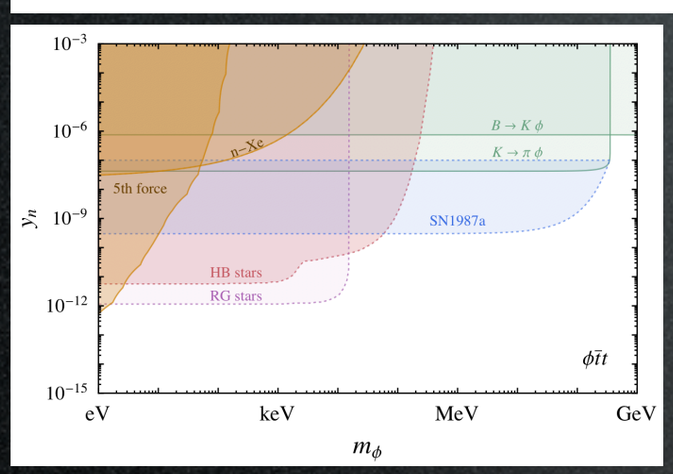

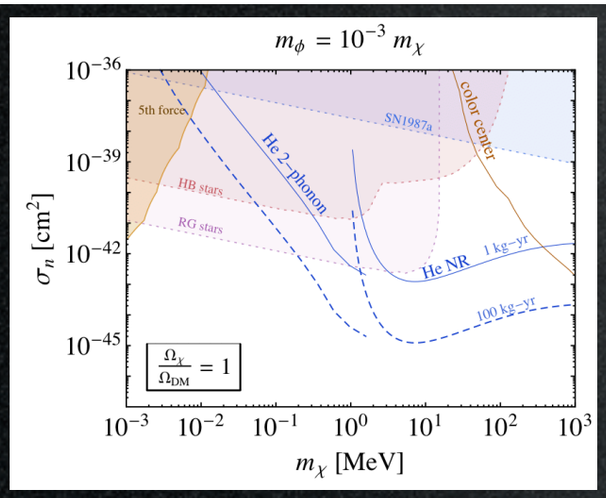

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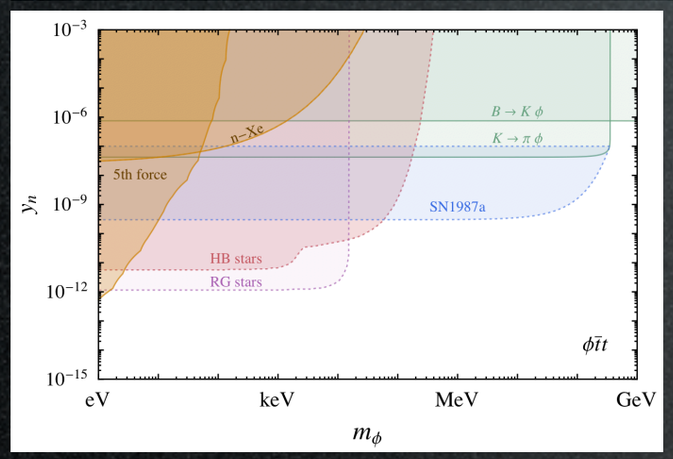

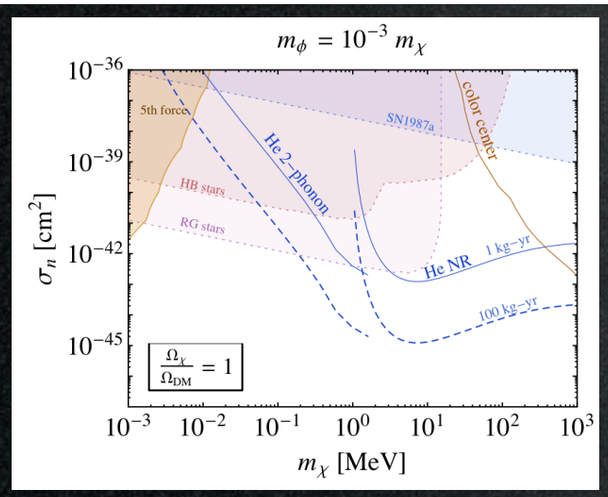

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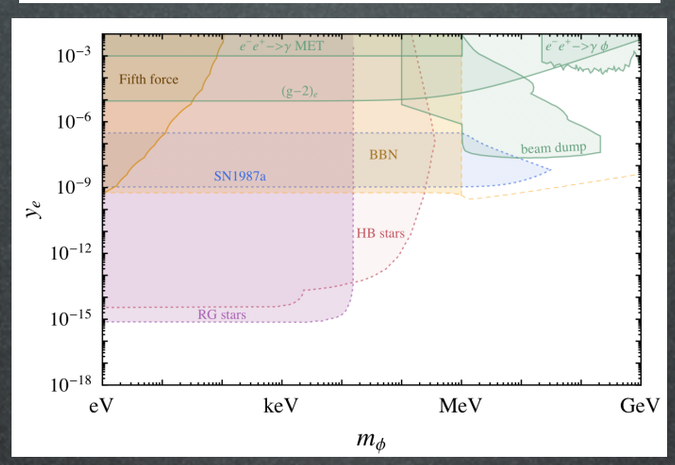

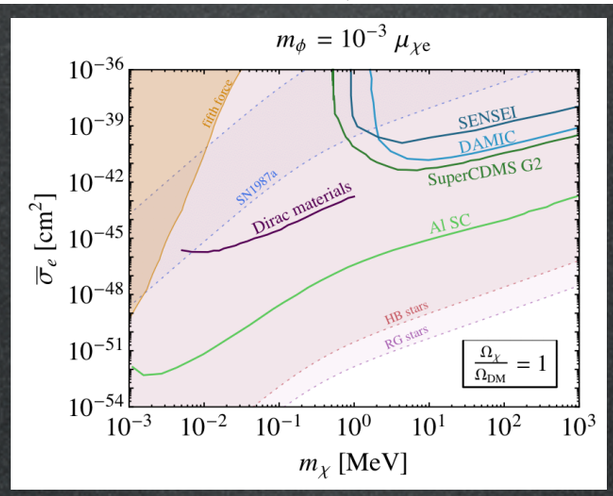

Theory

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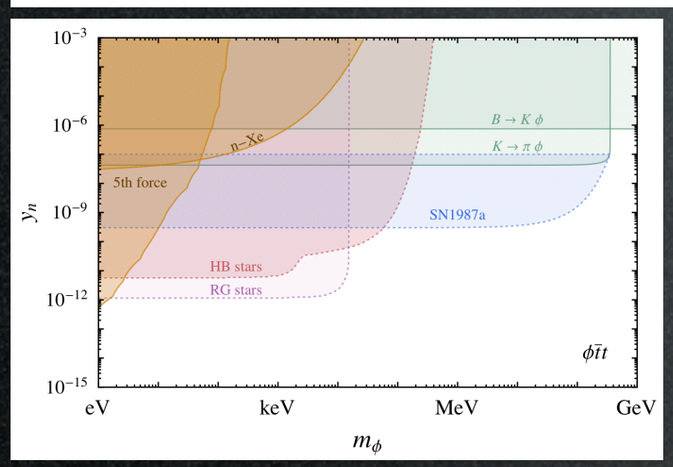

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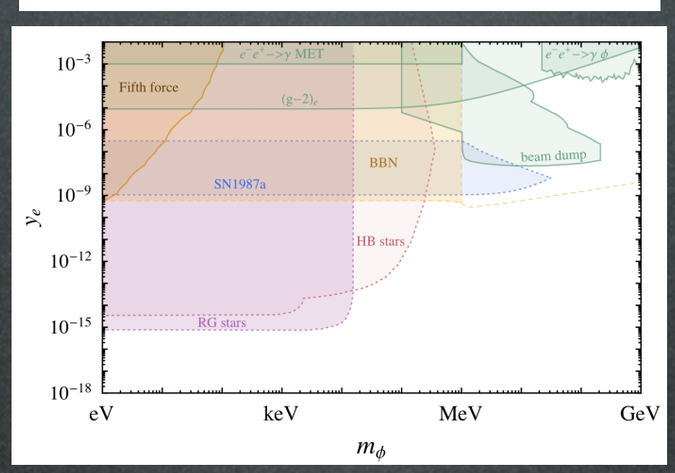
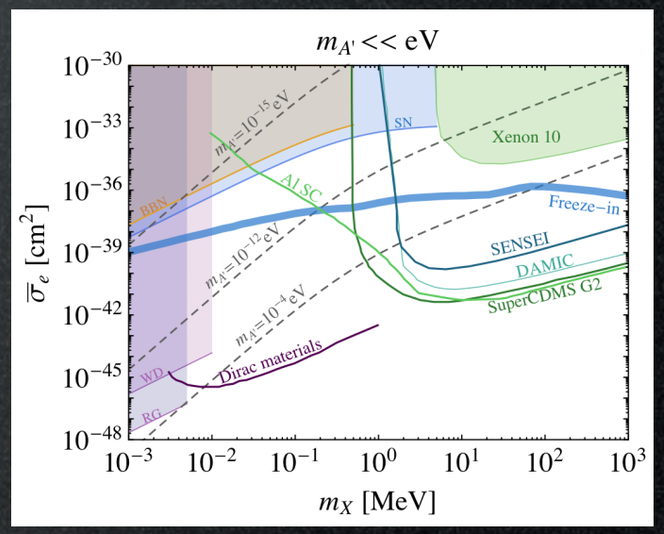
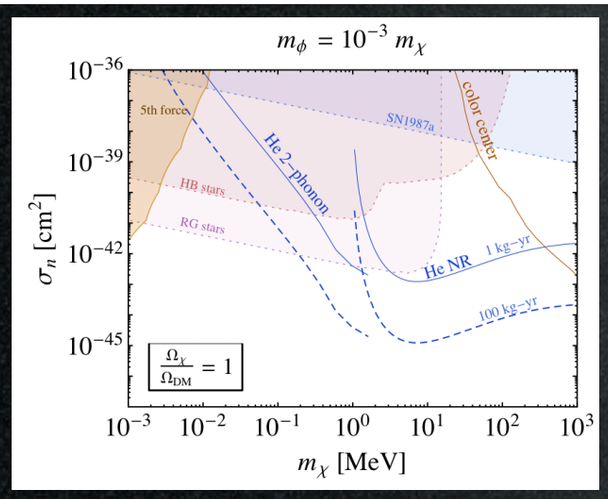
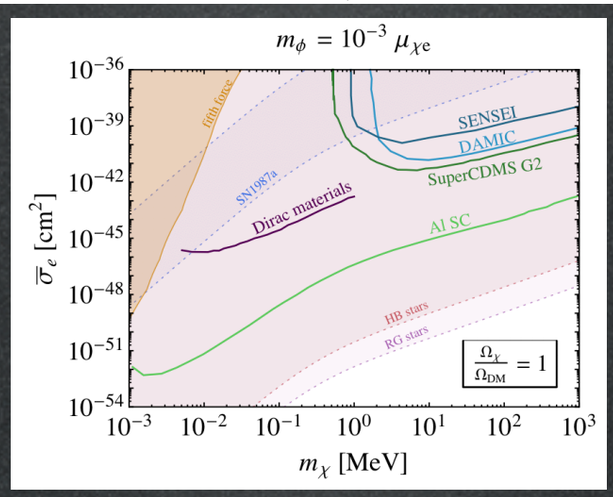


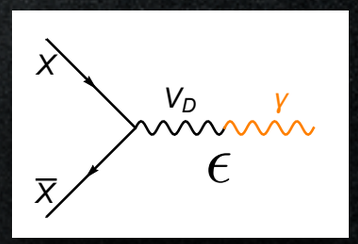
fermionic DM and vector mediator (e.g. dark photon)

$$\mathcal{L} \supset= -\frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} - y_\chi A'_\mu \bar{\chi}\gamma^\mu\chi$$









Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

Asymmetric DM: a completely different relic

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Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

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$$m_{\rm DM} \simeq 5 \text{ GeV}$$

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BBN, CMB...

'Darko'genesis:

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A variety of specific models/ideas:

transferring or co-genesis

cfr J. March-Russell

DM stores the anti-B number

via leptogenesis

connection to neutrino masses

Asymmetric DM: a completely different relic

$$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \to f\bar{f} \qquad \chi\,? \nrightarrow \ldots$$

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- 'heavy' (e.g. $\gtrsim$ GeV)
- 'stable'
- in an expanding Universe
- **A**symmetric abundance
- large annihilation cross sec

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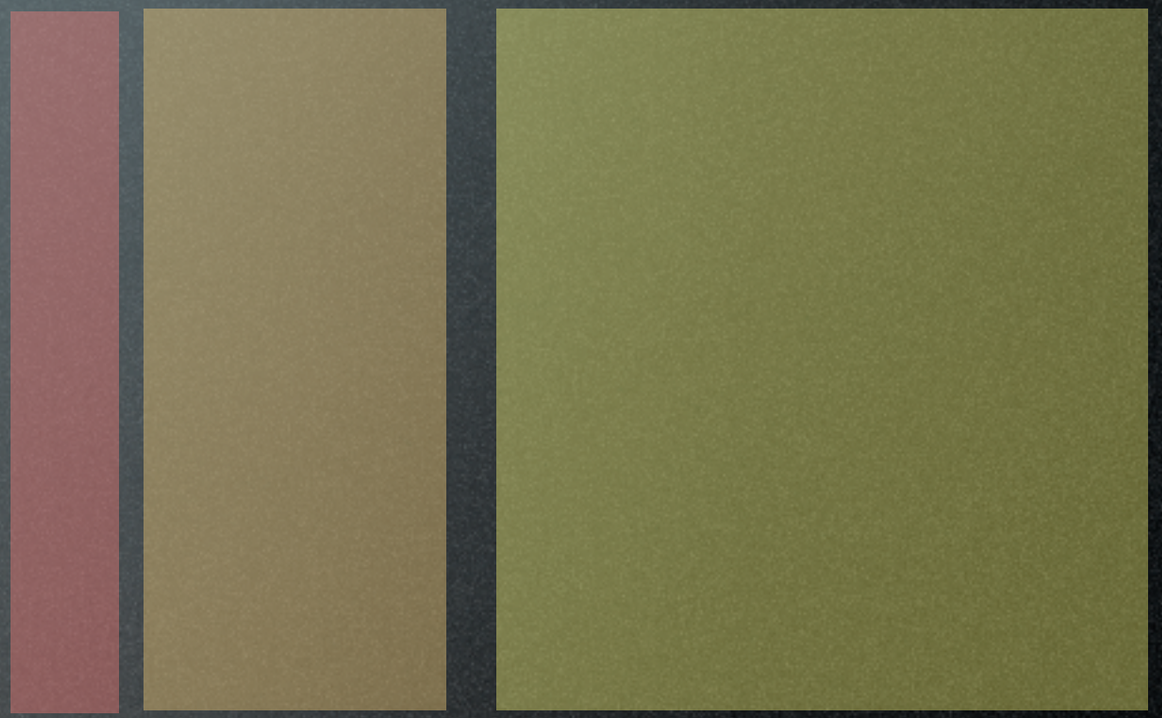

$$\Omega_{\rm X} \simeq \frac{m_{\rm X}\, s}{\rho_{\rm crit}} \eta_0$$

The relic abundance is determined by η_0 and $m_{\rm X}$.

Theory

Sub-GeV DM?

- WIMPless Dark Matter
- 'SIMP miracle'
- Asymmetric DM
- 'MeV (scalar) DM' (Integral 511 KeV excess)
- 'simplified (light) DM models'
- ...

Theory

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theory

production

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Collider Searches?

Indirect Detection?

Direct Detection?

Candidates

theory

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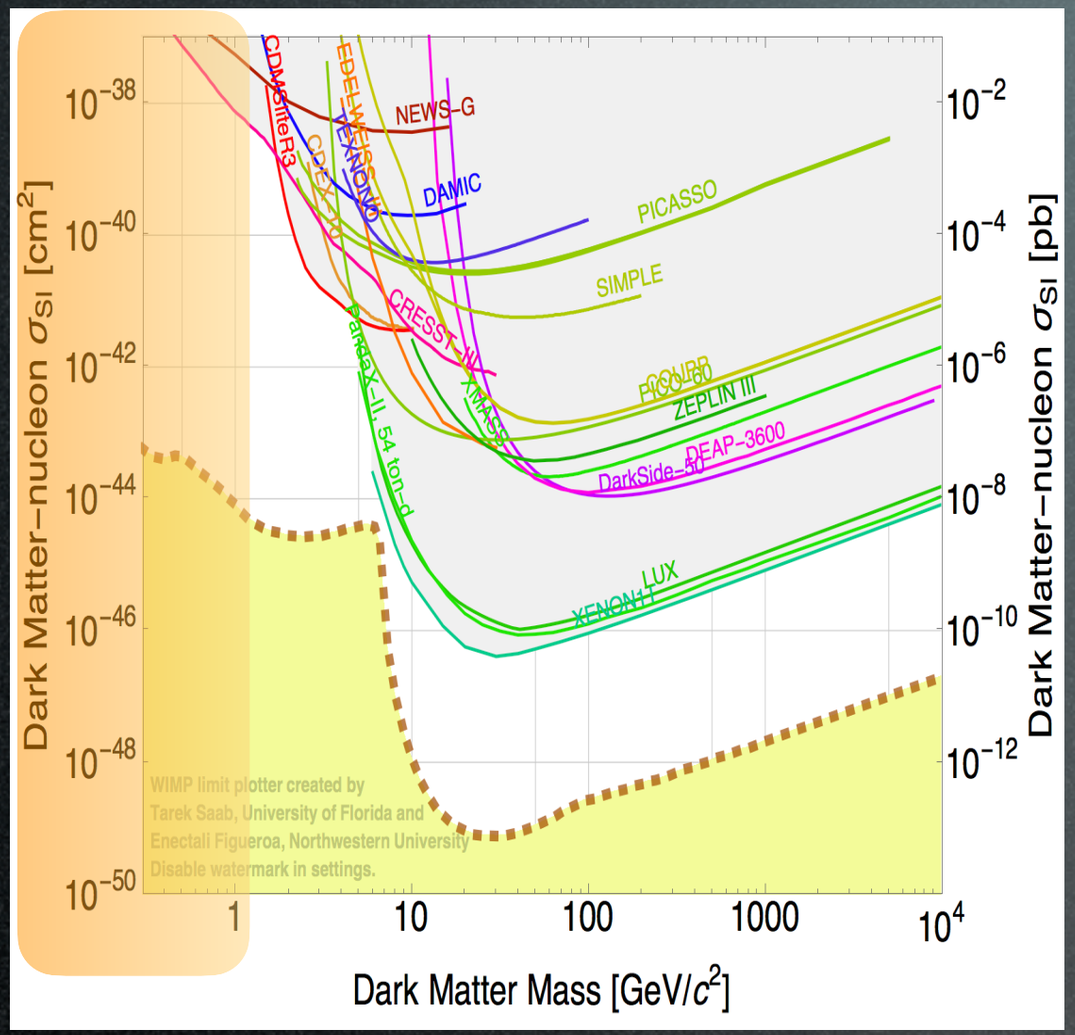
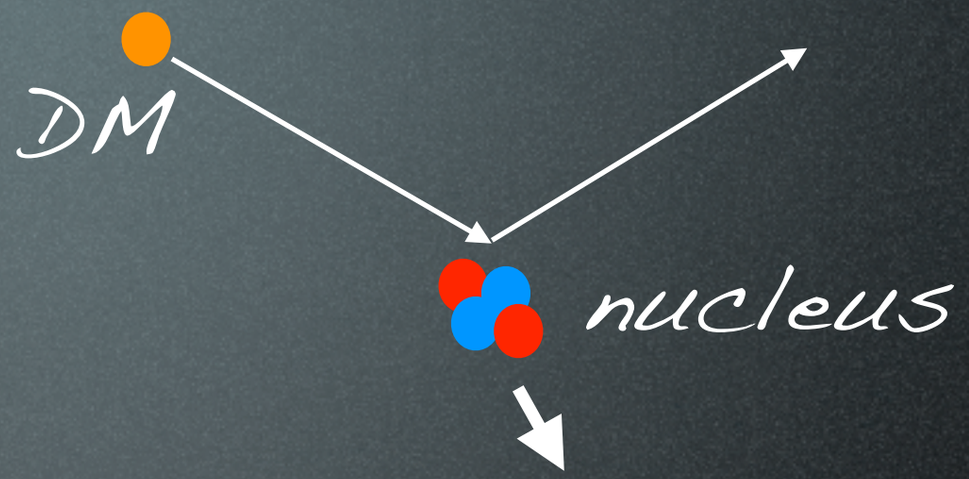
Direct Detection?

Direct Detection of sub-GeV DM

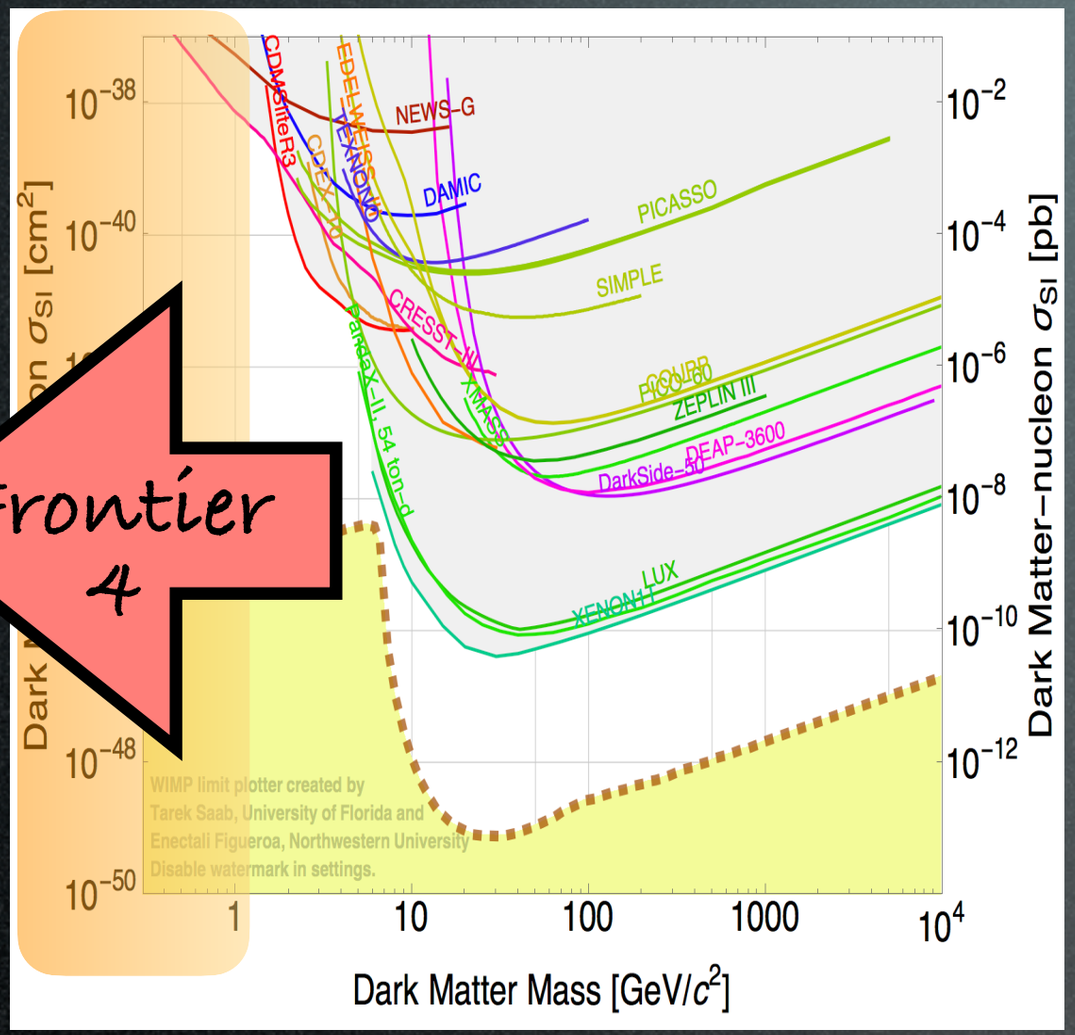


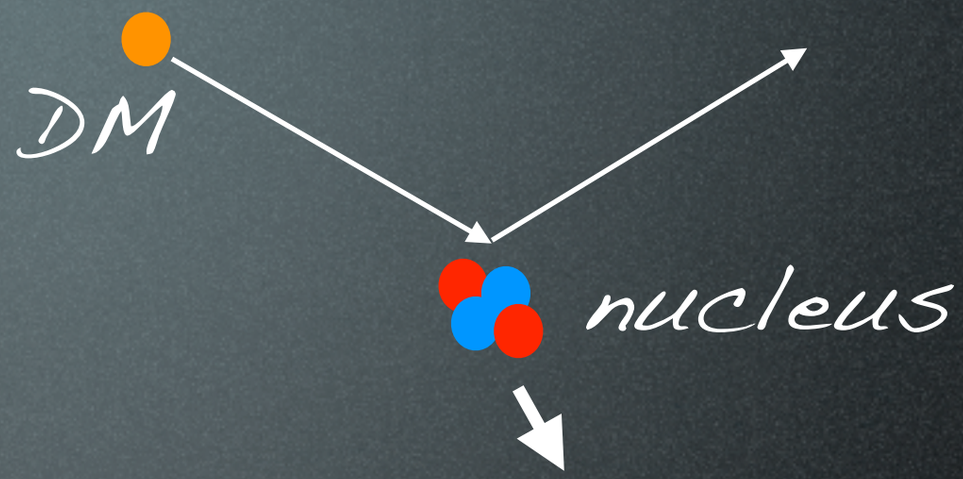


deposited energy is below threshold for typical nuclear recoil experiments

- electron recoil signal
- Migdal effect
- new experimental strategies

Direct Detection of sub-GeV DM





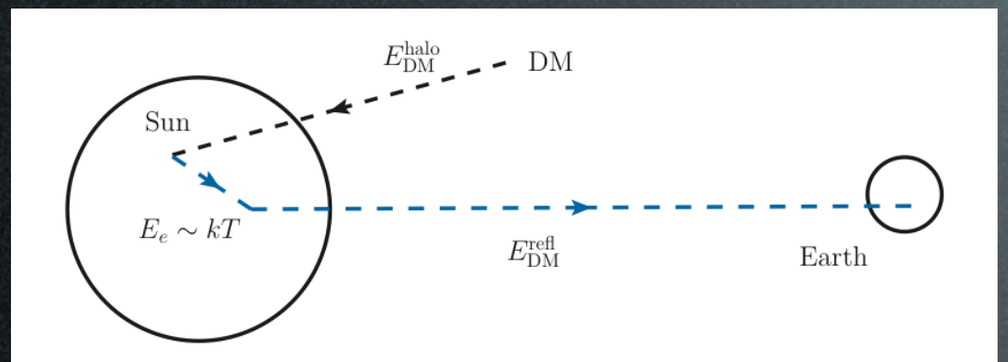
deposited energy is **below threshold** for typical nuclear recoil experiments

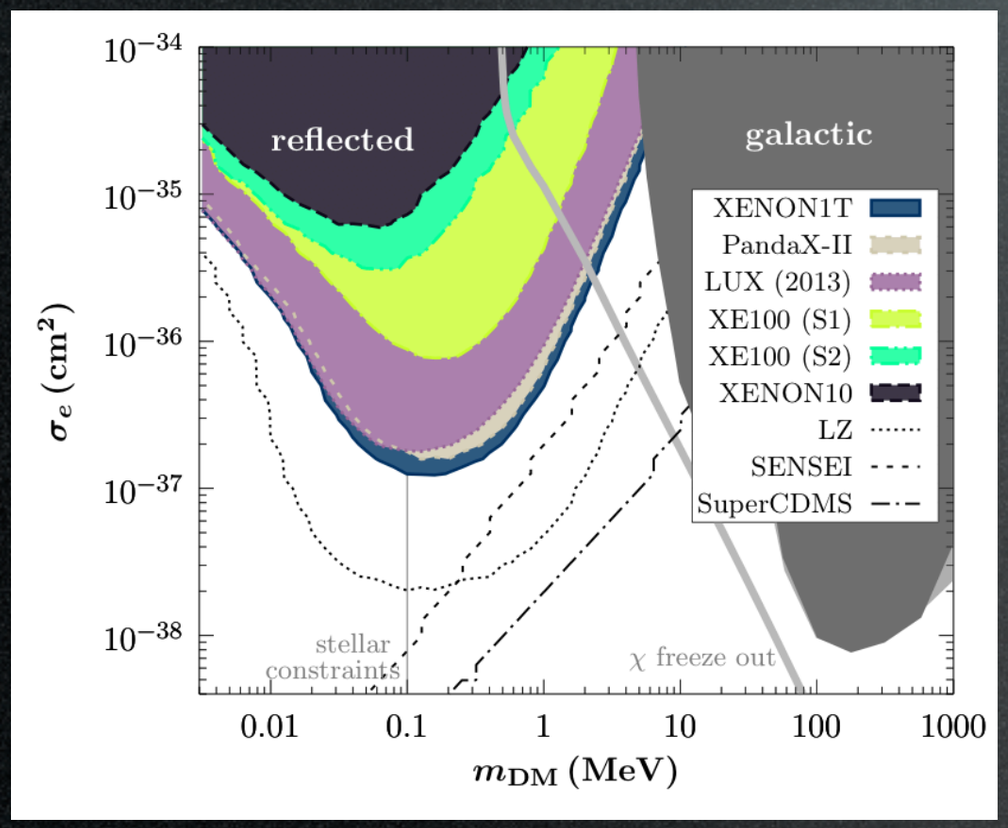
- electron recoil signal
- Migdal effect
- new experimental strategies

“Direct Detection” of sub-GeV DM

‘Reflected DM’

light DM upscattered by hot e^- in the Sun gives signal above threshold
(DM-e scattering, twice)



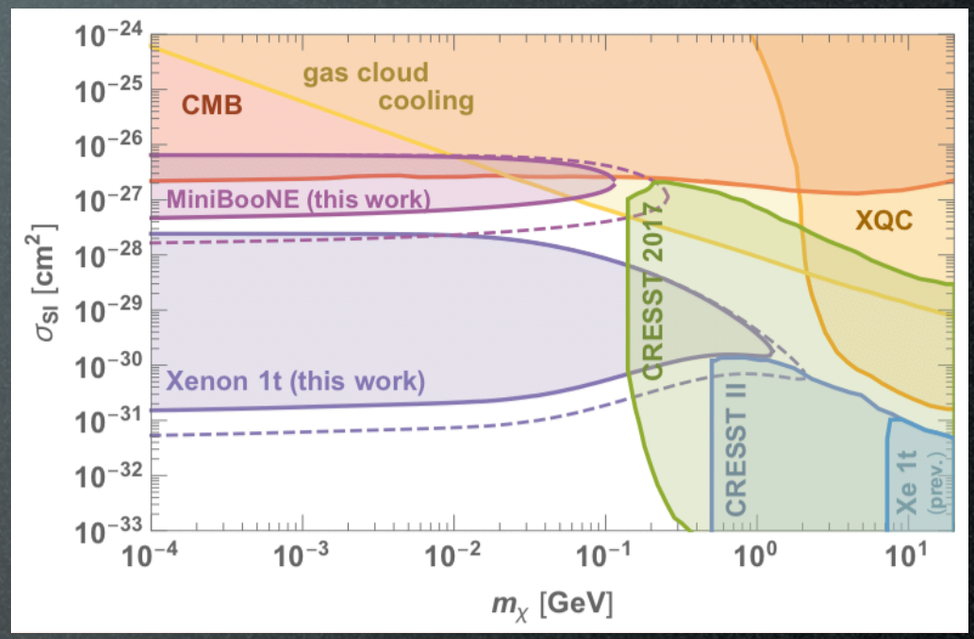


An, Pospelov, Pradler, Ritz 1708.03642

original idea with DM-nucleon scattering:
Kouvaris+ 1506.04316, 1709.06573

‘CR DM’

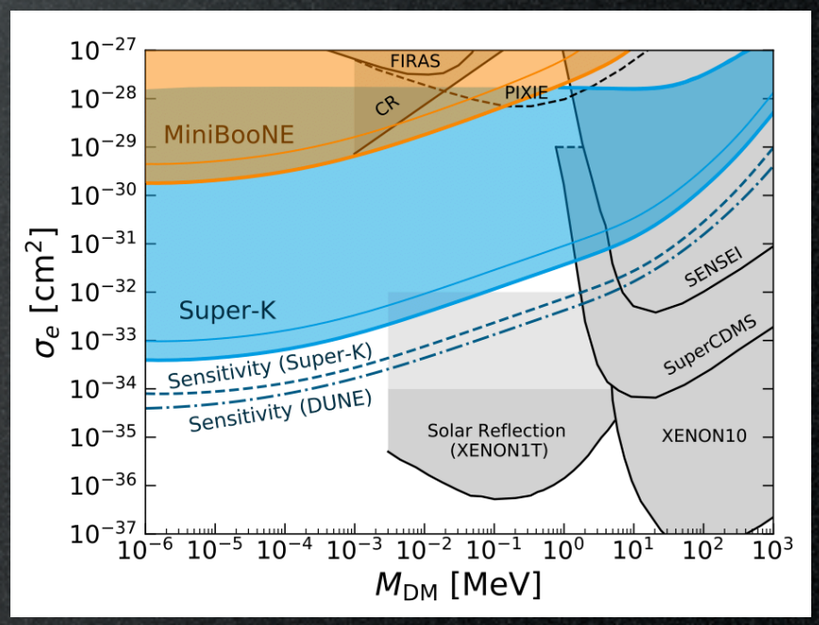
DM upscattered by HE CRs gives signal above threshold in DD even if light



Bringmann, Pospelov 1810.10543

same idea with electron scattering and signal in SK

Ema, Sala, Sato 1810.10543



improvements: Cappiello & Beacom 1906.11283

another incarnation: light DM produced in spallations of CR on atmosphere
Alvis, Fairbairn+ 1905.05776

Candidates

theory

production

Sub-GeV DM?

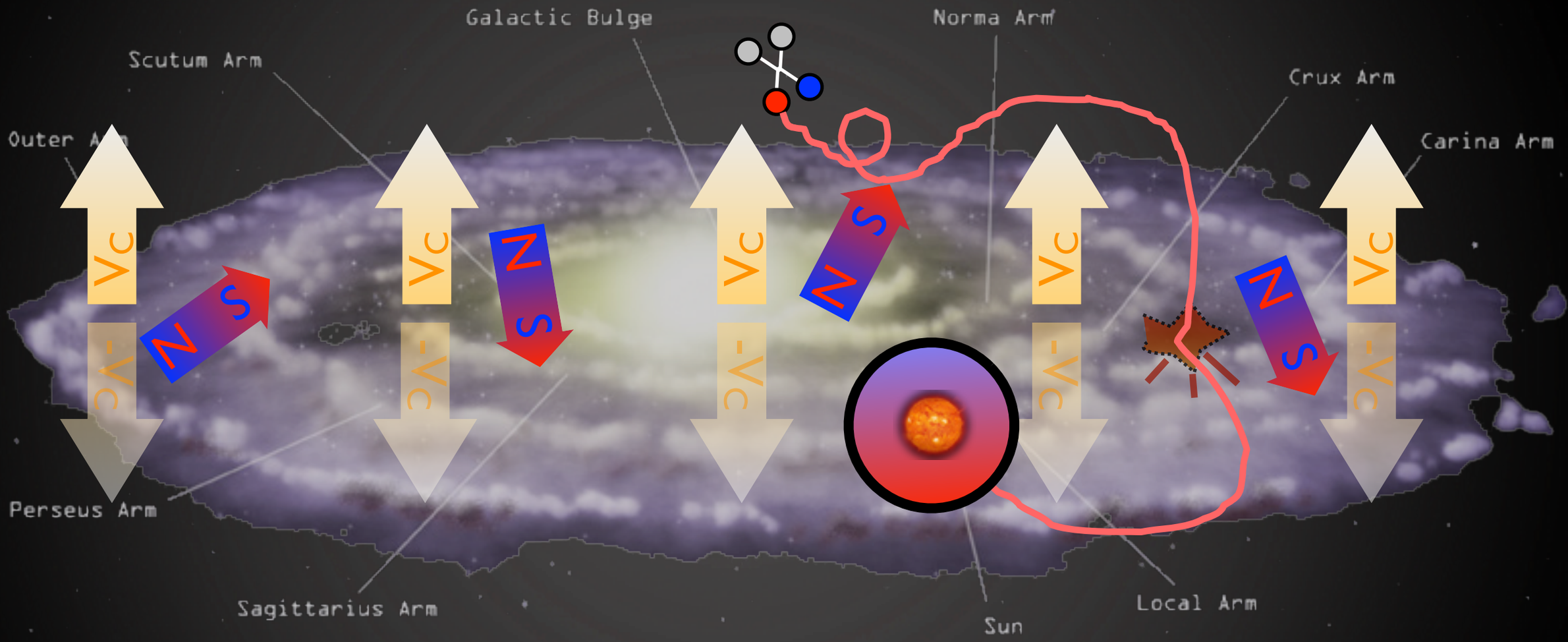
Collider Searches

Indirect Detection?

Direct Detection

Indirect Detection: charged CRs

$\bar{p}$ and e^+ from DM annihilations in halo



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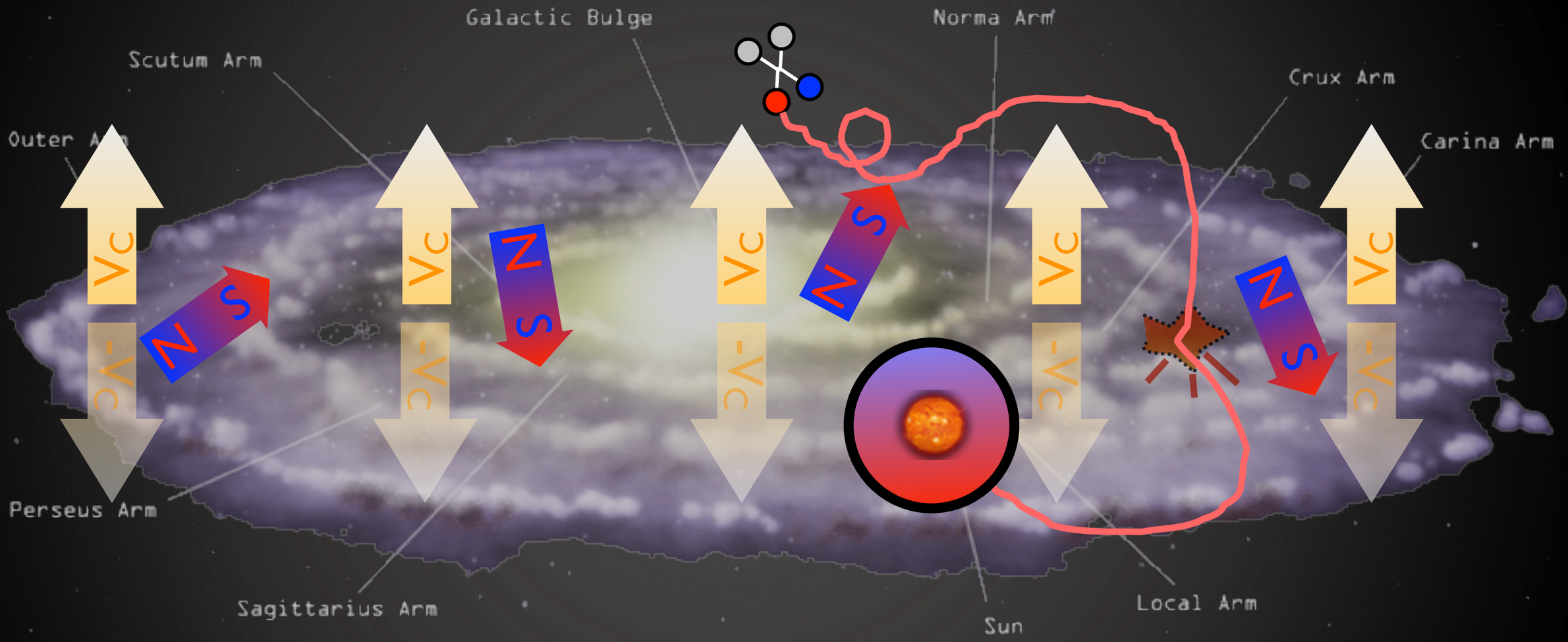

Problem:

sub-GeV charged CRs do not penetrate the heliosphere, experiments cannot collect

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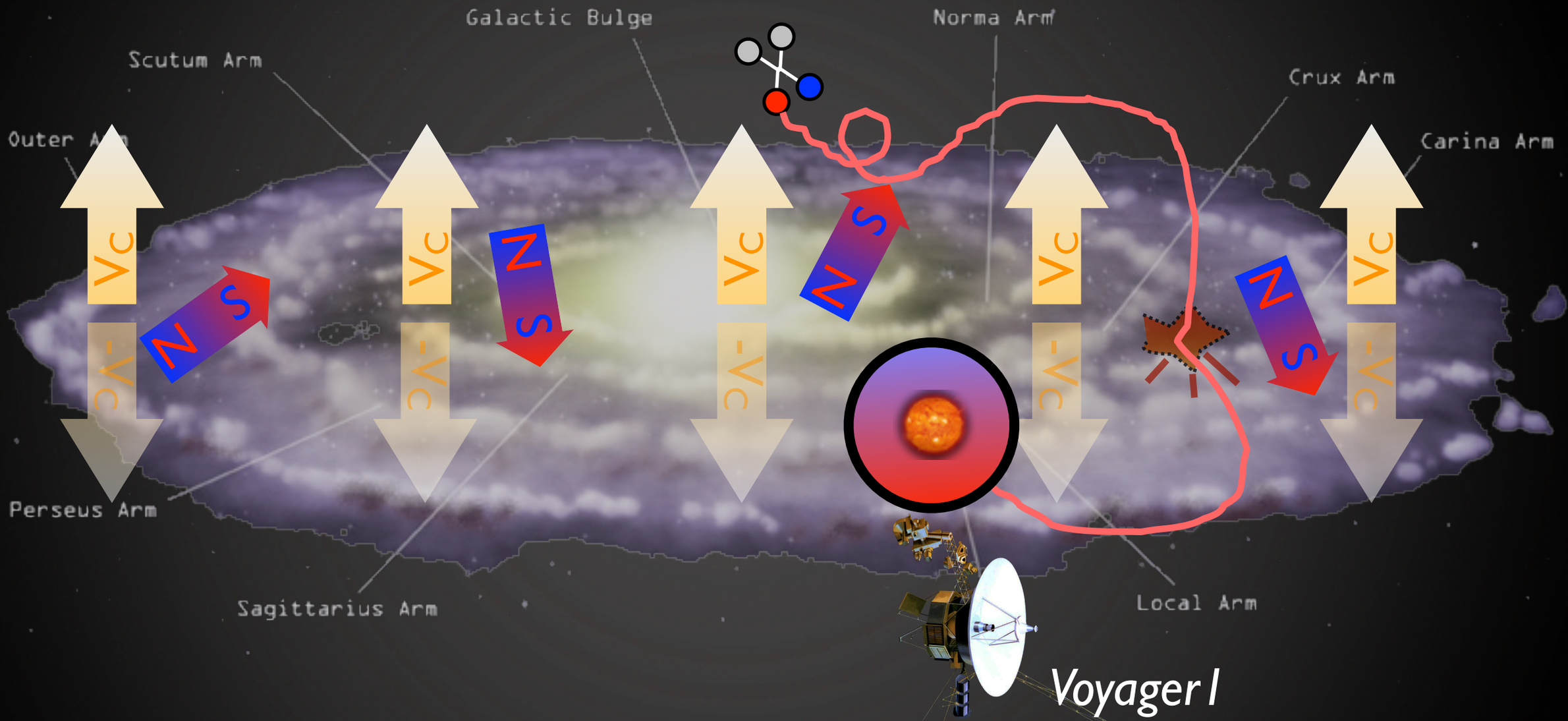


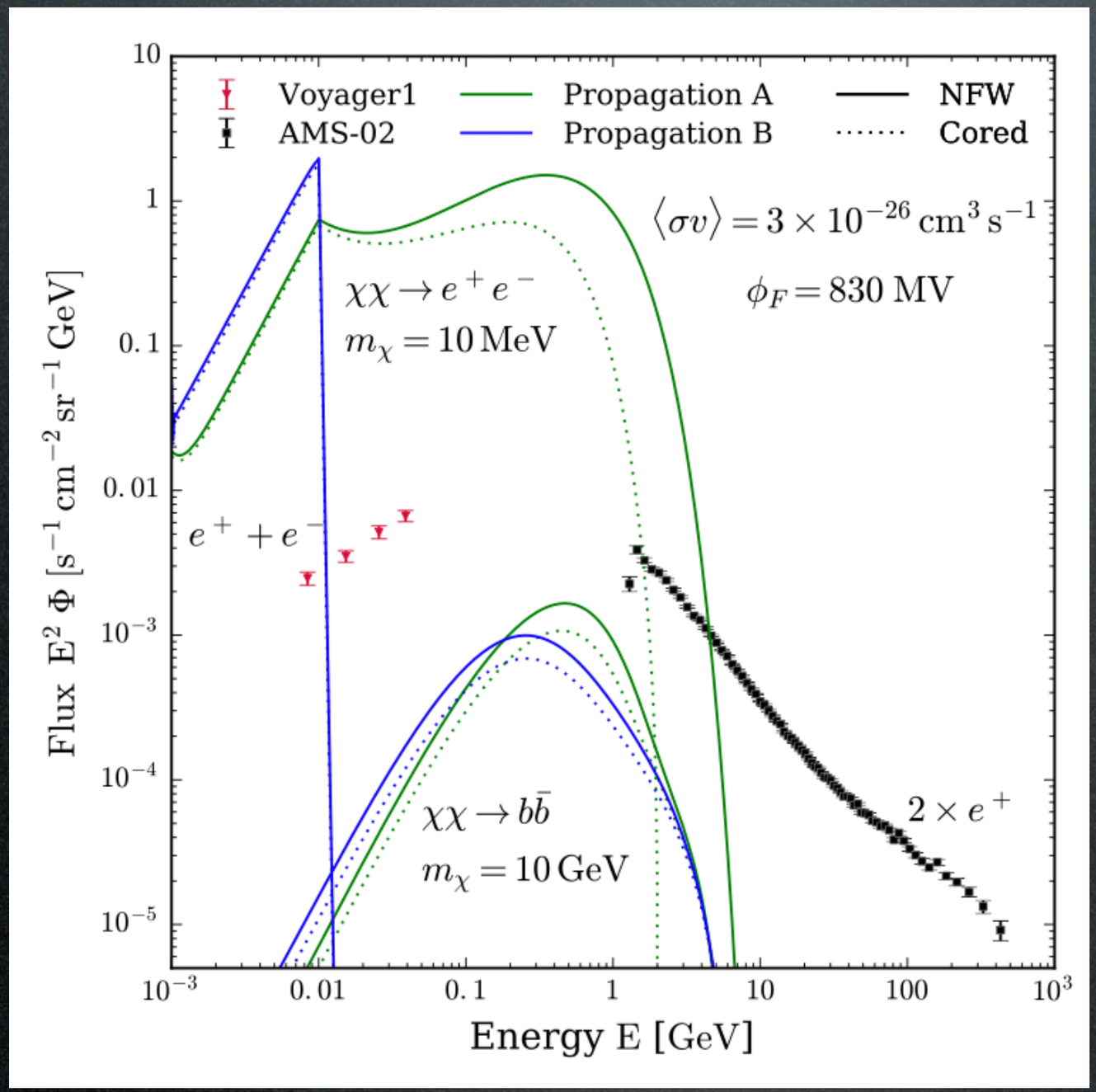
Problem:

sub-GeV charged CRs do not penetrate the heliosphere, experiments cannot collect... with one exception!

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I



Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

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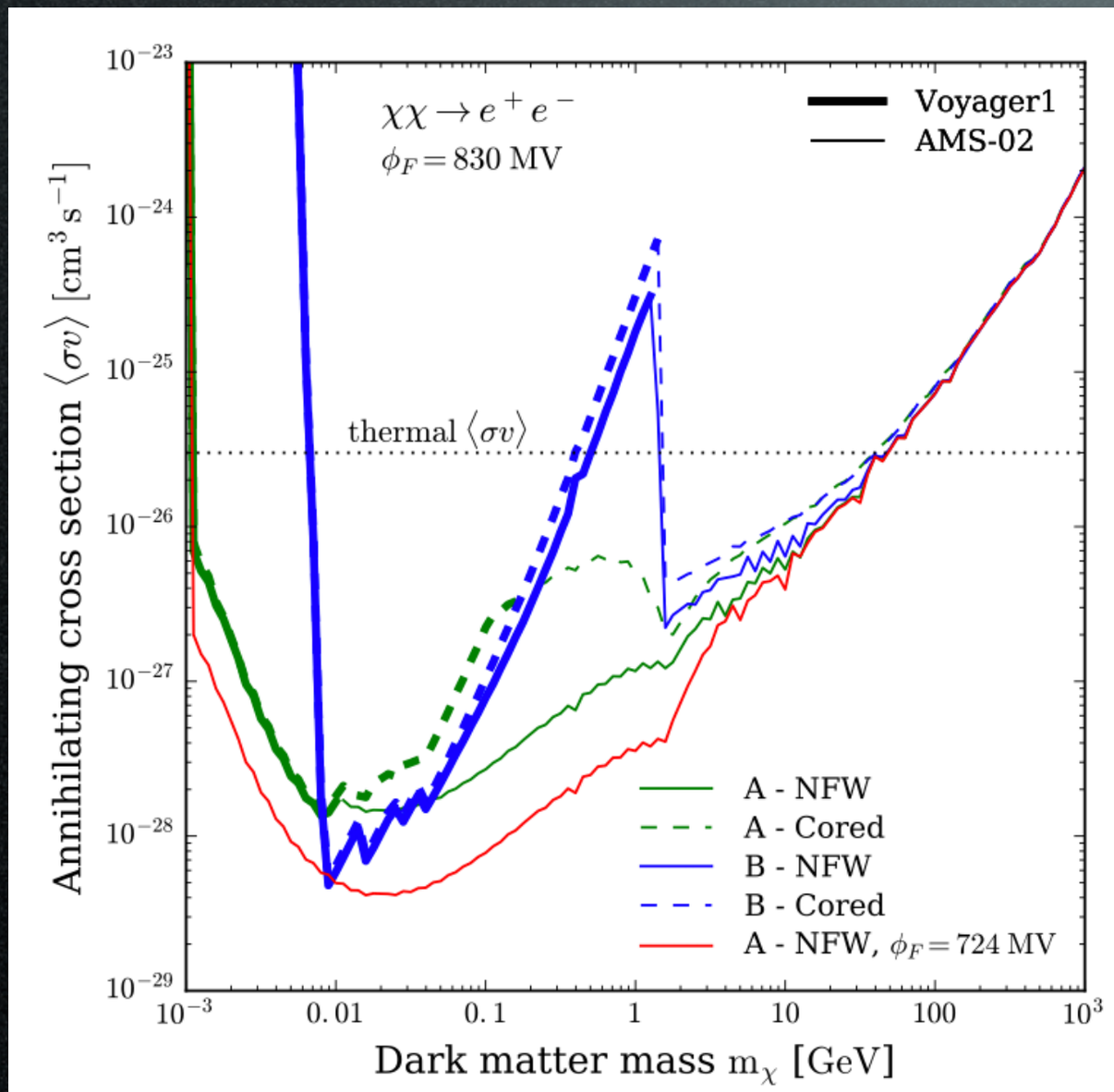

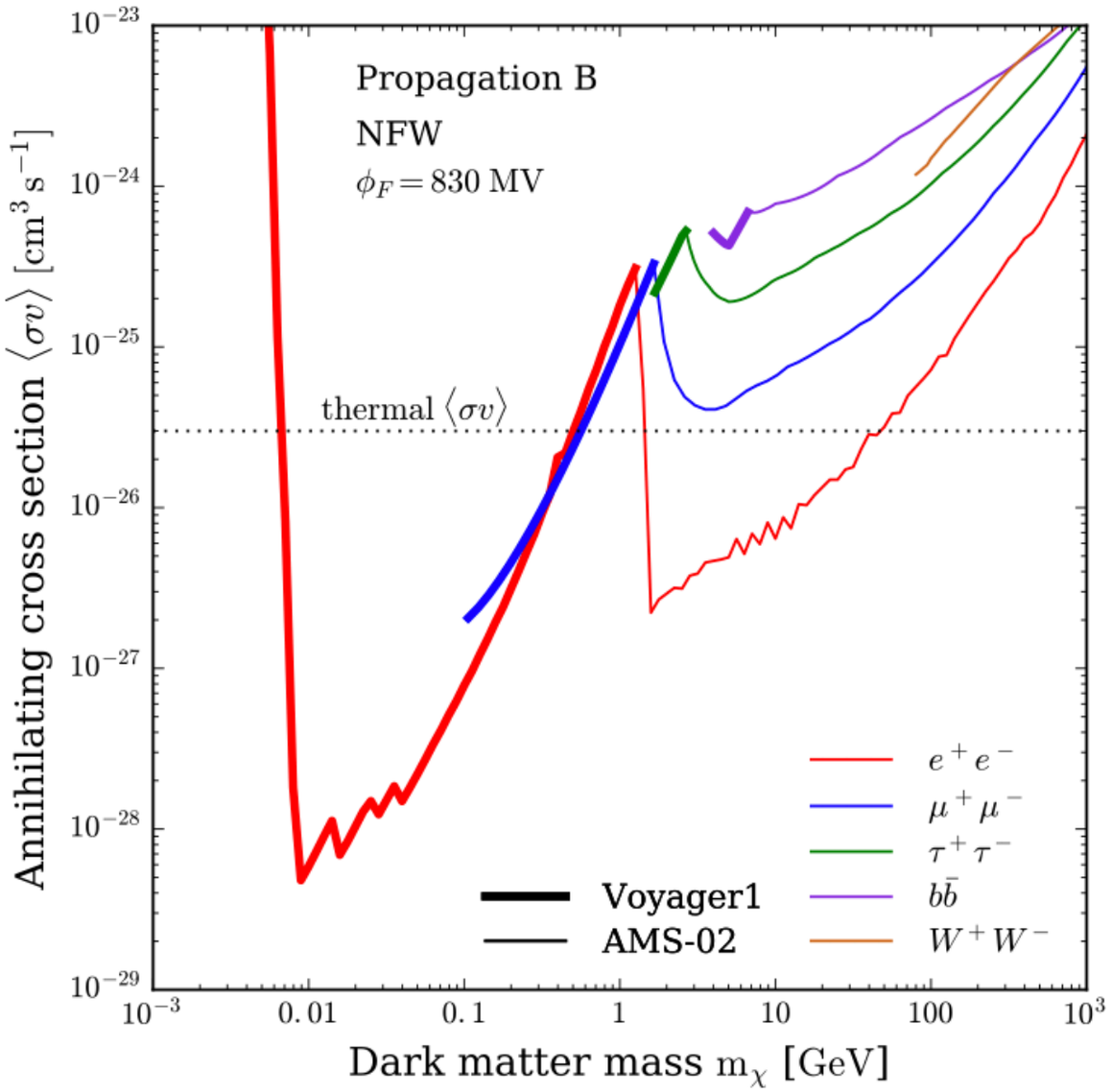

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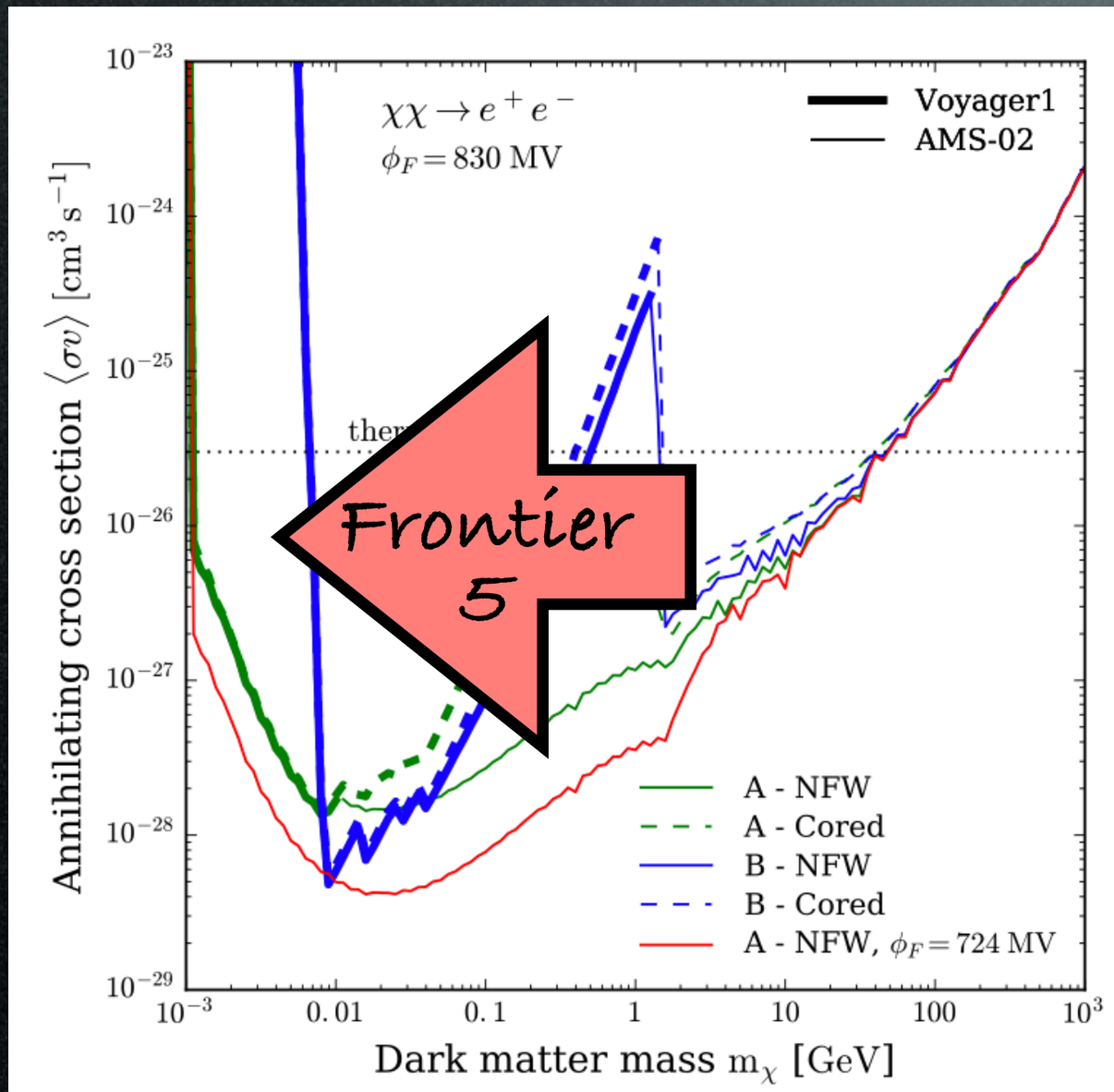
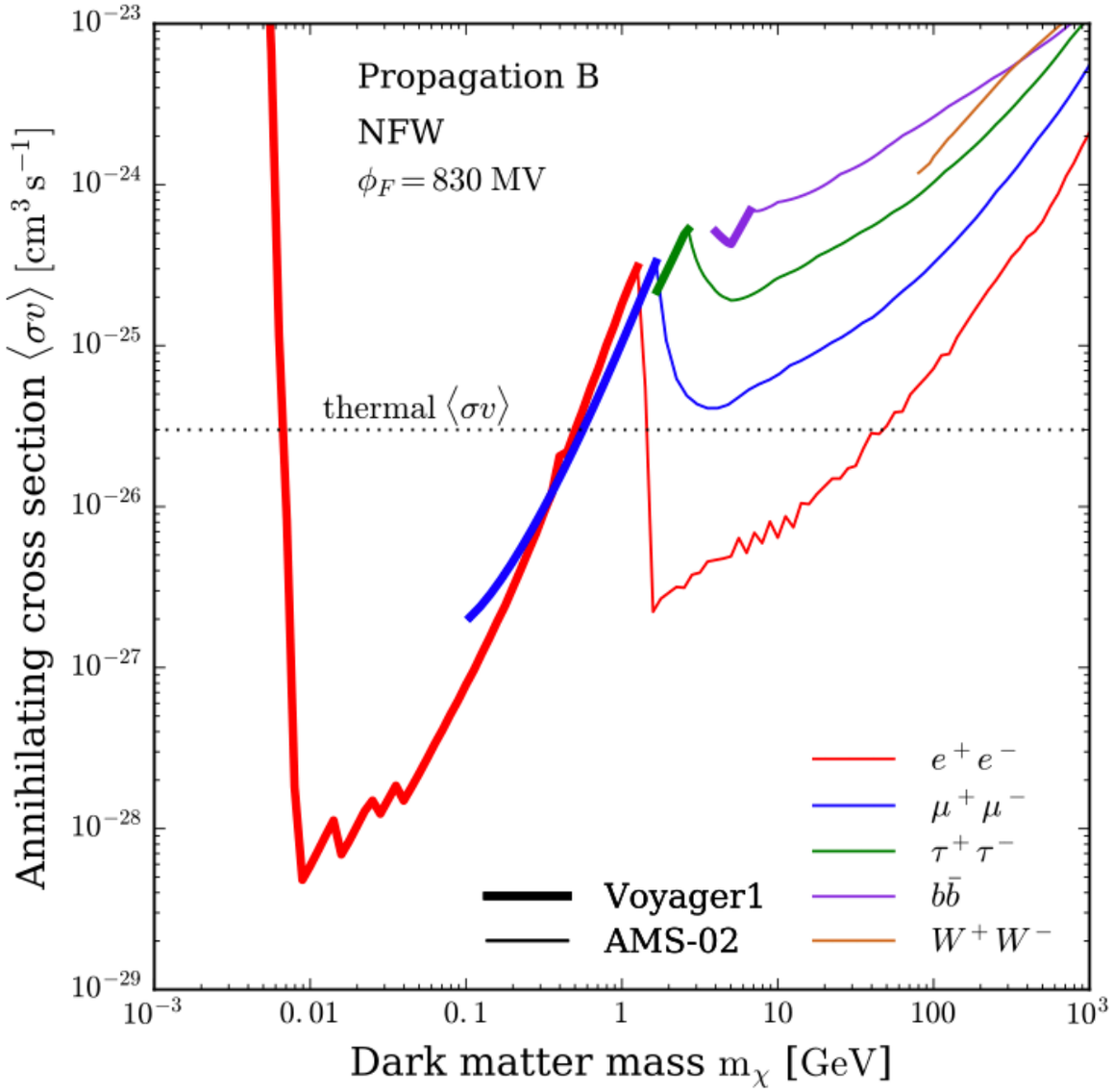
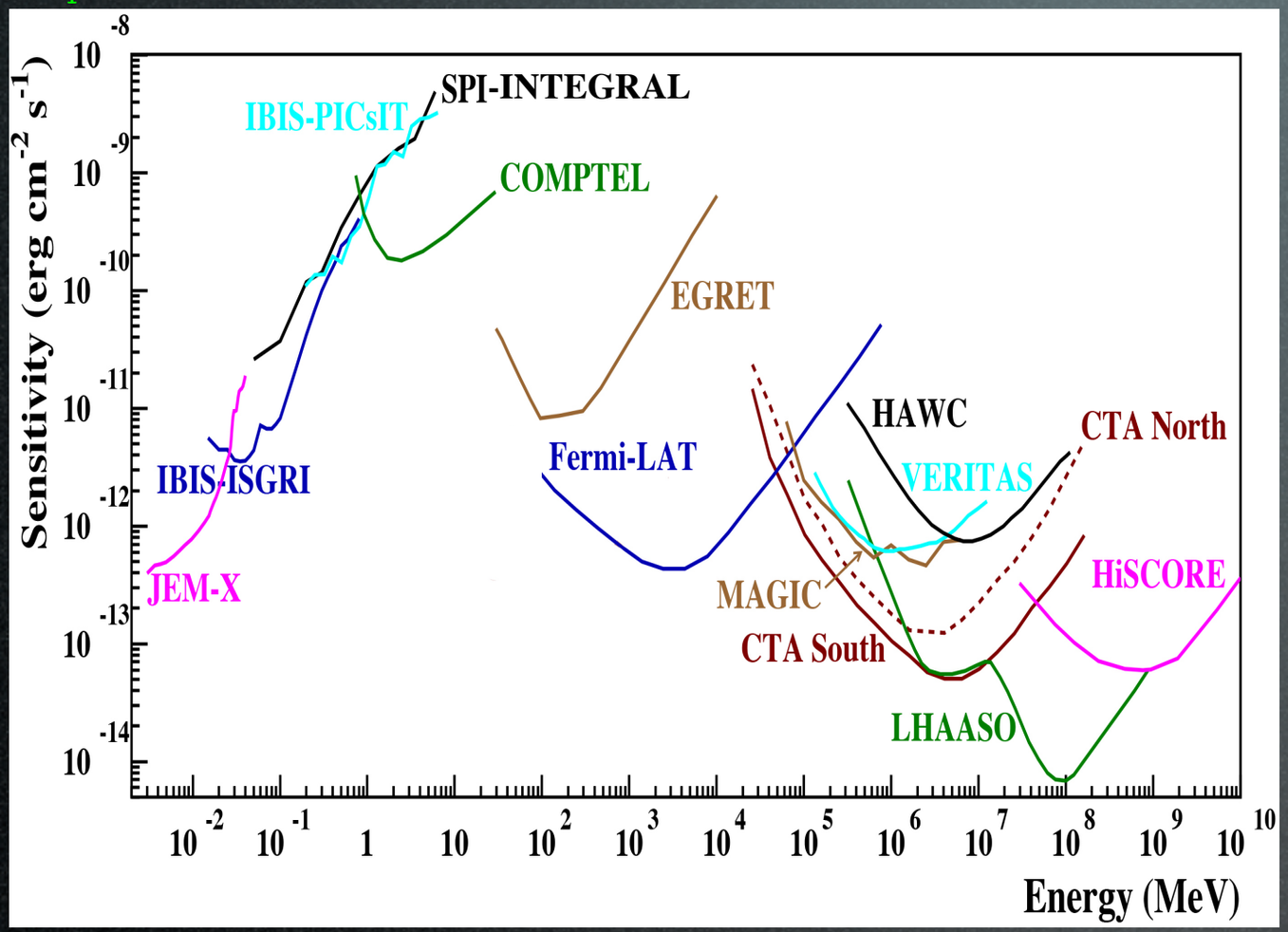




Indirect detection: photons

adapted from 1611.02232



Past/current experiments:

Integral, Comptel, Fermi

(2002⟶) *(1991-2000)* *(2009⟶)*

Planned/proposed experiments:

e-Astrogam?, Compair?, Amego?

HERD	Chinese SS	2020s?	HEP detectors	charged CRs	50 GeV – PeV
Amego	satellite	2020s?	HEP detectors	γ-rays	0.2 – 10 GeV
Compair	satellite	2020s?	HEP detectors	γ-rays	0.2 – 500 MeV
Ska	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz
Ino-Ical	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
e-Astrogam	satellite	2030s?	HEP detectors	γ-rays	0.3 MeV – 3 GeV

Cirelli, Strumia, Zupan to appear

Indirect detection: photons

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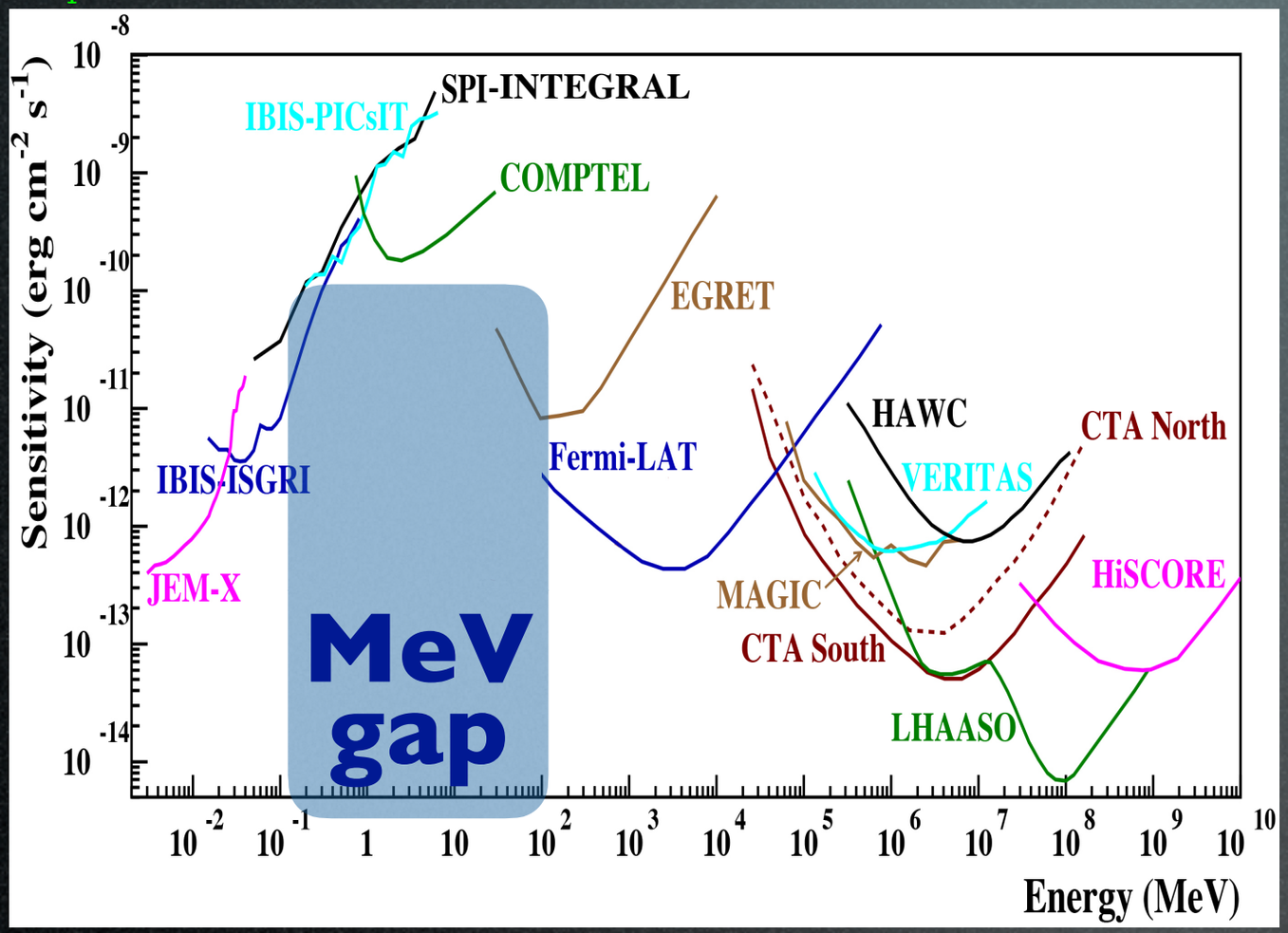

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COMPAIR	satellite	2020s?	HEP detectors	γ-rays	0.2 – 500 MeV
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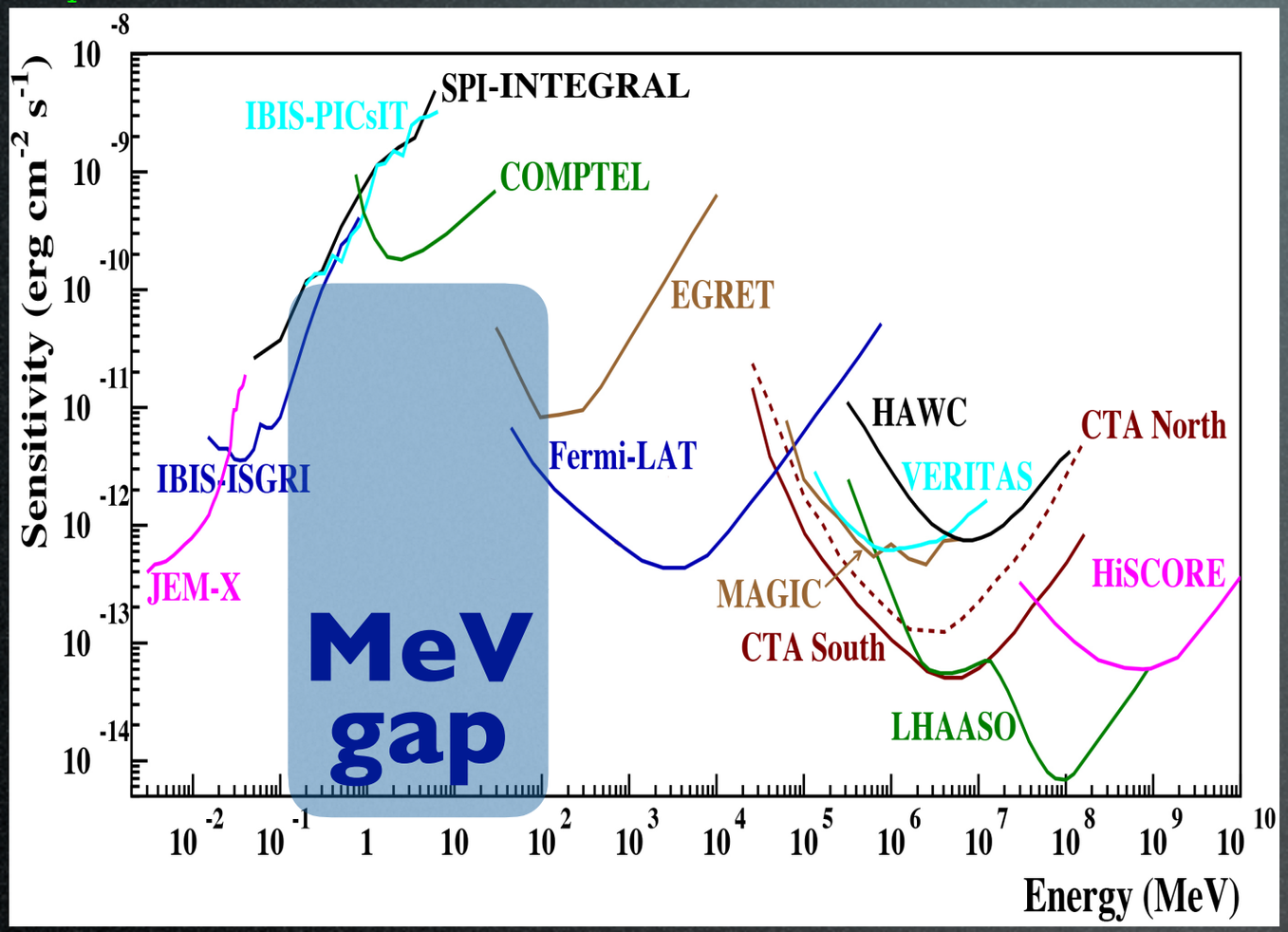

How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Sub-GeV DM & X-rays

Annihilation channels, focus on the MW (assume standard NFW profile)

$\mathrm{DM\ DM} \to e^+e^-$

$\mathrm{DM\ DM} \to \mu^+\mu^-$

$\mathrm{DM\ DM} \to \pi^+\pi^-$

Sub-GeV DM & X-rays

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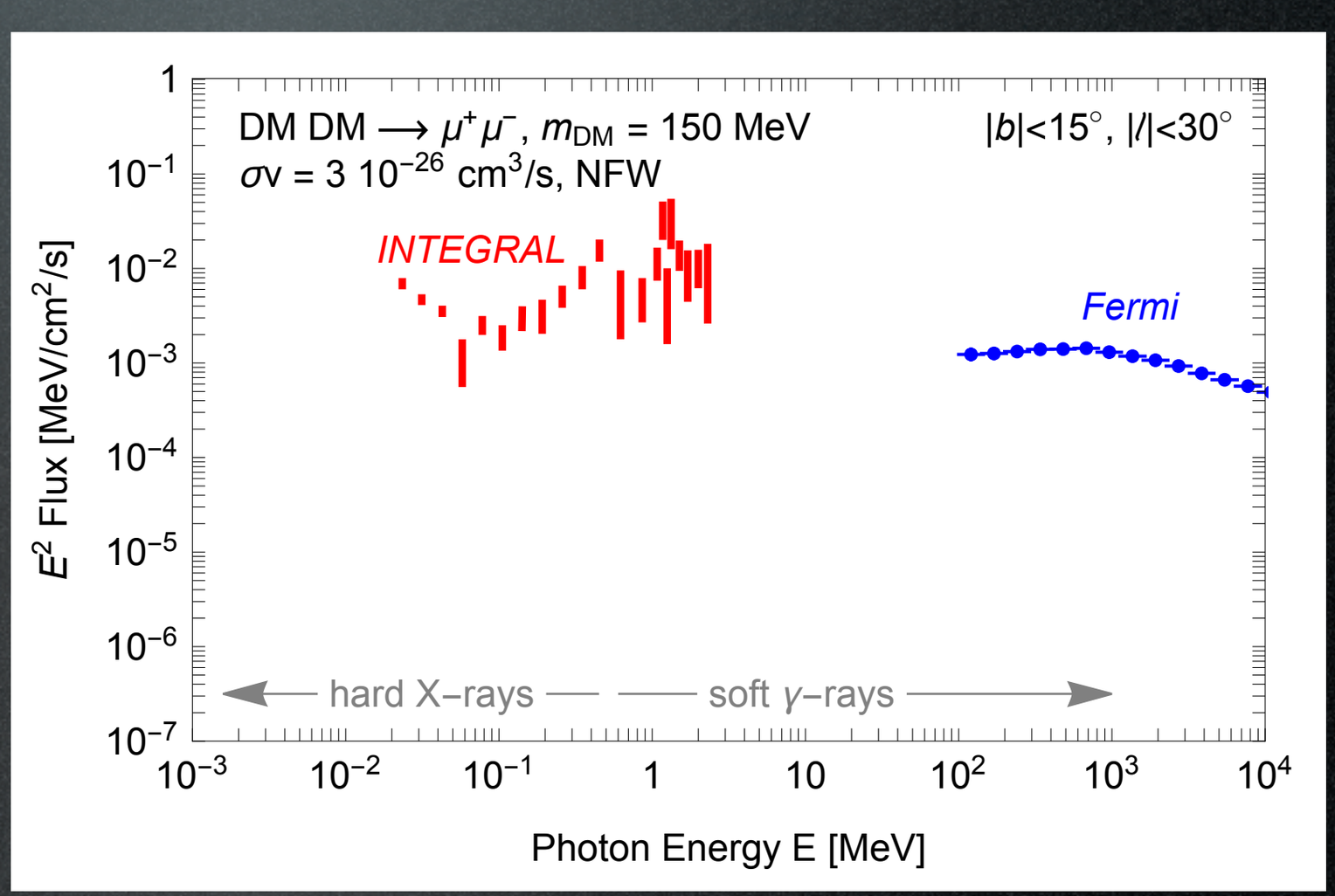

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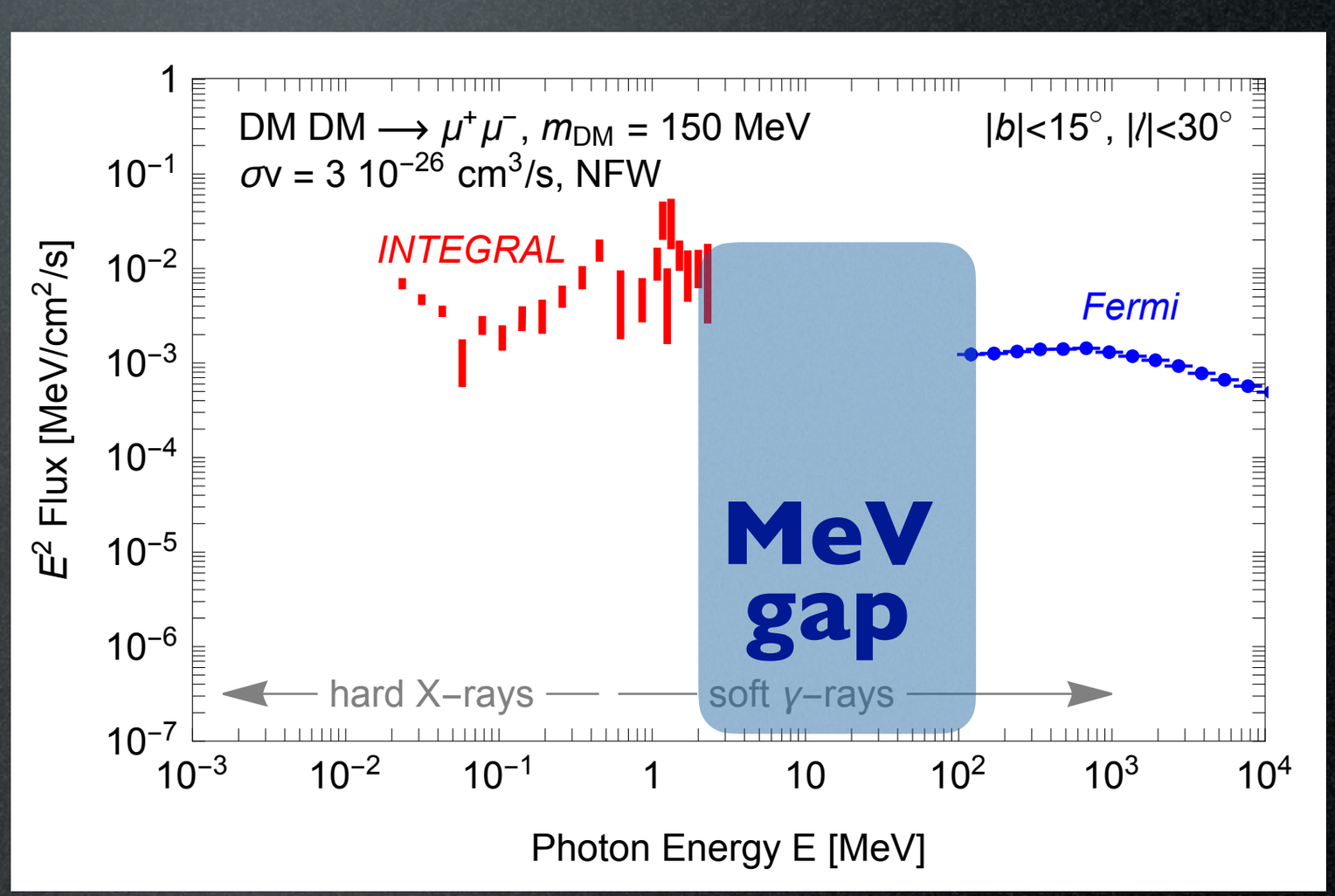

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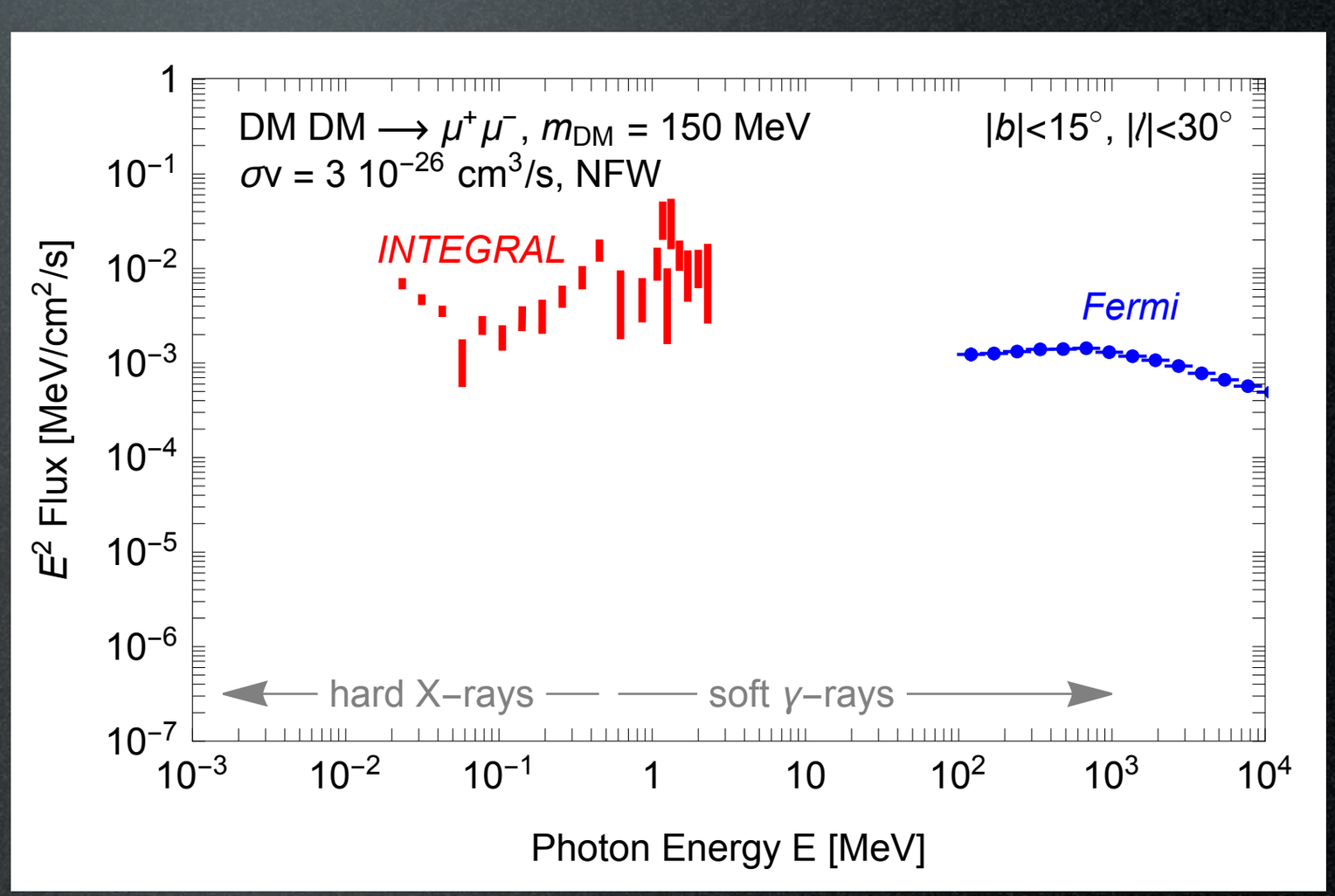

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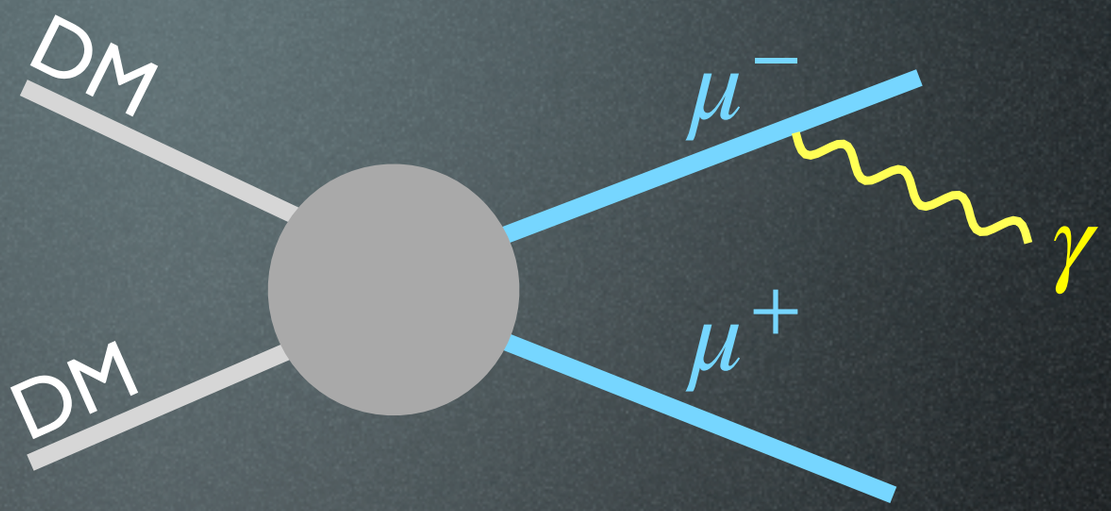
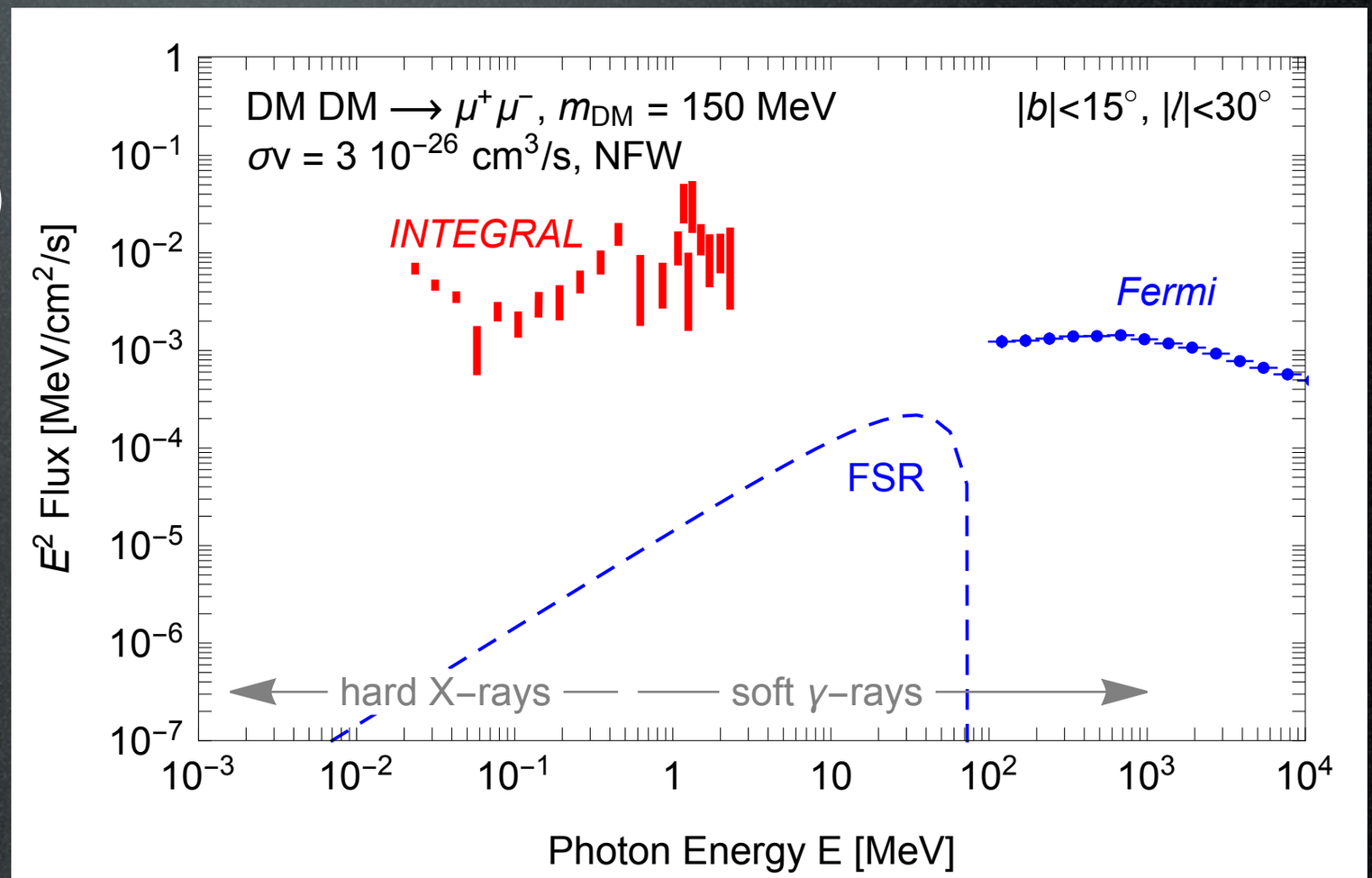


'Prompt' emission:

Final State Radiation (FSR)



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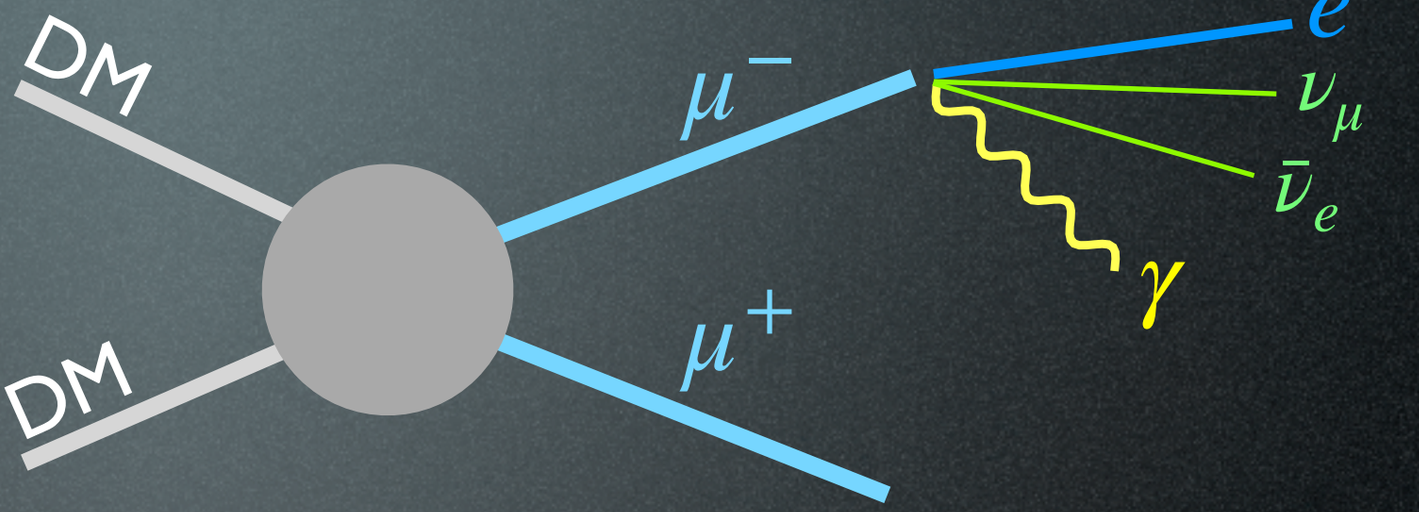
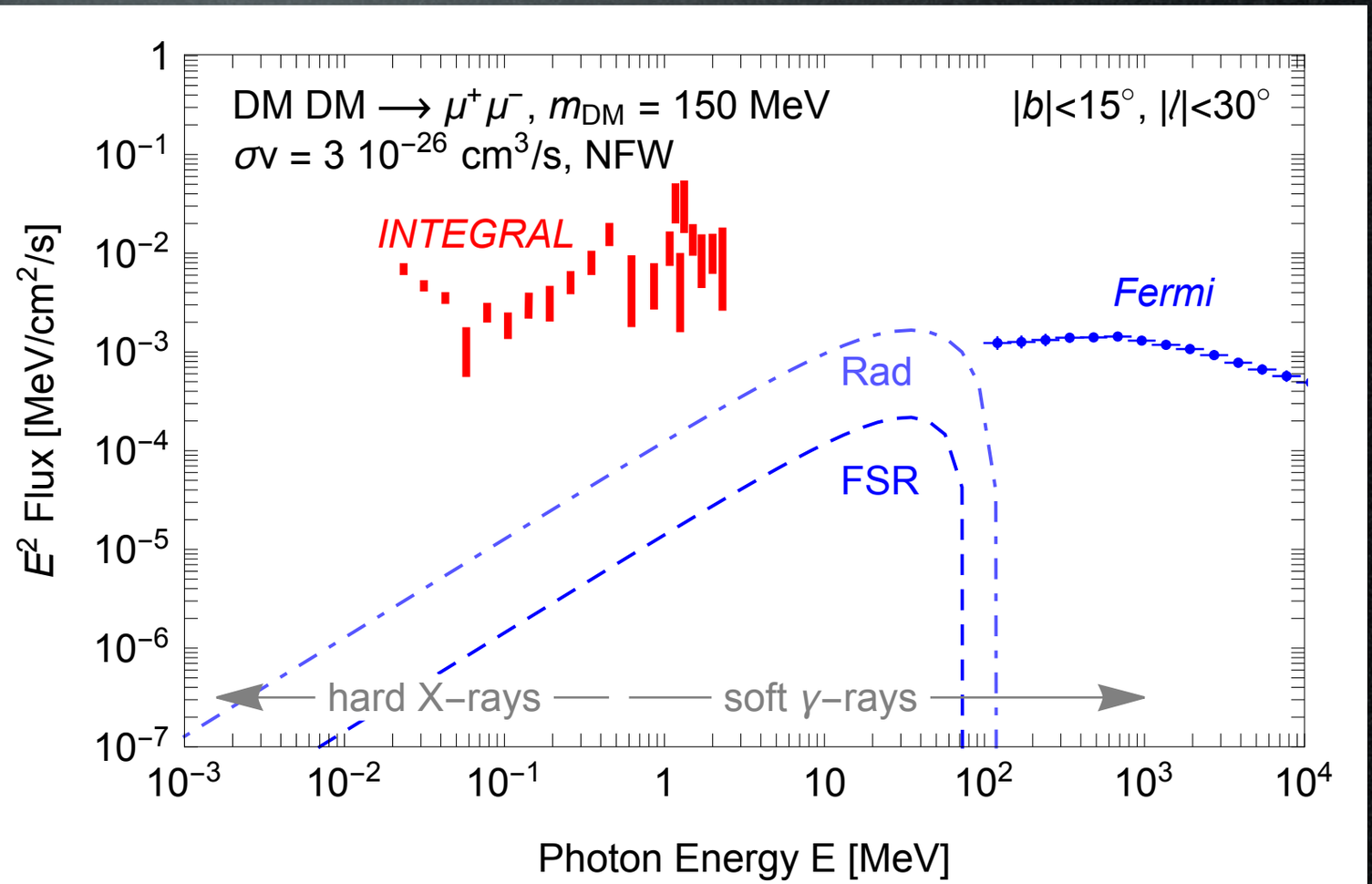


'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

Usually irrelevant, but <u>not</u> for μ decaying 'at rest'!



Sub-GeV DM & X-rays

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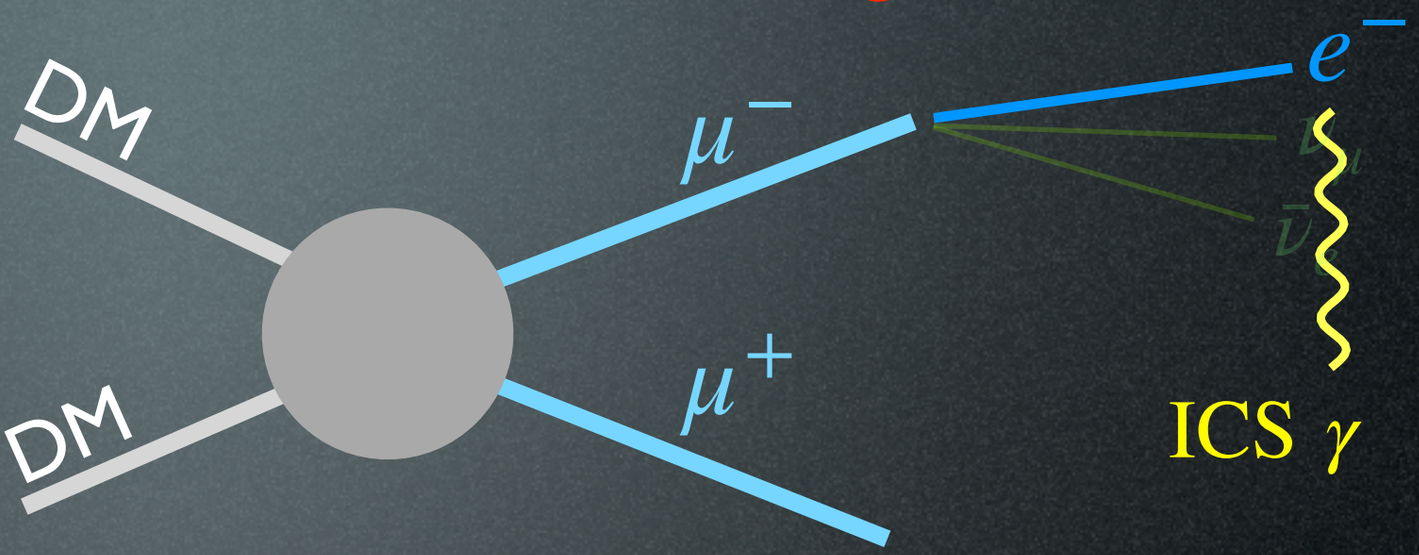


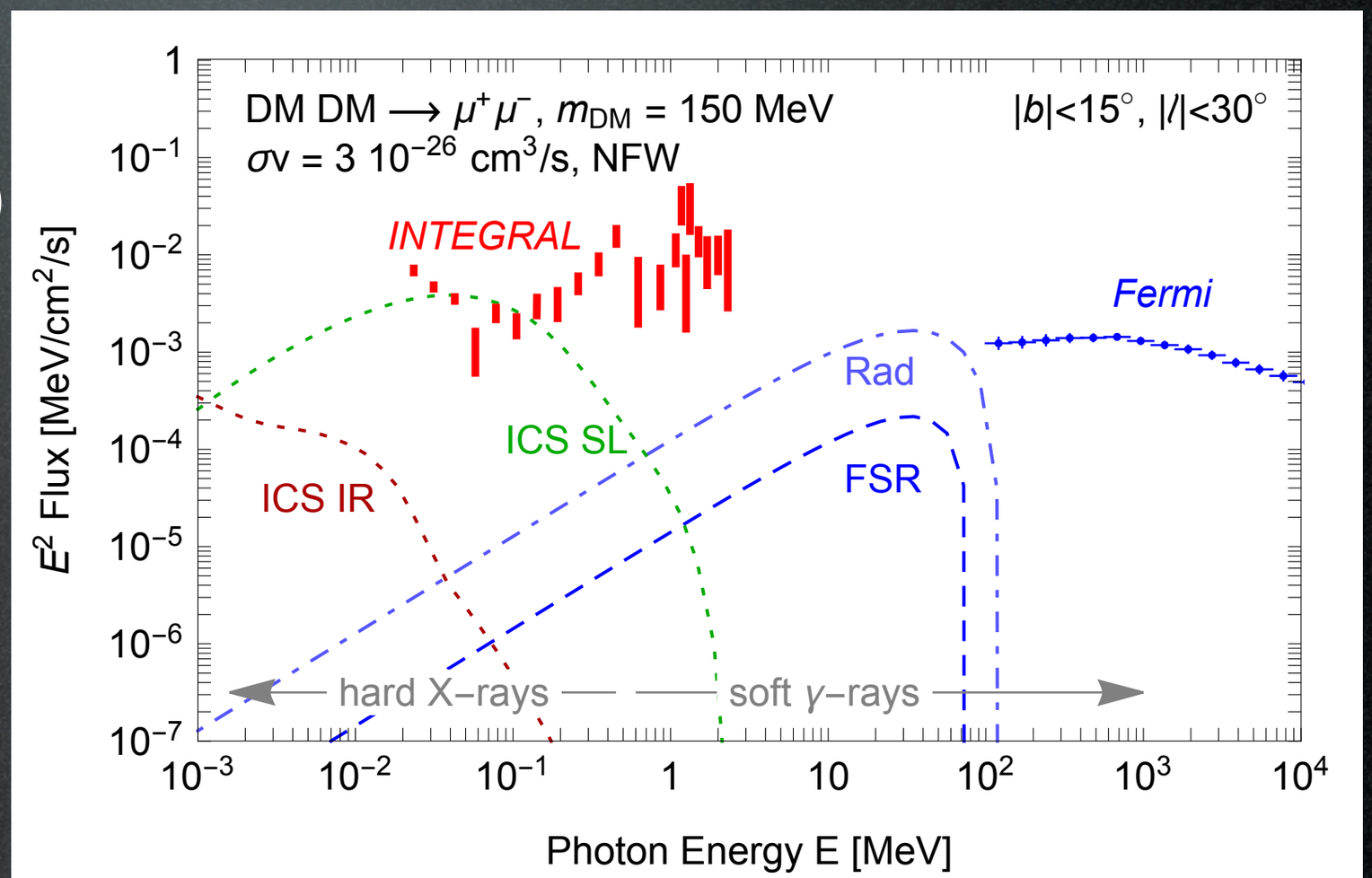
'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

Secondary emission:

ICS: inevitably associated to annihil to charged states



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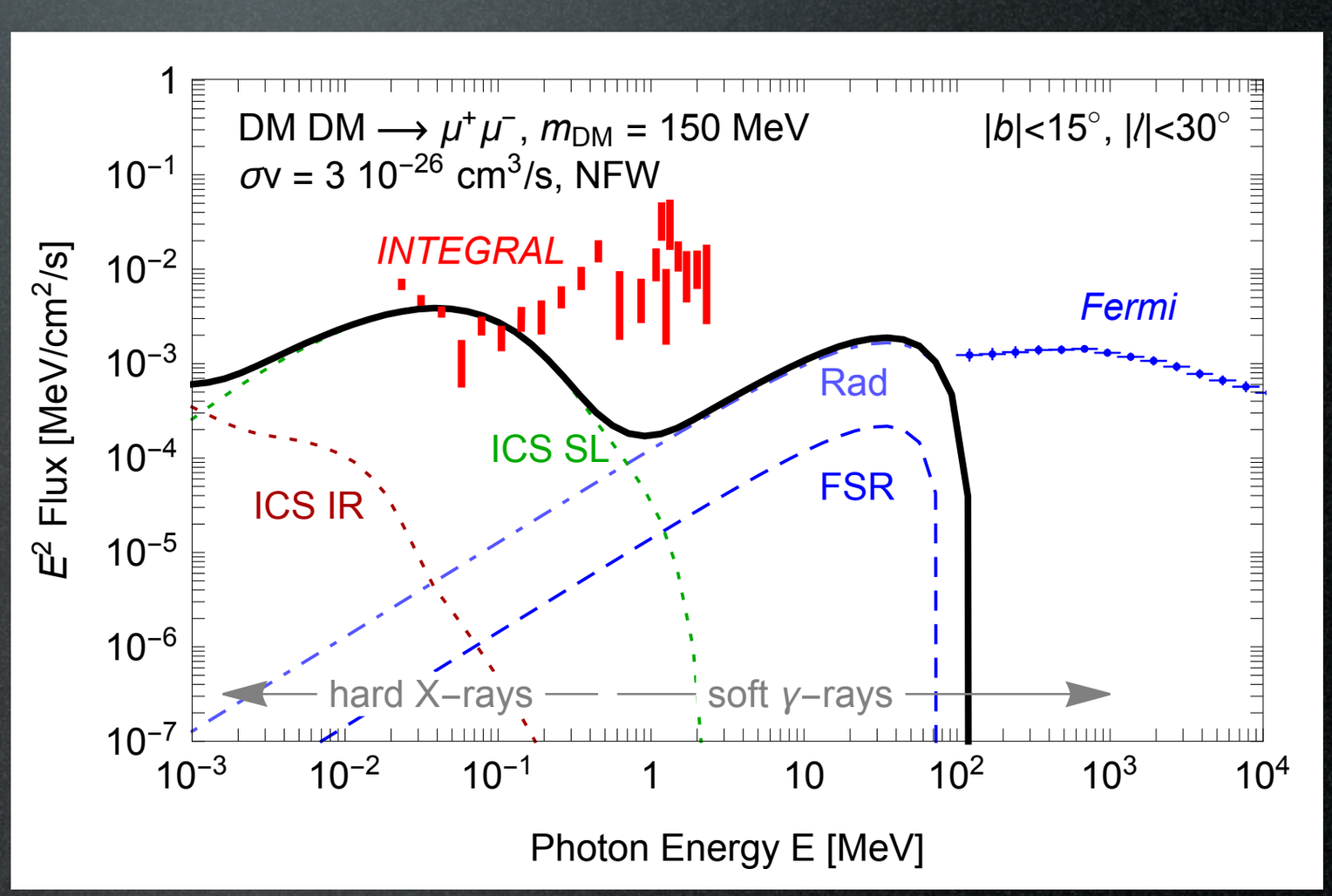
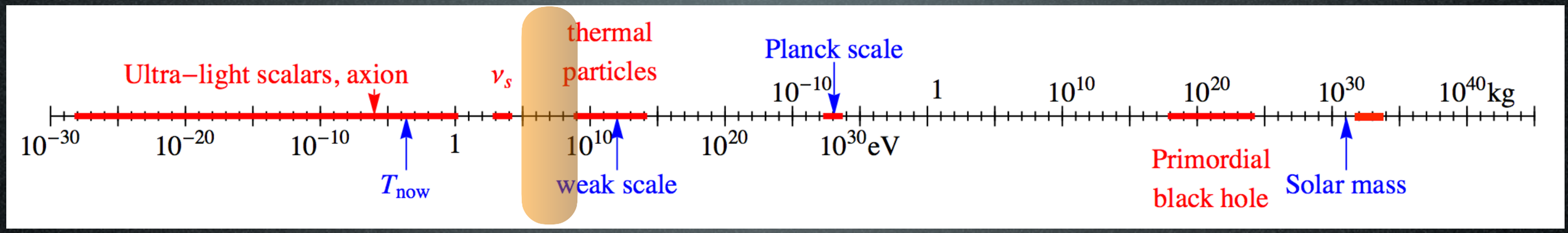
ICS allows to probe sub-GeV DM with X-ray data



Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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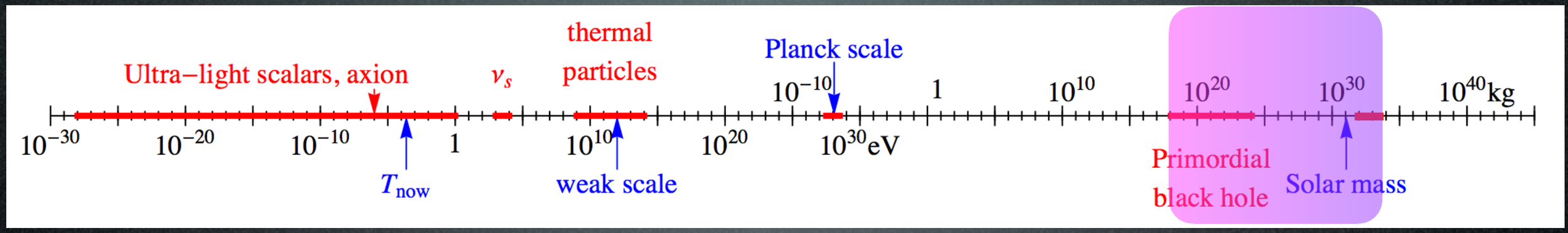

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PBH DM?

DM can **NOT** be:

an astro *je ne sais pas quoi*:

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- gas

- Black Holes
- brown dwarves

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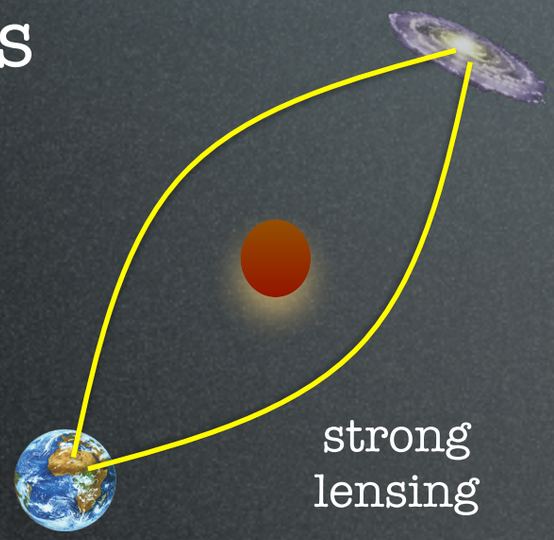
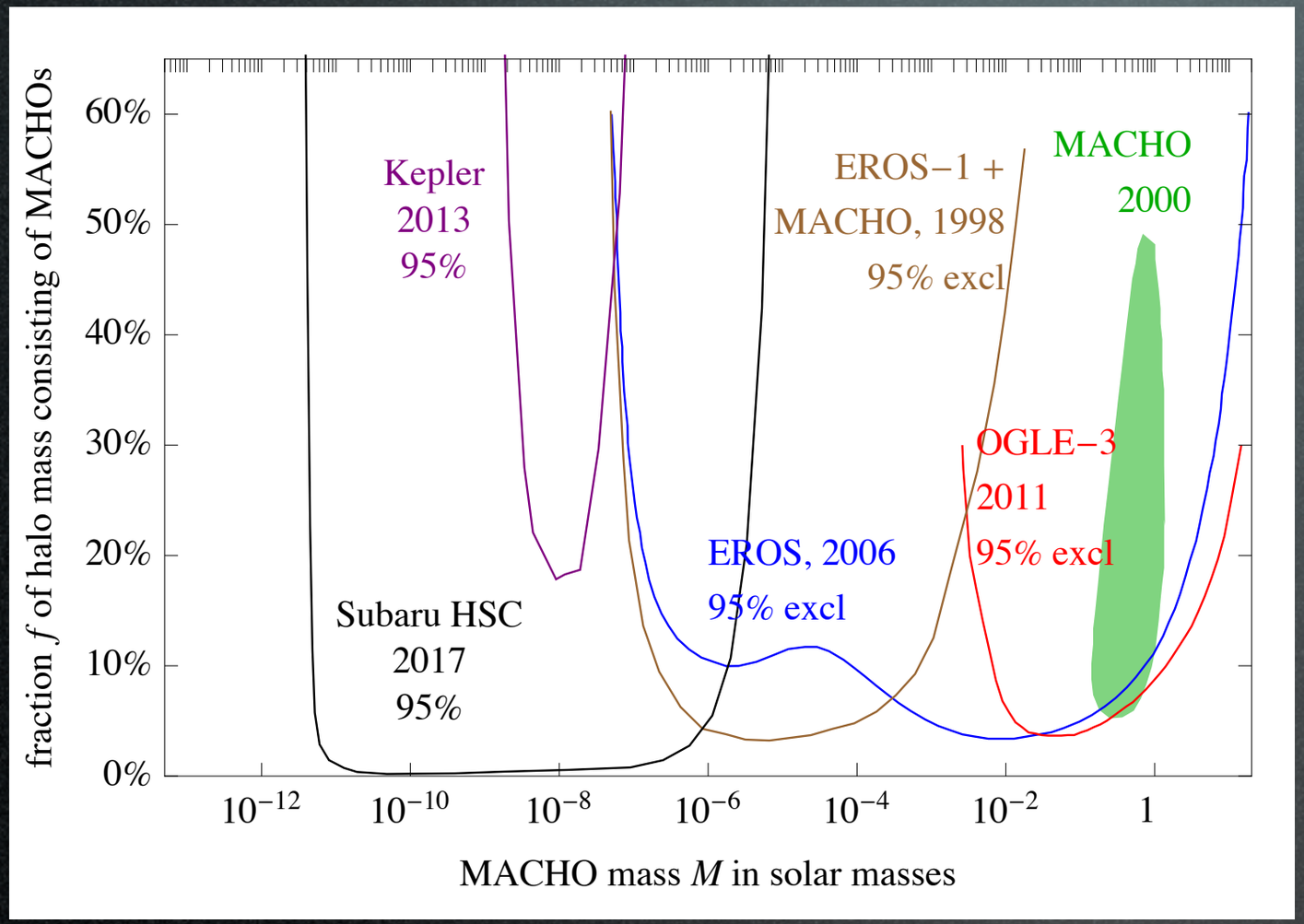


strong
lensing

MACHOs or PBHs as DM



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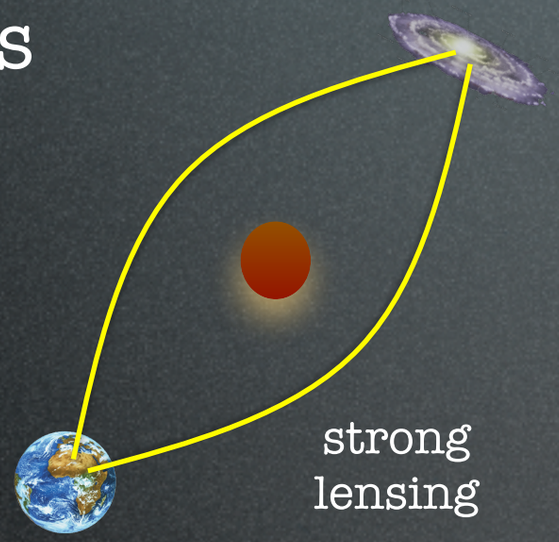

a baryon of the SM:

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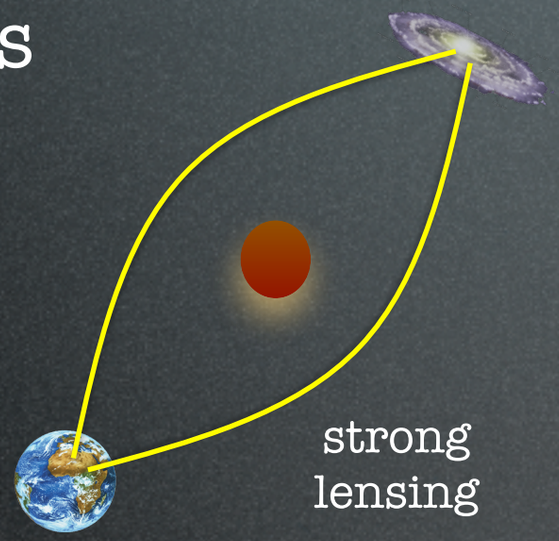

a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium

- CMB says baryons are 4% max

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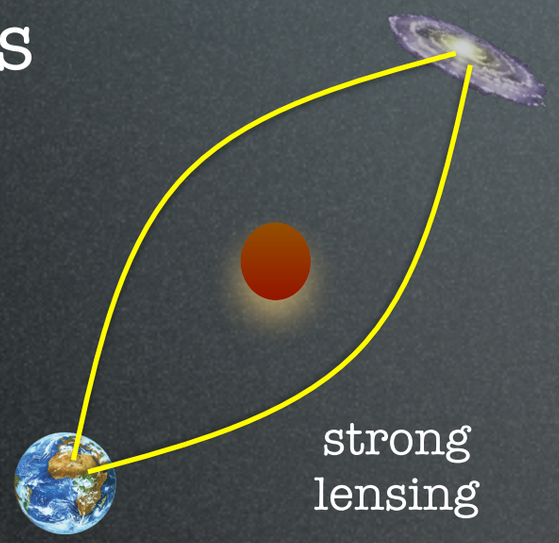

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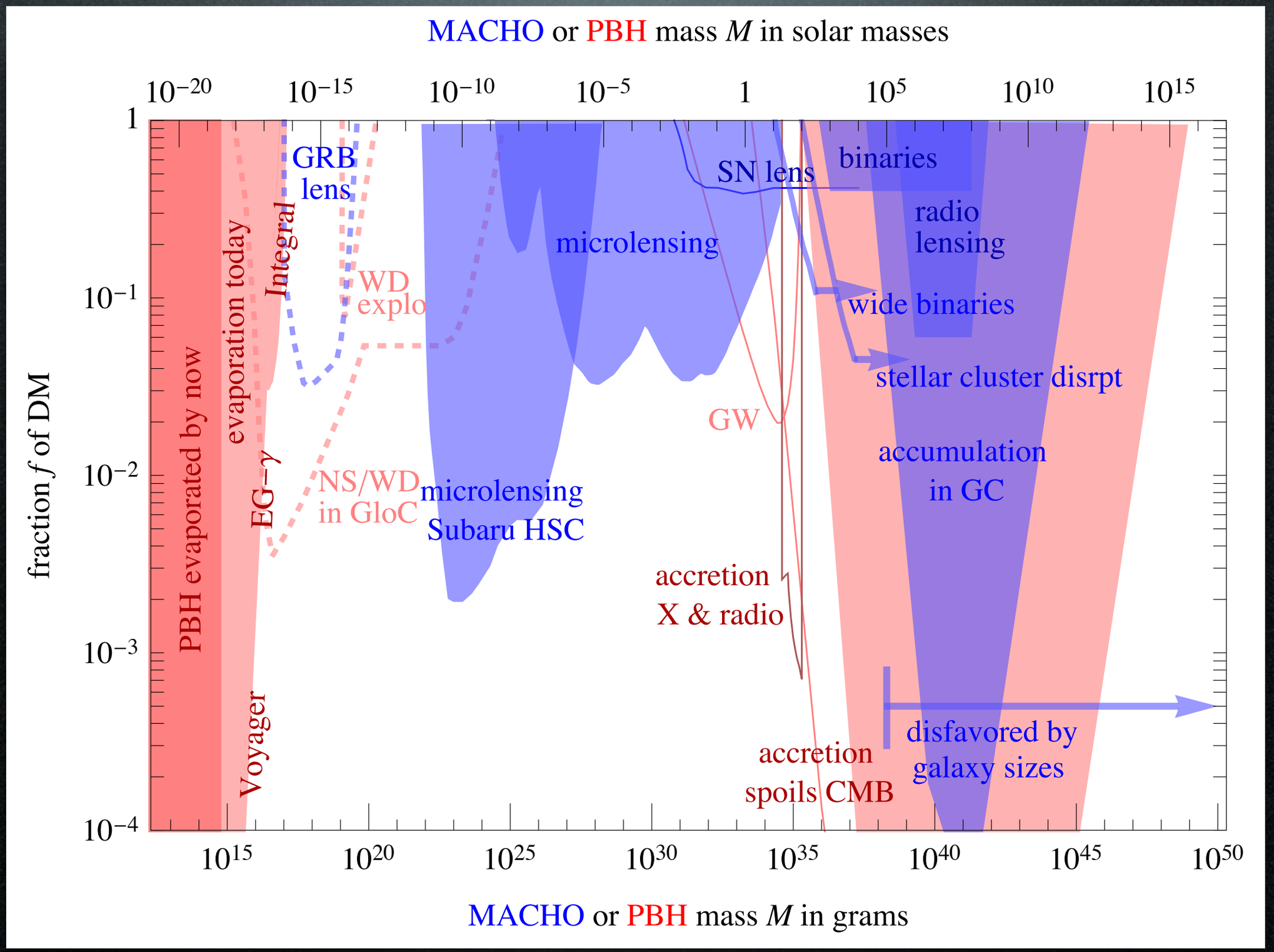
A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps LIGO is seeing them?

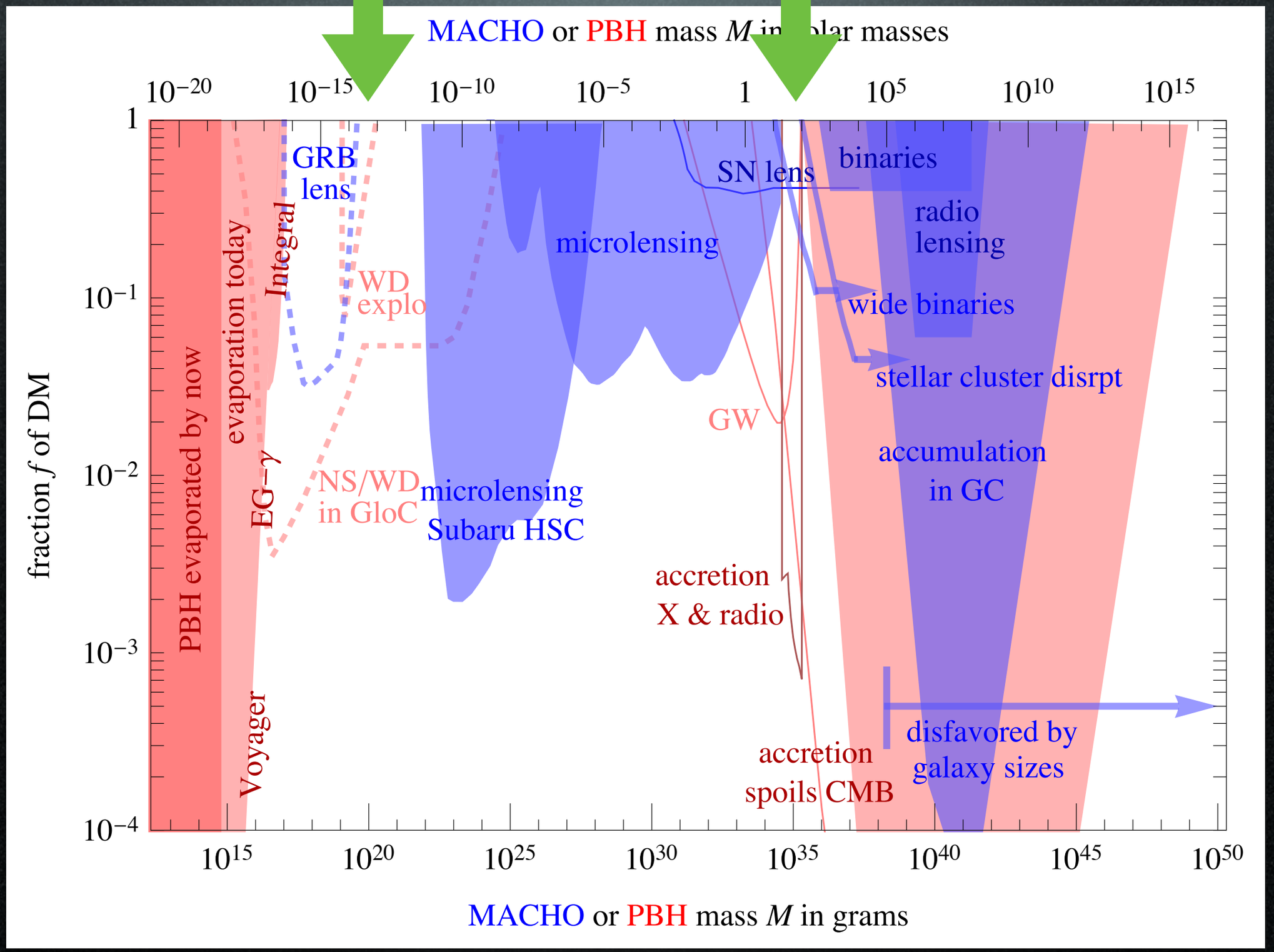
PBHs as DM



M. Cirelli, A. Strumia, J. Zupan to appear

PBHs as DM

slivers still open?



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PBHs as DM

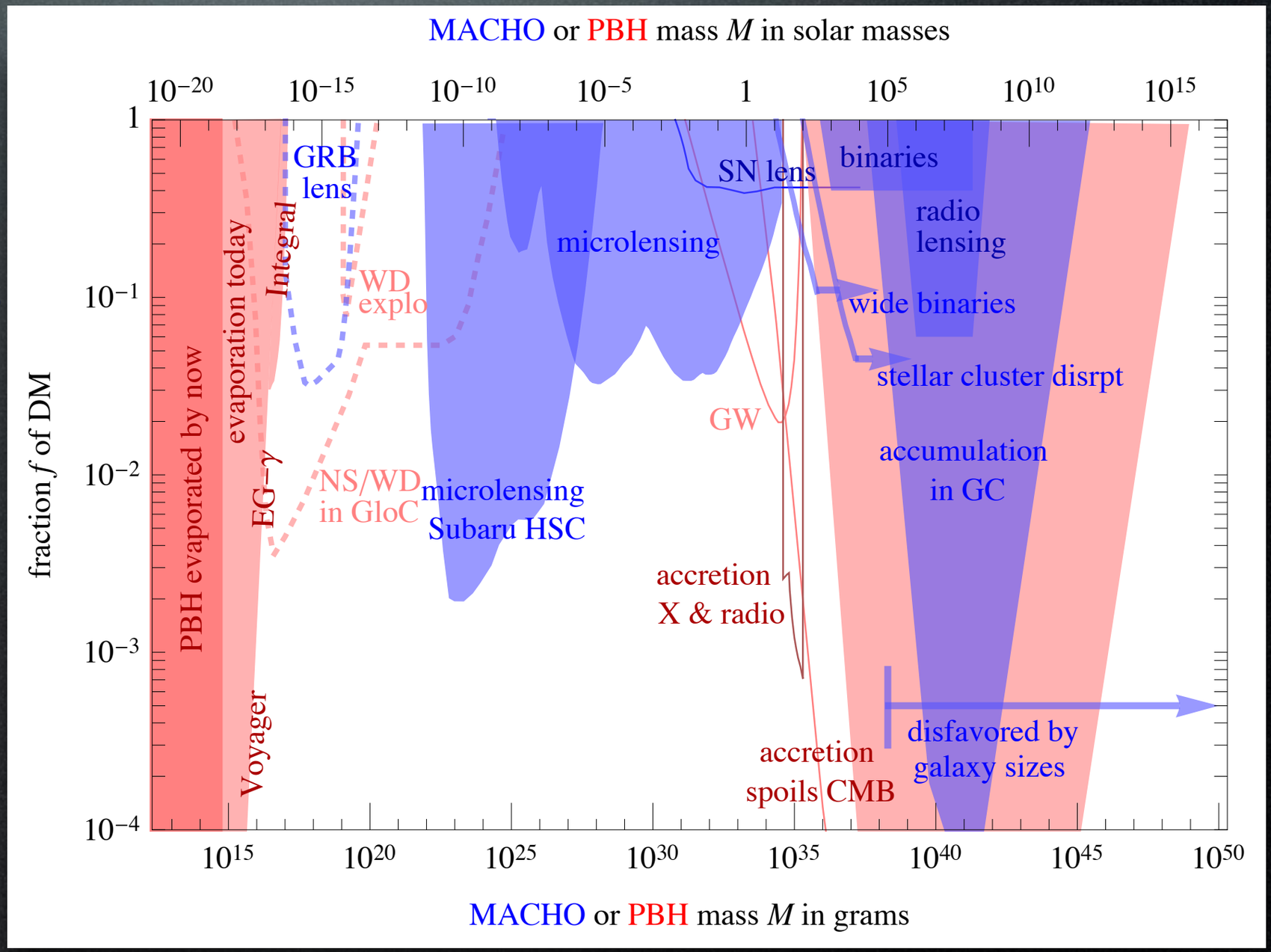
Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints



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‘small’ PBHs emit today by Hawking evaporation

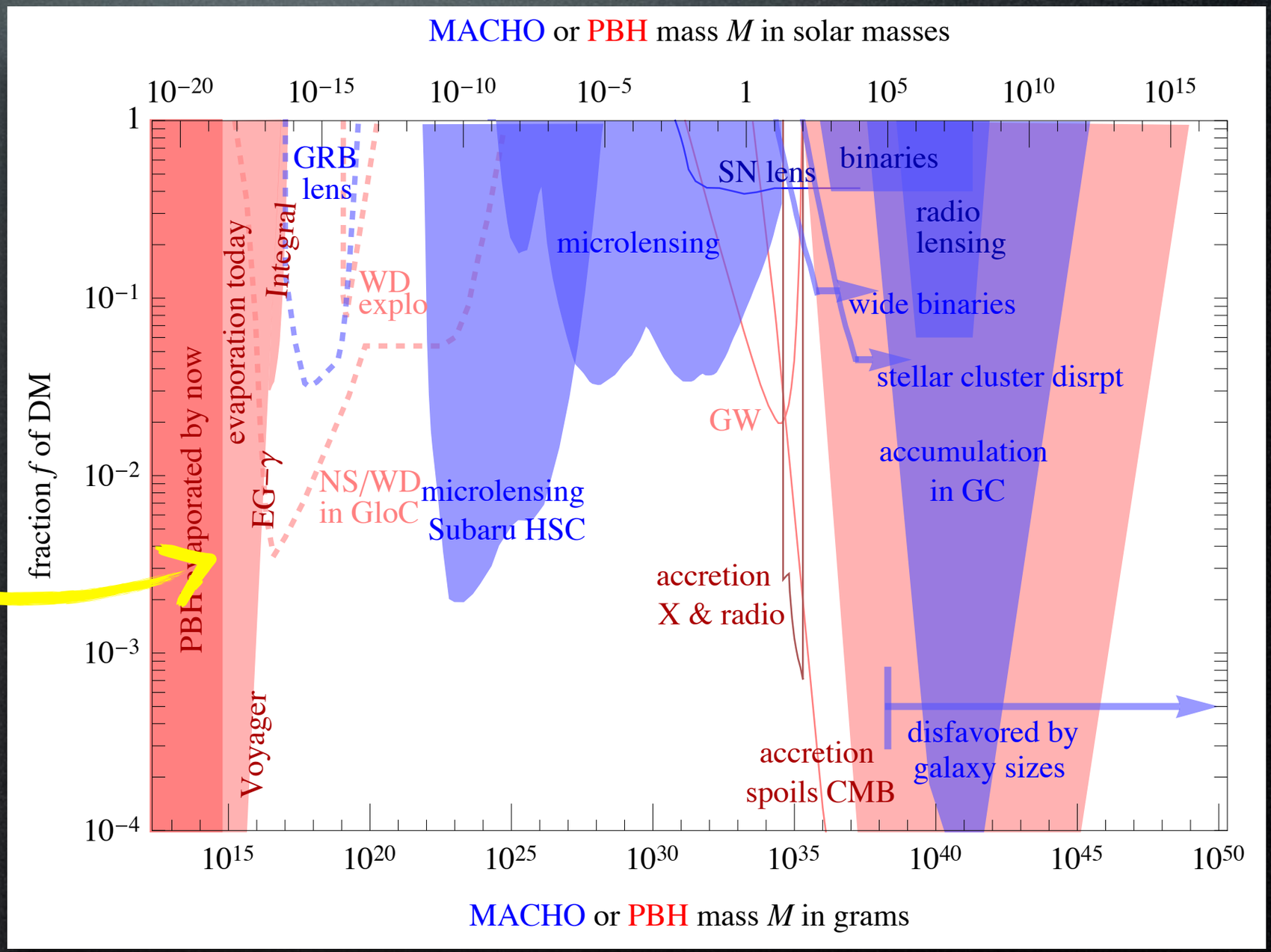
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



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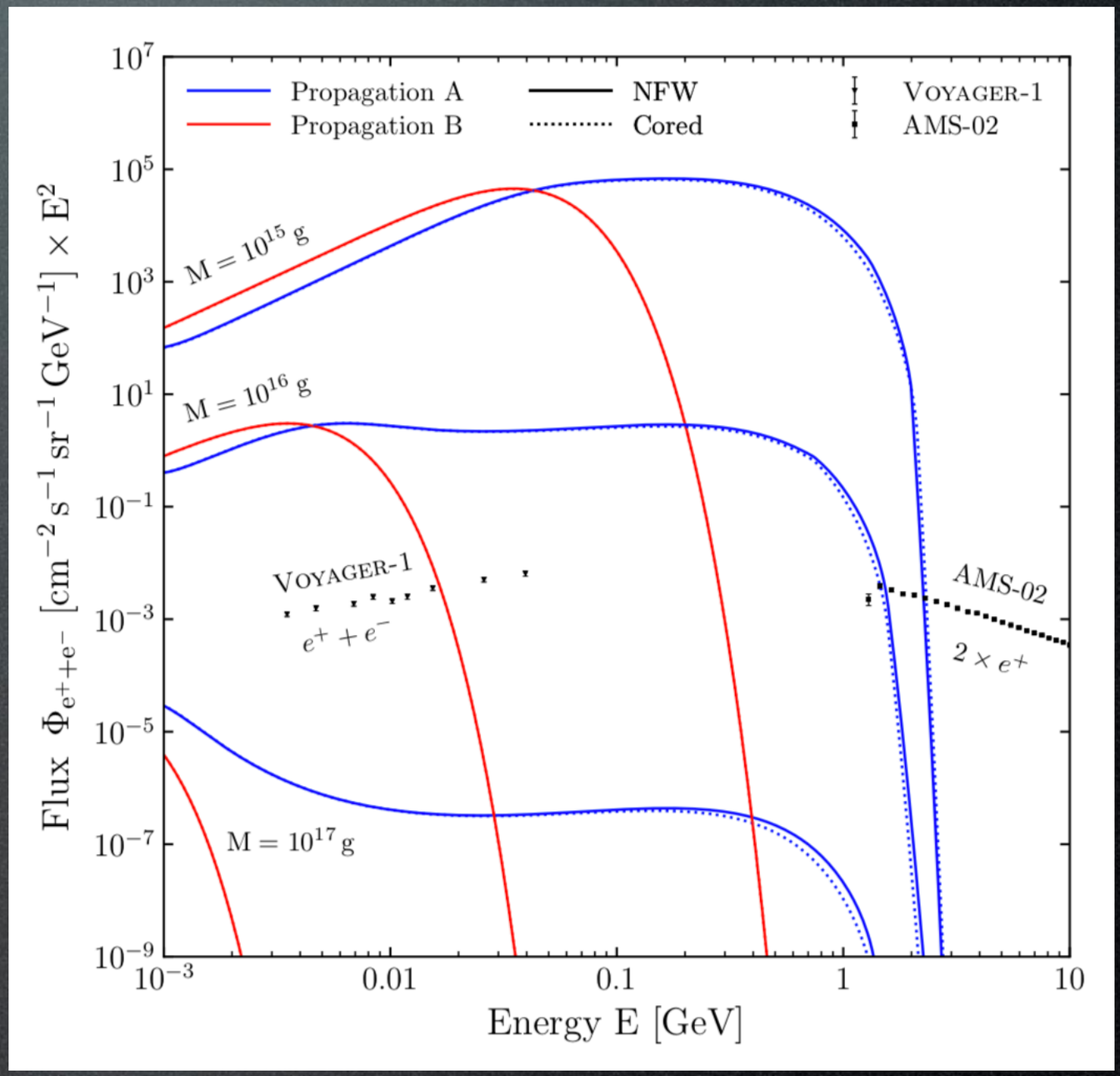

Boudaud, Cirelli 1807.03075, PRL

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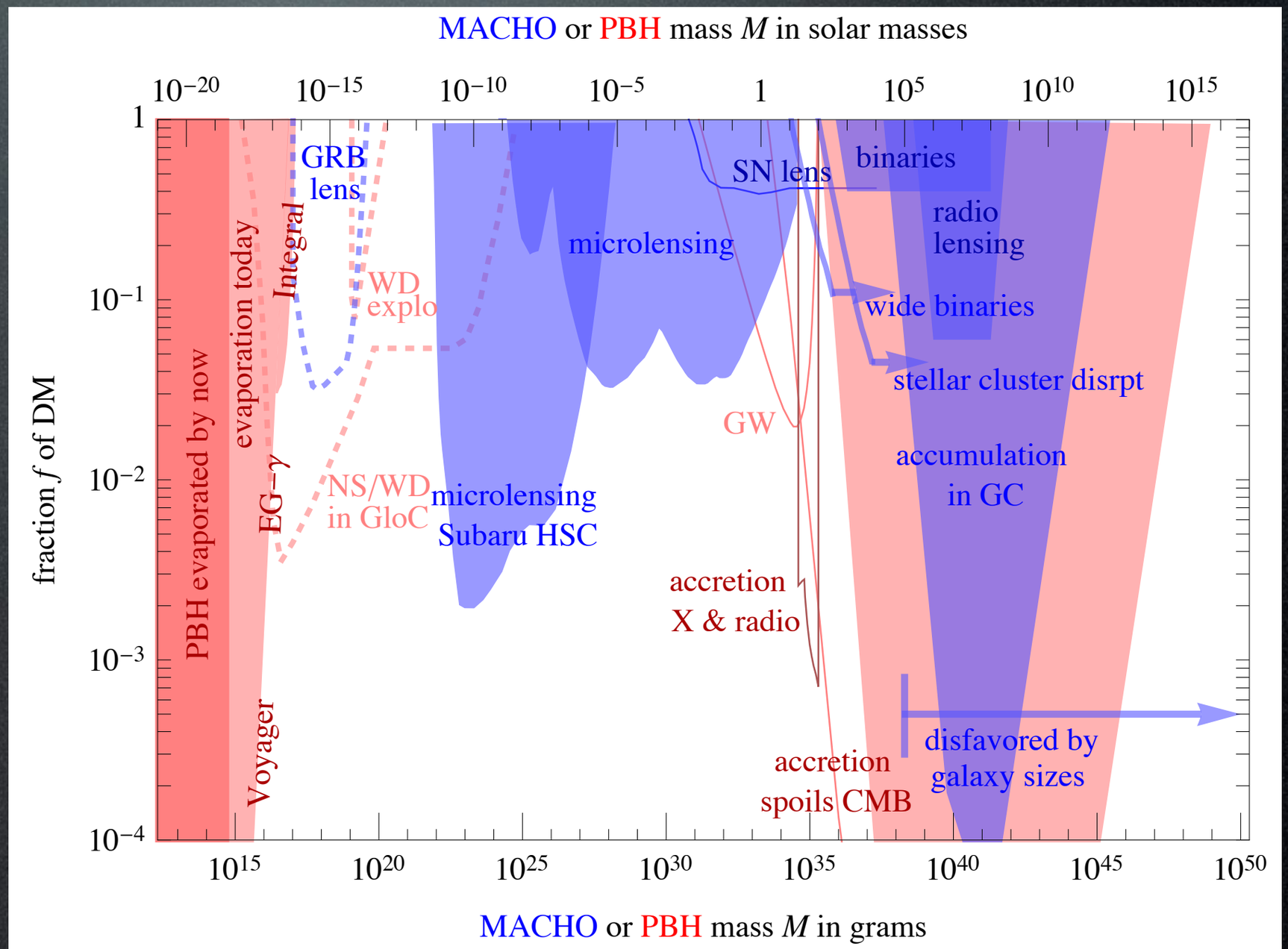

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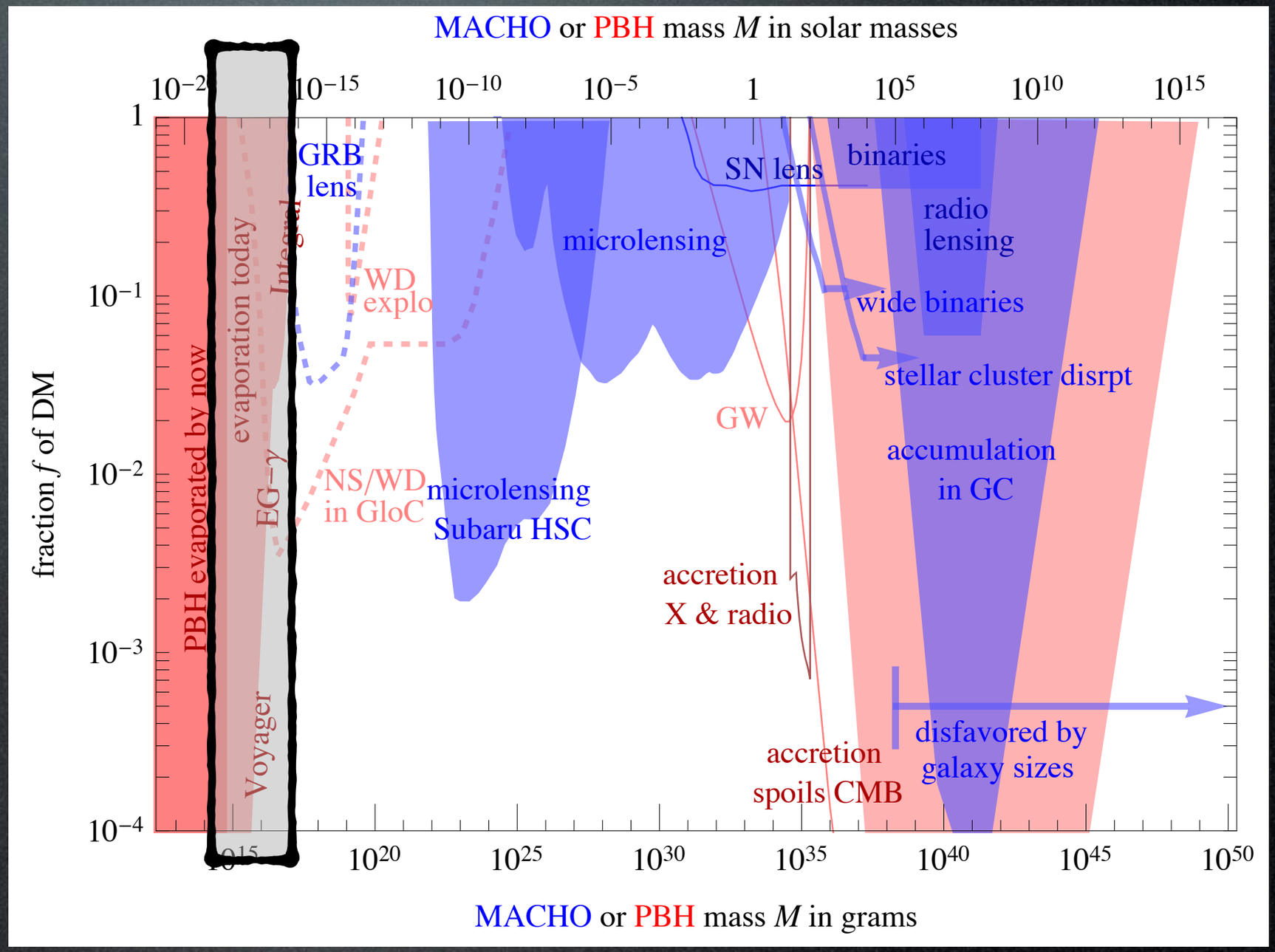
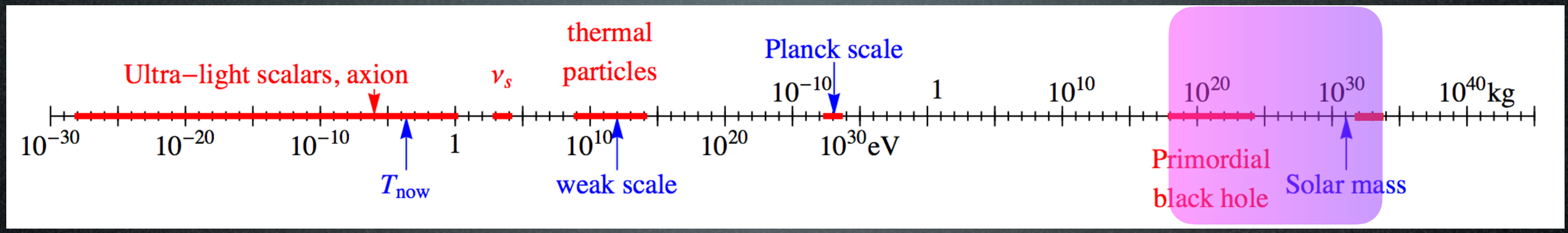
$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



M. Cirelli, A. Strumia, J. Zupan to appear

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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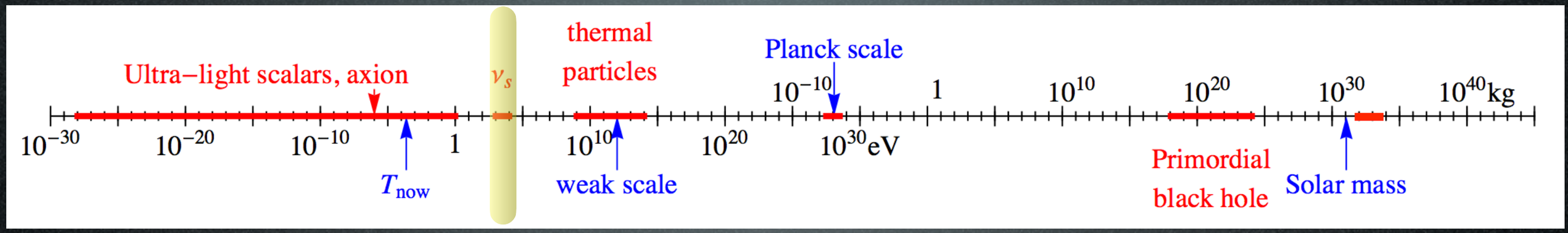


90 orders of magnitude!

KeV DM?

X-ray line

Bulbul et al., 1402.2301

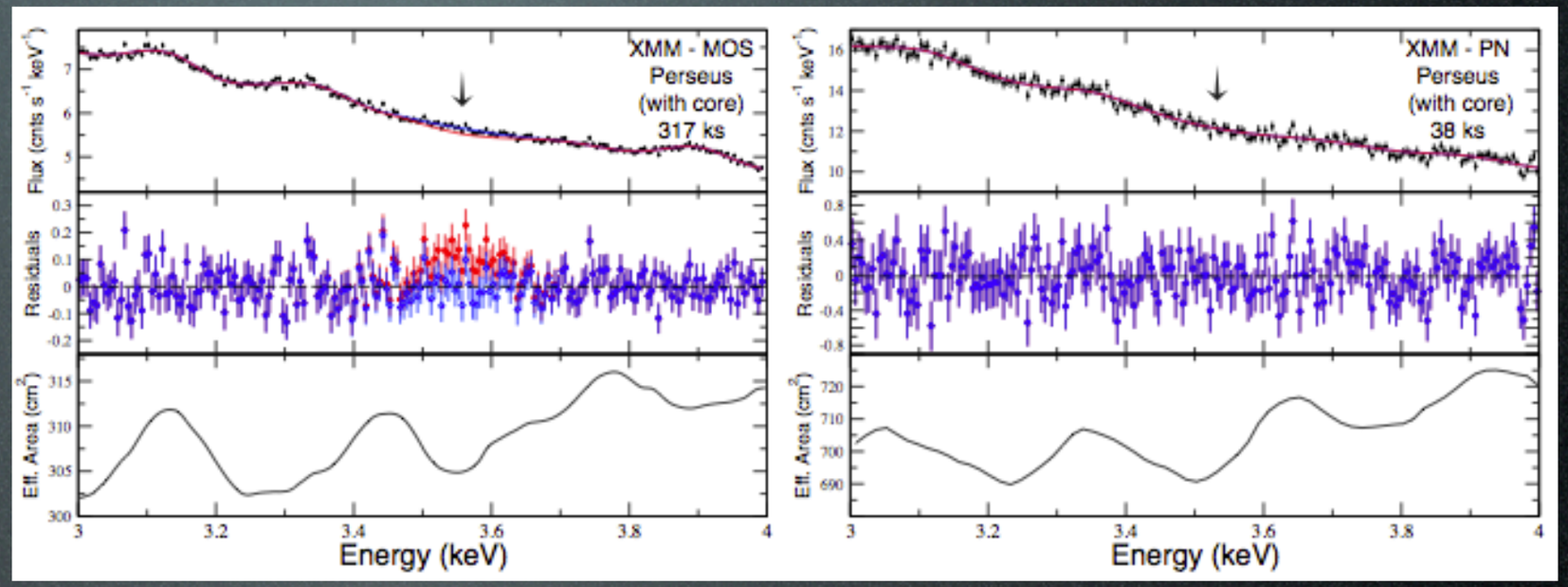
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

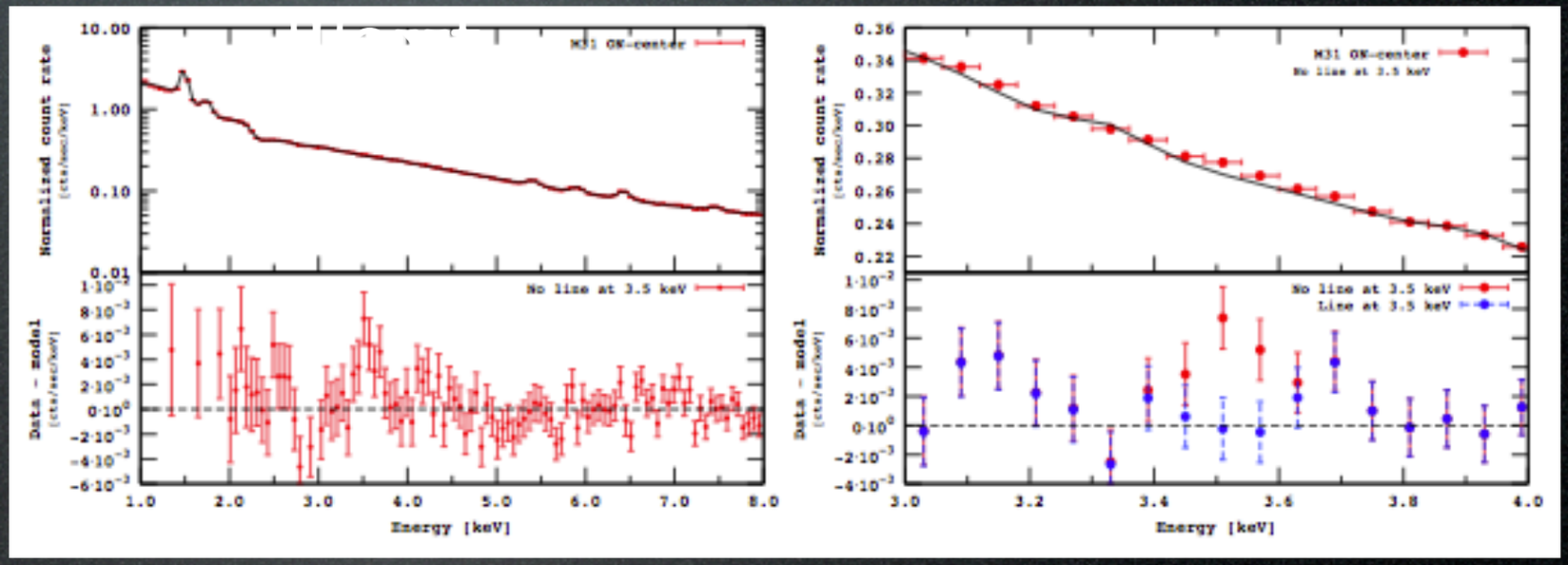
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

4.4σ



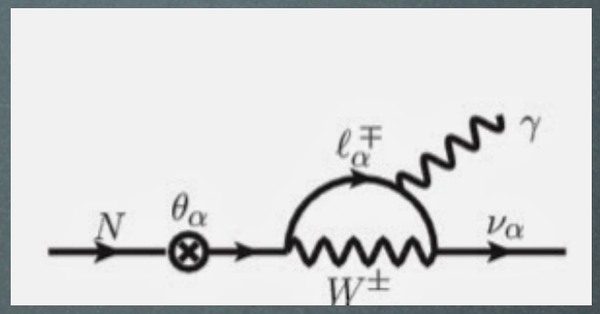
X-ray line

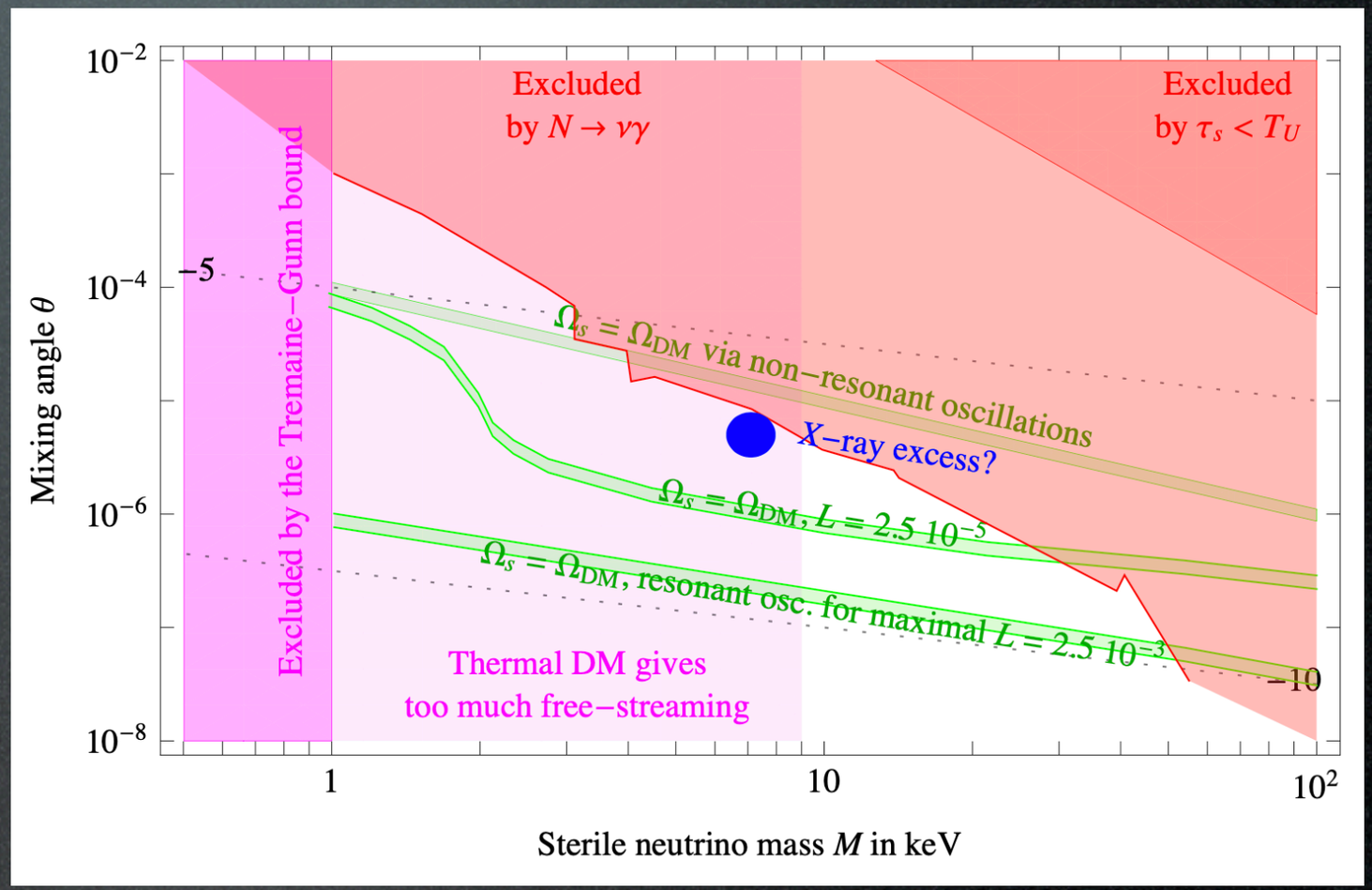
Sterile neutrino decay

$m_\nu = 7.1$ KeV

$\tau \simeq 10^{29}$ sec

$\sin^2 2\theta \sim$ few 10^{-11}





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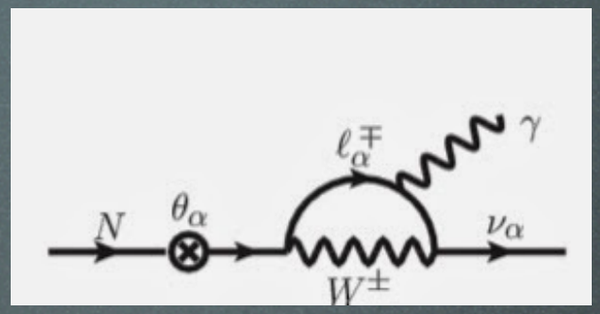

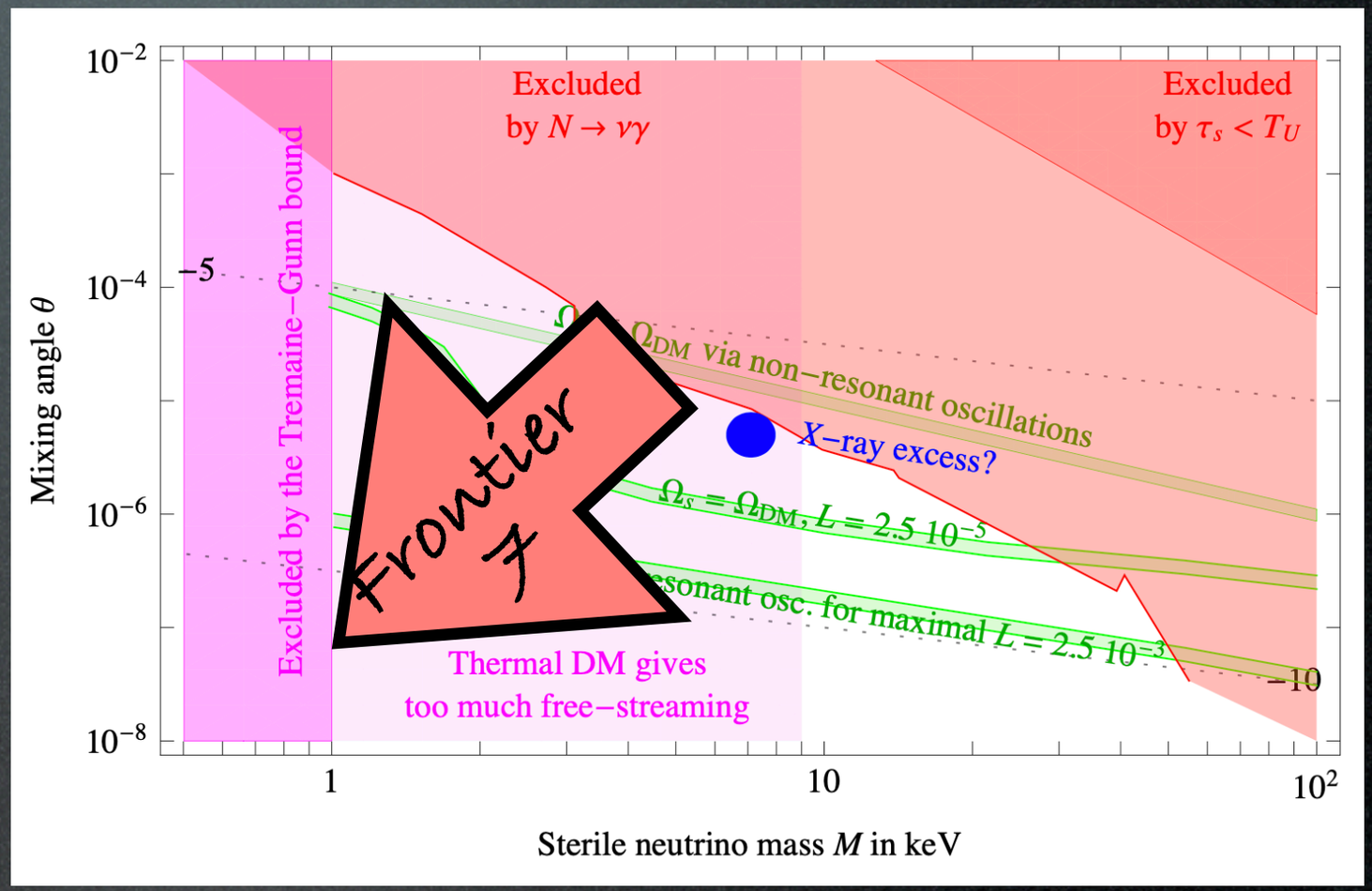

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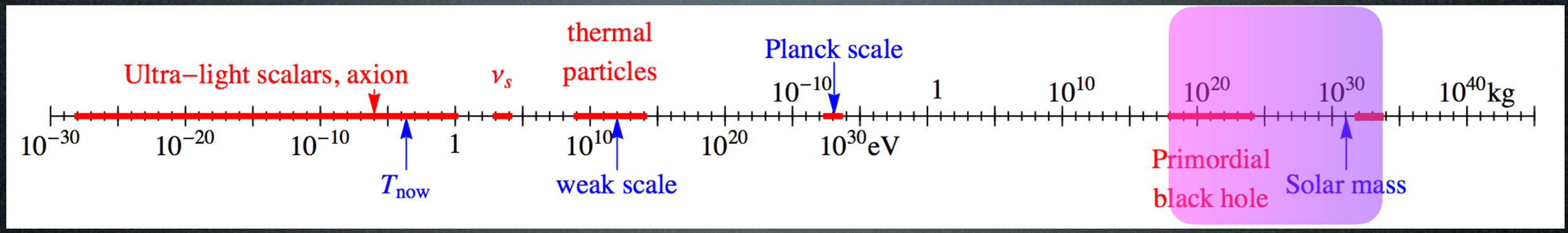

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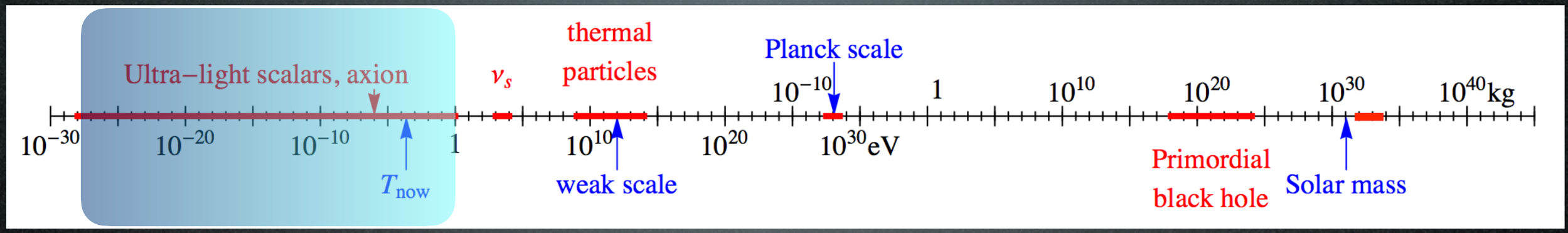
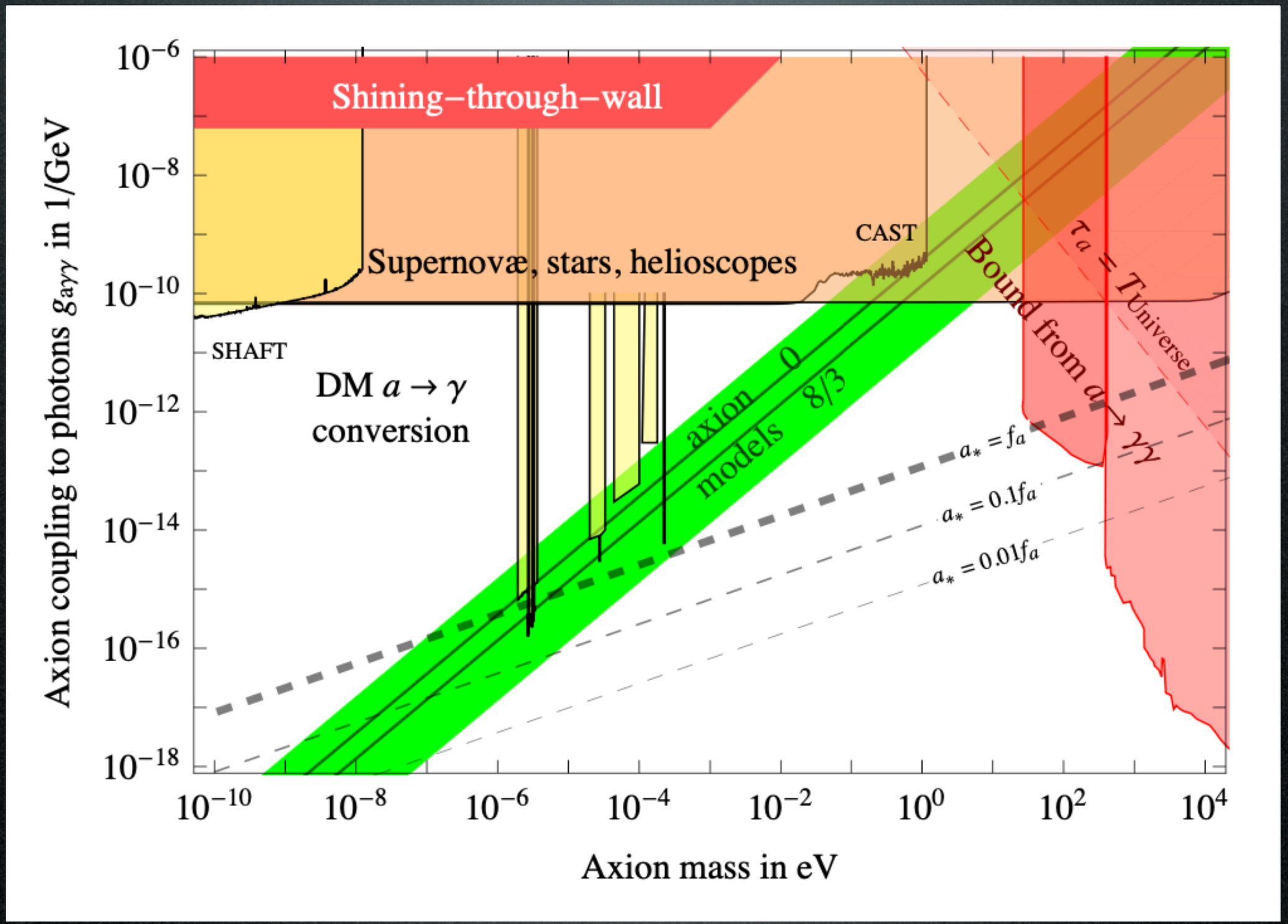


90 orders of magnitude!

Axions

Searches:



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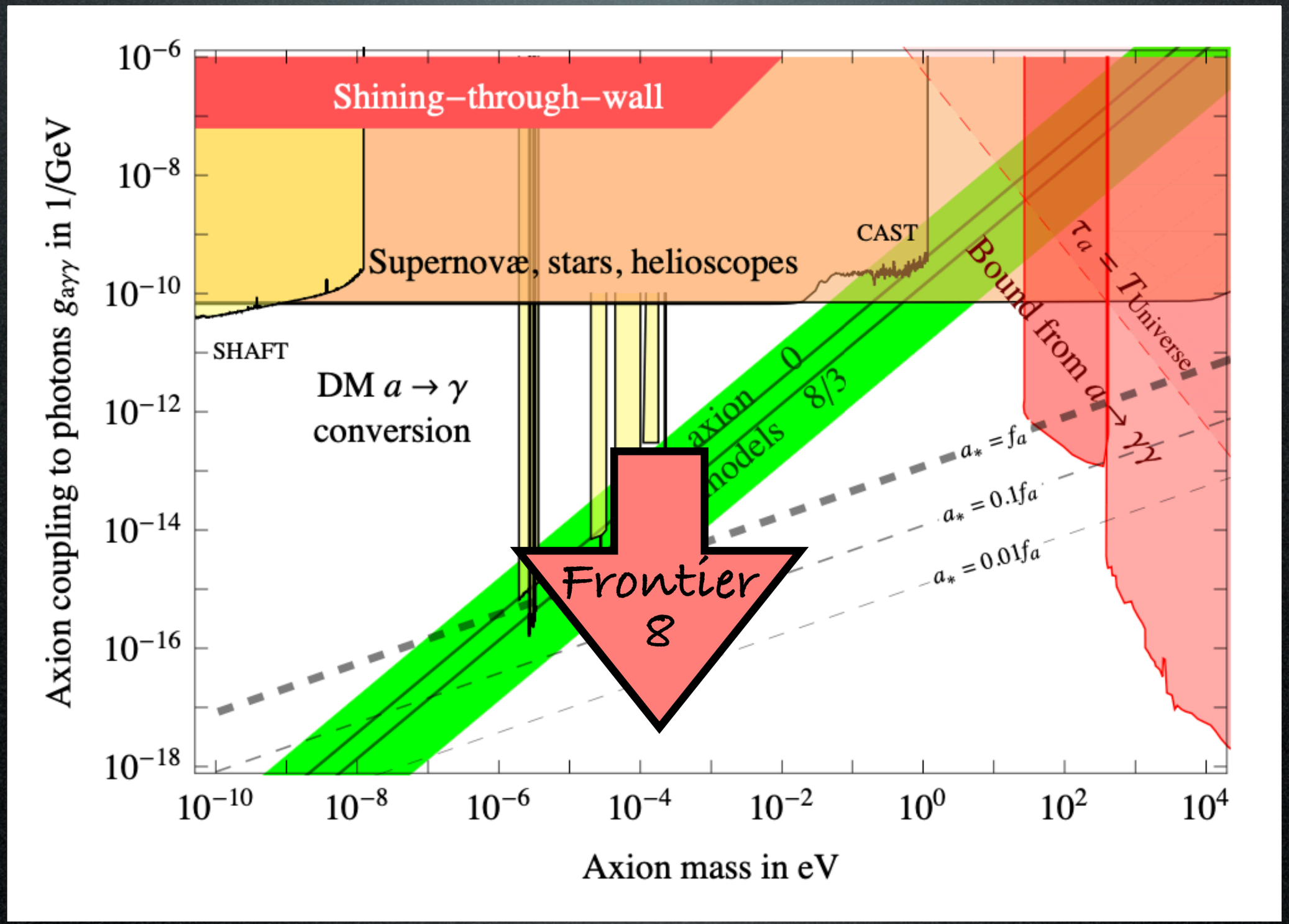

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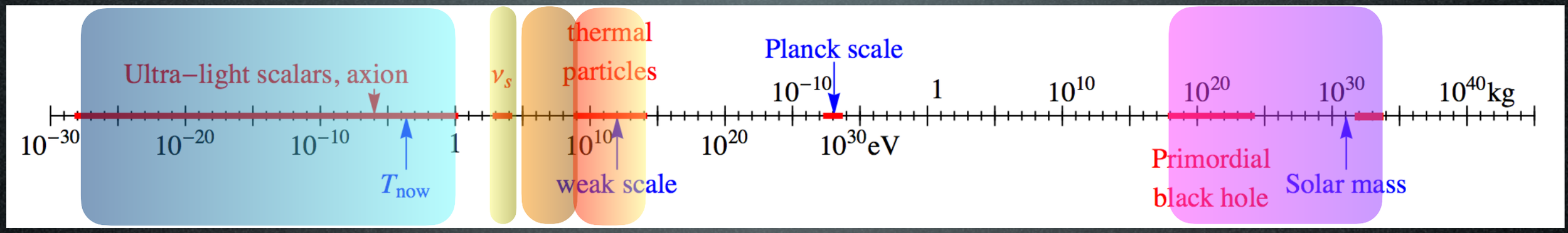

90 orders of magnitude!

Thermal DM?
Sub-GeV DM?
PBH DM?
KeV DM?
Ultralight DM?

Conclusions

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The physics of Dark Matter is
in an experiment driven phase

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Conclusions

The physics of Dark Matter is
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Theory can (does) point to preferred directions,
but actually too many...

Thermal DM?	still motivated, frontier is heavy DM
Sub-GeV DM?	why not? Challenging detection
PBH DM?	old idea with new vibes
KeV DM?	phenomenological
Ultralight DM?	old idea with new vibes

Conclusions

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Frontier 4
Frontier 5
Frontier 6
Frontier 3
Frontier 1
Frontier 7
Frontier 2
Frontier 8

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