Experimental Searches for Dark Matter

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GraSPA2024

Outline

1. Introduction
   a) Standard Model of particle physics
   b) Dark matter and candidates
2. WIMP searches
3. Axion searches
4. Focus study: solar axion searches
5. Conclusions

References

Introductions:

- S. Profumo book: “An introduction to particle dark matter”, [arXiv:1910.05610]
- D. F. Jackson Kimball and K. Van Bibber (editors) book: “The Search for Ultralight Bosonic Dark Matter” (Open Access Book)

Some lectures:

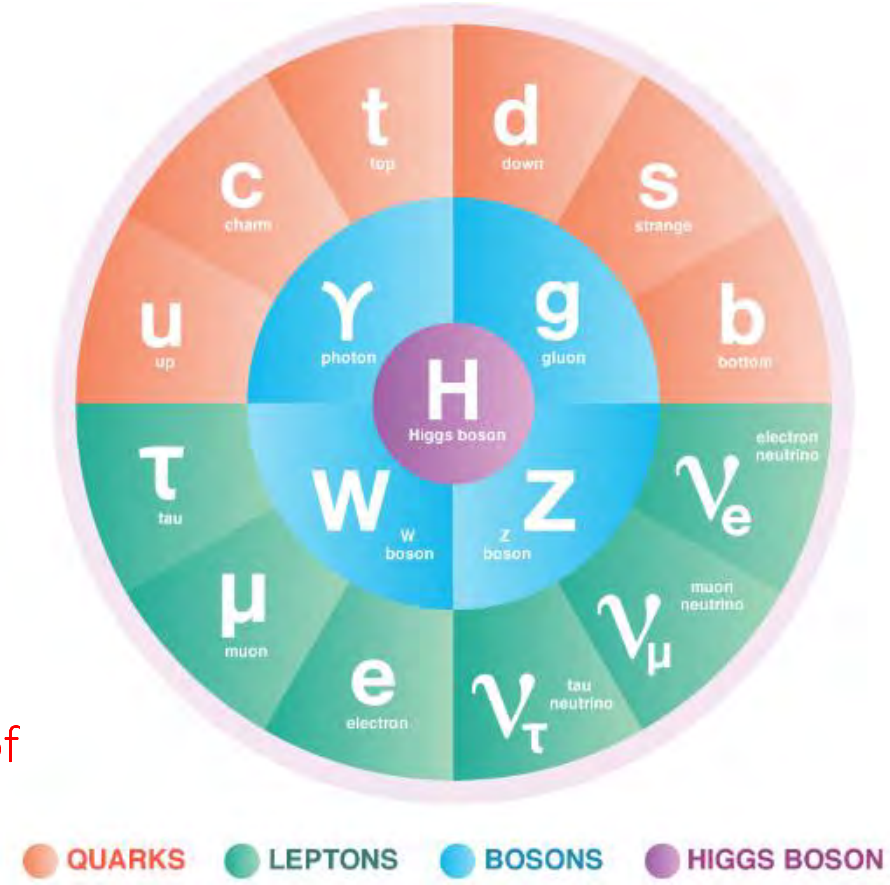
- G. Gelmini, “TASI 2014 LECTURES: The Hunt for Dark Matter”, [arXiv:1502.01320]
- T. Lin, “TASI lectures on dark matter models and direct detection” [arXiv:1904.07915]
- P.J. Fox, ”TASI Lectures on WIMPs and Supersymmetry”, PoS(TASI2018)005
- A. Hook, “TASI Lectures on the Strong CP Problem and Axions” [arXiv:1812.02669]
- M. Reece, : “TASI Lectures: (No) Global Symmetries to Axion Physics” [arXiv:2304.08512]

Some good reviews:

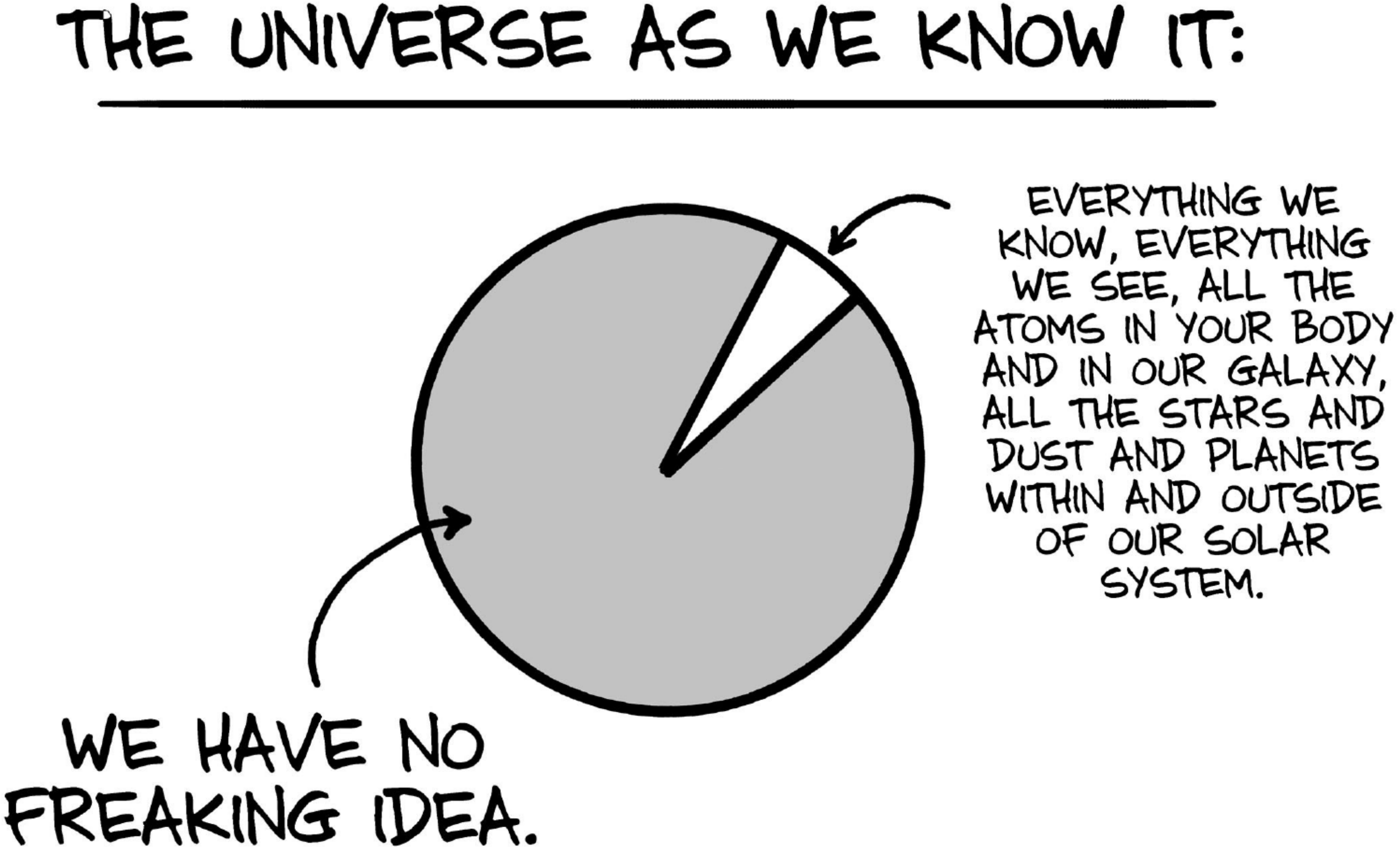
- Particle Data group (https://pdg.lbl.gov/2024/reviews/rpp2024-rev-dark-matter.pdf and https://pdg.lbl.gov/2024/reviews/rpp2024-rev-axions.pdf)
- J.L. Feng “Dark Matter Candidates from Particle Physics and Methods of Detection” Annu. Rev. Astron. Astrophys. 2010. 48:495–545
- M. Schumann,” Direct detection of WIMP dark matter: concepts and status”, J. Phys. G: Nucl. Part. Phys. 46 103003 [1903.03026]
- I. G. Irastorza and J. Redondo, “New experimental approaches in the search for axion-like particles”, [arXiv:1801.08127]
- A. Ringwald, “Review on Axions” [arXiv:2404.09036]

STANDARD MODEL (SM) OF PARTICLE PHYSICS

- **Extremely successful theory** describing many observations up to energies of ~1000 m_{proton}
- Merely an effective theory that could be considered the **low energy limit** of a **Theory of Everything**
- Expect observation of new phenomena at higher energies (e.g. LHC at CERN)
- **SM cannot explain**:
  - What is the nature of dark matter?
  - Why is the electric dipole moment of the neutron so small?

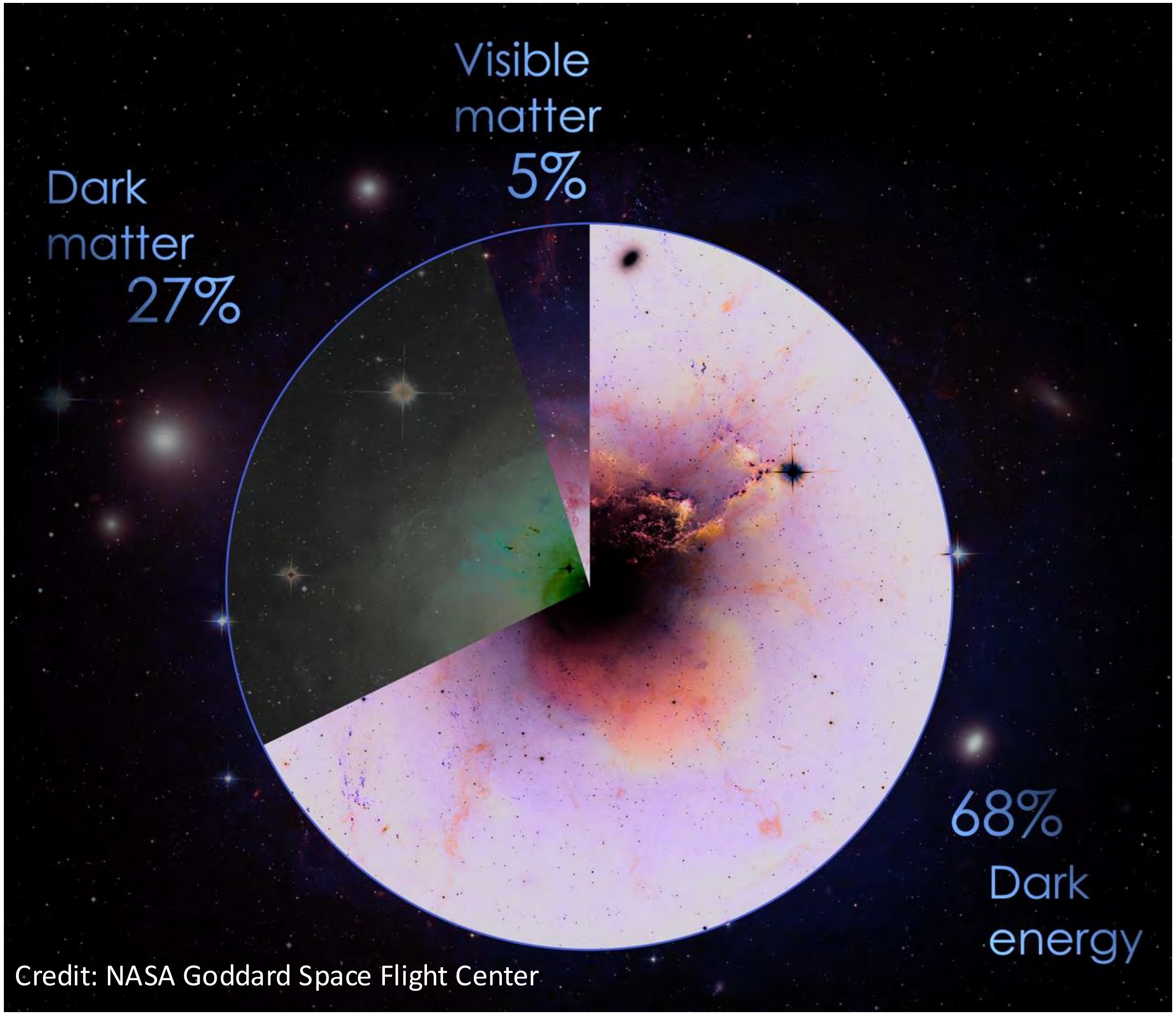


Introduction



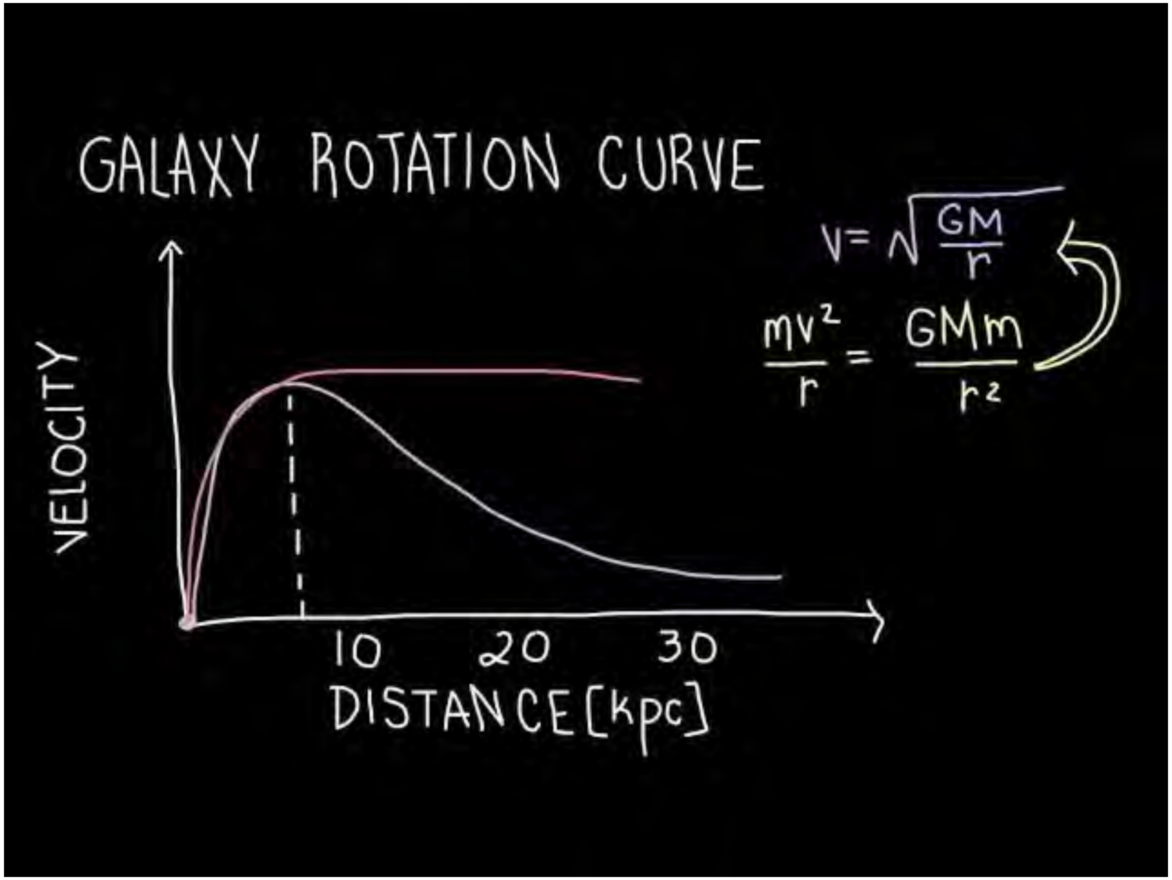
https://phdcomics.com/noidea/

Introduction



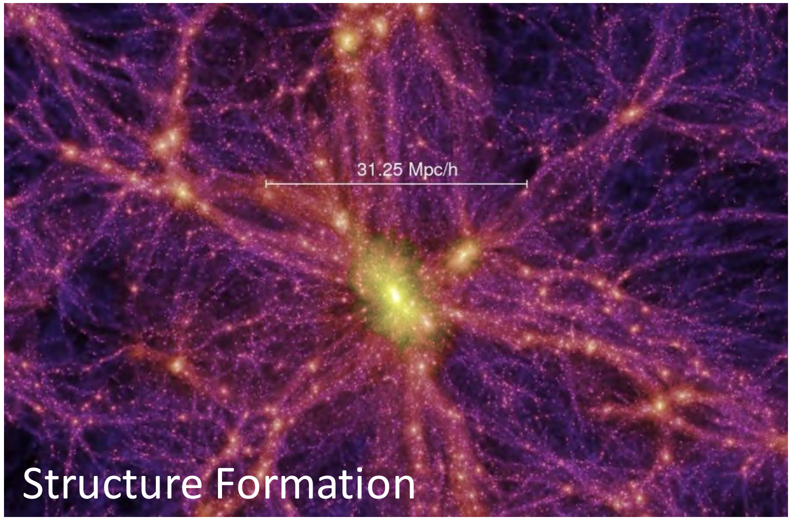
EVIDENCE FOR DARK MATTER

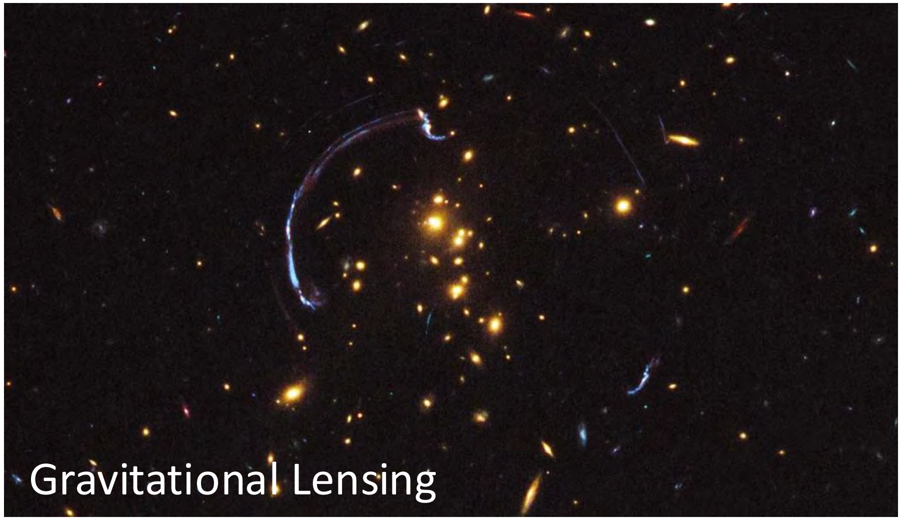
- Galaxy rotation curves



EVIDENCE FOR DARK MATTER

- Galaxy rotation curves
- Bullet Cluster
- Gravitational lensing
- Structure formation

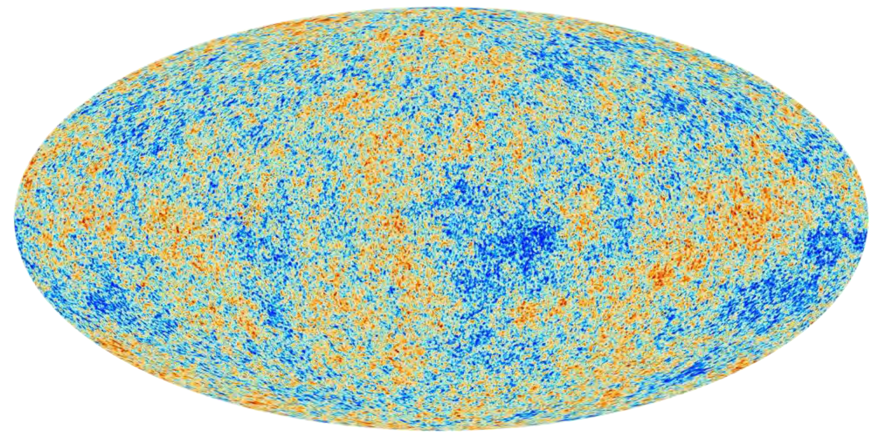


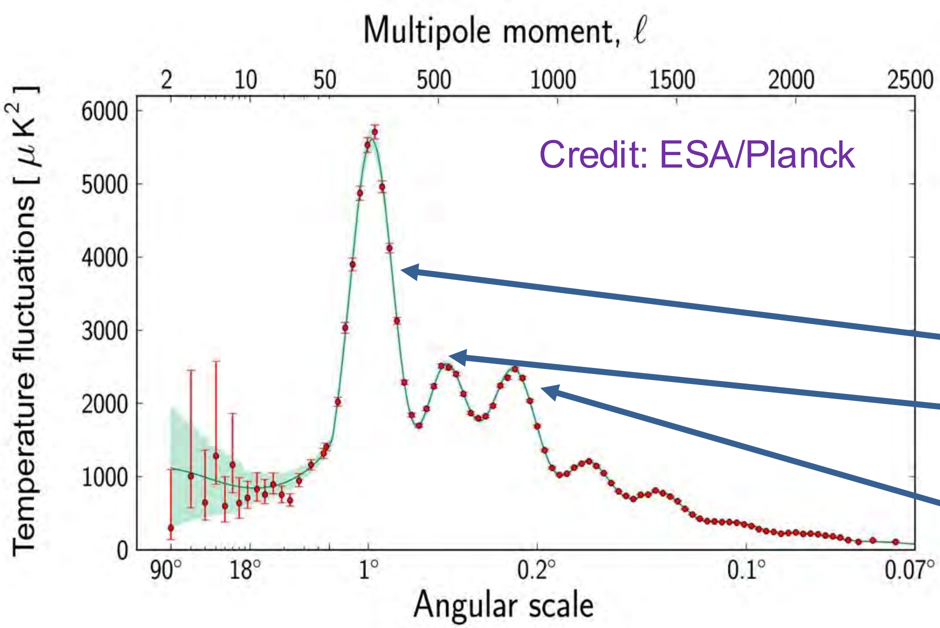


Springle et al 2005, doi:10.1038/nature03597

EVIDENCE FOR DARK MATTER

- Galaxy rotation curves
- Bullet Cluster
- Gravitational lensing
- Structure formation
- Cosmic Microwave Background (CMB)





PLANCK power spectrum of the CMB radiation temperature anisotropy

Location and height of peaks determines cosmological parameters

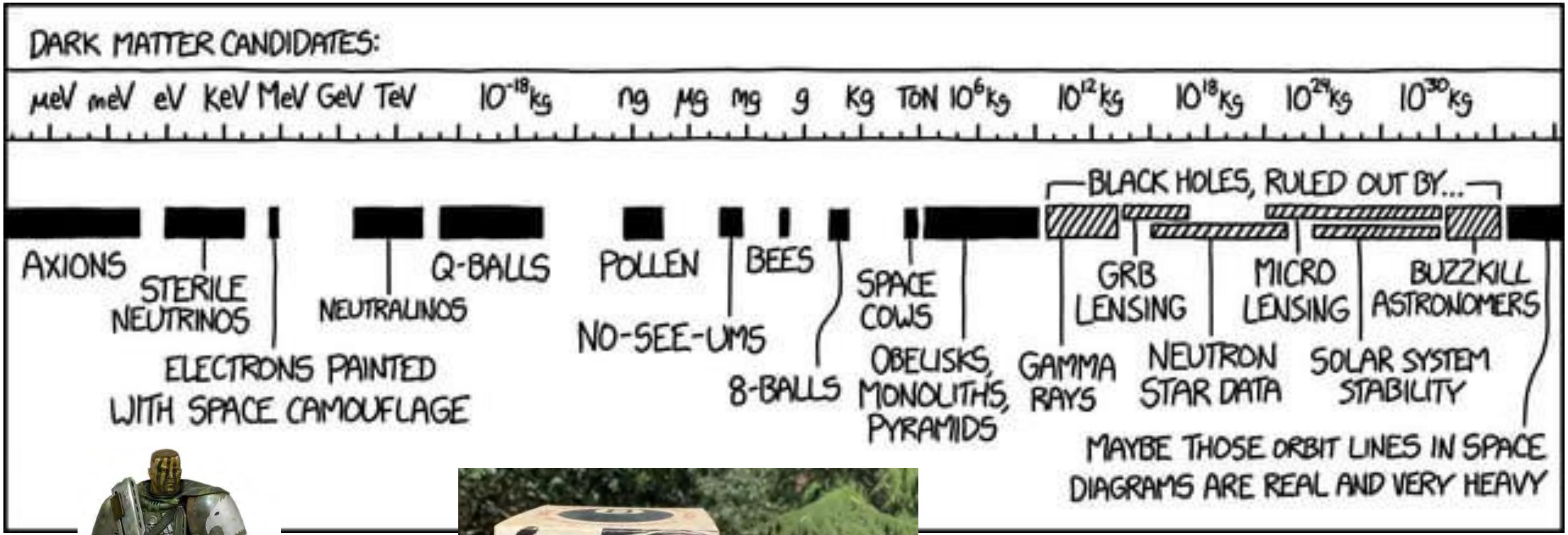
Flat universe

Baryonic matter ~5% of the total mass/energy of the universe

Amount of **dark matter** ~27%

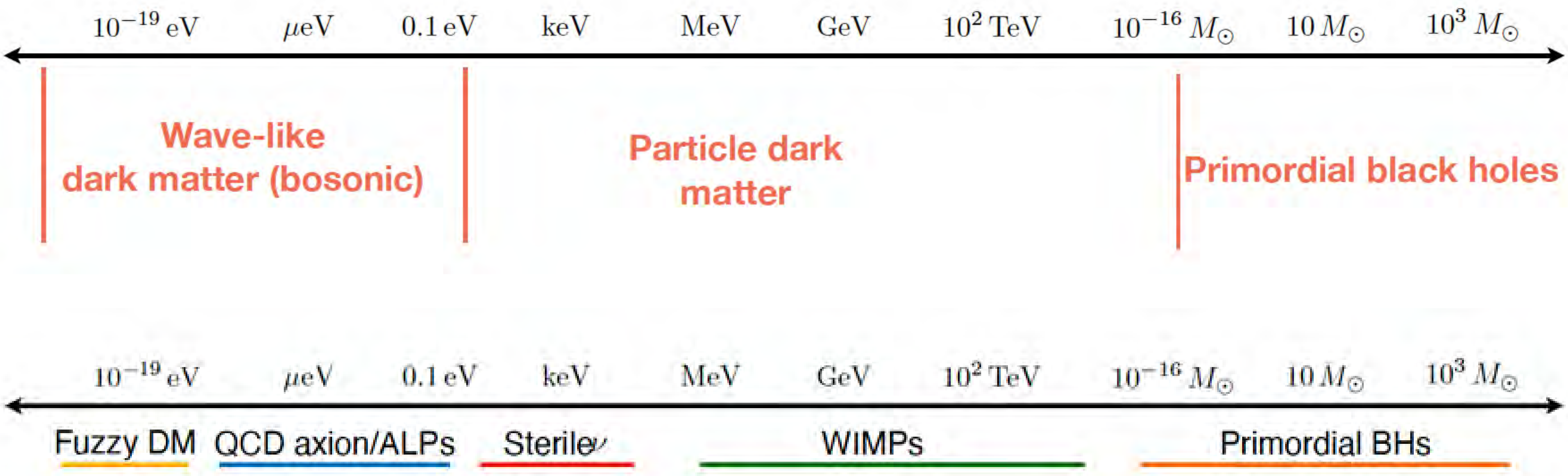
DARK MATTER PROBLEM: WE KNOW IT EXISTS BUT WHAT IS ITS NATURE?

So, we need DM. But what is it?!?



https://xkcd.com/2035/

Introduction



DARK MATTER wish list in the 2000s 2010s 20s

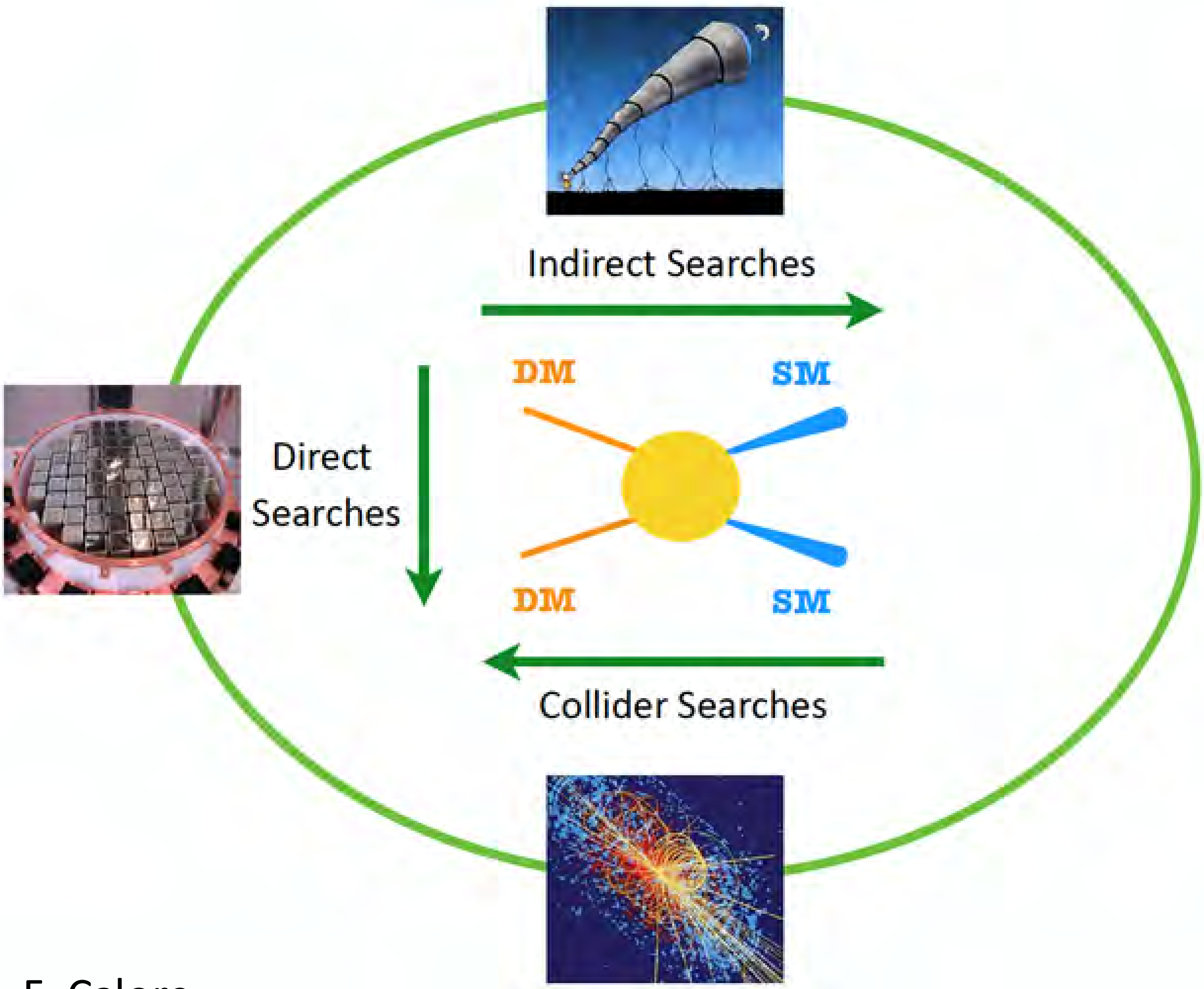
- Experimental detection (direct, indirect, collider searches)
- DM distribution (in the DM halo and in larger structures)
- Determination of DM parameters (mass and cross sections)
- What is the model for physics Beyond the SM (BSM)?

Outstanding experimental advances
→ Can we get there in the near future?

WIMP Searches

Credits “WIMP Searches”: M. Martinez, J. Monroe, F. Calore, …

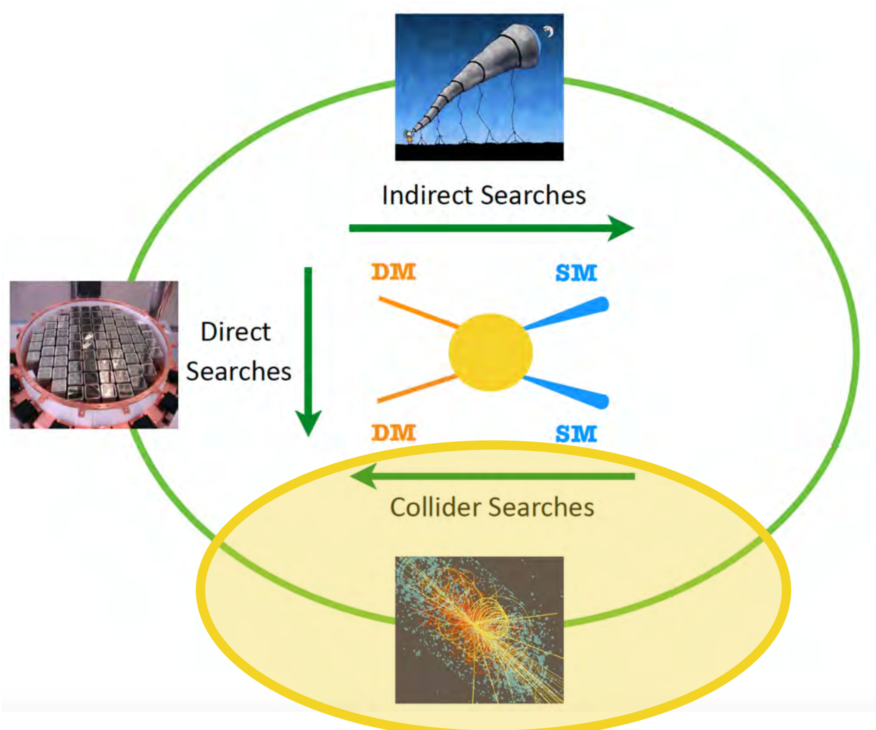
Detection strategies for WIMPs



MAKE THEM SHAKE THEM OR BREAK THEM

F. Calore

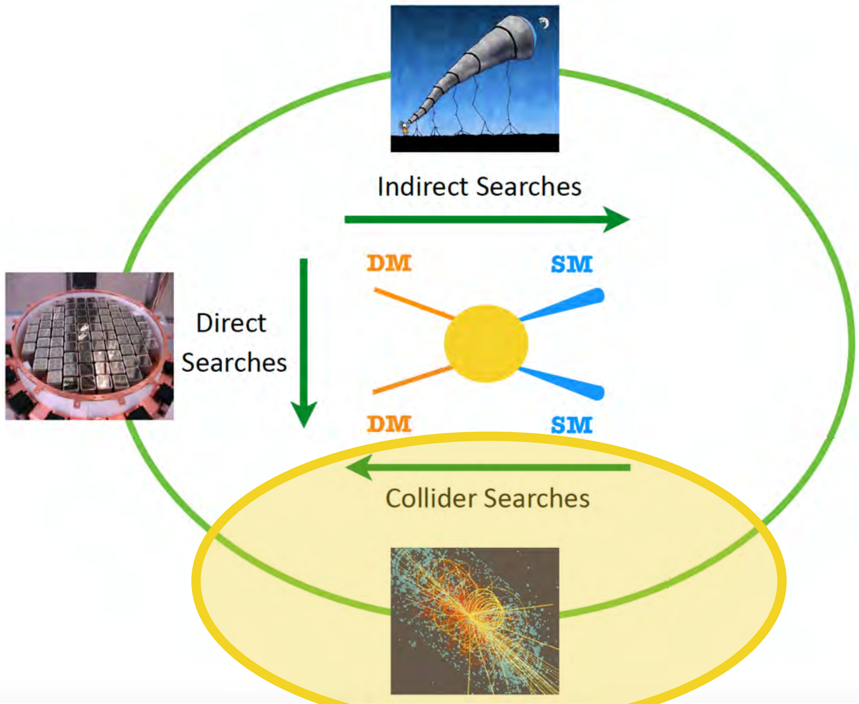
Detection strategies for WIMPs

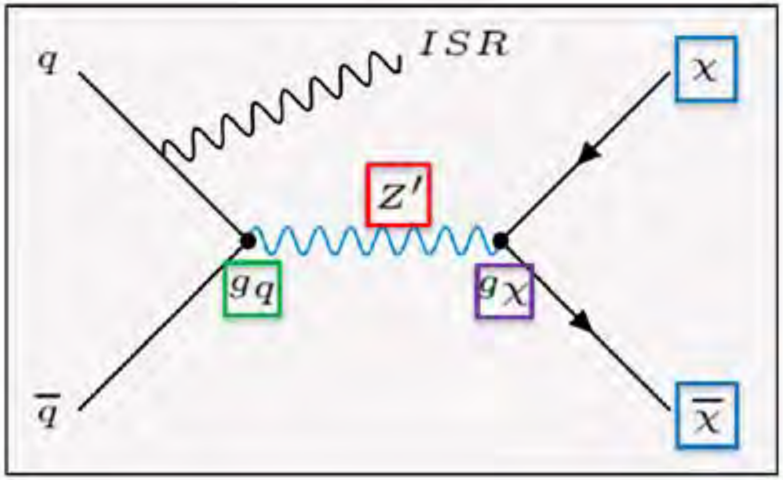


MAKE THEM

- Assumption: DM couple sufficiently strongly to the SM (as freeze-out suggest)
  → Can probe DM at colliders
- DM searches at the LHC fully underway!
- How to predict the signals and interpret the results?
  1. EFT approach
  2. Dark Matter Simplified Models (e.g. DP)
  3. Complete models (e.g. SUSY)

Detection strategies for WIMPs



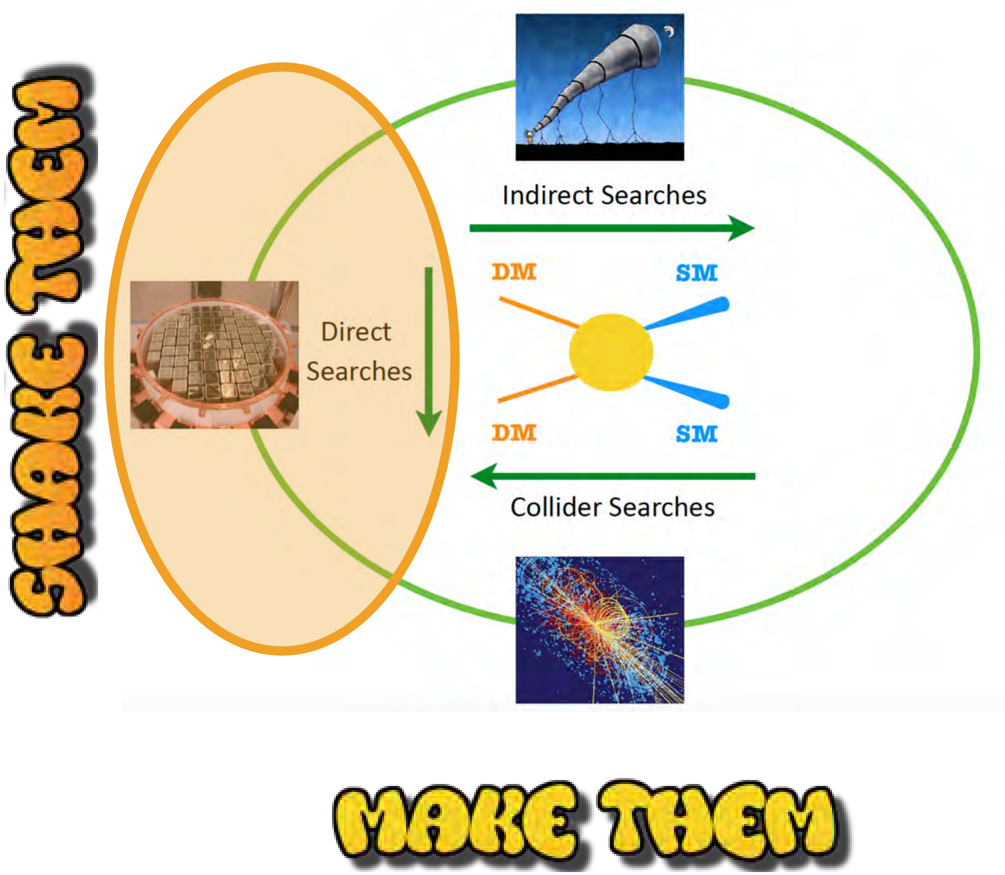


- Simple picture introducing new mediator
- 4 tunable parameters
  1. M_{med} Mediator mass
  2. M_χ Dark matter mass
  3. g_q Mediator's coupling to SM quarks
  4. g_χ Mediator's coupling to dark matter

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} - \underbrace{\frac{1}{2}m_A^2 A_\mu A^\mu}_{1.} + \underbrace{\bar{\chi}(i\gamma^\mu\partial_\mu - m_\chi)\chi}_{2.} - \sum_q \underbrace{g_q A_\mu \bar{q}\gamma^\mu(\gamma^5)q}_{3.} - \underbrace{g_\chi A_\mu \bar{\chi}\gamma^\mu(\gamma^5)\chi}_{4.}$$

WIMP Searches

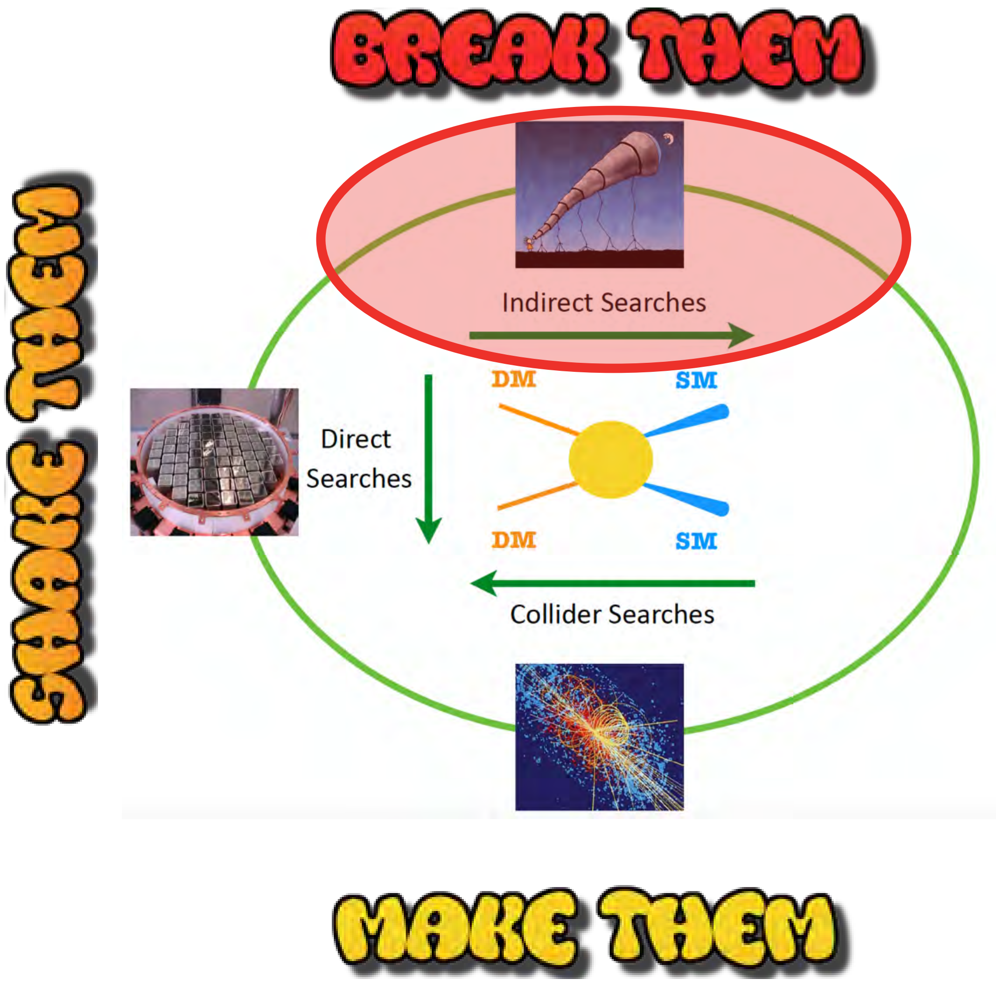
Detection strategies for WIMPs



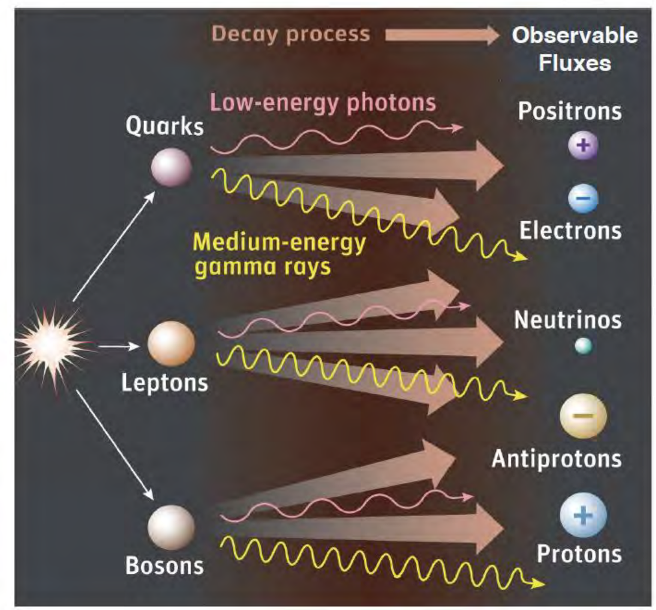
We will get back to this in a moment…

WIMP Searches

Detection strategies for WIMPs

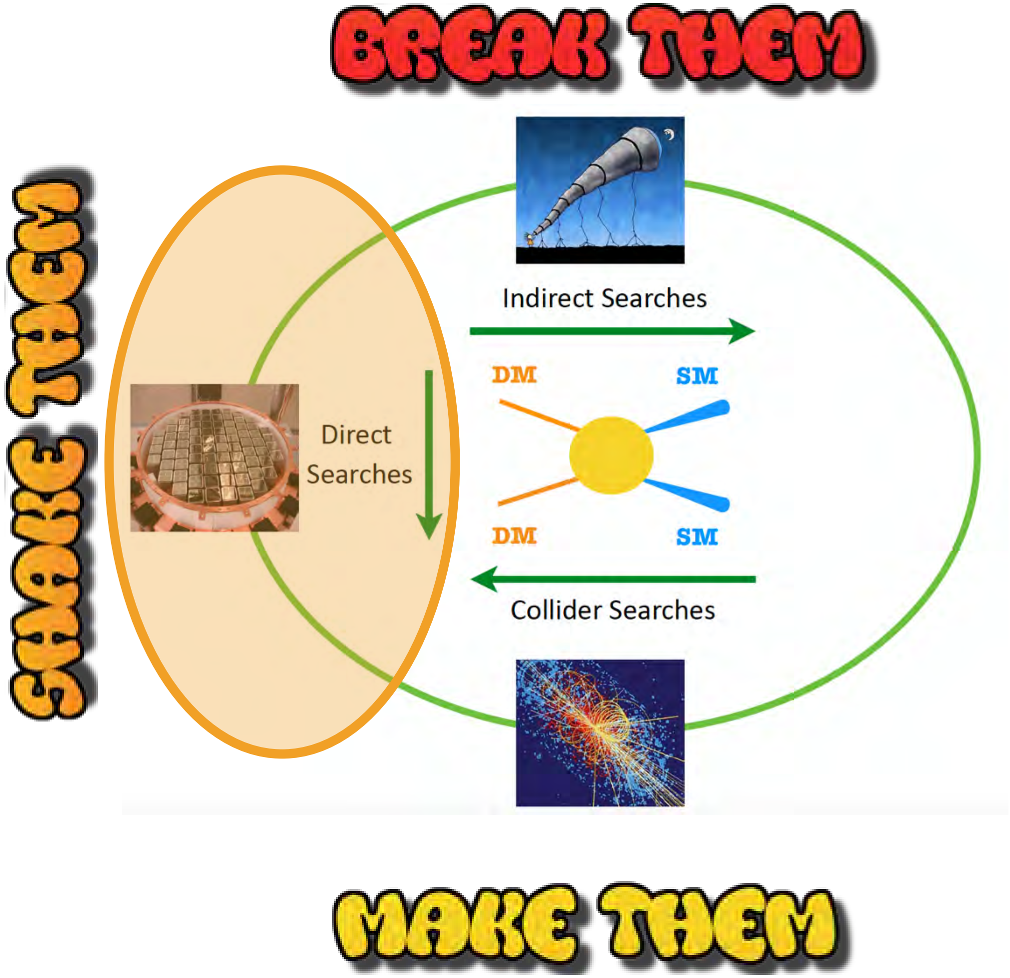


DM annihilation/decay



See F. Calore's talk

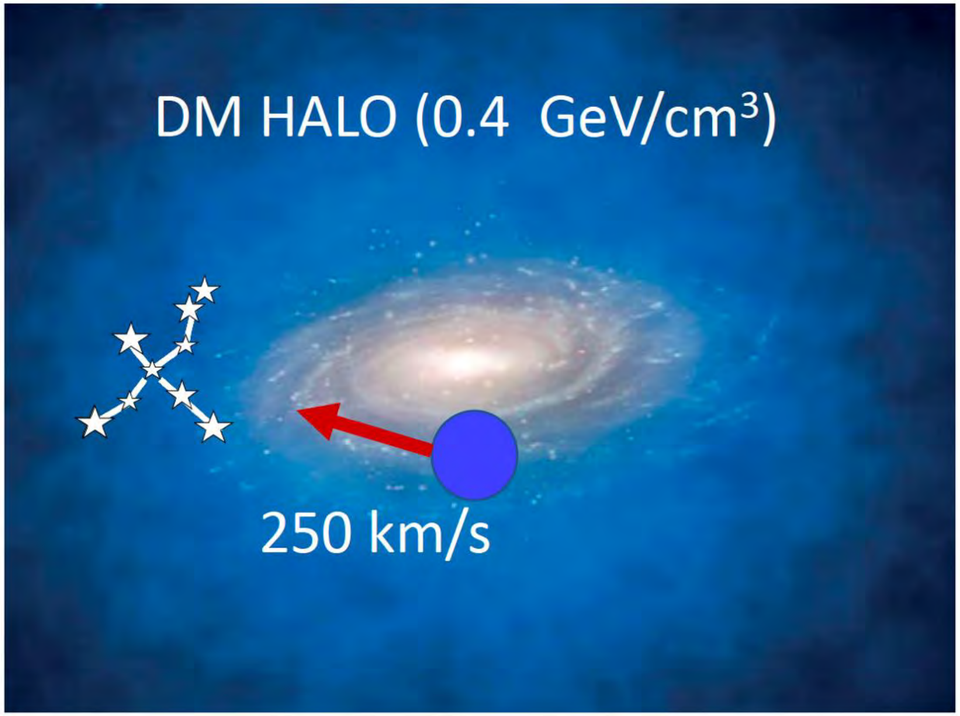
Detection strategies for WIMPs

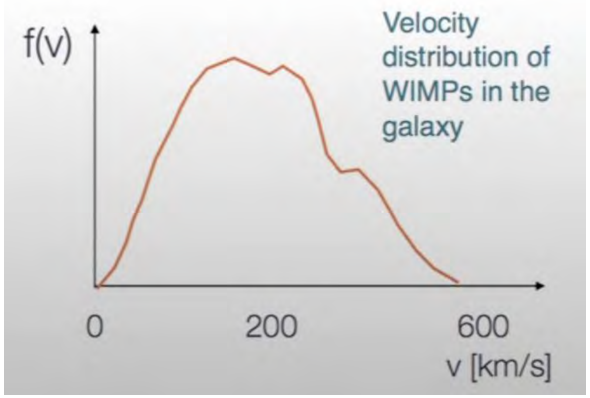


Here we go…

- Core idea: observe rare and faint interactions between WIMPs and atomic nuclei in a detector.
- WIMPs are expected to pass through the Earth and occasionally collide with nuclei, causing them to recoil
- Can detect this recoil using various techniques

Dark matter direct detection

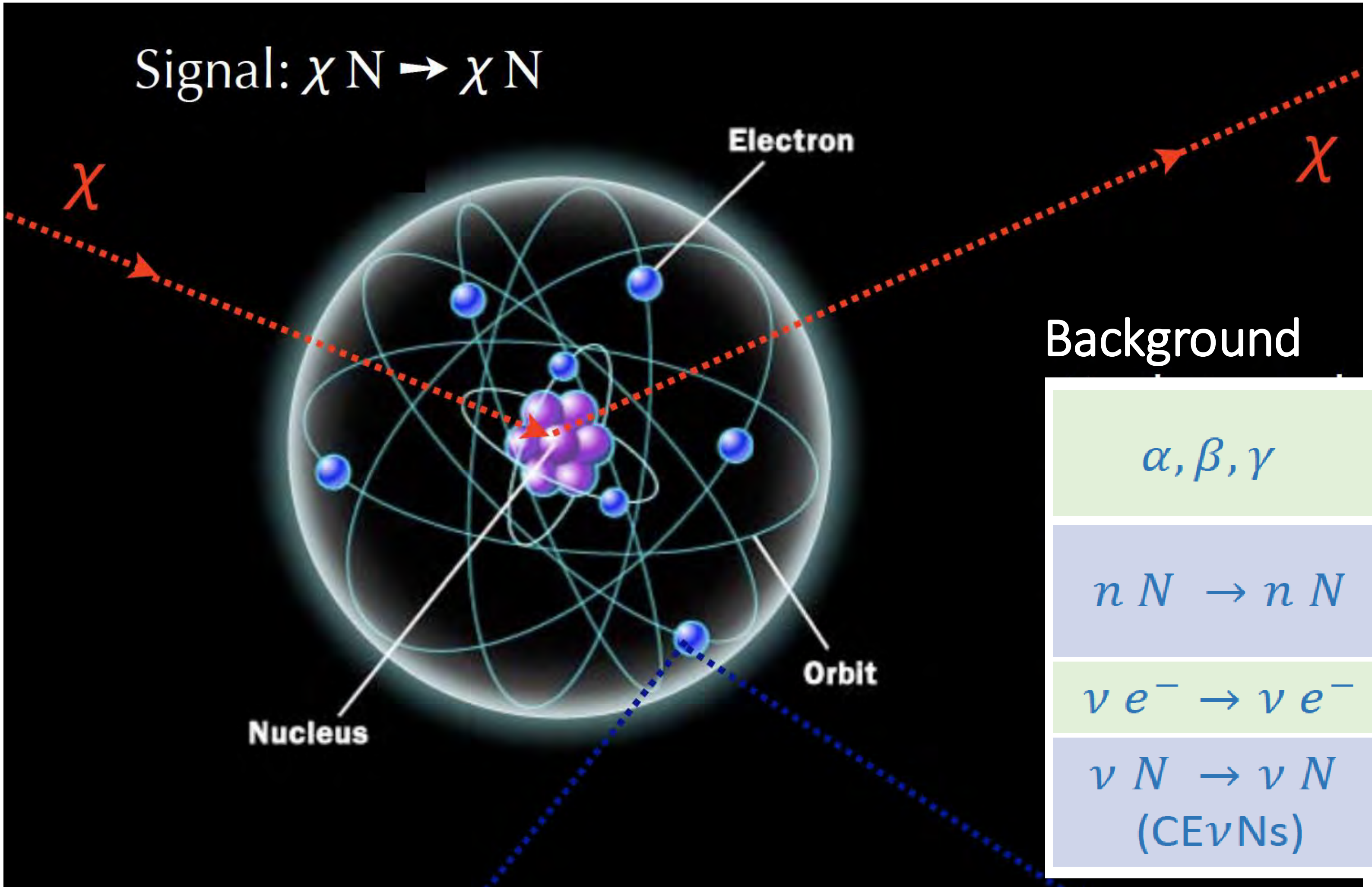




$$\phi = \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\langle v\rangle = 10^5 \frac{\mathrm{part}}{\mathrm{cm}^2 \times s}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)\left(\frac{\rho}{0.4\ \mathrm{GeV/cm}^3}\right)\left(\frac{v}{250\ \mathrm{km/s}}\right)$$

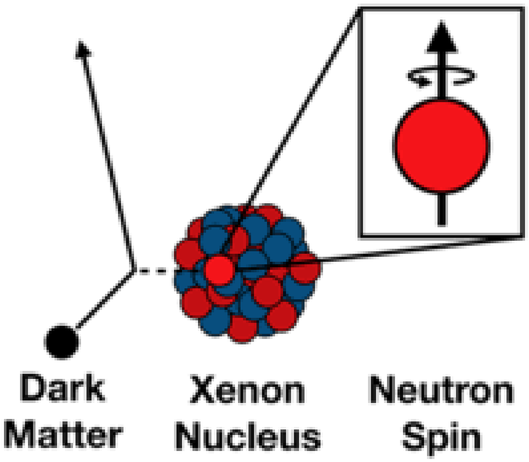
Compare e.g. to flux of pp neutrinos: 6.5×10^{10} particles cm^{-2} sec^{-1}

Dark matter direct detection

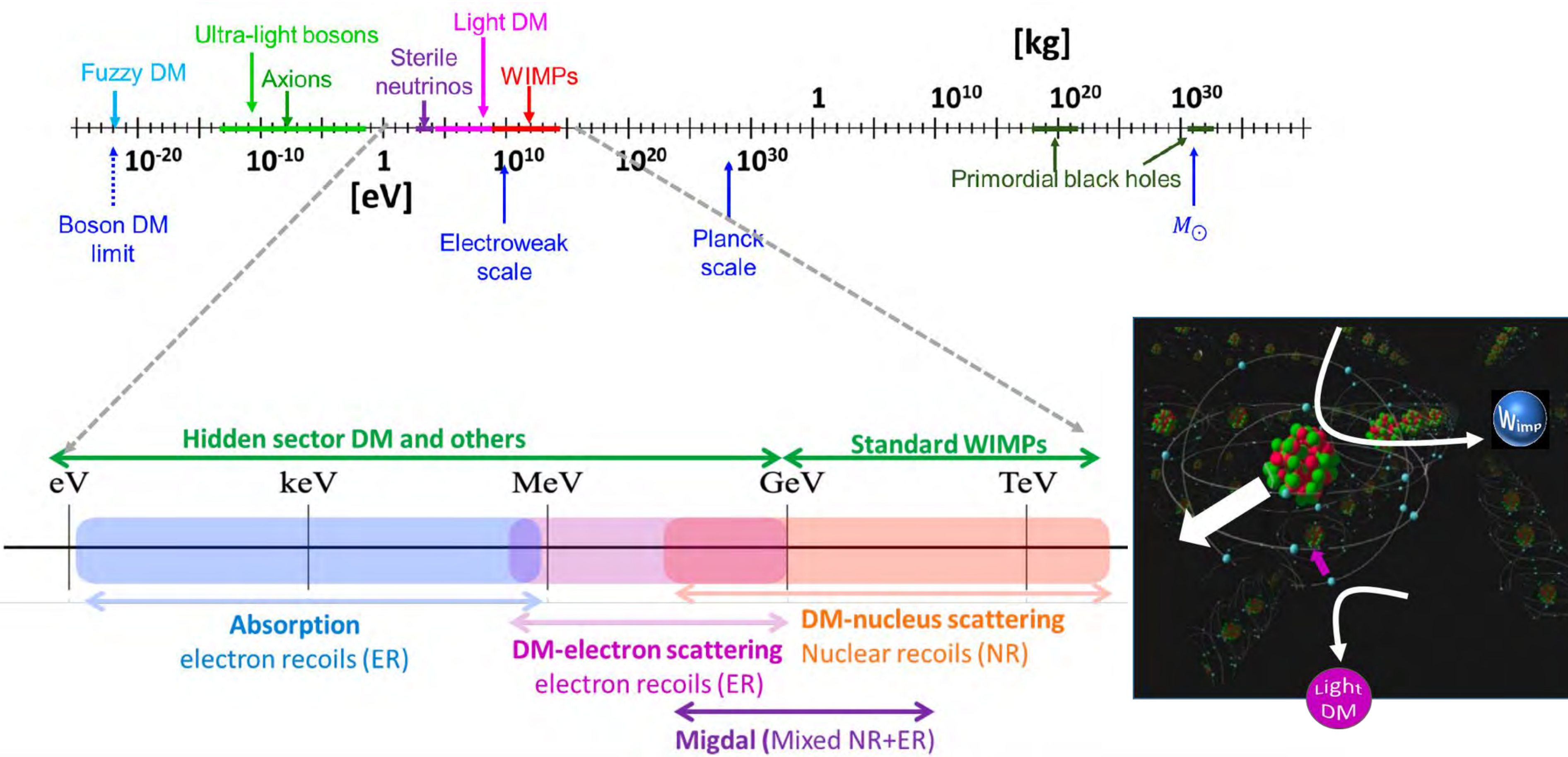


Spin-independent (SI) and Spin-dependent (SD) searches

- Variety of well-motivated DM candidates
- How they couple to SM is **model-dependent**
- Typically, need to consider only two cases
  1) **Spin-independent interaction**
     χ scatters coherently off of the entire nucleus A
     → Signal adds coherently $\sigma \propto A^2$
     → Typically dominant
  2) **Spin-dependent interaction**
     χ couples to the spin of the nucleus
     → Mainly unpaired nucleons contribute to the scattering amplitude: $\sigma \propto J(J+1)$



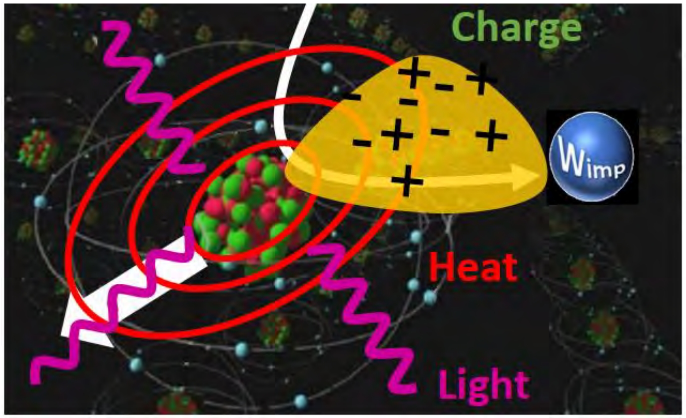
Ranges and interactions



Adapted from M. Martinez

WIMP Searches

Rate and cross-section



$$R \approx N_T \times \phi_{DM} \times \sigma$$

$\phi_{DM} \sim 10^4 - 10^6 \ \mathrm{s^{-1}\,cm^{-2}}$

$N_T \sim \frac{10^3 \times N_A}{A}$ nuclei/kg

$\sigma \sim \sigma_{weak} \sim 10^{-40} \ \mathrm{cm^2}$

} 1 c/kg/y – 1 c/ton/y

DM local density

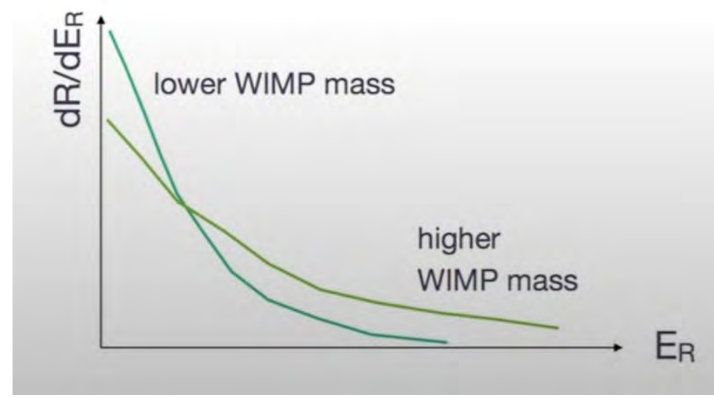
DM velocity distribution in detector's frame

$$\frac{dR}{dE_R} = \frac{M_{det}\rho_\chi}{2m_\chi \mu_{\chi N}^2} \sigma^0 F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v,t)}{v} d^3v$$

DM mass

scattering cross section

where $v_{min} = \sqrt{\frac{E_R m_N}{2\mu_{\chi N}^2}}$



Few counts per kg × year!!! Energy O(10keV)

No distinctive signatures and target dependent

Adapted from M. Martinez

Design of a DM direct detection(DD) experiment

$$\frac{dR}{dE_R} = \frac{M_{det}\rho_\chi}{2m_\chi\mu_{\chi N}^2}\sigma^0 F^2(q)\int_{v_{min}}^{\infty}\frac{f(v,t)}{v}d^3\boldsymbol{v}$$

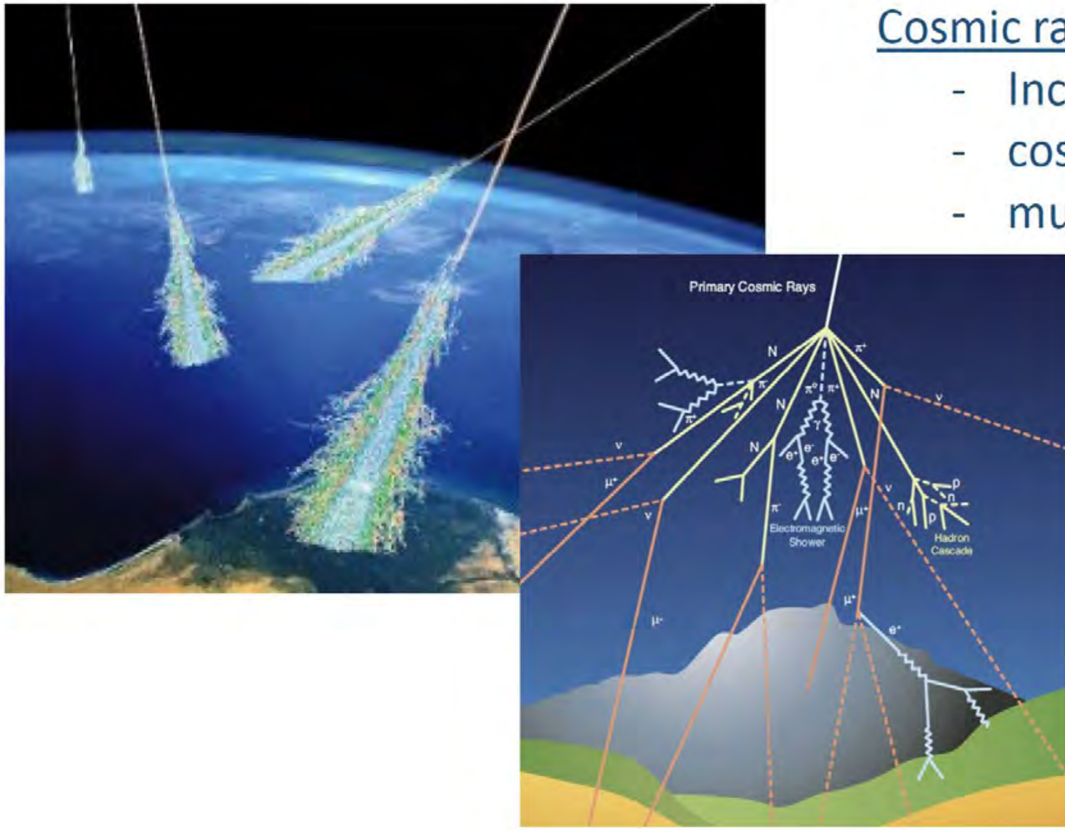
$$v_{min} = \sqrt{\frac{E_R m_N}{2\mu_{\chi N}^2}}$$

We need a particle detector with

- Large exposure (mass × time)
- High A for SI coupling, $m_\chi \sim 10 - 1000$ GeV
- Low A for light Wimps ($\mathcal{O}$(GeV))
- Isotopes with $J \neq 0$ for SD
- **Low energy threshold**
- Good efficiency in the low energy region
- Good knowledge of the detector response to NR (quenching factors)
- **Ultra-low background at low energy for NR → particle discrimination!**

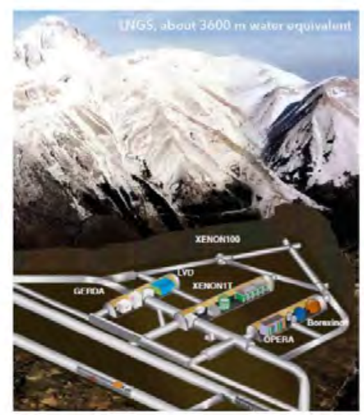
Adapted from M. Martinez

Backgrounds: Cosmic Rays



Cosmic ray-induced muons

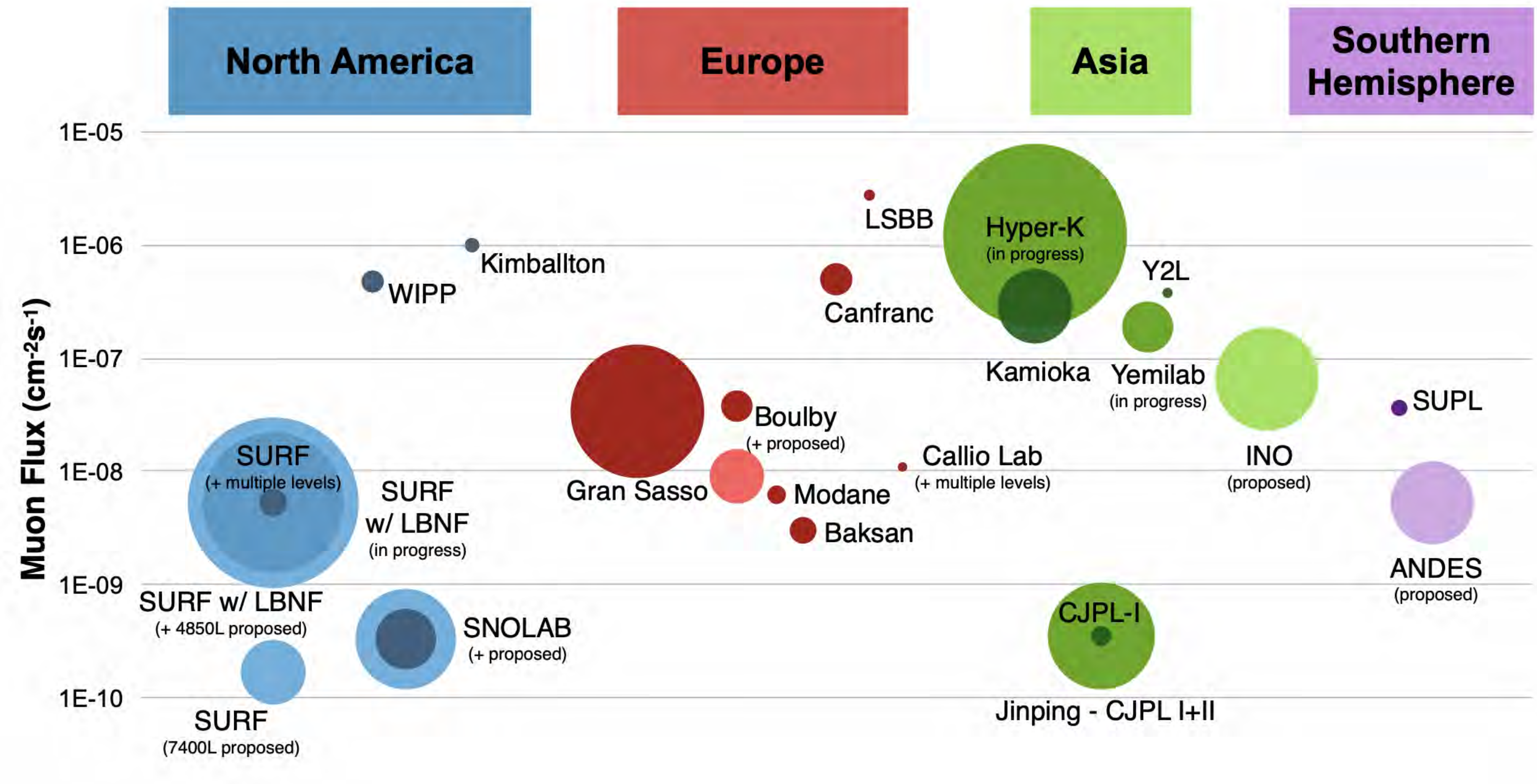
- Increase the counting rate
- cosmogenic activation of materials
- muon-induced neutrons



Go underground!

Adapted from M. Martinez

Underground Laboratories

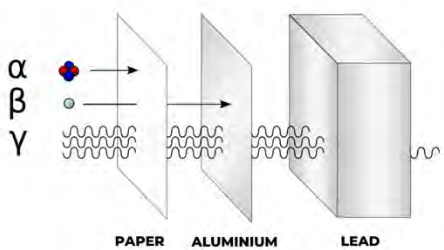


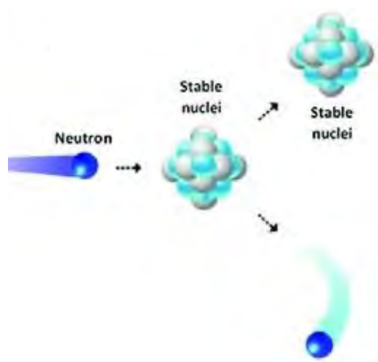
J. Heise, arXiv:2203.08293

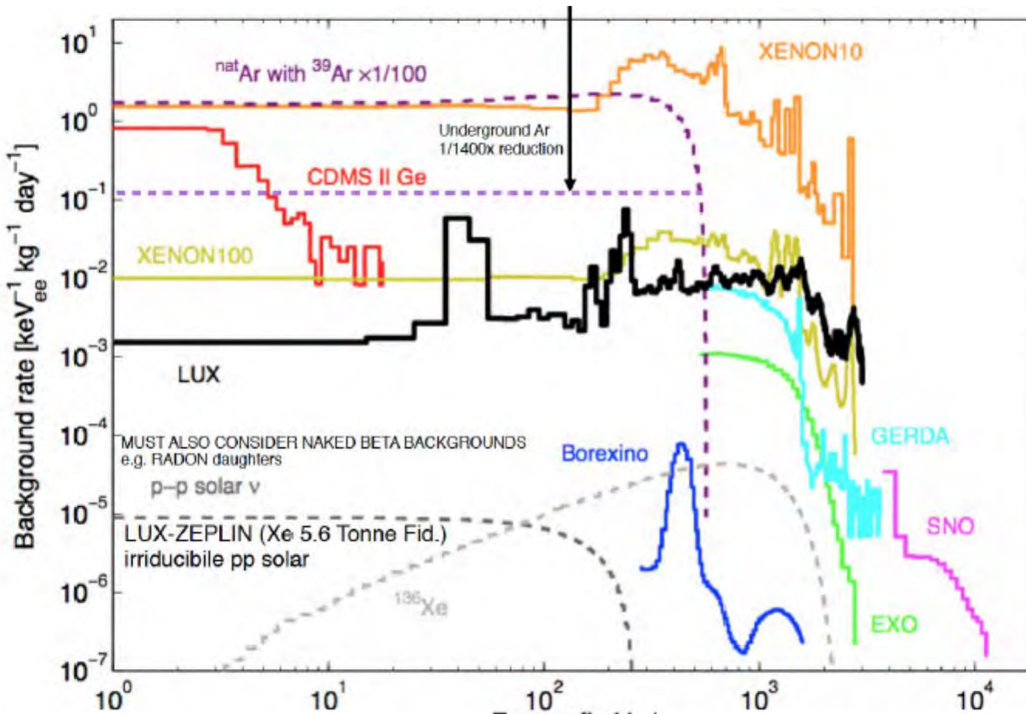
Experiments in Underground Laboratories

Backgrounds in dark matter direct detection

α, β, γ	material selection, shielding, **particle discrimination techniques**
$n\,N \rightarrow n\,N$	most critical (mimic WIMP signal). Shielding, active rejection (multiplicity)
$\nu\,e^- \rightarrow \nu\,e^-$	ultimate background for ER recoils



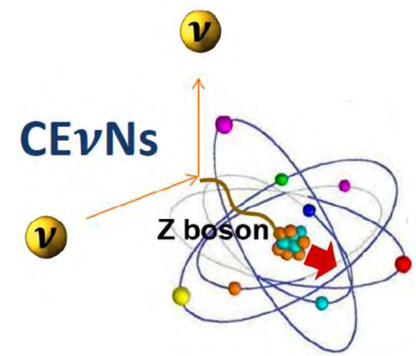




D. Malling, UCLA DM'16

Adapted from M. Martinez

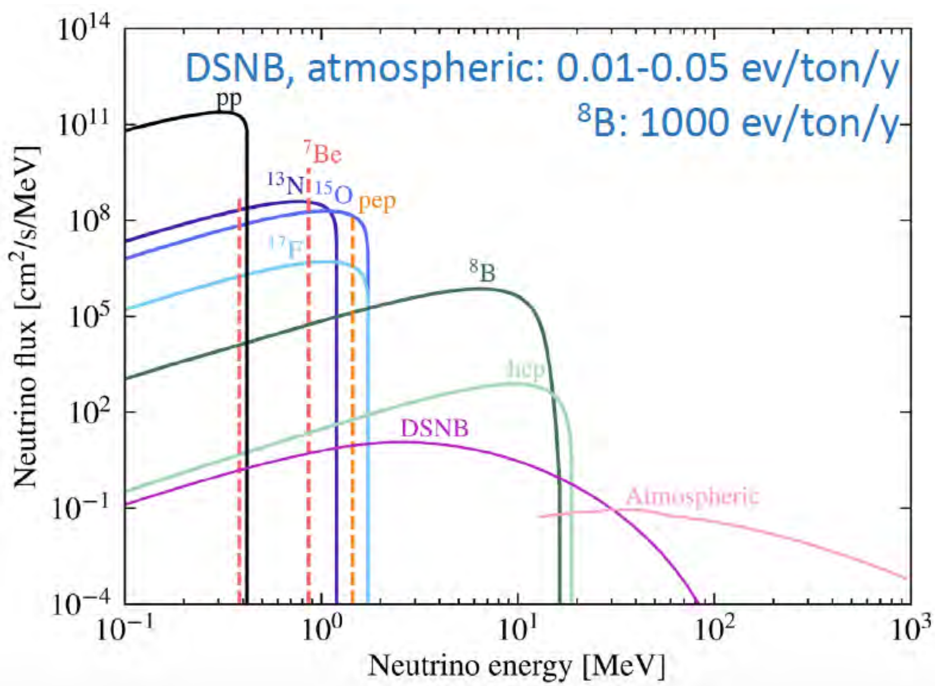
Backgrounds in dark matter direct detection

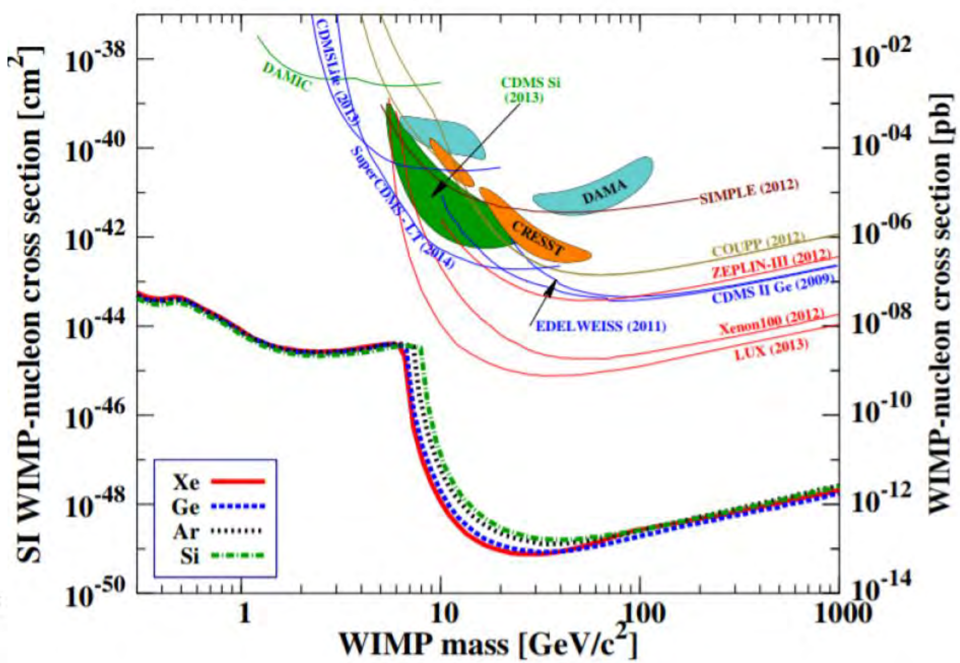


$\nu\, N \rightarrow \nu\, N$ (CEνNs)	ultimate background for WIMP search **(neutrino ~~floor~~ → fog)**

Coherent Elastic Neutrino-Nucleus Scattering

- ▸ ^{8}B, DSNB and atmospheric neutrinos produce nuclear recoil indistinguishable from WIMP signal





Adapted from M. Martinez

Detection categories

- High WIMP mass
  - Double-phase noble TPC: Lux/LZ, PandaX, Xenon, DarkSide
  - Noble liquid (single phase): Deap, XMass
- Low WIMP mass
  - Cryogenic detectors: Edelweiss, CRESST, SuperCDMS
  - CCDs: Damic, Sensei
  - High-pressure gas chambers: News-G, T-Rex
- Testing the DAMA/LIBRA signal
  - Scintillators: DAMA, Anais, Cosine, Sabre-N, Sabre-S, Picolon
  - Bolometers: Cosinus
- Bubble chambers
  - PICO
- Directionality
  - Low-pressure Gas TPCs: Newage, Mimac, Drif, Cygno, Cygnus

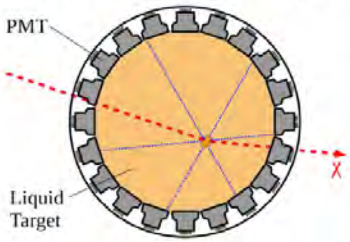
Adapted from M. Martinez

WIMP Searches

Detector working principles

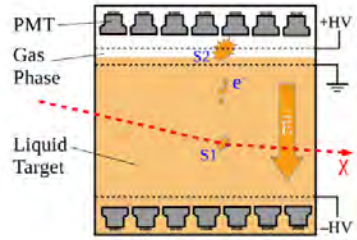
High WIMP mass, Low WIMP mass, Testing DAMA/LIBRA, Bubble chambers, Directionality

Liquid scintillators (light)



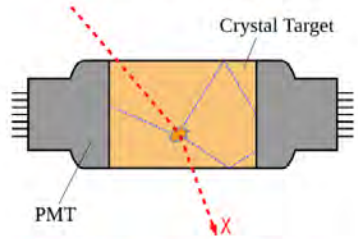
Deap, XMass

Double phase (liquid-gas) noble elements (light-charge)



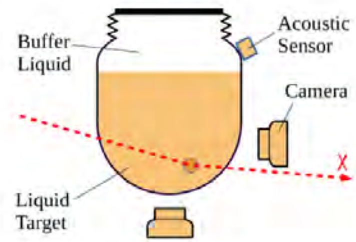
Lux/LZ, PandaX, Xenon, DarkSide

Solid state scintillators (light)



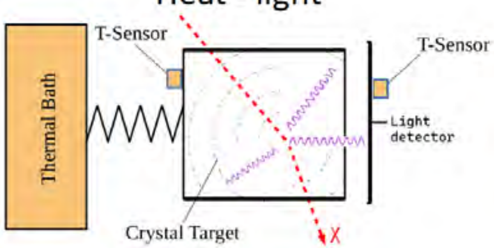
DAMA, Anais, Cosine, Sabre-N, Sabre-S, Picolon

Bubble chambers



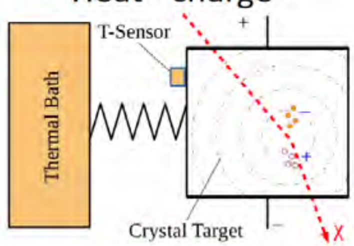
PICO

Cryogenic detectors Heat - light



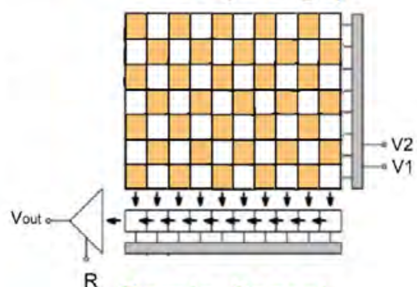
CRESST, Cosinus

Cryogenic detectors Heat - charge



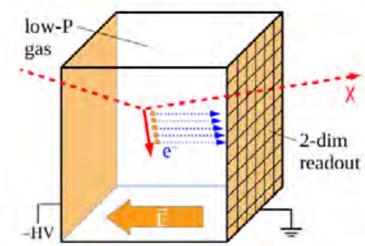
Edelweiss, SuperCDMS

CCDs (charge)



Damic, Sensei

Gaseous-TPC (charge)

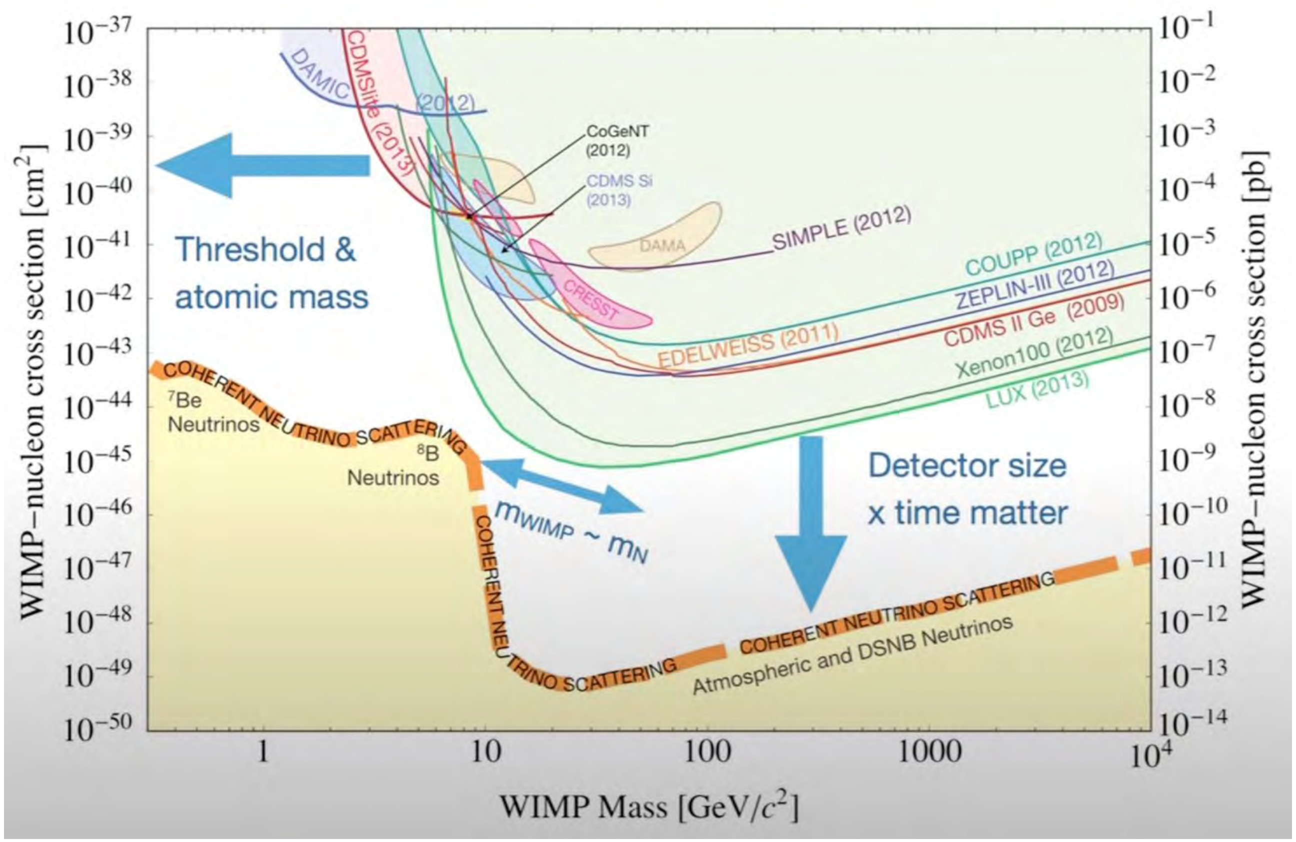


News-G, Trex, Newage, Mimac, Drif, Cygno, Cygnus

Adapted from APPEC Committee Report 2021

Status of DM DD Experiments about 10 years ago

- Exclude WIMPs that would produce a measurable rate over known backgrounds

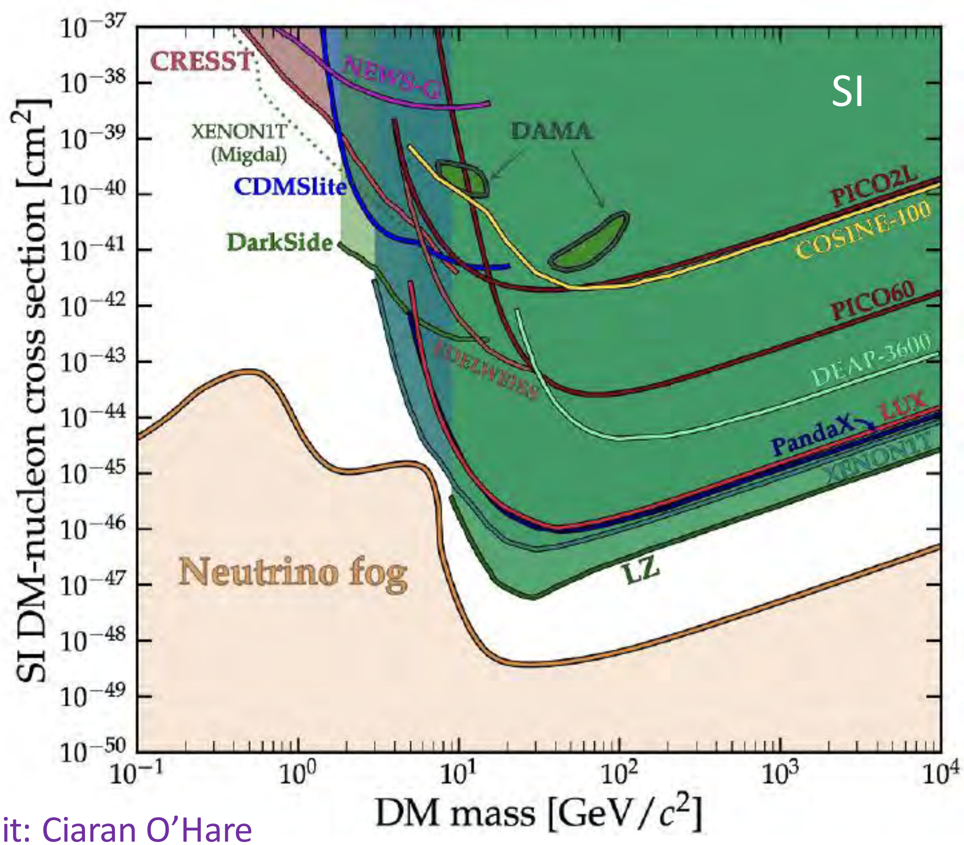


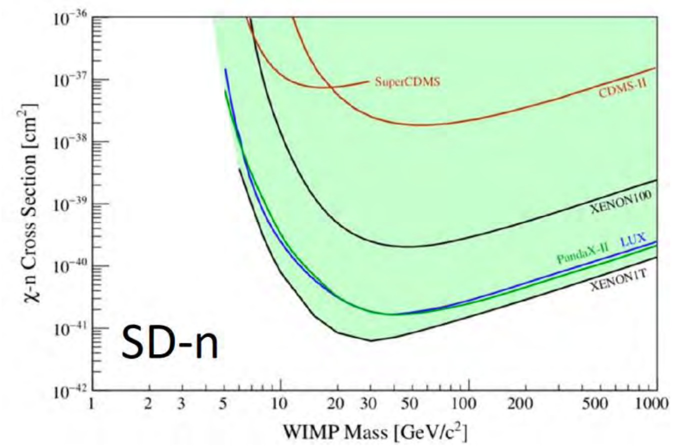
Credit: L. Baudis

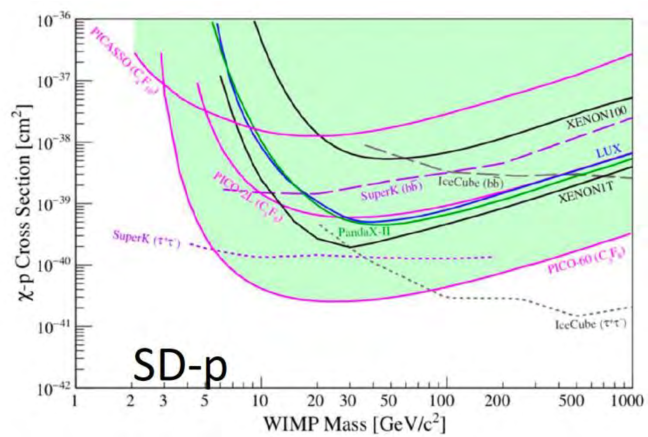
WIMP Searches

Status of DM DD Experiments today

- Exclude WIMPs that would produce a measurable rate over known backgrounds
- Assuming WIMPs coupling only spin-independent (SI) or only spin-dependent to neutrons (SD-n) or protons (SD-p)



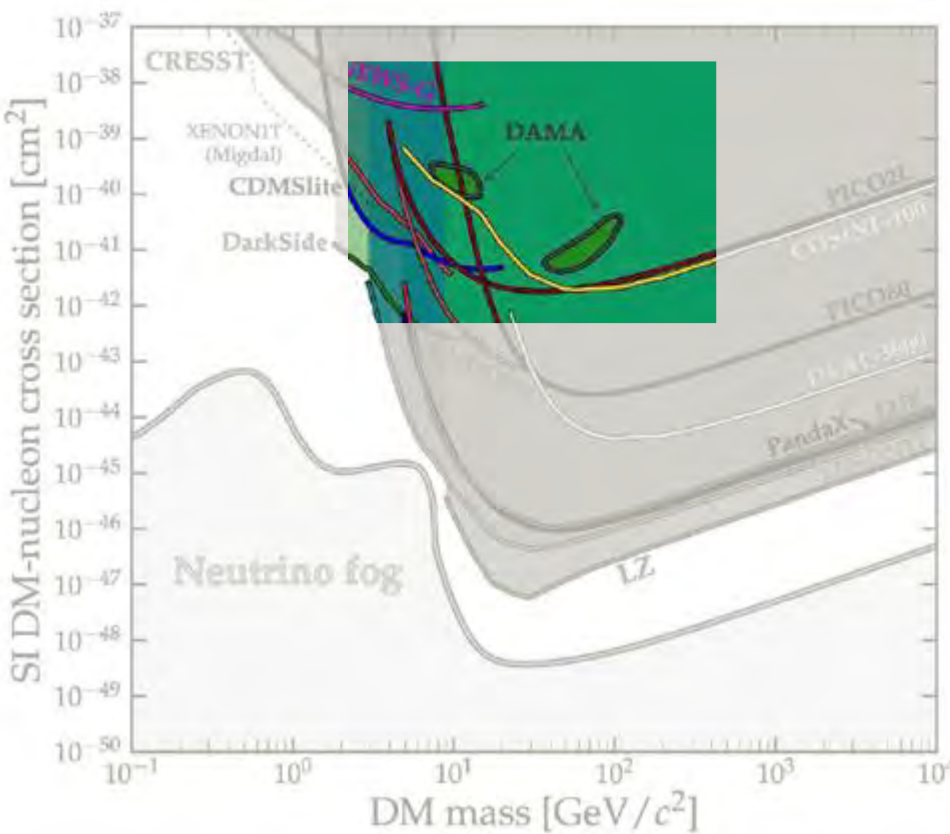


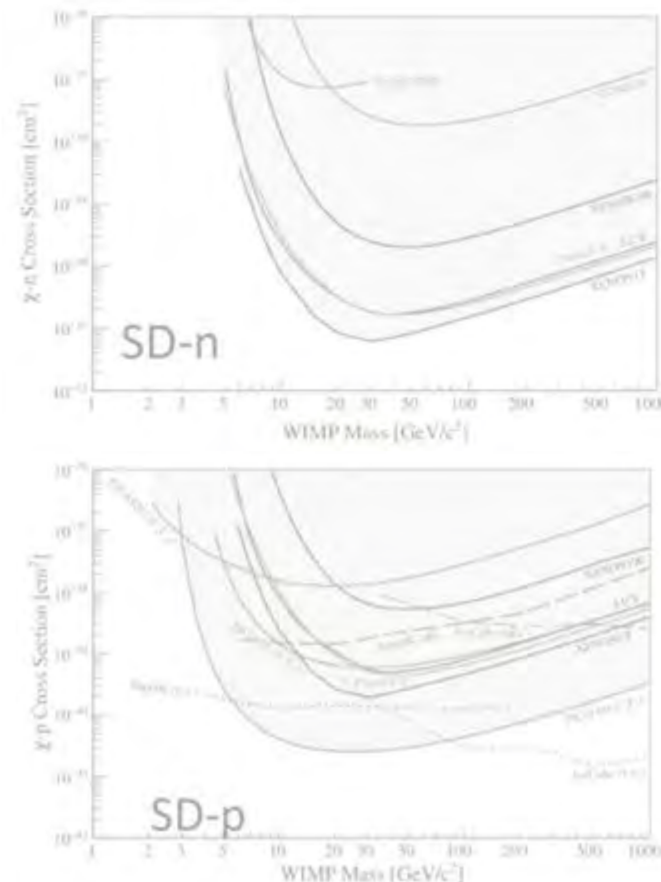


Credit: Ciaran O'Hare

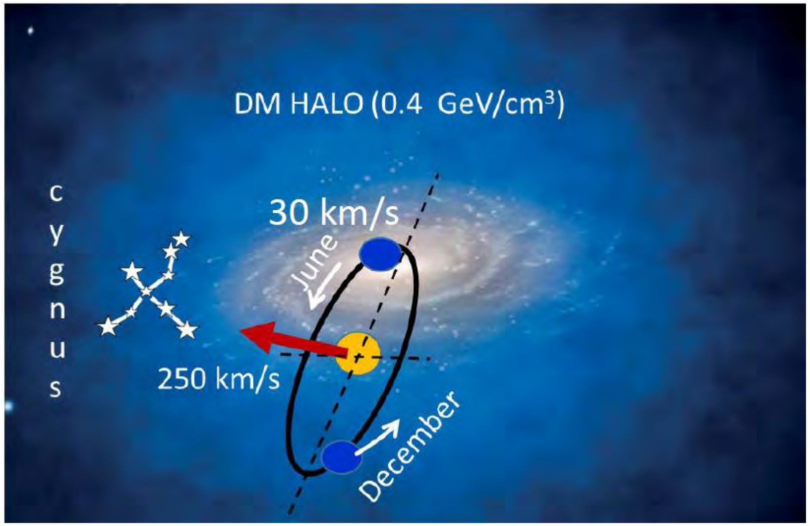
Status of DM DD Experiments

Only one positive signal (surviving for more than 20 years…)

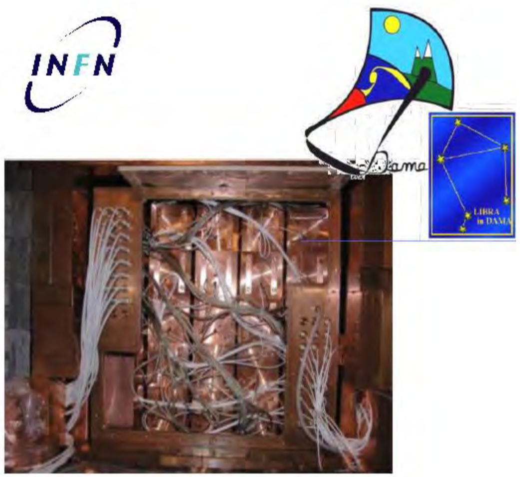




The DAMA/LIBRA annual modulation signal



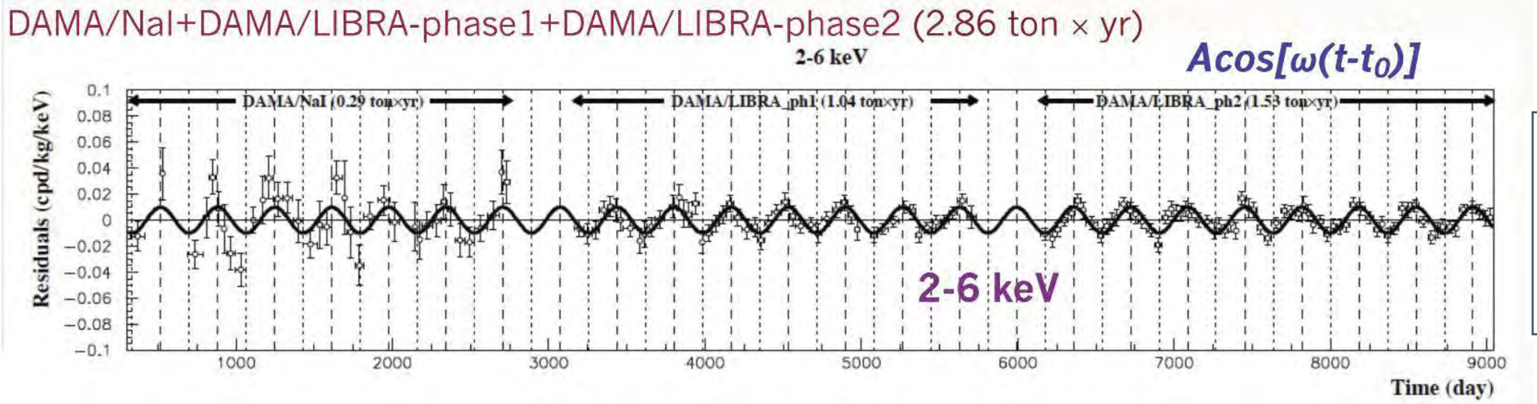
LABORATORI NAZIONALI DEL GRAN SASSO



DAMA / NaI (1995-2002)
- 100 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

DAMA / LIBRA ph1 (2003-2010)
- 250 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

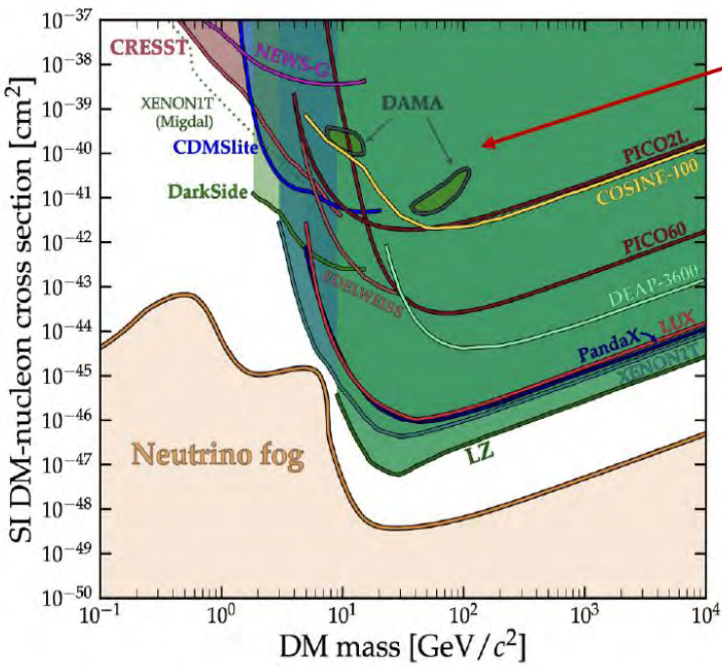
DAMA / LIBRA ph2 (2011-today)
- 250 kg NaI(Tl) scintillators
- Eth = 1 keVee
- 10 annual cycles



DAMA clearly sees an annual modulation at 13.7σ C.L.

Adapted from M. Martinez

Testing the DAMA/LIBRA signal



The parameter's region singled out by DAMA/LIBRA is excluded by many DM experiments, but **this comparison is model dependent**.

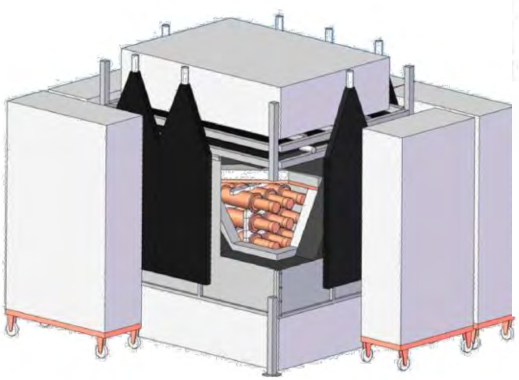
To avoid any model dependence: USE NaI(Tl)

Adapted from M. Martinez

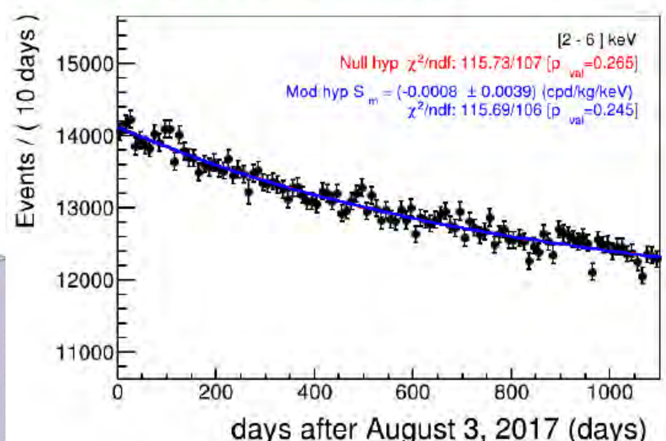
ANAIS-112 vs DAMA/LIBRA

ANAIS-112: First model independet test of the DAMA/LIBRA signal (same target and technique)

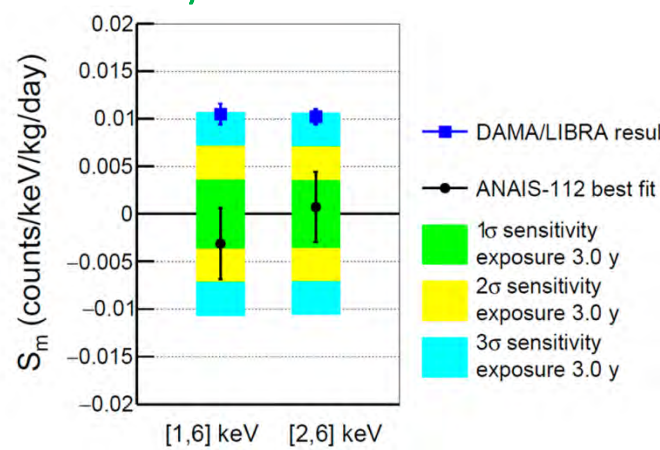
112 kg NaI(Tl) scintillators @ Canfranc Underground Lab
Data acquisition since August 2017
1 keVee energy threshold and Background@ ROI x3 DAMA/LIBRA



PRD 103, 102005 (2021)



3-year results



Best fit incompatible with DAMA/LIBRA at 3.3 (2.6) σ
Current sensitivity: 2.5-2.7σ

Adapted from M. Martinez

ANAIS-112 vs DAMA/LIBRA

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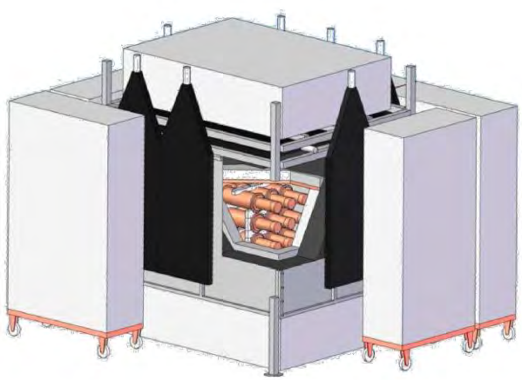
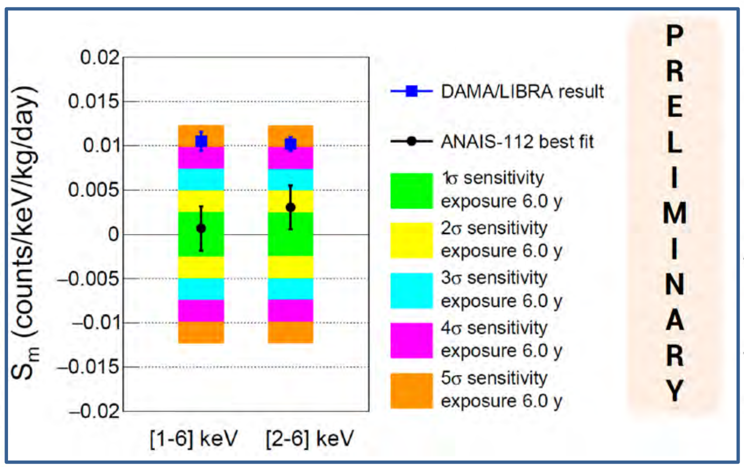
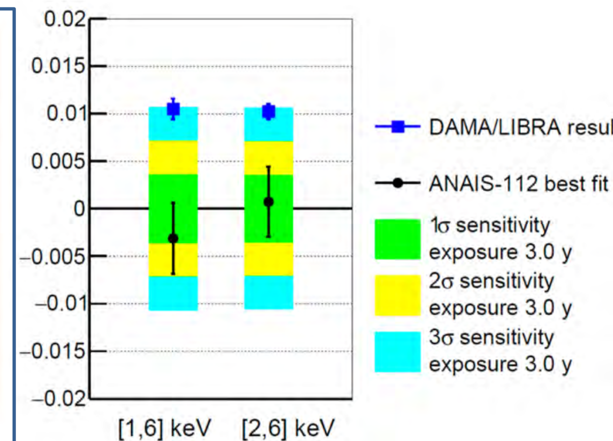


6-year results



3-year results



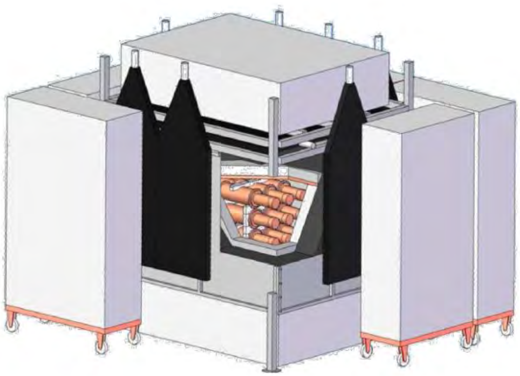
Best fit incompatible with DAMA/LIBRA at 3.3 (2.6) σ/~3.9 (2.9) ***σ***
Current sensitivity: 2.5-2.7***σ***/4.2-4.1 ***σ***

Adapted from M. Martinez

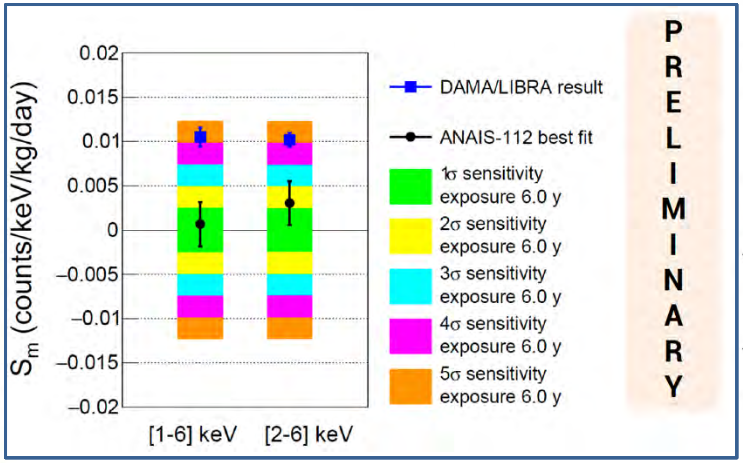
ANAIS-112 vs DAMA/LIBRA

ANAIS-112: First model independet test of the DAMA/LIBRA signal (same target and technique)

112 kg NaI(Tl) scintillators @ Canfranc Underground Lab
Data acquisition since August 2017
1 keVee energy threshold and Background@ ROI x3 DAMA/LIBRA



6-year results

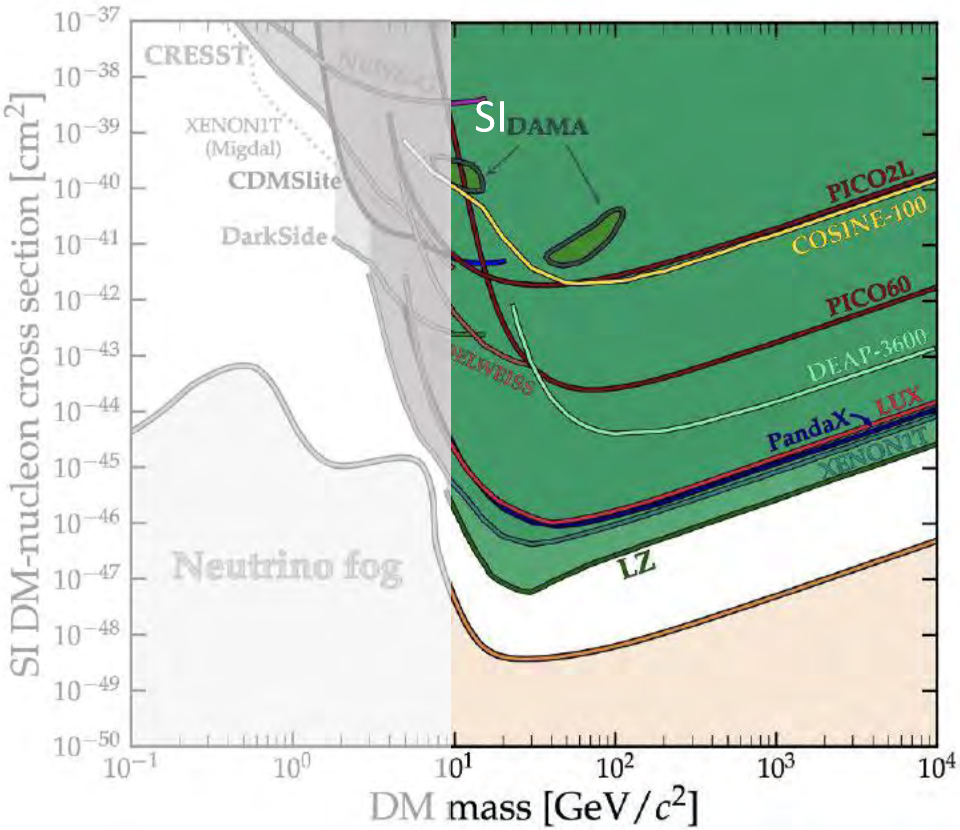


Best fit incompatible with DAMA/LIBRA at 3.3 (2.6) σ/~3.9 (2.9) ***σ***
Current sensitivity: 2.5-2.7***σ***/4.2-4.1 ***σ***

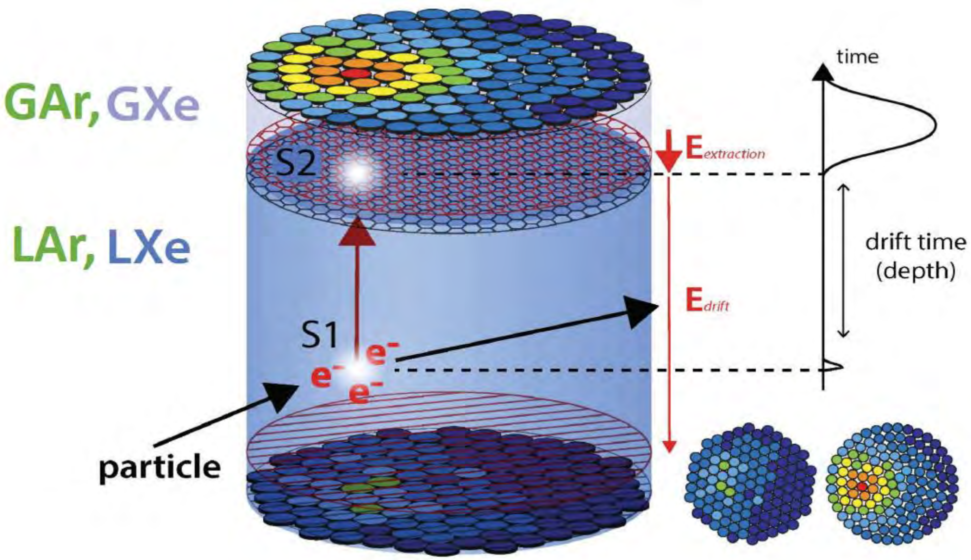
Adapted from M. Martinez

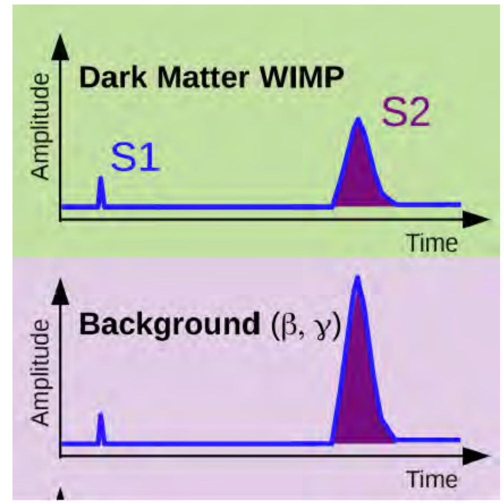
High WIMP mass

- Double-phase noble elements TPC: Lux/LZ, PandaX, Xenon, DarkSide
- Noble liquid (single pase): Deap, XMass



Double-phase noble elements TPC (light + charge)



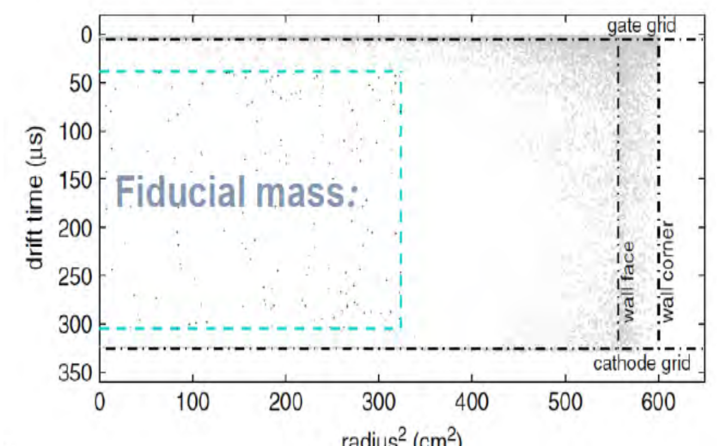


Ratio S1/S2 different for nuclear recoils (WIMPs) and electron recoils (background)

Reconstruction of the hit position

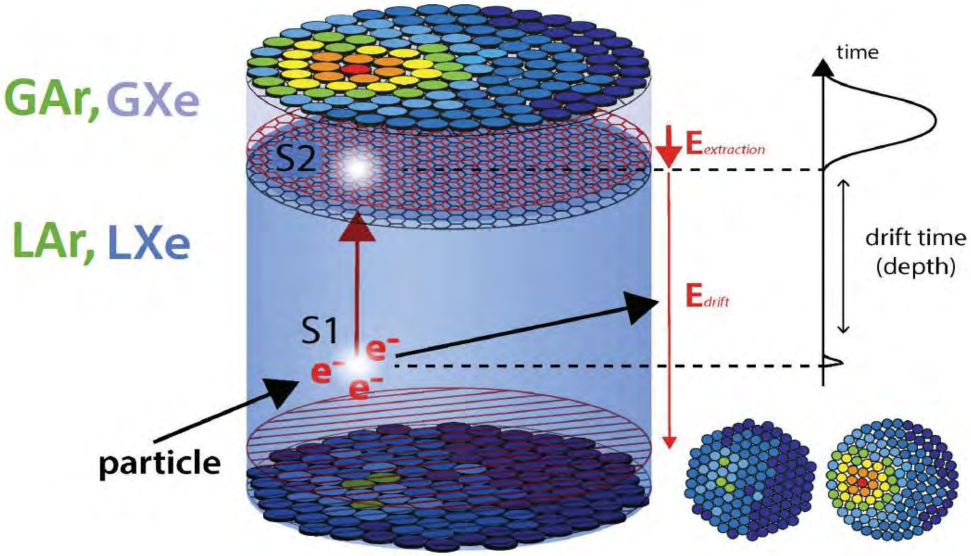
- Top/bottom photomultipliers → (x, y)
- Drift time → z

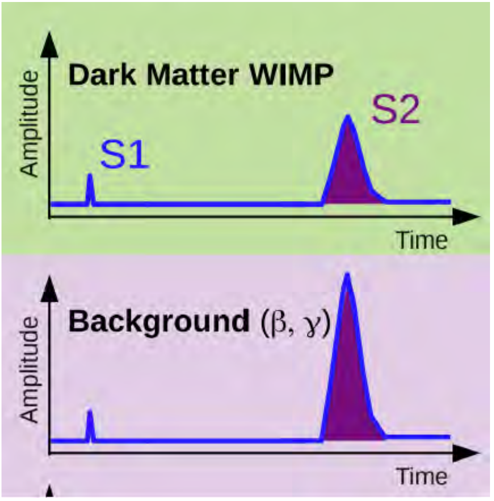
→ Fiducialization (use only the inner (cleaner) part)



Adapted from M. Martinez

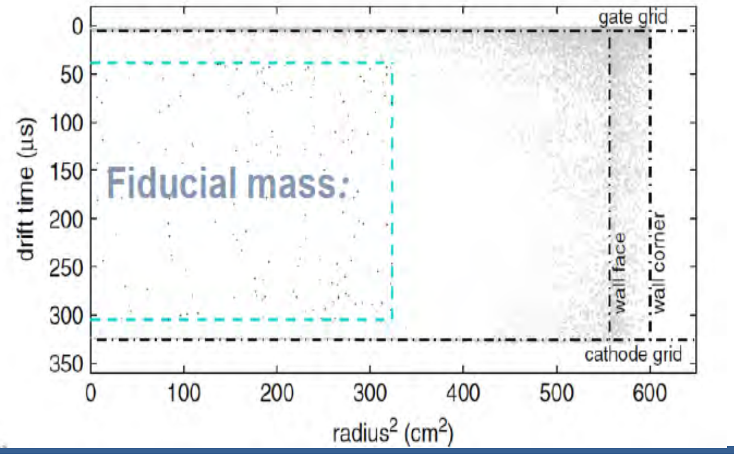
Double-phase noble elements TPC (light + charge)





Ratio S1/S2 different for nuclear recoils (WIMPs) and electron recoils (background)

- ER Background rejection
- Fiducialization
- Possibility to reduce the threshold working only with charge readout (no bkg discrimination!)

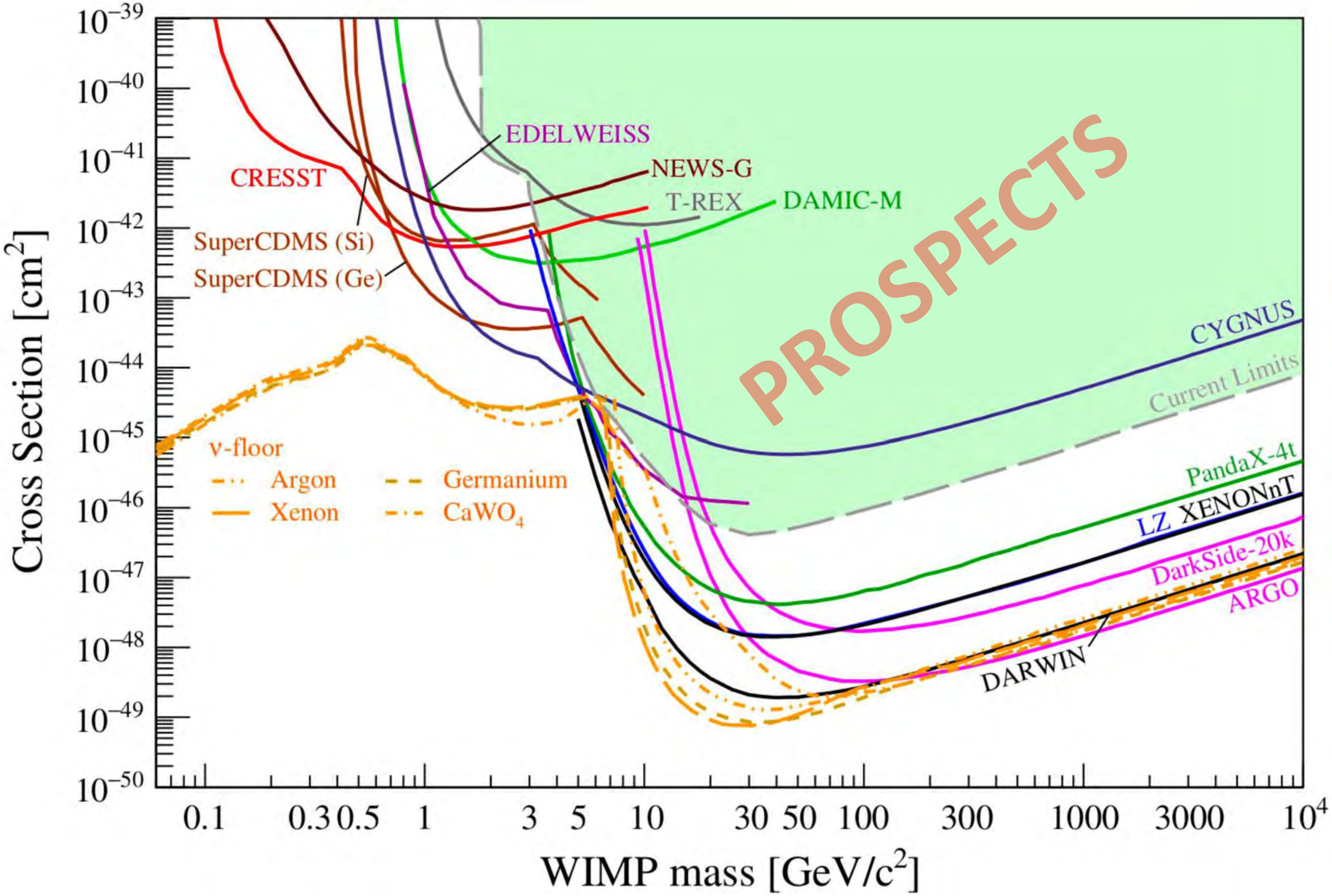


Adapted from M. Martinez

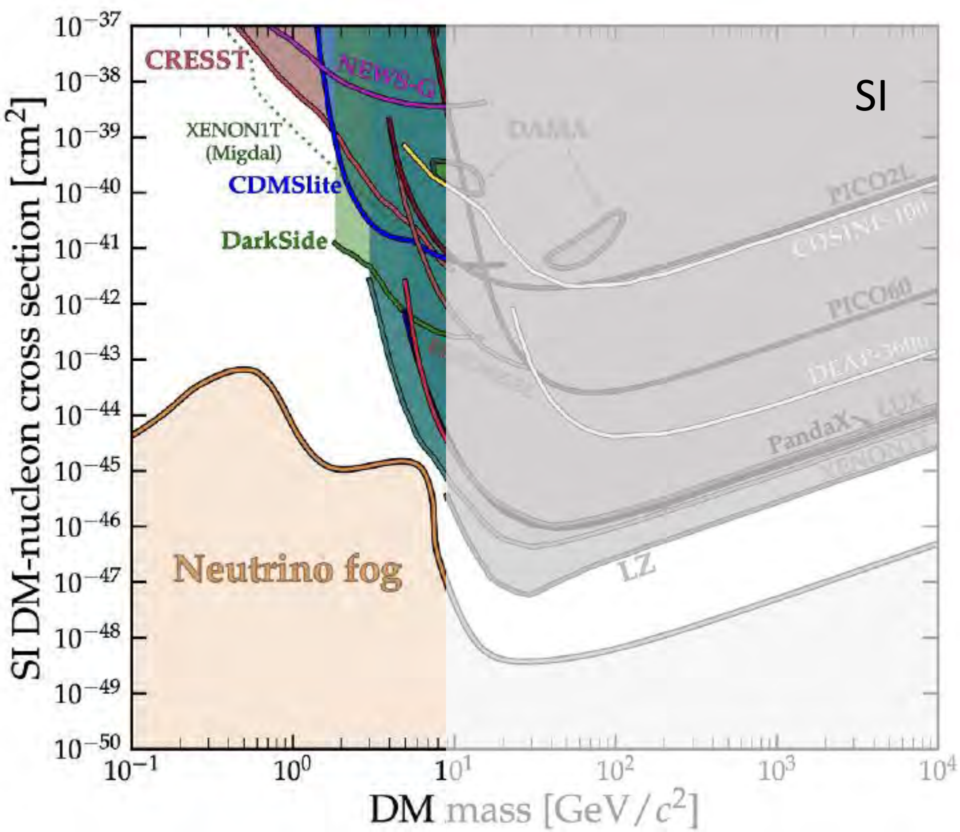
WIMP Searches

Adapted from M. Martinez

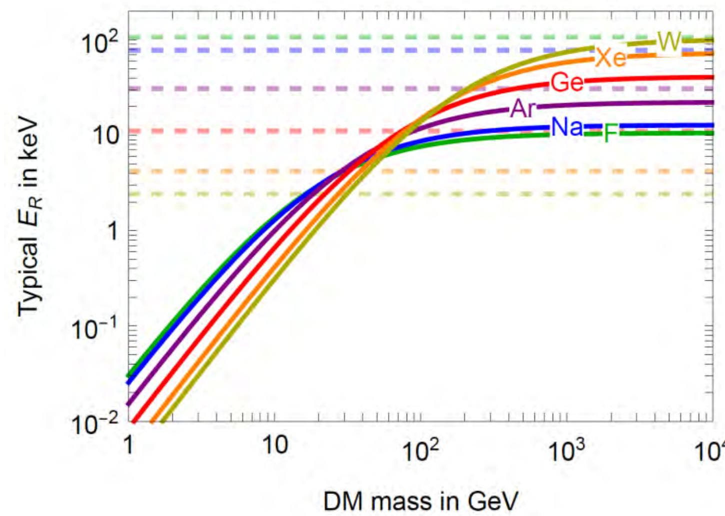
Dark matter direct detection prospects



Low WIMP Masses (<10 GeV)

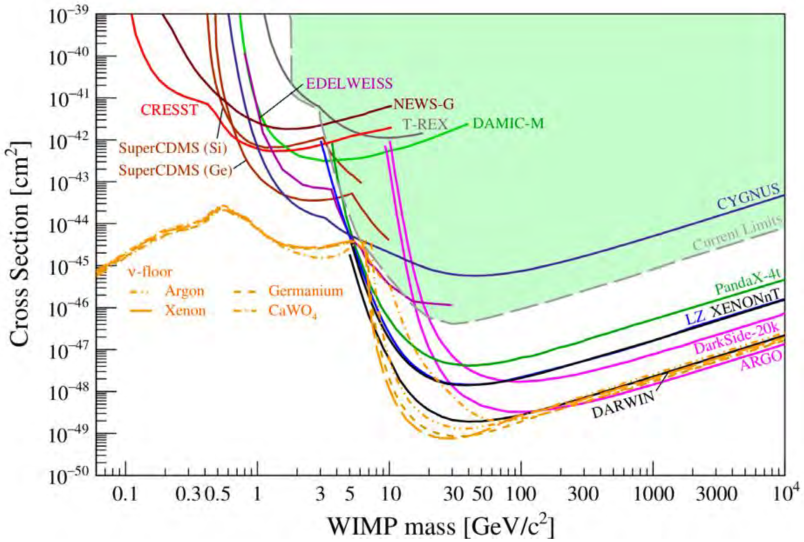


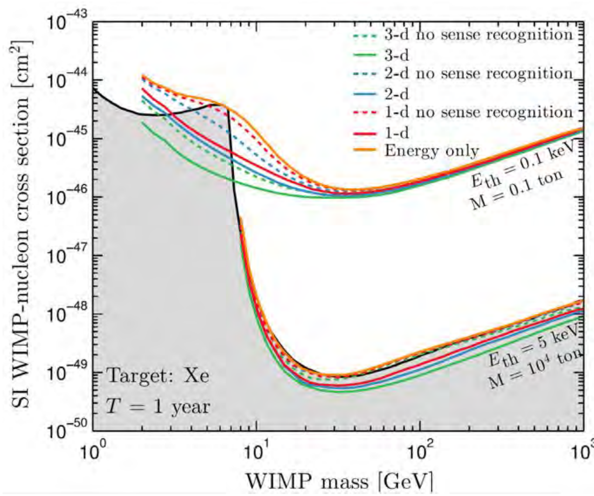
Need very low energy threshold to explore the low-mass region



- Cryogenic detectors: Edelweiss, CRESST, SuperCDMS
- CCDs: Damic, Sensei
- High-pressure gas chambers: News-G

Dark matter direct detection





- World-wide effort to detect WIMP DM "directly", but no signal yet
- DAMA/LIBRA positive signal not confirmed at 3-4σ by ANAIS-112/COSINE-100 experiments
- Xe & Ar multi-ton experiments planned to reach the neutrino floor in the next decade
- Many new ideas/experiments to explore DM scenarios in the GeV (NR), MeV (ER), keV down to eV (absorption) regions
- Beyond the neutrino fog? Multiple target detectors? Directionality (i.e. using directional detectors to differentiate between isotropic neutrino bgrd and anisotropic WIMP signals)?→CYGNUS collaboration

See e.g. F.Mayetet al, "A review of the discovery reach of directional Dark Matter detection", Phys. Rep. 627,1 (2016)

Axion Searches

Credits “Axion Searches”: K. van Bibber, I. G. Irastorza, A. Ringwald,…

Why is the electric dipole moment of the neutron (nEDM) so small?

- QCD Lagragian contains a CP violating term (with θ-parameter of QCD vacuum)

$$\mathcal{L}_{\not{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$$

- Observational Consequences: Prediction of electric dipole moments (EDM) to hadrons, most importantly, to neutrons

$$d_n \sim 10^{-16}\ \bar{\theta}\ e\,\mathrm{cm}$$

Crewther,Di Vecchia,Veneziano,Witten 1979;...; Pospelov,Ritz 2000

- Latest measurements of the nEDM

$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$$

Abel et al. 2020

- Therefore expect $|\bar{\theta}| \lesssim 10^{-10}$

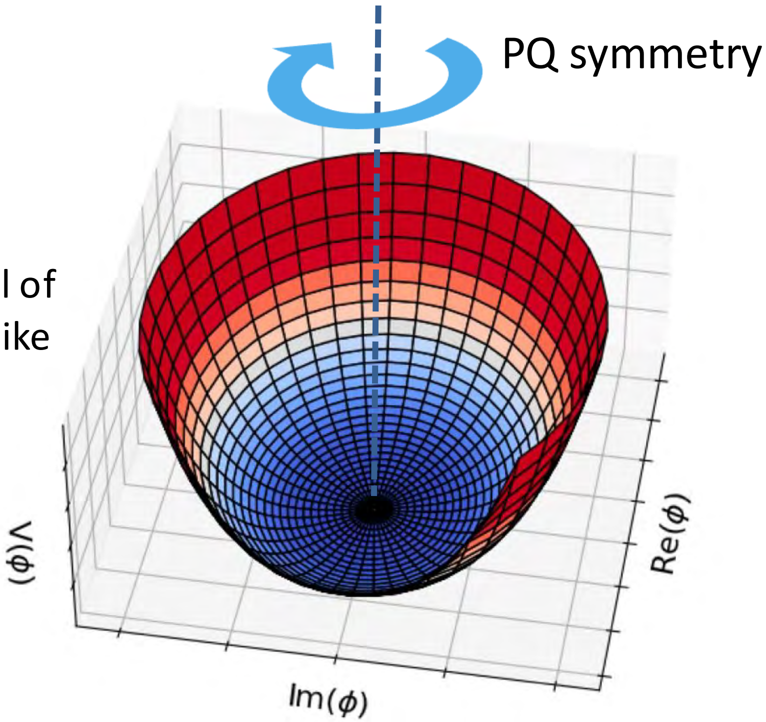
STRONG CP PROBLEM or WHY IS THETA SO SMALL?

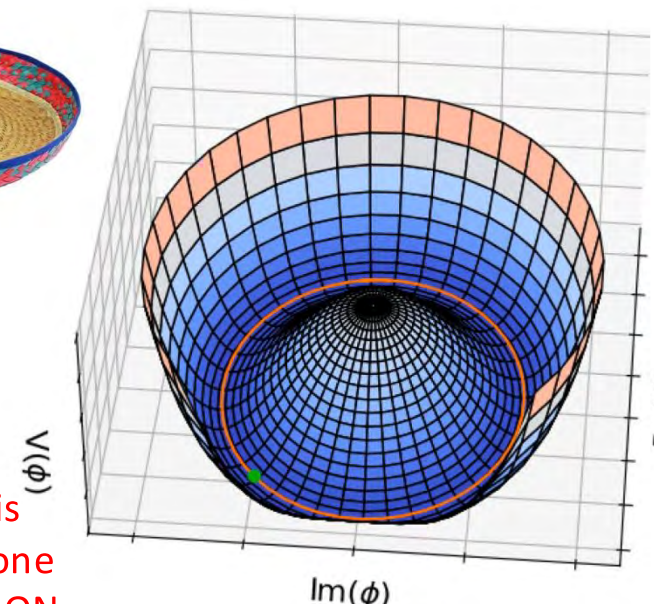
PECCEI QUINN MECHANISM AND AXIONS

Peccei,Quinn 1977; Weinberg 1978; Wilczek 1978

- Extension of the SM by a complex scalar field featuring a spontaneously broken global U(1) symmetry (Peccei-Quinn symmetry)
- Pseudo-Goldstone boson field a(x) arising from PQ symmetry breaking – axion field – turns theta into dynamical variable $\theta(x) = a(x)/f_A$
- QCD dynamics leads to $< \theta >$ =0 and thus explains tiny neutron EDM

Potential of a Higgs-like field

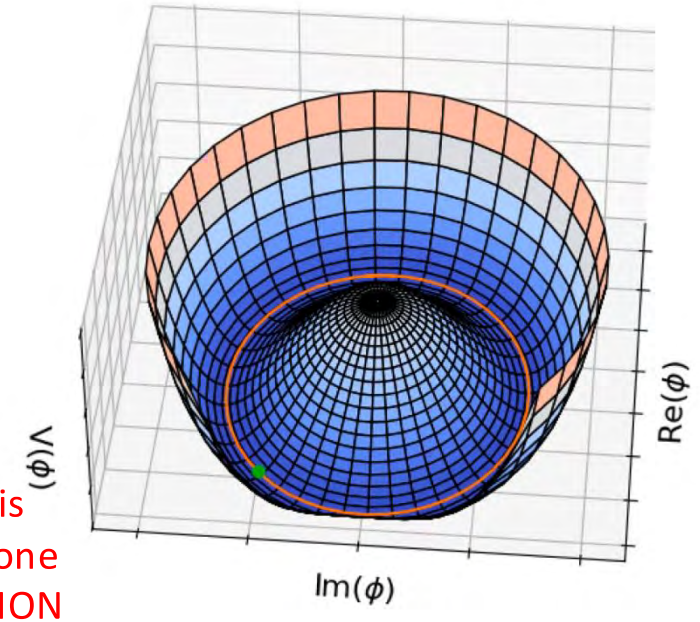




Angular mode is Nambu Goldstone boson: THE AXION

PECCEI QUINN MECHANISM AND AXIONS

- At this stage, the axion is massless
- Rotational symmetry of the potential: value of θ not yet fixed
- The axion can be seen as the massless degree of freedom.

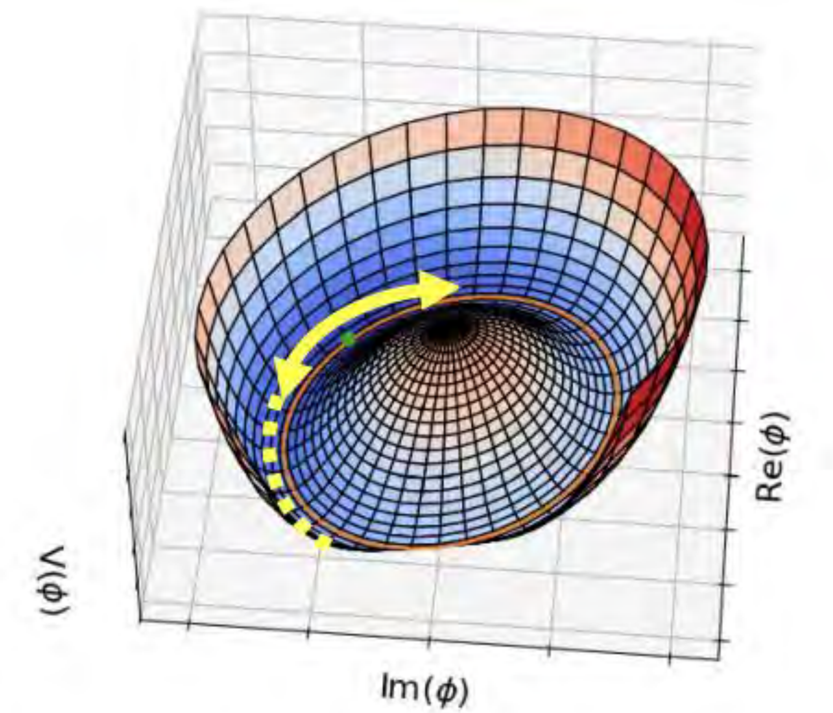


Angular mode is Nambu Goldstone boson: THE AXION

PECCEI QUINN MECHANISM AND AXIONS

- At this stage, the axion is massless
- Rotational symmetry of the potential: value of θ not yet fixed
- The axion can be seen as the massless degree of freedom.
- Instanton effects: "tilting" of the Mexican hat potential of ϕ

- CP conserving minimum
- The axion field starts rolling from (random) θ_{initial} to minimum of the potential.
- Oscillations around minimum



VACUUM REALIGNMENT

AXION (with a small mass) SOLVES STRONG CP

Axion Searches

$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a\,\partial^\mu a - \frac{1}{2}m_a^2 a^2 + C_{a\gamma}\frac{\alpha}{8\pi}\frac{a}{f_a}\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Phenomenological properties of the axion are mainly determined by the scale f_a and closely related to those of the neutral pion.
- Axion mass

$$m_{\rm a} = \frac{\sqrt{z}}{1+z}\,\frac{f_\pi m_\pi}{f_{\rm a}} = 6\,{\rm eV}\left(\frac{10^{\,6}\,{\rm GeV}}{f_{\rm a}}\right)$$

- f_a was initially thought to be of order f_{EW} (250 GeV), but ruled out quickly, now expected to be much larger (up to $f_{Planck} = 10^{19}$ GeV)
- Generic coupling of axions to photons (most important for experiments)
- Suppressed by axion decay constant and thus proportional to axion mass m_a

$$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a}C_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi}\frac{m_a}{m_\pi}\frac{1+z}{\sqrt{z}}\,C_{a\gamma}$$

Note: Wilson Coefficients for vary for different models

$$C_{a\gamma} = \frac{E_Q}{N_Q} - \frac{2}{3}\frac{4+z}{1+z}$$

Kaplan 1985;Srednicki 1985

$z \equiv m_u/m_d \approx 1/2$

Adapted from A. Ringwald

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi}\frac{m_a}{m_\pi}\frac{1+z}{\sqrt{z}}\left(\frac{E_Q}{N_Q} - \frac{2}{3}\frac{4+z}{1+z}\right)$$

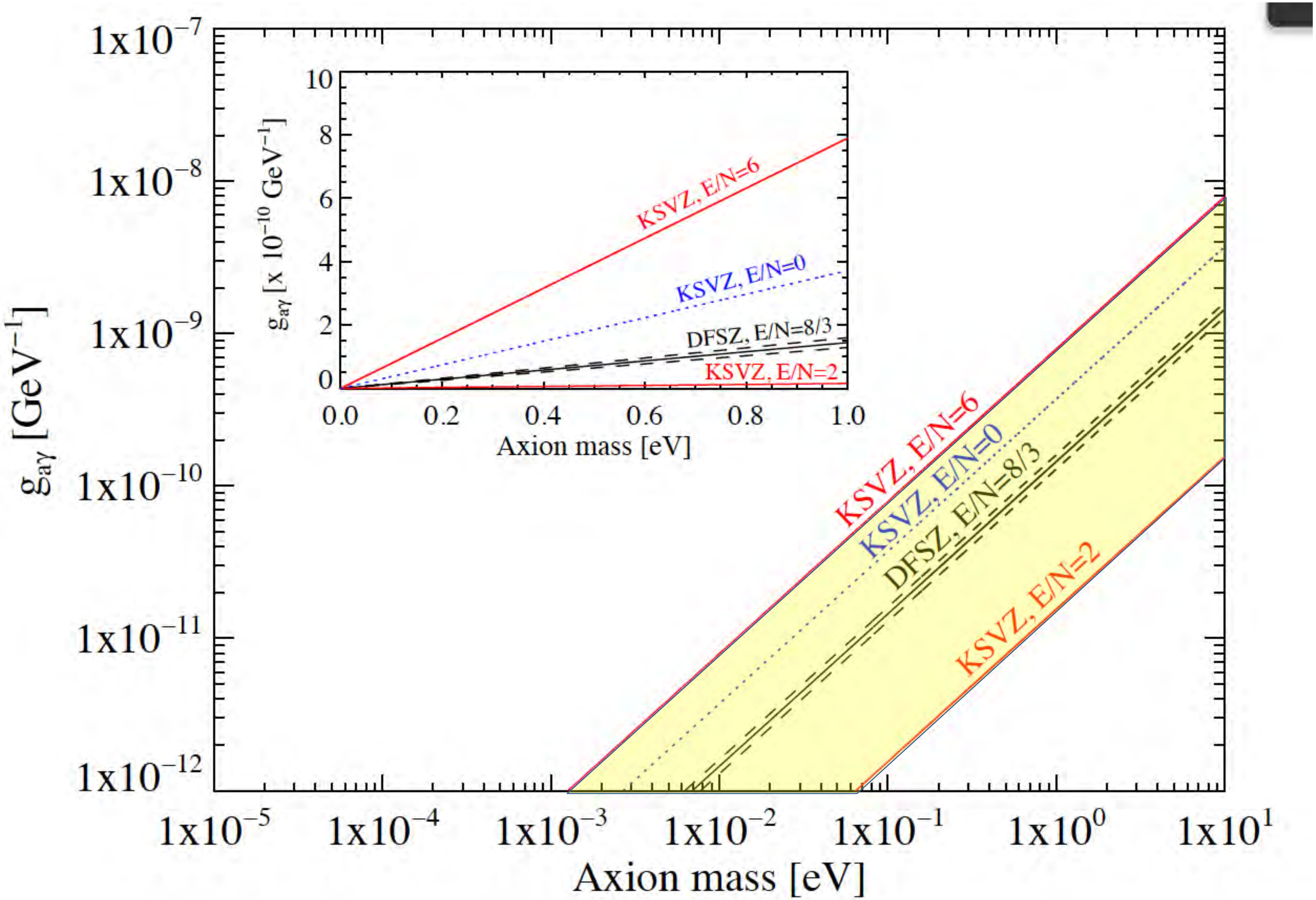
- Varying number of PQ-charged colored fermions and their electric charges results in “yellow band” of predictions for photon coupling
- Standard QCD Axion models:
  - **KSVZ (Kim-Shifman-Vainshtein-Zakharov)**
    - SM fermions don’t carry effective PQ charge
    - Generic axion-photon interaction, no interaction with SM fermions on tree-level

Kim 1979 PRL 43 103
Shifman,Vainshtein,Zakharov 1980 Nucl. Phys.B 166 493

  - **DFSZ (Dine-Fischler-Srednicki-Zhitnitsky)**
    - No exotic heavy quark needed
    - (At least) 2 supplementary Higgs doublets introduced, such that both Higgs doublets and light quarks carry non-zero PQ-charges

Adapted from A. Ringwald

Zhitnitskiy, 1980 Sov. J. Nucl. Phys. 31 260
Dine, Fischler, Srednicki 1981 Phys. Lett. B 104 199



$1x10^{-7}$
$1x10^{-8}$
$1x10^{-9}$
$1x10^{-10}$
$1x10^{-11}$
$1x10^{-12}$
$g_{a\gamma}$ [GeV^{-1}]
$1x10^{-5}$
$1x10^{-4}$
$1x10^{-3}$
$1x10^{-2}$
$1x10^{-1}$
$1x10^{0}$
$1x10^{1}$
Axion mass [eV]
KSVZ, E/N=6
KSVZ, E/N=0
DFSZ, E/N=8/3
KSVZ, E/N=2
$g_{a\gamma}$ [x 10^{-10} GeV^{-1}]
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
Axion mass [eV]

Axion Searches

Axion in a Nutshell

- **Strong CP problem**

  CP violation expected in QCD, but not observed experimentally (θ, nEDM)

- **Peccei-Quinn solution**

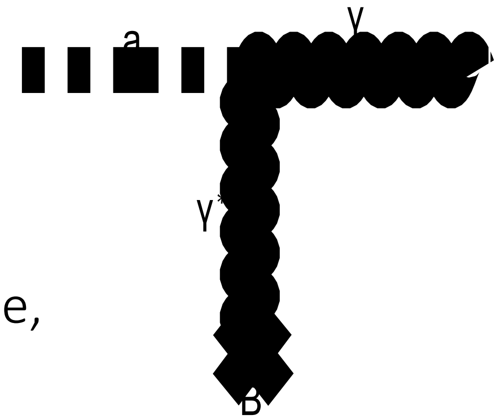
  New global U(1) symmetry, θ turn into a dynamical variable, relaxes to zero

- **Axion**

  Pseudo Goldstone-Boson of spontaneous symmetry breaking of PQ at yet unknown scale f_a

- **Properties of this potential DM candidate**
  - Extremely weakly-coupled fundamental pseudo-scalar
  - Generic coupling to two photons
  - Mass unknown $m_a \mu\, g_{a\gamma}$,
  - Astrophysics: $g_{a\gamma} < 10^{-10}$ GeV^{-1}

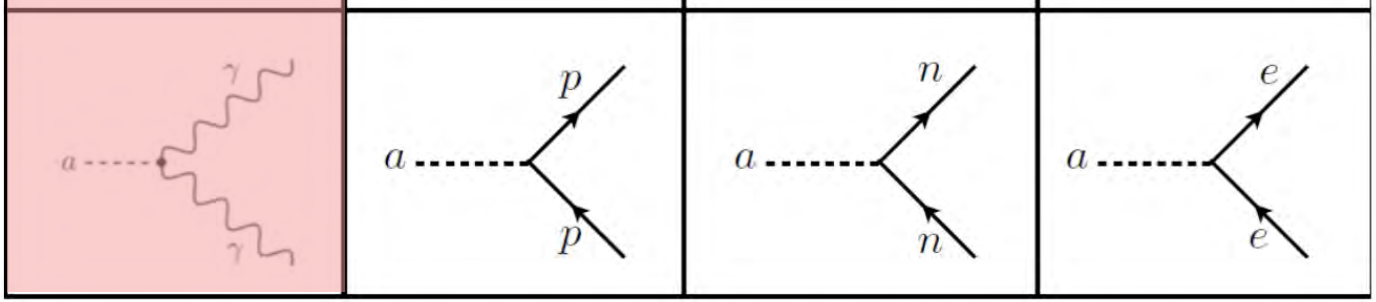
  → **Dark matter candidate & solves strong CP**



Coupling of axions to photons exploited by many experiments

- Relatively “simple” and generic for all axion models
- Model-dependencies exist however

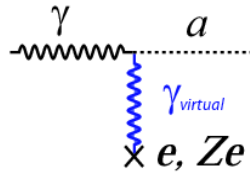
2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{4}$ +	$C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +

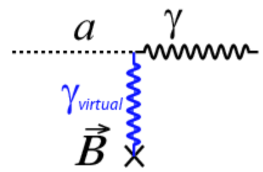


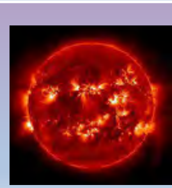
$$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a} \qquad g_{ap} = C_{ap}\frac{m_p}{f_a} \qquad g_{ap} = C_{an}\frac{m_n}{f_a} \qquad g_{ap} = C_{ae}\frac{m_e}{f_a}$$

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Axion Searches / Axion Detection





Source	Experiments	Model & cosmology dependency
Relic axions 	Haloscopes	High (assume axions are all of the DM)
Lab axions 	Light-Shining-Through-Wall Experiments	Very low
Solar axions 	Helioscopes	Low

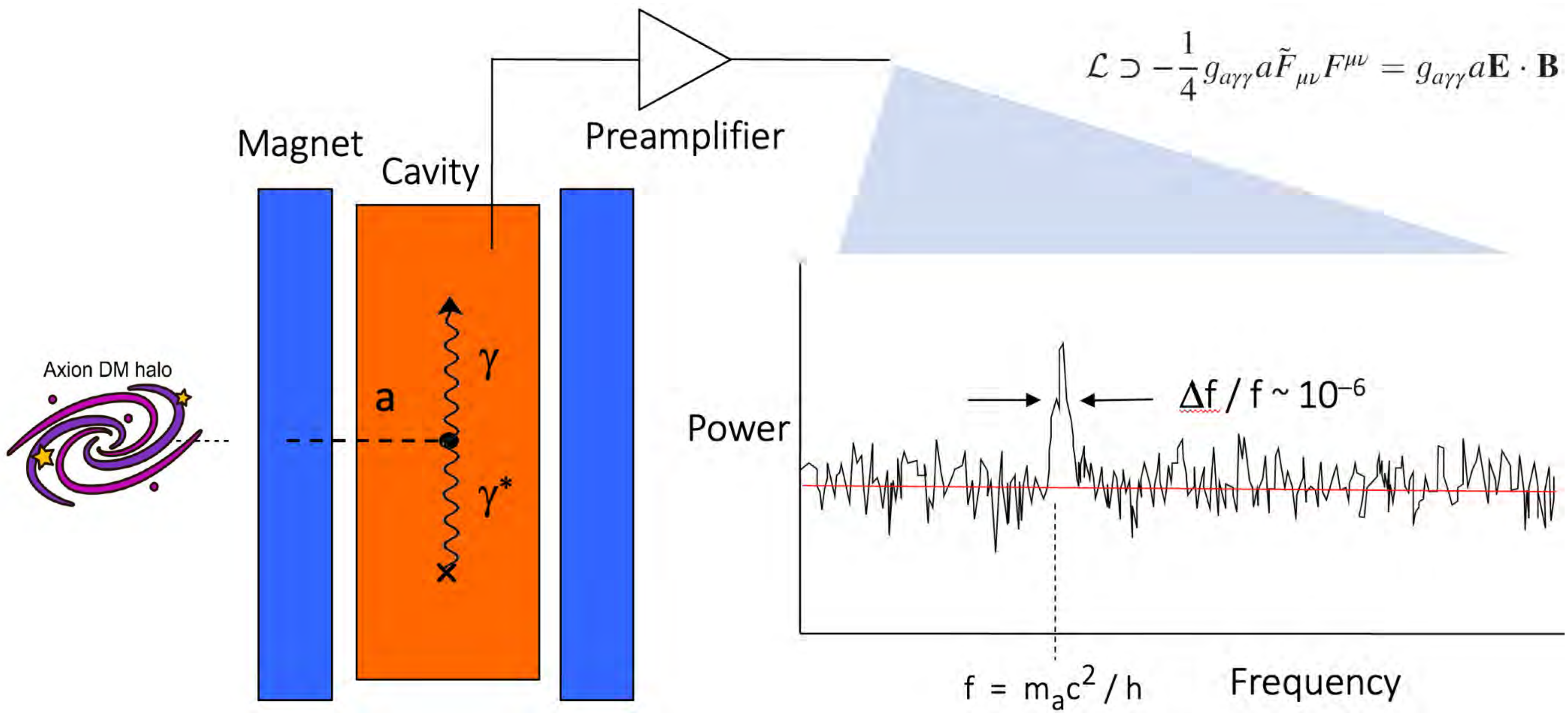
Large complementarity between different experimental approaches!
Some astrophysical hints favor regions outside typical haloscope range

EXPERIMENTS RELYING ON AXIONS BEING DARK MATTER

- HALOSCOPES: Laboratory searches looking for galactic axions

P. Sikivie 1983 PRL 51 1415

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



EXPERIMENTS RELYING ON AXIONS BEING DARK MATTER

- HALOSCOPES: Laboratory searches looking for galactic axions P. Sikivie 1983 PRL 51 1415

Concept:

DM axion converts into photon in microwave cavity placed inside magnetic field

- If axion mass matches resonance frequency of cavity

$$m_a = 2\pi\nu_{\text{res}} \sim 4\,\mu\text{eV}\left(\frac{\nu_{\text{res}}}{\text{GHz}}\right)$$

then power output is $P_{\text{out}} \sim g_{a\gamma}^2\,\rho_{\text{a}}\,B_0^2\,V\,Q \qquad (Q \sim 10^5)$

- Need to tune resonance frequency to scan axion mass range
- Figure of merit: $FOM \propto \frac{B^4V^2C^2Q}{T_{SYS}}$

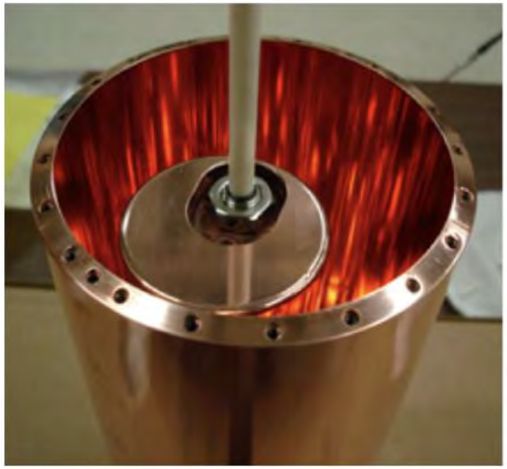
- HALOSCOPES: Laboratory searches looking for galactic axions

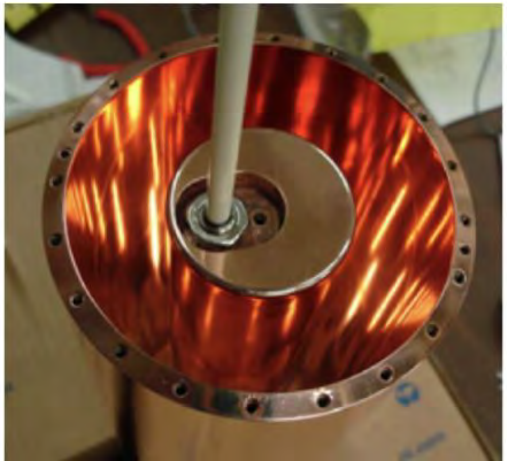
Microwave cavities

Currently active :
ADMX, HAYSTAC,
CAPP, GrAHal,
ORGAN, **QUAX**,
CAST-CAPP, RADES

ADMX

HAYSTAC



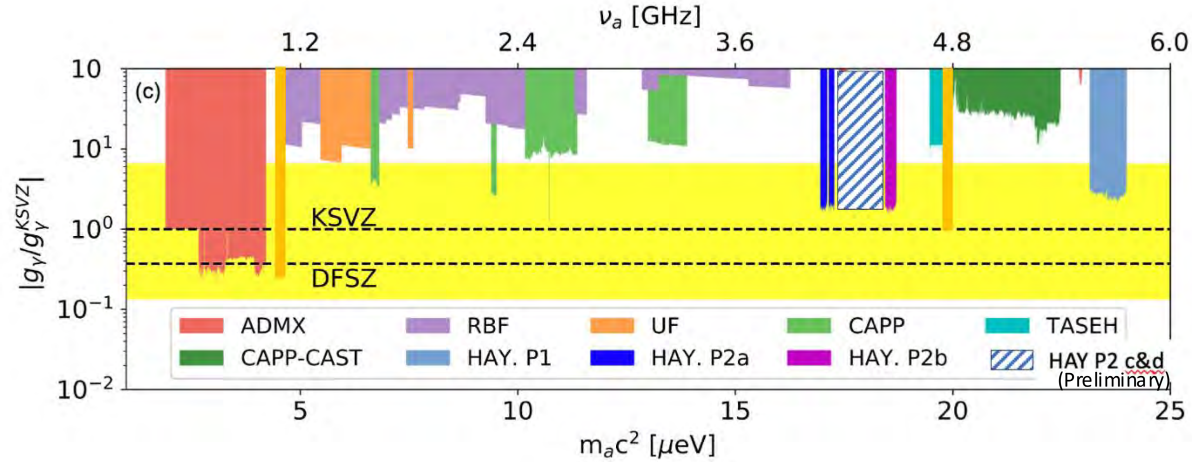


▸ HALOSCOPES: Laboratory searches looking for galactic axions

Microwave cavities

Currently active :
ADMX, HAYSTAC,
CAPP, GrAHal,
ORGAN, **QUAX**,
CAST-CAPP, RADES

Vacuum Realignment
$m_a \backsim O(10\ \mu eV)$
$\nu \backsim O(GHz)$



For more details: IDM 2024 talks by K. van Bibber (#174), H. Jackson (#169) & G. Carugno (#267)

- **HALOSCOPES**: Laboratory searches looking for galactic axions

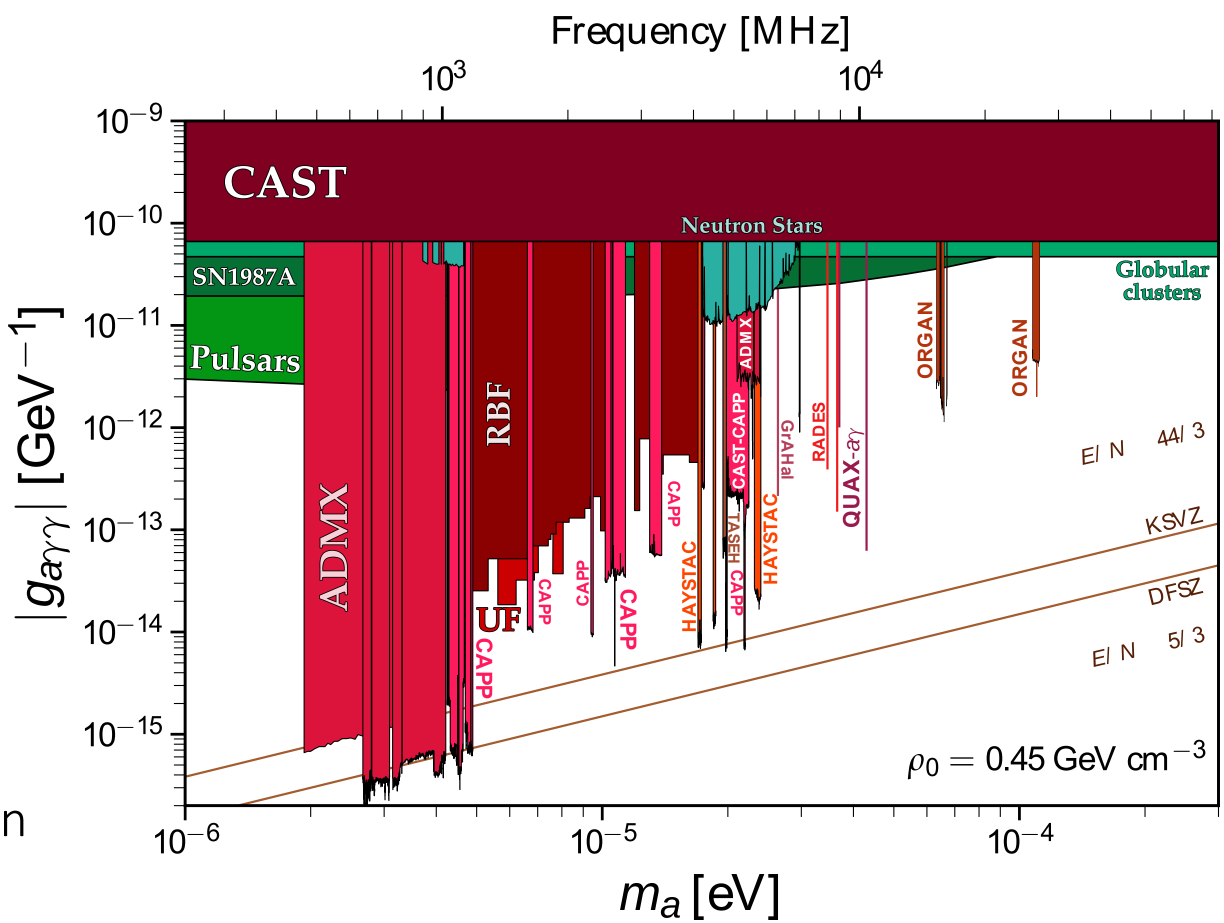
Microwave cavities

Currently active :

ADMX, HAYSTAC,
CAPP, GrAHal,
ORGAN, **QUAX**,
CAST-CAPP, RADES

Vacuum Realignment
$m_a \backsim O(10\ \mu eV)$
$\nu \backsim O(GHz)$

Future upgrades in preparation



Adapted from https://cajohare.github.io/AxionLimits/

Axion Searches

High-Mass Haloscopes

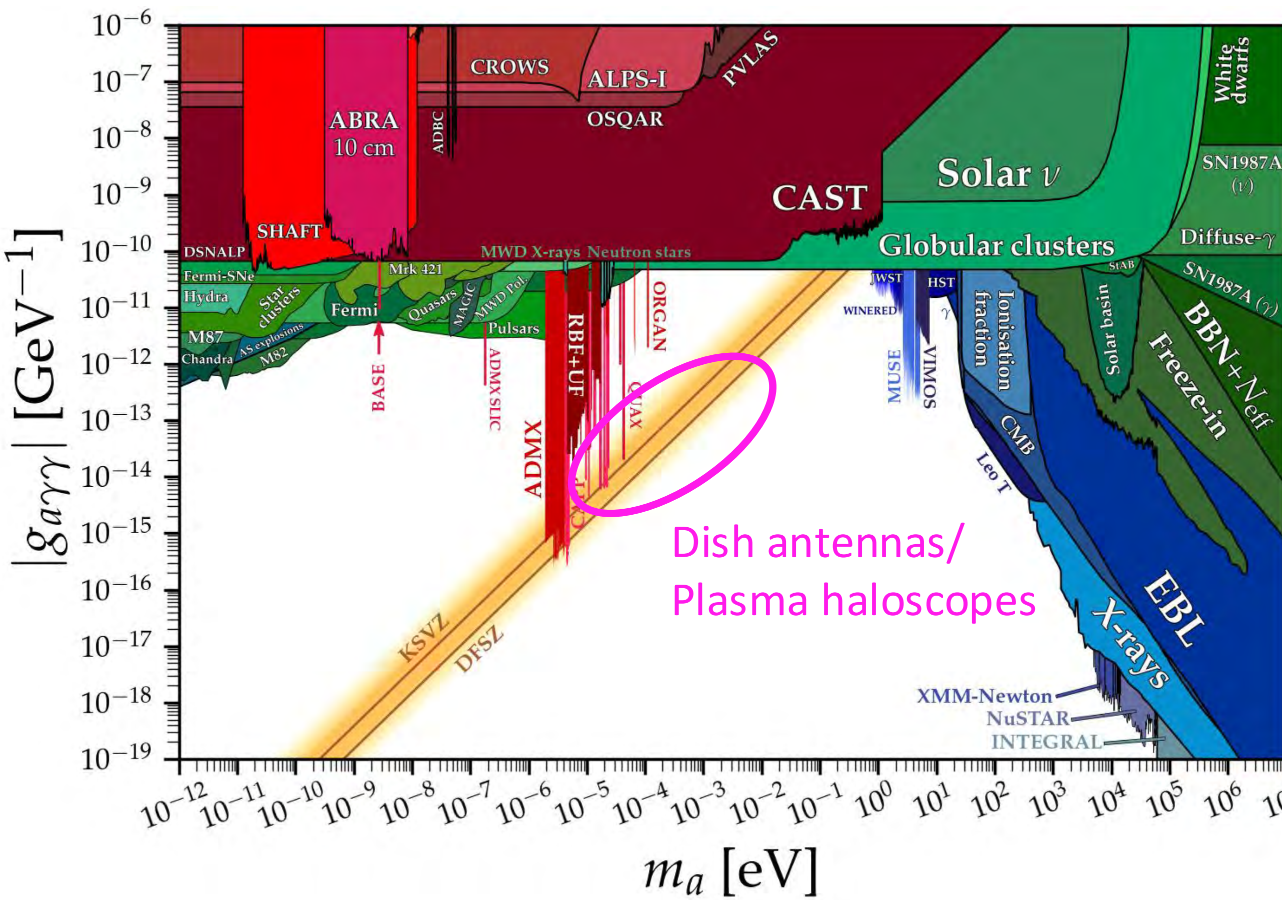
- HALOSCOPES: Laboratory searches looking for galactic axions

How to go to higher masses to search for **post-inflation** axions?

Higher frequencies, (i.e. higher m_a) requires smaller cavities and scans get slower!

Dish Antennas & Plasma Haloscopes!

$m_a \backsim O(100\ \mu eV)$
$\nu \backsim O(10\text{-}100\ GHz)$

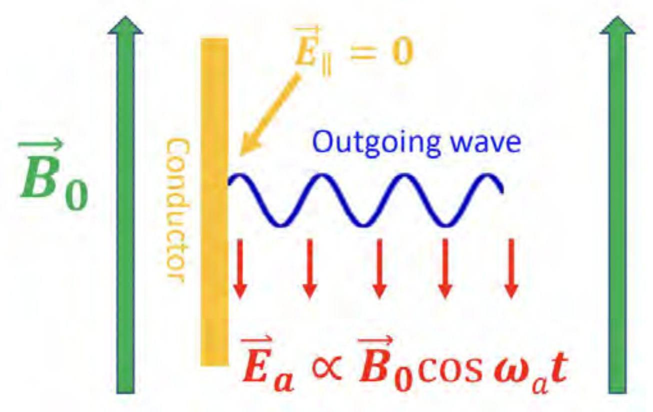


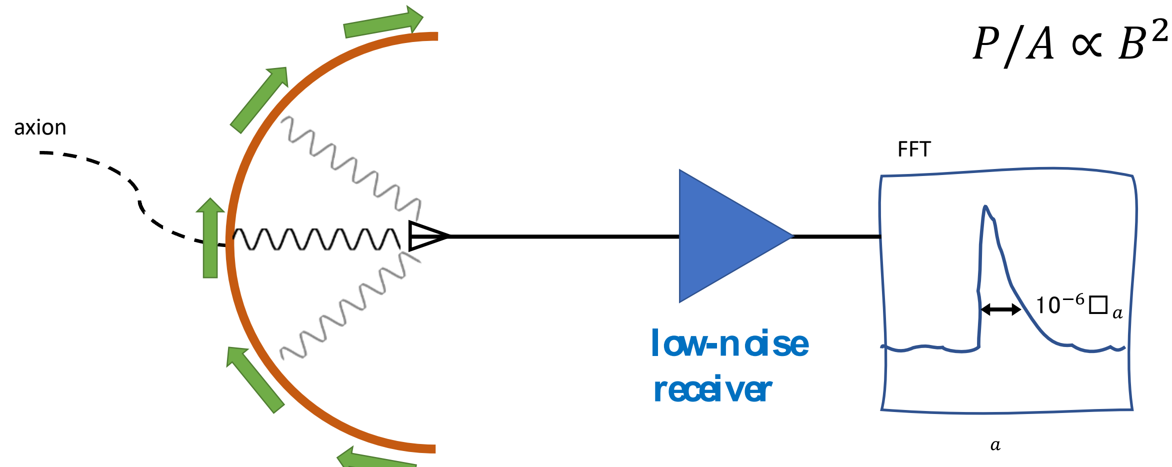
Adapted from https://cajohare.github.io/AxionLimits/

Horns *et al* JCAP04(2013)016

- HALOSCOPES: DISH ANTENNAS

$P/A \propto B^2$





Concept: Axion induced radiation from a magnetized metal slab

- DM axions interact with a static magnetic field
  → producing oscillating parallel E-field.
  Conducting surface in this field emits plane wave ⊥ surface with $\upsilon \propto m_a$
- Radiated power is low, however, no tuning required!

For more details see IDM 2024 talks by Stefan Knirck (#231)

▸ HALOSCOPES: DISH ANTENNAS

Horns *et al* JCAP04(2013)016
F. Bajjali et al., JCAP 08 (2023), 077

$P/A \propto B^2$

BRASS@ U. Hamburg

- Consists of plane permanently magnetized conversion panel
  $$B = 0.8\,\mathrm{T}$$
  $$A = 4.7\,\mathrm{m}^2$$
- Spherical reflector

Concept: Axion induced radiation from a magnetized metal slab

- DM axions interact with a static magnetic field
  → producing oscillating parallel E-field.
  Conducting surface in this field emits plane wave ⊥ surface with $\upsilon \propto m_a$
- Radiated power is low, however, no tuning required!
- BRASS@ U. Hamburg

▸ HALOSCOPES: DISH ANTENNAS

Horns *et al* JCAP04(2013)016
Liu et al., PRL 128 (2022) 131801

$P/A \propto B^2$

BREAD@ Fermilab

- Cylindric parabolic conversion panel allows use of solenoidal magnetic field

$$B \sim 10\,\mathrm{T}$$

$$\mathcal{A} \sim 10\,\mathrm{m}^2$$

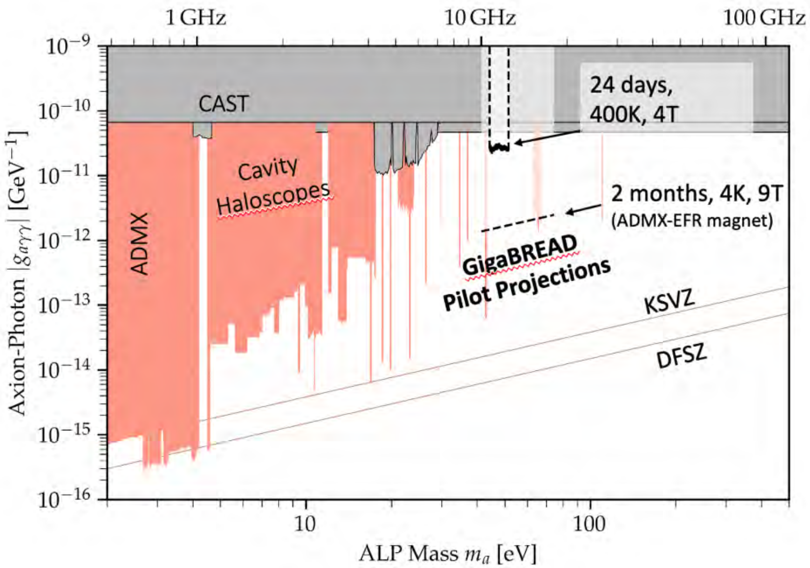
Concept: Axion induced radiation from a magnetized metal slab

- DM axions interact with a static magnetic field
  → producing oscillating parallel E-field.
  Conducting surface in this field emits plane wave ⊥ surface with $\upsilon \propto m_a$
- Radiated power is low, however, no tuning required!
- BRASS@ U. Hamburg, BREAD@ Fermilab

For more details see IDM 2024 talks by Stefan Knirck (#231)

Horns *et al* JCAP04(2013)016
Liu et al., PRL 128 (2022) 131801

- HALOSCOPES: DISH ANTENNAS



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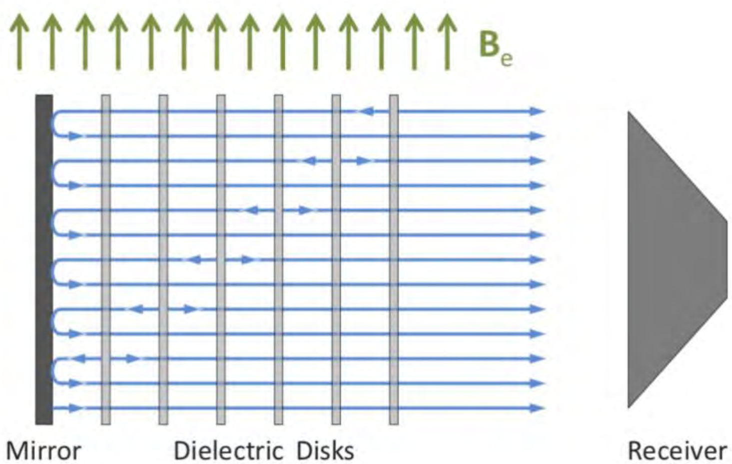
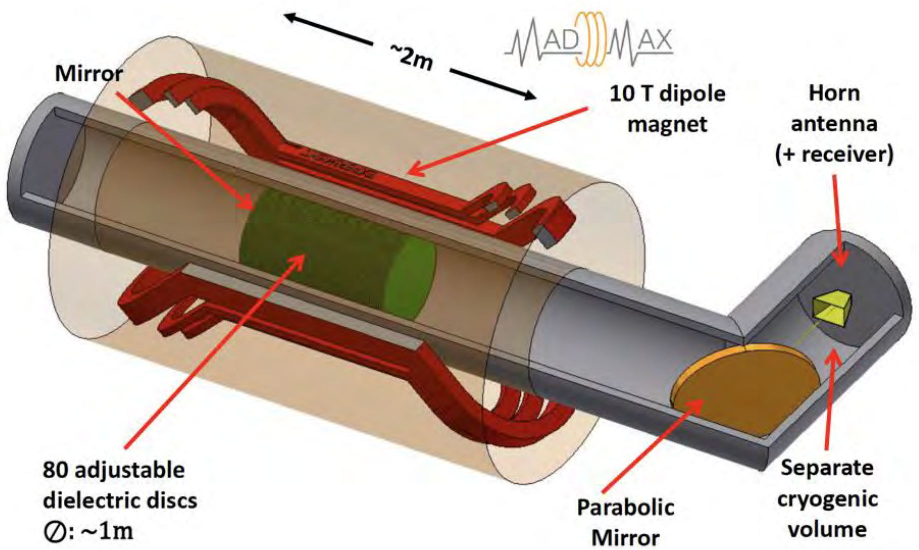
- BRASS@ U. Hamburg, BREAD@ Fermilab

For more details see IDM 2024 talks by Stefan Knirck (#231)

- HALOSCOPES: DISH ANTENNAS

Analysis ongoing for measurements with closed booster prototype in Morpurgo magnet at CERN (expect 3×10^{-11} GeV^{-1})





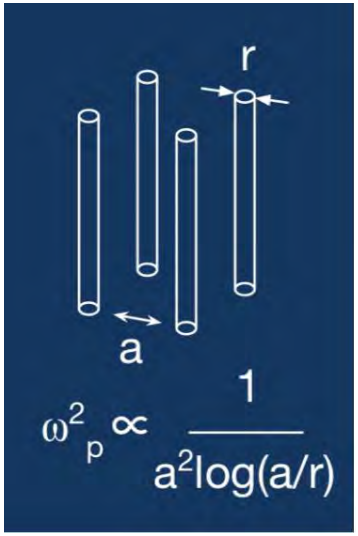
Enhanced Concept: Boosted dish antenna aka open dielectric resonator concept

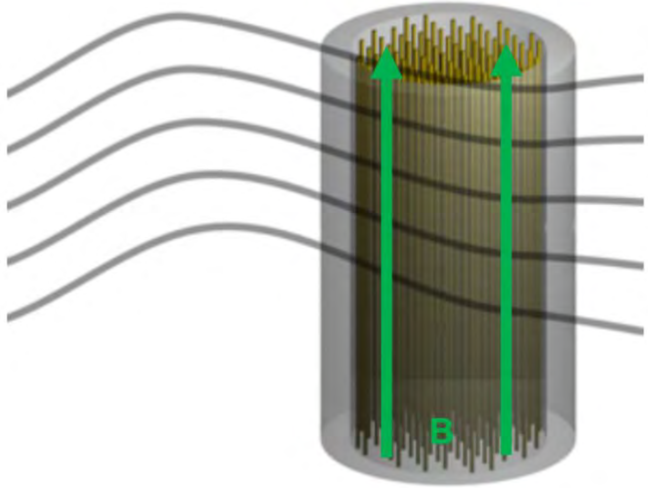
- Stack of dielectric plates as booster inside a magnetic field
- Tuned to the radiofrequencies (m_a around 100 μeV)
- Can enhance measured power by several 10^4, but tradeoff bandwidth/"boost factor"

For more details see IDM 2024 talk by Jacob Egge (#243) on MADMAX

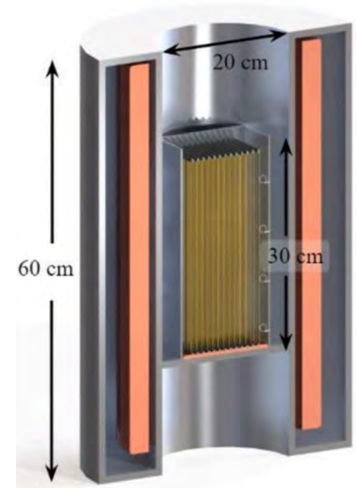
Axion Searches — Plasma Haloscopes

▶ HALOSCOPES: PLASMA HALOSCOPES





ALPHA Pathfinder

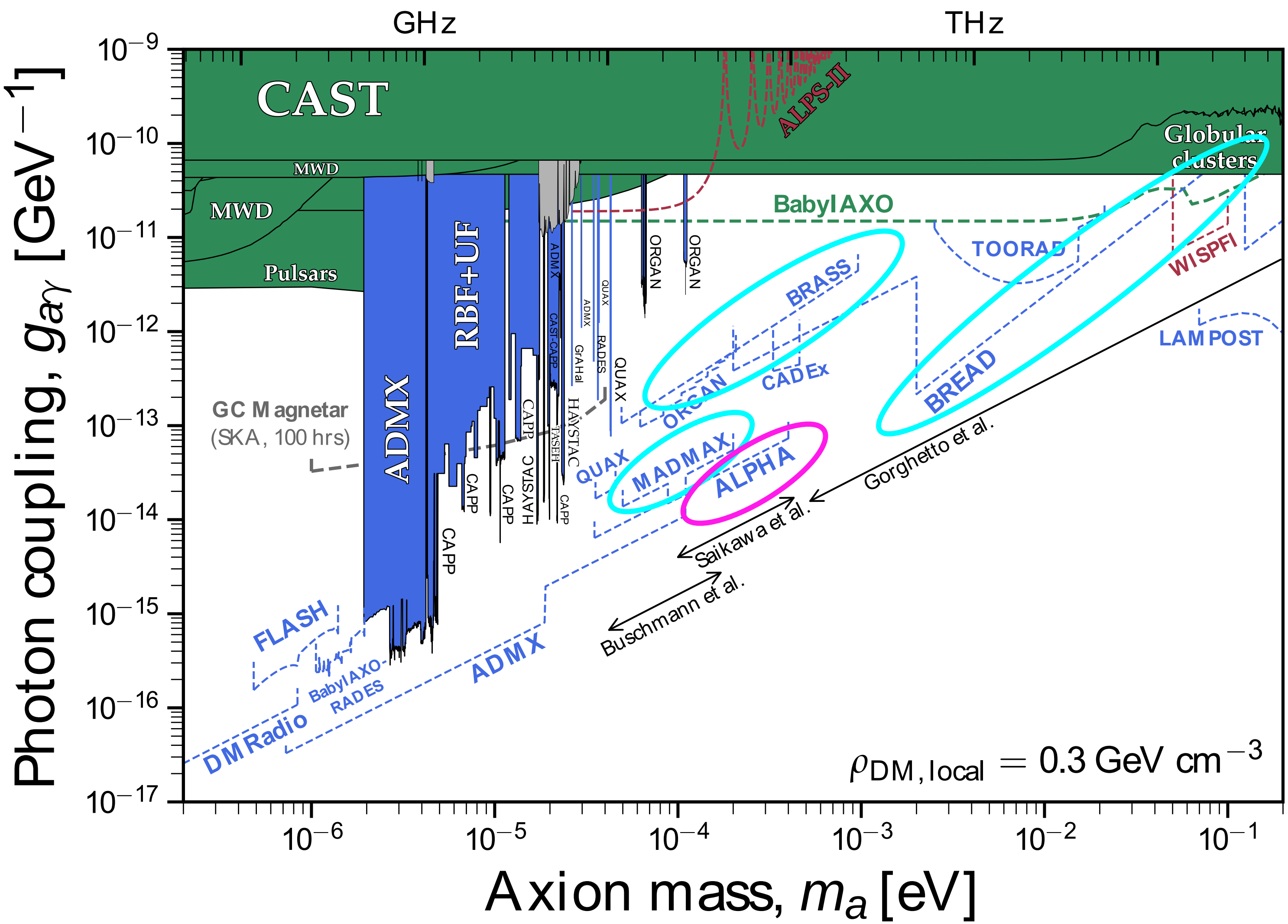


Concept: Oscillating DM axions induce plasmon excitations in magnetized plasma

- Resonant enhancement when plasma frequency matches axion mass:
- Can create plasma with tunable plasma frequency in GHz range using wire metamaterial (wire array with variable interwire spacing)
- Tuning then possible via geometry, limited by losses
- ALPHA@ORNL

For more details see IDM 2024 talk by Andrea Gallo Rosso (#215) on ALPHA

Axion Searches High-Mass Haloscopes



Adapted from https://cajohare.github.io/AxionLimits/

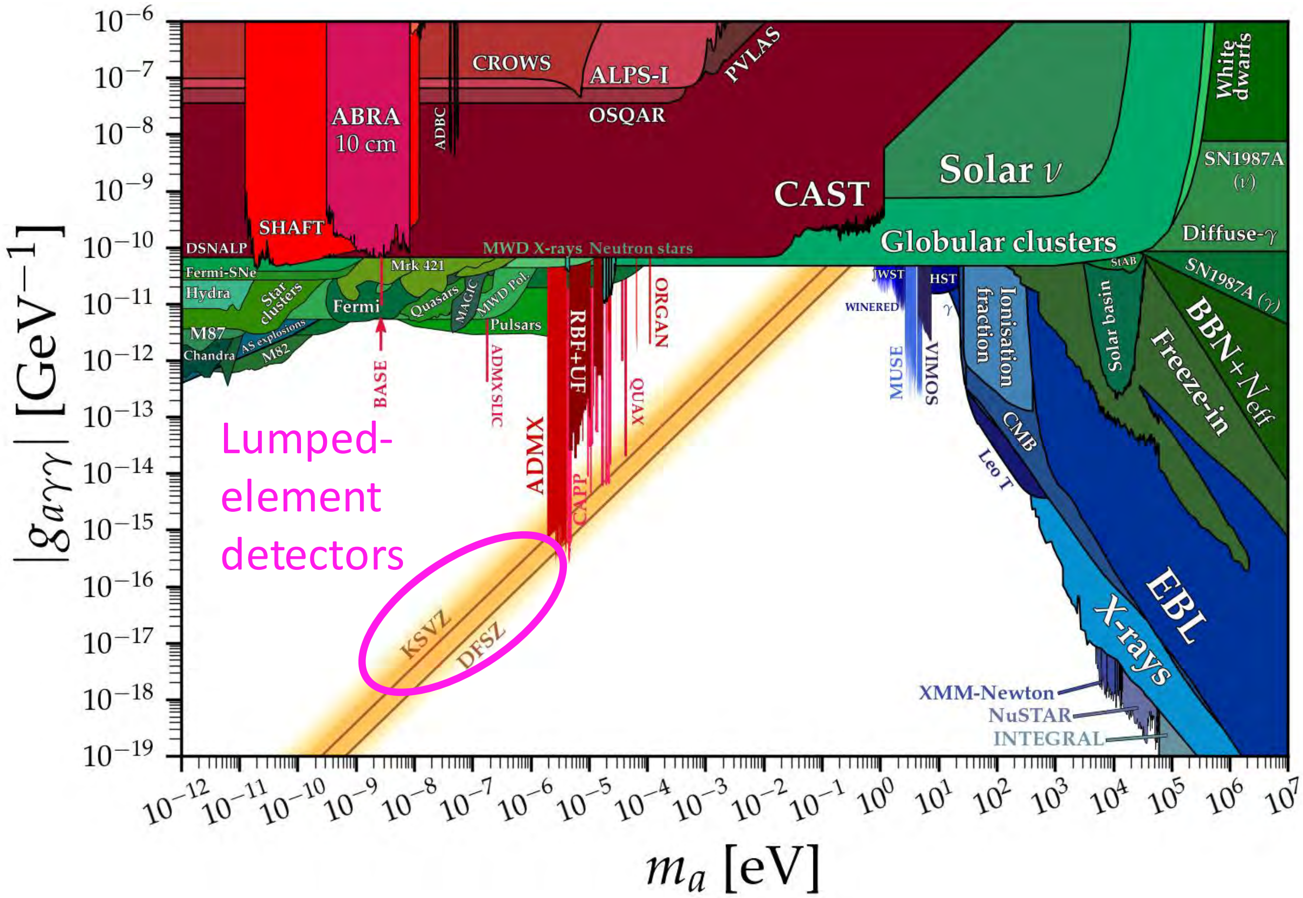
- HALOSCOPES: Laboratory searches looking for galactic axions

How to go to lower masses to search for GUT-scale axions?

Lower frequencies, (i.e. smaller m_a) requires increasingly large cavities

Lumped Element Detectors!

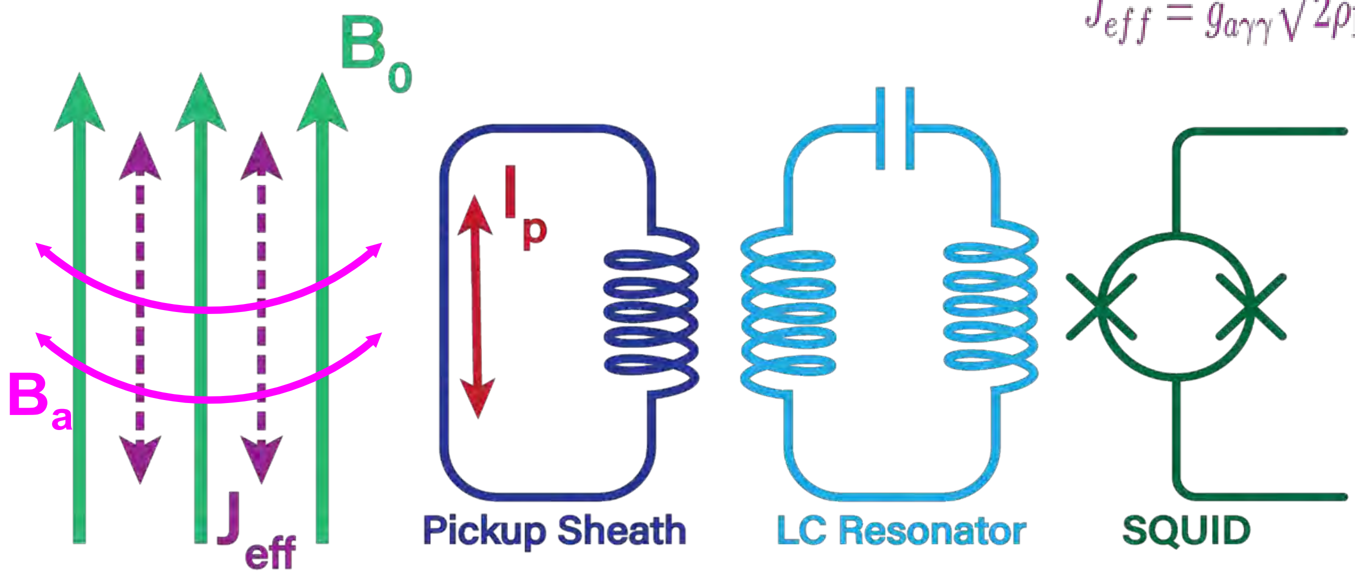
$m_a \backsim O(\text{neV})$
$\nu \backsim O(\text{kHz-GHz})$



Adapted from https://cajohare.github.io/AxionLimits/

- HALOSCOPES: LUMPED-ELEMENT DETECTORS

$$\vec{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t)\vec{\mathrm{B}}_0$$



Concept: Axion generates oscillating effective current J_{eff} parallel to B_0 in toroidal or solenoidal magnet

- J_{eff} in turn generates oscillating magnetic flux B_a (azimuthal)
- Can use pickup structure to read this
- Couple LC resonator inductively and use SQUID readout scheme

For more details see IDM 2024 talk by Alex Droster (#165) on DMRadio

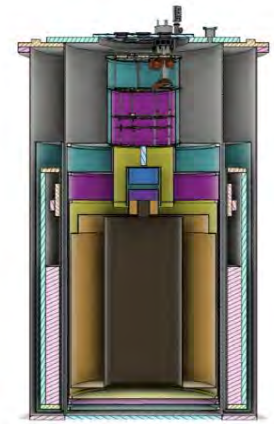
▶ HALOSCOPES: LUMPED-ELEMENT DETECTORS

Pilot experiments
ABRACADABRA
ADMX SLIC
SHAFT

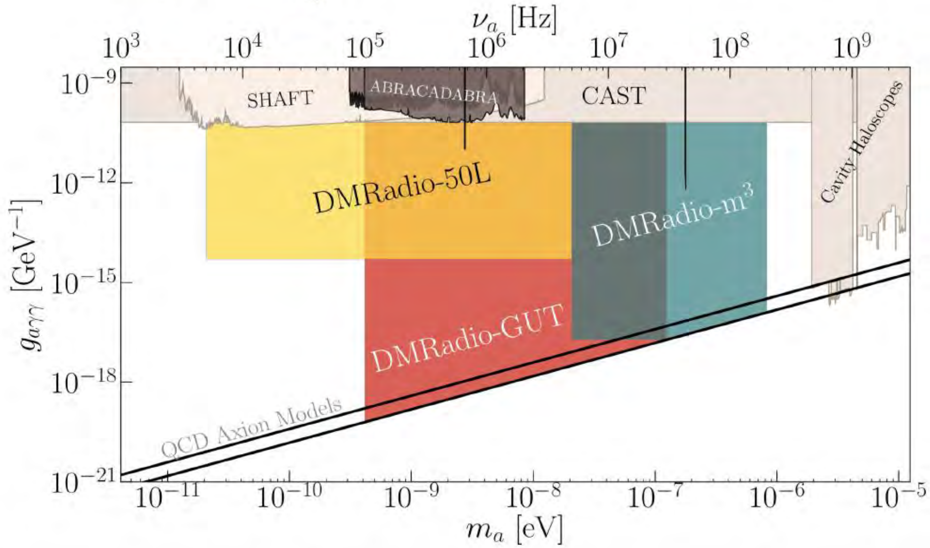
Next Generation
WISPLC
DMRadio
- DMRadio-50L
- DMRadio-m^3
  (improvements in Q, V, B)
- DMRadio-GUT
  (ambitious next-next gen)

DMRadio

50L

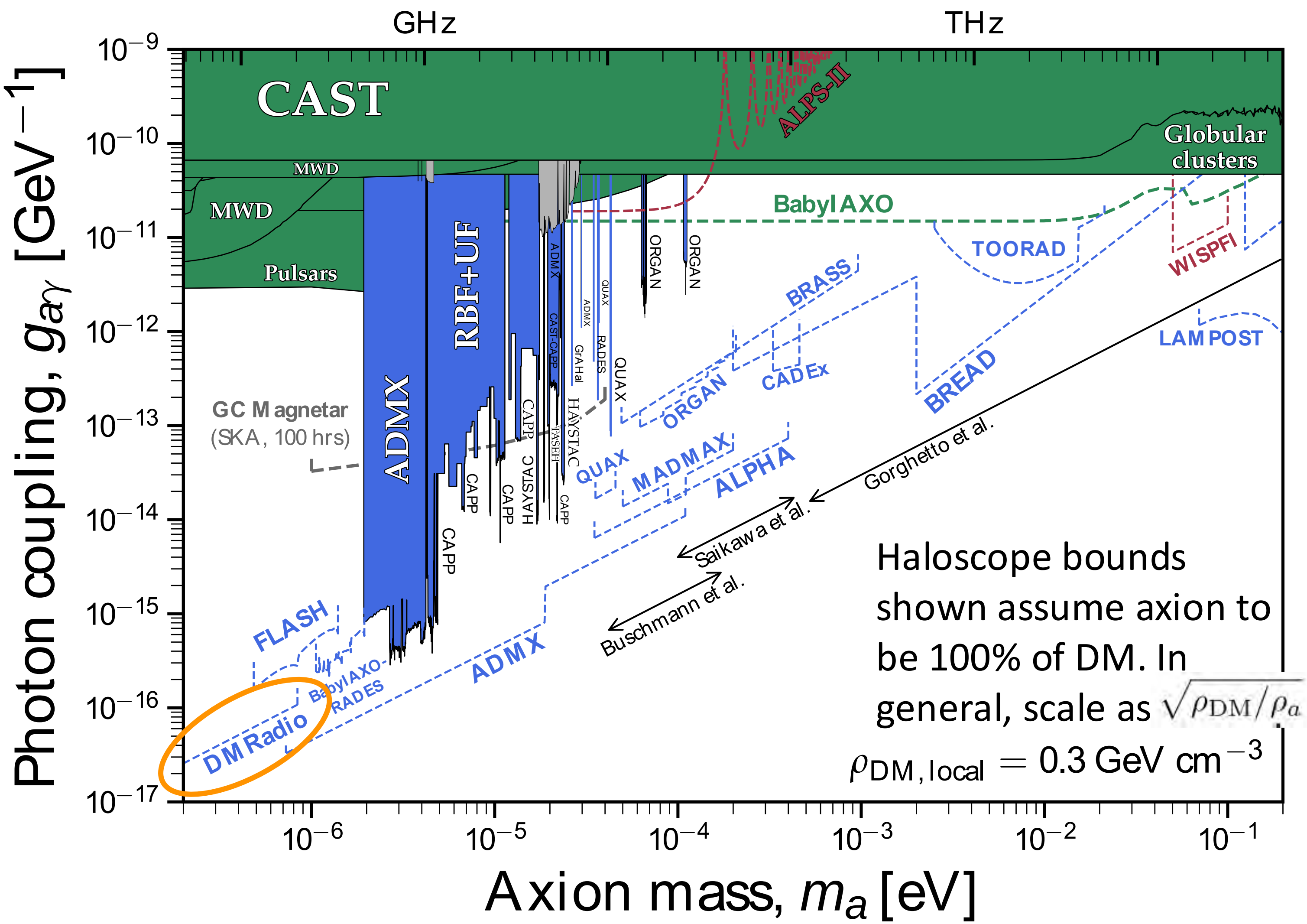


m^3



For more details see IDM 2024 talk by Alex Droster (#165) on DMRadio

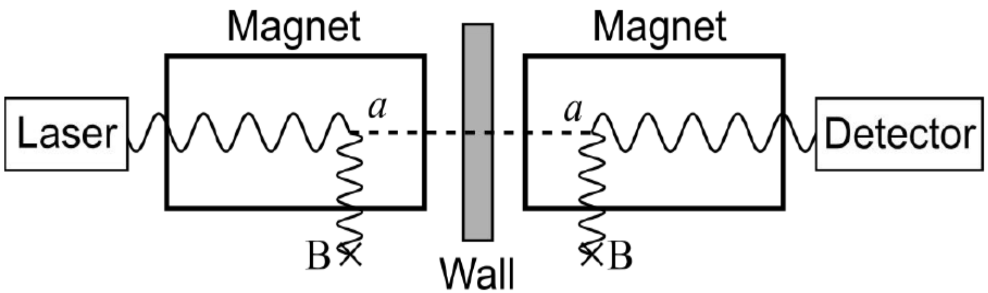
Axion Searches



Adapted from https://cajohare.github.io/AxionLimits/

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER (PART I)

- LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches



ALPS, OSQAR, ALPS-II

Anselm 85;
Van Bibber *et al* 1987 *PRL* **59** 759

Concept: Axions mixing with photons in external electromagnetic field

- Conversion probability for a photon with energy w converts into axion after having traversed a distance L_B in magnetic field of strength B:

$$P(\gamma \leftrightarrow a) \simeq 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

- For very light axions, $m_a \ll (2\pi\omega/L_B)^{1/2} \approx \mathrm{meV}((\omega/\mathrm{eV})(\mathrm{m}/L_B))^{1/2}$:

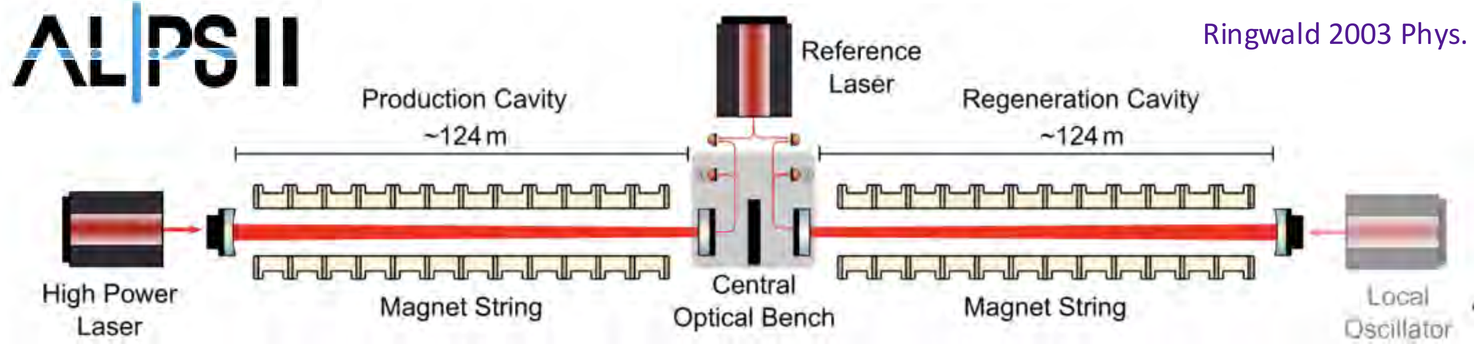
$$P(\gamma \to a \to \gamma) \simeq \frac{1}{16}(g_{a\gamma}BL_B)^4$$

▶ LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches

– ALPS

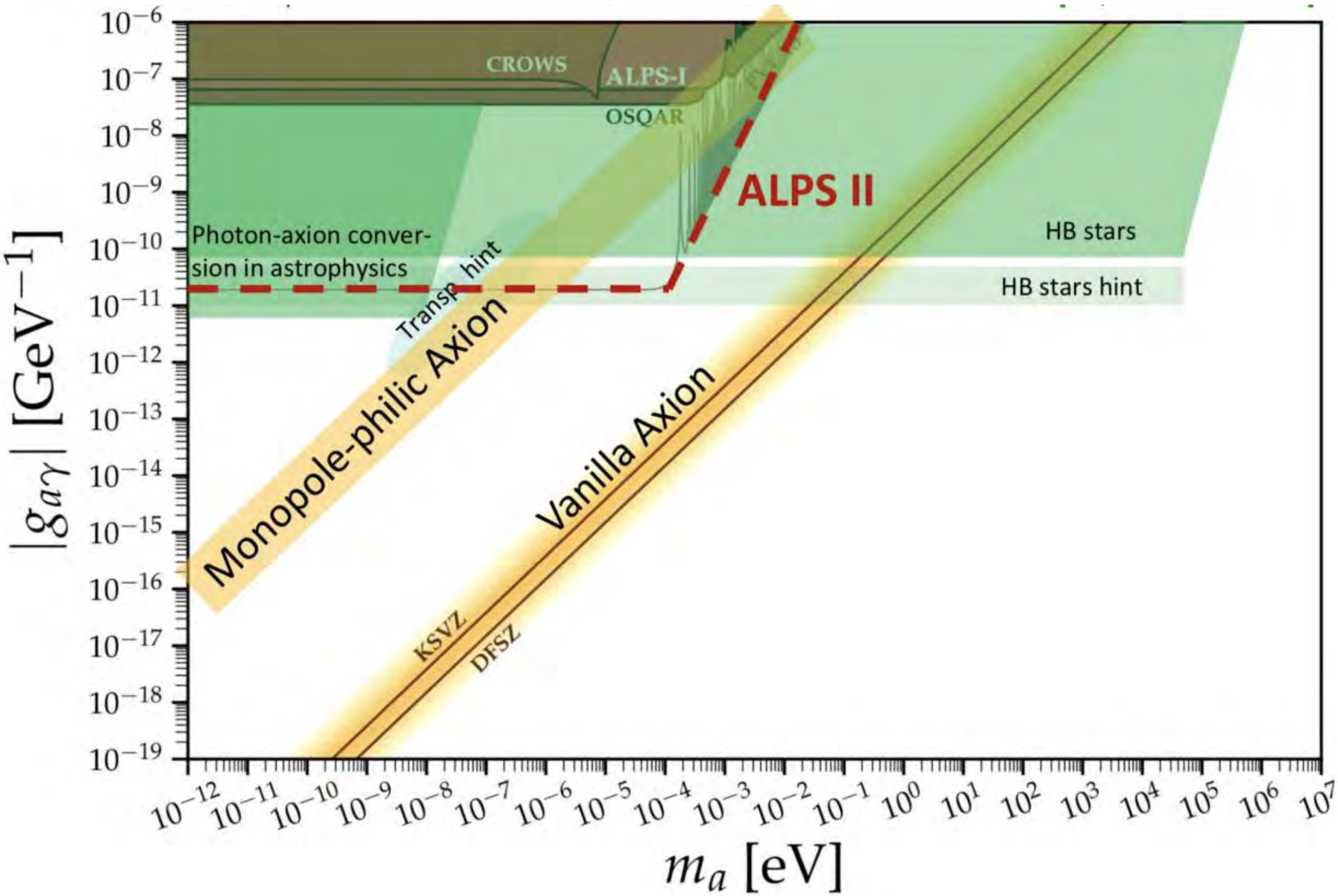
Most basic layout of a LSTW experiment

– ALPS-II
- 12 + 12 straightened HERA magnets
- Optical cavities both at production and regeneration sites
- Sensitivity 3000×ALPS



Ringwald 2003 Phys. Lett. B 569 51

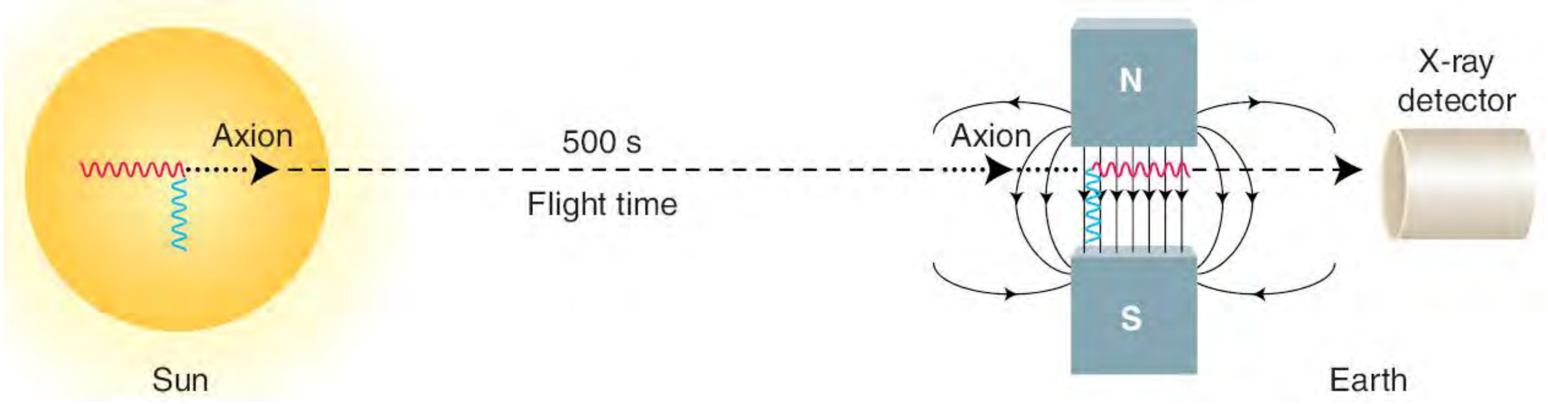
Axion Searches



Adapted from Ringwald et al [arXiv: 2306.08978]

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER (PART II)

- AXION HELIOSCOPES: laboratory axion searches looking for solar axions



SUMICO, CAST, IAXO

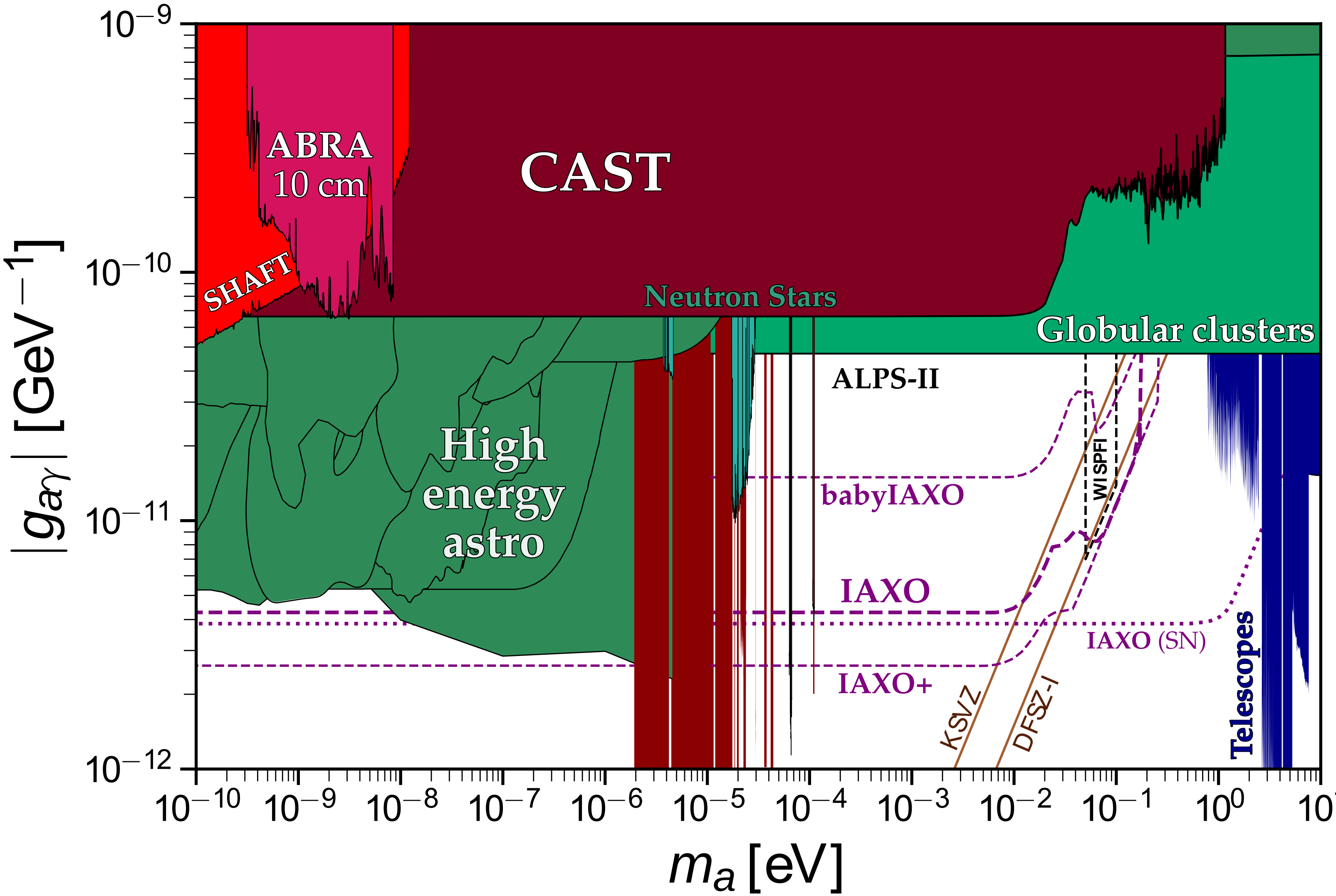
P. Sikivie 1983 PRL 51 1415

van Bibber et al 1989 PRD 39 2089

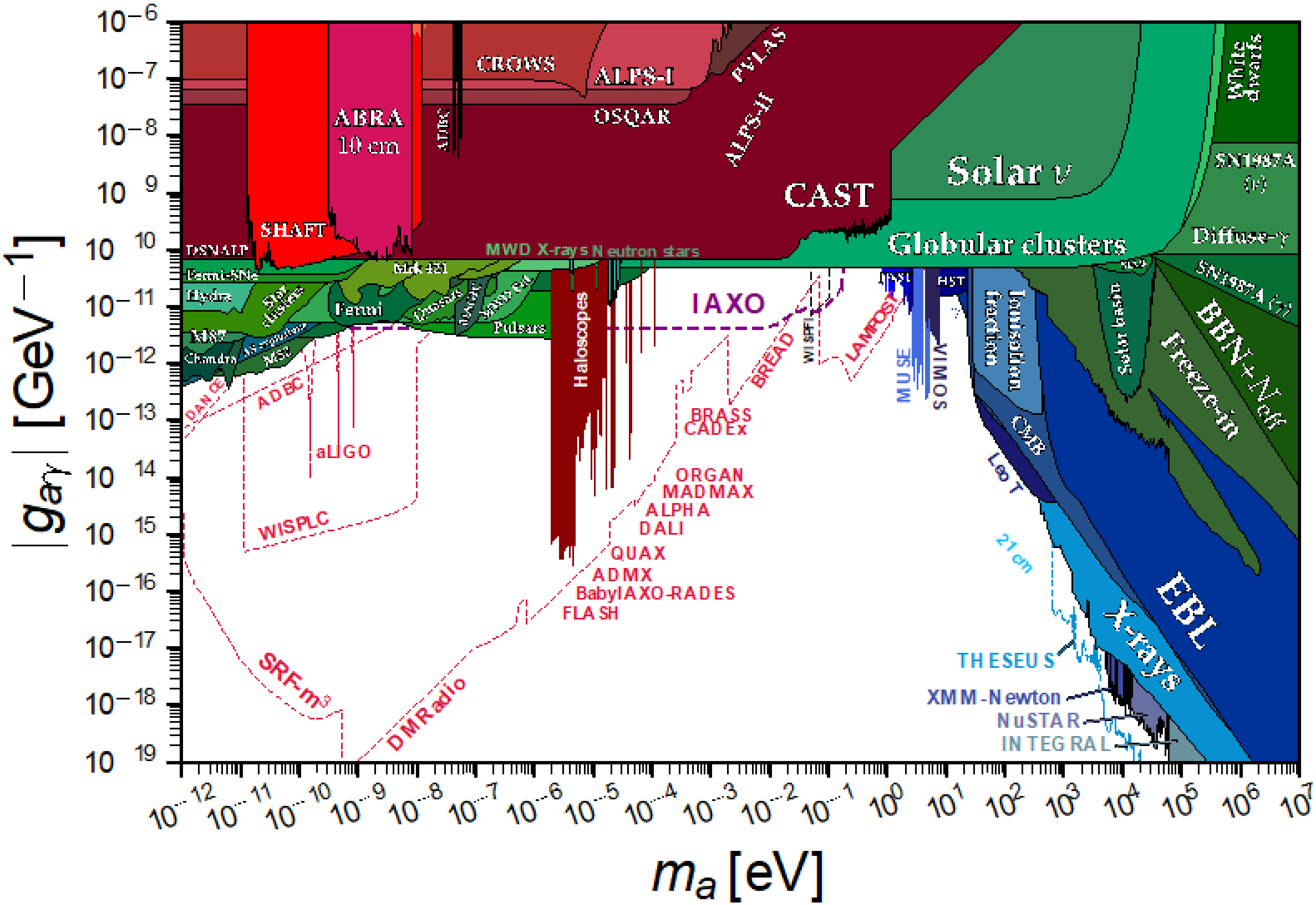
Concept: Axions produced in strong electromagnetic fields of the solar core. and reconversion into x-ray (keV) photons in transverse laboratory B-field

- Use gas to expand axion mass search range
- Helioscope Figure of Merit $\propto B^2L^2A$

Solar Axion Searches



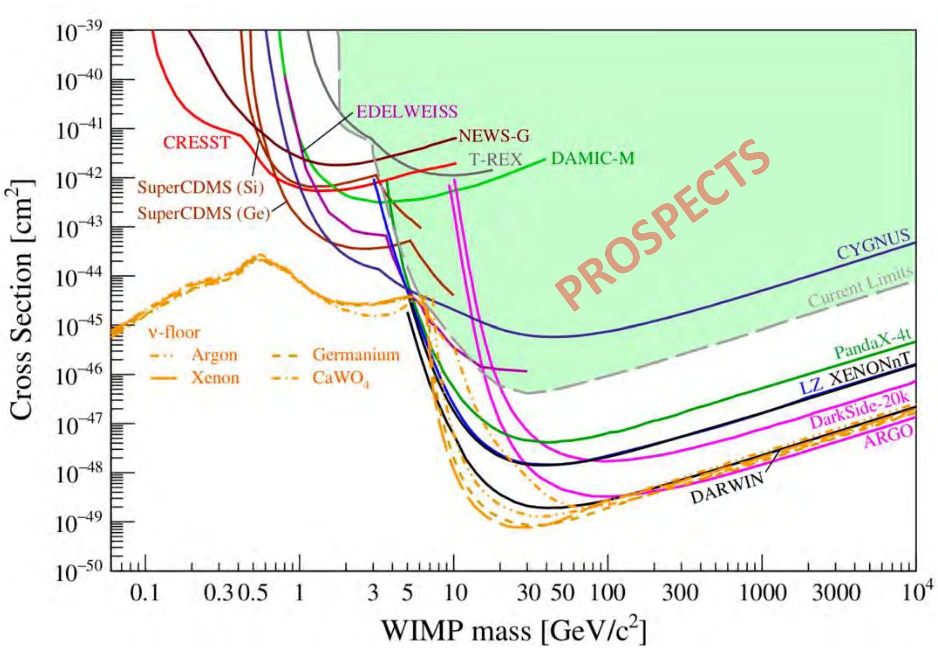
Solar Axion Searches

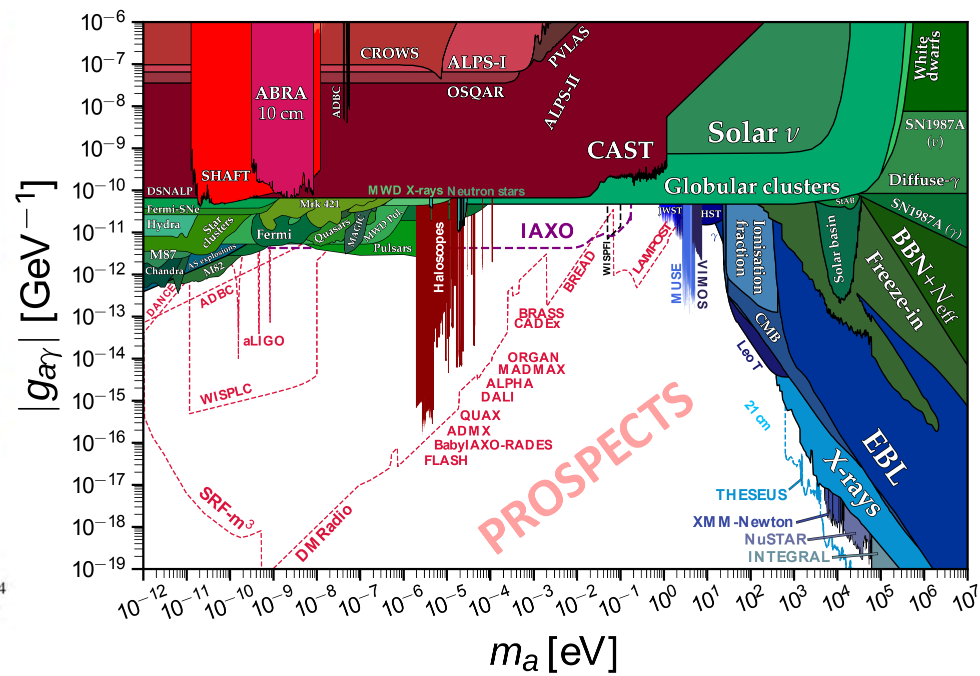


Take-home messages

Conclusions

- WIMPs and axions are leading DM candidates (and DM could be a mixture)
- A vast variety of experiments are looking for dark matter in different ways
- No (confirmed) DM signal yet, but huge progress in sensitivity over last decades
- Discovery could be just around the corner! Sensitivities keep getting better!
- **Help us find the little buggers!**





Thanks! Questions?

Happy to talk more today or email me

(Julia.Vogel@cern.ch)