European Strategy
for Particle Physics

Experimental programmes to address open issues in Dark Matter and Dark Sector Physics

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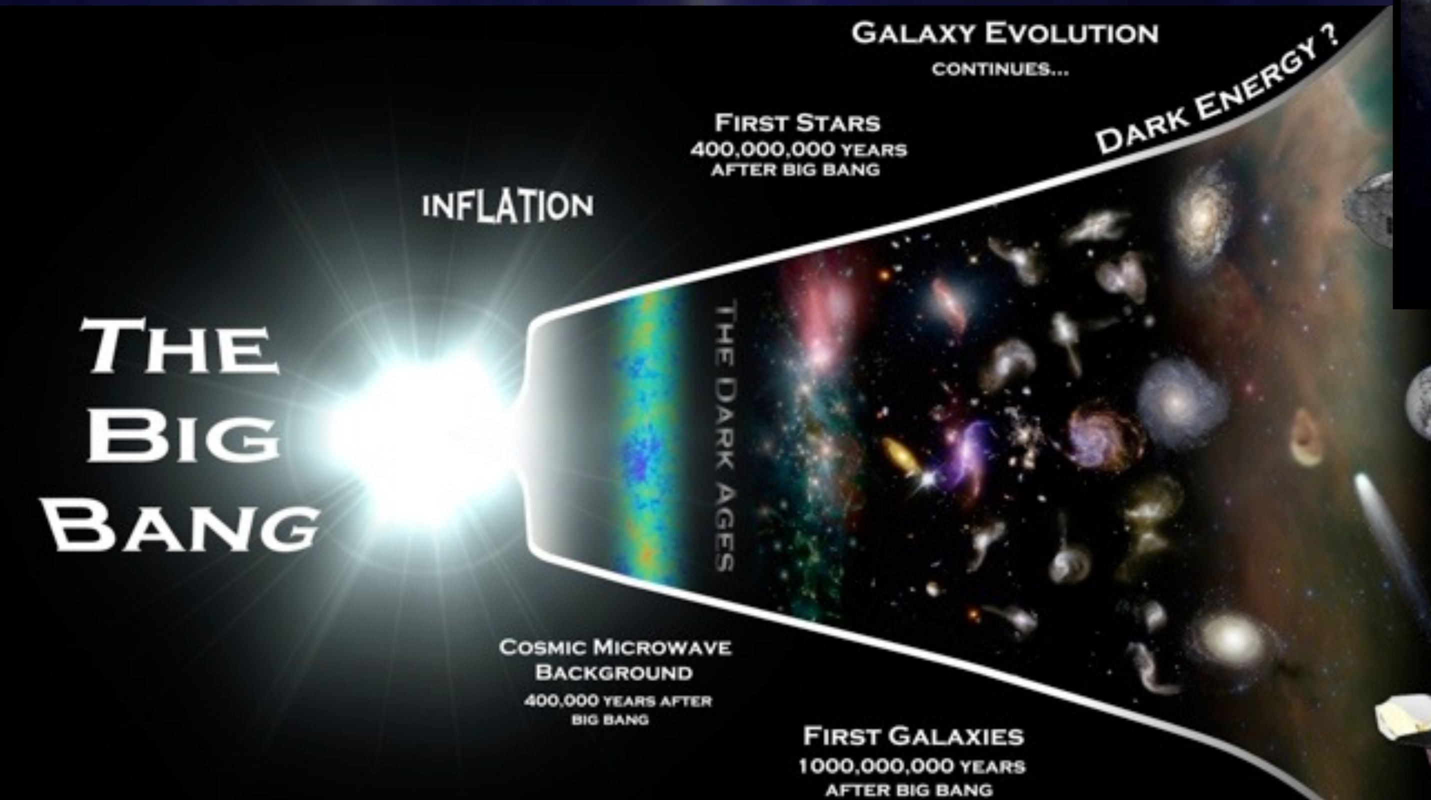
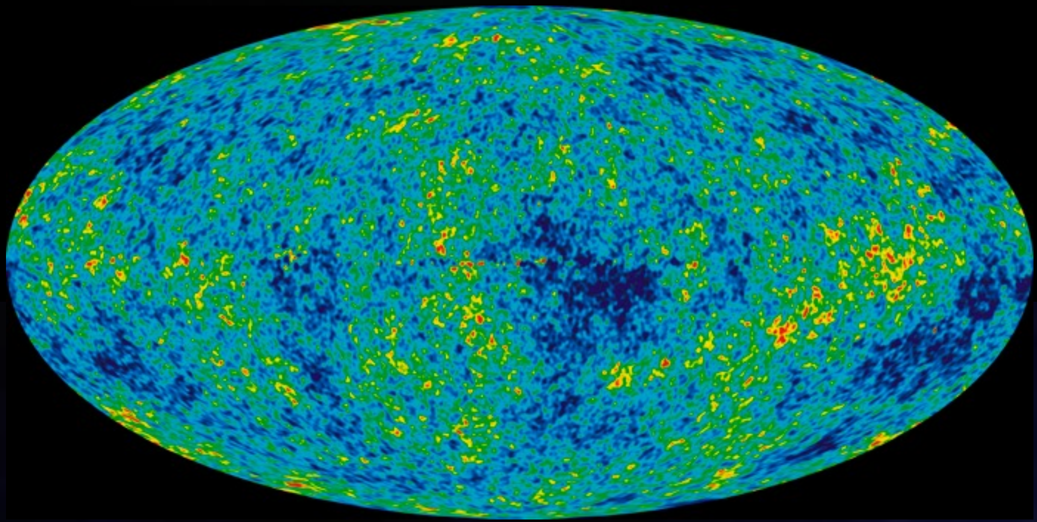
University of Oxford / Rutherford Appleton Laboratory

23-27 **JUNE** 2025 **Lido di Venezia**

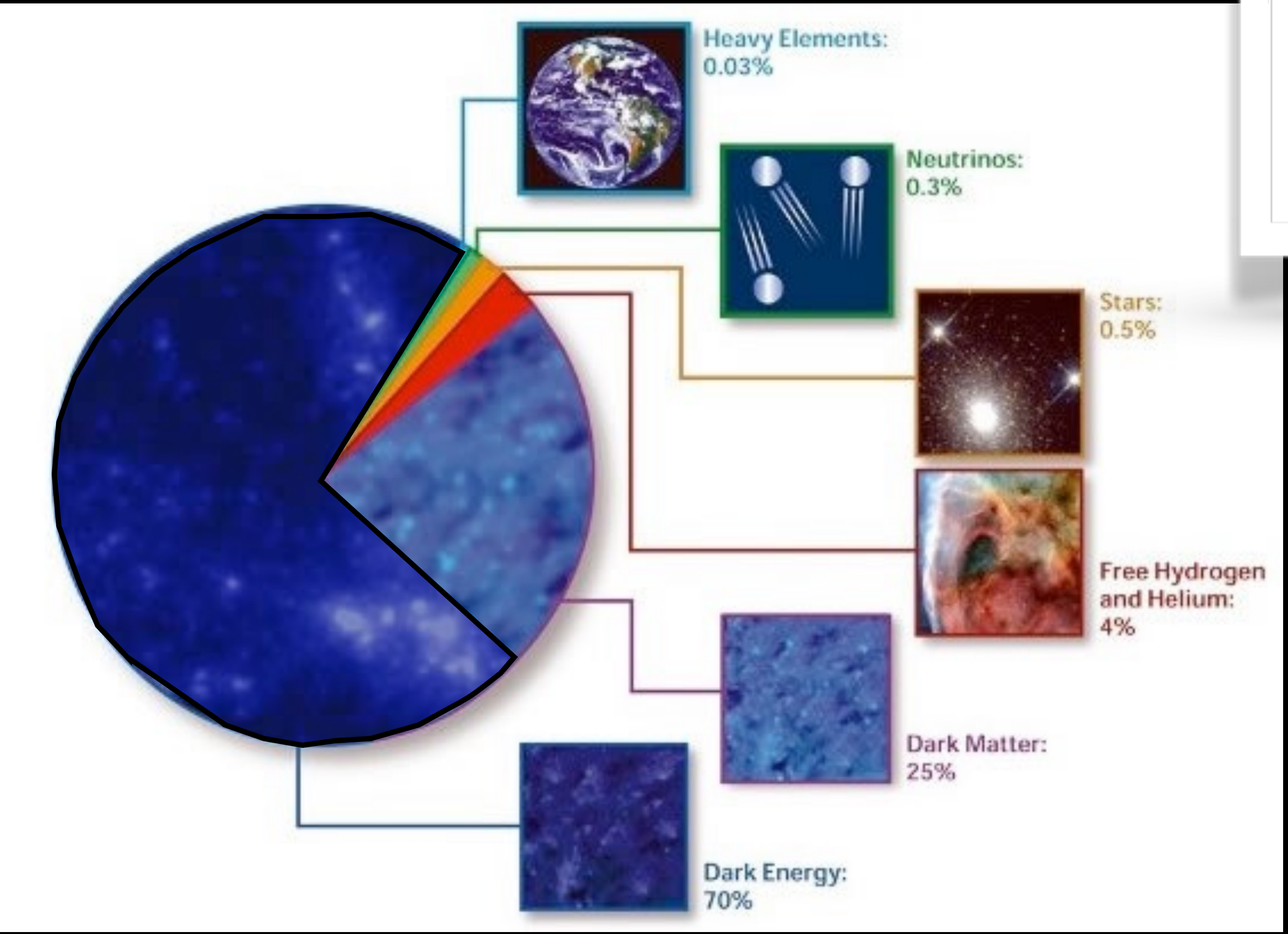
Experimental Evidence for Dark Matter

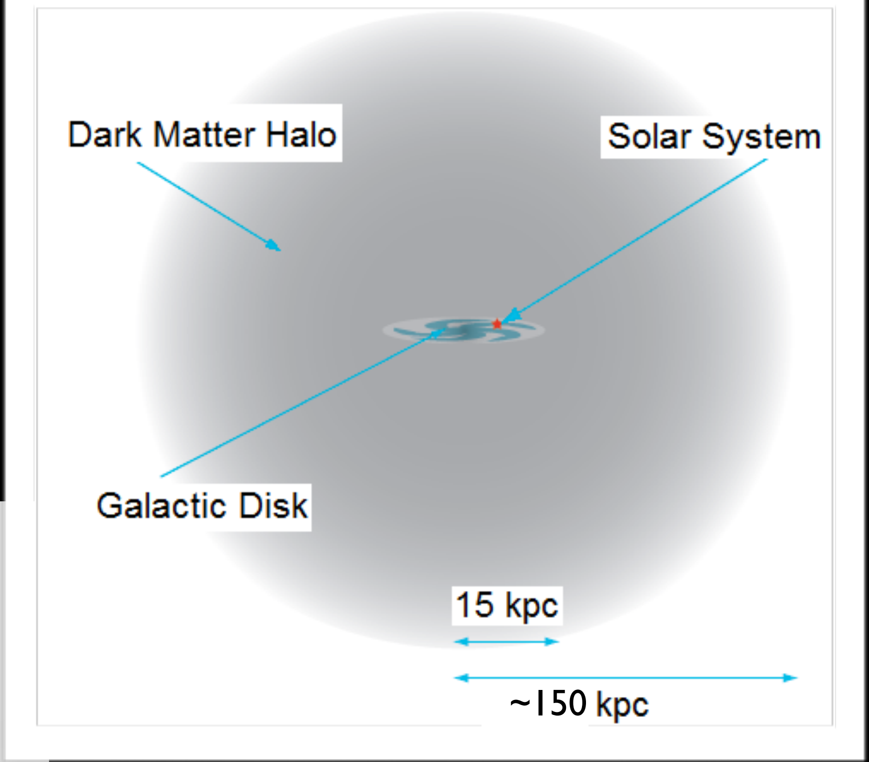




Evidence from a range of times,
from a range of scales

What is established experimentally about Dark Matter?





optically dark

bound to our galaxy

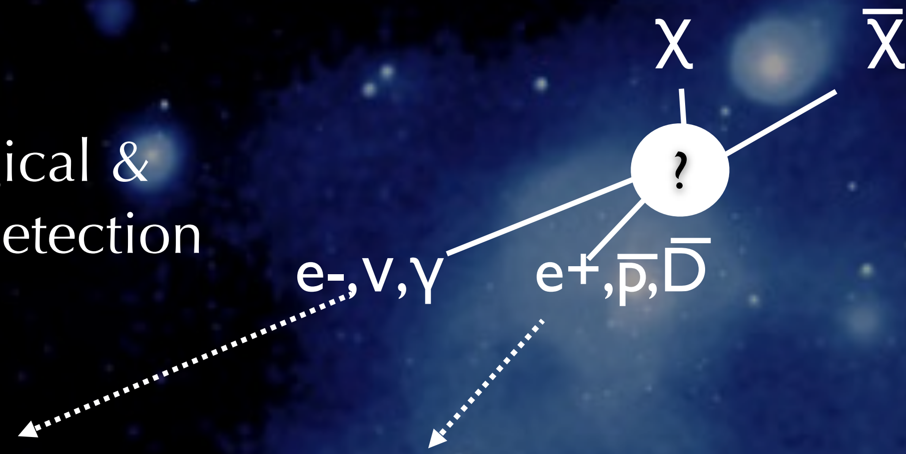
density ~ 0.3 GeV/cm^3

dark matter particle mass: ?

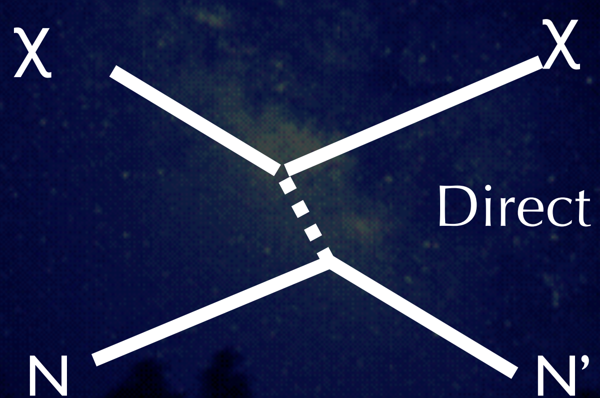
interactions: very weak

Experimental Tools

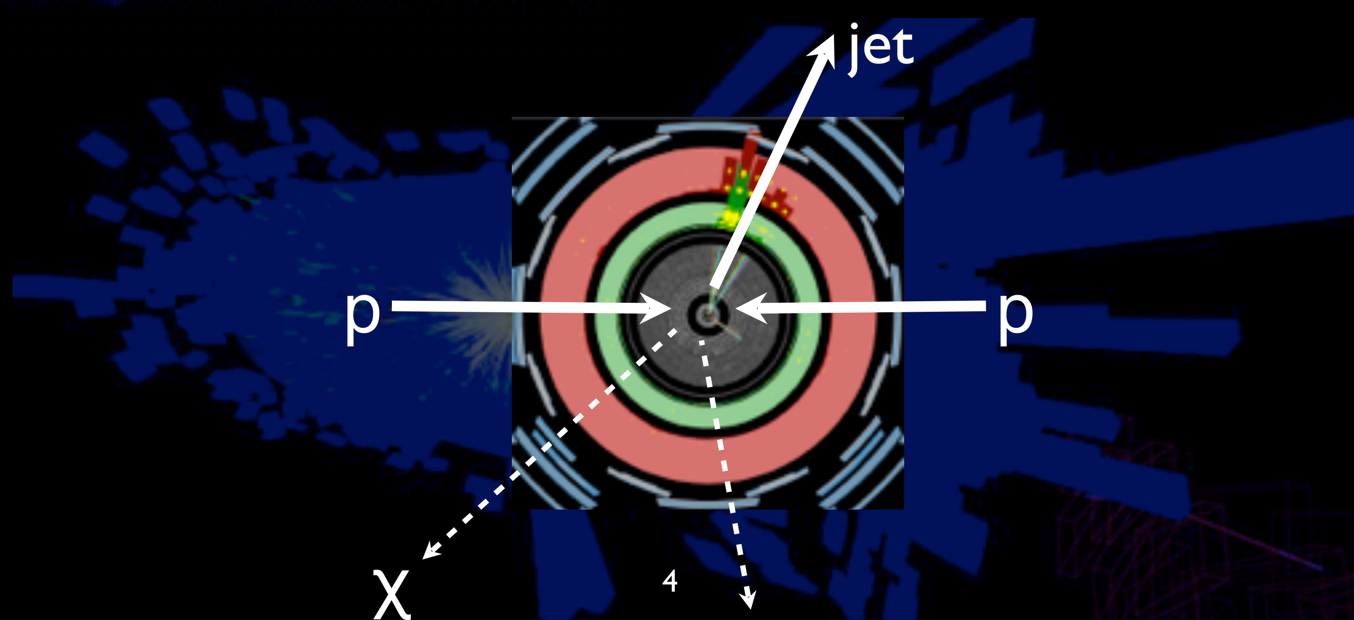
Cosmological & Indirect Detection



Direct Detection

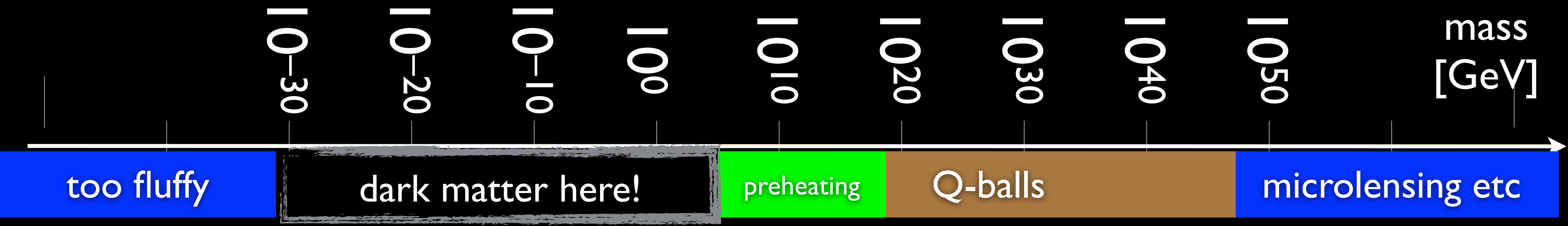


Accelerator Production



What could Dark Matter be?

H. Murayama, *ESPP2019*



What could Dark Matter be?

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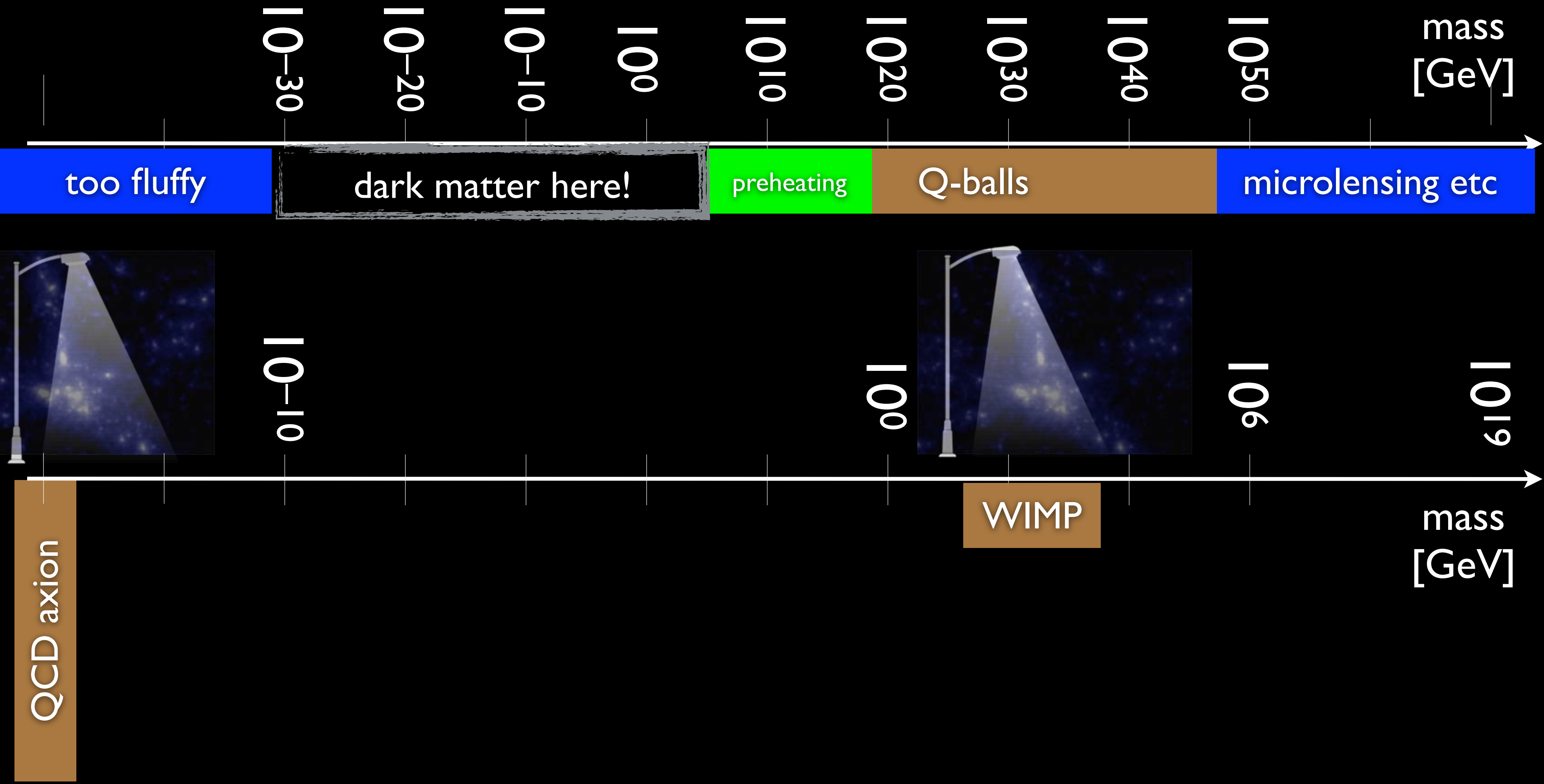
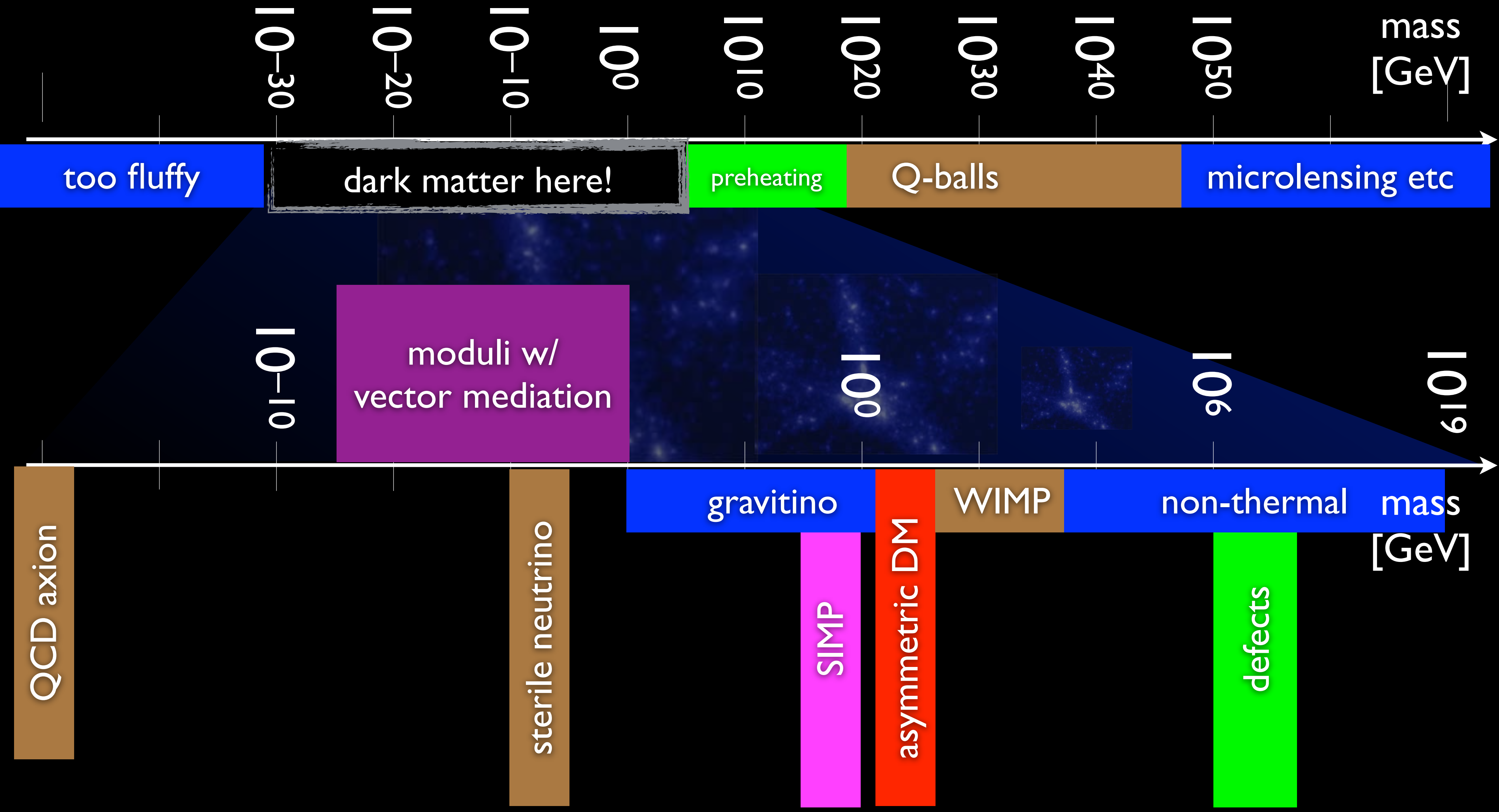


Old sociology: dark matter candidates emerge from theories that solve (other) problems in the Standard Model.

What could Dark Matter be?

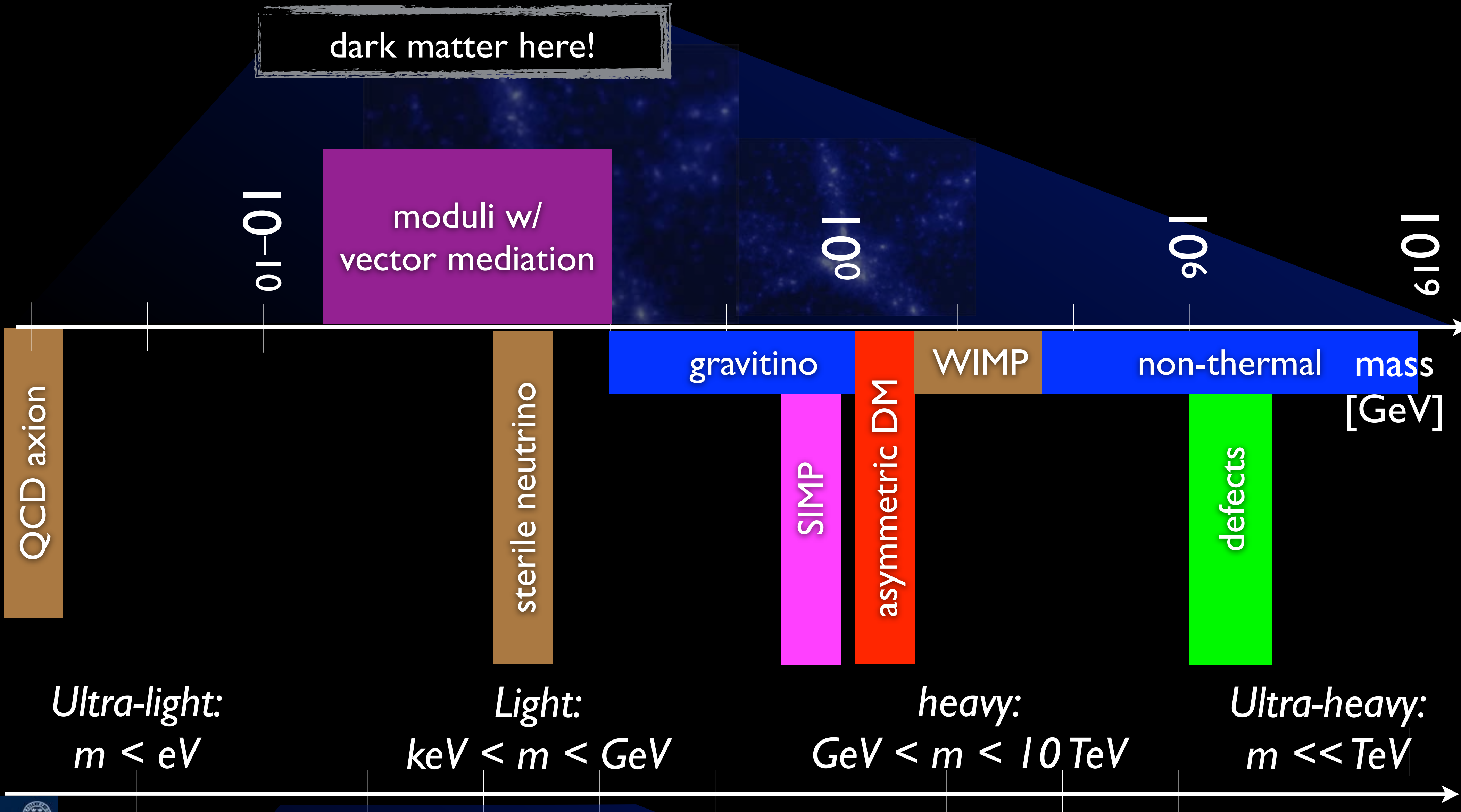
H. Murayama, *ESPP2019*



New sociology: dark matter definitely exists!
Need to explain dark matter on its own.

ESPP2026 Schema

New sociology for experiments: many well-defined places to look, beyond "the streetlight effect".



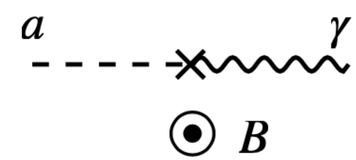
Y. Ema

Ultralight mass range: experiment

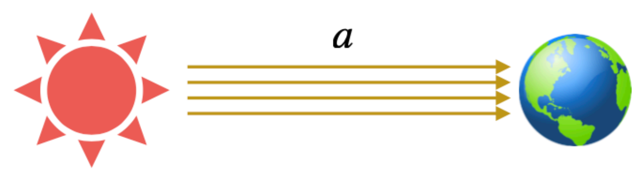
- Dark matter as a classical wave.

  ➡ Affecting e.g. electromagnetic response.

$$\dot{\vec{E}} - \vec{\nabla} \times \vec{B} = g_{a\gamma\gamma} \left(\underbrace{\dot{a}\vec{B} + \vec{\nabla} a \times \vec{E}}_{\text{DM-induced current}} \right)$$

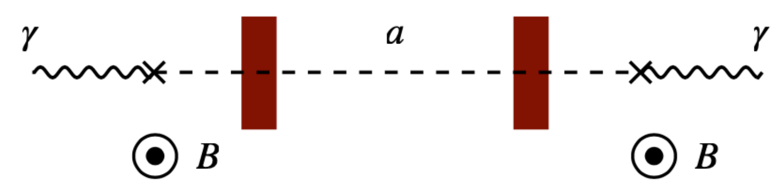
➡ 

- Astrophysical/cosmological production also important.



- Can be produced in the laboratory.

e.g. “Light-shining-through-a-wall”



Disclaimer: showing only non-exhaustive lists.

10^{-10}

10^{19}

QCD axion

Ultra-light: *m < eV*

Light: *keV < m < GeV*

heavy: *GeV < m < 10 TeV*

Ultra-heavy: *m >> TeV*

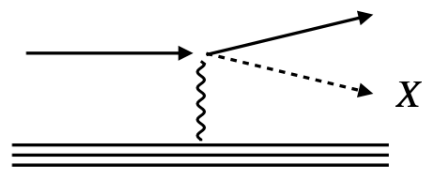
Y. Ema

Light mass range: experiment

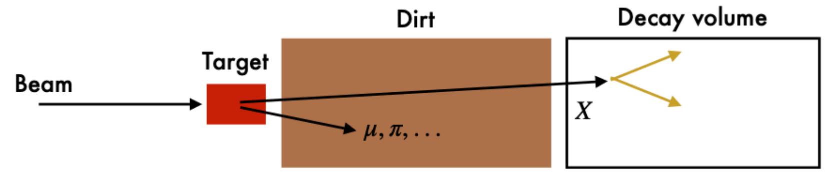
- Light but weakly coupled. ➡ Precision is crucial.

<u>e.g.</u>

Missing energy experiments:

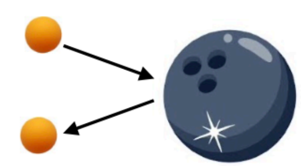


Beam-dump experiments:



- DM direct detection (DD) with lower threshold/lighter target:

$$E_{\text{recoil}} \sim \frac{m_\chi^2}{m_{\text{target}}} v^2 \sim 0.1\,\text{keV} \left(\frac{m_\chi}{1\,\text{GeV}}\right)^2 \left(\frac{10\,\text{GeV}}{m_{\text{target}}}\right)$$



for $m_\chi \ll m_{\text{target}}$.

- Astrophysics/cosmology relevant, especially for $m_\chi \lesssim 10\,\text{MeV}$.

Disclaimer: showing only non-exhaustive lists.

10^{-10}

10^{19}

QCD axion

Ultra-light: *m < eV*

Light: *keV < m < GeV*

heavy: *GeV < m < 10 TeV*

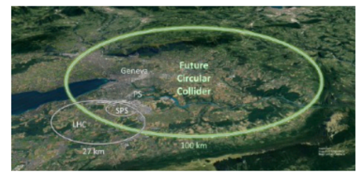
Ultra-heavy: *m >> TeV*

Y. Ema

Heavy mass range: experiment

- Sizable coupling but heavier.

  High energy colliders crucial.

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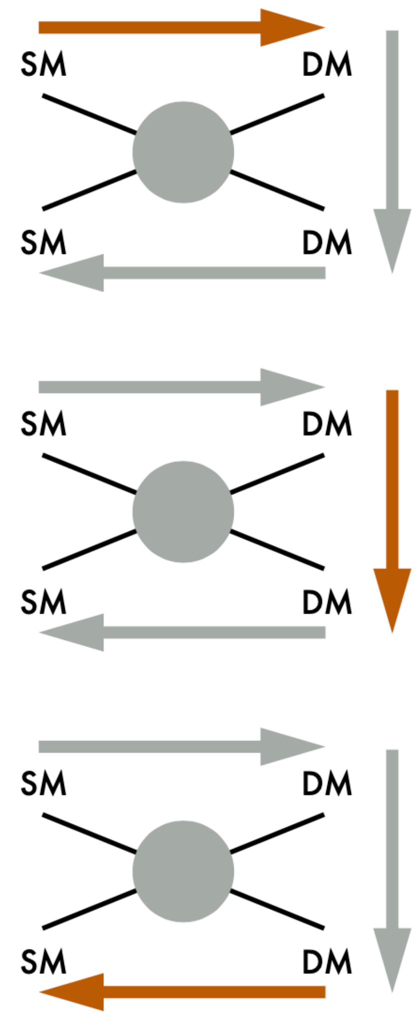
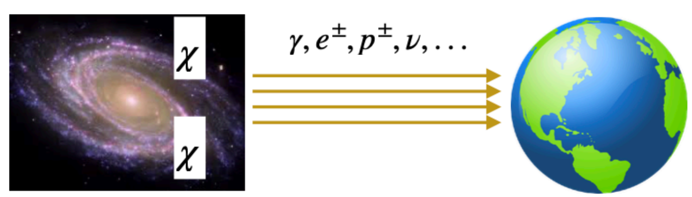


- DM direct detection most sensitive here.

$$E_{\rm recoil} \sim m_{\rm target} v^2 \sim 10\,{\rm keV} \left(\frac{m_{\rm target}}{10\,{\rm GeV}}\right) \quad \text{for } m_\chi \gtrsim m_{\rm target}\,.$$

- Indirect detection provides another strong probe.



QCD axion

10^{-10} 10^{19}

Ultra-light:	*Light:*	*heavy:*	*Ultra-heavy:*
m < eV	*keV < m < GeV*	*GeV < m < 10 TeV*	*m >> TeV*

Y. Ema

Ultraheavy mass range

- Simple (perturbative) thermal production does not work

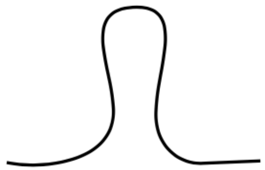
$$\Omega_\chi h^2 \sim \frac{10^{-26}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{1}{g_\chi^2}\right)^2 \left(\frac{m_\chi}{10\,\mathrm{TeV}}\right)^2$$

⇨ Coupling becomes non-perturbative for $m_\chi \gg 1\,\mathrm{TeV}$.

- Can be composite and/or non-thermally produced.

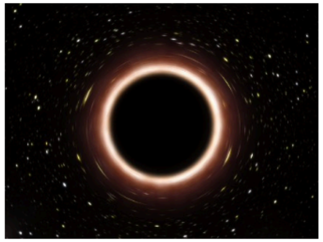
e.g.

Primordial Black Hole (PBH) :



$$\frac{\delta\rho}{\rho} \gtrsim 1$$

⇨



- DM direct detection, astrophysics, ... can probe these models.

10^{-10}

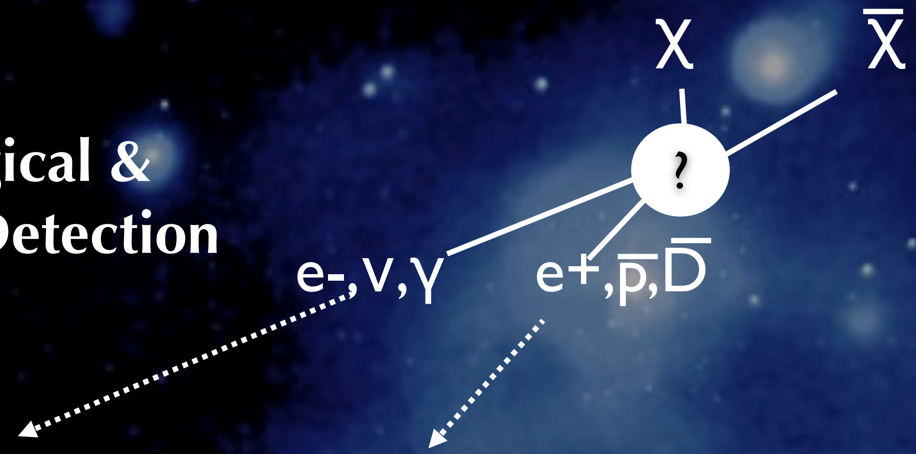
10^{19}

QCD axion

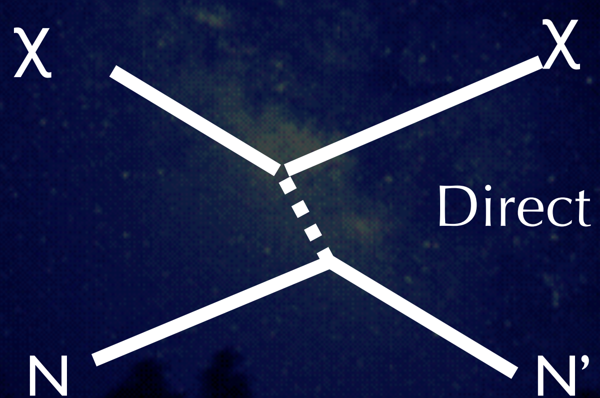
Ultra-light: m < eV	Light: keV < m < GeV	heavy: GeV < m < 10 TeV	Ultra-heavy: m >> TeV

Experimental Tools

Cosmological & Indirect Detection



Direct Detection



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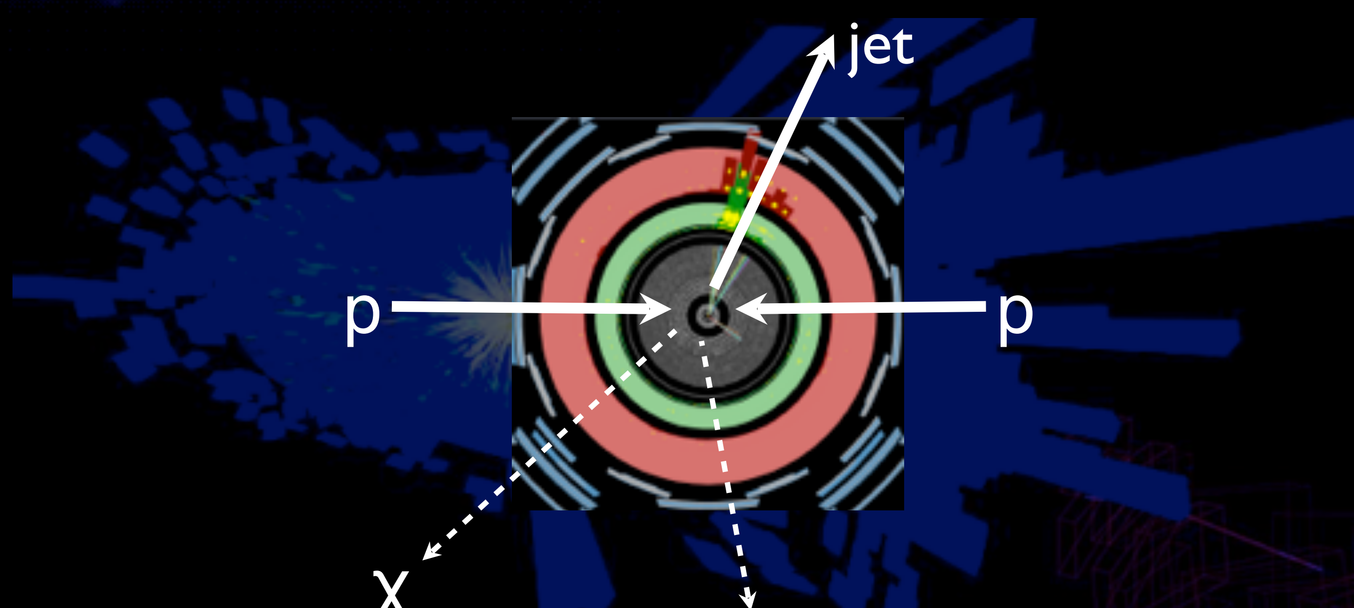
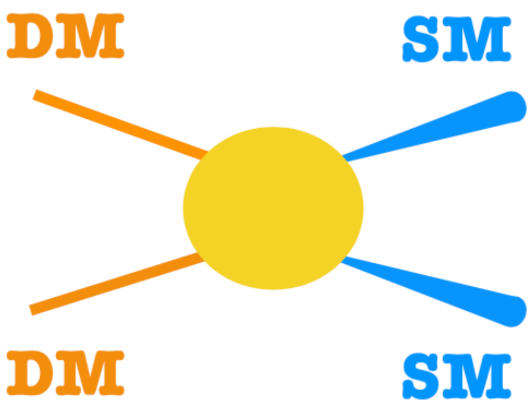
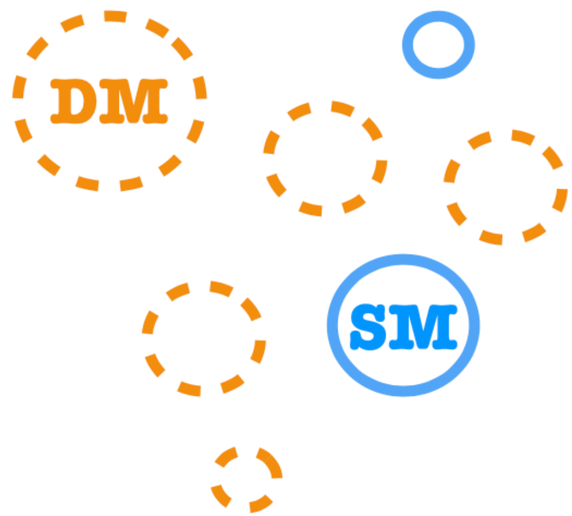


What dark matter does with/to the environment

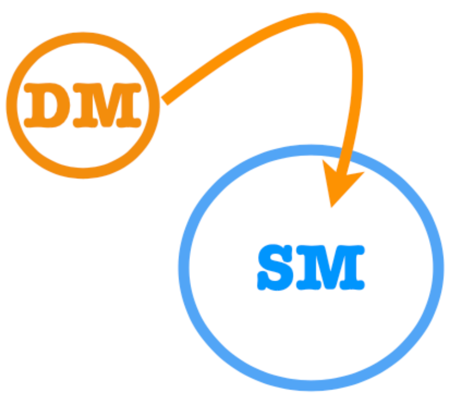
J. Pradler



Energetic particle fluxes



Dynamics of astrophysical objects through gravitational interaction



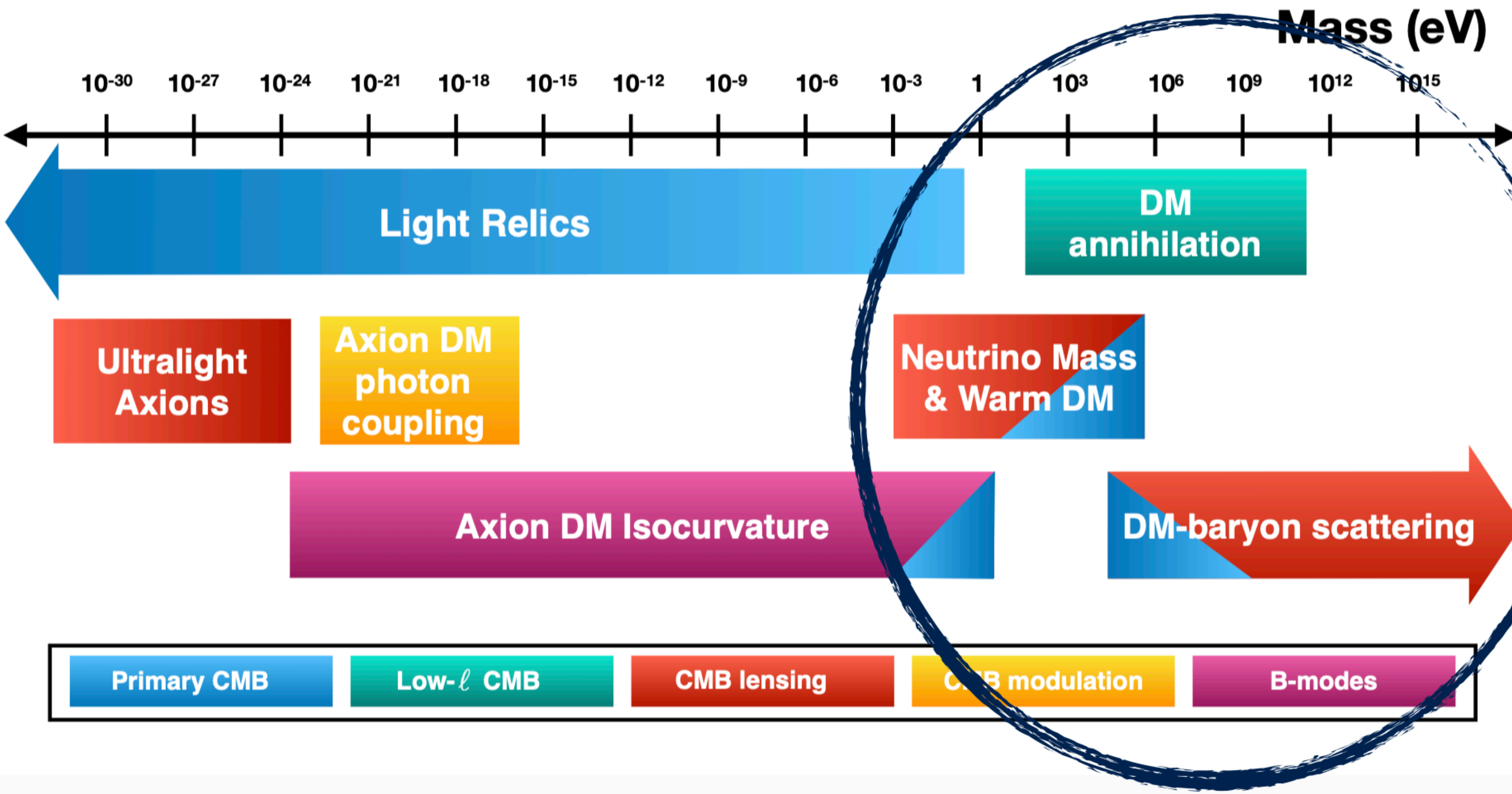
Capture/scattering/accretion in/onto astrophysical objects

CMB Observables

Rich science program associated with (ultra-)light DM

J. Pradler

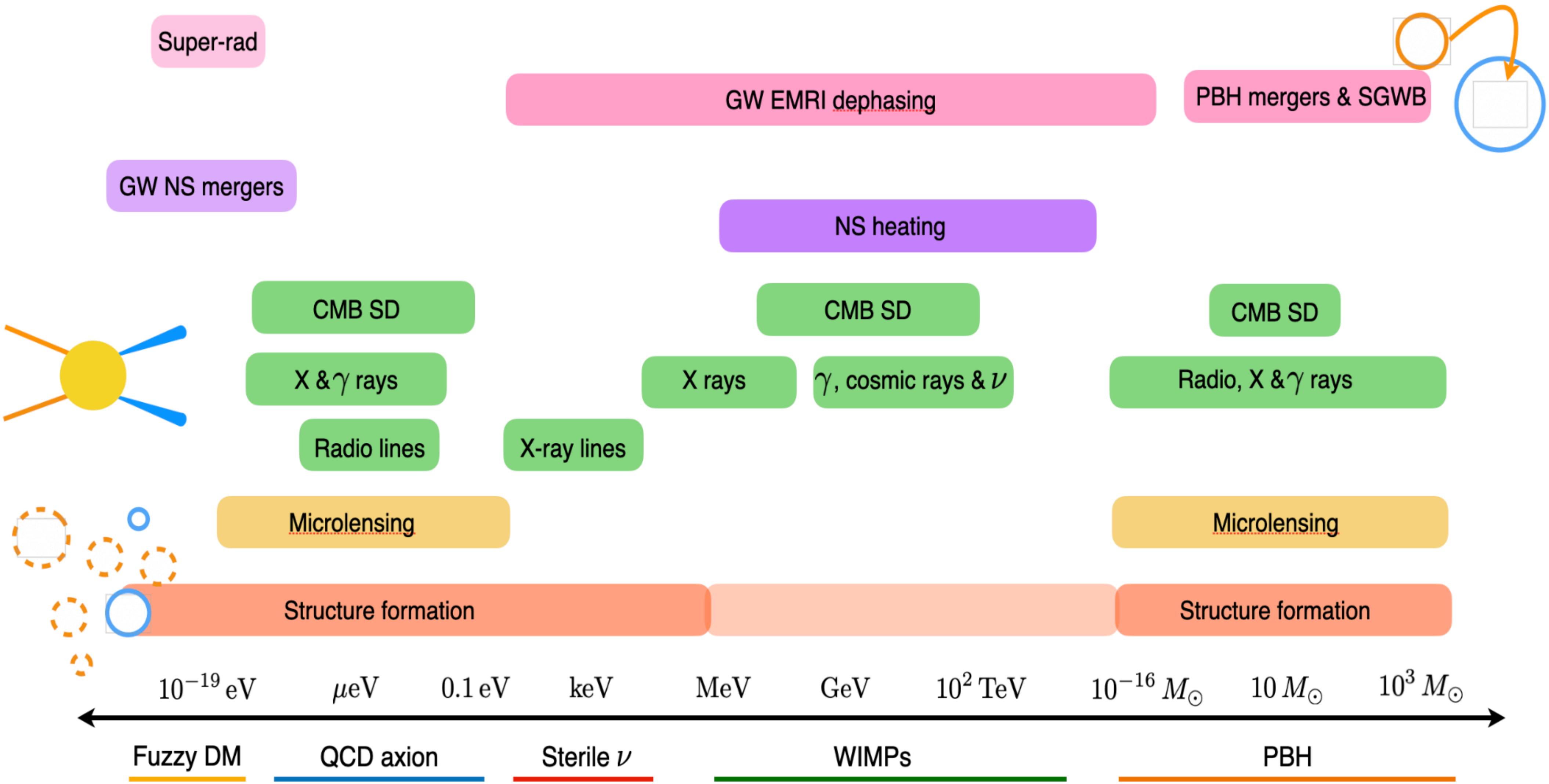
CMB-S4 collaboration
1907.04473



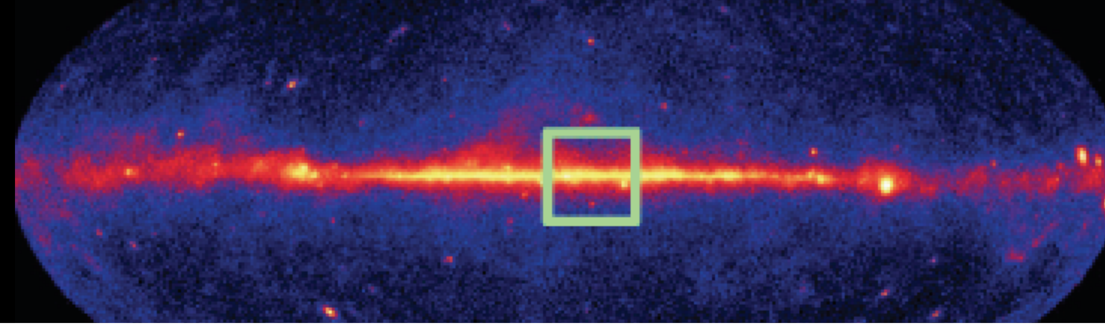
Indirect Detection Observables

J. Pradler

EuCAPT White Paper, arXiv:2110.10074



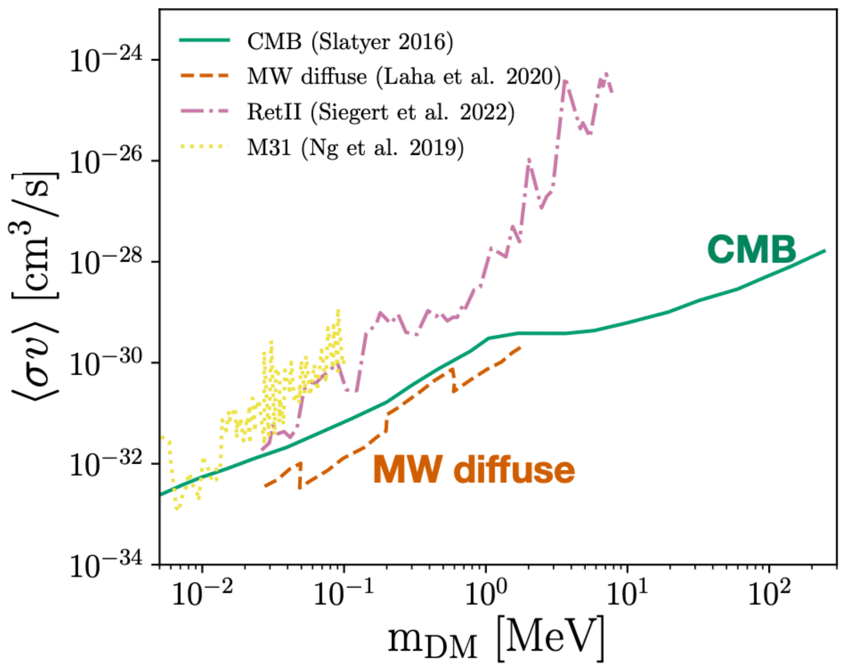
Visible Final States: Light Dark Matter



F. Calore

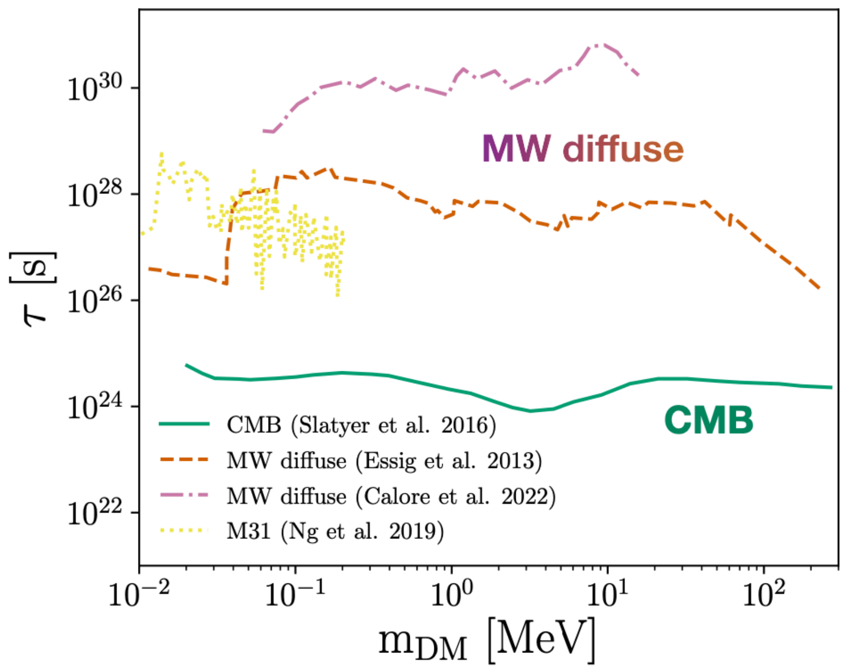
- Simple thermal freeze-out scenario for s-wave annihilation generically ruled out
- But p-wave models (many of the portals) still viable

FC FIPs2022 Proceedings



Two-photons annihilation

Siegert, FC+ MNRAS'24

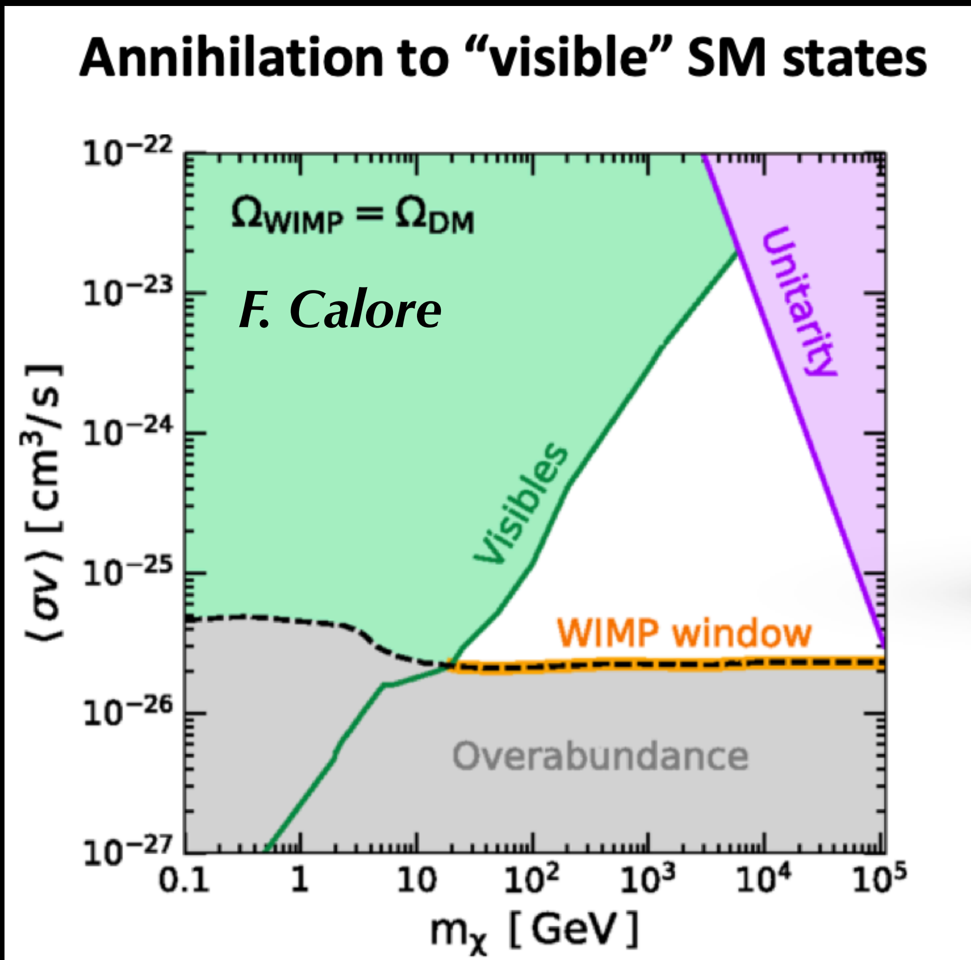


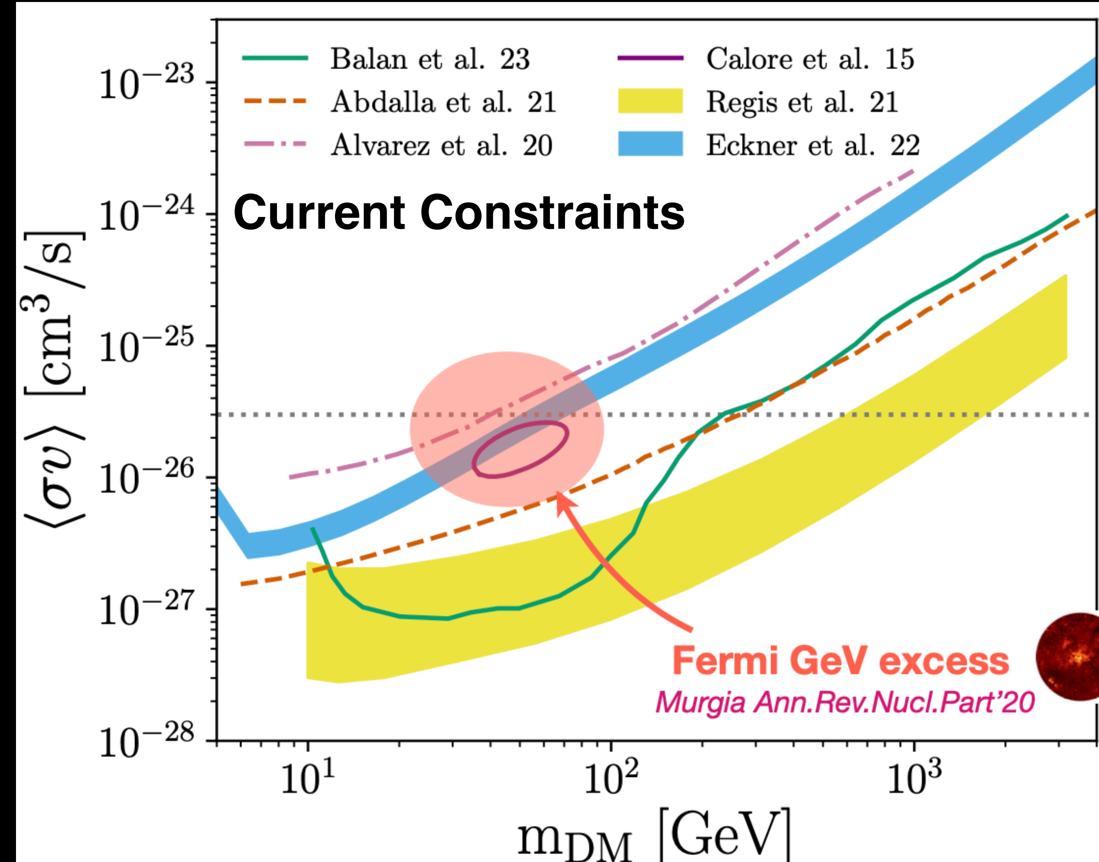
Two-photons decay

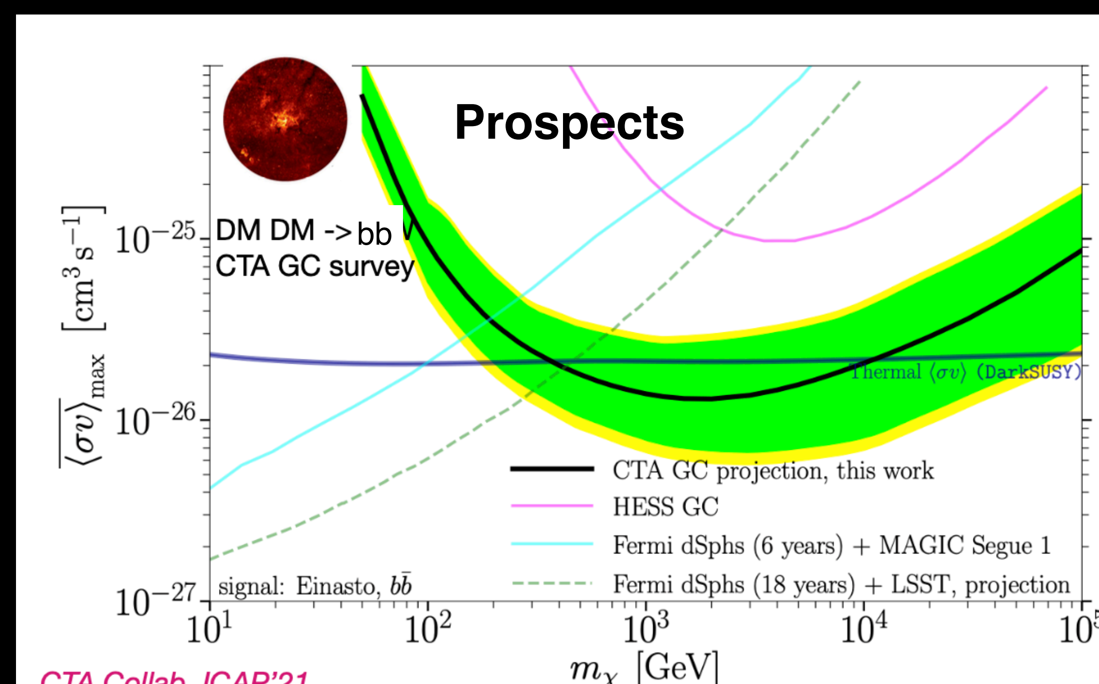
FC+ MNRAS'23

https://zenodo.org/record/7984451

Self-Annihilation Searches: Heavy Dark Matter

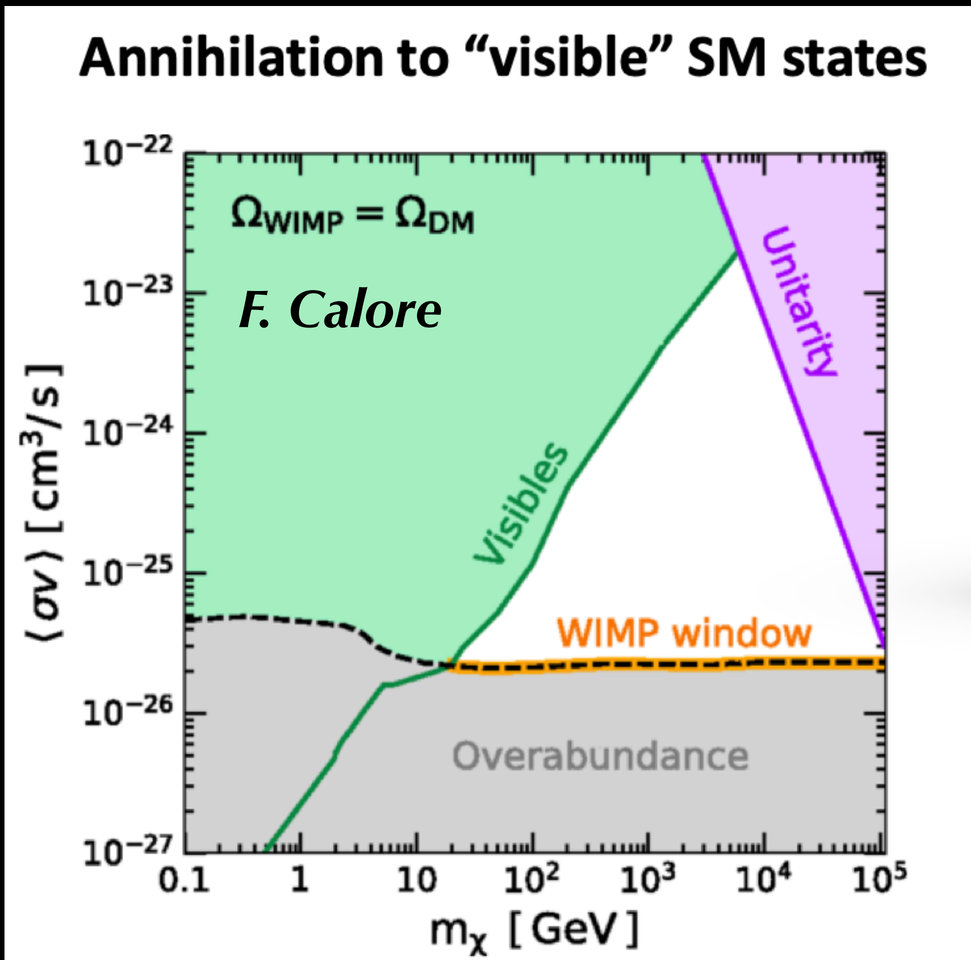


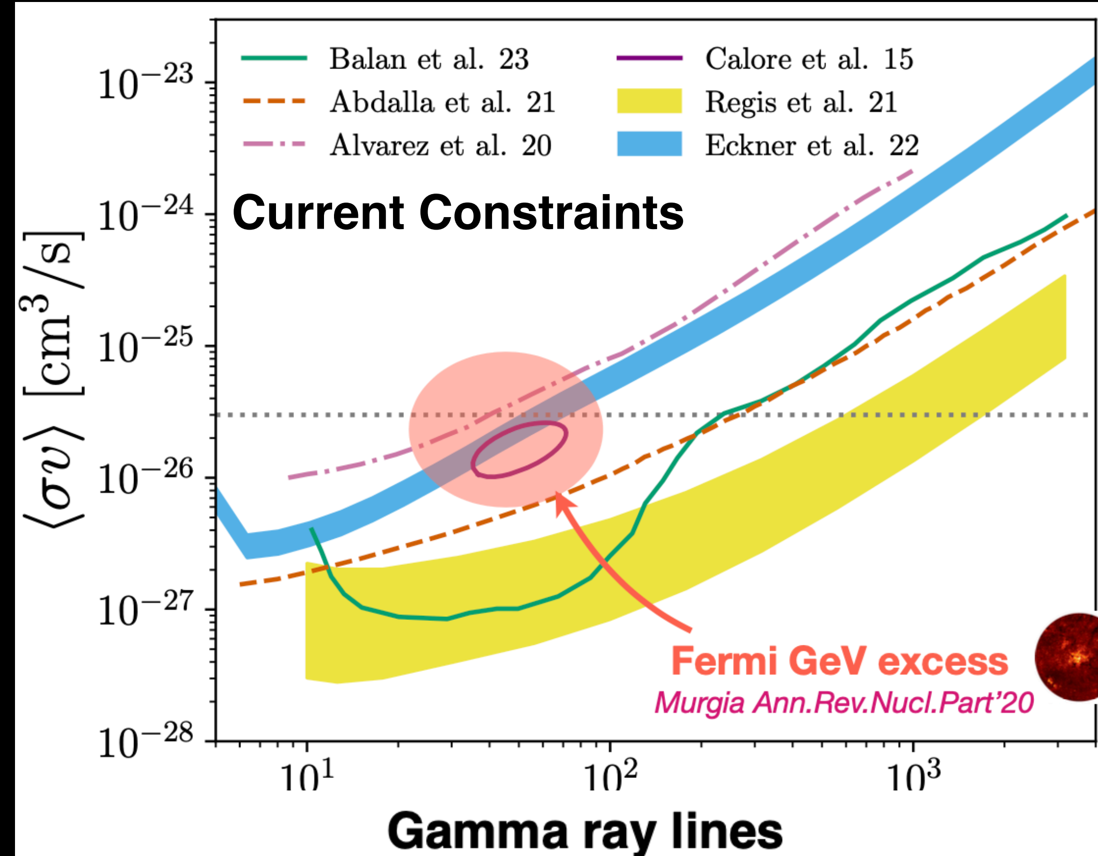




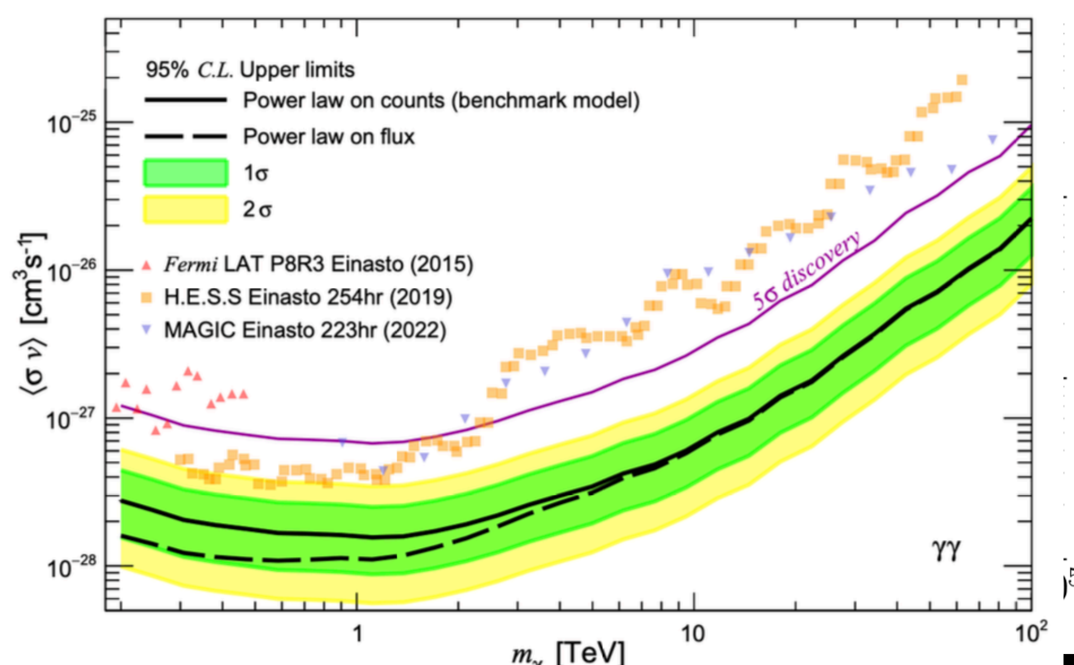
Higgsino DM exclusion in reach of CTA by end of decade

Self-Annihilation Searches: Heavy Dark Matter





CTA Collab 2403.04857



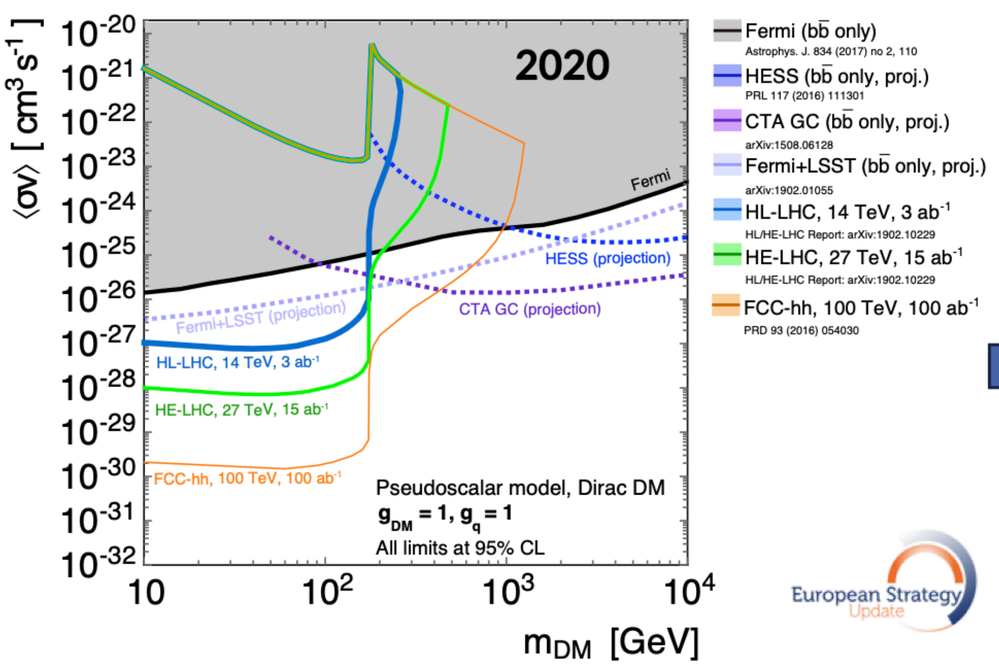
Higgsino DM exclusion in reach of CTA by end of decade

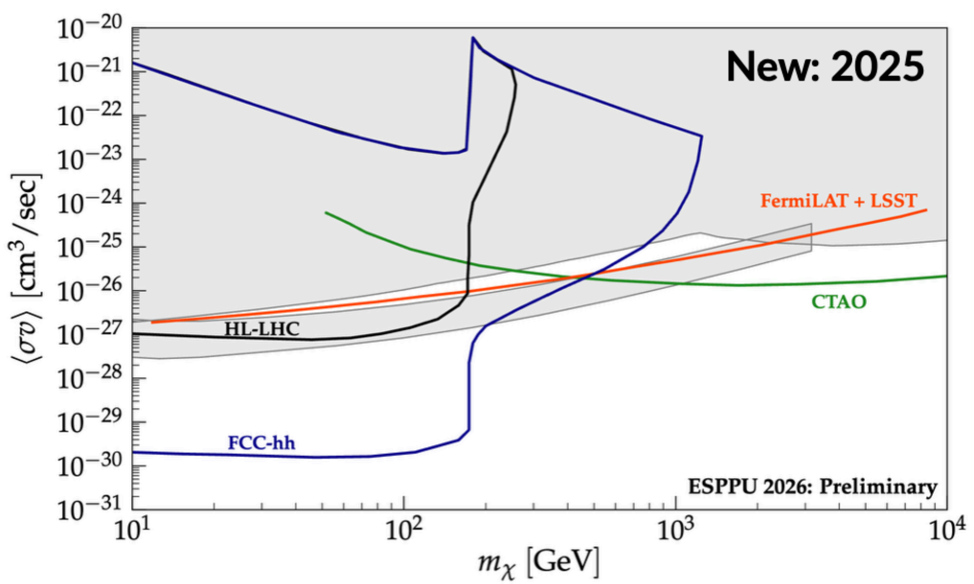
Complementarity with Accelerator Searches

Simplified models: scalar mediators

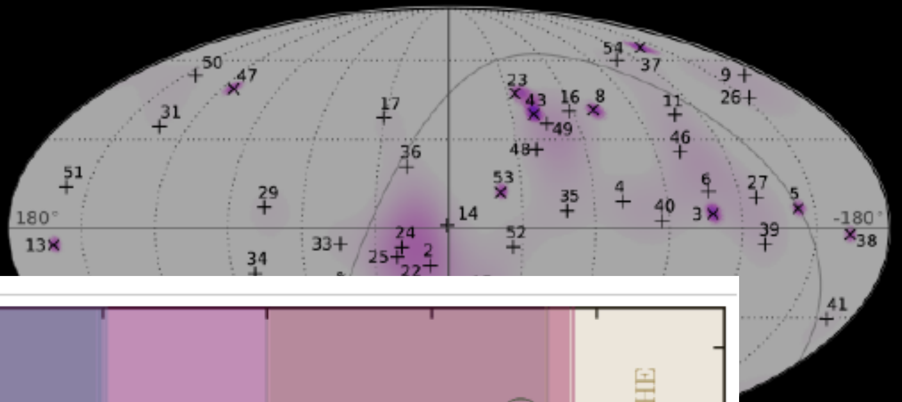
M. D'Onofrio

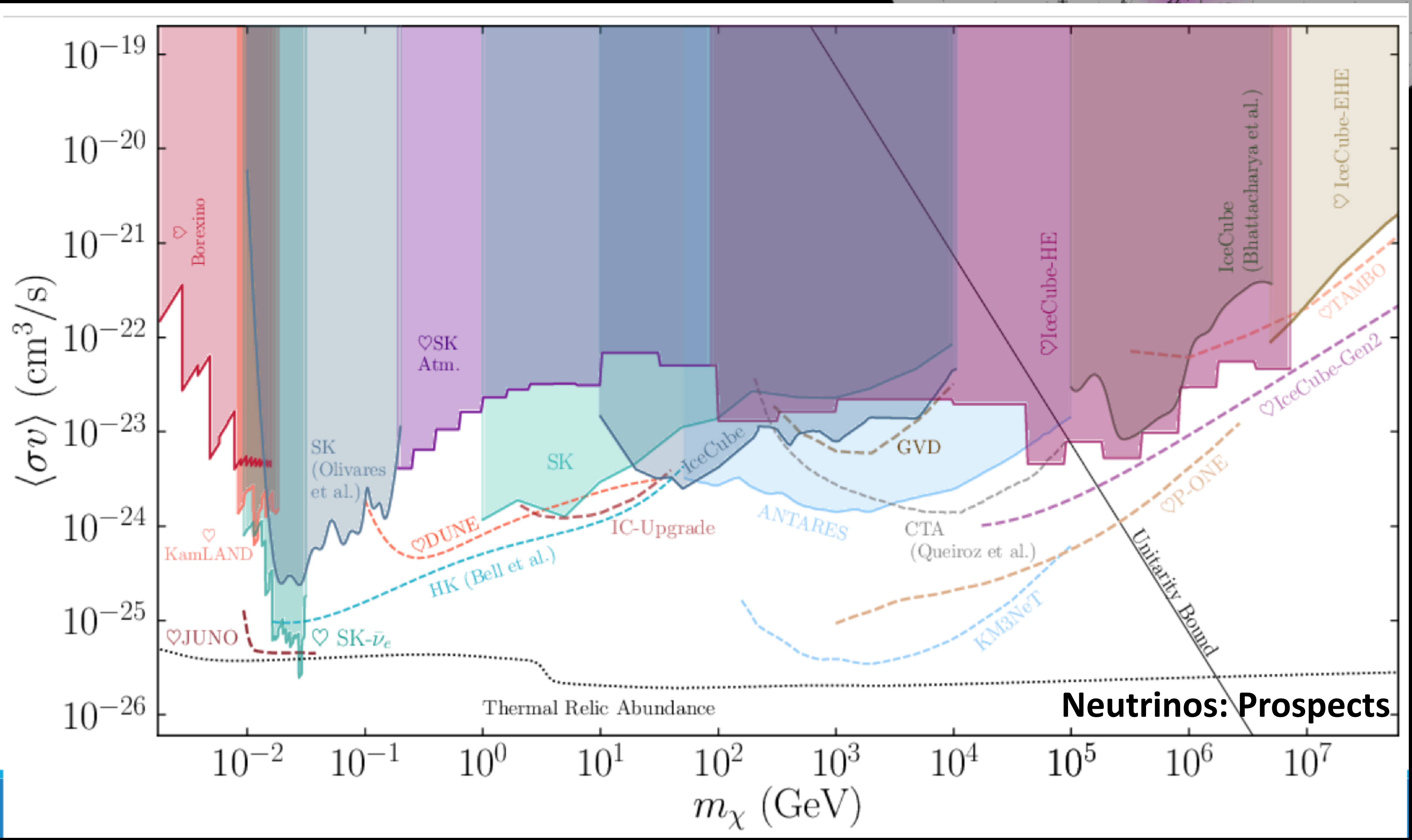
- Further interplays with indirect detection
  - collider searches have better sensitivity for DM masses below the top mass, complementary to indirect searches more powerful for higher DM masses.
  - No major updates on the colliders side wrt ES2020 but several updates in indirect detection





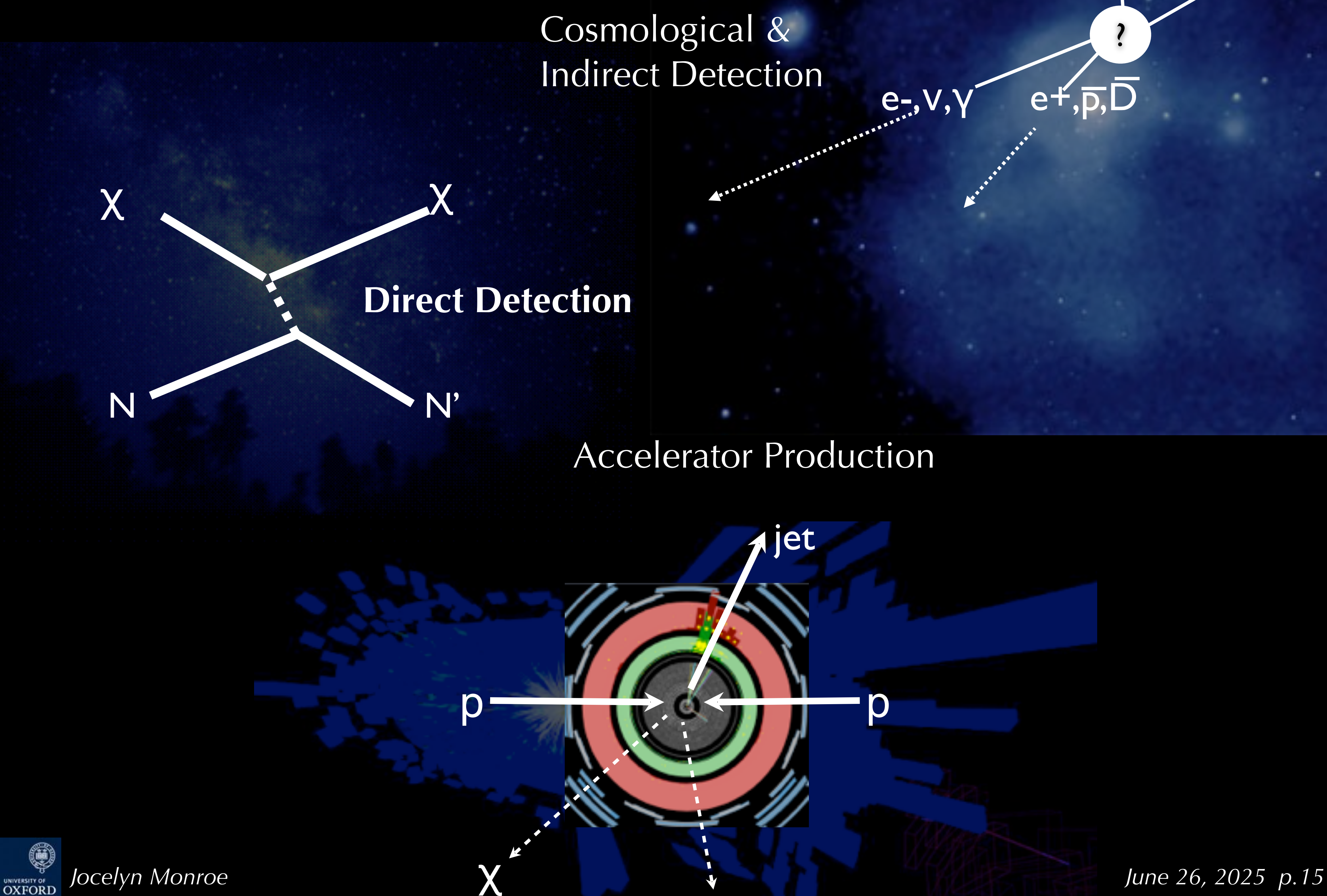
Self-Annihilation Searches: Invisible Final States





Arguelles et al. Rev. Mod. Phys. 93, 35007 (2021)

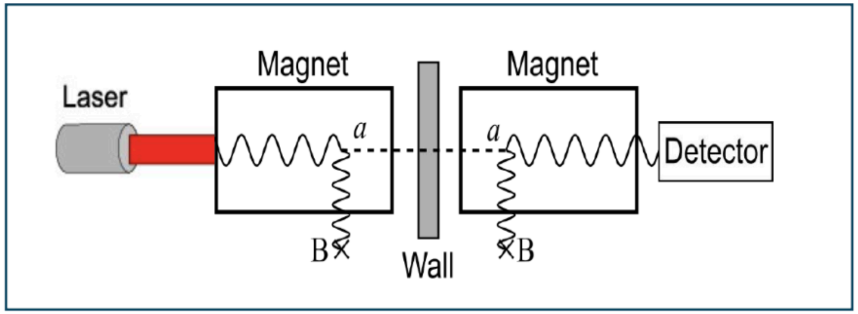
Experimental Tools



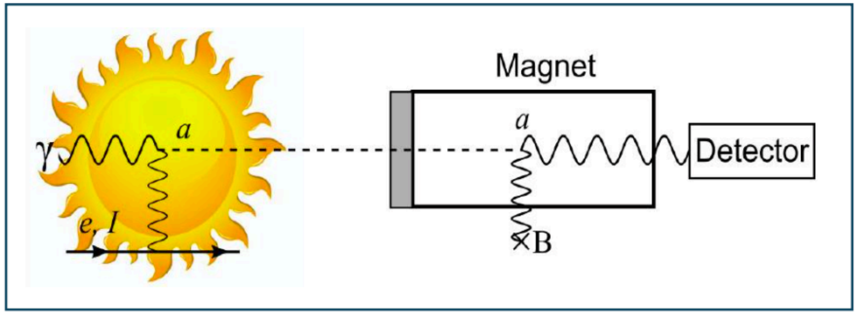
Categories of Axion Search Experiments

J. Vogel

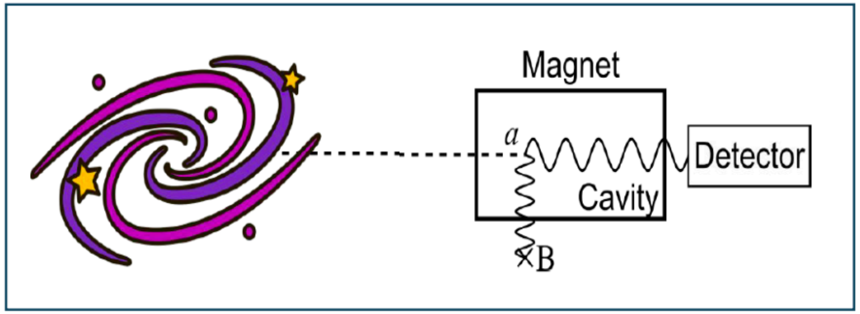
- Light-Shining-Through-Wall-Searches (no DM assumption)



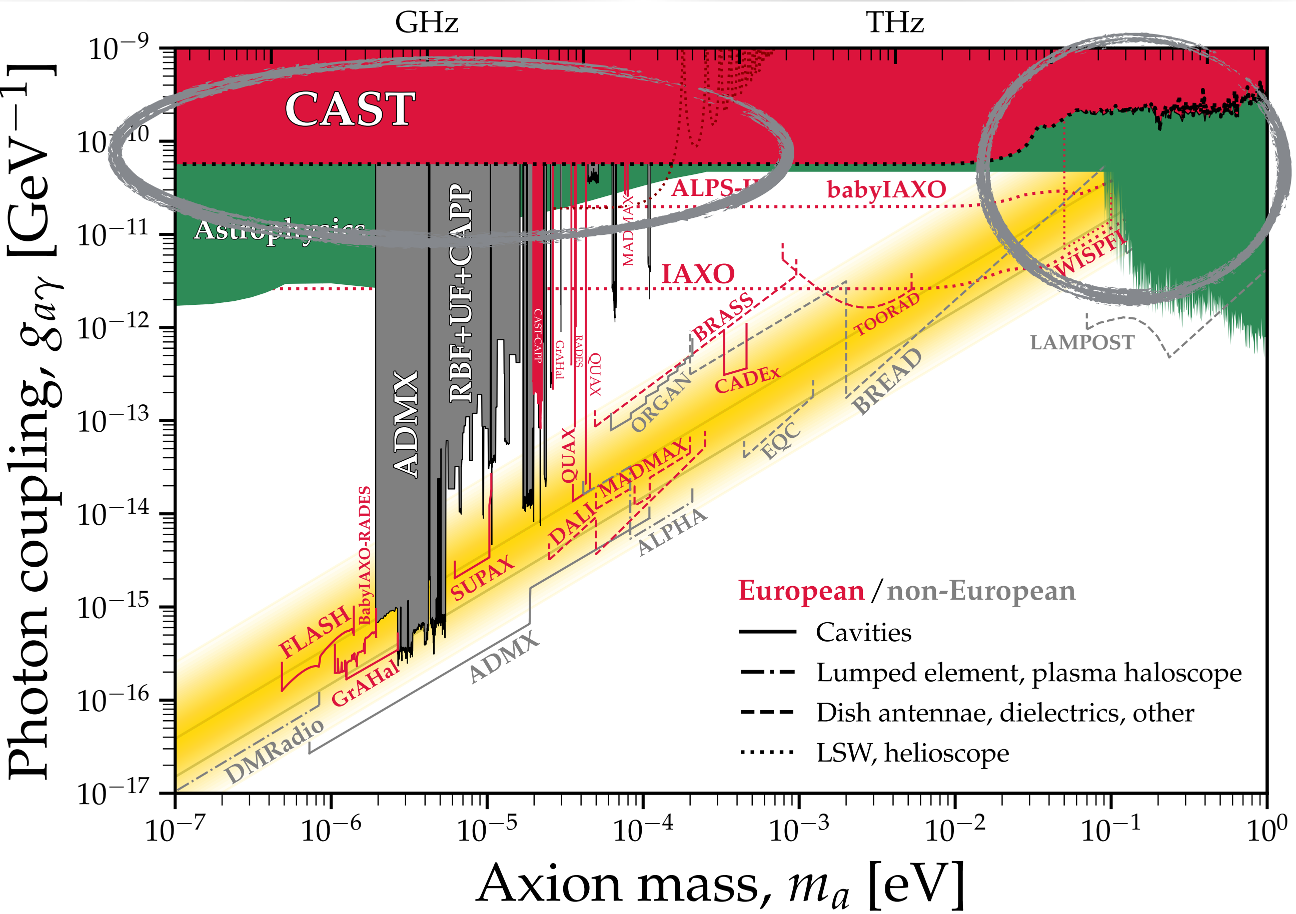
- Helioscopes (no DM assumption)



- Haloscopes
  - (Conventional) Microwave cavities
  - Dish antennas/dielectric/plasma Haloscopes (higher m_a)
  - Lumped element detectors (lower m_a)

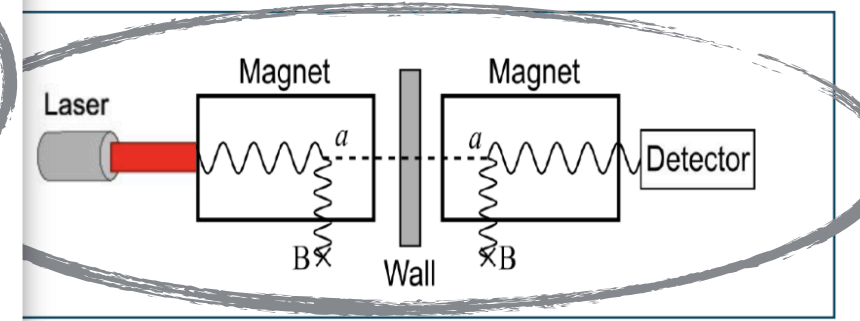


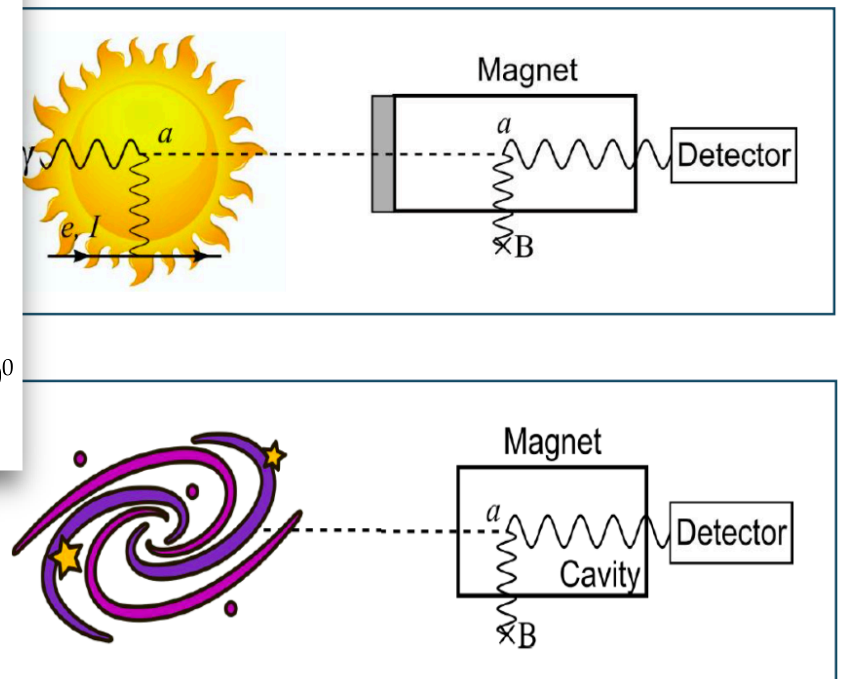
Ultralight Dark Matter



C. O'Hare, *https://github.com/cajohare*

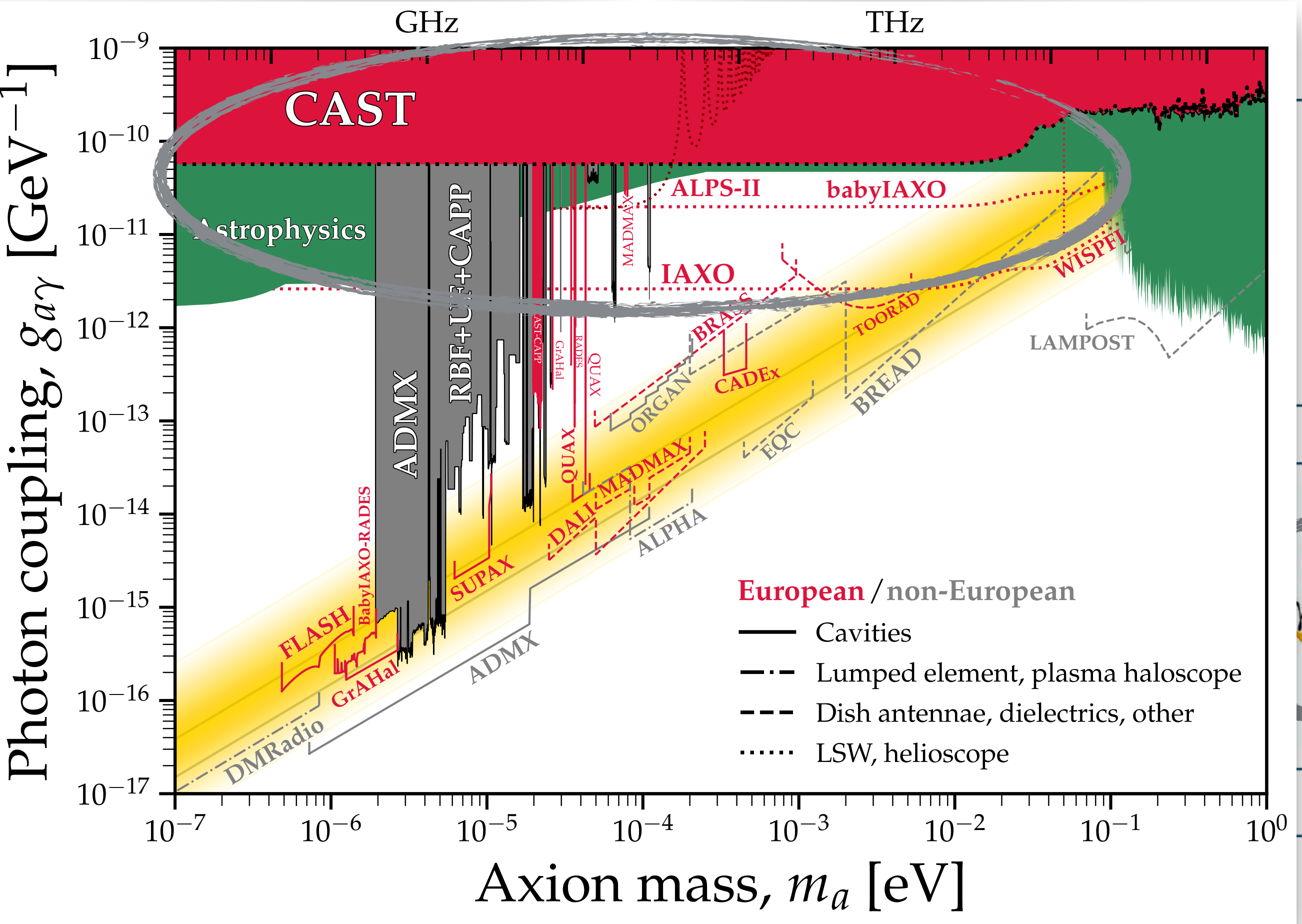
J. Vogel





Ultralight Dark Matter

J. Vogel



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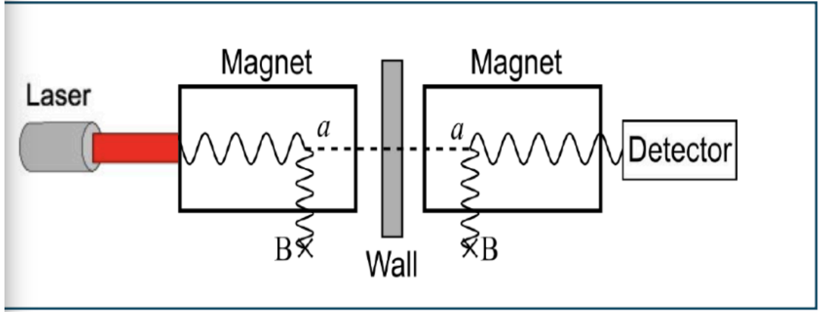
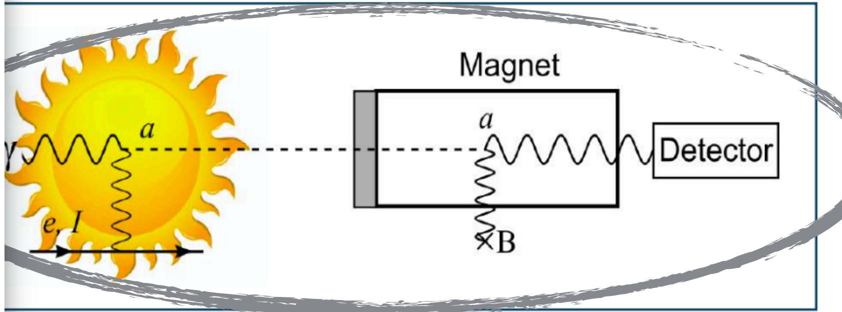
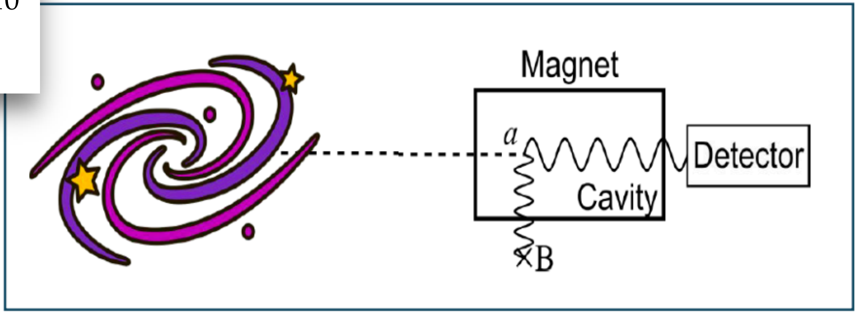
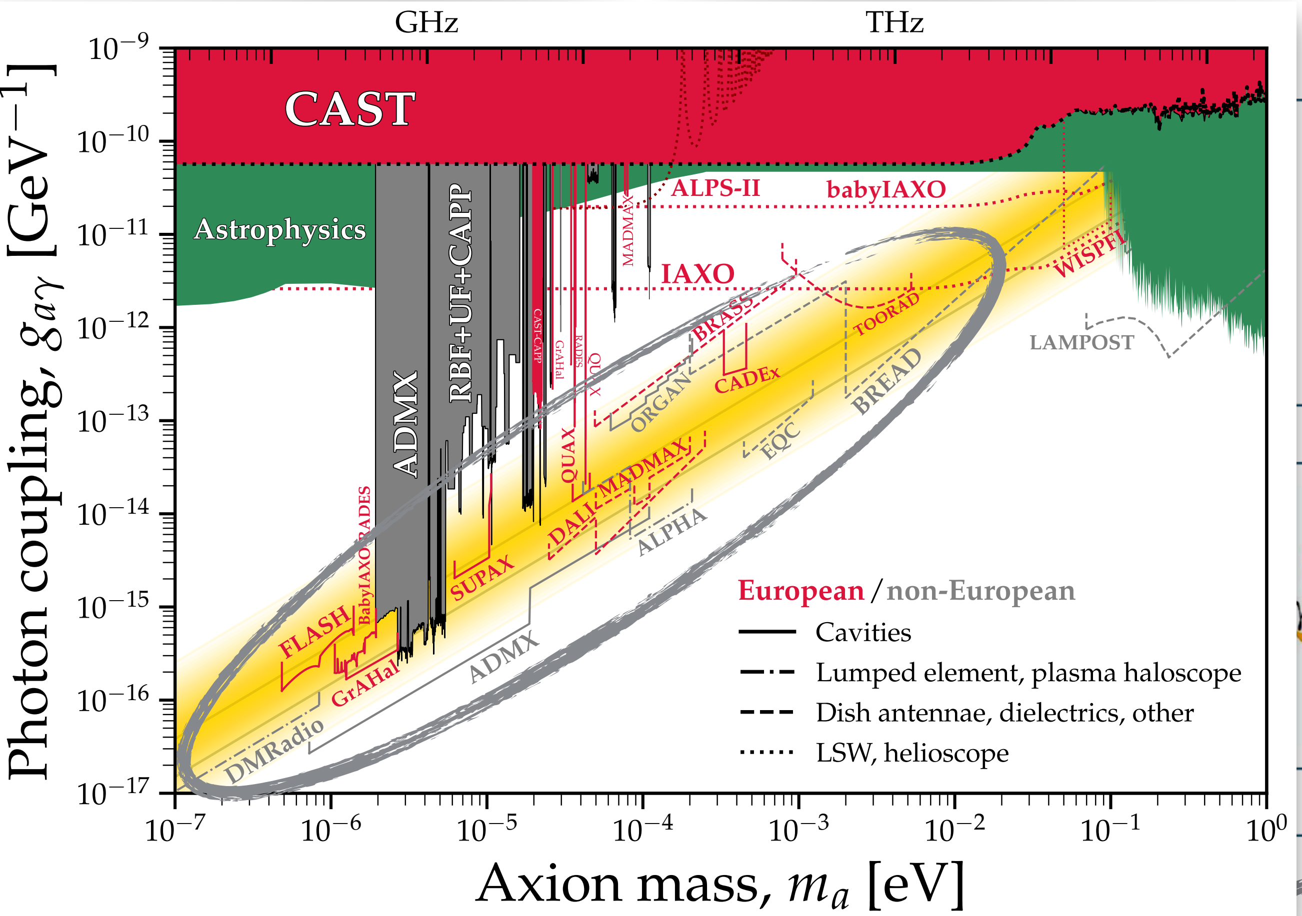






Ultralight Dark Matter

J. Vogel



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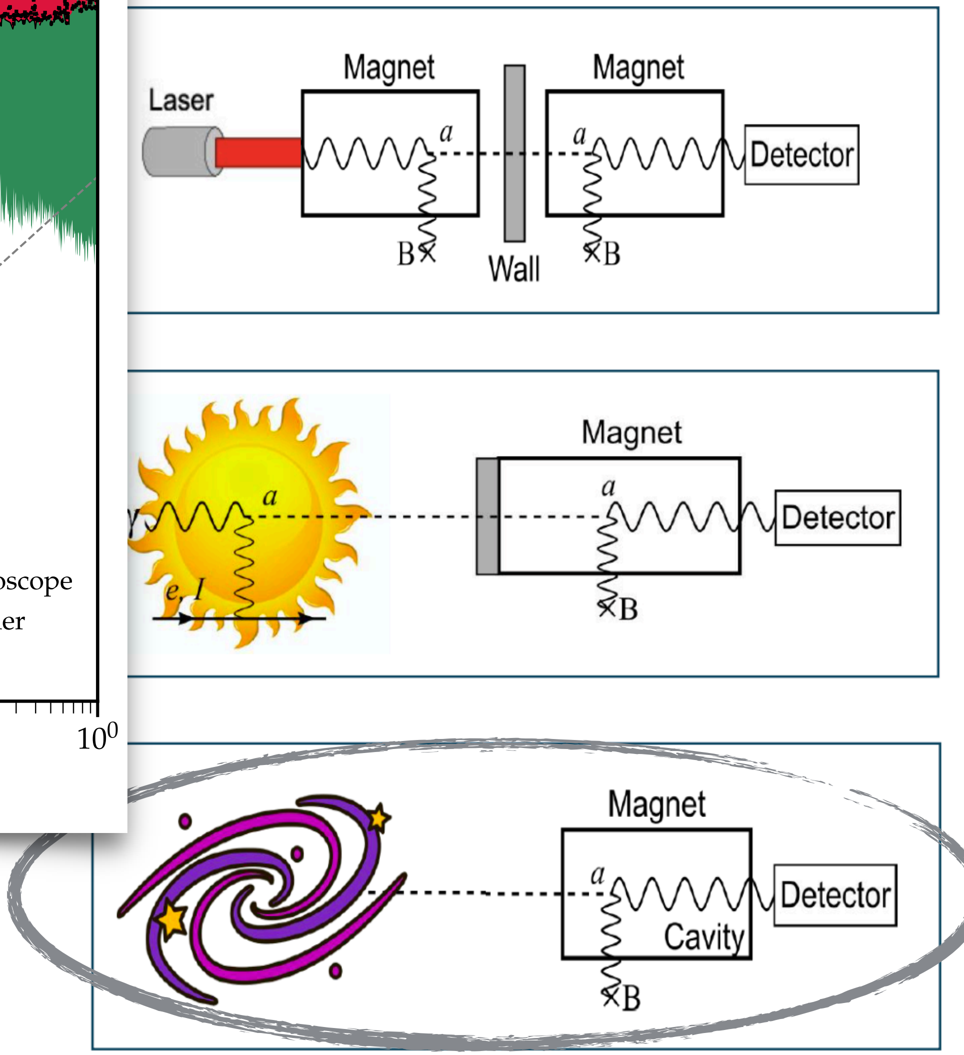


ESPP2019 vs ESPP2026

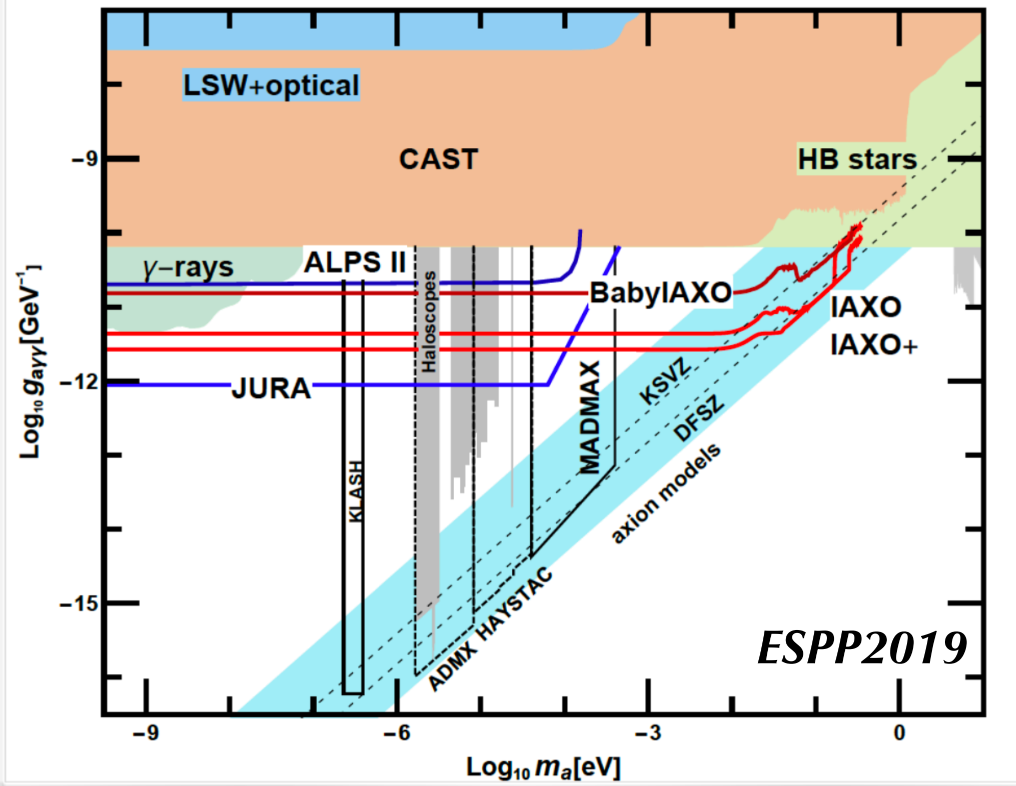
Challenges / Opportunities:

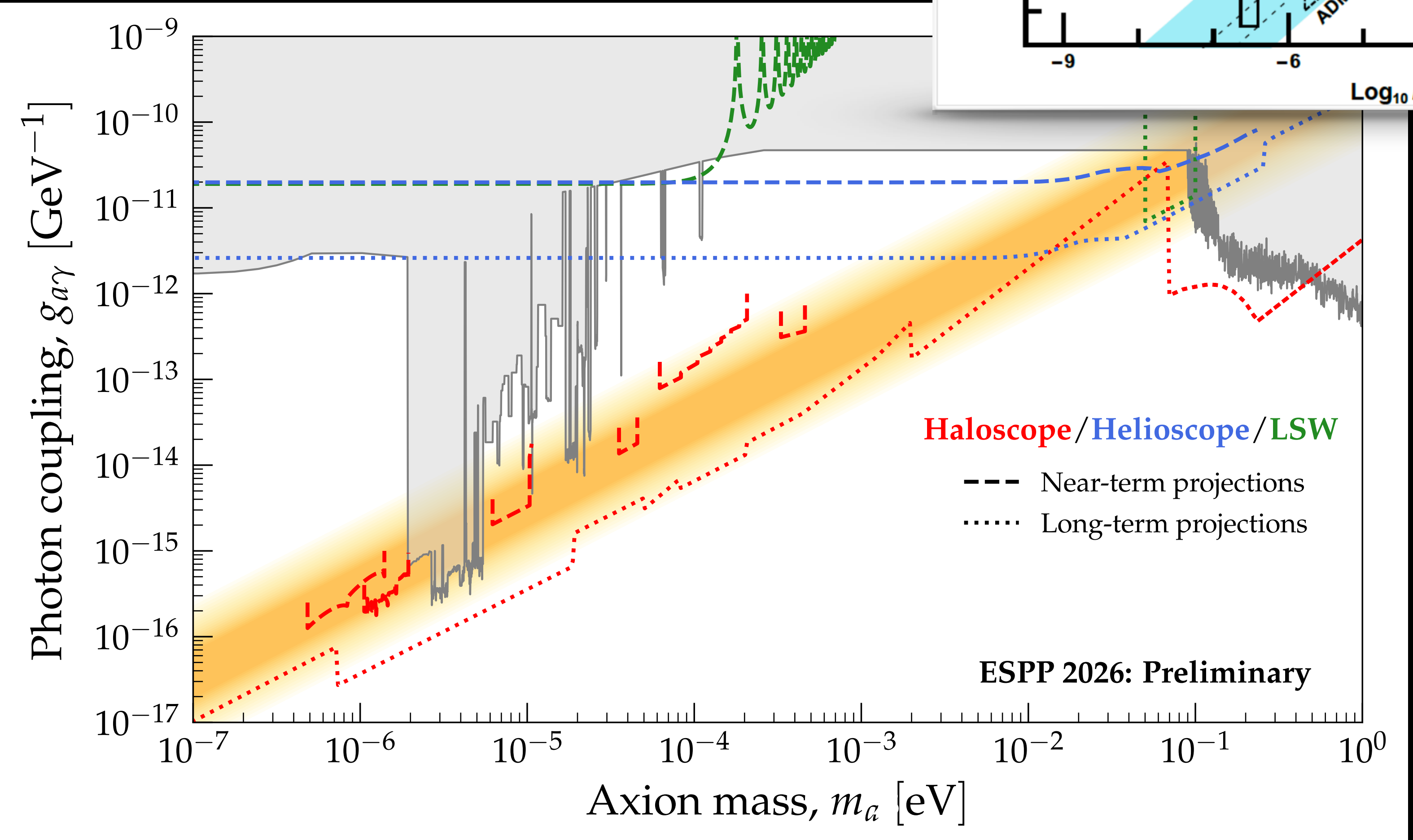
Large parameter space to cover!

- Need for complementary approaches

Mostly smaller experiments so far

- Now upscaling started/needed





"near-term"
~ 5-10 years

"long-term"
> 10 years

ESPP2019 vs ESPP2026

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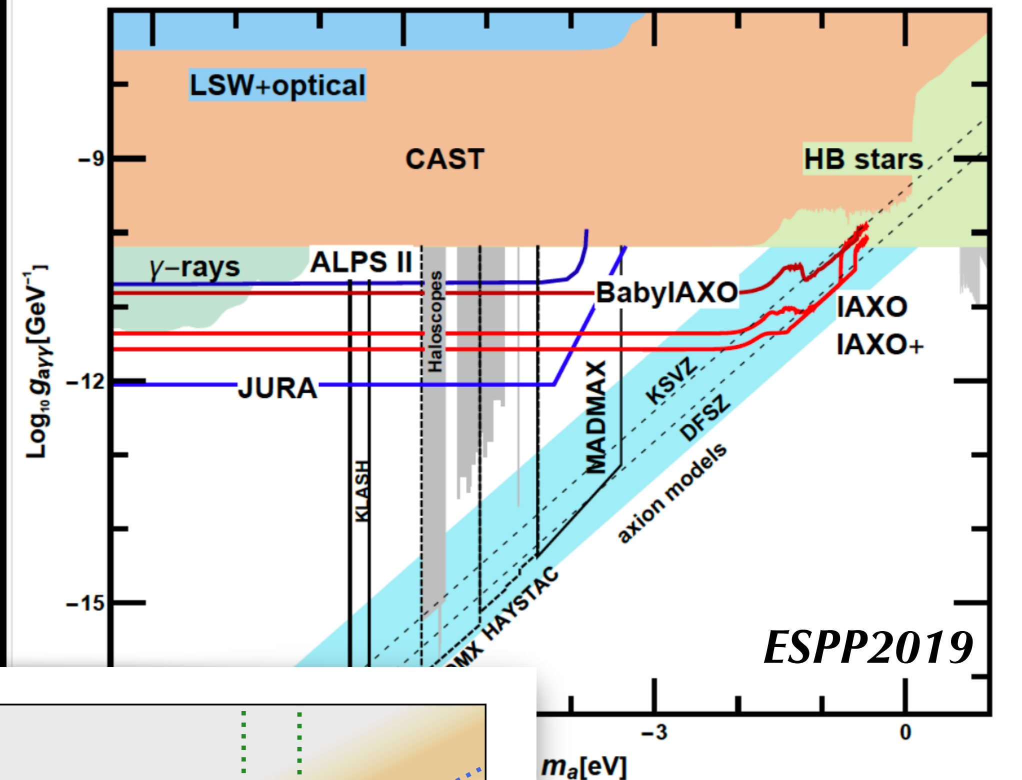
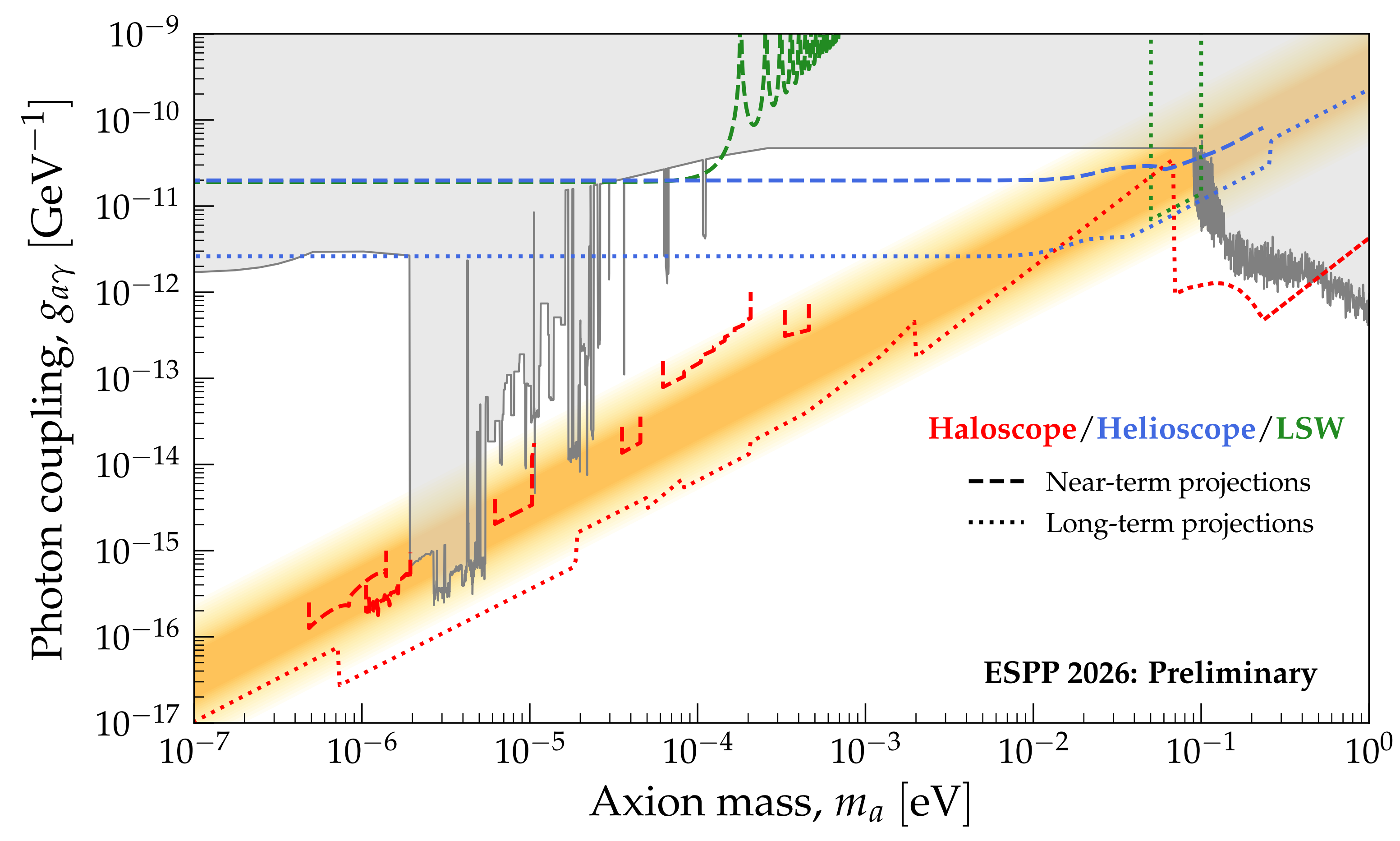
- Now upscaling started/needed





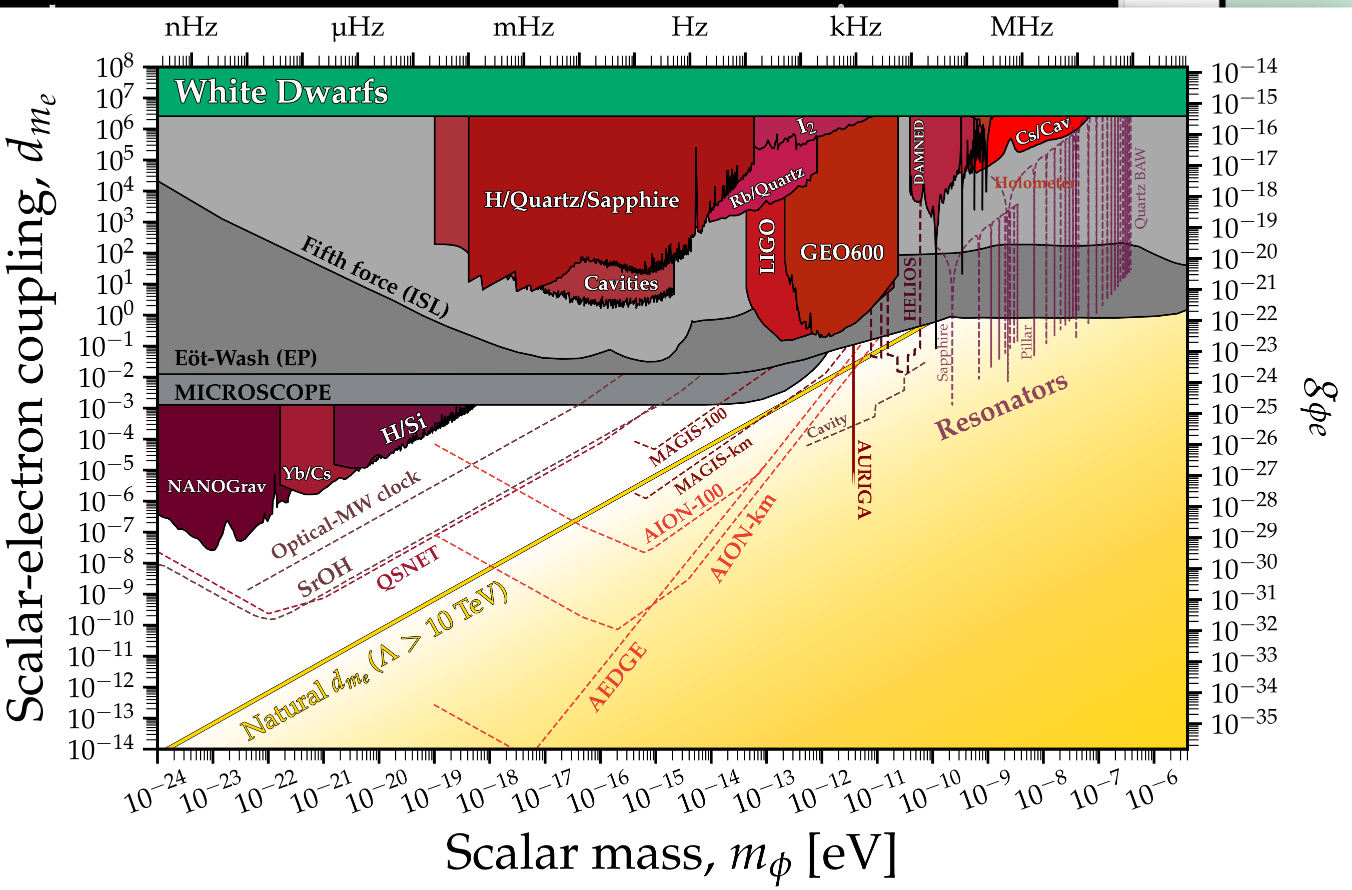
Cross-cutting topics:

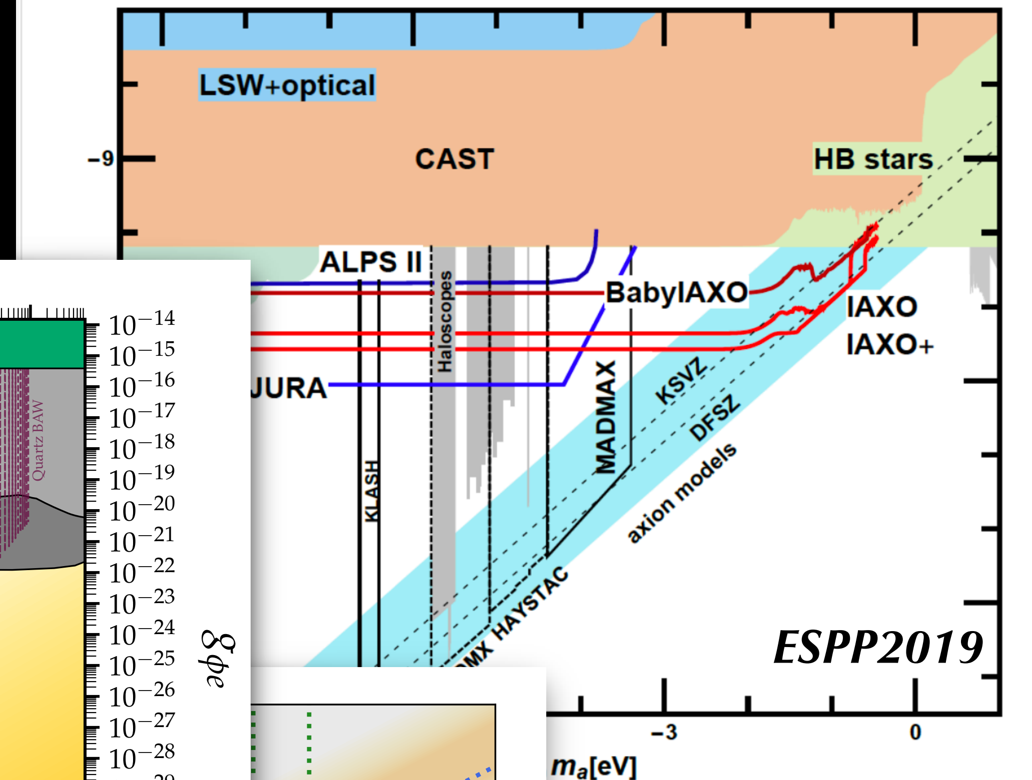
X-ray astronomy, radio astronomy, NMR, gravitational waves, *quantum sensing*

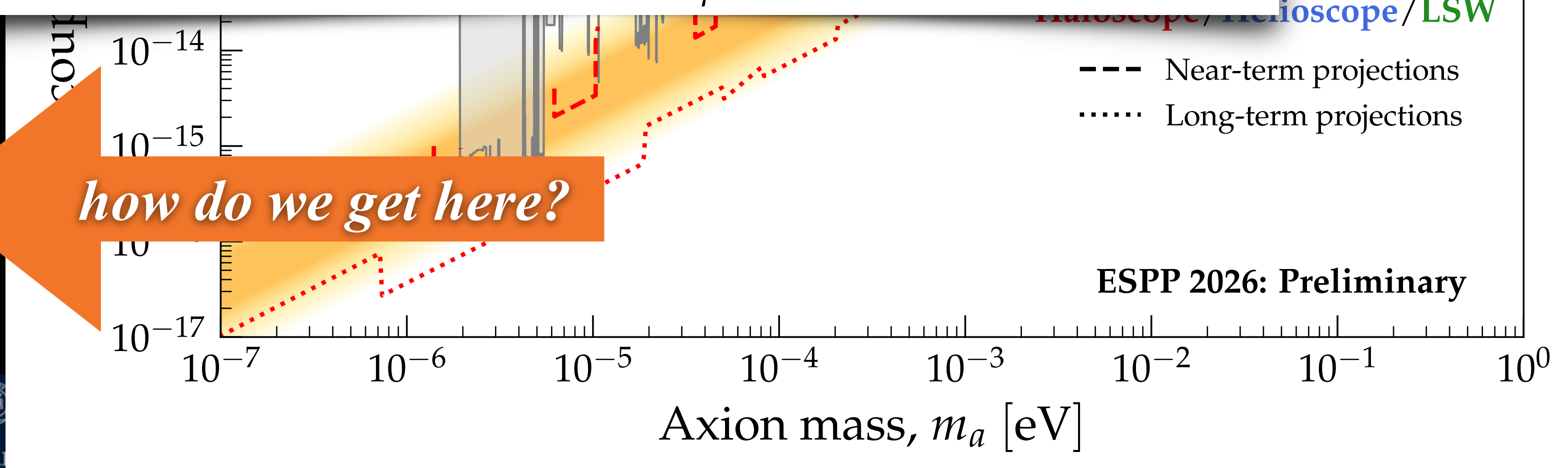
…

ESPP2019 vs ESPP2026

Challenges / Opportunities:







Cross-cutting topics:

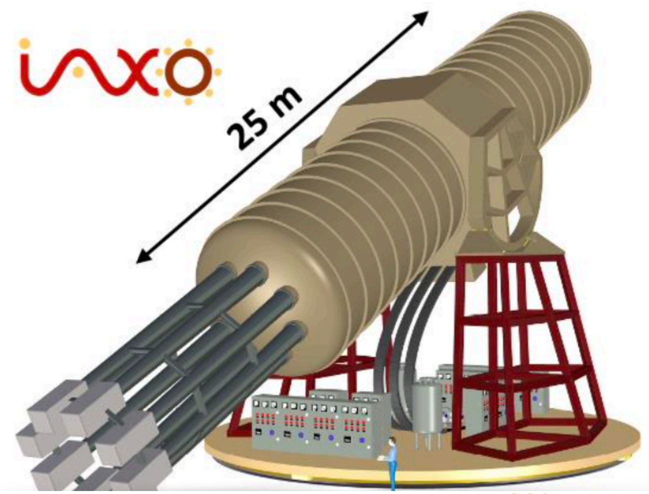
X-ray astronomy, radio astronomy, NMR, gravitational waves, *quantum sensing*

…

Axion Search Programme Upscaling

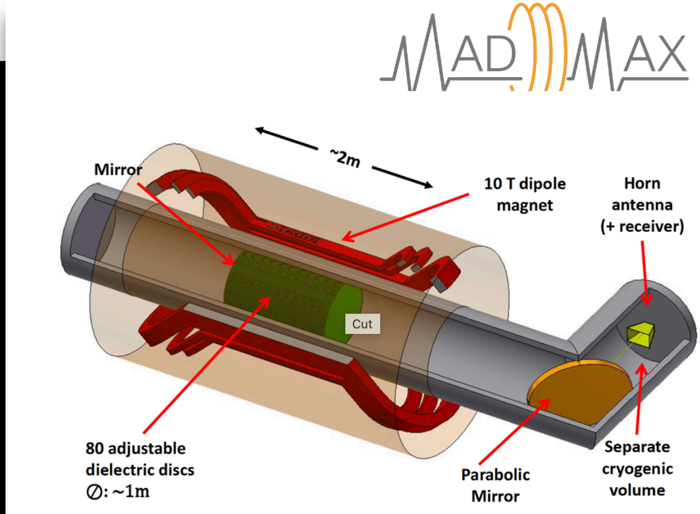
J. Vogel

- Major international effort: International Axion Observatory (IAXO) and intermediate stage BabyIAXO
- Goal: Probe QCD axions at high mass end (meV-eV)
  → Complementary to low mass searches +ALPs+DP+…
- Mature design: upscaling technology
- BabyIAXO@DESY entering construction phase
- Axion-photon, but can also study other couplings (a-e, a-N), post-discovery science capabilities
- Includes haloscope setup for DM searches and HFGW studies

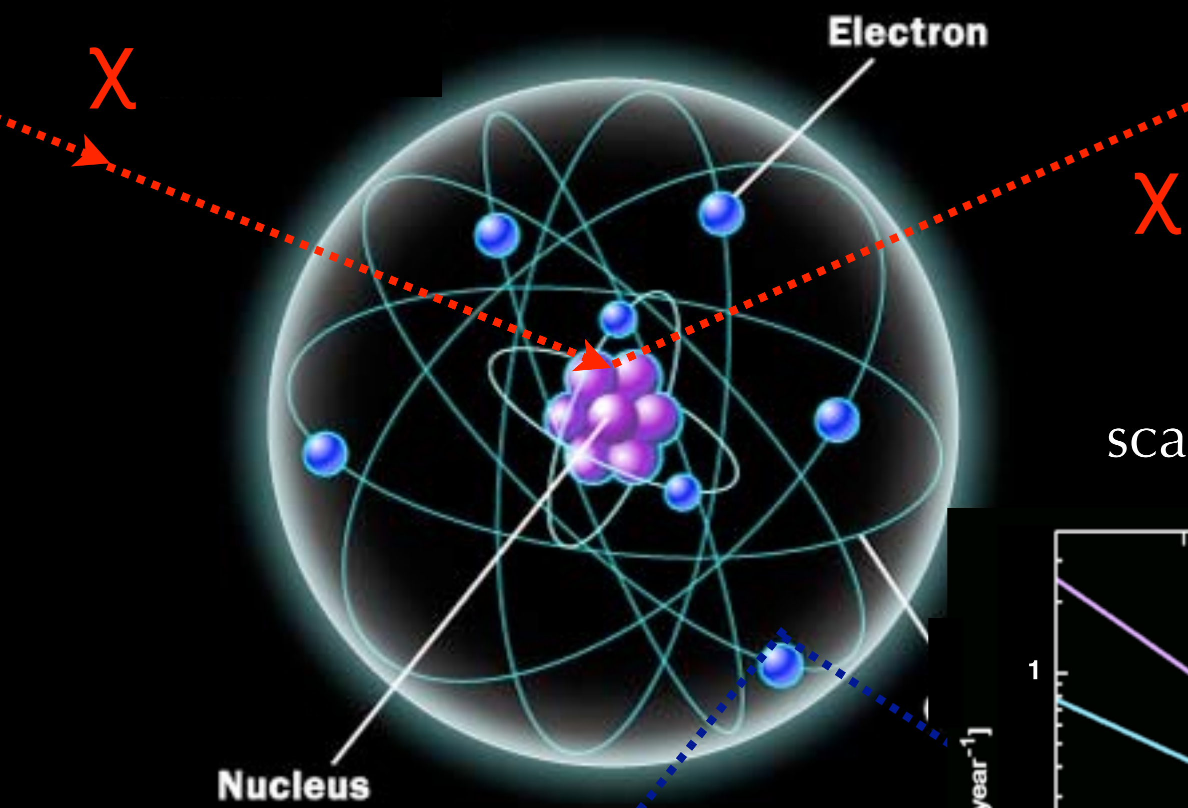


MADMAX @ DESY scaling up

CERN magnet synergy for both



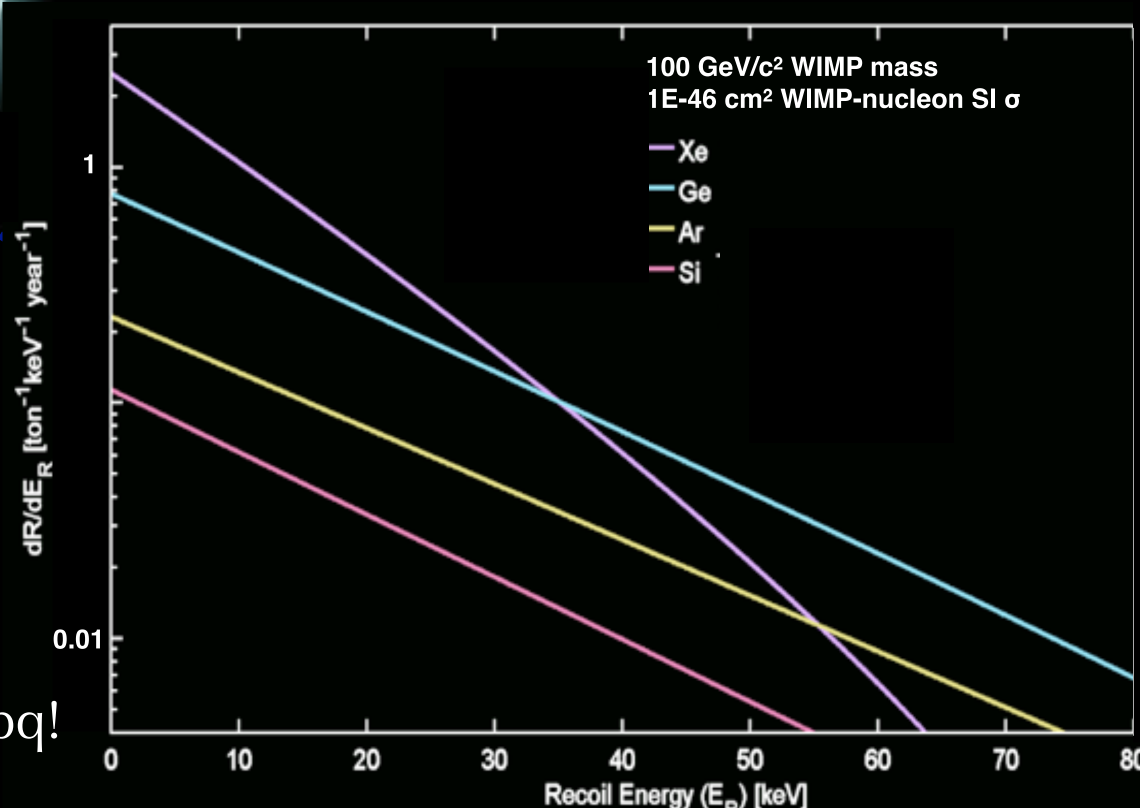
Direct Detection: Particle Dark Matter



Signal: $\chi N \rightarrow \chi N$

(or $\chi e^- \rightarrow \chi e^-$)

scattering kinematics: *v/c ~ 8E-4!*

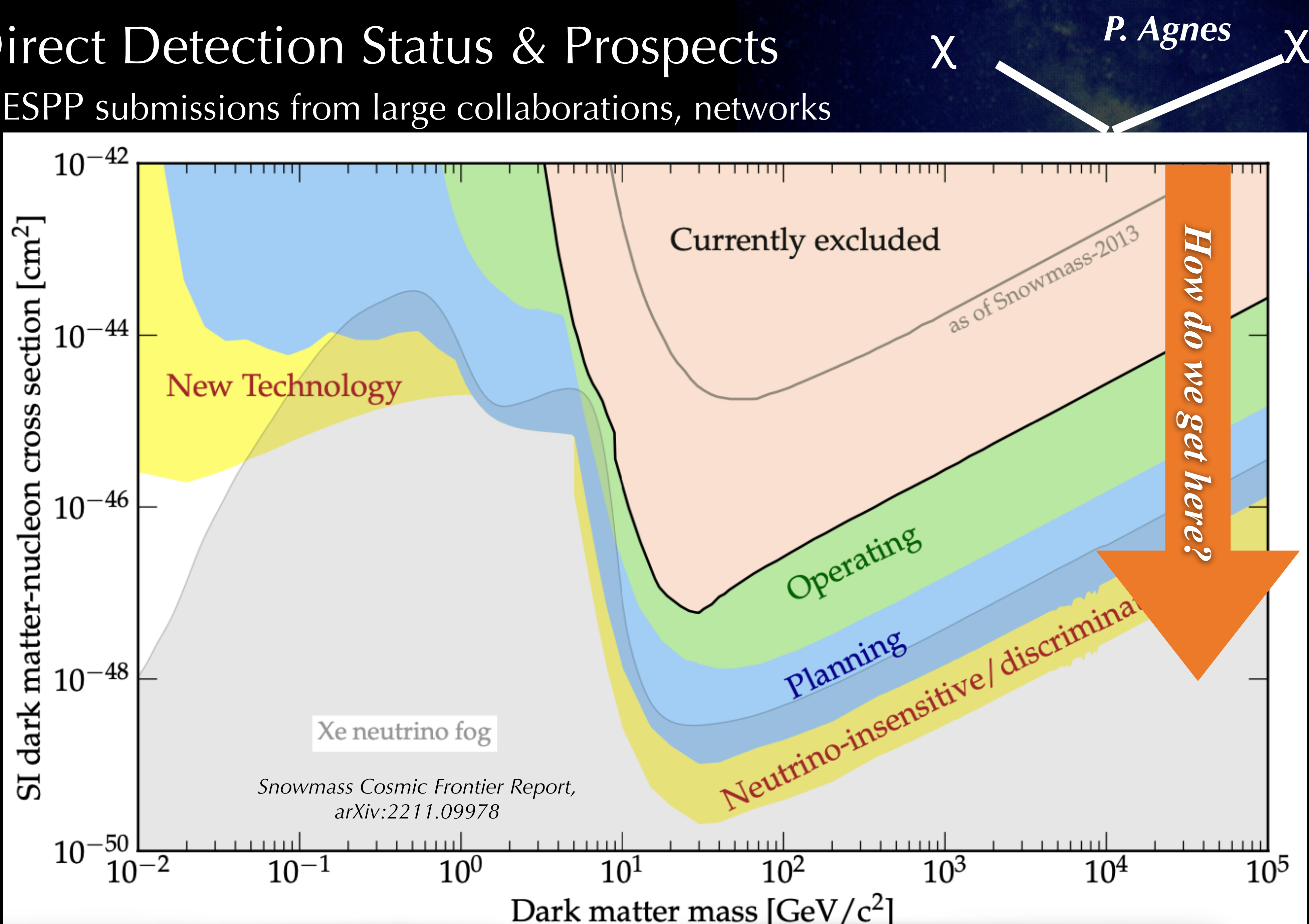


experimental challenges:

1. keV-scale energy threshold +
2. <1/t/y event rate
3. need particle ID at ppm-ppb-ppt-ppq!

Direct Detection Status & Prospects

ESPP submissions from large collaborations, networks



Well established programme (>decade) to reach the neutrino floor > 10 GeV. Most established theoretical synergy (complementarity) and technological synergy

Direct Detection Status & Prospects

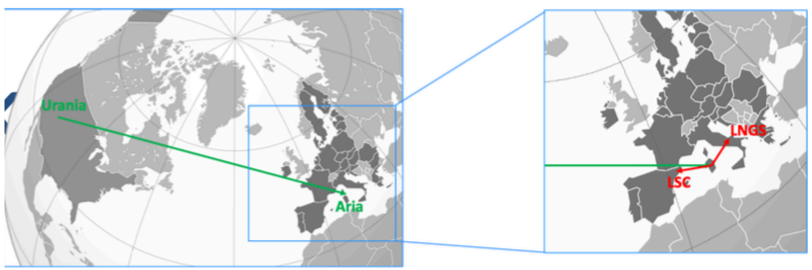
Argon programme: DarkSide-

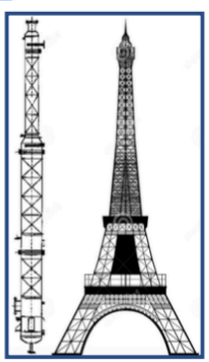
DarkSide-20k, currently in construction at LNGS (**50 t active**)

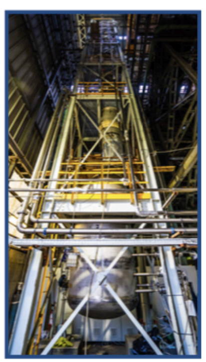
— protoDUNE-like cryostat delivered by **CERN**, already built underground

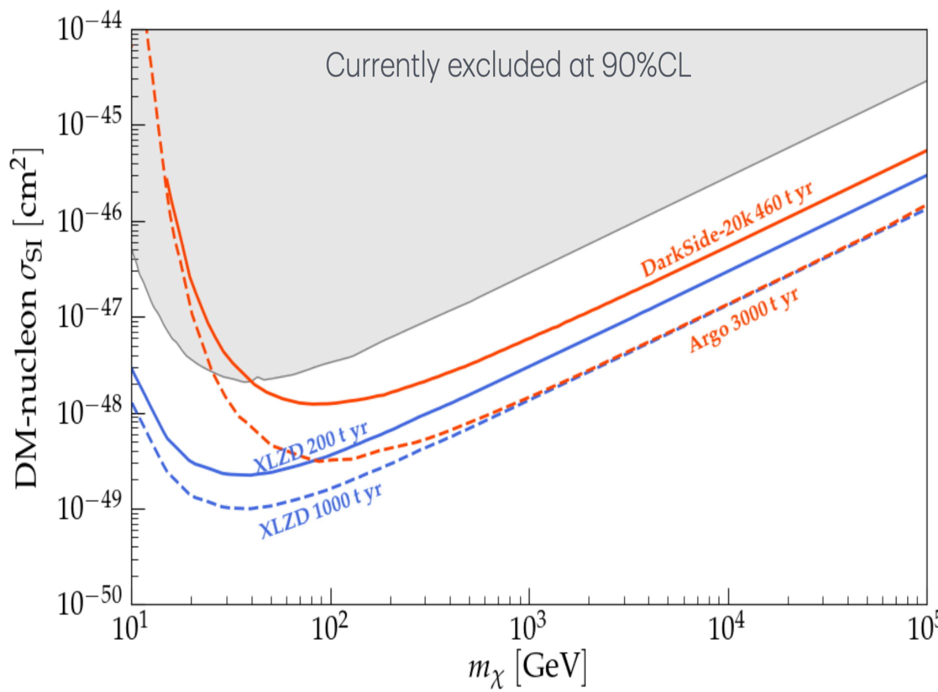
— will use need extraction and purification of **100 t** of argon from underground CO2 well (depleted from radioactive 39Ar)

— pioneers large area SiPM light detectors (25 m^2)









URANIA (Colorado) and ARIA (Sardinia)

P. Agnes

Direct Detection Status & Prospects

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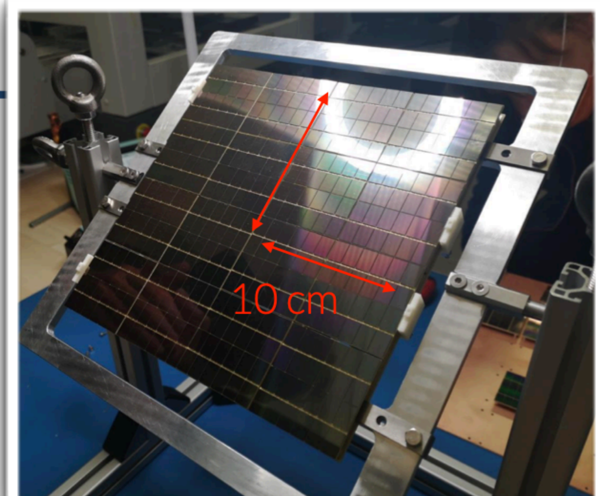

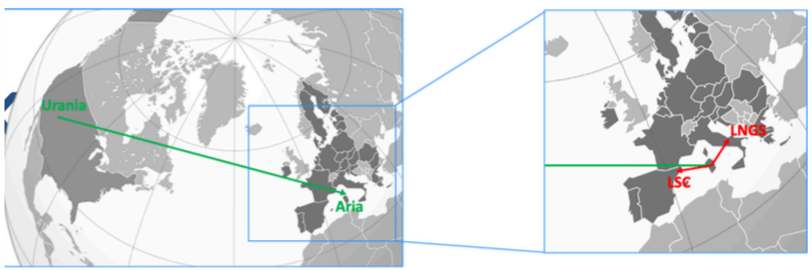

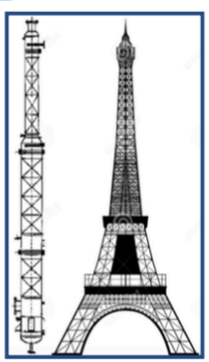

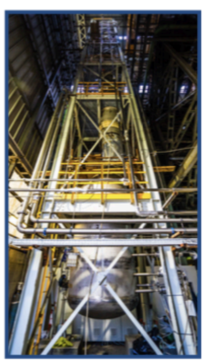

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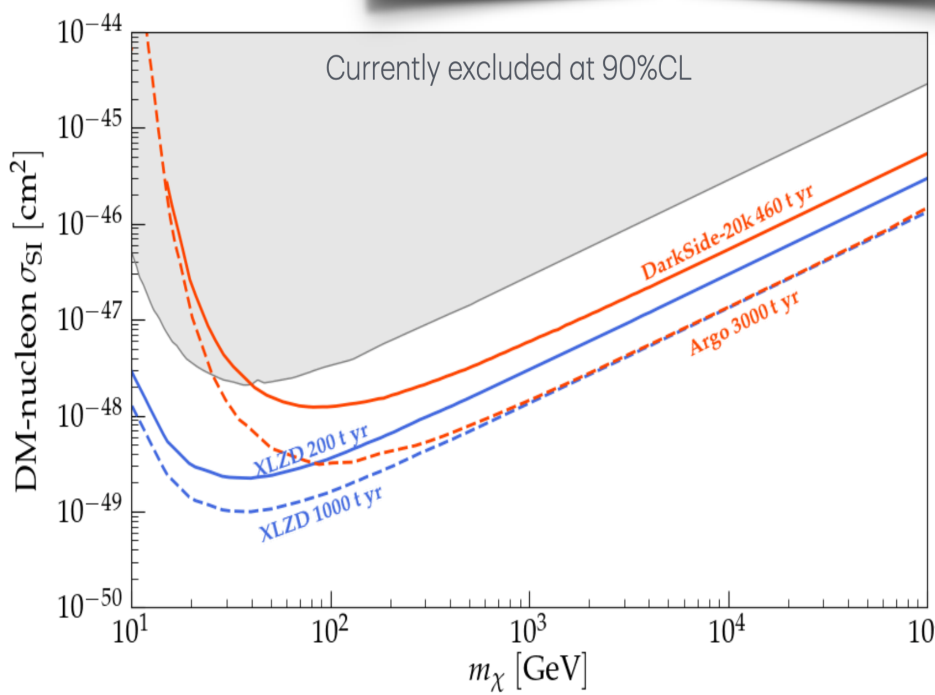

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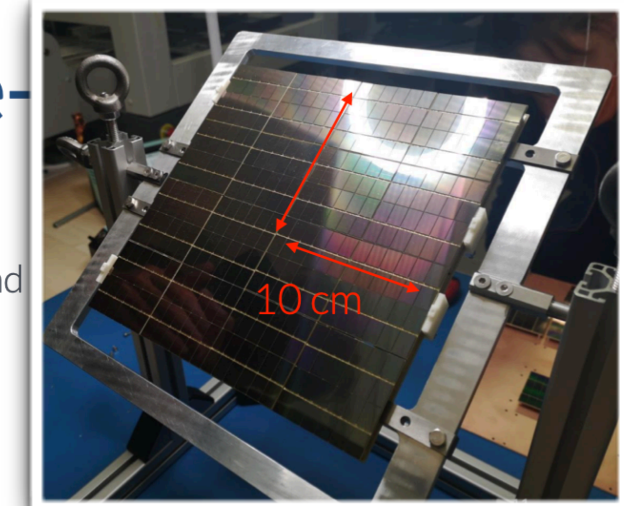

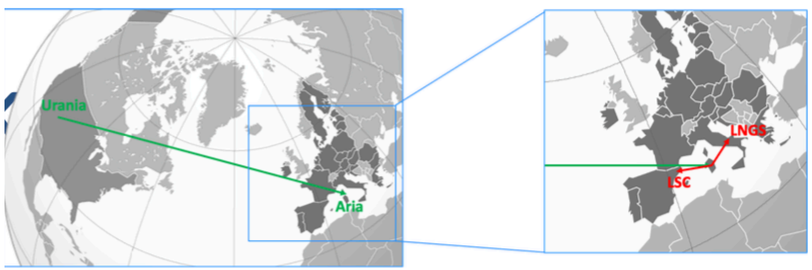

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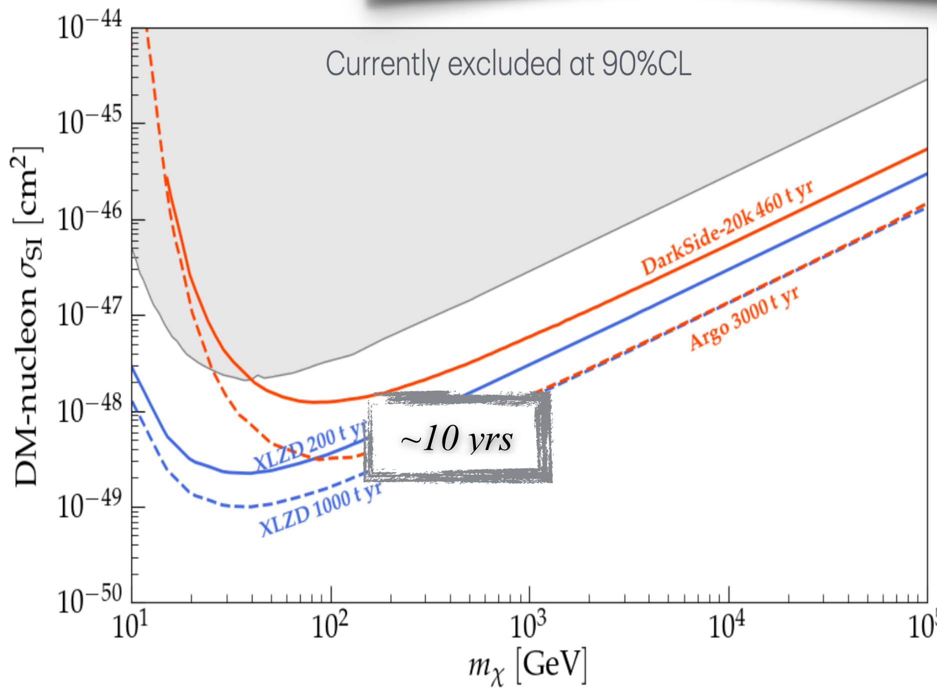

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Direct Detection Status & Prospects

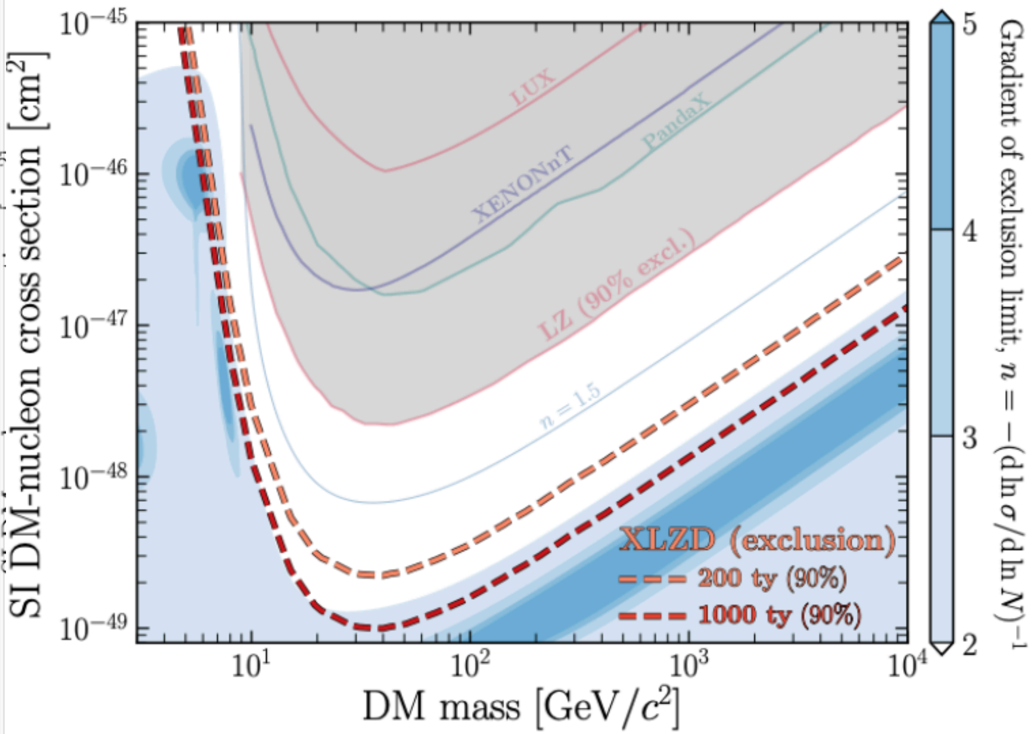
Xenon programme XLZD

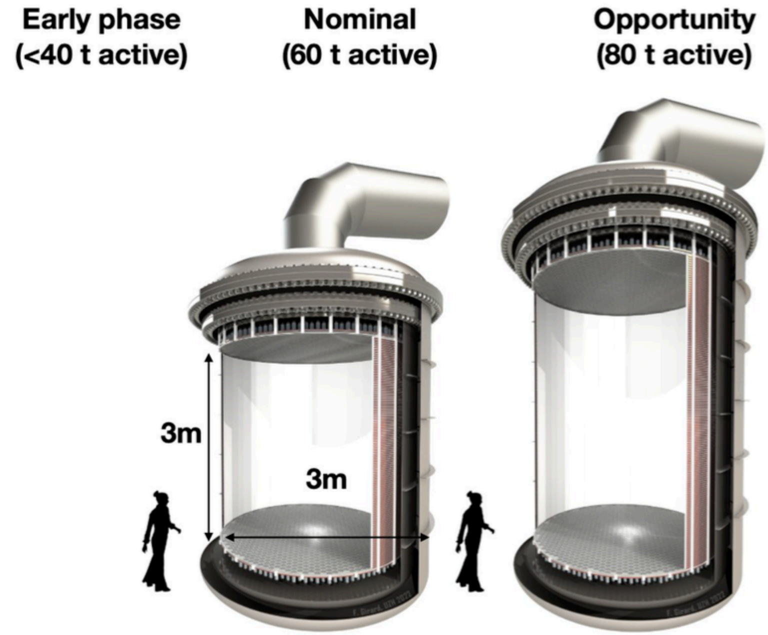
XENONnT+LZ

Reach physics reach, including **DM**, **0νββ (136Xe),** SN and solar neutrinos, double electron capture…

R&D ongoing for drift field (3 m), internal 222Rn contamination (target: 0.1 μBq/kg)

Selection of hosting underground site (LNGS, Boulby) in 2026, **TDR** expected in 2027





How do we get here?

P. Agnes

Direct Detection Status & Prospects

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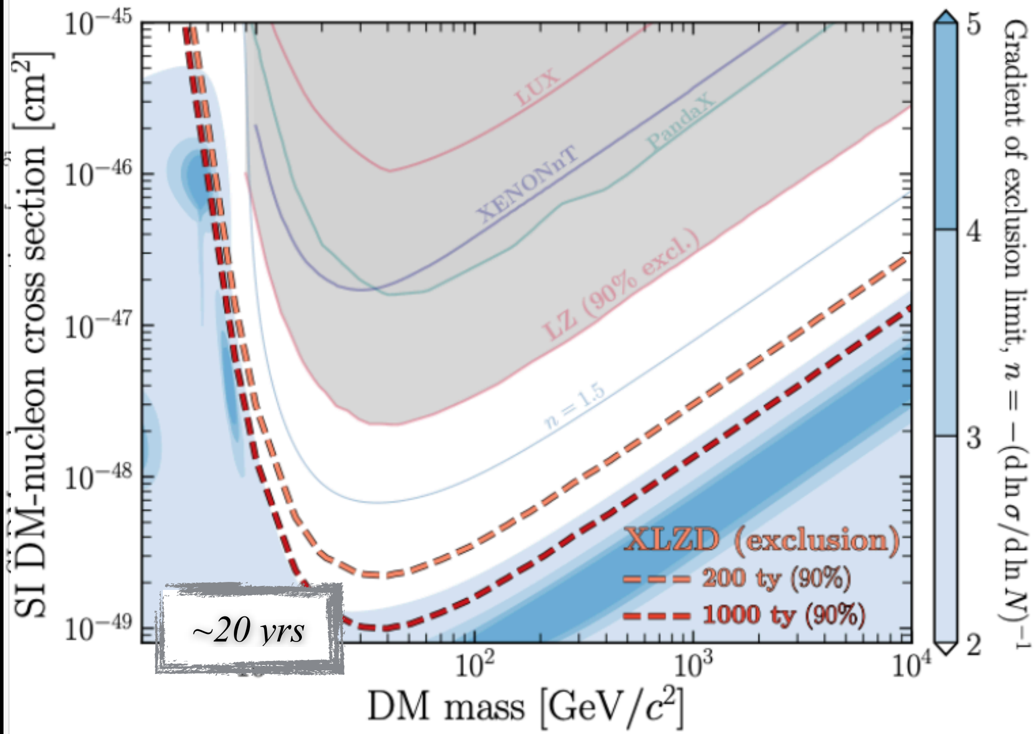

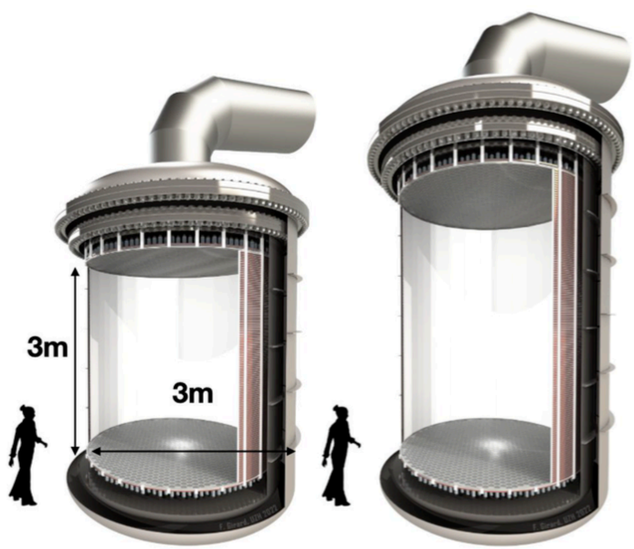

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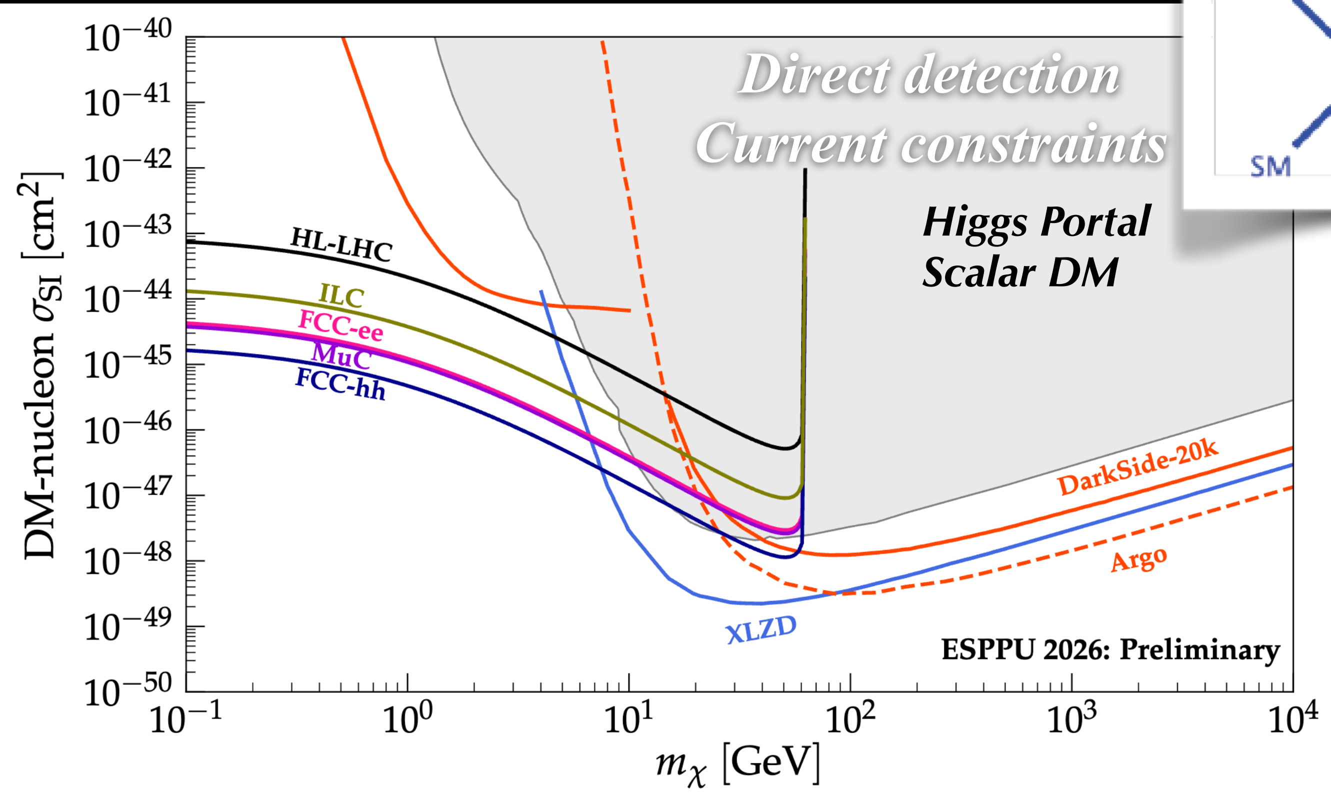
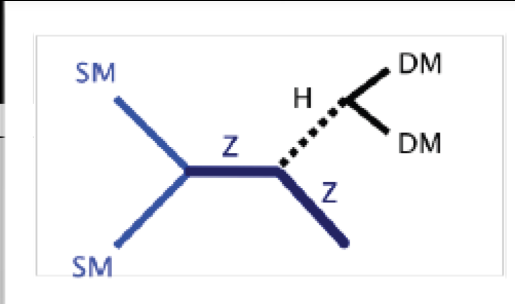
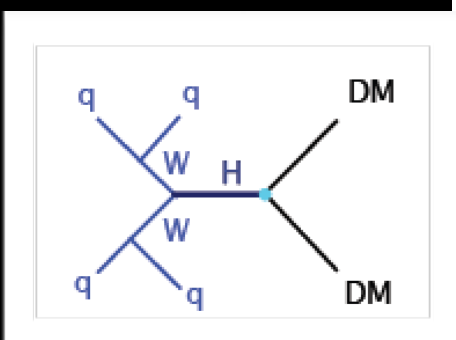
Collider Complementarity

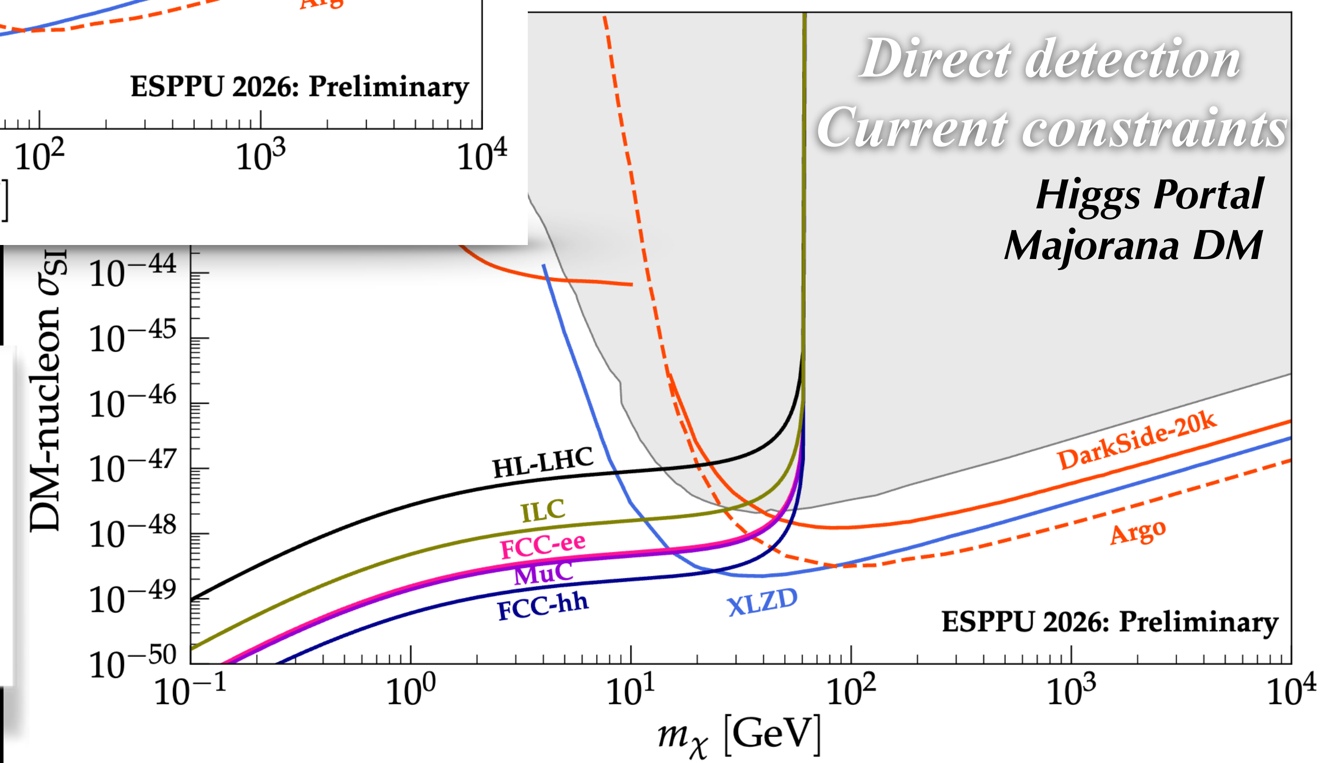




limits on branching ratio translated to limits on cross section vs. mass

Caveat: model dependence In conversion





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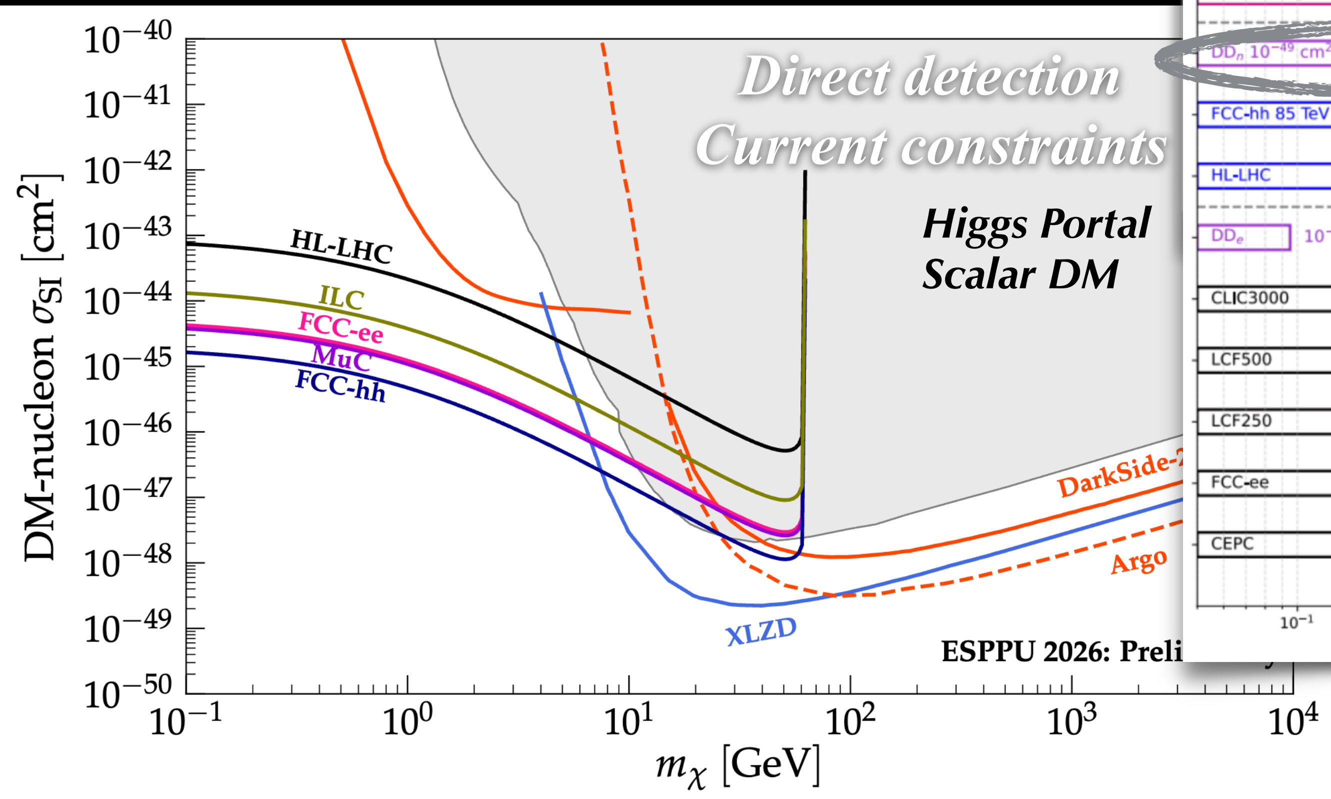

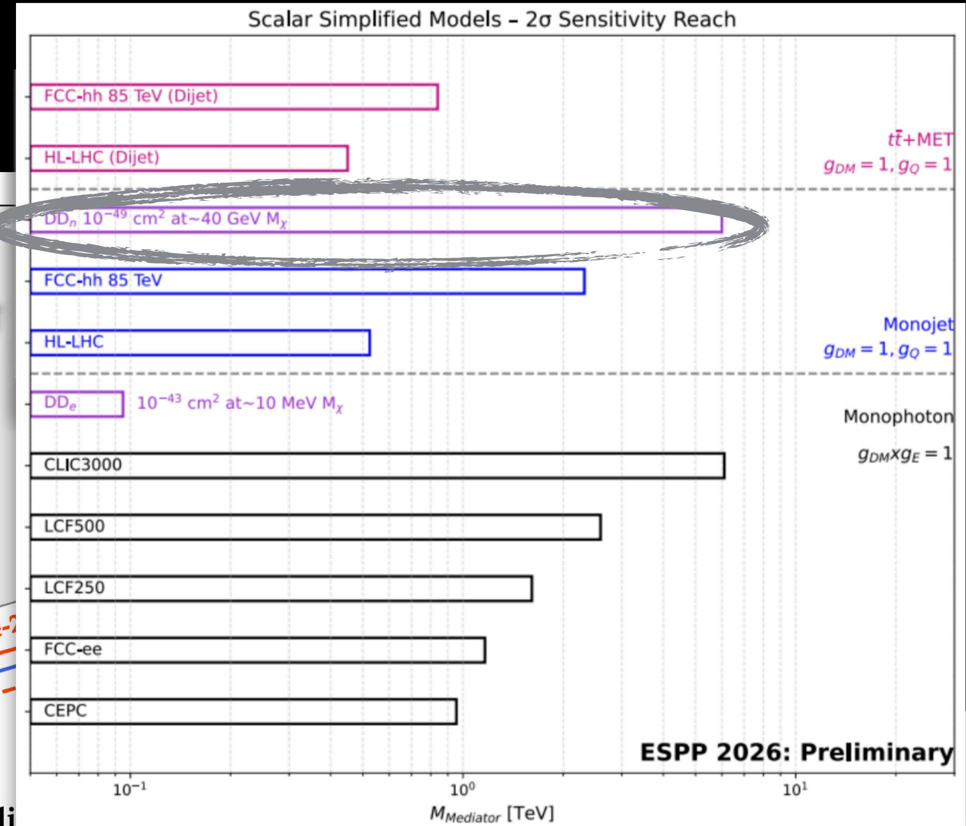

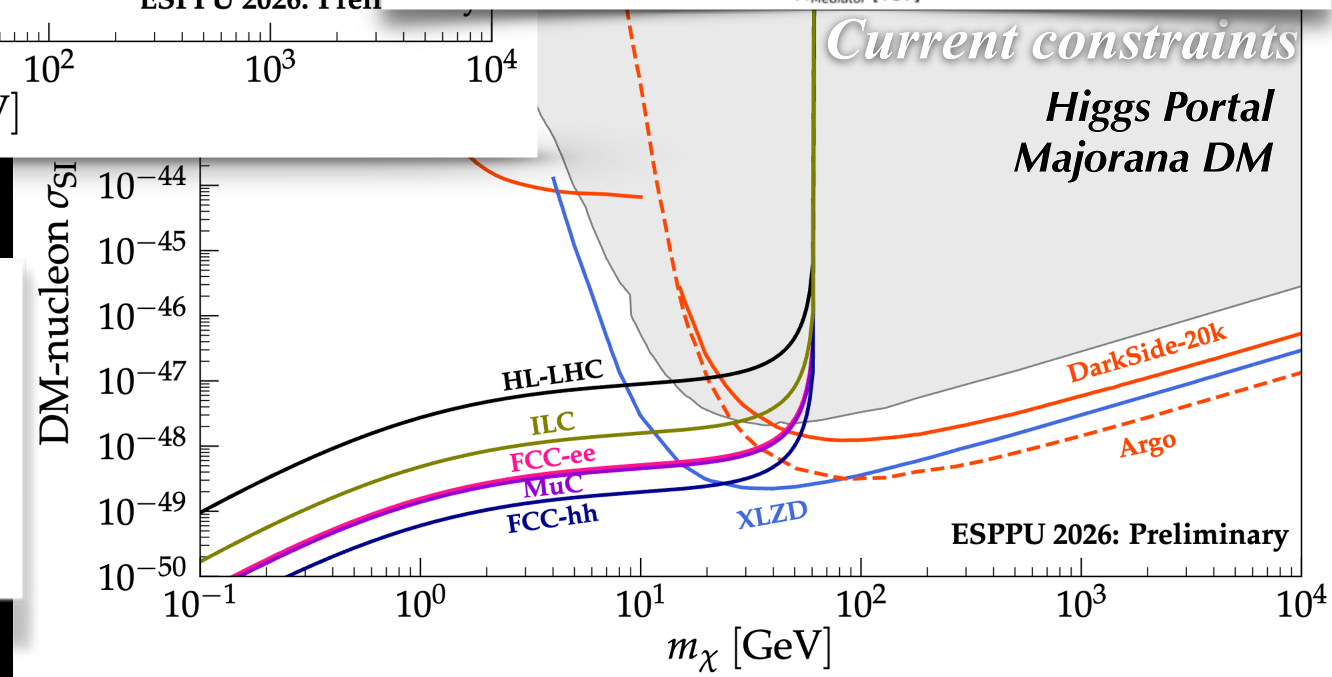

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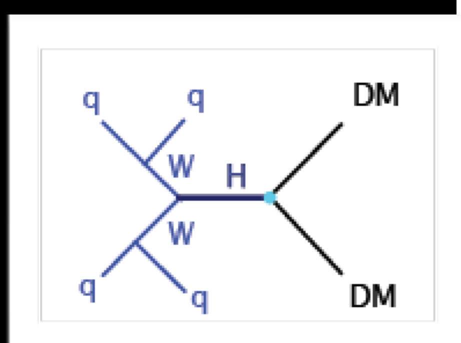
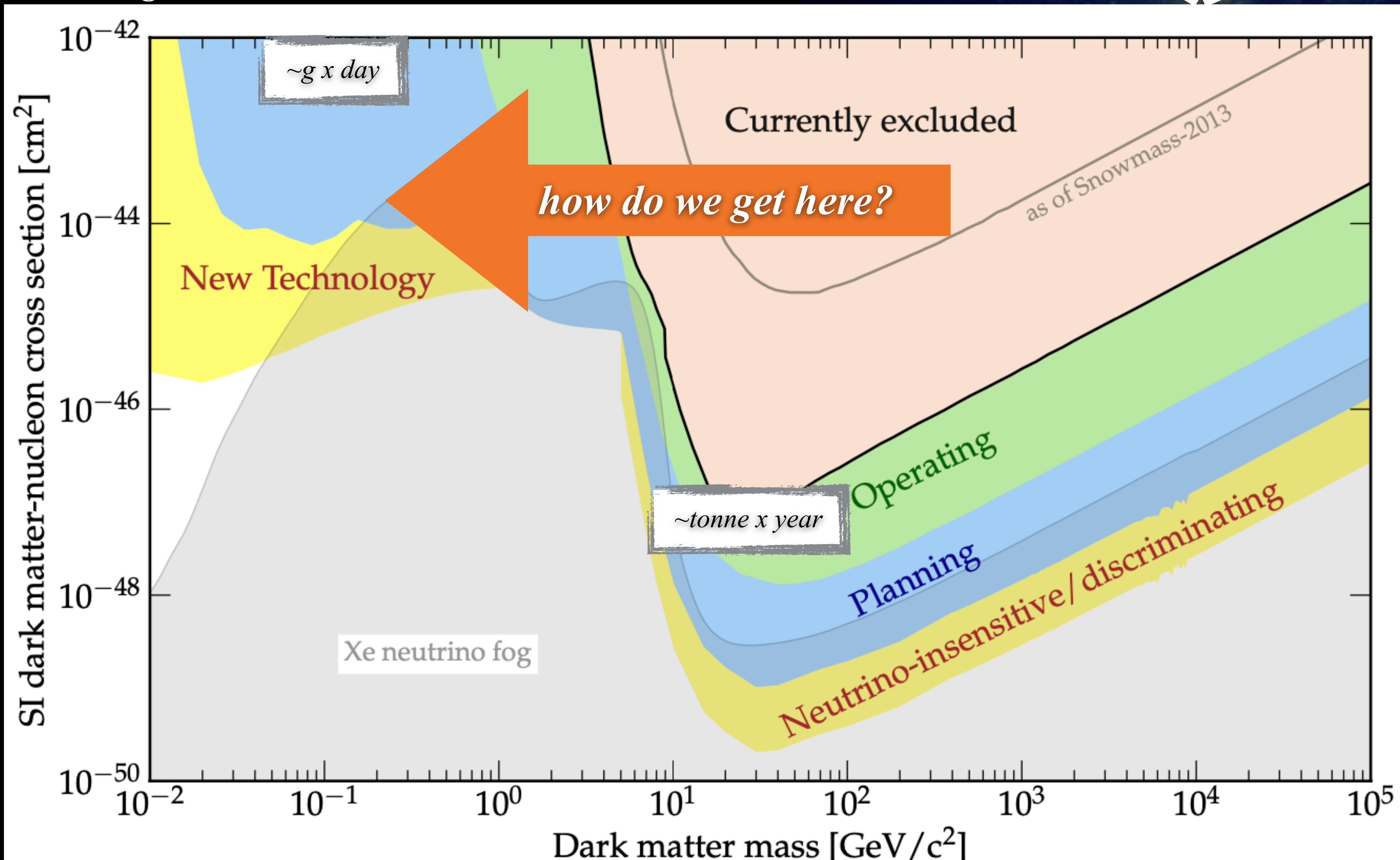


Light Dark Matter

area of growth since ESPP2019

Snowmass Cosmic Frontier Report, arXiv:2211.09978



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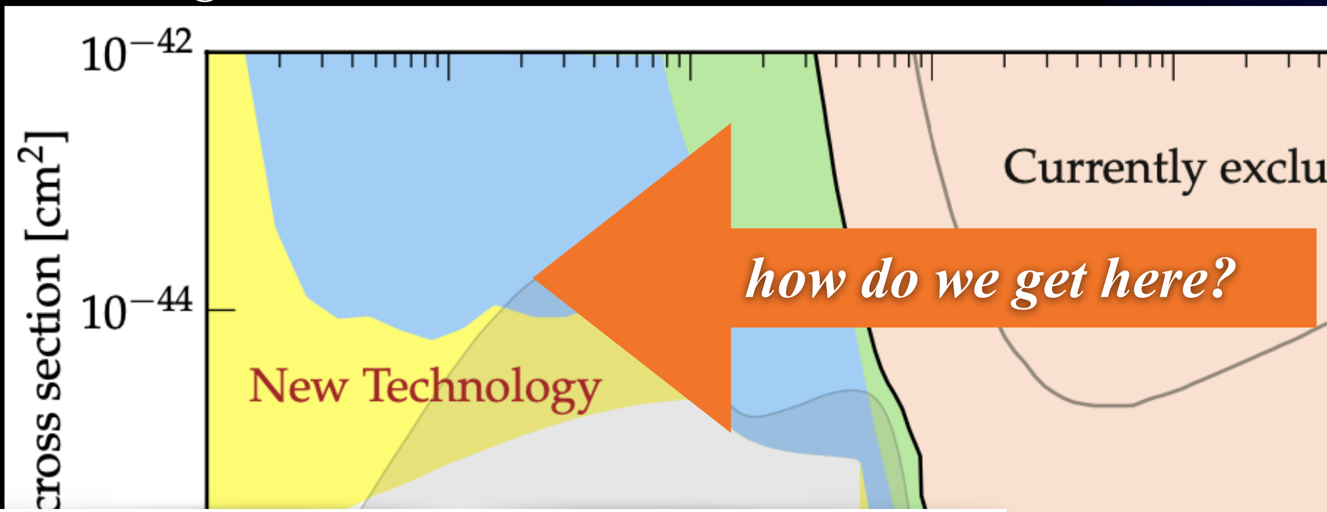
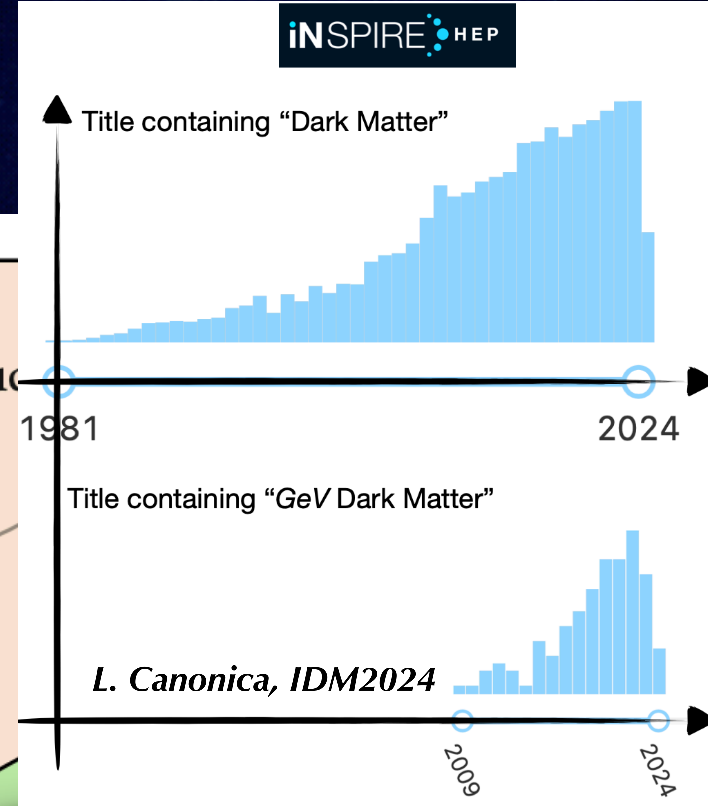
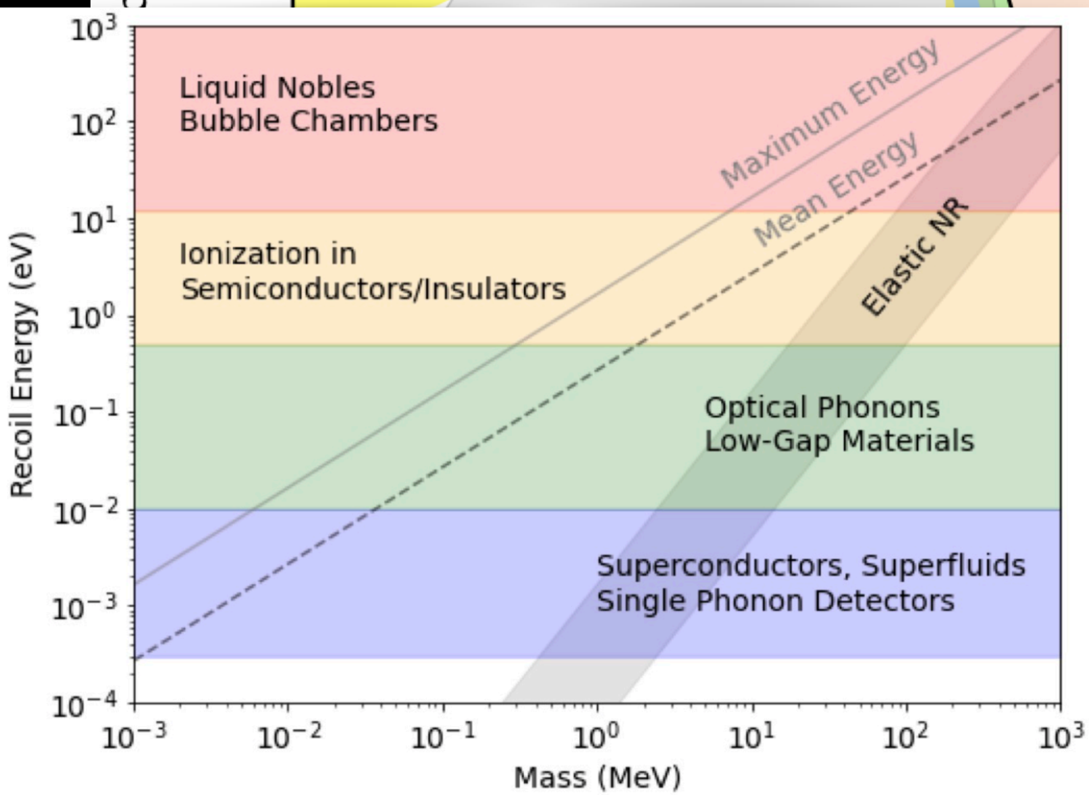
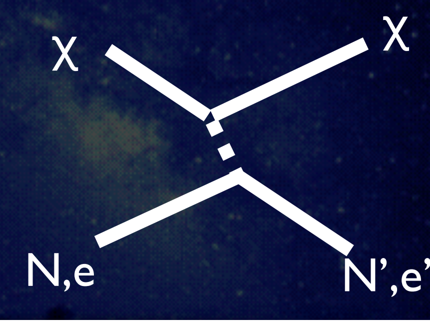


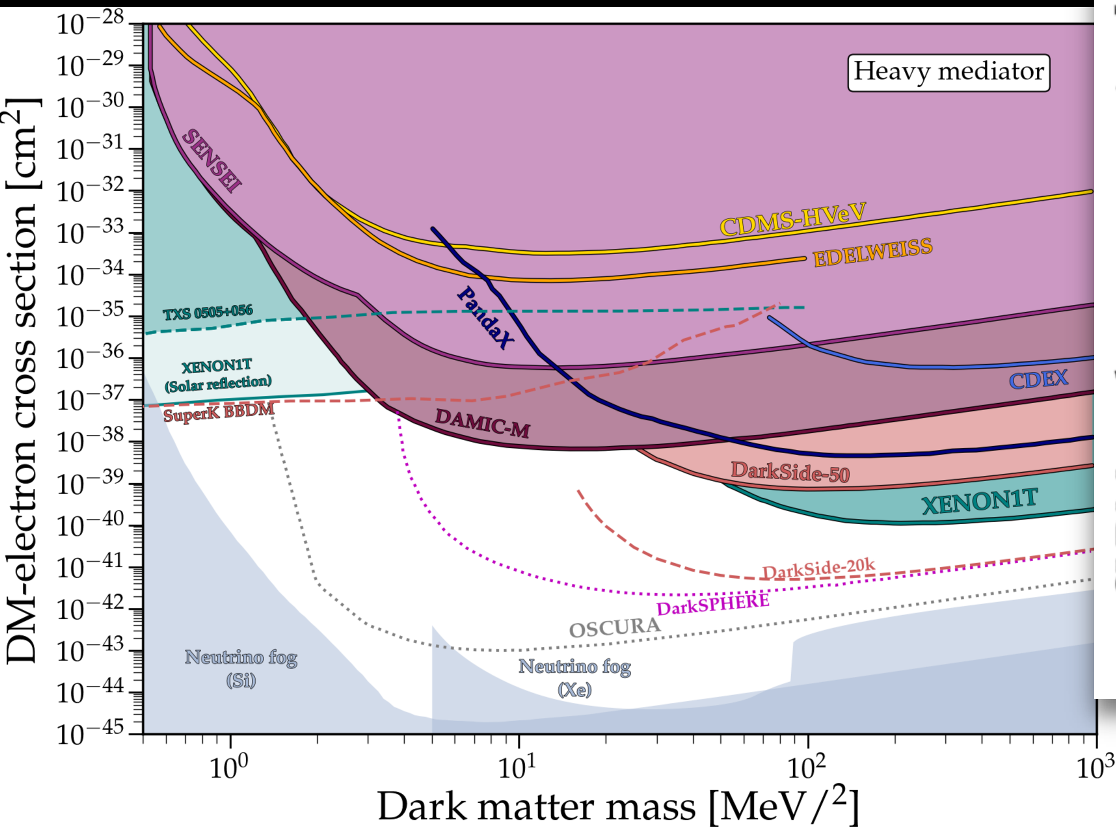


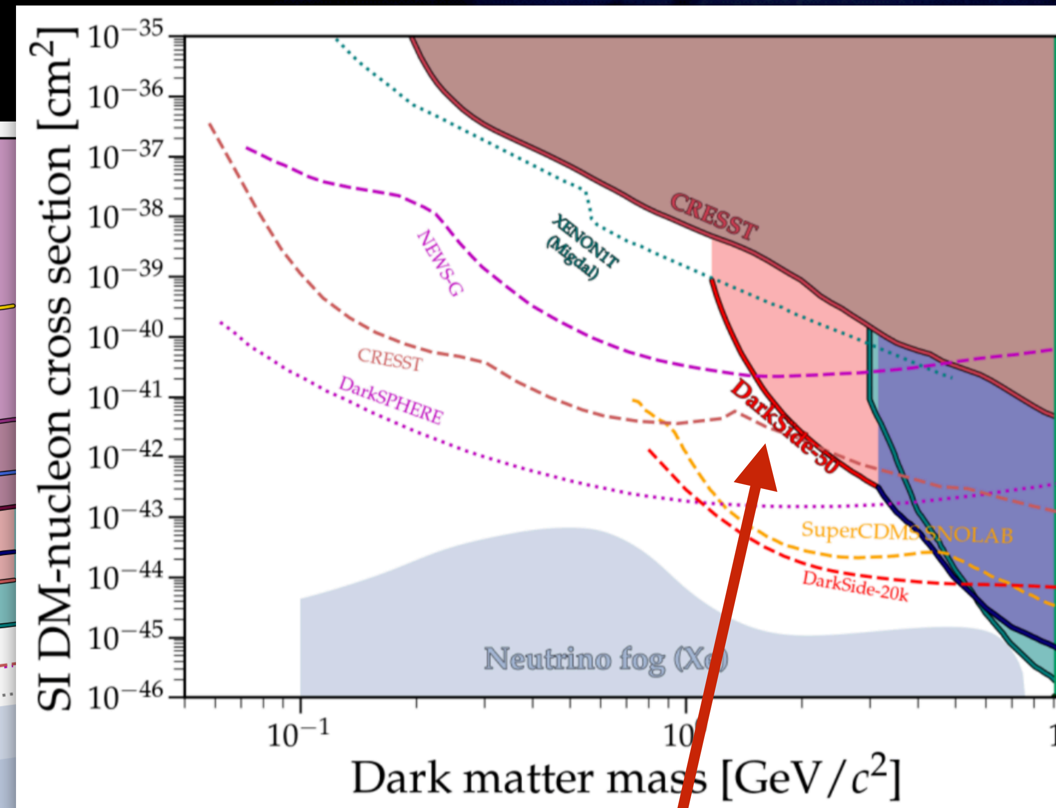


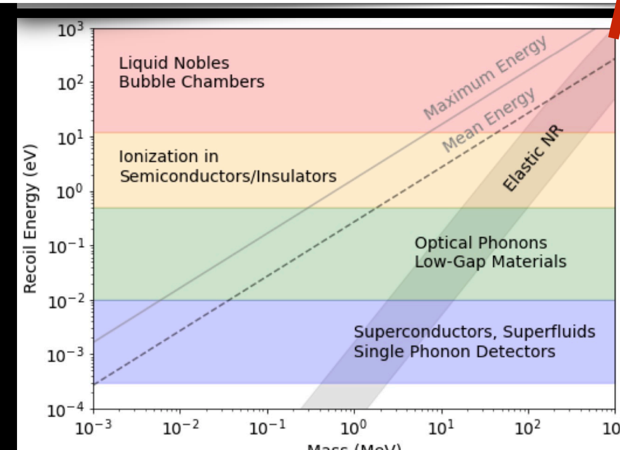
Light Dark Matter

Combination of new analysis strategies and dedicated, small experiments



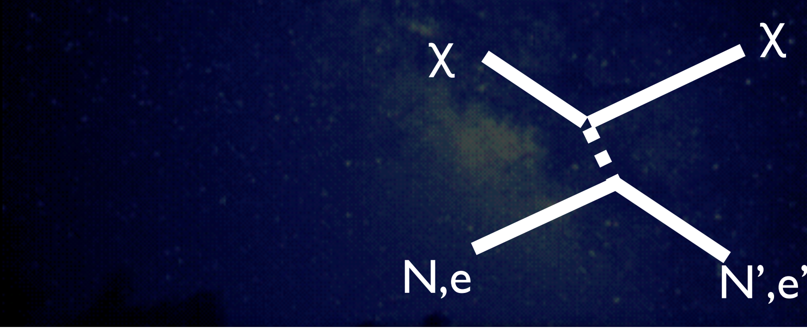




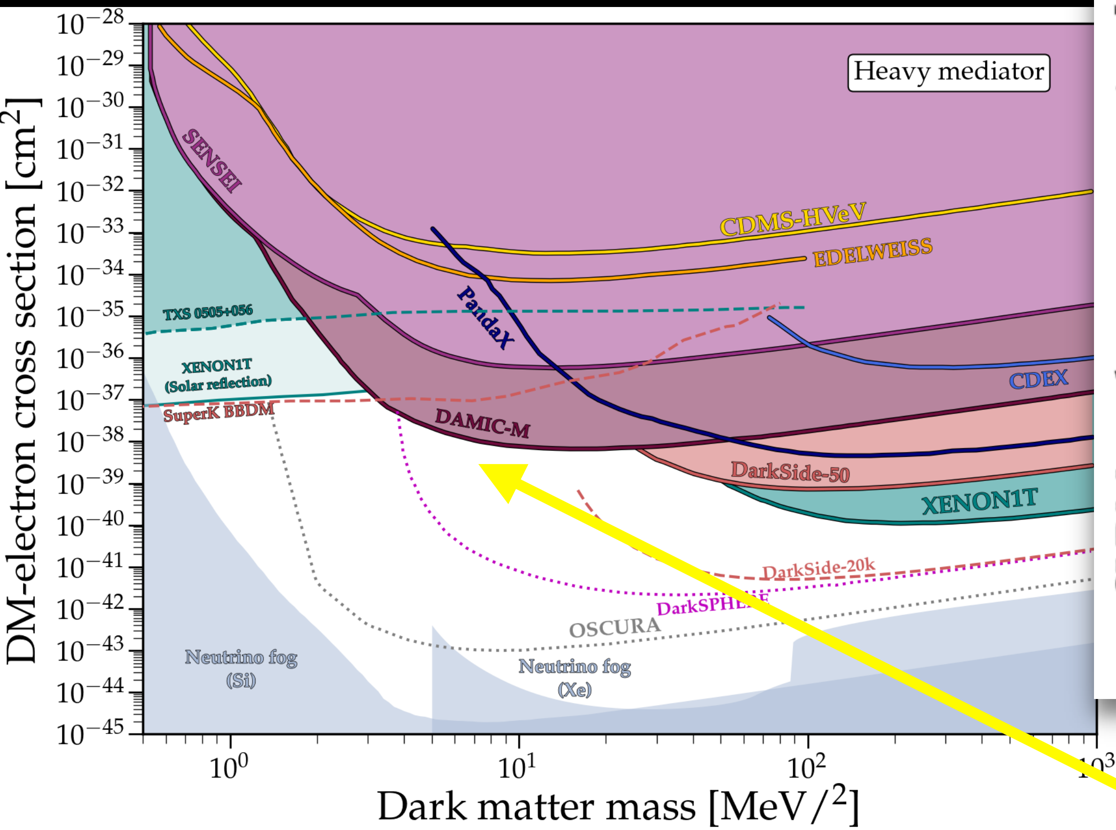


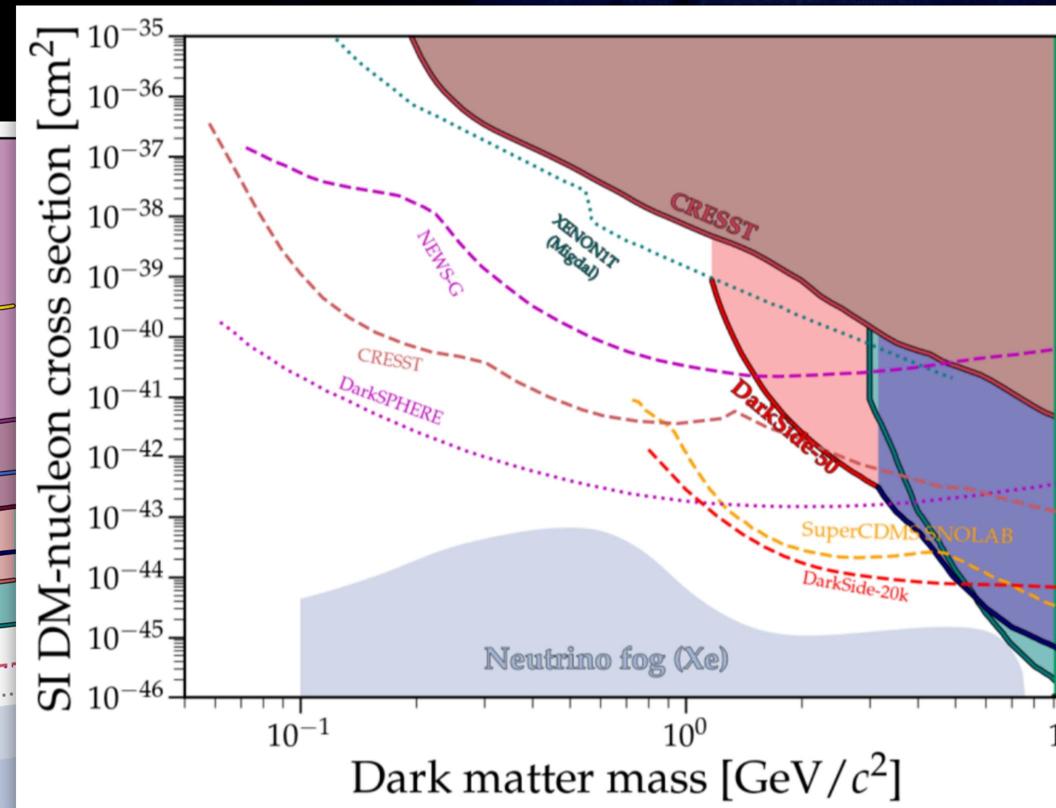
C. O'Hare, *https://github.com/cajohare*

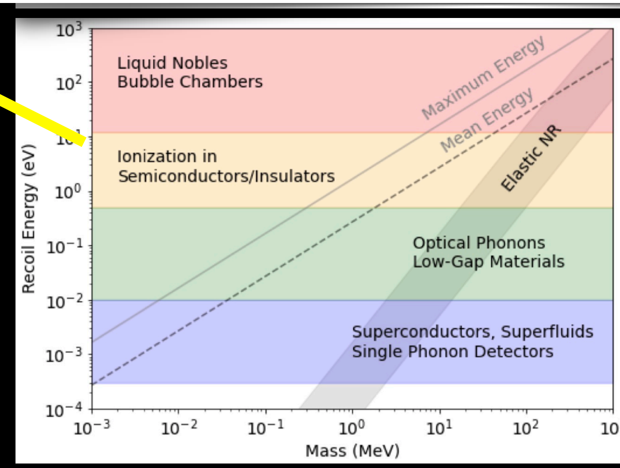
Light Dark Matter



Combination of new analysis strategies and dedicated, small experiments

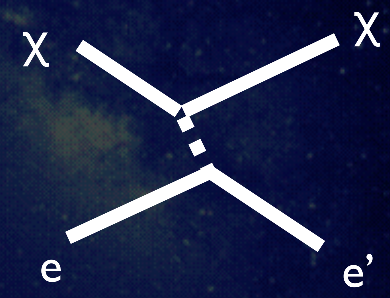






Since ESPP2019, increased focus on electron final states

Light Dark Matter



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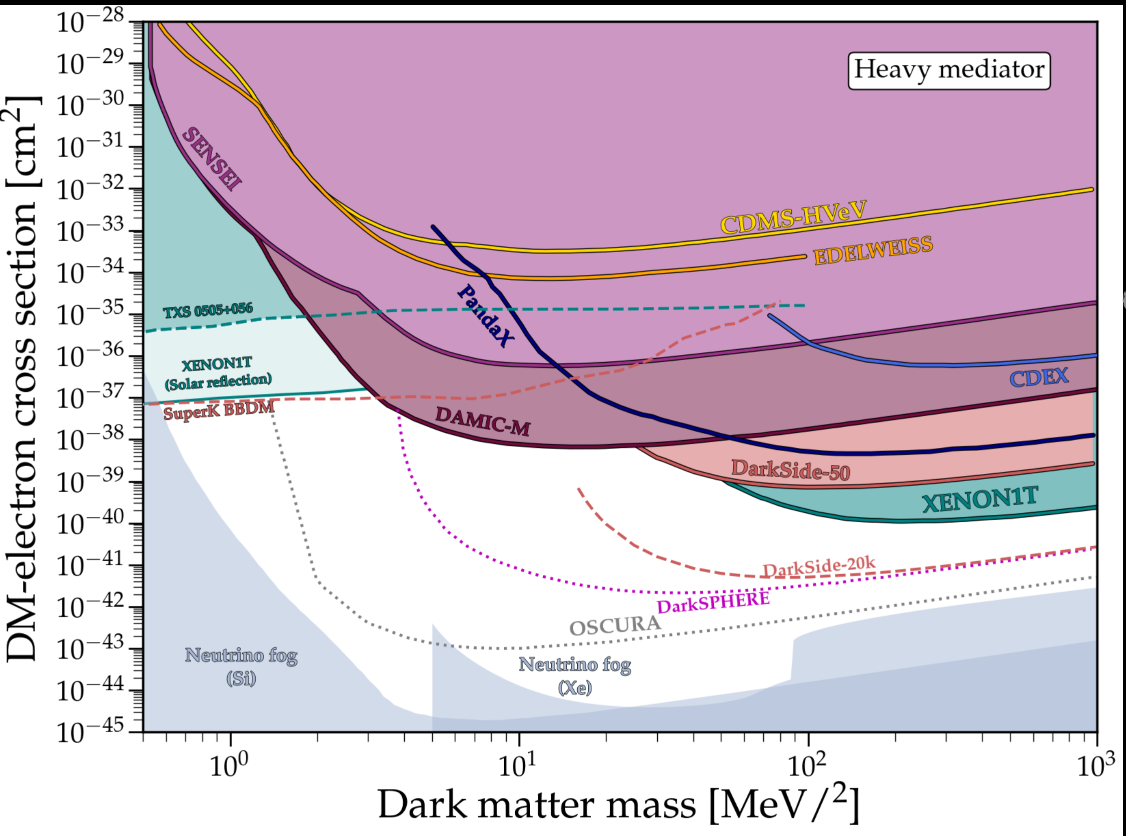
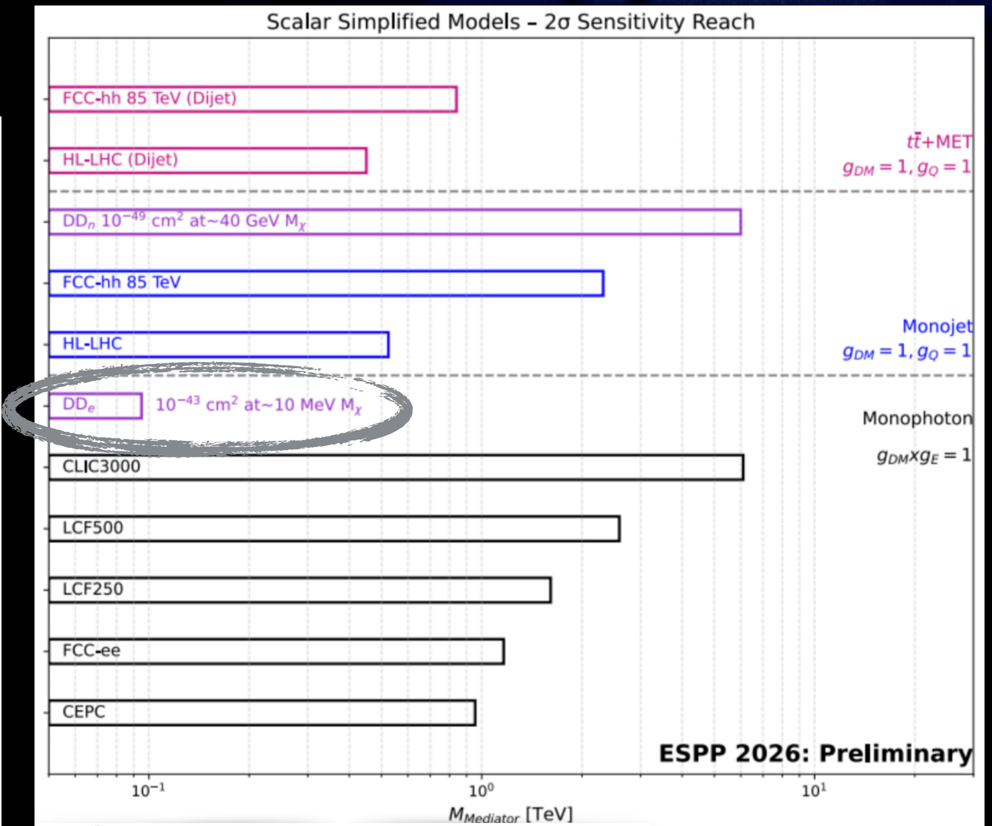
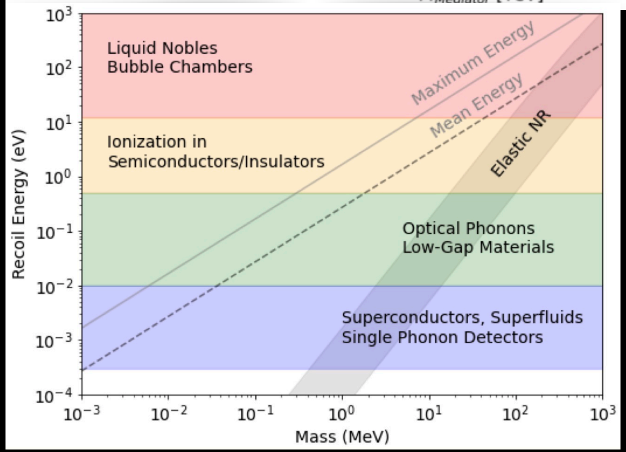
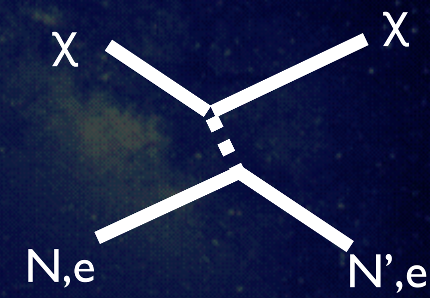






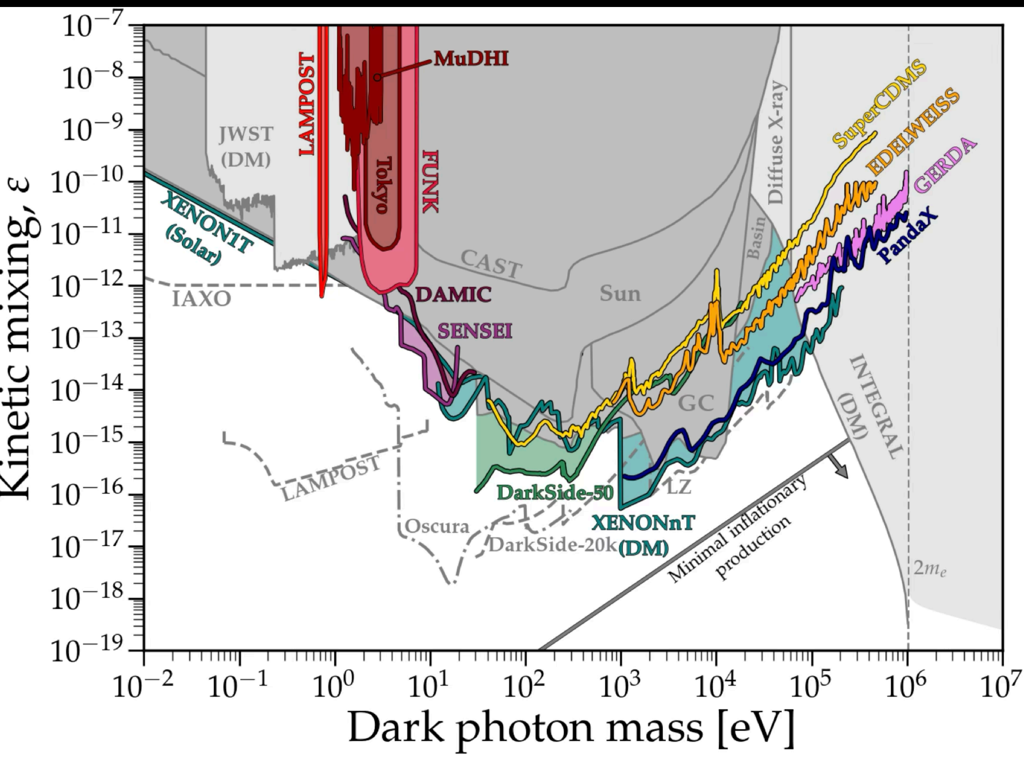
Since ESPP2019, increased focus on electron final states

Light Dark Matter: Complementarity



DM - electron final states access dark photon, ALPs portals

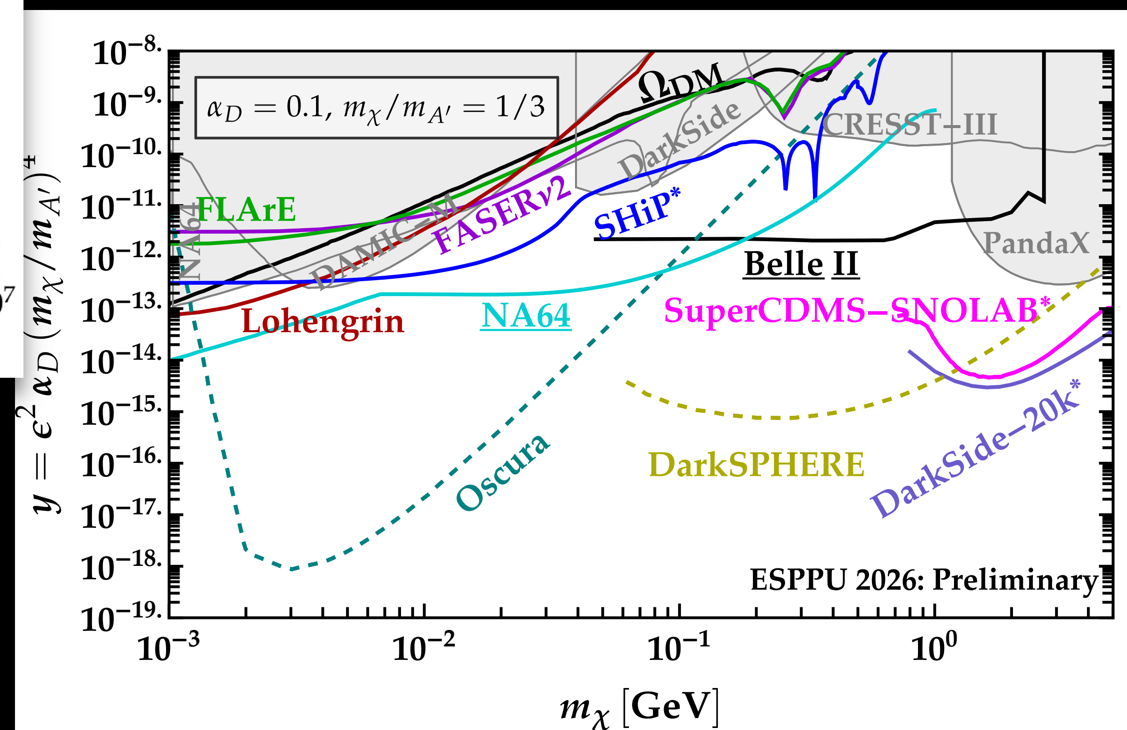
P. Agnes



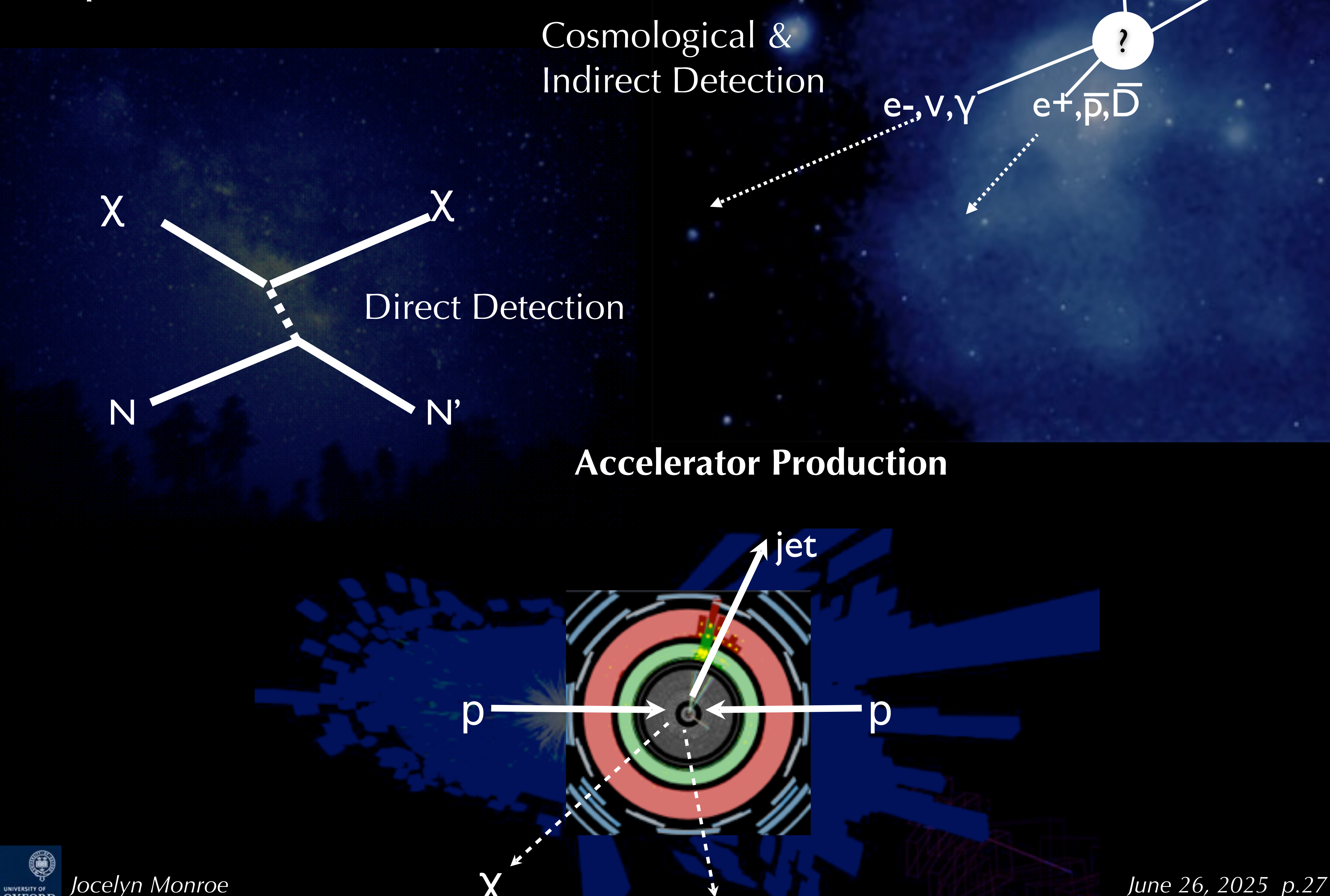
C. O'Hare, *https://github.com/cajohare*

Both DM-e and DM-N address quasi-elastic models targeted by accelerator searches

M. Ovchynnikov

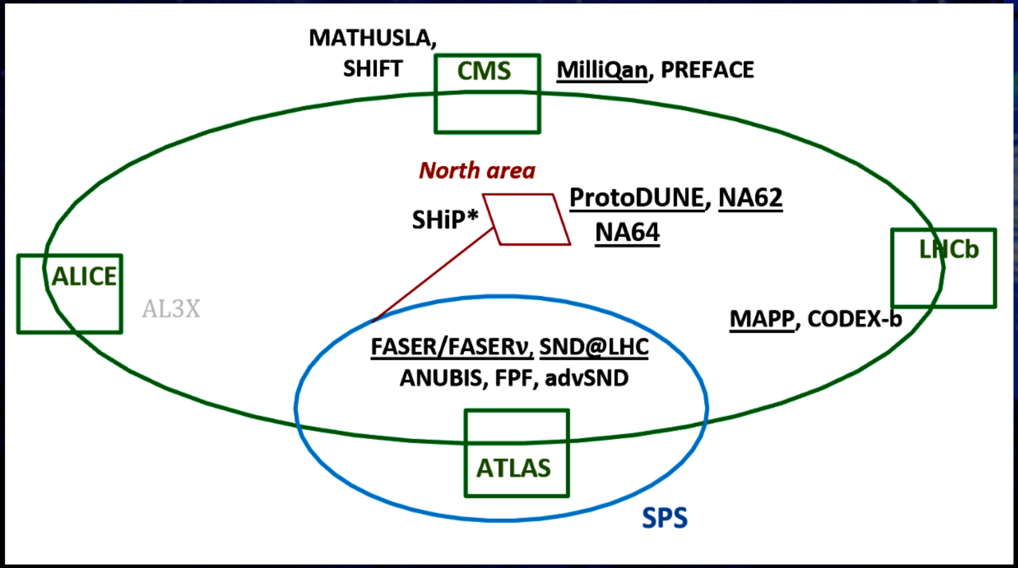


Experimental Tools

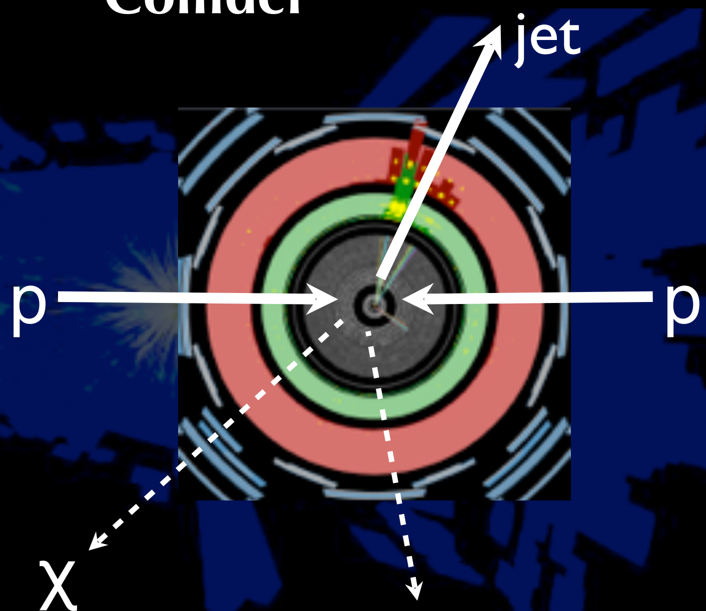


Accelerator-Adjacent Searches

Since ESPP2019: SHIP approved!



Collider



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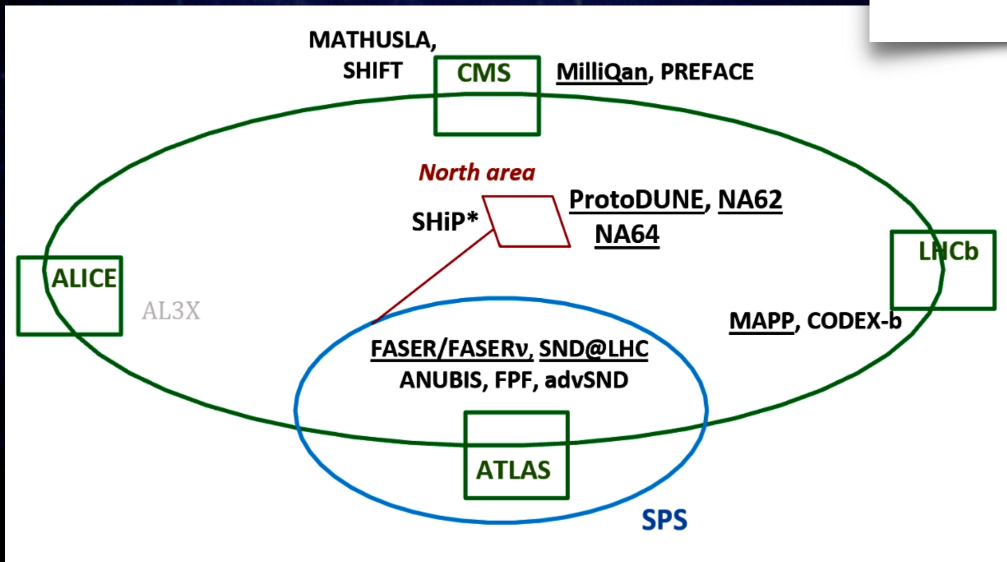

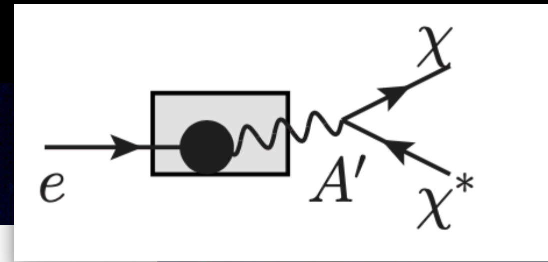

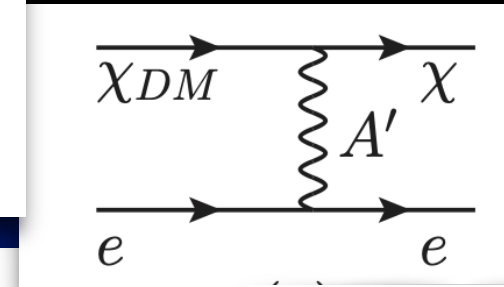

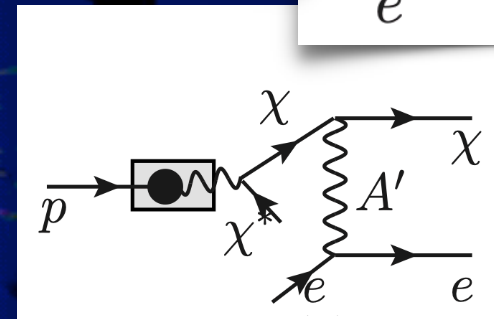

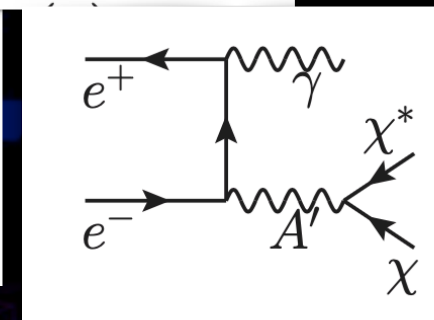

Collider

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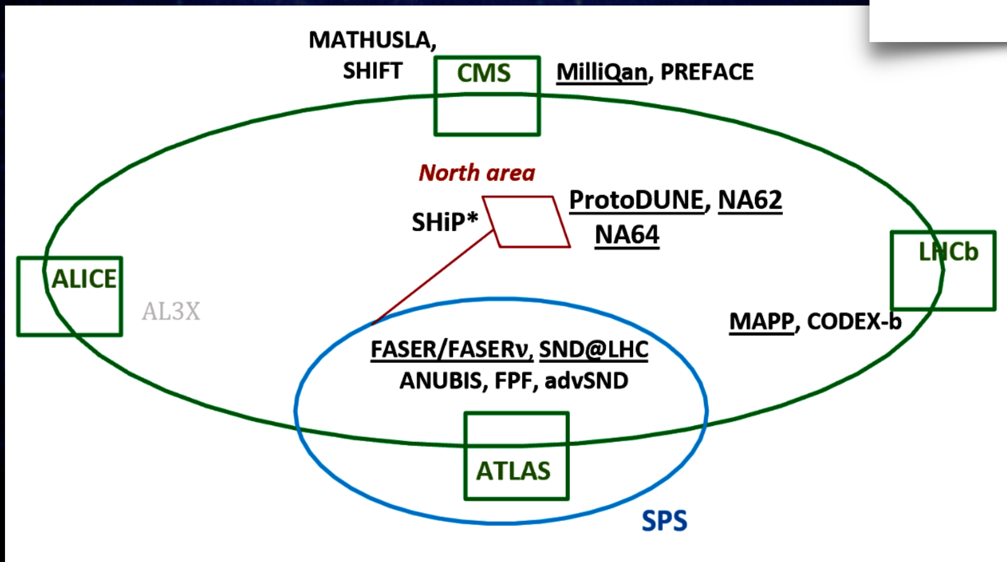
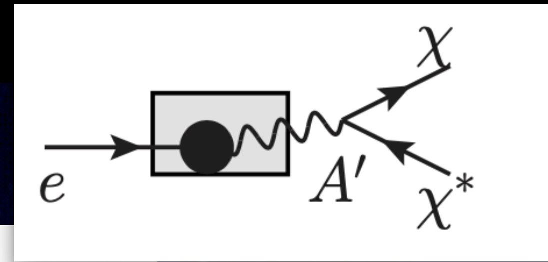
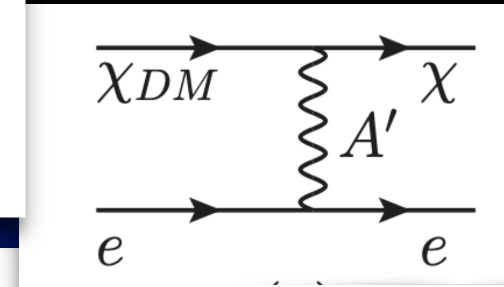
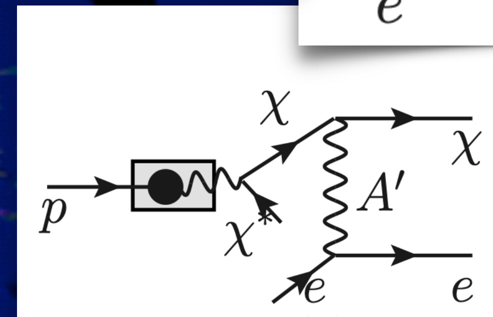
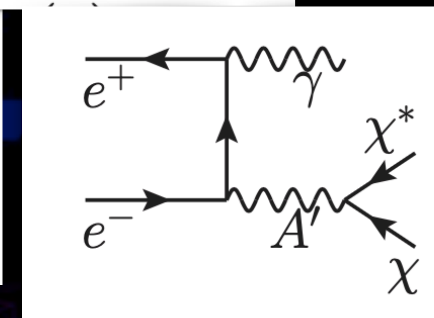
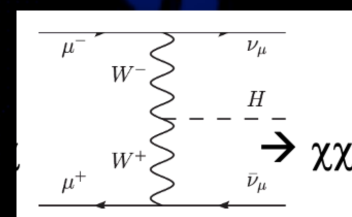


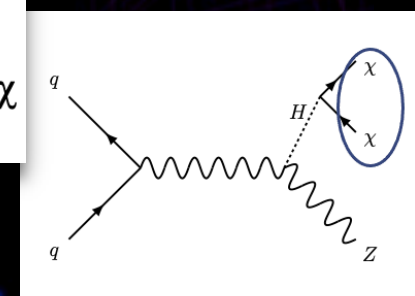


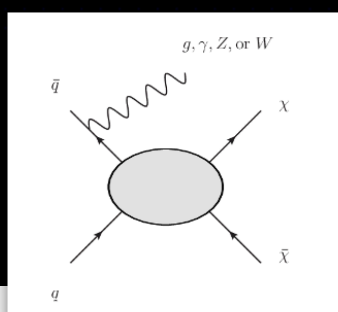


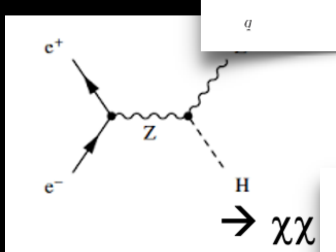


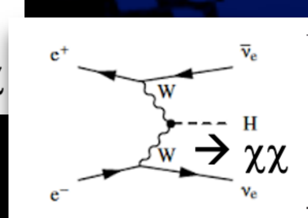




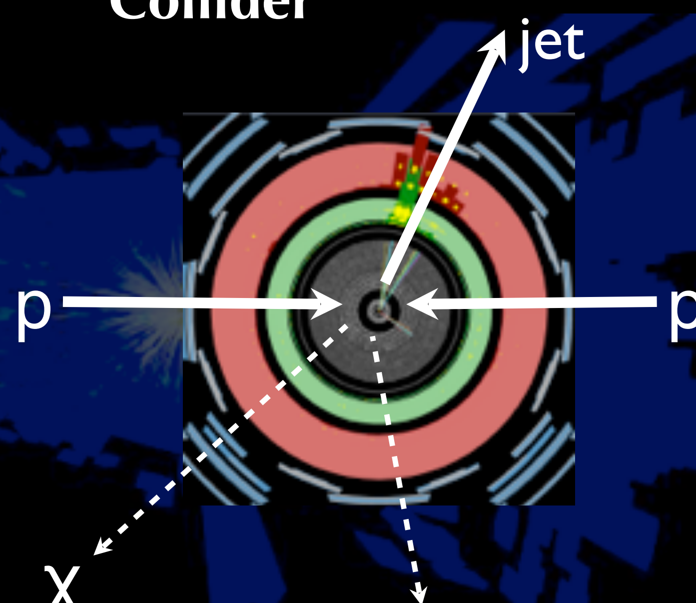


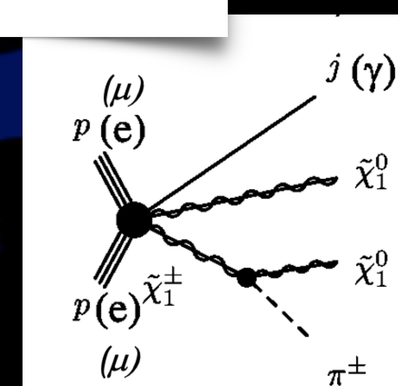






Collider

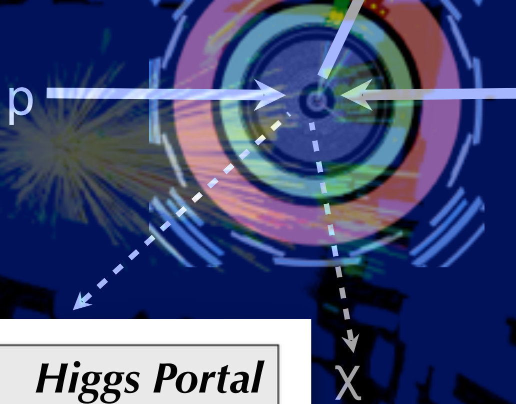




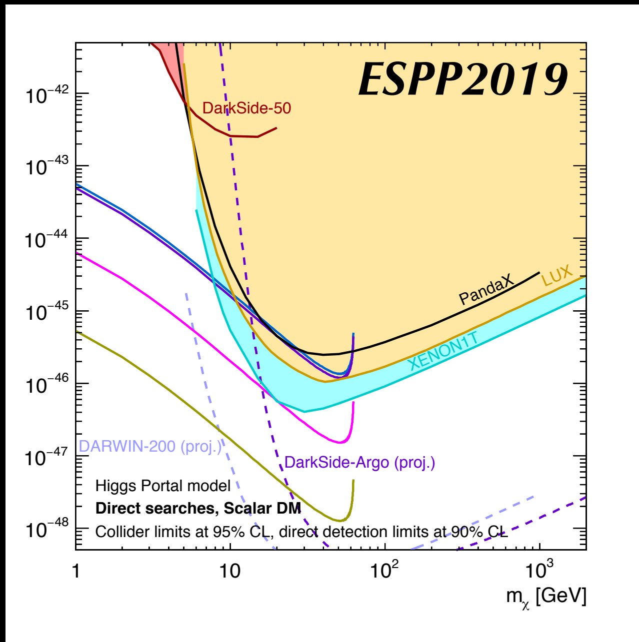
ESPP2019 vs. ESPP2026

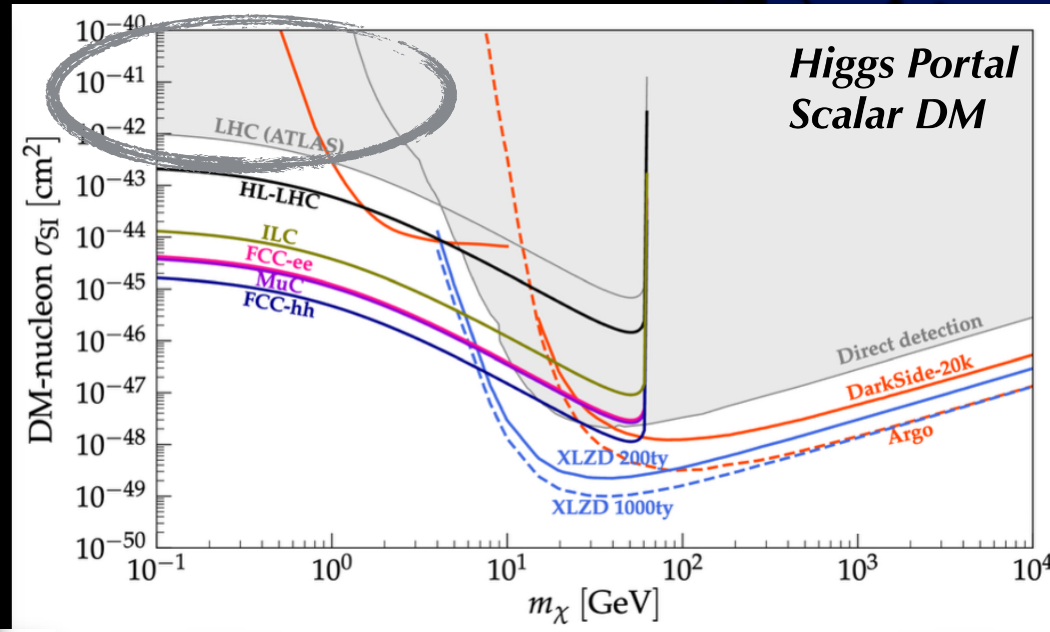
Big advances in LHC dark matter searches!

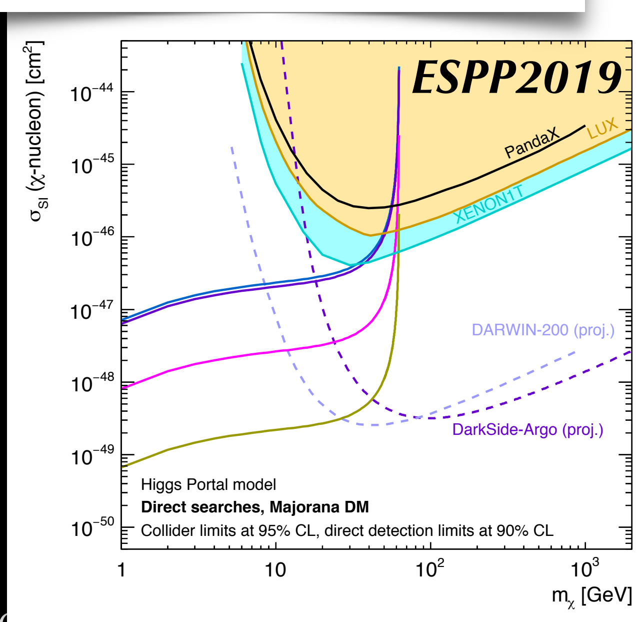
Caveat: model dependence In conversion

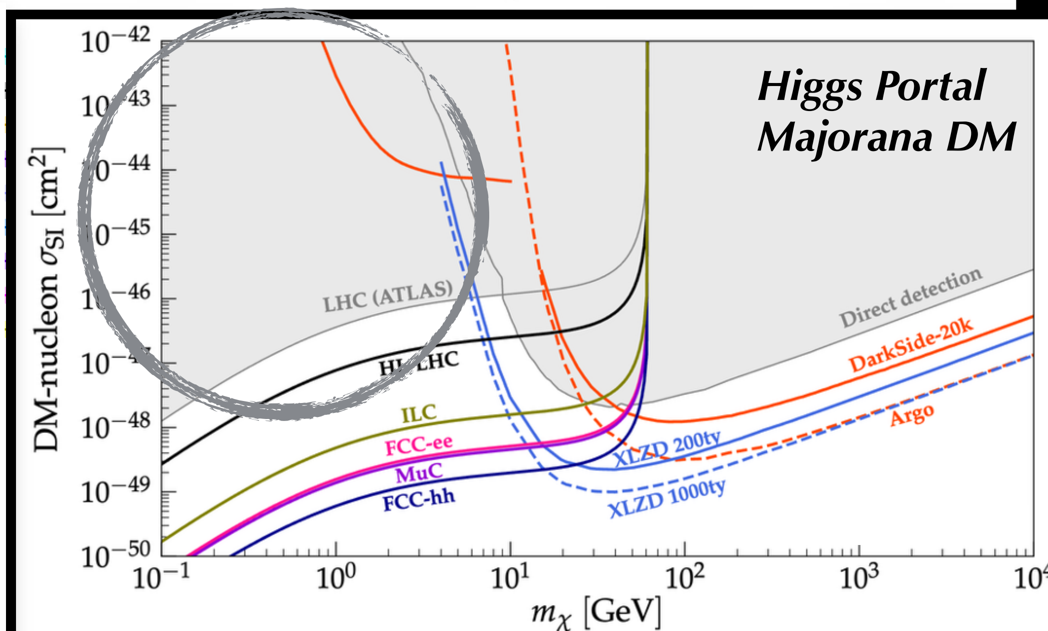


M. D'Onofrio



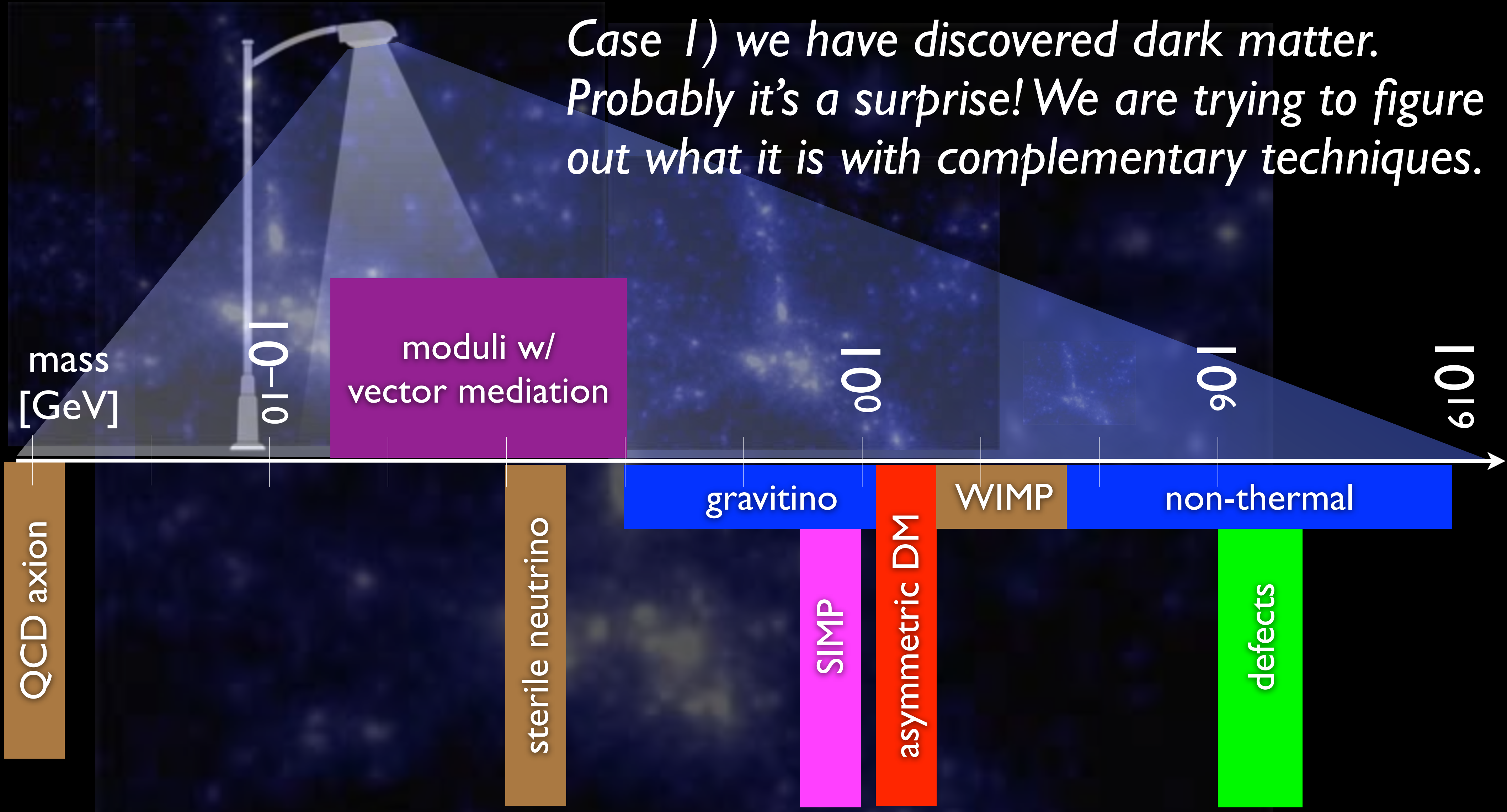






ESPP2032 Prediction

Case 1) we have discovered dark matter. Probably it's a surprise! We are trying to figure out what it is with complementary techniques.



Case 2) we have not discovered dark matter, yet. We will be searching for dark matter beyond the places we already know how to look!

Summary & Outlook

Dark matter searches are evolving rapidly since ESPP2019…

New technologies and ideas deployed in experiments across all scales — strong incubator for creativity in experimental approaches, new analysis strategies, and technology innovation.

Important progress has been, and will continue to be, made by relatively small/rapid projects. This is great for training and skills development.

Dark Matter and Dark Sectors have important complementarity across a (uniquely) broad range of non-accelerator and accelerator-based experimental techniques.

Strong support in ESPP inputs for diversity of experiments/techniques.

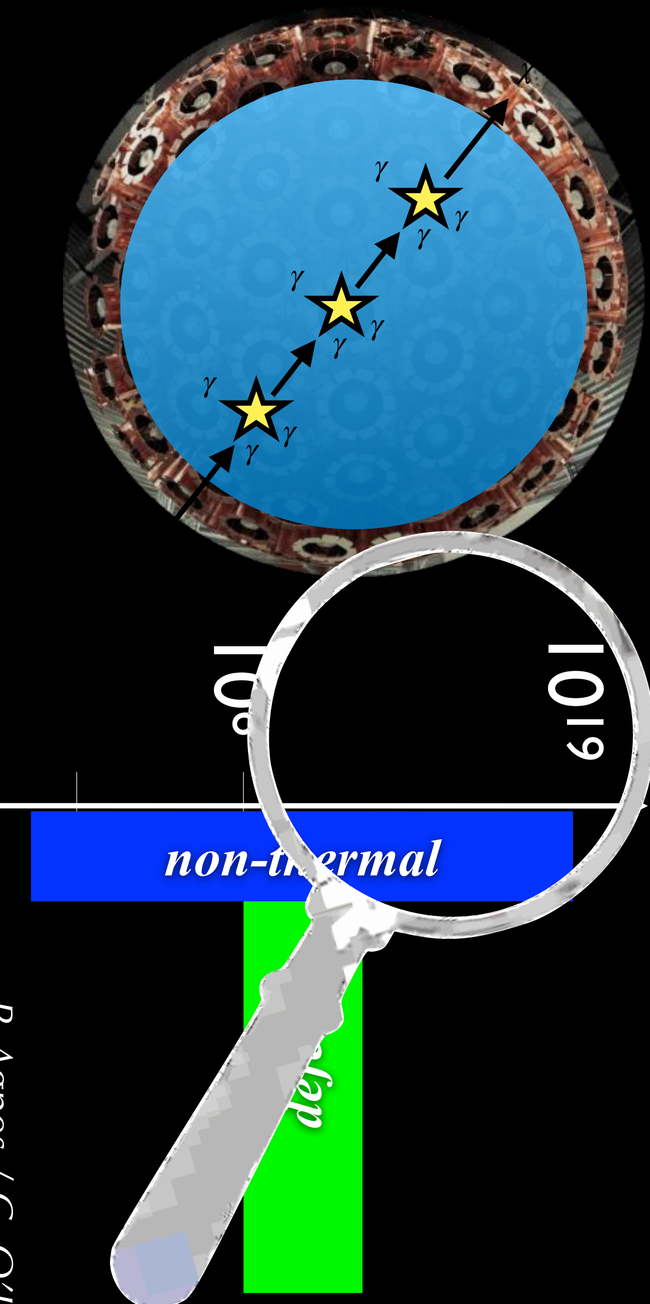
Complementary measurements required for a convincing discovery!

Extra Slides

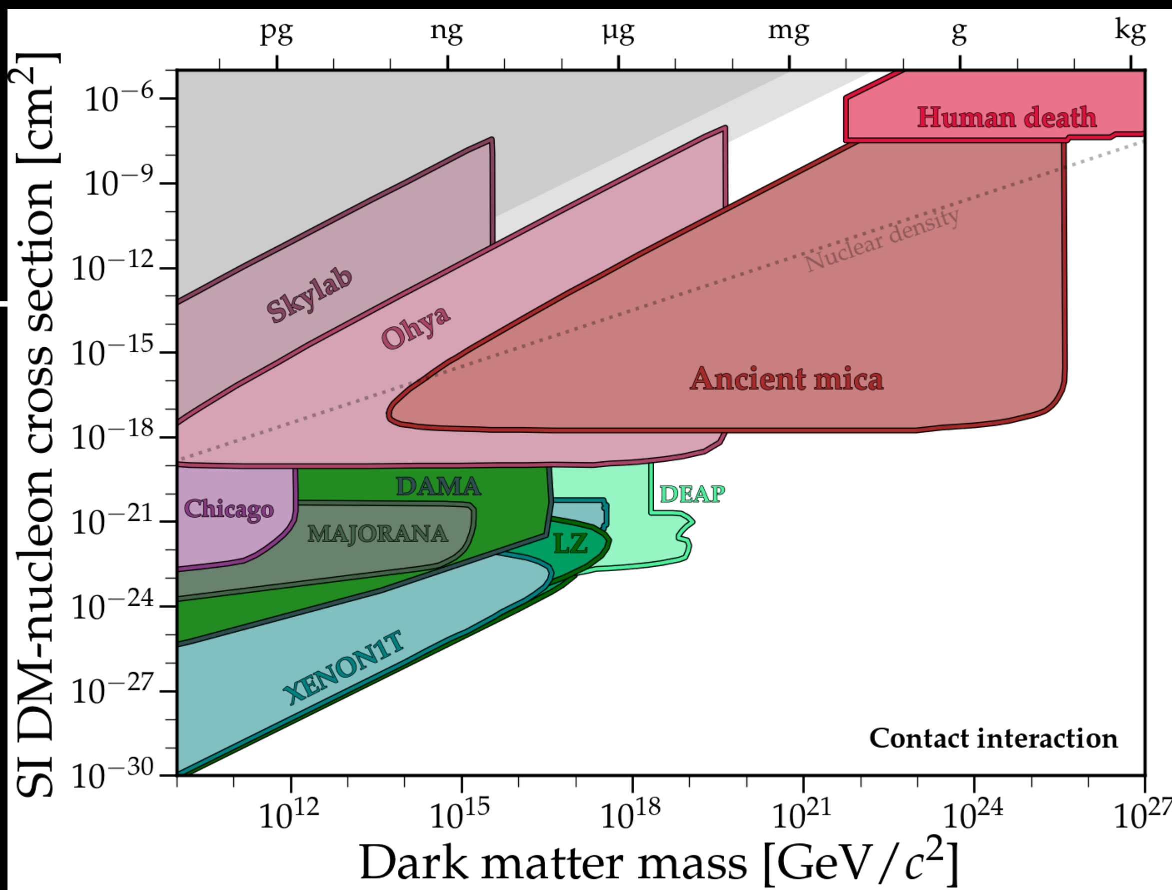
Ultra-heavy Dark Matter

Planck-scale dark matter may be produced non-thermally in GUTs, primordial black hole radiation or extended thermal production

Unlike WIMPs, super heavy dark matter may scatter multiple it traverses a detector… signal: multiple nuclear recoils



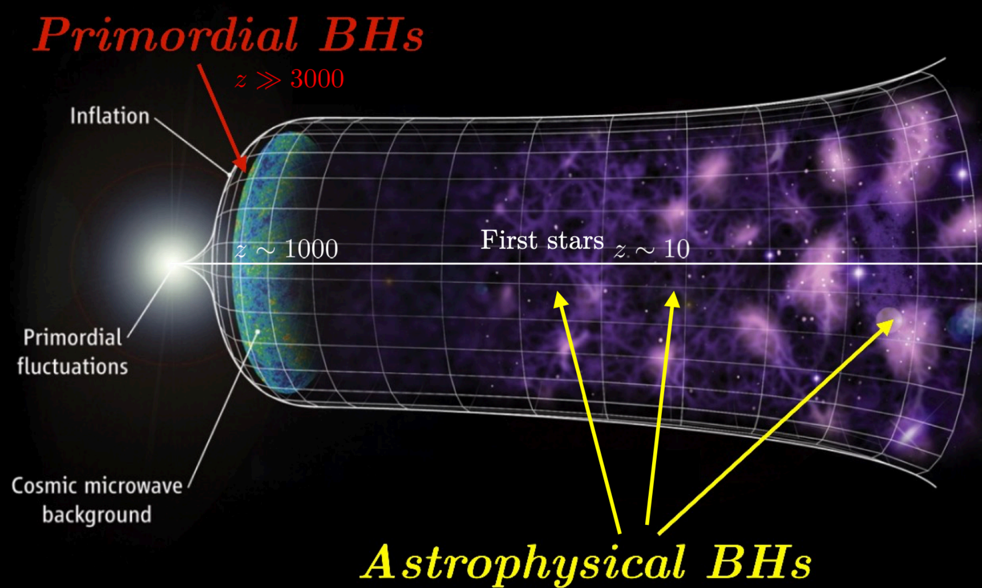
mass
[GeV]

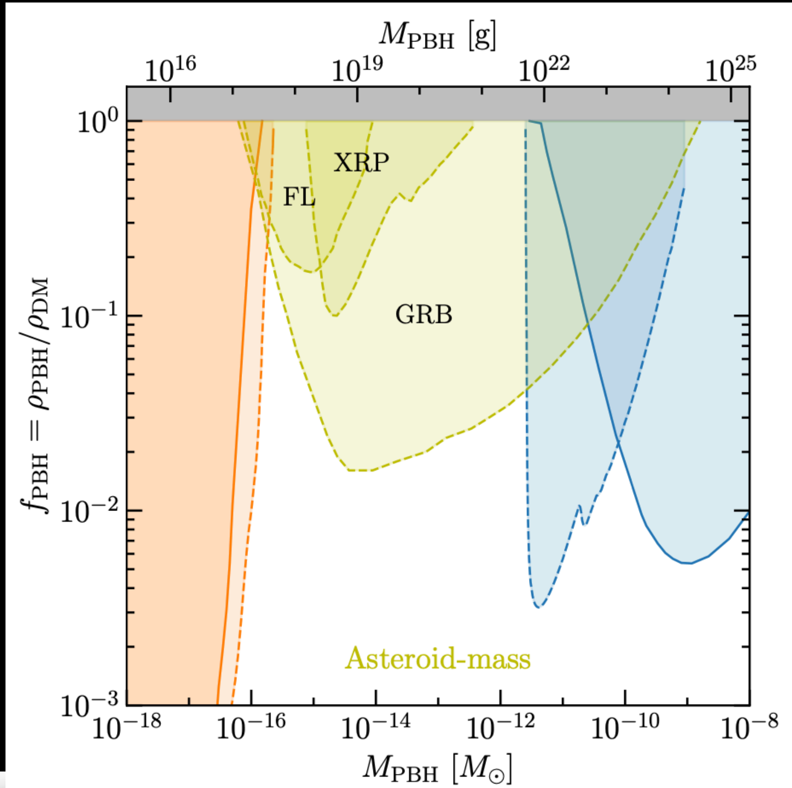


P. Agnes / C. O'Hare

C. O'Hare, *https://github.com/cajohare*

Ultra-heavy Dark Matter





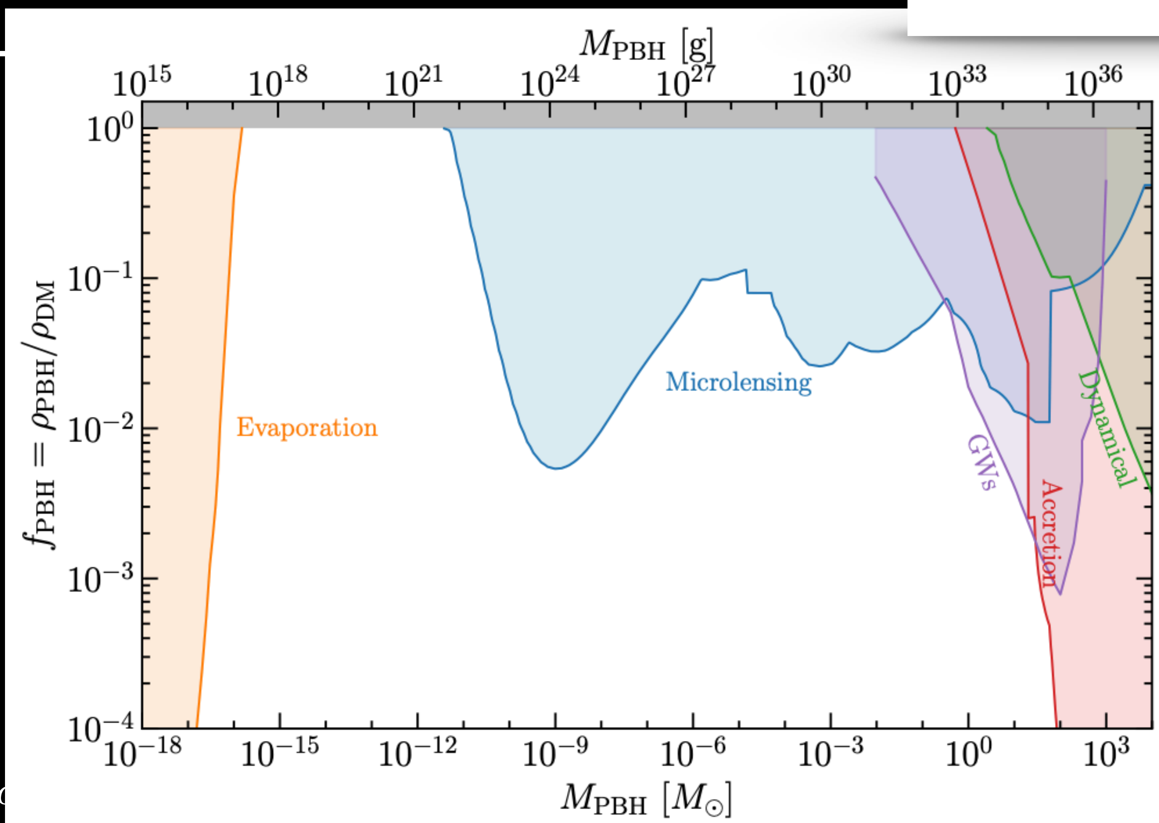
mass [GeV]

10^{19}

non-thermal

defects

Green et al, 2402.15211

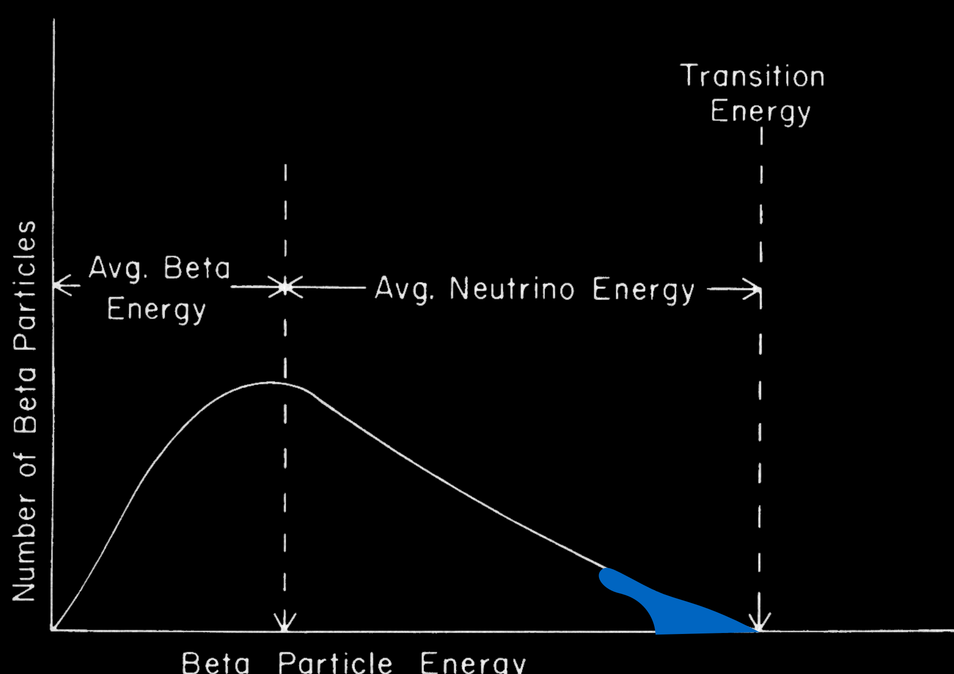


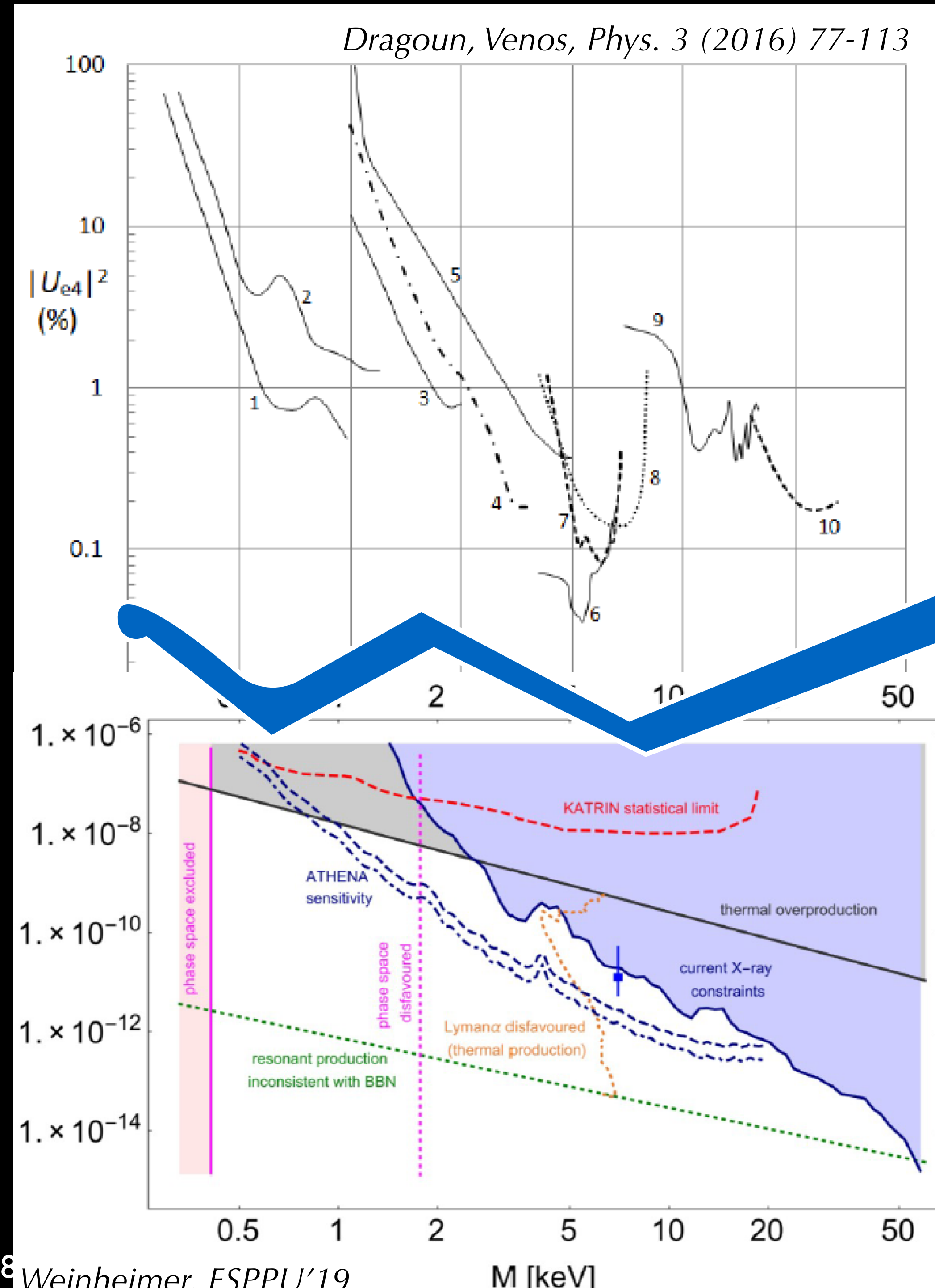
Warm Dark Matter

Sterile neutrino dark matter can scatter with electrons $N_S\, e^- \rightarrow \nu_e\, e^-$

Constraints on $|U_{e4}|^2$ from beta decay: energy spectrum modified by sterile neutrino mixing.

Constraints from indirect detection: x-ray energy spectrum strongly limits $|U_{e4}|^2$





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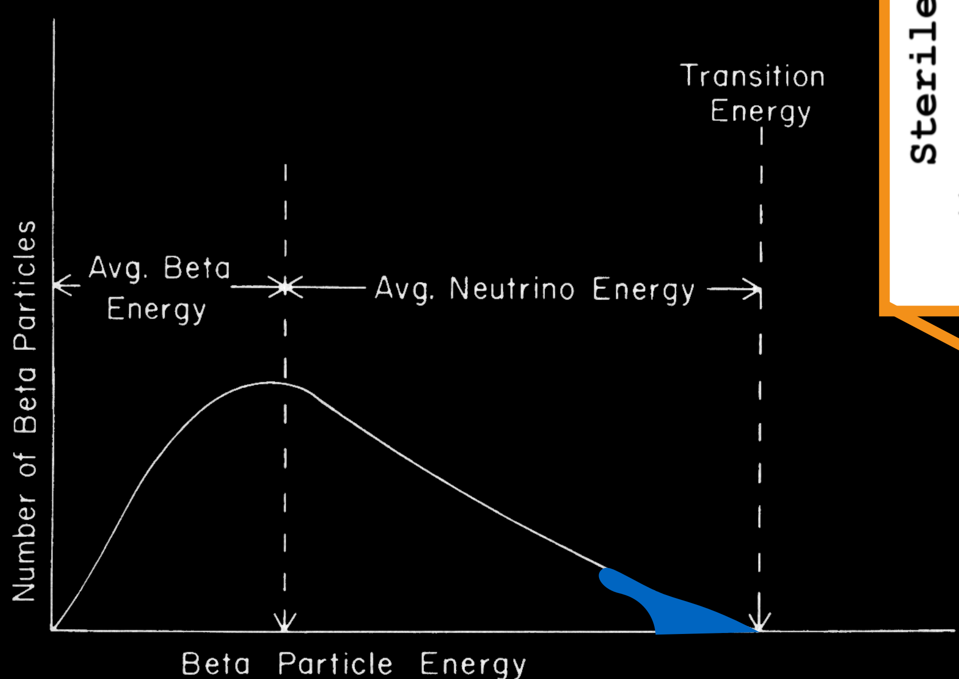
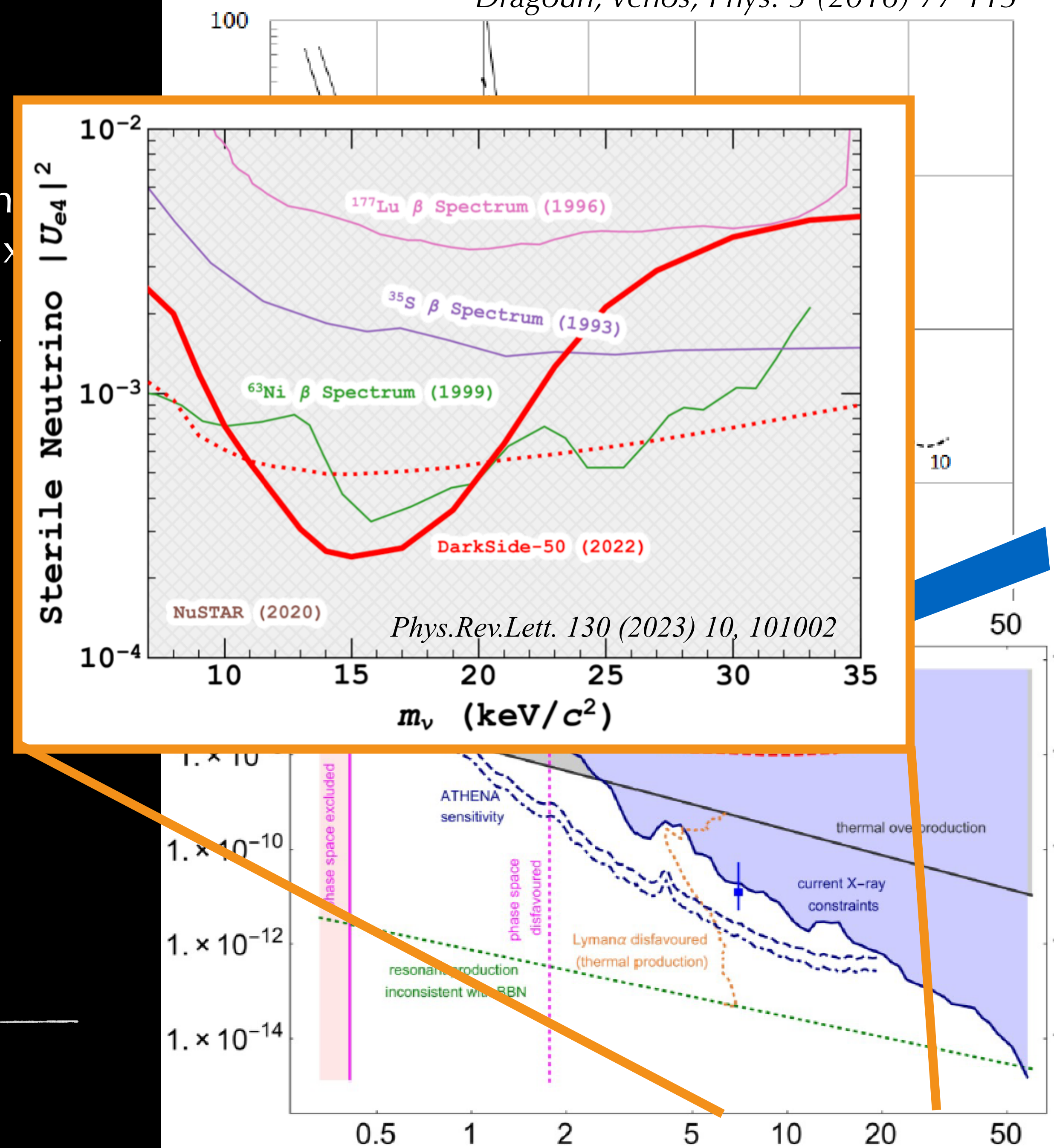
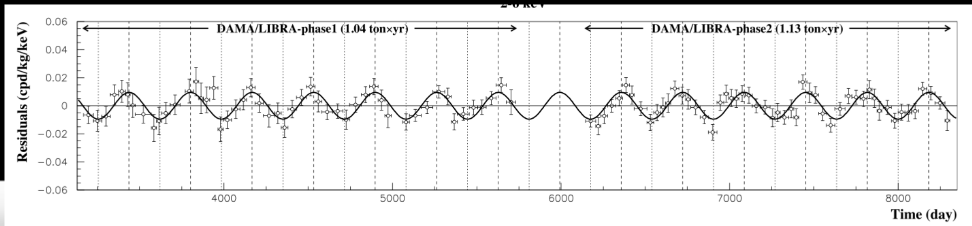


Dragoun, Venos, Phys. 3 (2016) 77-113



Weinheimer, ESPPU'19

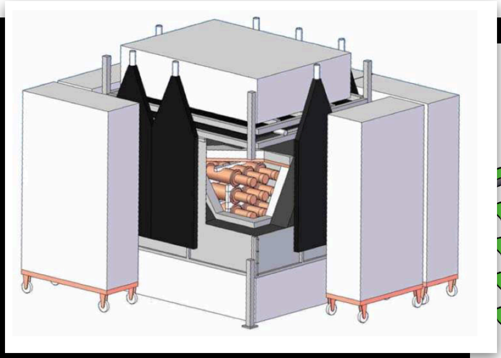
Direct Detection … any Signals?

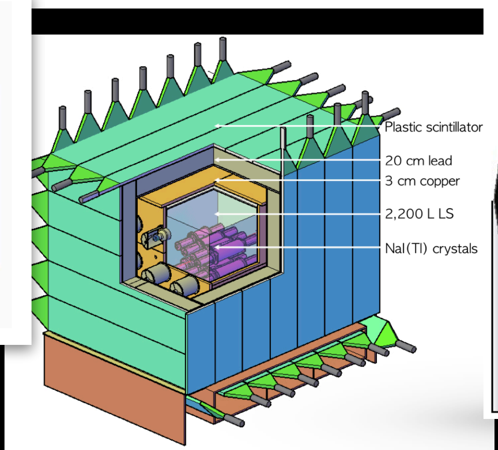


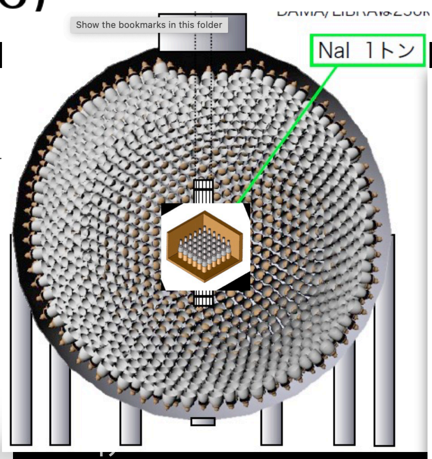
- **DAMA/LIBRA**: end of data taking by 2024
  - ✓ Outstanding crystal development achieved, still unmatched
  - ✓ A **crucial anomaly** in DM direct detection standing still
  - ✓ Currently taking data with new PMT dividers since 2021
  - ✓ Since 2021 in data taking without interruptions till Feb 2024 (Phase 2 empowered, ~0.5 ton x yr)
  - ✓ Crucial comprehensive analysis of background time dependence ongoing

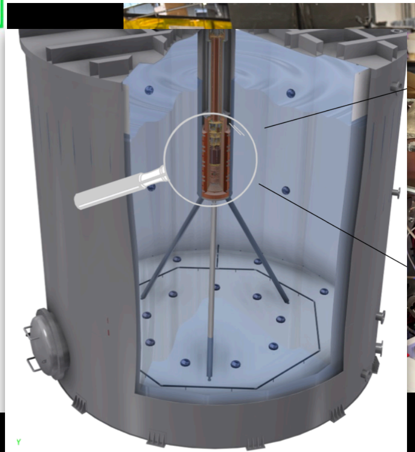
—A. Ianni, IDM2024

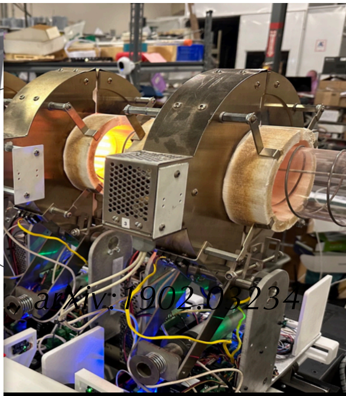
- **ANAIS-112 and COSINE-100**
  - ✓ Achieved outstanding noise events rejection in the ROI
  - ✓ Time-dependent background MC simulations: more details on systematics
  - ✓ Stronger **tests of DAMA/LIBRA accessible** from preliminary analysis reported at this meeting (goal: towards 5σ)











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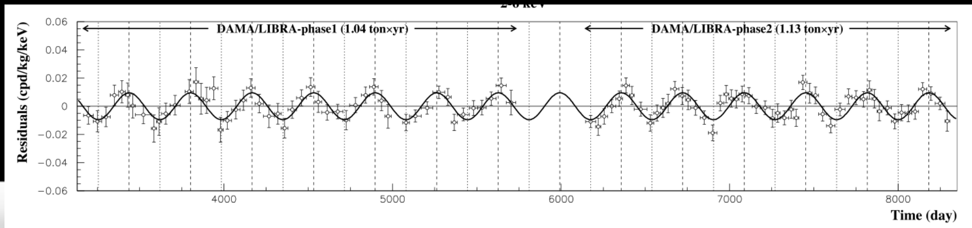

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Exclude DAMA at ~3 sigma