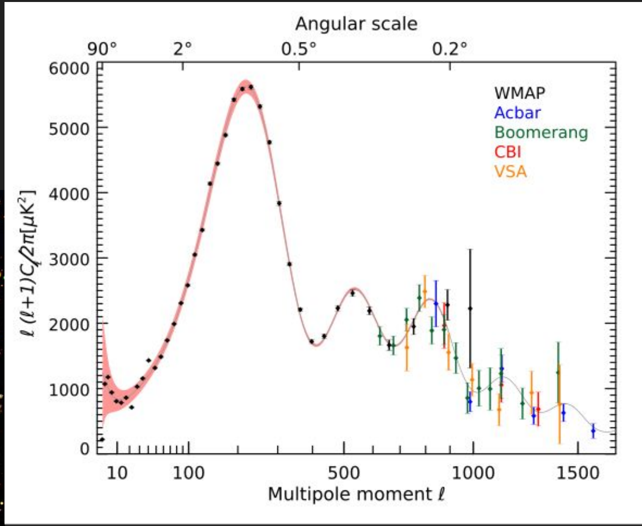
Particle Dark Matter

The WE-Heraeus and NARIT Cosmology School 2025

Patipan Uttayarat

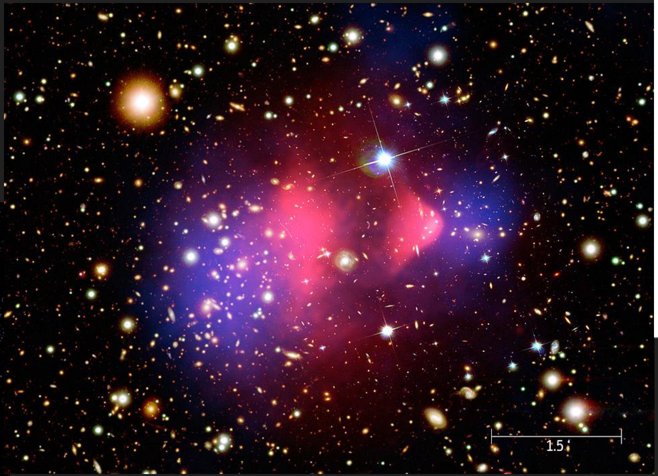
Evidences for DM

The Universe



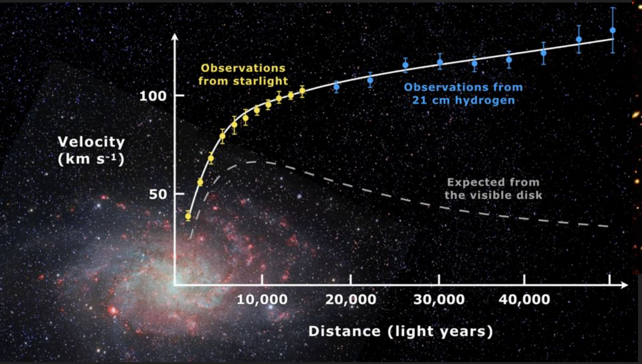
NASA/WMAP Science Team

Galaxy clusters



NASA/CXC/M. Weiss - Chandra X-Ray Observatory

Galaxy



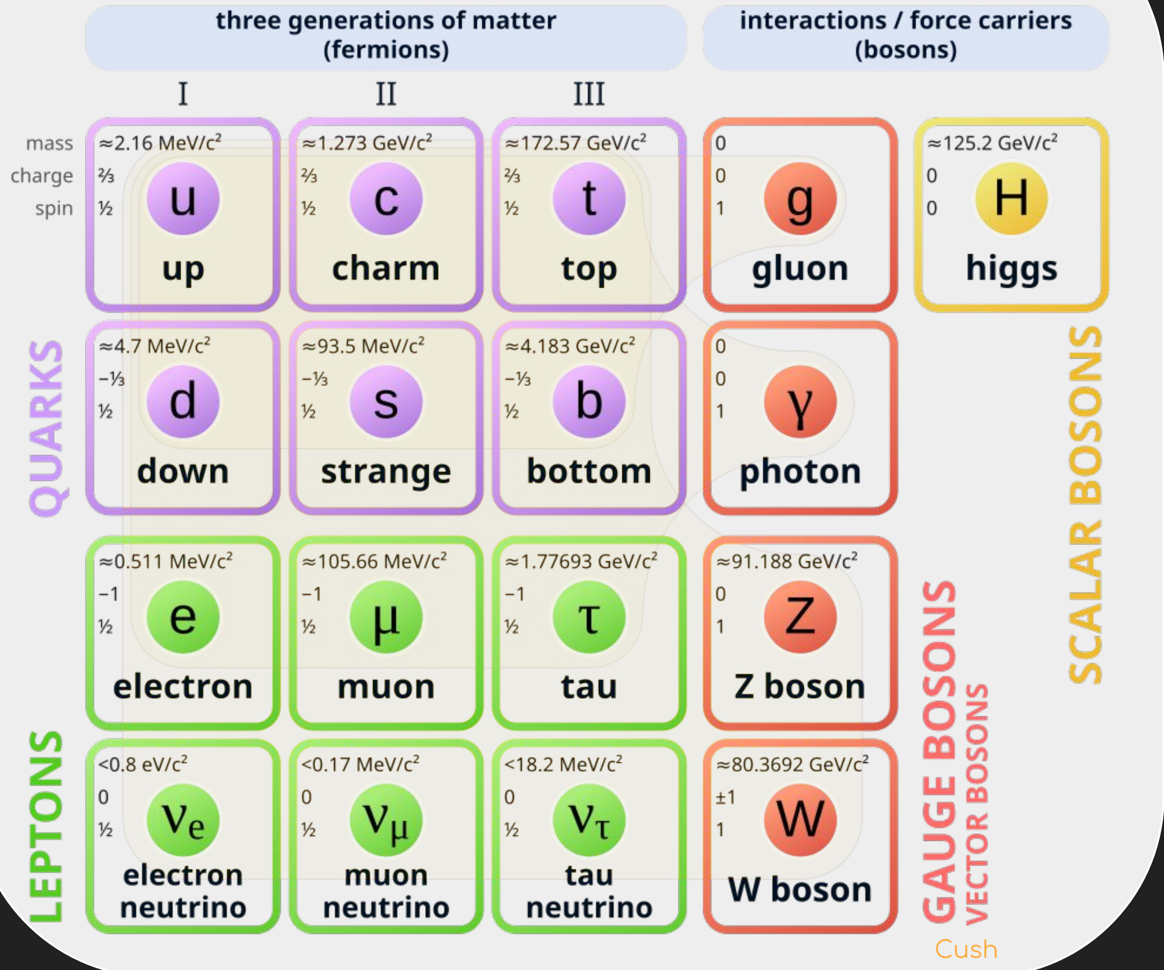
Mario De Leo

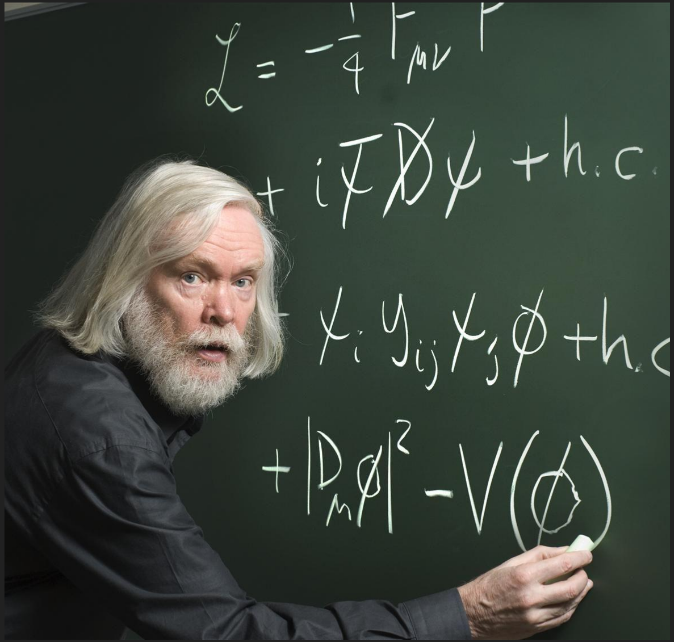
Dark matter properties

1. Massive
2. Dark, i.e. electrically neutral
3. Interact very weakly with normal matter
4. Cold, i.e. slow moving
5. Stable on cosmological time scale

Do we know any particle with such properties?

Standard Model of Elementary Particles

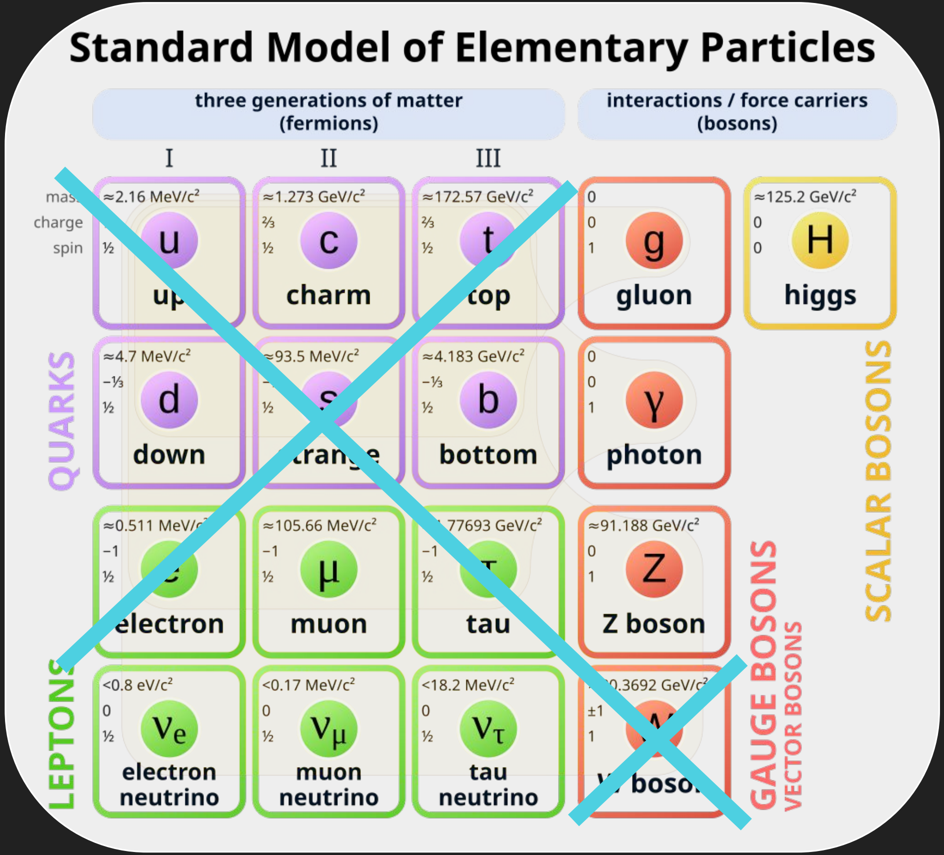




CERN

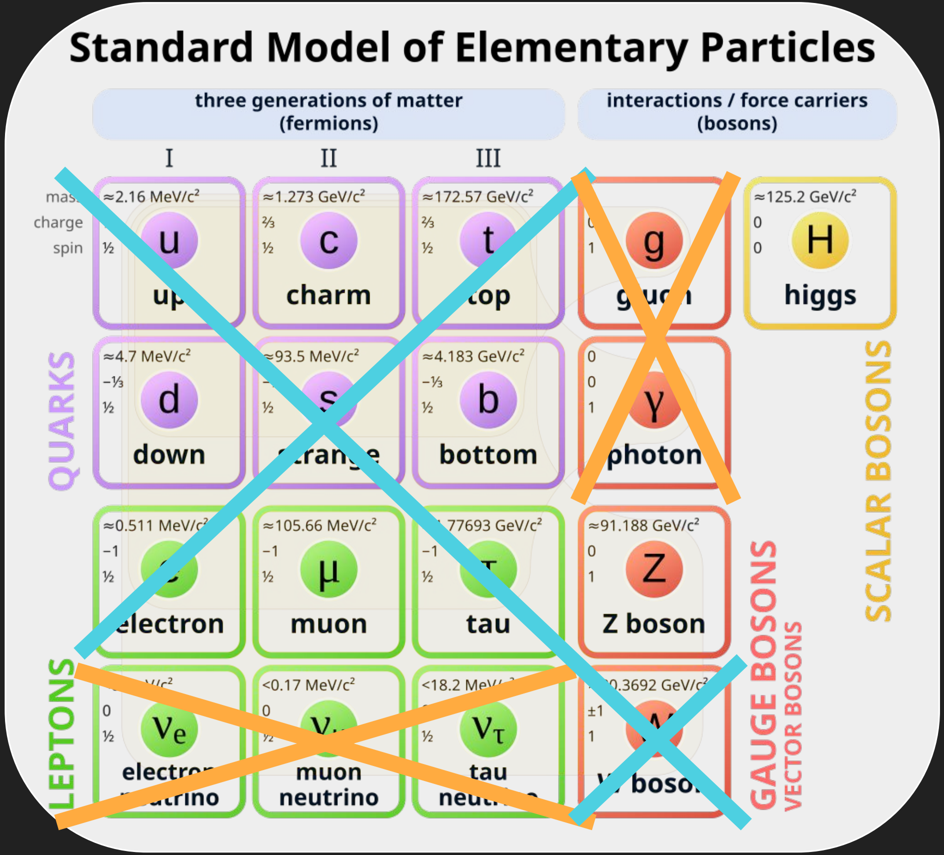
Is DM a particle in the SM?

- Electrically neutral



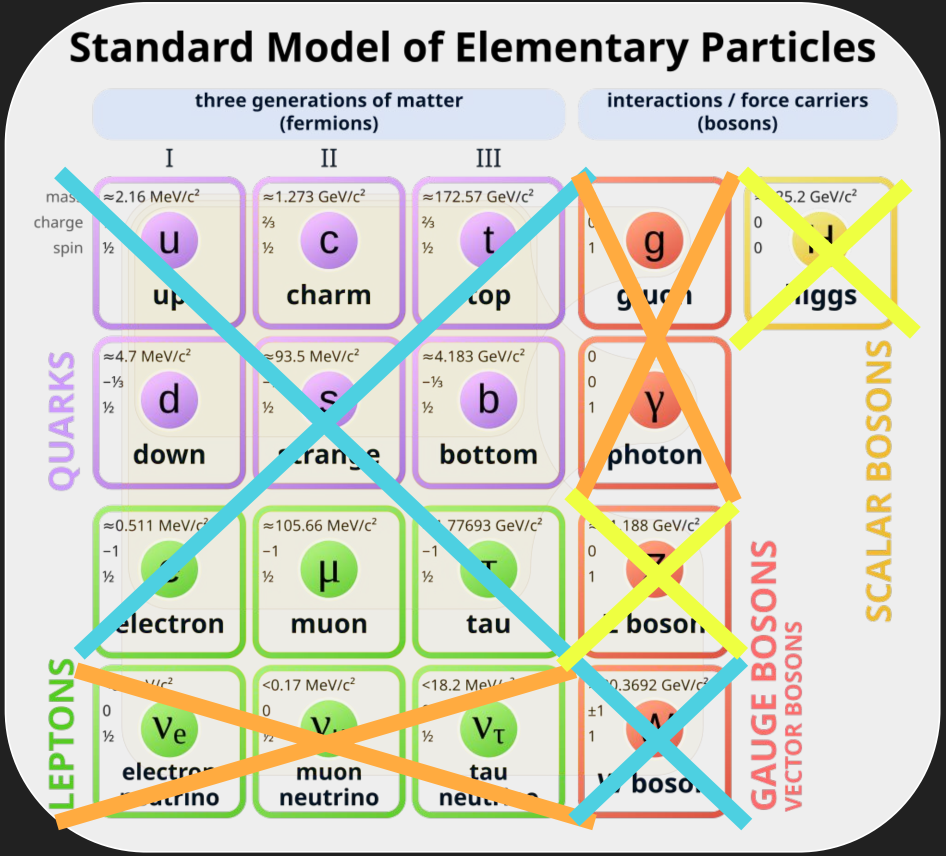
Is DM a particle in the SM?

- Electrically neutral
- Slow moving



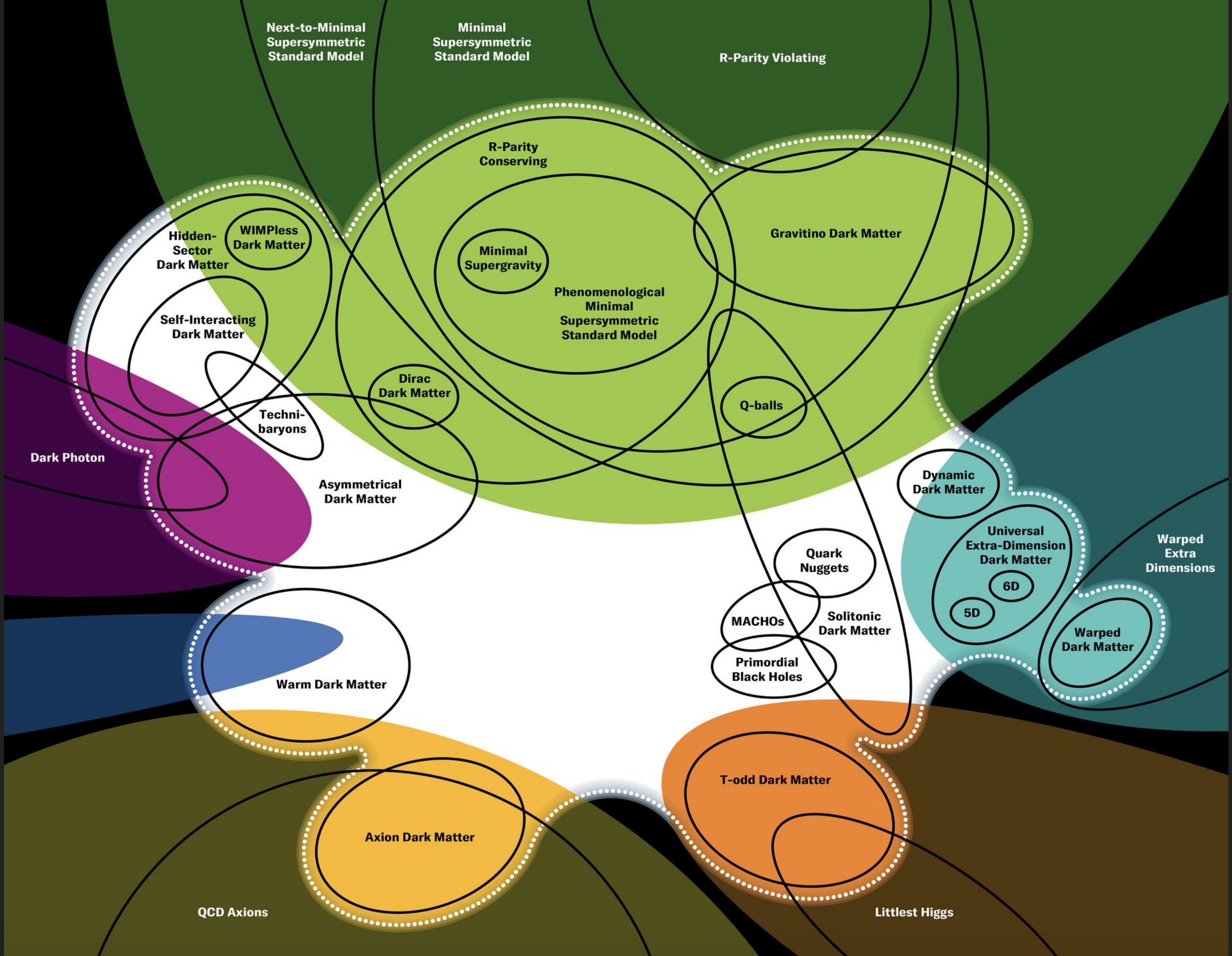
Is DM a particle in the SM?

- Electrically neutral
- Slow moving
- Stable



DM must be new physics!

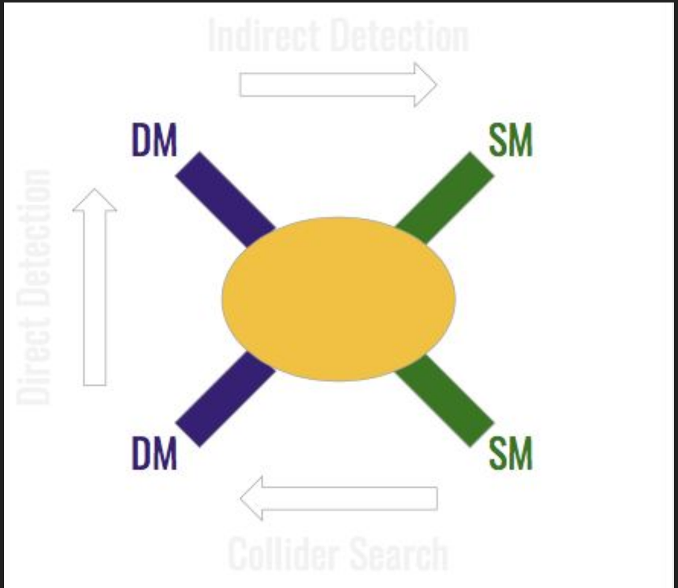
Landscape of DM candidates

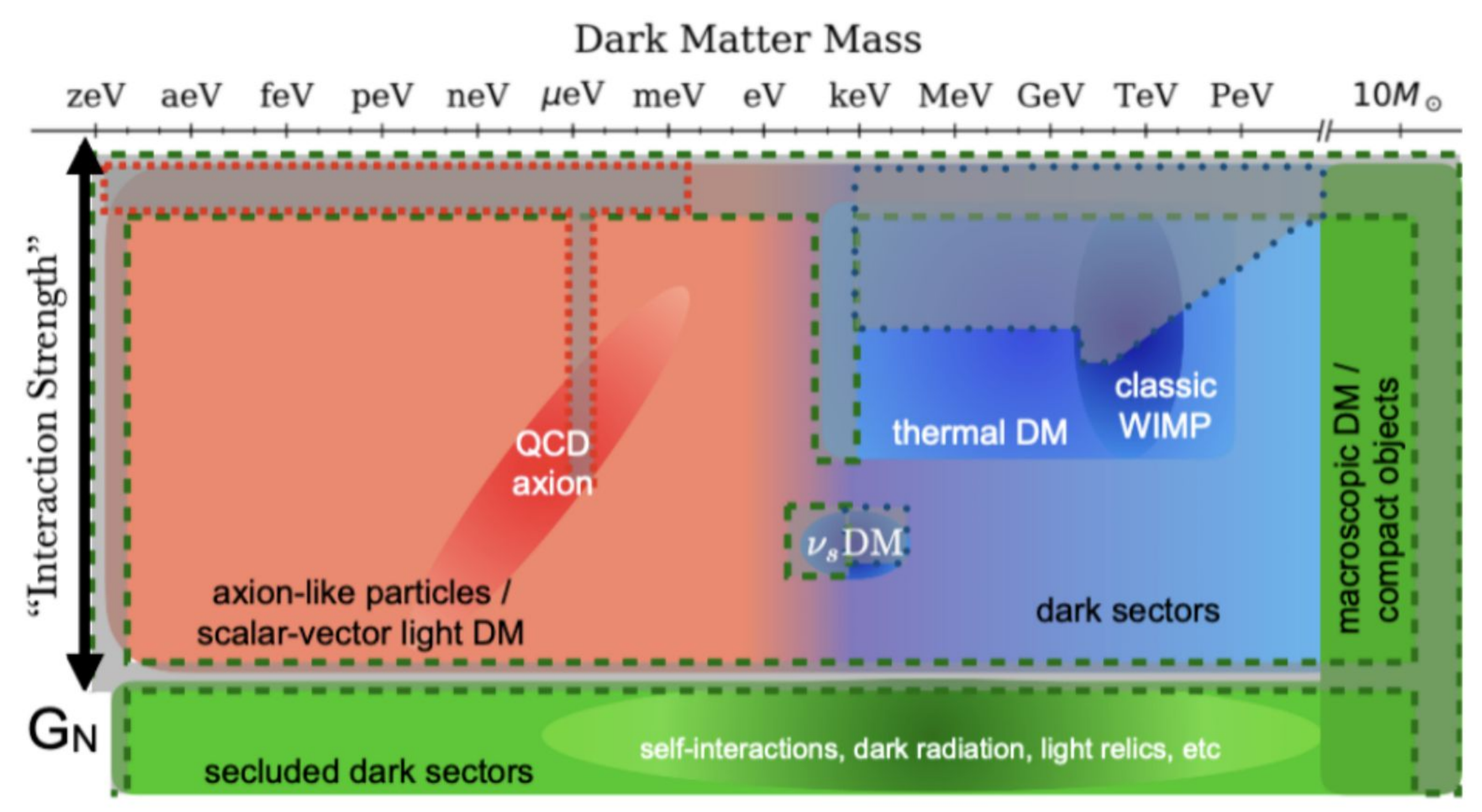


Tim Tait and Jen Christiansen

Simplified framework for DM

- DM is a massive particle
  - Boson $m_{DM} > 10^{-20}$ eV
  - Fermion $m_{DM} > 100$ eV
- Interacts (weakly) with the SM, characterized by xsection.
  - DM SM → DM SM scattering
  - DM DM → SM SM annihilation

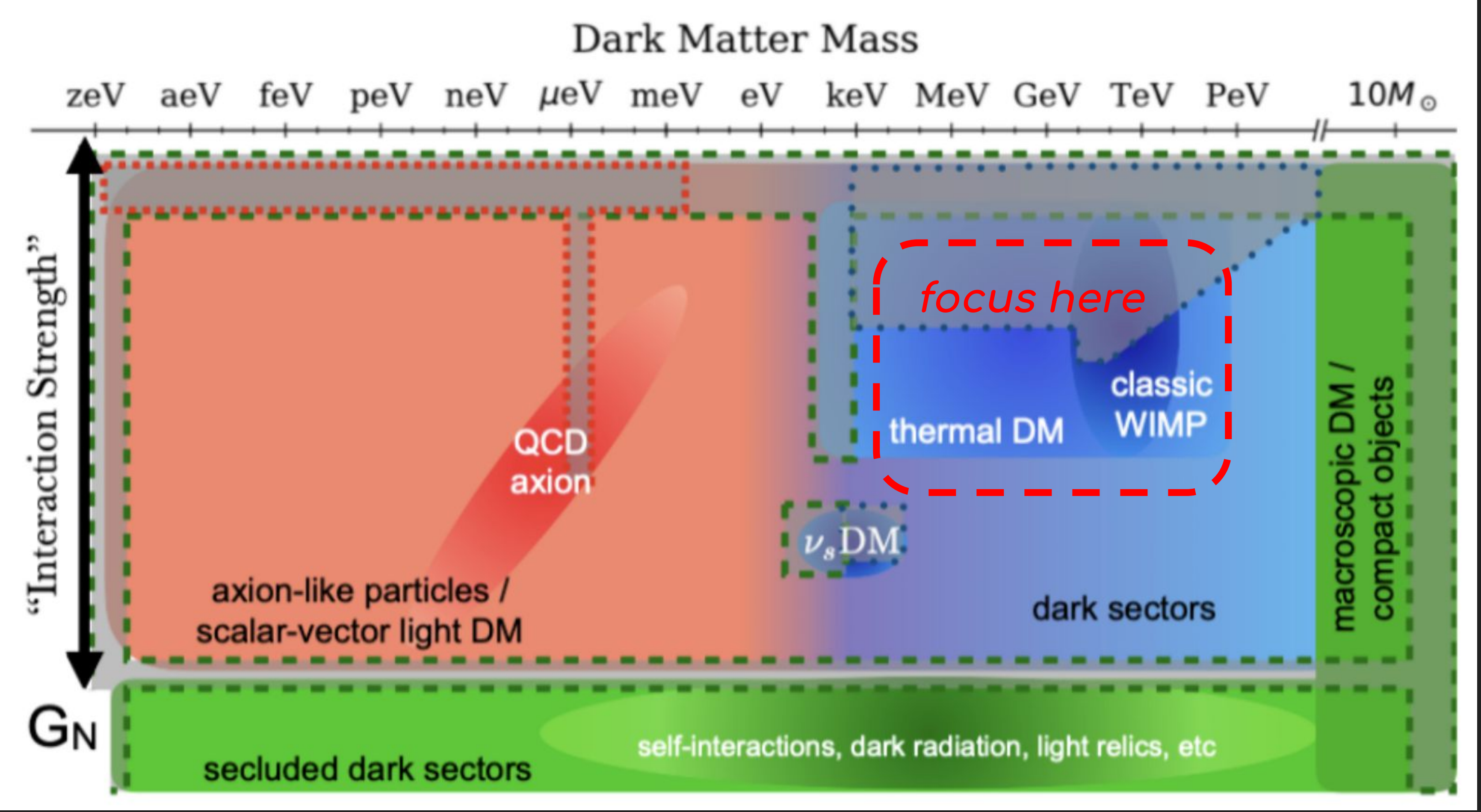




Snowmass Report [2111.09978]

Wave-like DM

Particle-like DM



Snowmass Report [2111.09978]

Wave-like DM

Particle-like DM

How does DM get here?

phase-transition

freeze-in

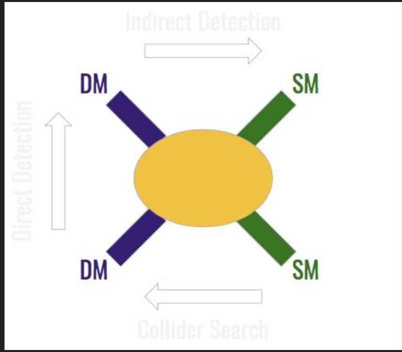
freeze-out

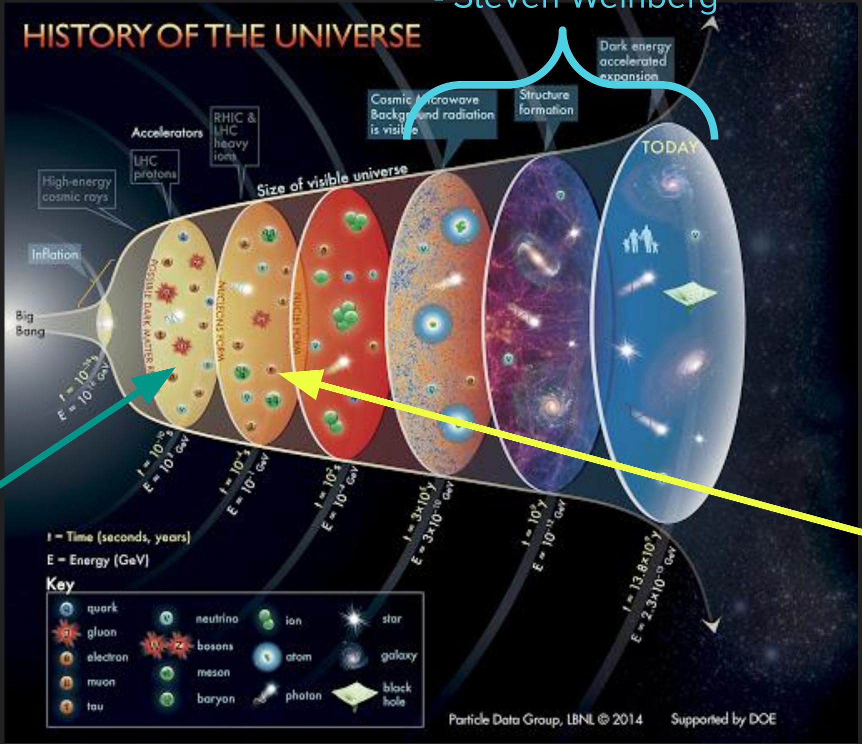
decay

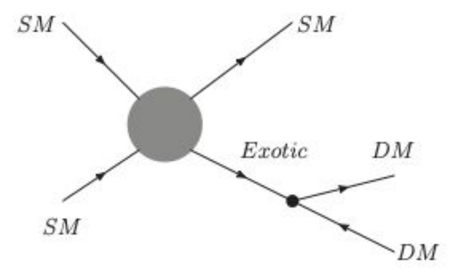
misalignment

Thermal history of the Universe

“Nothing interesting happening here”
- Steven Weinberg







With the rest of other particles after the Big Bang “freeze out”

Later on once the Universe cools down “freeze in”

Freeze out

- DM number density evolve with Boltzmann equation

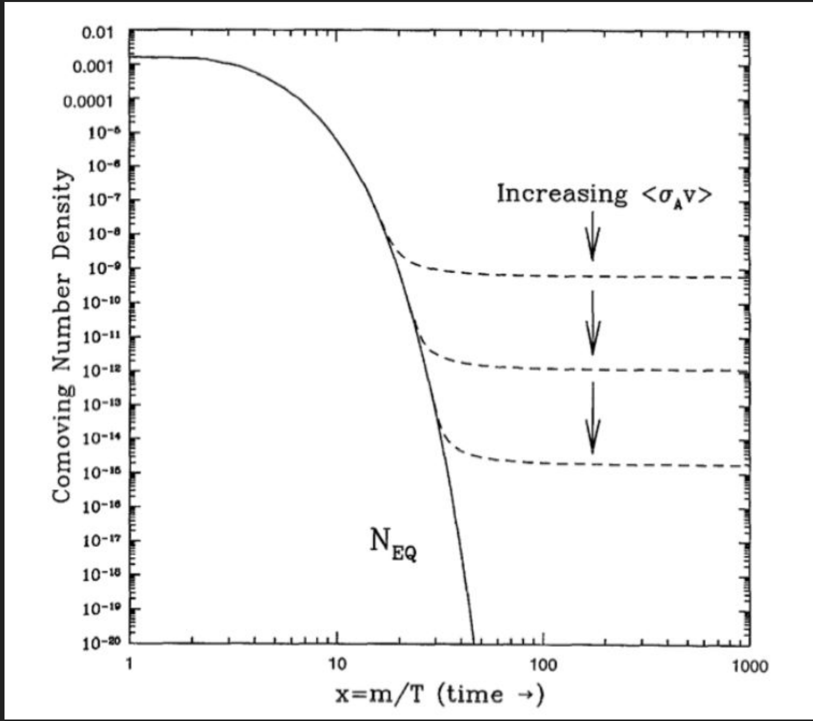
$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\mathrm{eq}}^2\right)$$

- Freezes out condition

$$\Gamma = n\langle \sigma v \rangle = H$$

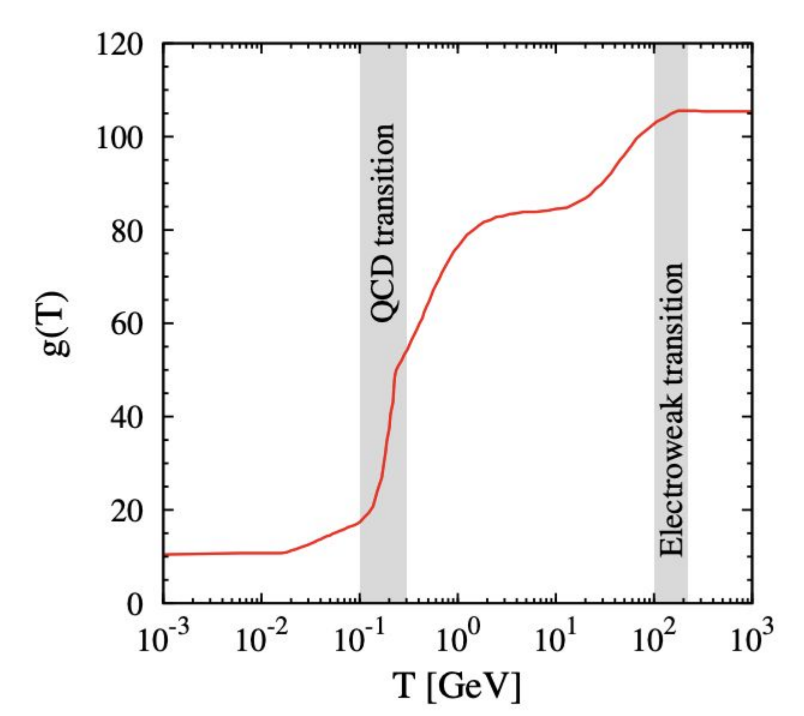
- Freeze out temperature

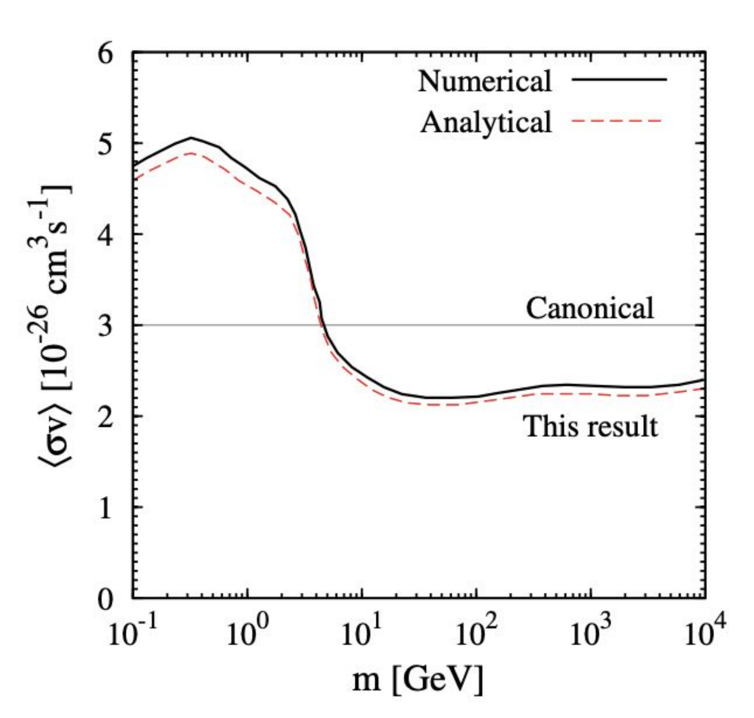
$$x_F \sim \log \frac{m_{DM}\langle \sigma v \rangle}{g_*^{1/2} x_F^{1/2}}$$



Kolb and Turner

Thermal relic cross-section



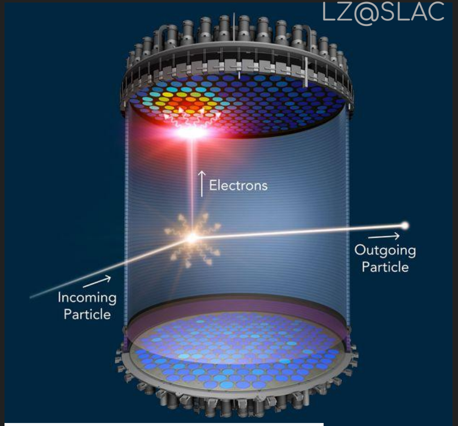


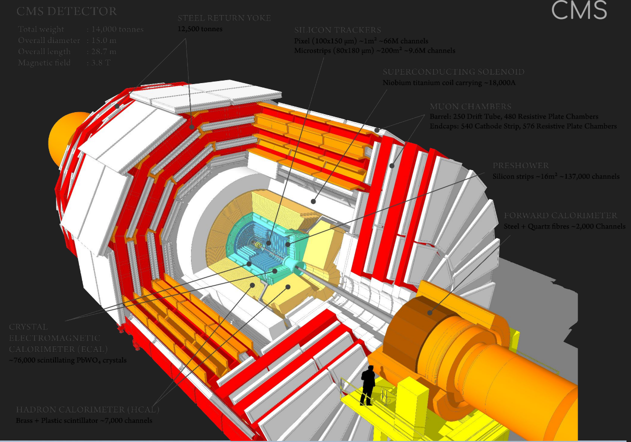
1204.3622

Further readings on DM production

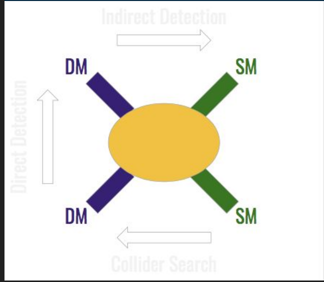
1. “Lecture on Dark Matter Physics,” M. Lisanti [arXiv:1603.03797]
2. “Yet Another Introduction to Dark Matter”, M. Bauer & T. Plehn [arXiv:1705.01987]
3. “Dark Matter,” M. Cirelli, A. Strumia & J. Zupan [arXiv:2406.01705]
4. “The Early Universe,” E. W. Kolb & M. Turner, 1990

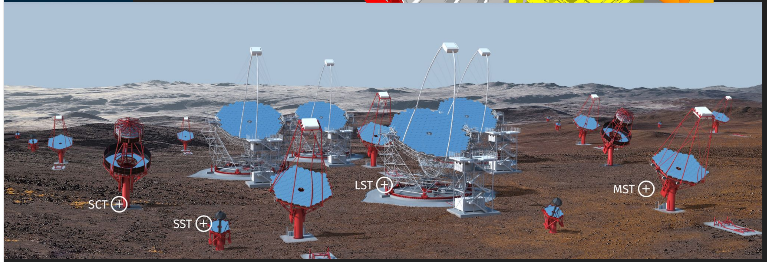
How to detect DM?





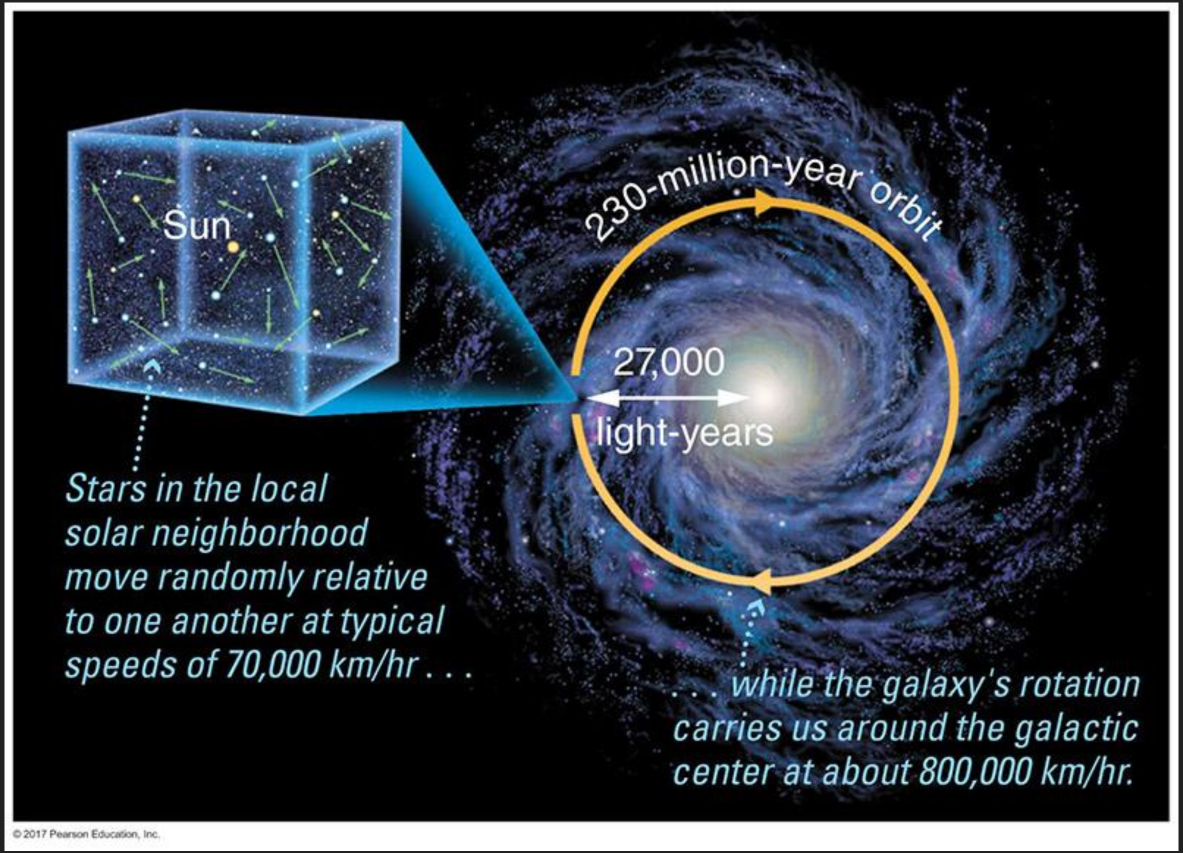
CMS



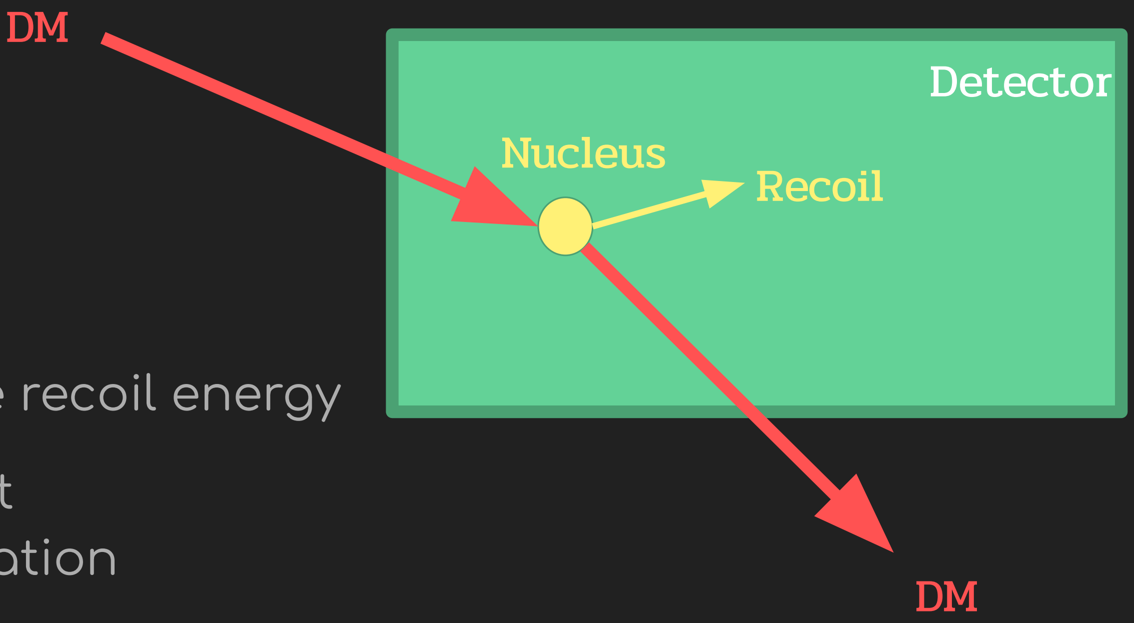


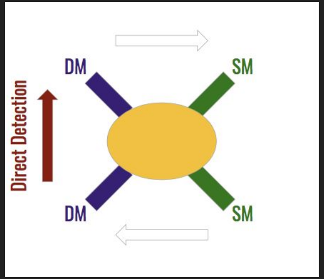
CTA

Direct detection



Schematic of direct detection





Measure recoil energy

- Light
- Vibration
- etc

Direct detection: the basics

DM particle collide with target nucleus at rest

$$E_R = \frac{2m_\chi^2 m_N v^2 \cos^2\theta}{(m_\chi + m_N)^2} \implies 2m_N v^2 \sim \mathcal{O}(10 - 100)\ \mathrm{keV}$$

Event rate in the detector

$$R \sim n_\chi \langle v \rangle \sigma$$

DM flux

ρ_0 / m_χ

Sensitive to local DM density and velocity distribution

$A\sigma_{\chi n}$

Depends on DM-nucleon scattering cross-section

Direct detection experiments

Challenges: Many things can give a nucleus a kick

- Cosmic ray
- Radioactivity in/around the detector

Strategies:

- Use the Earth as the shield.
- Use trigger to filter out background

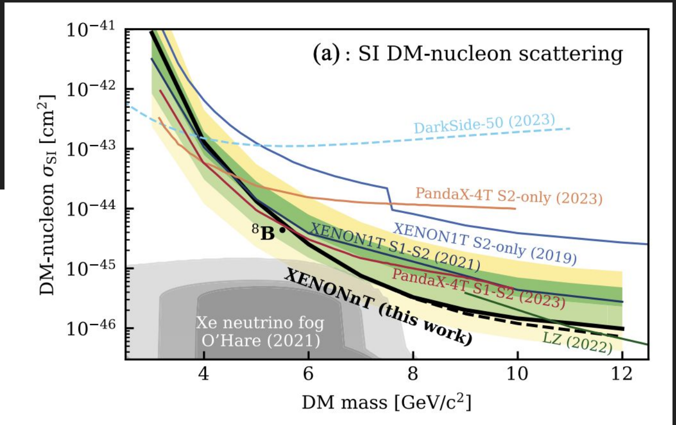
Implementations:

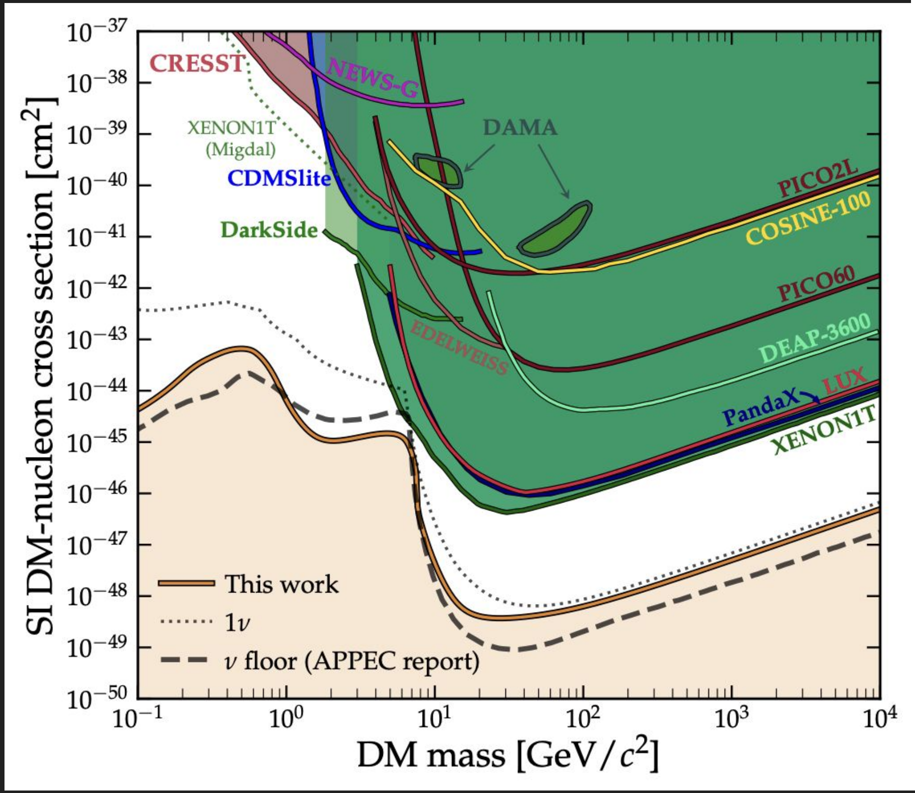
- Absolute rate: XENONnT, LZ, PANDAX-III, Super-CDMS
- Modulation: DAMA-Libra, COGENT

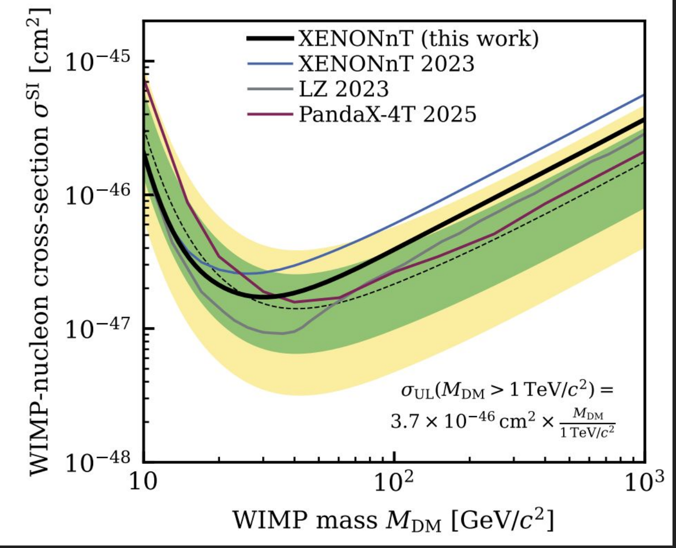
XENONnT

Direct detection status

2409.17868







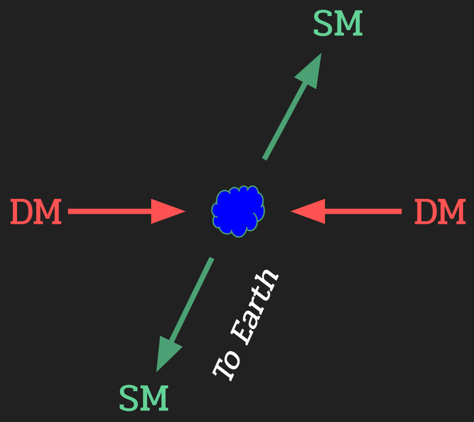
2109.03116

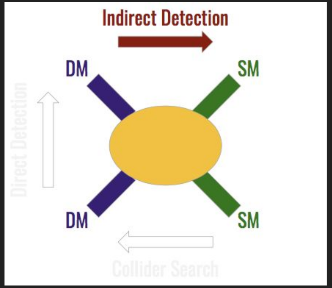
2502.18005

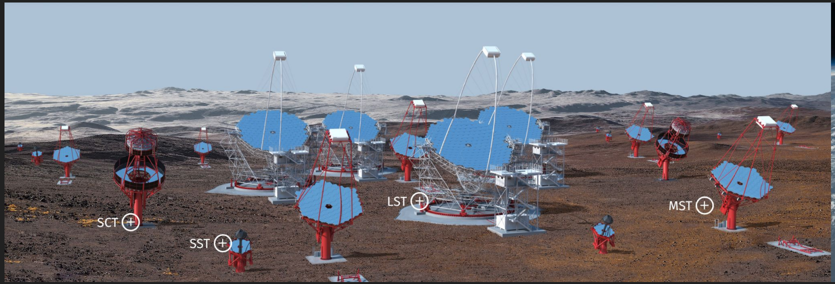
Further readings on direct detection

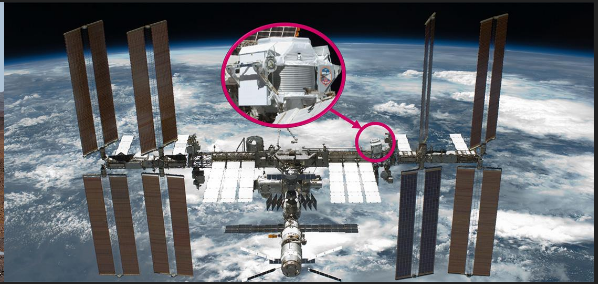
1. “Dark matter models and direct detection,” T. Lin [arXiv:1904.07915]
2. “An Introduction to Dark Matter Direct Detection Searches & Techniques,” T. Saab [arXiv:1203.2566]
3. “Introduction to dark matter experiments,” R. W. Schnee [arXiv:1101.5205]

Indirect detection









CTA

AMS-02 on ISS. cr: ESA

Basics of indirect detection

- DM self annihilate into SM (j)

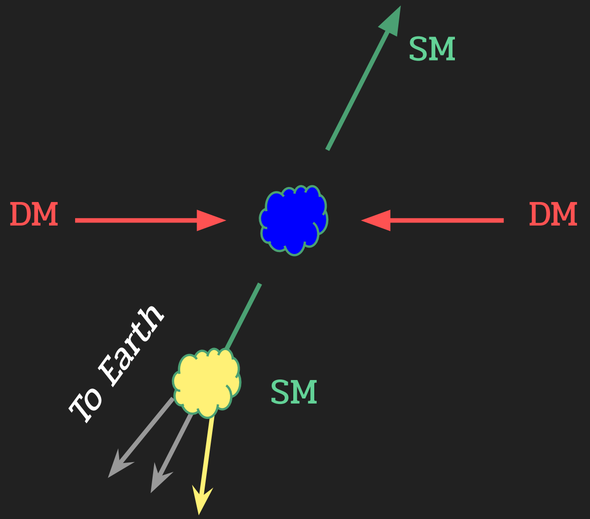
$$R \sim (n\bar{n}v)\sigma(\chi\bar{\chi} \to j\bar{j})$$

- Particle j decays to secondary particle x

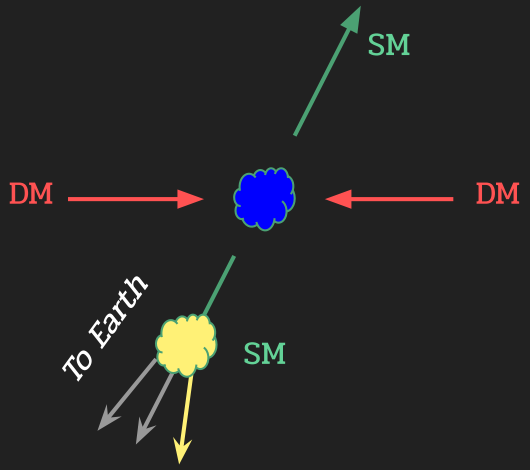
$$\frac{dR}{dE} \sim (n\bar{n}v)\sigma(\chi\bar{\chi} \to j\bar{j})\frac{dN_x^j}{dE}$$

- Only 1/(4π) fraction of x heads to the Earth

$$\frac{d^2\Phi_x}{dEd\Omega} \sim \frac{1}{4\pi}n\bar{n}\langle\sigma(\chi\bar{\chi} \to j\bar{j})v\rangle \frac{dN_x^j}{dE}$$



Basics of indirect detection (cont)



- More convenient to use mass density

$$n = \bar{n} = \rho/2m_\chi$$

$$\frac{d^2\Phi_x}{dEd\Omega} \sim \frac{1}{4\pi}\frac{\rho^2}{4m_\chi^2}\langle\sigma(\chi\bar{\chi}\to j\bar{j})v\rangle\frac{dN_x^j}{dE}$$

- Integrate along the line-of-sight and adding up all annihilation channels

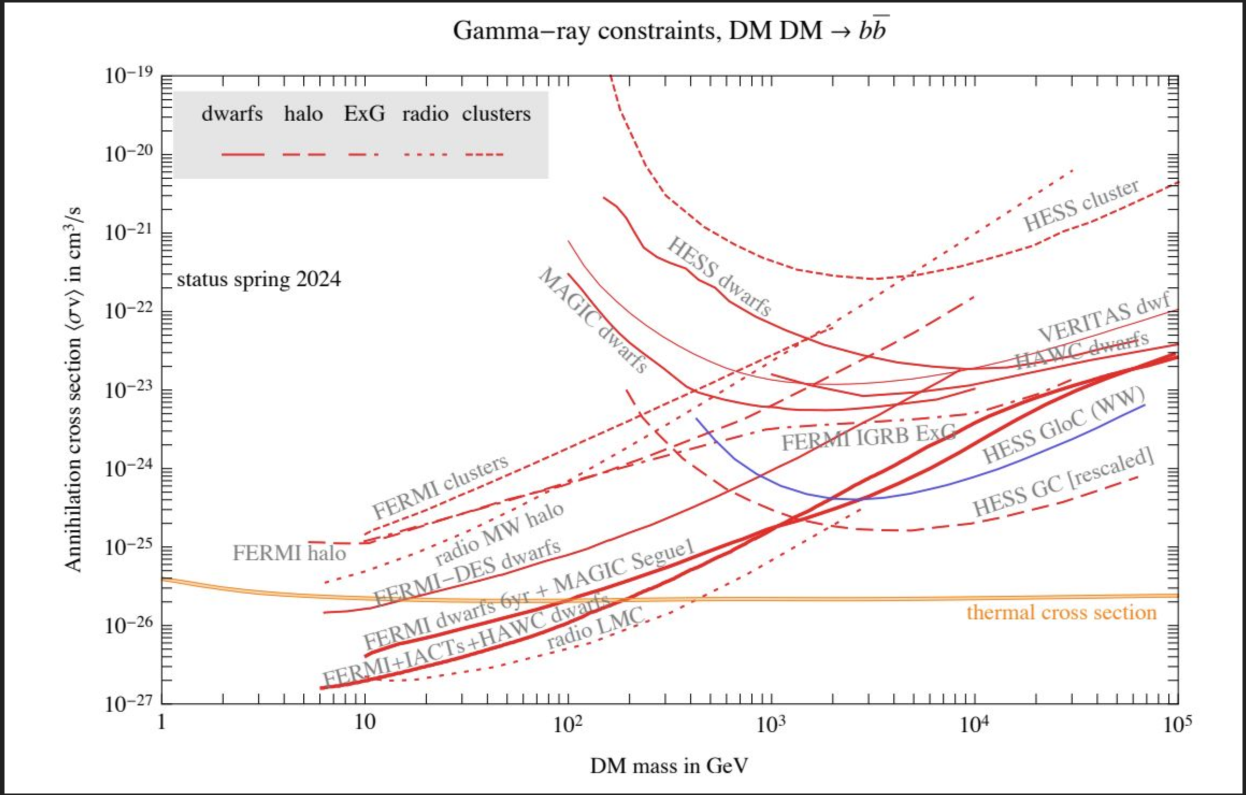
$$J(\psi) = \int_{los} \rho^2(r)dr$$

$$\frac{d^2\Phi_x}{dEd\Omega} = \frac{1}{16\pi}J(\psi)\frac{1}{m_\chi^2}\sum_j\left[\langle\sigma(\chi\bar{\chi}\to j\bar{j})v\rangle\frac{dN_x^j}{dE}\right]$$

- If DM is its own antiparticle

$$n(r)\bar{n}(r) \Rightarrow n(r)^2/2 \quad n = \rho/m_\chi$$

Indirect detection status



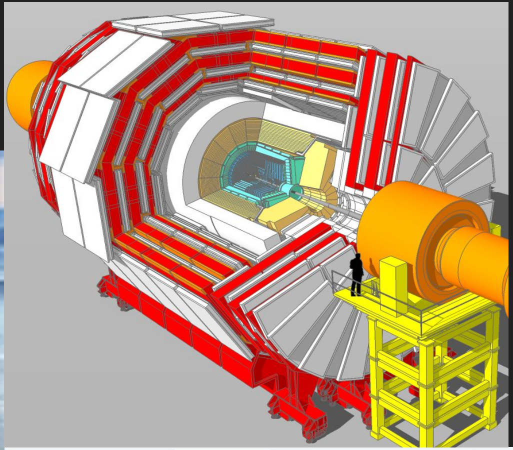
2406.01705

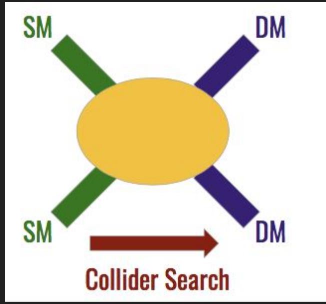
Further readings on indirect detection

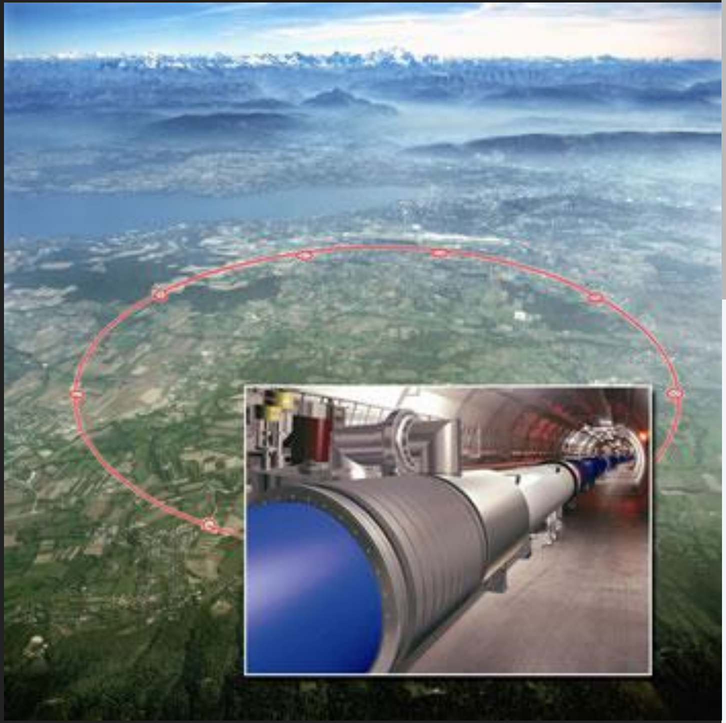
1. “Indirect Detection of Dark Matter,” T. R. Slatyer [arXiv:1710.05137]
2. “TASI Lectures on Indirect Searches For Dark Matter,” D. Hooper [arXiv:1812.02029]

Collider search

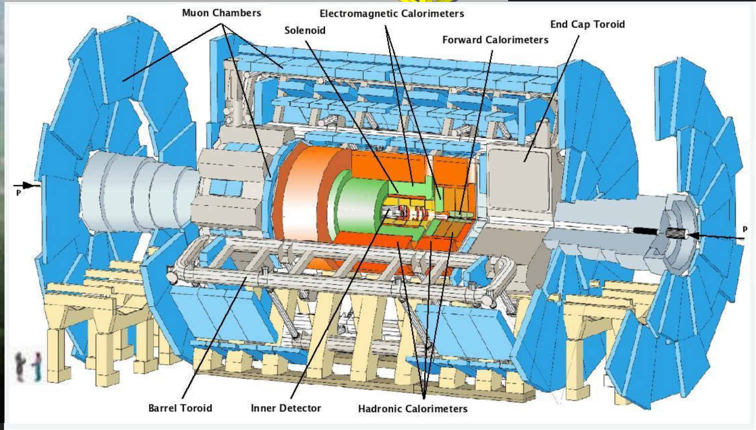
CMS detector







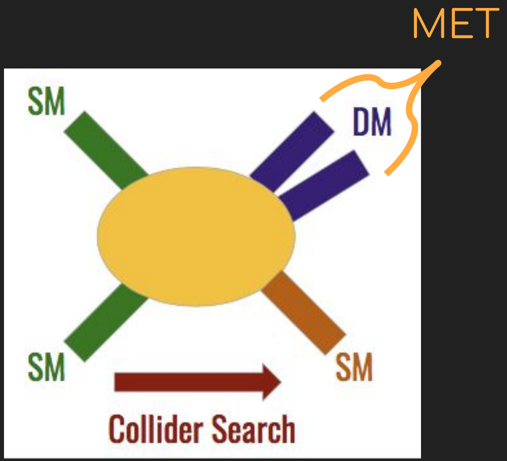
Large Hadron Collider

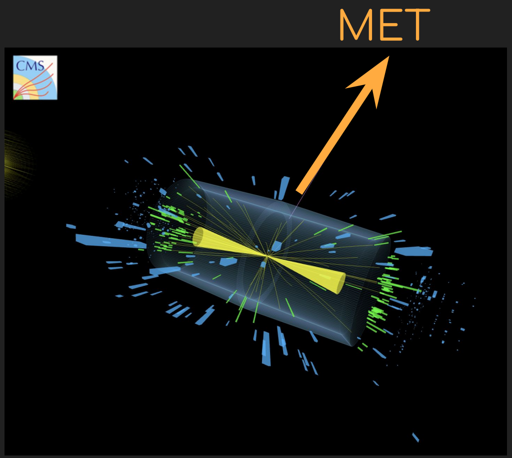


ATLAS detector

More realistic collider search

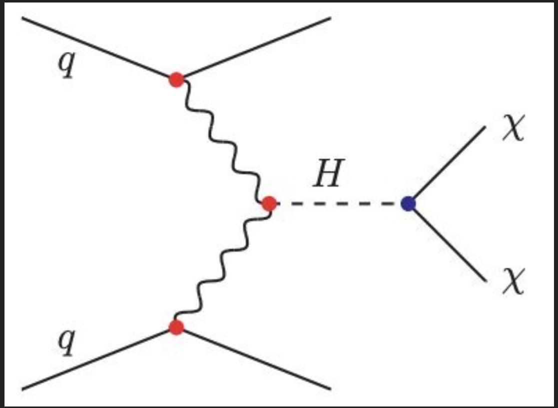
- DM leaves detector undetected
  - Missing energy/momentum
- Trigger on SM particles
  - Jet, photon, lepton
- Typical signatures
  - Mono-X
  - Higgs invisible decay

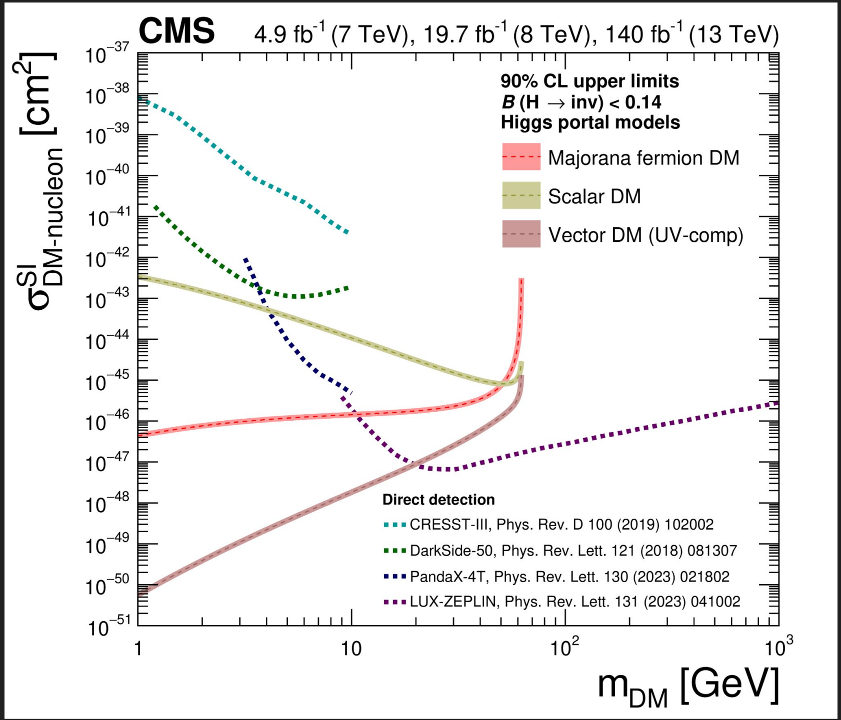




Collider search: Higgs invisible decay

2405.13778

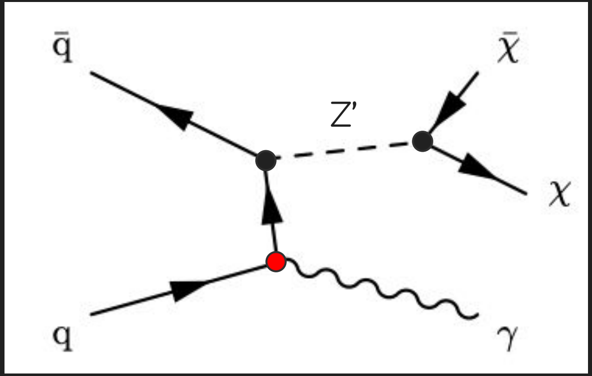




Higgs couples directly to DM

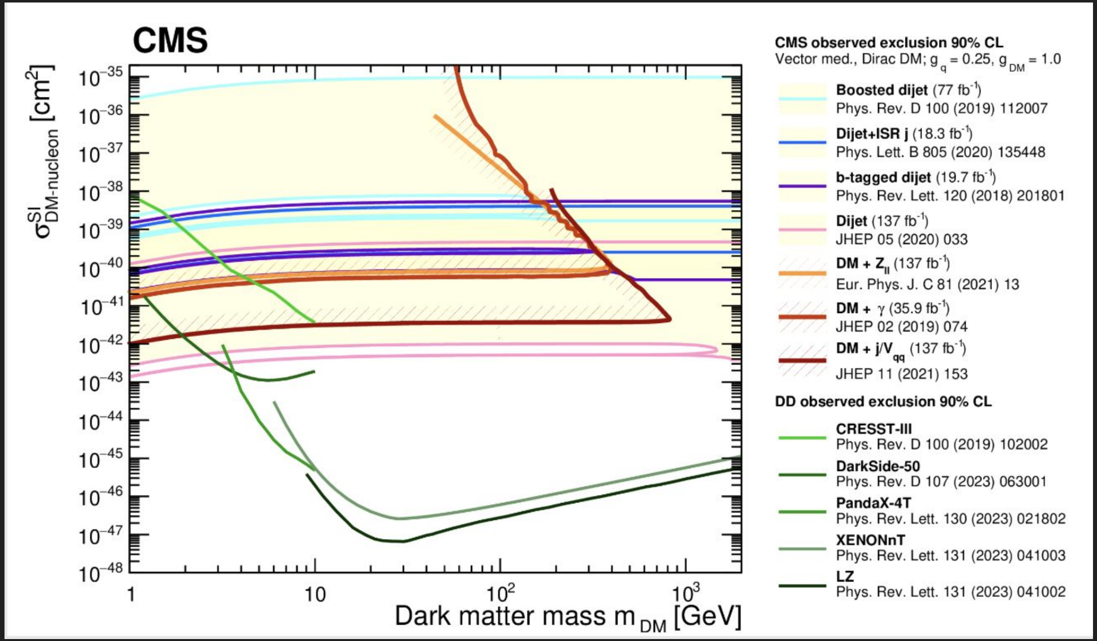
- DM must me lighter than mH/2
- Two free parameters: mDM and gDM

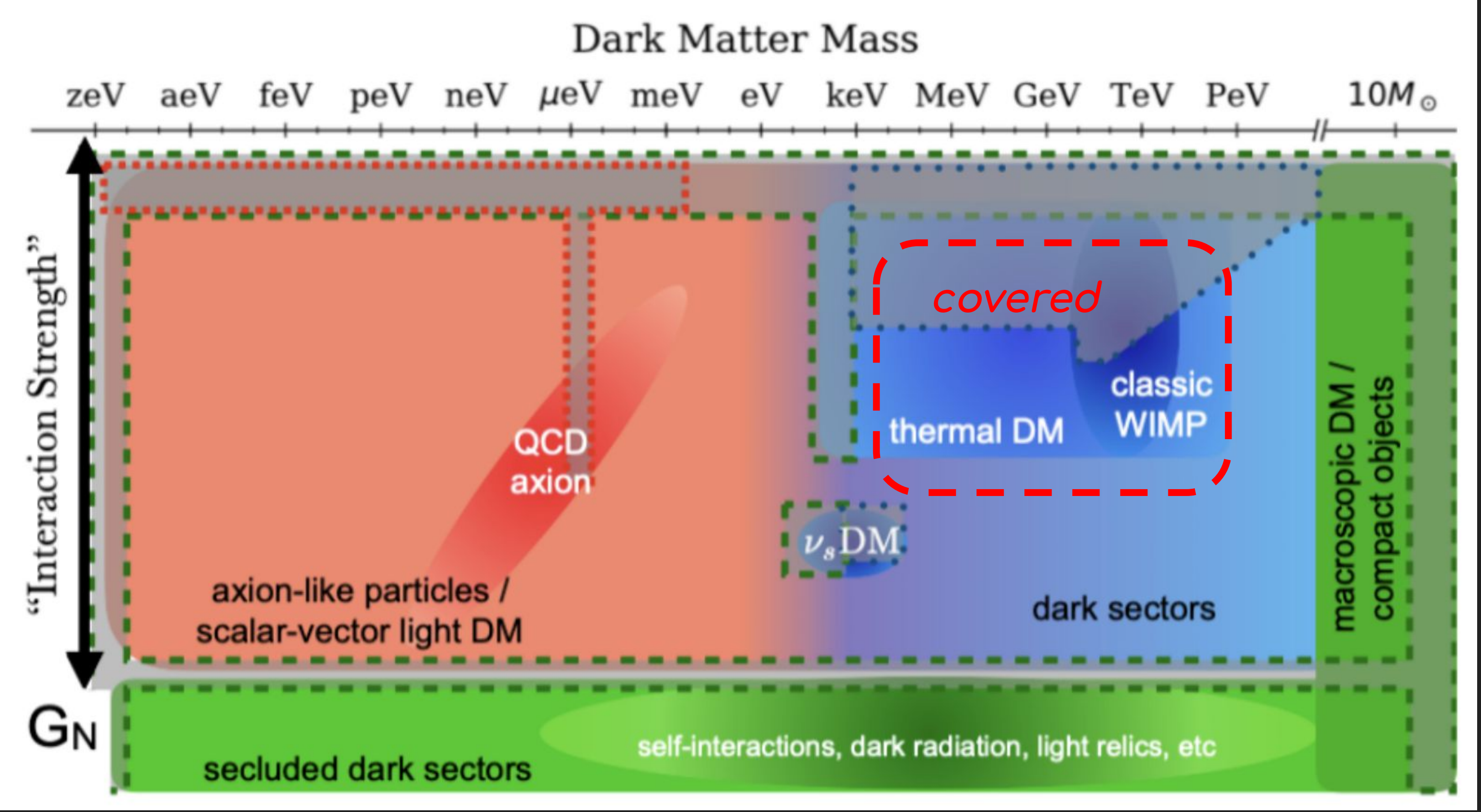
Collider search: Mono-x



New mediator (Z') couples DM to SM particles

2405.13778





Snowmass Report [2111.09978]

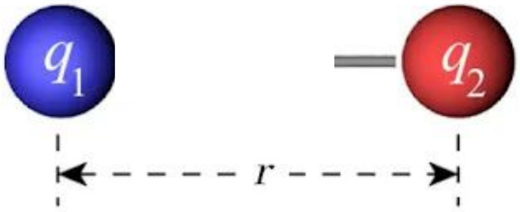
Wave-like DM

Particle-like DM

Are we asking the right questions?

Dark photon as dark matter

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\widetilde{F}_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

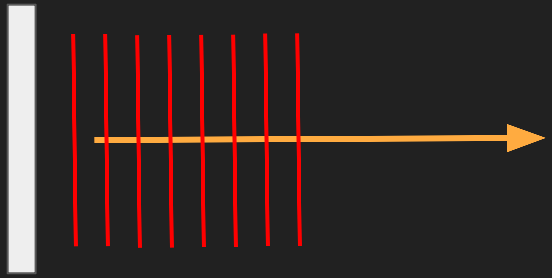


$$V(r) = -\frac{Z\alpha}{r}\left(1 + \epsilon^2 e^{-m_\gamma r}\right)$$

- Photon is massless due to gauge symmetry
- Beyond the SM can include a new massive gauge boson, the dark photon, which breaks a different gauge symmetry
- Gauge symmetry allows it to mix with the usual photon

How to detect dark photon

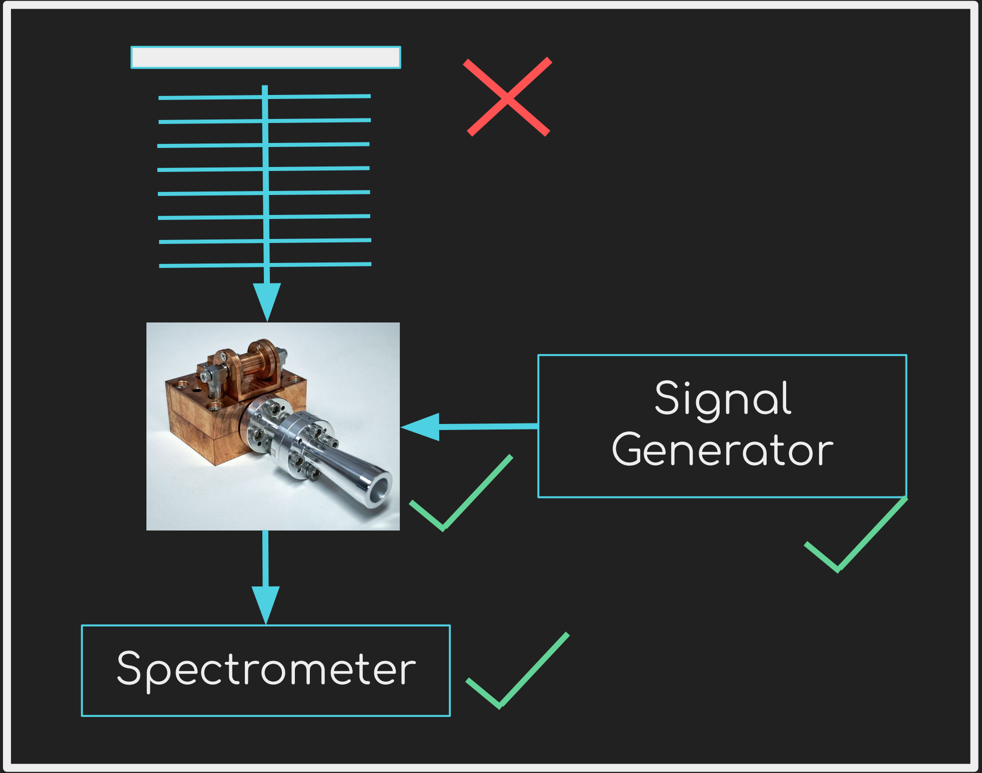
$$\omega = m_{\gamma'}$$

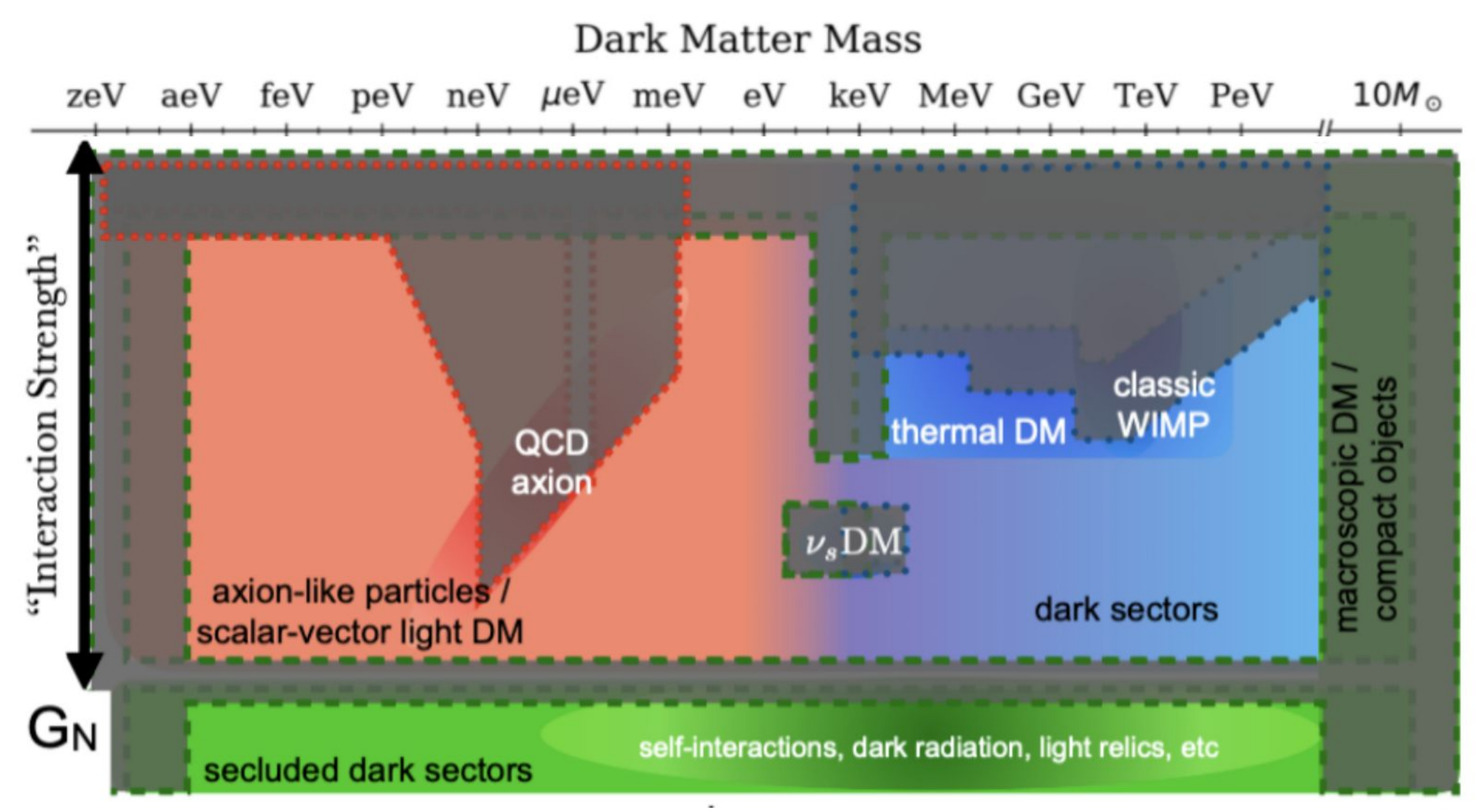


- Dark photons, as a background field throughout space, oscillate with frequency ~ mass
- Contain a small component electric field component
  - Cause electron in the metal plate to oscillate with the same frequency → real photon

Dark photon search at NARIT (coming soon)

Cryogenic
+ Dark box





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Wave-like DM

Particle-like DM