Thermal Relic Dark Matter in the Modern Era

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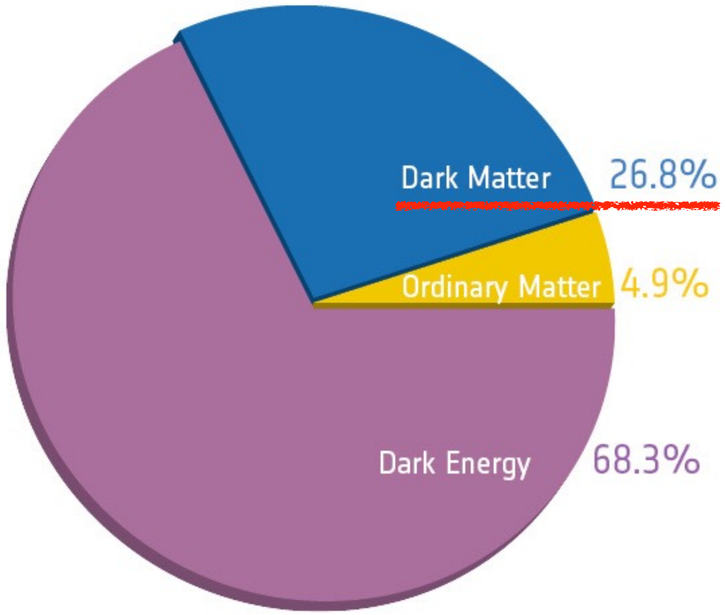
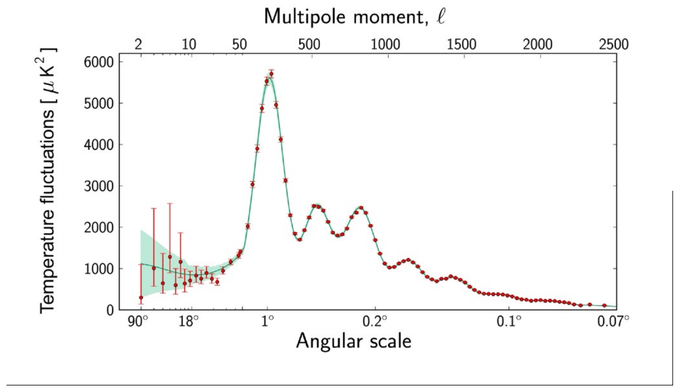
(Ph.D 2018) —> (04.2018 -) —> (09.2018 -) —> (11.2021 -)

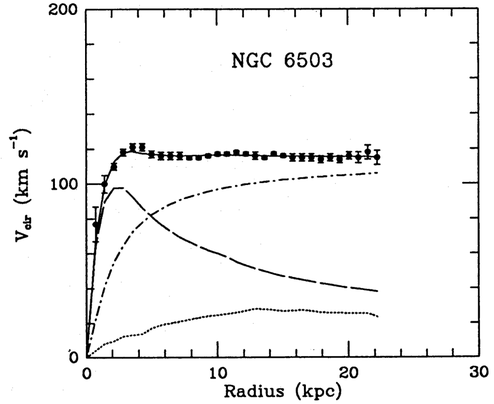
ICCUB Winter Meeting, 07/02/2023

Evidence of Dark Matter

Energy density of the Universe

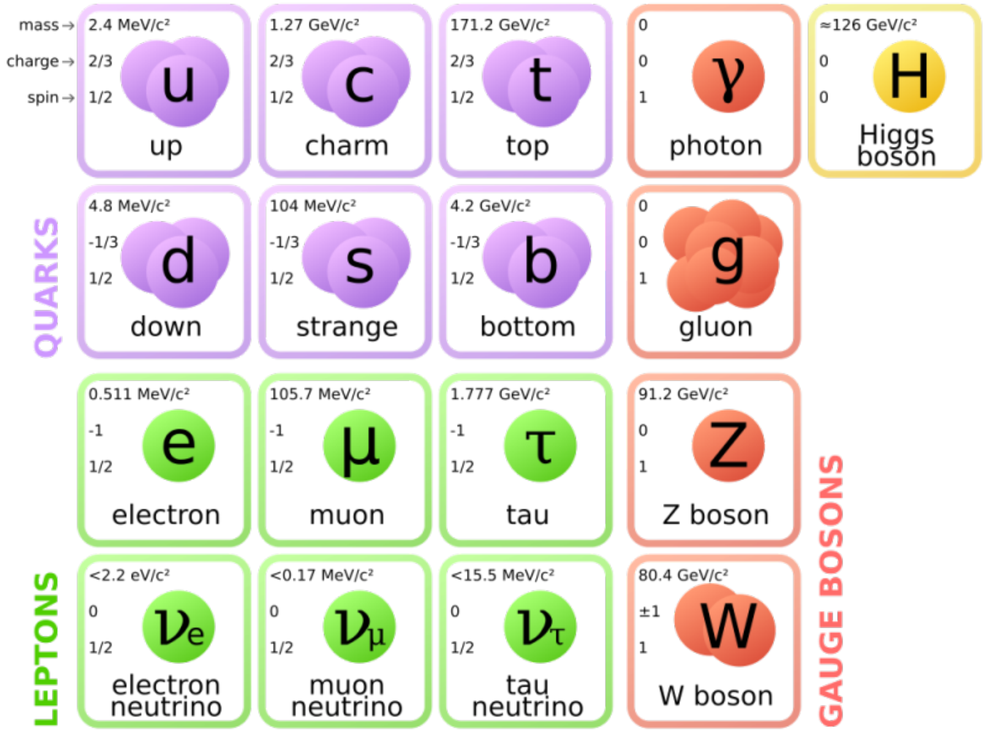






- Known: gravitational interaction, relic abundance
- Unknown: all other fundamental nature
  (mass, spin, non-gravitational interactions, etc.)

DM is not in the Standard Model



- Required properties:
  - EM neutral or millicharged
  - long-lived
  - non-relativistic ("cold")

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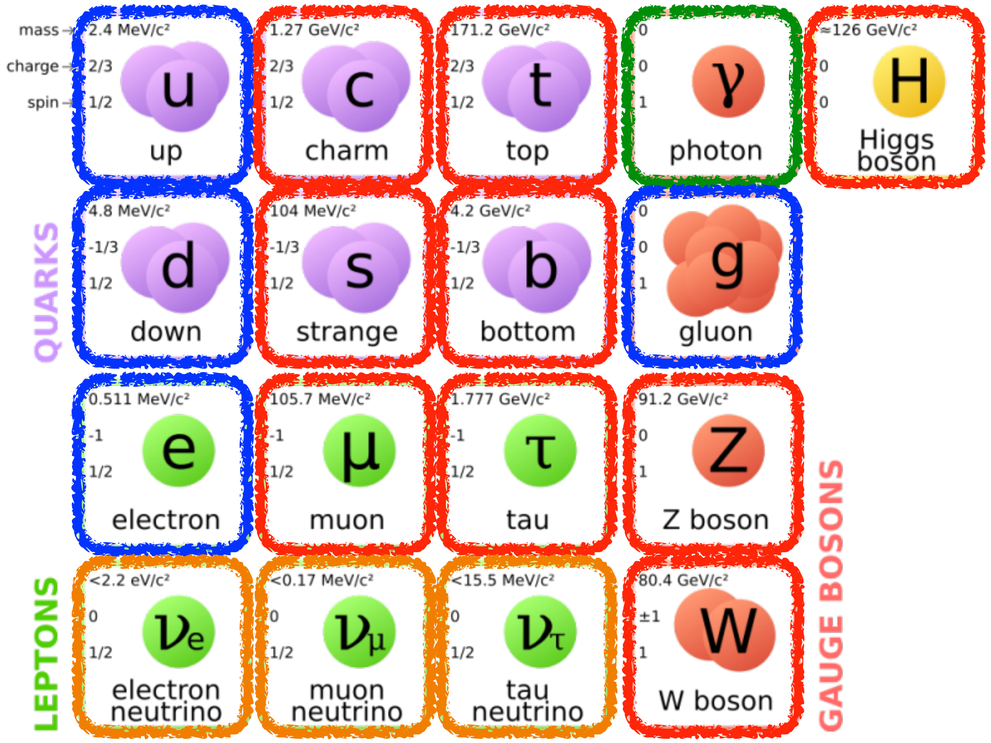

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  - long-lived
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❌ Unstable

❌ Radiation

❌ Ordinary Matter (Baryon)

❌ Relativistic (Hot DM)

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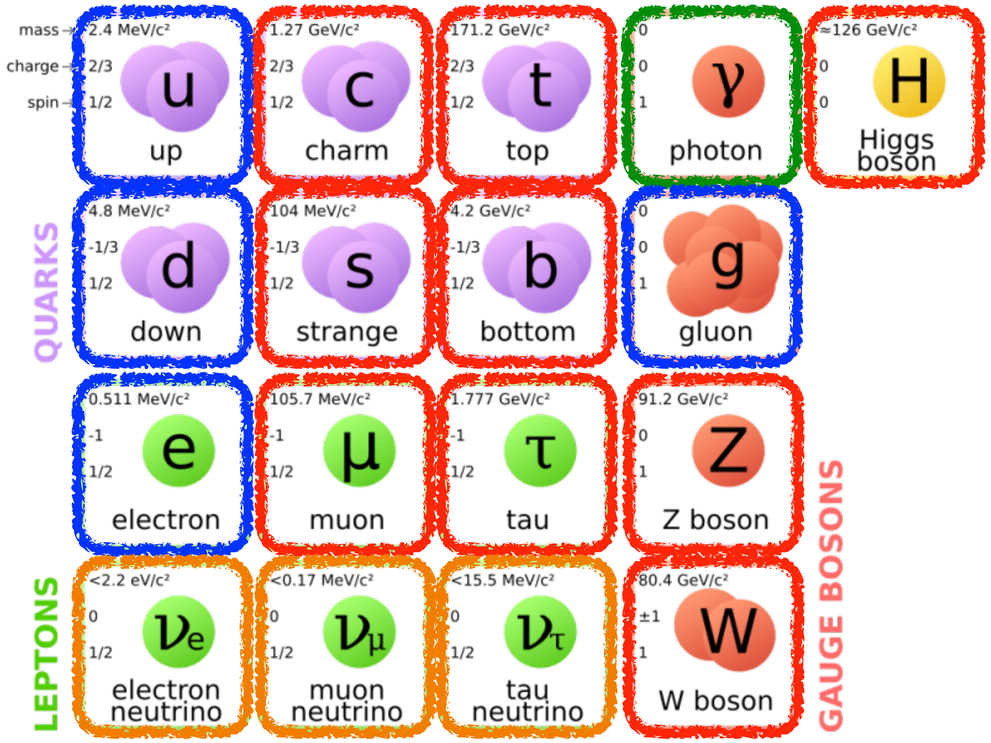

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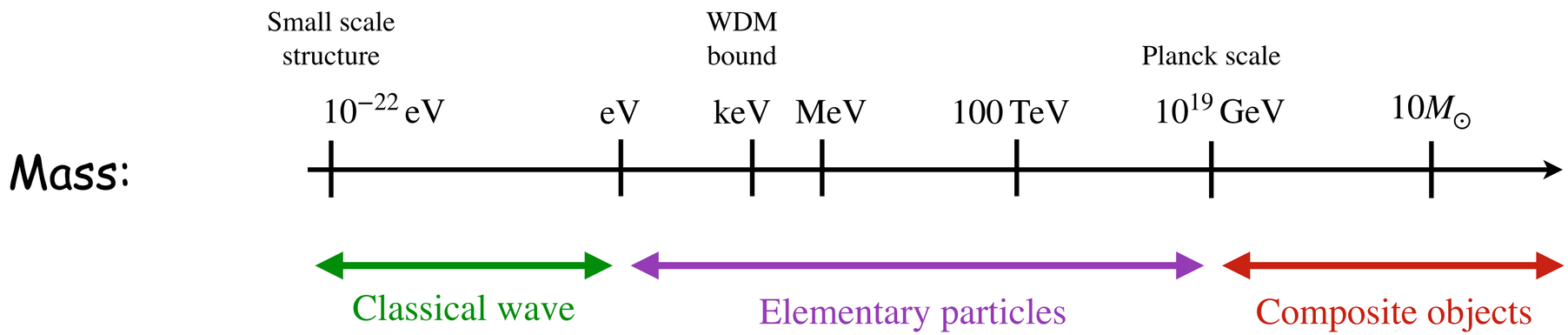
=> **Physics Beyond the SM (BSM)**

*Electroweak-Skyrmion can be DM but BSM physics needed

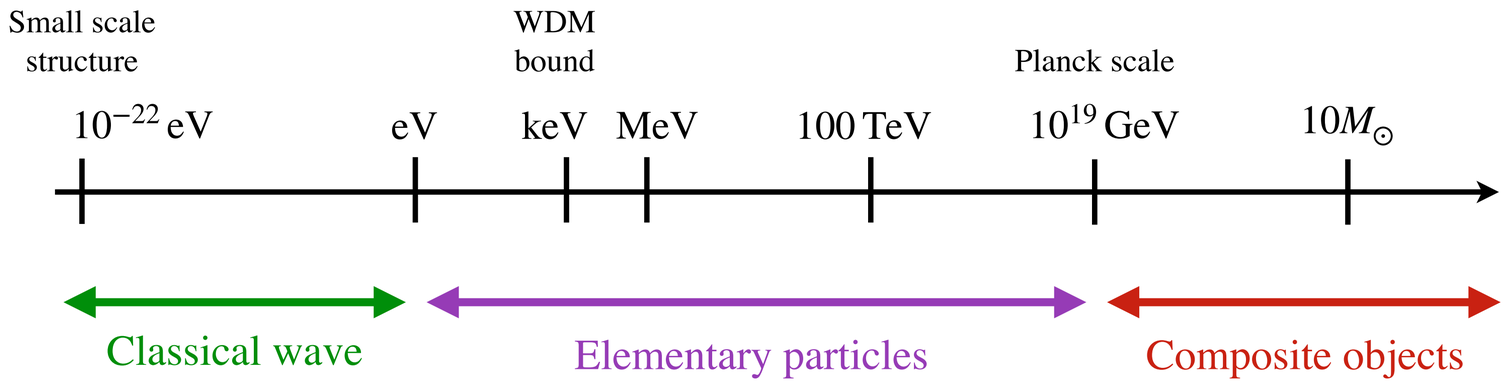
[See e.g. 1605.07355, 1703.06397, 2108.12185]

Cold Dark Matter Landscape

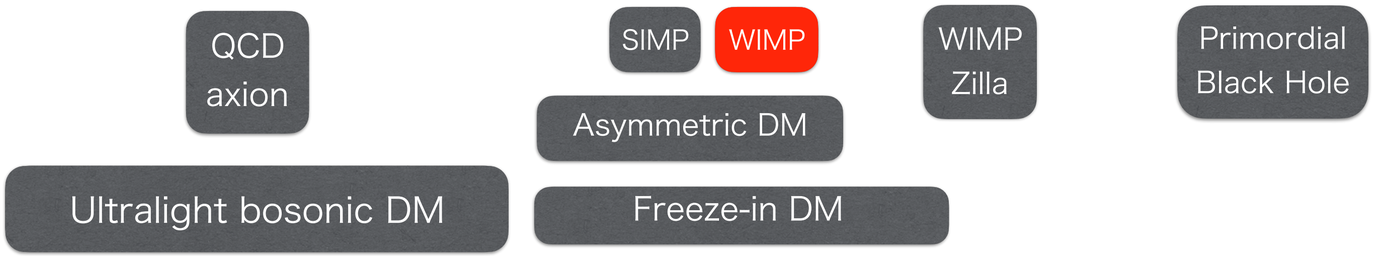


Cold Dark Matter Landscape

Mass:

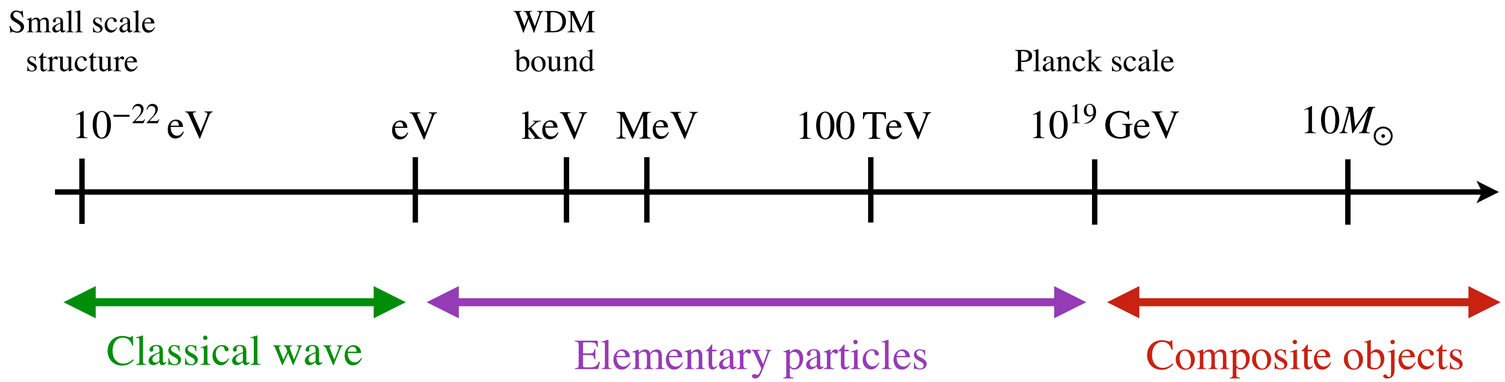


Candidates:



Cold Dark Matter Landscape

Mass:



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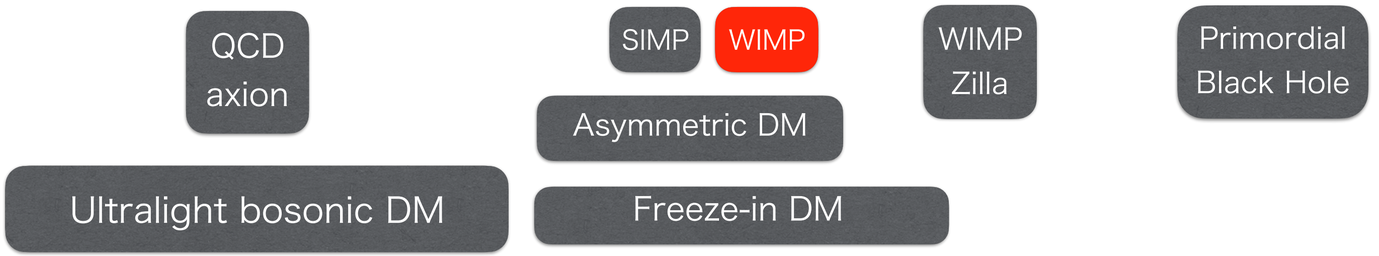
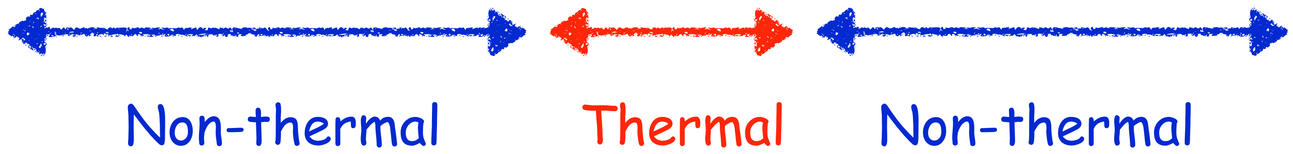
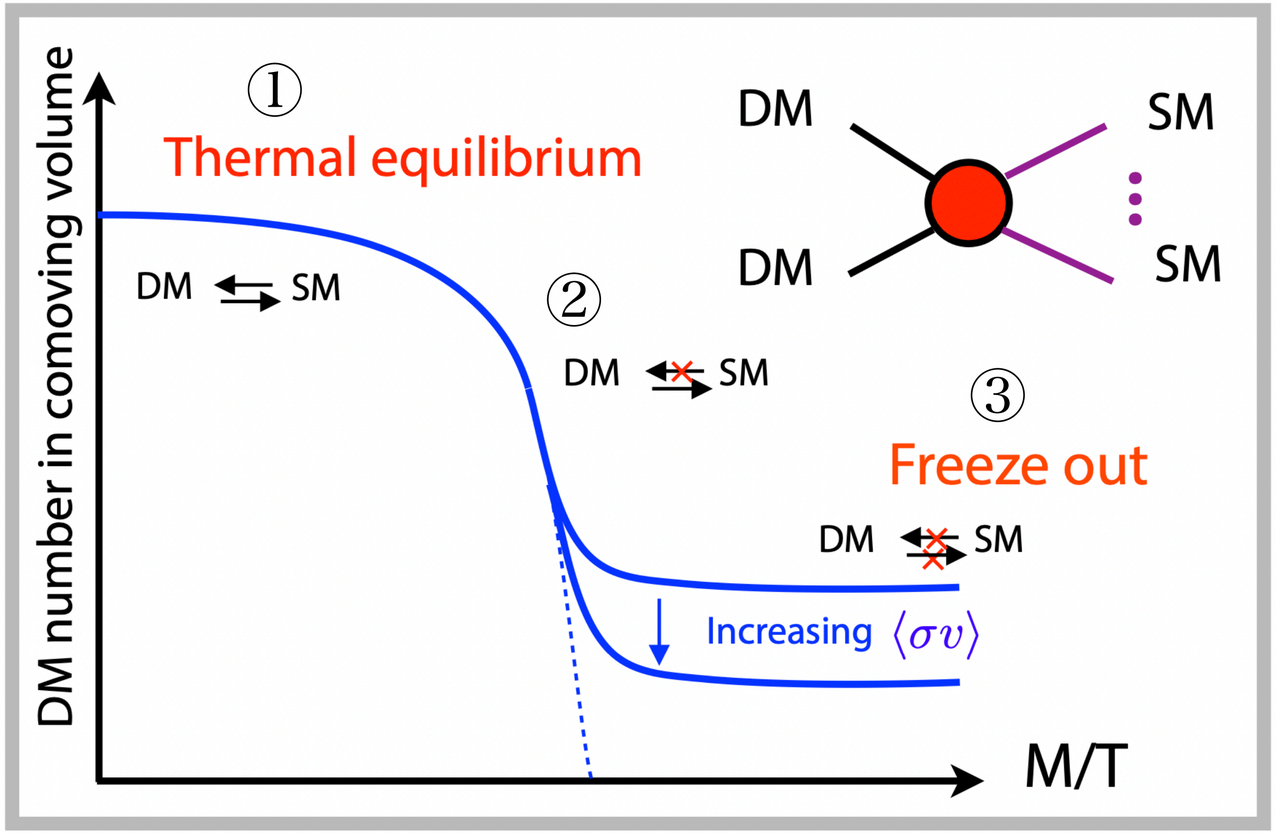


Production:



Weakly Interacting Massive Particles (WIMPs)



■ **Thermal relic scenario**

1. DM is in thermal equilibrium for M<T
2. For M>T, DM is not created from plasma
3. DM cannot find annihilation partner

   -> DM comoving density freezes out

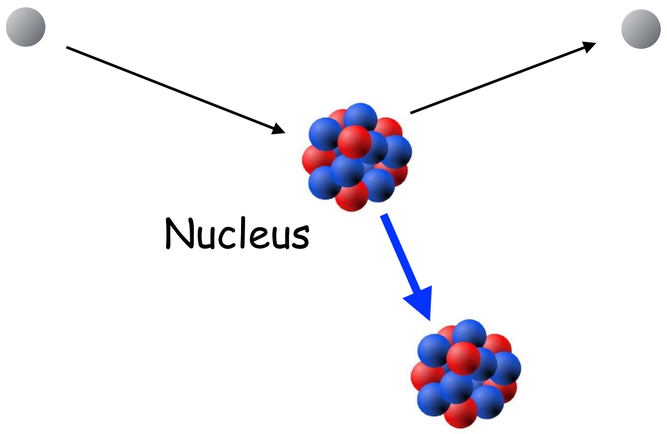
Relic abundance:

$$\Omega_{DM}h^2 \sim 0.1 \times \frac{3\times10^{-26}\ cm^3/s}{\sigma_{ann}v}$$

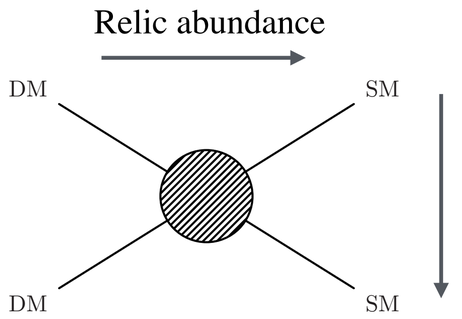
Direct detection of WIMPs

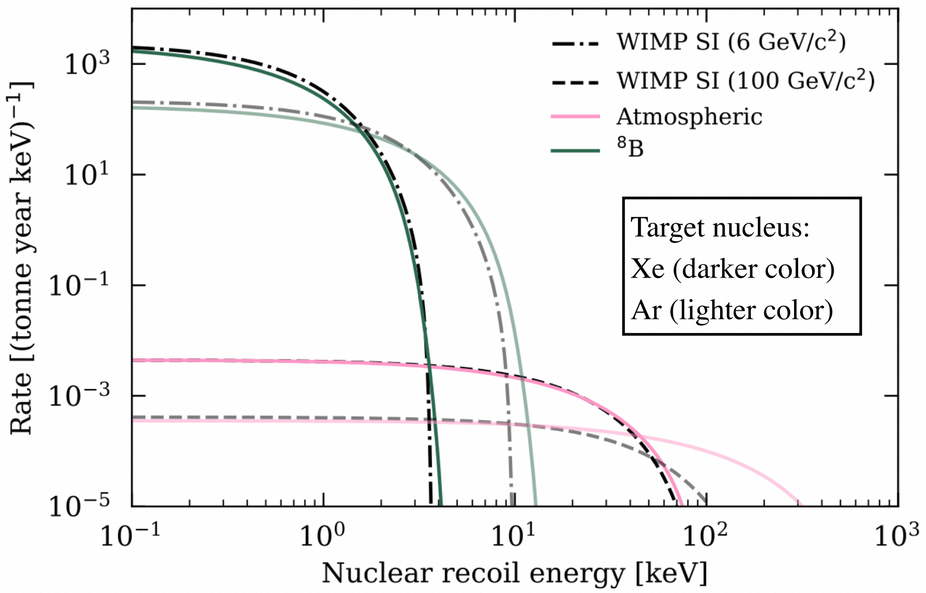
DM particle

v_{DM}~220km/s



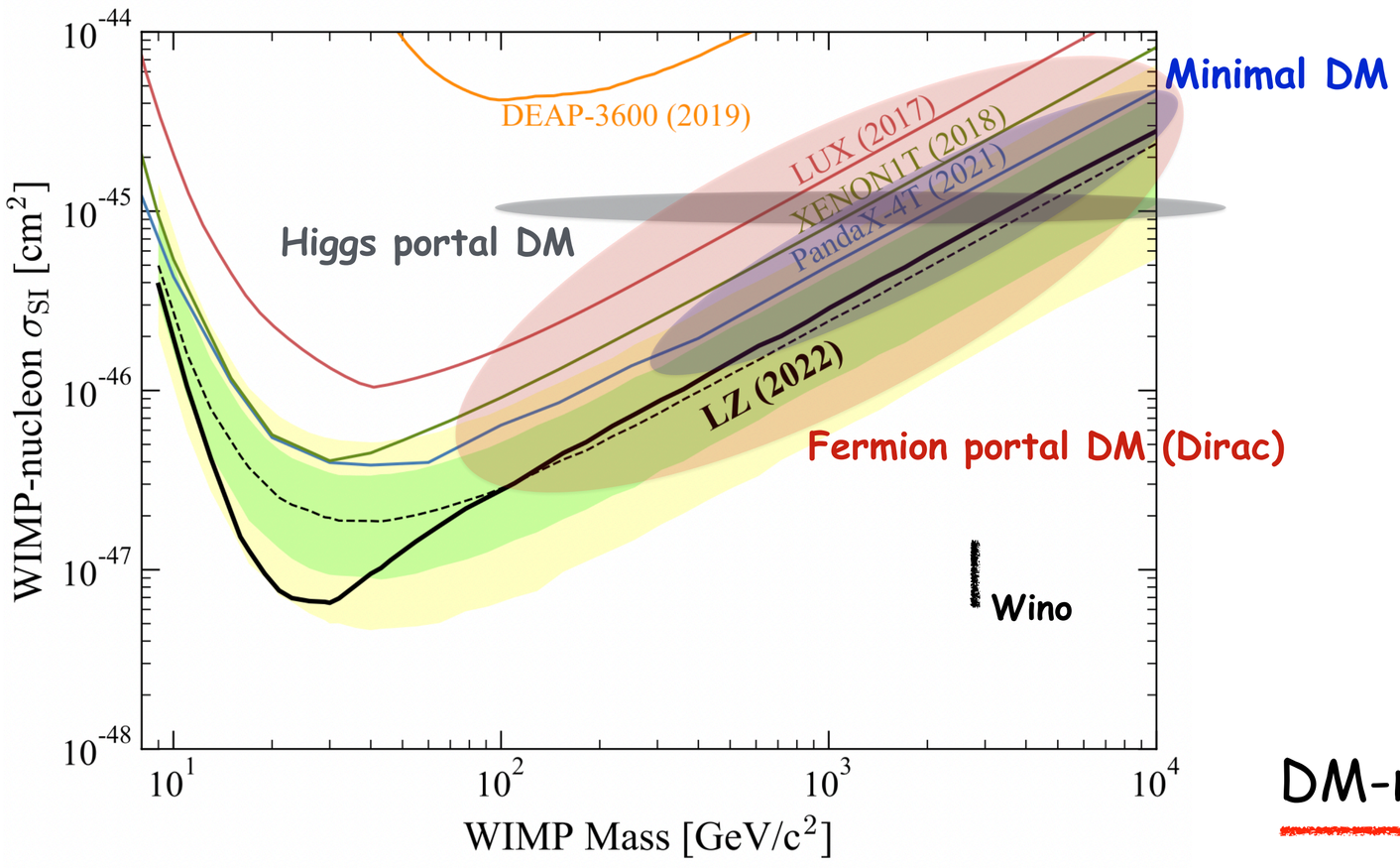
$$E_N^{\text{recoil}} \sim 1 - 10\,\text{keV}$$



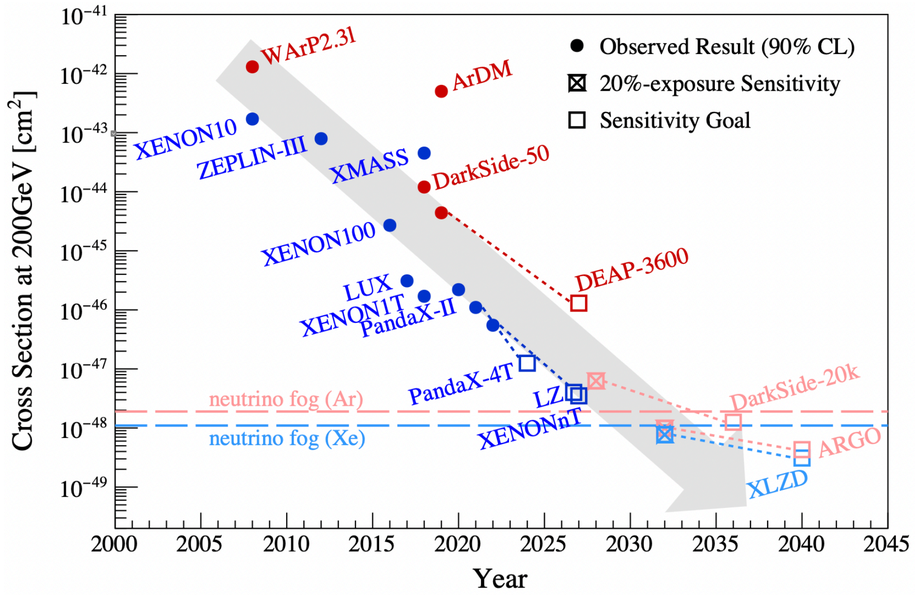


Direct detection of WIMPs

■ LUX-ZEPLIN (LZ) experiment (22)



Sensitivity development



DM-nucleon scattering is very suppressed

Recent study of thermal relic DM

- Model building in light of the direct detection results

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  1. Sub-GeV DM

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     - $E_{DM,kin}$ << typical detector threshold ~ O(keV)

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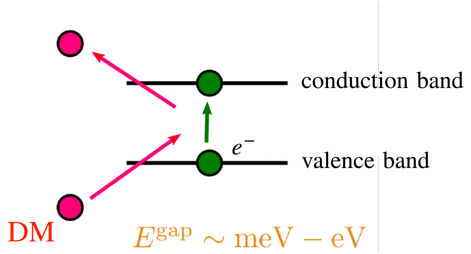
     - a mediator below GeV scale

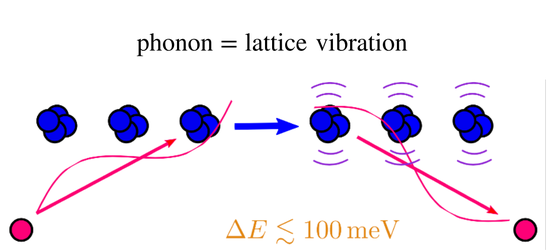
Recent study of thermal relic DM

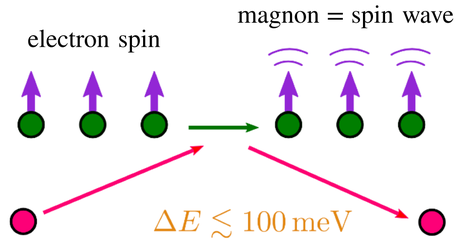
- Model building in light of the direct detection results

1. Sub-GeV DM
   - $E_{DM,kin}$ << typical detector threshold ~ O(keV)
   - a mediator below GeV scale
   - new detection techniques with condensed matter systems

     e.g.) semiconductors, Dirac materials, insulator, ferromagnet …







Recent study of thermal relic DM

- Model building in light of the direct detection results

1. Sub-GeV DM
   - $E_{DM,kin}$ << typical detector threshold ~ O(keV)
   - a mediator below GeV scale
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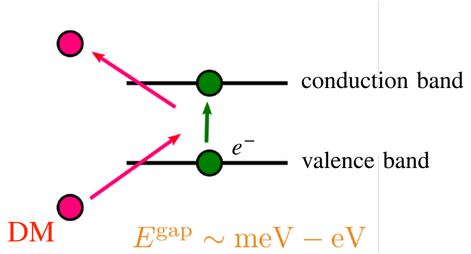
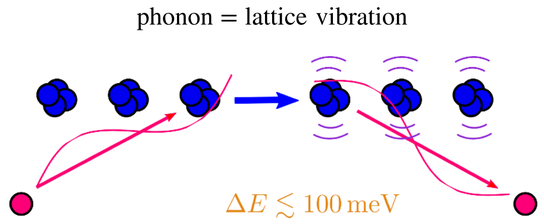
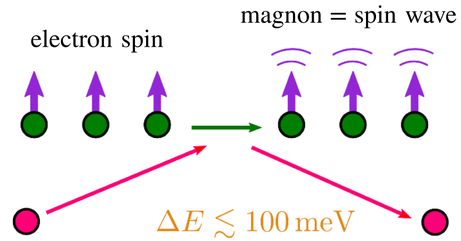


2. Suppression mechanism (This Talk)
   - choice of force mediators
   - symmetry
   - etc.





Secluded WIMPs

[Pospelov, Ritz, Voloshin (08)]

- DM annihilates predominately into light unstable mediators

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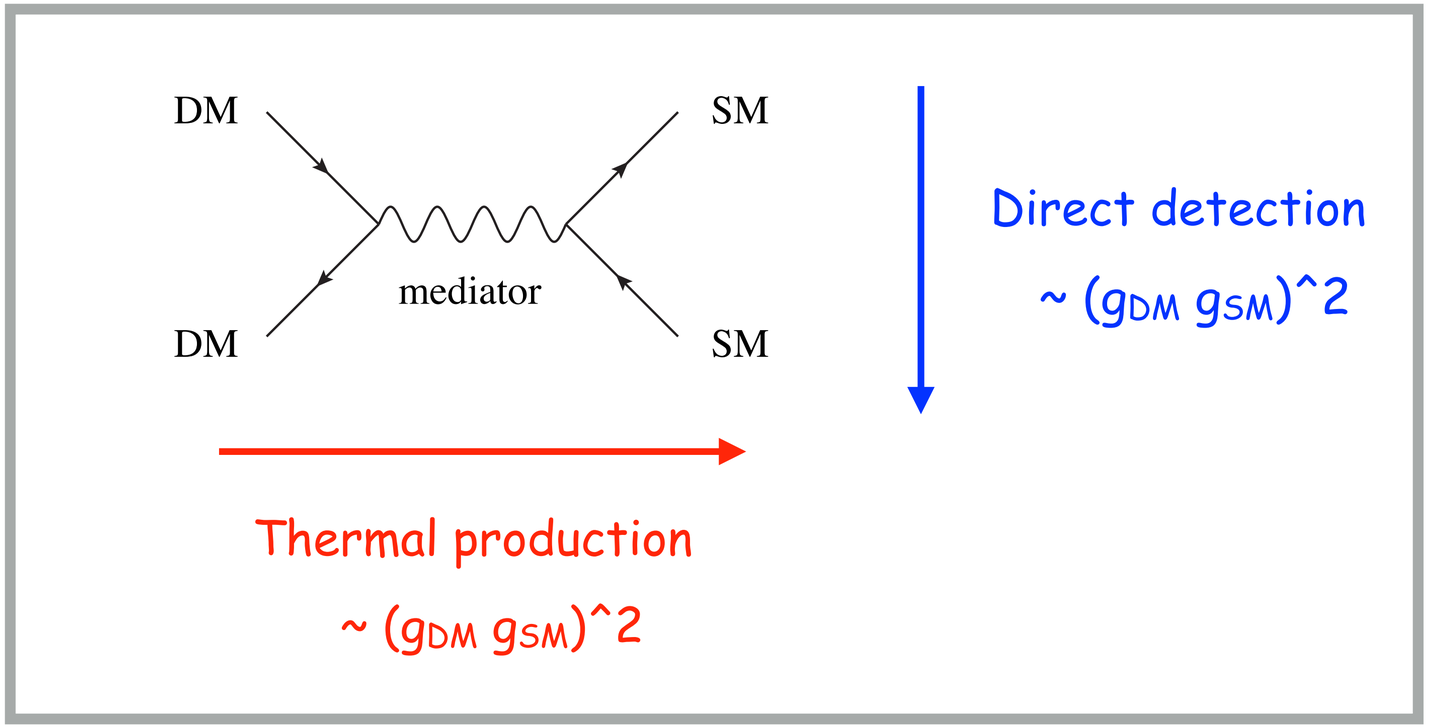
Traditional WIMPs ($g_{DM} \sim g_{SM}$)



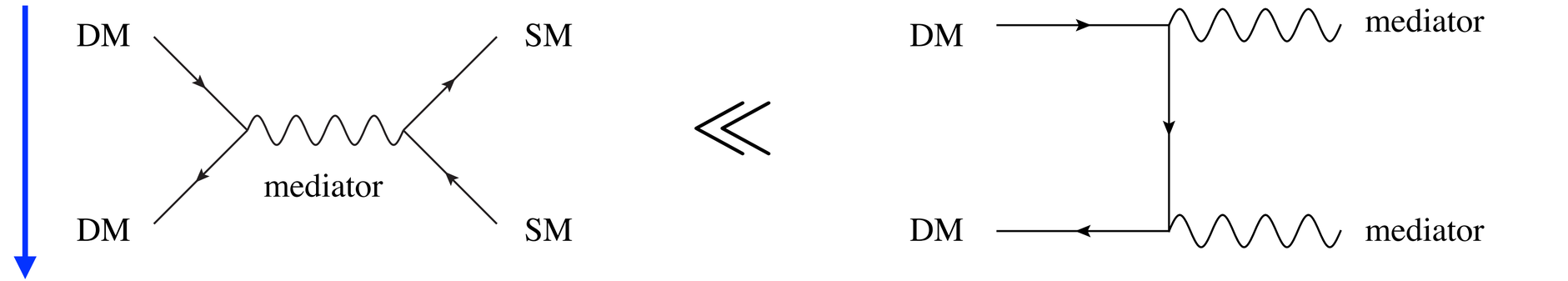
=> Production and direct detection have the same coupling scaling

Secluded WIMPs

[Pospelov, Ritz, Voloshin (08)]

- DM annihilates predominately into light unstable mediators

Secluded WIMPs ($g_{DM} \gg g_{SM}$)



Direct detection

~ $(g_{DM}\, g_{SM})^2$

Thermal production ~ $(g_{DM})^4$

=> DM production separated from direct detection

Secluded WIMPs

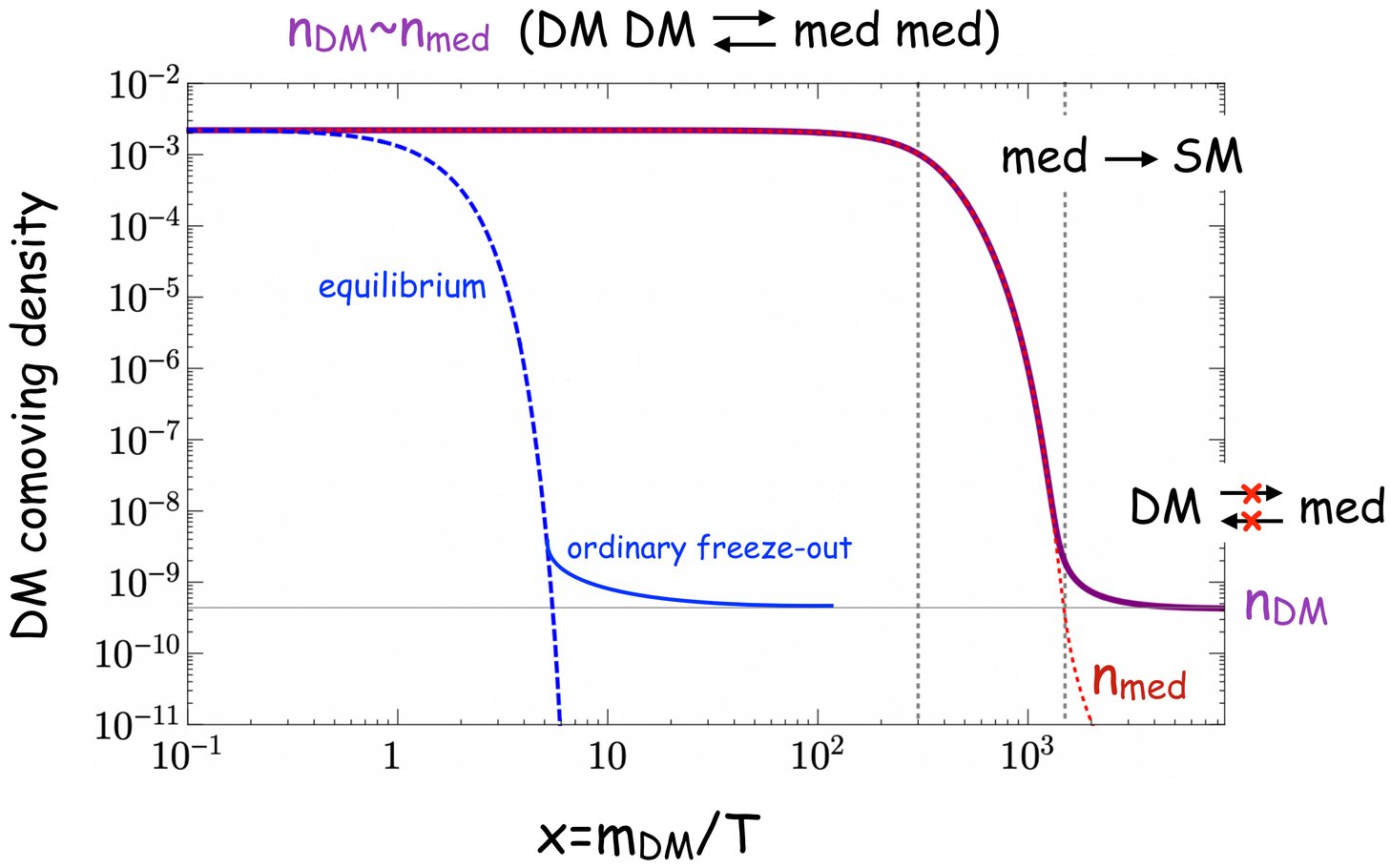
[Pospelov, Ritz, Voloshin (08)]

- popular mediators = dark photon, RH neutrinos, ALPs etc.
  - must decay before BBN

- signatures from present DM annihilation (indirect detection)
  - gamma-ray, X-ray, positron, etc. [Cirelli+ (20); Leane+ (18); etc.]
  - neutrinos [Yüksel+ (07); Argüelles+ (19); Asai, **SO**, Tsumura (20); etc.]

Co-decaying DM

[Dror+ (16); Farina+ (16); **SO**, Tanabashi, Yamanaka (16)]



- Secluded DM with a massive, long-lived mediator (m_{DM}~m_{med})
  - delayed freeze-out
  - early matter domination
  - enhanced DM annihilation rate

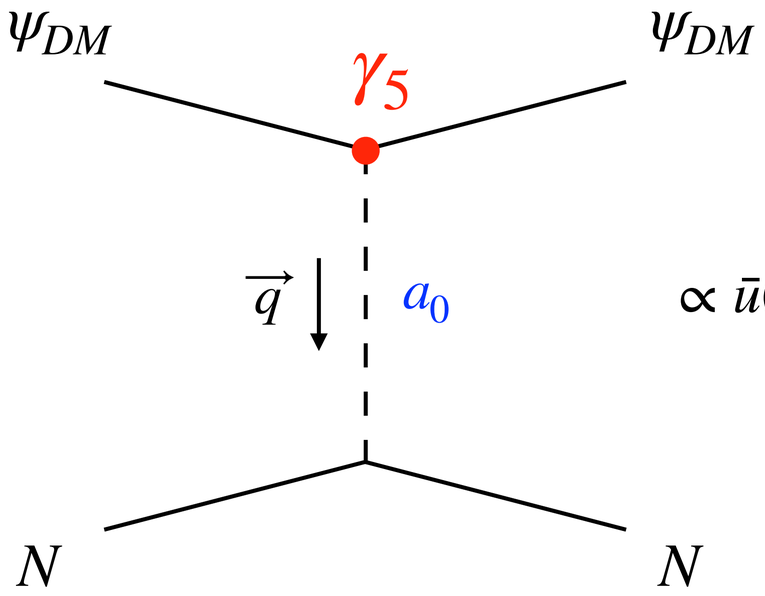
$\sigma_{ann}v \sim (x_f/20) \times 3\times10^{-26}$ cm^3/s

boost factor

Pseudo-scalar portal DM

[Pospelov, Ritz (11); Ipek, McKeen, Nelson (14)]

$$\mathscr{L} \supset a_0 \, \bar{\psi}_{DM} \, i\gamma_5 \, \psi_{DM}$$



$$\propto \bar{u}(p') \, \gamma_5 \, u(p) = \vec{q} \cdot \vec{\sigma}$$

$$|\vec{q}| \sim m_{DM} v_{DM}$$

$\sigma_{DM\text{-}N} < 10^{-48}\ \mathrm{cm}^2$

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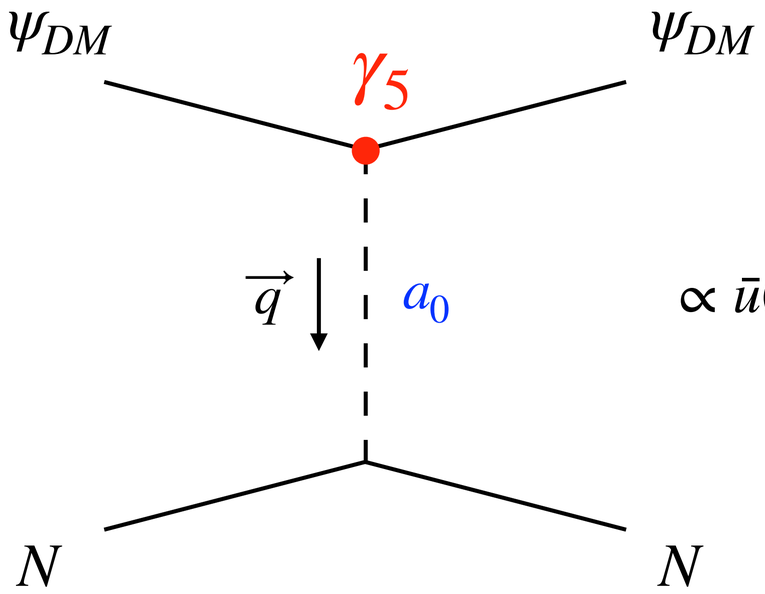

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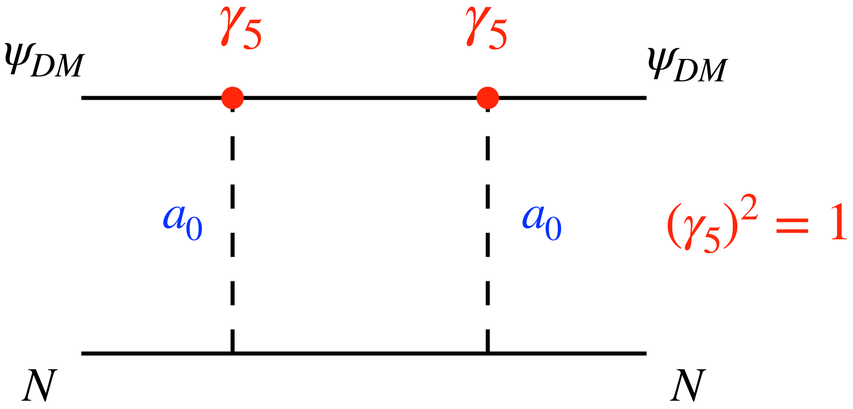
$\sigma_{DM\text{-}N} < 10^{-48}$ cm^2

Still within the reach of future experiments



$\sigma_{DM\text{-}N} \sim 10^{-47}$ cm^2

[Abe, Fujiwara, Hisano (18)]

Pseudo Nambu-Goldstone DM

[Gross, Lebedev, Toma (17)]

- An approximate global symmetry: $S \to S^{i\theta}$
  - explicitly broken by $S^2 + (S^*)^2$
  - spontaneously broken by VEV of S => pNG boson = DM
  - $\sigma_{DM\text{-}N}$ ~ (DM velocity)^4 (cf. soft pion theorem)

- pNG DM often appears in gauge extensions of SM

  e.g. SO(10) GUT, U(1) B-L, dark SU(2), etc.

Abe, Toma, Tsumura (20); +Yamatsu (21)
Okada, Raut, Shafi, Thapa (21)
Abe, Hamada (22)
Otsuka, Shimomura, Tsumura, Yamatsu, Uchida (22)
etc.

Flavored mediators

[Galon, Kwa, Tanedo (16)]

- DM annihilates via mediators carrying SM flavor charge
  - DM-N scattering suppressed by the flavor symmetry

  e.g. Leptonic Z4: DM + DM -> Φ -> mu + tau [Asai, Miyao, **SO**, Tsumura (22)]

- Neutrino oscillation?

- Signatures (e.g. e-mu flavor case)
  - Neutron star heating: DM + mu -> DM + e heats up old NS to ~1700K
  - μTristan at J-PARC: $\bar{\mu}$ + e -> DM + DM + gamma

[Asai, Miyao, **SO**, Tsumura, work in progress]

Summary

- Domain of thermal relic DM is much broader than what was traditionally thought

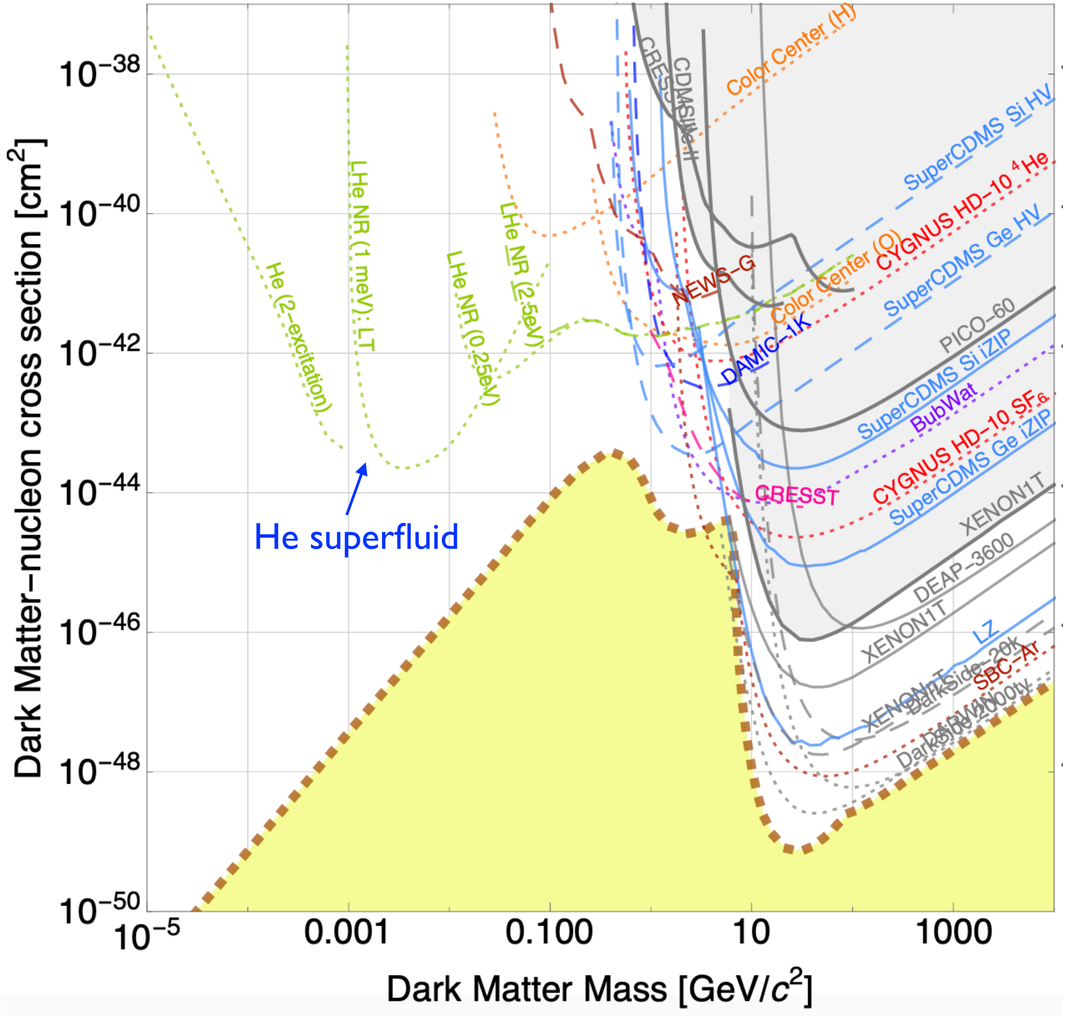
- Ideas for DM searches
  - low threshold materials for sub-GeV DM
  - astrophysical objects as a laboratory, e.g. NS heating
  - direct production at high-energy colliders

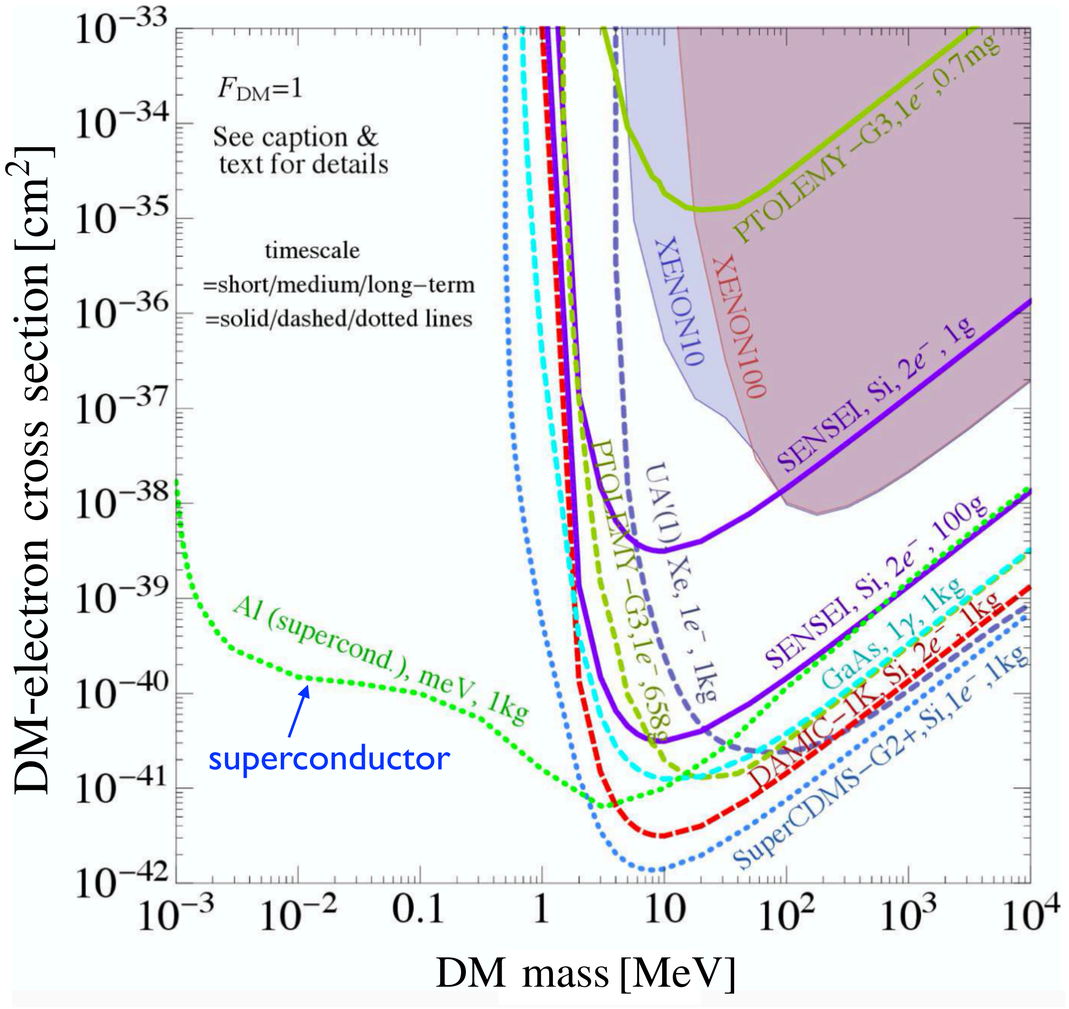
- Connection to UV theory? Naturalness?

Thanks for your attention

Back up

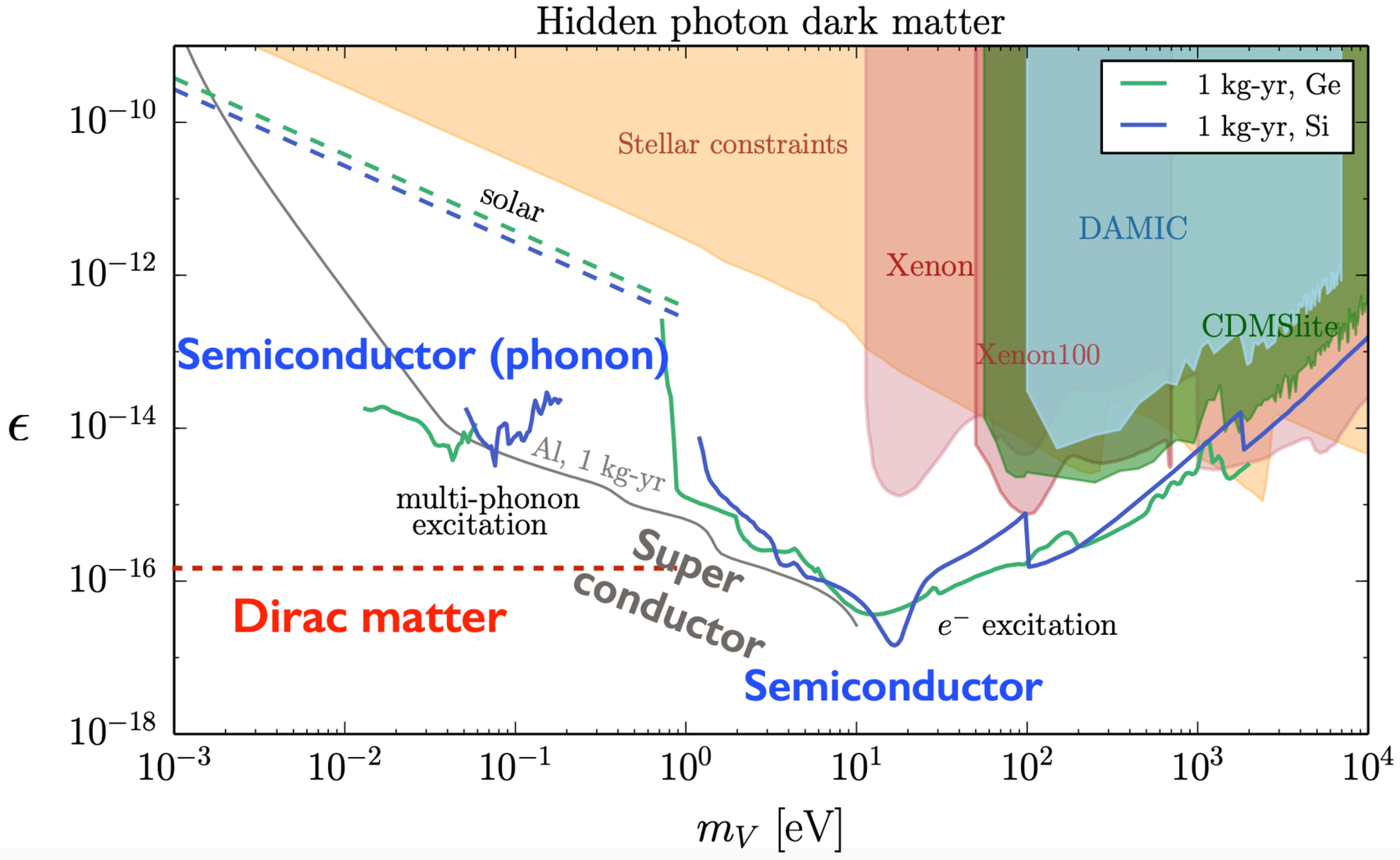
Direct detection with low threshold materials





Figures from US Cosmic Visions 2017

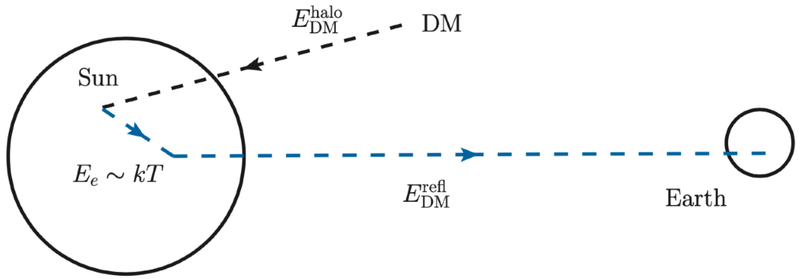
Limit on hidden photon dark matter (absorption)



[Hochberg, Lin, Zurek, 1608.01994]

Direct detection of boosted DM component

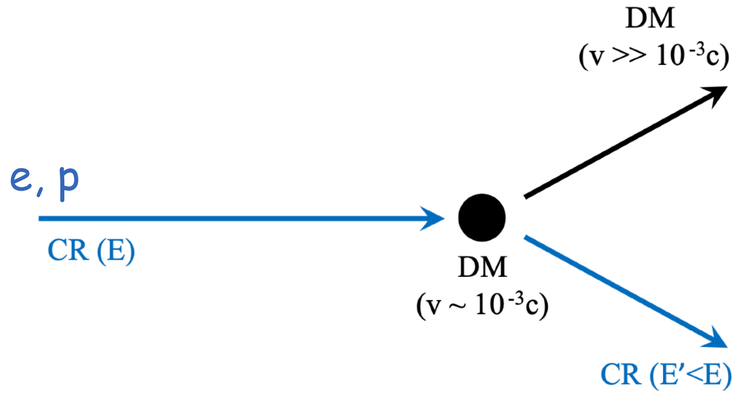
Solar reflection



$$\left(E_{\rm DM}^{\rm refl}\right)_{\rm max} \sim kT \sim \text{keV}$$

Kouvarious (15); +Emken, Nielsen (17);
An, Pospelov, Pradler, Ritz (17, 20, 21)
Emken (21)

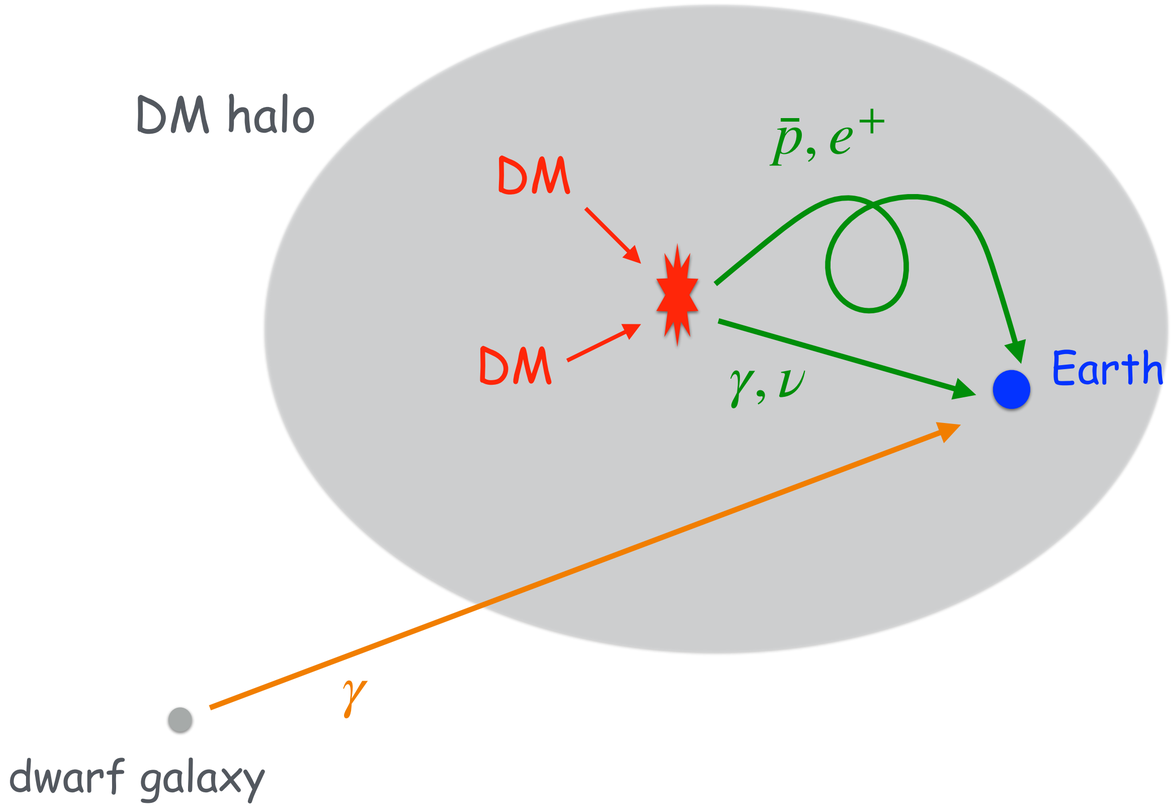
Cosmic-ray up-scattering



Bringmann, Pospelov (18)
Ema, Sala, Sato, (18, 21)

Indirect detection of DM

- Search for annihilation or decay products of DM in our galaxy or nearby galaxies



Extra cosmic-ray flux from DM annihilation

$$\frac{d\Phi_i}{dE_i} = \frac{1}{4\pi} \sum_f \frac{\langle \sigma v \rangle_f}{2m_{\rm DM}^2} \frac{dN_f}{dE_i} \times \int_{\rm l.o.s} dl d\Omega \left[\rho_{\rm DM}(l, \Omega)\right]^2$$

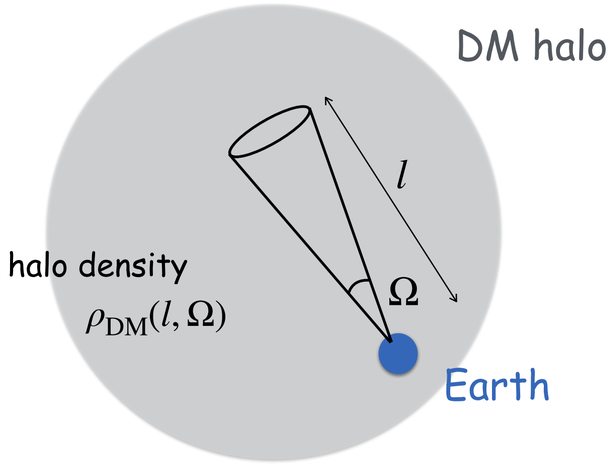
Particle physics

$\langle \sigma v \rangle_f$ DM annihilation cross section into a final state f

$\frac{dN_f}{dE_i}$ Energy spectrum of the considered particle for the final state f

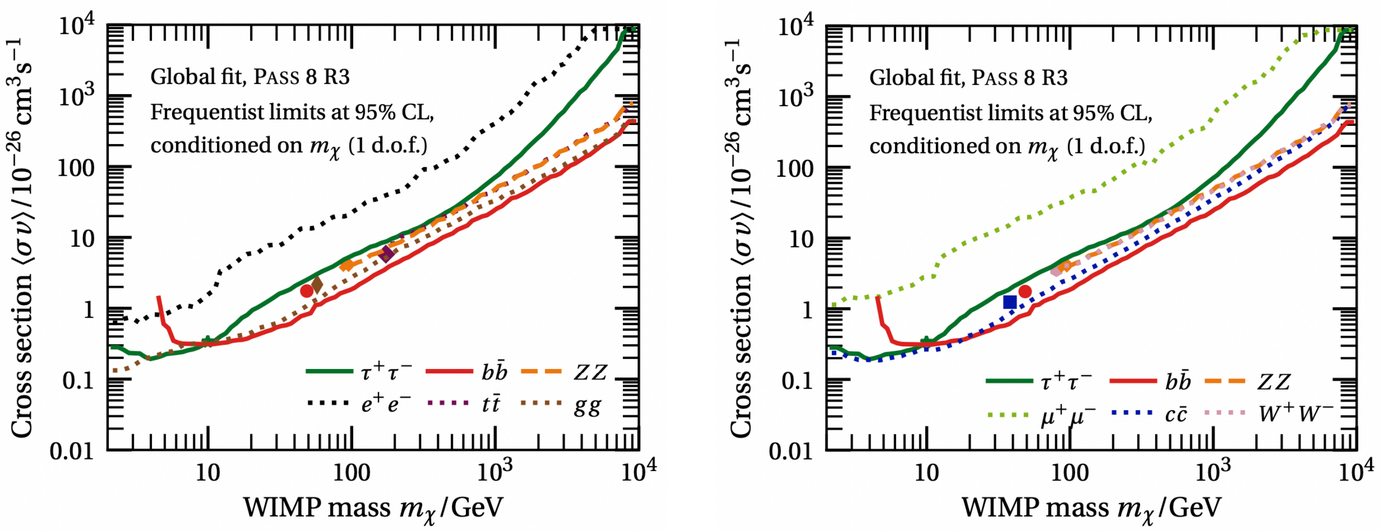
Astrophysics

sum up all contribution along the line-of-sight direction



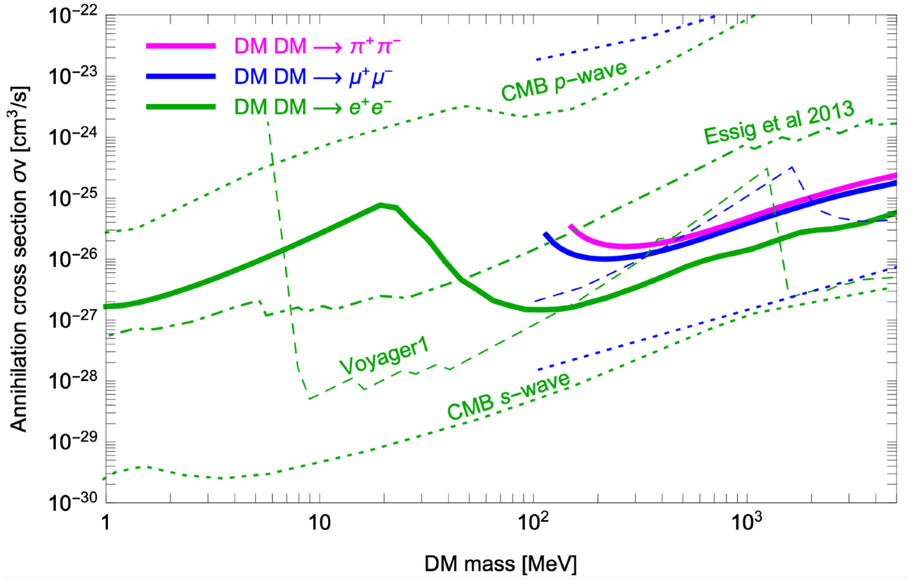
Indirect detection bounds with photon

■ Fermi-LAT (gamma-ray)



[Hoof, Geringer-Sameth, Trotta (18)]

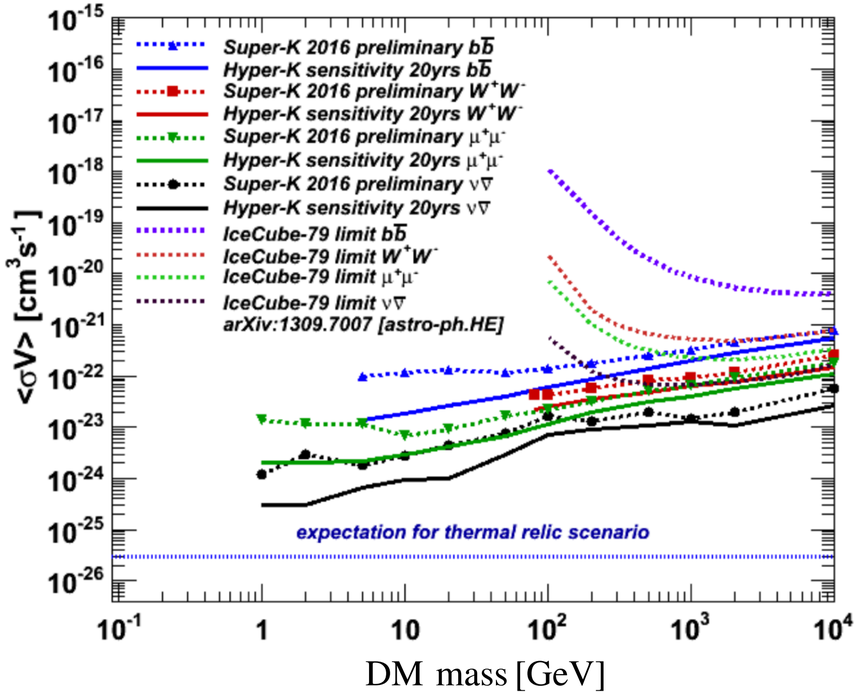
■ INTEGRAL (X-ray)



[Cirelli, Fornengo, Kavanagh, Pinetti (20)]

Indirect detection with neutrinos

■ Search for WIMP DM



Hyper-K design report (2018)

■ Search for sub-GeV DM

[Yüksel+ (07); Palomares-Ruiz, Pascoli (07); Argüelles+ (19); Asai, **SO**, Tsumura (20); etc.]

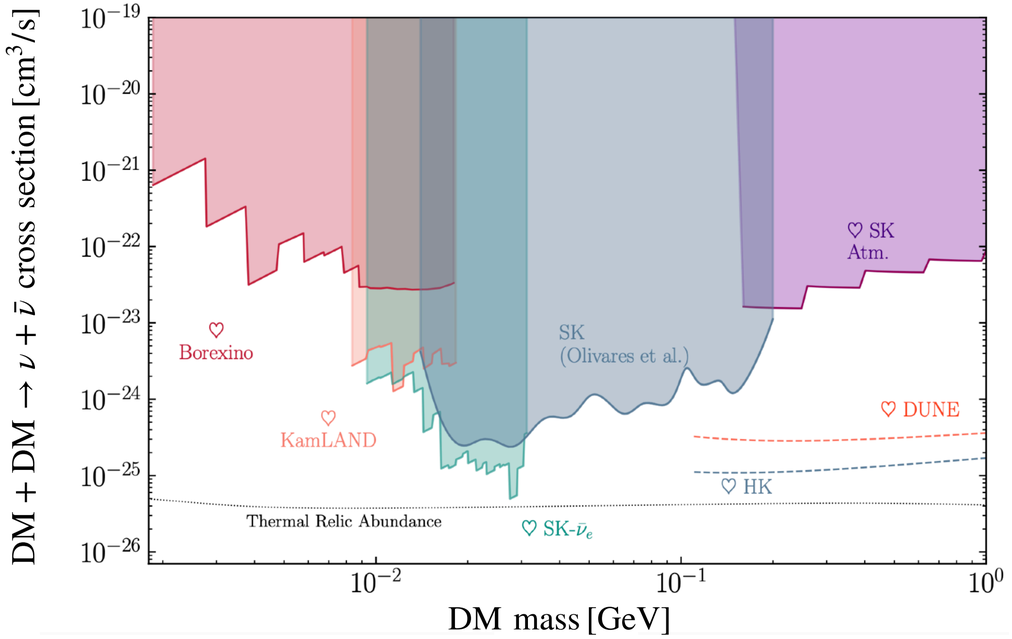
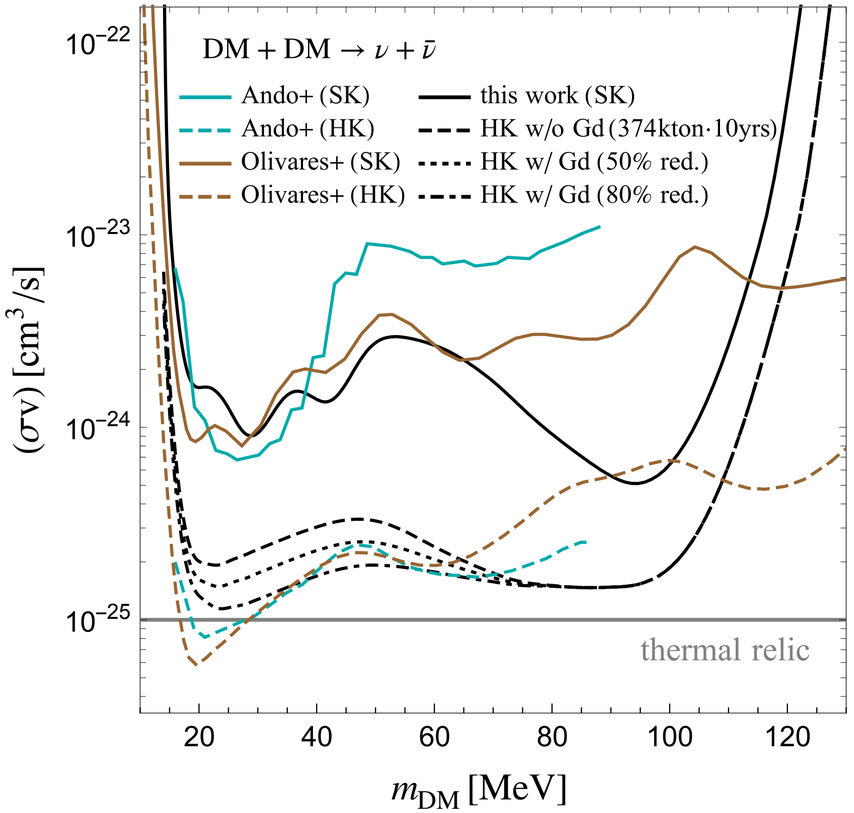


Figure from 1912.09486

Upper limit for DM annihilation to neutrinos

[Asai, **SO**, Tsumura, 2011.03165]

■ DM DM -> 2nu



■ DM DM -> X X -> 4nu (X: unpolarized boson)