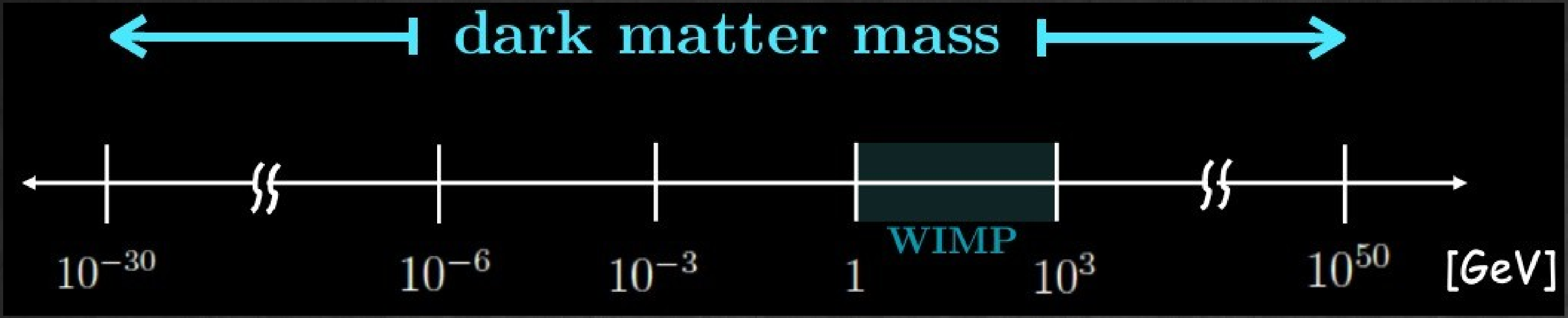
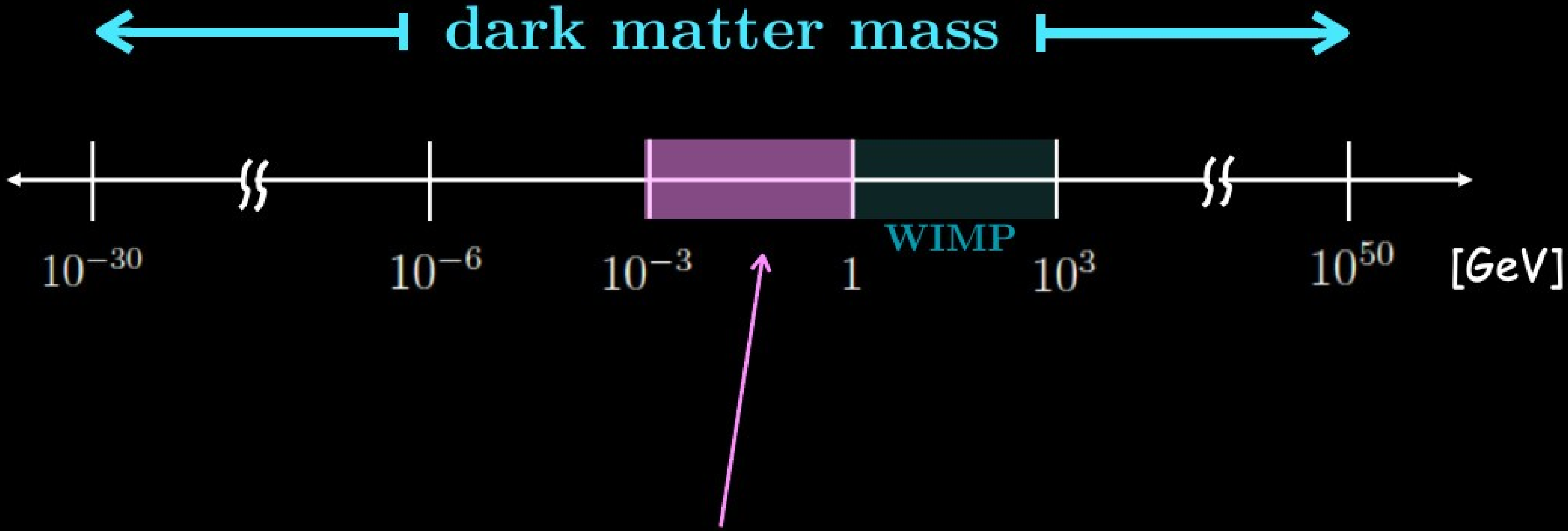
Light Dark Matter

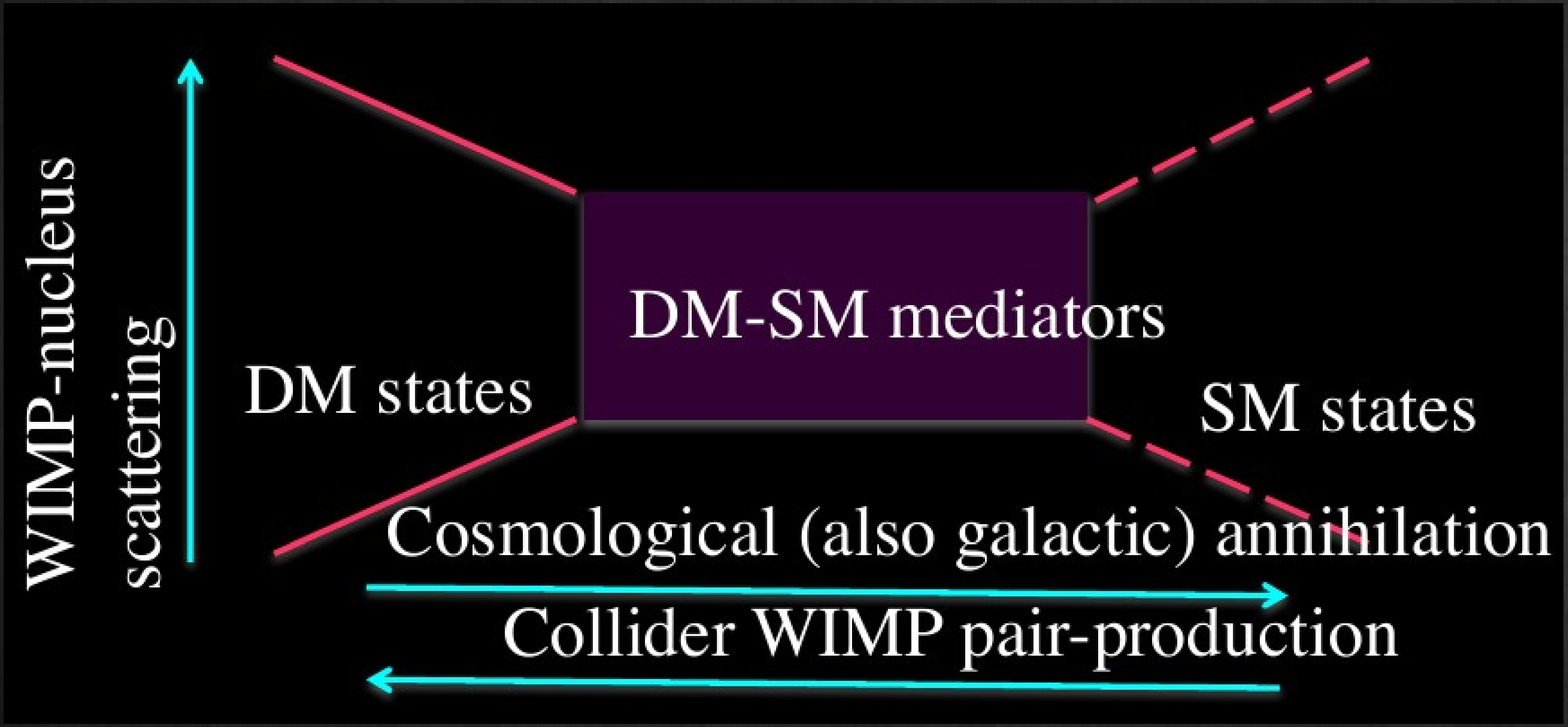
Ujjal Kumar Dey
IISER Berhampur

WHEPP XVI


dark matter mass
10^{-30}
10^{-6}
10^{-3}
1
WIMP
10^3
10^{50}
[GeV]



Lots of activity in recent years:
Theory & Experiment



WIMP-nucleus scattering

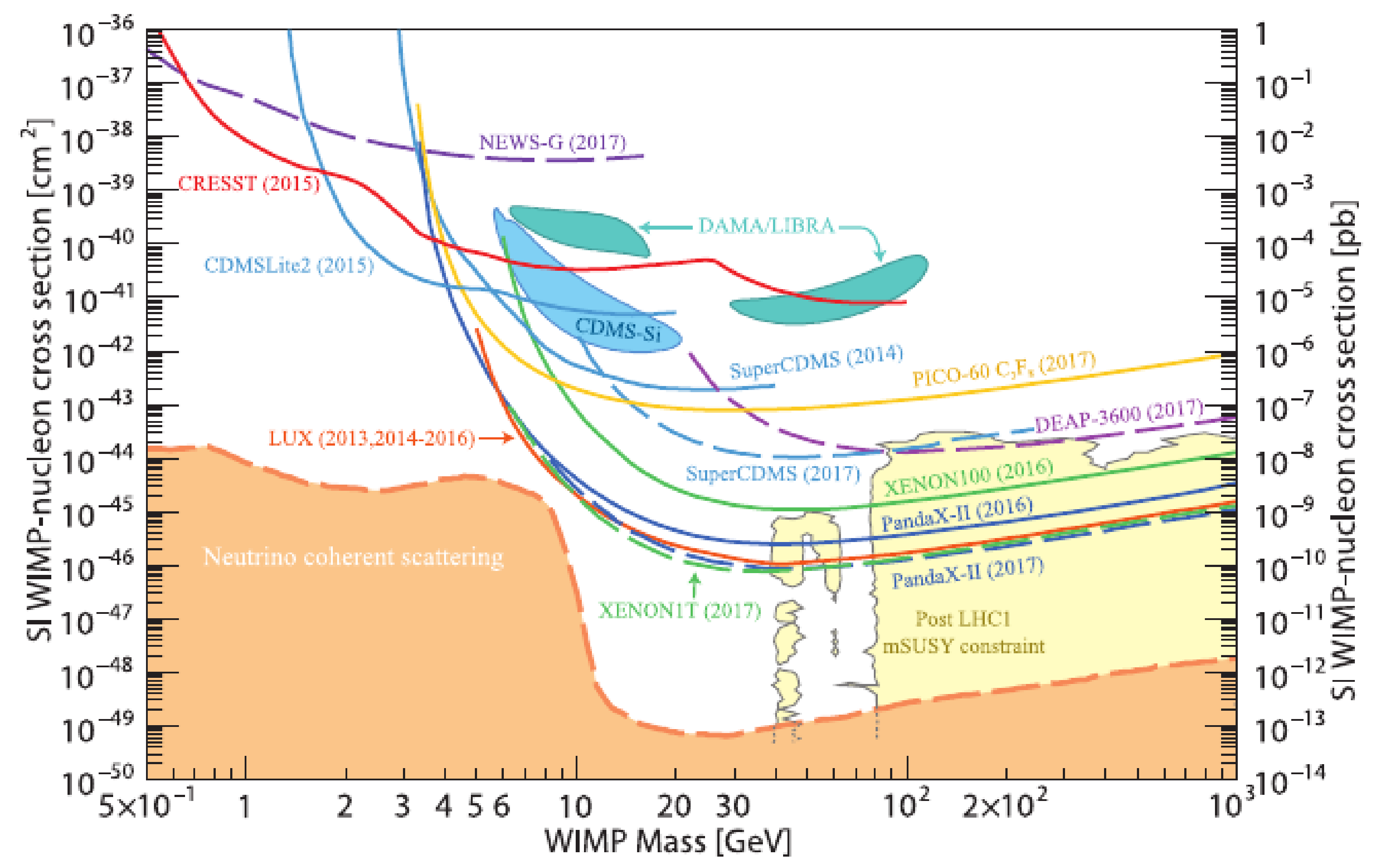
DM states

DM-SM mediators

SM states

Cosmological (also galactic) annihilation

Collider WIMP pair-production


SI WIMP-nucleon cross section [cm^2]
SI WIMP-nucleon cross section [pb]
WIMP Mass [GeV]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
5×10^{-1}
1
2
3
4
5
6
10
20
30
10^2
2×10^2
10^3
NEWS-G (2017)
CRESST (2015)
DAMA/LIBRA
CDMSLite2 (2015)
CDMS-Si
SuperCDMS (2014)
PICO-60 C$_3$F$_8$ (2017)
DEAP-3600 (2017)
LUX (2013,2014-2016)
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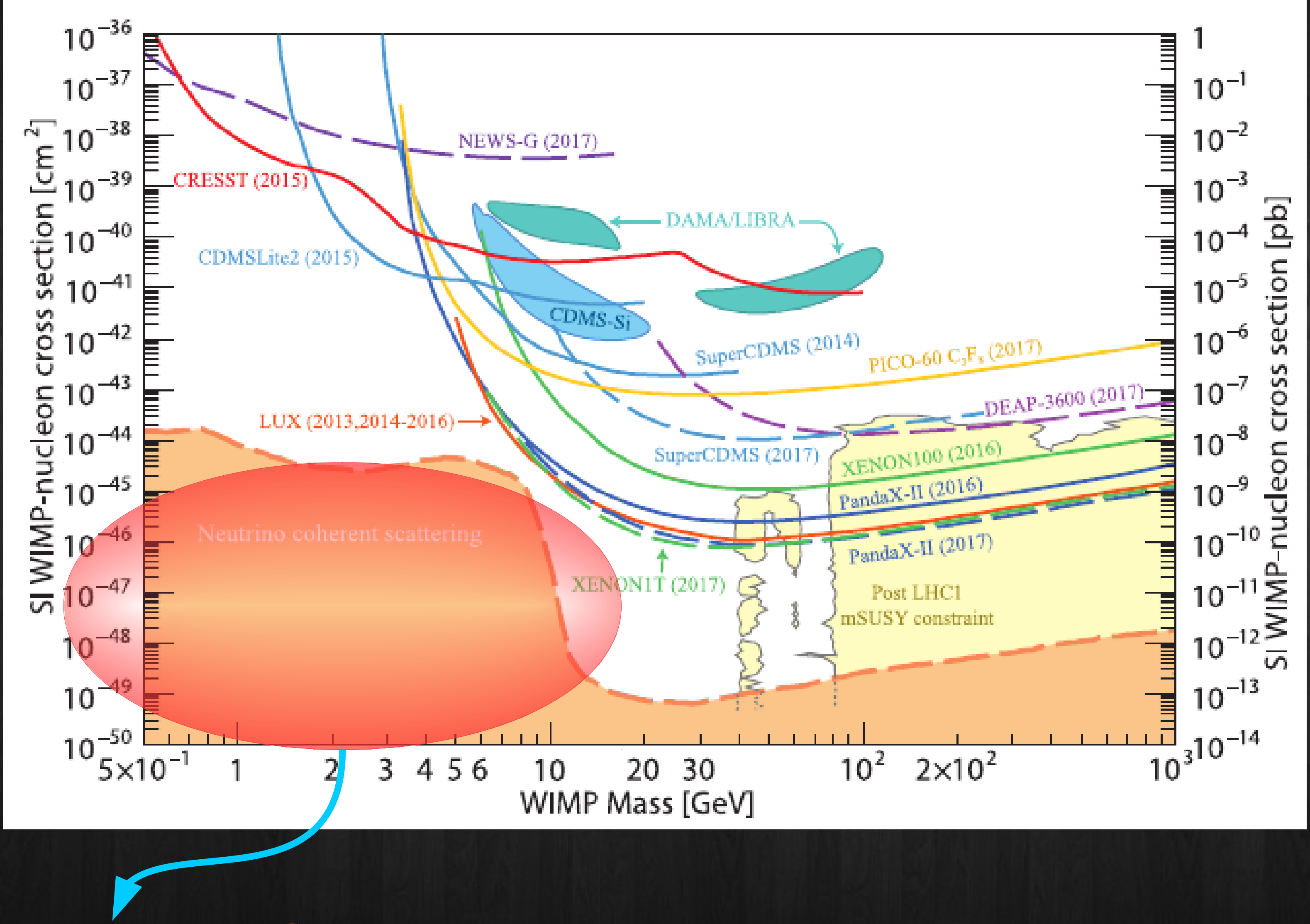
PandaX-II (2016)
PandaX-II (2017)
Neutrino coherent scattering
XENON1T (2017)
Post LHC1
mSUSY constraint



Neutrino floor → coherent elastic neutrino-nucleus scattering (CEvNS)

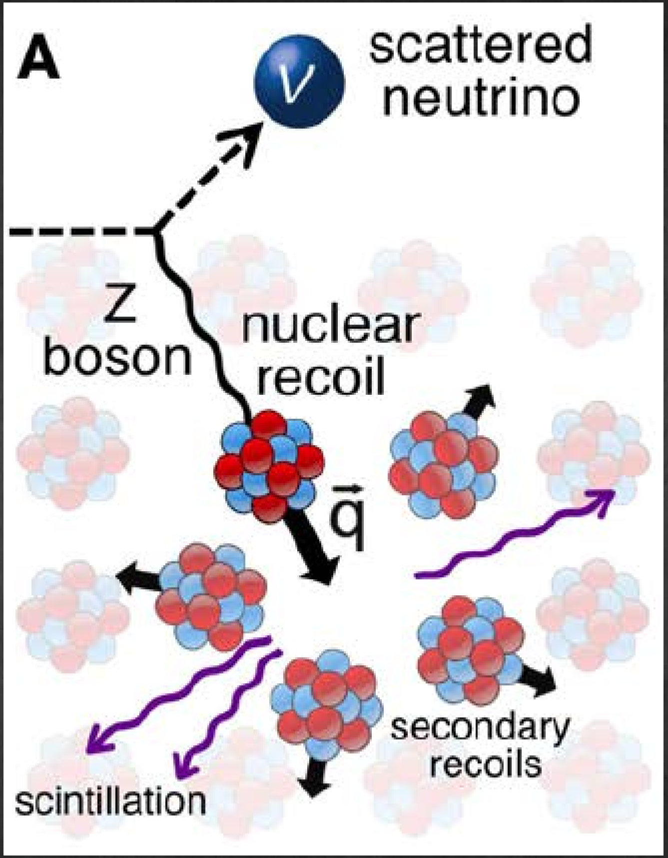
Neutrino floor:

- Neutrinos with energy 1-100 MeV → keV scale nuclear recoils

  e.g., recoil spectrum expected from ^{8}B solar neutrino flux would resemble that of a 6 GeV DM (Billard et al., PRD’14)

- Neutrino floor → *threshold below which the number of neutrino events is expected to be much larger than the number of DM events*

- New Physics (NP) in the neutrino sector (new mediators, effective NSI etc.) can alter the height of the floor (Boehm et al., JCAP’19, Chao et al., JCAP’19)



$$N = \frac{\epsilon}{m_N} \int_{E_T}^{E_{\max}} dE_R \int_{E_\nu^{\min}} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_{\nu N}}{dE_R}$$

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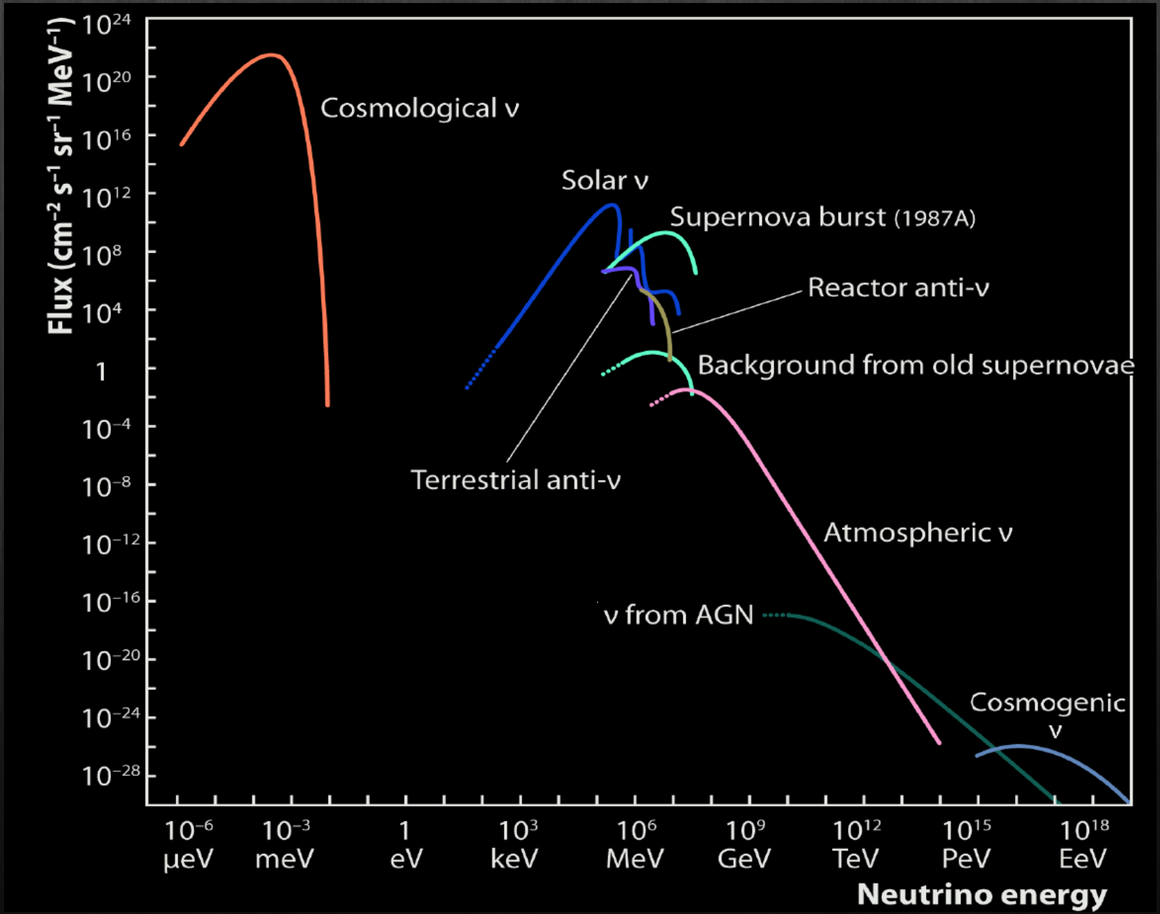
incoming neutrino flux



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neutrino-Nucleon cross section

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neutrino-Nucleon cross section

SM

$$\frac{G_F^2}{4\pi} Q_N^2 m_N F^2(E_R)\left(1 - \frac{m_N E_R}{2E_\nu^2}\right)$$

Constructing the specific form of the floor → see [Boehm et al., JCAP'19] for technical details

Examples:

- Vector/axial vector mediator

$$\mathcal{L} \supset -\sum_f g_f \bar{f} \gamma^\mu f Z'_\mu + \text{h.c.}$$

floor can be raised ~ a factor of 2 for small DM masses (below 10 GeV, where the main contribution is due to solar neutrinos) and by a factor of 1.3 for large DM masses (where atmospheric neutrinos dominate)

- Scalar/pseudoscalar mediator

$$\mathcal{L} = -Y_\nu \bar{\nu}_L^c \phi \nu_L - \sum_{f \neq \nu} Y_f \bar{f} \phi f - \sum_{f \neq \nu} Y_{af} \bar{f} i \phi \gamma_5 f + \text{h.c.}$$

raised by several orders of magnitude in the region of low-mass DM (below 10 GeV)

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NP/DM Models ???

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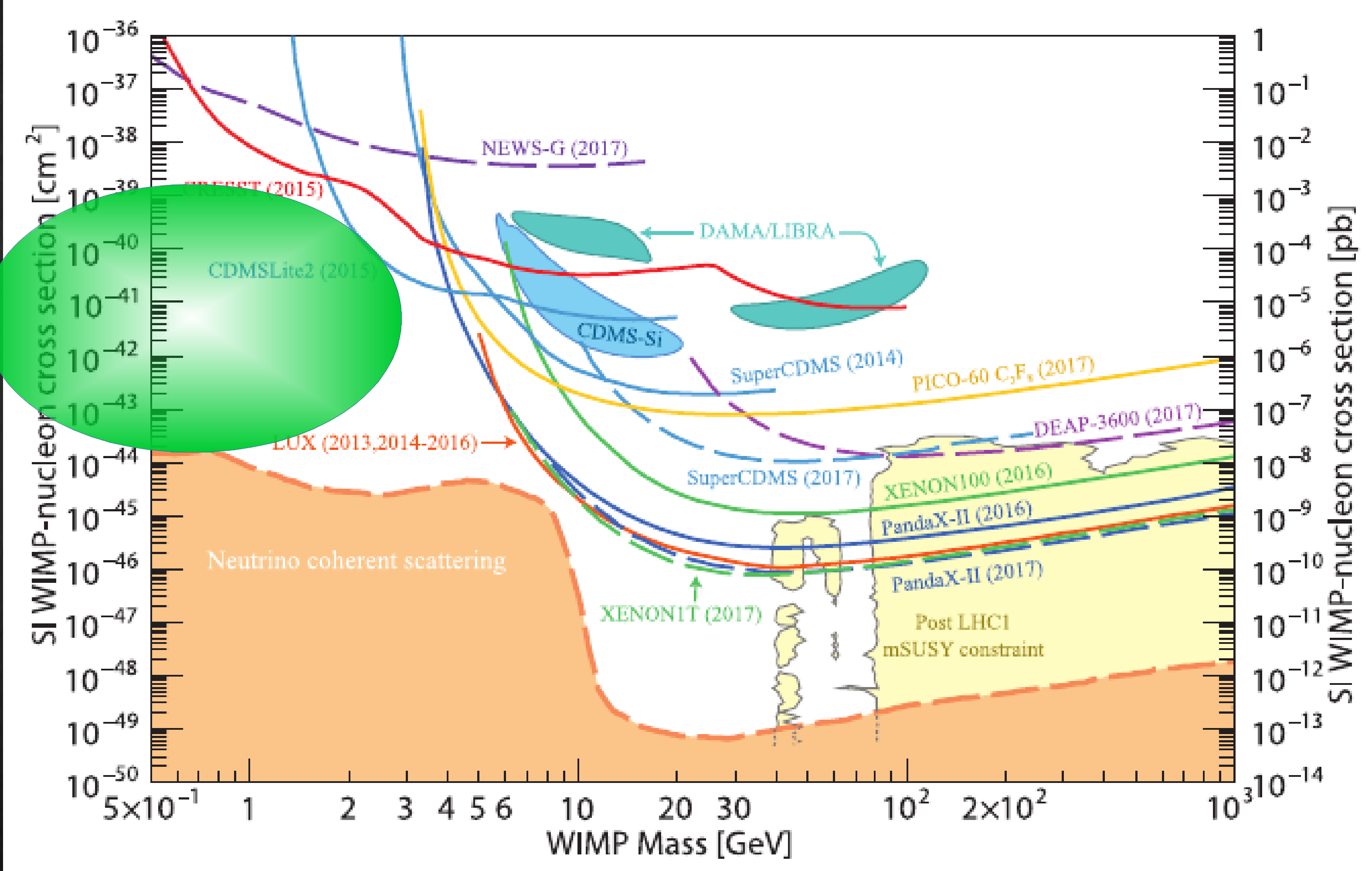
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10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
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10^{-14}
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1
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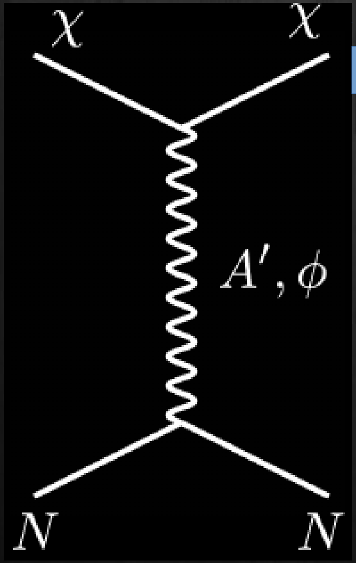
2×10^2
10^3

New directions to see DM

- Points to remember:

  (i) Velocity of bound DM within the Milky Way galaxy, v_χ , is non-relativistic and limited by galactic escape velocity (~$10^{-3}\,c$)

  (ii) The maximum possible energy transfer to the detector decreases as the DM mass, m_χ , is lowered



Traditional DM-nuclear scattering

$$E_{\rm NR} = \frac{q^2}{2m_N} \le \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} 190 \text{ eV} \times \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{16 \text{ GeV}}{m_N}\right)$$

As m_χ decreases → E_{NR} quickly falls *below the threshold sensitivity*

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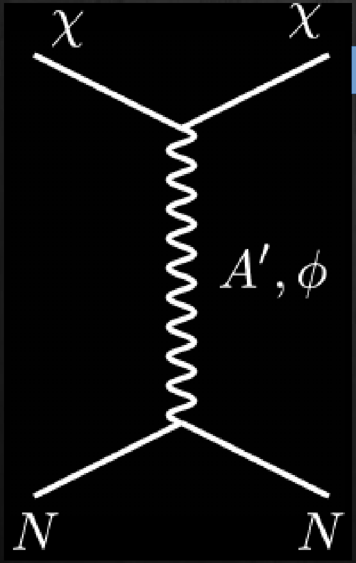

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Unbearable lightness of being DM w.r.t. usual DD by nuclear recoil

- *DM-electron scattering (1 keV – 1 GeV)*

For low-mass DM the energy is transferred far more efficiently to an electron than to a nucleus (Essig et al., PRD '12)

If the $m_\chi > m_e$, maximum energy transfer

$$E_e \leq \frac{1}{2} m_\chi v_\chi^2 \lesssim 3 \text{ eV} \left(\frac{m_\chi}{\text{MeV}} \right)$$

Bound electrons with binding energy E_B can thus in principle produce a measurable signal for

$$m_\chi \lesssim 0.3 \text{ MeV} \left(\frac{E_B}{1 \text{ eV}} \right)$$

(i) ionized excitations, in drift chambers ($E_B \sim 10$ eV) for $m_\chi \gtrsim 3$ MeV, in semiconductors by promote electrons from the valence band to conduction band (Lee et al., PRD '15)

(ii) scintillation photons (GaAs, NaI, CsI) ($E_B \sim 1$–5 eV) for $m_\chi \gtrsim 0.3$ MeV (Derenzo et al., PRD '17)

(iii) eject an electron from a two-dimensional material e.g., graphene (Hochberg et al., PLB '17)

- If, $m_\chi < m_e$, energy transfer (Hochberg et al., JHEP '16)

$$E_e \sim \frac{1}{2}\left(\frac{\vec{q}^2}{m_e} + 2\vec{q}.\vec{v}_i\right) + \delta$$

If the DM kinetic energy > δ, the quasi-particle binding energy (~ few meV), superconductors may probe DM as light as m_χ~ 1 keV

- Other options:

1. DM absorption on electrons (1 meV – 1 keV)

2. DM-low-Z elastic nucleus interactions (1 MeV – 10 GeV)

3. DM-off-shell nuclear interactions (1 keV – 1 MeV)

4. Bremsstrahlung in inelastic DM-nucleus scattering (10 MeV – 1 GeV)

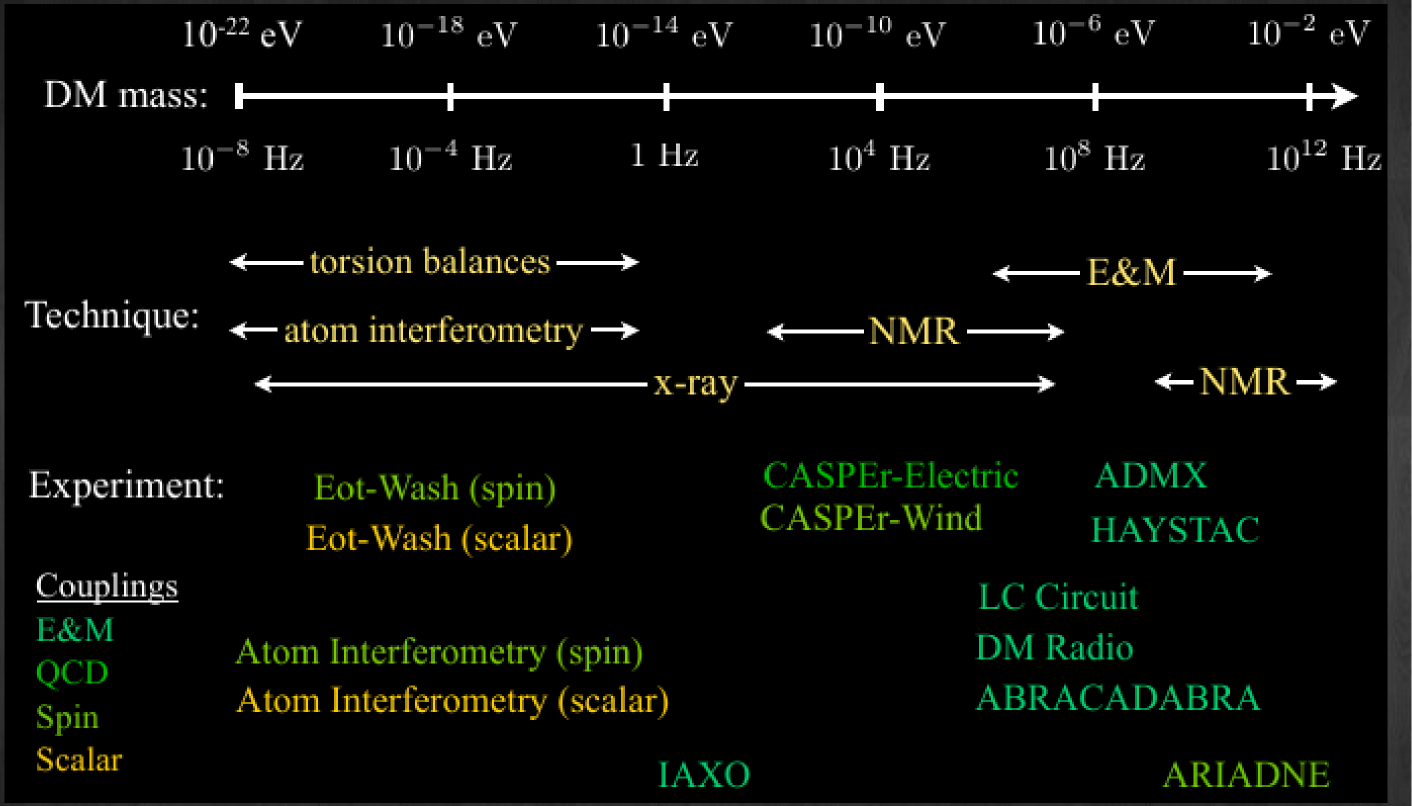
5. DM-induced chemical-bond breaking (10 MeV – 10 GeV)

6. DM-induced spin-flip avalanches (10 keV – 10 MeV)

- *Ultra-light (sub-meV)*

(i) In this range the dark matter can be thought of as a field (or wave) oscillating at a frequency equal to its mass

(ii) detectors searching for such light dark matter must look for the collective effect of all the dark matter particles in the wave



DM mass: 10^{-22} eV, 10^{-18} eV, 10^{-14} eV, 10^{-10} eV, 10^{-6} eV, 10^{-2} eV

10^{-8} Hz, 10^{-4} Hz, 1 Hz, 10^{4} Hz, 10^{8} Hz, 10^{12} Hz

Technique:

torsion balances

E&M

atom interferometry

NMR

x-ray

NMR

Experiment:

Eot-Wash (spin)

Eot-Wash (scalar)

CASPEr-Electric

CASPEr-Wind

ADMX

HAYSTAC

Couplings

E&M

QCD

Spin

Scalar

LC Circuit

DM Radio

ABRACADABRA

Atom Interferometry (spin)

Atom Interferometry (scalar)

IAXO

ARIADNE

(iii) utilize high precision sensors of continuous wave signals as opposed to the traditional impulse detectors used for single particle scattering

(iv) Sensors come from many areas of physics including condensed matter and atomic physics and are based on a wide range of techniques such as high-precision magnetometry, NMR, electromagnetic resonators, atomic clocks, and laser interferometry

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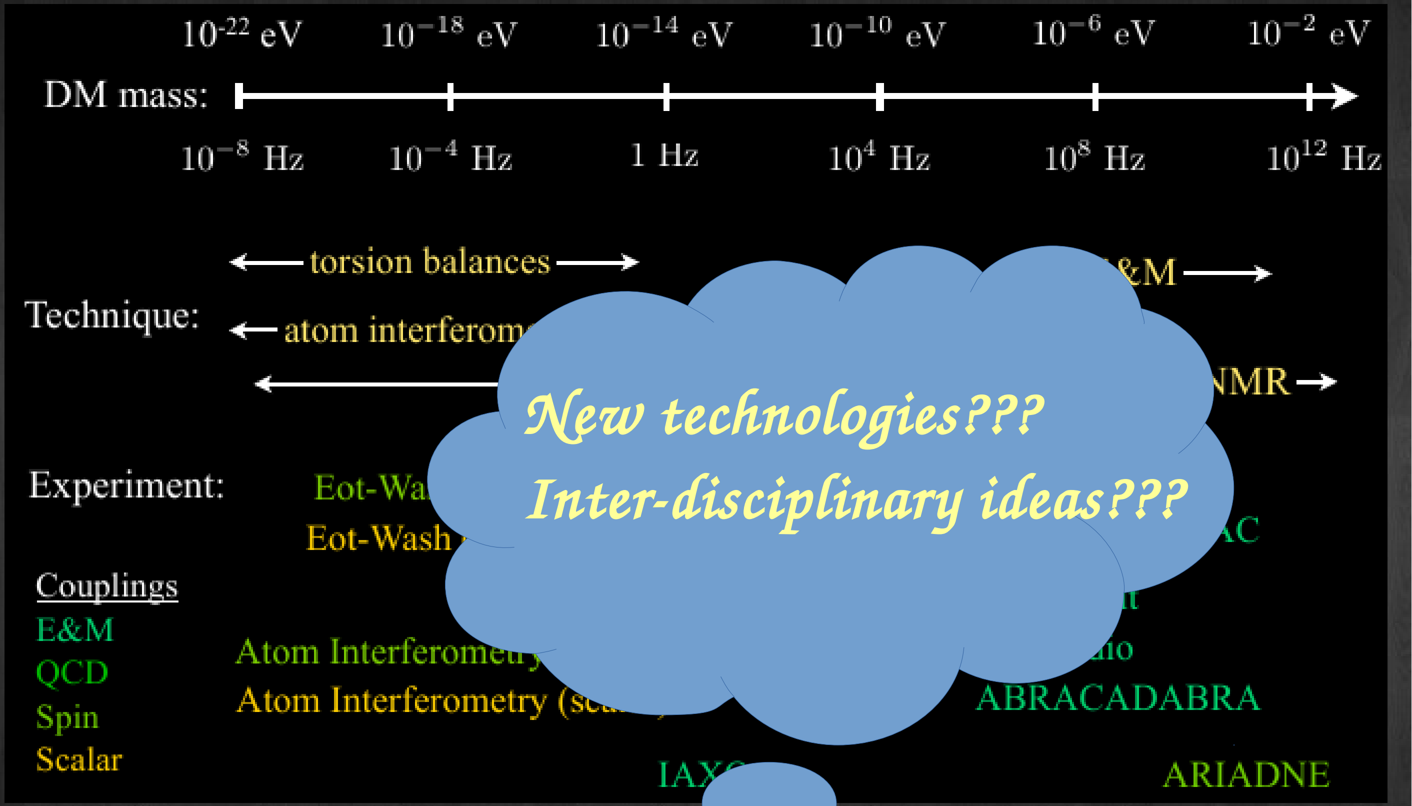

New technologies???
Inter-disciplinary ideas???

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Models

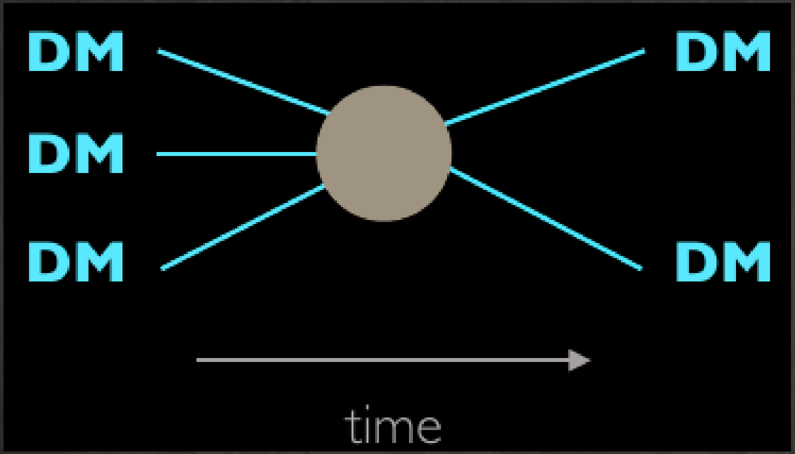
New ideas

- *Freeze-in DM* (Hall et al., JHEP '10; Review: Bernal et al., IJMPA '17)
- *SIMP* (Hochberg et al., PRL '14)
- *Forbidden DM* (D'Agnolo et al., PRL '15)
- *Co-decaying DM* (Dror et al., PRL '16)
- *ELDER* (Kuflik et al., PRL '16)
- *Co-scattering DM* (D'Agnolo et al., PRL '17)

.... many more

A couple of case details

(1) SIMP

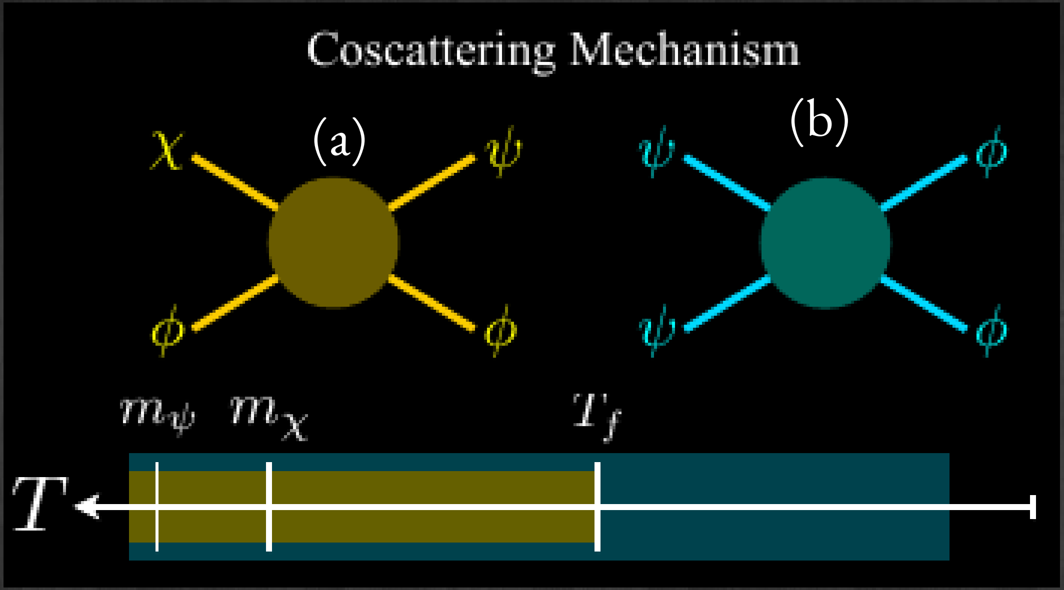


(i) keV-MeV range self-interacting DM

(ii) self-interaction can help ameliorating small scale structure formation issues

(2) Co-scattering DM

(D'Agnolo et al., PRL '17)



(i) χ and ψ charged under the symmetry that stabilizes DM χ

(ii) φ is an unstable state from the thermal bath

(iii) Unlike coannihilation, here process (a) shuts off before process (b), such that the DM abundance is determined by the freeze-out of inelastic scattering

(iv) Conditions for co-scattering:
  (1) $\psi\psi \to \varphi\varphi$ is in equilibrium,
  (2) $\chi\chi$, $\chi\psi \to \varphi\varphi$ can be neglected, and
  (3) 2-body decays are kinematically forbidden, $m_\varphi > m_\psi - m_\chi$

Coscattering → DM exponentially lighter than the weak scale & has a suppressed annihilation rate, avoiding stringent constraints from indirect detection

New ideas/mechanisms
(not necessarily models)