Caltech

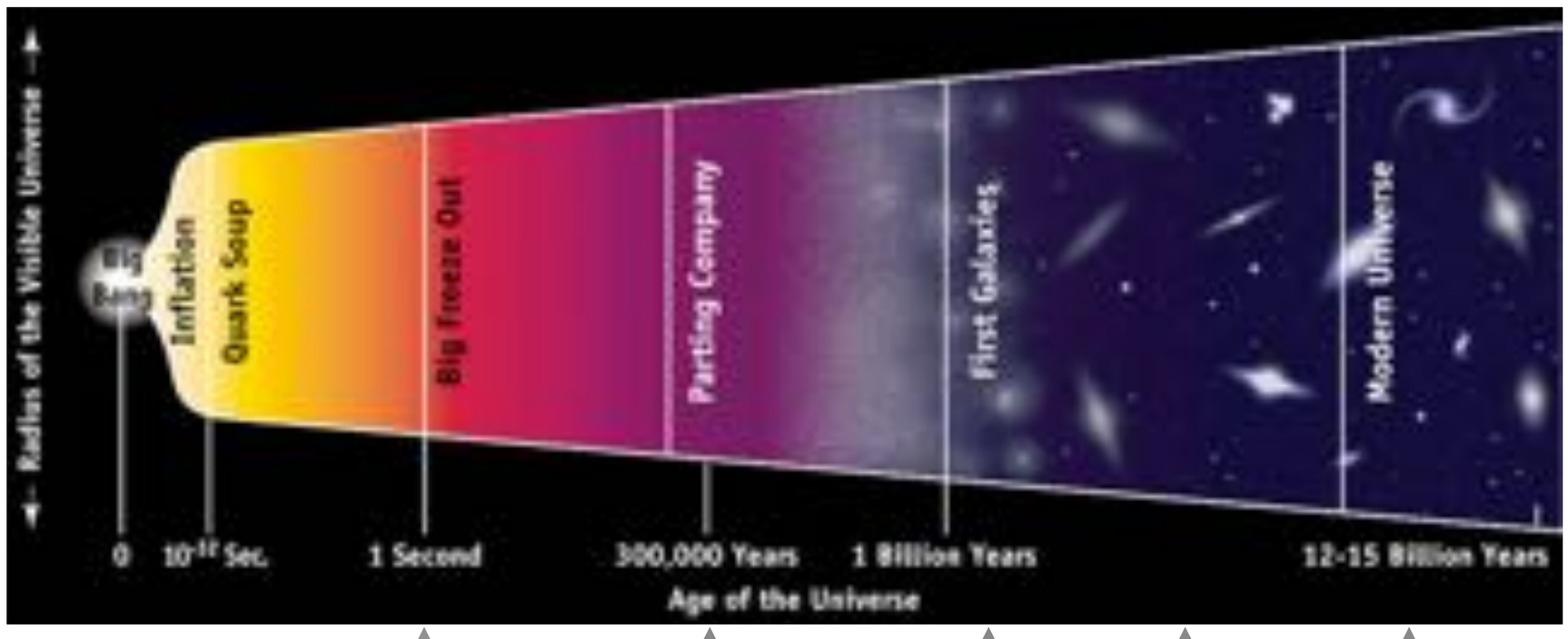
BURKE INSTITUTE

"DARK MATTER PARTICLE CANDIDATES" . . . BEYOND THE WIMP

Kathryn M. Zurek

WHY DARK MATTER? (WHY NEW PARTICLE PHYSICS?)

- The dark matter paradigm is the only successful framework for understanding the entire range of observations from the time the Universe is 1 sec old.



BBN (baryons) | CMB (curvature) | LSS (matter) | Supernovae (DE) | Galaxy curves (matter)

DARK MATTER DETECTION: A FULL COURT PRESS

(deBroglie wavelength of galaxy)

WIMP paradigm

(Lyman-alpha forest)

$1\ M_\odot \sim 10^{57}$ GeV

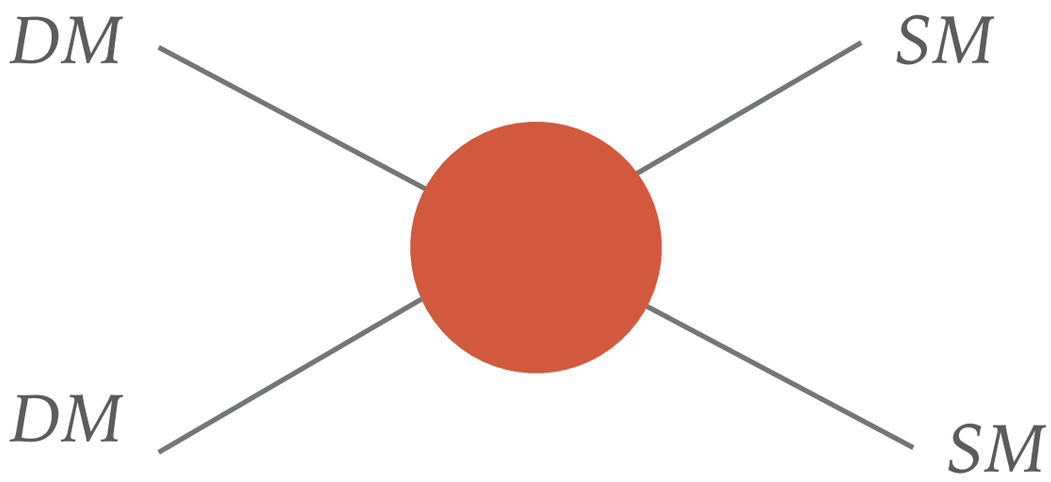
DARK MATTER DETECTION: A FULL COURT PRESS

- WIMP paradigm: a good place to start looking
- Reason: weak forces have the right scale, for abundance, cosmology and detection

$$\sigma_{wk} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \simeq 10^{-34}\ \mathrm{cm}^2 \left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

SETTING ABUNDANCE THROUGH INTERACTIONS WITH SM

- Freeze-out paradigm



$$\rho_{DM} = \rho_{obs}$$

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

DARK MATTER DETECTION: A FULL COURT PRESS

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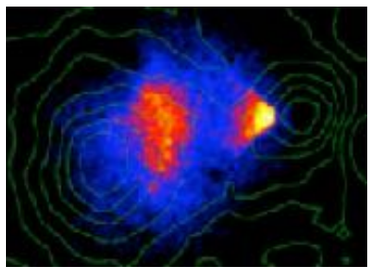
$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \frac{c}{3} \simeq 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{100\ \mathrm{GeV}}{M} \right)^2$$

DARK MATTER DETECTION: A FULL COURT PRESS

- Cross-sections are too small to have relevant impacts on structure formation

$$\sigma_{SIDM} \lesssim 10^{-24}\ \mathrm{cm}^2/\mathrm{GeV}$$

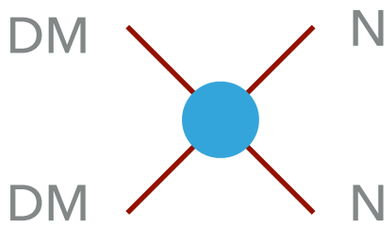


- Interaction cross-sections with nuclei are detectable

$$\sigma_{wk} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \simeq 10^{-34}\ \mathrm{cm}^2 \left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

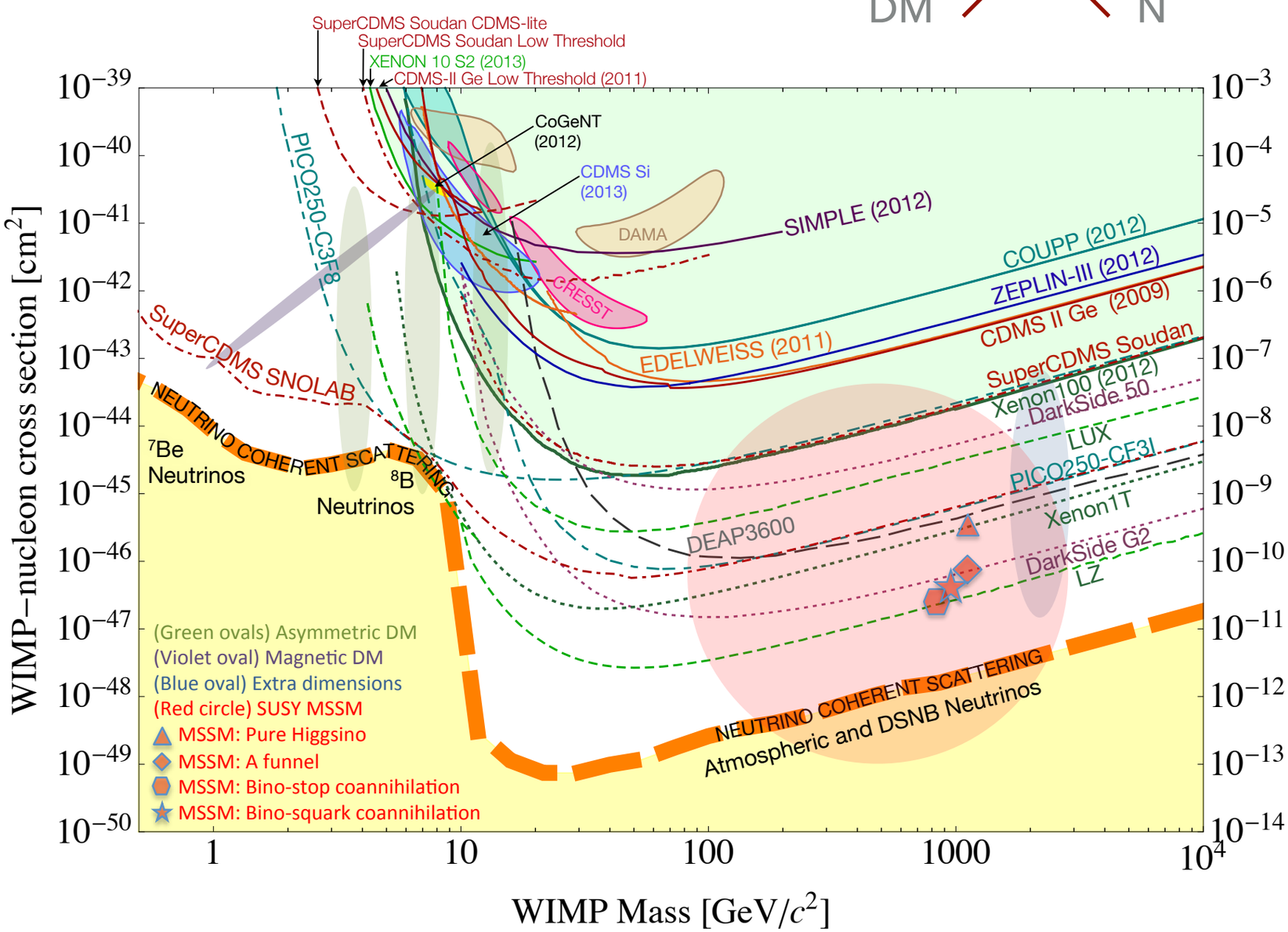
DETECTABLE INTERACTION RATES

- WIMP: not dead but continually pressured



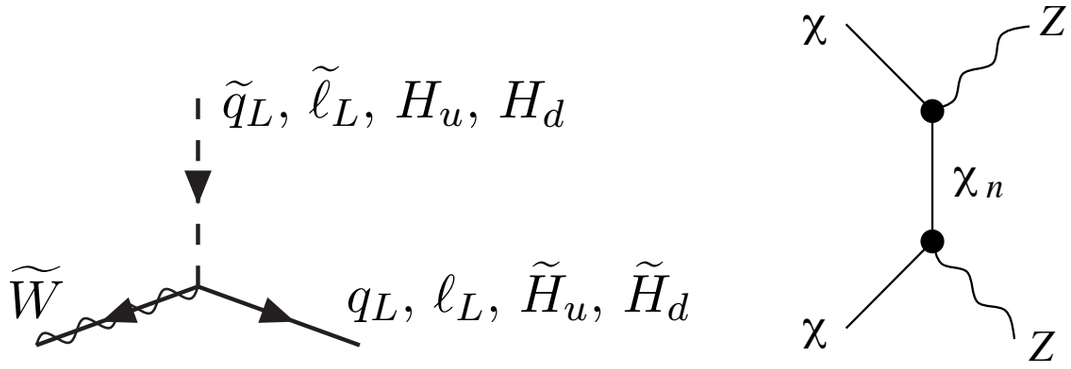
Z-boson interacting dark matter: ruled out

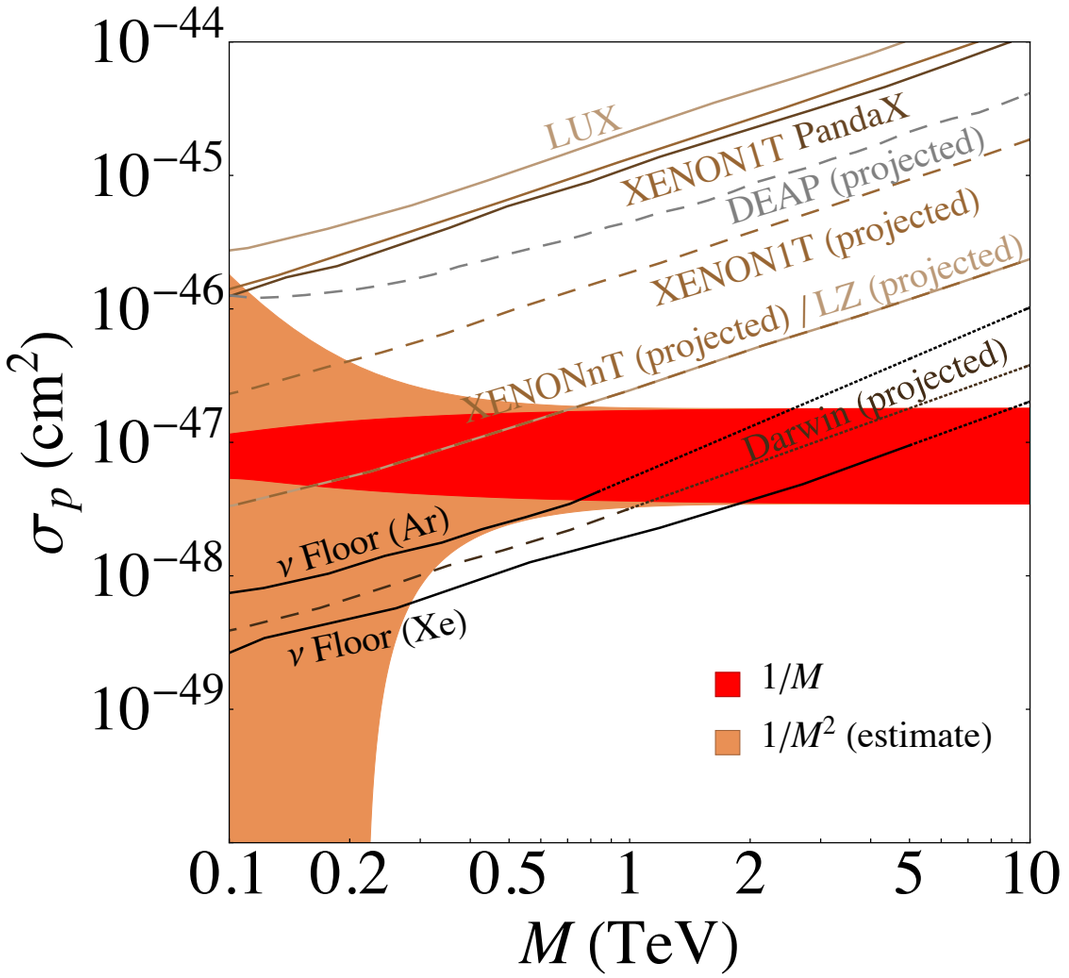
Higgs interacting dark matter: active target



BLOB CLOSURE DECEPTIVE

- "Pure" neutralino does not couple to Higgs at tree level
- e.g. pure Wino or Higgsino or Bino
- One-loop: wino not quite detectable
- But, Wino has detectable indirect detection signature through coupling to gauge bosons
- Cherenkov telescopes have (unique) sensitivity to such weak dark matter





Chen, Hill, Solon, Wijanco

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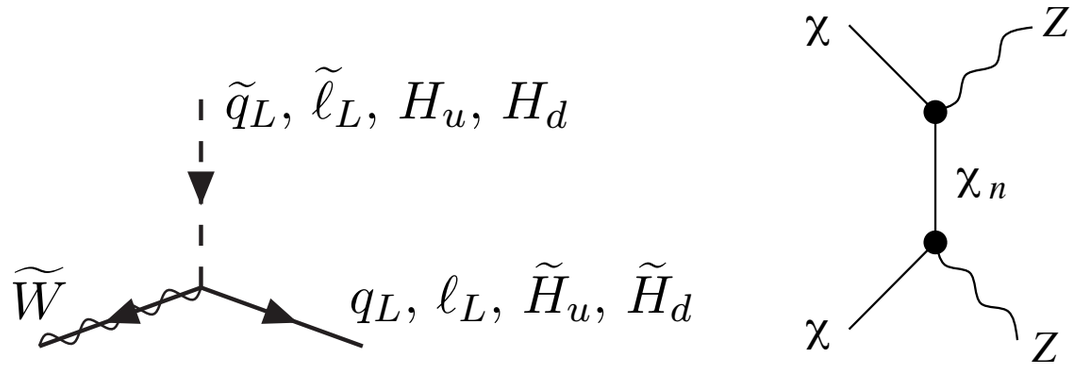

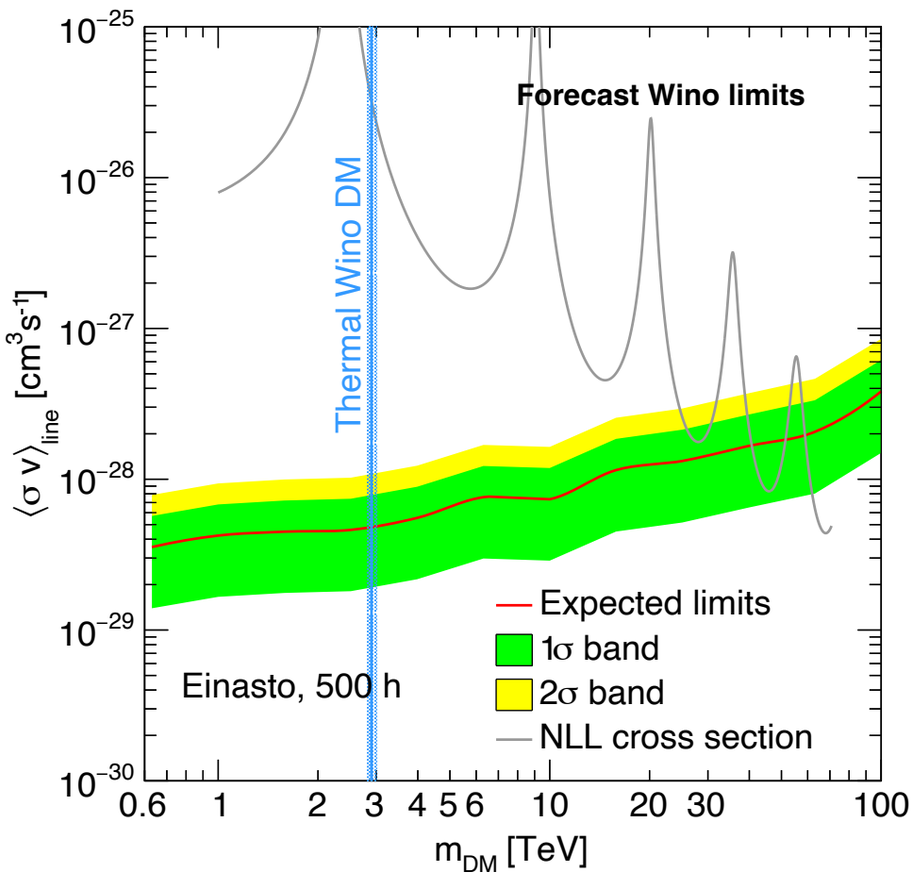

But, not a case for larger than n-ton direct detection!

Rinchiuso et al 2008.00692

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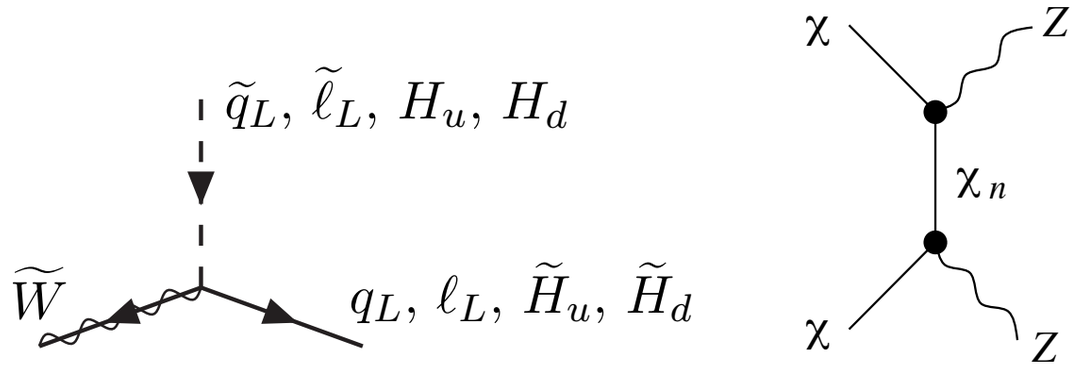

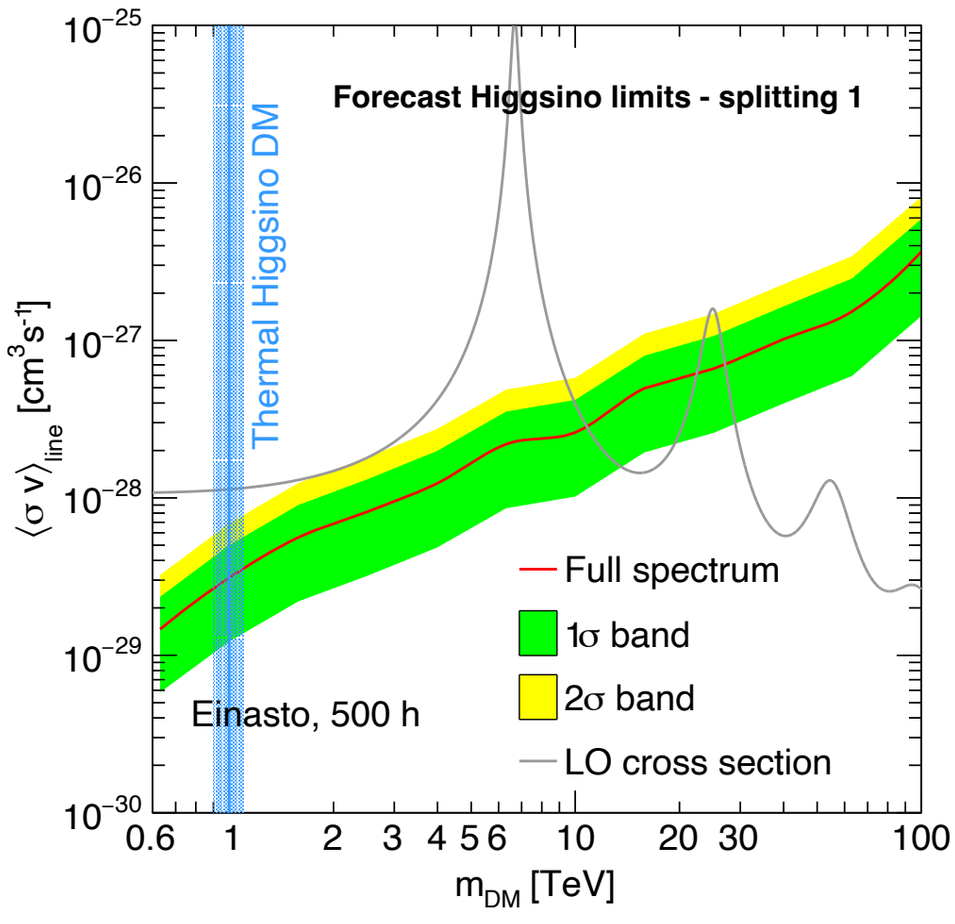

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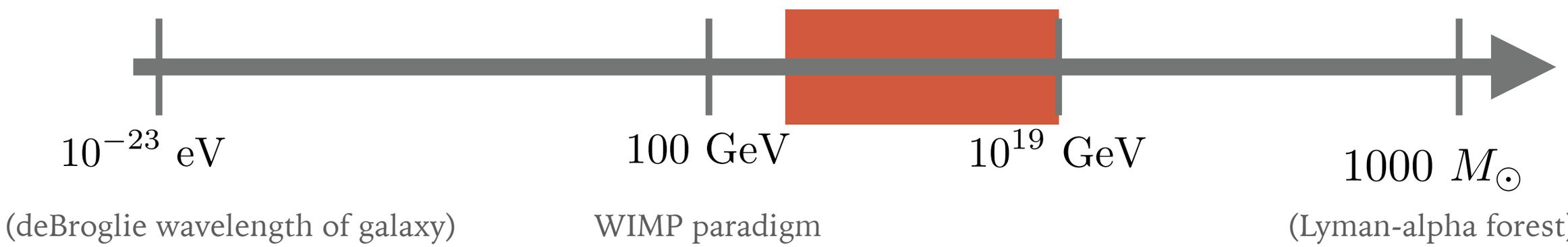
DARK MATTER DETECTION: A FULL COURT PRESS



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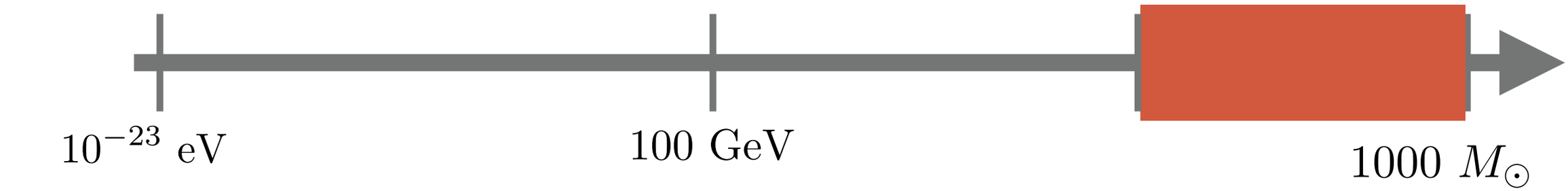
- Heavier dark matter: setting relic abundance through interactions with Standard Model is challenging (NB: exceptions)
- At heavier masses, detection through Standard Model interactions is (generally) not motivated by abundance

DARK MATTER DETECTION: A FULL COURT PRESS



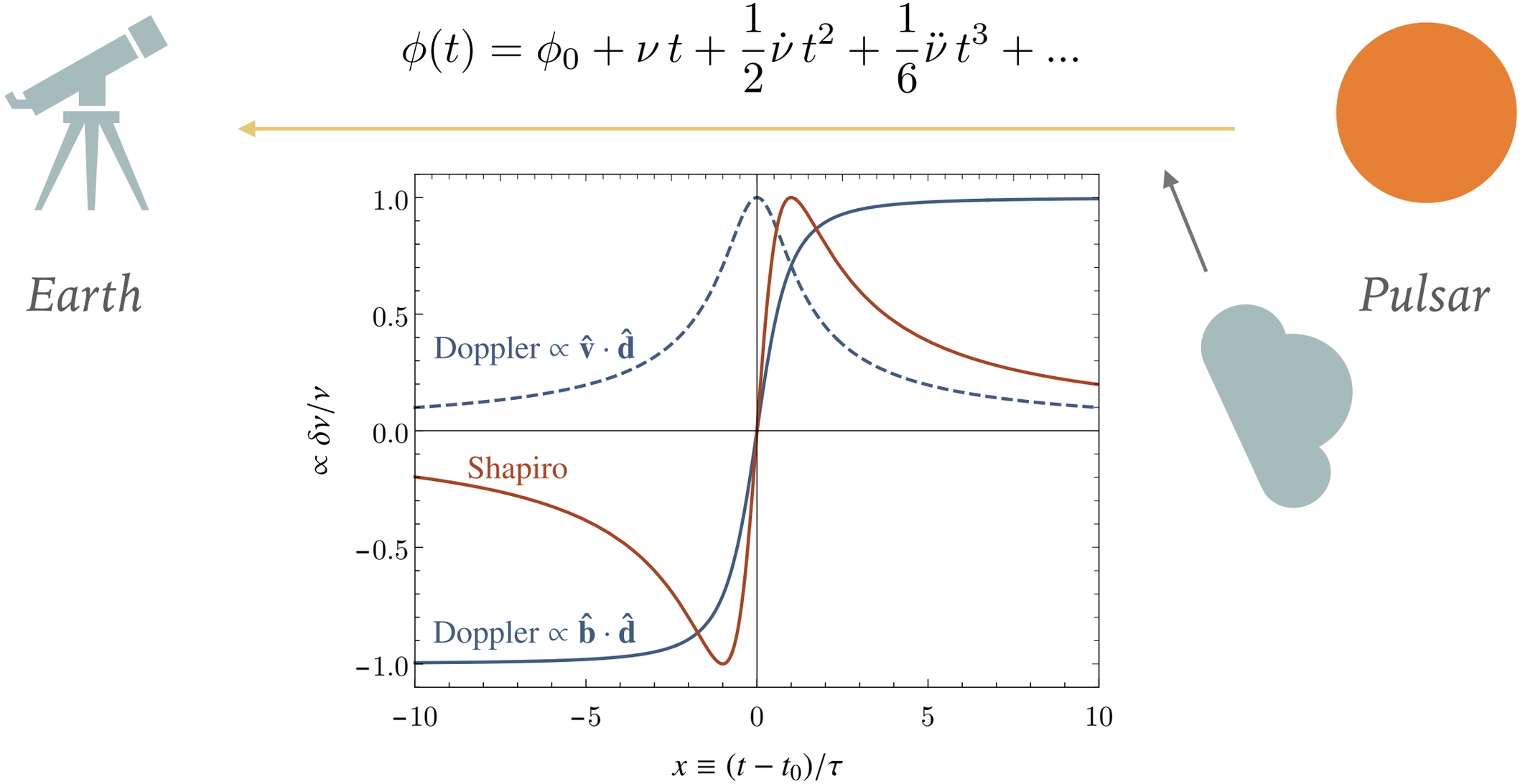
(deBroglie wavelength of galaxy) WIMP paradigm (Lyman-alpha forest)

- Look for gravitational means to detect structure
- Above 10^{-13} $M_\odot$ Pulsar timing can be effective
- Project of the (far) future to use laboratory clocks to detect small gravitational redshift effects

GRAVITATIONAL EFFECTS OF DARK MATTER SUBSTRUCTURE

- Pulsars, observed over decades, are accurate clocks — the time-of-arrival of a pulse is very stable

$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots$$



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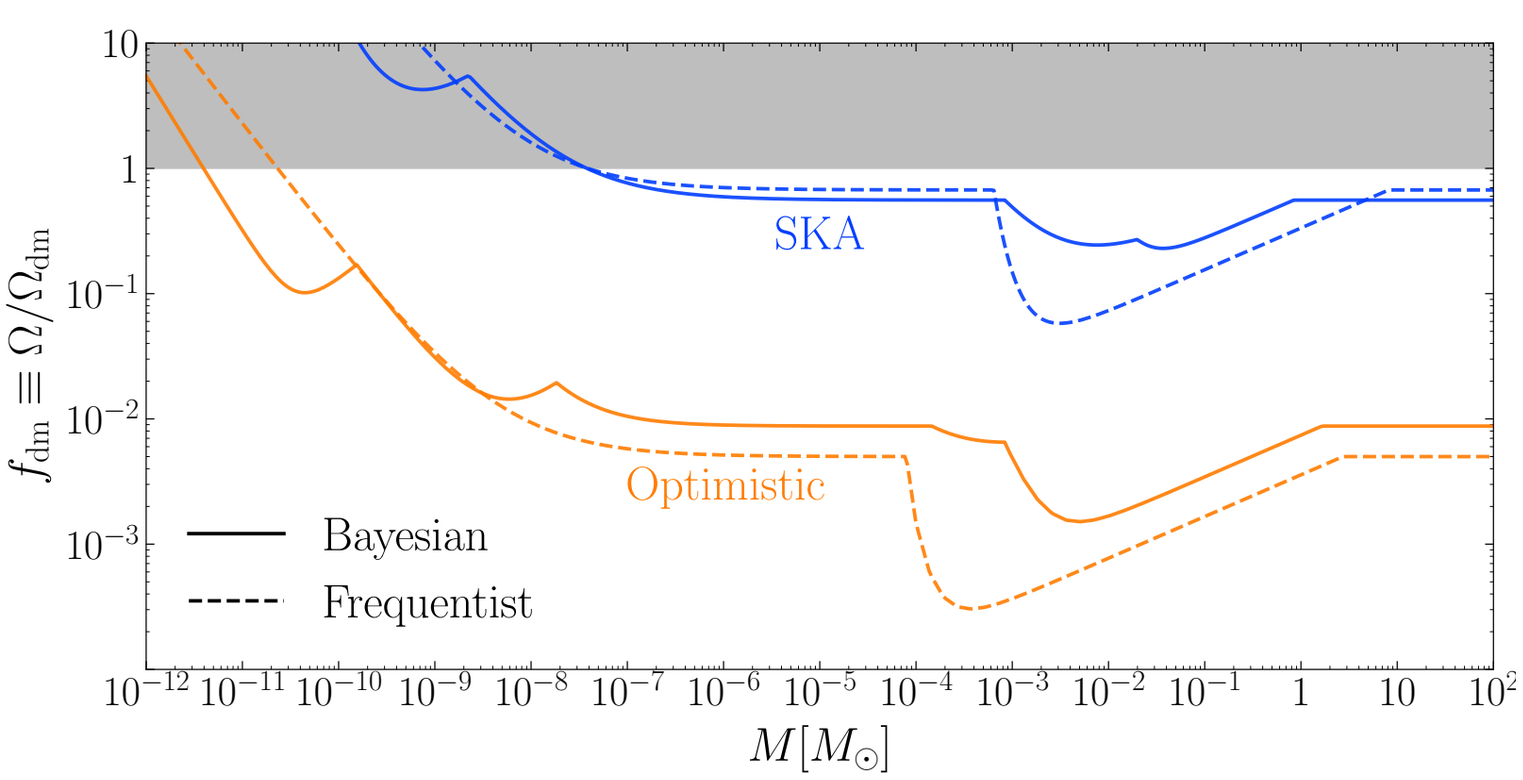
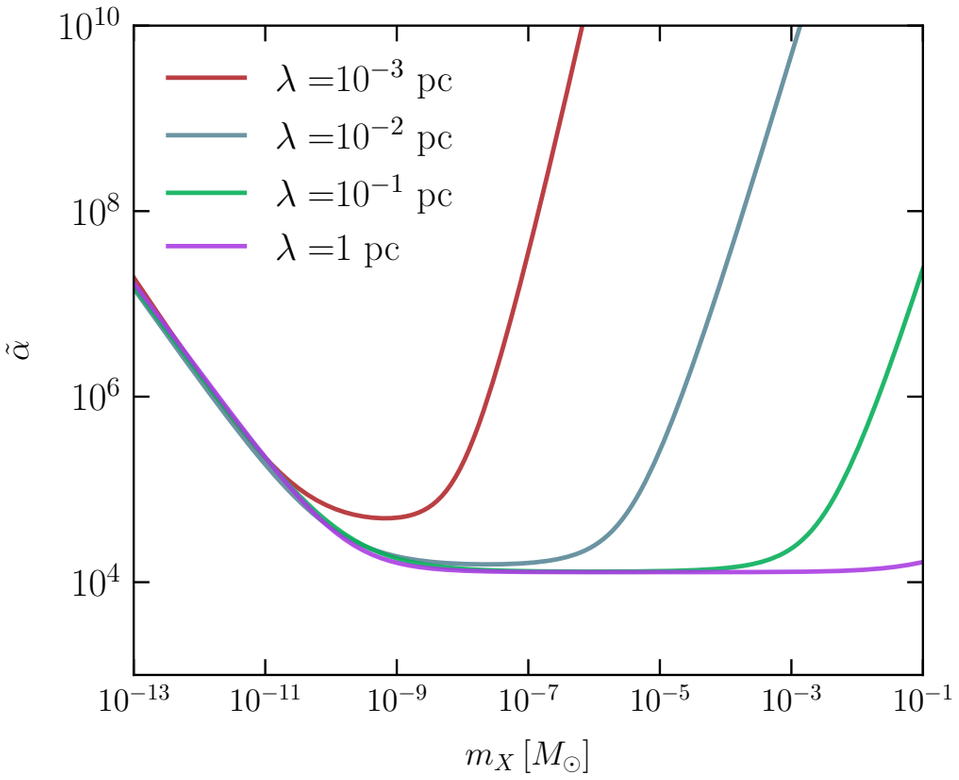


Lee, Taylor, Trickle, KZ 2104.05717

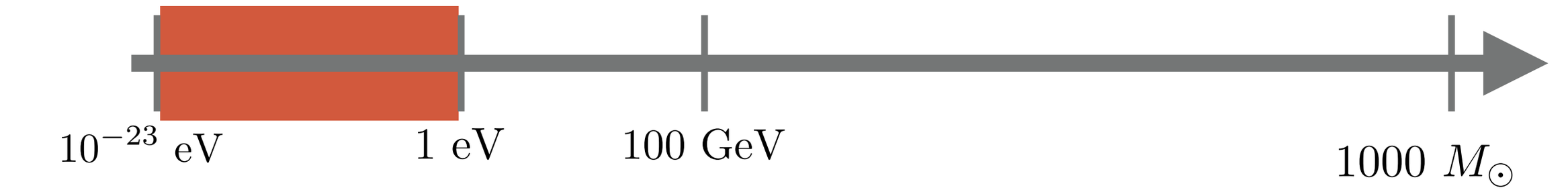


Gresham, Lee, KZ 2209.03963

*Gravitational-only interactions — **future***

*DM-baryon 5th force **currently** constrained by PTAs*

DARK MATTER DETECTION: A FULL COURT PRESS

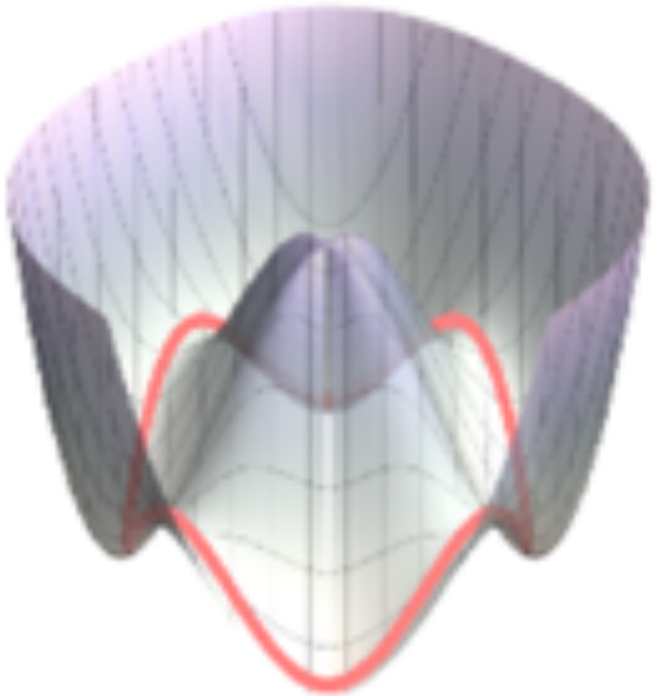


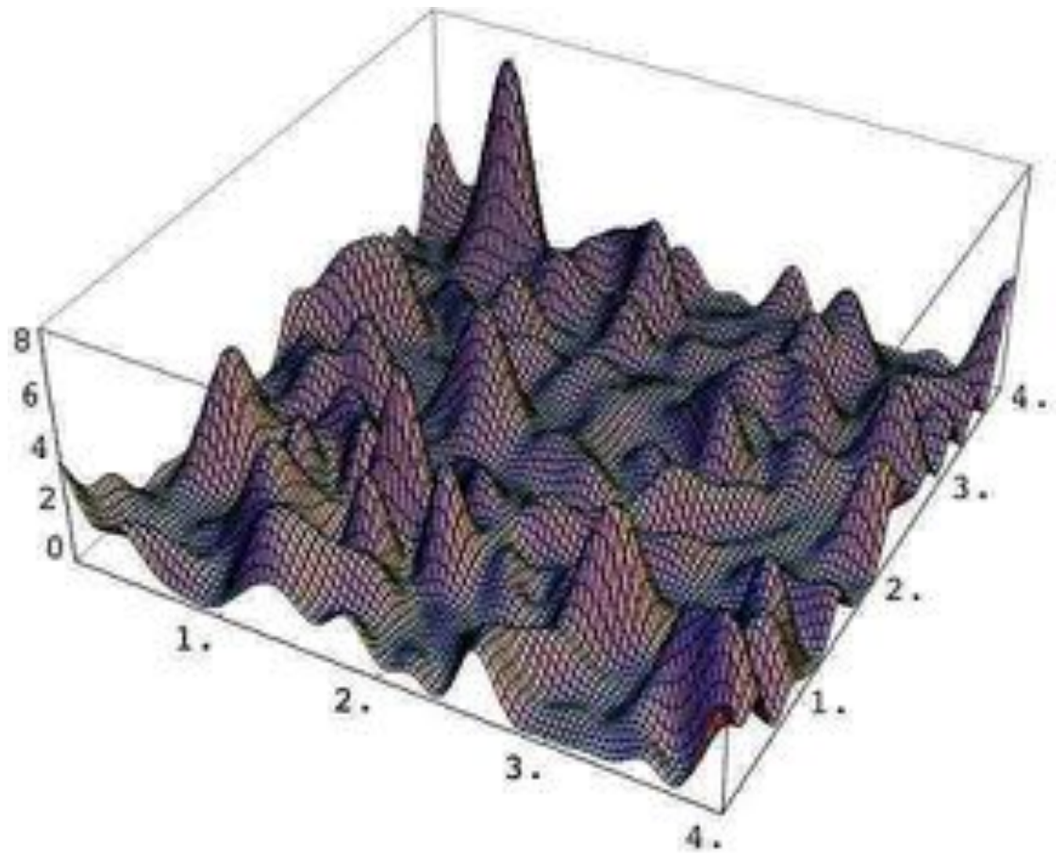
- Ultralight dark matter: dark matter behaves like a wave rather than an individual particle, e.g. axion
- Detection techniques focus on utilizing this coherence
- Cavities, AMO techniques

ULTRALIGHT DARK MATTER AND DARK CLUMPS

- Theories of dark matter predict departures from scale invariant density perturbations on small scales
- Axion dark matter (symmetry breaks after inflation):

$$\rho_X \propto \theta_i^2$$





- MC mass set by DM mass in horizon at QCD PT

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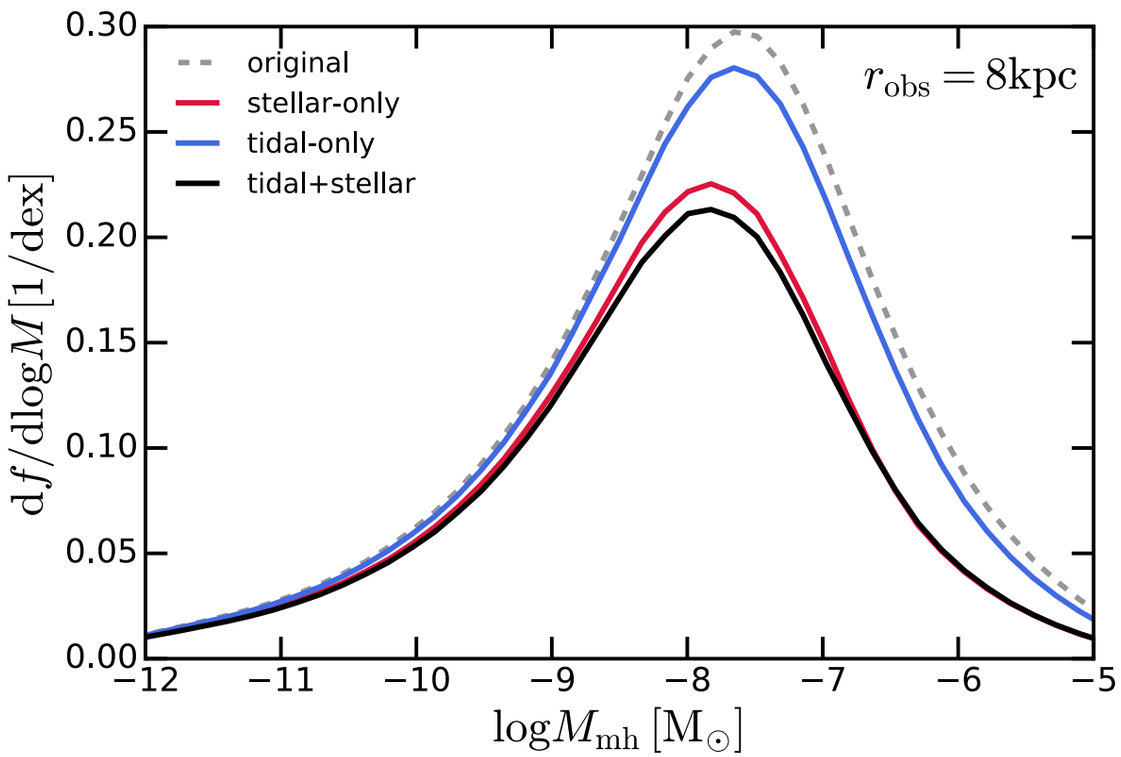
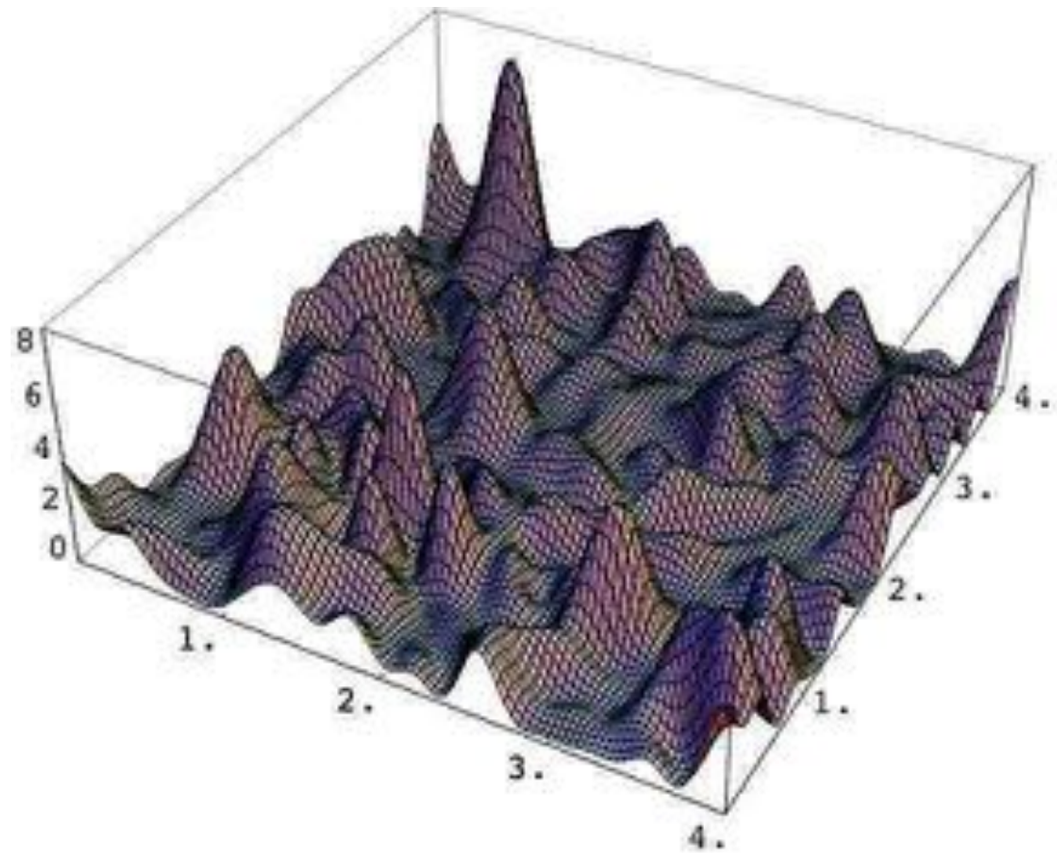


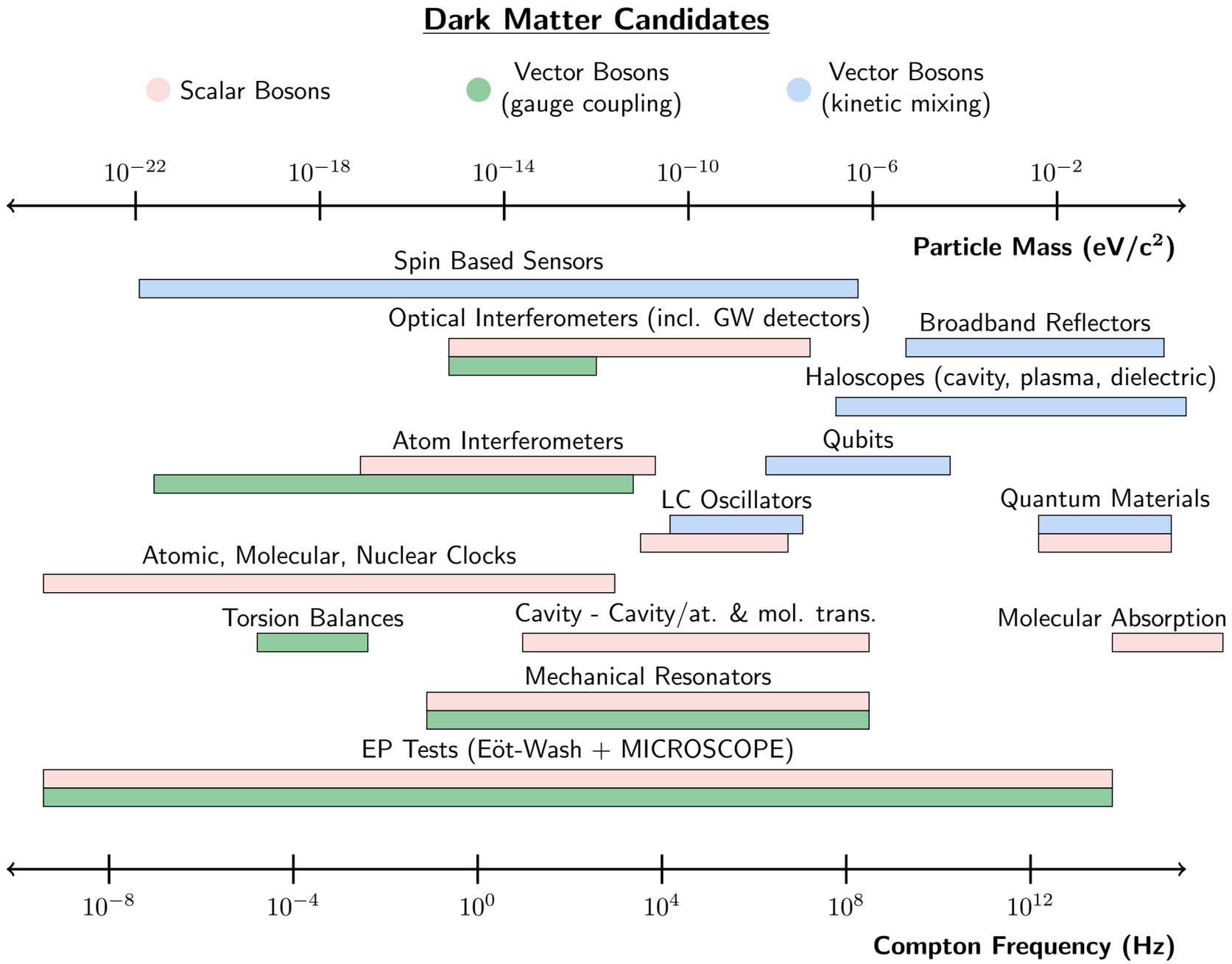


Shen, Xiao et al 2207.11276

- MC mass set by DM mass in horizon at QCD PT

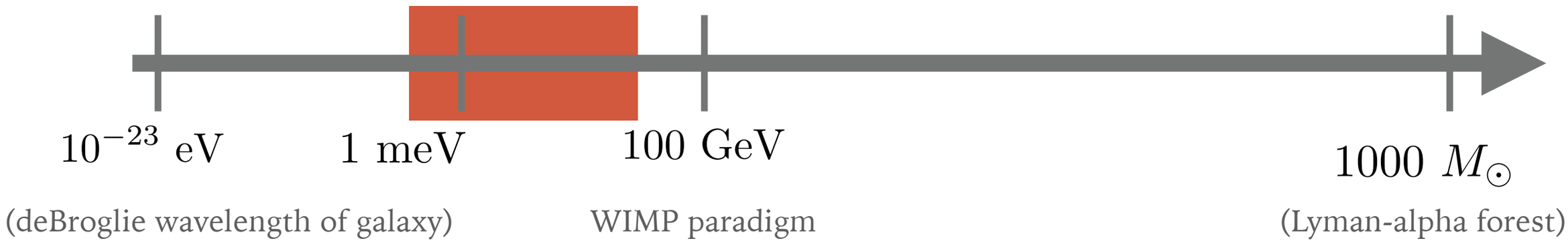
DETECTING WAVELIKE DARK MATTER

- Use Dark Matter Coherence



Snowmass whitepaper 2203.14915

DARK MATTER DETECTION: A FULL COURT PRESS



- Intermediate range where observation via particle interactions with SM is still highly motivated *though not detectable with traditional WIMP experiments*
- *Arise generically in top-down constructions*

DARK MATTER DETECTION: A FULL COURT PRESS

- Dark sector dynamics are complex and astrophysically relevant.

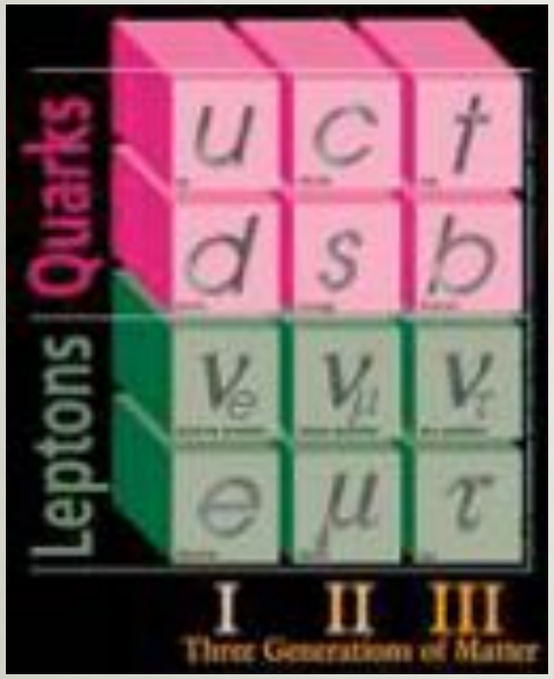
$$\sigma_{str} \simeq \frac{4\pi\alpha_s^2}{M^2} \simeq 10^{-24}\ \mathrm{cm}^2 \left(\frac{1\ \mathrm{GeV}}{M}\right)^2$$

- Abundance may still be set by (thermal) population from SM sector

$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \frac{c}{3} \simeq 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

Paradigm Shift

Our thinking has shifted



Energy

$M_p \sim 1$ GeV

Standard Model

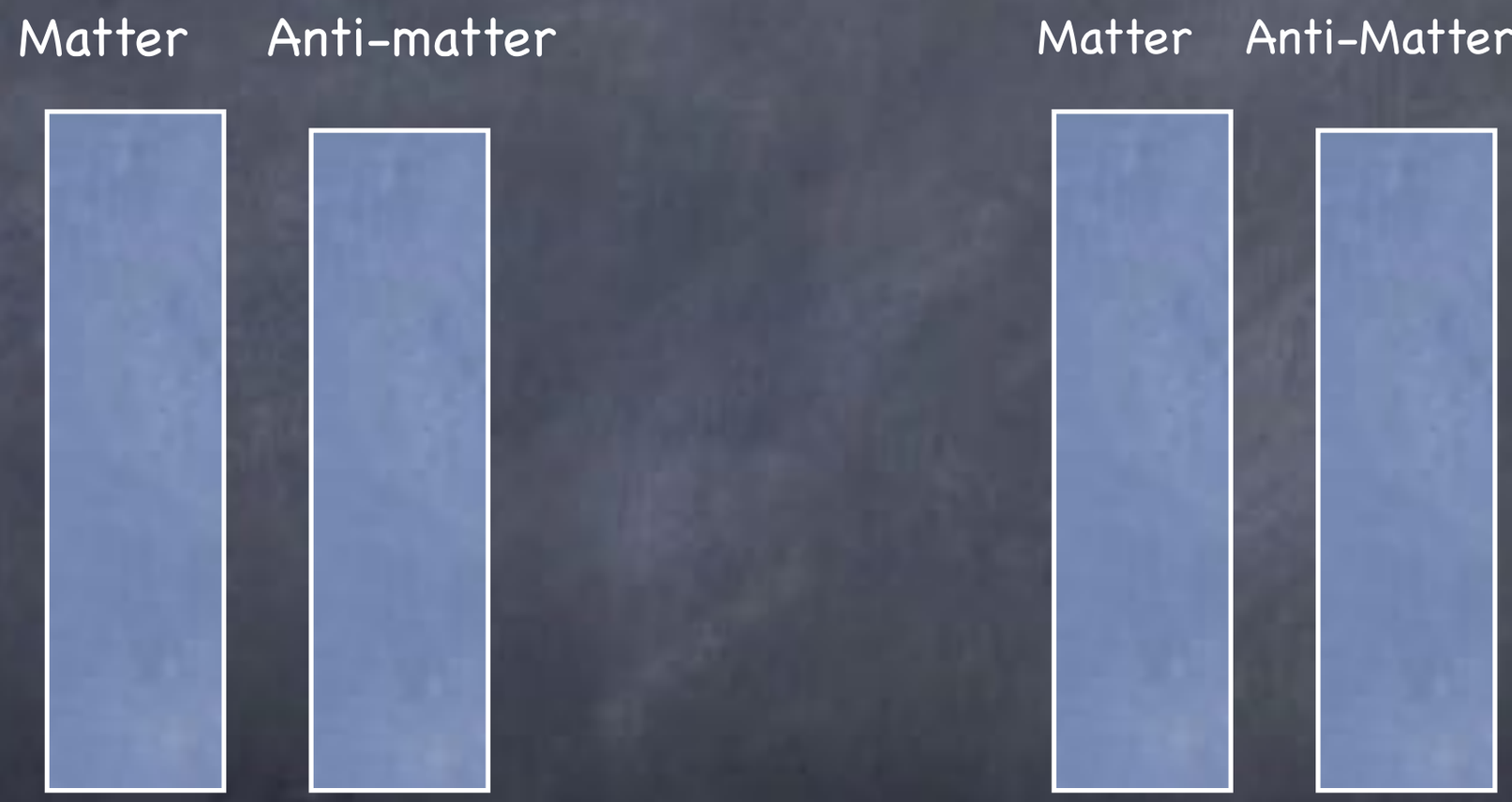
Inaccessibility

From a single, stable very weakly interacting particle .....
(WIMP, axion)

Models: Light DM sectors,
Secluded WIMPs, Dark Forces, Asymmetric DM .....
Production: freeze-in, freeze-out and decay,
asymmetric abundance, non-thermal mechanisms .....

...to a hidden world or "hidden valley" with multiple states, new interactions

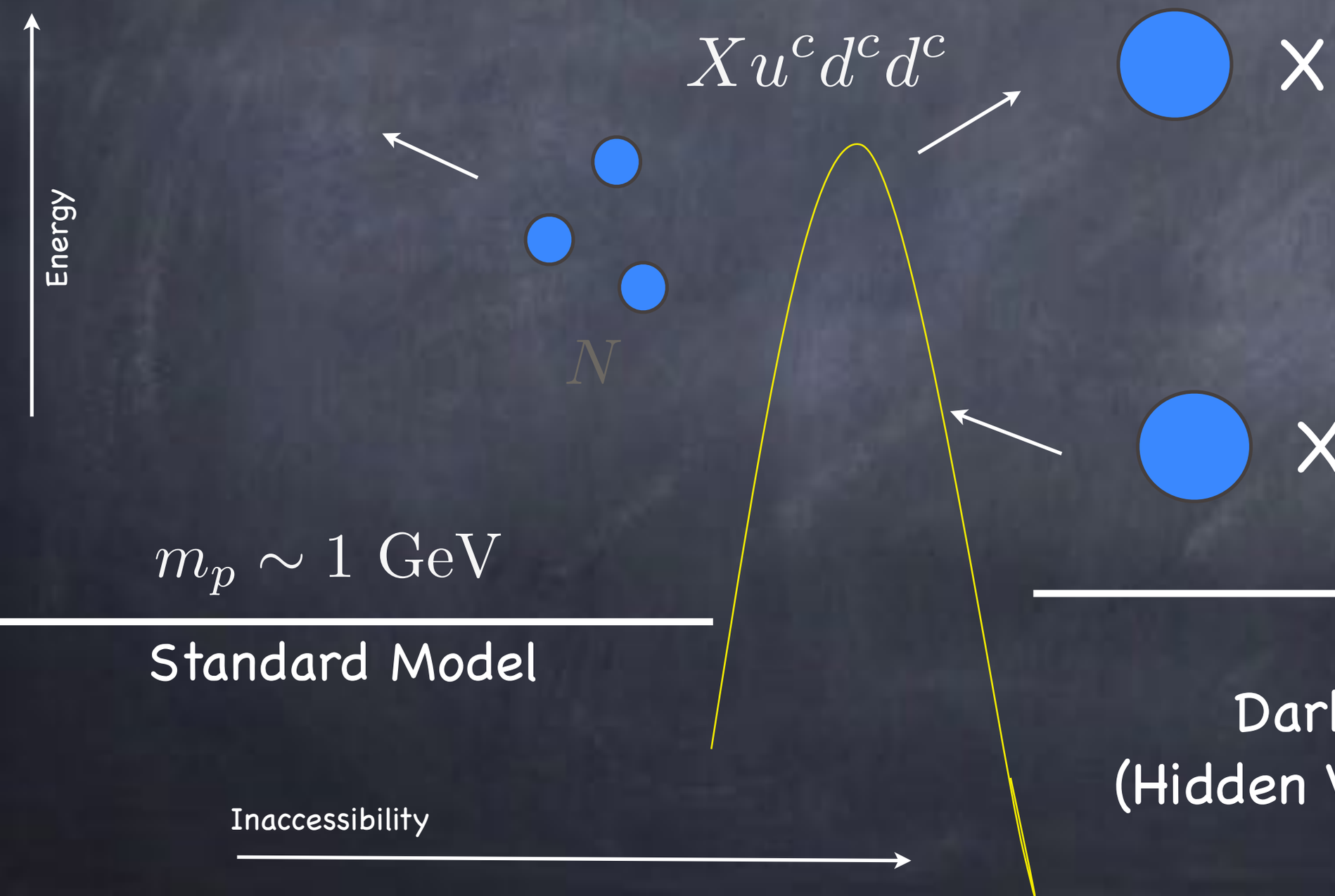
Chemical Potential Dark Matter



Asymmetric DM

"Integrate out" heavy state
Higher dimension operators:

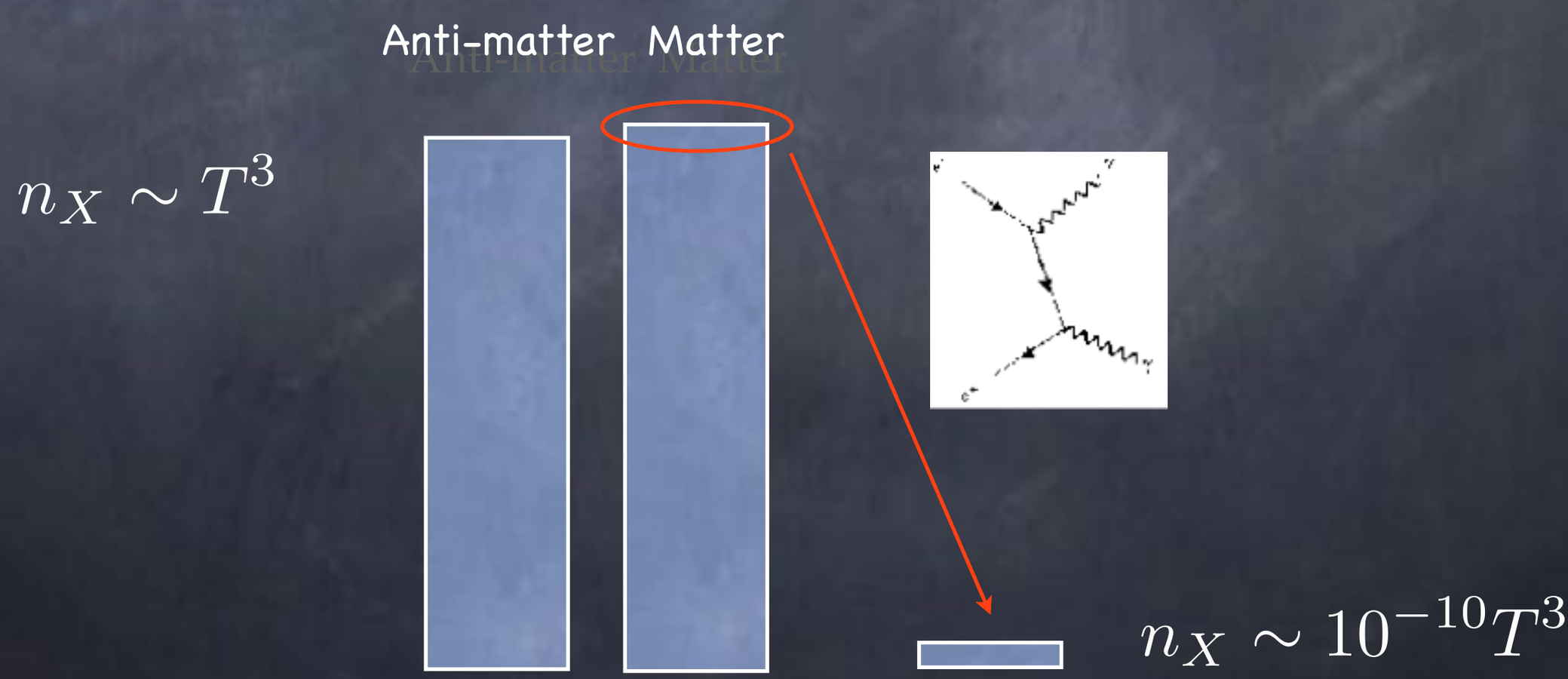
$$X u^c d^c d^c$$



Review: 1308.0338

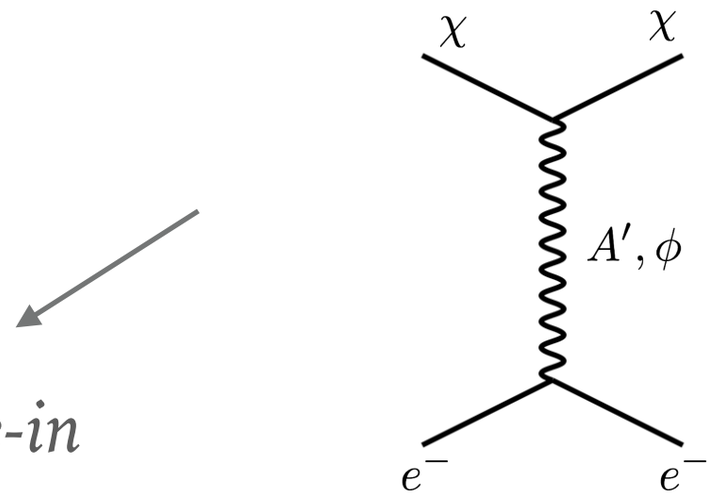
Chemical Potential Dark Matter

- Another way to stop the annihilation is simply to run out of anti-particles. This is what happens with baryons in the SM.

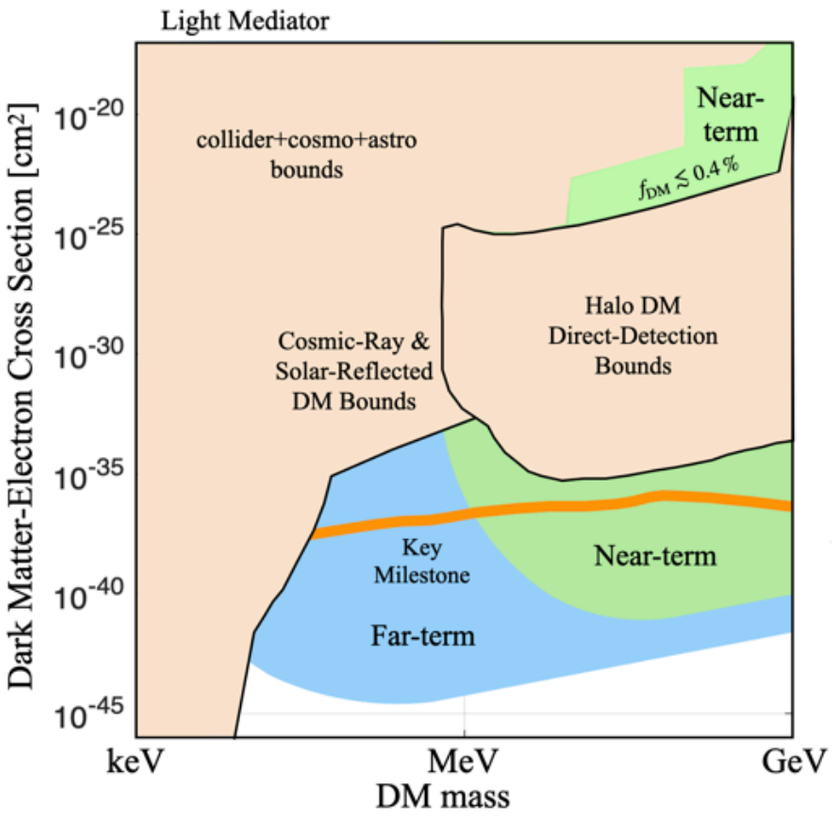


CROSSING SYMMETRY

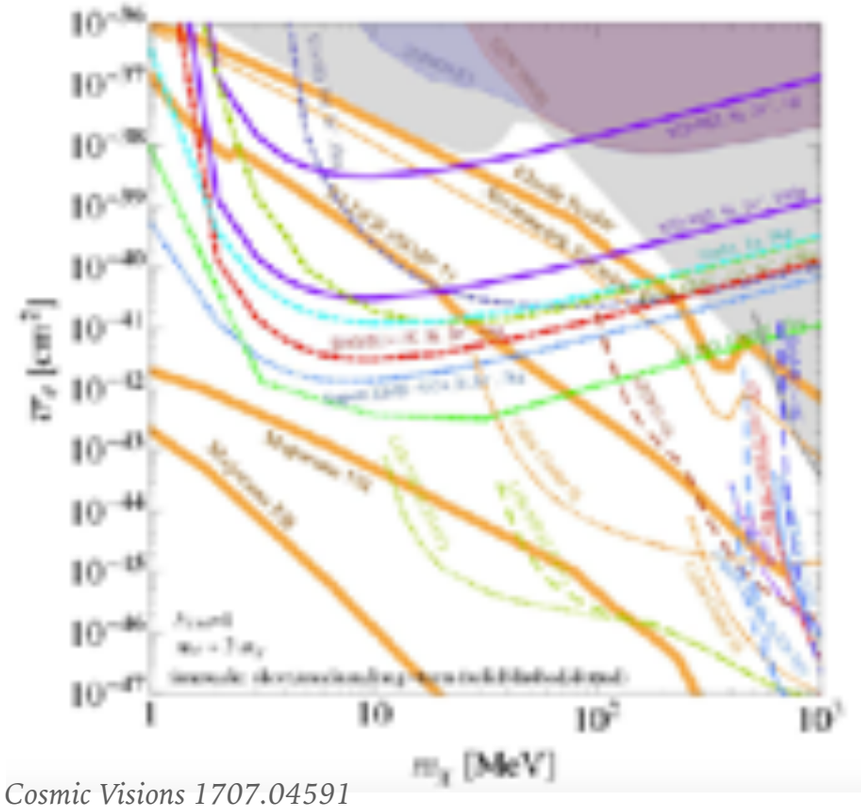
- Utilize DM Abundance and crossing symmetry as guide for interaction rates



Freeze-in



Asymmetric Dark Matter

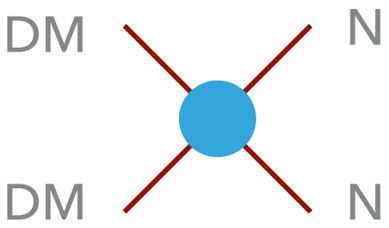


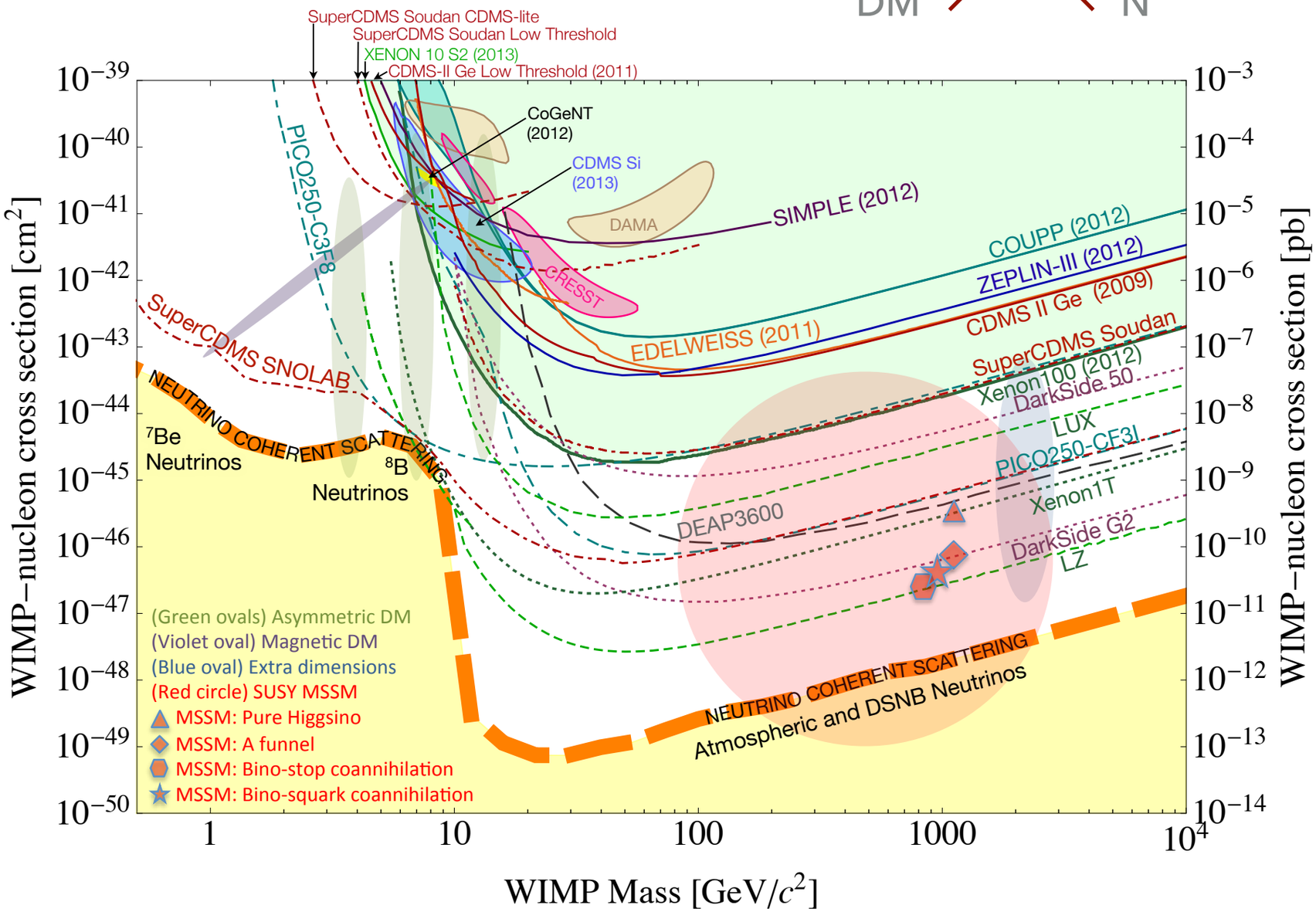
US Cosmic Visions 1707.04591

TOWARDS HIDDEN SECTOR DARK MATTER

- Developments in condensed matter make this possible

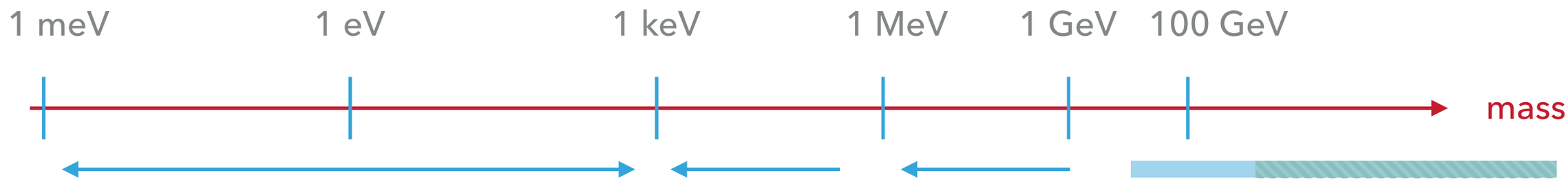
???





LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama



Absorption

Super-conductors

Semiconductors

Traditional WIMP

SuperCDMS

XENON1T

Dirac Materials

DAMIC, SENSEI

LZ

Polar Crystals

Superfluid Helium

Graphene

QCD axion, “ultralight frontier”

~meV energy resolution

~eV energy resolution

~keV energy resolution

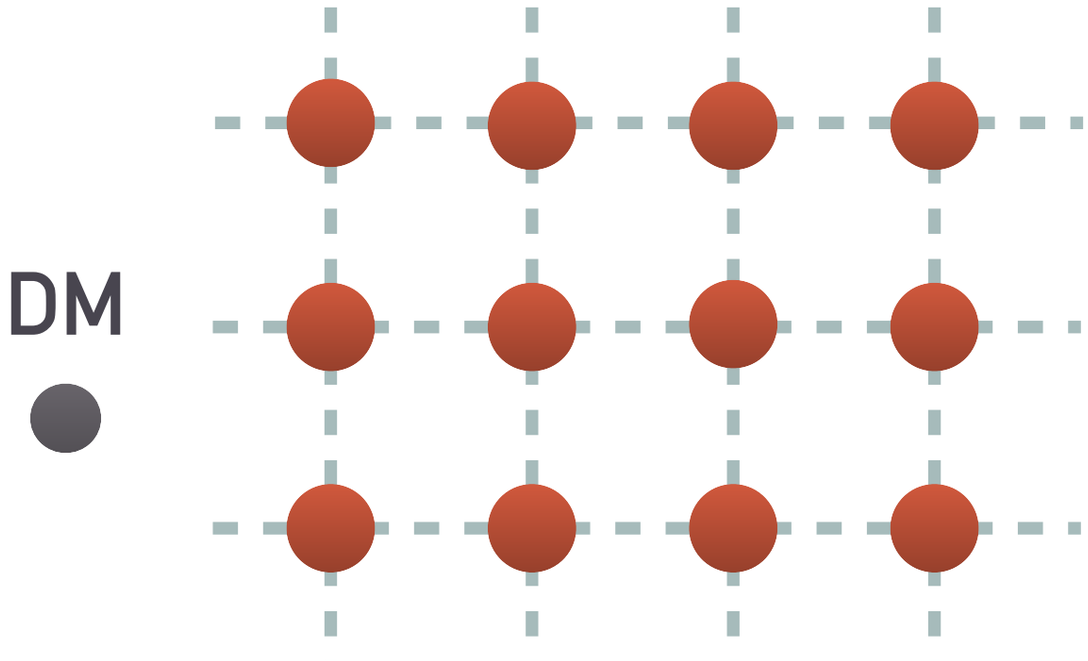
Collective excitation

Electron excitation

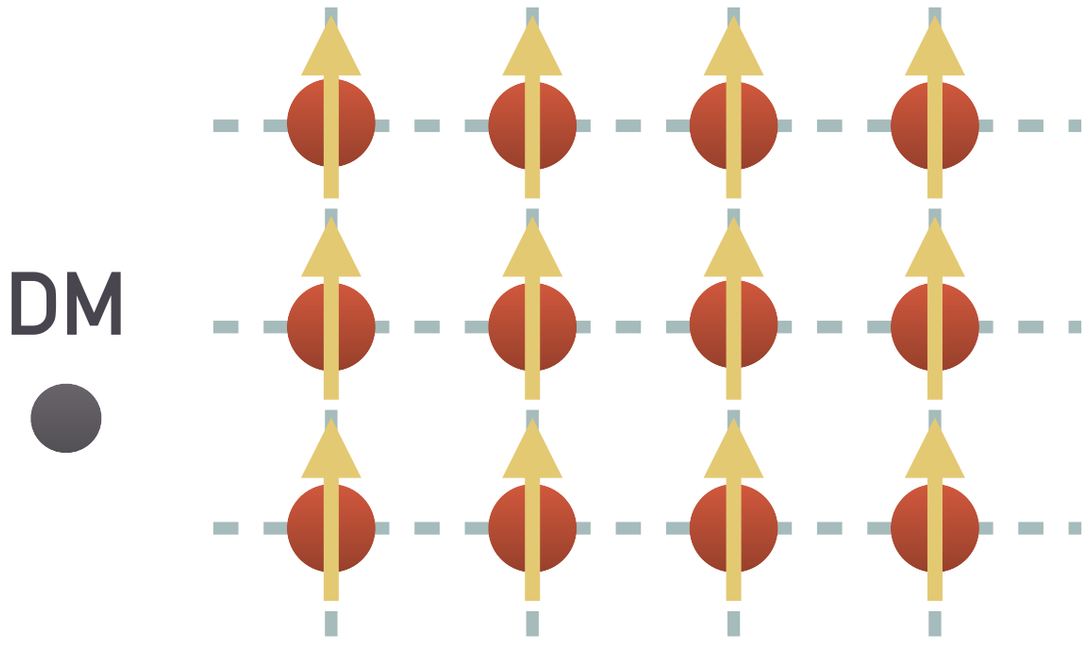
Nuclear recoil

COLLECTIVE EXCITATIONS

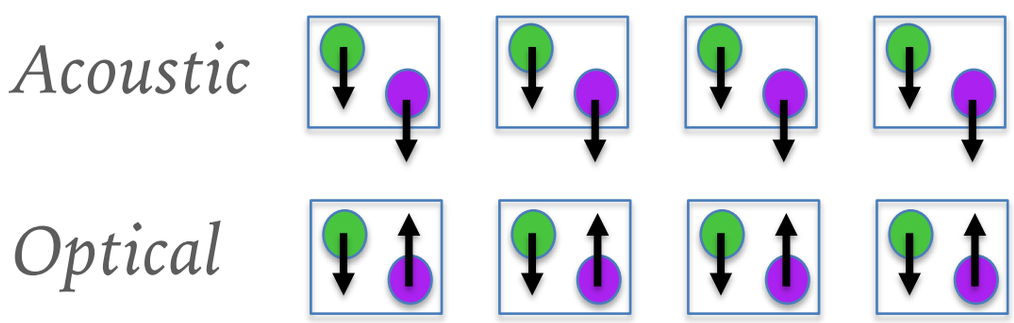
- When deBroglie wavelength is longer than inter-article spacing, collective excitations are relevant degrees-of-freedom



Phonons

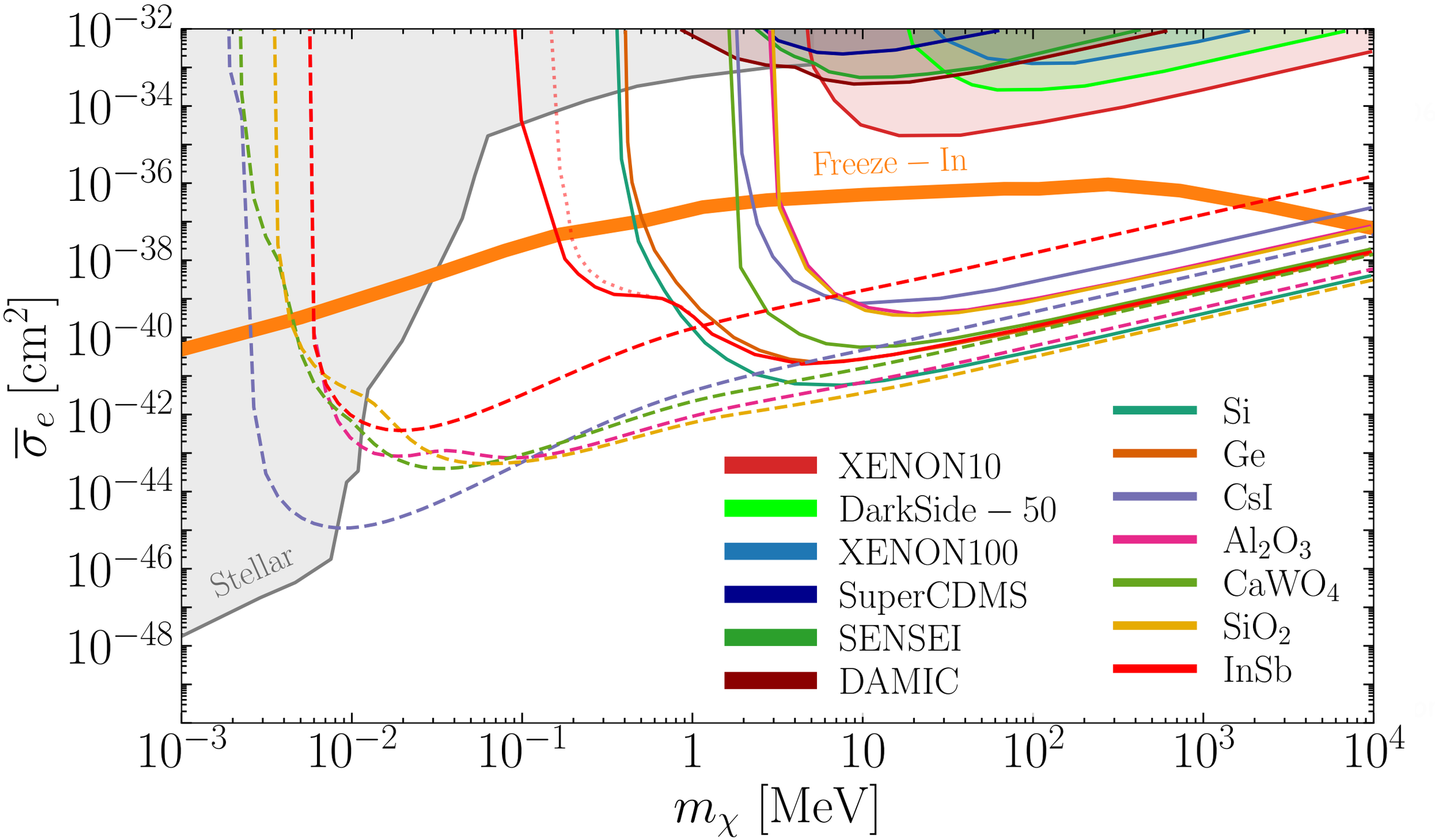


Magnons



OPTICAL PHONONS IN POLAR MATERIALS

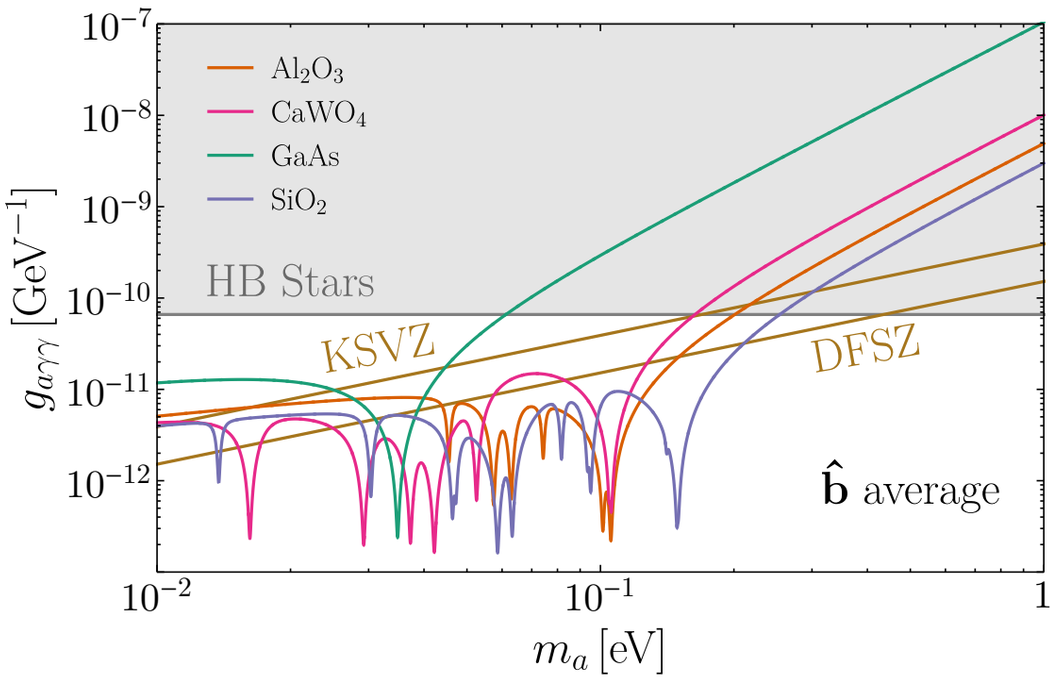
Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716

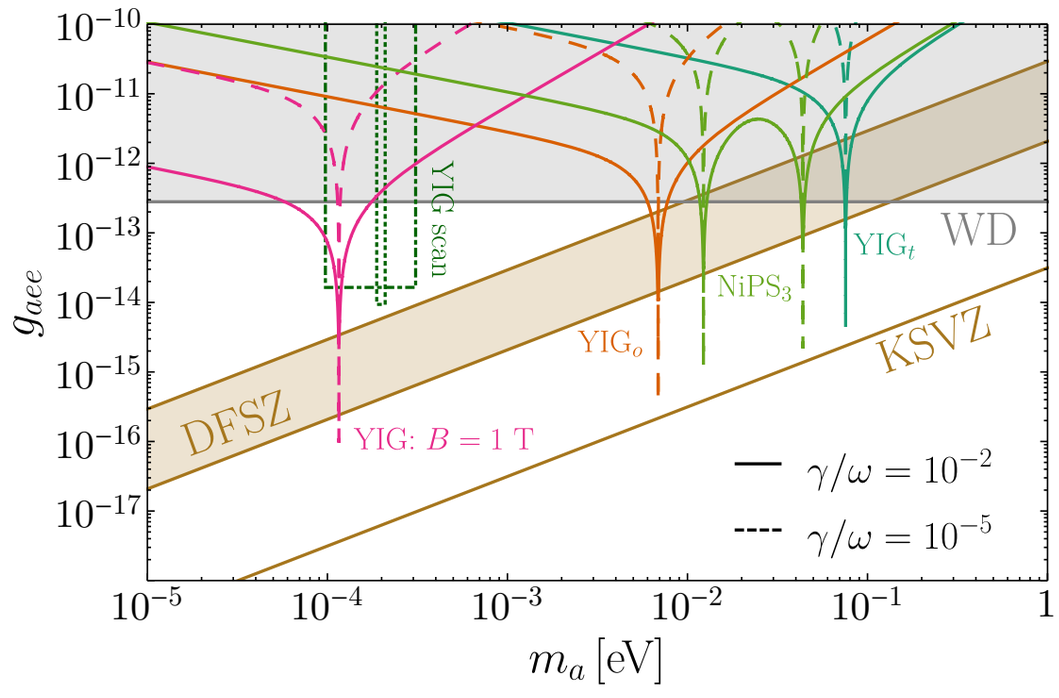


ABSORPTION OF BOSONIC DARK MATTER

Trickle, Zhang, KZ 2005.10256

- Rather than depositing kinetic energy, entire mass energy can be absorbed.
- How about 1-100 meV mass axions?

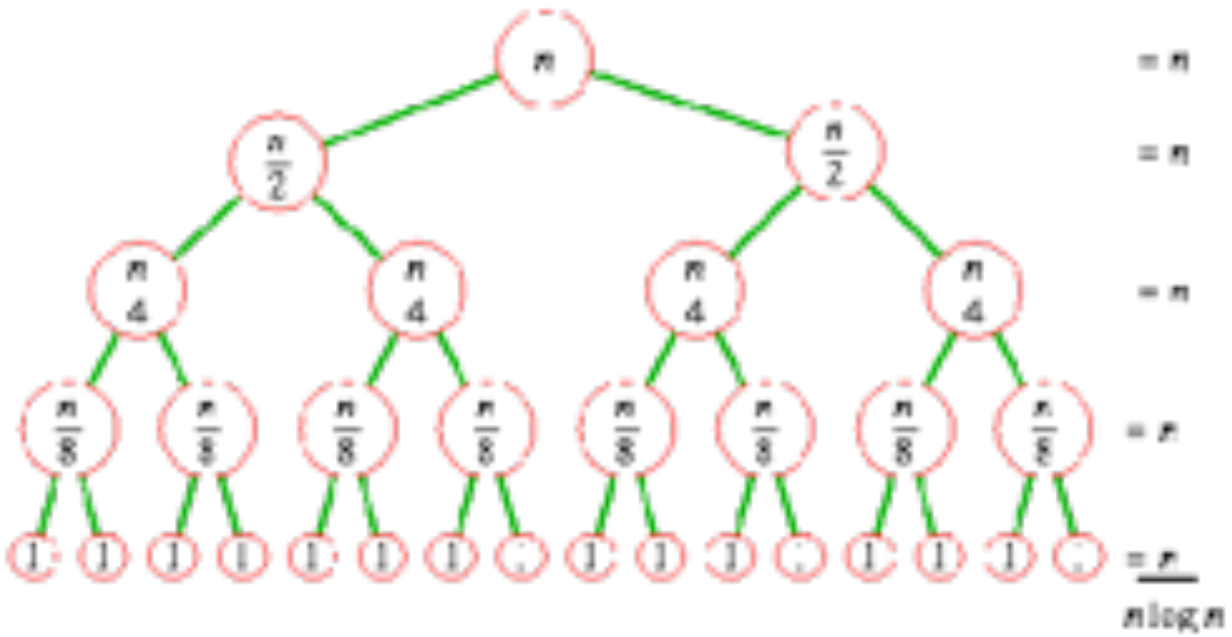




Process	Fundamental interaction	Effective coupling in Eq. (4)	Rate formula
Axion + B field $\to$ phonon	$a\boldsymbol{E}\cdot\boldsymbol{B}$	$\boldsymbol{f}_j = \frac{1}{\sqrt{2}}\, g_{a\gamma\gamma}\, \frac{e\sqrt{\rho_a}}{m_a}\, \boldsymbol{B}\cdot\boldsymbol{\varepsilon}_\infty^{-1}\cdot\mathbf{Z}_j^*$	Eq. (18)
Axion $\to$ magnon	$\nabla a\cdot\boldsymbol{s}_e$	$\boldsymbol{f}_j = -\frac{i}{\sqrt{2}}\, g_{aee}\,(g_j-1)\,\frac{\sqrt{\rho_a}}{m_e}\,\boldsymbol{v}_a$	Eq. (27)

OUTLOOK

- The landscape of DM candidates has exploded



The universe is dominated by invisibles!

WIMP or (axion)

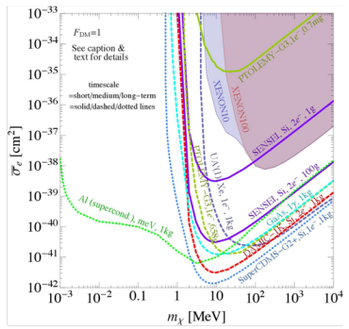
How to be ready for anything? Hidden Sectors

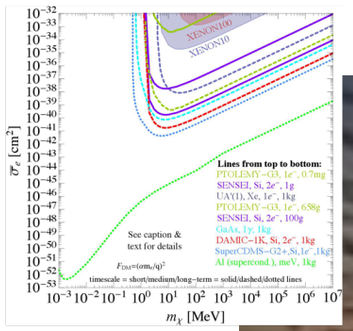
How do we search for these things?

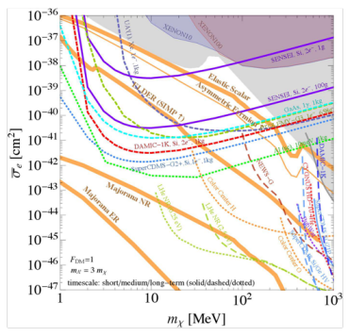
- How do we evaluate dark matter candidates and prioritize directions to pursue?

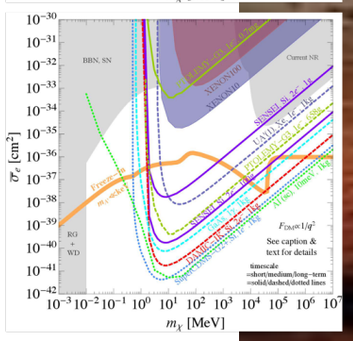
OUTLOOK

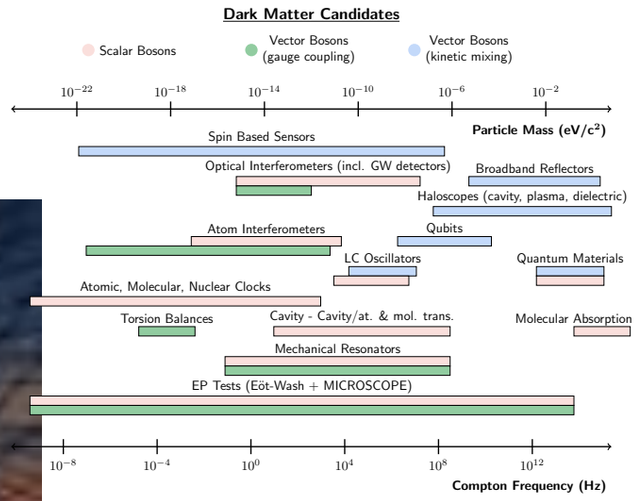
- A wide net has been cast.

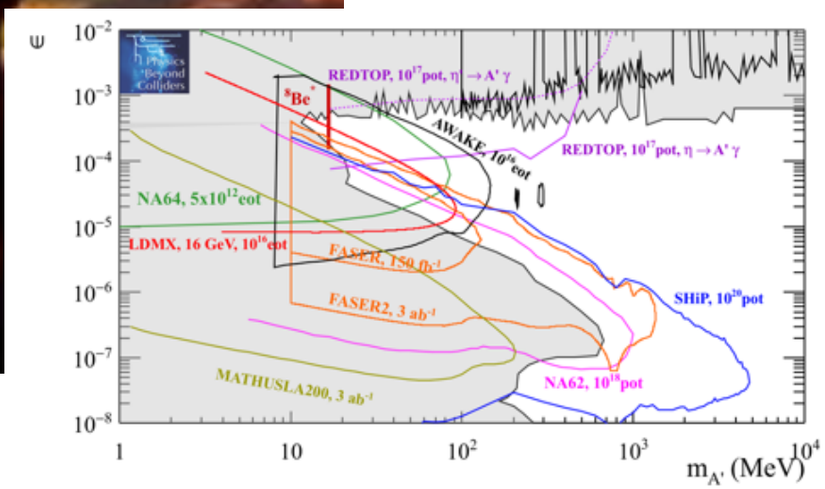












- How do we evaluate dark matter candidates and prioritize directions to pursue?