Caltech

BURKE INSTITUTE

"STATUS OF DM THEORY"

Kathryn M. Zurek

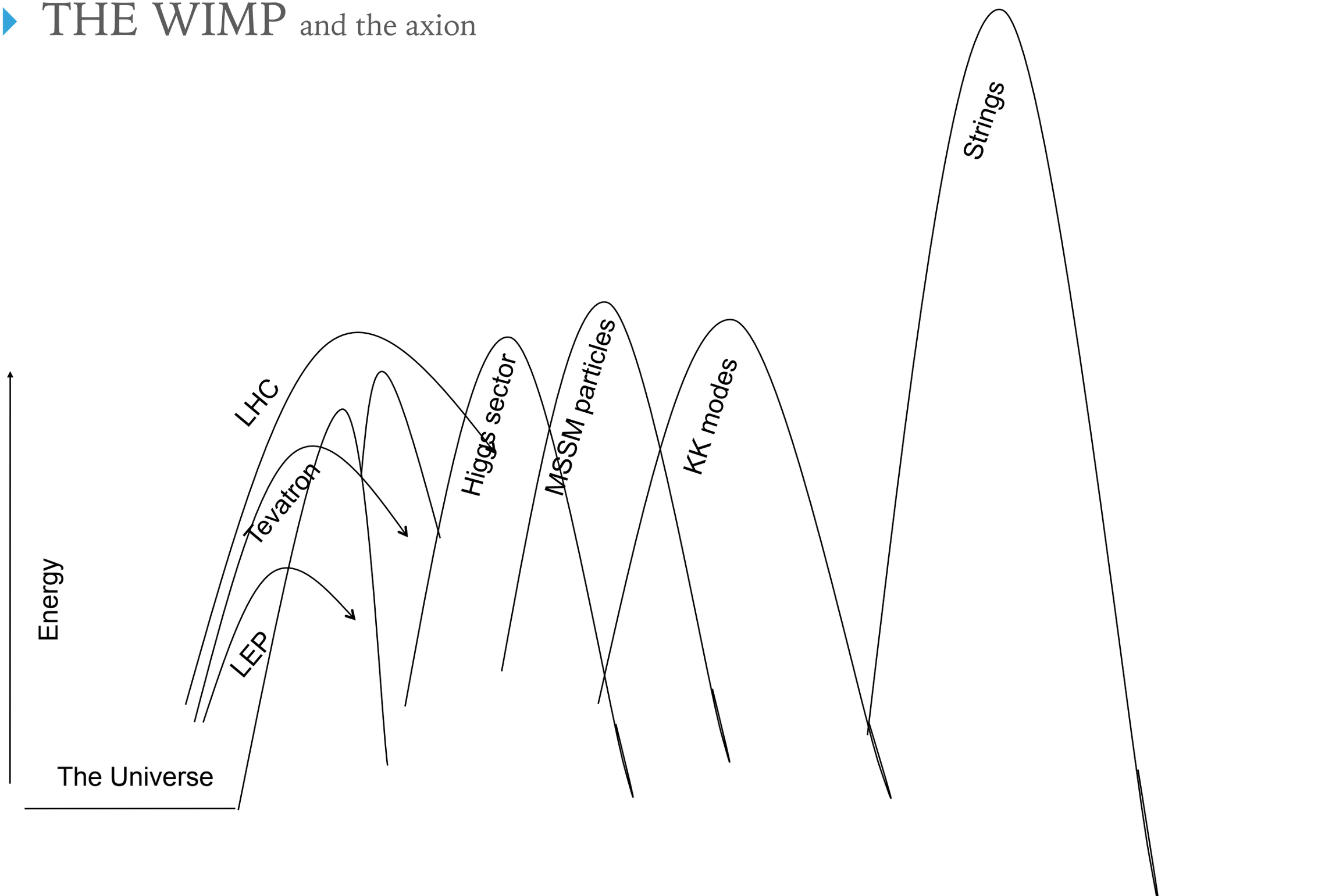
A HITCHHIKER'S GUIDE TO DARK MATTER: THE ROAD AHEAD

Kathryn M. Zurek

Proceedings of Nobel Symposium, Published in Phys Lett B 1003 (2024): 116438

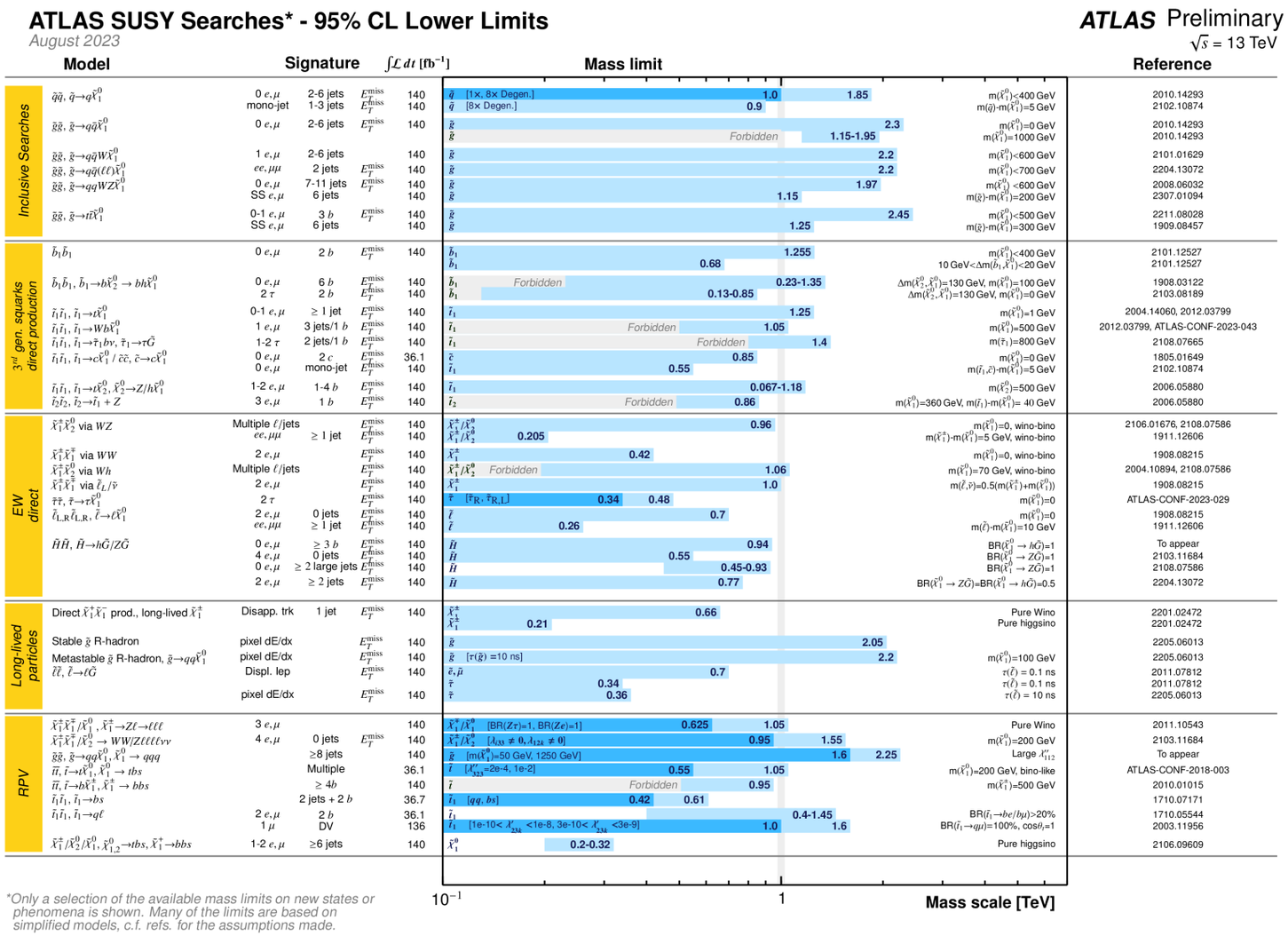
PRE-LHC — A FOCUS ON THE PEAKS OF HIGH ENERGY PHYSICS

- THE WIMP and the axion



WE HAVEN'T FOUND NEW PHYSICS

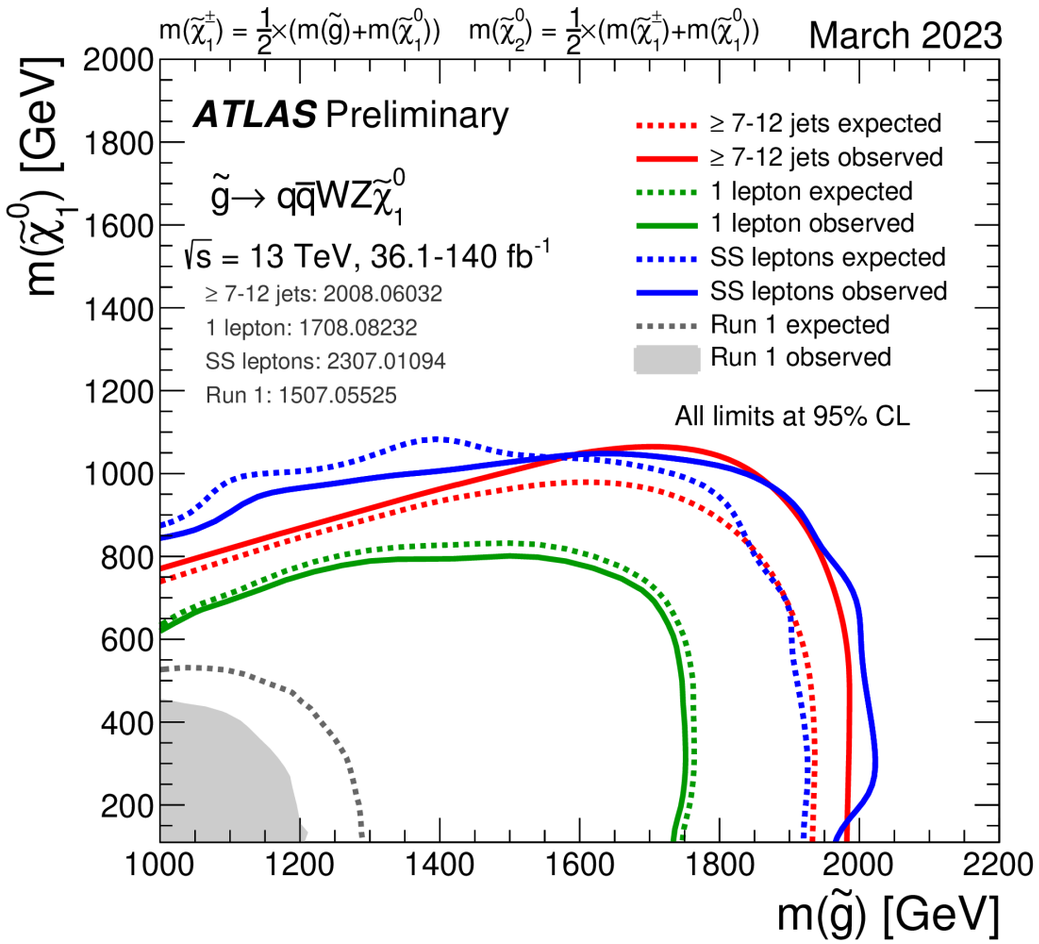
- Further advances in accelerator physics are on long timescales

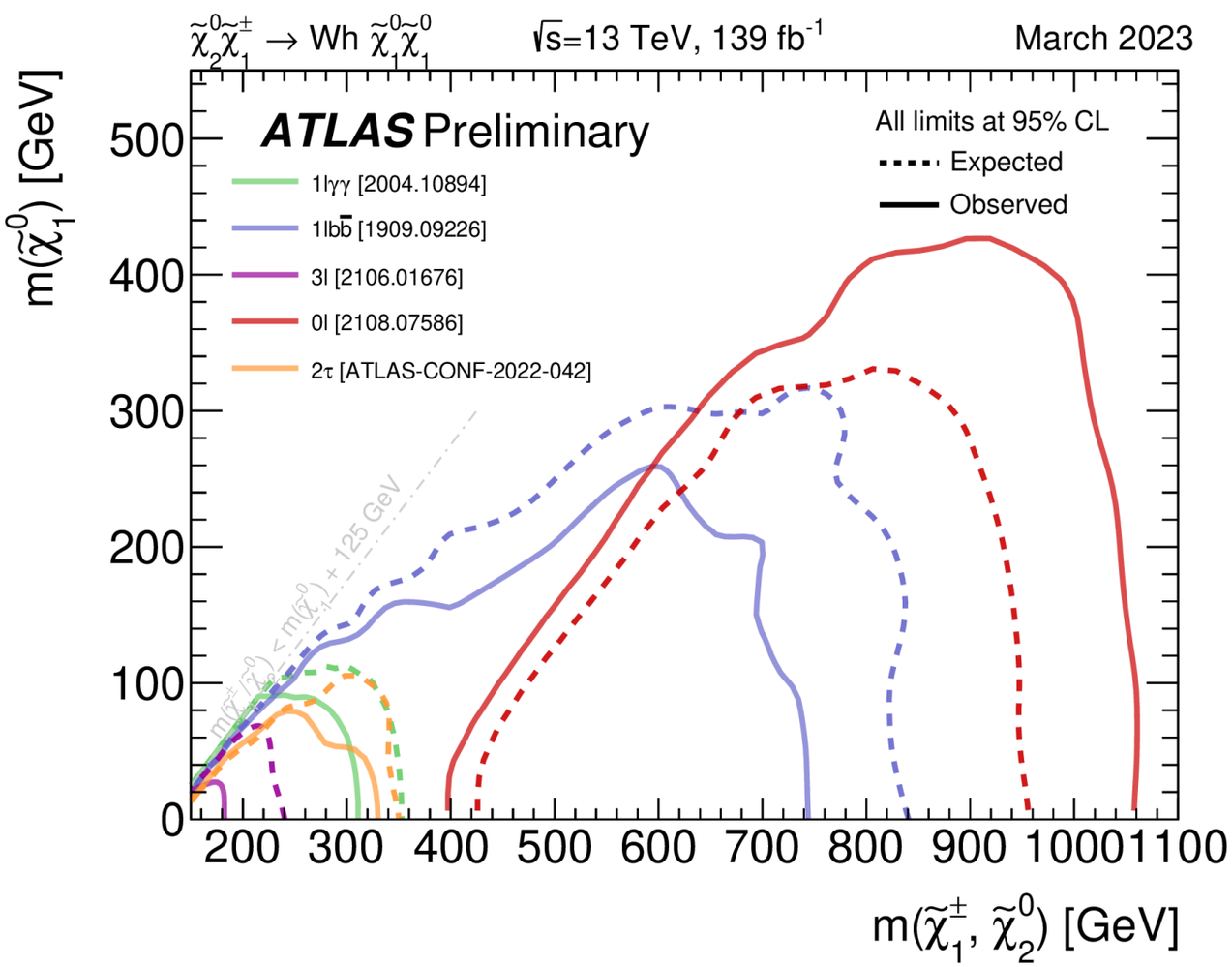


- But, collider experiments are **not** dark matter experiments

PROTON COLLIDERS ARE COLORED PARTICLE MACHINES

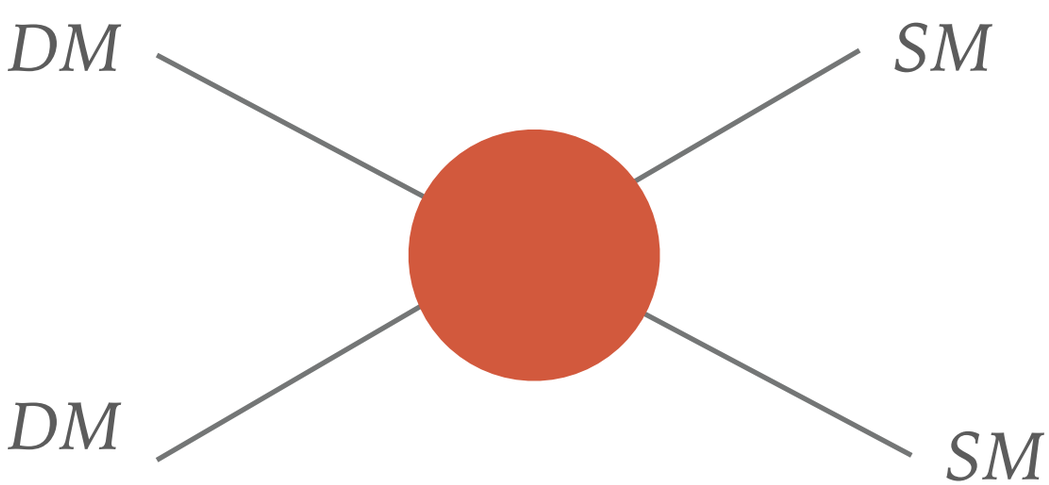
- Direct constraints on electroweak multiplet states (to which WIMP DM belongs) are comparatively weak





WIMPS THROUGH INDIRECT DETECTION

- Relic abundance considerations for DM (generally)



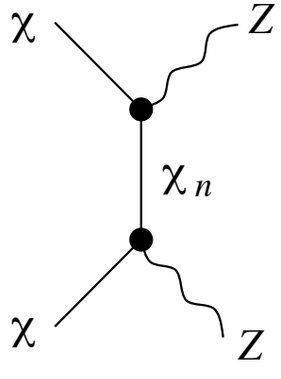
$$n_{DM}\langle\sigma v\rangle \simeq H(T_{\rm fo})$$

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

$$\langle\sigma v\rangle \simeq 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

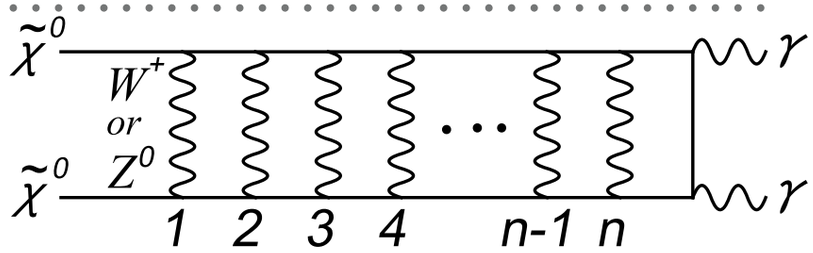
- Naive back-of-the-envelope for WIMPs:

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



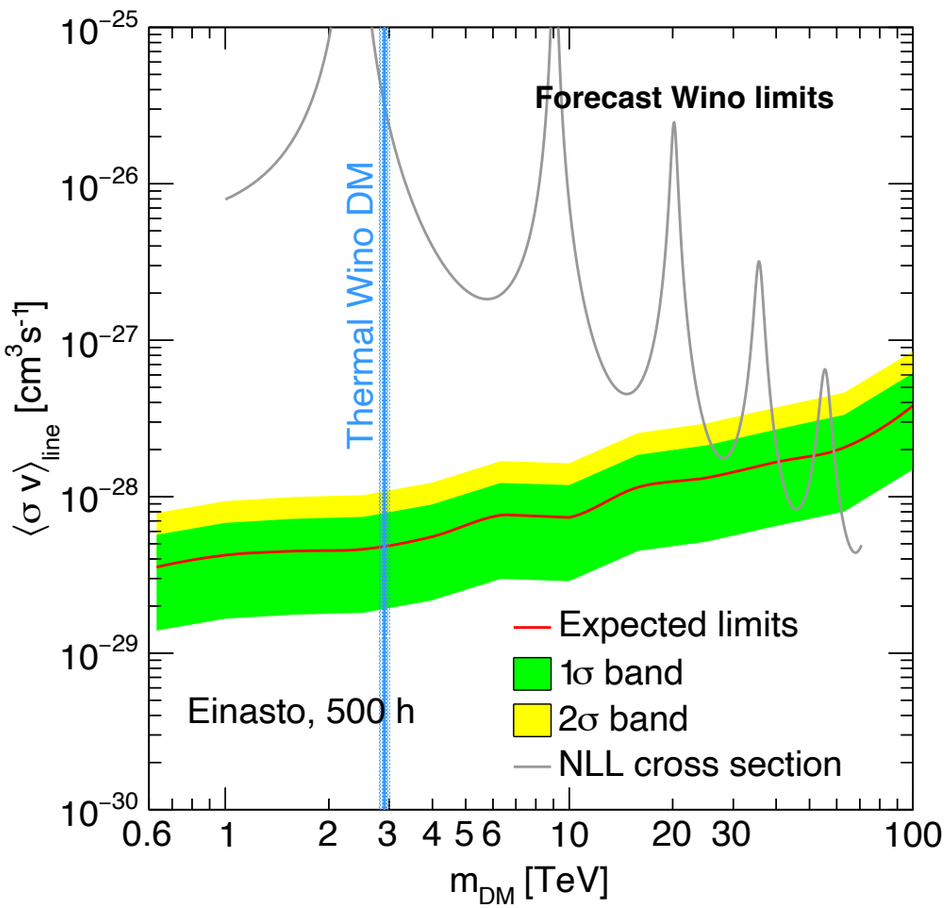
WIMPS THROUGH INDIRECT DETECTION AT CHERENKOV TELESCOPES

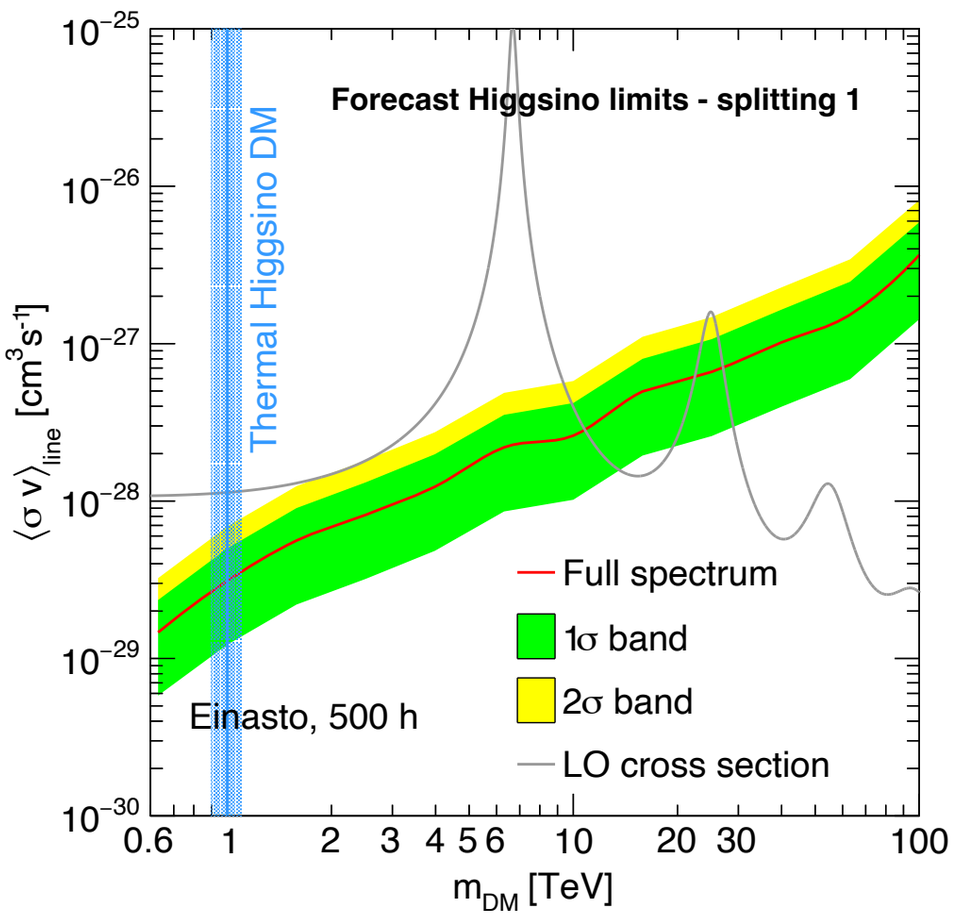
- EW doublet and triplet states



Rinchiuso et al 2008.00692

Hisano, Matsumoto, Nojiri, Saito, 0412403

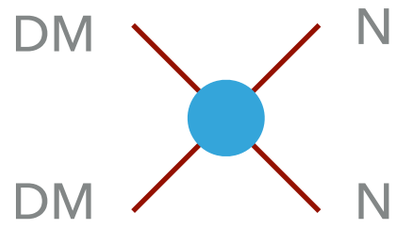




- Cherenkov telescopes have (unique) sensitivity to such weak dark matter *Challenge #1*

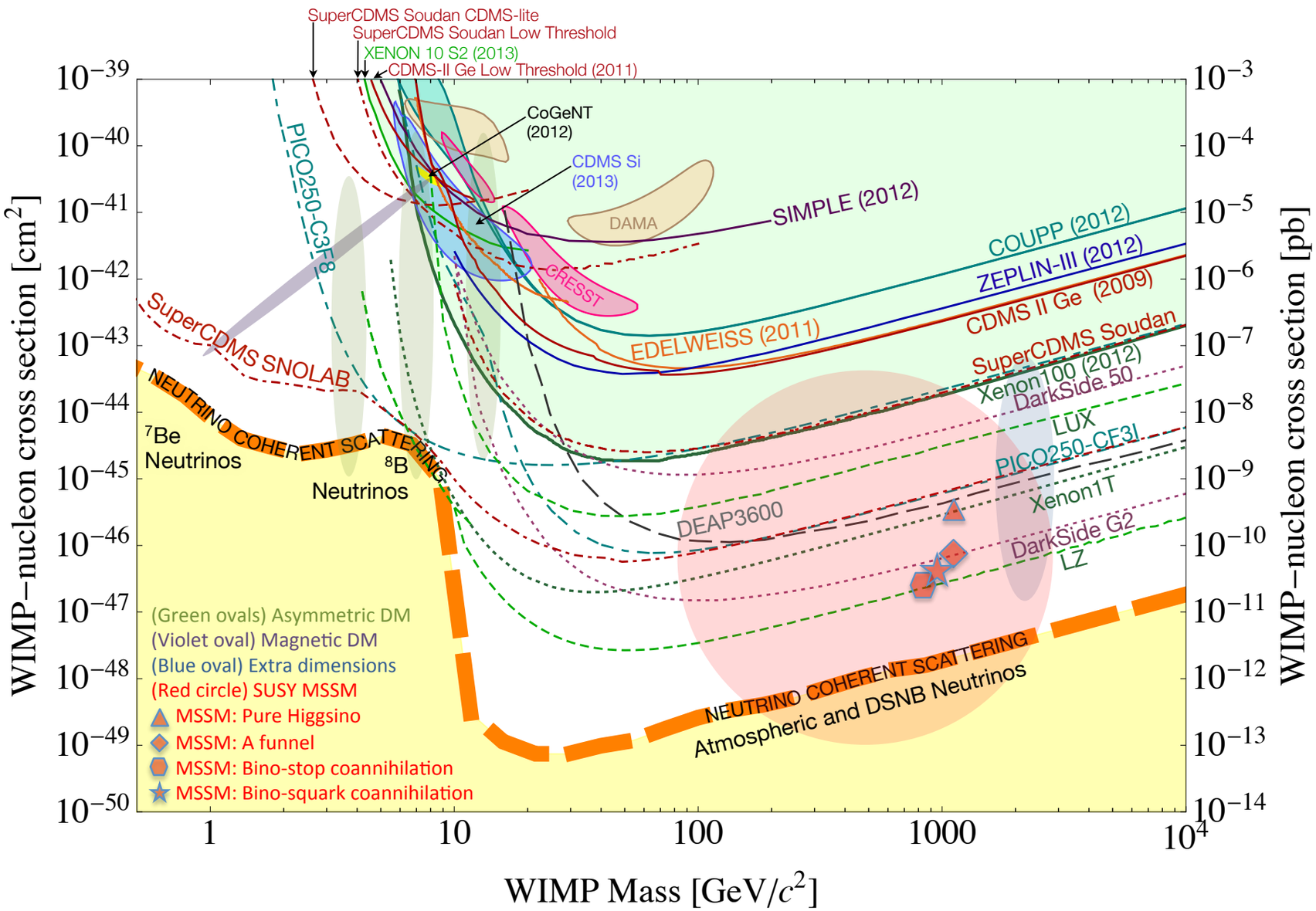
WIMPS THROUGH DIRECT DETECTION

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



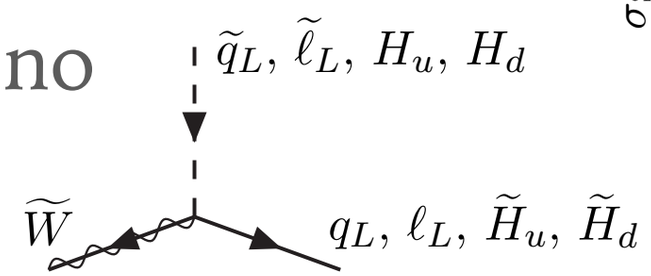
Z-boson interacting dark matter: ruled out

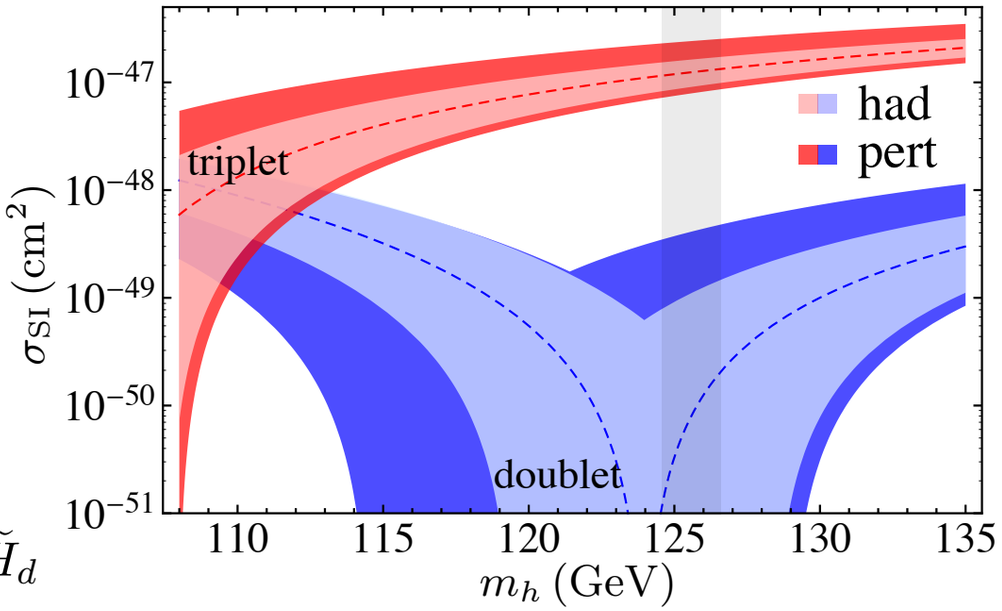
Higgs interacting dark matter: active target



DIRECT DETECTION — PURE STATES HARD TO DETECT

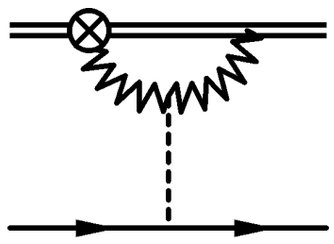
- "Pure" neutralino does not couple to Higgs at tree level, e.g. pure Wino or Higgsino or Bino



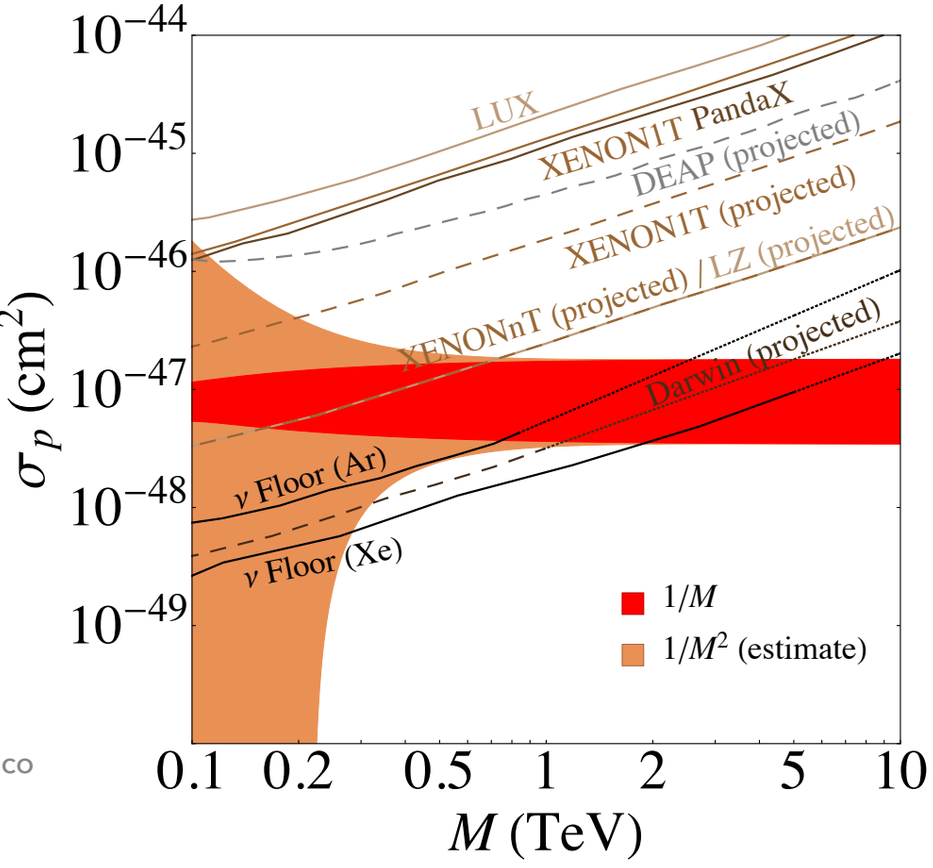


Hill, Solon 1309.4092

- One-loop: wino *may be* detectable with XLZD/ DARWIN



- *It's still important to finish the large-scale DD program to the neutrino fog (Challenge #2)*



Chen, Hill, Solon, Wijanco

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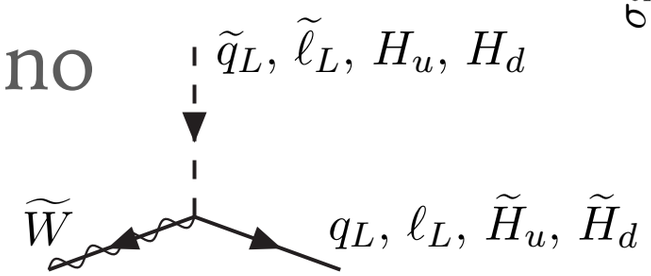

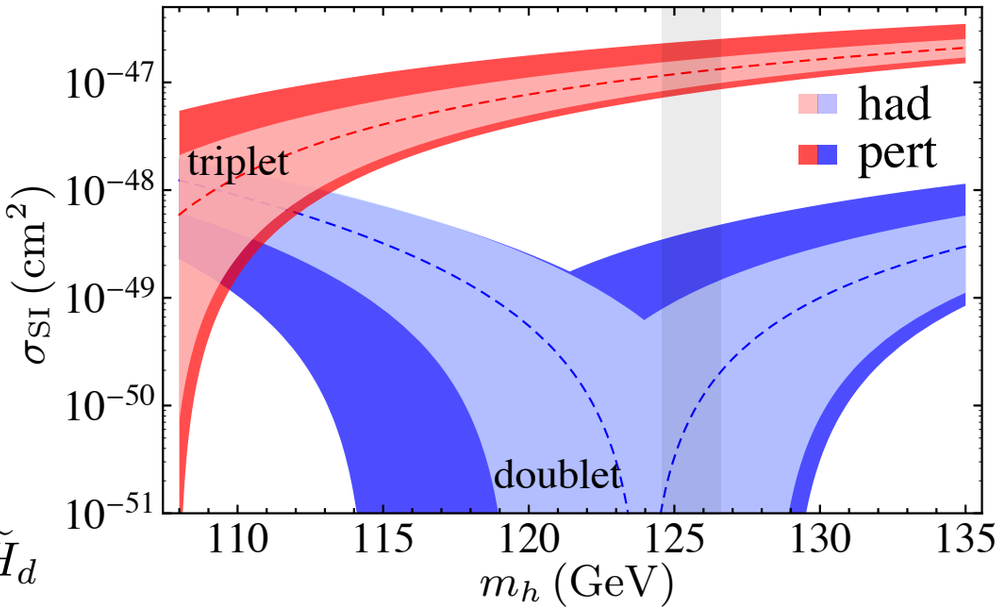

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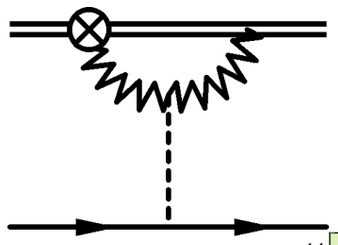

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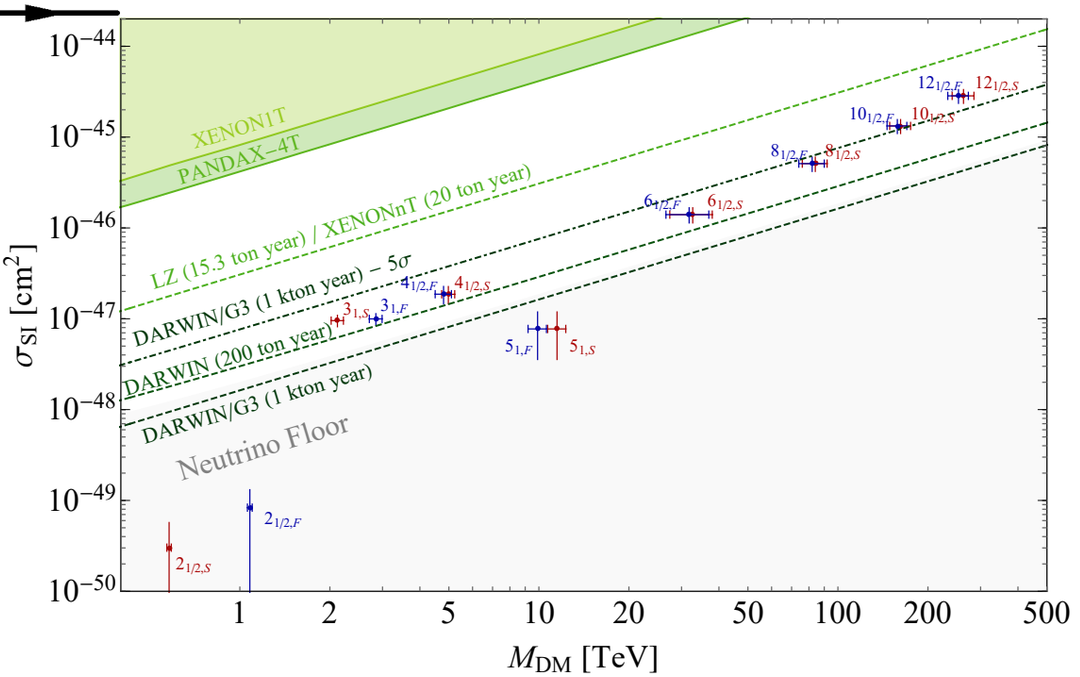


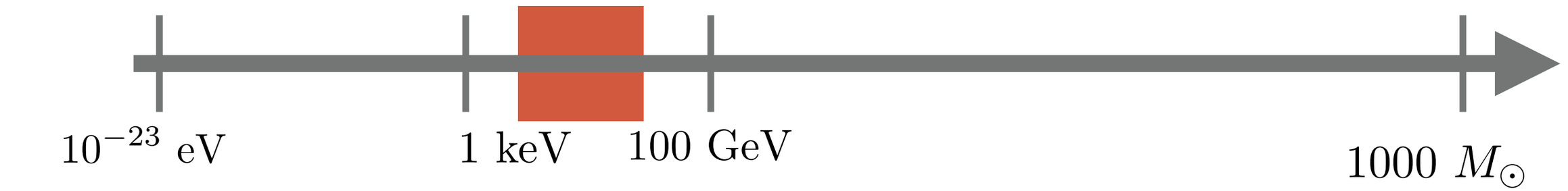
Bottaro et al 2205.-4486

WHEN LOOKING FOR DM, USE THE SM AS A SPRINGBOARD

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

- Focus on WIMPs. Reason: weak forces have the right scale, for abundance, cosmology and detection, and solve SM problem (hierarchy problem)
- Axions
- *Lighter WIMPs — 1-100 MeV DM (Boehm/Fayet '05)* and keV sterile neutrinos

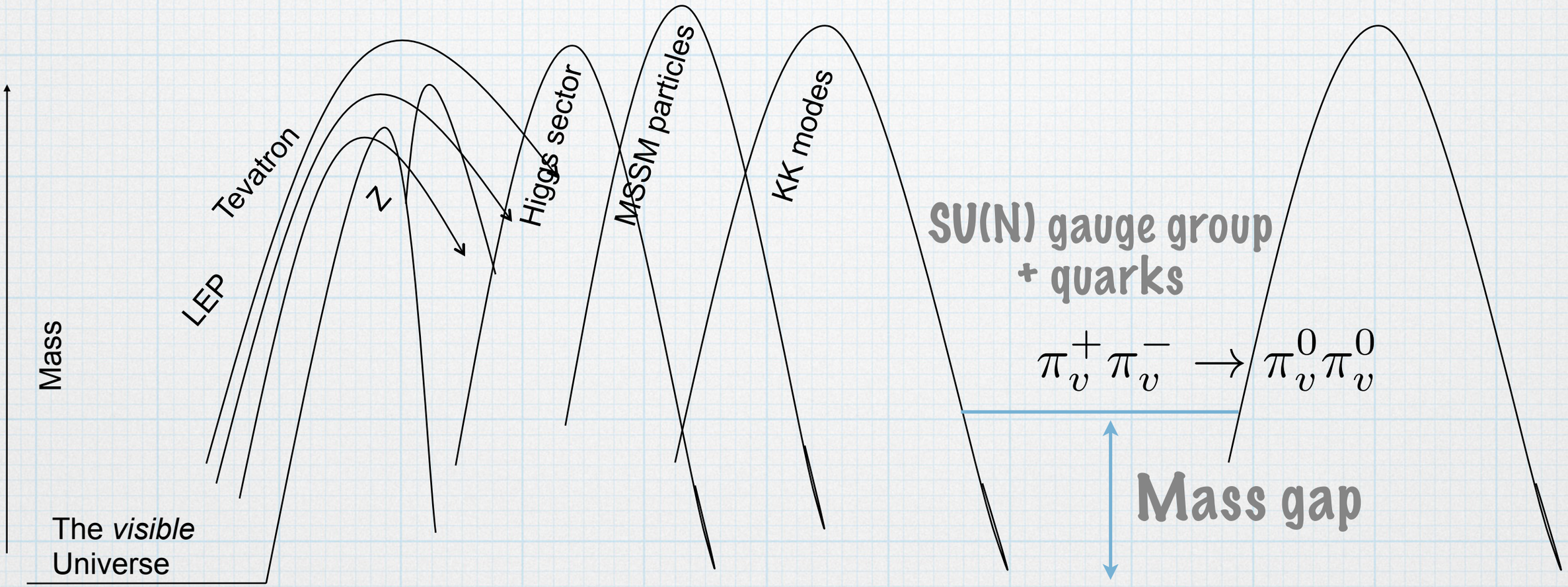
BROADENING THE SCOPE



- Intermediate range where observation via particle interactions with SM is still highly motivated *though not detectable with traditional WIMP experiments*
- Hidden Sector/Valleys generically have complexity
- Qualitatively different observational signatures
- *Arise generically in top-down constructions* *(Hidden Valley Strassler- KZ 2006)*

Slide 2007

What's in the hidden valley?



Many theories with this structure:

QCD-like theory with F flavors and N colors
QCD-like theory with only heavy quarks
QCD-like theory with adjoint quarks
Pure glue theory
UV-fixed point = confining
N=4 SUSY Conformal
RS throat

Seiberg duality cascade
KS throat
Remnant from SUSY breaking
Partially higgsed SU(N) theory
Banks-Zaks sector
Unparticles

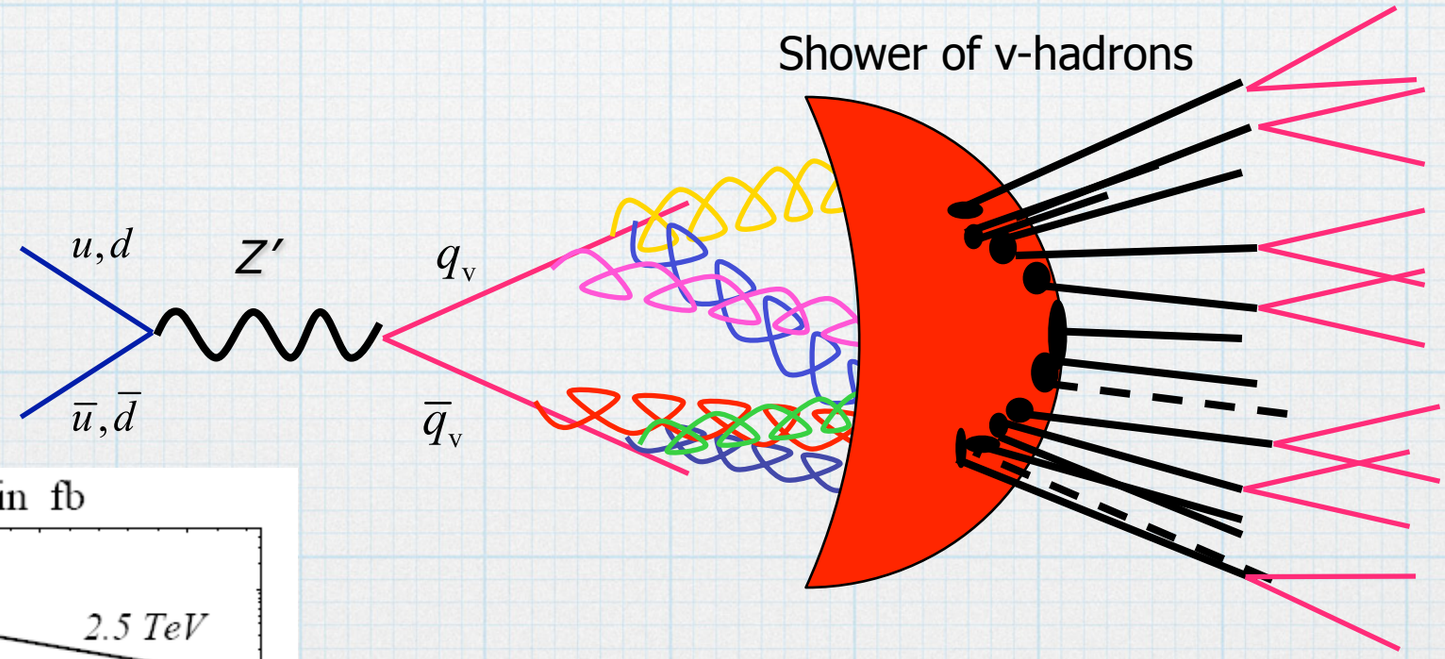
Slide 2007

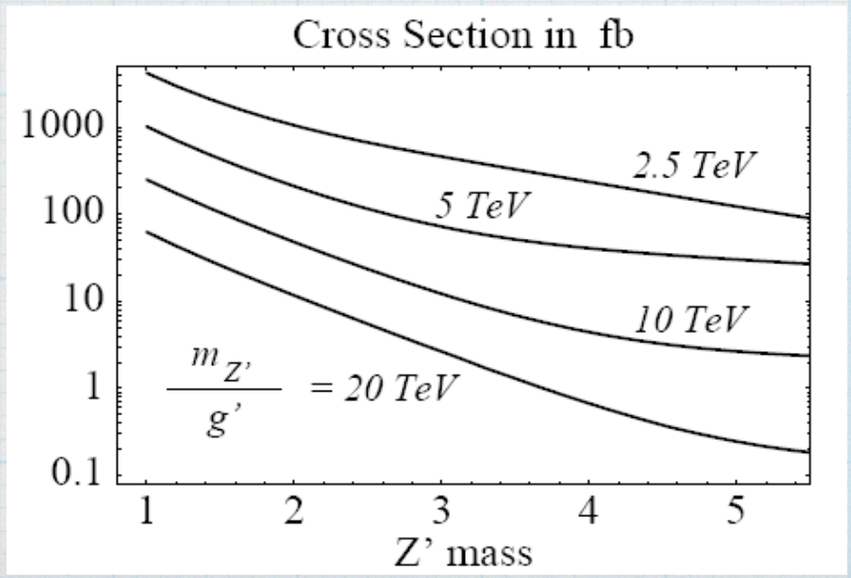
A concrete example

* Z' mediator

Challenge #3: build out the suite of LHC searches for dark sectors

* SU(N) gauge theory with 1 light quark





Each pair reconstructs to low mass v-hadron

Reconstruct entire event to Z' resonance

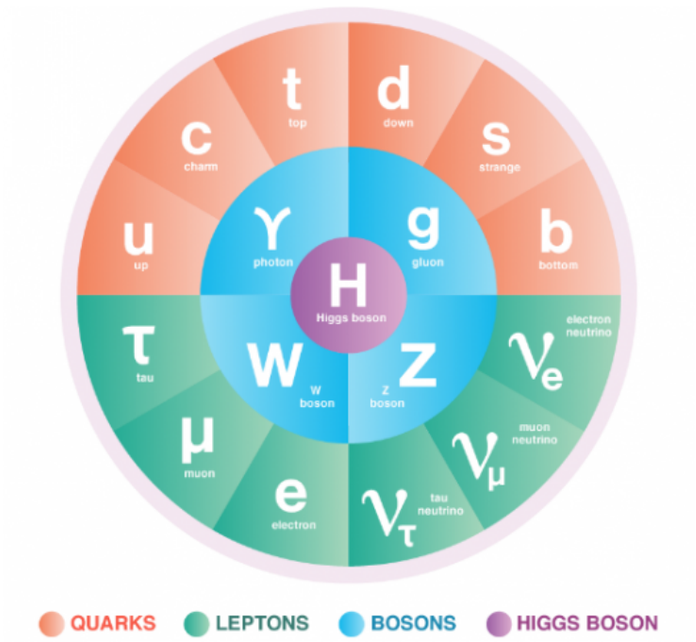
HIDDEN SECTOR / VALLEY

"DM Candidates of a Very Low Mass," Reviews of Nuclear and Particle Physics, 2401.03025

- Theory landscape broadened; search strategies broadened

Standard Model → Connector → Dark Matter

Energy



GUT

Weak

Light

pure glue, light flavors, heavy flavors, quirky asymmetric dark matter, Strongly Interacting Massive Particle (SIMP), Wess-Zumino-Witten SIMP

Darkogenesis, Xogenesis, Hylogenesis, Cladogenesis, ADM from Leptogenesis, Dark Affleck-Dine

Dark photons, Freeze-in, WIMPless miracle

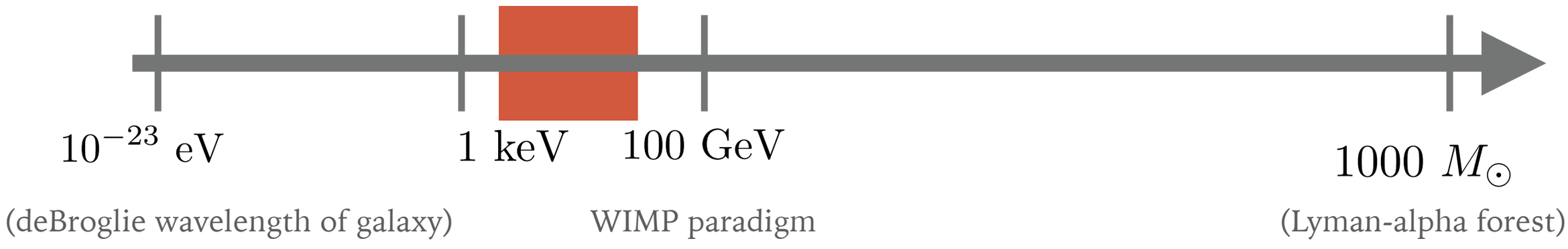
Mirror Matter, Atomic Matter, Self-Interacting Dark Matter, Magentic, Dark Anapole and EDMs

Visible Sector

Hidden Sector

Inaccessibility

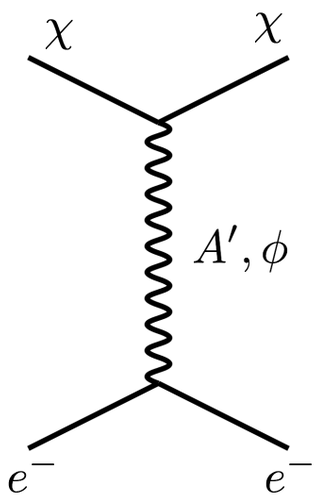
BROADENING THE SCOPE — TOO MANY POSSIBILITIES?

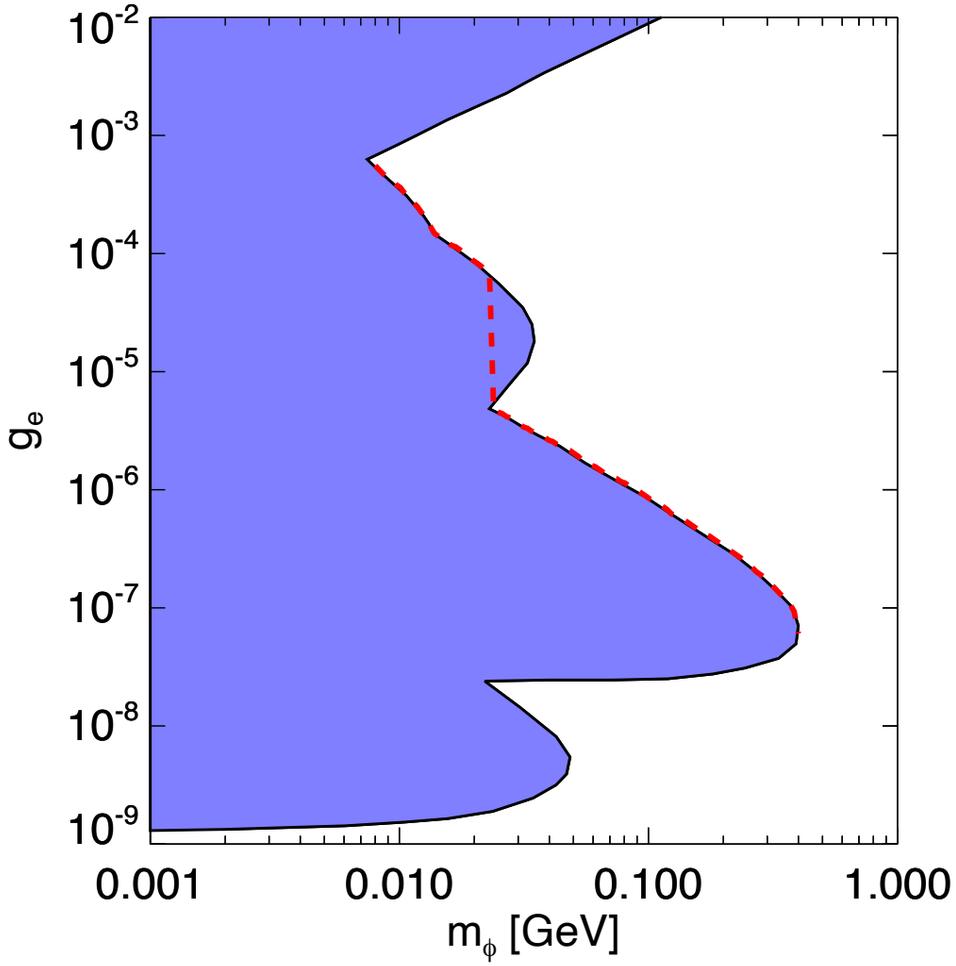


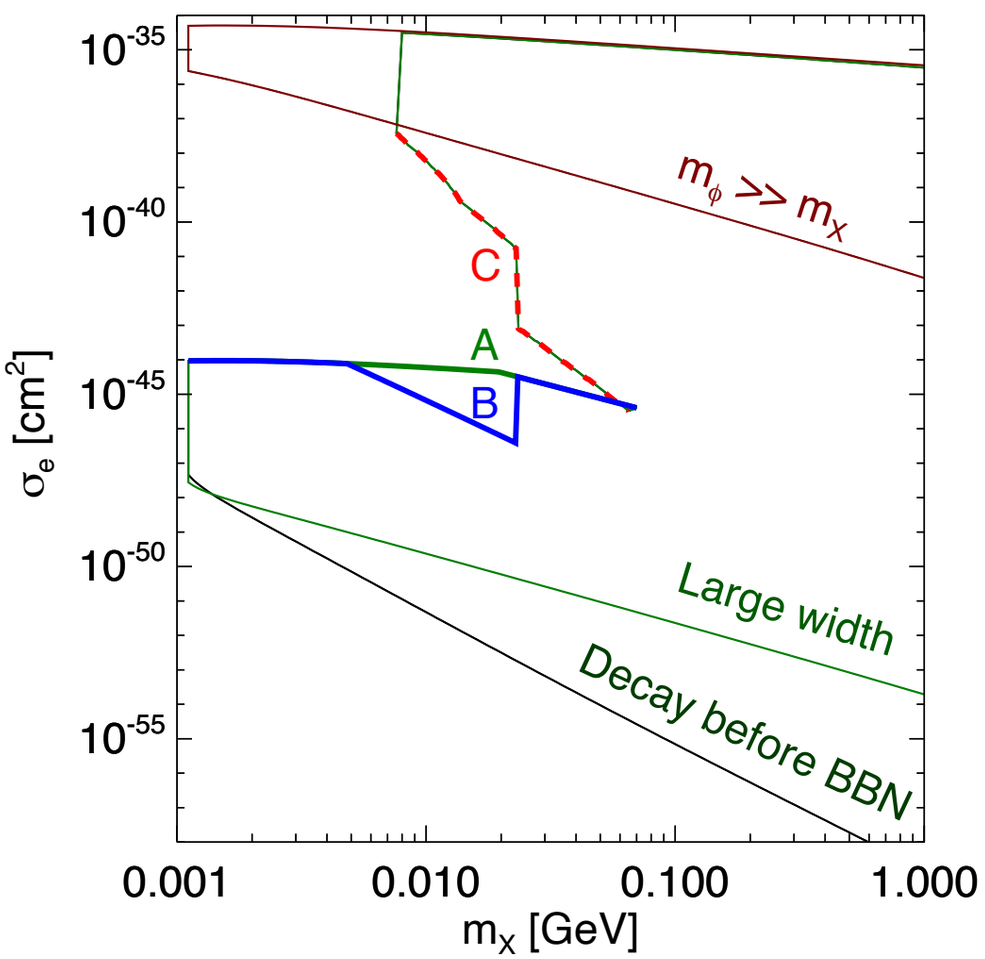
- *Motivated searches: candidate whose relic abundance is set by same interaction that gives rise to detectable signature*

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

DIRECT DETECTION — MAPPING THE THEORY SPACE







Lin, Yu, KZ 1111.0293

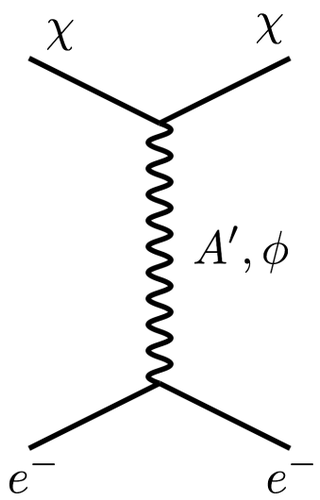
Lin, Knapen, KZ 1709.07882

- Collider, Stellar Cooling, and SIDM bounds all enter into terrestrial direct detection space

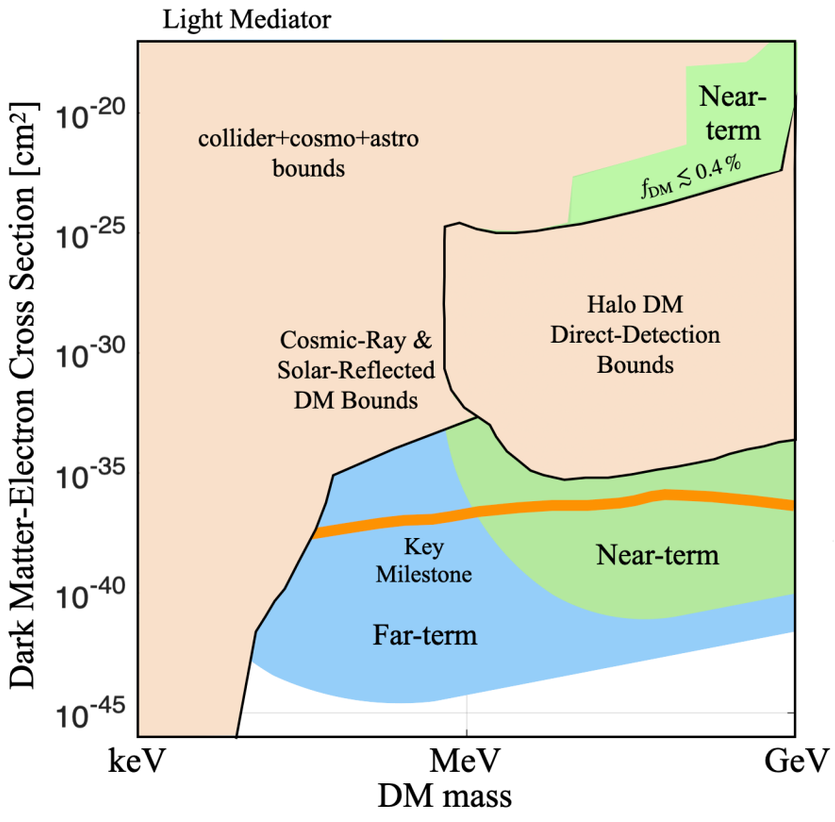
DEFINING TARGETS

- Utilize DM Abundance as guide for interaction rates

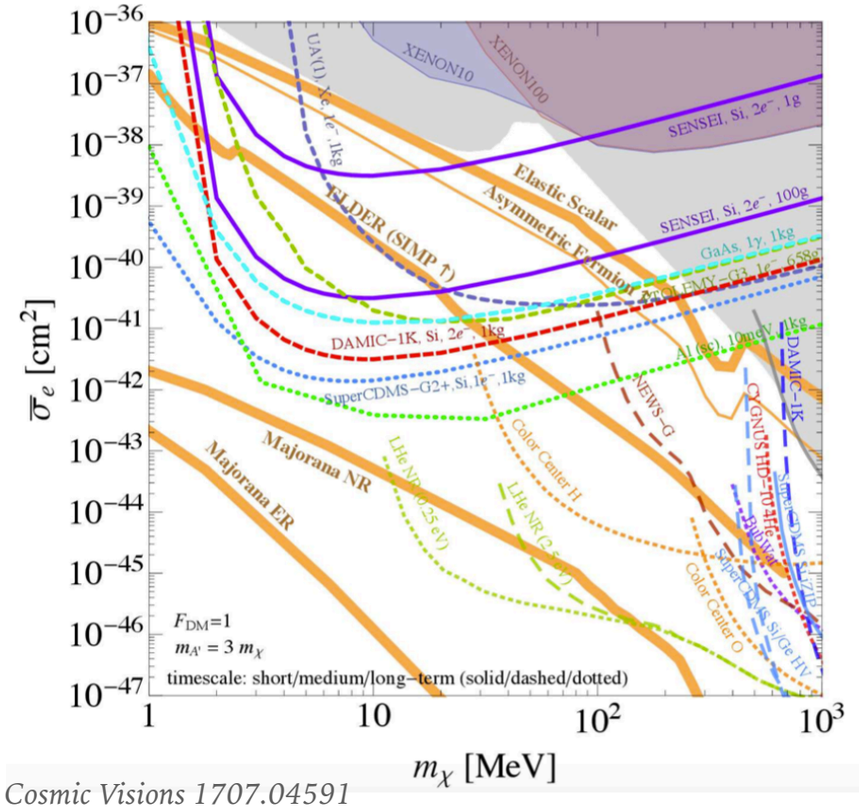
Challenge #4: cover the abundance-driven light DM models in laboratory detection experiments



Freeze-in



Asymmetric Dark Matter

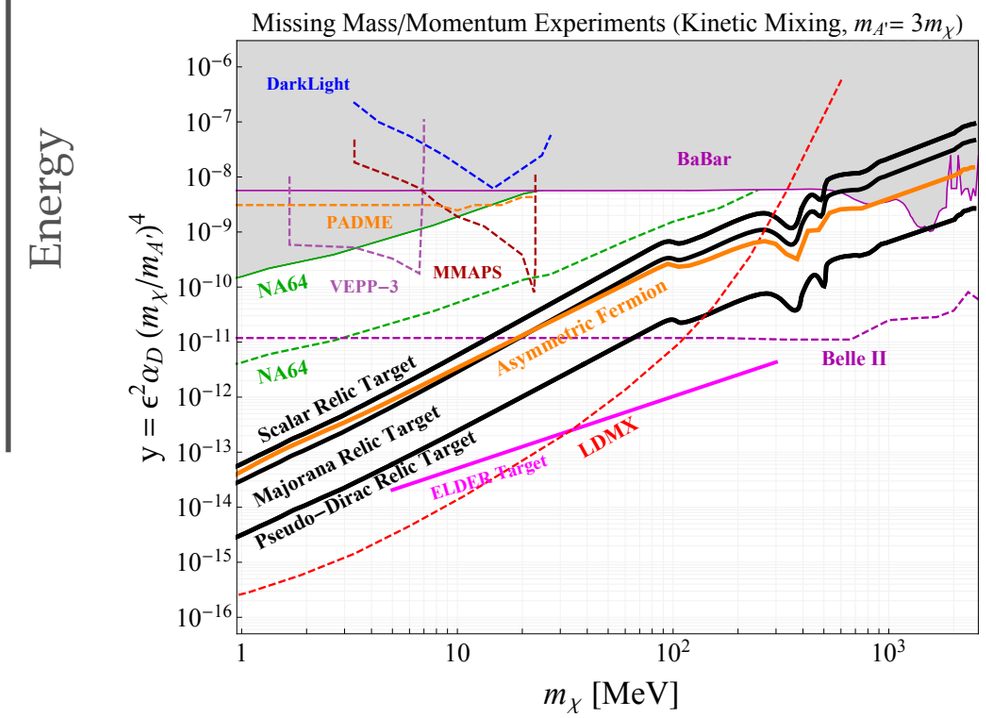


US Cosmic Visions 1707.04591

TERRESTRIAL EXPERIMENTS

- Probe dark sector via rare (tunneling) process at low energy

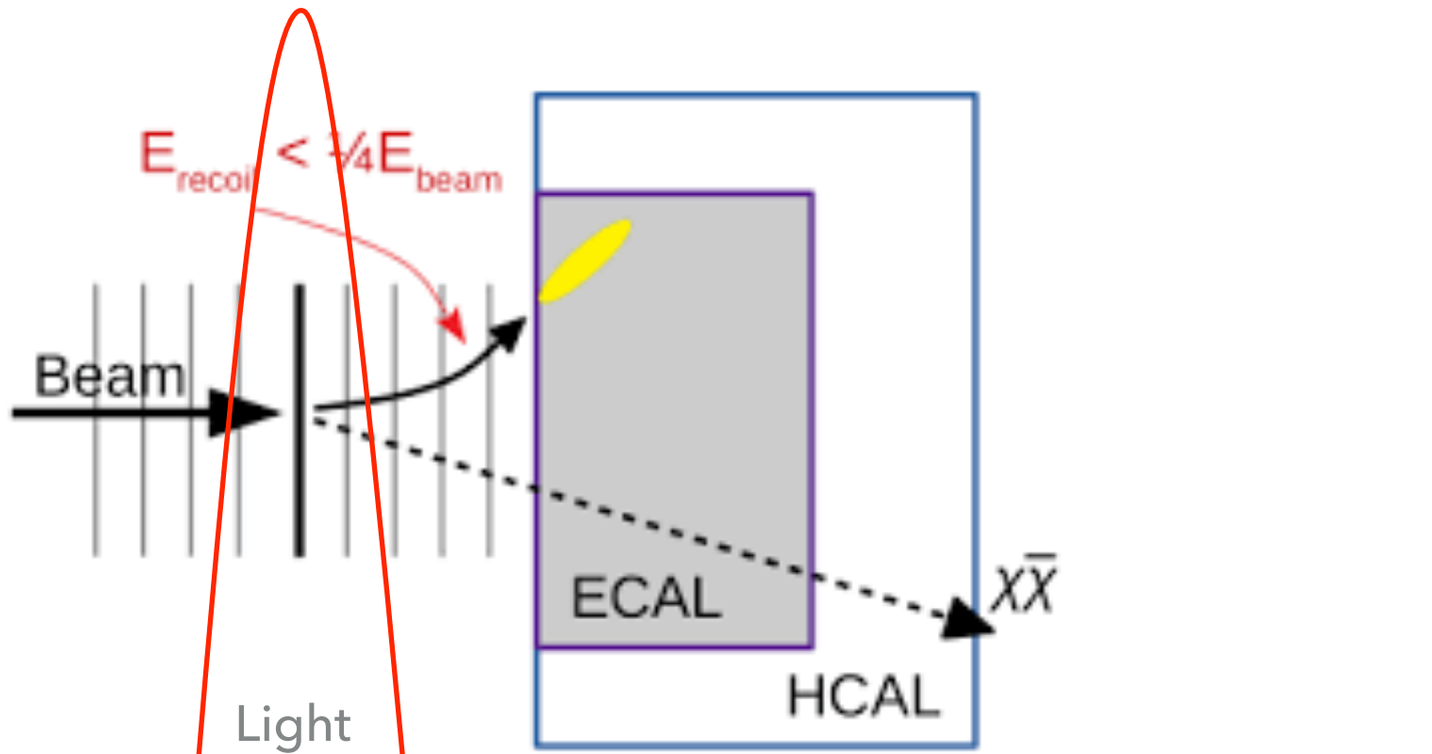
Standard Model → Connector → Dark Matter



Izaguirre, Krnjaic, Schuster, Toro

Energy

Inaccessibility



Visible Sector

Light

Intensity Experiment

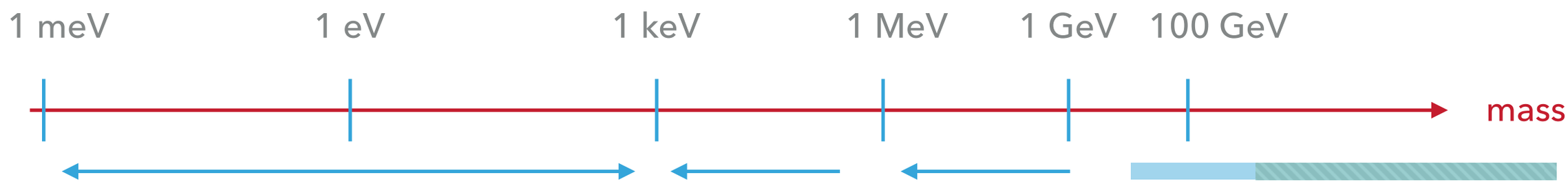
Direct Detection

Astrophysical Probes

Hidden Sector

NEW IDEAS FOR DIRECT DETECTION

- (Looking Beyond *Classical* Billiard Ball Nuclear Recoil)



Absorption

Super-conductors

Magnons

Semiconductors

SuperCDMS

Traditional WIMP

XENON1T

Dirac Materials

Polar Crystals

DAMIC, SENSEI

LZ

Superfluid Helium

Graphene

QCD axion, “ultralight frontier”

~meV energy resolution

~eV energy resolution

~keV energy resolution

Collective excitation

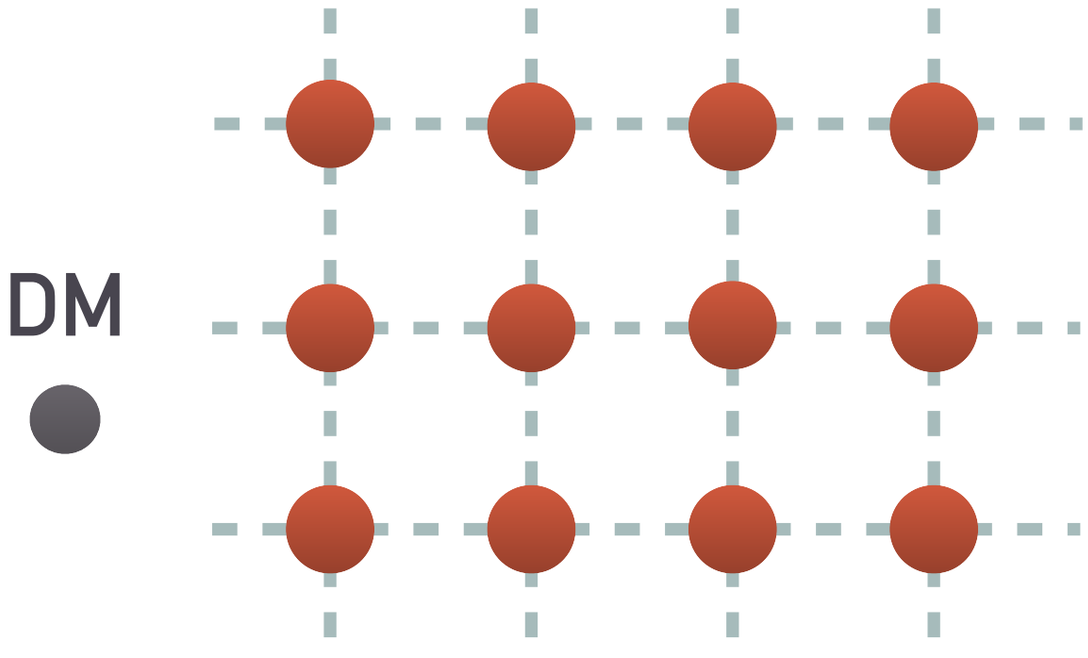
Electron excitation

Nuclear recoil

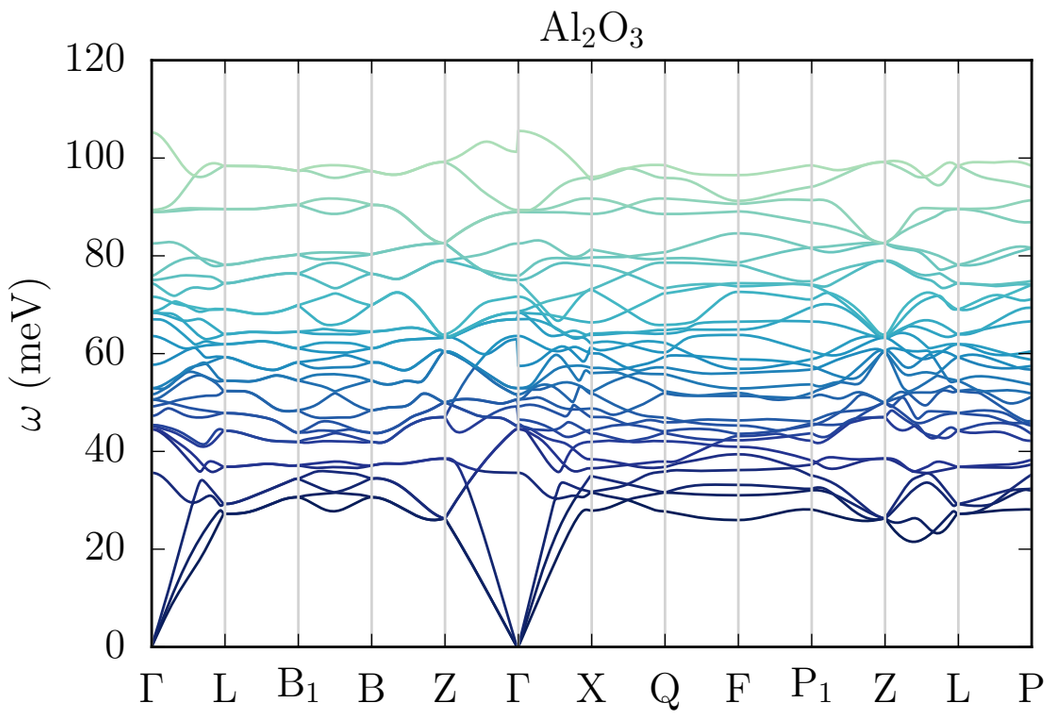
COLLECTIVE EXCITATIONS

Hochberg, Lin, KZ 1604.06800,
Schutz, KZ PRL 1604.08206,
Knapen, Lin, Pyle, KZ 1712.06598

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

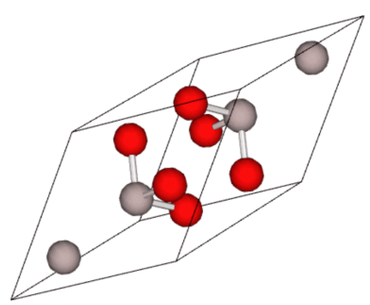


Phonons



Knapen, Lin, KZ 1807.10291

- Overarching goal is to find a target with a strong Dynamic Structure Factor



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Schutz, KZ PRL 1604.08206,
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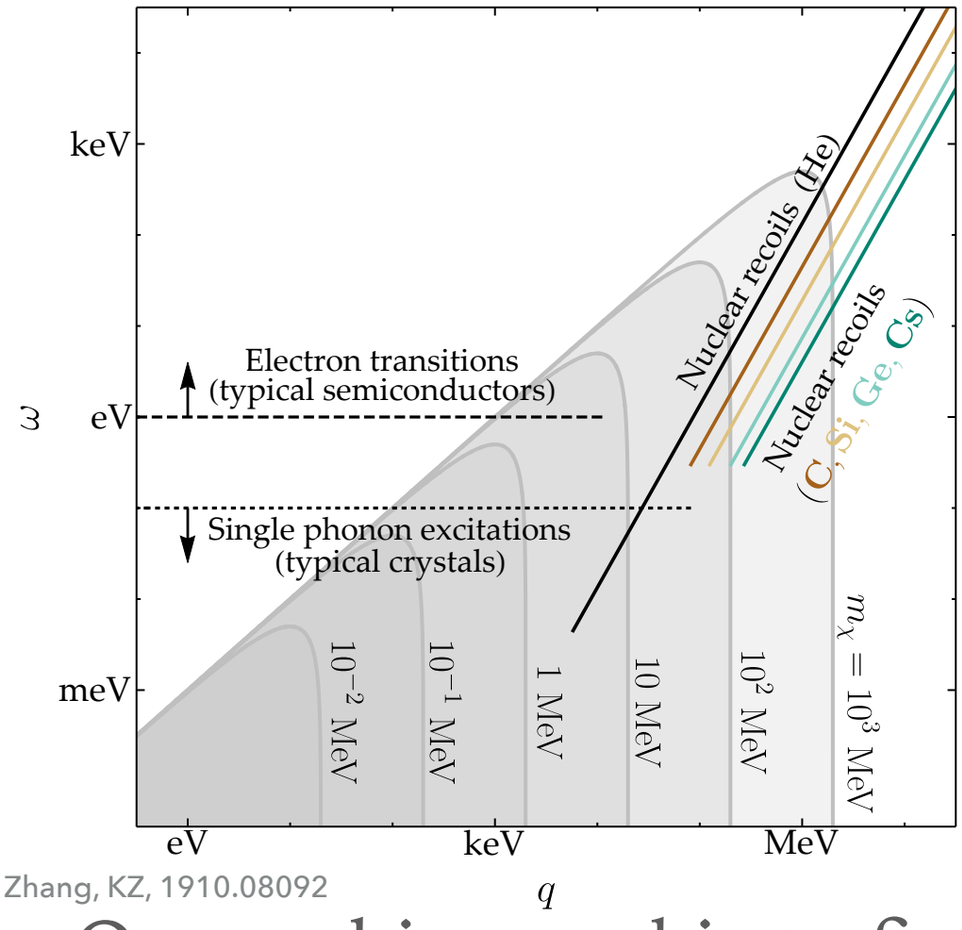
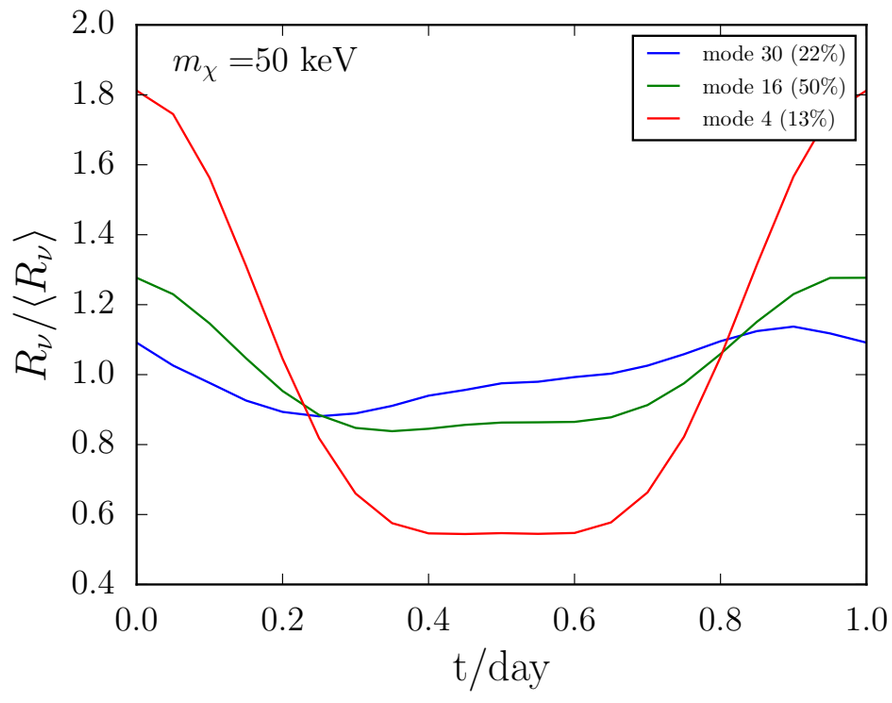


Trickle, Zhang, KZ, 1910.08092



Directionality for free!

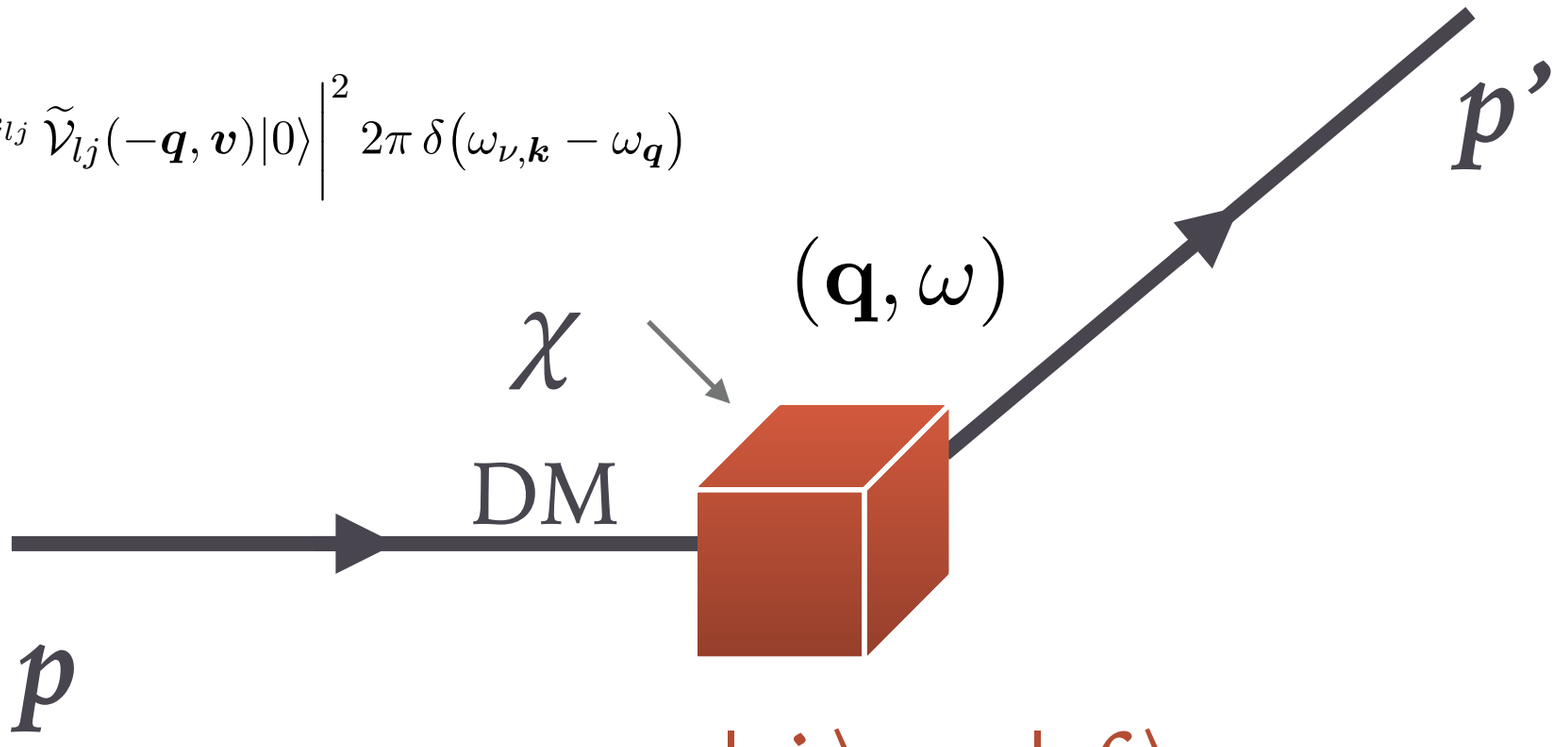
- Overarching goal is to find a target with a strong Dynamic Structure Factor

EFT OF DARK MATTER INTERACTION WITH QUANTUM MATERIALS

- Computing rates = lattice potential + eigenproblem

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int d^3v\, f_\chi(\boldsymbol{v})\,\Gamma(\boldsymbol{v})$$

$$\Gamma(\boldsymbol{v}) = \frac{1}{V}\int \frac{d^3q}{(2\pi)^3}\sum_{\nu,\boldsymbol{k}}\left|\sum_{l,j}\langle\nu,\boldsymbol{k}|\, e^{i\boldsymbol{q}\cdot\boldsymbol{x}_{lj}}\,\widetilde{\mathcal{V}}_{lj}(-\boldsymbol{q},\boldsymbol{v})|0\rangle\right|^2 2\pi\,\delta\left(\omega_{\nu,\boldsymbol{k}}-\omega_{\boldsymbol{q}}\right)$$

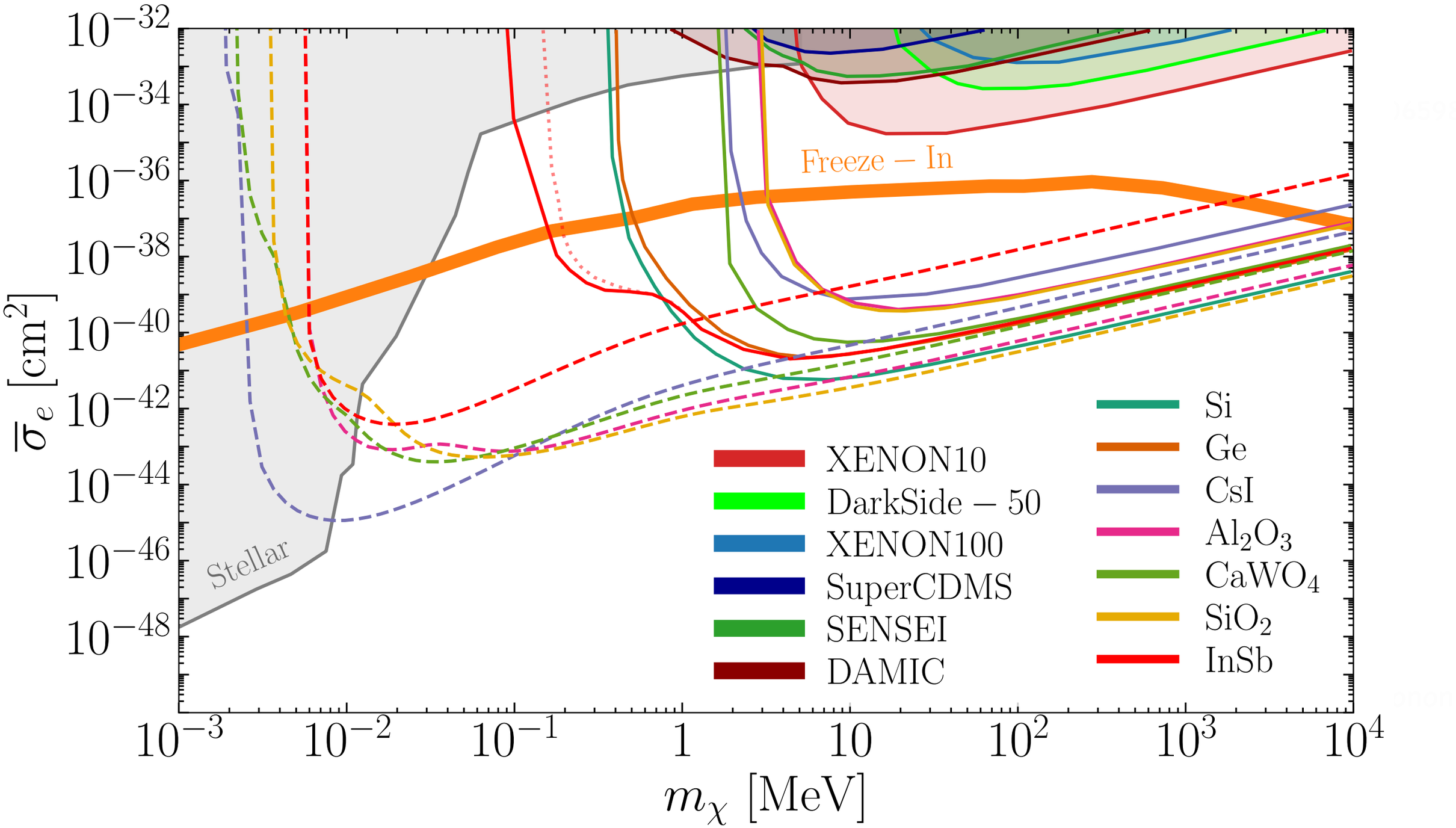


$$\widetilde{\mathcal{V}}_{lj}(-\boldsymbol{q},\boldsymbol{v}) \supset \sum_\alpha\Bigg[c_1^{(\psi)}\left\langle e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\alpha}\right\rangle_{lj} + c_4^{(\psi)}\,\boldsymbol{S}_\chi\cdot\left\langle e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\alpha}\boldsymbol{S}_{\psi,\alpha}\right\rangle_{lj}$$
$$+ c_{8b}^{(\psi)}\,\boldsymbol{S}_\chi\cdot\left\langle e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\alpha}\boldsymbol{v}_{\psi,\alpha}\right\rangle_{lj} + c_{3b}^{(\psi)}\,\frac{i\boldsymbol{q}}{m_\psi}\cdot\left\langle e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\alpha}\,\boldsymbol{v}_{\psi,\alpha}\times\boldsymbol{S}_{\psi,\alpha}\right\rangle_{lj}\Bigg]$$

Knapen, Lin, KZ, 1712.06598 Trickle, Zhang, KZ, 2009.13534

MATERIALS COMPARISON — SI INTERACTION

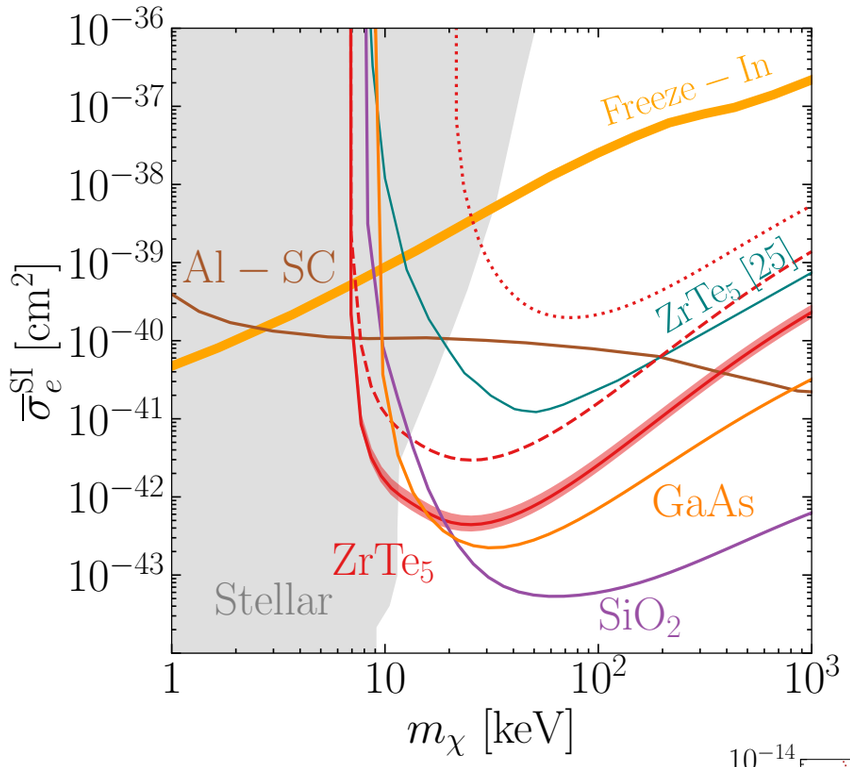
Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716



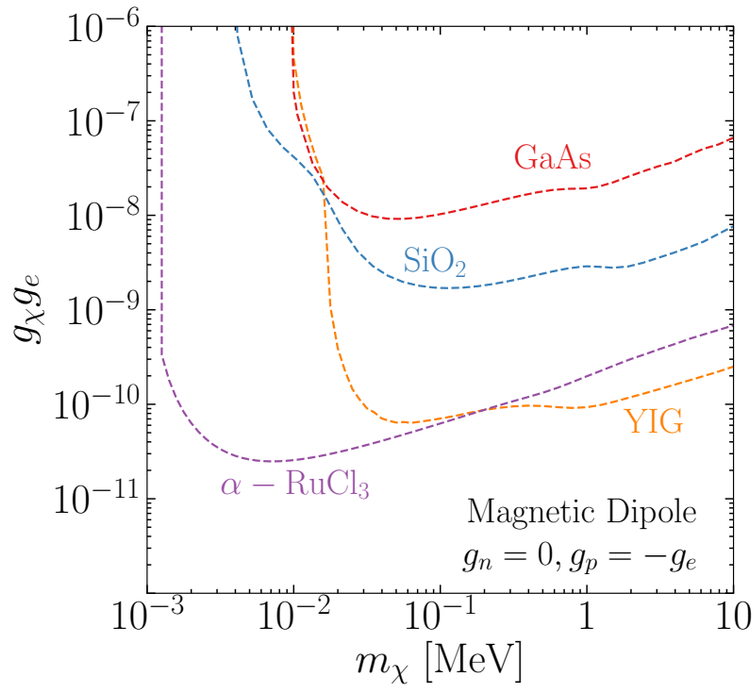
CM-TARGET COMPARISON

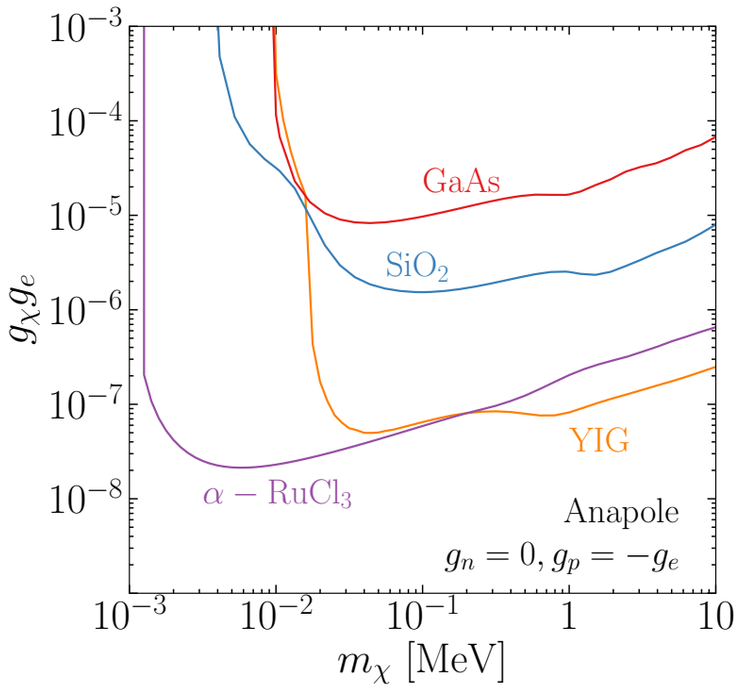
- *Overall, standard materials fare well*

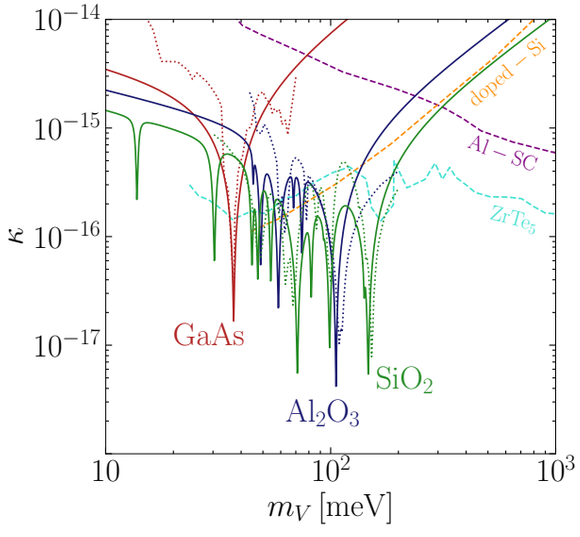
Trickle, Zhang, KZ, 2009.13534

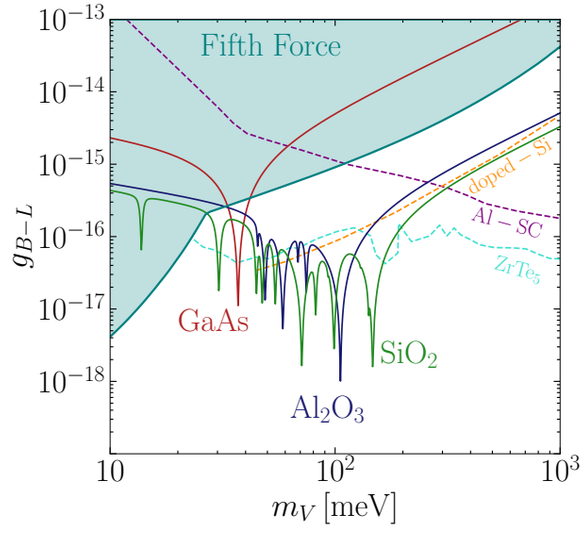


Mitridate, Trickle, Zhang, KZ, 2202.11716





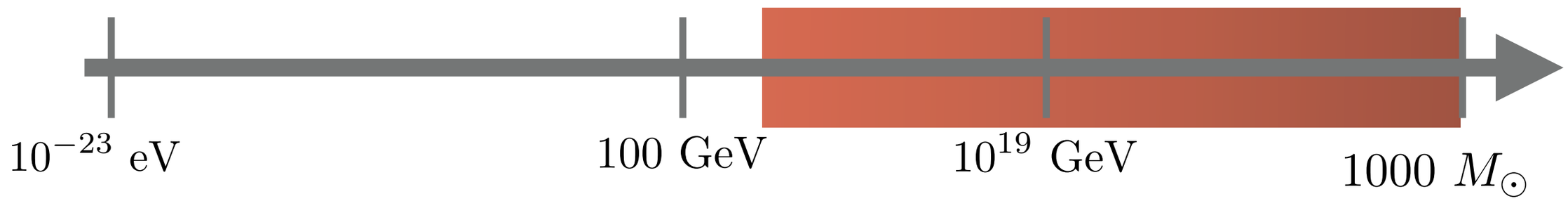




Mitridate, Trickle, KZ, 2308.06314

PhonoDark and PhonoDark-abs fully implement EFT and publicly available

HEAVIER DARK MATTER



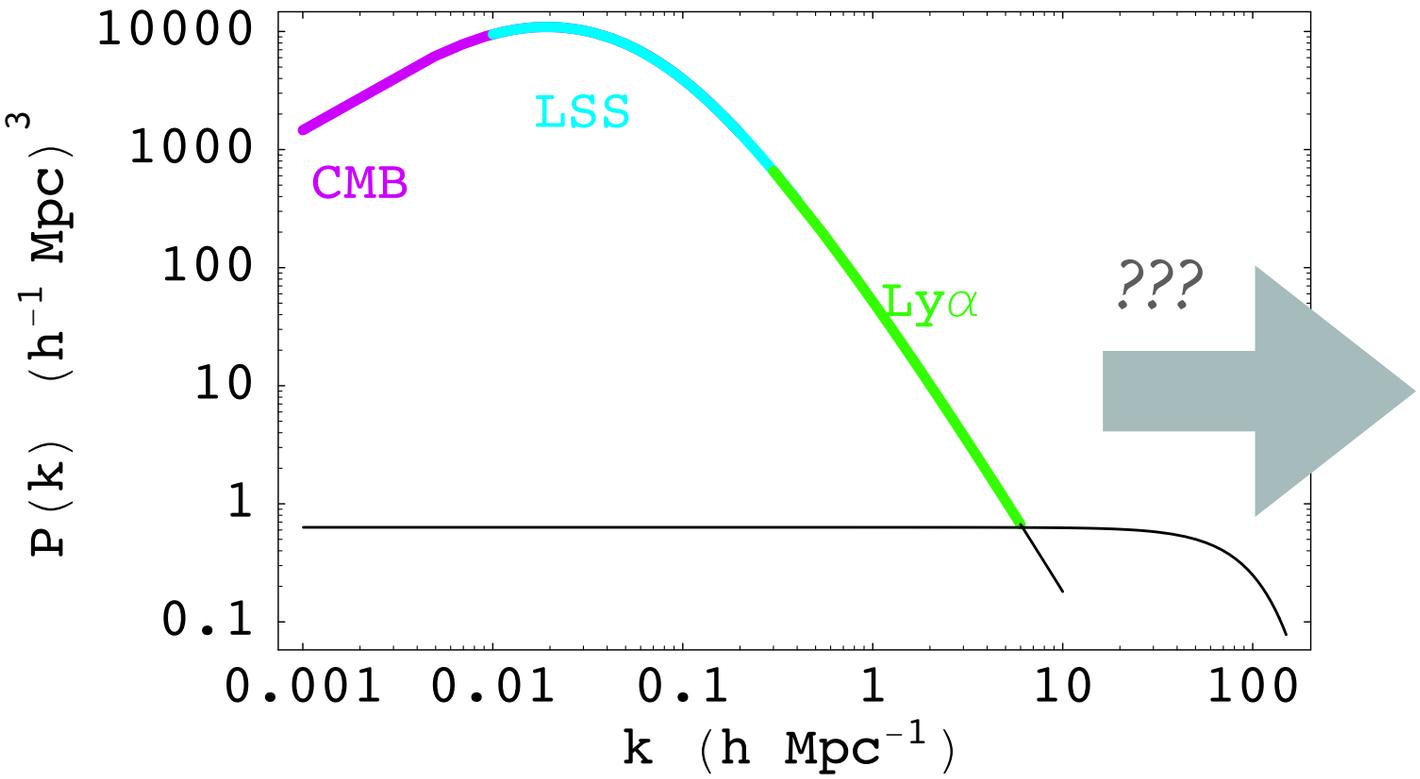
(deBroglie wavelength of galaxy) WIMP paradigm (Lyman-alpha forest)

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

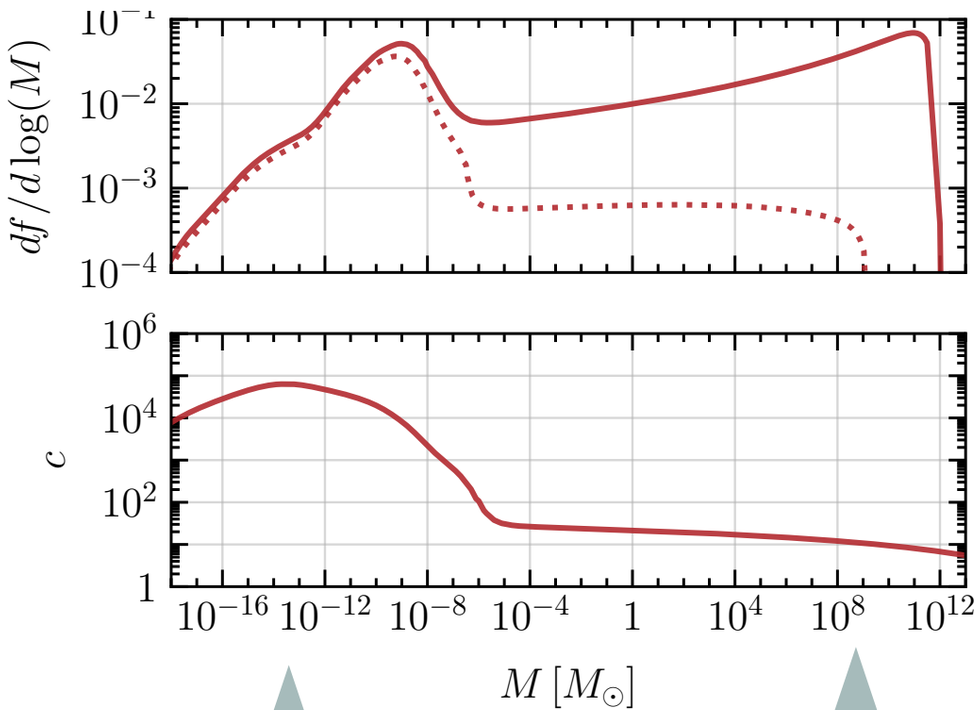
- Heavier dark matter: setting relic abundance through interactions with Standard Model is challenging (NB: exceptions), so detection through Standard Model interactions is (generally) not motivated by abundance
- Gravitational means to detect structure?

DARK MATTER SUBSTRUCTURE

Grand Challenge #5: Observe Smaller Scale DM Substructure



Axion miniclusters



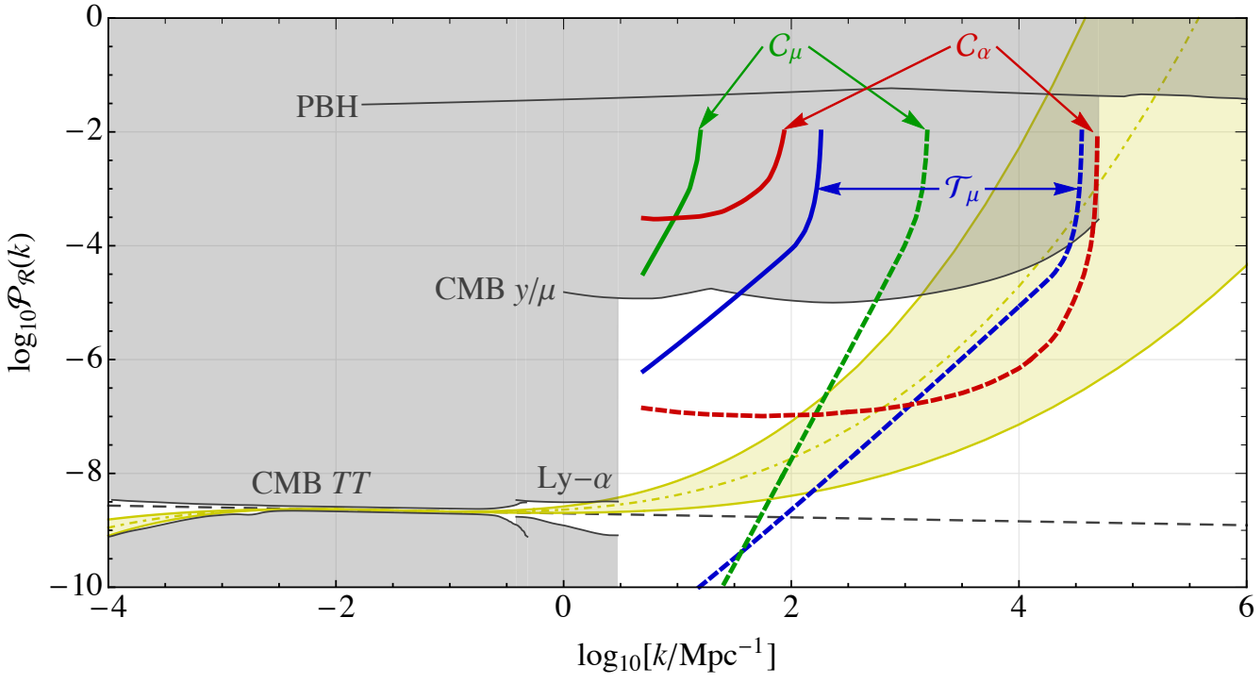
Particle Imprints of DM

CDM

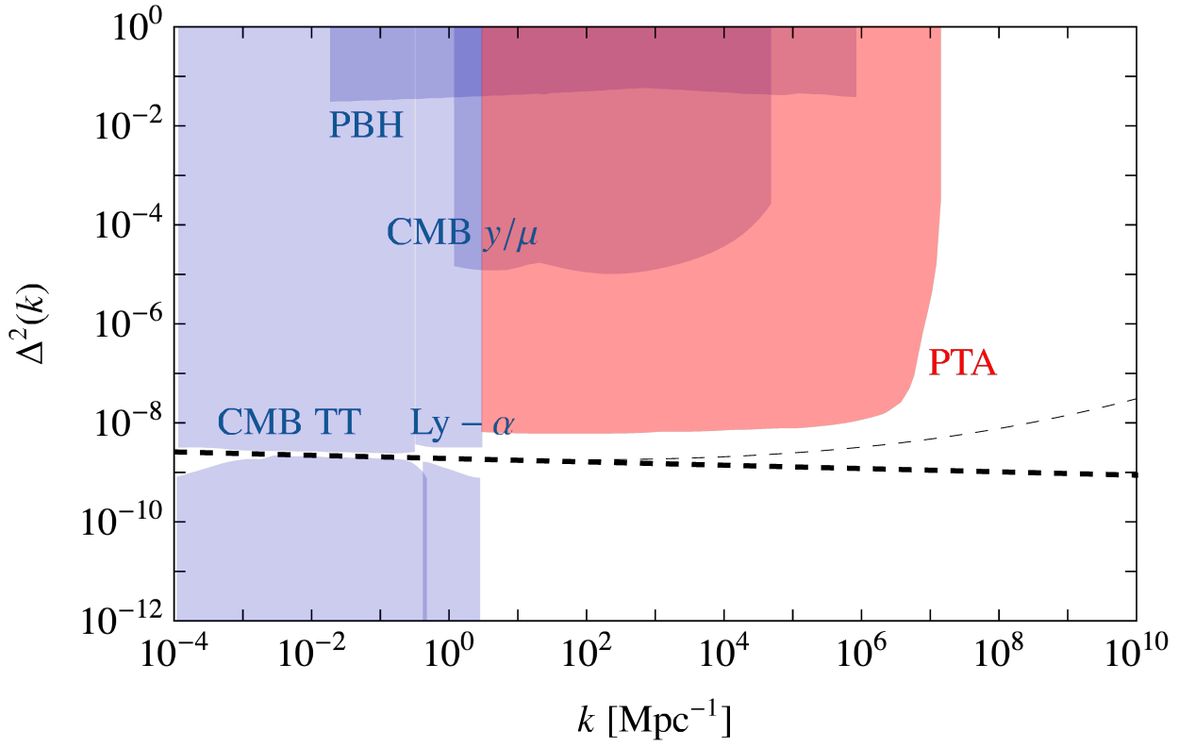
Huge pay-off for theories of DM which leave particle imprints on small scales

SEARCHING FOR SMALLER SCALE STRUCTURE

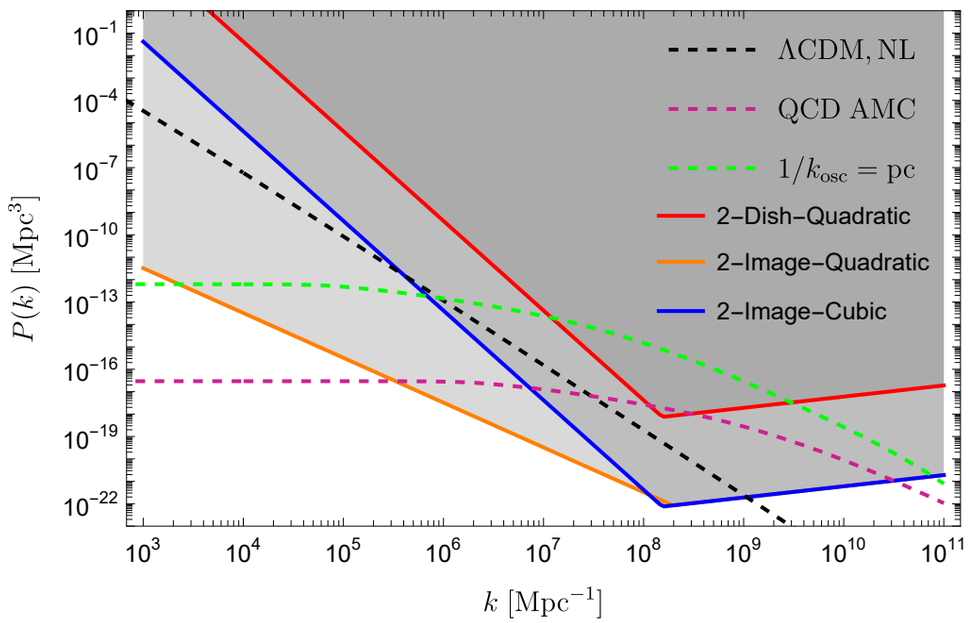
- Astrometric Lensing, PTAs, FRBs …. other ideas?



Tilburg, Taki, Weiner 1804.01991



Lee, Mitridate, Trickle, KZ 2012.09857



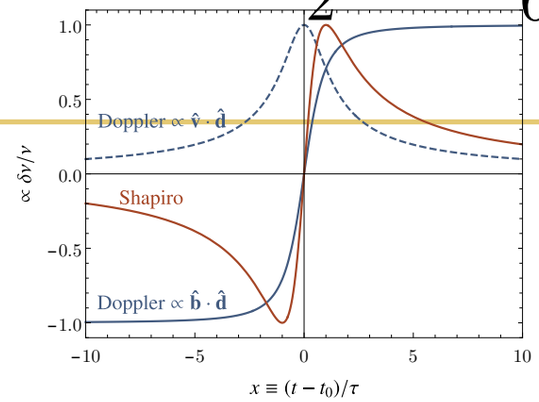
Xiao, Dai, McQuinn 2401.08862

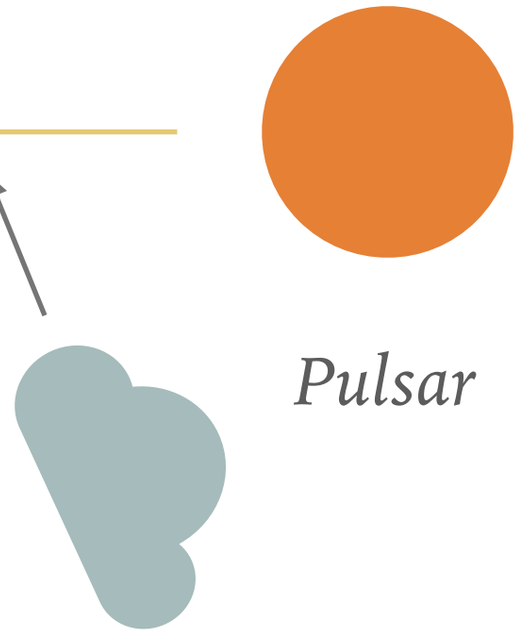
DETECTING DARK MATTER SUBSTRUCTURE IS AN EXTREMELY IMPORTANT PROBLEM

- Pulsars, observed over decades, are accurate clocks

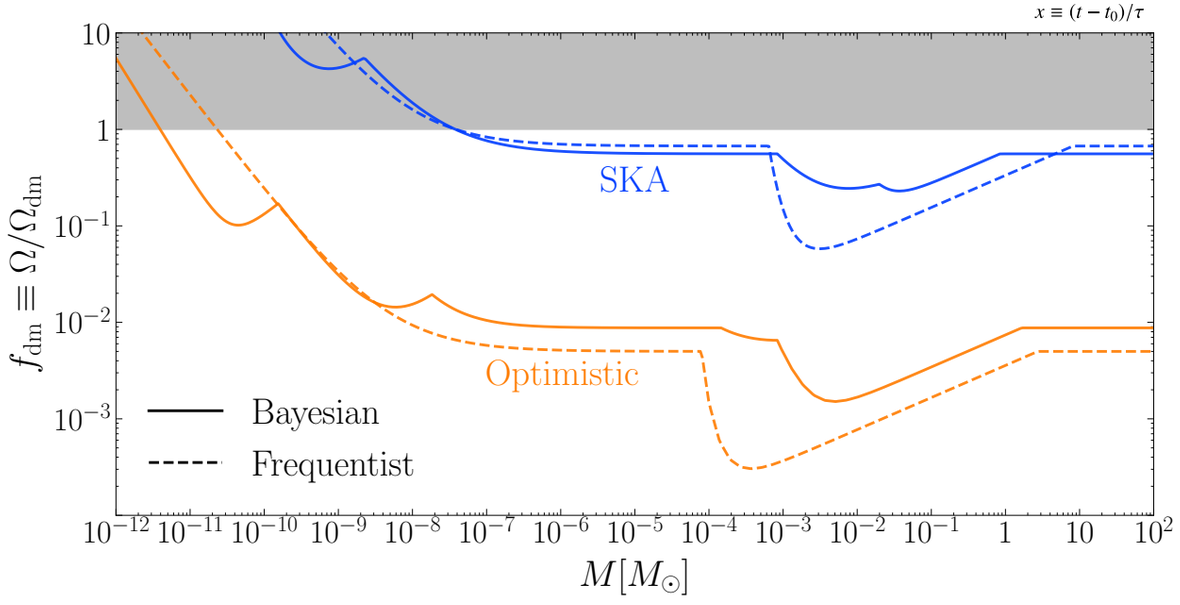
$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots$$

Earth





Pulsar



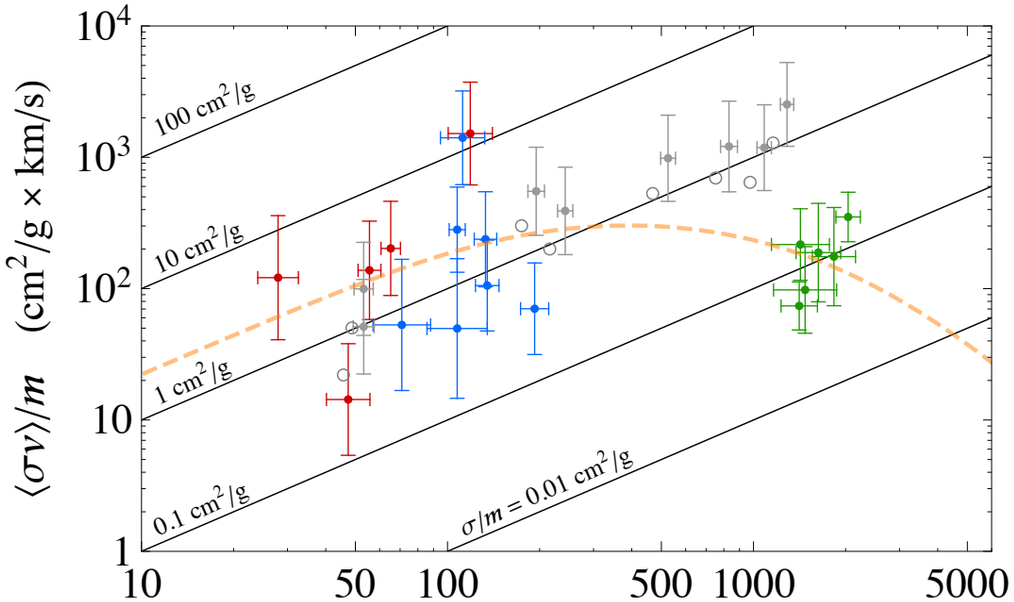
Lee, Taylor, Trickle, KZ 2104.05717

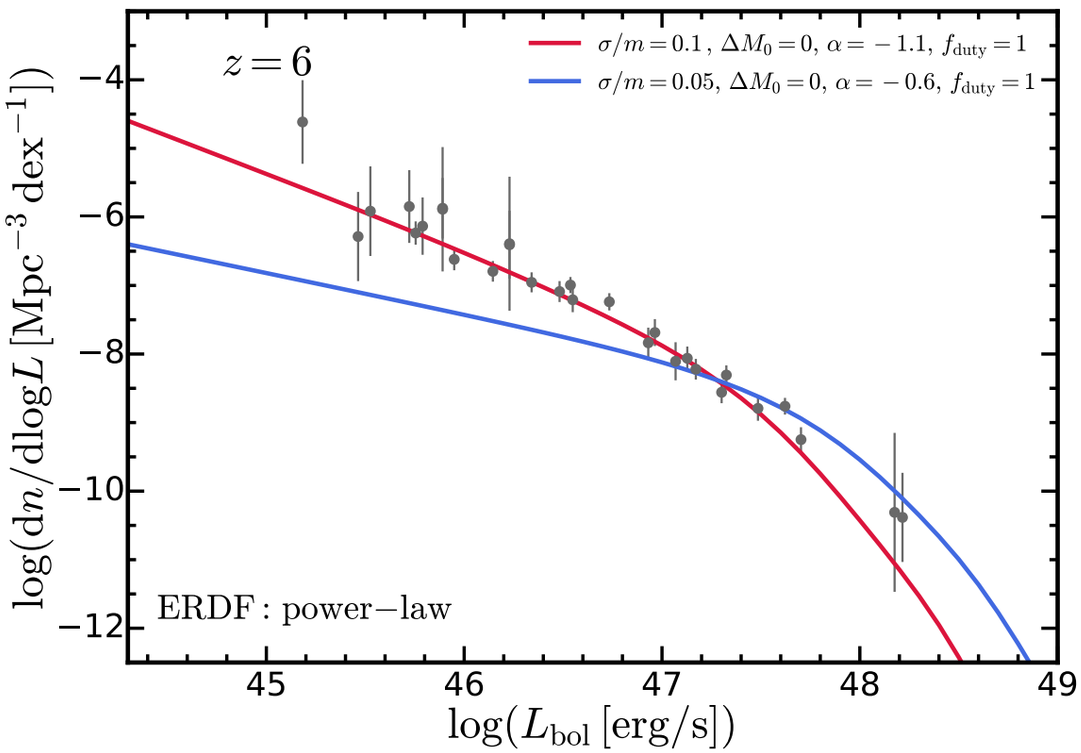
- These projections were done in absence of SMBHB. Are there promising ideas to beat this background?

UNDERSTANDING DM SUBSTRUCTURE WILL BE IMPORTANT

- What are realistic constraints on DM (elastic) self-interactions?
- If DM interactions are dissipative, can easily sink to the center of a halo, eventually forming Super Massive Black Holes
- It's not currently known how SMBHs form
- Could Dark Matter play a role?

Kaplinghat, Tulin, Yu 1508.03339

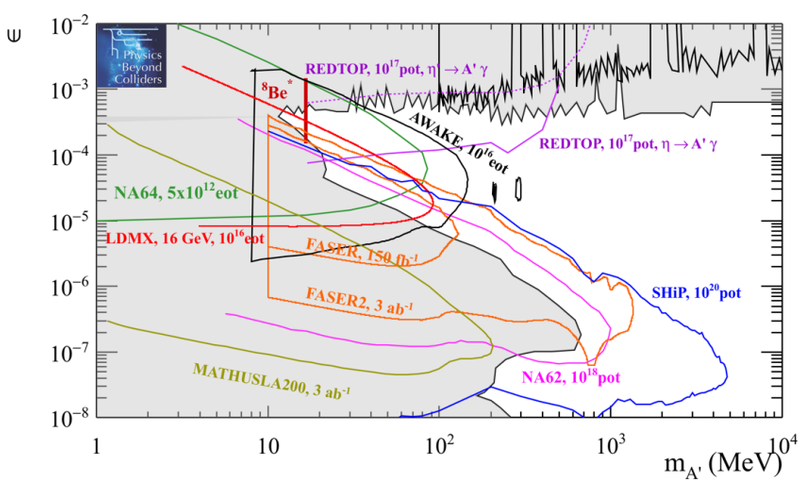


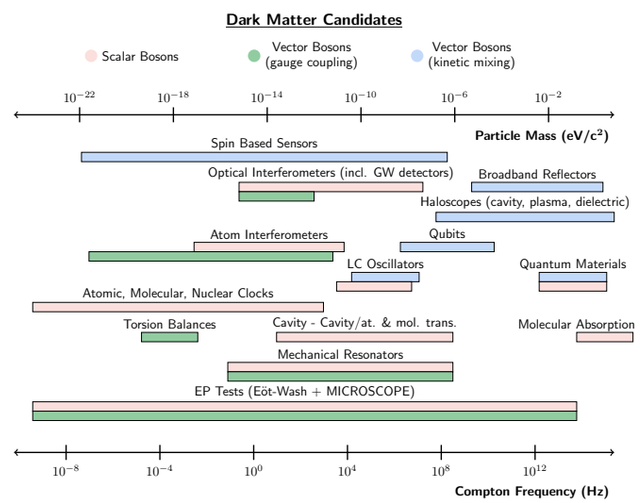


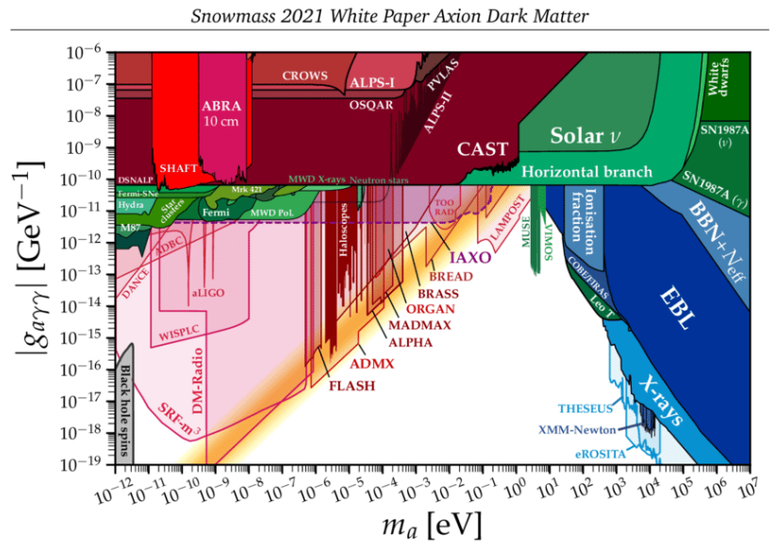
Xiao, Shen, Hopkins, KZ, 2103.13407

DISCUSSION

- A wide net has been cast.
- The theory frameworks and ideas have been proposed, e.g. QCD axion, hidden sector/valley
- The theoretical ideas for experiments to search for these theories are available, e.g. collective excitations
- There is a *well-defined* and *exciting* experimental program that, in some cases (e.g. axions), is limited by funding







DISCUSSION

- There is a range of important astrophysical observations to make
  - What is the nature of the GCE? *Challenge #6*
  - Can we separate baryonic effects from DM sufficiently to make definitive statements on SIDM?
    - Observe DM substructure below Dwarf Mass Scales
    - Map the cosmic history of the Universe
- Where should the important contributions from high energy theory going forward come from?
  - Support for experimental program … (and?)

OUTLOOK

- A wide net has been cast, and the experimental landscape is sure to look radically different in 10 years