Caltech

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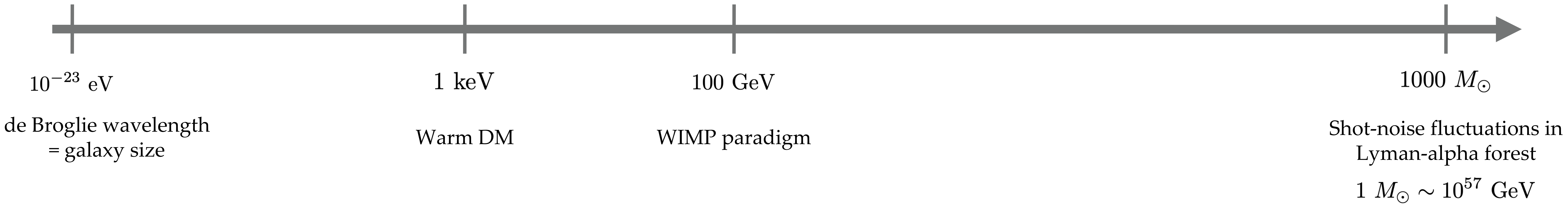
Dark Matter

Theoretical Framework and Candidates

Kathryn M. Zurek, ICHEP 2024, Prague

Dark Matter Requires Physics Beyond the Standard Model

The Range of Possibilities is Stunning.



10^{-23} eV

de Broglie wavelength
= galaxy size

1 keV

Warm DM

100 GeV

WIMP paradigm

$1000\ M_\odot$

Shot-noise fluctuations in
Lyman-alpha forest

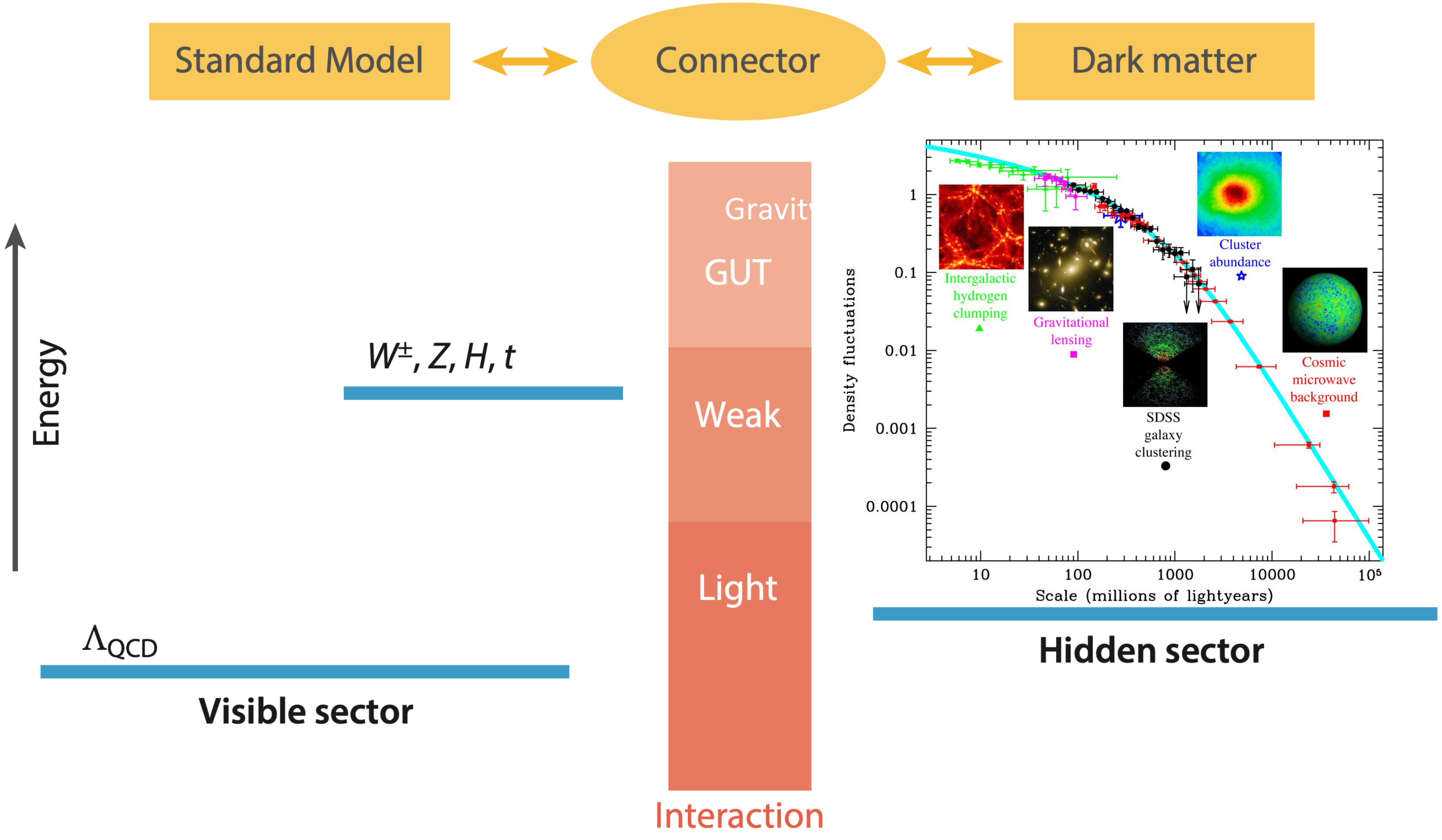
$1\ M_\odot \sim 10^{57}$ GeV

- In this talk, we will parse probing this entire mass range as a series of theoretically-well-motivated experimental challenges
- The question for the progress of the field is: how many of these challenges can we meet in the next 10-20 years?

The Challenge.

All known properties of dark matter are via the gravitational interaction.

- Gravity is weak.
- Gravity gives the gross properties of dark matter — density and large-scale clustering.
- Learning about particle properties will require stronger-than-gravitational interactions.



Standard Model ⟷ Connector ⟷ Dark matter

Visible sector

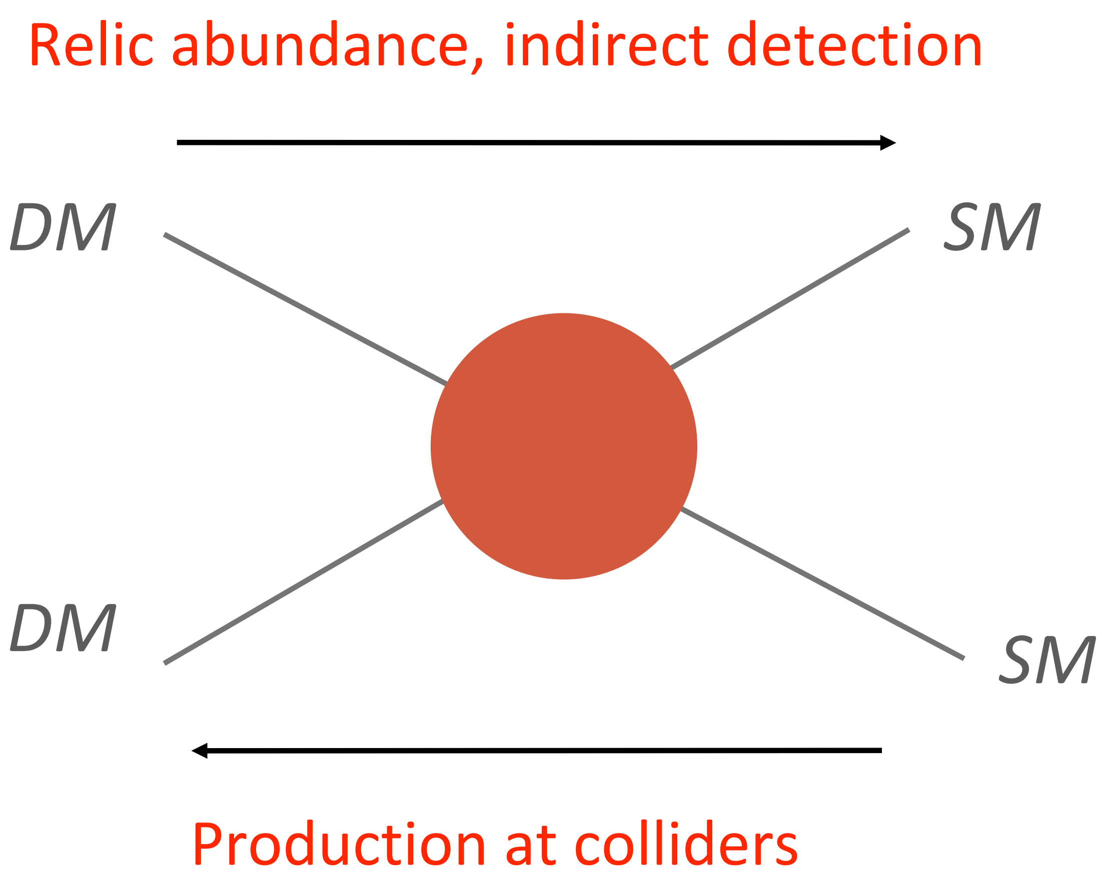
Interaction

Hidden sector

Weakly Interacting Massive Particles

Theoretically Well-Motivated and Experimentally Still Viable

- WIMPs have not been found but are not theoretically eliminated.
- They remain well-motivated by their observed abundance.



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

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

➡

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

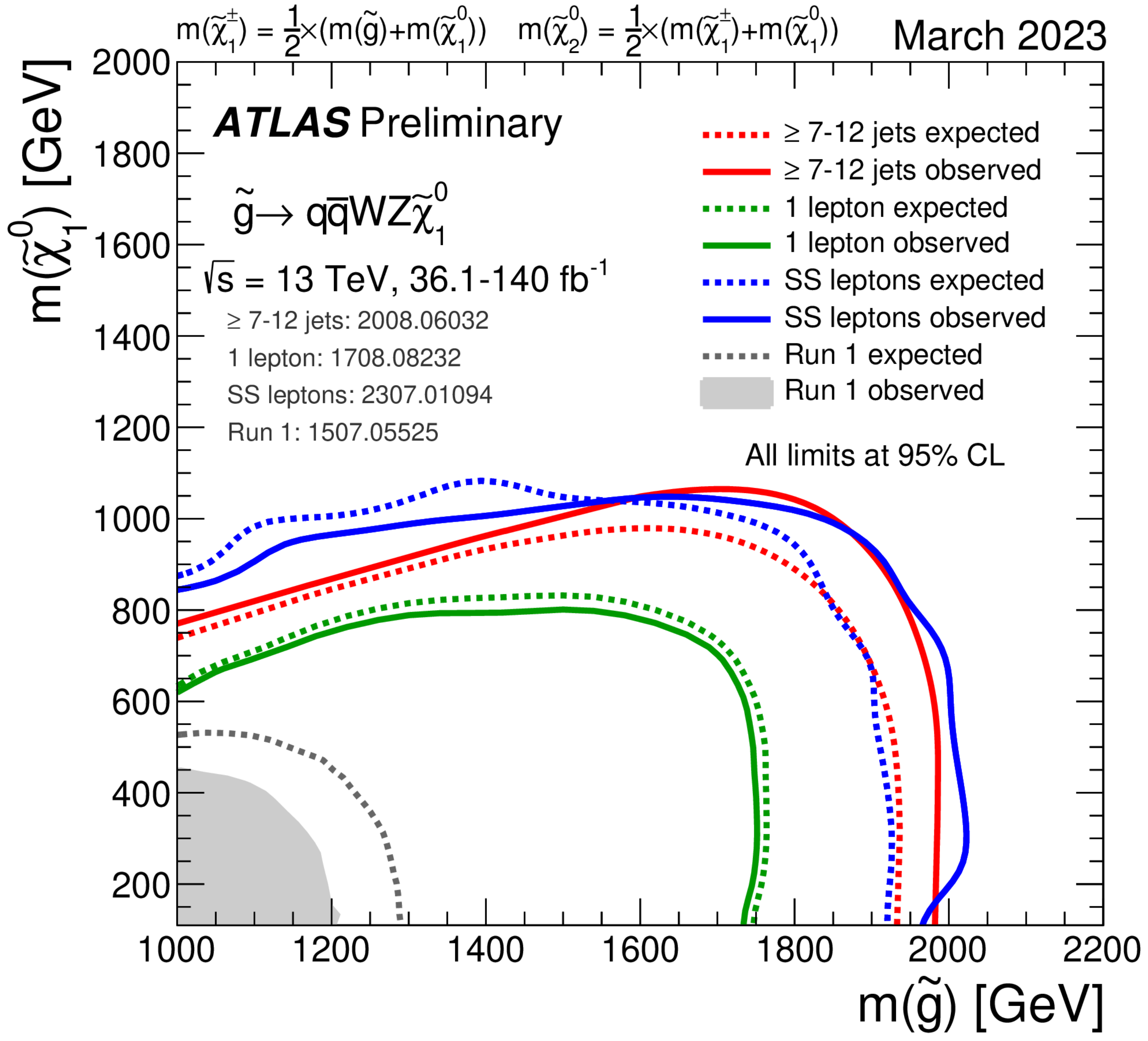
- The relic abundance estimate for WIMPs gives:

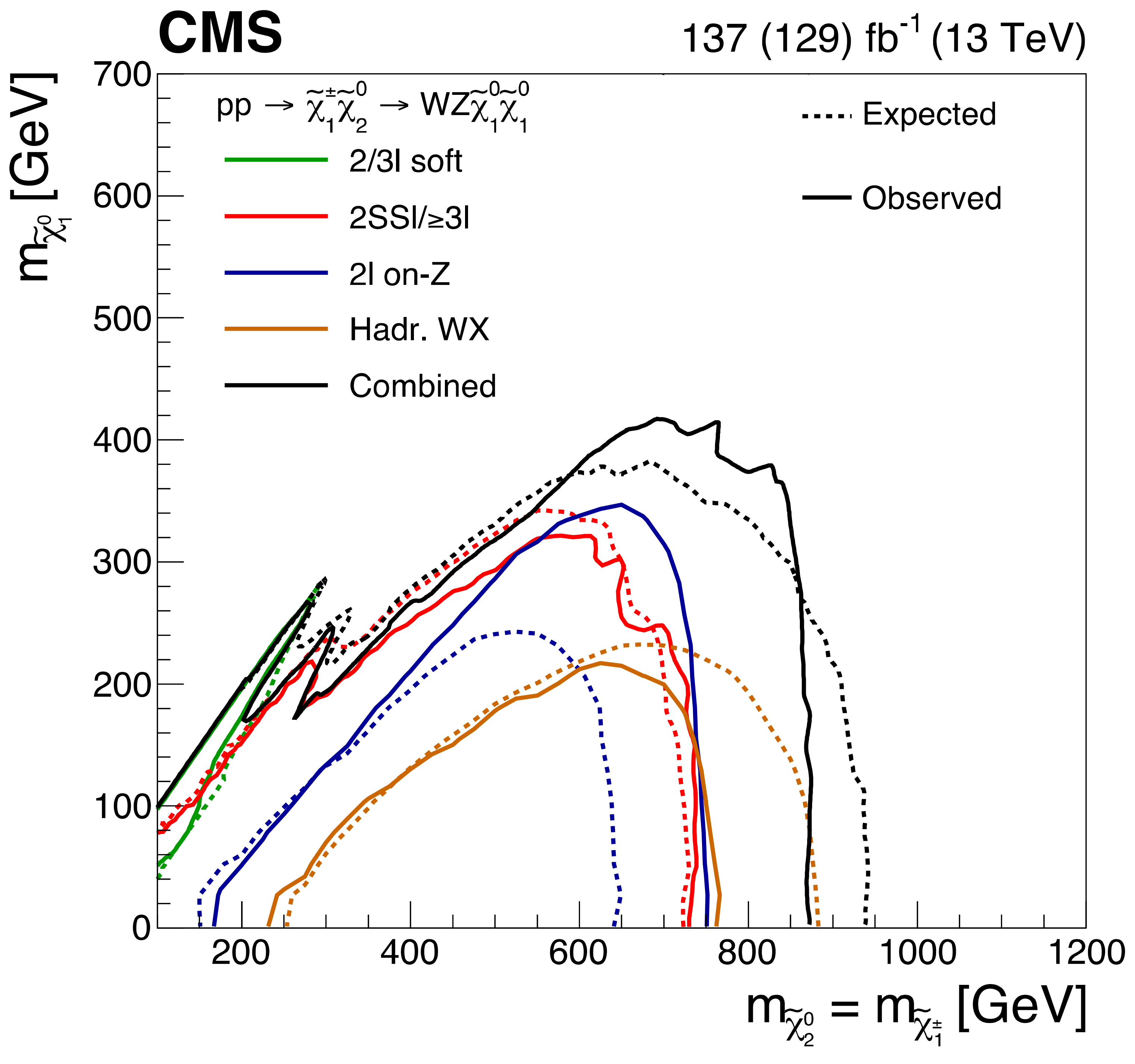
$$\langle\sigma v\rangle \simeq \frac{\pi\alpha_\chi^2}{m_\chi^2}\sqrt{1-\left(\frac{m_M}{m_\chi}\right)^2} \simeq 3\times 10^{-26}\,\frac{{\rm cm}^3}{\rm s}\left(\frac{g_\chi}{0.4}\right)^4\left(\frac{2\ {\rm TeV}}{m_\chi}\right)^2$$

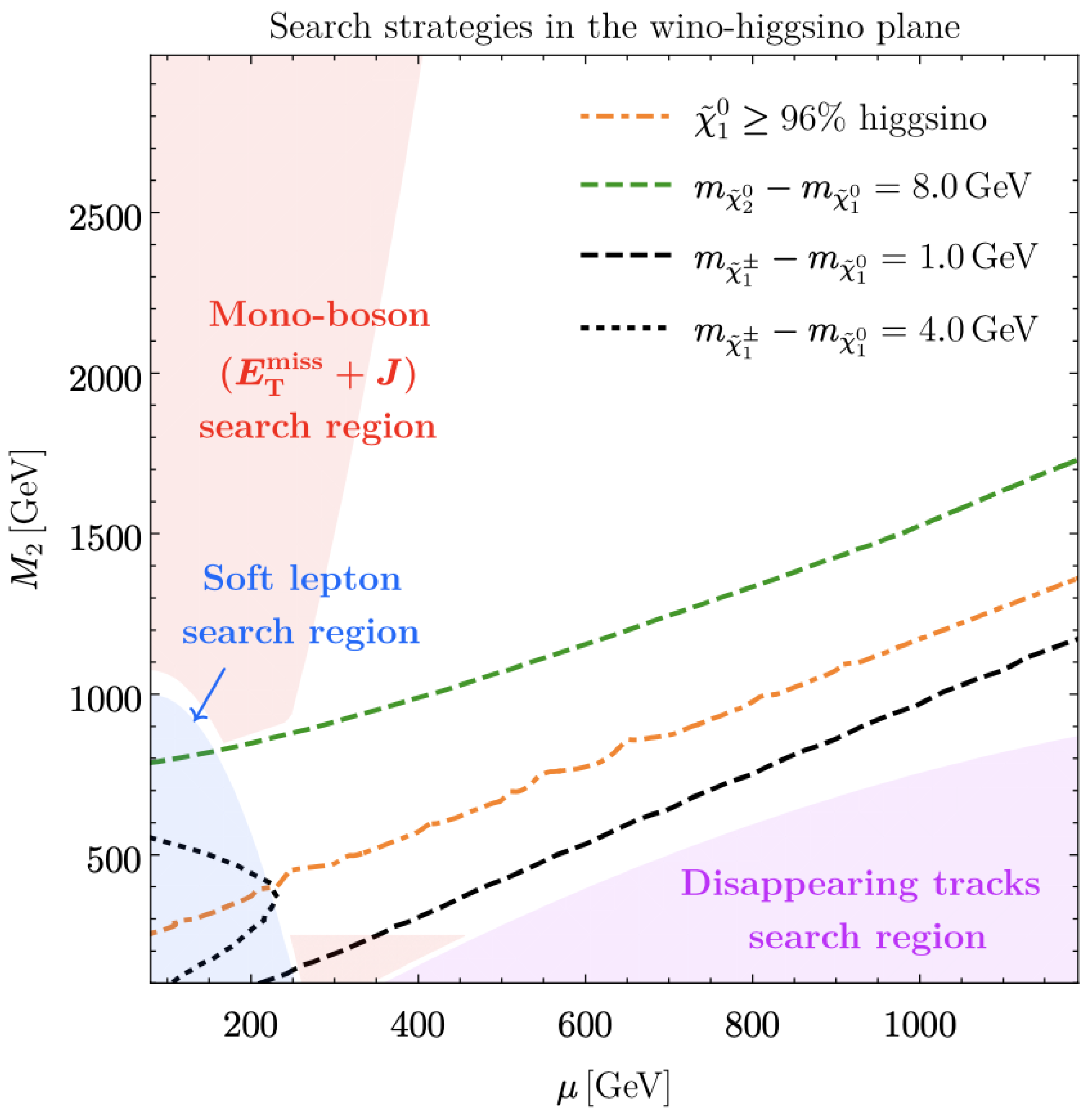
Weakly Interacting Massive Particles

Theoretically Well-Motivated and Experimentally Still Viable

- WIMPs have not been found but are not theoretically eliminated.
- Cosmologically-favored pure electroweakino masses have not been eliminated by LHC, which more strongly constrains colored particles.







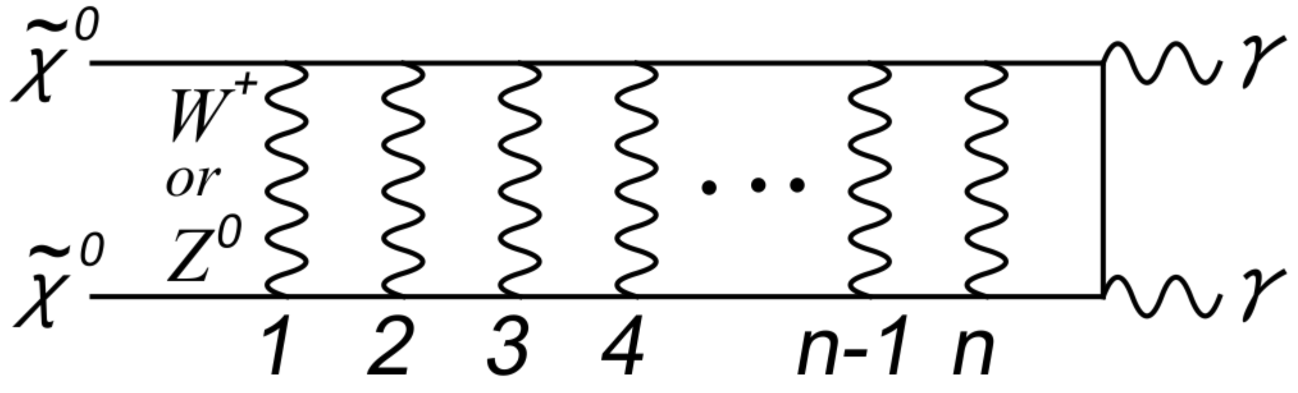
Carpenter et al 2309.07213

Weakly Interacting Massive Particles

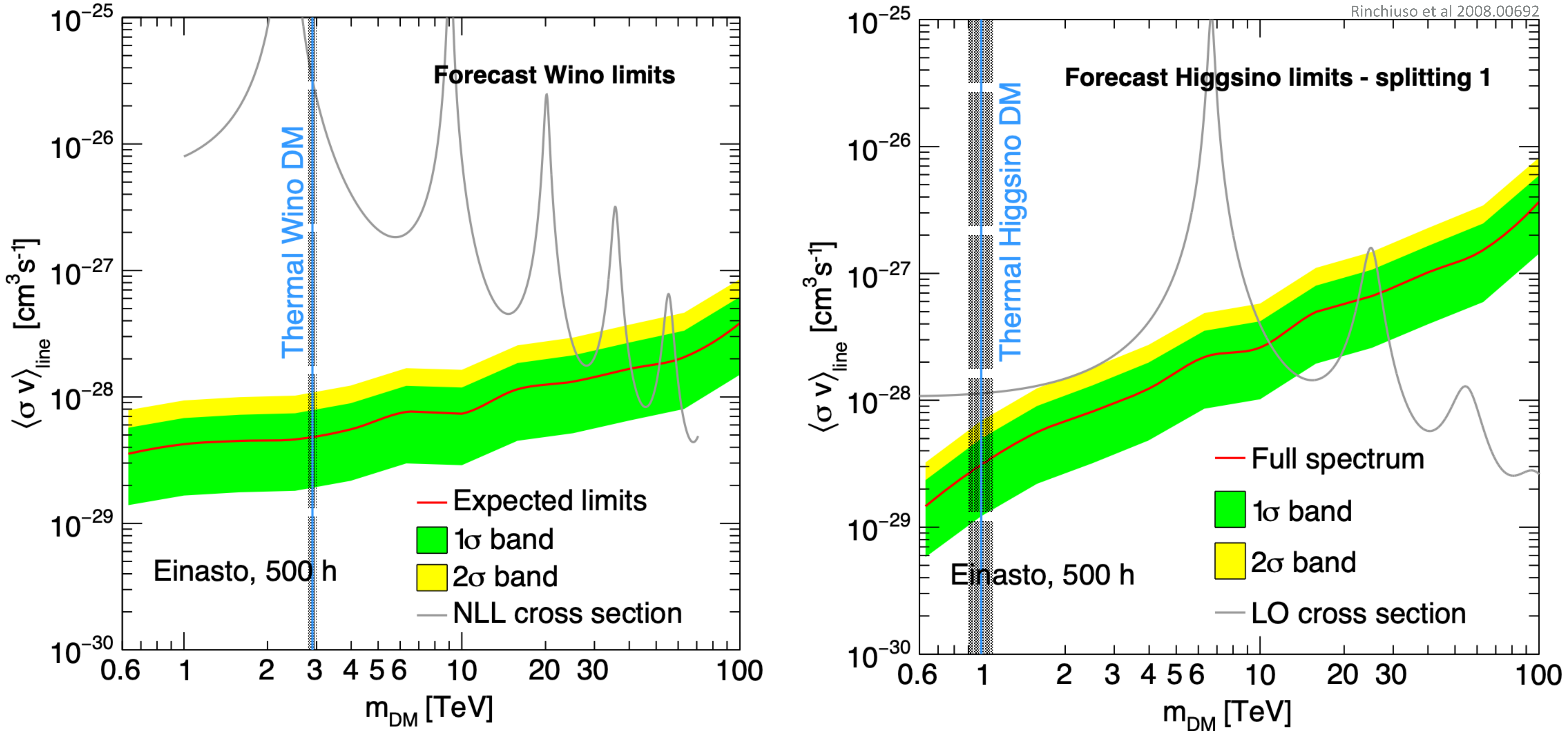
Theoretically Well-Motivated and Experimentally Still Viable

- WIMPs have not been found but are not theoretically eliminated.
- Pure electroweakinos produce detectable annihilation by-products in Cherenkov Telescopes

Hisano, Matsumoto, Nojiri, Saito, 0412403



Rinchiuso et al 2008.00692

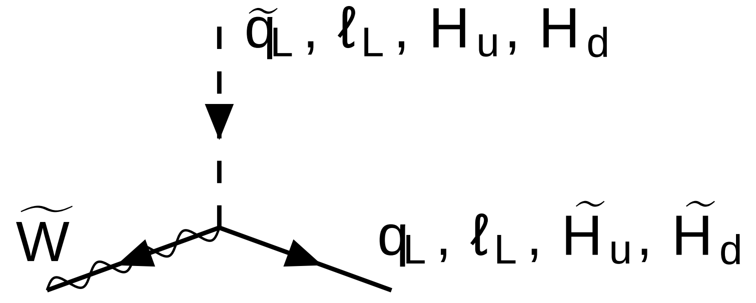


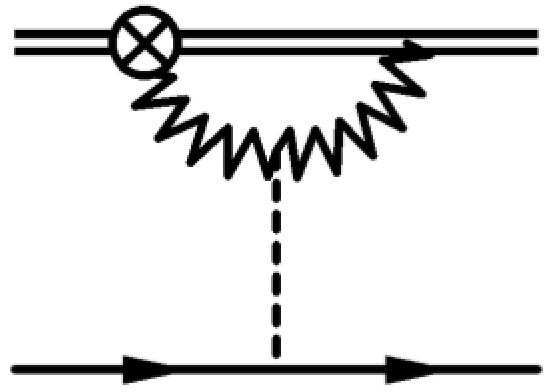
Challenge #1: Fully Cover Electroweakino DM, e.g. with Cherenkov Telescopes

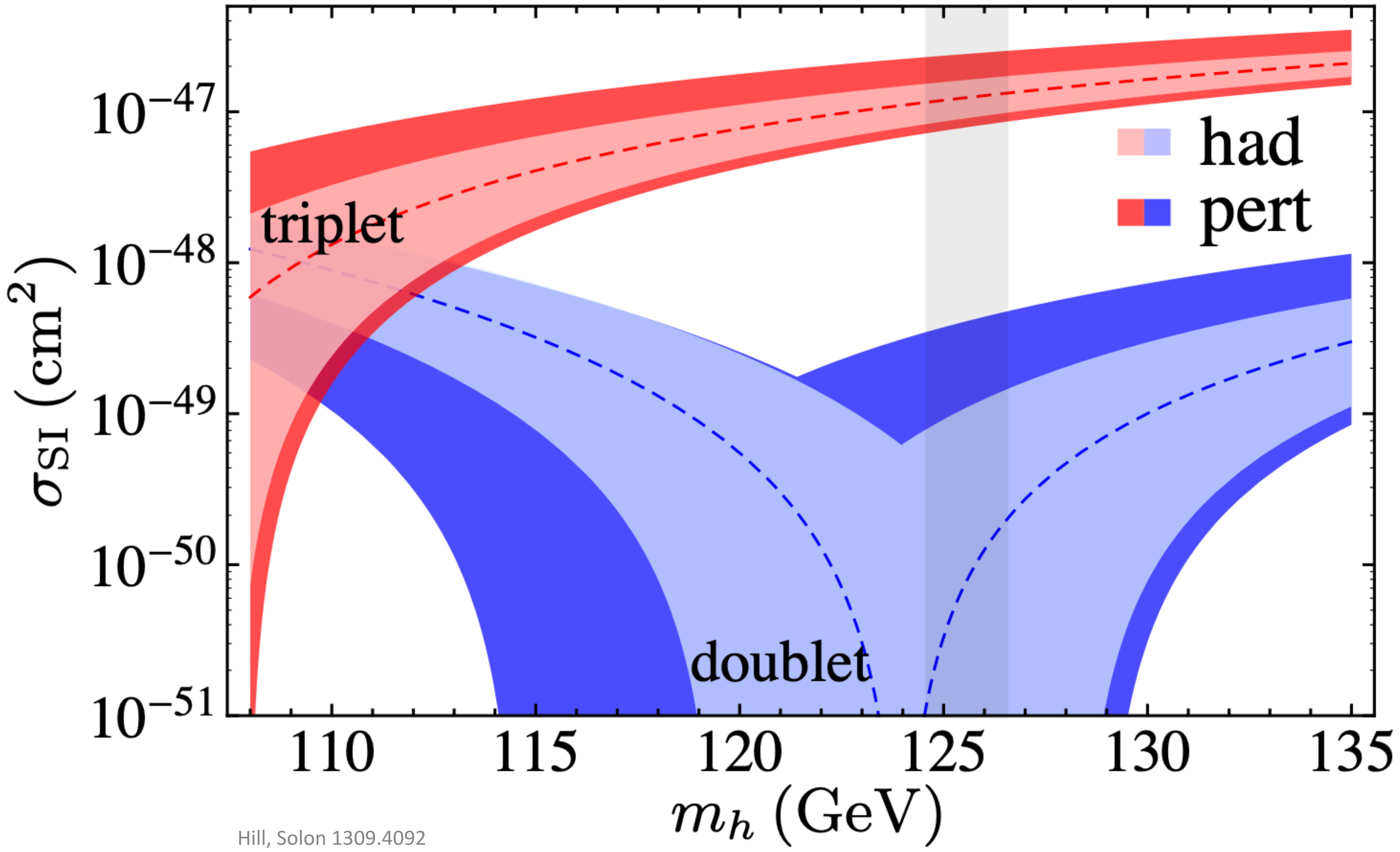
Weakly Interacting Massive Particles

Theoretically Well-Motivated and Experimentally Still Viable

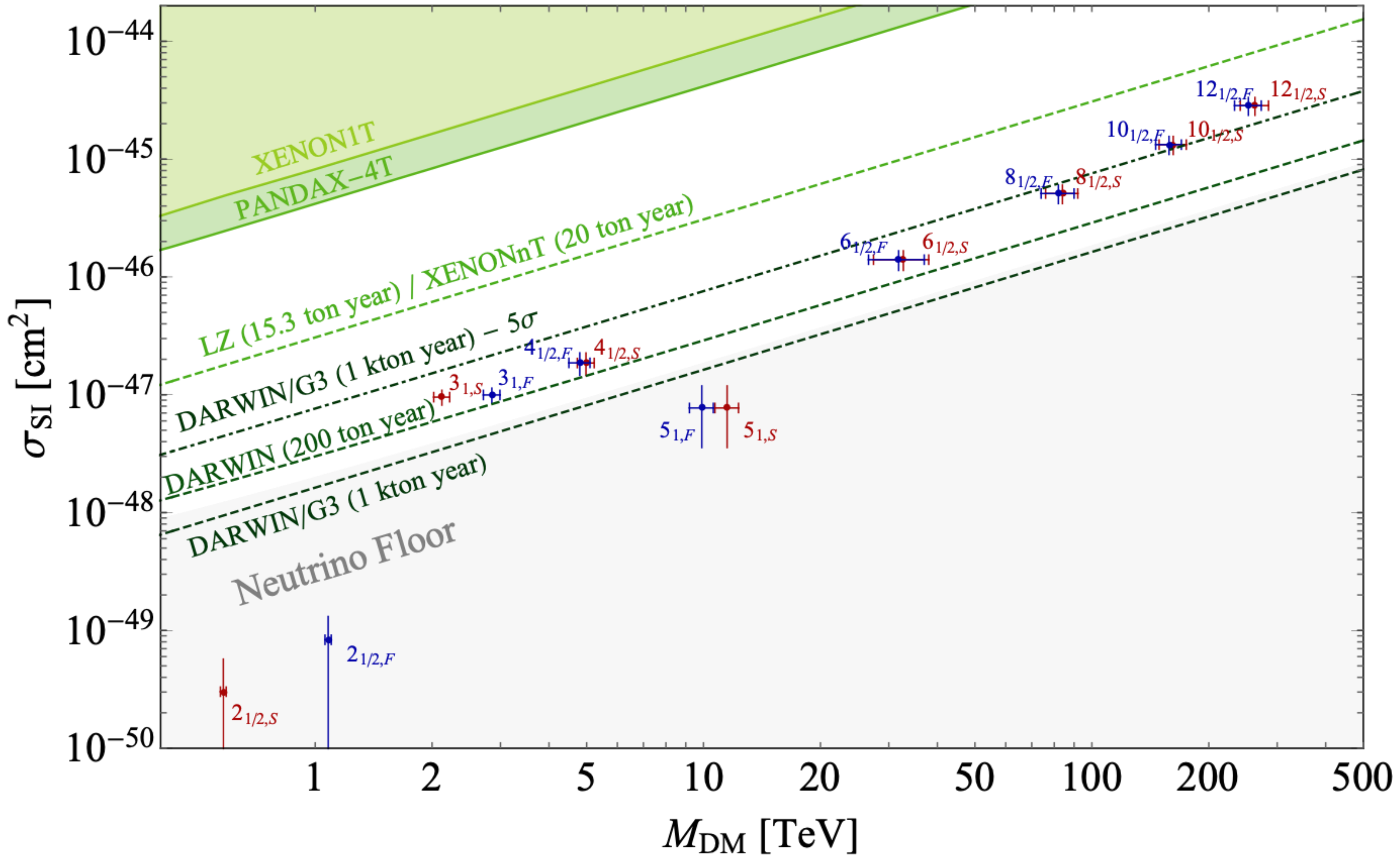
- WIMPs have not been found but are not theoretically eliminated.
- Pure electroweakinos have small scattering cross-sections in Direct Detection, because the tree-level Higgs-mediated process vanishes.







Hill, Solon 1309.4092

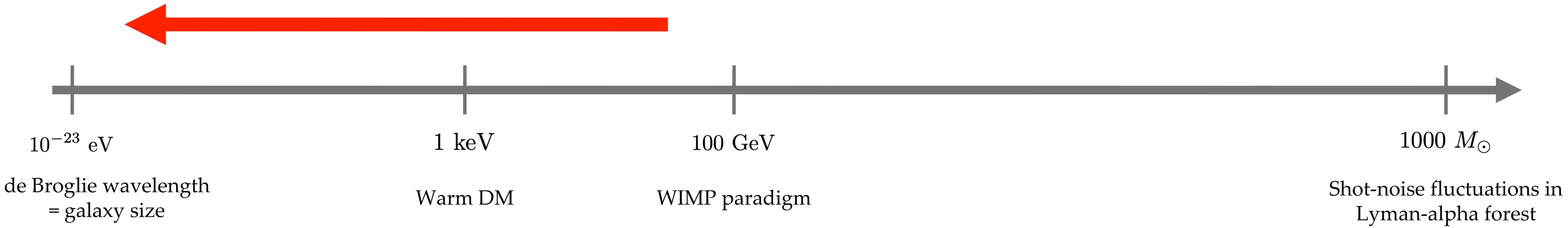


Bottaro et al 2205.-4486

Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection

Dark Matter of a Very Low Mass

Dark Matter with Mass Below the Weak Scale



10^{-23} eV

de Broglie wavelength
= galaxy size

1 keV

Warm DM

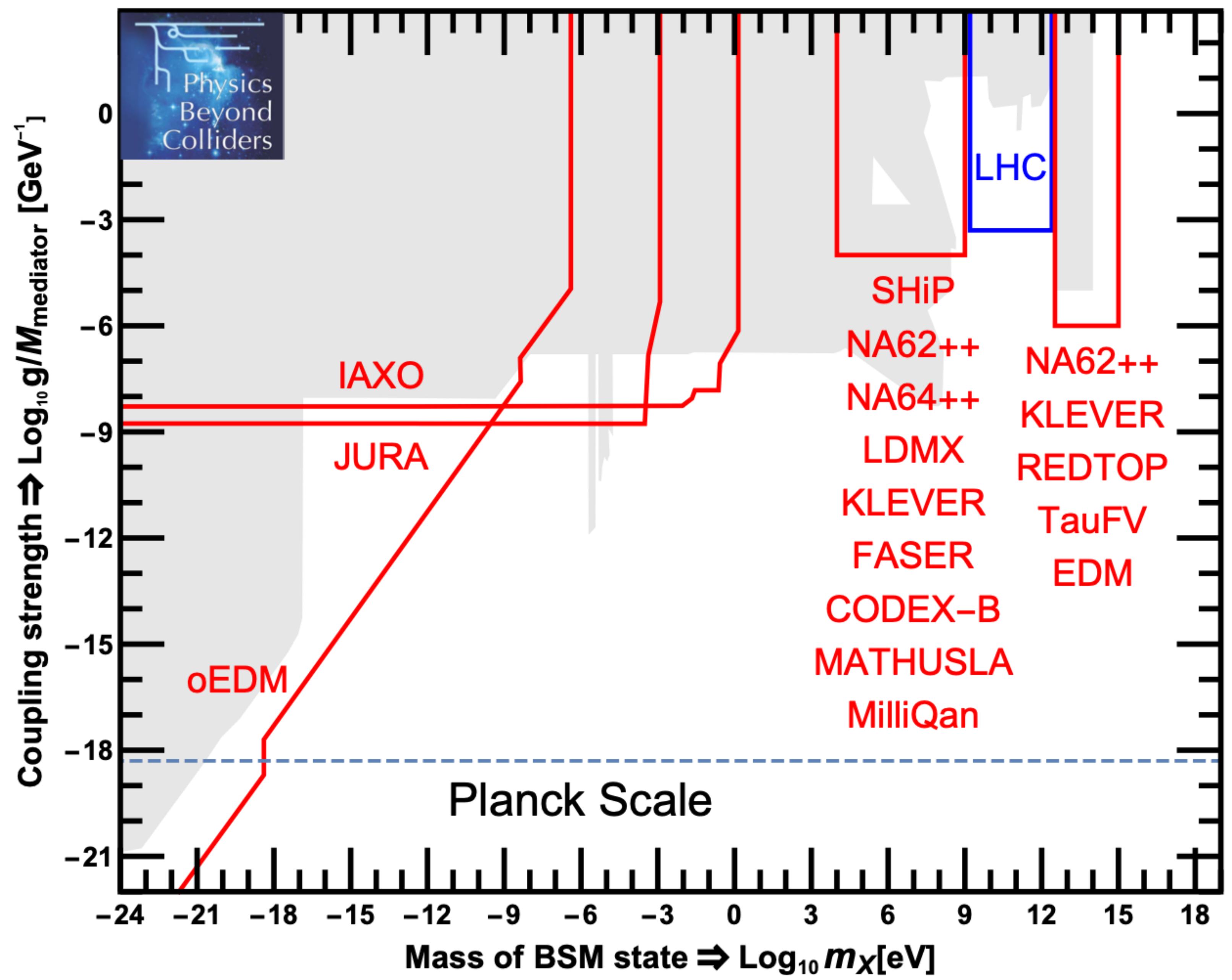
100 GeV

WIMP paradigm

$1000\ M_\odot$

Shot-noise fluctuations in
Lyman-alpha forest

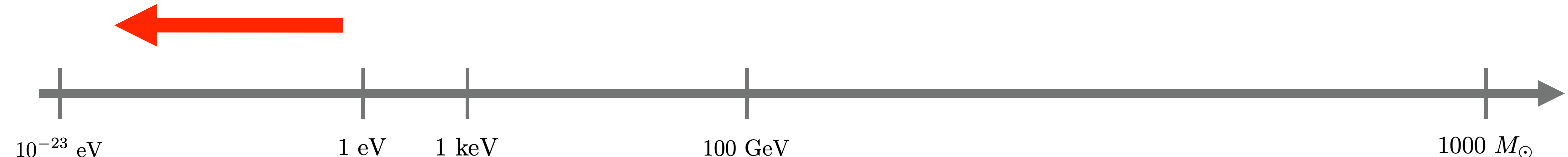
- Such low-mass states have evaded detection by having small couplings to the SM.



1901.09966

Dark Matter of a Very Low Mass

Dark Matter with Mass Below the Weak Scale



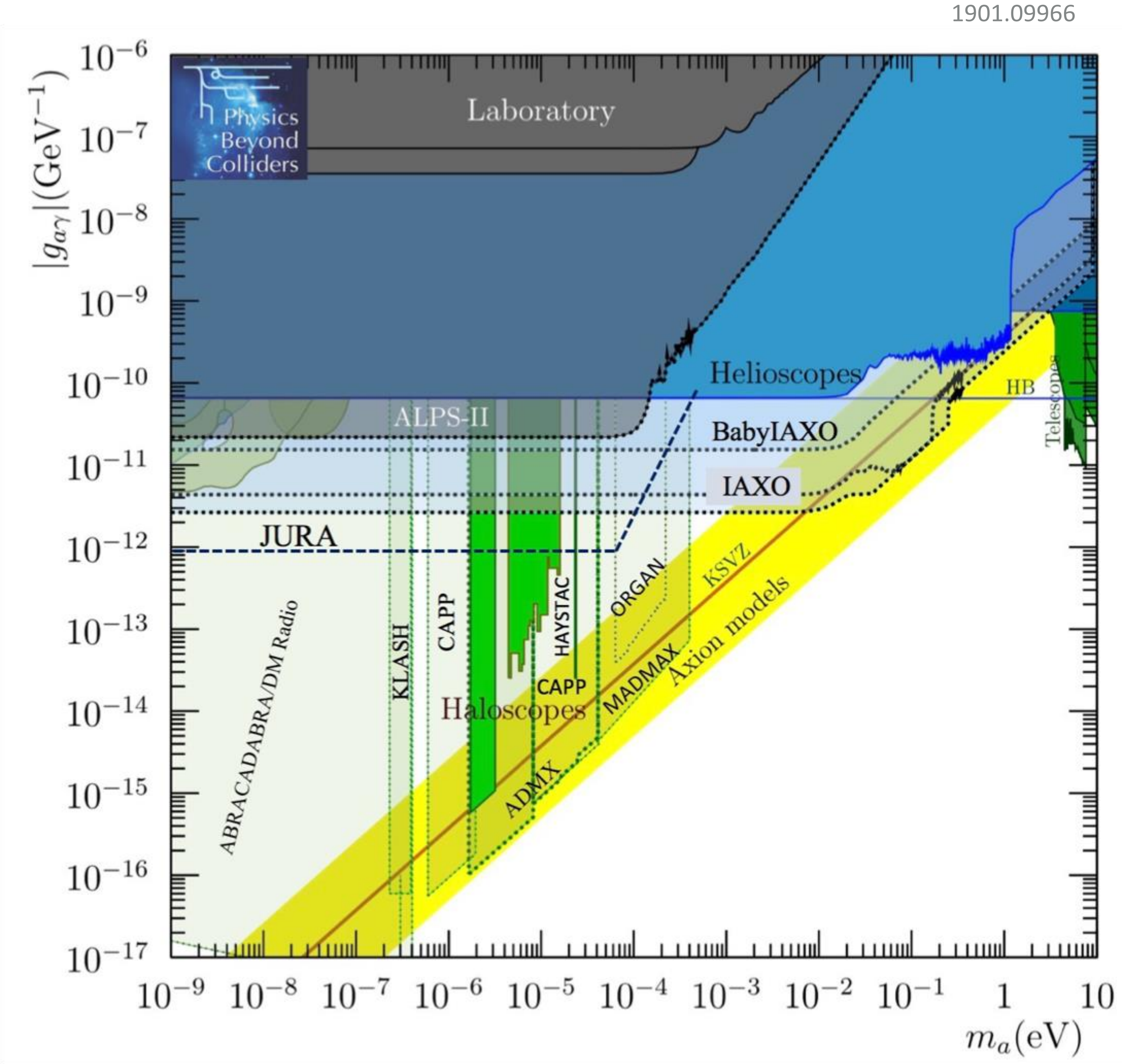
de Broglie wavelength
= galaxy size

Wavelike Warm DM

WIMP paradigm

Shot-noise fluctuations in
Lyman-alpha forest

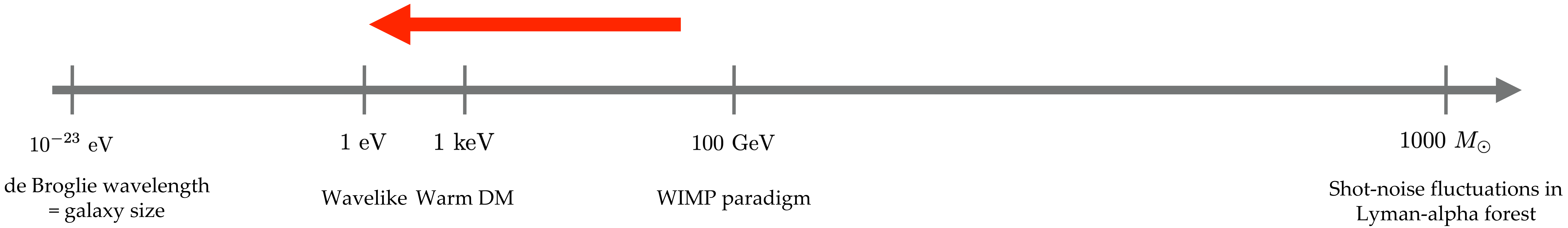
- Such low-mass states have evaded detection by having small couplings to the SM.
- One powerful motivation for searches is dark matter density, while satisfying cosmological constraints, such as the axion.



Challenge #3: Build out the suite of axion searches

Dark Matter of a Very Low Mass

Dark Matter with Mass Below the Weak Scale



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1 eV

Wavelike

1 keV

Warm DM

100 GeV

WIMP paradigm

1000 $M_\odot$

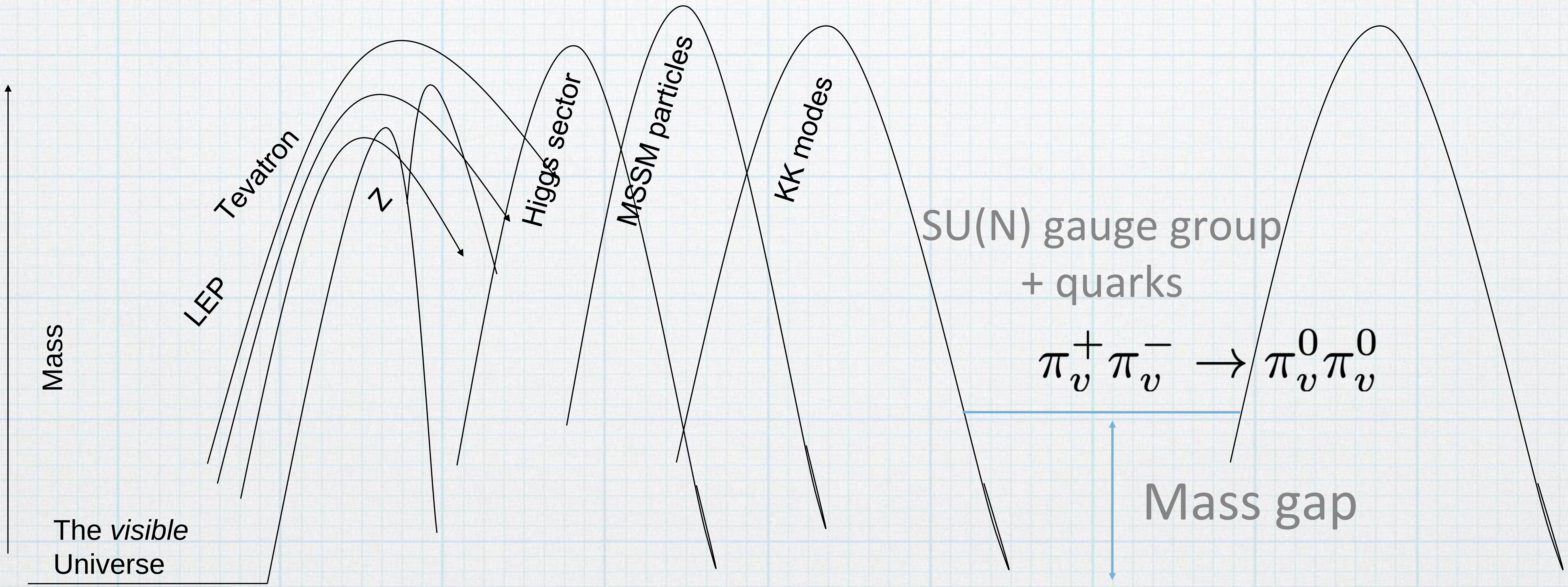
Shot-noise fluctuations in
Lyman-alpha forest

- Next, we discuss an intermediate range where observation via particle interactions with SM is still highly motivated though not detectable with traditional experiments
- These are hidden sector/valley DM models, which arise generically in top-down constructions, and give rise to qualitatively different observational signatures

Review KZ 2401.03025

Slide 2007

What's in the hidden valley?



Many theories with this structure:

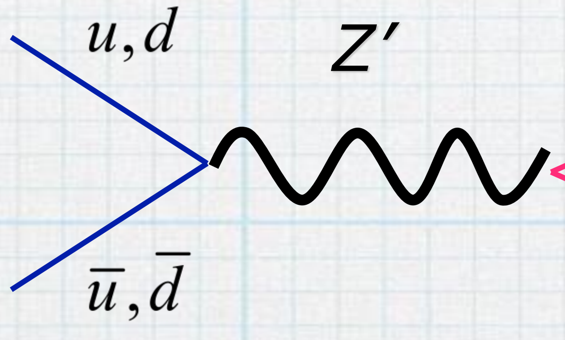
- QCD-like theory with F flavors and N colors
- QCD-like theory with only heavy quarks
- QCD-like theory with adjoint quarks
- Pure glue theory
- UV-fixed point = confining
- N=4 SUSY Conformal
- RS throat

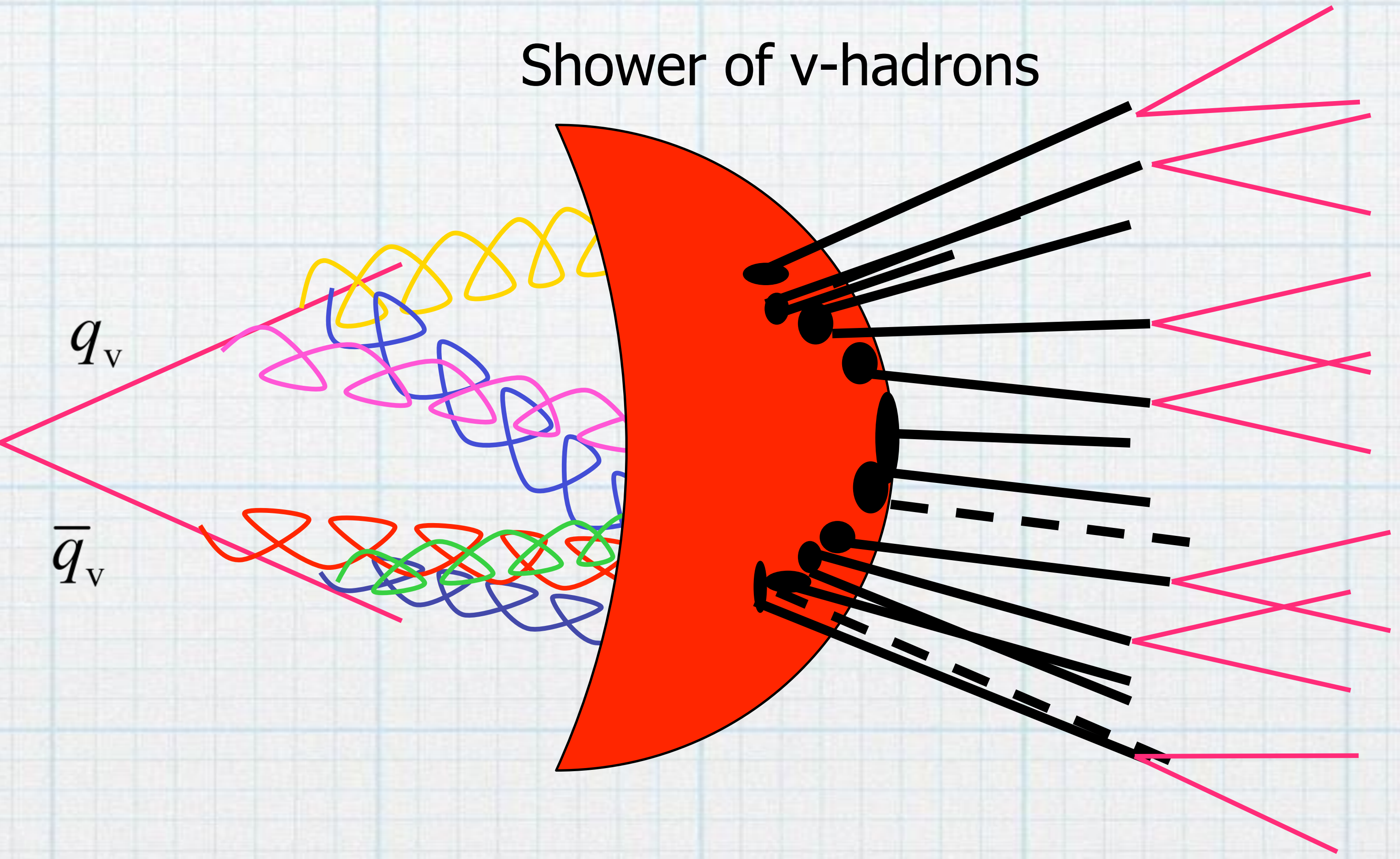
- Seiberg duality cascade
- KS throat
- Remnant from SUSY breaking
- Partially higgsed SU(N) theory
- Banks-Zaks sector
- Unparticles

Slide 2007

A concrete example

- Z’ mediator
- SU(N) gauge theory with 1 light quark

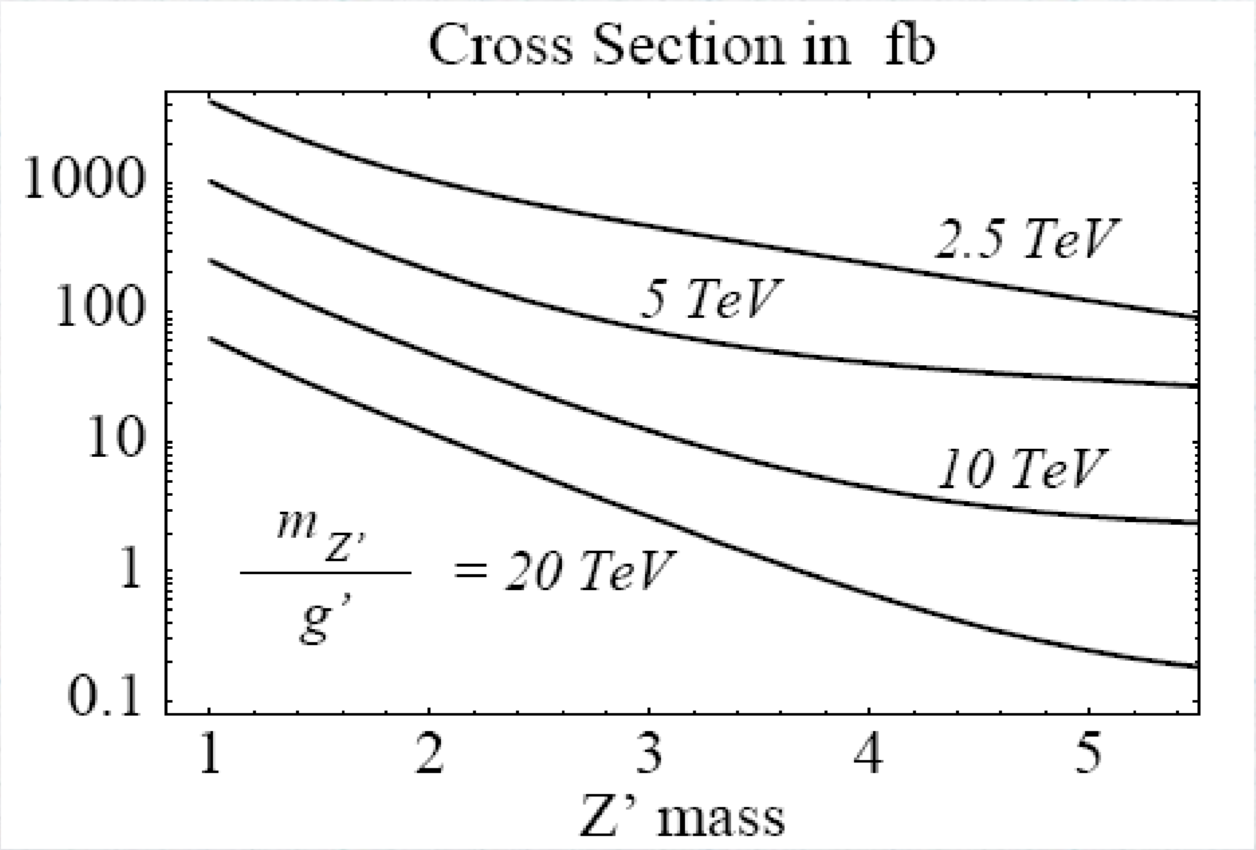




Shower of v-hadrons

Each pair reconstructs to low mass v-hadron

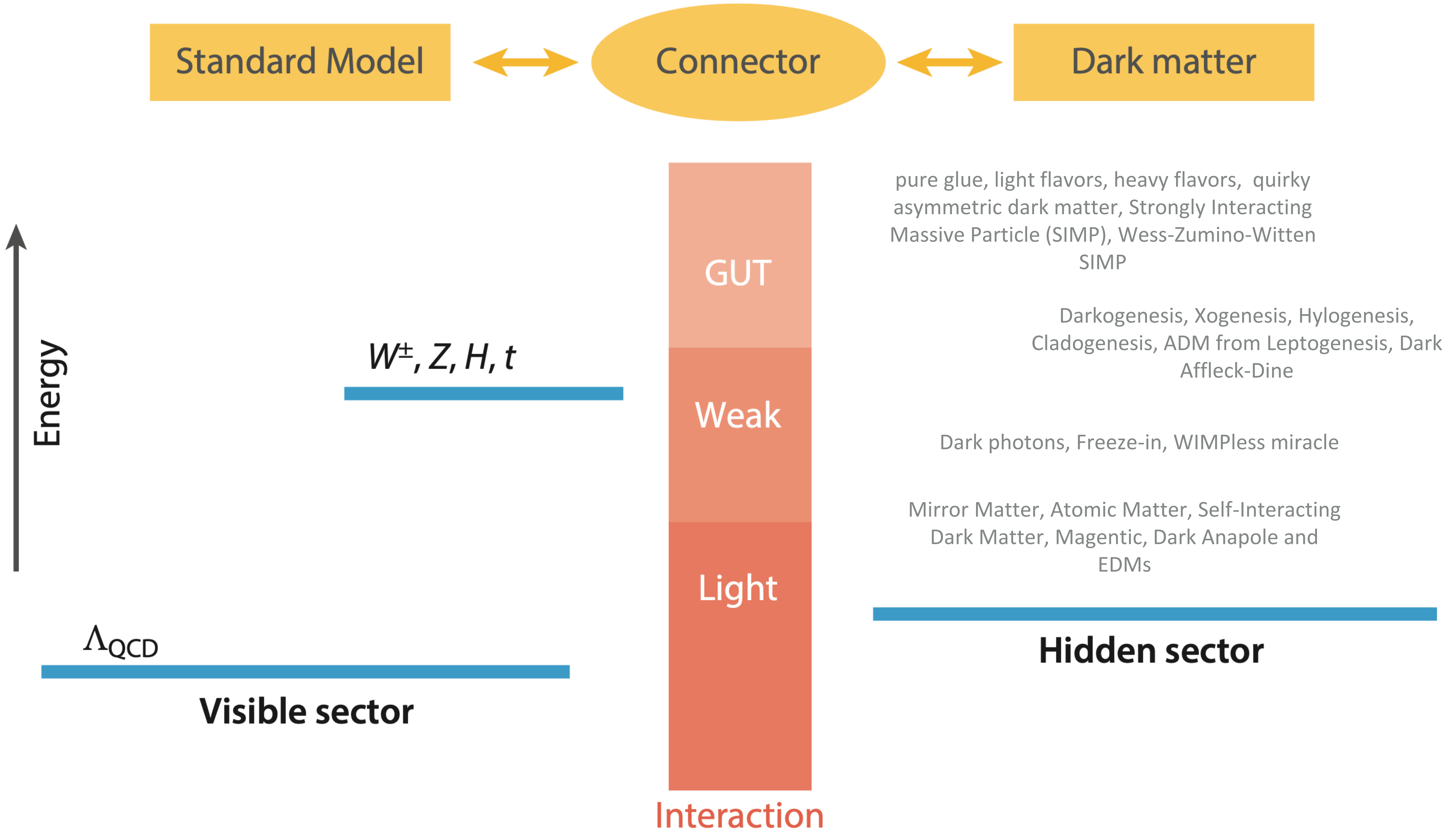
Reconstruct entire event to Z′ resonance



Hidden Sector Dark Matter

Theories have broadened the scope of experimental searches.

- Hidden sectors have their own forces and dynamics that are not parasitic on the SM forces.
- New experiments look at new mass scales with new forces at weaker couplings



Standard Model ⟷ Connector ⟷ Dark matter

Energy

$W^{\pm}, Z, H, t$

Λ_{QCD}

Visible sector

GUT

Weak

Light

Interaction

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

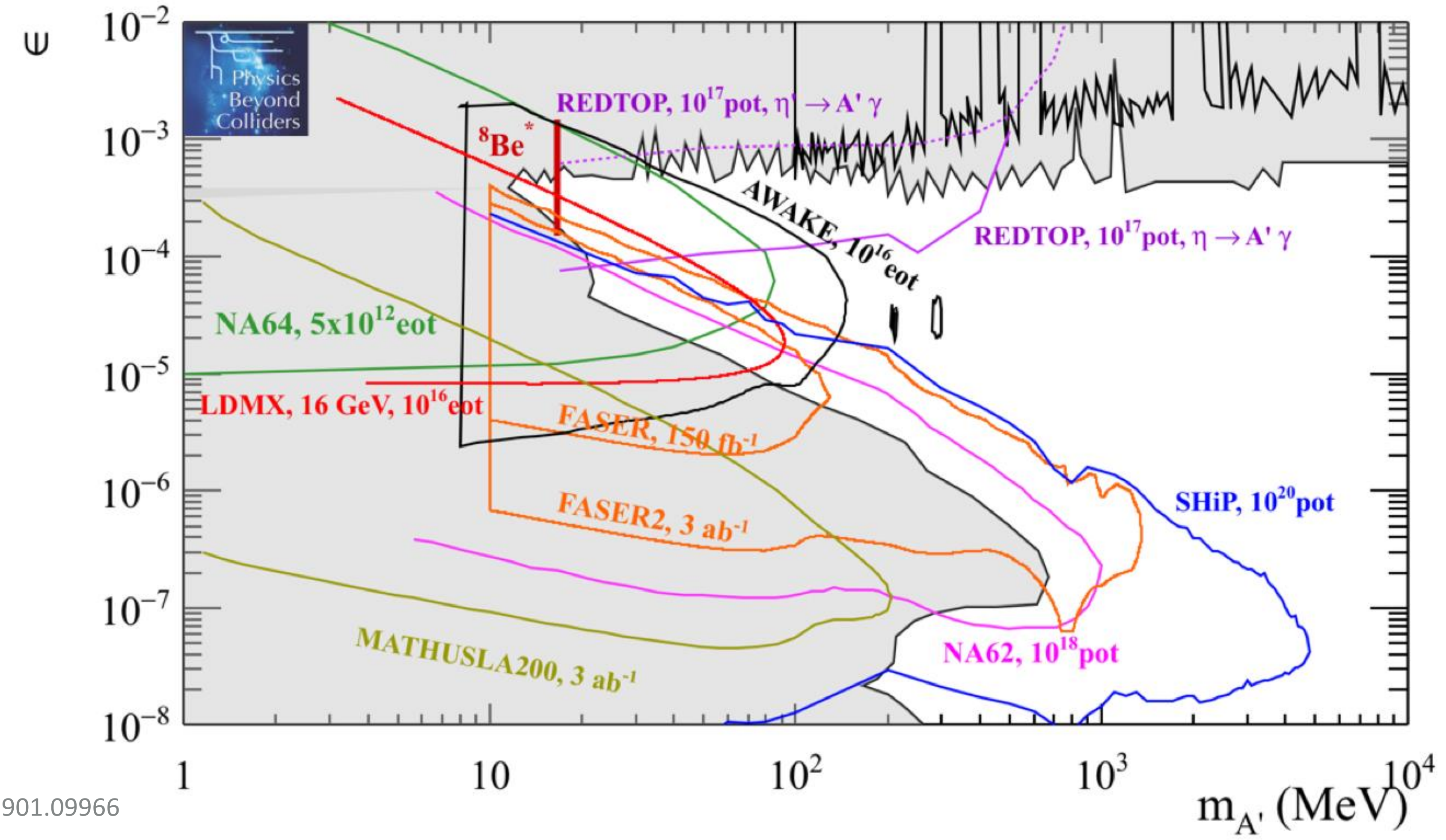
Mirror Matter, Atomic Matter, Self-Interacting Dark Matter, Magentic, Dark Anapole and EDMs

Hidden sector

Challenge #4: Build out the suite of accelerator searches—high energy and intensity—for hidden sectors

Hidden Sector Dark Matter

Theories have broadened the scope of experimental searches.



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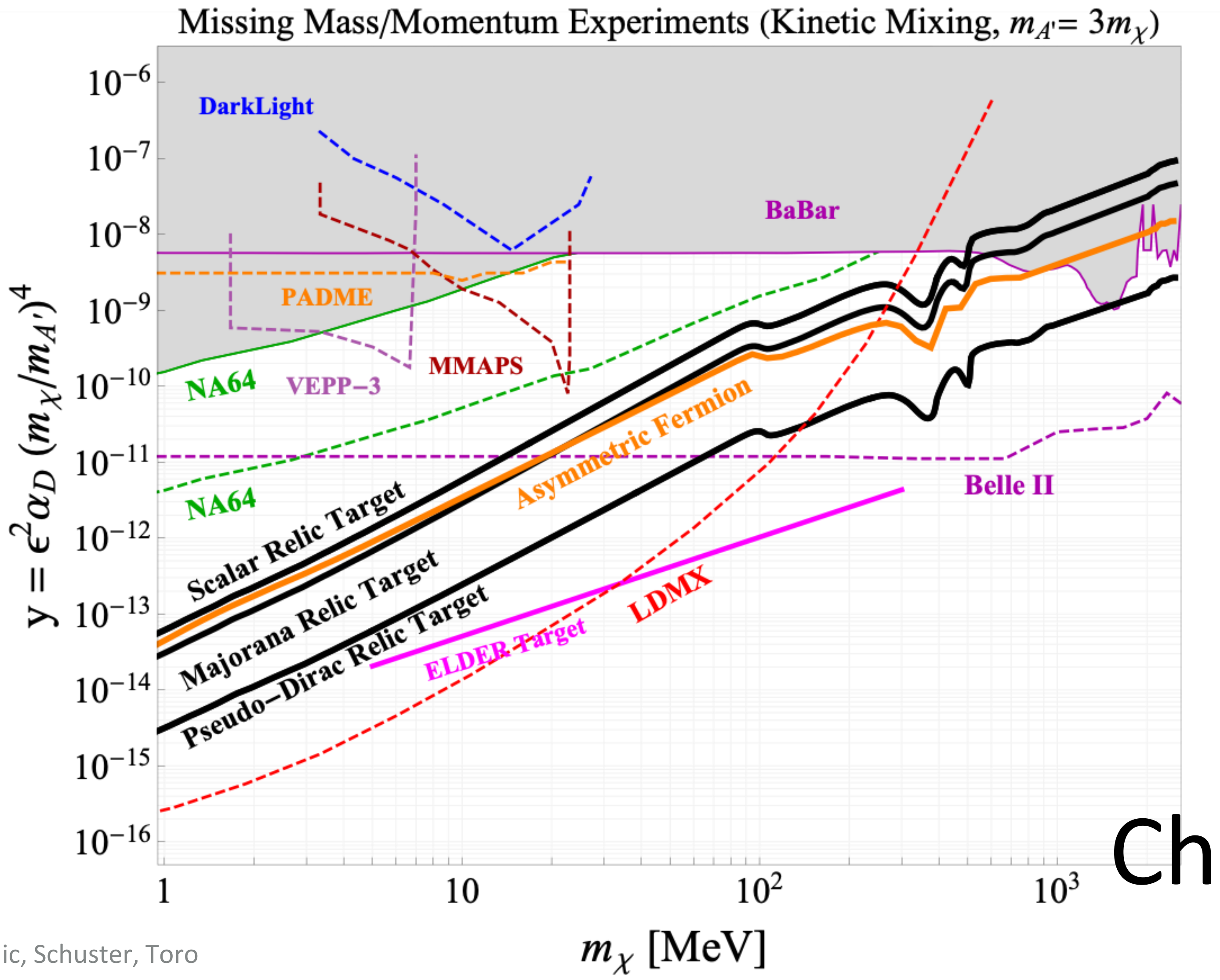
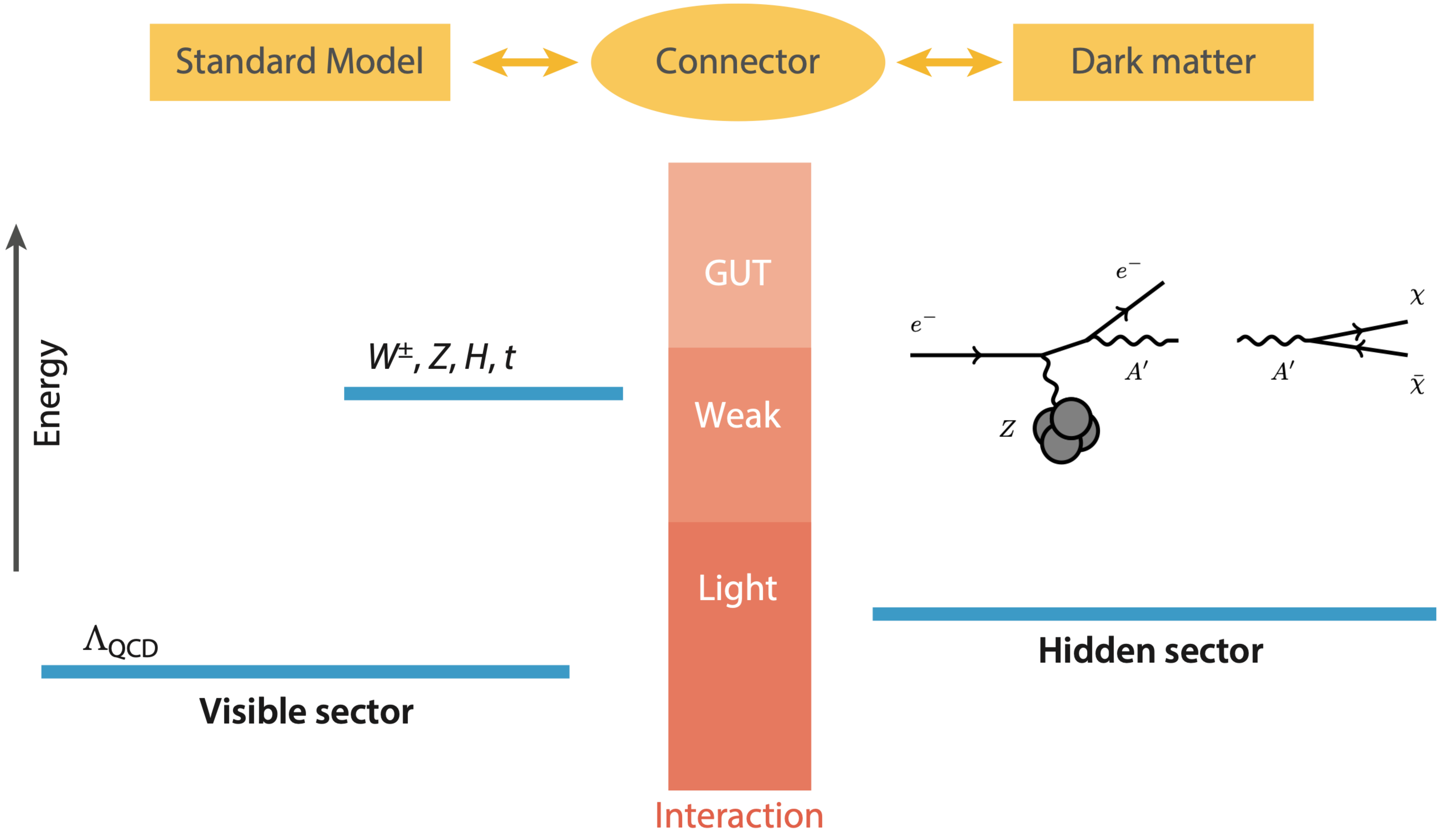


Izaguirre, Krnjaic, Schuster, Toro



Standard Model ⟷ Connector ⟷ Dark matter

Energy

$W^\pm, Z, H, t$

Λ_{QCD}

Visible sector

GUT

Weak

Light

Interaction

Hidden sector

Challenge #4: Build out the suite of accelerator searches—high energy and intensity—for hidden sectors

Hidden Sector DM in Experiments

Focusing the Lamplight

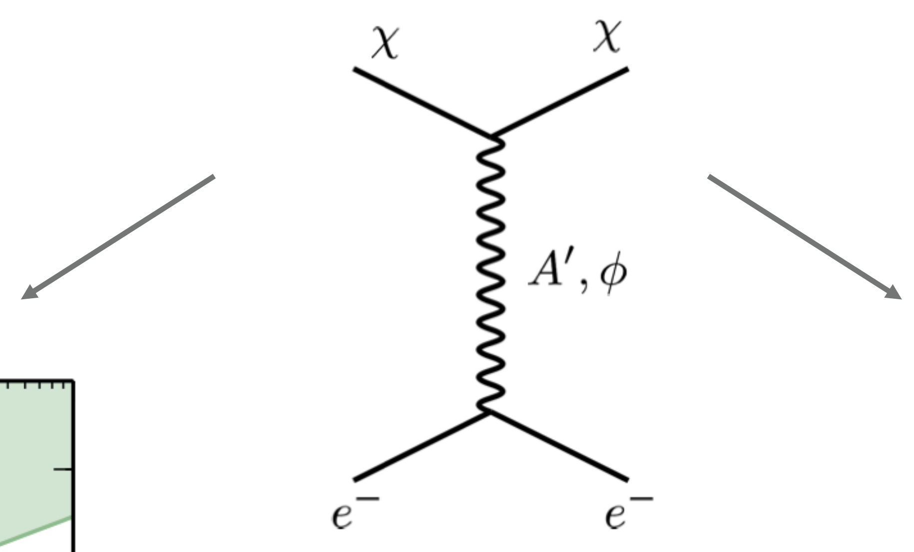
- HSDM has dramatically broadened the scope of DM theory.
- In 2008, they said the direct detection of light DM was not possible. We have come a long way.
- Since HSDM does not solve a SM problem, unlike WIMP and axion, its couplings to SM are less determined. Can we hope to have an experimentally predictive theory?

Hidden Sector DM in Experiments

Models Best-Motivated by Relic Abundance Can be Reach with 1 kg-yr exposure

- Yes, if we utilize DM abundance as a guide.

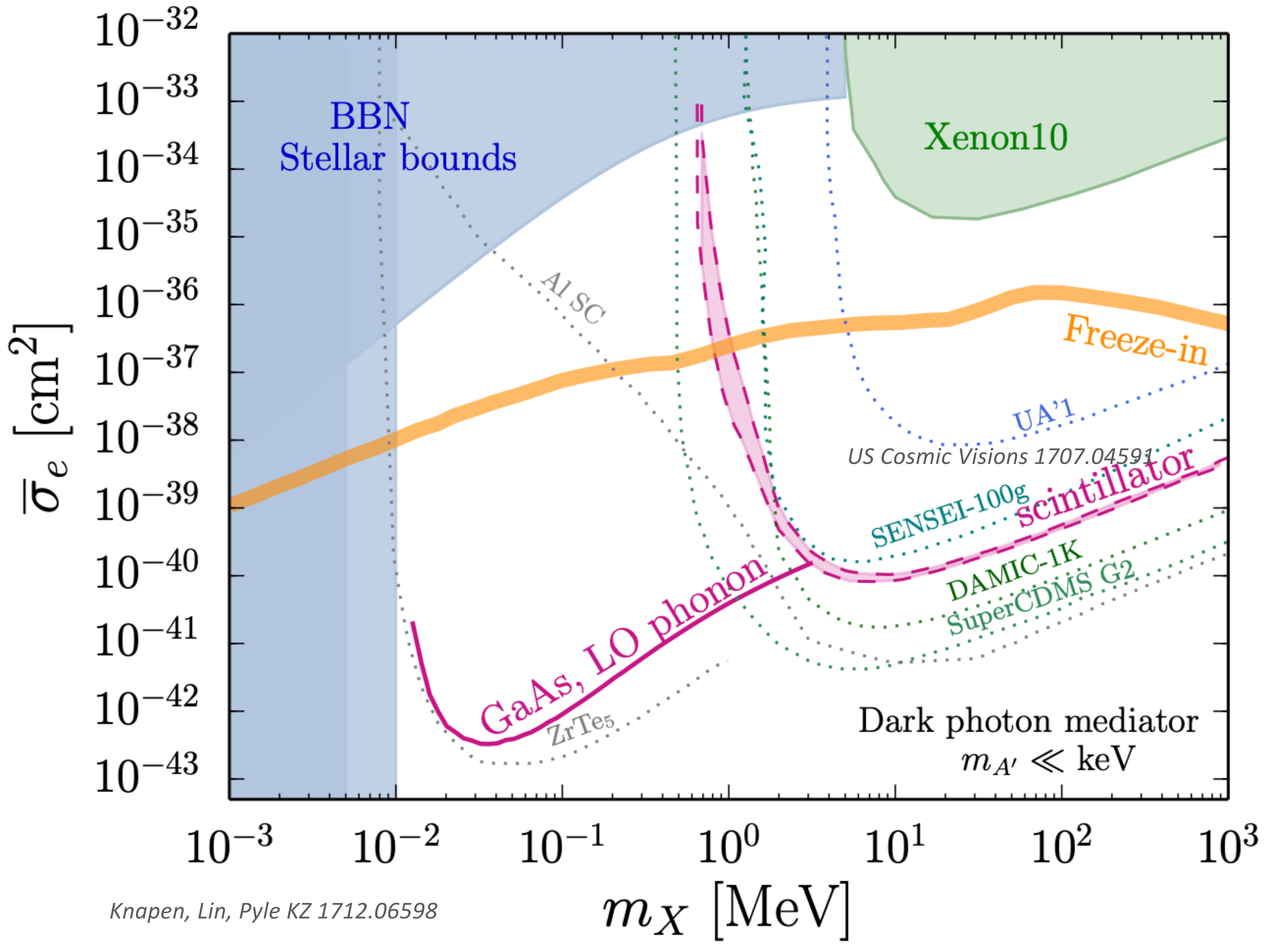
Freeze-in



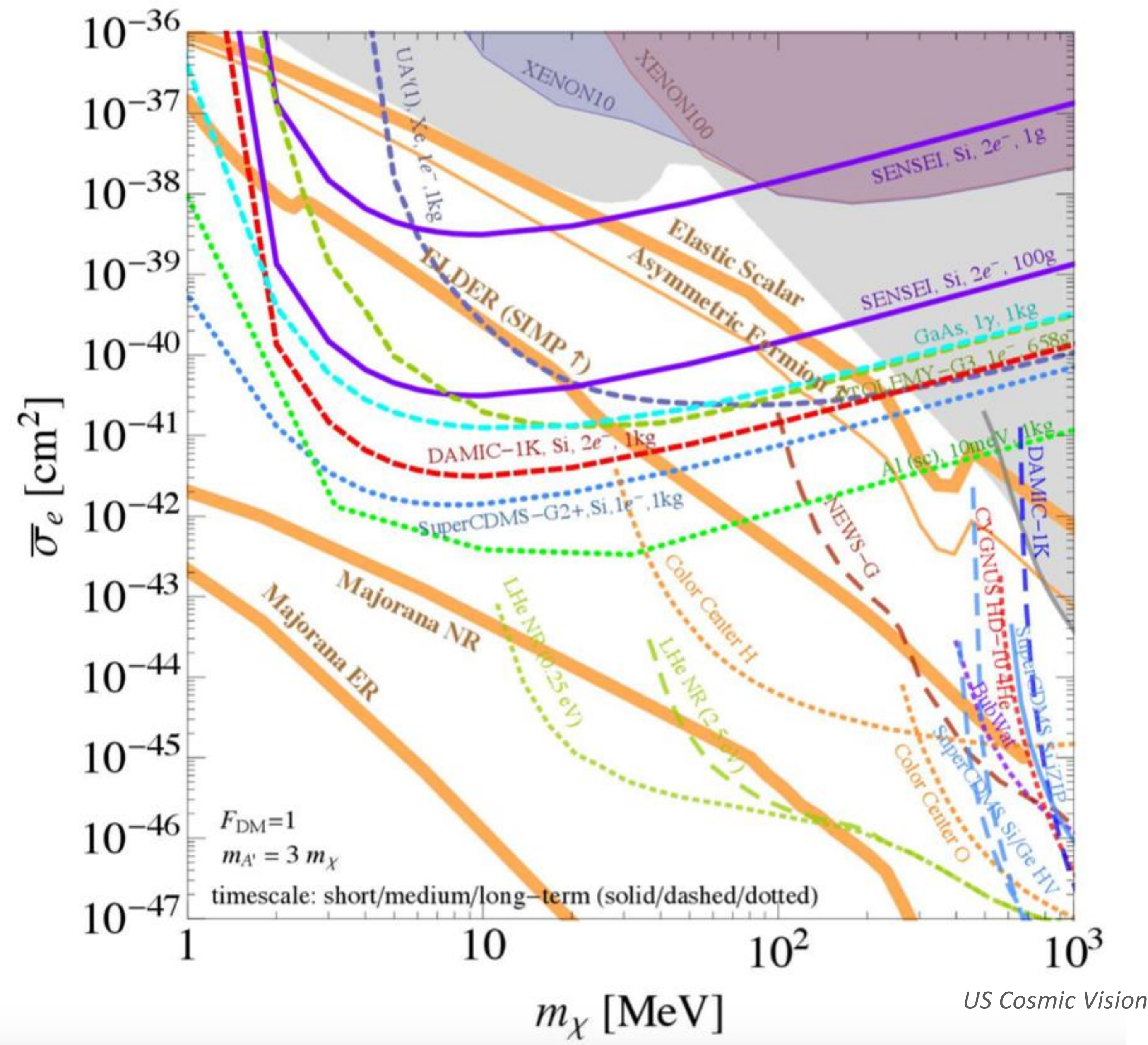
Thermal Freeze-out

Asymmetric Dark Matter

SIMP



Knapen, Lin, Pyle KZ 1712.06598



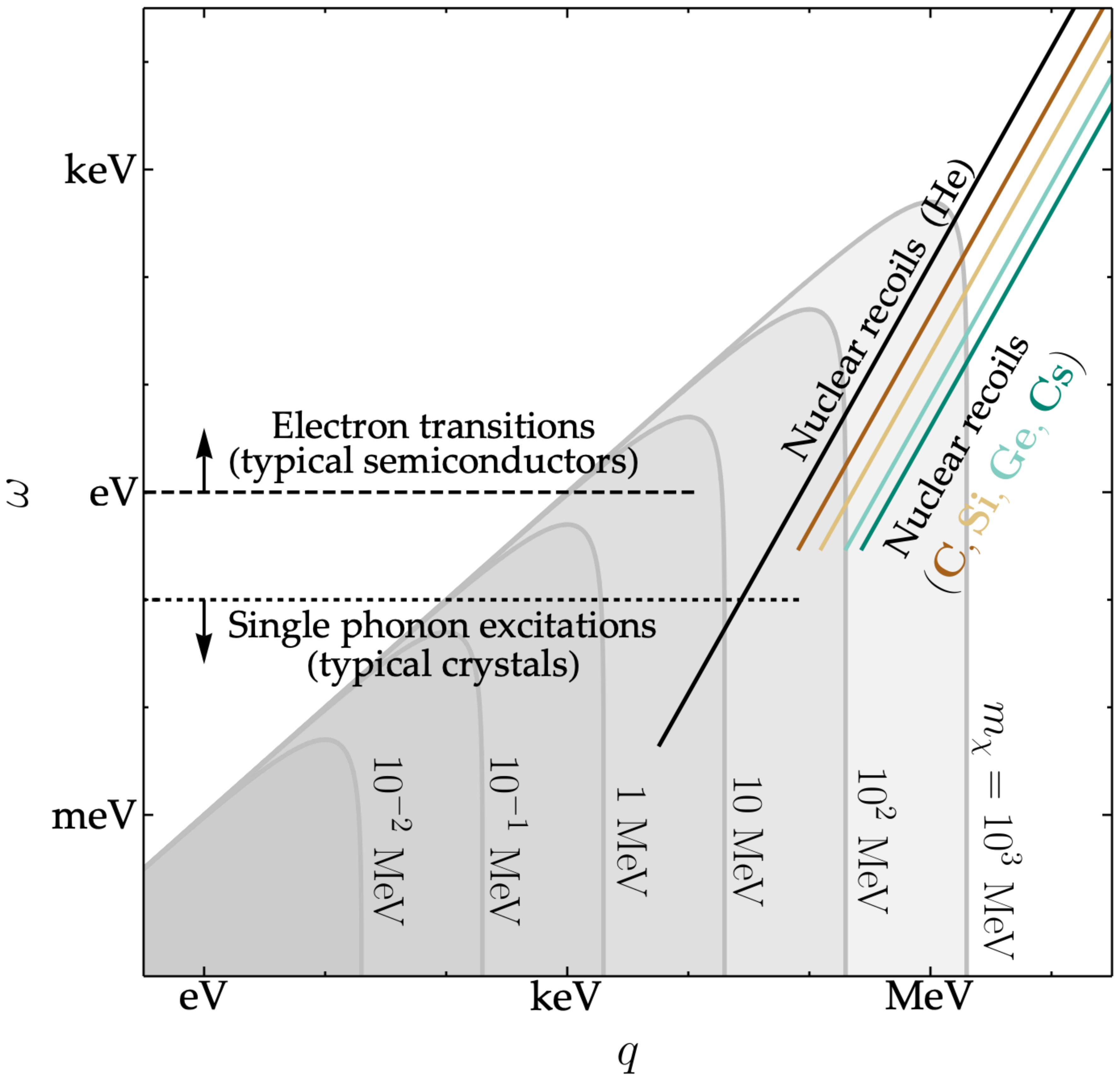
US Cosmic Visions 1707.04591

Challenge #5: Cover the abundance-driven light DM models in direct detection

The Landscape of sub-GeV Dark Matter Direct Detection

Beyond Nuclear Recoil in Direct Detection

- Nuclear Recoil utilized in WIMP searches is poorly matched to light DM detection.
- At low momentum transfer and energy deposition, free nuclei are not correct d.o.f.

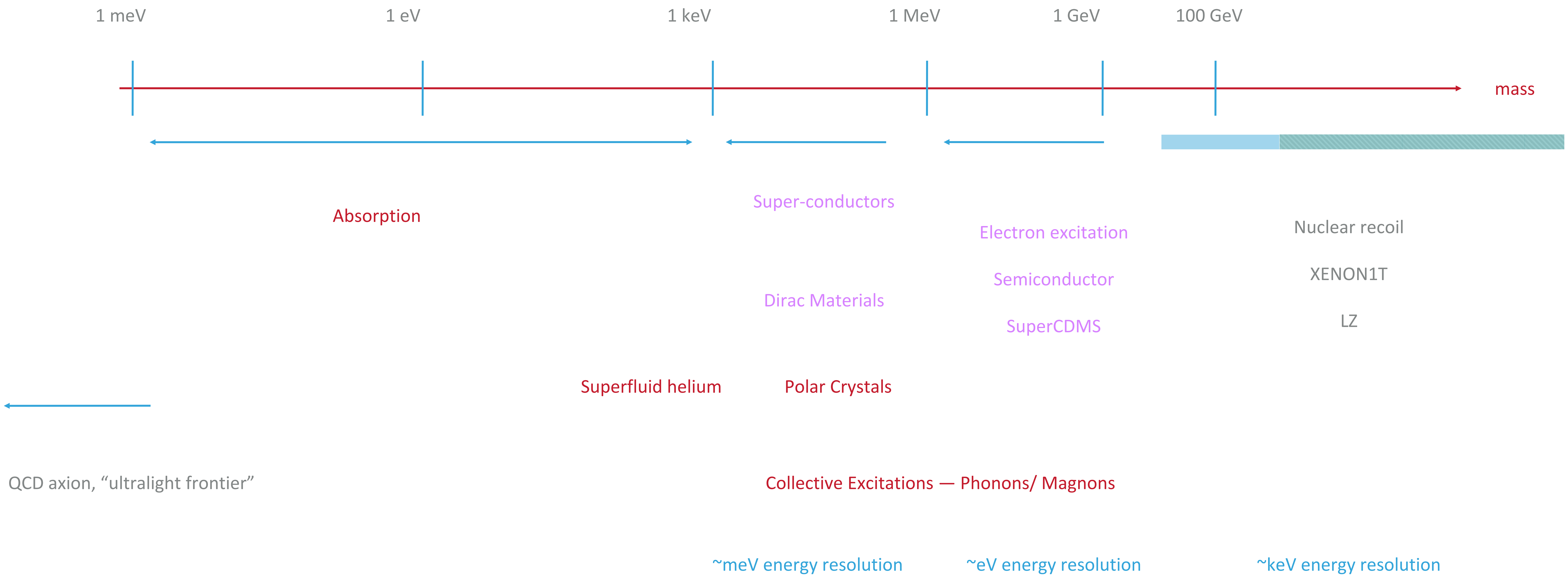


Trickle, Zhang, KZ, 1910.08092

$$\omega = \frac{2m_\chi^2 v^2}{m_N} \ll \frac{m_\chi v^2}{2}$$

The Landscape of sub-GeV Dark Matter Direct Detection

An understanding of condensed matter systems, and its collective behavior, is crucial



Absorption

Super-conductors

Dirac Materials

Superfluid helium

Polar Crystals

Electron excitation

Semiconductor

SuperCDMS

Nuclear recoil

XENON1T

LZ

QCD axion, “ultralight frontier”

Collective Excitations — Phonons/ Magnons

~meV energy resolution

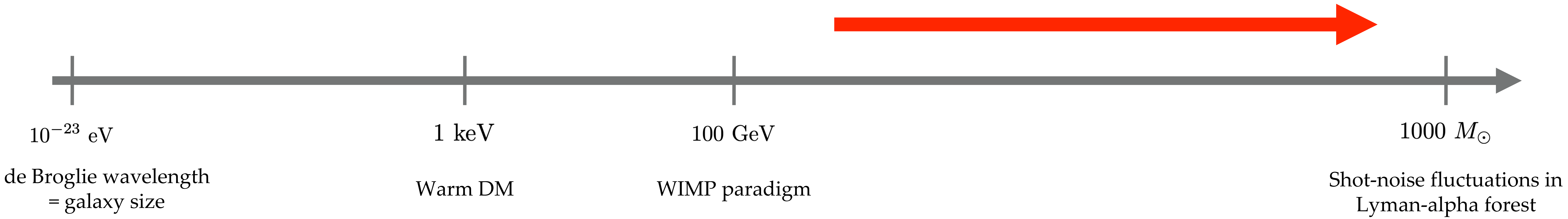
~eV energy resolution

~keV energy resolution

Models Best-Motivated by Relic Abundance Can be Reached with 1 kg-yr exposure

Dark Matter of a Very High Mass

Learning about Microscopic Properties of DM Through Gravitational Force



10^{-23} eV
de Broglie wavelength
= galaxy size

1 keV
Warm DM

100 GeV
WIMP paradigm

1000 $M_\odot$
Shot-noise fluctuations in
Lyman-alpha forest

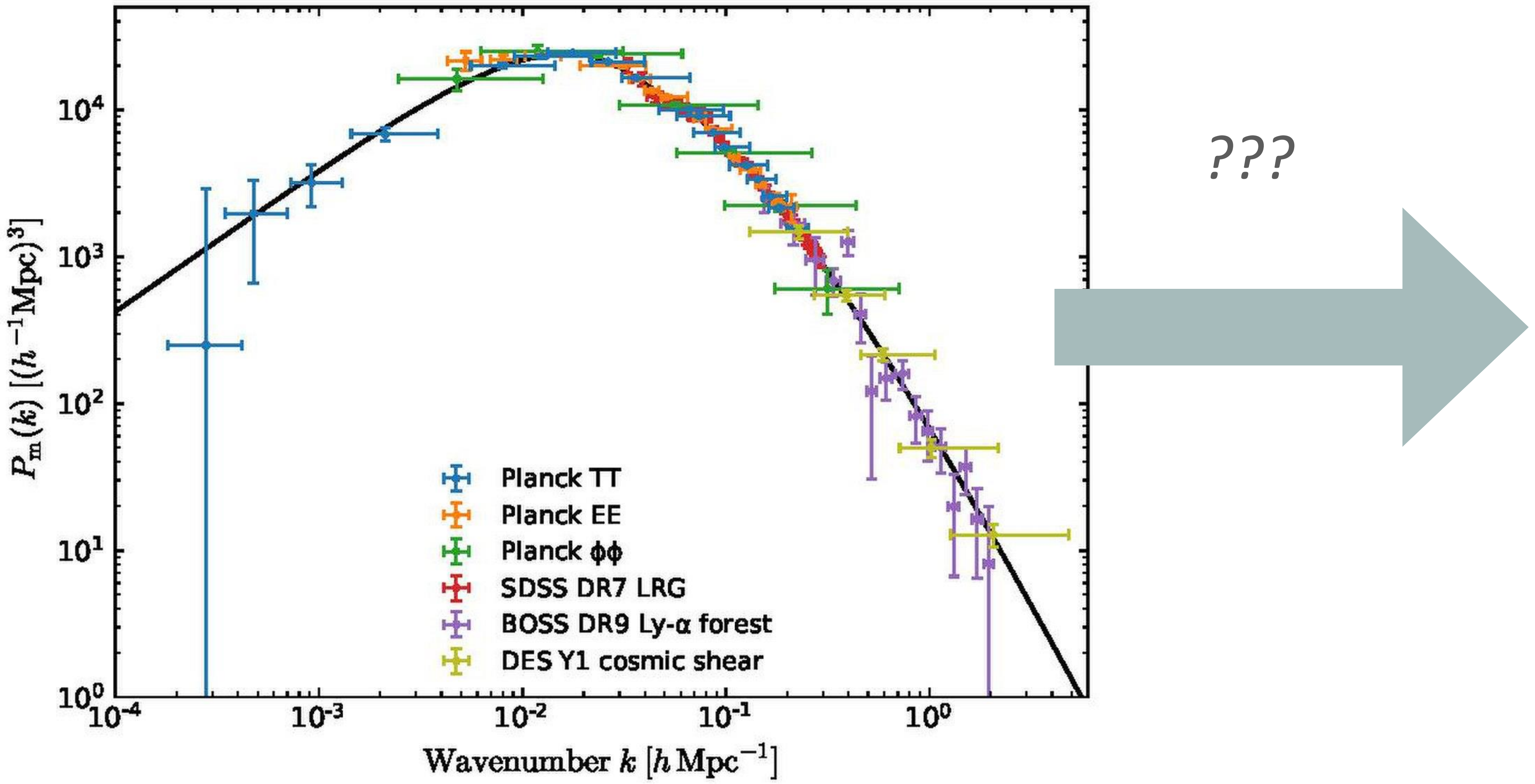
- It is challenging to set the relic abundance of DM through SM interactions when it is heavier than ~10 TeV, because cross-sections are not sufficiently large.

$$\langle \sigma v\rangle \simeq \frac{\pi\alpha_\chi^2}{m_\chi^2}\sqrt{1-\left(\frac{m_M}{m_\chi}\right)^2} \simeq 3\times 10^{-26}\,\frac{\text{cm}^3}{\text{s}}\left(\frac{g_\chi}{0.4}\right)^4\left(\frac{2\ \text{TeV}}{m_\chi}\right)^2$$

Gravitational Detection of DM

Microscopic Nature of DM Can Leave Imprints on Sub-Halos

- It might be possible to detect sub halos as light as $M \sim 10^{-13}\ M_\odot \sim 10^{44}\ \ \mathrm{GeV}$
- Many theories (e.g. PBH, axions, WDM, SIDM, early MD) predict different behavior than LambdaCDM at different sub-halo mass scales, requiring a wide range of new measurements of small scale power.

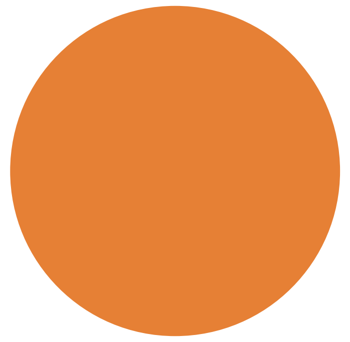


Challenge #6: Observe the Dark Matter Power on Small Scales

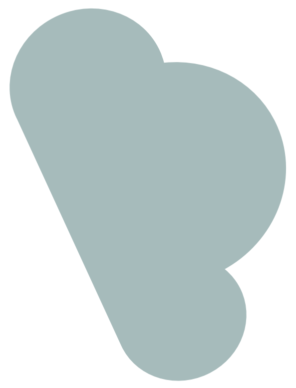
Dark Matter Substructure

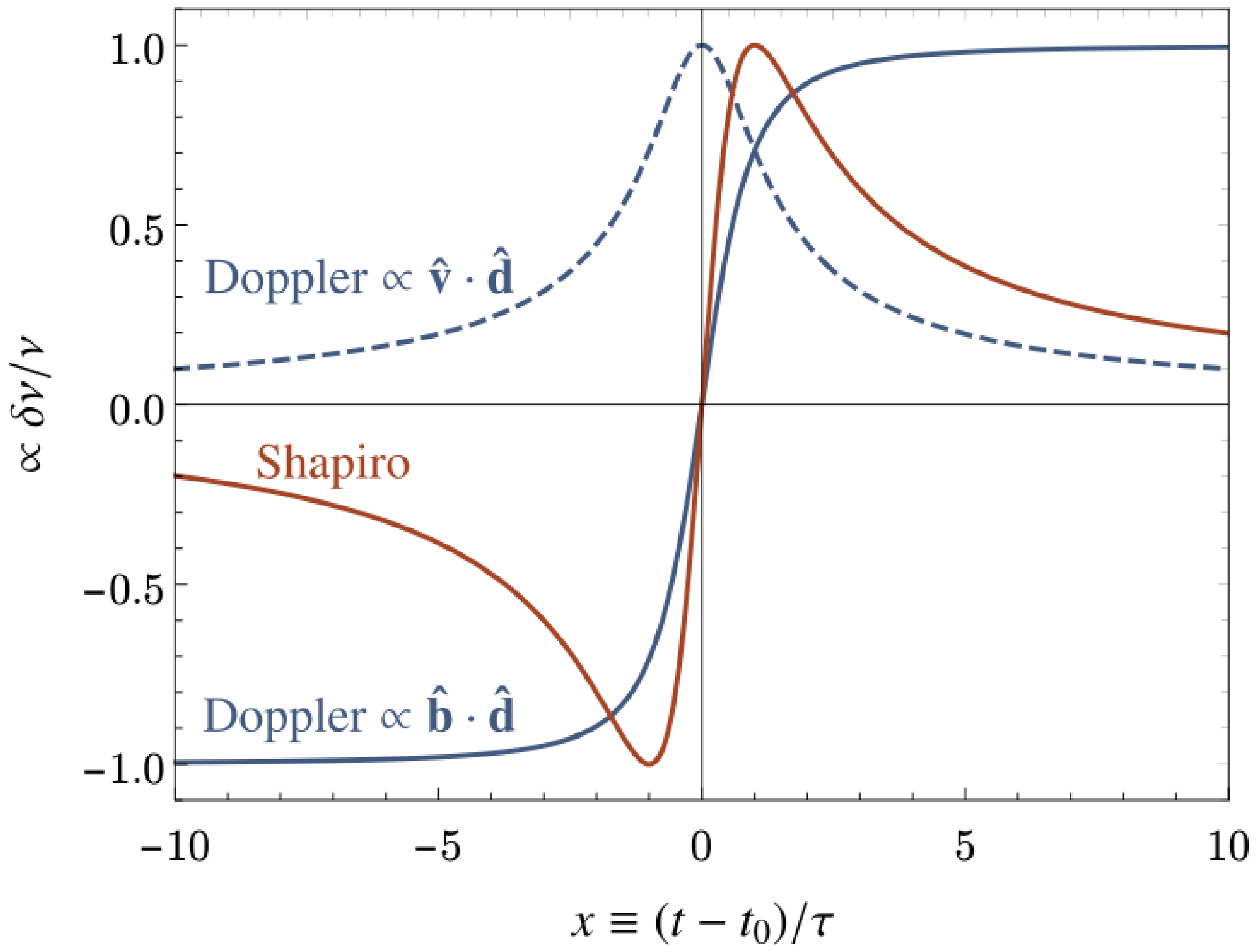
Observing DM substructure is a long-term, challenging but extremely important problem.

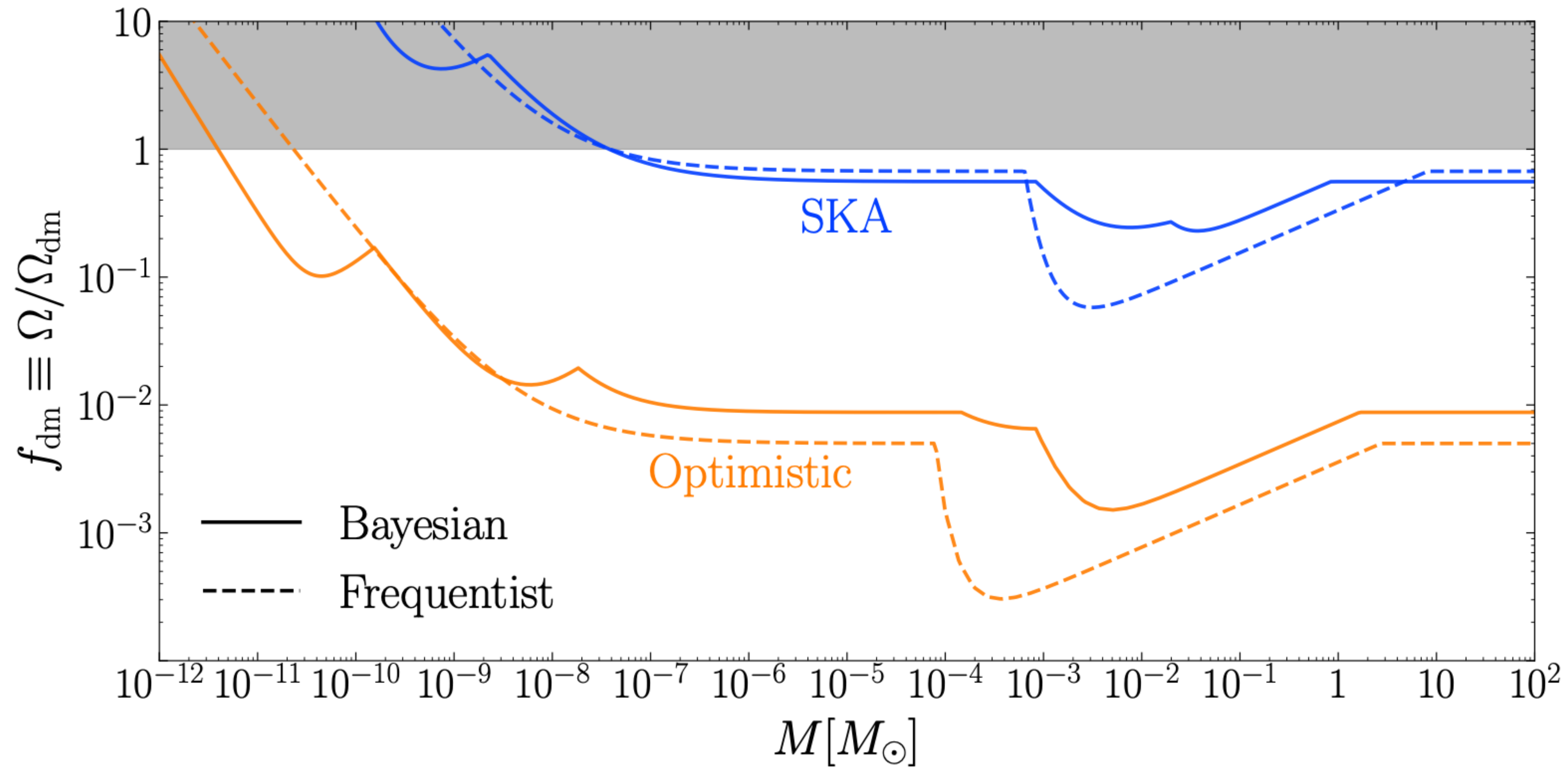
- All involve utilizing changes in the metric due to transiting DM substructure.
- e.g. Changes in pulse time-of-arrival due to metric fluctuations.



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





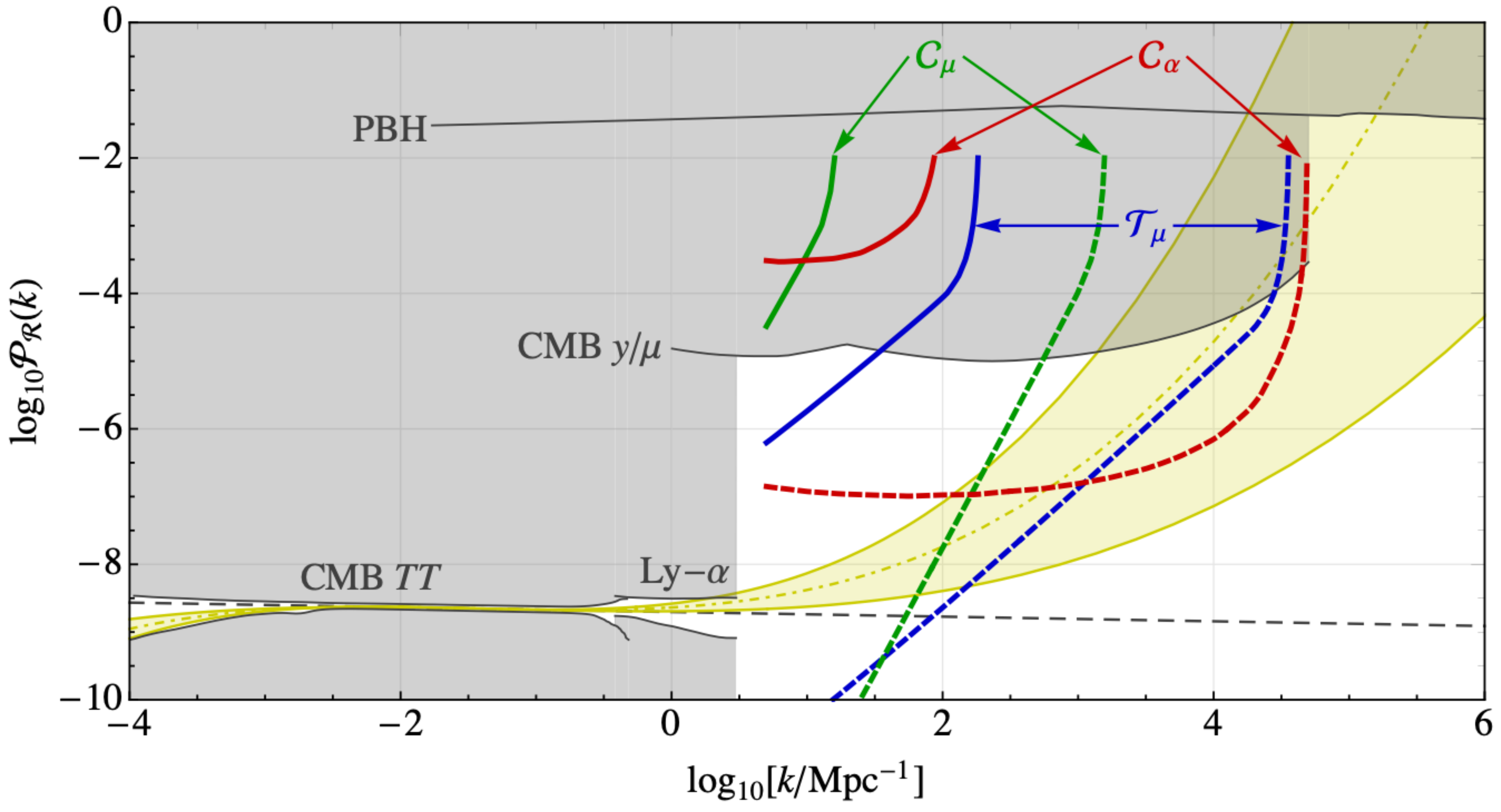


Lee, Taylor, Trickle, KZ 2104.05717

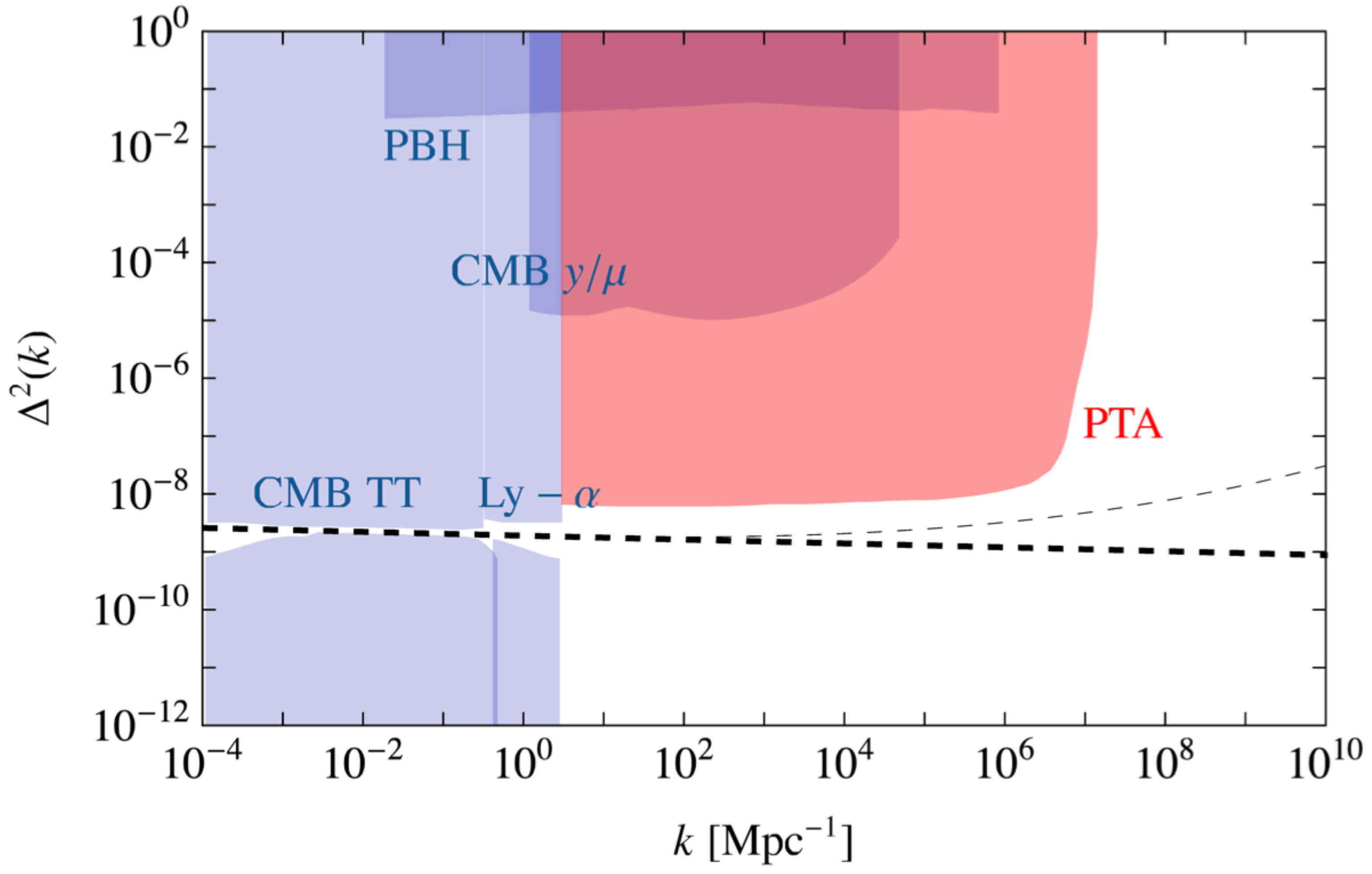
Dark Matter Substructure

Observing DM substructure is a long-term, challenging but extremely important problem.

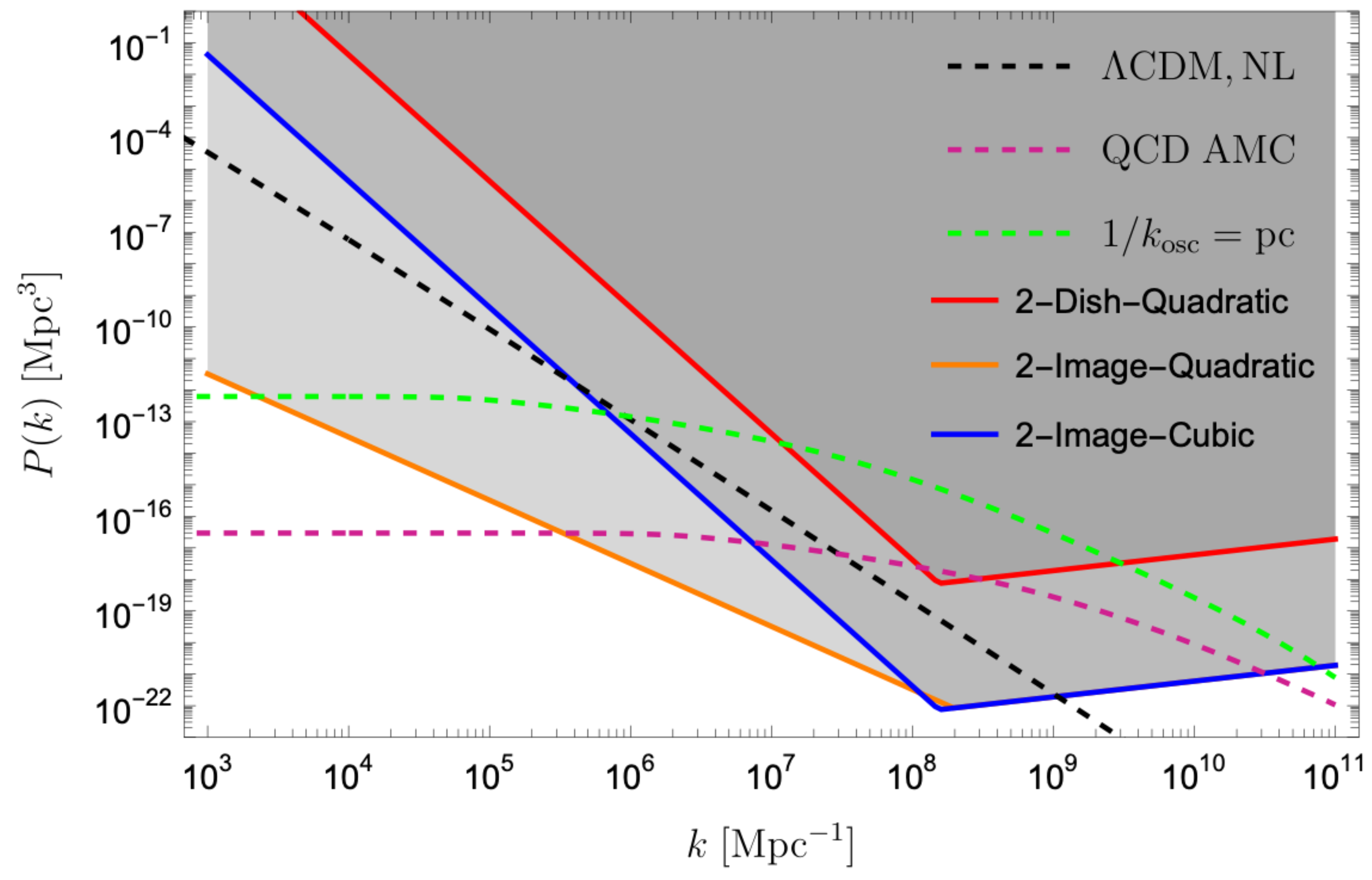
- All involve utilizing changes in the metric due to transiting DM substructure.
- Existing ideas involve astrometric lensing, PTAs, FRBs and make optimistic assumptions. How can we bring this closer to an achievable goal?



Tilburg, Taki, Weiner 1804.01991



Lee, Mitridate, Trickle, KZ 2012.09857

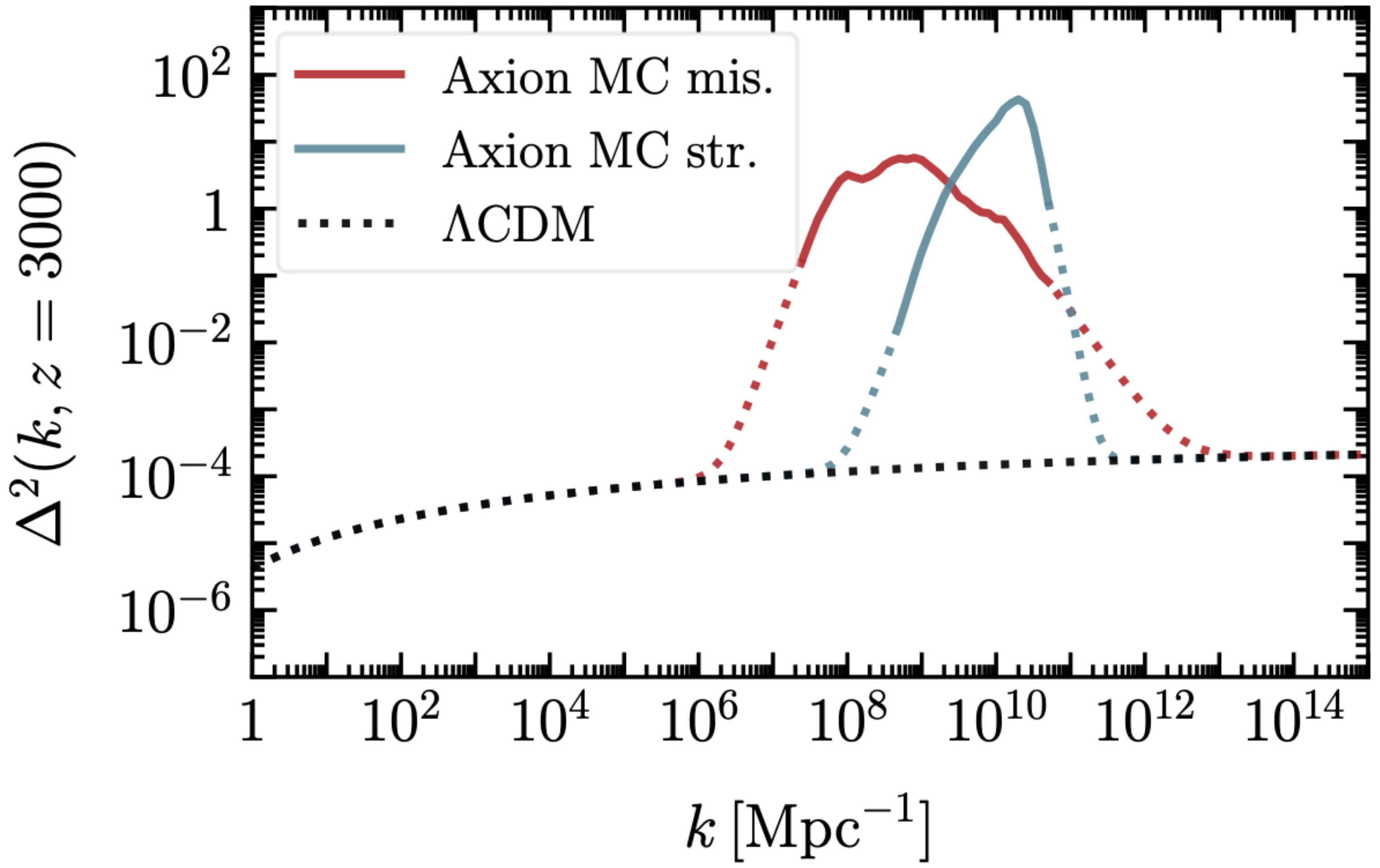


Xiao, Dai, McQuinn 2401.08862

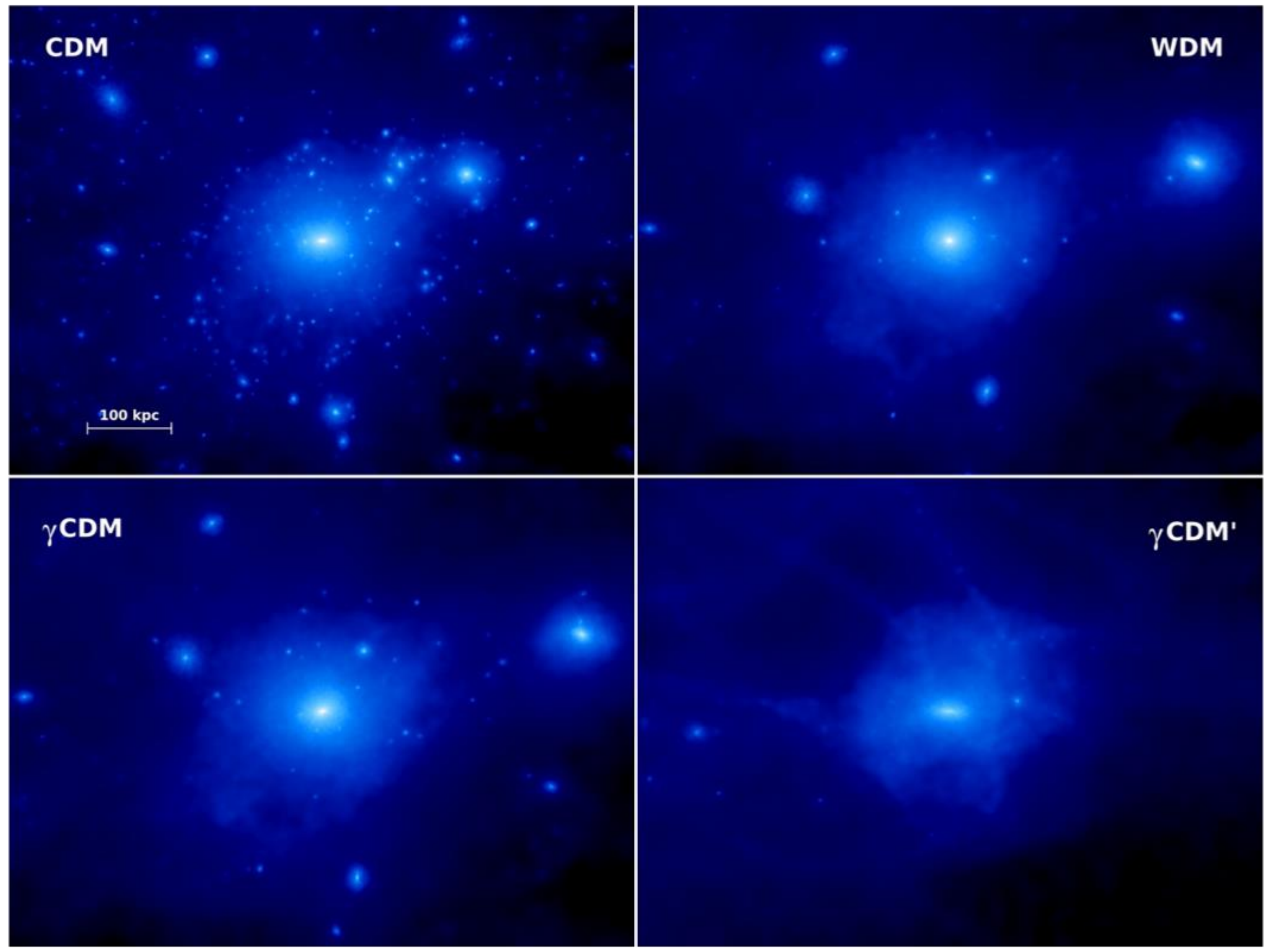
Dark Matter Substructure

Tests Microscopic Nature of Dark Matter

- LambdaCDM model predicts scale invariant power spectrum, and only gravitational dynamics in dark matter sub-halos.
- A measurement of the power spectrum on small scales is a gravitational imprint of the microphysical nature of dark matter



Lee, Mitridate, Trickle, KZ 2012.09857



Boehm et al 1404.7012

Challenge #7: Robustly Constrain Non-gravitational DM Self-interactions

Discussion

The Dark Matter Road Ahead

- A broad theoretical net has been cast.
- Many theory frameworks and ideas have been proposed to tile the astrophysically and cosmologically viable model space.
- The theoretical ideas for experiments to search for these theories are available, such as collective excitations.
- There is a well-defined and exciting experimental search program underway.
- This will remain an experimentally-driven field, with crucial theoretical support.