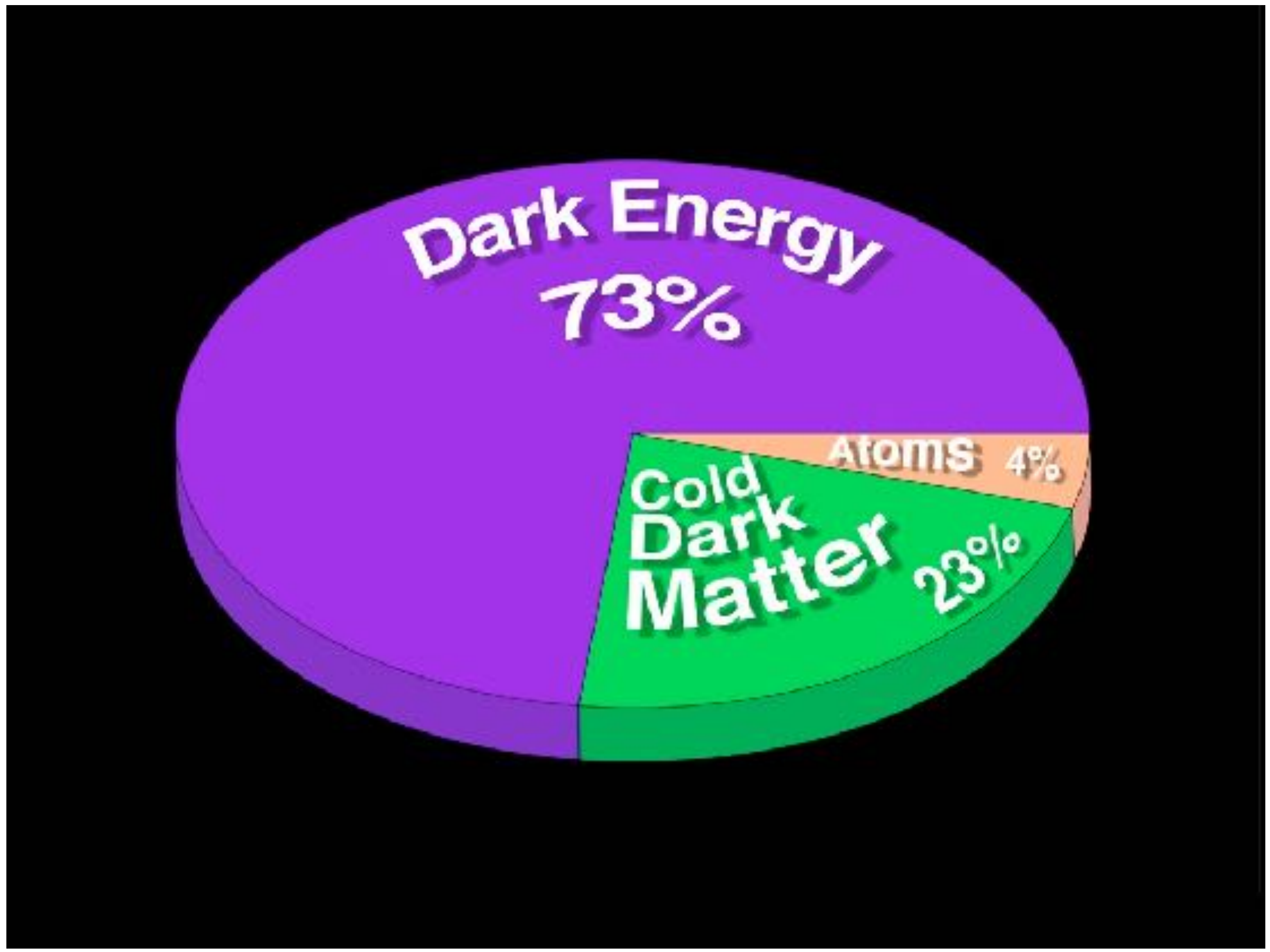
DARK SECTORS AND THEIR OBSERVABILITY

Kathryn M. Zurek

NEW PHYSICS

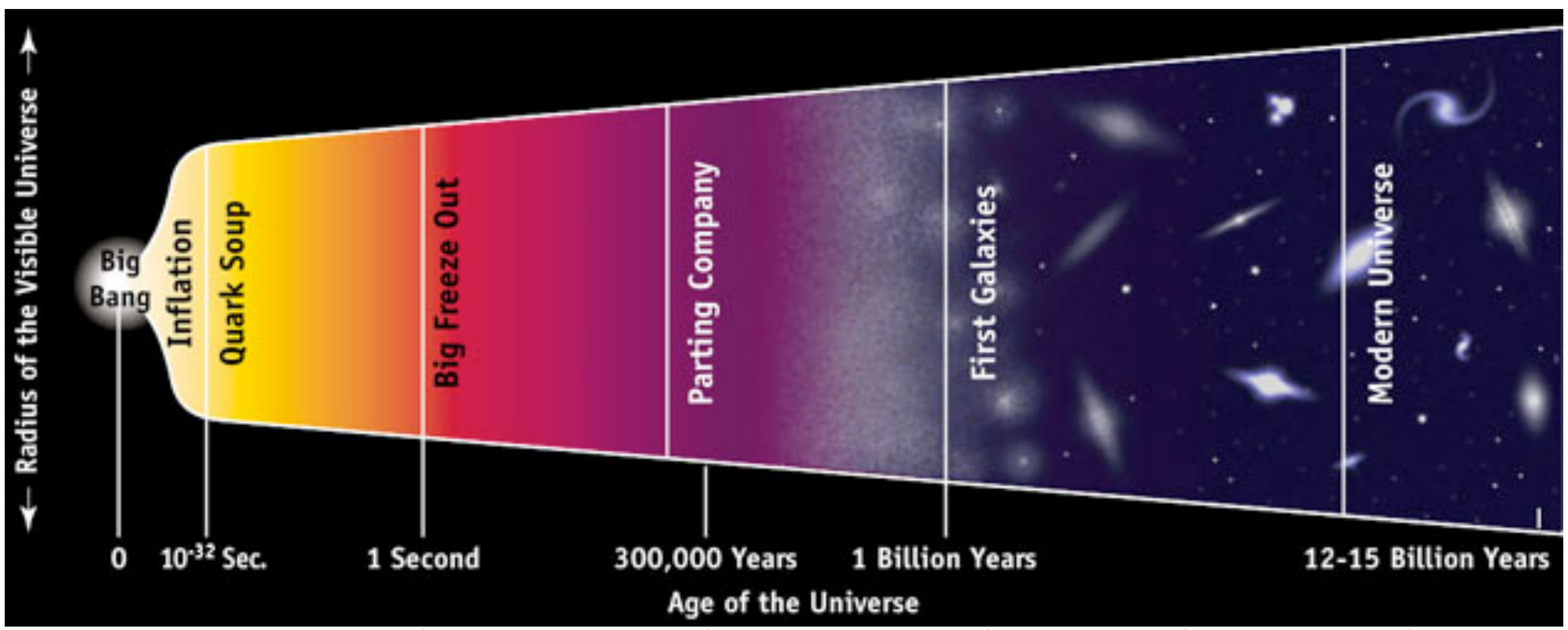
Dynamical
Selection?



New Dynamics
in Particles

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)

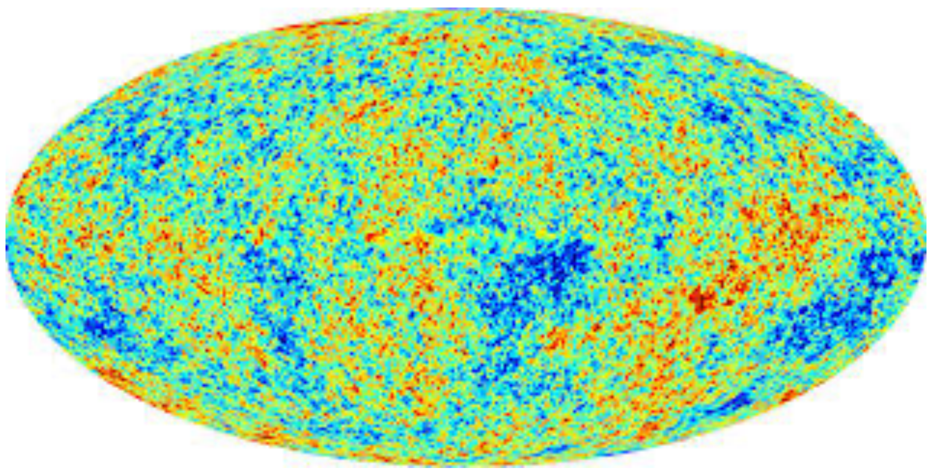
LSS (matter)

Supernovae (DE)

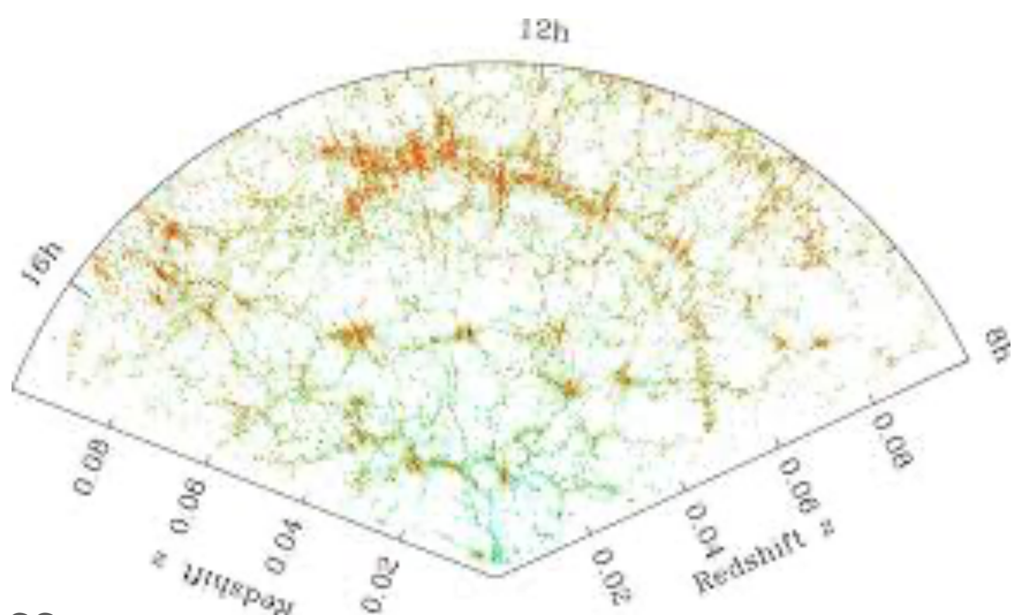
Galaxy curves (matter)

DARK MATTER HALOS AND FORMATION OF STRUCTURE IN THE UNIVERSE

On large scales, dark matter moves slowly (cold) and doesn't interact much other than with gravity (collisionless)



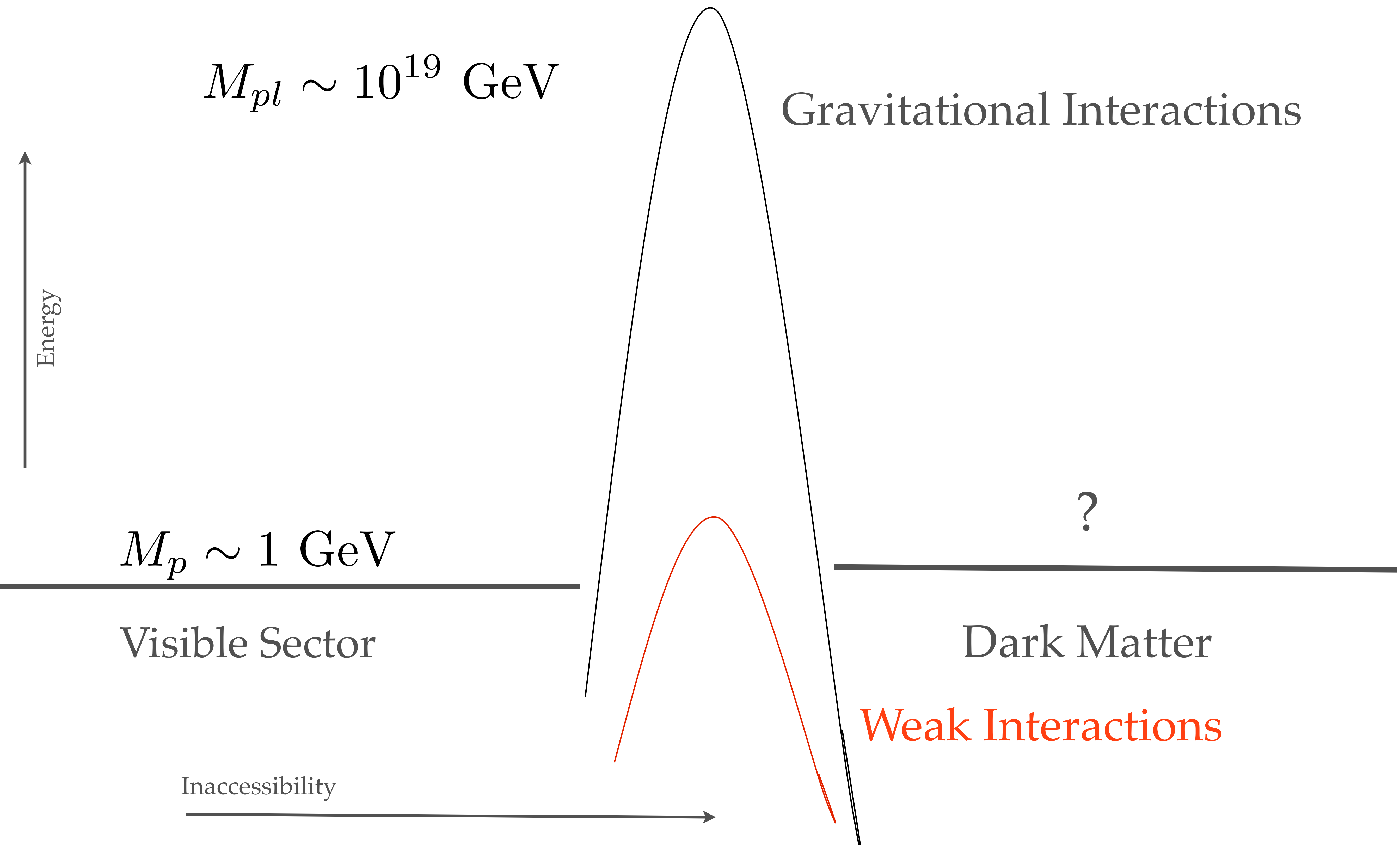
CMB Planck map



SDSS

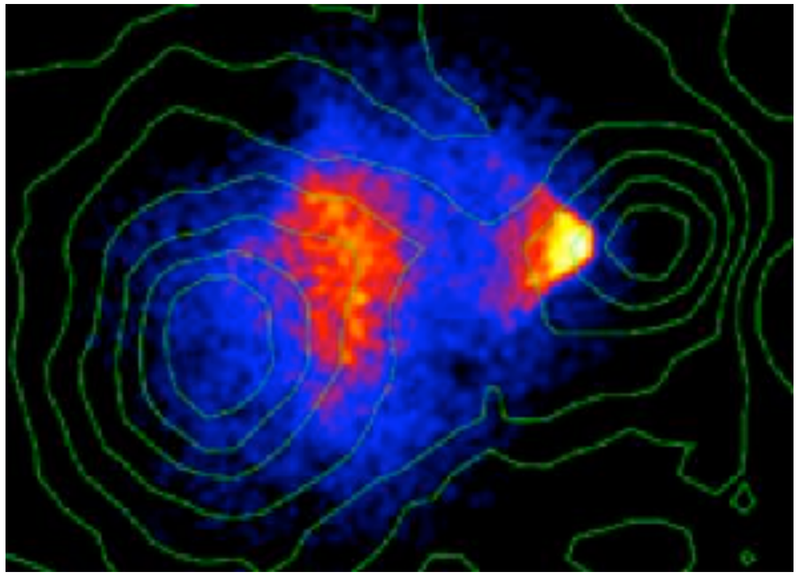
ESO/L Calcada

EVERYTHING WE KNOW ABOUT DM COMES FROM GRAVITY



SUPER-WEAKLY INTERACTING

- Gravitational Coherence ….



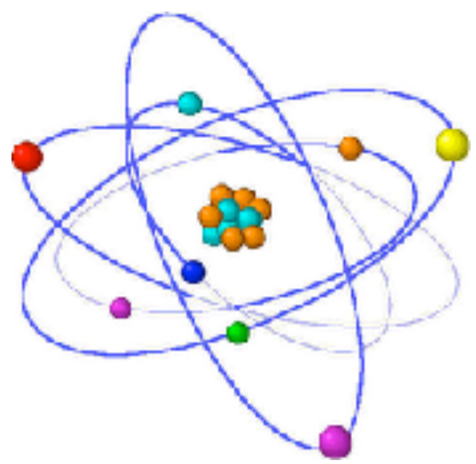
… on cosmological scales!

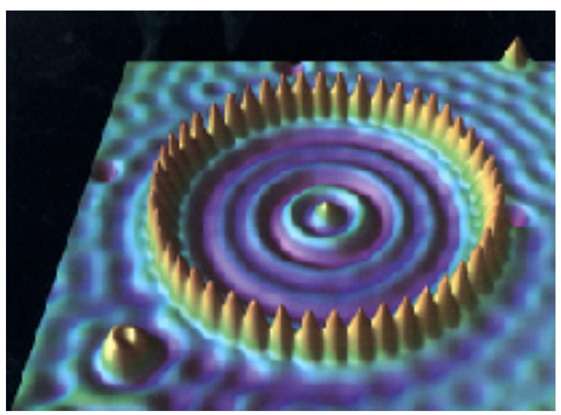
  - Helps us learn about aggregate properties of dark matter

- Particle properties much harder

- Fundamental premise: DM has interactions other than gravitational

PARTICLE PHYSICS PROVIDES SOME IDEAS



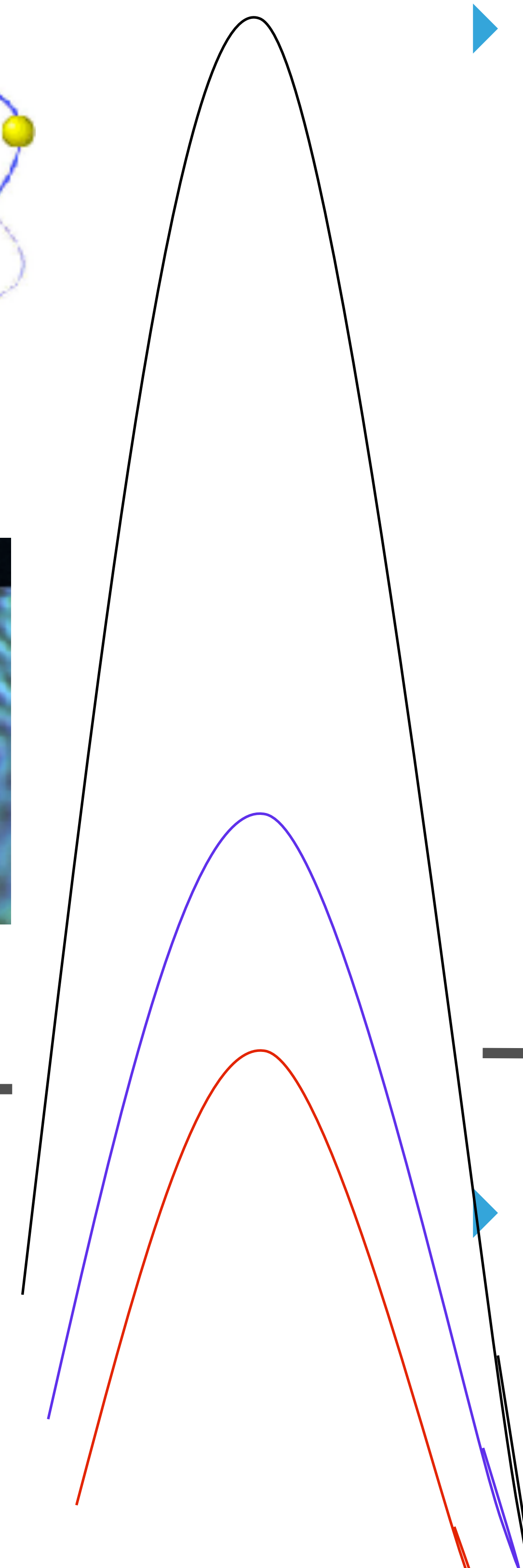


$M_p \sim 1 \text{ GeV}$

Visible Sector

Sub-weak Interactions

Weak Interactions



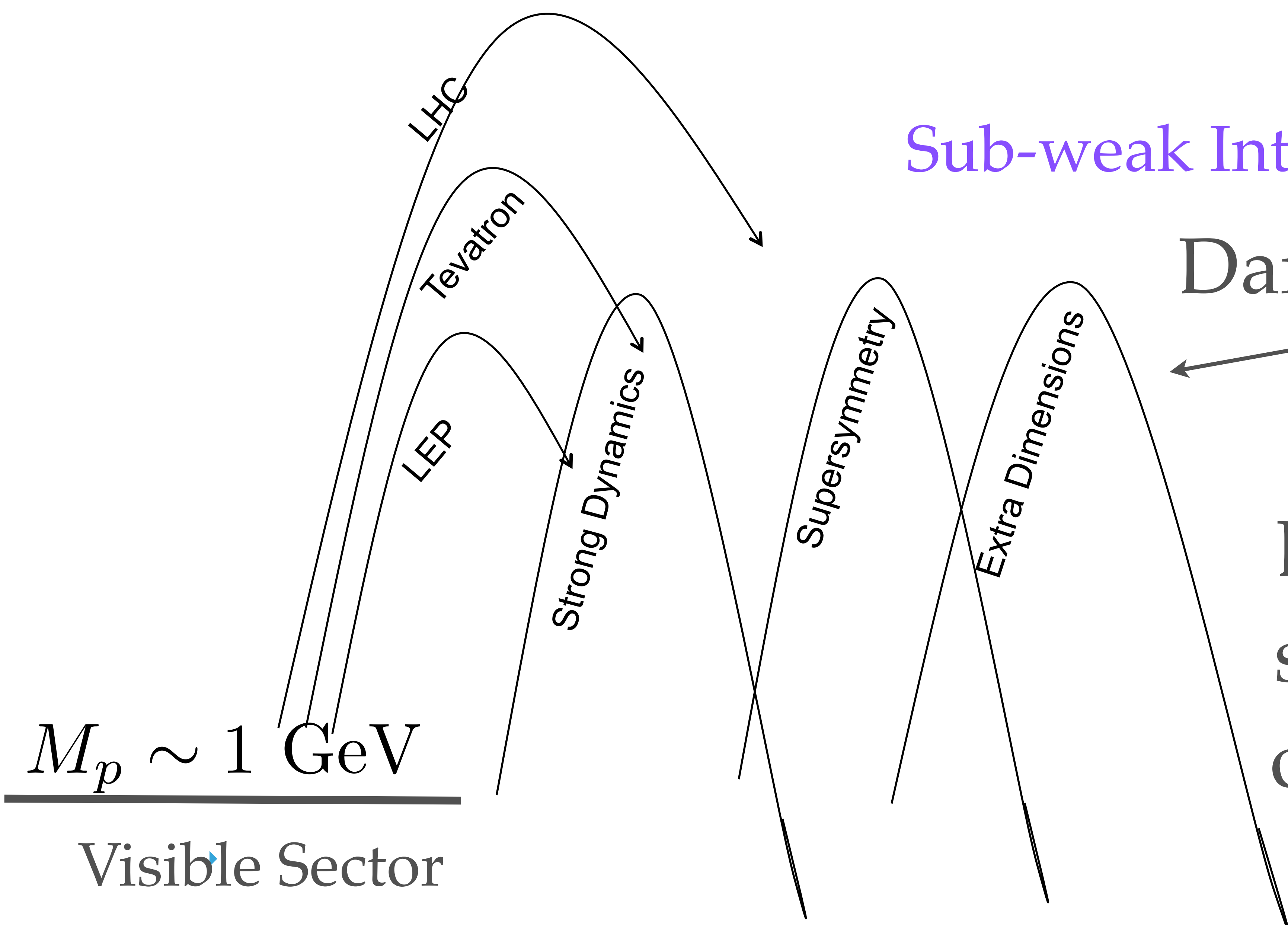
- Fundamental premise: DM has interactions other than gravitational

?

Dark Matter

PARTICLE PHYSICS PROVIDES SOME IDEAS

- Dark Matter is part of solution to “deeper” problems



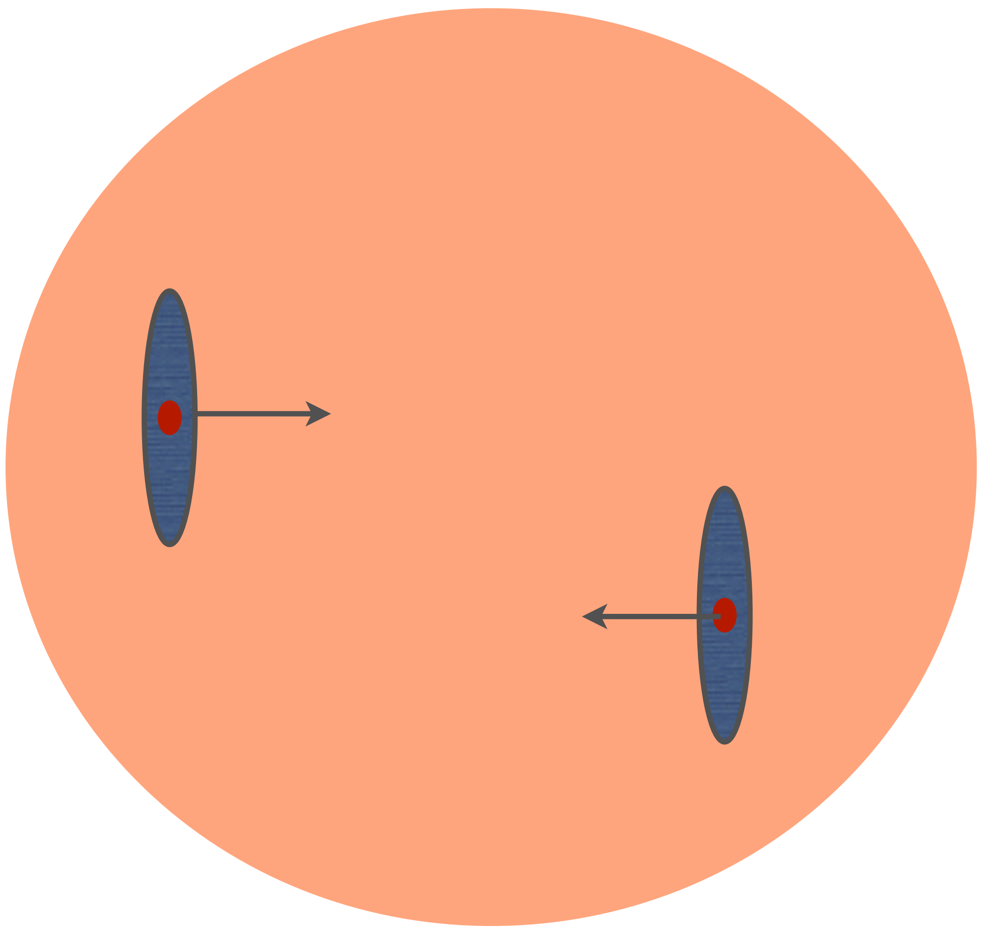
Sub-weak Interactions

Dark Matter Resides Here!

Dark Matter itself is simple, and *parasitic* on the Visible Sector

WHY THE (SUB-)WEAK SCALE IS COMPELLING

- Abundance of new stable states set by interaction rates *in the early universe*



Freeze-out

Dark matter energy density is measured

$$\Gamma = n\sigma v = H \qquad \Longrightarrow \sigma \sim \frac{g^4}{4\pi M^2} \sim \frac{1}{(20\ \mathrm{TeV})^2}$$

WHY THE (SUB-)WEAK SCALE IS COMPELLING

- No new dynamics required from the Dark Matter!
- Forces for the dynamics is provided by the weak force
- As a byproduct, this scenario is *quite predictive*
- *When looking for Dark Matter it helps to know what you are looking for!*

DARK MATTER DETECTION: A FULL COURT PRESS

10^{-23} eV

(deBroglie wavelength of galaxy)

100 GeV

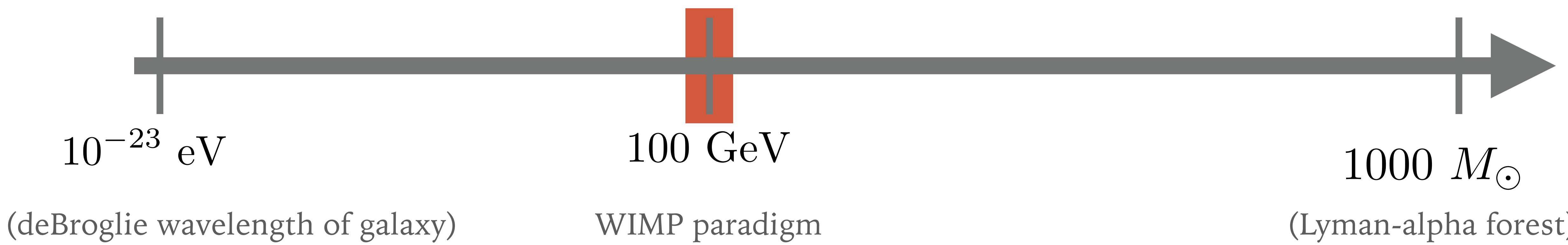
WIMP paradigm

$1000\ M_\odot$

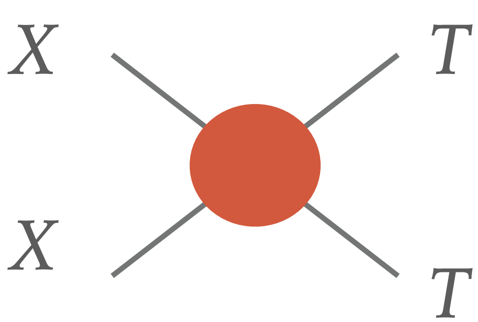
(Lyman-alpha forest)

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

DARK MATTER DETECTION: A FULL COURT PRESS



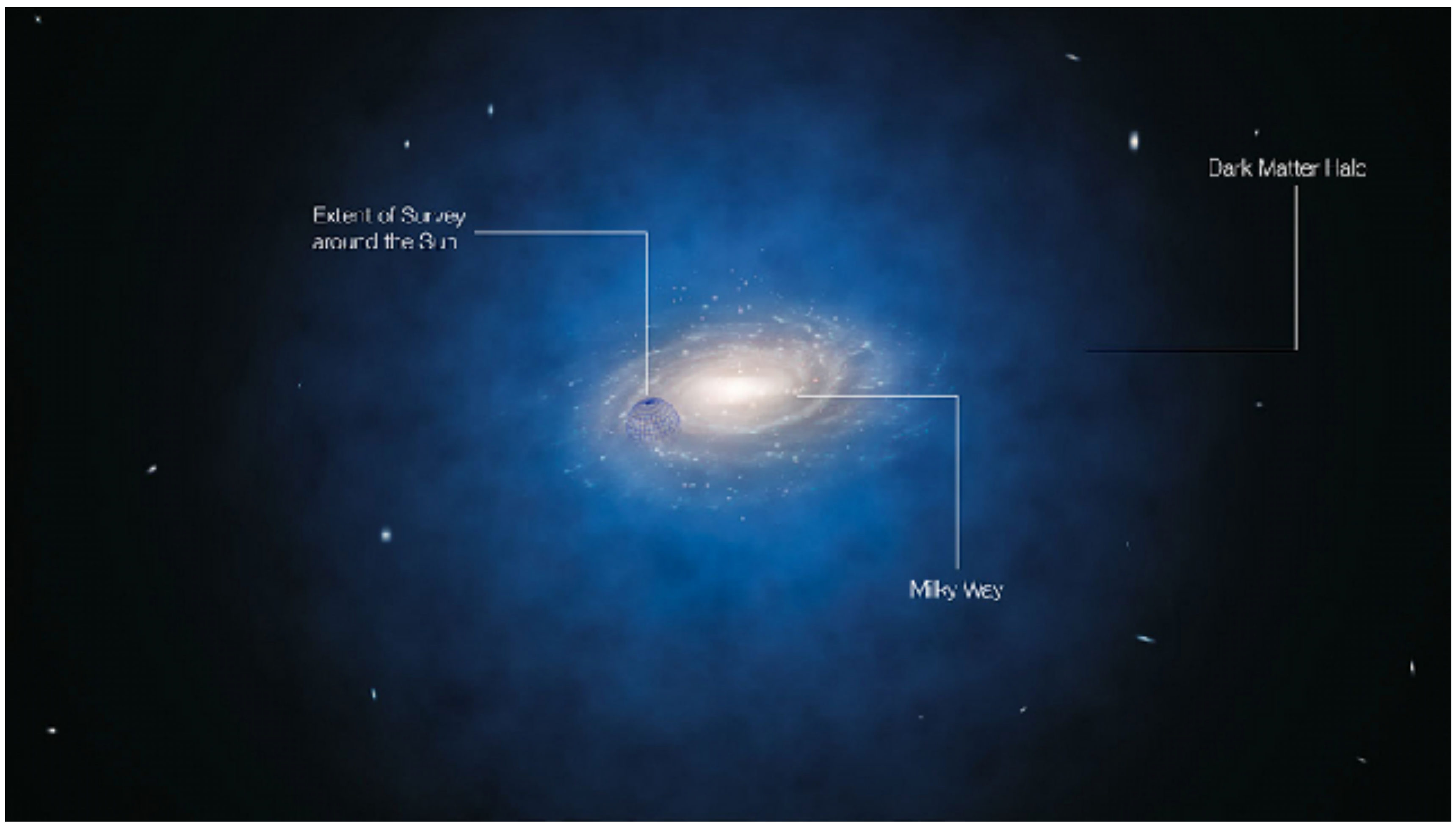
- WIMP paradigm: a good place to start looking
- Reason: weak forces have the right scale, for detection, abundance, and cosmology



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

DETECTION OF DARK MATTER BY NUCLEAR RECOIL

- Milky way galaxy provides a source of dark matter streaming through the earth

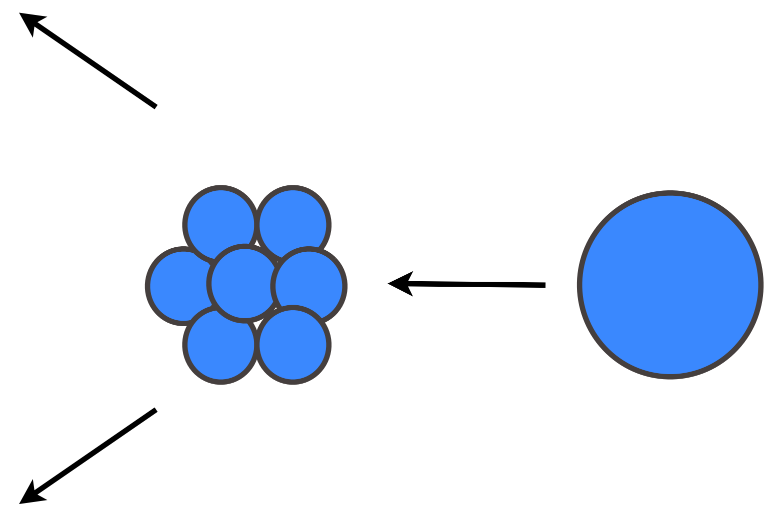


$$v \sim 300 \text{ km/s} \sim 10^{-3}c$$

DETECTION OF DARK MATTER BY NUCLEAR RECOIL

- Nuclear recoil experiments: a billiard ball experiment

$q, \ E_D$



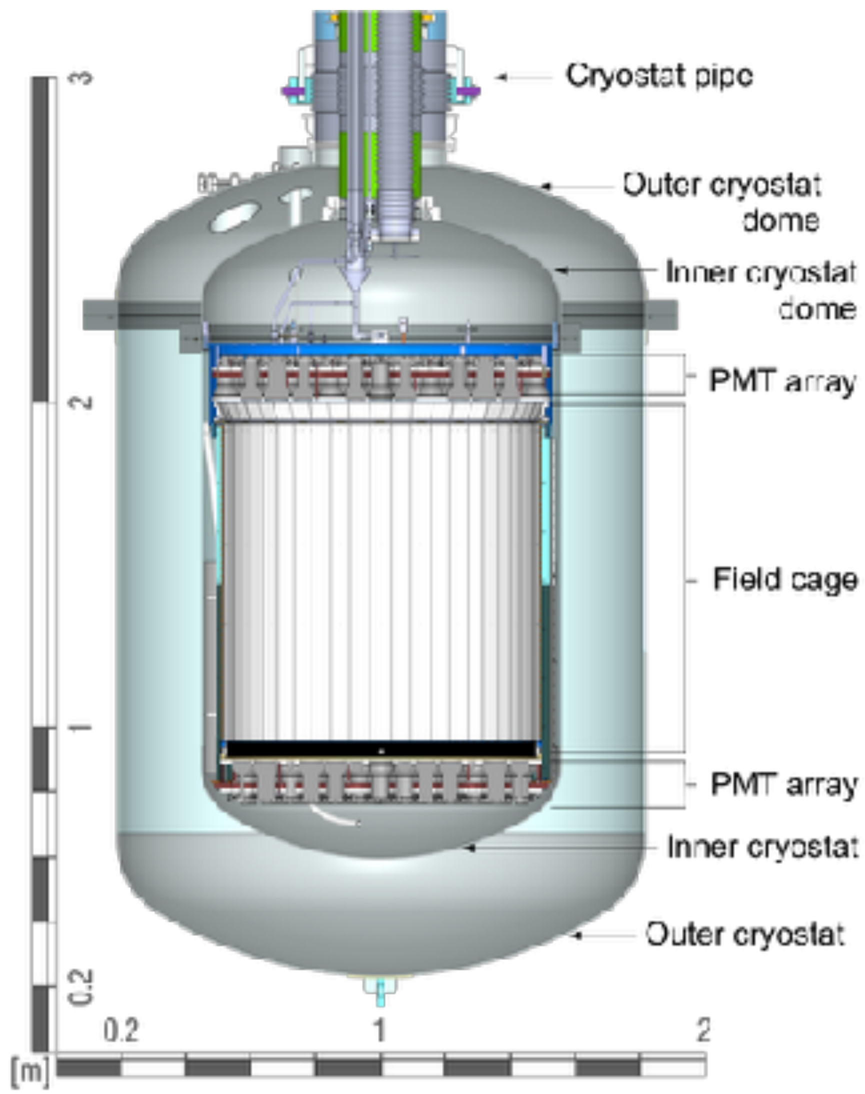
$v \sim 10^{-3} c$

$$v \sim 300 \ \mathrm{km/s} \sim 10^{-3} c \quad \Longrightarrow \quad E_D \sim 100 \ \mathrm{keV}$$

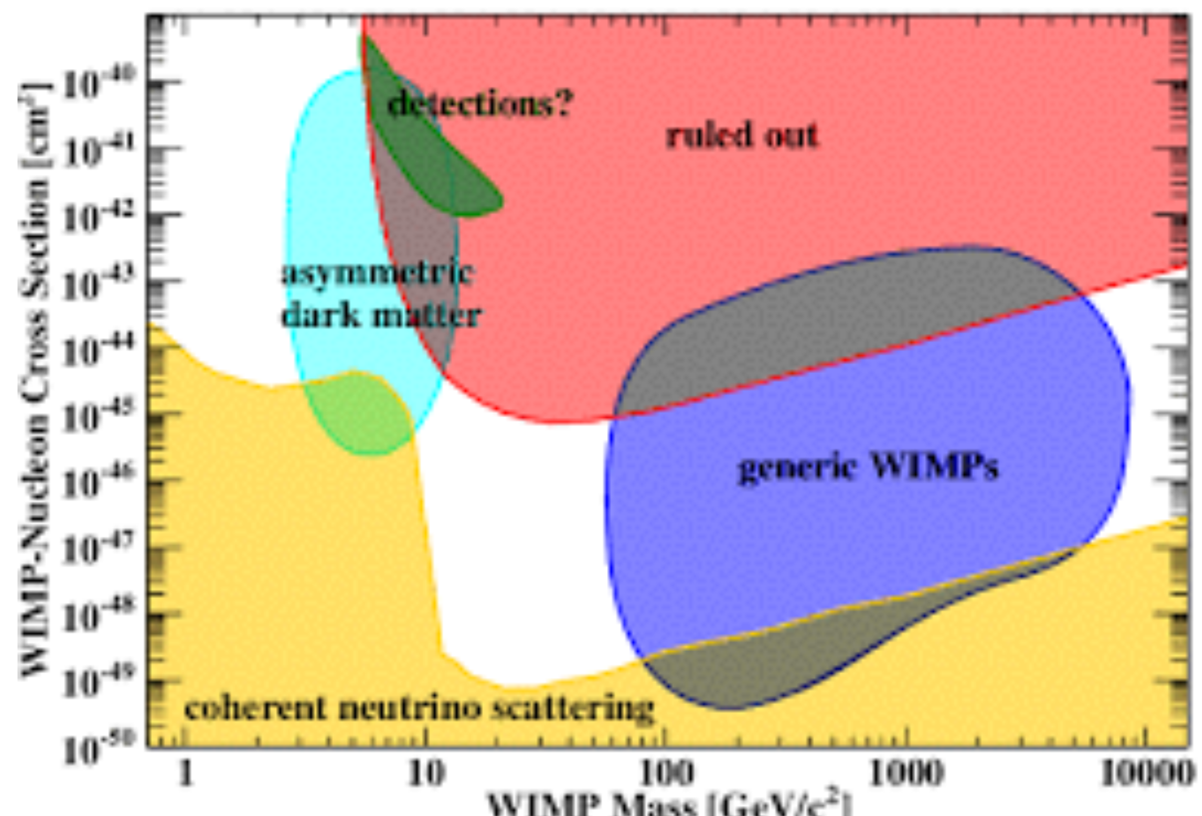
$$E_D = \frac{q^2}{2 m_N} \qquad\qquad q_{\mathrm{max}} = 2 m_X v$$

THEORY AND EXPERIMENT INTERPLAY

- Predictive Dark Matter Interaction Rates



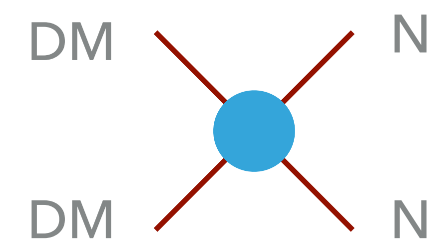
XENON



APS Physics Today

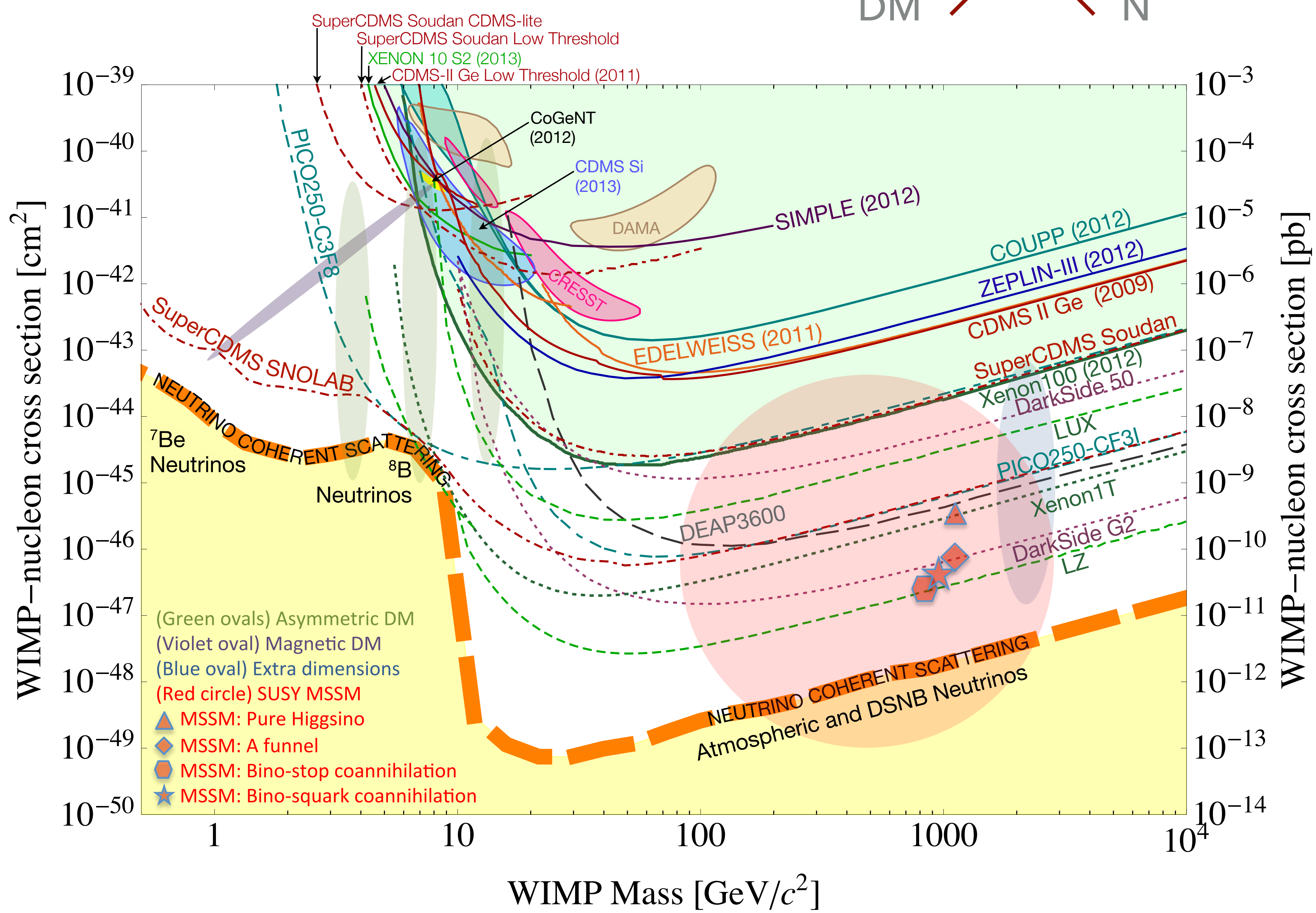
THEORY AND EXPERIMENT INTERPLAY

- Predictive Dark Matter Interaction Rates

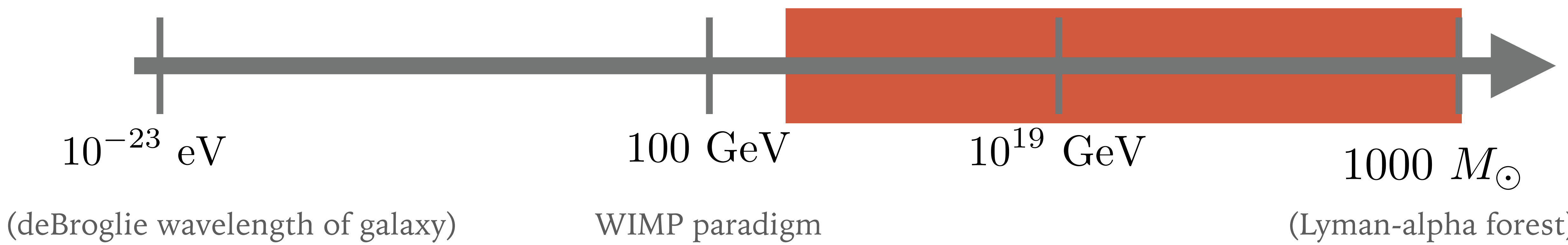


Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



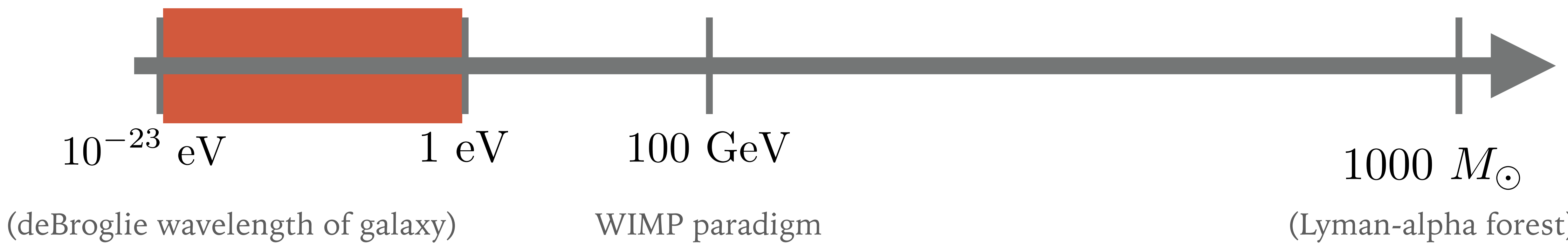
DARK MATTER DETECTION: A FULL COURT PRESS



$$\Gamma = n\sigma v = H \qquad \Longrightarrow \sigma \sim \frac{1}{(20\ \mathrm{TeV})^2}$$

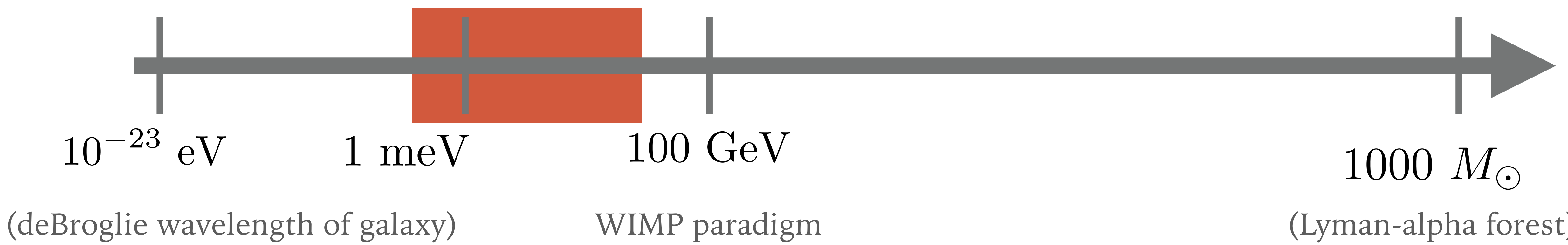
- Heavier dark matter: setting relic abundance through interactions with Standard Model is challenging
- At heavier masses, detection through Standard Model interactions is (generally) not motivated by abundance

DARK MATTER DETECTION: A FULL COURT PRESS



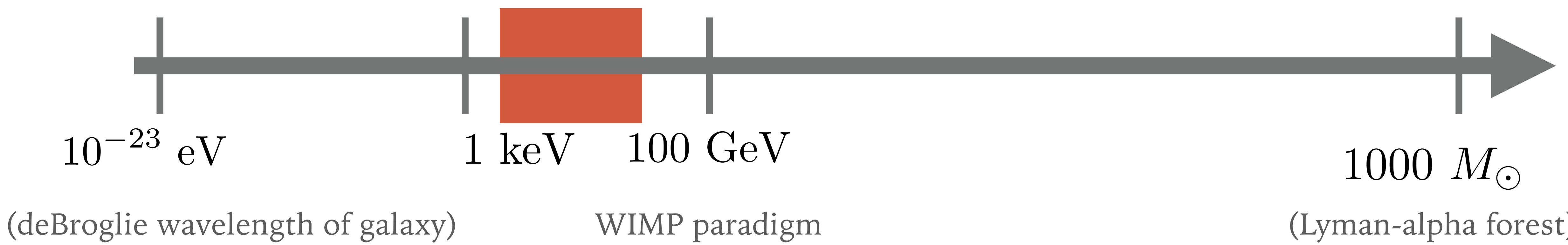
- Ultralight dark matter: dark matter behaves like a wave rather than an individual particle, e.g. axion
- Detection techniques focus on utilizing this coherence
- Cavities, AMO techniques

DARK MATTER DETECTION: A FULL COURT PRESS



- Focus on an 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.

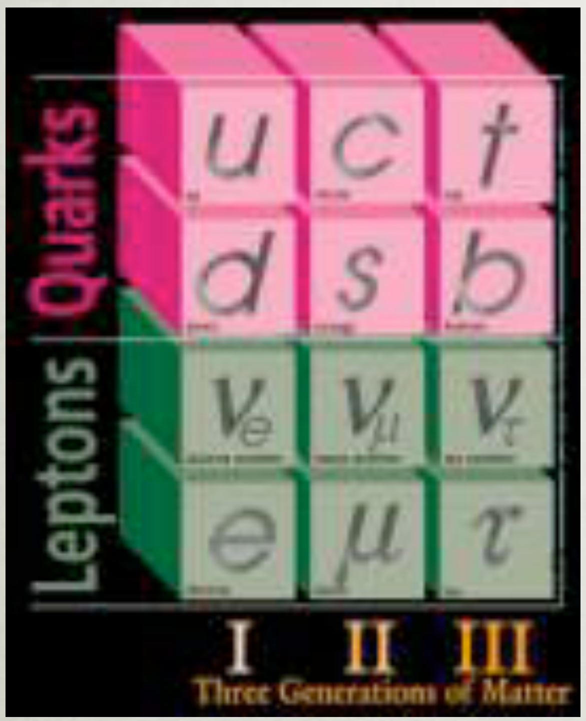
$$\sigma_{str} \simeq \frac{4\pi\alpha_s^2}{M^2} \simeq 10^{-24}\ \mathrm{cm}^2 \left(\frac{1\ \mathrm{GeV}}{M}\right)^2$$

- 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

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 .....

$M_p \sim 1$ GeV

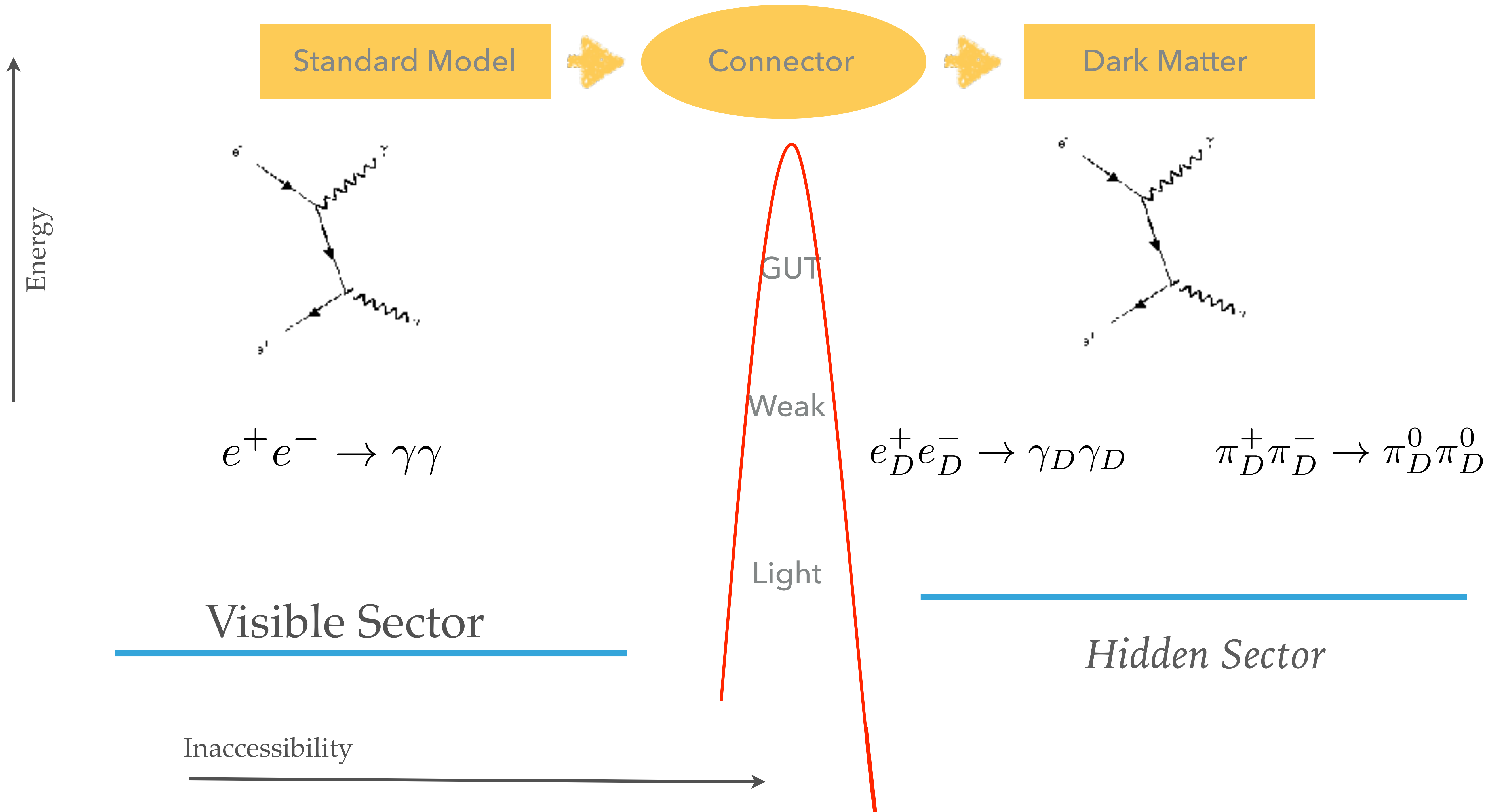
Standard Model

...to a hidden world with multiple states, new interactions

Inaccessibility

HIDDEN SECTOR / VALLEY

- Presence of dark force allows for many new dark matter theories



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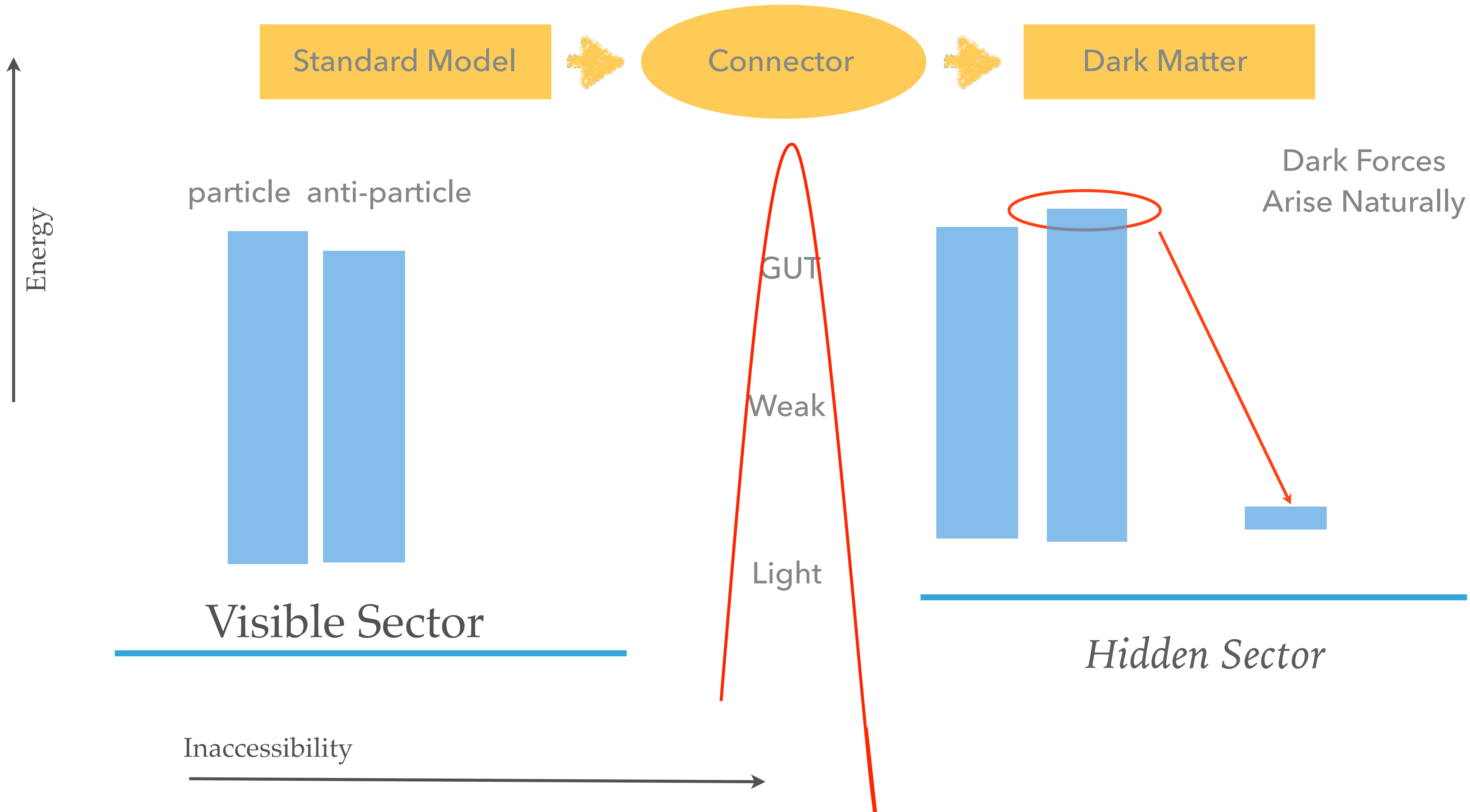
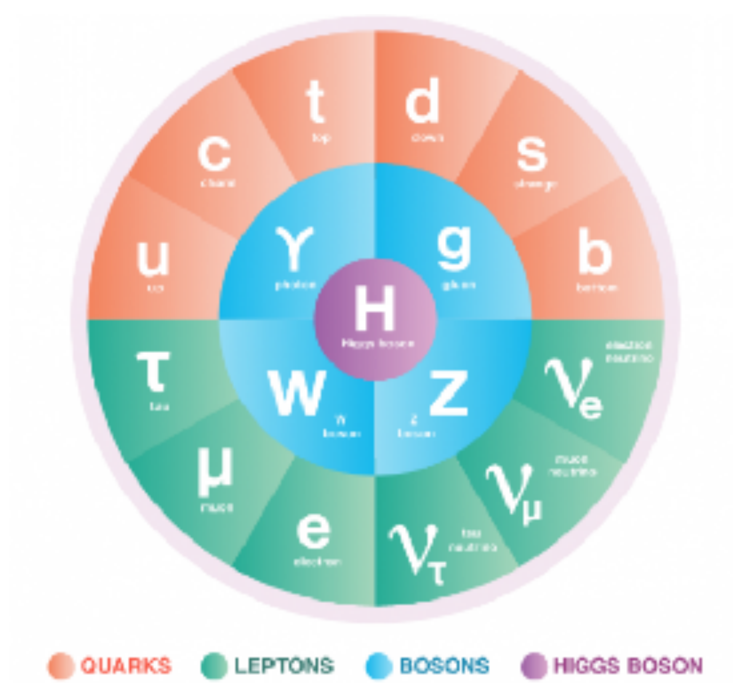


HIDDEN SECTOR / VALLEY

- Presence of dark force allows to lower mass scale in DM sector; dramatically opens possible DM theories

Standard Model → Connector → Dark Matter

Energy



GUT

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

Weak

Dark photons, Freeze-in, WIMPless miracle

Light

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

Visible Sector

Hidden Sector

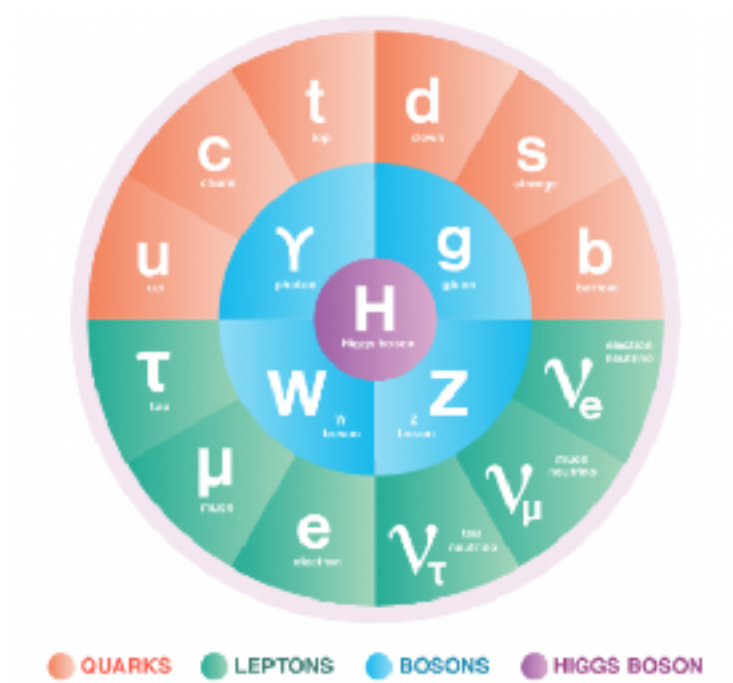
Inaccessibility

HIDDEN SECTOR / VALLEY

- When is it worth realizing a new model of dark matter?

Standard Model → Connector → Dark Matter

Energy



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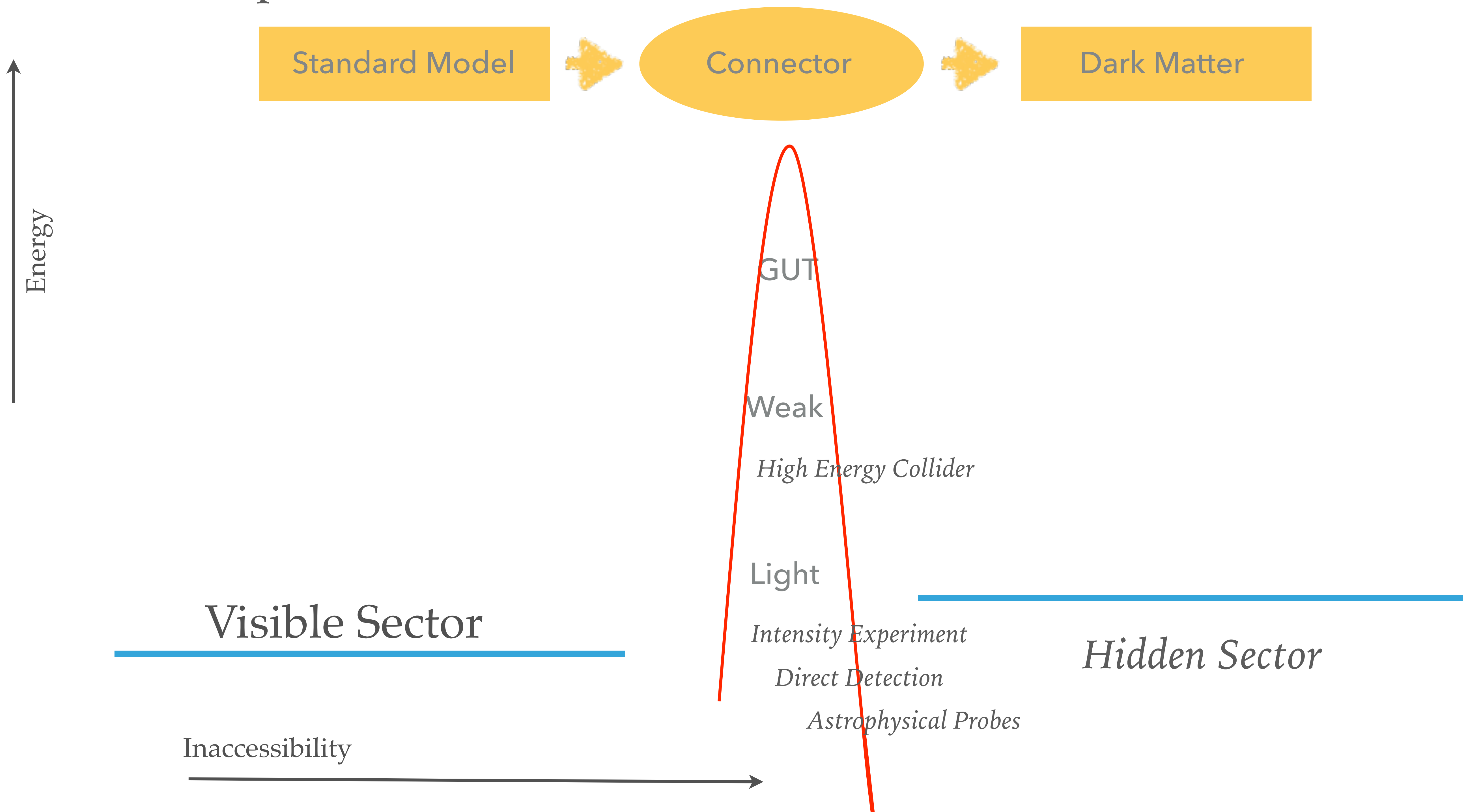
Visible Sector

Hidden Sector

Inaccessibility

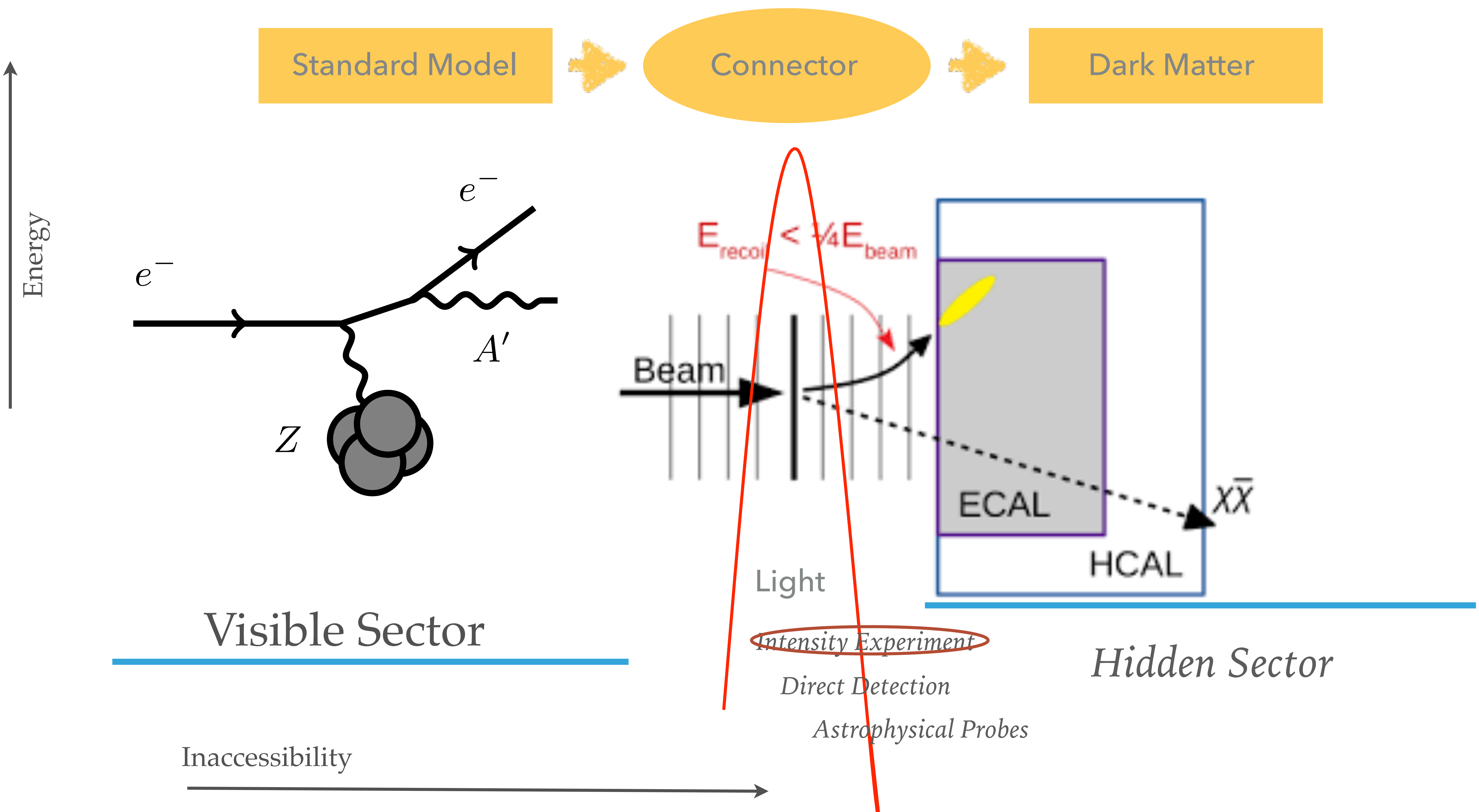
TERRESTRIAL EXPERIMENTS

- New Hidden Sector Mechanisms Require New Experimental or Observational Probes



TERRESTRIAL EXPERIMENTS

- Probe dark sector via rare tunneling process at low energy



TERRESTRIAL EXPERIMENTS

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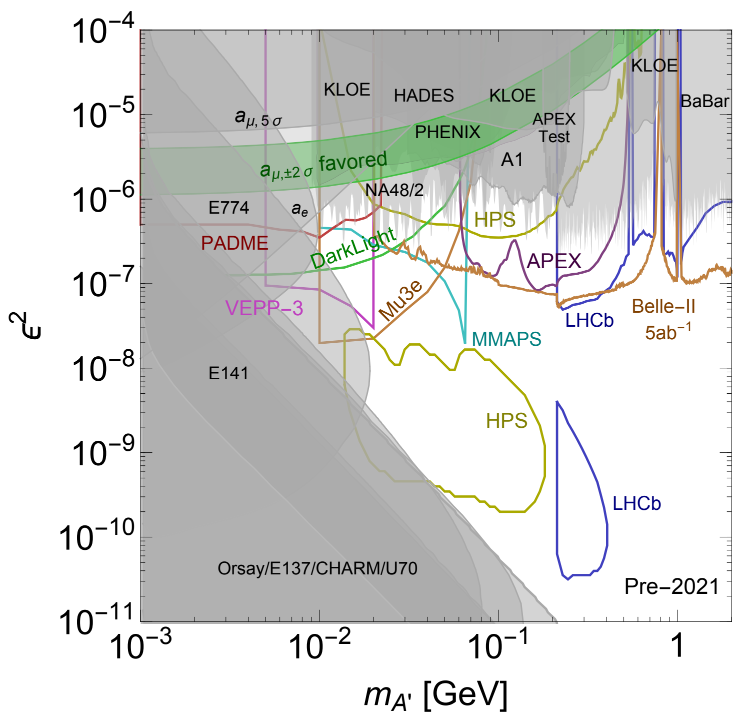
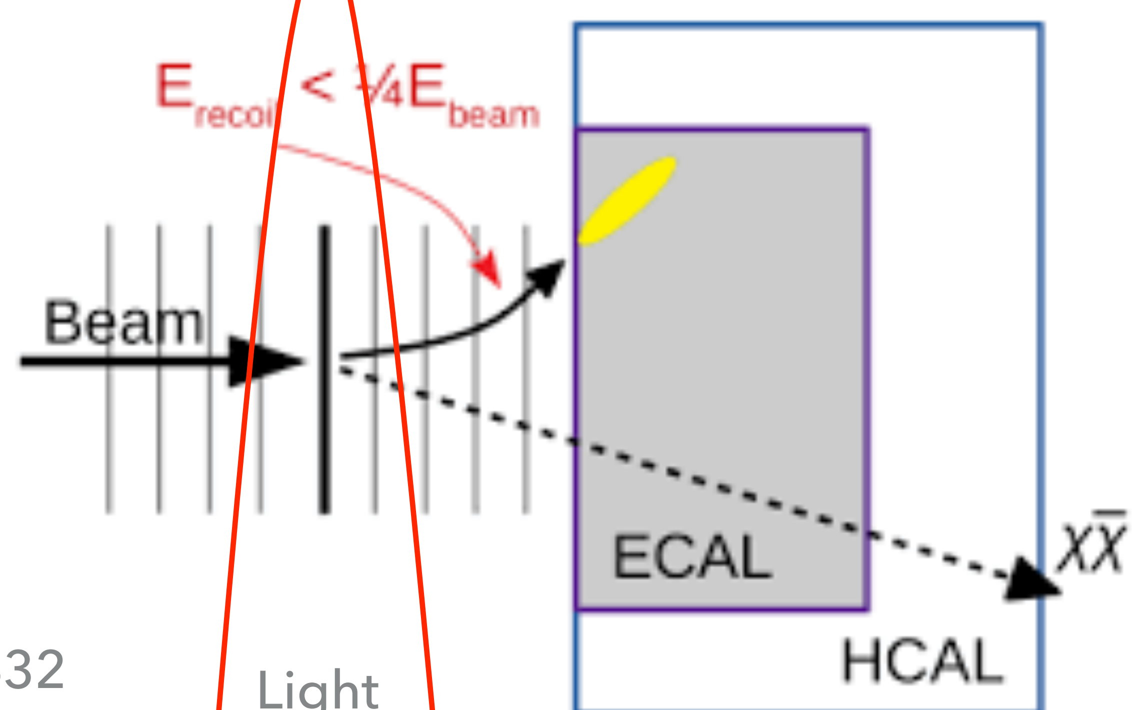
Standard Model → Connector → Dark Matter

Energy



Dark Sectors community report 1608.08632

Visible Sector



Light

Intensity Experiment

Direct Detection

Astrophysical Probes

Hidden Sector

Inaccessibility

TERRESTRIAL EXPERIMENTS

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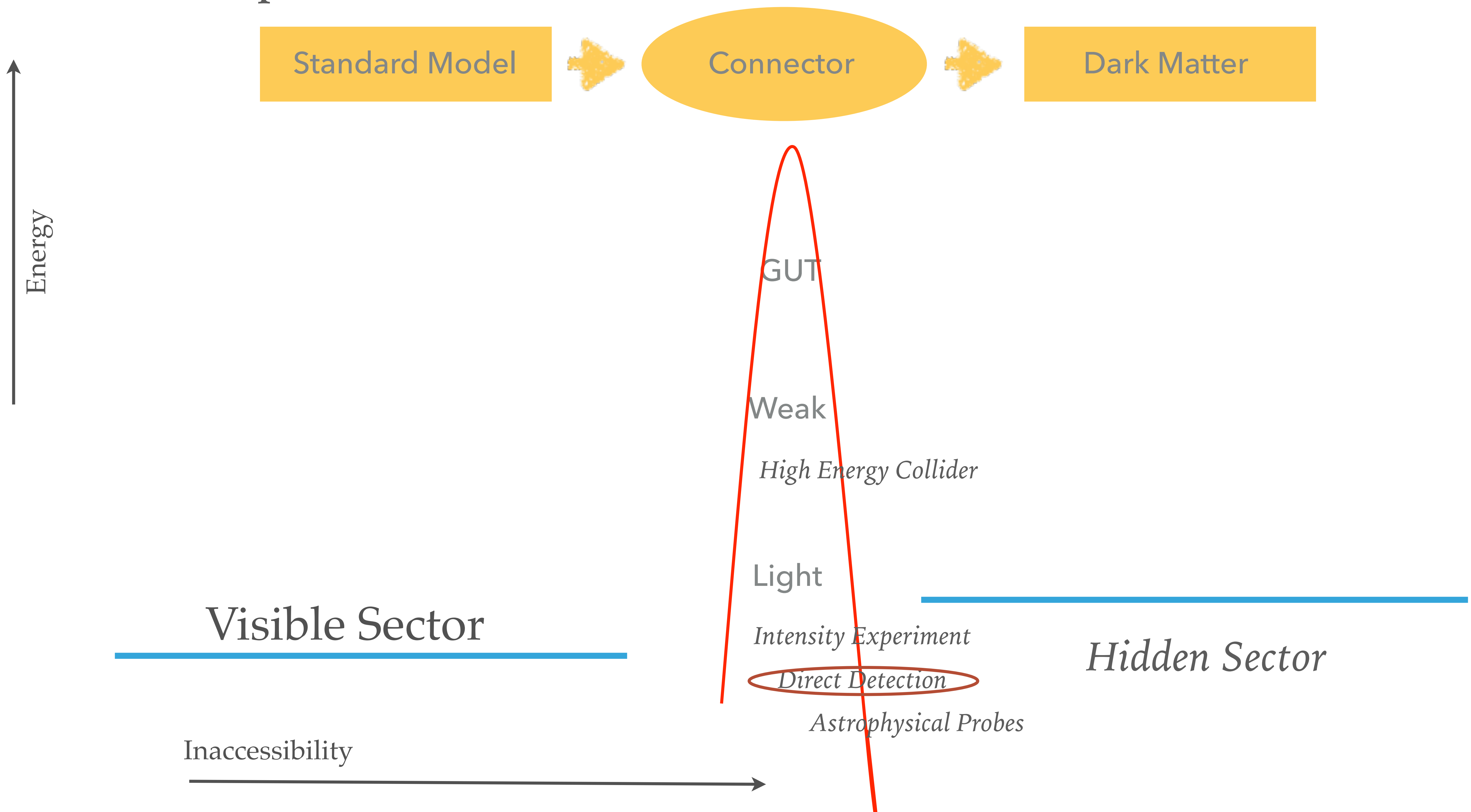
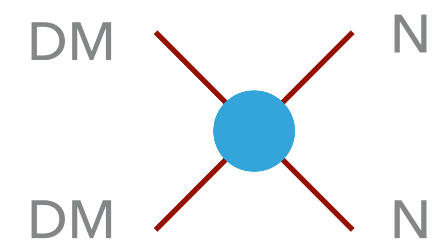
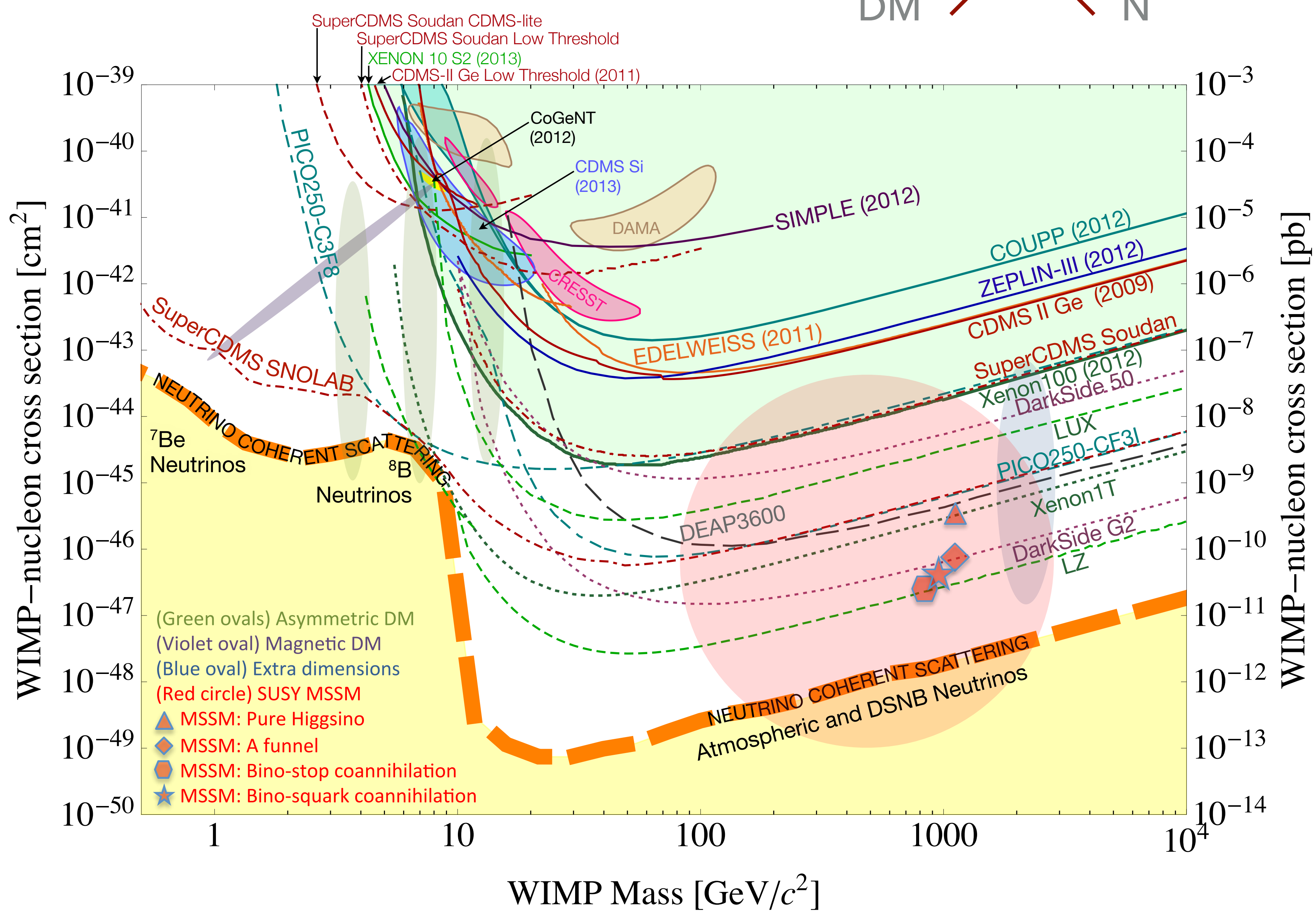


TOWARDS HIDDEN SECTOR DARK MATTER

- Push towards light dark matter

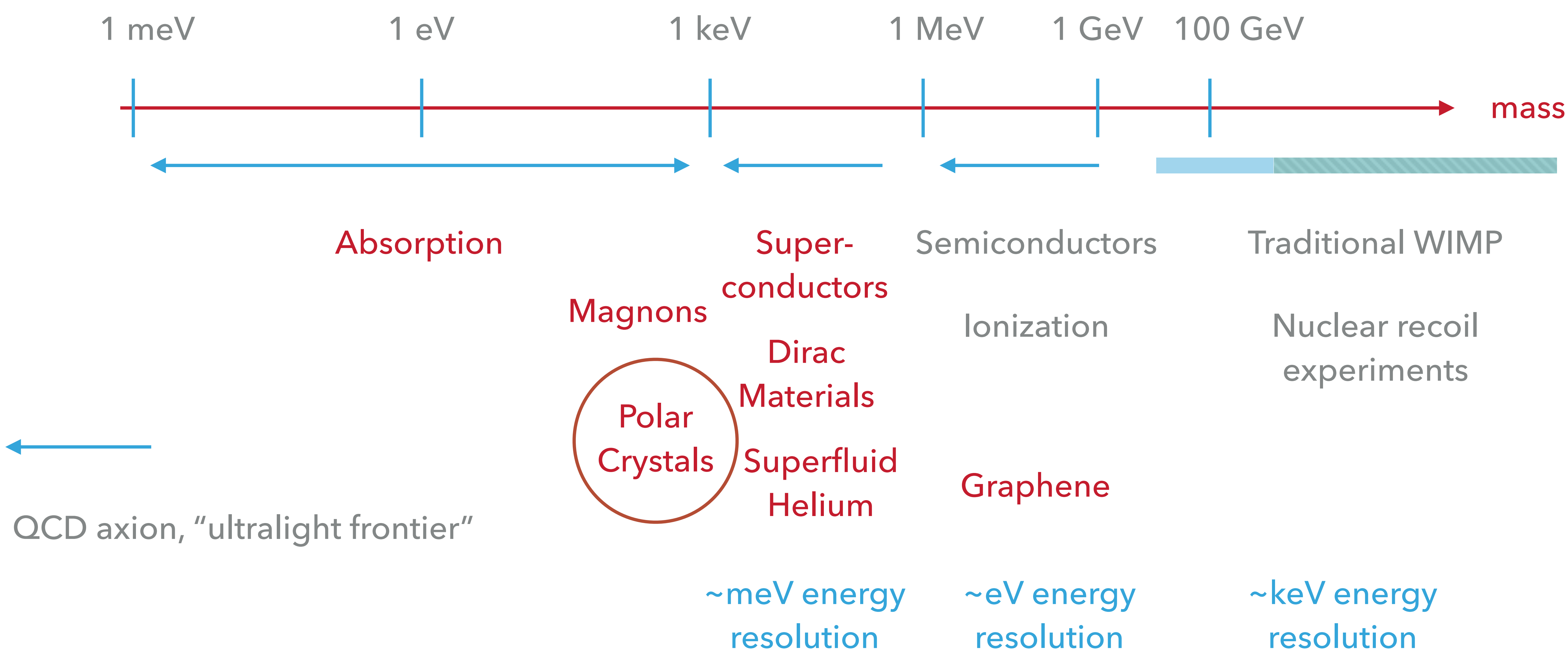


???



LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama



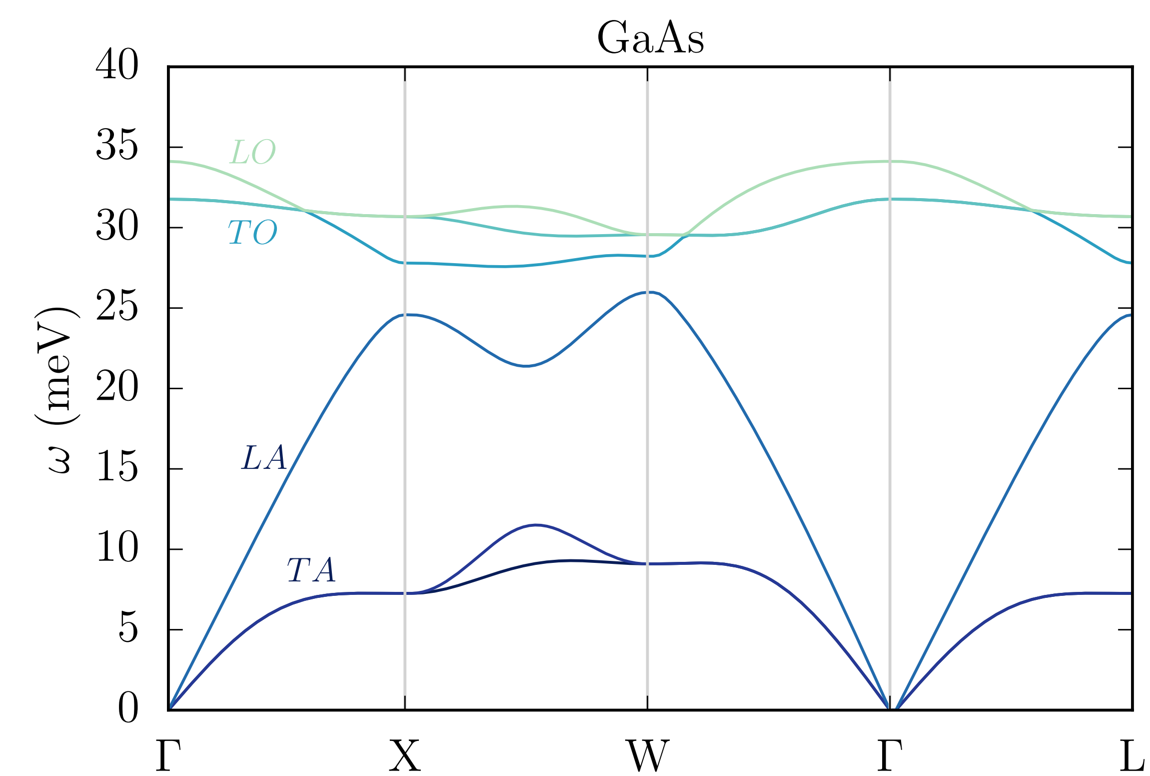
EXCITING COLLECTIVE MODES

Schutz, KZ 1604.08206,
Knapen, Lin, Pyle, KZ
1712.06598

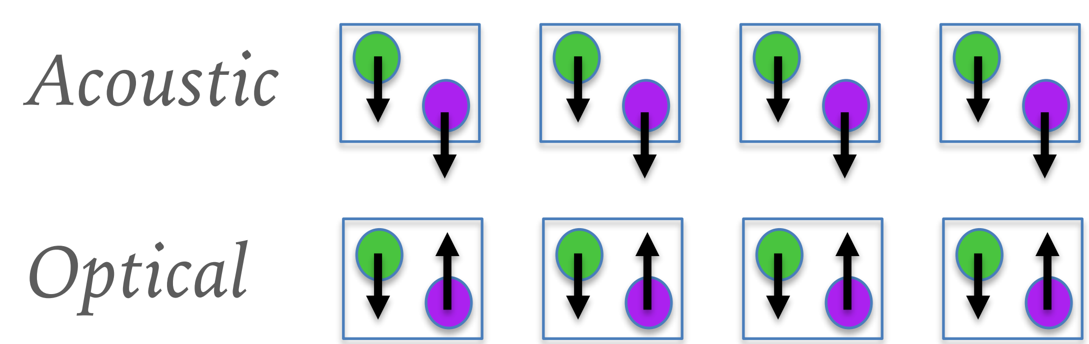
- Once DM drops below an MeV, its deBroglie wavelength is longer than the inter particle spacing in typical materials
- Therefore, coupling to collective excitations in materials makes sense!
- Collective excitations = phonon modes, spin waves (magnons)
- Can be applied to just about any material
- Calculations exist for superfluid helium, semiconductors, superconductors, polar materials
- Details depend on
  - 1) *nature of collective modes in target material*
  - 2) *nature of DM couplings to target*

NATURE OF COLLECTIVE OSCILLATIONS OF IONS — PHONONS

- Number of collective modes: 3 x number of ions in unit cell
- 3 of those modes describe in phase oscillation — acoustic phonons — have a gapless dispersion
- The remaining modes are gapped



Momentum transfer

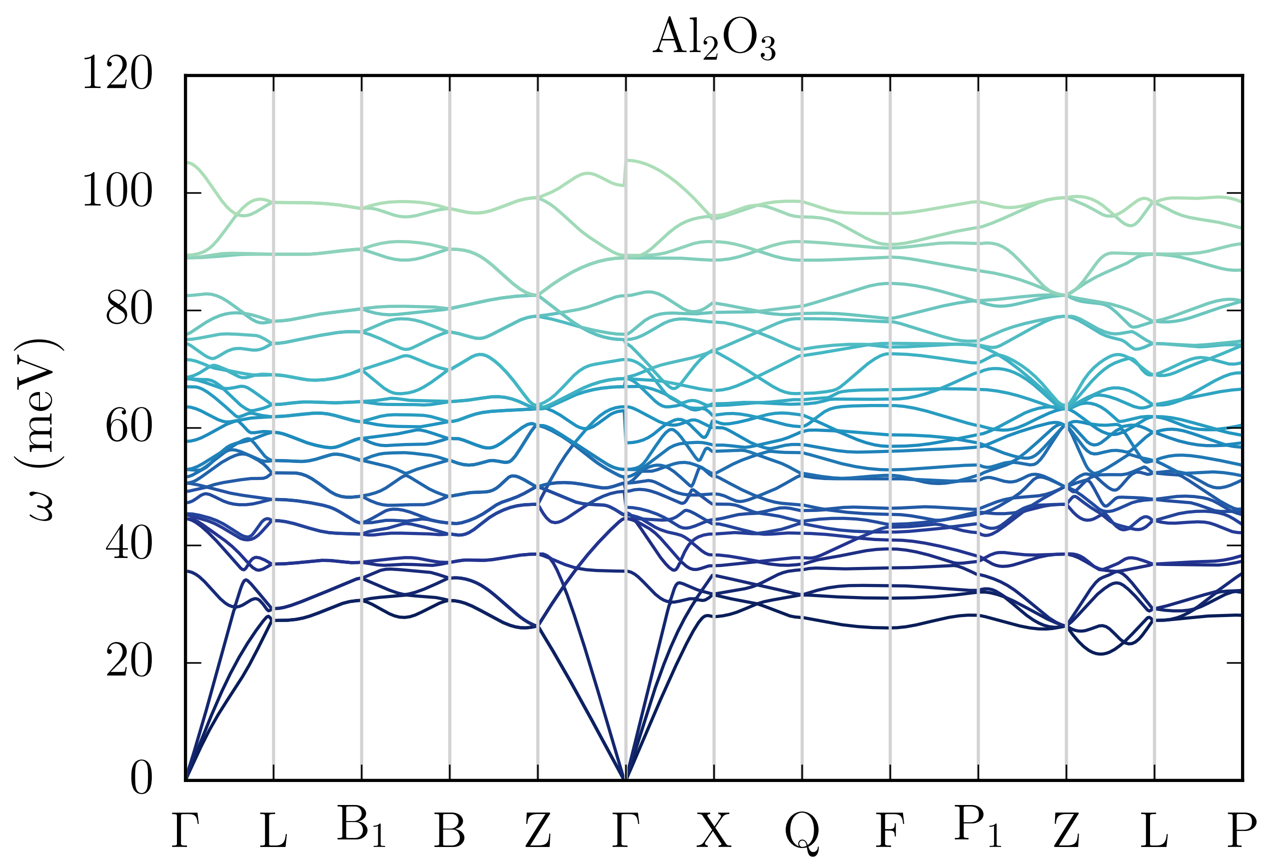


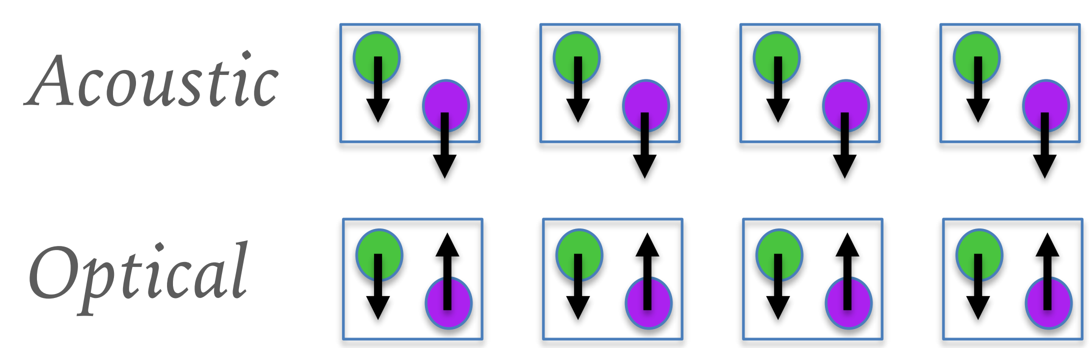
Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

NATURE OF COLLECTIVE MODES

- Some materials have an abundance of these modes
- When these gapped modes result from oscillations of more than one type of ion, it sets up an oscillating dipole
- *Polar Materials*

Sapphire

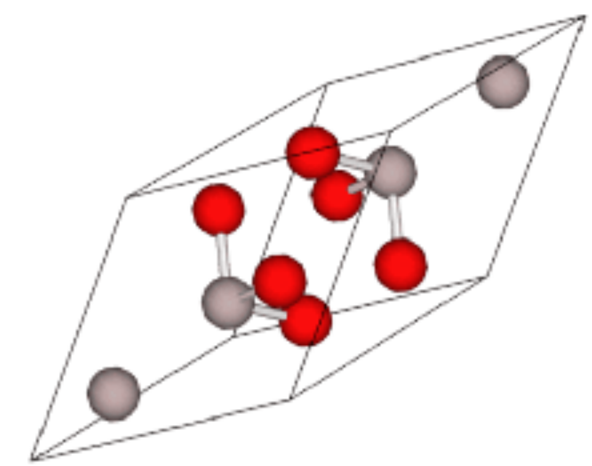


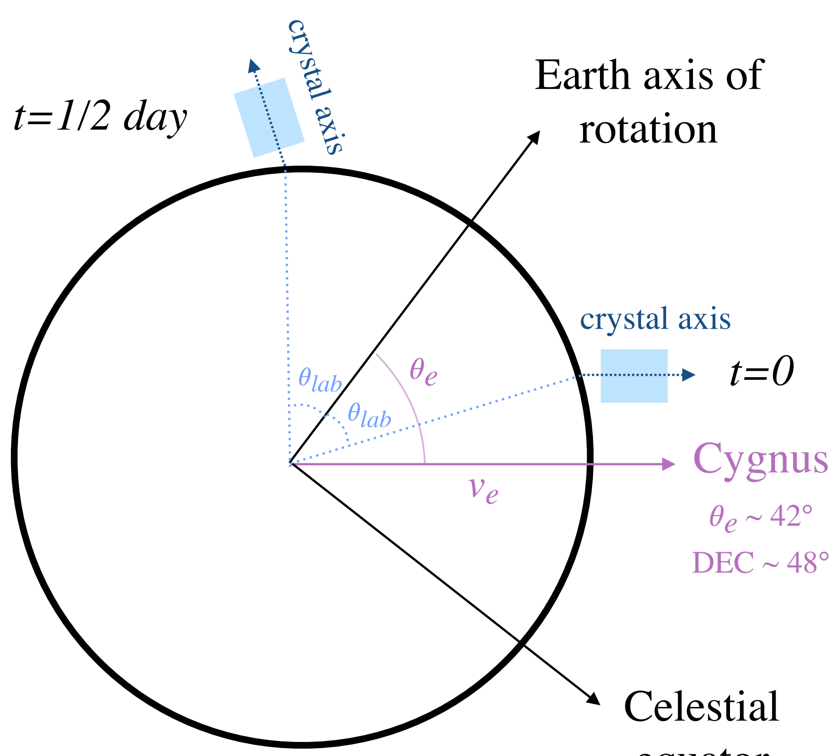


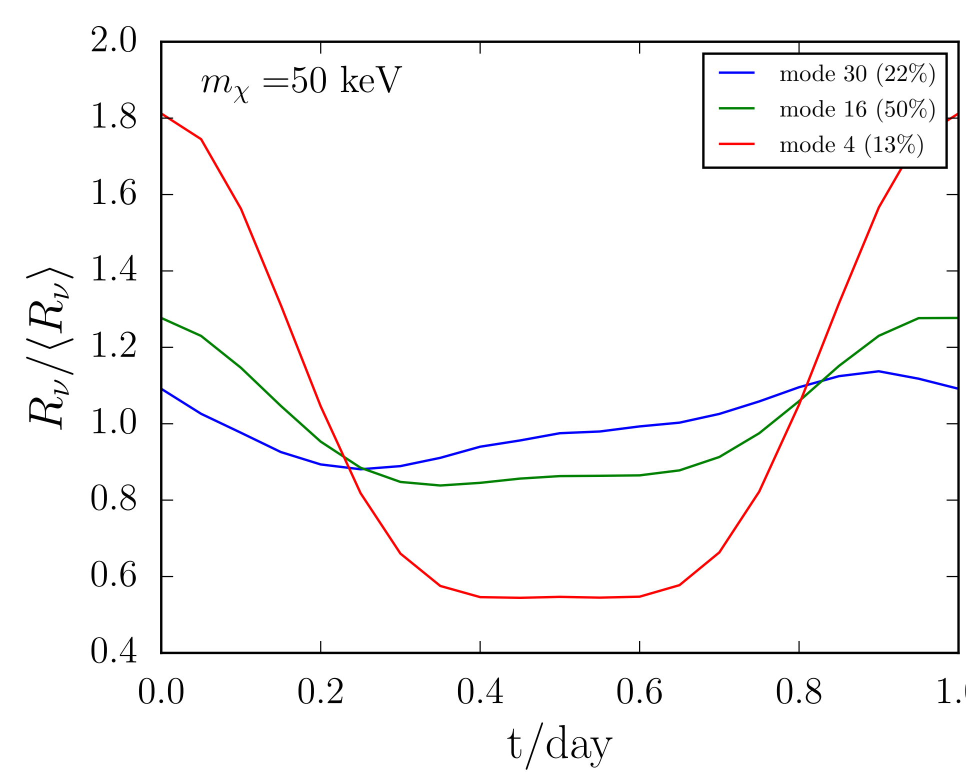
DIRECTIONALITY IN ANISOTROPIC MATERIALS!

Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

- Crystal Lattice is not Isotropic
- Especially pronounced in sapphire

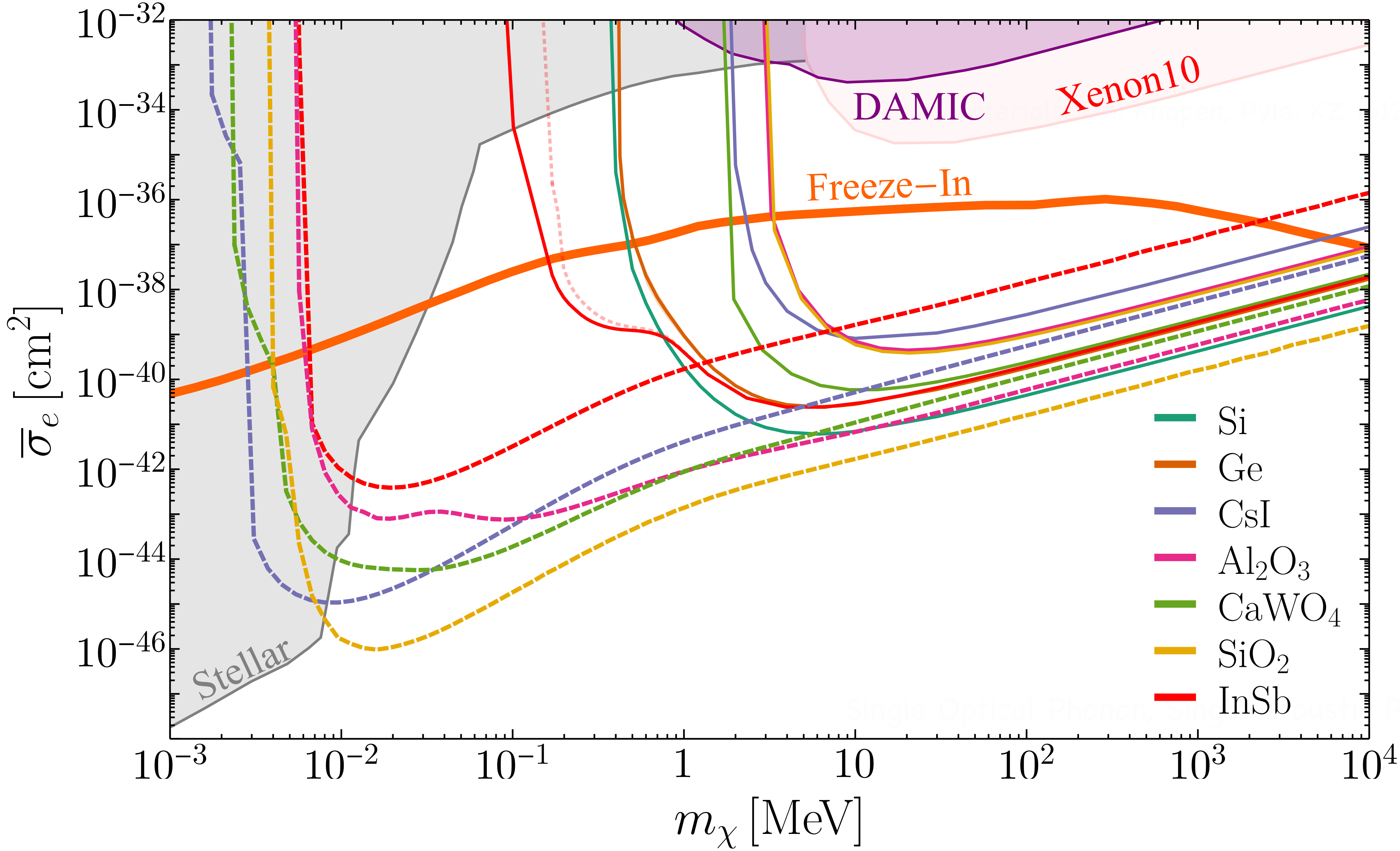






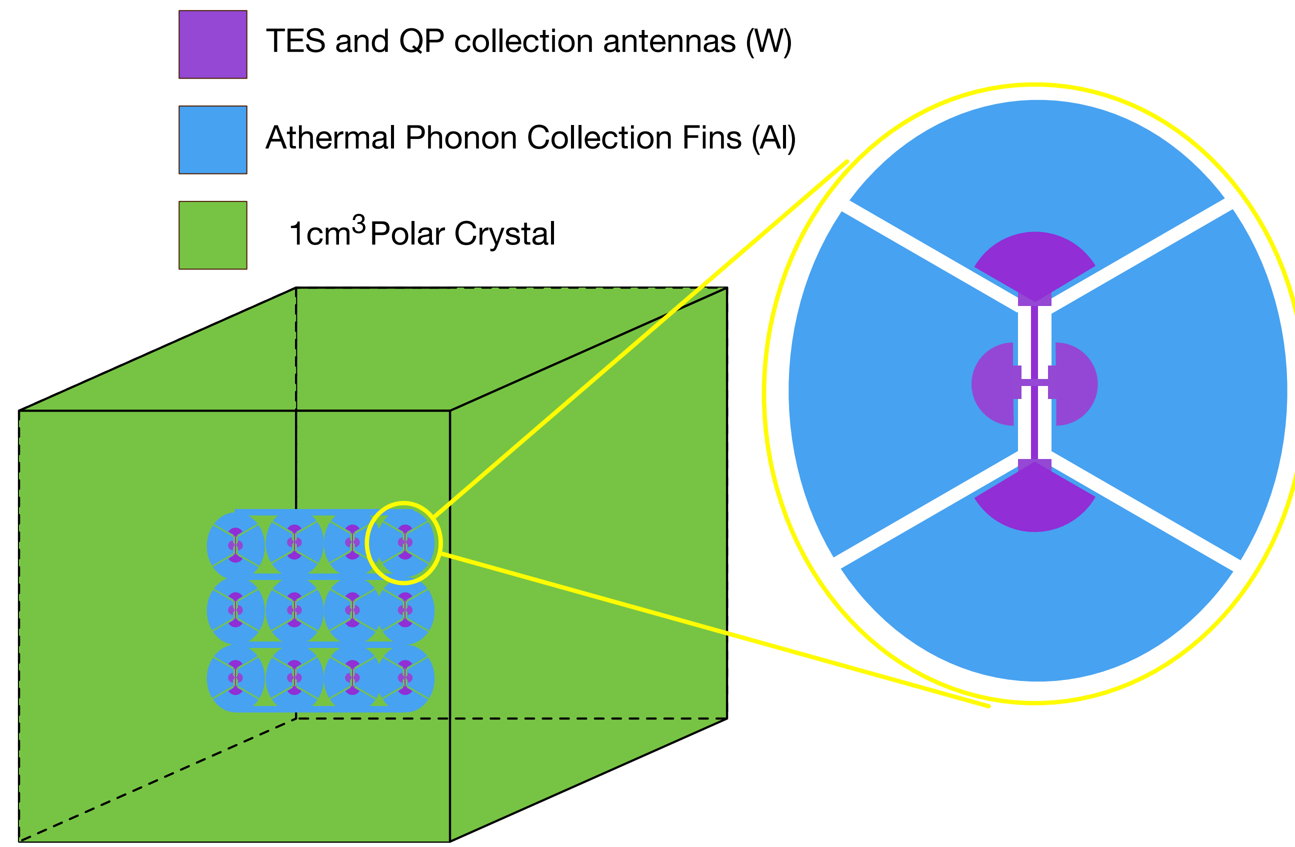
OPTICAL PHONONS IN POLAR MATERIALS

Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716



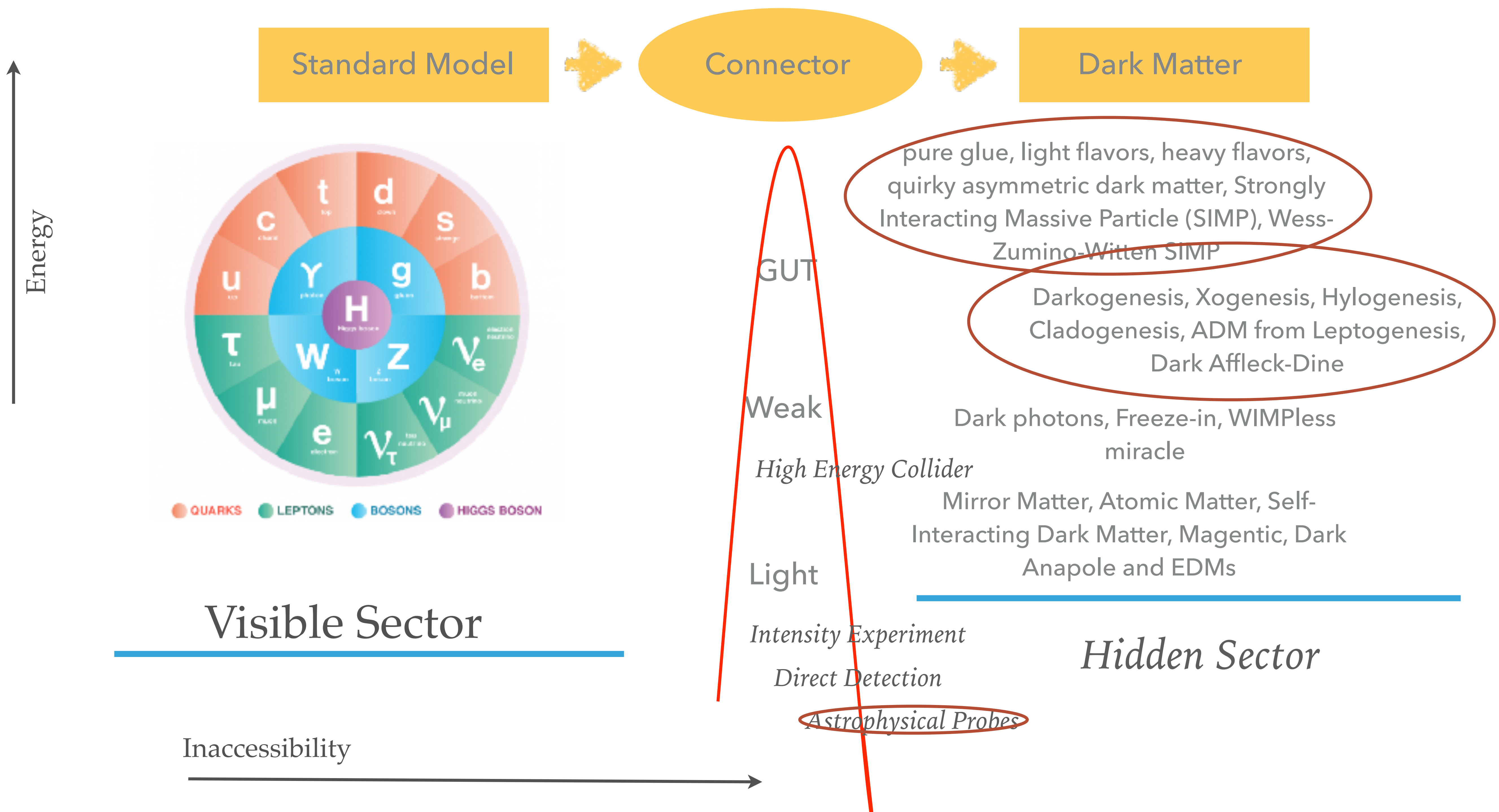
COMMON R&D PATH

- Sensor can be coupled to multiple targets
- Zero-field read-out of phonons
- Now funded by DoE — TESSERACT (TES with Sub-EV Resolution and Cryogenic Targets)
- For a polar crystal target — Sub-eV Polar Interactions Cryogenic Experiment (SPICE)



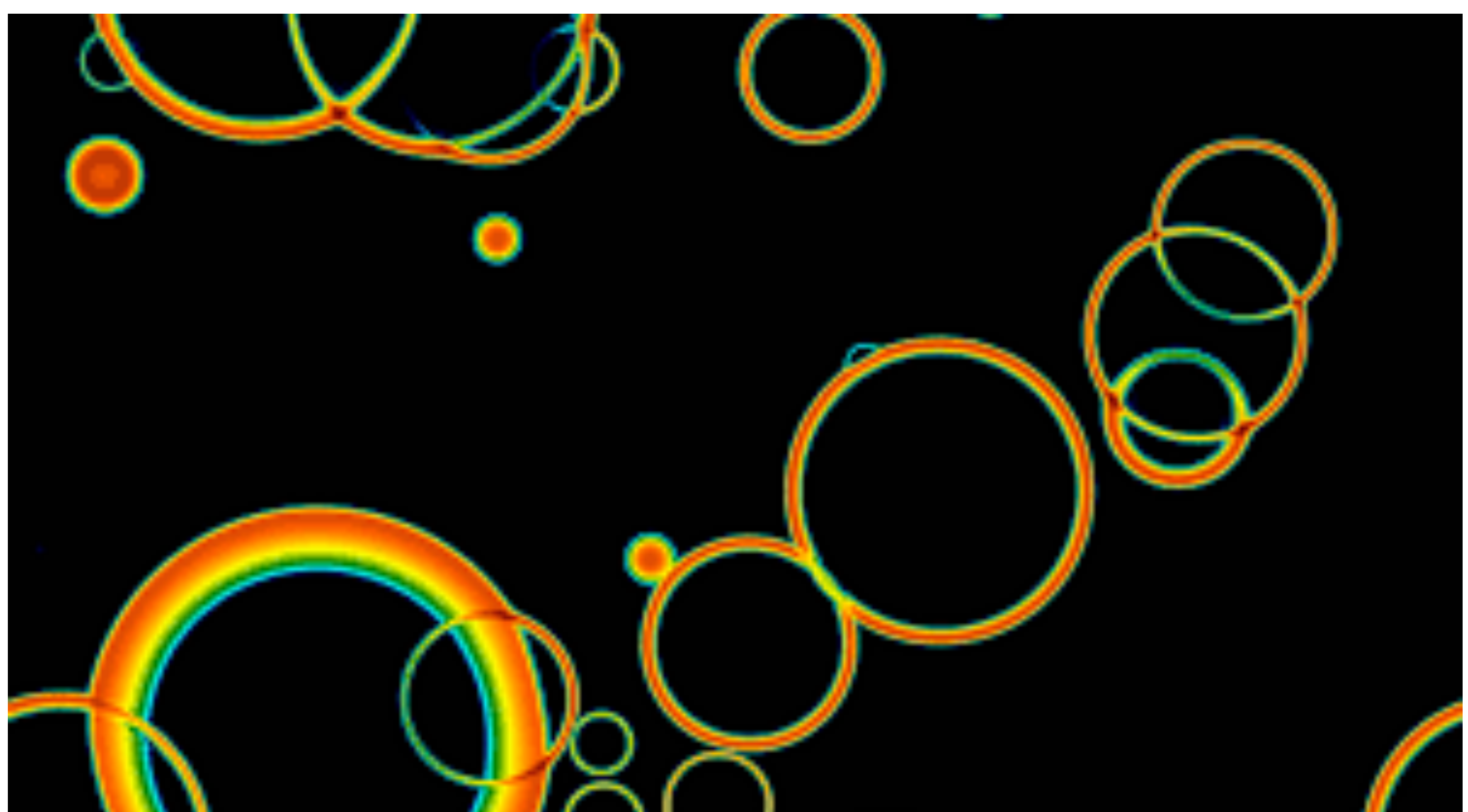
HIDDEN SECTOR / VALLEY

- When is it worth realizing a new model of dark matter?



IMPLICATIONS OF A NEW QCD-LIKE OR WEAKLY COUPLED HIDDEN SECTOR

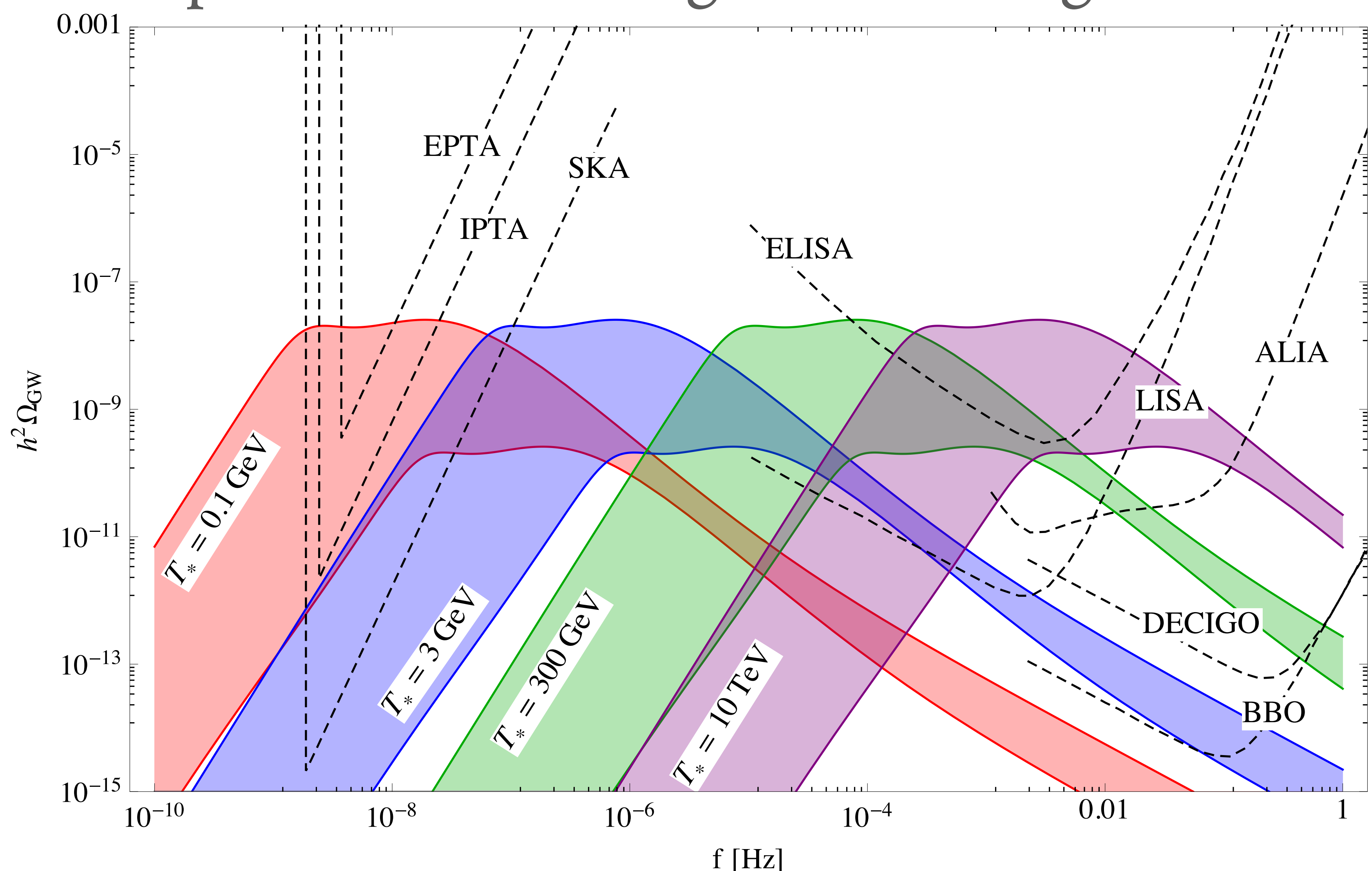
- Strong First-Order Phase Transitions?
- Baryogengesis can be done in the dark sector = "darkogenesis" Shelton, KZ 1008.1997 Hall, Konstandin, McGehee, Murayama, Servant 1910.08068
- First-order phase transition forms bubbles
- Bubbles collide and generate gravitational waves



Weir 1705.01783

IMPLICATIONS OF A NEW QCD-LIKE OR WEAKLY COUPLED HIDDEN SECTOR

- Strong First-Order Phase Transitions?
- Baryogengesis can be done in the dark sector = "darkogenesis"
- The first-order phase transition gives rise to gravitational waves



Schwaller 1504.07263

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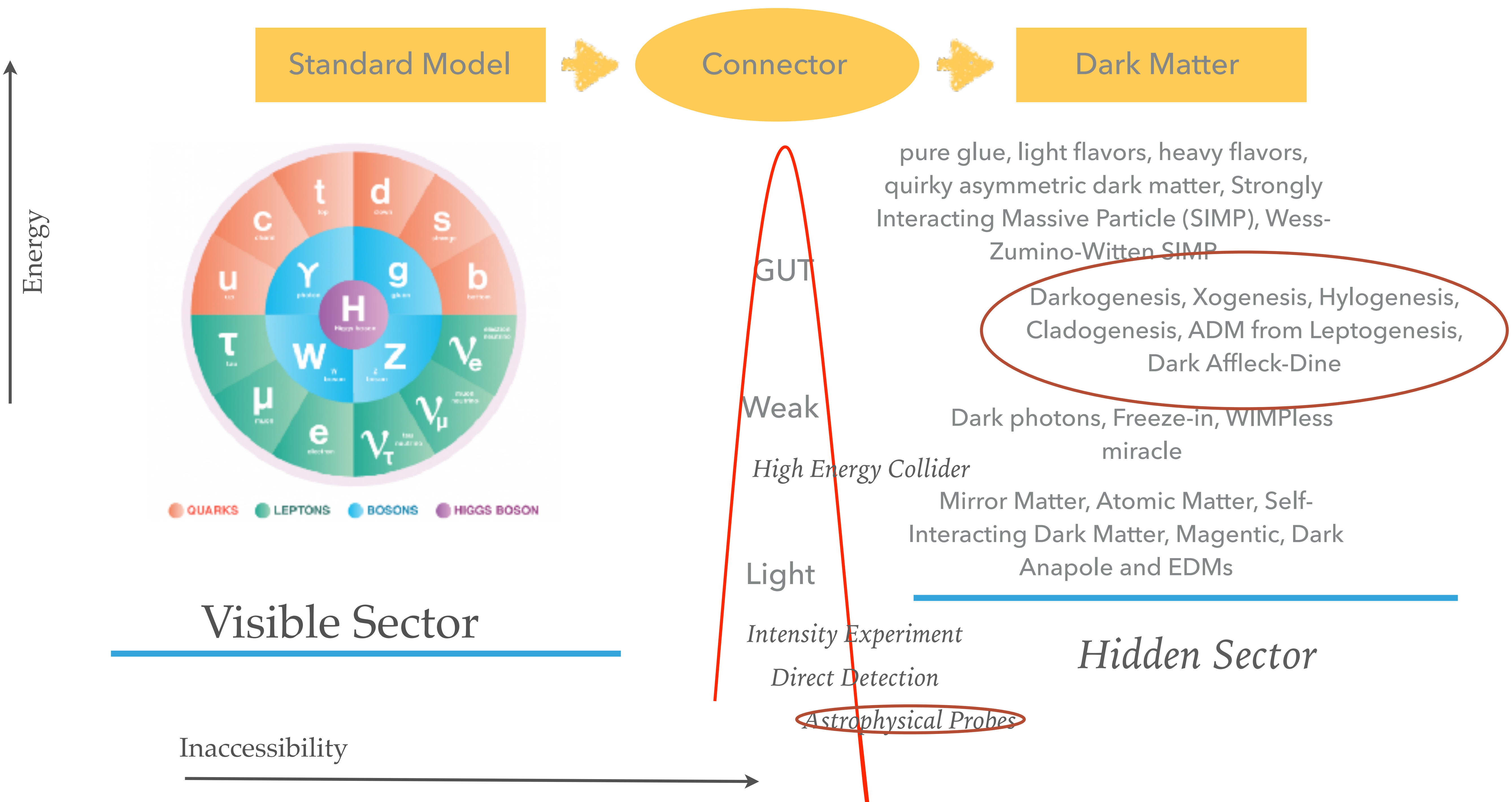
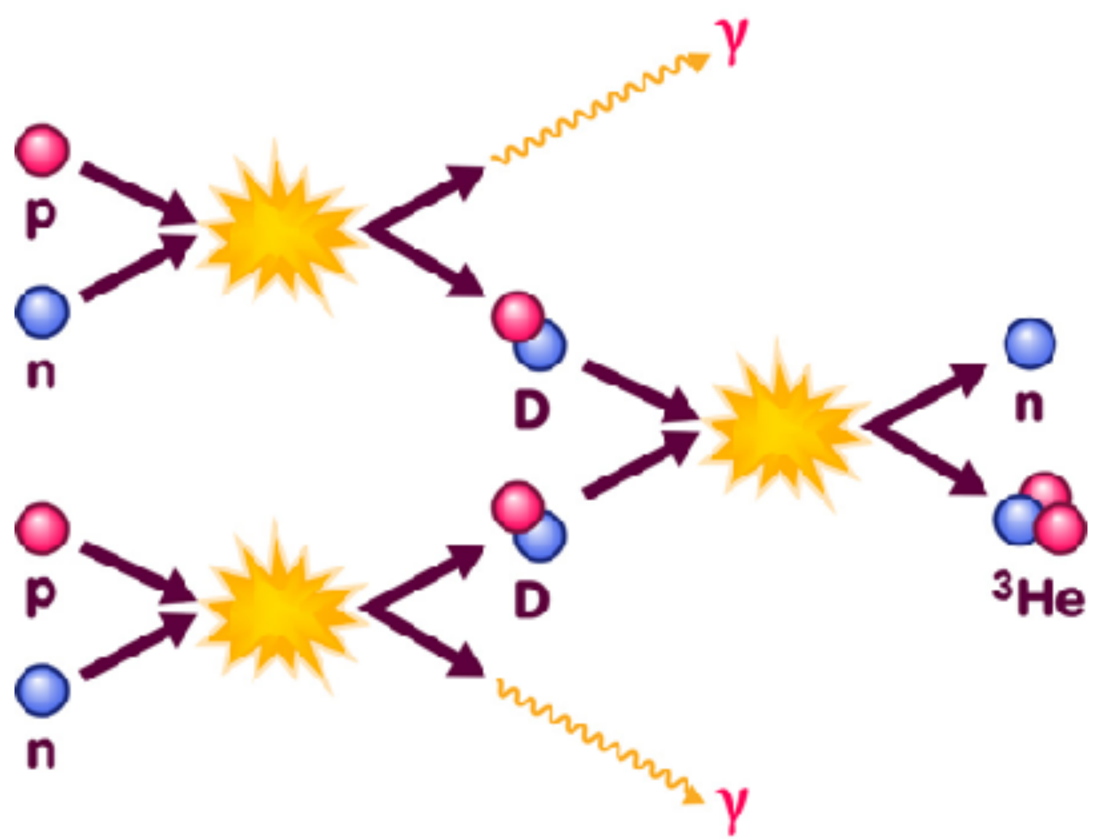
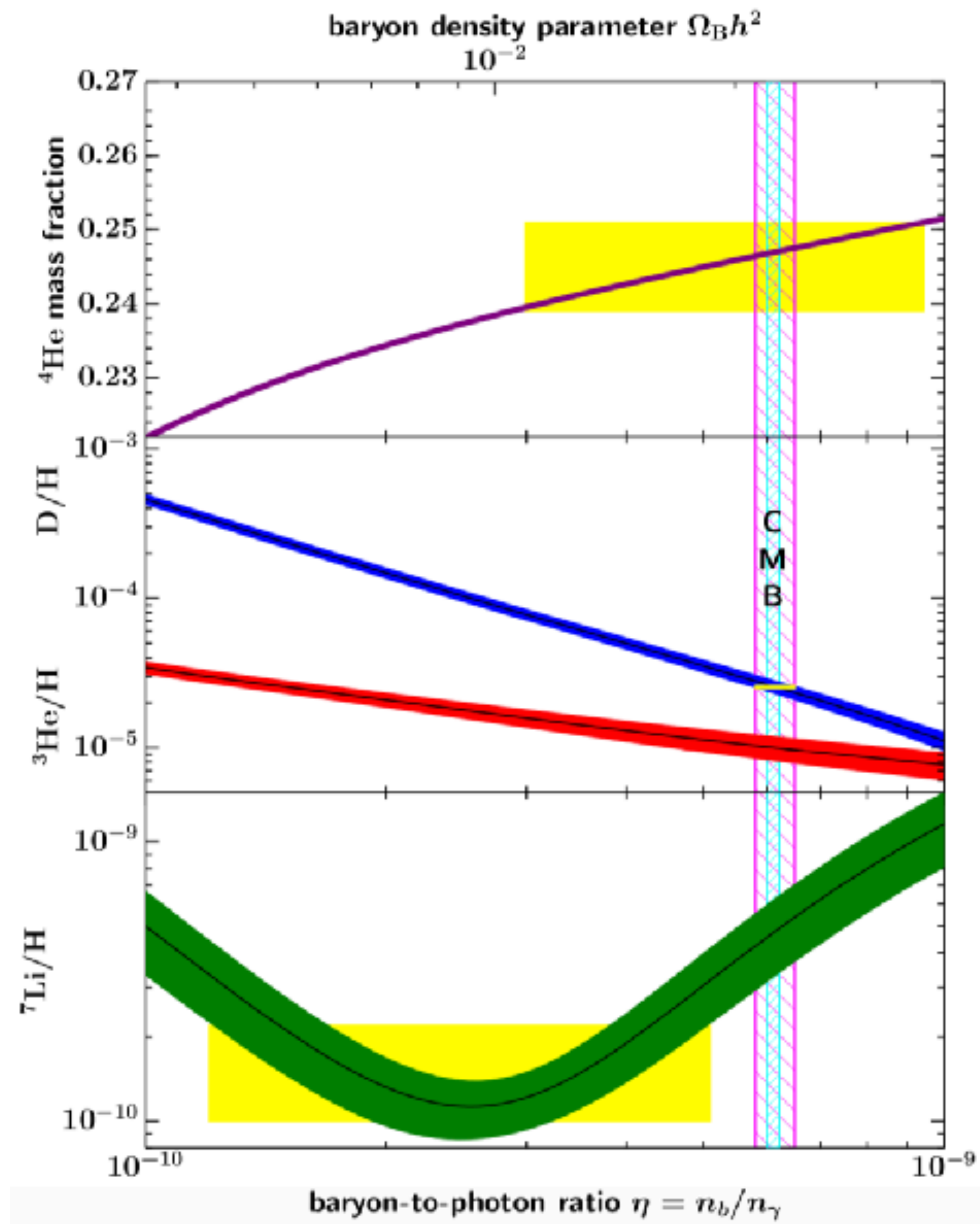


BIG BANG NUCLEOSYNTHESIS AND THE DARK SECTOR

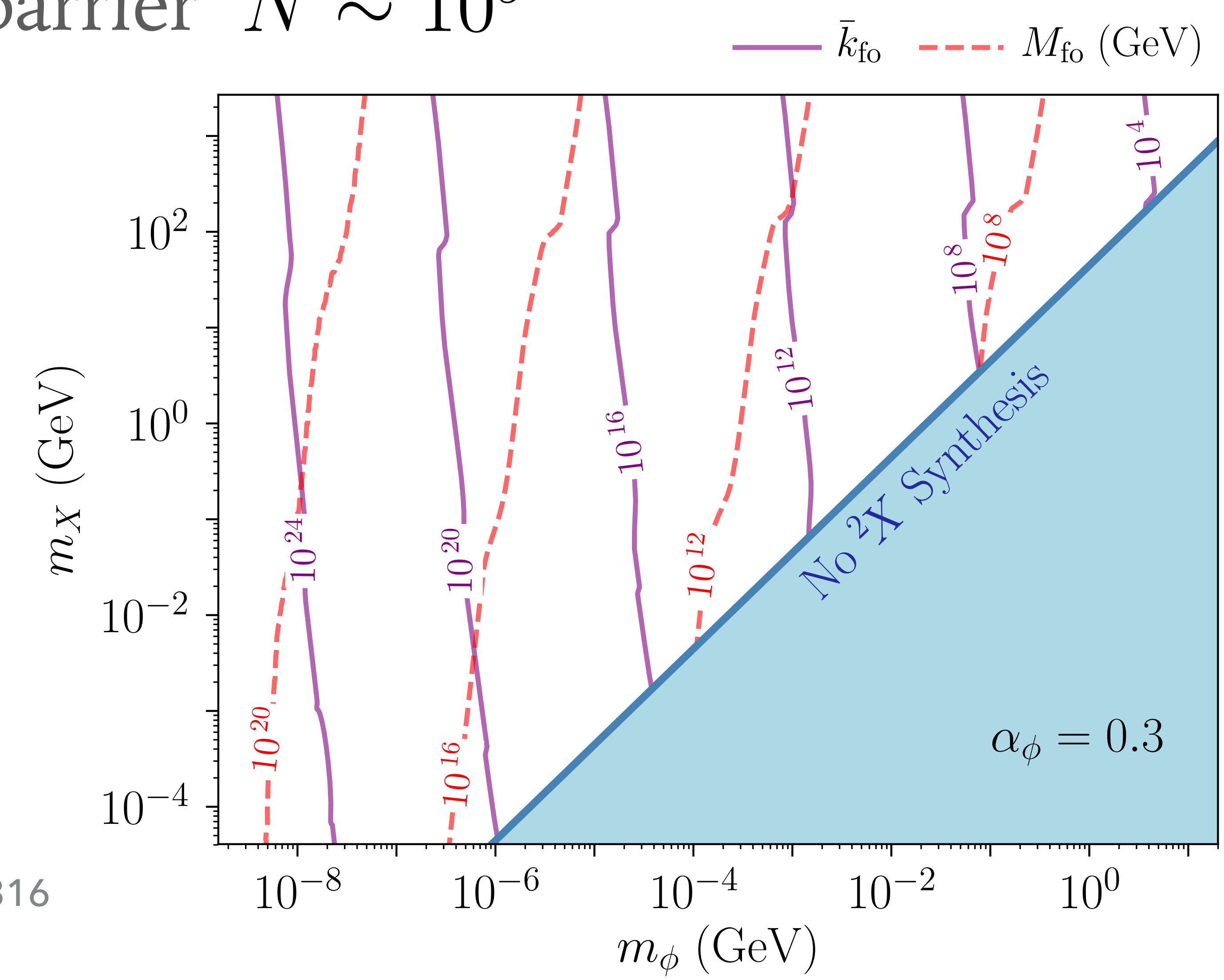




2018 PDG Review

REMOVE ELECTROMAGNETISM FROM STANDARD MODEL

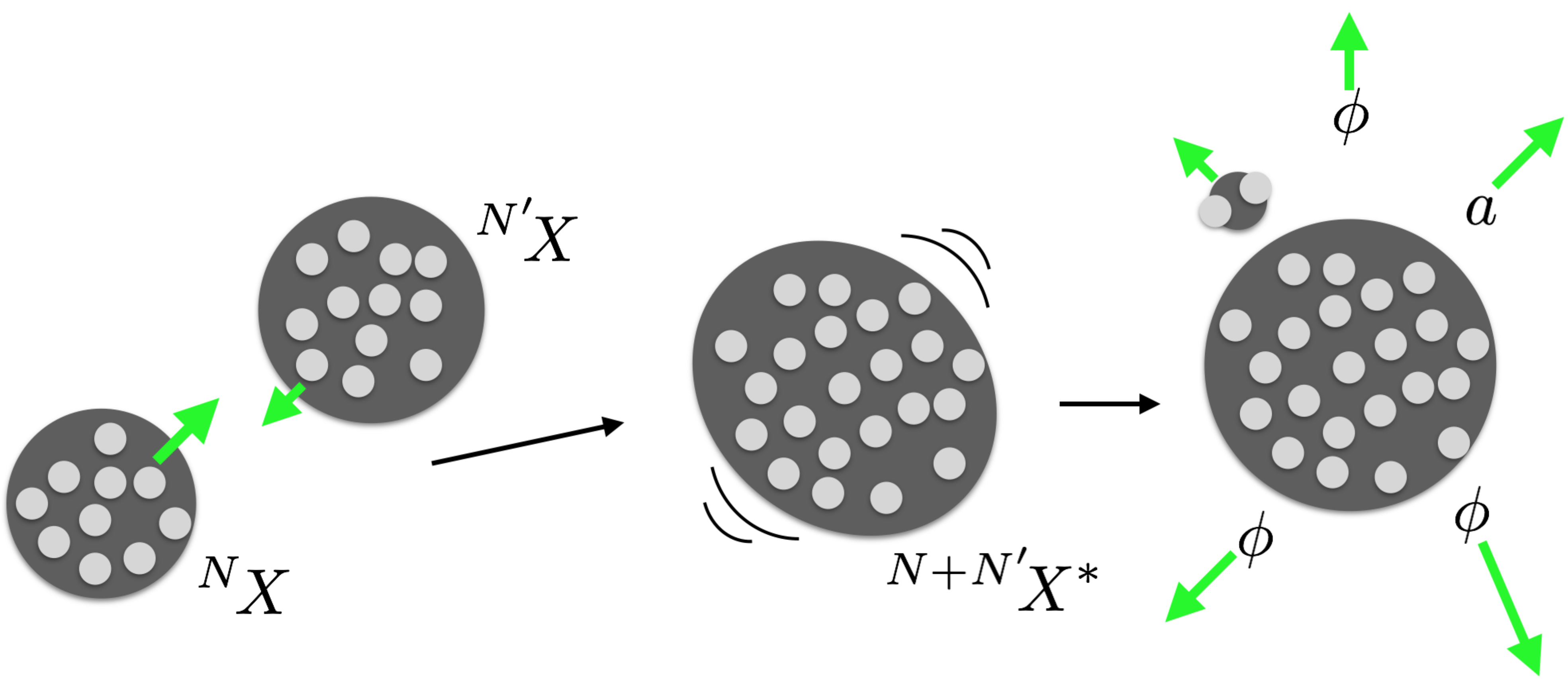
- Take BBN temp at 0.1 MeV (due to deuterium bottleneck)
- Solve Boltzmann equation $$\frac{dN}{dt} = k n_k \sigma_{kN} v_k$$
  - With Coulomb barrier $N \sim 9.5$
  - Without Coulomb barrier $N \sim 10^9$



Gresham, Lou, KZ 1707.02316

LARGE BOUND STATES WITH LARGE INTERACTION CROSS-SECTIONS

- Usual picture is that dark matter is collisionless
- Large bound states have geometric interaction cross-sections
- Interactions are dissipational = "hit-and-stick"



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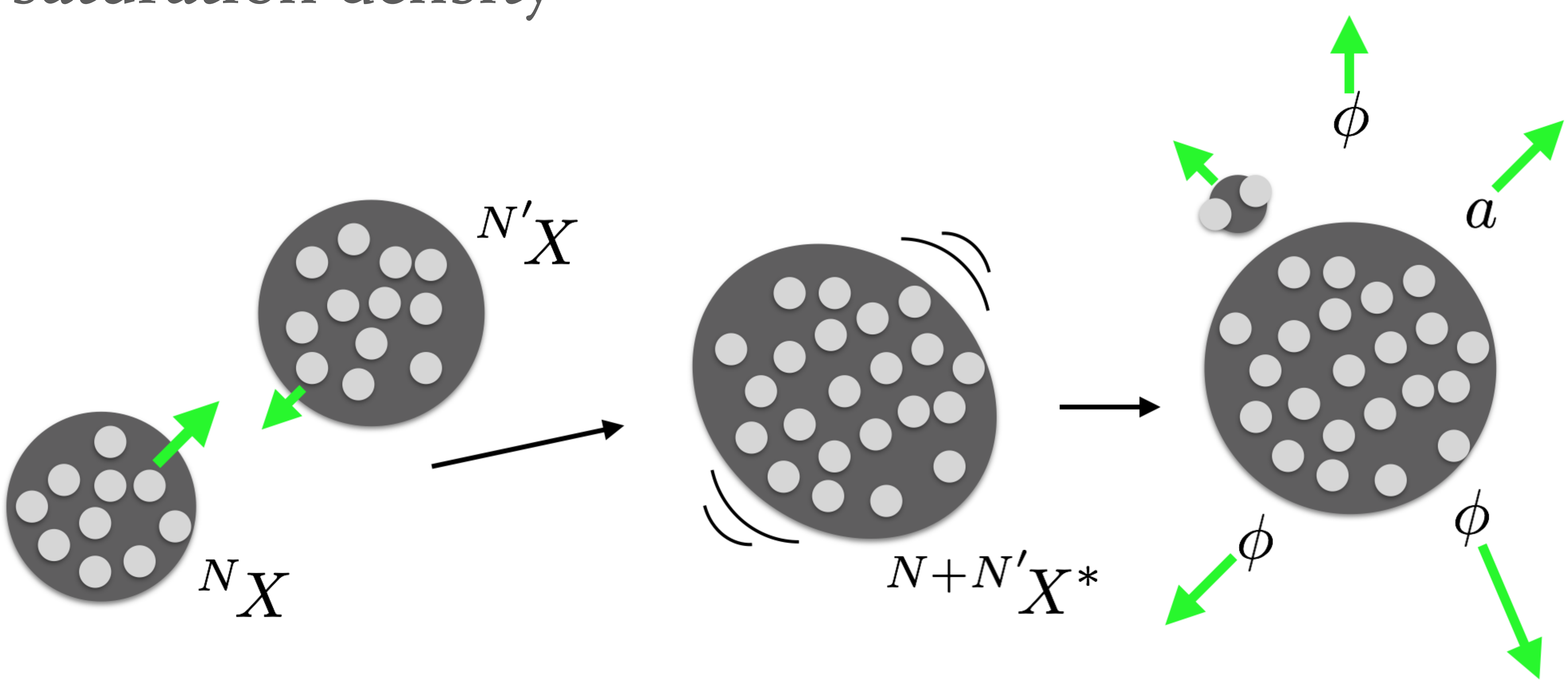
LARGE BOUND STATES WITH LARGE INTERACTION CROSS-SECTIONS

- Usual picture is that dark matter is collisionless
- Large bound states have geometric interaction cross-sections
- Nugget properties are predictive and characterized by saturation density



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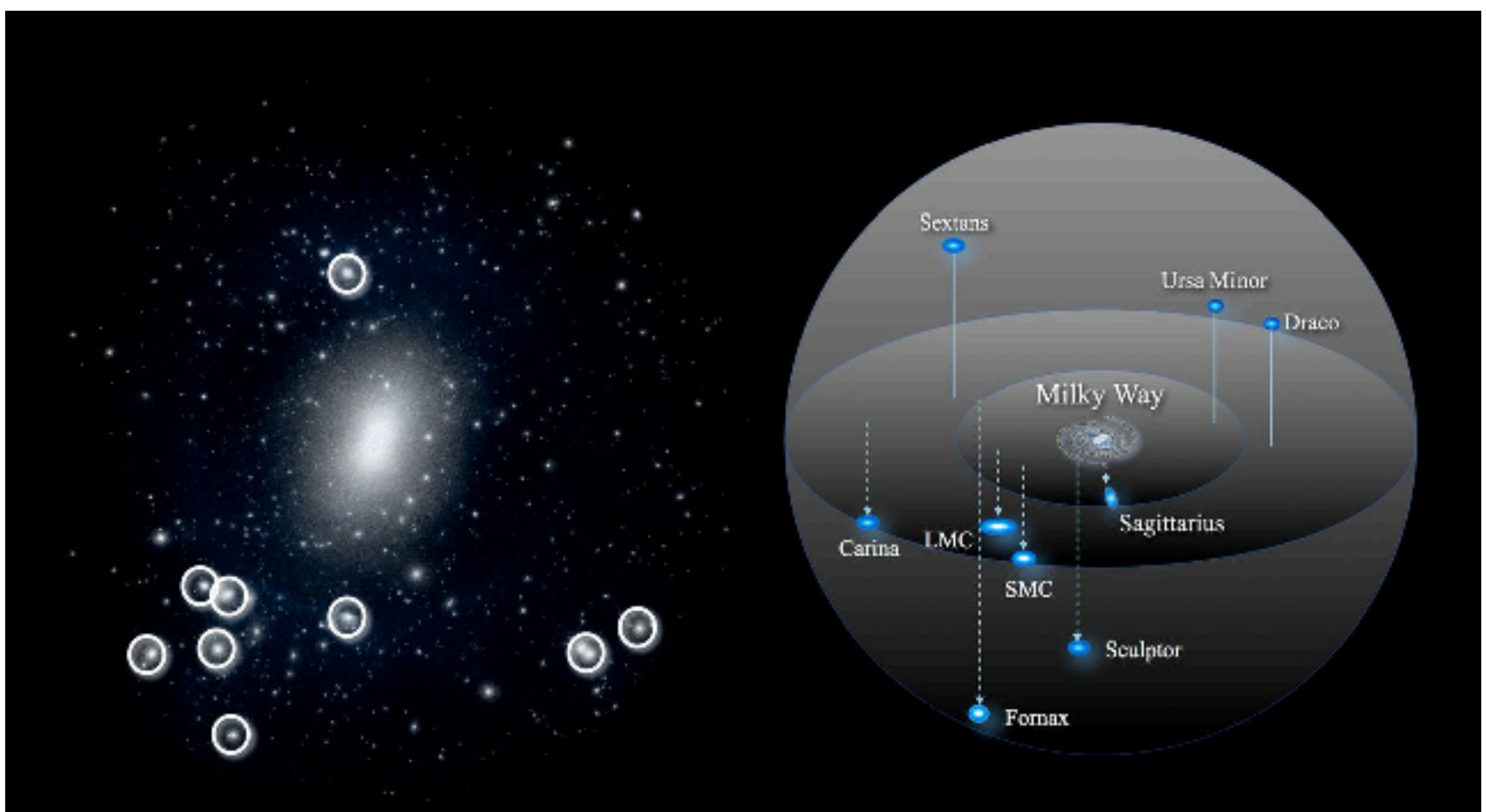
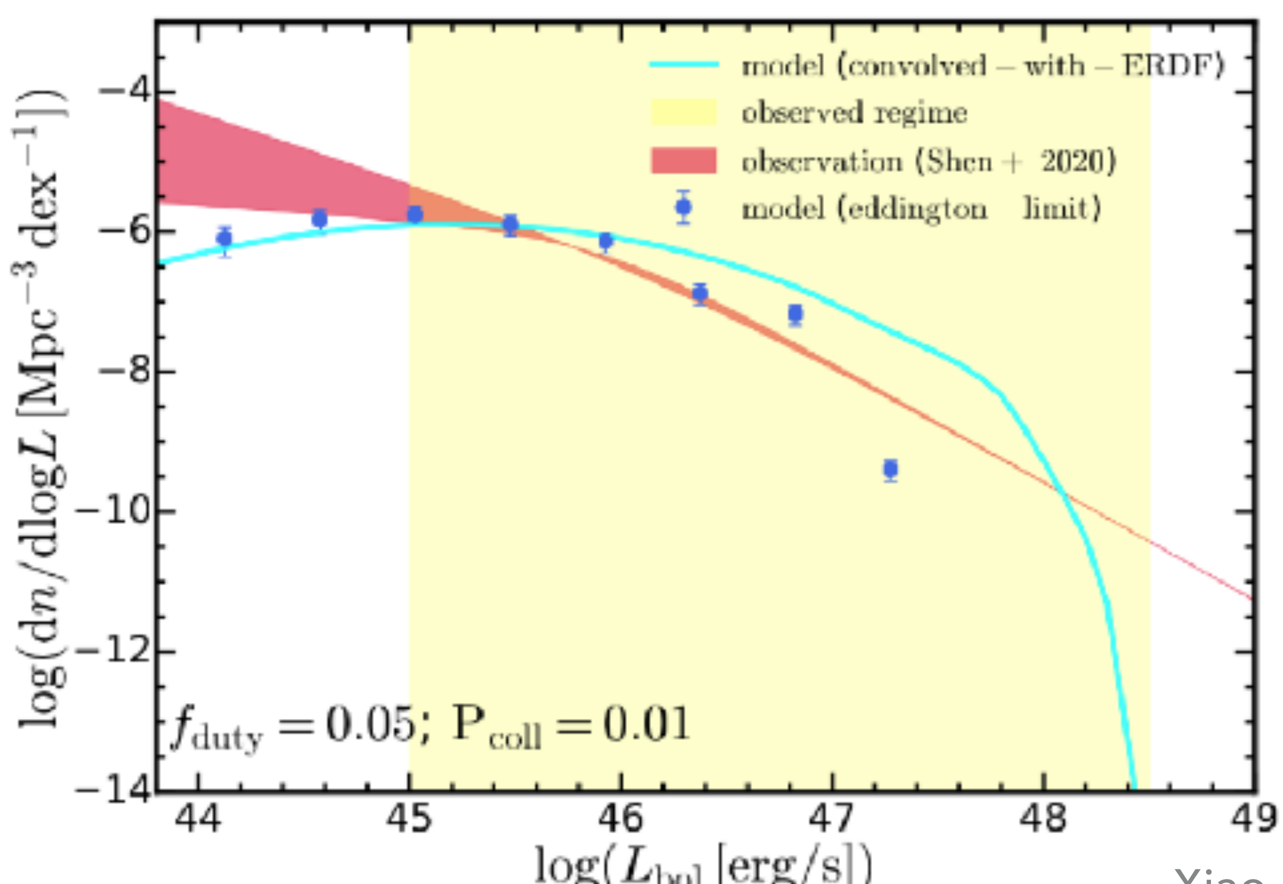
DARK MATTER SELF-INTERACTIONS AND DARK MATTER HALOS

- Dark matter self-interactions (elastic or dissipational) change the shape of dark matter halos, their density profiles, and the amount of substructure
- How much and whether current observation agrees with collisionless CDM paradigm is a source of active debate



DISSIPATIONAL DARK MATTER AND BLACK HOLE FORMATION

- If dark matter interactions “hit-and-stick”, dark matter kinetic energy dissipates and 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?



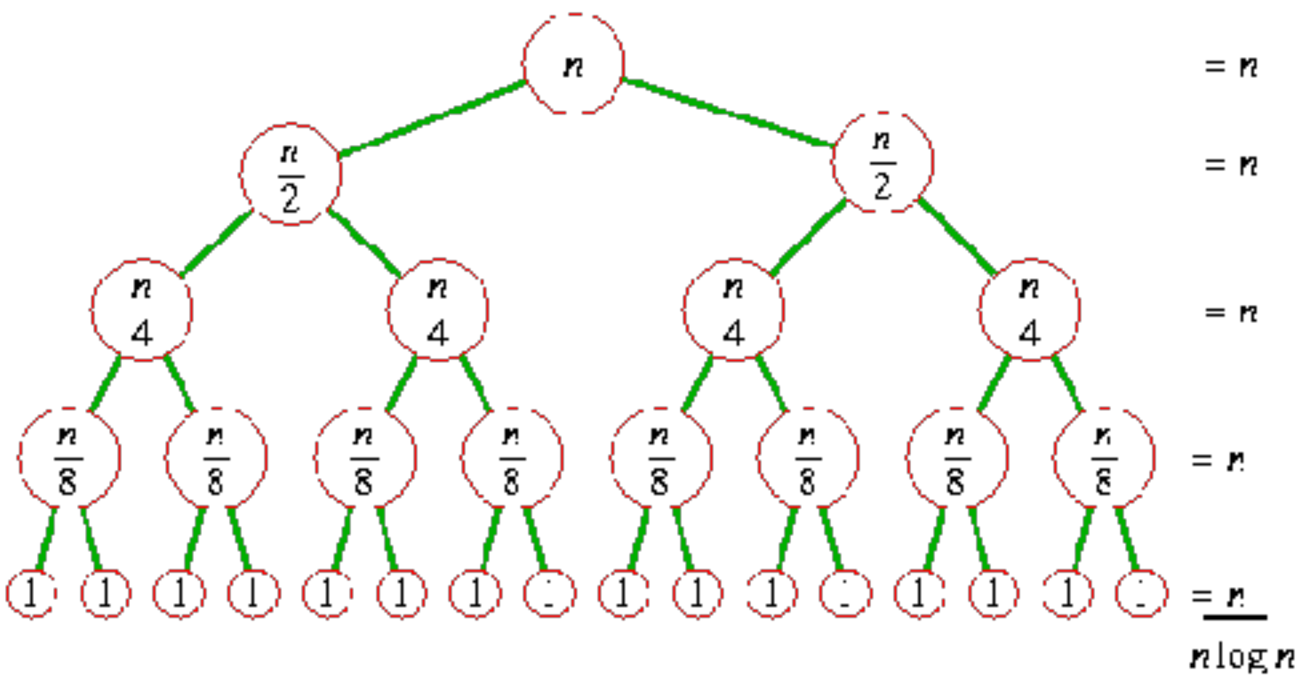
Xiao, Shen, Hopkins, KZ, in progress

SUMMARY

- Field of identifying the nature of dark matter is broad and vibrant
- We are, every year, learning more about the history and structure of the Universe
- Traditionally, the field has focused on weak scale dark matter as the leading hypothesis
- The WIMP tyranny has been broken and new experiments are moving forward
- e.g. Direct detection with solid state devices and novel intensity experiments
- Potentially important implications for cosmology and formation of structure

THE OUTLOOK

- We are not without tools!



The universe is dominated by invisibles!

WIMP or (axion)

How to be ready for anything? Hidden Sectors

How do I search for these things?