Les Houches Summer School on Dark Matter

F. Piazza - Università degli Studi & INFN - Milano

Les Houches Summer School on Dark Matter

- 3 weeks of lectures

- DM approached from several sides
  - Theory & phenomenology:
    - Particle DM
    - Primordial Black Holes
    - Modified gravity
  - Experimental techniques and present constraints
    - Cosmology and astrophysics
    - Direct Detection
    - Indirect Detection
    - Production at Colliders
    - New future research strategies

Lecturers

- Anne Green (Nottingham) DM in cosmology
- Joshua Ruderman (NYU) DM Production
- Tracy Slatyer (MIT) DM Indirect Detection: from KeV to multi TeV
- Philip Harris (MIT) DM at accelerators
- Igor Irastorza (Zaragoza) Axion Dark Matter (including theory and experiments)
- Jonathan Feng (UC Irvine) Standard WIMPs
- Jody Cooley (SMU Texas) Direct Detection of classical WIMPs
- Joachim Brod (Cincinnati) DM Effective Field Theories
- Justin Khoury (U Penn) Modified gravity for DM and alternatives to particle DM
- Clare Burrage (Nottingham) Connection between DM and DE and extended gravity
- Bernard Carr (Queen Mary London) and Florian Kühnel (LMU Munich) Primordial Black Holes as DM candidates
- Lam Hui (Columbia) 'Fuzzy' ultralight Dark Matter
- Surjeet Rajendran (JHU) New avenues in experimental searches for DM
- Yonit Hochberg (Hebrew U Jerusalem) SIMPs
- Tongyan Lin (UCSD) Sub-GeV Dark Matter
- Joachim Kopp (CERN) Sterile Neutrinos
- Jim Cline (McGill) Dark atoms, composite dark states

- I will focus on particle DM
  - Start from Ruderman lectures => overview of production mechanisms for wide range of DM candidates
  - Some example of present constraints mainly from DD and ID

Les Houches Summer School on Dark Matter

- 3 weeks of lectures

- DM approached from several sides
    - Theory & phenomenology:
        - Particle DM
        - Primordial Black Holes
        - Modified gravity
    - Experimental techniques and present constraints
        - Cosmology and astrophysics
        - Direct Detection
        - Indirect Detection
        - Production at Colliders
        - New future research strategies

- I will focus on particle DM
    - Start from Ruderman lectures => overview of production mechanisms for wide range of DM candidates
    - Some example of present constraints mainly from DD and ID

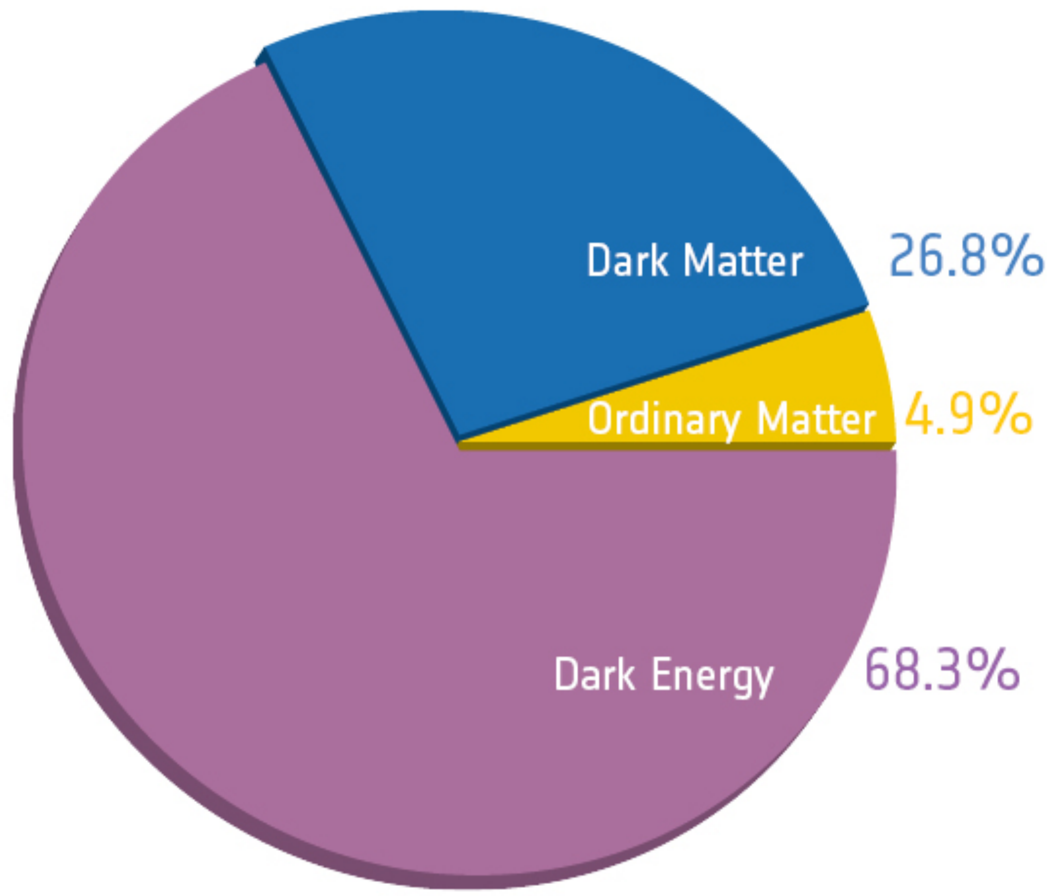
Lecturers

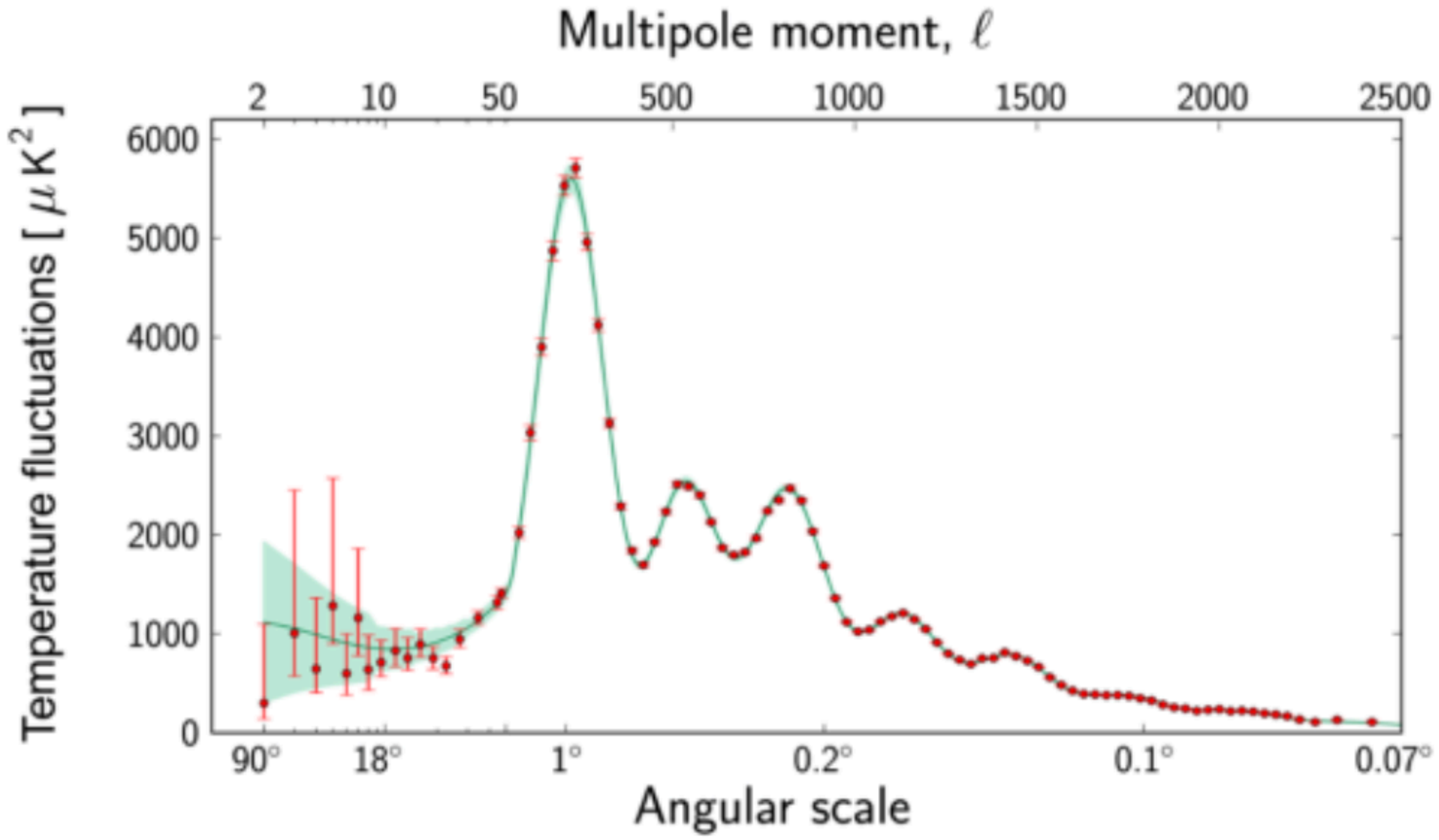
- Anne Green (Nottingham) DM in cosmology
- Joshua Ruderman (NYU) DM Production
- Tracy Slatyer (MIT) DM Indirect Detection: from KeV to multi TeV
- Philip Harris (MIT) DM at accelerators
- Igor Irastorza (Zaragoza) Axion Dark Matter (including theory and experiments)
- Jonathan Feng (UC Irvine) Standard WIMPs
- Jody Cooley (SMU Texas) Direct Detection of classical WIMPs
- Joachim Brod (Cincinnati) DM Effective Field Theories
- Justin Khoury (U Penn) Modified gravity for DM and alternatives to particle DM
- Clare Burrage (Nottingham) Connection between DM and DE and extended gravity
- Bernard Carr (Queen Mary London) and Florian Kühnel (LMU Munich) Primordial Black Holes as DM candidates
- Lam Hui (Columbia) 'Fuzzy' ultralight Dark Matter
- Surjeet Rajendran (JHU) New avenues in experimental searches for DM
- Yonit Hochberg (Hebrew U Jerusalem) SIMPs
- Tongyan Lin (UCSD) Sub-GeV Dark Matter
- Joachim Kopp (CERN) Sterile Neutrinos
- Jim Cline (McGill) Dark atoms, composite dark states

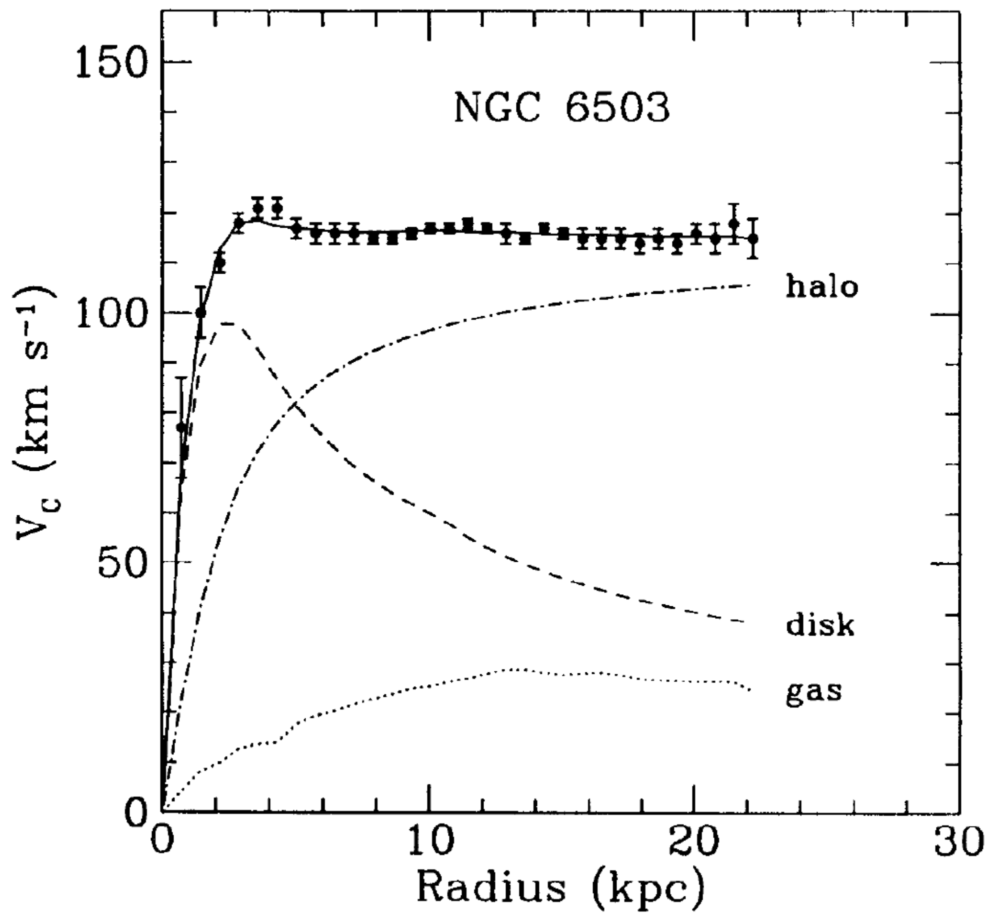
The Dark Matter problem

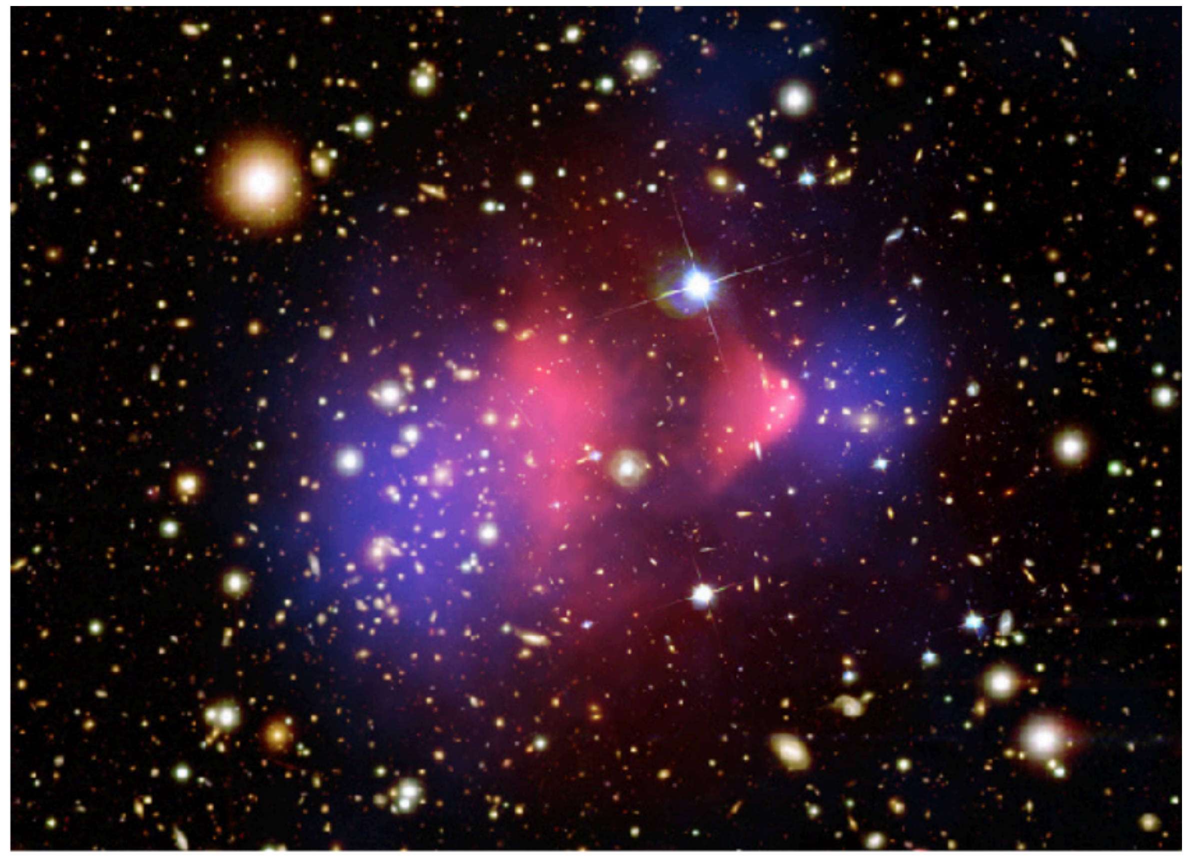
According to the latest CMB measurements by Planck experiment, DM accounts for about 27% of the Universe mass-energy.

- Several astrophysical and cosmological evidences, all related to it's gravitational interactions with ordinary matter
- No evidence of non-gravitational interactions observed so far:
  - it's nature is still largely unknown
  - Several possible candidates in a wide mass range
  - Need complementary approaches to DM detection

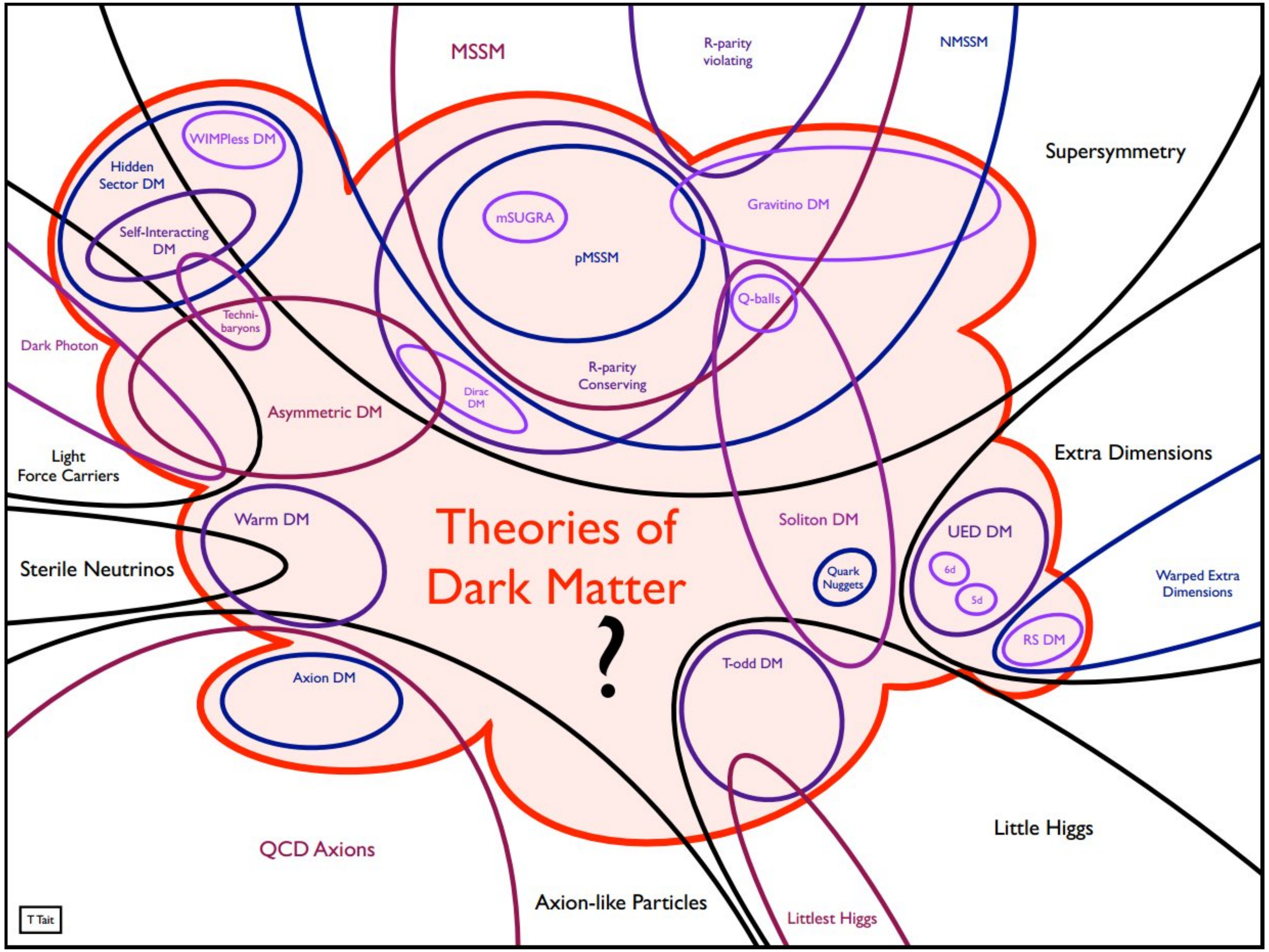


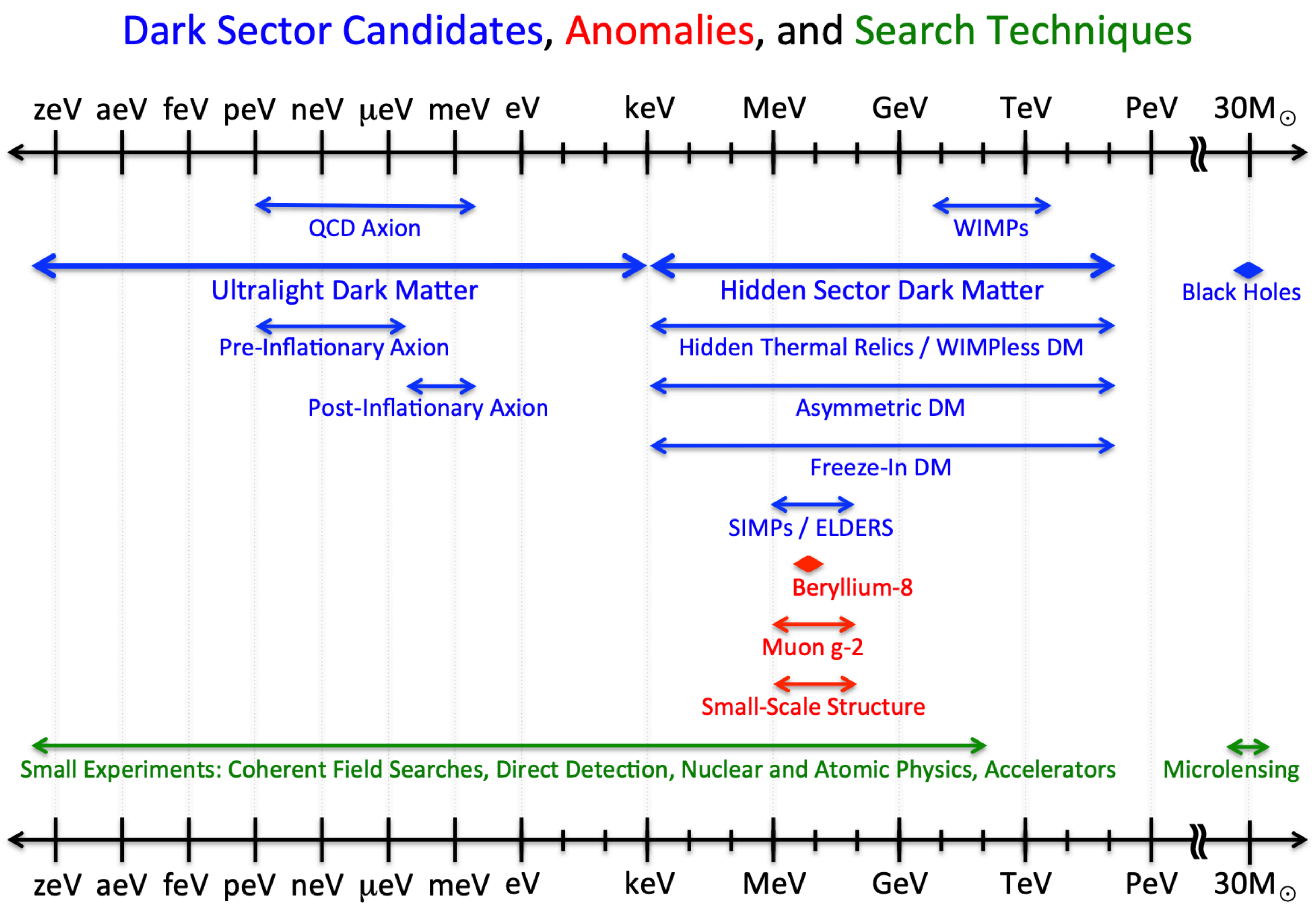


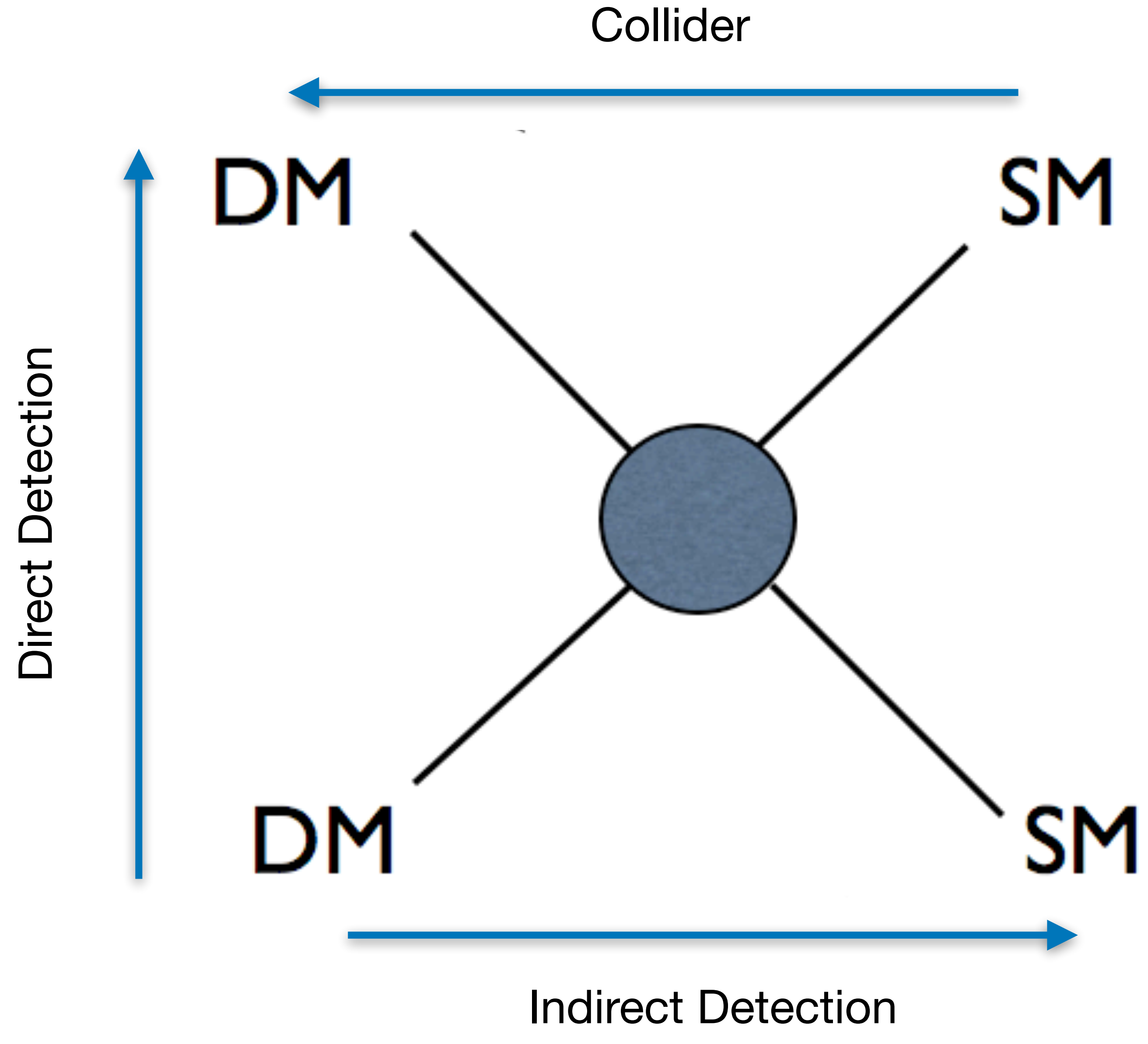




The Dark Matter problem







Knowns and unknowns

What we know about (particle) Dark Matter

- not a SM particle
- massive (gravitational interactions)
- "weakly" interacting with SM particles and long-lived
- cold (according to standard cosmological model)
- It's abundance today is: $\Omega h^2 \sim 0.12$

And what we don't know

- What kind of particle? Onle one or more particles?
- Which mass?
- How does interact with the SM particles
- How much "cold" is it?
- How was it produced?

DM abundance

$\Omega_\chi h^2 \sim 0.12$ (from Plank)

$$Y_\chi = \frac{n_\chi}{s} = \frac{\rho_\chi}{m_\chi s}$$

$$\Rightarrow \Omega_\chi h^2 = \left(\frac{s_0}{\rho_c h^{-2}}\right) m_\chi Y_\chi \implies m_\chi Y_\chi = 0.44 \text{ eV}$$

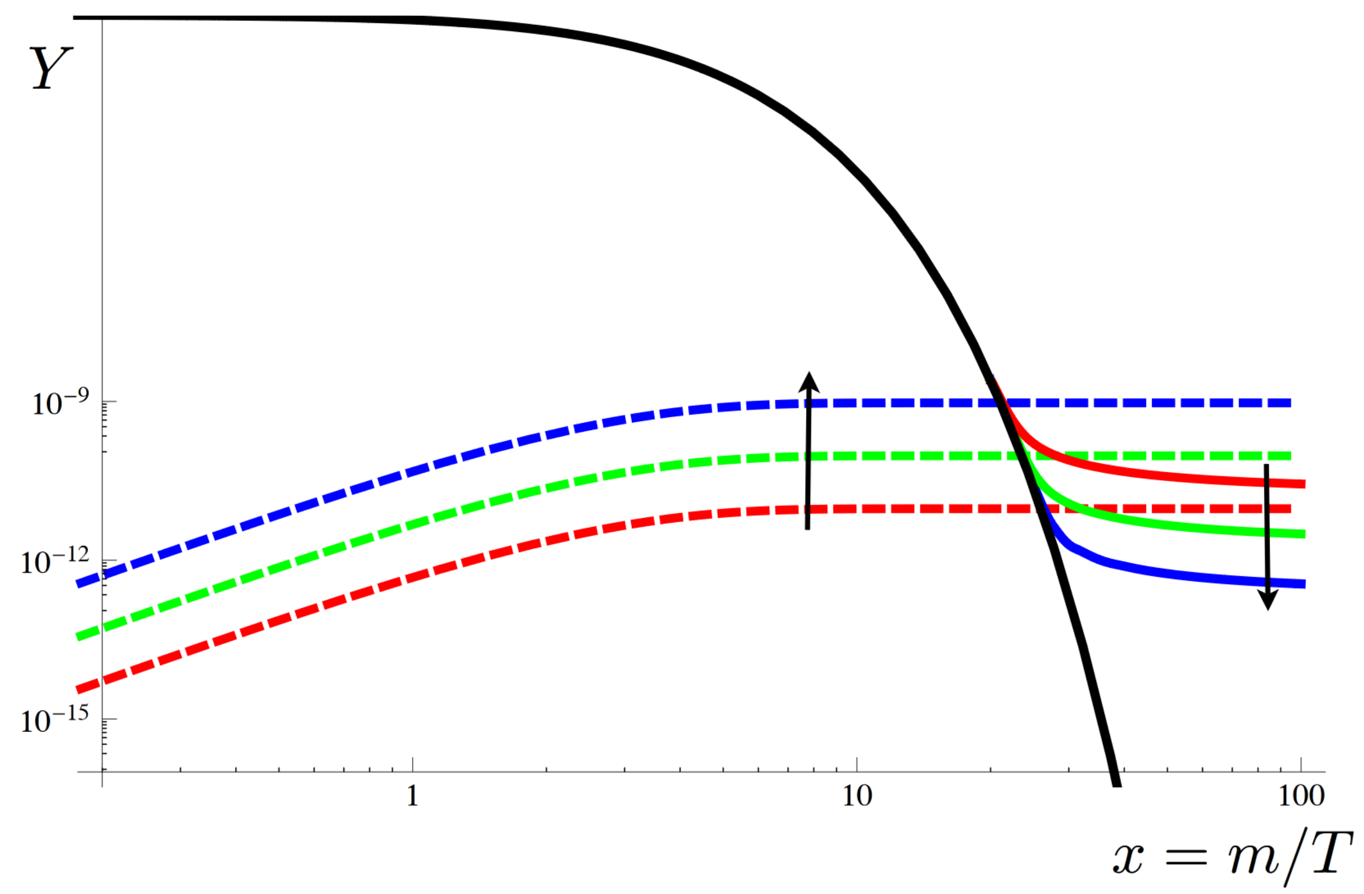
$\Omega_i = \rho_i/\rho_c$ with ρ_c the critical density, i.e. the total energy density for k=0

$$\rho_c = \frac{3H_0^2}{8\pi G_N} \sim 1.05 \times 10^{-5} h^2 \text{ GeV/cm}^3$$

Building a DM model satisfying abundance today

J. Ruderman lectures

- Different models depending on:
  - Nonzero DM abundance in early Universe and subsequent depletion (**freeze out**) or smal/zero abundance in early universe and production from thermal bath (**freeze-in**)
  - Interactions dominating DM depletion/production
  - Initial conditions) and interactions enforcing equilbrium
  - Symmetric or asymmetric DM
  - One single new state or hidden sector?



- Building a model satisfying DM abundance today
  - DM density at the end of (FO) or before (FI) equilibrium can be described by Boltzman equation with C[f] the collision operator

$$\begin{cases} \dot{n} + 3Hn = \dfrac{1}{a^3}\dfrac{d(na^3)}{dt} = 0 & \text{Inert particles} \\ \dot{n} + 3Hn = \dfrac{g}{(2\pi)^3}\displaystyle\int \dfrac{d^3p}{E} C[f] & \text{interacting particles} \end{cases}$$

- Examples:

  Annihilating DM $\dot{n} + 3Hn = \underbrace{-n_\chi^2 < \sigma v >_{\chi\chi}}_{\chi\chi \to \phi\phi} + \underbrace{n_\phi^2 < \sigma v >_{\phi\phi}}_{\phi\phi \to \chi\chi}$

  SM decay into DM $\dot{n} + 3Hn = \underbrace{-n^\psi < \Gamma_\psi >}_{\psi \to \chi\phi} + \underbrace{n_\chi n_\phi < \Gamma_\psi >}_{\chi\phi \to \psi}$

- Detailed balance at eq: $(n_\chi^{eq})^2 < \sigma v >_{\chi\chi} = (n_\phi^{eq})^2 < \sigma v >_{\phi\phi}$

  $(n_\psi^{eq}) < \Gamma_\psi > = (n_\chi n_\phi)^{eq} < \Gamma_\psi >$

➡ Solving Boltzman equation and comparing with observed relic density, can derive sclaes of $< \sigma v >$ or $< \Gamma_\psi >$ and m_χ

Thermal relic: single state

J. Ruderman lectures

DM starts in kinetical and chemical equilibrium

2 → 2 annihilations: $\chi\chi \to \phi\phi$

$$\dot{n} + 3Hn = -n_\chi^2 < \sigma v >_{\chi\chi} + n_\phi^2 < \sigma v >_{\phi\phi}$$

- $\phi \in$ SM (WIMP)

$$< \sigma v > \sim \frac{1}{T_{eq}M_{pl}} \sim \frac{\alpha_w^2}{m_\chi^2} \sim 1\,\mathrm{TeV}$$

$$m_\chi \sim \alpha_w \sqrt{T_{eq}M_{pl}} \sim \mathrm{TeV}$$

- $\phi \in$ BSM with $m_\phi < m_\chi$ (hidden sector).

$$< \sigma v > \sim \frac{1}{T_{eq}M_{pl}} \sim \frac{\alpha_d^2}{m_\chi^2}$$

$$m_\chi \sim \alpha_d \sqrt{T_{eq}M_{pl}} \sim \alpha_d/\alpha_w \times \mathrm{TeV}$$

$m_\phi > m_\chi$ (forbidden sector)

$$< \sigma v >_{\chi\chi} = \left(\frac{n_{\gamma_d}^{eq}}{n_\chi^{eq}}\right)^2 < \sigma v >_{\gamma_d\gamma_d} \sim e^{-2\delta m/T} \frac{\alpha_d^2}{m_{\gamma_d}^2}$$

From detailed balance, starting from inverse process

$$m_\chi \sim e^{-2\delta m/T_{FO}} \alpha_d \sqrt{T_{eq}M_{pl}} \ll \mathrm{TeV}$$

(ϕ and χ singlet under SM gauge group, but charged under new dark gauge group)

3 → 2 annihilations: $\chi\chi\chi \to \chi\chi$ (SIMP)

$$\dot{n} + 3Hn = -n_\chi^3 < \sigma v^2 >_{3\chi} + n_\chi^2 < \sigma v >_{2\chi}$$

- Possible only for bosonic DM
- Forbidden if DM is charged under Z_2 but consistent with Z_3 symmetry

$$< \sigma v^2 > \sim \frac{\alpha_d^2}{m_\chi^5}$$

$$m_\chi \sim \alpha_d \left(T_{eq}^2 M_{pl}\right)^{1/3} \sim \alpha_d \times \mathrm{GeV}$$

Semi-annihilation: $\chi\chi \to \chi\phi$

$$\dot{n}_\chi + 3Hn_\chi = -n_\chi^2 < \sigma v >_{\chi\chi} + n_\chi n_\phi^{eq} < \sigma v >_{\bar{\chi}\phi}$$

e.g. Z_3 symmetry

$$< \sigma v > \sim \frac{1}{T_{eq}M_{pl}} \sim \frac{\alpha_w^2}{m_\chi^2} \sim 1\,\mathrm{TeV}$$

$$m_\chi \sim \alpha_w \sqrt{T_{eq}M_{pl}} \sim \mathrm{TeV}$$

Thermal relic: multiple states
J. Ruderman lectures

Multiple new states, all charged under a given symmetry that forbid their decay into other particles, but not among the χ_i states

- **Co-annihilation:** $\chi_i \to \chi_{i-1}\phi$, with $m_{\chi_i} > m_{\chi_{i-1}}$ $\qquad \dot{n} + 3Hn = - < \sigma v >_{eff} (n^2 - (n^{eq})^2)$ $\qquad < \sigma v >_{eff} = \frac{1}{T_{eq} M_{pl}}$
    - If the inverse process and scatterings with thermal bath particle are rapid => $\frac{n_i}{n_j} = e^{\mu_i - \mu_j} \frac{n_i^{eq}}{n_j^{eq}} = \frac{n_i^{eq}}{n_j^{eq}}$ => N Boltzman equations simplified to same as WIMP case, with $n = \sum_i n_i$ and $< \sigma v >_{eff} = \sum_{i,j} (n_i^{eq} n_j^{eq}/n_{eq}^2) < \sigma_{ij} v >$
    - Several possible scenarios depending on dominant annihilation channels. If annihilations dominated by heavier states, fimilar to forbidden sector => light DM
- **Co-scattering:** $\chi\phi \to \psi\phi$ with $m_\chi < m_\psi$ and $\phi \in SM || BSM$ $\qquad \dot{n} + 3Hn = - n_\chi n_\phi^{eq} < \sigma v >_{\chi\phi} + n_\psi^{eq} n_\phi < \sigma v >_{\psi\phi}$ $\qquad < \sigma v >_{eff} = \frac{e^{-(m_\chi - m_\phi)/T_{FO}}}{T_{eq} M_{pl}}$
- Co-annihilation and co-scattering complementary: the one that decouples first is dominant process for DM production, the other one enforces chemical equilibrium

---

Asymmetric DM

- Asymmetry between DM particle and anti-particle, potentially same origin as baryonic asymmetry
- Asymmetry might arise for same processes independently, or be propagated from baryonic to dark matter
- If baryon and DM masses are same order, baryon and DM abundances are similar as well => $\frac{\Omega_\chi}{\Omega_b} \sim 5$
- But most asymmetric DM models do not relate baryonic and dark matter asymmetries

$$\Omega_b h^2 \sim = \left(\frac{s_0}{\rho_c h^{-2}}\right)\left(\frac{n_B - n_{\bar{B}}}{s}\right) m_p \sim 0.022$$

$$\Omega_\chi h^2 \sim = \left(\frac{s_0}{\rho_c h^{-2}}\right)\left(\frac{n_\chi - n_{\bar{\chi}}}{s}\right) m_p \sim 0.12$$

Thermal relic: dark temperature

J. Ruderman lectures

- If DM in kinetic equilibrium with SM plasma, Dark temperature T_d is equal to T_γ. What if $T_d \neq T_\gamma$ (dm-SM coupling small enough)?
  - The two temperatures can evolve independently and the total entropy of each sector is separately conserved at equilibrium
  - $\xi = \frac{s_{SM}}{s_d} = \frac{g_{*S}^{SM} T_\gamma^3}{g_{*S}^{d} T_d^3} = \text{const}$ => $r = T_\gamma / T_d = \xi^{1/3} \left(\frac{g_{*S}^{d}}{g_{*S}^{DM}} \right)^{1/3}$
  - Impact on relic density: $\Omega_\chi h^2 = (\Omega_\chi h^2)_{r=1} r_{FO}^{-1}$ => DM in a cooler dark sector requires smaller annihilation rate to reproduce relic density, in a hotter dark sector it requires larger annihilation rate

- Cannibalism: **3 → 2 annihilations**: $\chi\chi\chi \to \chi\chi$
  - If there are no non-relativistic states
  - Assuming DS dominates by lightest state and $\mu_1 = 0$
  - $\xi = \frac{s_{SM}}{s_d} \sim \frac{g_{*S}^{SM} T_\gamma^3}{g_1 (m_1/T_d)^{5/2} T_d^3 e^{-m_1/T_d}}$ => $r = T_\gamma / T_d = \xi^{1/3} \left(\frac{g_1}{g_{*S}^{DM}} \right)^{1/3} (m_1/T_d)^{5/6} e^{-m_1/(3T_d)}$ => $T_\gamma \propto a^{-1}$, $T_d \propto 1/(\log a)$

"As the Universe expand, DM cannibalizes itself to keep warm"

Fleebly Interacting Massive Particles (FIMP)

J. Ruderman lectures

UV dominated if Γ_χ/H maximized at high temperatures, IR dominated otherwise

Freeze-in: $\psi \to \chi\phi$ with ψ in thermal eq. (IR) $\quad \dot{n} + 3Hn = <\Gamma_\psi> \left(n_\psi^{eq} - \frac{n_\chi}{n_\chi^{eq}} n_\psi^{eq}\right) \sim n_\psi^{eq} <\Gamma_\psi>$ for $n_\chi << n_\chi^{eq}$ (true for small initial abundance and DM far from eq)

- All particles in initial state in thermal equilibrium
- Thermally averaged decay rate: $<\Gamma_\psi> \sim \begin{cases} (m/2T)\Gamma_\psi & (T \gg m) \\ \Gamma_\psi & (T \ll m) \end{cases}$
- Boltzman equation => $\frac{dY_\chi}{d\log x} \sim Y_\psi^{eq} \frac{<\Gamma_\psi>}{\tilde{H}}$ with $Y_\chi = n_\psi/s,\ x = m_\psi/T,\ \tilde{H} = H$ if g_{*s} constant,

$$\frac{Y_\psi^{eq}}{H} <\Gamma_\psi> \propto \begin{cases} \Gamma_\psi T^{-3} & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$

Dominant production for $T \sim m_\psi$

Pandemic: transmission $\chi\psi \to \chi\chi, \chi$ not at eq, (UV) $\psi \in$ thermal bath $\quad \dot{n} + 3Hn = <\sigma v>_{tr} \left(n_\chi n_\psi^{eq} - \frac{n_\chi^2}{n_\chi^{eq}} n_\psi^{eq}\right) \sim n_\chi n_\psi^{eq} <\sigma v>_{tr}$ for $n_\chi << n_\chi^{eq}$ (true for small initial abundance and DM far from eq)

- Solving the Boltzman equation => $Y_\chi \sim Y_\chi^0 \exp\left[\int_0^\infty \frac{dx}{x} \frac{n_\psi^{eq} <\sigma v>_{tr}}{\tilde{H}}\right]$ => exponential growth with $n_\psi^{eq} <\sigma v>_{tr} / \tilde{H}$ rate

Fleebly Interacting Massive Particles (FIMP)

J. Ruderman lectures

SuperWIMP: $\psi \rightarrow \chi X$ with DM production mainly after ψ thermal decoupling (IR)

Rapid $\psi\bar{\psi} \rightarrow \phi\phi$, froze out after ψ becomes non-relativistic => $n_\psi < \sigma v > \sim H$

- ψ initially in thermal equilibrium, decay rate far slower than H => $\Gamma_\psi \sim H$
- Considering $Y_\chi = Y_\psi^{FO}$ => $\Omega_\chi h^2 = \left(\frac{s_0}{\rho_c h^{-2}}\right) m_\chi Y_\chi = \left(\frac{s_0}{\rho_c h^{-2}}\right) m_\chi Y_\psi = \frac{m_\chi}{m_\psi}(\Omega_\chi h^2)_{FO}$
- This contribution should be sum to FI one: some DM produced by FI when $T \sim m_\psi$, some after ψ annihilation decoupling and ψ decays to DM

Sterile neutrinos

- Neutrino state ν_s which couples to active neutrinos ν_α through Yukawa coupling with Higgs
- Mixing between sterile and active neutrinos => $\nu_s \rightarrow \nu_\alpha \gamma$. If mixing angle small enough
  - good DM candidate (long lived)
  - Kinetically and chemically decoupled from SM => FIMP
- Assuming 0 initial abundance => production by oscillations from thermal neutrinos (Dodelson-Widrow)

Relic density can be resonantly enhanced in presence of large lepton asymmetry in early Universe

$$\Gamma_{\nu_s} \sim G_F^2 T^5 \sin^2(2\theta) \qquad \sin^2(2\theta) \sim \frac{m^2}{(M/2 \ + cG_F^2 T^5)^2}$$

=> relic density if $m_s \sim 3.4 \text{ keV} \times \left(\frac{\text{sen}^2 2\theta}{10^{-8}}\right)^{-0.6}$

Misalignement (axions)

J. Ruderman lectures

- Scalar DM field produced with large occupation number => classical field in FRW metric
  - Klein-Gordon equation of motion :

Homogeneity => $\phi = \phi(t)$

Inflation. => $\phi(0) = \phi_*$

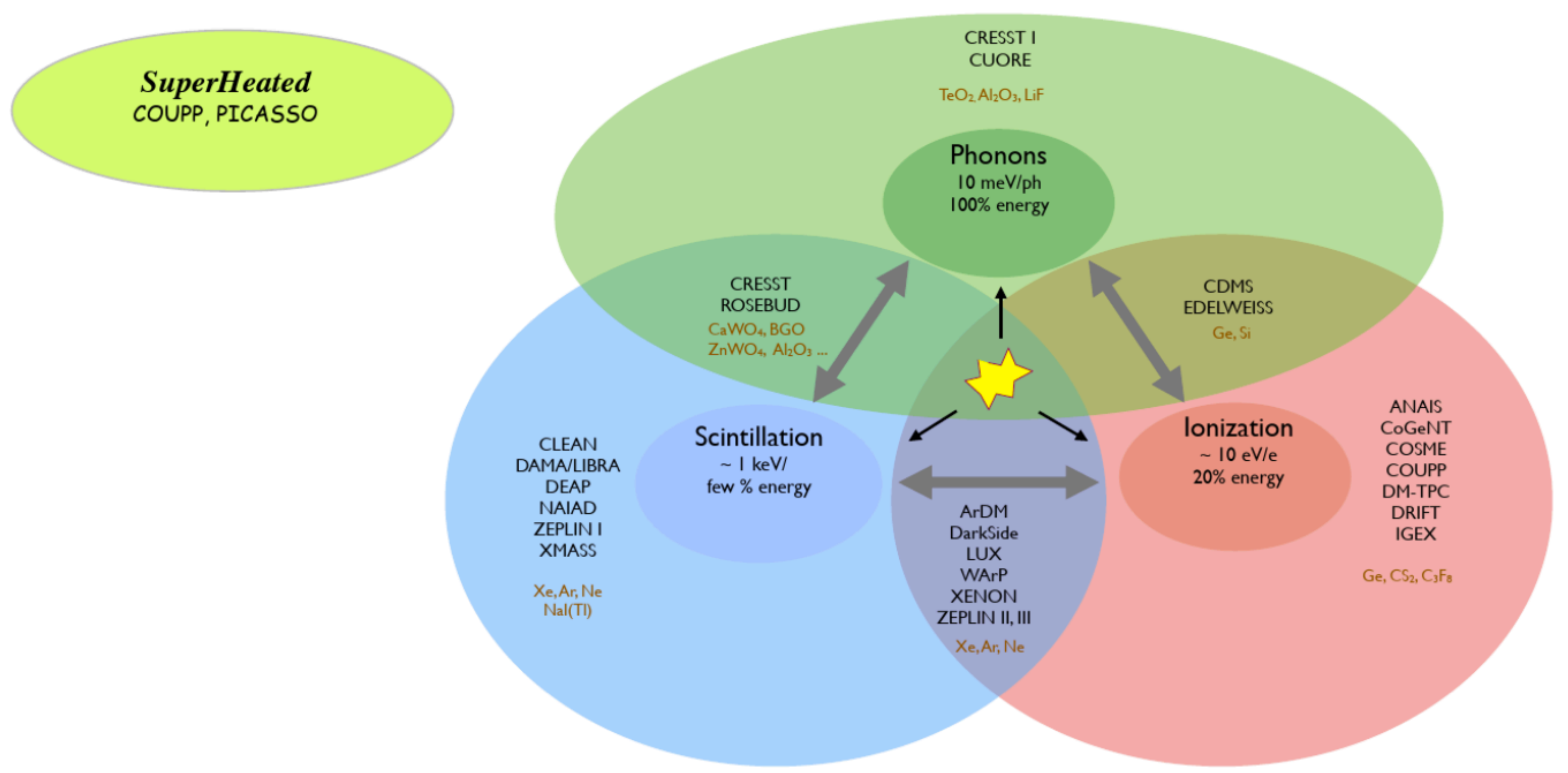
$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$
$$V'(\phi, T) \sim 1/2\ m_\phi^2(T)\phi$$

=>. $\ddot{\phi} + 3H\dot{\phi} \sim 0$ At high temperatures ($H(T) \gg m_\phi(T)$) => ϕ constant (Hubble friction)

- Misalignement: production of scalar field, with nonzero initial field value (ϕ_*) seeded by inflation
  - Hubble friction => $\phi = \phi_*$ as long as $H(T) \gg m_\phi(T)$
  - When $H(T_*) = m_\phi(T_*) = m_*$ => start of ϕ oscillation
    - Assuming $H \ll m_\phi$ and using time-averages: $w = < P_\phi > / < \rho_\phi > = \dfrac{\dot{A}^2}{2m_\phi^2 A^2} \sim 0$ => acts as DM (fluid of NR particle)
    - Evolution in time: $\dfrac{<\dot{\rho}_\phi>}{<\rho_\phi>} = -3\dfrac{\dot{a}}{a} + \dfrac{\dot{m}_\phi}{m_\phi}$ => $\dfrac{<\rho_\phi>}{m_\phi}a^3 = \text{const}$ => $n_\phi/s = \text{const}$ => particle DM
  - Relic density: $\Omega_\phi h^2 = \left(\dfrac{s_0}{\rho_c h^{-2}}\right)\dfrac{m_\phi^0 n_\phi}{s} \sim 3.9\left(\dfrac{s_0}{\rho_c h^{-2}}\right)\dfrac{g_*^{3/4}}{g_{*S}}\theta_0^2\dfrac{m_\phi^0 f^2}{(m_\phi)^{1/2}M_{pl}^{3/2}}$ if the initial amplitude is $A_* = \theta_0 f$

Direct Detection
J. Cooley lectures

- Especially targeting WIMP(like) DM
- Interaction of WIMP "wind" with detectors. Mainly two signatures:
  - WIMP-nucleon (/electron) scattering
  - Modulation



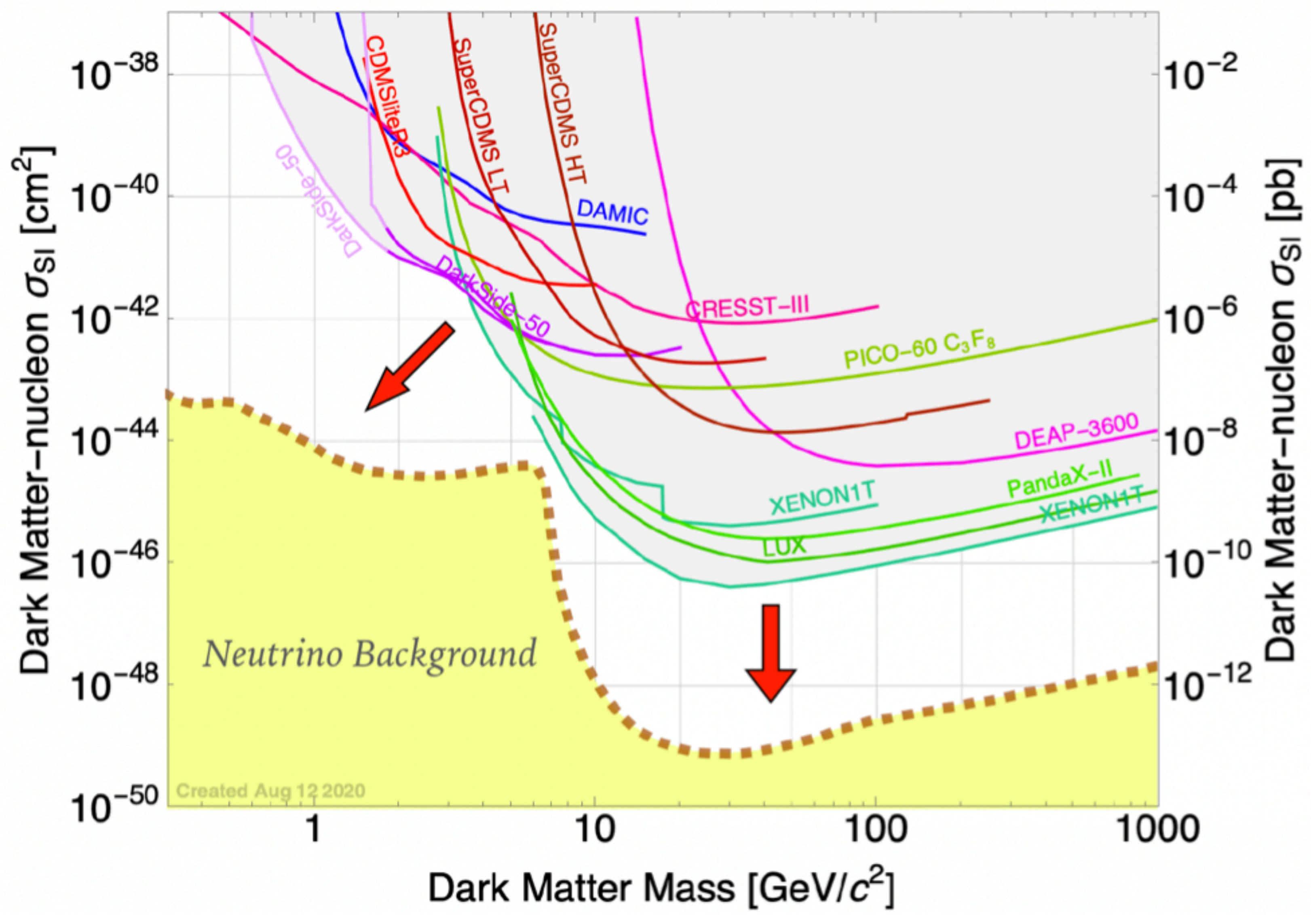


Figure 26: Experimental exclusion regions in spin-independent cross-section vs. mass space. The neutrino "fog" background expectation is shown in yellow at the bottom of the plot. The red arrows indicate directions that forthcoming experiments will push into the parameter space, toward better sensitivity at low mass and increased sensitivity at high mass. Image generated using [38].

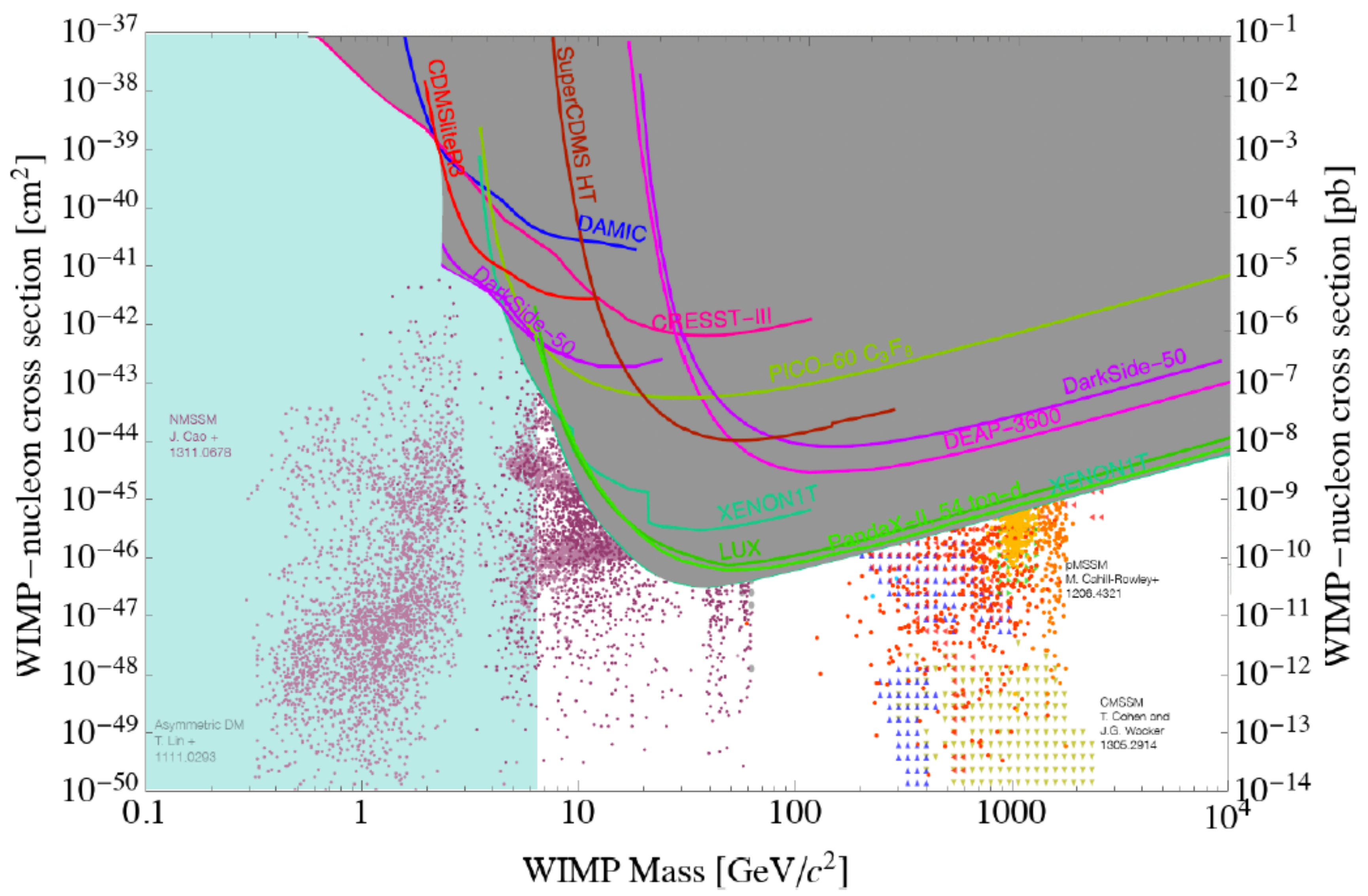
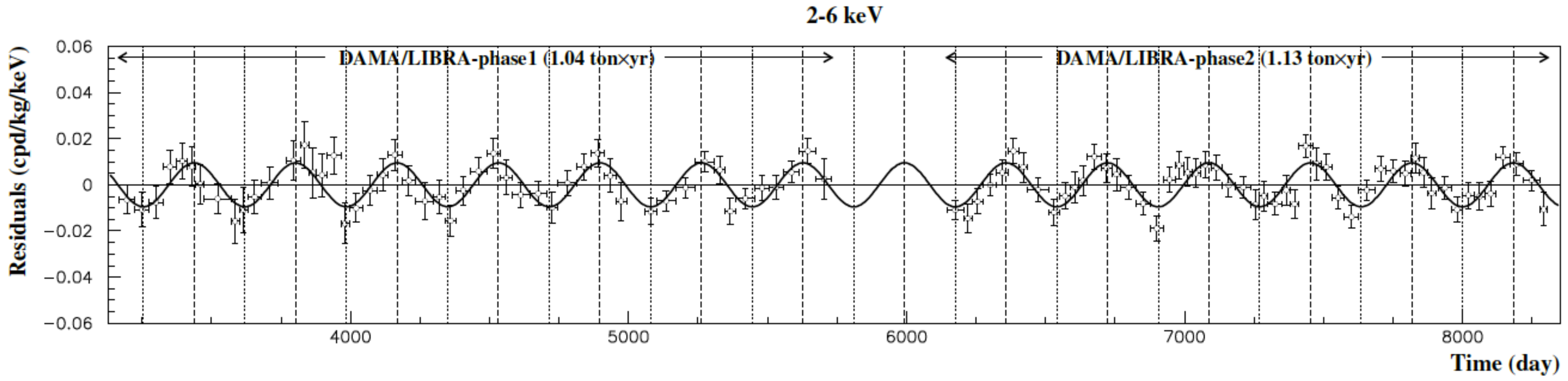
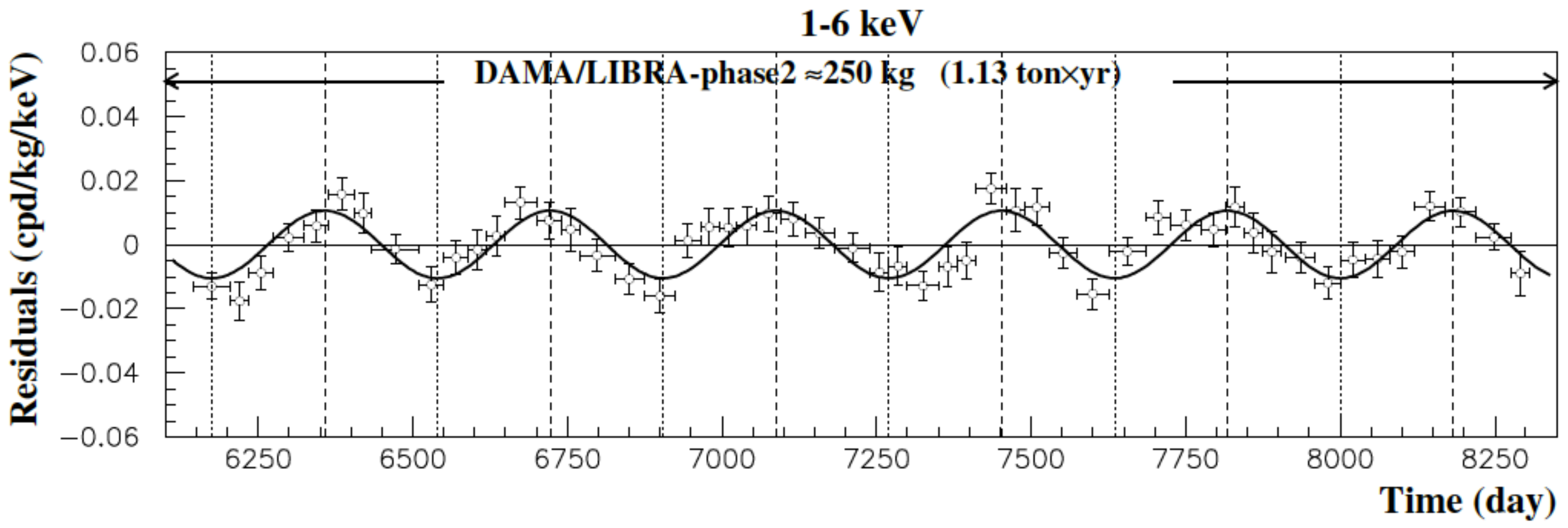


Figure 25: An example of the theory-driven search space for dark matter across a portfolio of plausible theoretical models for dark matter. Superimposed exclusions of that space based on current experimental efforts. Figure generated using [38].

- Especially targeting WIMP(like) DM
- Interaction of WIMP “wind” with detectors. Mainly two signatures:
  - WIMP-nucleon (/electron) scattering
  - Modulation



(a) DAMA/LIBRA Annual Modulation



(b) LIBRA-only Annual Modulation

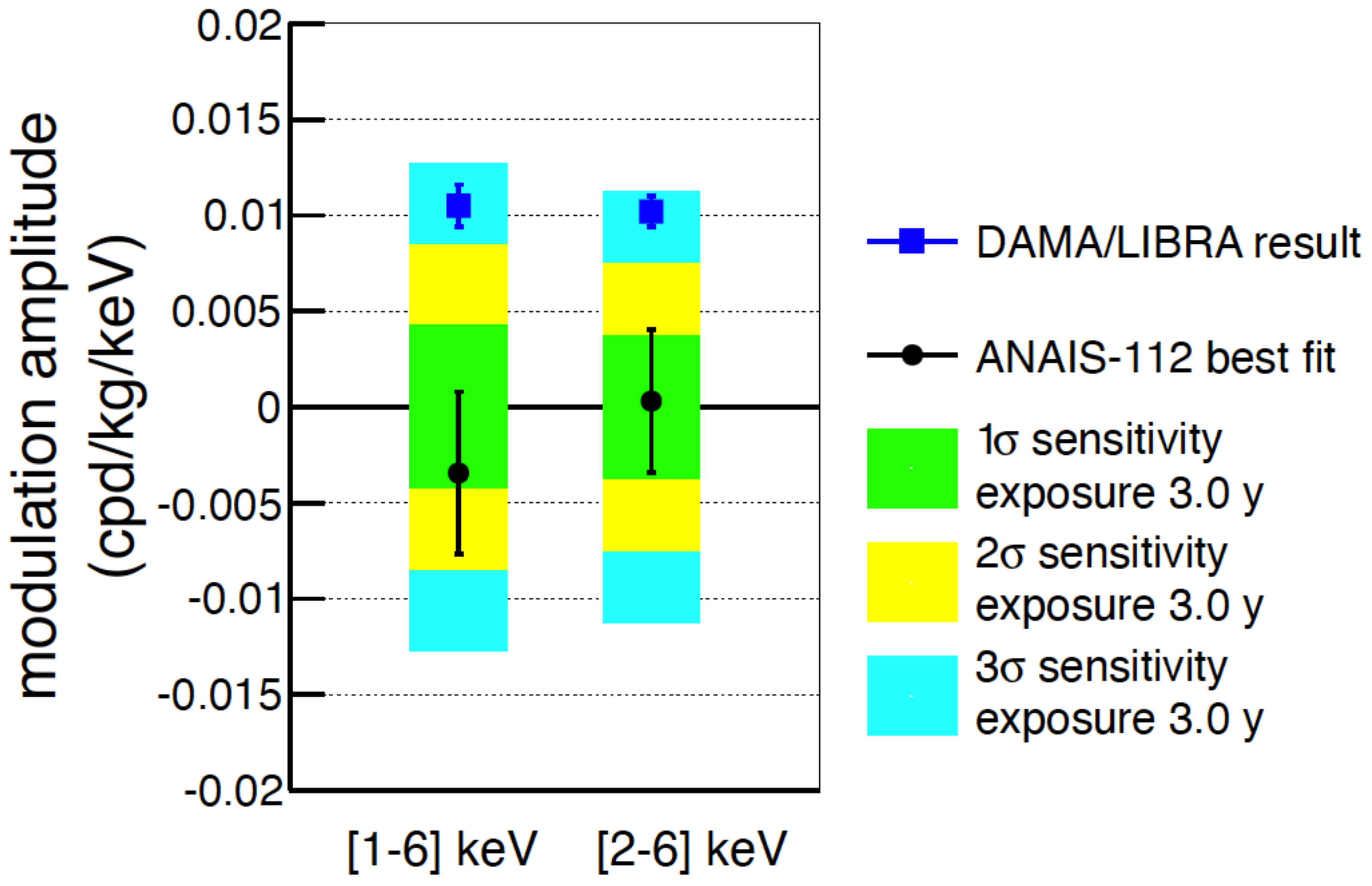
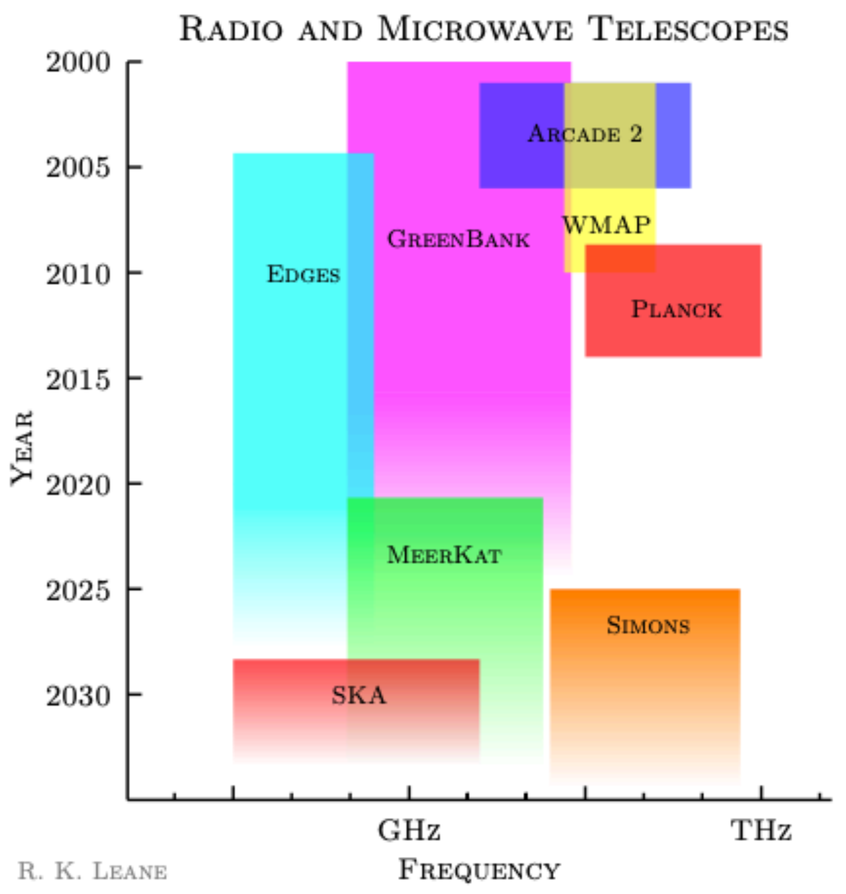


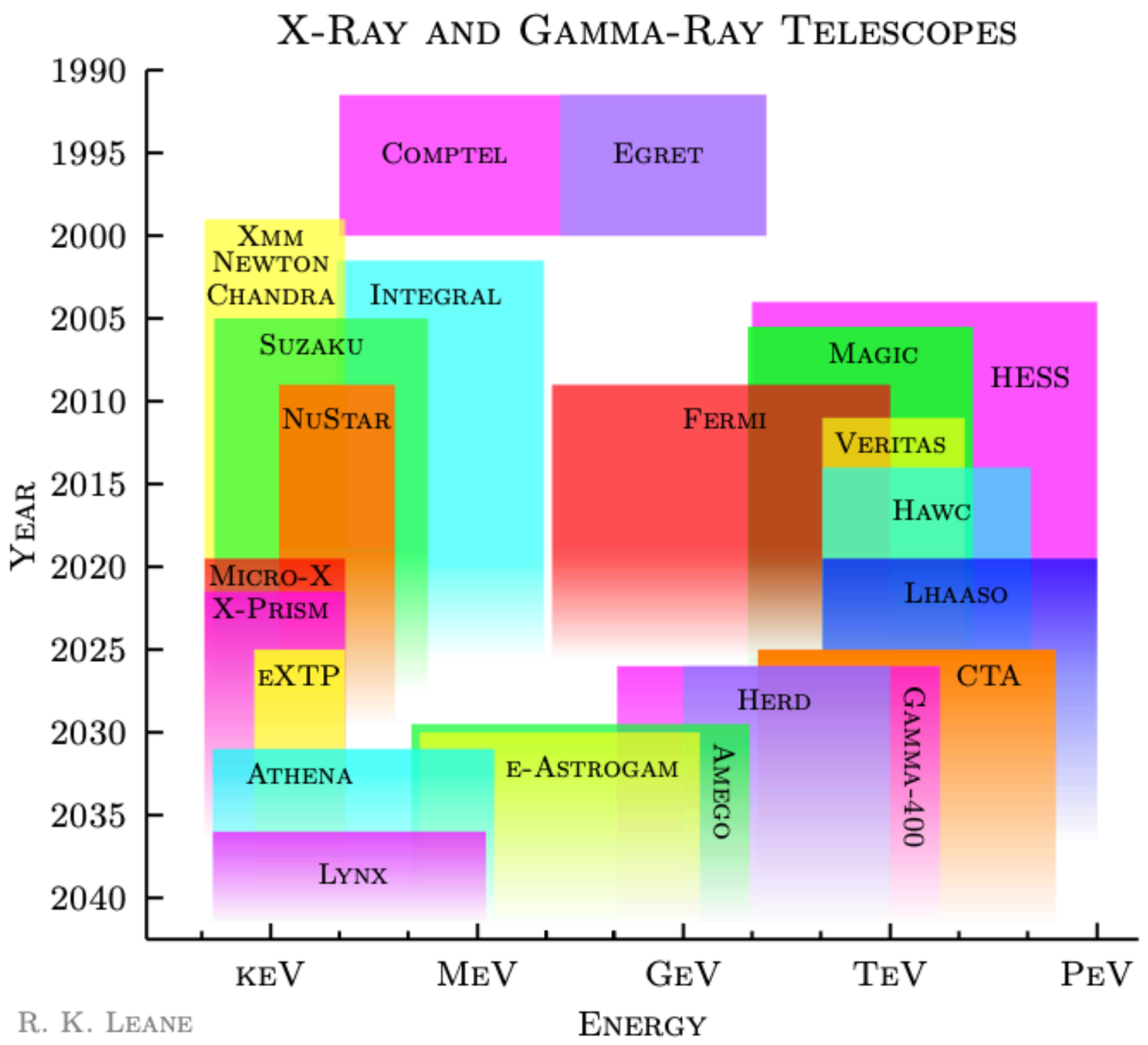
Figure 29: The ANAIS best-fit modulation amplitude result compared with the DAMA/LIBRA best-fit result for both recoil energy ranges considered by DAMA/LIBRA. Figure from Ref. [41].

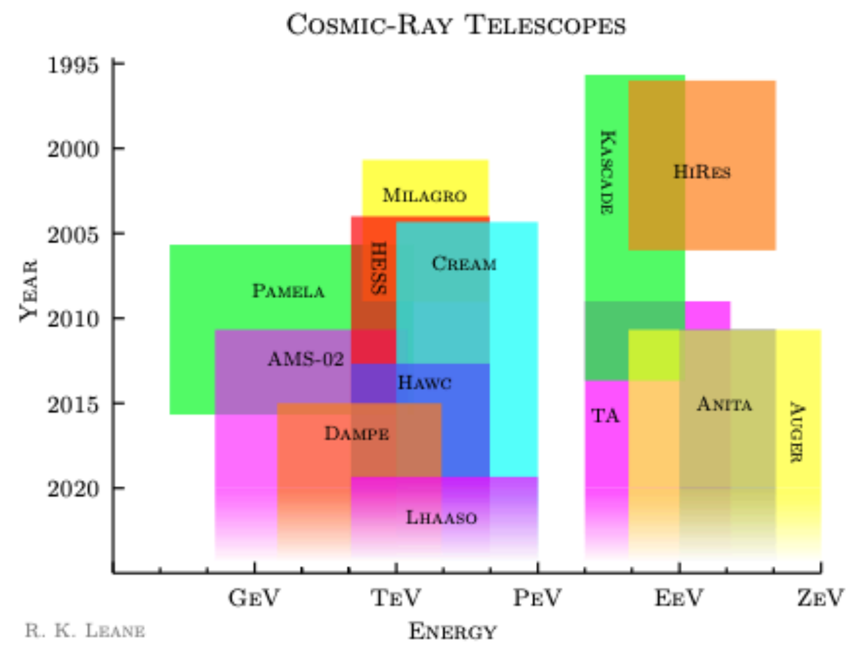
Figure 27: Results from the DAMA/LIBRA Experiment. (Top) The full 14-cycle DAMA/LIBRA annual modulation result, after subtracting flat background contributions. This analysis uses a higher energy threshold in the range of 2 − 6 keV of recoil energy. (Bottom) The LIBRA-only results allowing for a lower-energy threshold of 1 − 6 keV in recoil energy. Figures extracted from [39].

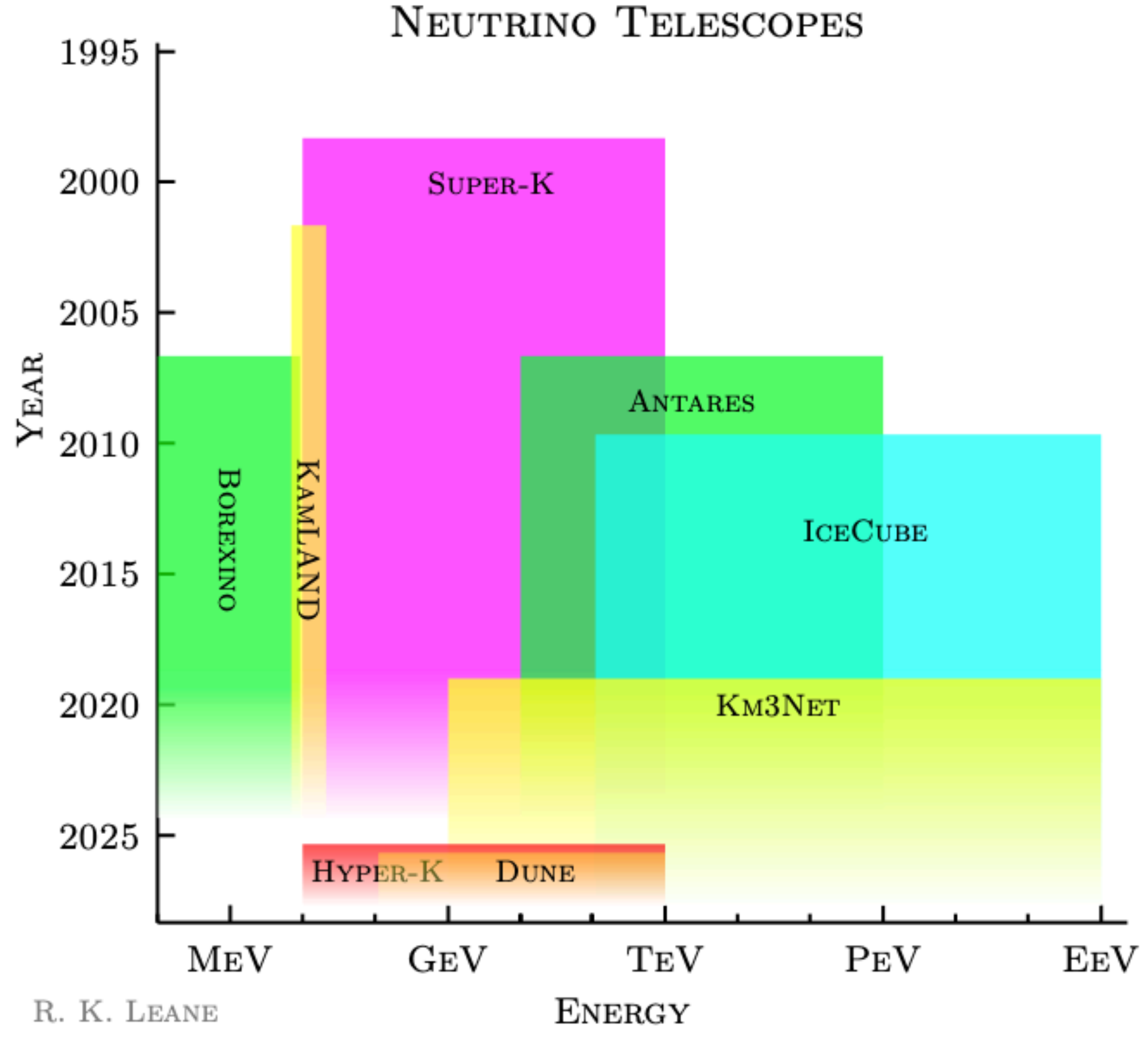
Indirect detection
T. Slatyer lectures

- Mainly detecting DM annihilation signals
- “Nightmare” scenario: asymmetric DM and co-annihilation
- Different strategies:
  - Radio & Microwave: synchrotron radiation from weak-scale DM annihilation products
  - X-ray: sterile neutrino
  - Gamma-rays: high energy lines or continuum, WIMP annihilation, heavy DM (>> TeV) decay and annihilation
  - Cosmic ray: WIMP annihilation. In particular positron and antiproton channels
  - Neutrino telescopes: heavy DM annihilation and decay
  - CMB & Lyman-α: light (sub GeV) DM









- WIMP annihilation limits from γ ray
  - From dwarf galaxies: main contraints from Fermi telescope VERITAS, MAGIC, HAWC and H.E.S.S dominate limits from Fermi for DM masses well above 1 TeV
  - gamma rays from galactic centre
  - gamma ray line enhanced if there are charged particles of about same mass as DM, especially if long-range force couples 2-particle DM to 2-charged particle states (WINO)
- WIMP annihilation limits from cosmic rays
  - Positrons => leptonic annihilation
  - Antiprotons => hadronic annihilation
  - Radio measurements can be sensitive up to 500 GeV DM mass
- Heavy DM from gamma-ray and neutrino: annihilation or decay
- Light DM : dominated by cosmological constraints
  - Fermi angular resolution degrade below GeV and 100 MeV scale cannot decay into hadronic channels => suppress photon signals
  - low-E e^- deflected by solar wind => limit lepton channel constraint

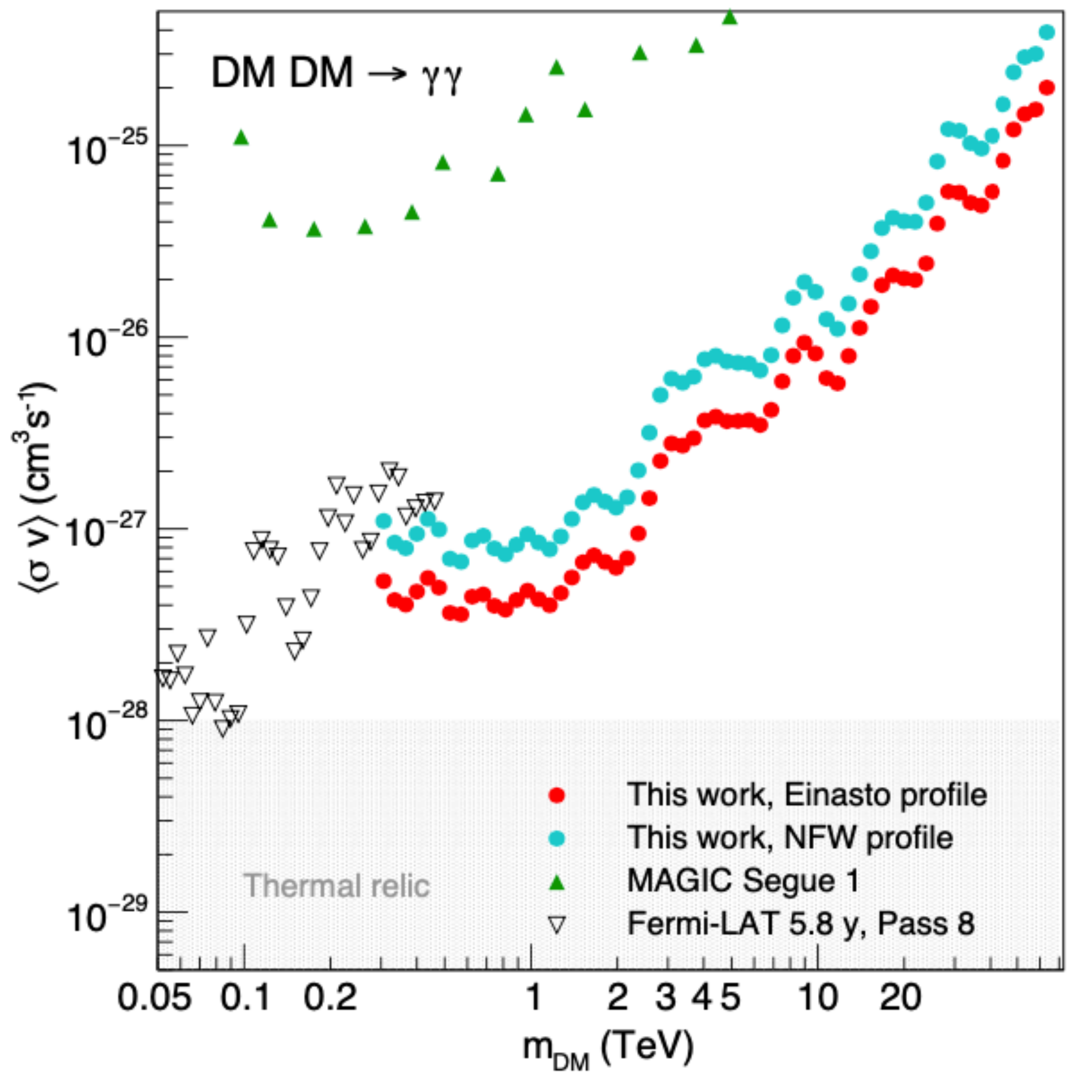


Figure 7: Upper bounds on the cross section for DM annihilation to $\gamma\gamma$, from *Fermi* (black triangles), MAGIC (green triangles), and H.E.S.S (red and cyan dots). Red and cyan dots correspond to the Einasto and NFW profiles respectively. The gray-shaded area is a theoretical forecast for the natural scale of the line cross-section. Figure reproduced from Ref. [94]; see that work for details.

Indirect detection

T. Slatyer lectures

Sensitivities

- WIMP annihilation limits from y ray
  - From dwarf galaxies: main contraints from Fermi telescope VERITAS, MAGIC, HAWC and H.E.S.S dominate limits from Fermi for DM masses well above 1 TeV
  - gamma rays from galactic centre
  - gamma ray line enhanced if there are charged particles of about same mass as DM, especially if long-range force couples 2-particle DM to 2-charged particle states (WINO)
- WIMP annihilation limits from cosmic rays
  - Positrons => leptonic annihilation
  - Antiprotons => hadronic annihilation
  - Radio measurements can be sensitive up to 500 GeV DM mass
- Heavy DM from gamma-ray and neutrino: annihilation or decay
- Light DM : dominated by cosmological constraints
  - Fermi angular resolution degrade below GeV and 100 MeV scale cannot decay into hadronic channels => suppress photon signals
  - low-E e^- deflected by solar wind => limit lepton channel constraint

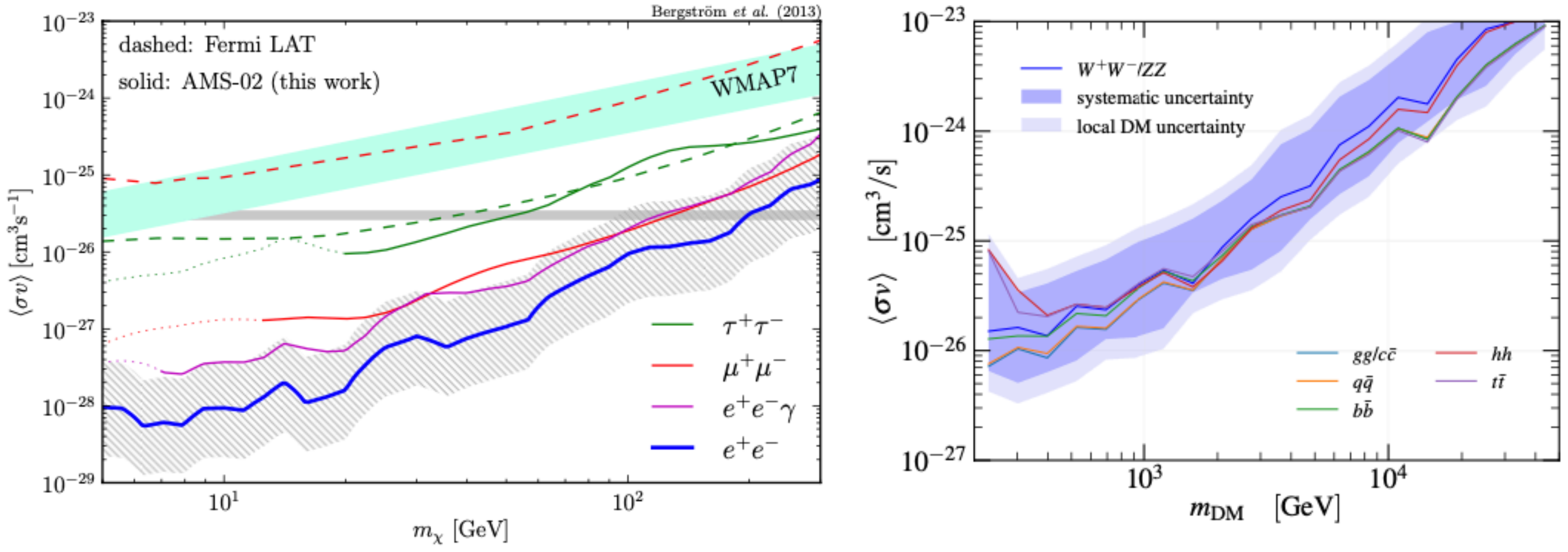


Figure 6: Limits from AMS-02 data on DM annihilation to (left) leptonic channels and (right) hadronic channels. In the *left panel*, dashed lines indicate bounds from *Fermi* observations of dwarf galaxies; the dotted portions of the solid constraint curves from AMS-02 are potentially affected by solar modulation effects. The hatched band around the e^+e^- constraint line indicates the estimated uncertainty due to systematic uncertainties in the local DM density and energy loss rate. In the *right panel*, the different colored lines represent the nominal constraint from antiproton observations for different hadronic final states, and the blue bands denote systematic uncertainties in the limit for annihilation to W and Z bosons. Reproduced from Ref. [95] (*left panel*) and Ref. [96] (*right panel*).

Indirect detection
T. Slatyer lectures

- WIMP annihilation limits from γ ray
  - From dwarf galaxies: main contraints from Fermi telescope VERITAS, MAGIC, HAWC and H.E.S.S dominate limits from Fermi for DM masses well above 1 TeV
  - gamma rays from galactic centre
  - gamma ray line enhanced if there are charged particles of about same mass as DM, especially if long-range force couples 2-particle DM to 2-charged particle states (WINO)
- WIMP annihilation limits from cosmic rays
  - Positrons => leptonic annihilation
  - Antiprotons => hadronic annihilation
  - Radio measurements can be sensitive up to 500 GeV DM mass
- Heavy DM from gamma-ray and neutrino: annihilation or decay
- Light DM : dominated by cosmological constraints
  - Fermi angular resolution degrade below GeV and 100 MeV scale cannot decay into hadronic channels => suppress photon signals
  - low-E e^- deflected by solar wind => limit lepton channel constraint

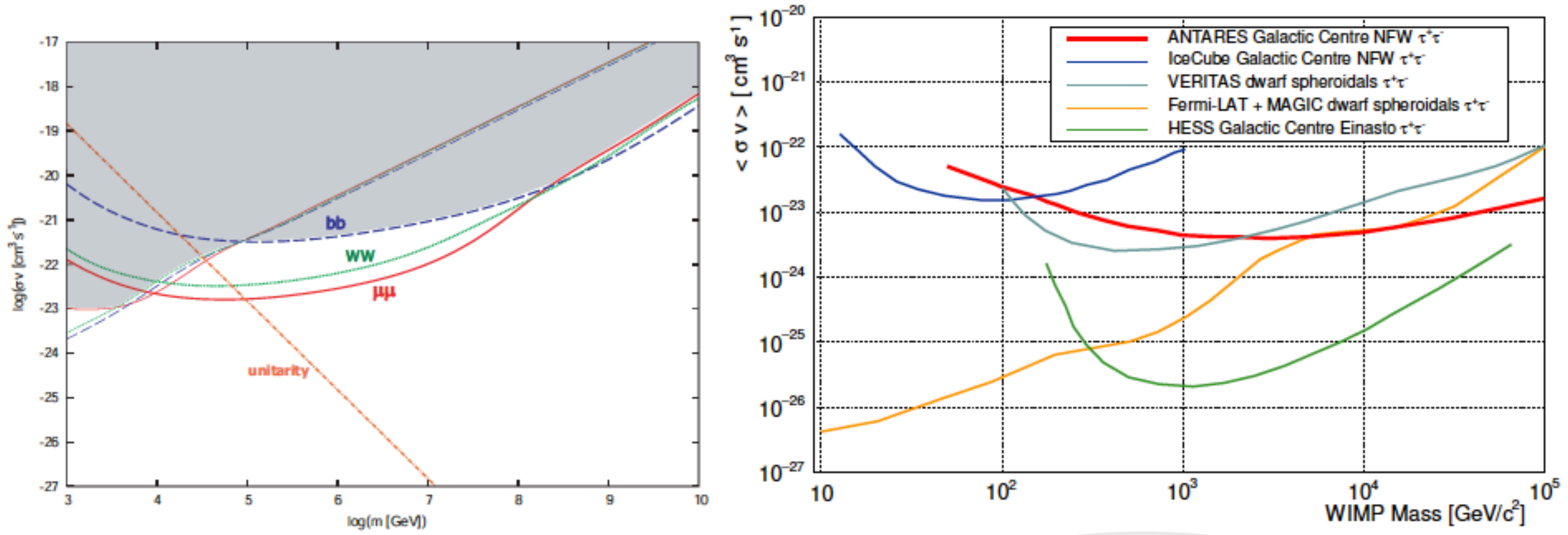


Figure 10: *Left panel*: neutrino (thick curves) and cascade gamma-ray (thin curves) constraints on the annihilation cross section of very heavy DM. The shaded region is determined by taking the more stringent of the neutrino and gamma-ray bounds, for the least constrained of the three channels. Reproduced from Ref. [115]. *Right panel*: updated limits for masses below 100 TeV for the sample channel of annihilation to τ leptons, using observations of the Galactic Center. Reproduced from Ref. [116].

Sufficiently high-energy photons can pair produce via interactions with the interstellar radiation field, producing an electron-photon cascade that results in a spectrum of gamma rays at lower energies

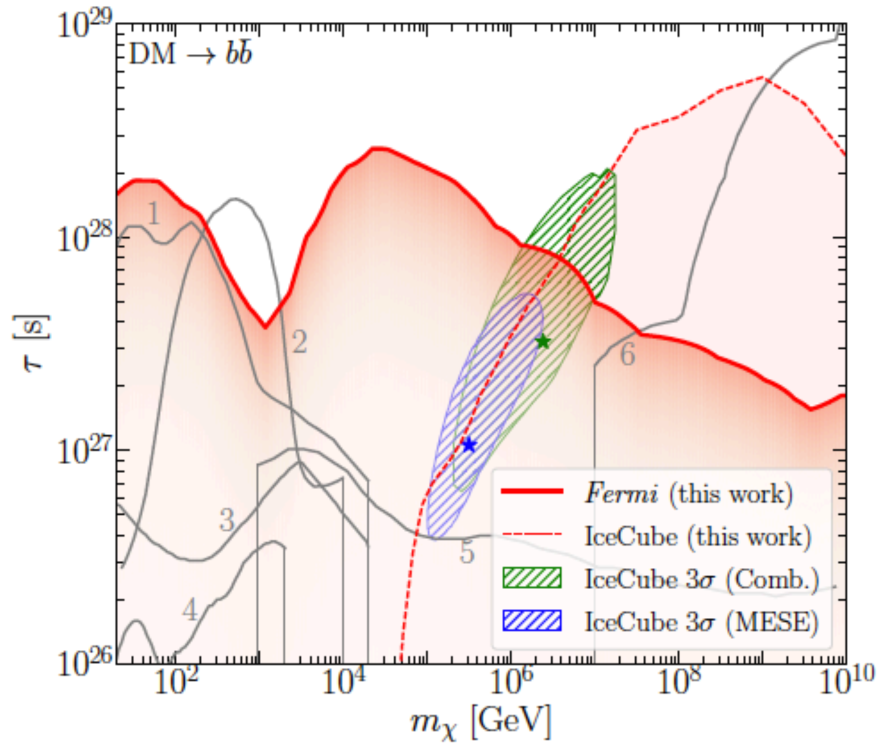


Figure 11: Lower bounds on the decay lifetime for DM decaying to b quarks. The red line is determined by Ref. [56] using *Fermi* data; gray lines with numbers denote existing bounds using data from *Fermi* (2,3,5), AMS-02 (1,4), and PAO/KASCADE/CASAMIA (6). The hashed green (blue) region suggests parameter space where DM decay may provide a $\sim 3\sigma$ improvement to the description of the combined maximum likelihood IceCube neutrino flux. The red dotted line provides a limit if a combination of DM decay and astrophysical sources are responsible for the observed high-energy neutrinos. Reproduced from Ref. [56].

Indirect detection
T. Slatyer lectures

- WIMP annihilation limits from γ ray
  - From dwarf galaxies: main contraints from Fermi telescope VERITAS, MAGIC, HAWC and H.E.S.S dominate limits from Fermi for DM masses well above 1 TeV
  - gamma rays from galactic centre
  - gamma ray line enhanced if there are charged particles of about same mass as DM, especially if long-range force couples 2-particle DM to 2-charged particle states (WINO)
- WIMP annihilation limits from cosmic rays
  - Positrons => leptonic annihilation
  - Antiprotons => hadronic annihilation
  - Radio measurements can be sensitive up to 500 GeV DM mass
- Heavy DM from gamma-ray and neutrino: annihilation or decay
- Light DM : dominated by cosmological constraints
  - Fermi angular resolution degrade below GeV and 100 MeV scale cannot decay into hadronic channels => suppress photon signals
  - low-E e^- deflected by solar wind => limit lepton channel constraint

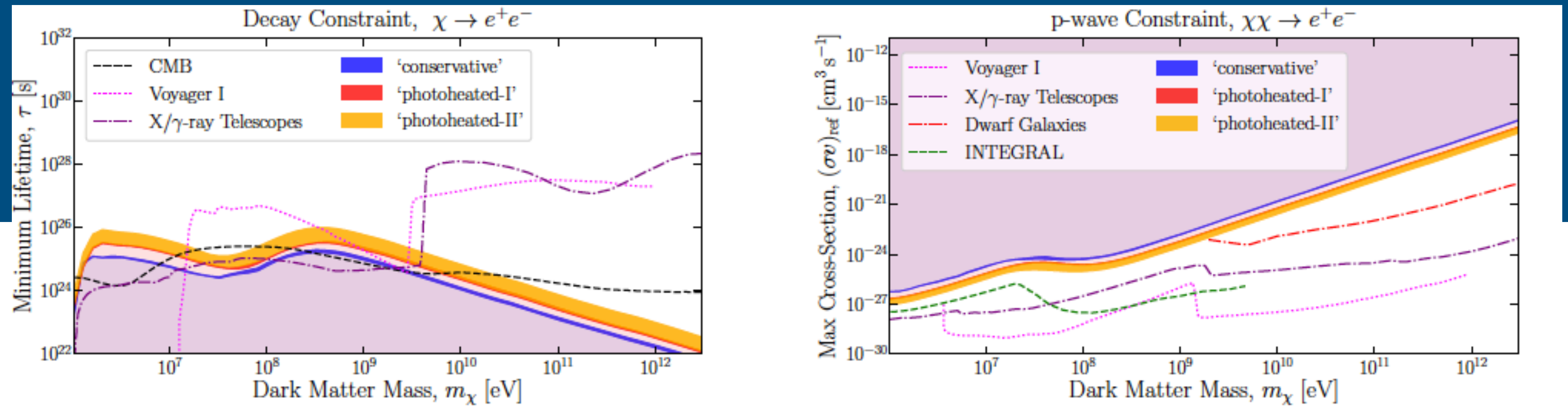


Figure 13: Selected bounds on the DM decay lifetime (*left panel*) and annihilation cross section (*right panel*) for annihilation/decay to e^+e^-. The blue and red lines and orange bands represent constraints derived from the Lyman-α forest under various assumptions for the astrophysical background; the black dashed line indicates the CMB bound (driven primarily by excess early ionization); the pink dotted line indicates limits on low-energy cosmic rays from Voyager I; green-dashed and purple dot-dashed lines indicate limits from X-ray and gamma-ray telescopes. Reproduced from Ref. [71]; see that work for further details.

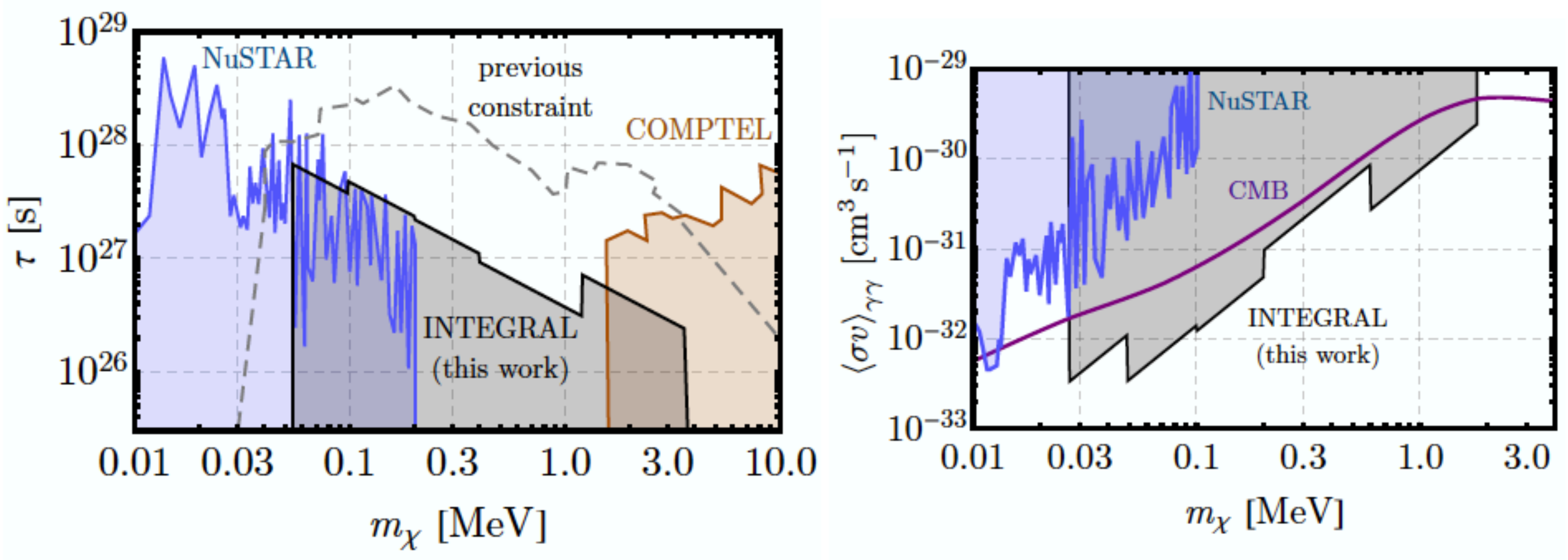


Figure 12: Selected bounds on the DM decay lifetime (*left panel*) and annihilation cross section (*right panel*) for annihilation/decay to $\gamma\gamma$, using data from the NuSTAR X-ray telescope, the CMB, and the INTEGRAL and COMPTEL gamma-ray telescopes. Reproduced from Ref. [119]; see that work for further details. A compilation of bounds at lower/higher masses can be found in Ref. [120].

Sterile neutrinos detection

J. Copp lectures

- Constraints from searches for x-ray emission in regions of high DM density (Galactic Center, galaxy clusters, etc.)
- In 2014, XMM-Newton X-Ray telescope data => unidentified X-ray line near 3.55 keV. Might be hint radiative decay of a 7 keV sterile neutrino => hypothesis not completely ruled out yet

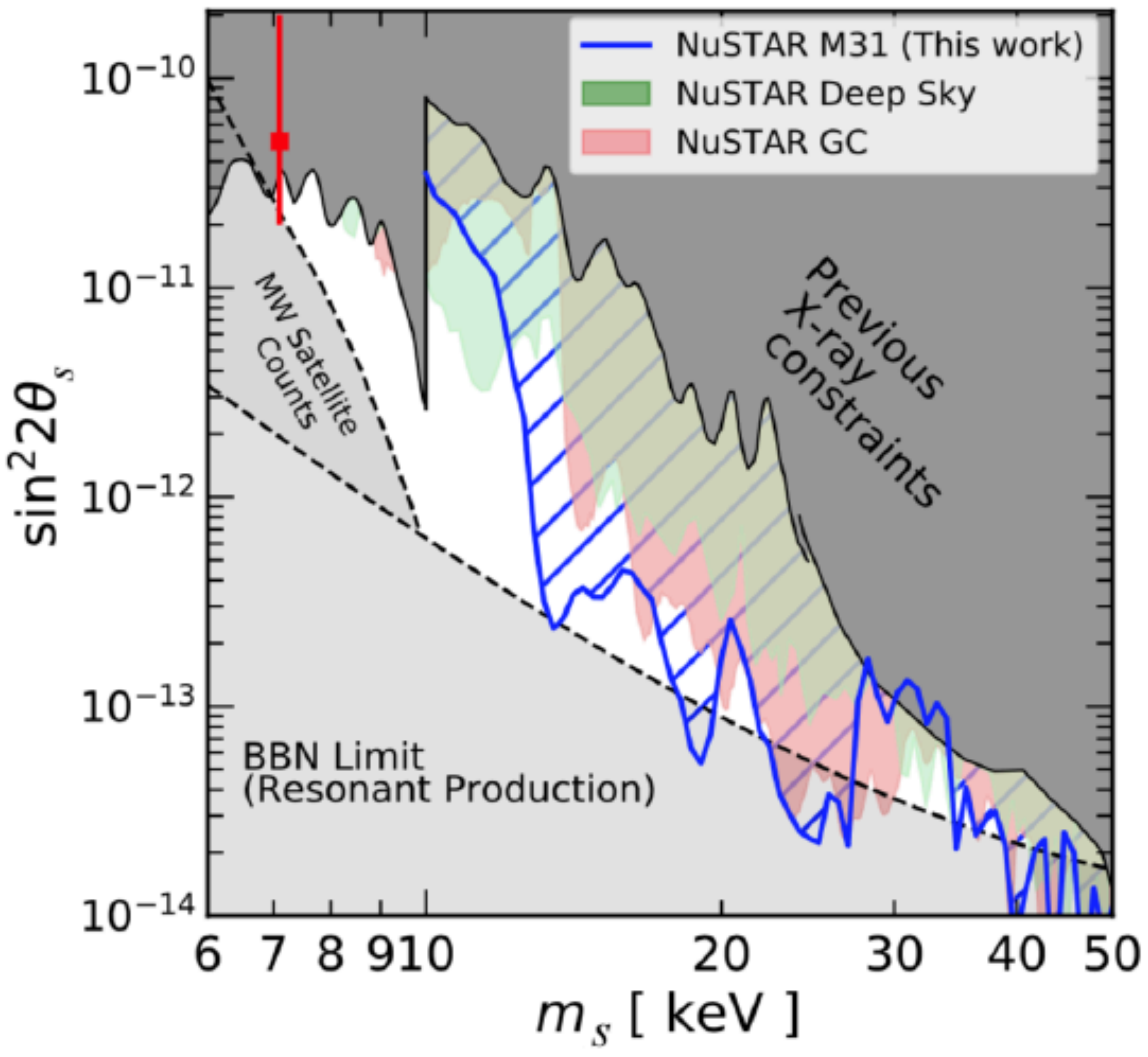
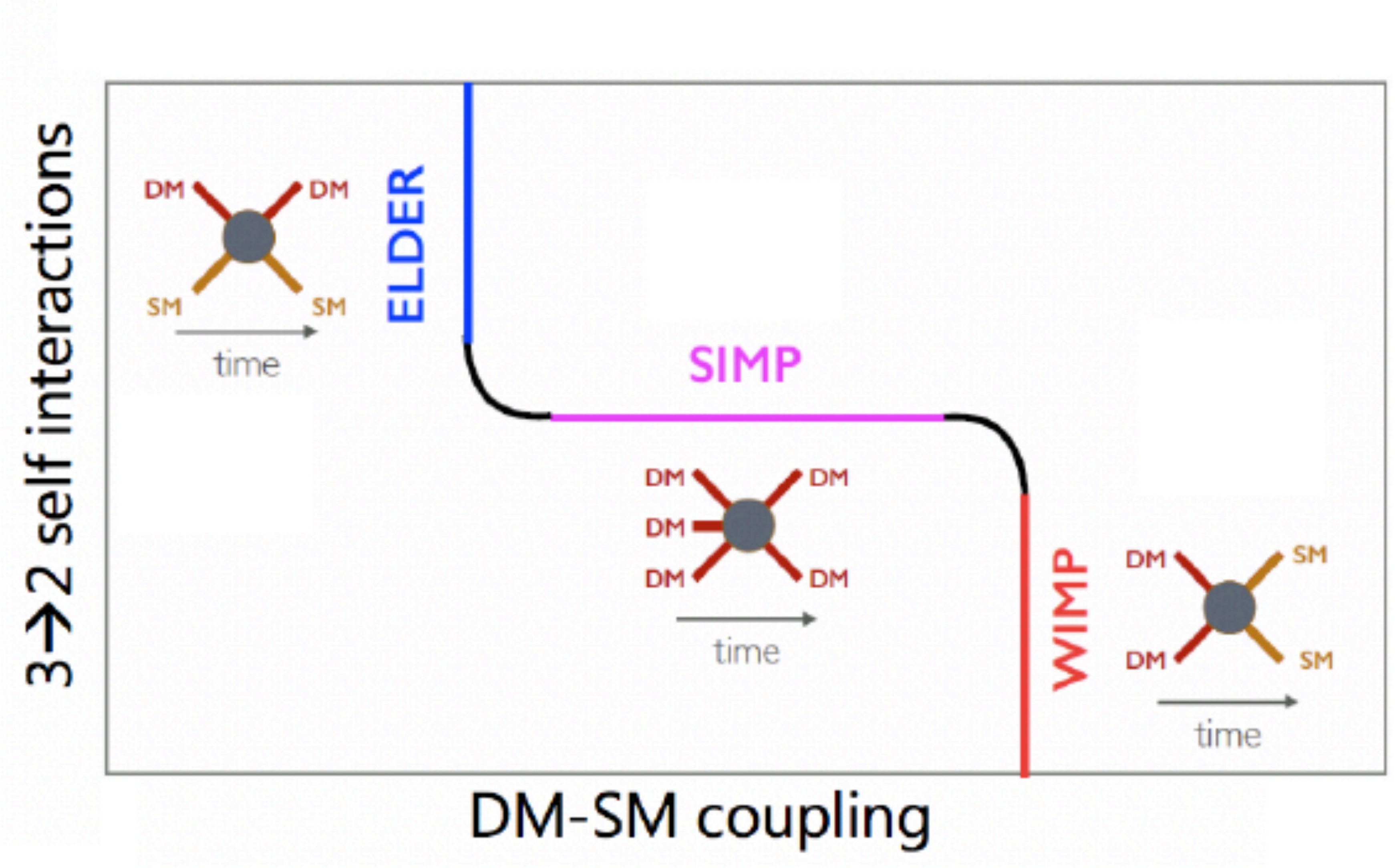


Figure 1: Constraints on sterile neutrino dark matter. Figure taken from [8]. The colored and gray regions show limits from X-ray searches, while the medium gray region on the left labeled "MW Satellite Counts" is based on structure formation arguments [9]. The region labeled "BBN Limit (Resonant Production)" is disfavored by BBN constraints on the lepton asymmetry if the latter is invoked to enhance sterile neutrino production. The red dot with an error bar indicates the parameters corresponding to the sterile neutrino explanation of the 3.5 keV line [10, 11].

3 → 2 models parameter space
Y. Hochberg lectures

SIMP & cannibalization & ELDER

SIMP:	Decouples 1st	Decouples 2nd
ELDER:	Decouples 2nd	Decouples 1st



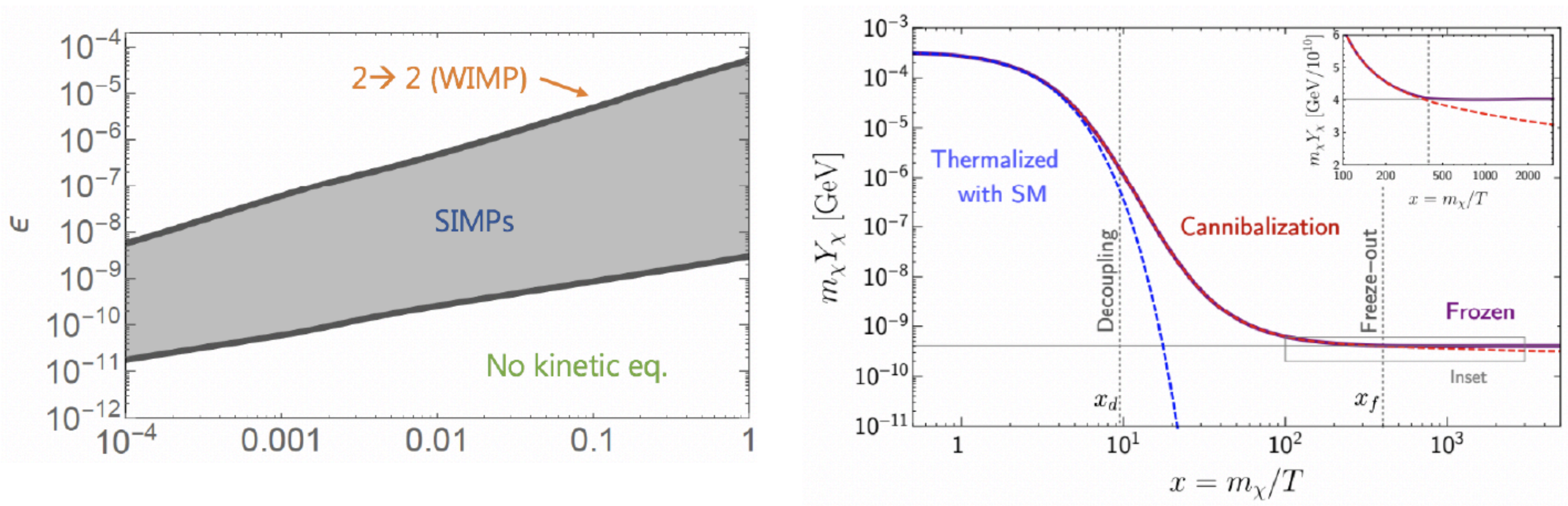


Figure 3: *Left:* Range of couplings between the DM and the SM where SIMP DM emerges. *Right:* Reproduced from [7], the DM yield as a function of SM temperature for ELDER DM, for DM mass 10 MeV, $\epsilon \sim 10^{-9}$ and strong $\alpha_{\rm eff}$ (solid purple).

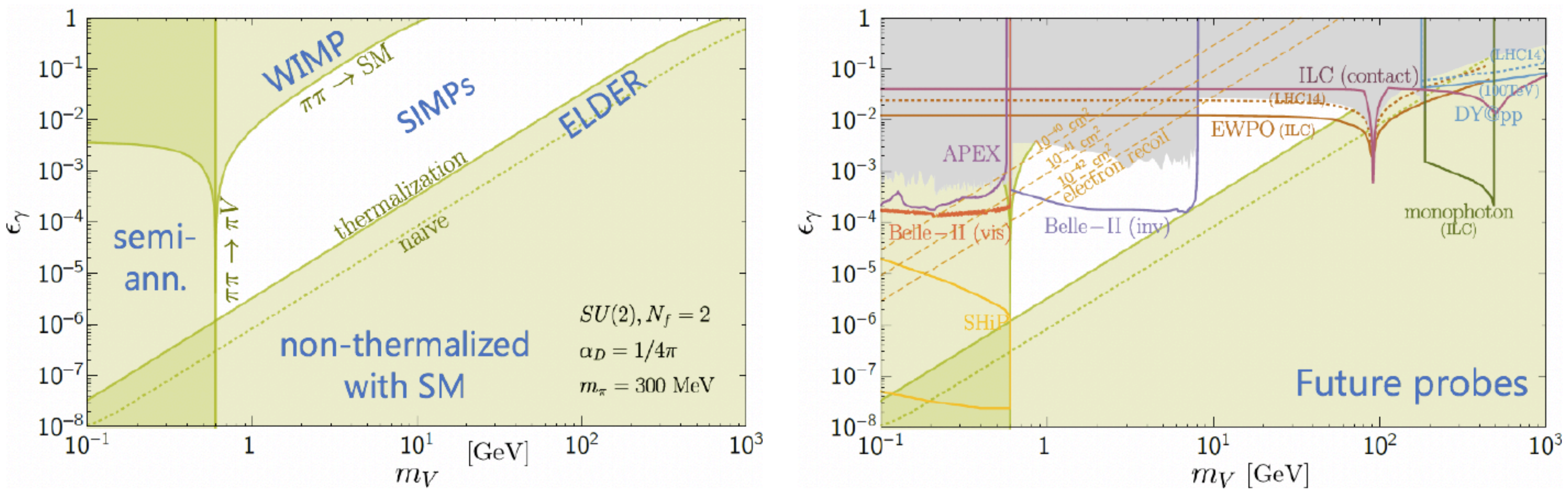
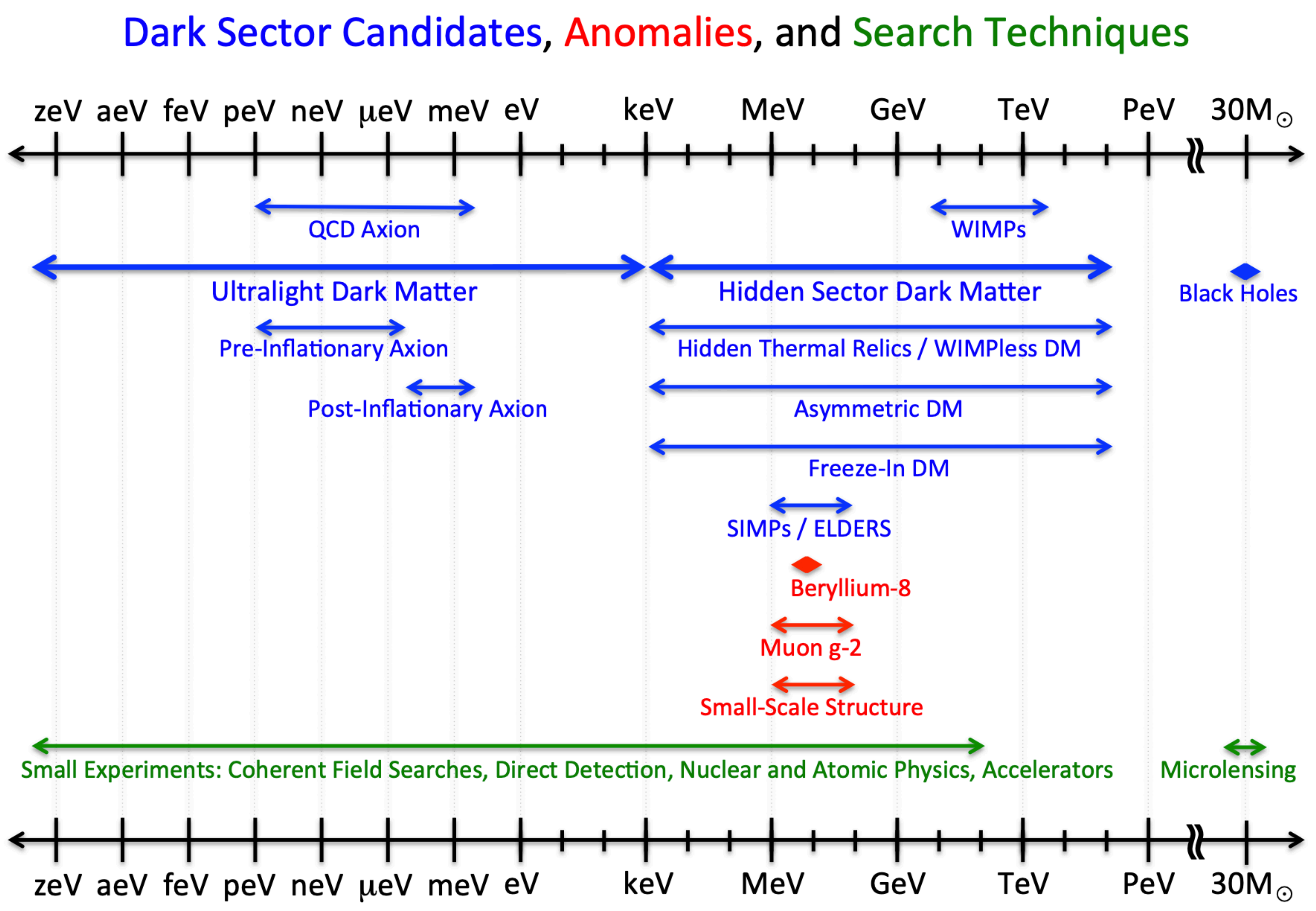


Figure 7: Reproduced from [16]. *Left:* Dark photon parameter space for fixed gauge group, dark coupling and dark pion mass, showing how different regions realize different DM mechanisms. *Right:* Constraints on the parameter space (shaded gray) and future probes (solid colored curves).

Sub GeV DM & hidden sector prospects

T. Lin lectures

- Sub GeV range gives access to hidden sector: important focus on dark photon searches (either as DM itself or as interaction mediator)



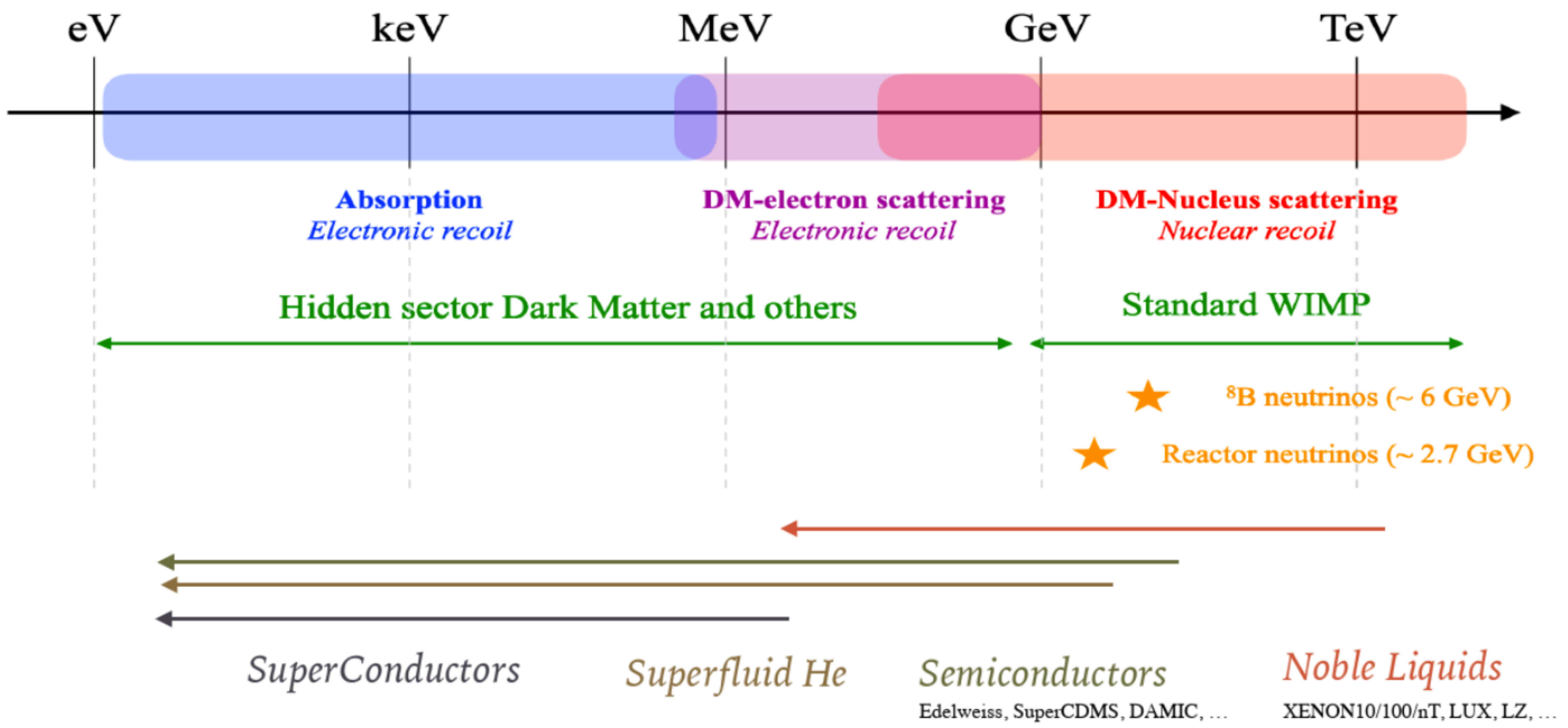


Figure 1: A logarithmic plot of possible masses for dark matter particles, as well as general techniques and specific experiments in various ranges that have, are, or will attempt to constrain dark matter in that region. In these lectures, the focus is on

Sub GeV DM & hidden sector prospects

T. Lin lectures

- Sub GeV range gives access to hidden sector: important focus on dark photon searches (either as DM itself or as interaction mediator)
- Light DM searches mainly based on DM-electron scattering, and phonon excitations
- Some sensitivity also from DM-nucleon scattering

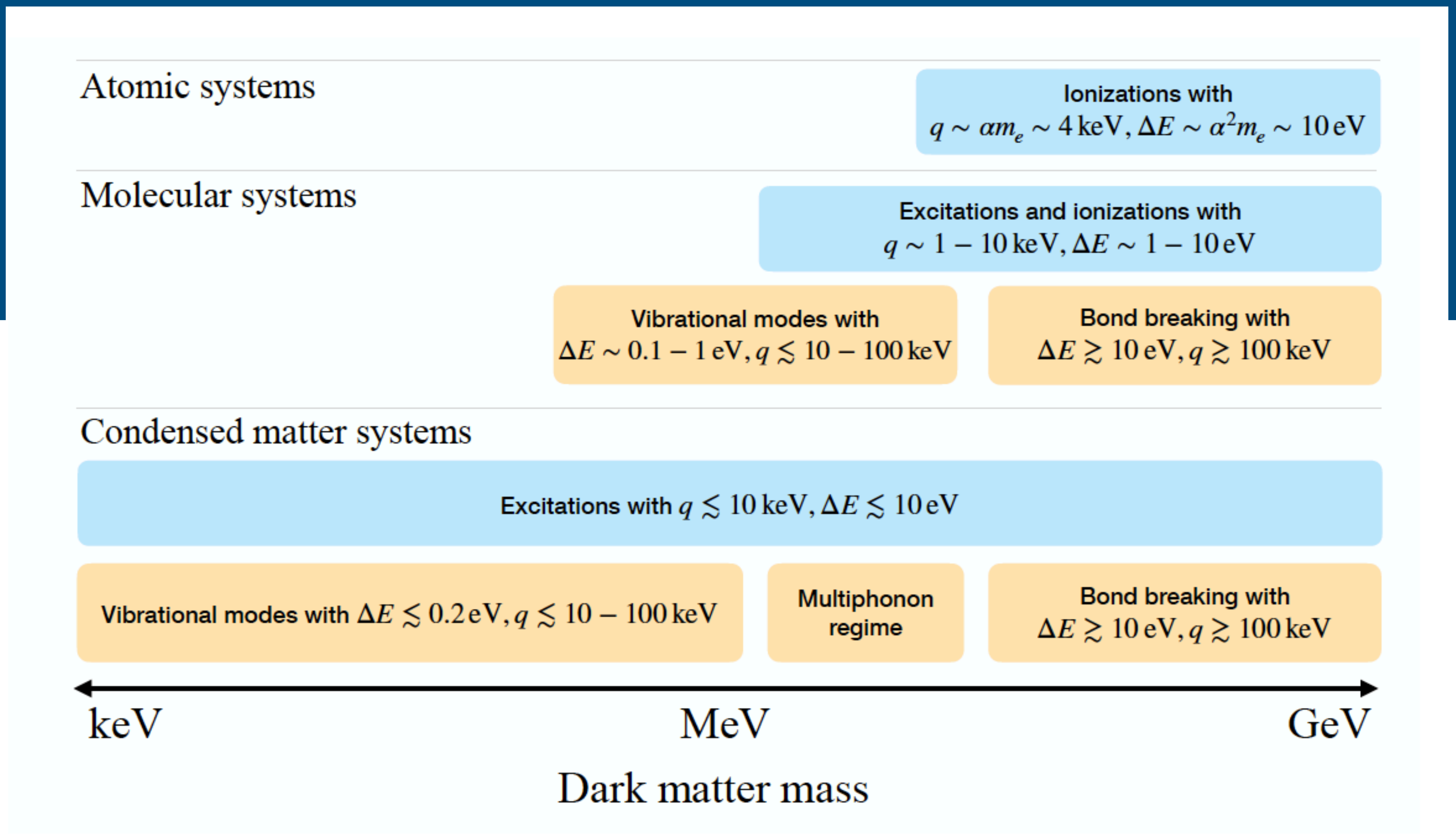


Figure 2: For various bound systems, we indicate some possible excitation modes in the system, some typical $(q, \omega \sim \Delta E)$ where they give a large response, and the corresponding range of DM masses which are well-matched to that system. Blue shaded boxes indicate electronic excitations, while orange shaded boxes indicate modes that can be excited by a DM-nucleus coupling.

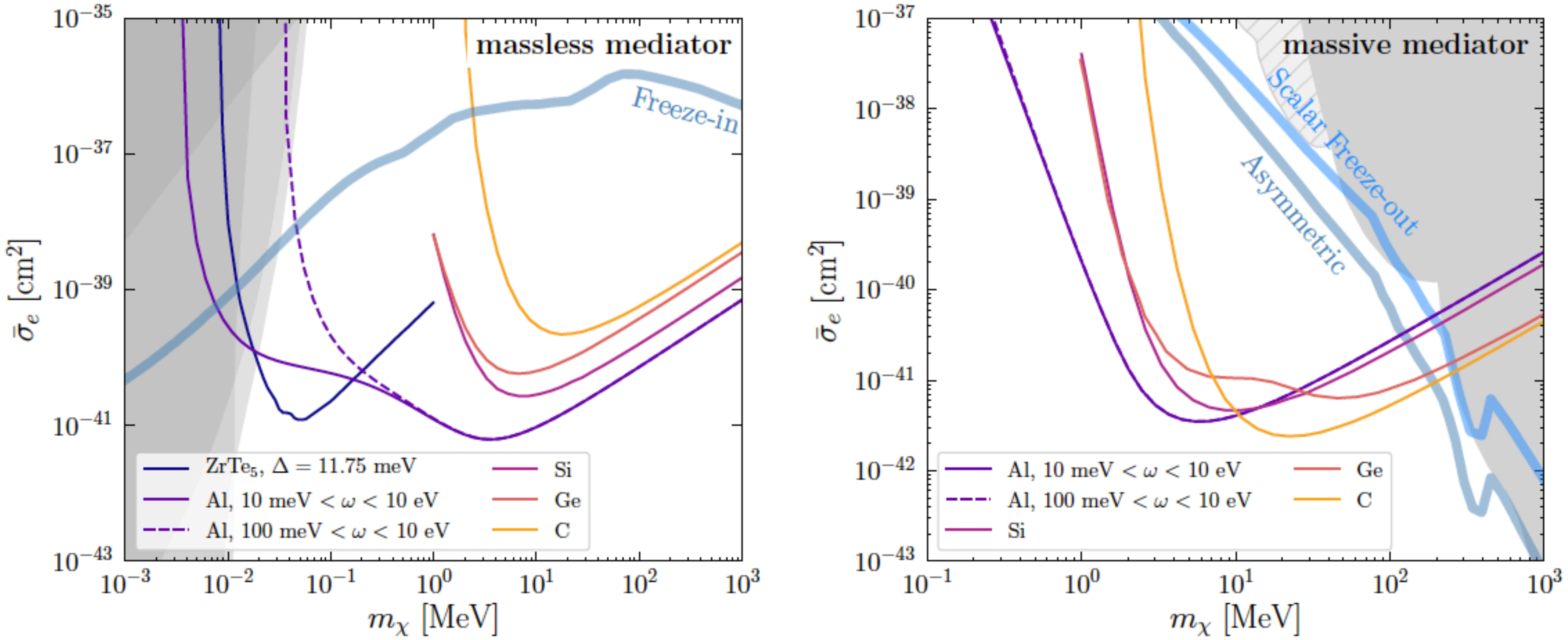


Figure 7: Reach to DM-electron cross section in different solid state targets for scattering through a heavy mediator (left) and light mediator (right), assuming kg-year exposure and zero background. Diamond (C) gives an example of a somewhat high gap target $E_{\mathrm{gap}} = 5.5$ eV; the reach shown is from Ref. [44]. Si and Ge have O(eV) gaps and have been studied extensively as target materials. The reach for Ge with a massless mediator and Si in both cases is from Ref. [42]. For Ge and a massive mediator, the reach shown is from Ref. [45]; for DM masses above ~ 20 MeV, the reach is dominated by the excitation of semi-core electrons. For sub-MeV DM, lower gap materials are needed and we show projections for an example Dirac material from Ref. [46] and for Al from Refs. [42, 43]. In the left plot, the thick blue line is the predicted cross section if all of the relic DM is produced by freeze-in interactions [8, 30] and the shaded regions are constraints from stellar emission [7, 47]. In the right plot, the thick blue lines are cross sections for freeze-out of scalar DM or asymmetric DM, and the shaded region shows combined direct detection bounds (solid grey) and model-dependent accelerator bounds when the dark photon mass is $m_{A'} = 3m_\chi$ (hatched grey) [48]. All bounds and relic density lines assume a dark photon mediator.

Freeze-out models: detection

T. Lin lectures

- Sub GeV range gives access to hidden sector: important focus on dark photon searches (either as DM itself or as interaction mediator)
- Light DM searches mainly based on DM-electron scattering, and phonon excitations
- Some sensitivity also from DM-nucleon scattering

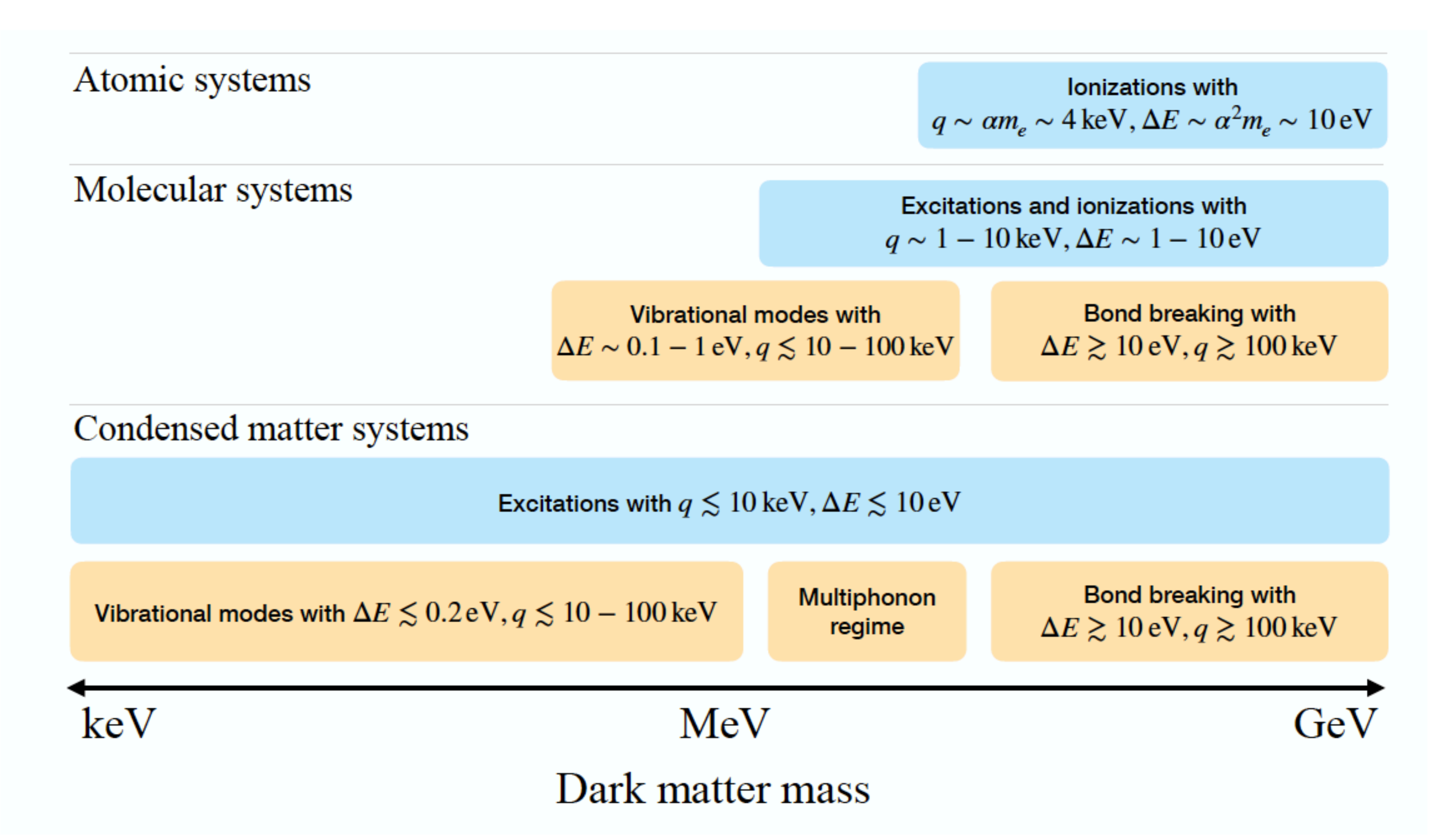


Figure 2: For various bound systems, we indicate some possible excitation modes in the system, some typical $(q, \omega \sim \Delta E)$ where they give a large response, and the corresponding range of DM masses which are well-matched to that system. Blue shaded boxes indicate electronic excitations, while orange shaded boxes indicate modes that can be excited by a DM-nucleus coupling.

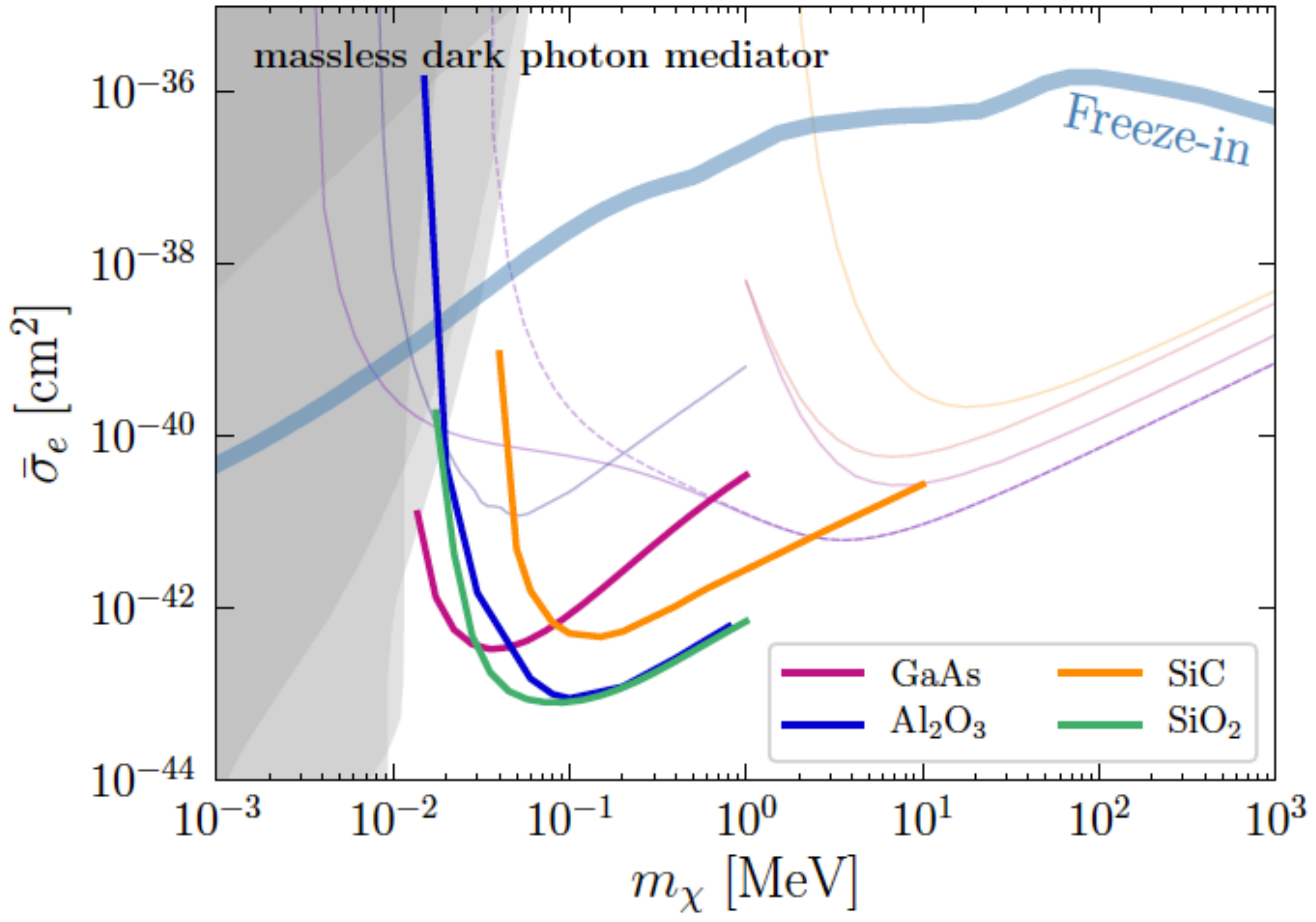


Figure 13: Cross section for 3 events/kg-year for single optical phonon excitations in various polar materials, and assuming a massless dark photon mediator. For this mediator, the convention in the literature is to show projections in terms of the DM-electron cross section $\bar{\sigma}_e$ even when the scattering is into phonons. This is for easier comparison with experiments searching for DM-electron scattering, which can probe the same model; in particular, the different faint lines in this plot are the various projections for DM-electron scattering proposals shown in Fig. 7. The thick blue line is the predicted cross section if all of the relic DM is produced by freeze-in interactions [8,30] and the shaded regions are constraints from stellar emission [7,47].

Freeze-out models: detection

T. Lin lectures

- Sub GeV range gives access to hidden sector: important focus on dark photon searches (either as DM itself or as interaction mediator)
- Light DM searches mainly based on DM-electron scattering, and phonon excitations
- Some sensitivity also from DM-nucleon scattering

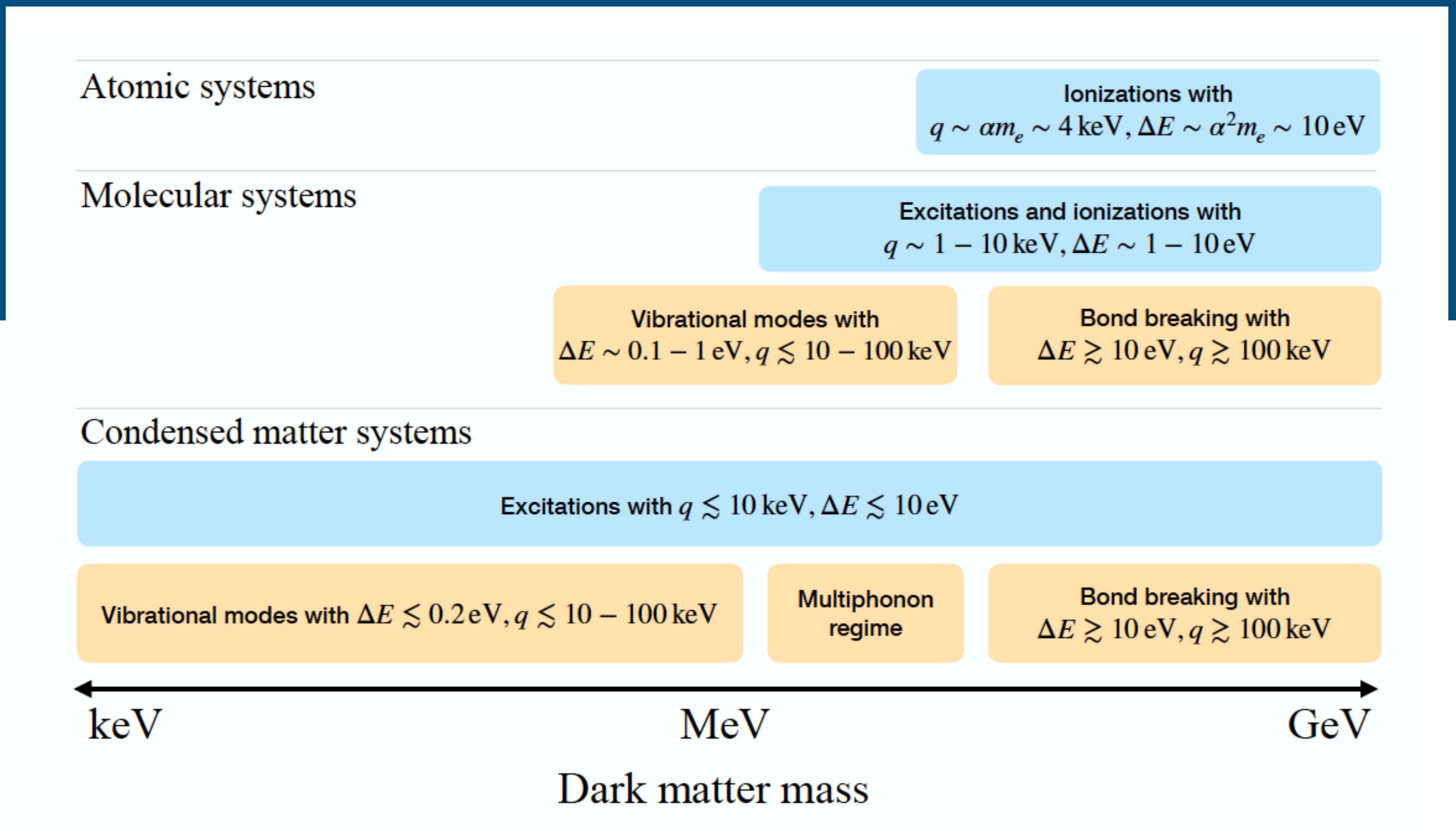


Figure 2: For various bound systems, we indicate some possible excitation modes in the system, some typical $(q, \omega \sim \Delta E)$ where they give a large response, and the corresponding range of DM masses which are well-matched to that system. Blue shaded boxes indicate electronic excitations, while orange shaded boxes indicate modes that can be excited by a DM-nucleus coupling.

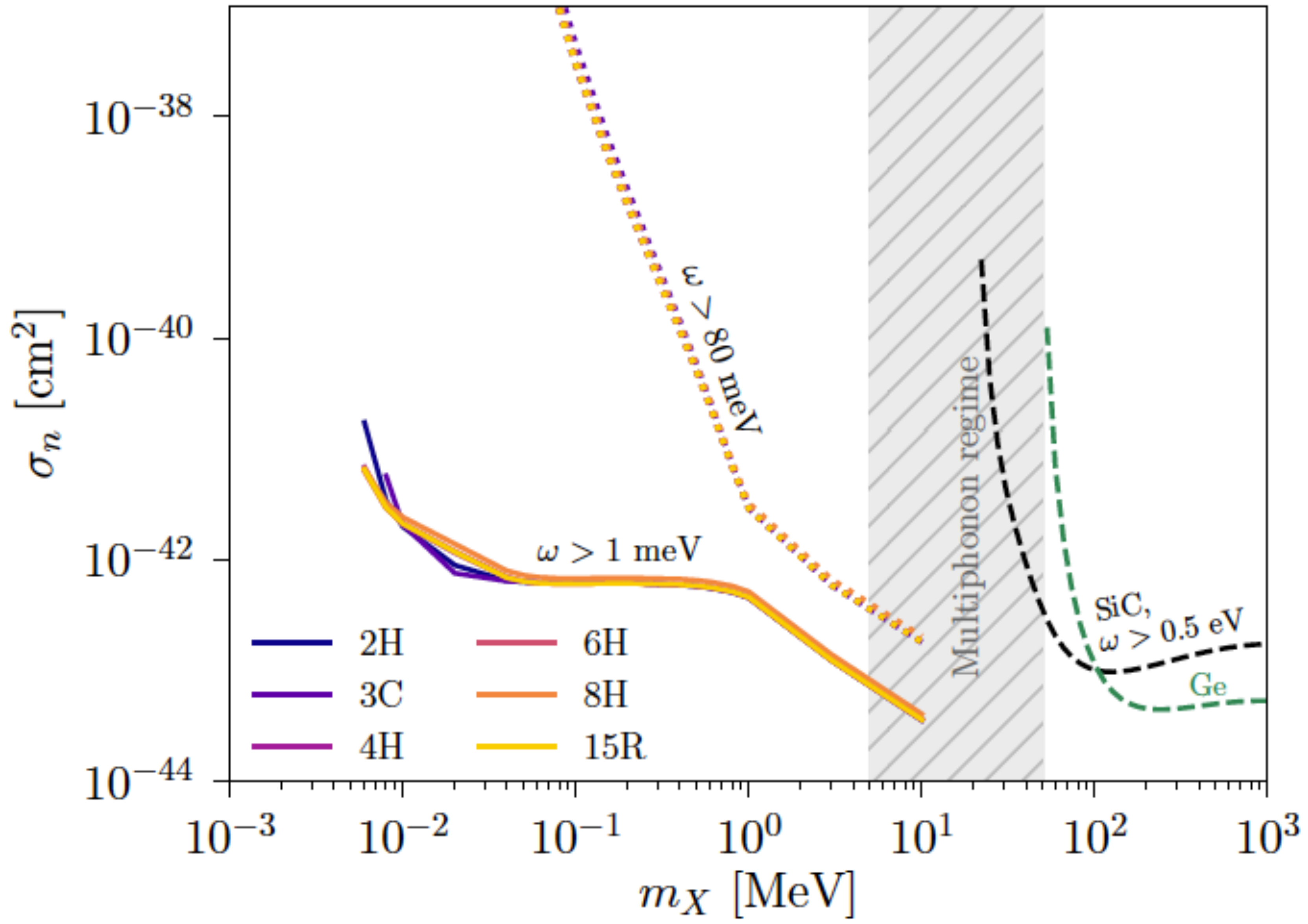


Figure 12: Reproduced from Ref. [63]. Sensitivity of a SiC target to DM-nucleon interactions mediated by an massive mediator. Results are shown assuming kg-year exposure and zero background and for scattering into acoustic phonons ($\omega >$ meV) and for scattering into optical phonons ($\omega = \omega_{\mathrm{LO}} \approx 35$ meV). Also shown are example nuclear recoil sensitivities.

Axions: detection

I. Irastorza lectures

- Detection techniques:
  - LSW (ALPS-II): magnetic field to convert photons in axions and back into photons
  - Polarization experiments (PVLAS): photon-axion oscillation in the presence of the external B-field => depletion + phase-delay (birefringence) of polarization component of laser that is parallel to the B-field (dichroism)
  - Haloscopes (ADMX; RADED; ORPHEUS): high quality factor Q microwave cavity inside magnetic field, where Q can be of order 10^5. Primakow conversion of the axion to photon enhanced by factor Q if the resonant frequency of the cavity matches that of the axion field => resulting photons appear as an excited mode of the cavity
  - Solar axions helioscopes (CAST, IAXO, BabyIAXO): conversion of the solar axions back to photons in a strong laboratory magnet. The resulting photons keep the same energy as the incoming axions
  - DM radios: measurement of tiny oscillating B-field associated with the axion dark matter field in an external constant magnetic field

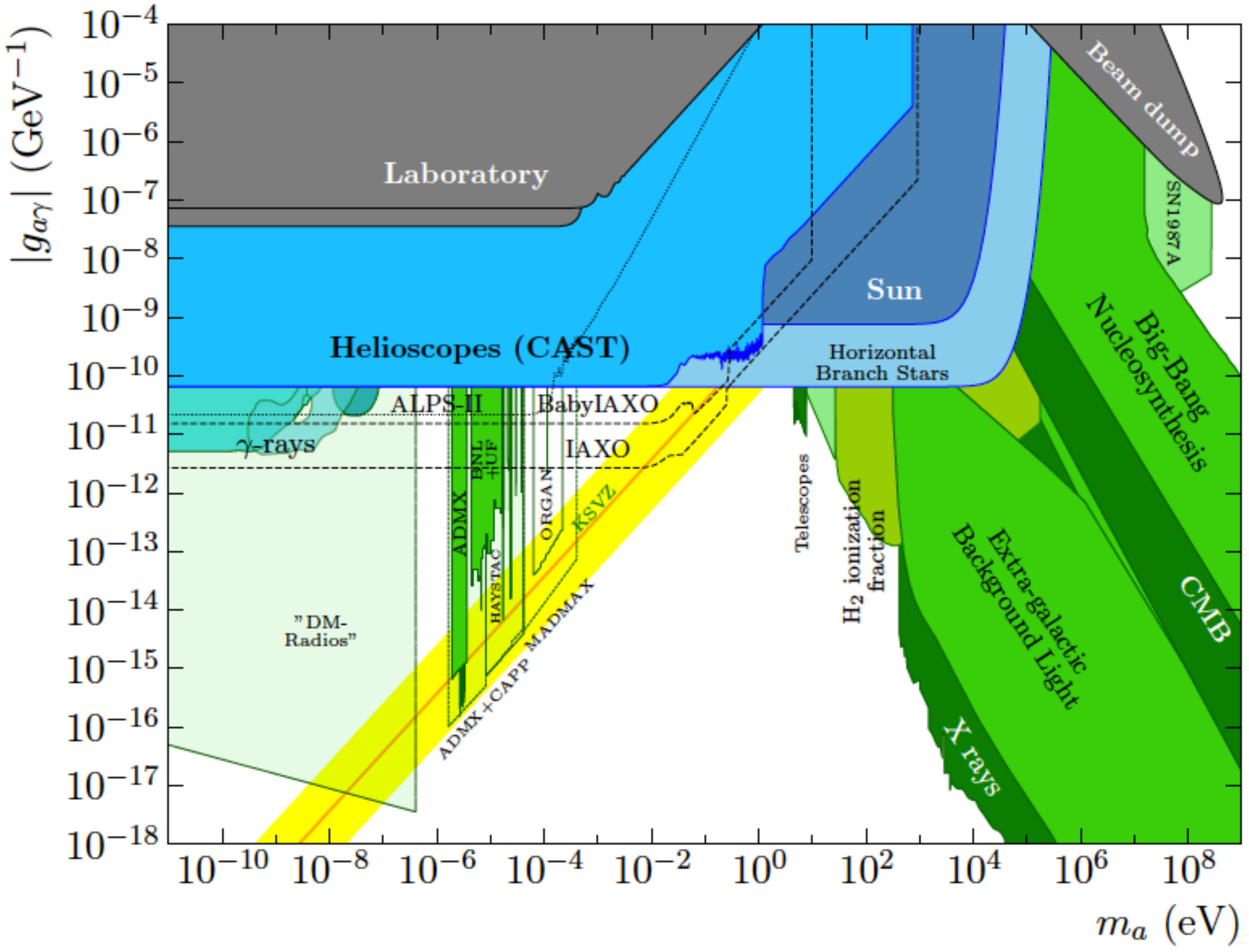
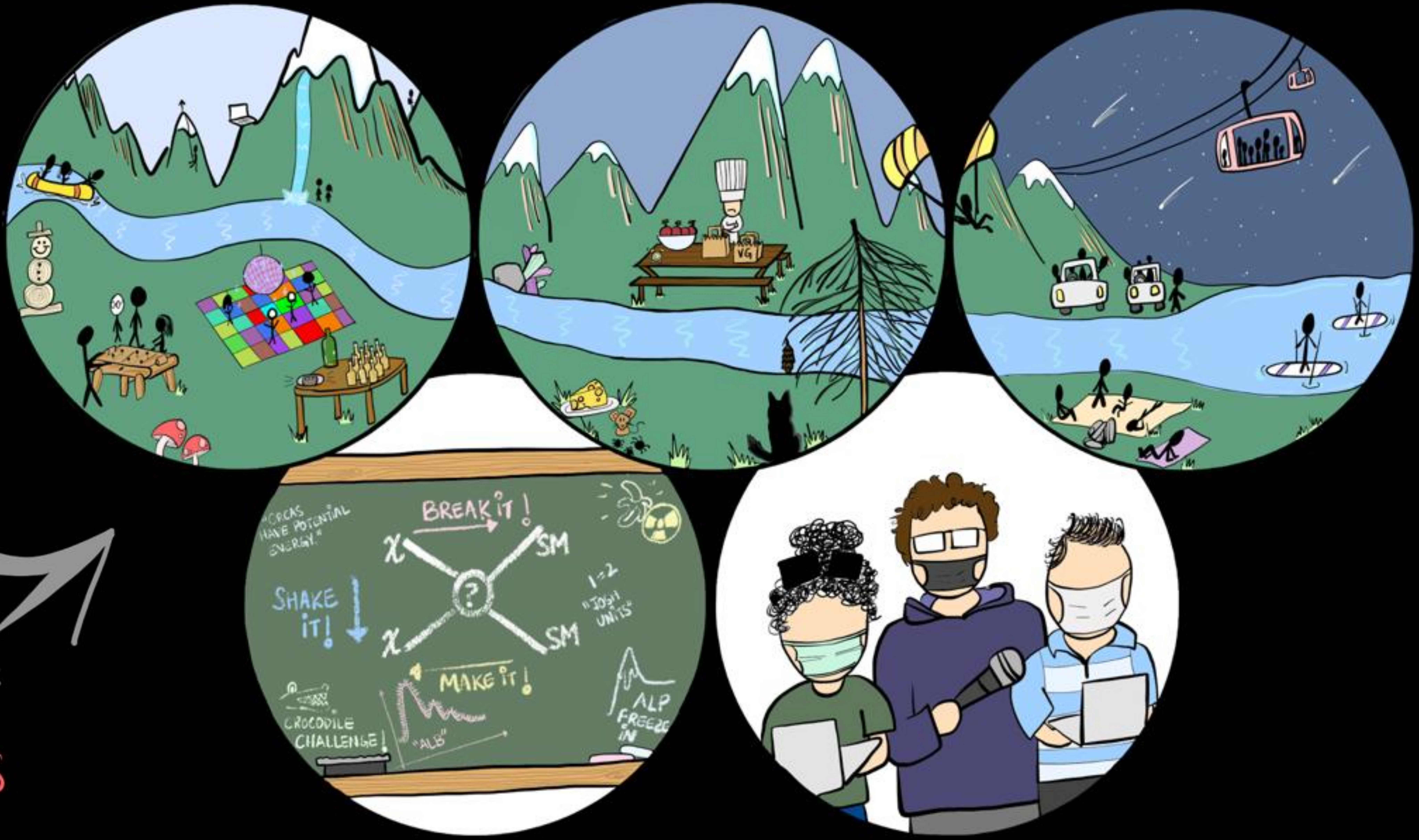


Figure 4: Overall panorama of current bounds (solid areas) and future prospects (semi-transparent areas or dashed lines) in the $g_{a\gamma}$-m_a plane. See explanation in the text and reference [2] for details on the different lines



ÉCOLE DE PHYSIQUE DES HOUCHES