COSMOFondue, UniGe, 11.06.2025

Introduction to particle cosmology

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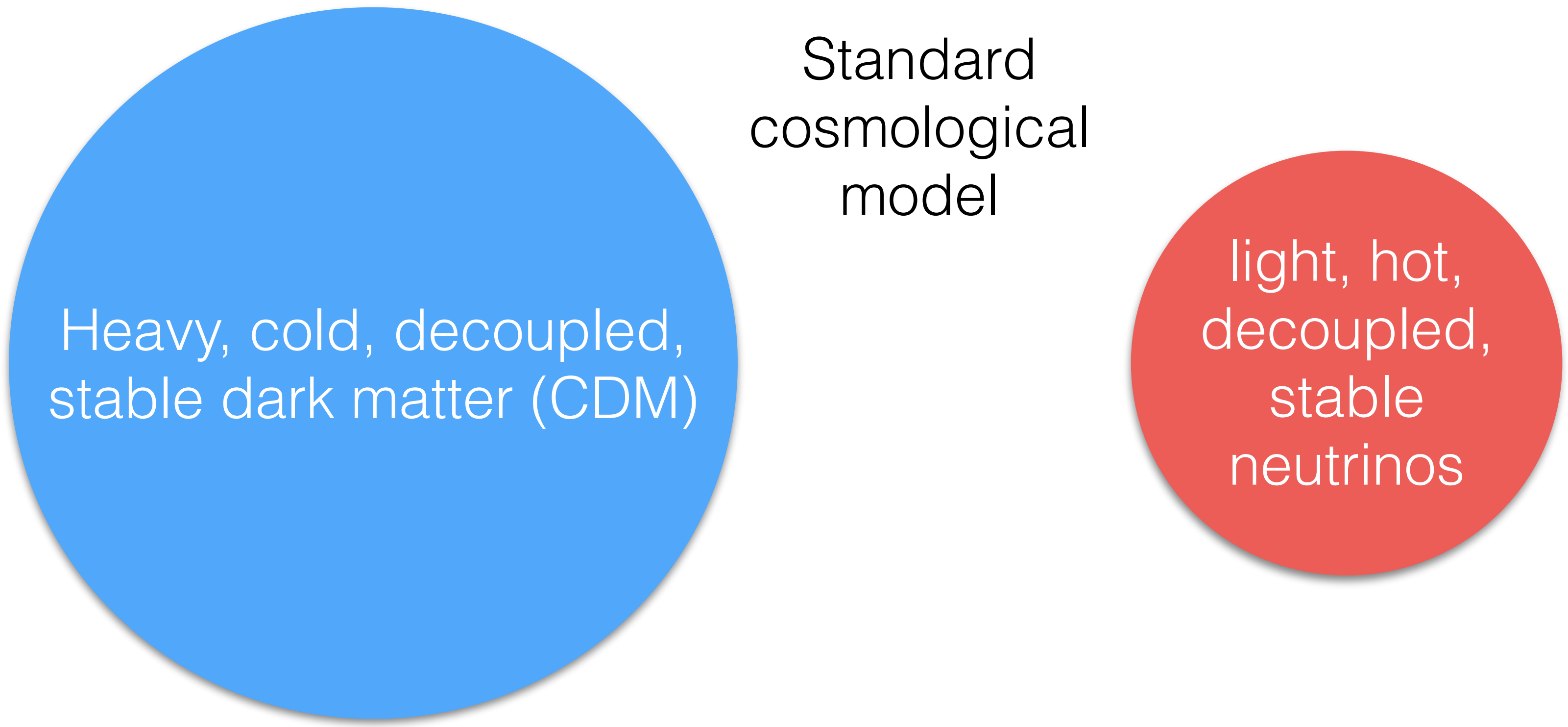
Testing particle properties with cosmology



Testing particle properties with cosmology

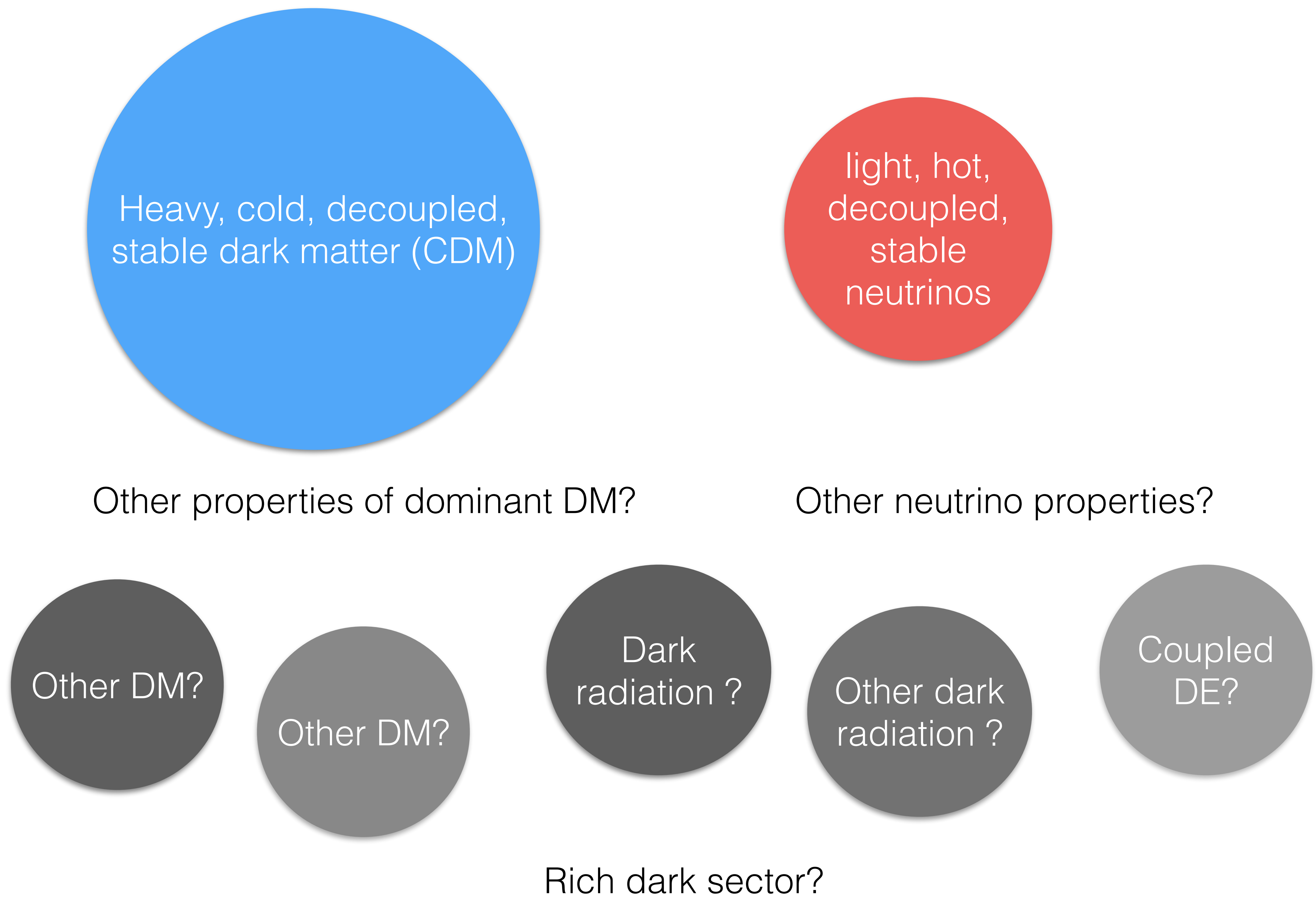
Heavy, cold, decoupled, stable dark matter (CDM)

light, hot, decoupled, stable neutrinos

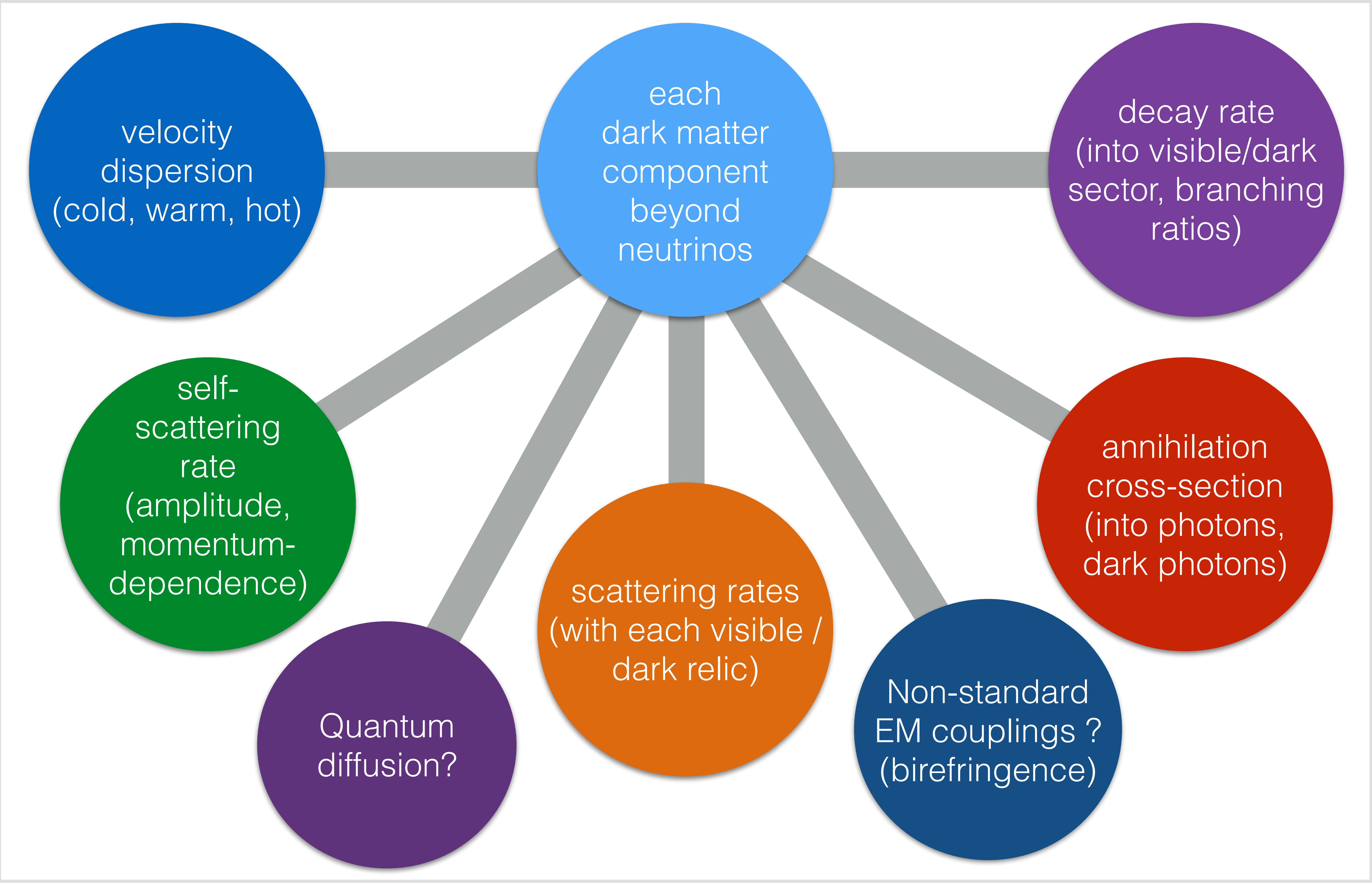
Other properties of dominant DM?

Other neutrino properties?

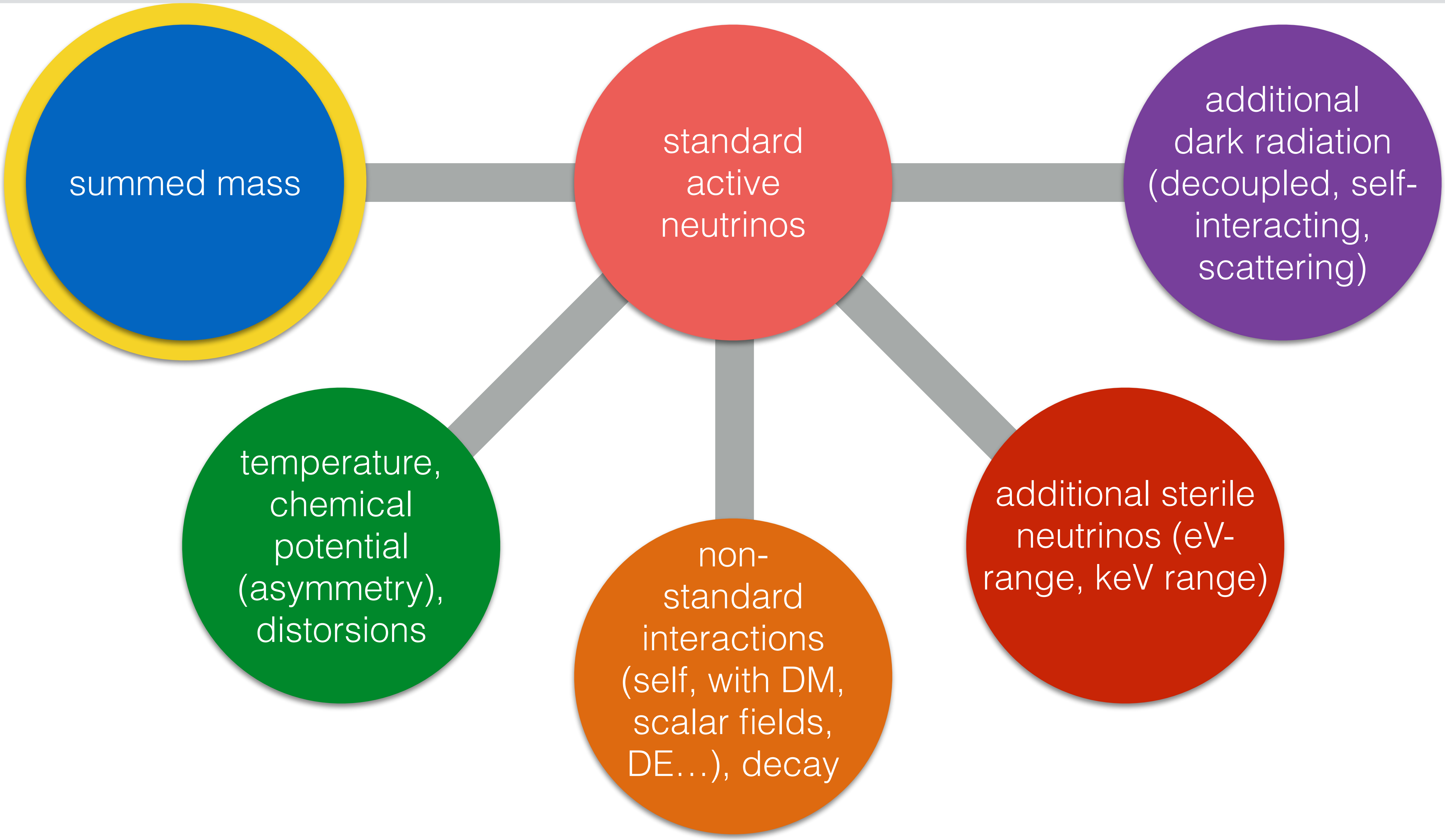
Testing particle properties with cosmology



Dark Matter properties relevant for cosmology

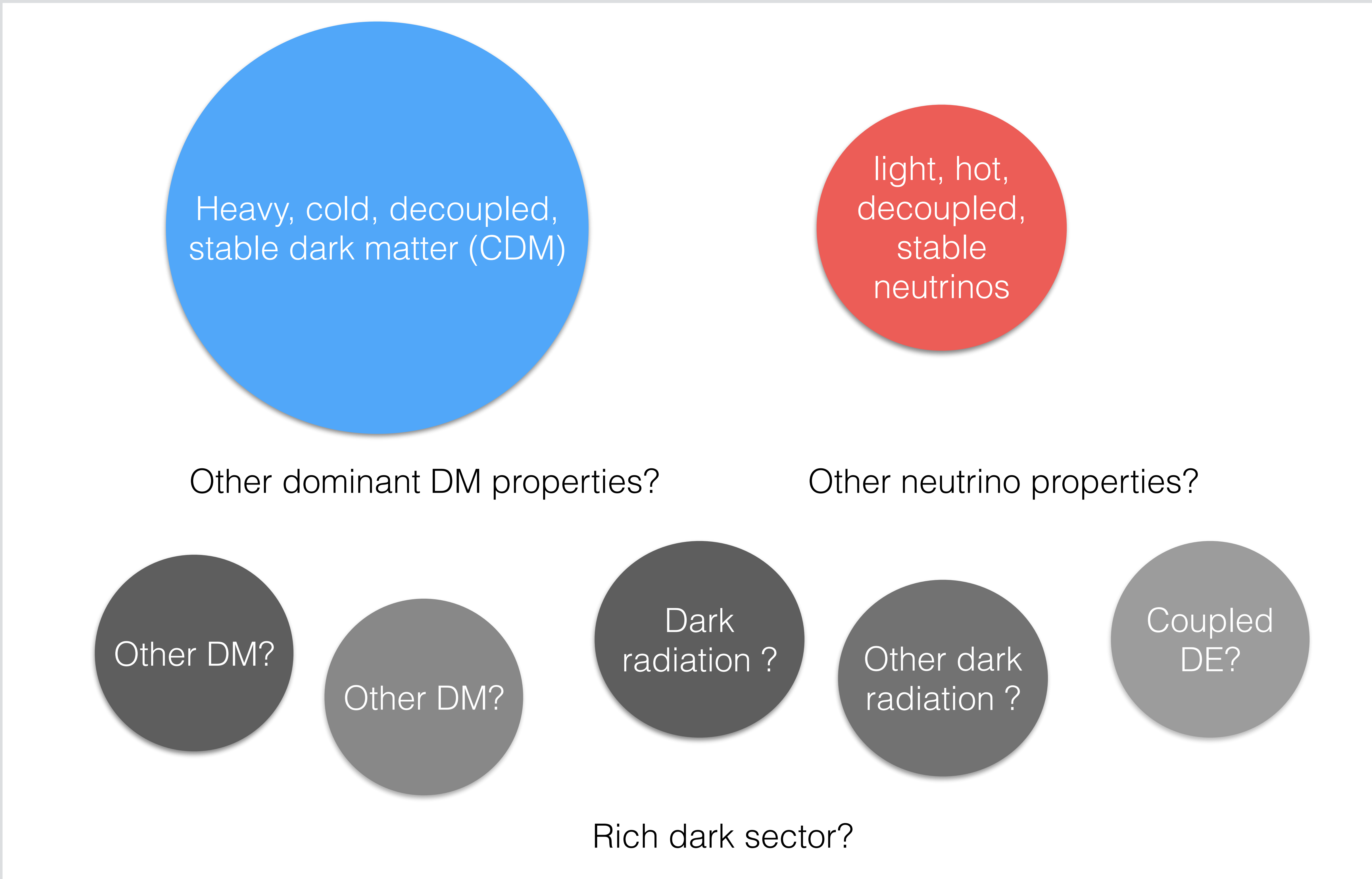


Testable properties of neutrinos

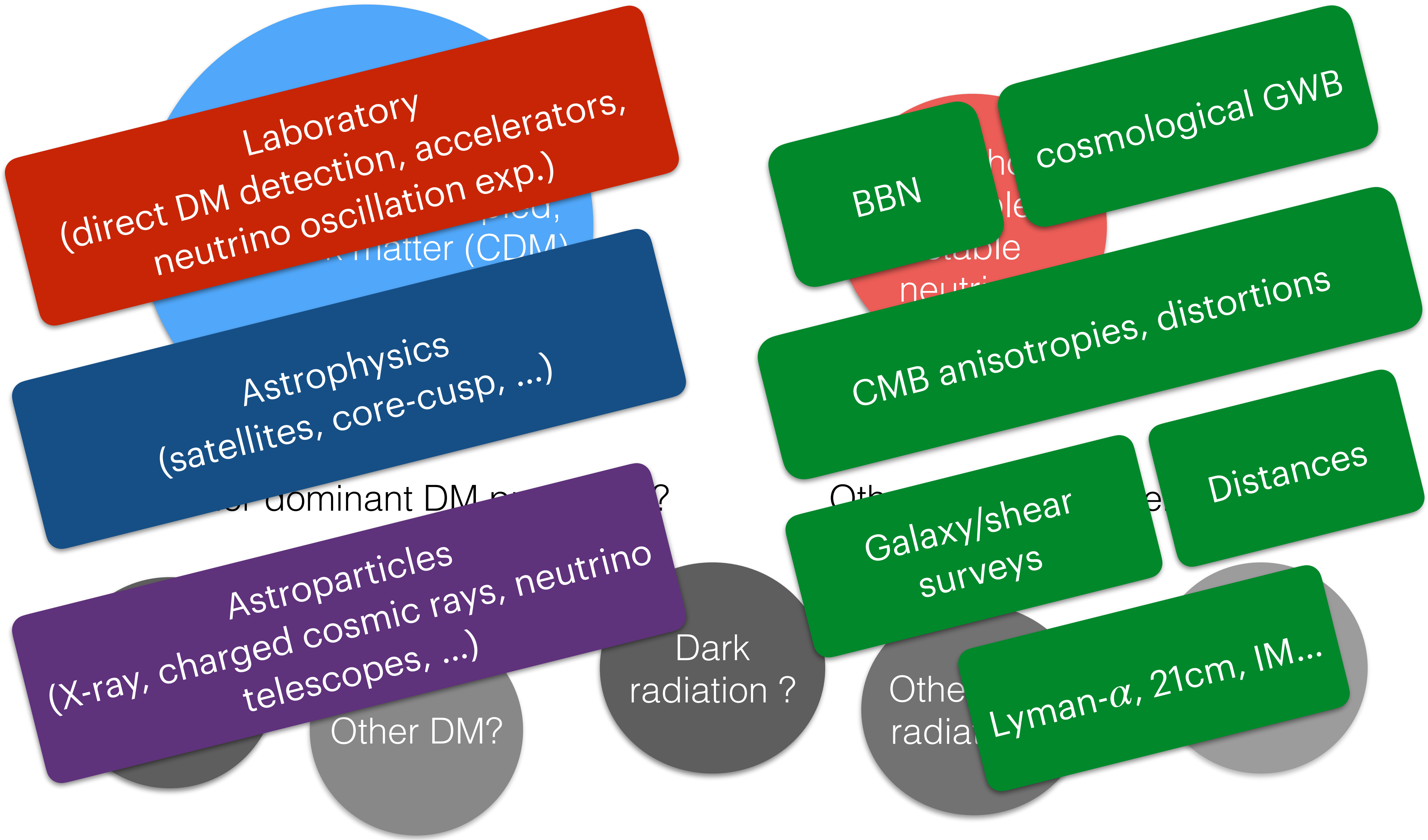


Minimal model:
- 3 mass eigenstates with NO or IO, decoupled, stable, free-streaming;
- $T \sim 2.9$ K, $\Sigma m_\nu \geq 0.06$ eV, asymmetry ~ 10^{-9}

Testing particle properties with cosmology

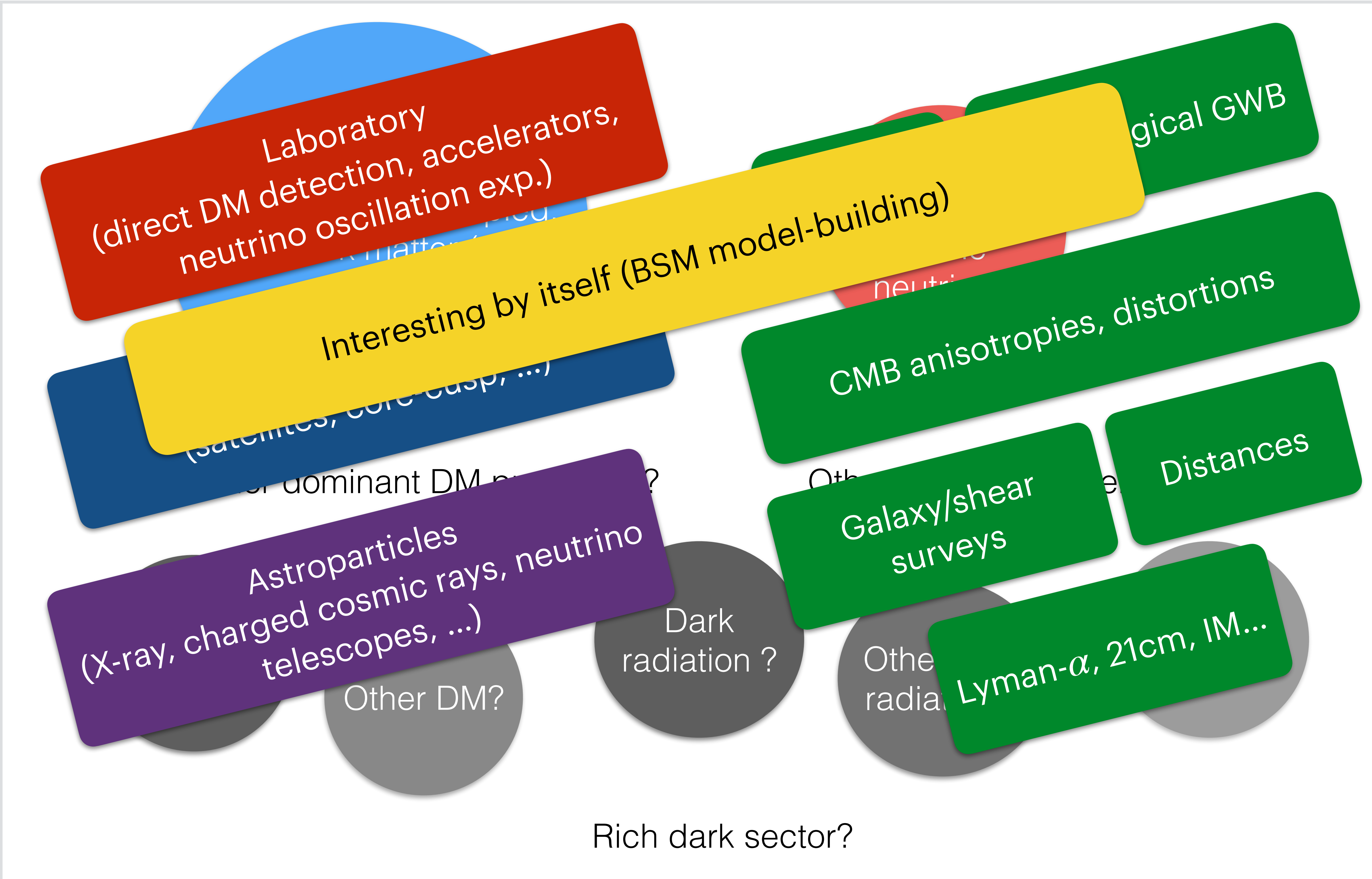


Testing particle properties with cosmology

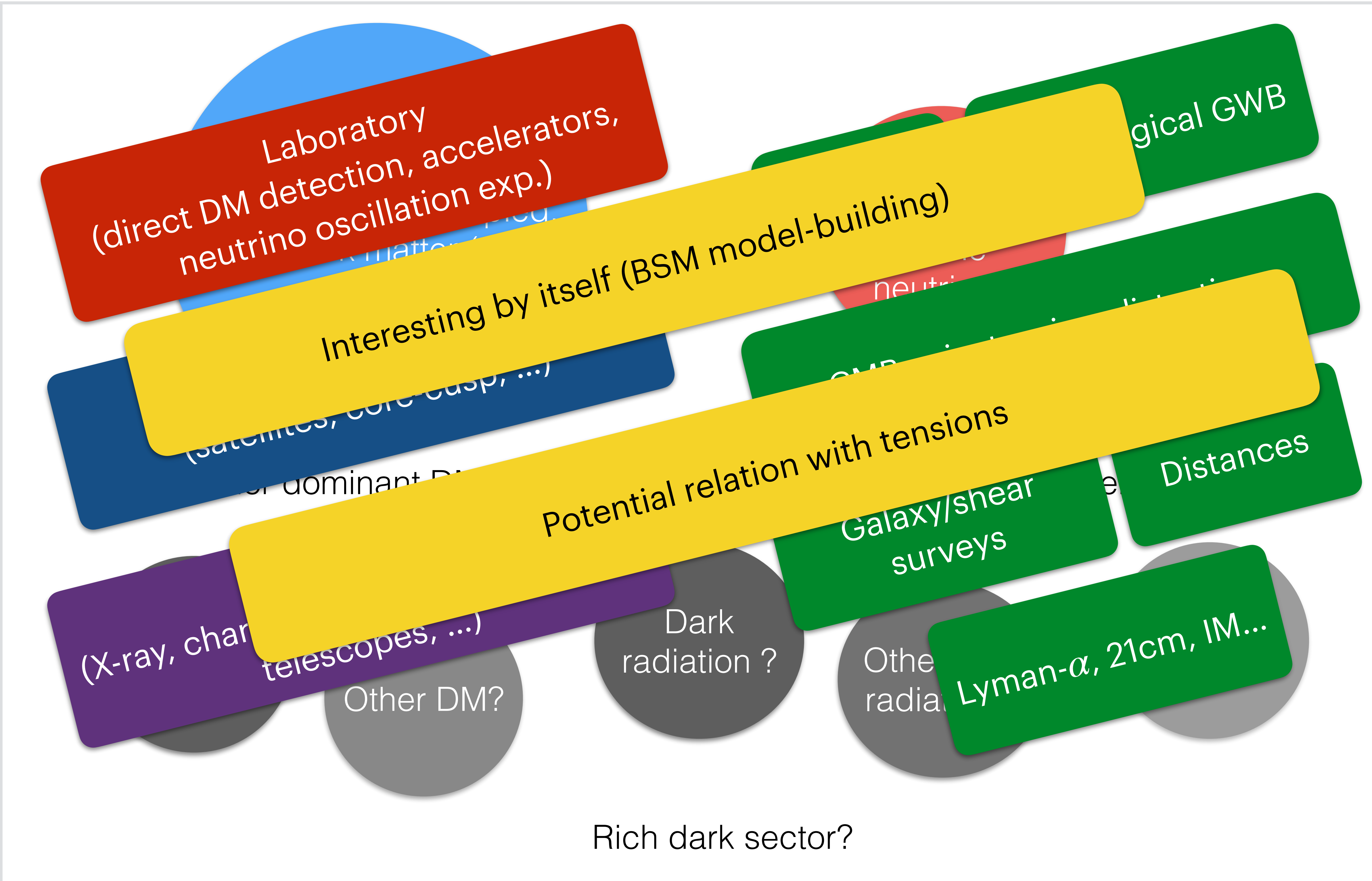


Rich dark sector?

Testing particle properties with cosmology



Testing particle properties with cosmology



Testing particle properties with cosmology

- Post-Planck: ΛCDM + more ingredients, to get bounds on particle properties

  e.g. on keV sterile neutrinos from Lya, DM interactions from CMB/LSS…

- Post-SHOES, DES, KiDS: particle properties as potential solutions to emerging tensions

  e.g. H_0 , S_8 tensions with DM/DR scattering, self-interacting neutrinos…

- Recent SHOES + CCHP, DESI: big confusion in particle cosmology!

  What is the correct baseline model?

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Testing particle properties with cosmology

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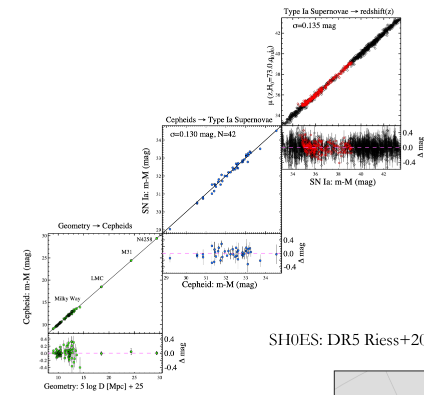
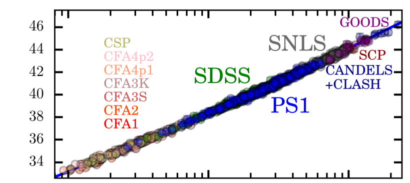
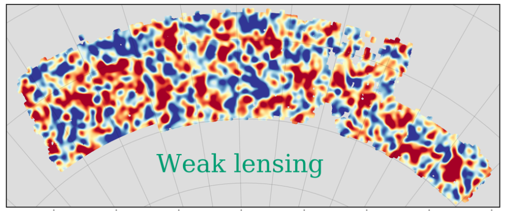
Main tensions for ΛCDM versus data:

1. on Ω_m from DESI BAO versus others (SNIa, CMB)
2. on H_0 from SHOES or CCHP versus others
3. on A_L: lensing amplitude from high-ℓ lensed CMB temperature (CAMSpec vs. HilliPop)
4. on S_8: amplitude of fluctuations from galaxy weak lensing (decreases with recent KiDS)



SH0ES: DR5 Riess+2022





see E. Di Valentino's talk

- Bounds very different as function of which data set you cherry-pick…

- Example with neutrino mass

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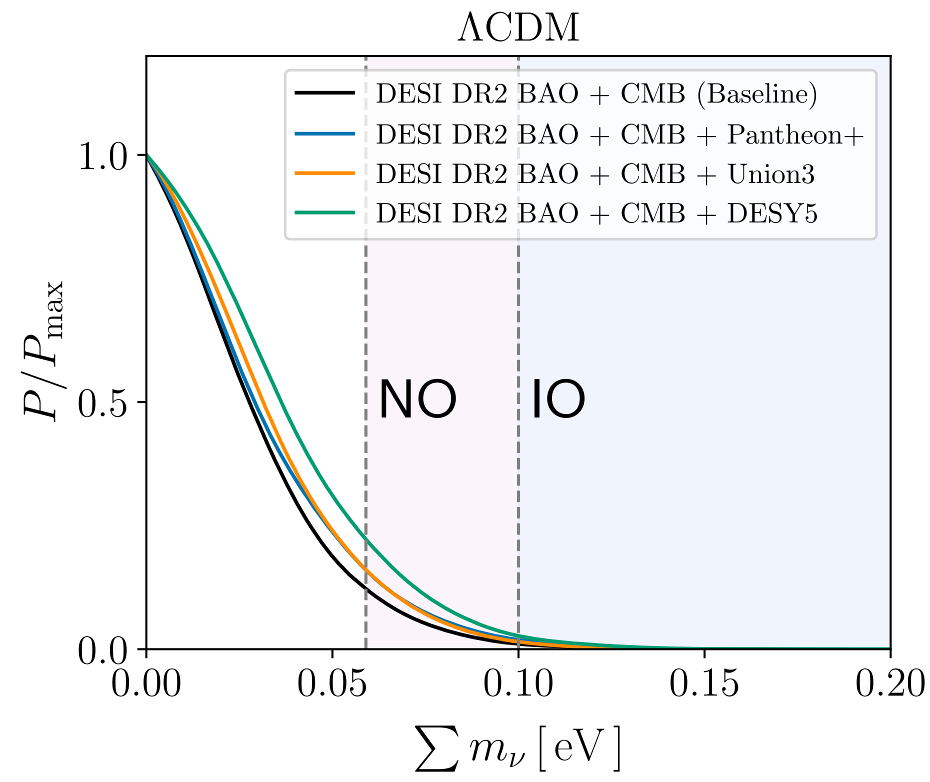
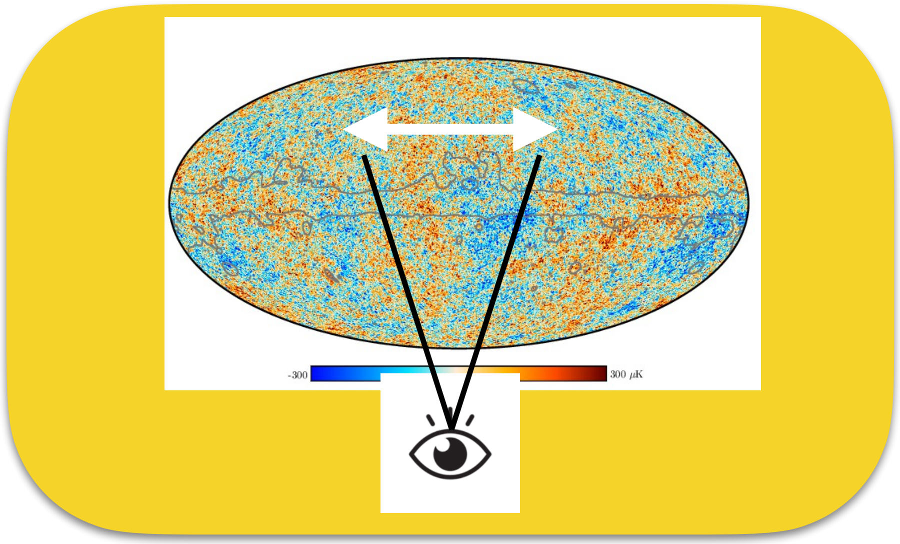
Do we live in a neutrinoless universe?

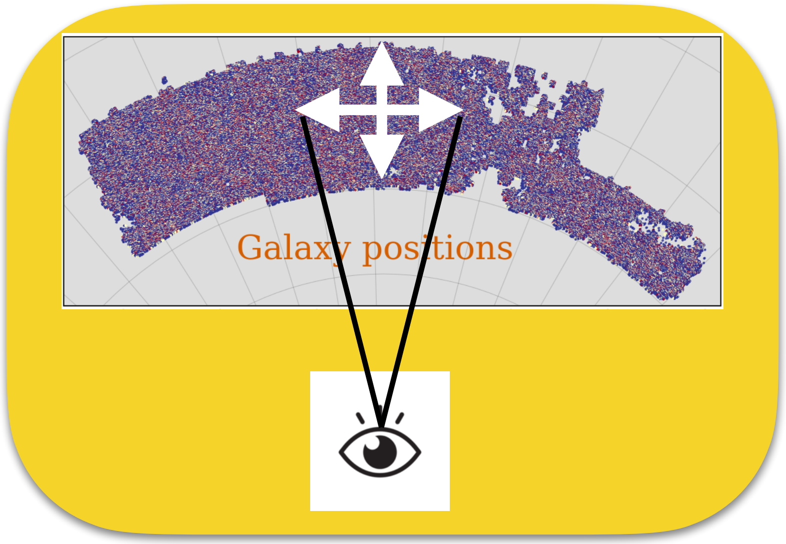
- DESI BAO Y2 (+ CMB) Elbers et al. 2025



- Theoretical possibility that neutrinos explain $N_{\rm eff} \simeq 3$ but decay into lighter / massless relics
  Escudero et al. 2007.04994, Barenboim et al. 2011.01502, Franco Abellan et al. 2112.13862, Craig et al. 2405.00836…

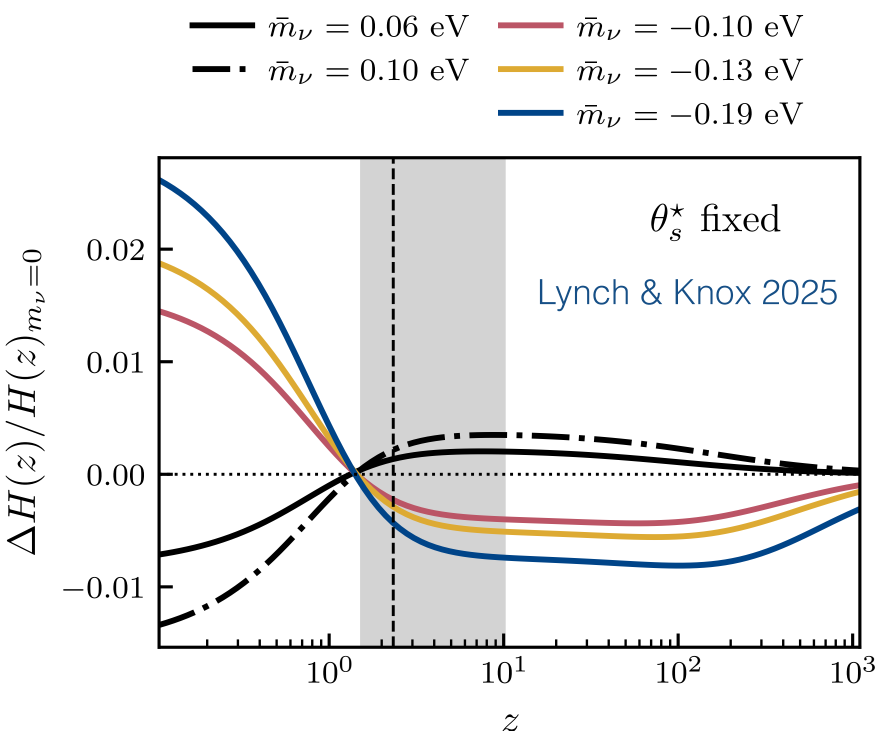
Probing neutrino mass through geometrical effects





Angular diameter distance affected by m_ν for $z > z_{\rm nr}$:

$$D_A^\star = \int_0^{z_\star} \frac{c}{H(z)} \mathrm{d}z$$



… or at all z when fixing θ_s rather than $H_0, \Omega_{\rm m}$

Neutrino free-streaming suppresses power spectrum and lensing spectrum for $k > k_{\mathrm{nr}} \sim k_{\mathrm{eq}}$:

CMB lensing spectrum residual w.r.t. $M_\nu = 0$

LoVerde & Weiner 2024

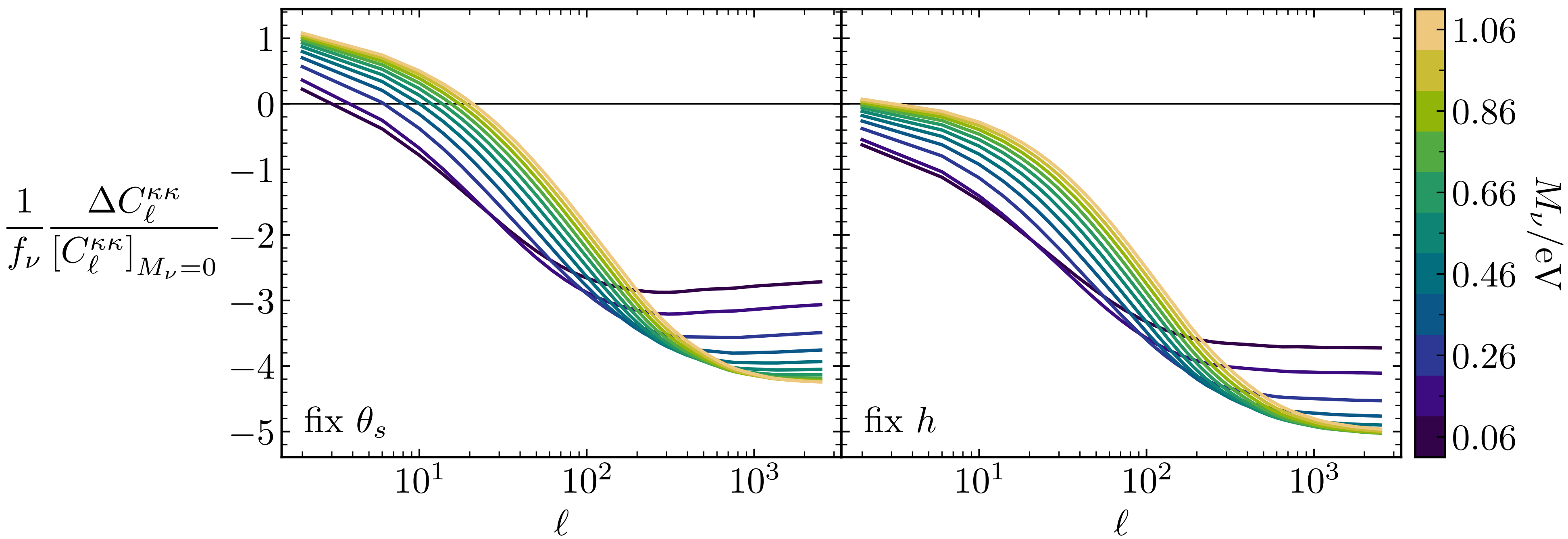
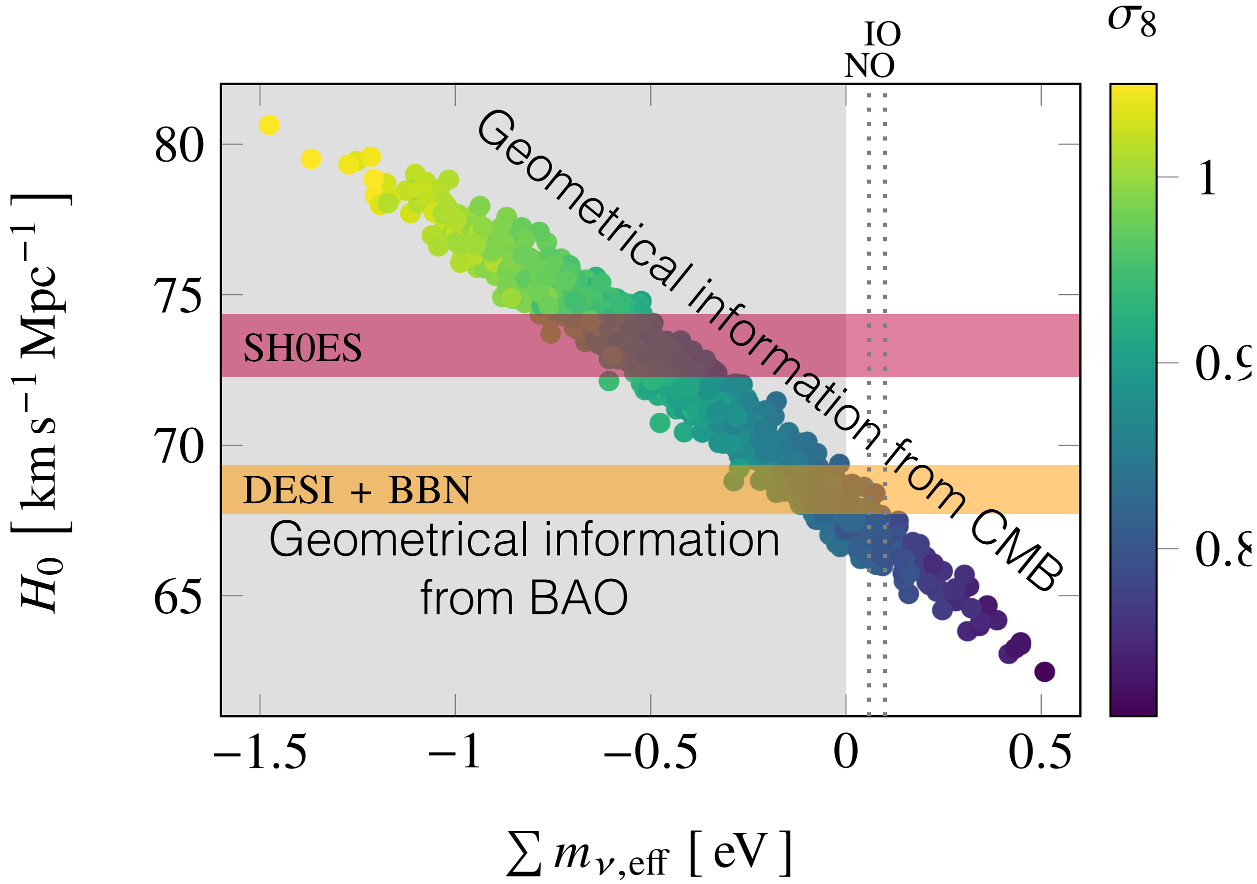


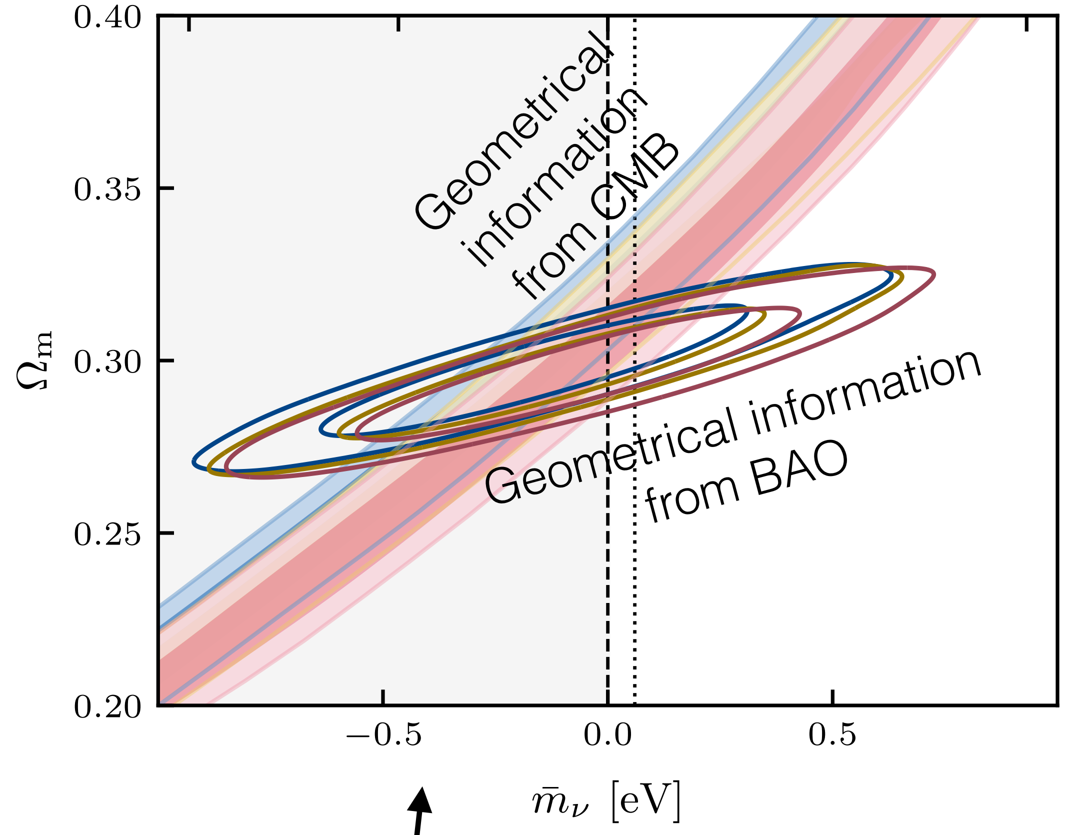
Figure 2. Residual of the CMB lensing spectrum for cosmologies varying the neutrino mass sum (by color) relative to a cosmology with massless neutrinos, measured in units of the neutrino fraction f_ν [Eq. (2.4)].

(assuming ΛCDM!)

From Elbers et al. 2024



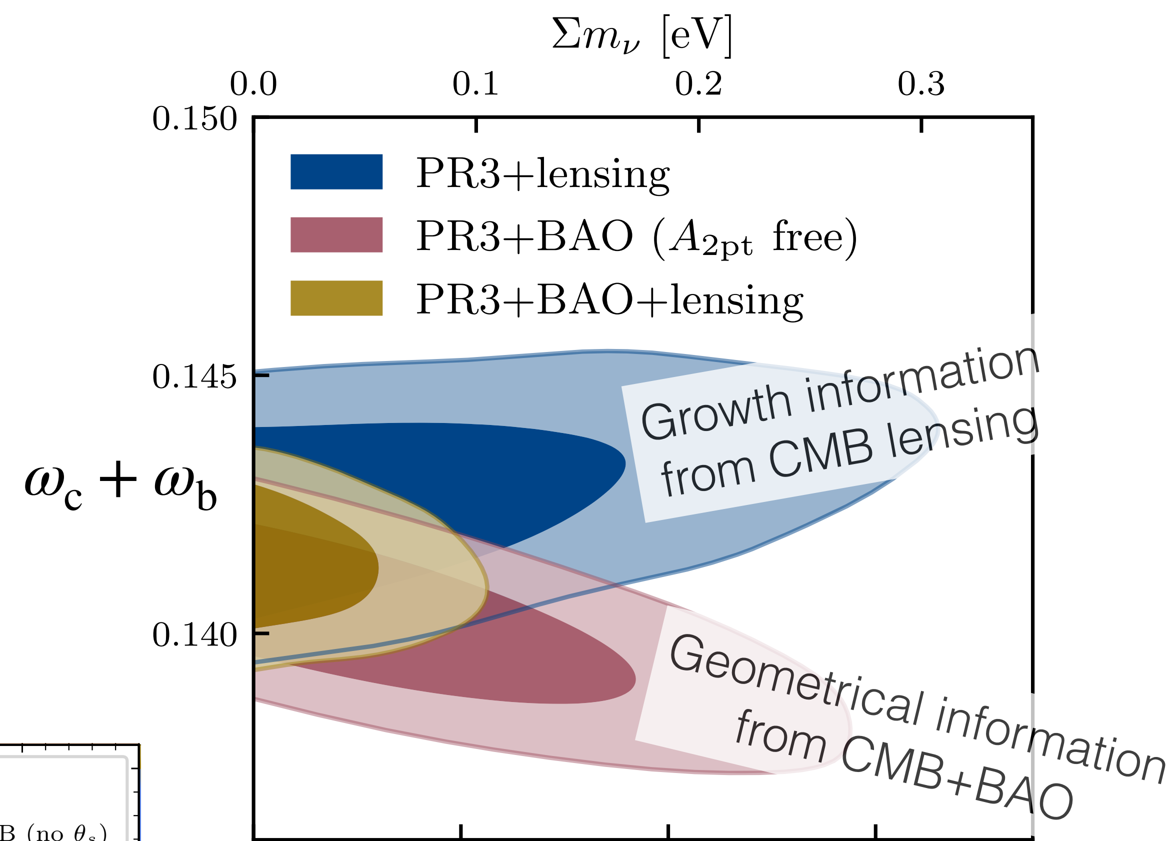
From Lynch & Knox 2025



Analytic extrapolation
to (unphysical) negative masses

Putting geometrical and growth effects together

(assuming ΛCDM!)



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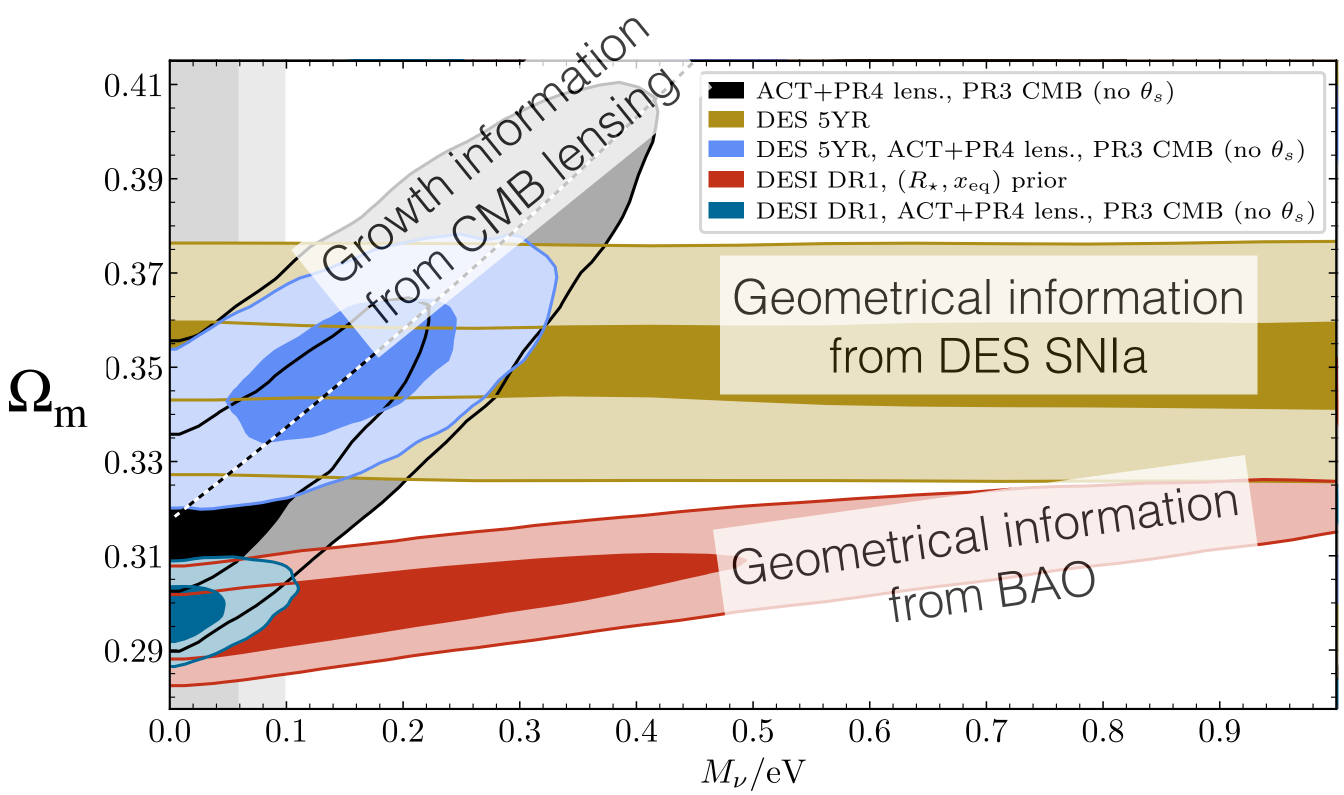


From Lynch & Knox 2025

Constraints agnostic on sound horizon/early universe physics

- "Geometrical information" usually means:
  "distances + standard sound horizon $r_s(\omega_\mathrm{b}/\omega_\gamma\,, z_\mathrm{eq})$ "

- Get "pure geometrical information" from:
  ratio of geometrical probes (CMB θ_s over BAO θ_s , BAO || over ⊥) + SNIa magn.

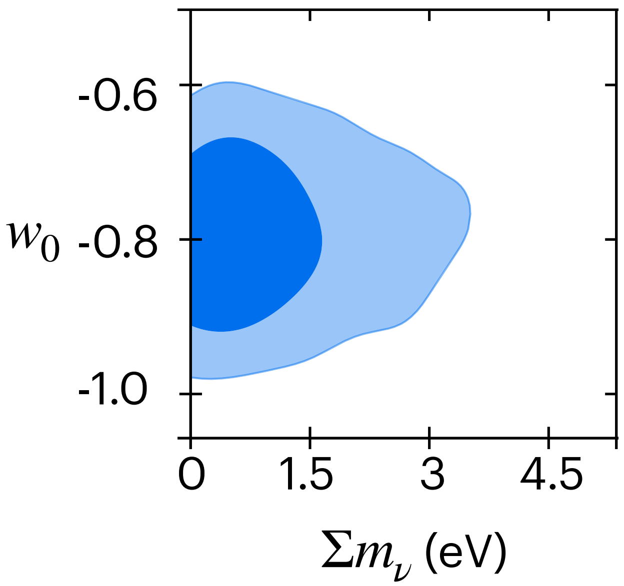
Ravi Sharma & JL (in prep.): constraints agnostic on sound horizon:

"pure geometrical" + growth from CMB lensing :

- with Λ : Σm_ν posterior peaks at positive values

  but Ω_m tensions remains and pushes e.g. for DDE

- with w_0, w_a : Σm_ν posterior still peaks at positive values



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Putting geometrical and growth effects together

Multiple ways to reduce or solve some (or all) of these tensions (hardest is SH0ES):

- Non-physical models ("diagnosis")
  - Extrapolated effect of "negative neutrino mass" would save ΛCDM and solve all tensions but H_0 ; no simple equivalent physical mechanism (comb. of DDM and MG?)
  - Free A_L improves fit to CMB TT only, relaxes Σm_ν bound

- Physical models:
  - Late DE (e.g. w_0, w_a) solves Ω_m tension (not H_0), relaxes Σm_ν bound (<0.13 eV, 95%CL)
  - Early DE reduces Ω_m , H_0 tensions, relaxes Σm_ν bound
  - Decaying DM reduces Ω_m tension (not S_8, A_L, H_0), relaxes Σm_ν bound Lynch & Knox 25
  - High $\tau_{\rm reio}$ reduces Ω_m , S_8, A_L tensions (not H_0), relaxes Σm_ν bound Sailer et al. 25, Jhaveri et al. 25

All lead to significantly different Σm_ν bounds!

Need more independent measurements & other experimental techniques (CMB polarisation, Stage-IV LSS surveys, 21cm, standard sirens…)

Extended DM & EFTofLSS: theoretical challenges

- Models with suppression of structures imprinted during radiation-dominated (RD) era. Examples:
  - warm DM (WDM), hot DM (HDM), mixed C+WDM, mixed C+HDM (mass in 10 eV - 10 keV range) when neglecting thermal velocity effects during MD
  - DM scattering off dark radiation (DR). DR can be free-streaming or self-interacting. Either dark decoupling (ETHOS n>0) or $\Gamma/H =$ constant during RD (ETHOS n=0)
  - DM scattering off neutrinos; some models of DM scattering off baryons
- Models with suppression of structures imprinted during matter-dominated (MD) era. Examples:
  - WDM, HDM, C+WDM, C+HDM (mass in 1 eV - 100 eV range) if high precision required (thermal velocity effects during MD)
  - Decaying dark matter. Simplest: relativistic daughters. Next level: relativistic + lighter daughter (CDM—> DR+WDM)
  - DM with self-interactions (SIDM): short-range; long-range, with interacting DM-dark energy as possible limit
  - Some models of DM scattering off baryons

Extended DM & EFTofLSS: theoretical challenges

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different ICs but same growth as ΛCDM

$\Rightarrow$ separability in k, z

$\Rightarrow$ standard EFTofLSS with EdS kernels

- Models with suppression of structures imprinted during matter-dominated (MD) era. Examples:
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    (thermal ve
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scale-dependent growth

$\Rightarrow$ no separability in k, z

$\Rightarrow$ beyond EdS kernels

SPT, EFTofLSS, … with scale-dependent growth

- Full integral over time- and scale-dependent kernels (Garny & Taule 20,22)
  - doublet: $\Psi_a = (\delta_{\rm cb}, -\theta_{\rm cb}/\mathscr{H}f)$
  - e.o.m: $\partial_\eta \psi_a(\mathbf{k},\eta) + \Omega_{ab} \psi_b(\mathbf{k},\eta) = \int_{\mathbf{k}_1,\mathbf{k}_2} \delta_D(\mathbf{k}-\mathbf{k}_{12})\gamma_{abc}(\mathbf{k},\mathbf{k}_1,\mathbf{k}_2)\psi_b(\mathbf{k}_1,\eta)\psi_c(\mathbf{k}_2,\eta)$
  - time-dependent kernels:

$$(\partial_\eta + n)F_a^{(n)}(\mathbf{q}_1,\ldots,\mathbf{q}_n;\eta) + \Omega_{ab}(k,\eta)F_b^{(n)}(\mathbf{q}_1,\ldots,\mathbf{q}_n;\eta)$$
$$= \sum_{m=1}^{n-1}\Big[\gamma_{abc}(\mathbf{k},\mathbf{q}_{1\cdots m},\mathbf{q}_{m+1\cdots n})F_b^{(m)}(\mathbf{q}_1,\ldots,\mathbf{q}_m;\eta)F_c^{(n-m)}(\mathbf{q}_{m+1},\ldots,\mathbf{q}_n;\eta)\Big]_{\rm sym.}$$

- FOLPS: taking into account k-dependence of $\delta_{\rm cb}$ and $\theta_{\rm cb}$ at each time (Aviles et al. 21, 22..)
  - At given eta, kernels get multiplied by $D(k,\eta)$ or $f(k,\eta)$

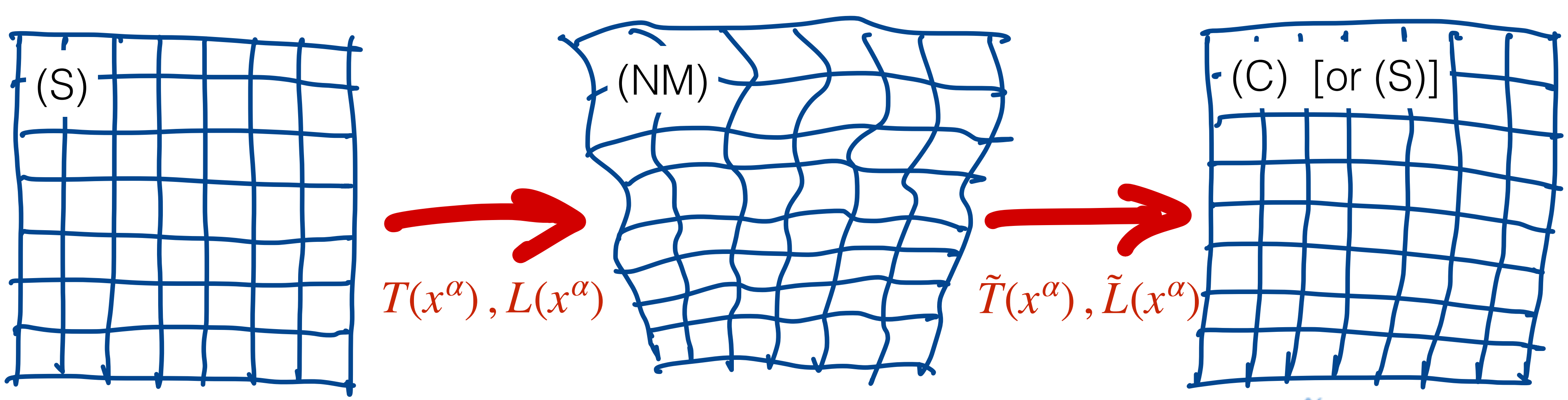
- Potentially much quicker and still nearly exact method inspired from N-body: Newtonian Motion gauges (C. Fidler, JL, A. Moradinezhad, in prep.)

Newtonian Motion gauges

3 gauges:

- Gauge of Boltzmann code (Synchronous gauge, Poisson/Newtonian/longitudinal gauge)
- Gauge matching gauge-independent observables (Comoving gauge, $V_{\rm tot} = B$, with $H_{\rm T} = 0$)
- Gauge designed to get effectively Newtonian variables:
  - N-body, N-boisson, Newtonian Motion gauge (C. Fidler, C. Rampf, T. Tram, R. Crittenden, K. Koyama, D. Wands 2015, 2016, 2017)
  - particles follow same trajectories as if governed by Newtonian equations for single self-gravitating fluid
  - absorbs effects of GR, radiation, even massive neutrinos, modified gravity…

Self-consistency: perturbatively small coordinate transformation -> weak-field approximation holds also in NM gauge ($|H_{\rm T}^{\rm (NM)}| \ll 1$)



END

When cosmology returns stronger bound than laboratory or astroparticle

model-dependent by definition

- Summed neutrino mass

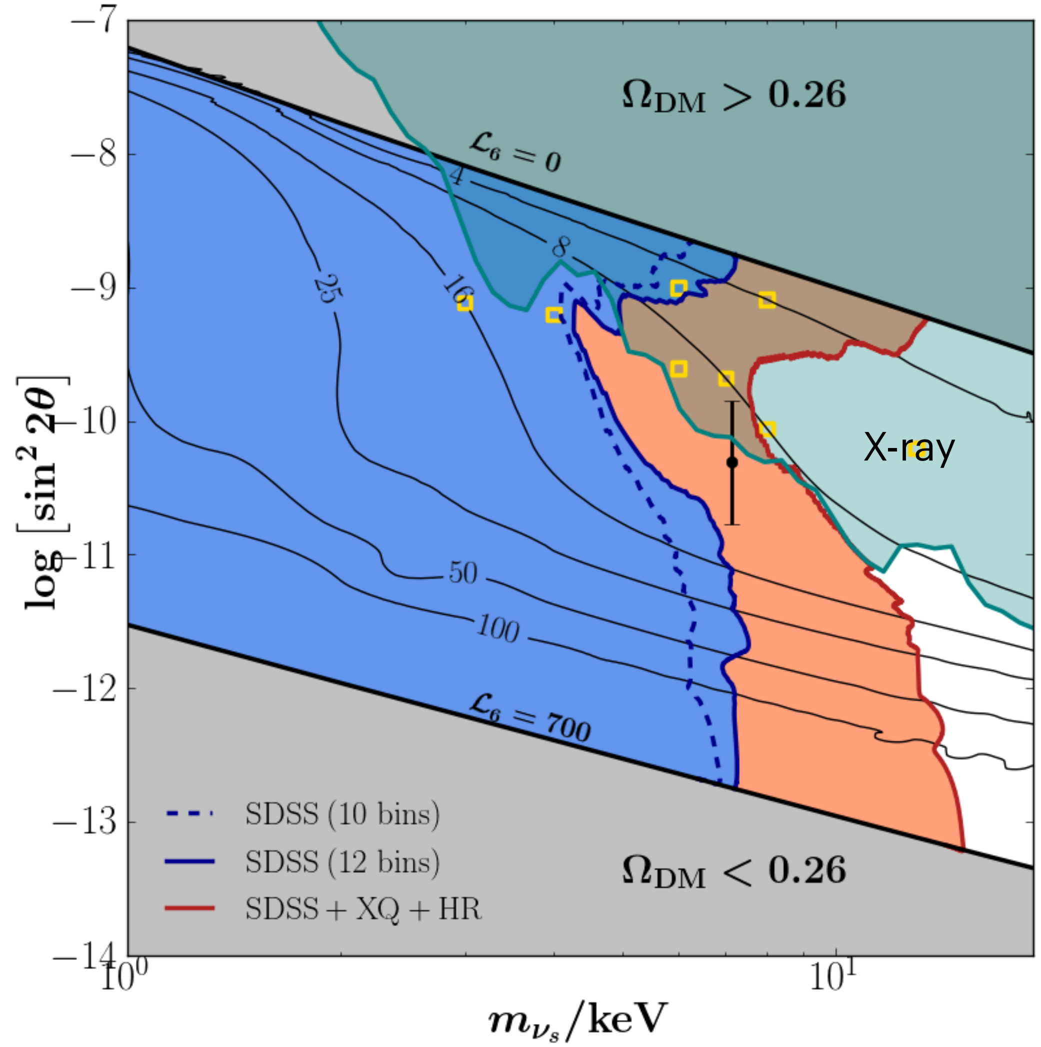
- Light thermalised sterile neutrinos -> incompatibility with LSND and MiniBoone anomalies [Planck coll. 1807.06209]

- Lower DM mass bound (assuming all DM is warm), e.g. for sterile neutrinos as DM -> incompatibility with 3.5keV X-ray line [Palanque-Delabrouille et al. 1911.09073]

- DM scattering rate over photons or neutrinos [Becker et al. 2010.04074, Ali-Haimoud et al. 1506.04745, Mosbech et al. 2011.04206]

- DM decay into non-electromagnetic product (less than 3.8% after CMB decoupling) [Poulin et al. 1606.02073]

DM sterile neutrino: mixing angle vs. mass
(incl. possibility of resonant production)



Baur et al. 1706.03118

When cosmology returns weaker bound than laboratory and astroparticle

- Neutrino self-interaction rate (Fermi-like)
  - SIν

    = strongly-interacting model

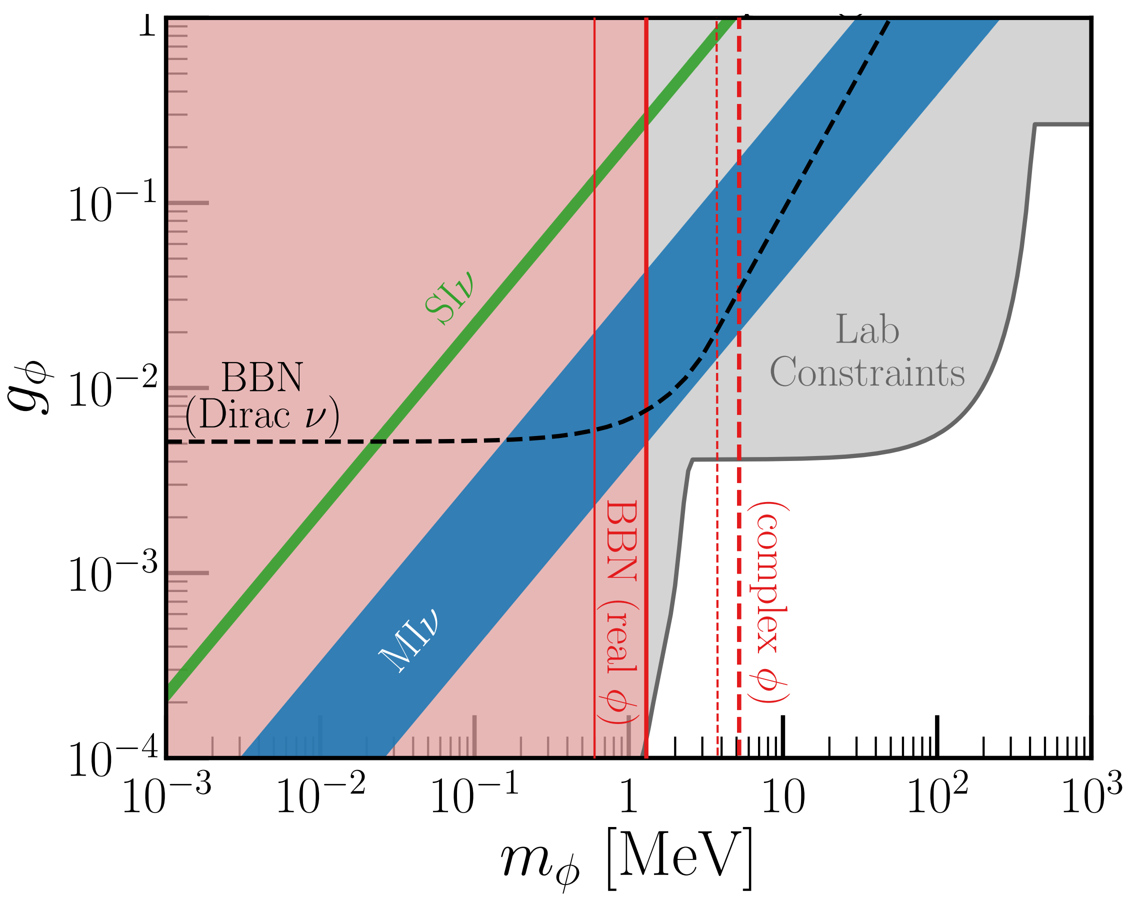
    = cosmological upper bound

    = potential solution to H_0 tension

    [Kreisch et al. 1902.00534, Archidiacono et al. 1311.3873]
  - Lab constraints

    = tau/meson decay, nuclei double-beta decay

$\nu\bar{\nu}\phi$ coupling vs. mediator mass

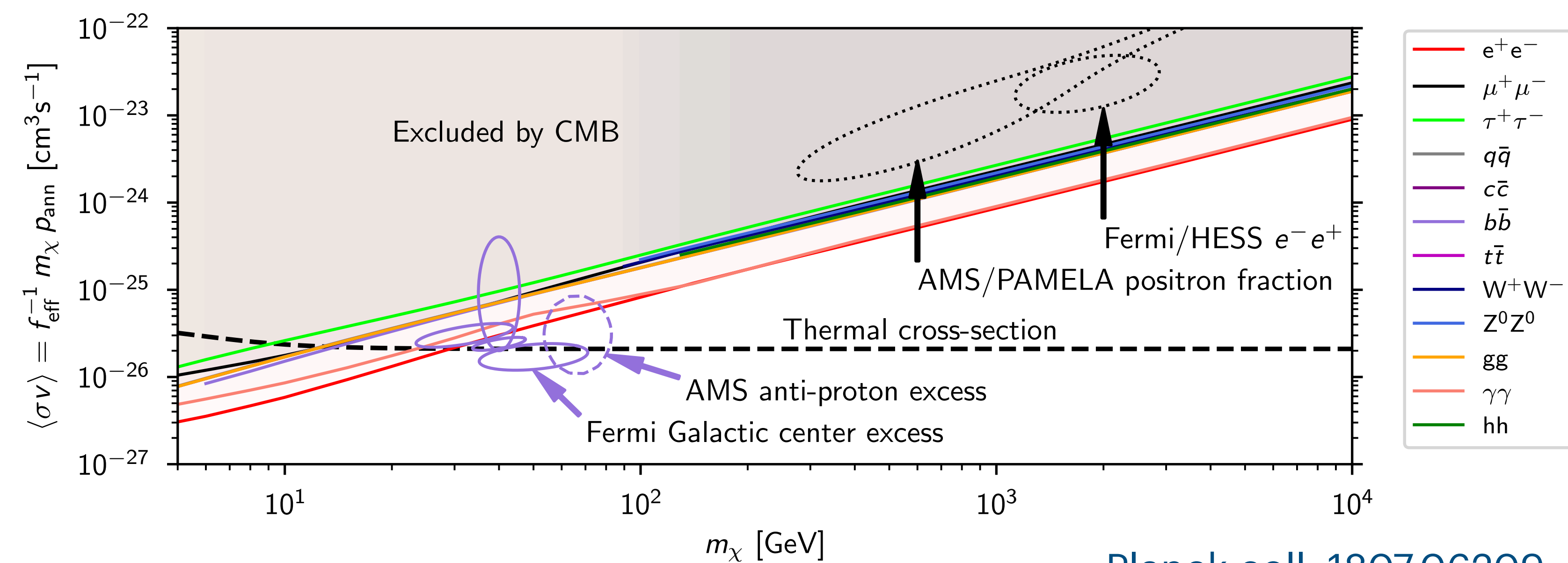


Blinov et al. 1905.02727

When cosmology, laboratory and astroparticle bounds are complementary

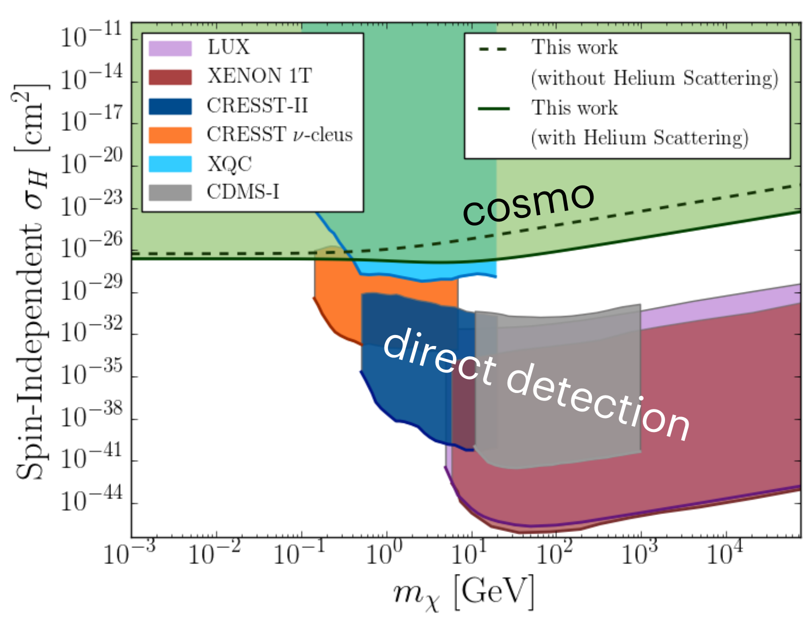
- DM annihilation
- electromagnetic DM decay (incl. PBH evaporation)
- DM-baryon scattering

DM annihilation cross-section vs. DM mass



Planck coll. 1807.06209

vel.-indep. DM-p cross-section vs. mass



Xu et al. 1802.06788

millicharged DM-p cross-section vs. mass