Dark Matter: Where and What?

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The Standard Model at 50: Successes and Challenges
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Goals

- Explain the arguments for dark matter, and what we know about its properties.
- Discuss the range of possibilities for dark matter, and how we might test different scenarios. Some examples:
  - Black holes
  - Thermal scenarios - e.g. WIMPs
  - Ultralight bosonic DM - e.g. axions

The missing mass

- Zwicky, 1933: estimated the mass in a galaxy cluster in two ways.

<u>Method 1</u>

Estimate mass from mass-to-light ratio, calibrated to local system.

- Count galaxies
- Add up total luminosity
- Convert to mass using mass-to-light ratio of ~3, calibrated from local Kapteyn stellar system.

Mass estimate 1

<u>Method 2</u>

Use virial theorem + measurements of galaxy velocities to estimate gravitational potential, and hence infer mass.

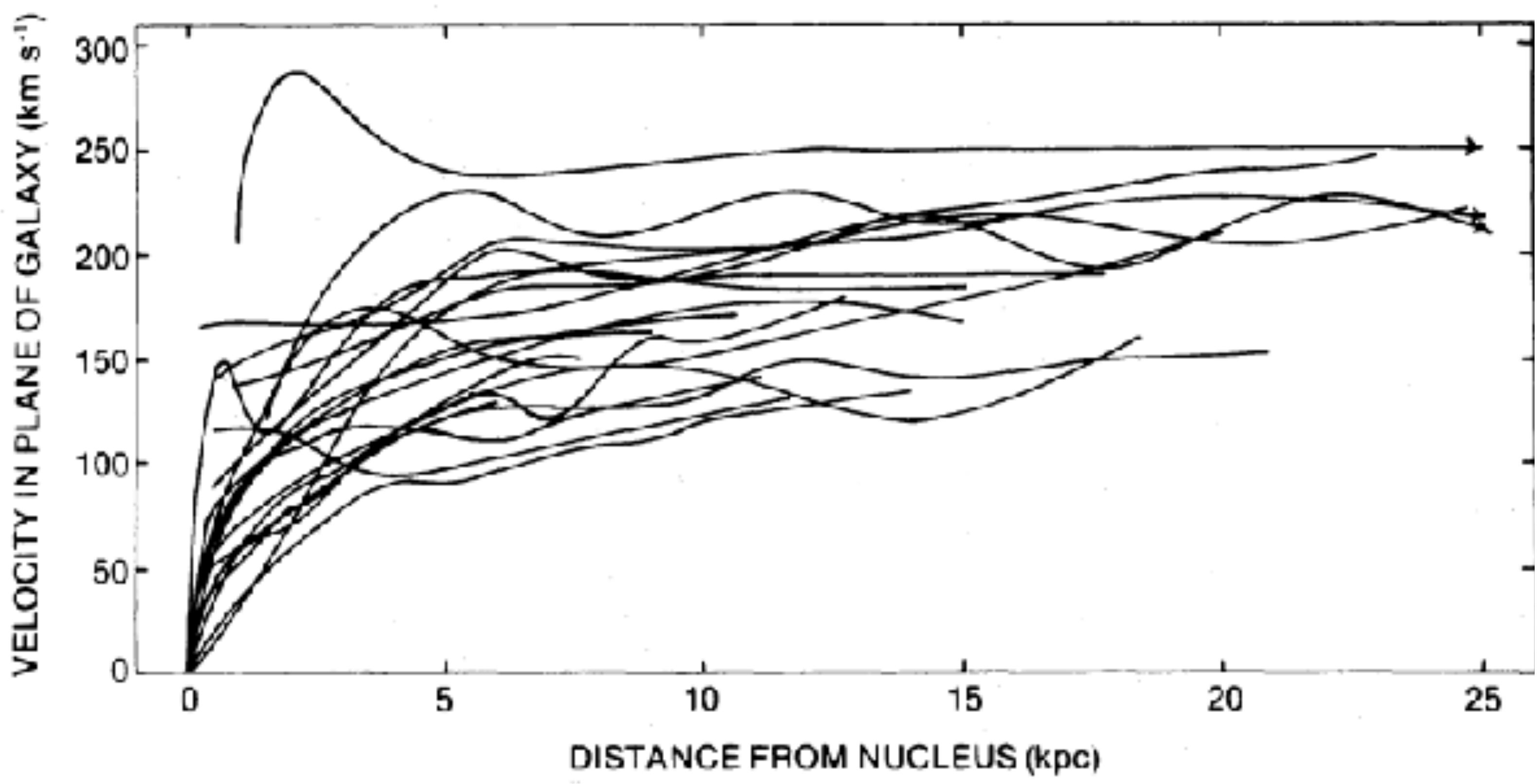
Galactic velocities measured by Doppler shifts

$$\mathrm{KE} = -\frac{1}{2}\mathrm{PE}$$ in equilibrium

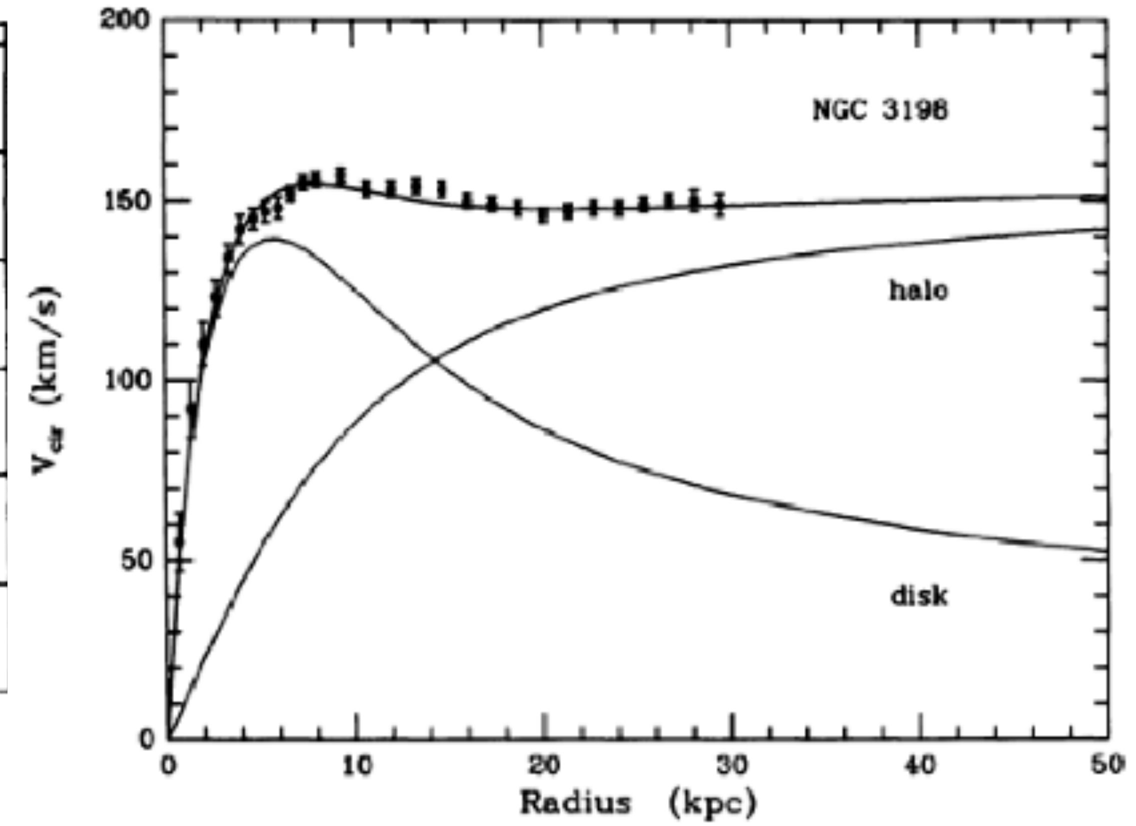
Mass estimate 2

- These numbers are different by 2+ orders of magnitude (second one is larger).
- One possibility: there is (lots of) gravitating non-luminous matter.

Dark matter in galaxies…



Rubin, Ford & Thonnard, 1980



van Albada, T. S., Bahcall, J. N., Begeman, K., & Sancisi, R., 1985

- Rubin, Ford & Thonnard 1980 (following work in the 1970s): galactic rotation curves are flat, not falling as one would expect if mass was concentrated in the bulge at the Galactic center.
- Modified gravity? Or some "dark" unseen matter? If the latter, needs to extend to much larger radii than the observed Galactic disk - "dark halo".

$$\frac{v^2}{r} = \frac{GM(r)}{r^2}$$

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$

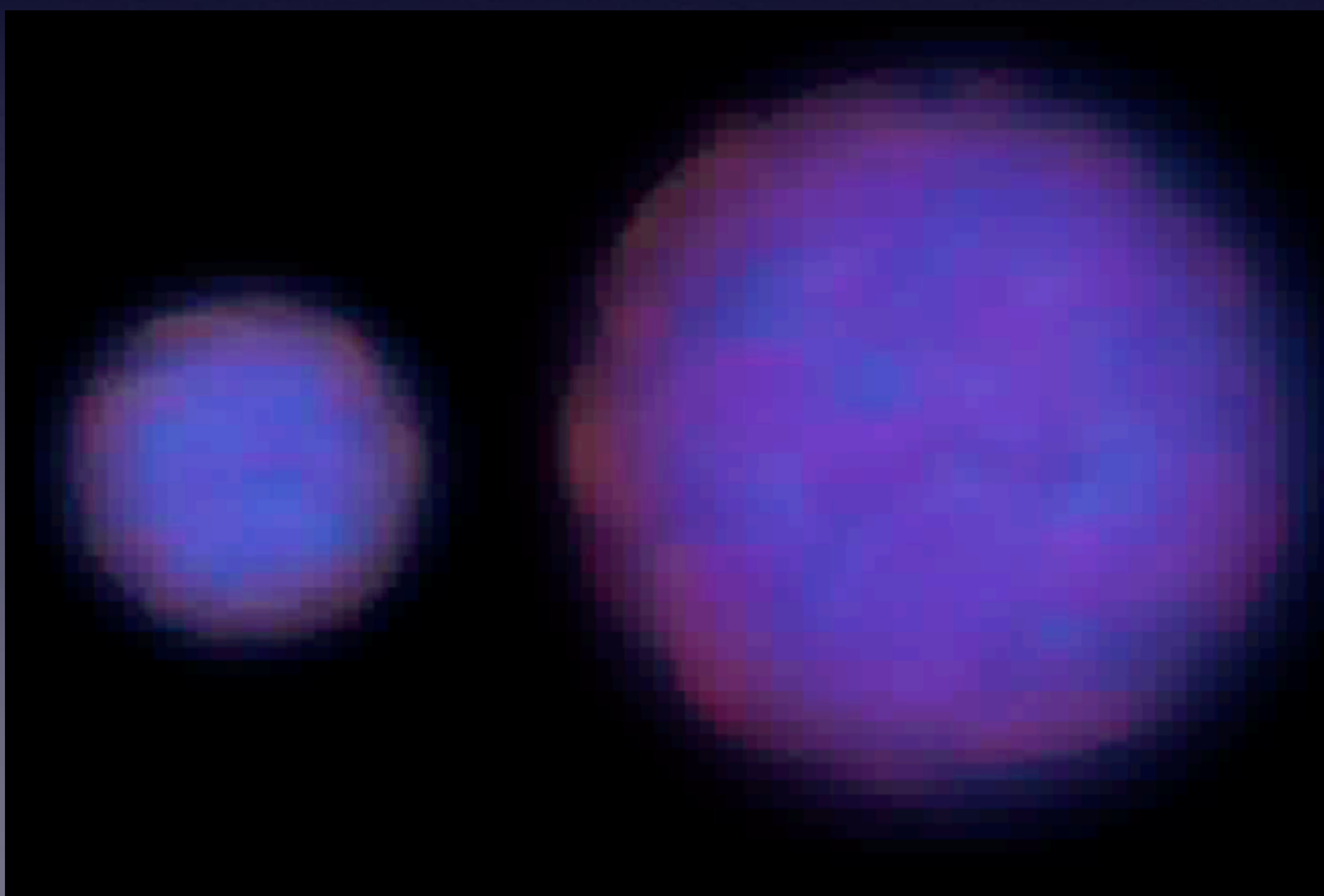
$$M(r) \propto r \Rightarrow v \,\mathrm{constant}$$

… or a change to gravity?

- Perhaps gravity is different on Galactic scales - doesn't weaken as quickly as expected with distance. How can we tell this apart from dark matter?
- Problem: dark matter and luminous matter are gravitationally bound to each other - tend to clump in the same places.
- But we know dark matter (if it exists) does not interact with the same strength as ordinary matter, or it would form its own disk (rather than halo).
- Solution: look at systems where galaxy clusters are colliding.

Dark matter in colliding clusters

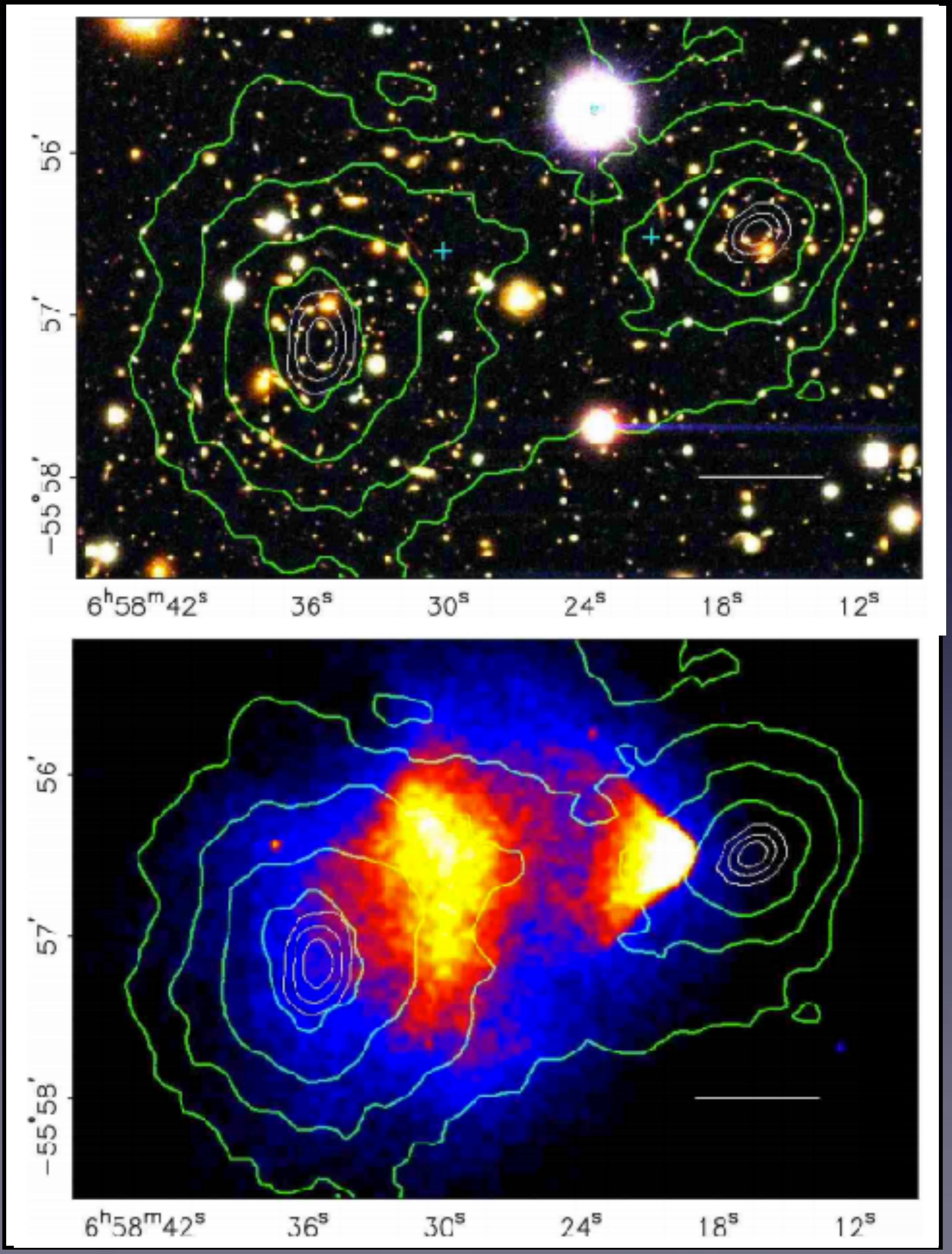
- When clouds of gas collide, there is compression and heating, producing X-ray radiation as the gas clouds slow down and heat up.
- But we believe dark matter doesn't interact and collide like ordinary matter - clouds of dark matter might pass straight through each other!



- Thus collisions could potentially separate the dark matter (and its gravitational pull) from the visible matter (shining in X-rays).

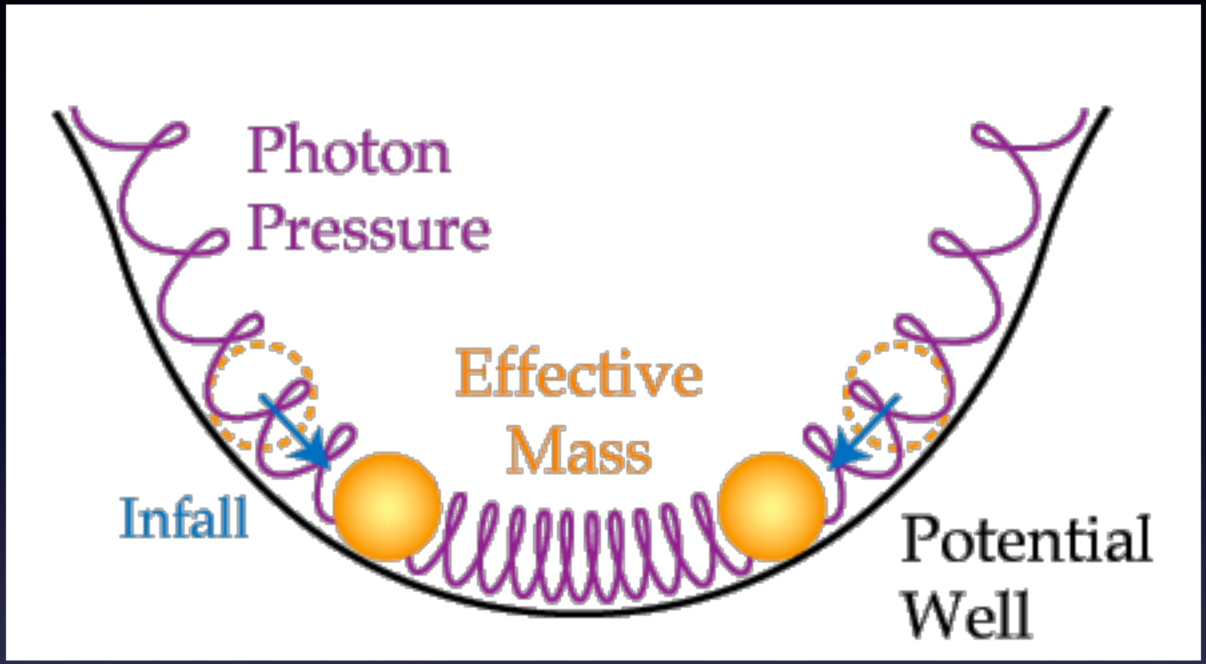
Filtering out the dark matter

- Clowe et al 2006: studied the Bullet Cluster, system of two colliding clusters.
  - X-ray maps from CHANDRA to study distribution of hot plasma (main baryonic component).
  - Weak gravitational lensing to study mass distribution.
- Result: a substantial displacement between the two.
- Attributed to a <u>collisionless cold dark matter</u> component. When the clusters collided, the dark matter halos passed through each other without slowing down - unlike the gas.
- Can be used to set upper limits on degree of dark matter self-interaction (however, early limits likely too strong [Robertson et al '16].)

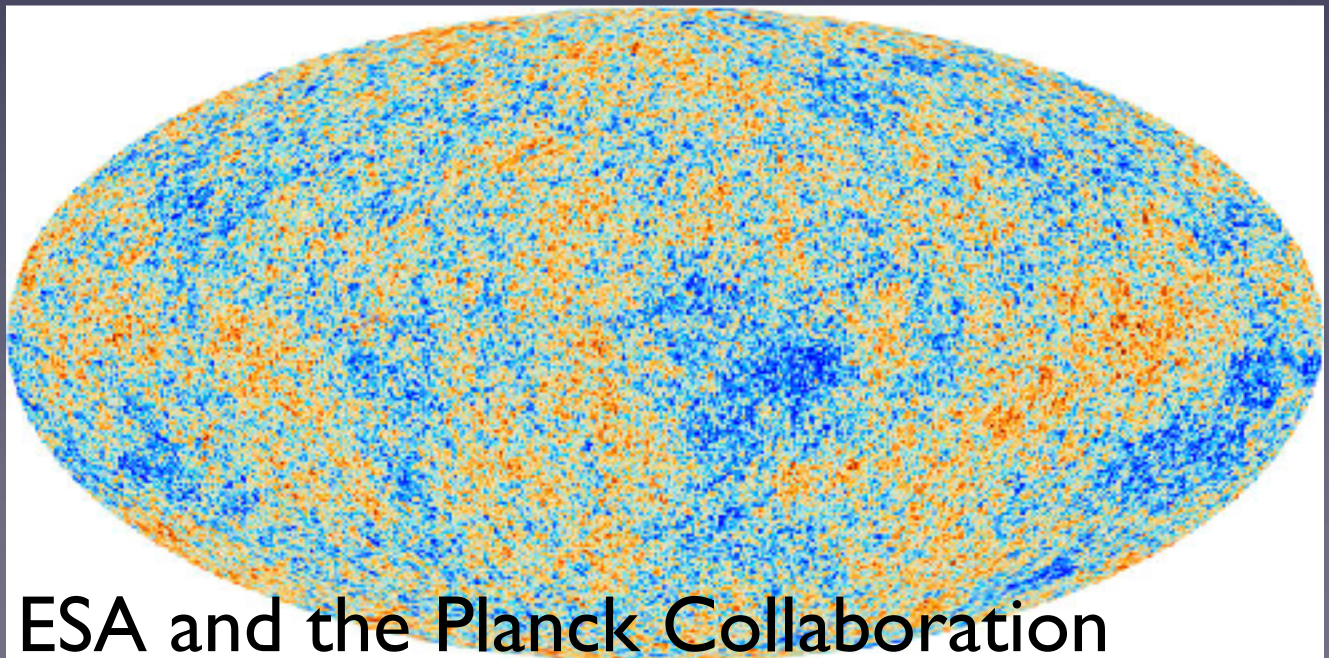


Dark matter in cosmic history

- When universe was ~400 000 years old, it was a nearly-homogeneous bath of photons, electrons, protons and dark matter.
- Density/temperature oscillations driven by gravity on one hand, radiation pressure on the other.
- The cosmic microwave background radiation consists of photons that last scattered at this time. Subsequently universe became neutral and ~transparent.



Wayne Hu, http://background.uchicago.edu/~whu/



CMB anisotropies

- Photon temperature anisotropies today provide a "snapshot" of temperature/density inhomogeneities at recombination.
- Peaks occur at angular scales corresponding to a harmonic series based on the sound horizon at recombination.

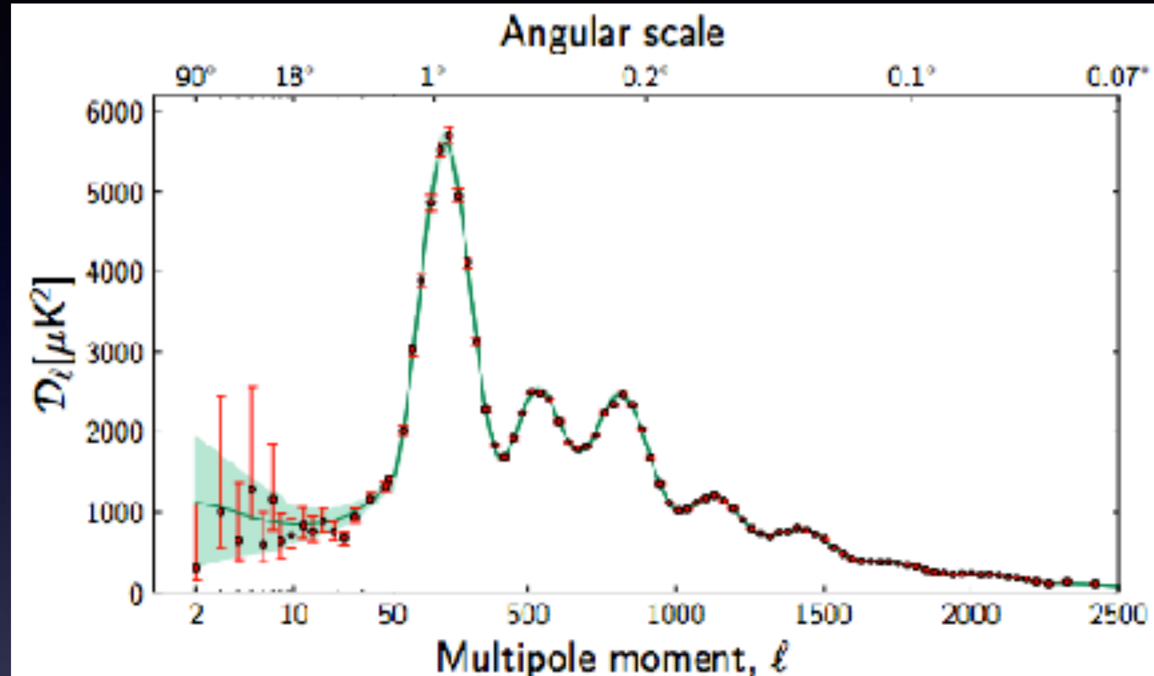


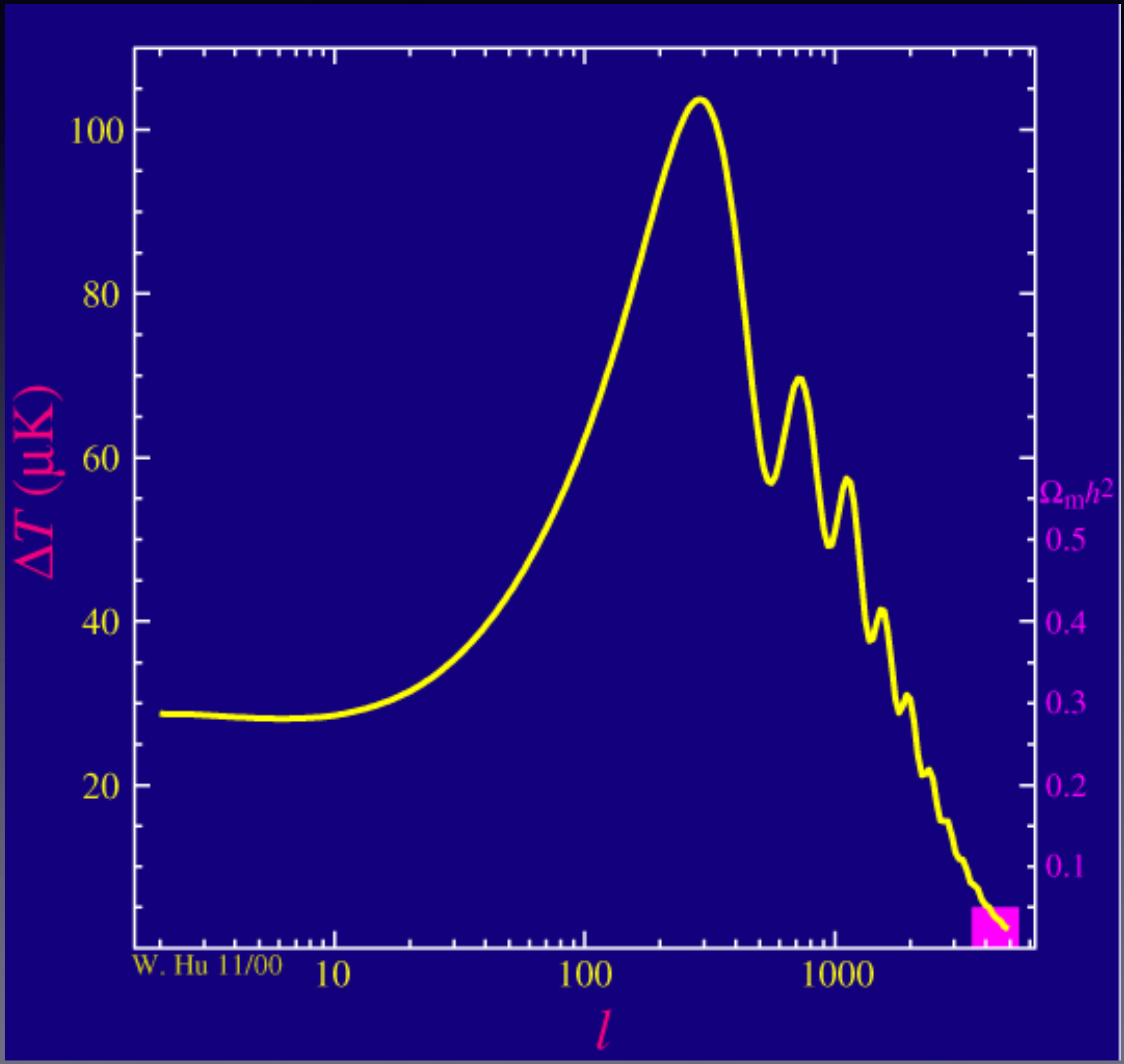
Figure 37. The 2013 *Planck* CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-ℓ values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.

Table 8. Constraints on the basic six-parameter ΛCDM model using *Planck* data. The top section contains constraints on the six primary parameters included directly in the estimation process, and the bottom section contains constraints on derived parameters.

	Planck		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14305	0.1426 ± 0.0025
Age/Gyr	13.819	13.813 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.48	1090.43 ± 0.54
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{eq}	3402	3386 ± 69	3403	3391 ± 60

Measuring the dark matter content

- Fit to data is poor with just photons + visible matter.
- Add a <u>dark</u> component: does not experience radiation pressure, only gravity.
- To match data, need a dark matter component with 5x more total mass than ordinary/baryonic matter.



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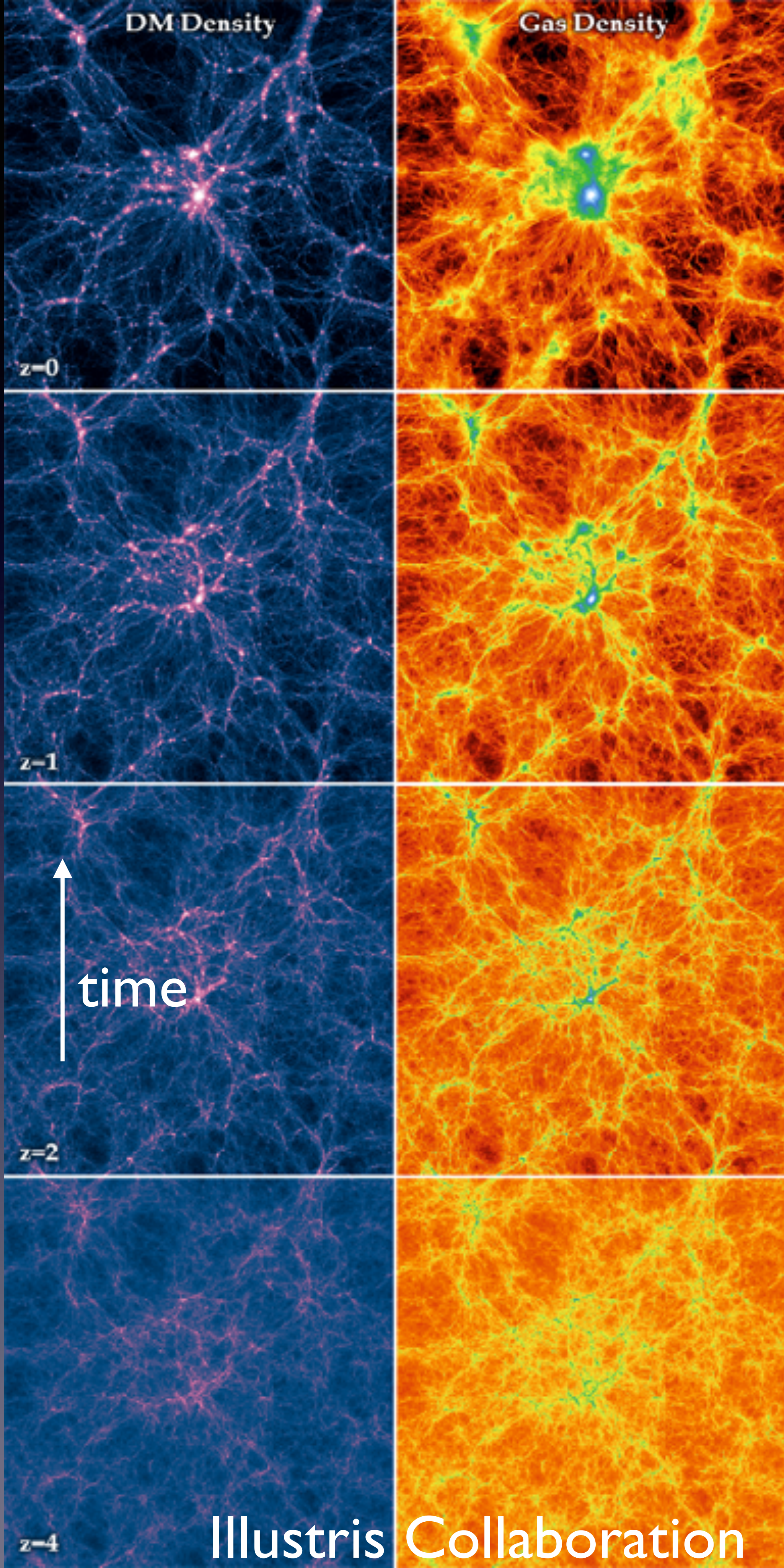
Structure formation

- CMB also maps out initial conditions for cosmic structure formation.
- After the photons decouple from the baryons, overdensities continue to grow under gravity, eventually collapsing into virialized structures.



Illustris Collaboration

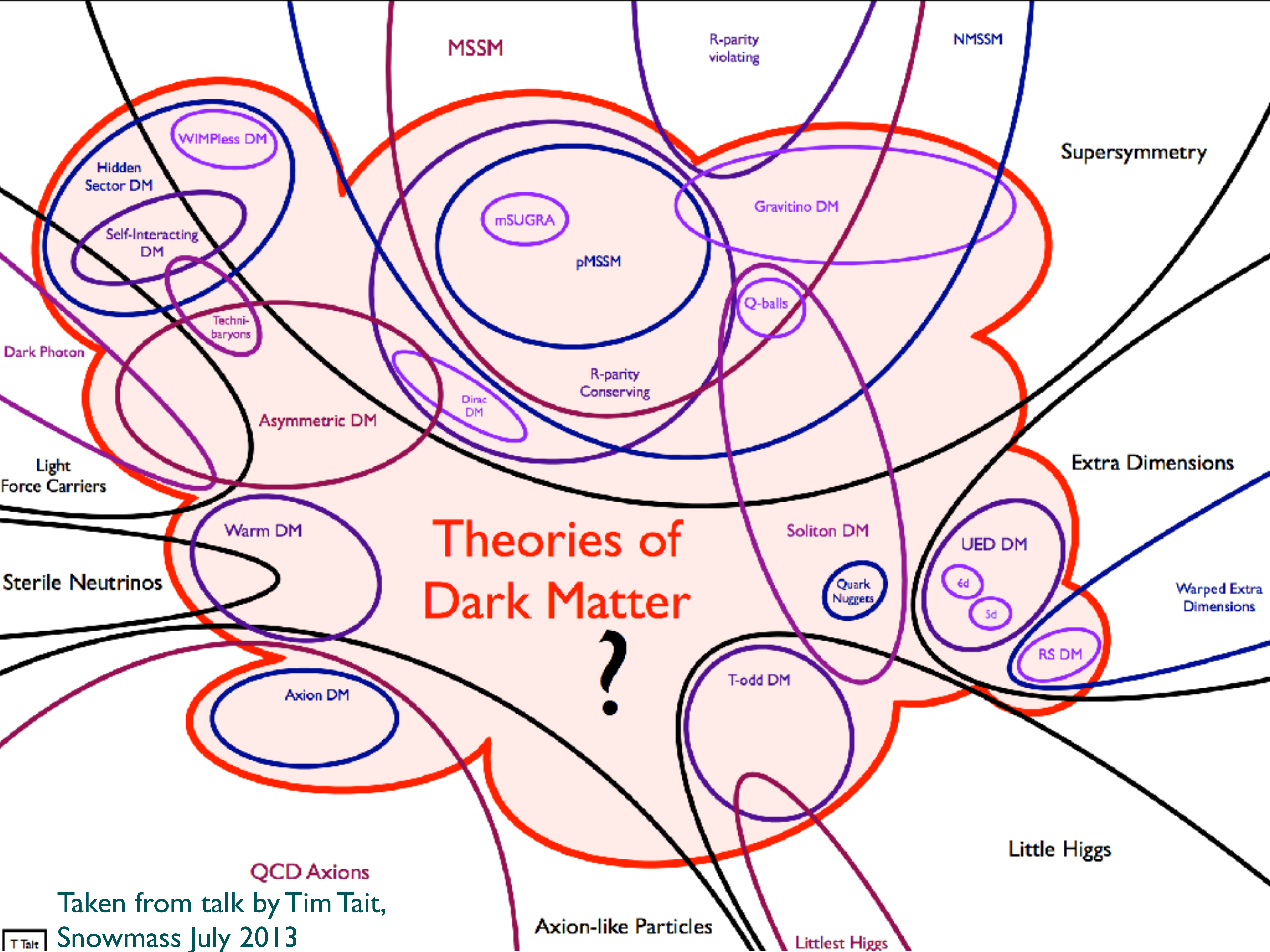
Hot or cold? (or warm)

- Structure formation varies markedly according to the kinematics of the dark matter, in particular whether it can free-stream during the growth of perturbations.
- If most DM is “hot” (relativistic during the early phases of structure formation), free-streaming erases structures on small scales. Large structures form first, then fragment.
- If most DM is “cold” (non-relativistic throughout this epoch), small clumps of DM form first, then accrete together to form larger structures.
- The relative ages of galaxies and clusters tell us that the bulk of DM must be cold - if dark matter was hot, galaxies would not have formed by the present day.
- Equivalently, hot dark matter predicts a low-mass cutoff in the matter power spectrum, that is not observed.
- Neutrinos <u>are</u> hot dark matter - but cannot be all the DM.

DM as new physics

- Standard Model (SM) of particle physics has been spectacularly successful - but no dark matter candidate. We need something:
  - Stable on cosmological timescales
  - Near-collisionless, i.e. electrically neutral
  - "Cold" or "warm" rather than "hot" - not highly relativistic when the modes corresponding to the size of Galactic dark matter halos first enter the horizon (around $z \sim 10^6$, temperature of the universe around 300 eV).
- Only stable uncharged particles are neutrinos, and they would be hot dark matter.

- DM is one of the most powerful pieces of evidence for physics beyond the SM.
- Everything we have learned so far has come from studying the gravitational effects of dark matter, or from its inferred distribution.



Taken from talk by Tim Tait, Snowmass July 2013

Dark matter models by mass

neutrinos | electrons | protons, neutrons | Higgs boson

~eV | ~keV | ~MeV | ~GeV | ~TeV | ~100 TeV

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Down to 10^{-21} eV
Cold condensates

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$>10^{19}$ GeV
Primordial black holes?

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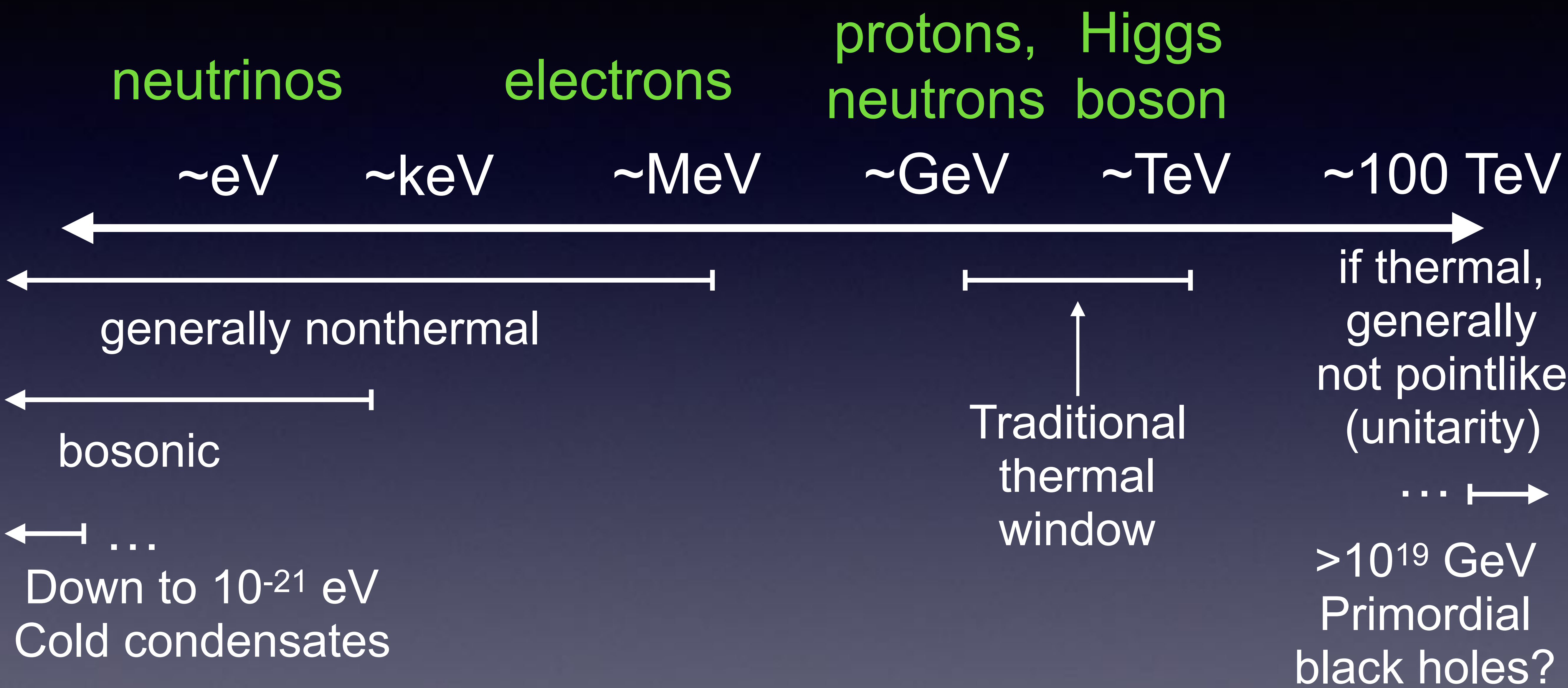

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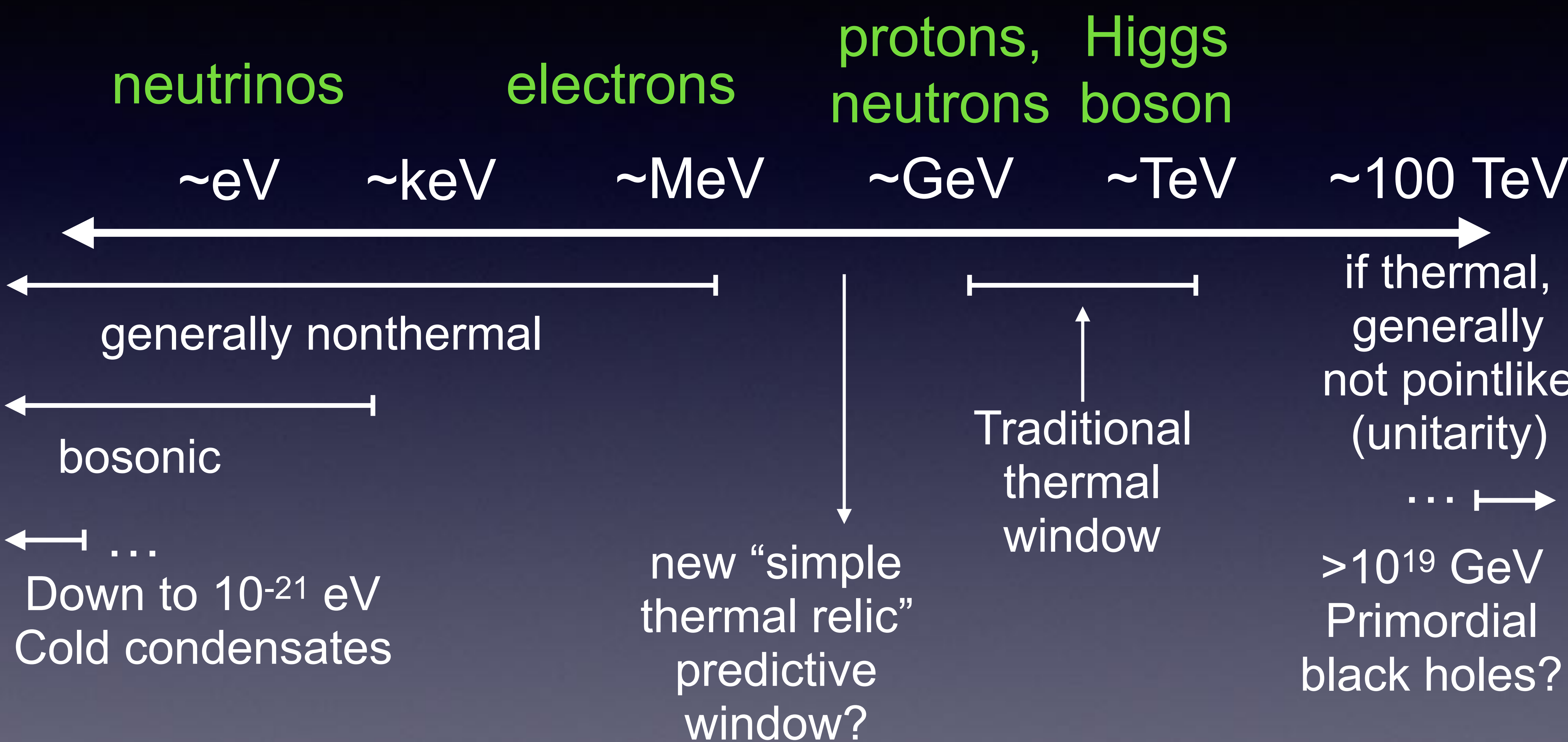

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new “simple thermal relic” predictive window?

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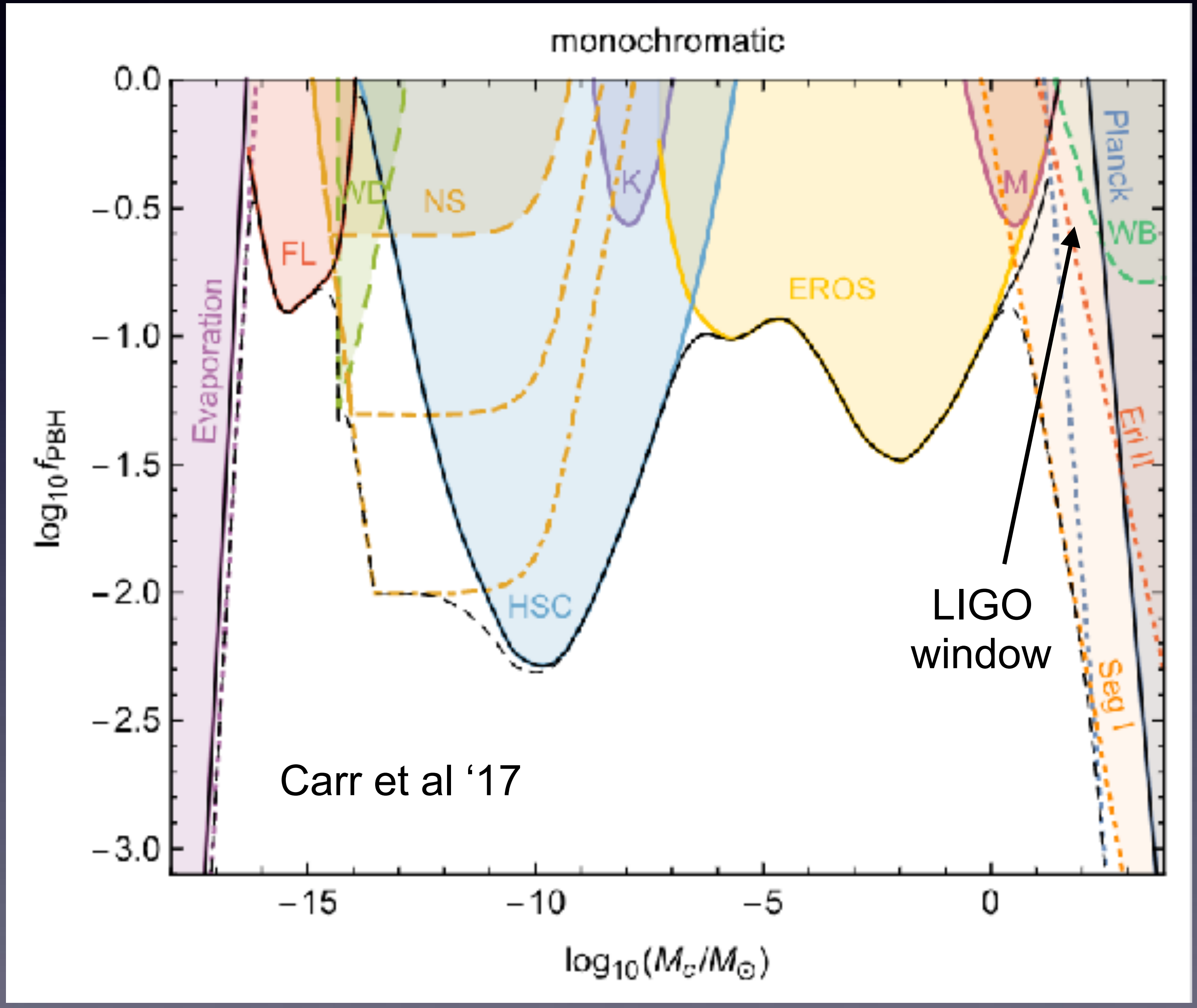
MACHOs

(MAssive Compact Halo Objects)

- Dark matter could be composed of macroscopic objects, e.g. stars or black holes.
- ~collisionless because they are rare, without long-range interactions (except gravity).
- Need to form very early in the universe, before CMB epoch.
- As a result, most-discussed candidate = primordial black holes (PBHs) formed in the very early universe, seeded by large perturbations after inflation.
- However, stringent constraints on this hypothesis - only a few small windows where PBHs could be an O(1) fraction of DM.
- Production mechanism also an open research question.

Constraints on MACHOs

- At low masses (below ~5 solar masses), stringent constraints from microlensing searches.
- Above ~100 solar masses, black holes would disrupt loosely-bound stellar systems in our Galaxy [e.g. Monroy-Rodriguez and Allen '14].
- Debatably open window in the 5-100 solar mass range - many constraints, but with some loopholes [see e.g. talk by Kamionkowski, TeVPA 2017].



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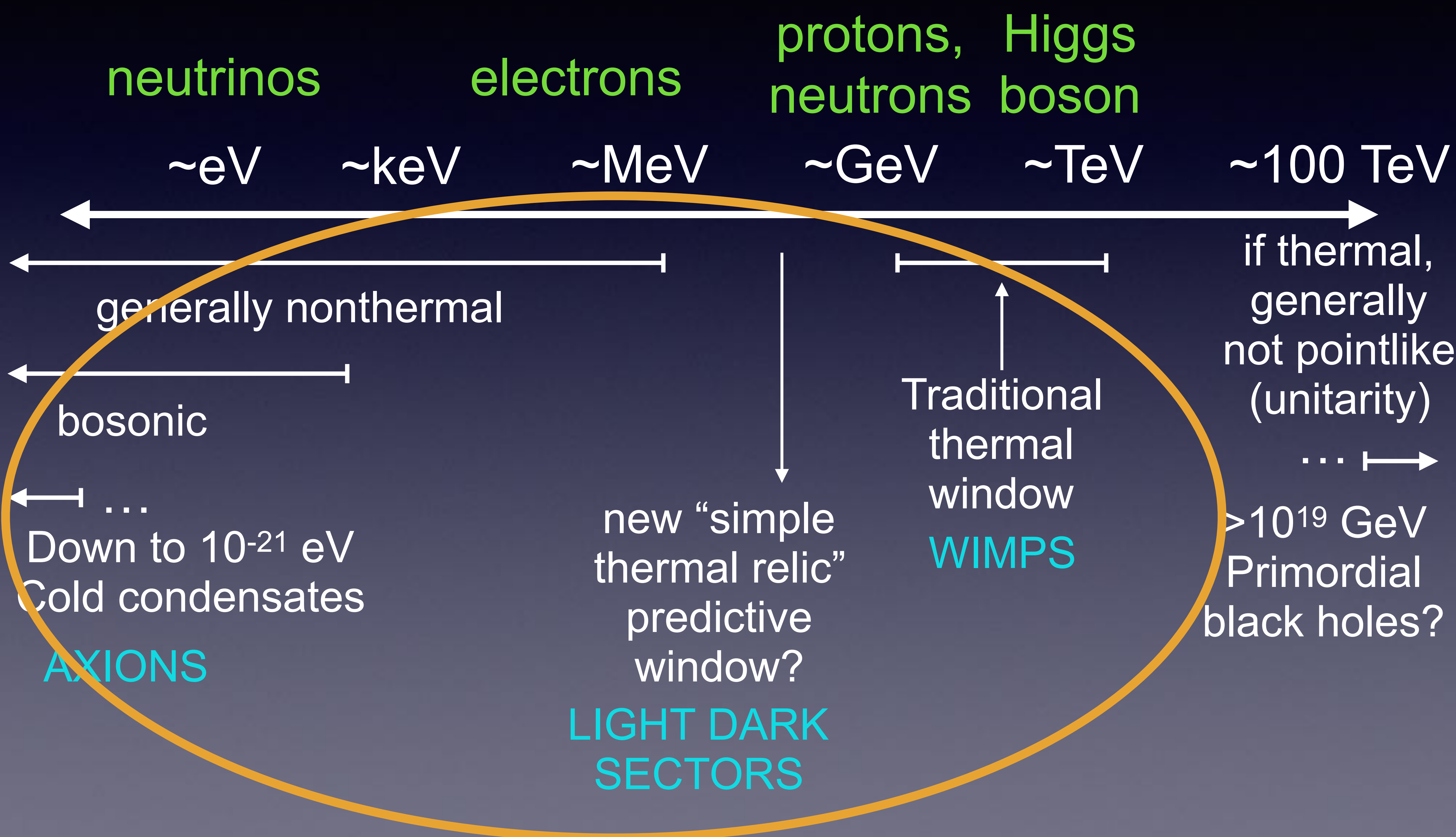
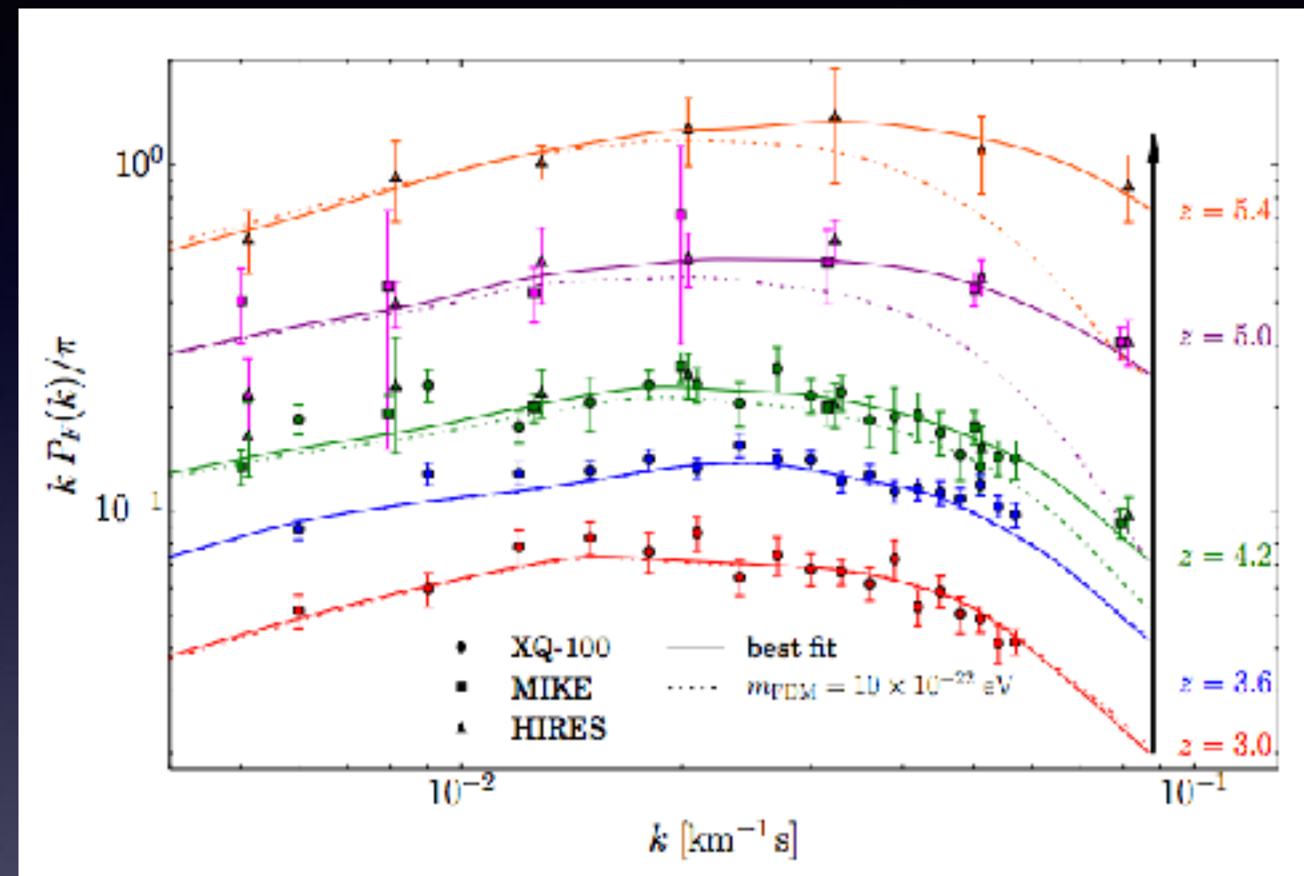


Below the Planck scale: particle dark matter

Irsic et al '17



- Enormous range of possibilities for dark matter as a new fundamental particle (or more than one).
- Model-independent lower mass limit comes from requiring de Broglie wavelength of DM < smallest observed DM structures.
- Dwarf galaxies: size O(kpc), typical velocity dispersion O(10) km/s.
- DM mass of 10^{-22} eV => de Broglie wavelength ~ kpc.
- Lower-mass DM would not allow for observed dwarf galaxies.
- Strongest limits arise from observations of the Lyman-alpha forest - probe of matter power spectrum at z=2-6.
- These bounds require the DM mass to be greater than 2-3 x10^{-21} eV [e.g. Irsic et al '17, Armengaud et al '17].
- To narrow down mass range further, need to specify further information about the model.

The Tremaine-Gunn bound

- Measurements of smallest DM clumps set additional limits on fermionic DM.
- Pauli exclusion principle limits maximum phase space density for fermions.
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$$\sim 100\mathrm{eV}$$

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More careful calculation gives minimum mass ~400 eV [Boyarsky et al ’09]

Dark matter models by mass

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electrons

protons, neutrons

Higgs boson

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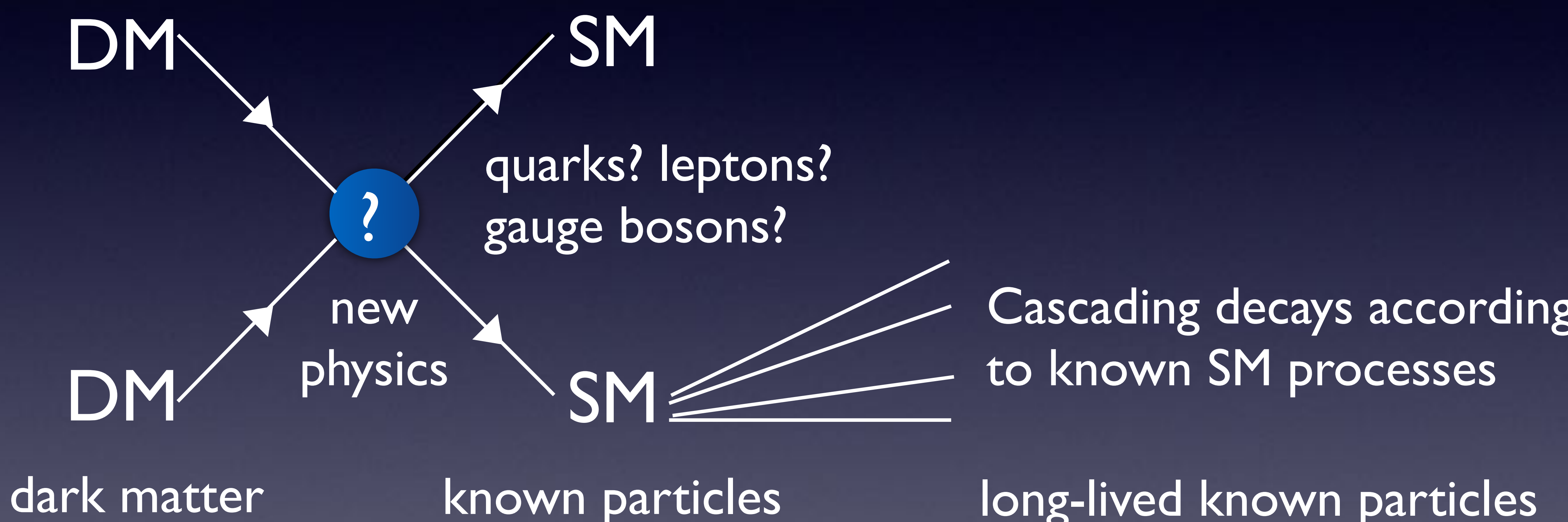
Thermal dark matter

- General class of scenarios: suppose DM was in thermal contact with visible matter in early universe, when temperature was >> DM mass.
- DM-number-changing interactions between DM and visible matter, if they exist, will produce DM during this epoch.
  - # density comparable to photon # density ~ T^3
  - if DM does not reach full thermal equilibrium with Standard Model, abundance can be (much) smaller - "freeze-in" scenario [Hall et al '10].
- Photon number density today factor of ~10^{10} greater than baryon density.
- If DM # density was still ~ photon # density, would overproduce observed amount of DM unless DM mass was <1 eV. In this case thermal DM would be "hot dark matter", and excluded.
- If DM reached full thermal equilibrium with SM, we need a way to <u>deplete</u> its abundance.

Dark matter annihilation



depletes DM density in the early universe

same process yields visible signatures in the present day

Thermal freezeout

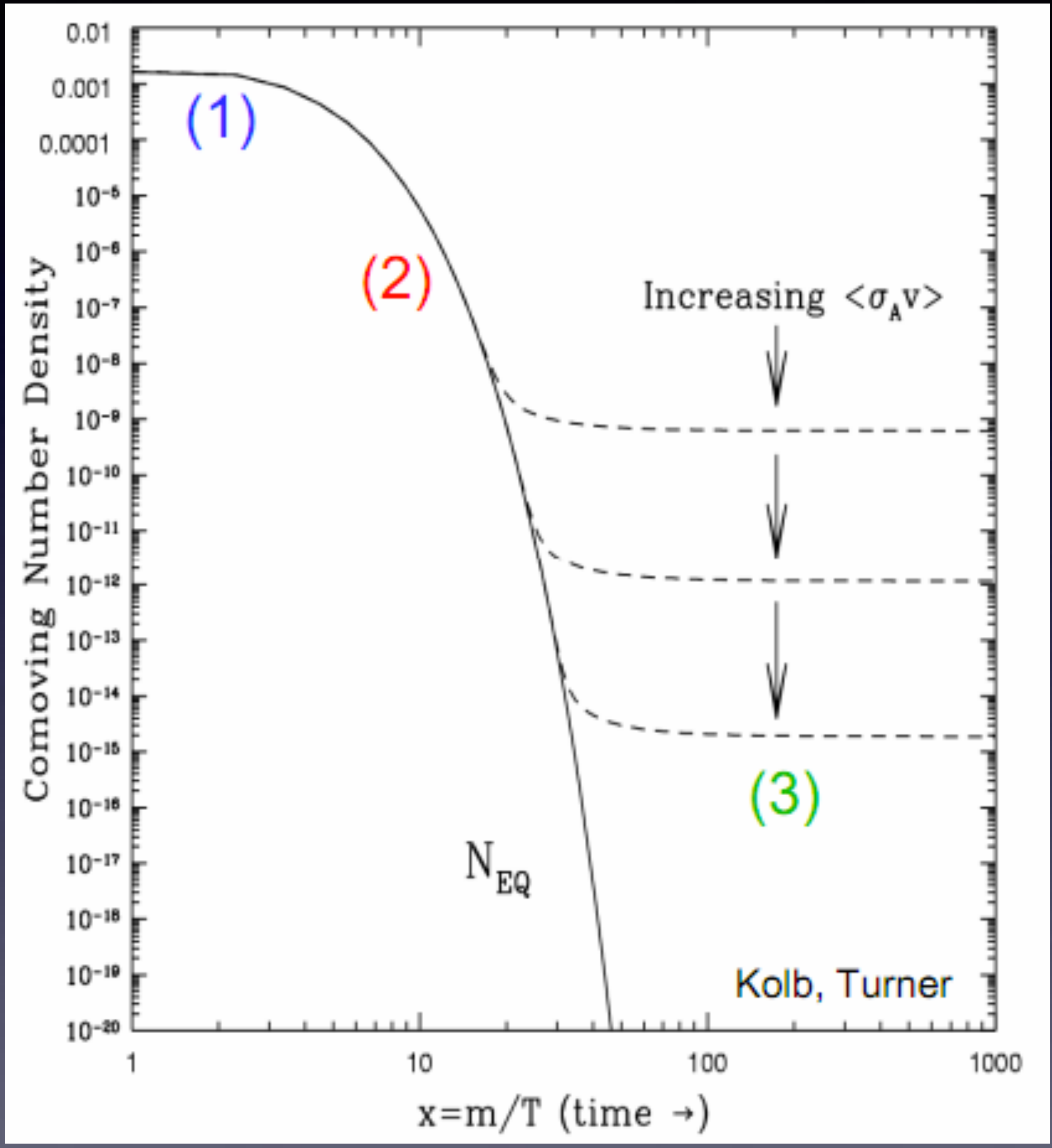
- In the early universe, suppose DM & visible matter (SM) in thermal equilbrium.
- DM can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM}\,\mathrm{SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The comoving dark matter density then freezes out.



So (known) late-time density is set by annihilation rate.

$$\langle\sigma v\rangle \sim 3\times 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$

A little more detail...

- Freezeout occurs when timescales for expansion and annihilation are similar: $H \sim n\langle\sigma v\rangle$
- Usually triggered by exponential depletion of DM around $T \sim m_{DM}$
- After freezeout, DM number density n scales as $(1+z)^3 \sim T^3$.
- Observation: we know that radiation and DM densities were similar at $T_{eq} \sim 1$ eV. Radiation density $\sim T^4$.
- Assuming freezeout happens during radiation domination,

$$T_f^2/m_{\mathrm{Pl}} \sim H_f \sim n_f\langle\sigma v\rangle \sim \left(\frac{T_f}{T_{\mathrm{eq}}}\right)^3 \frac{T_{\mathrm{eq}}^4}{m_{\mathrm{DM}}}\langle\sigma v\rangle$$

$$\langle\sigma v\rangle \sim \frac{m_{\mathrm{DM}}}{T_f}\frac{1}{m_{\mathrm{Pl}}T_{\mathrm{eq}}} \sim \frac{1}{m_{\mathrm{Pl}}T_{\mathrm{eq}}}$$

DM mass dependence largely cancels out

Parametrics for thermal DM

- Matter-radiation equality: T ~ 1 eV
- Planck scale: T ~ 10^{28} eV
- Natural mass scale for (2-body annihilation): 100 TeV x coupling strength ~ 1 TeV x α
- One solution ("WIMP miracle"): weak-scale mass, weak-scale coupling. No new force carriers required, has motivated many direct/indirect/collider searches. But other solutions also viable!
- For perturbative couplings, mass scale needs to be ~100 TeV or less (unitarity bound ~ 200 TeV [von Harling & Petraki '14])
  - Caveat: mass can be higher if DM density diluted by other mechanisms, e.g. large late-time entropy injection [Bramante & Unwin '17].
- For n-body annihilation, thermal-relic mass scale is naturally smaller:

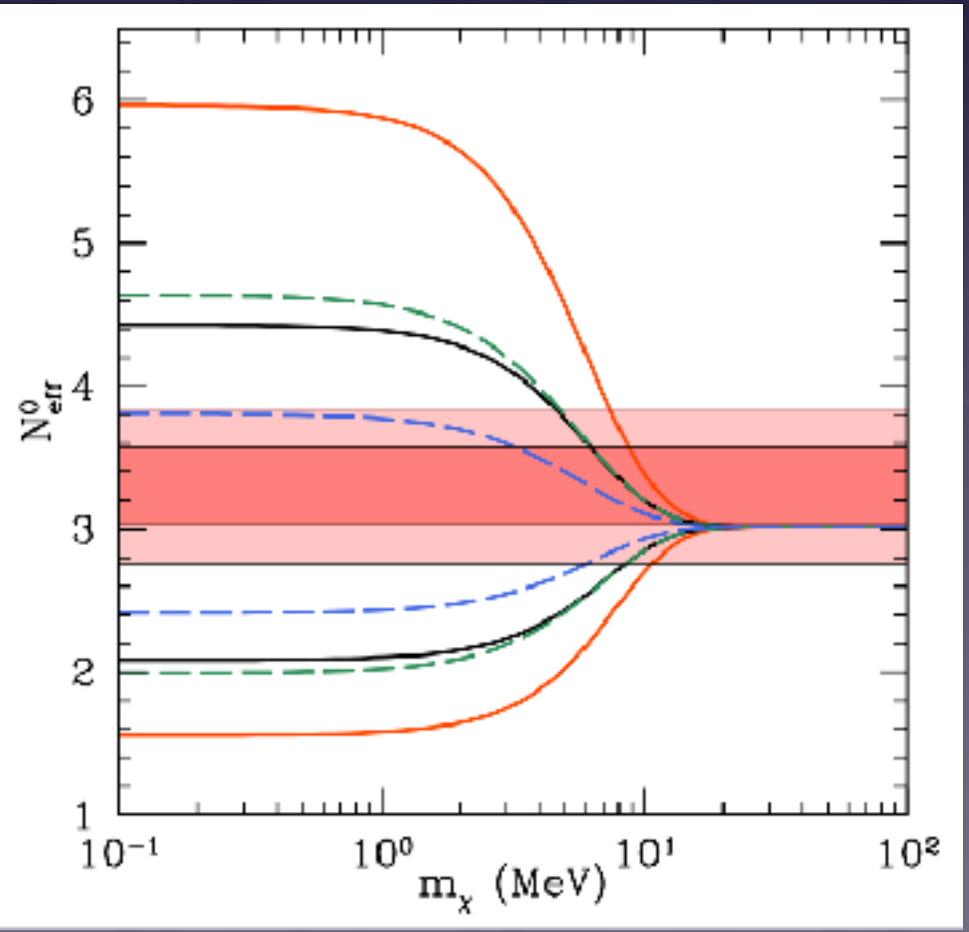
$$m_{\mathrm{DM}} \sim \alpha \sqrt[n]{m_{\mathrm{Pl}} T_{\mathrm{eq}}^{n-1}}$$

(see e.g. SIMP models [Hochberg et al '14])

How low can thermal DM go?

- n_{eff} bound: Big Bang nucleosynthesis (BBN) and CMB data constrain number of effective relativistic degrees of freedom.
- After electrons/positrons become non-relativistic, neutrinos have temperature $(4/11)^{1/3}\, T_{CMB}$; $\Delta n_{eff} = 1$ corresponds to the addition of one extra neutrino species (or other relativistic fermion species at neutrino temperature).
- Planck 2018 data: $n_{eff} = 2.99 \pm 0.17$ [Planck Collaboration '18, 1807.06209].

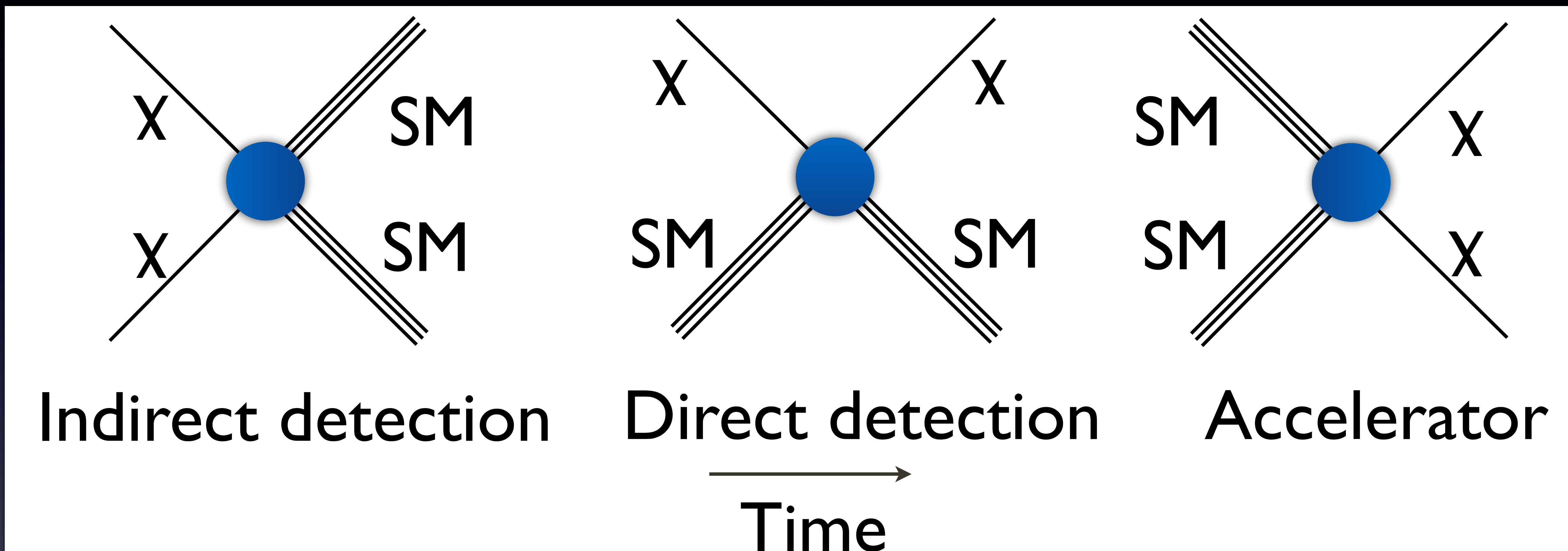
- If DM is in thermal equilibrium with the Standard Model down to O(MeV) temperatures, n_{eff} limit is generally violated [Nollett & Steigman '14, '15]:
  - If DM is still relativistic during BBN (T~1 MeV), can increase n_{eff} directly (independent of coupling to SM).
  - If DM annihilates away after neutrinos decouple from photon bath (T~1 MeV), either to photons or neutrinos, it can substantially modify the neutrino temperature relative to the photon temperature - alter n_{eff} indirectly.



How low can thermal DM go? (round II)

- n_{eff} bound can be evaded if:
  - DM undergoes thermal freezeout to its own dark sector, which is not thermally coupled to the SM, and is colder (e.g. because this sector decoupled from SM before QCD phase transition [Green & Rajendran '17]).
  - DM first reaches thermal equilibrium with SM at temperatures below 1 MeV (after BBN), then decouples again before the CMB epoch [Berlin & Blinov '17].
- Additional limitation: DM itself cannot be too warm/hot during structure formation.
  - Bounds from Lyman-alpha forest exclude thermal DM below ~2-5 keV [e.g. Garzilli et al '15, Irsic et al '17].
  - Limits relaxed for DM substantially colder than CMB photon bath - requires early thermal decoupling (or no thermal coupling at all).

Searching for thermal DM



- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions (e.g. annihilation or decay).
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
- Accelerators: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new particles coupled to the dark matter.

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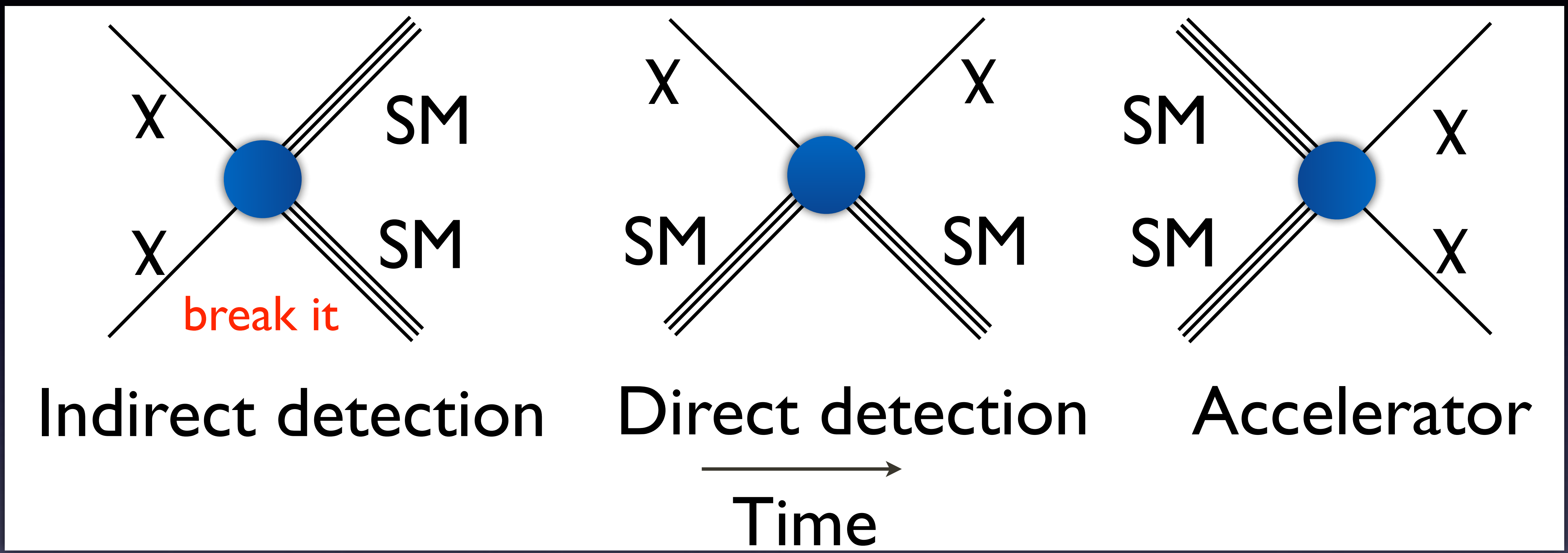

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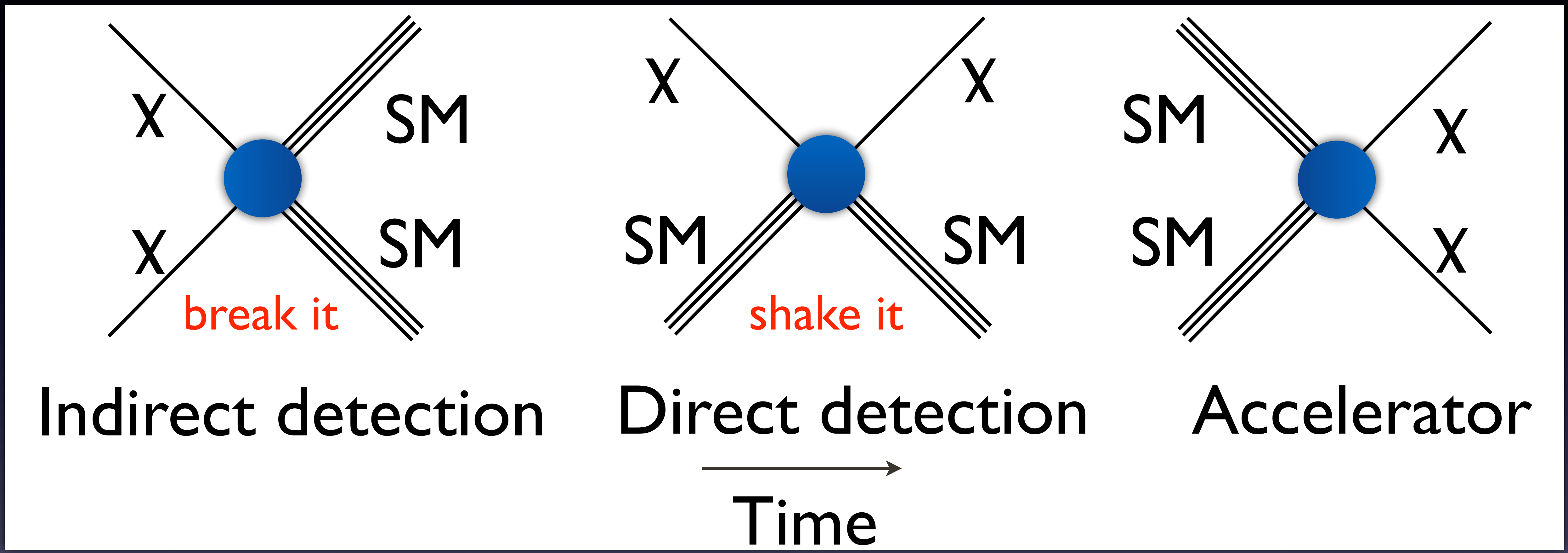

- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions (e.g. annihilation or decay).
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
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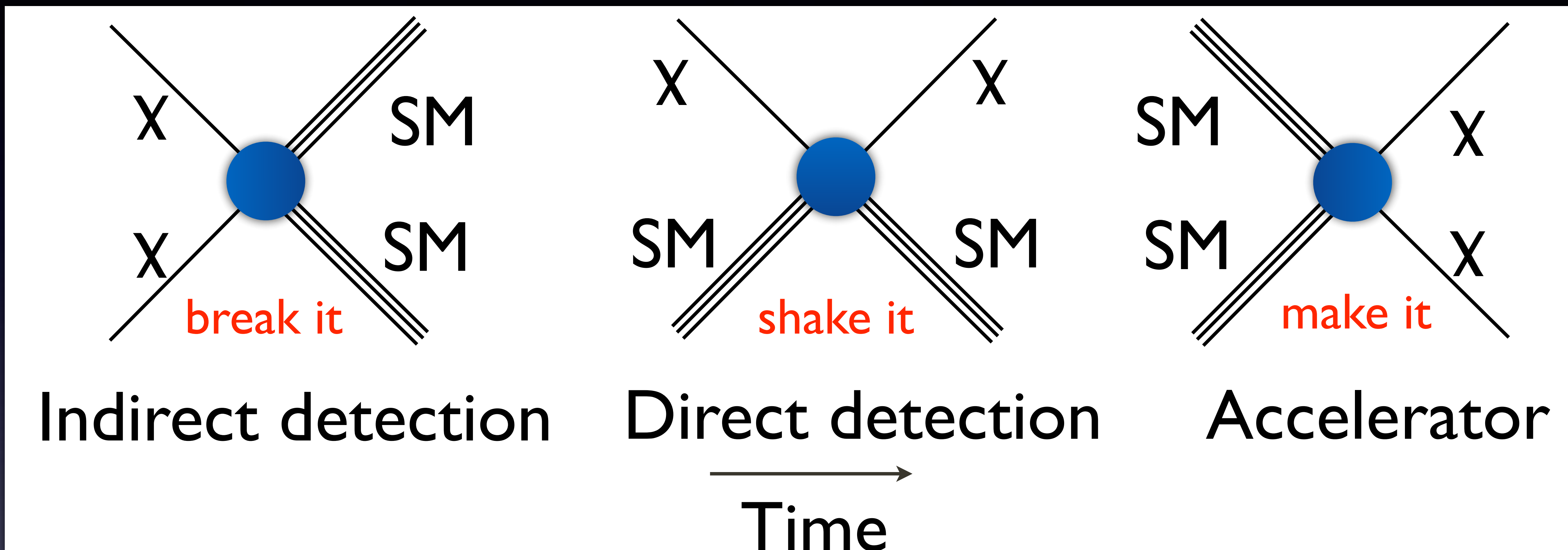

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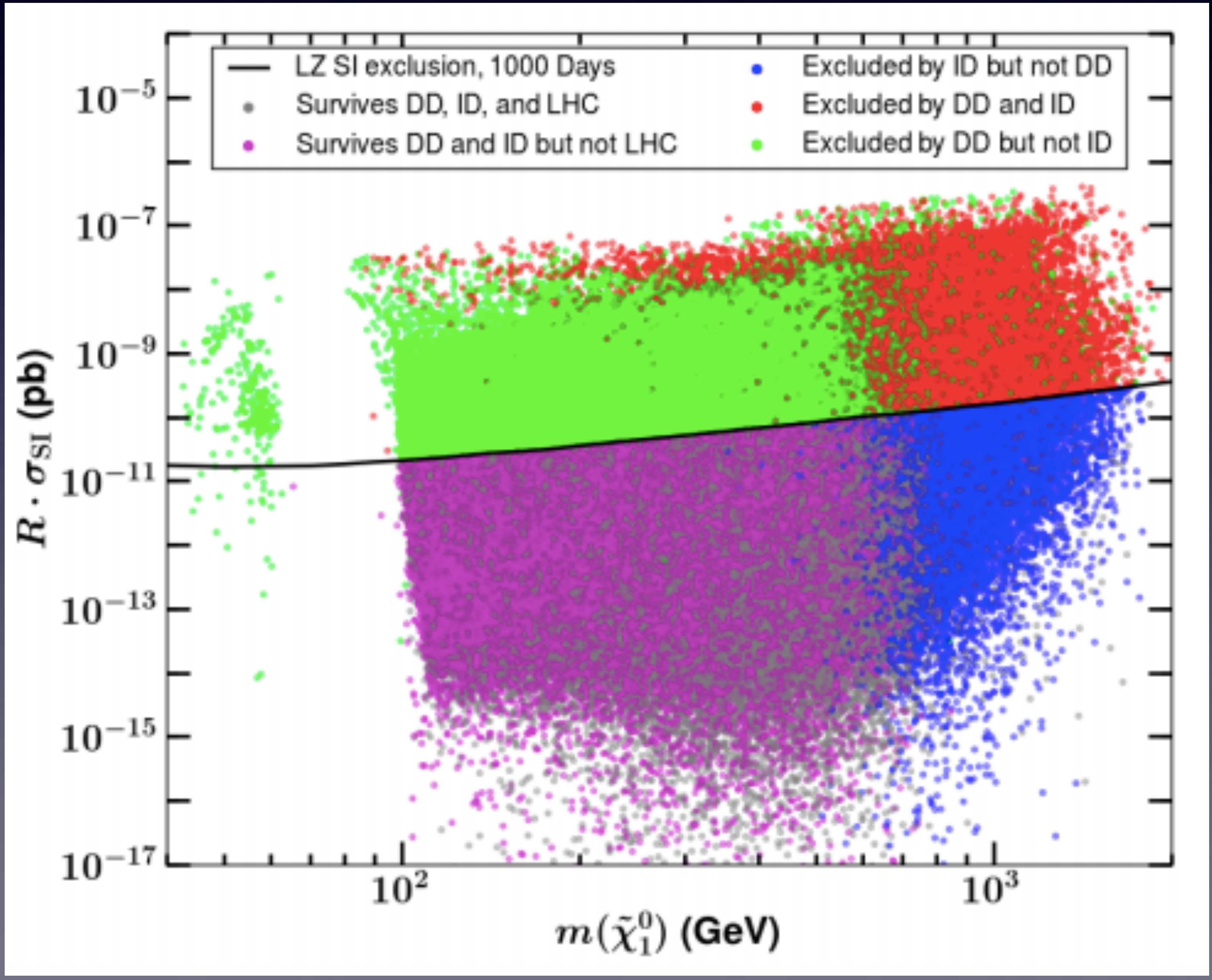
Complementarity in WIMP searches

- Example using the pMSSM, Cahill-Rowley et al '14
- Forecast limits for LZ (direct detection), CTA (indirect detection), 7-8 TeV LHC



Predictivity for thermal DM

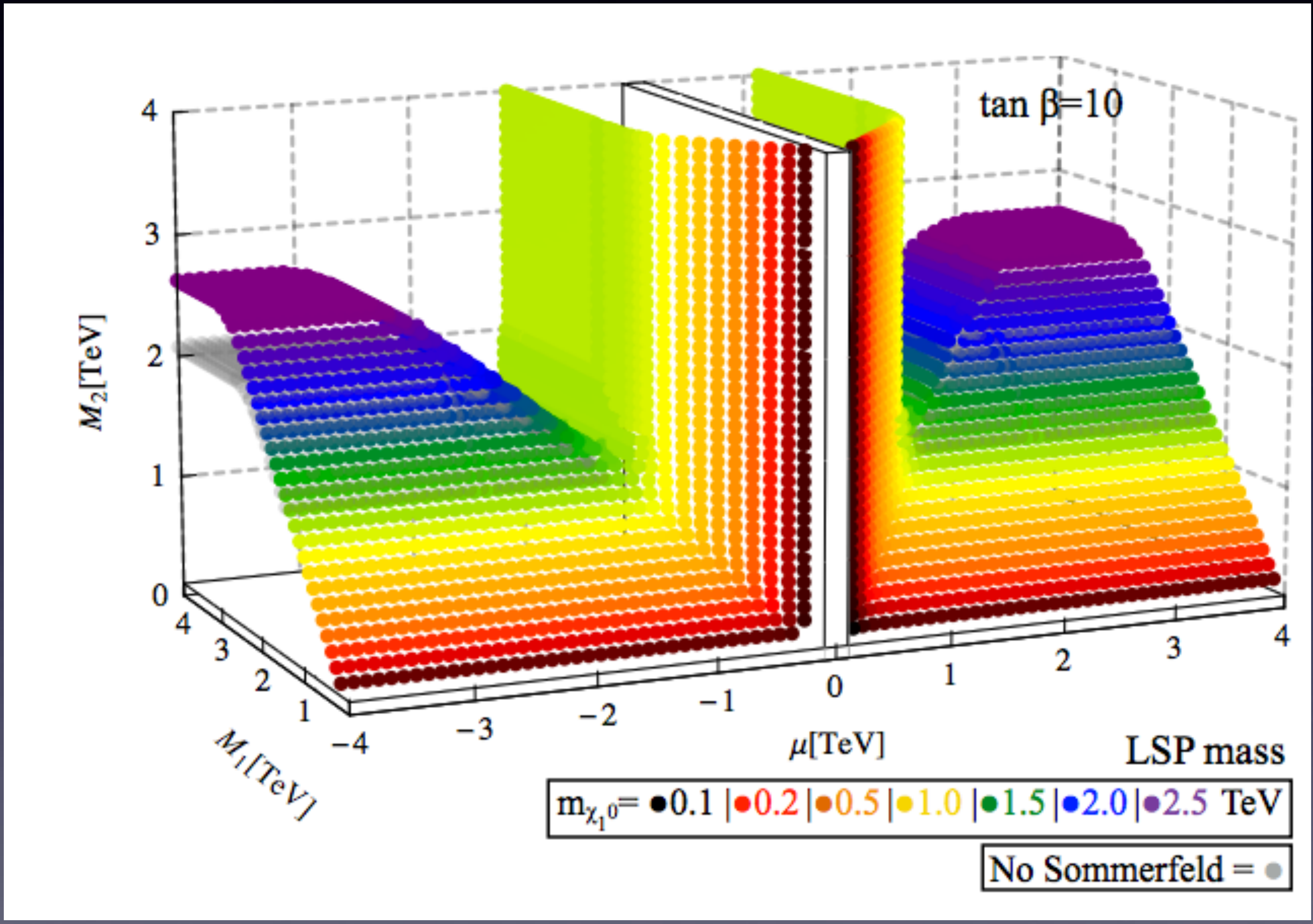
- In standard case, can immediately predict annihilation rate - "thermal relic benchmark" for <u>indirect</u> detection.
  - In simplest case (constant $\langle \sigma v \rangle$), can test DM masses below ~20 GeV, if annihilation is to any combination of visible channels [Leane, TRS et al '18].
  - Caveat: annihilation at freezeout may not be the same as in present day! e.g. because of suppression/enhancement at low velocities, or if annihilation at freezeout involves a non-DM particle that has decayed away at late times.
- In variations, abundance may be set by DM-SM scattering cross section (ELDER models [Kuflik et al '16]), or by freeze-<u>in</u> rather than freeze-out.
  - ELDER models make a robust prediction for <u>direct</u> detection.
- Within specific models for DM (complete or simplified), can relate DM abundance to signal strengths at the full range of experiments.

WIMPs under threat?

- No detection (yet) of new weak-scale physics at the LHC.
- No detection (yet) of WIMPs in direct or indirect dark matter searches - direct searches probing cross sections as small as 4×10^{-47} cm^2 [XENON1T Collaboration '18].
- Can we exclude thermal relic dark matter where:
  - The DM transforms under the gauge groups of the Standard Model, or
  - The DM simply has roughly weak-scale masses and couplings, potentially involving a new "mediator" particle?
  - The DM is much lighter than the standard "WIMP window", below the GeV scale, and has a thermal origin?

Example: the lightest SUSY neutralino

- In supersymmetric models, lightest superpartner (LSP) is stabilized by R-parity.
- Typically the LSP is the lightest neutralino - admixture of wino, bino, and higgsino.
- Plot shows "relic density surface" where correct relic density is obtained, in terms of neutralino mass parameters M_1, M_2, μ.
- Here all superpartners except neutralinos and charginos are assumed to be heavy and decouple.



Bramante et al '16

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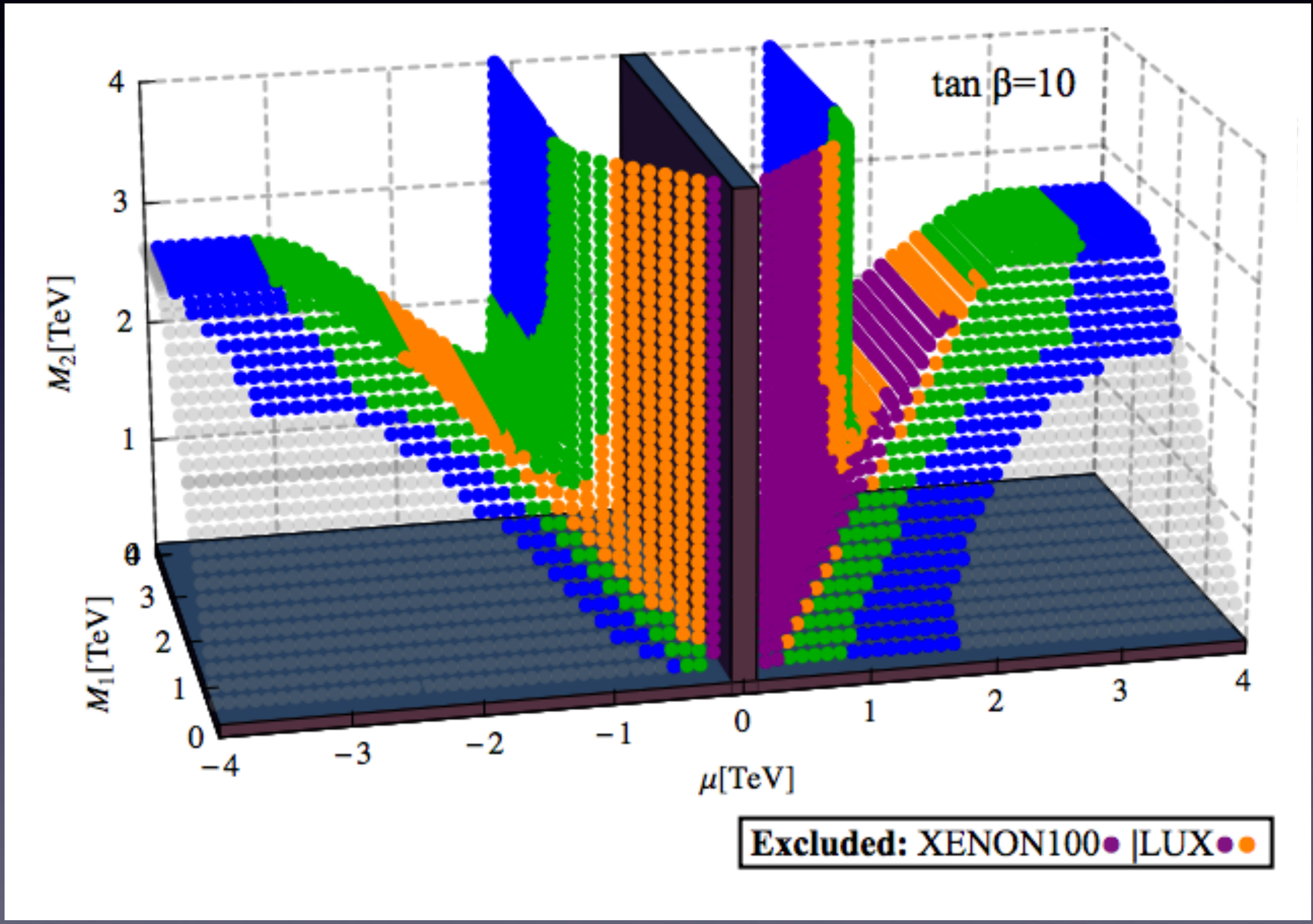
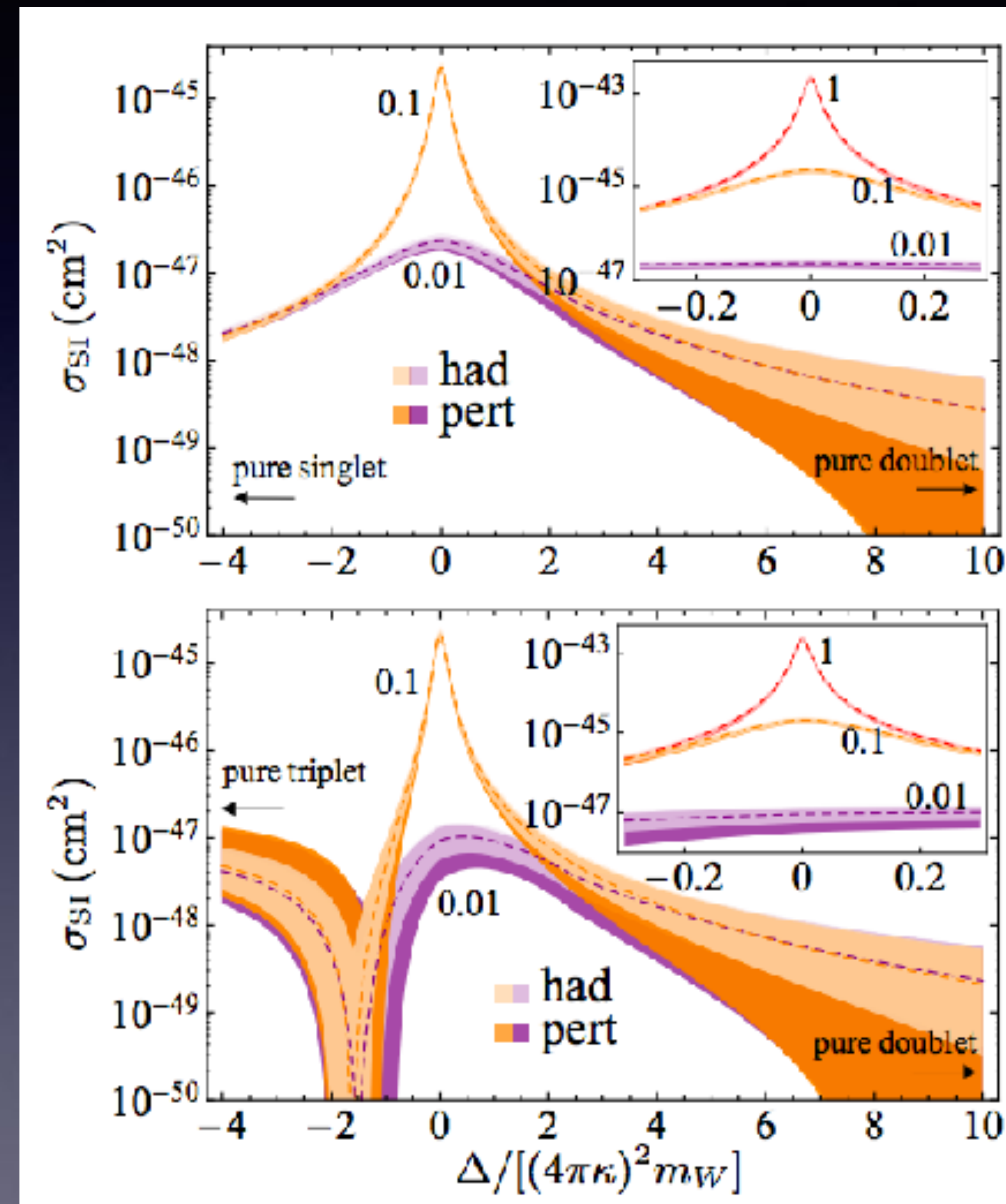


Bramante et al '16

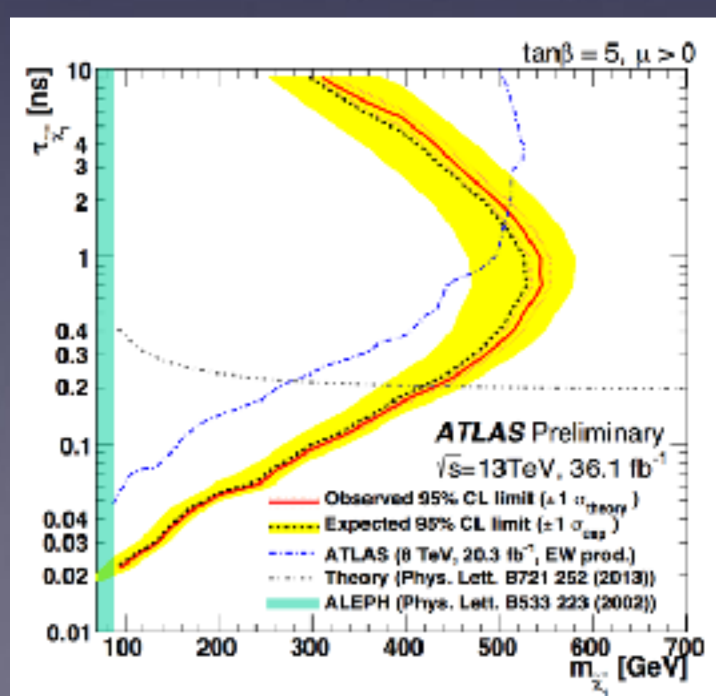
Example: the lightest SUSY neutralino

- Current set of constraints leaves open swathes of parameter space:
  - Pure higgsinos and winos, and much of bino-wino parameter space, still yield predicted DD signals below current limits.
  - Current collider limits on pure winos (higgsinos) only rule out masses below ~400 (~100) GeV [ATLAS-CONF-2017-017, Fukuda et al ’17].
  - Heavy winos can be probed by indirect detection, but limits depend on the DM density profile of the Milky Way [e.g. Baumgart, TRS et al ’17].

Hill & Solon ‘14



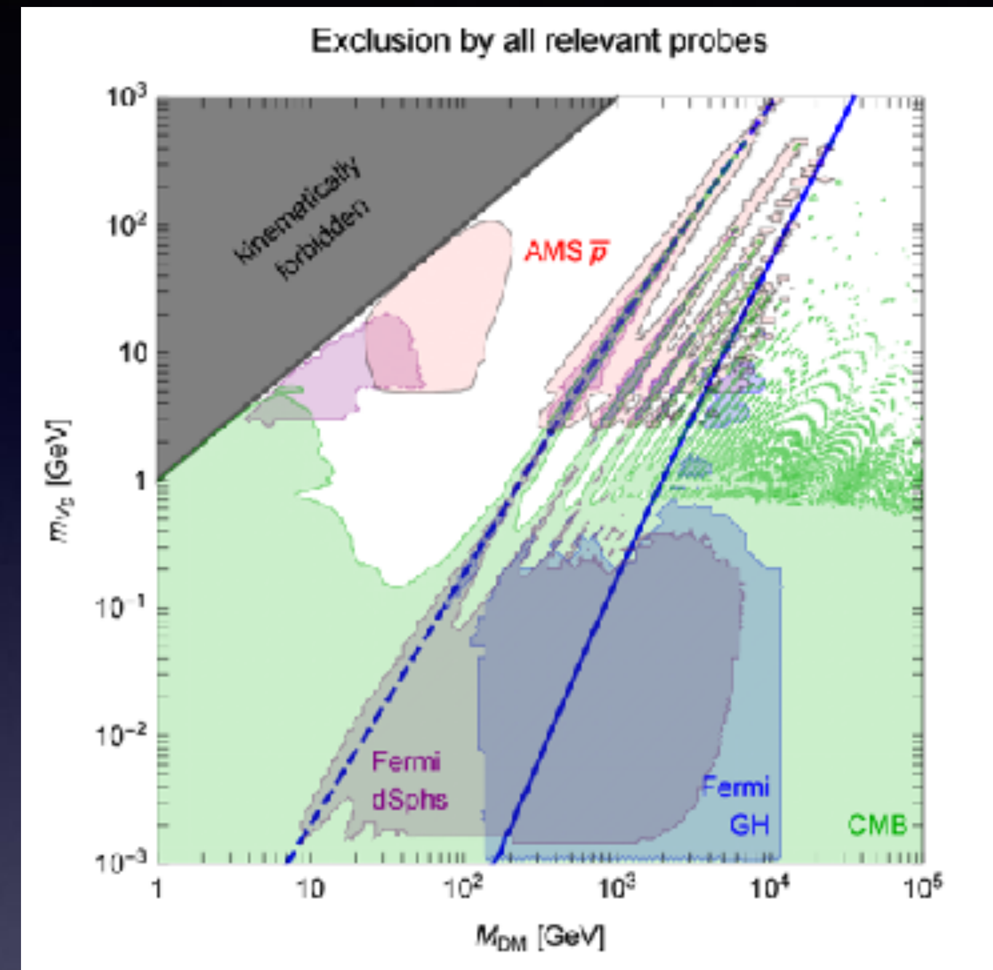
Predictions for direct detection of pure and mixed SU(2)$_L$ DM

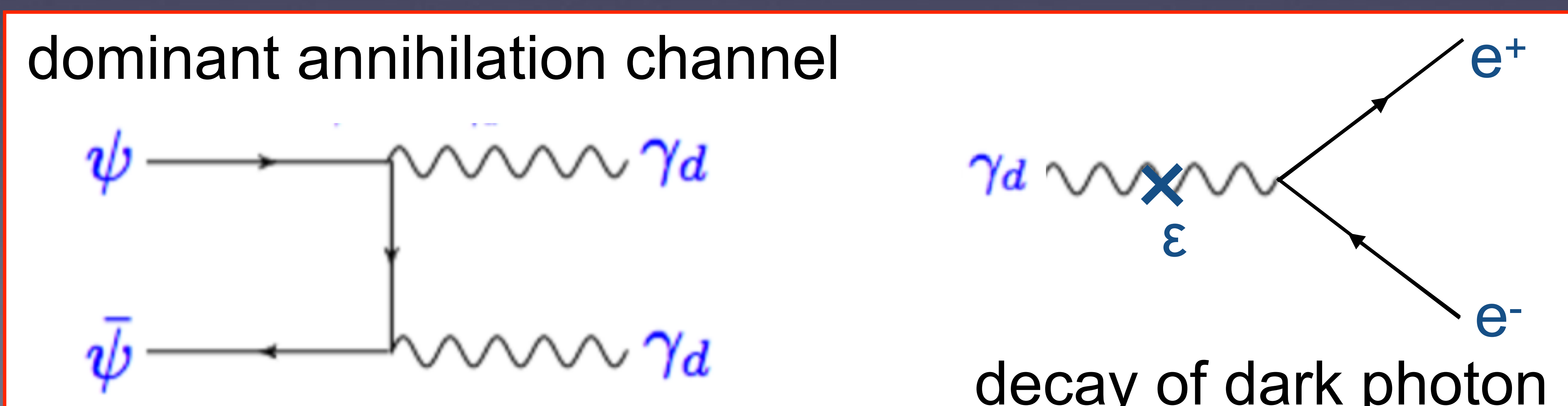


Limits on wino DM, ATLAS-CONF-2017-017

Example: dark vector portal

- Dark matter couples to dark photon which mixes slightly with Standard Model photon:
$$\mathcal{L}_{\mathrm{mix}} = \frac{\epsilon}{2} F^{\mu\nu} F^{D}_{\mu\nu}$$
- Direct and collider signatures are suppressed by small mixing.
- Relic density almost unaffected by small mixing if DM is heavier than dark photon.
- Can search with indirect detection, or by direct probes of the dark mediator - stringent limits for light dark photons and up to 100 TeV DM [Cirelli et al '17].





Dark matter models by mass

neutrinos

electrons

protons, neutrons

Higgs boson

~eV ~keV ~MeV ~GeV ~TeV ~100 TeV

generally nonthermal

bosonic

…

Down to 10^{-21} eV
Cold condensates

AXIONS

new "simple thermal relic" predictive window?

LIGHT DARK SECTORS

Traditional thermal window

WIMPS

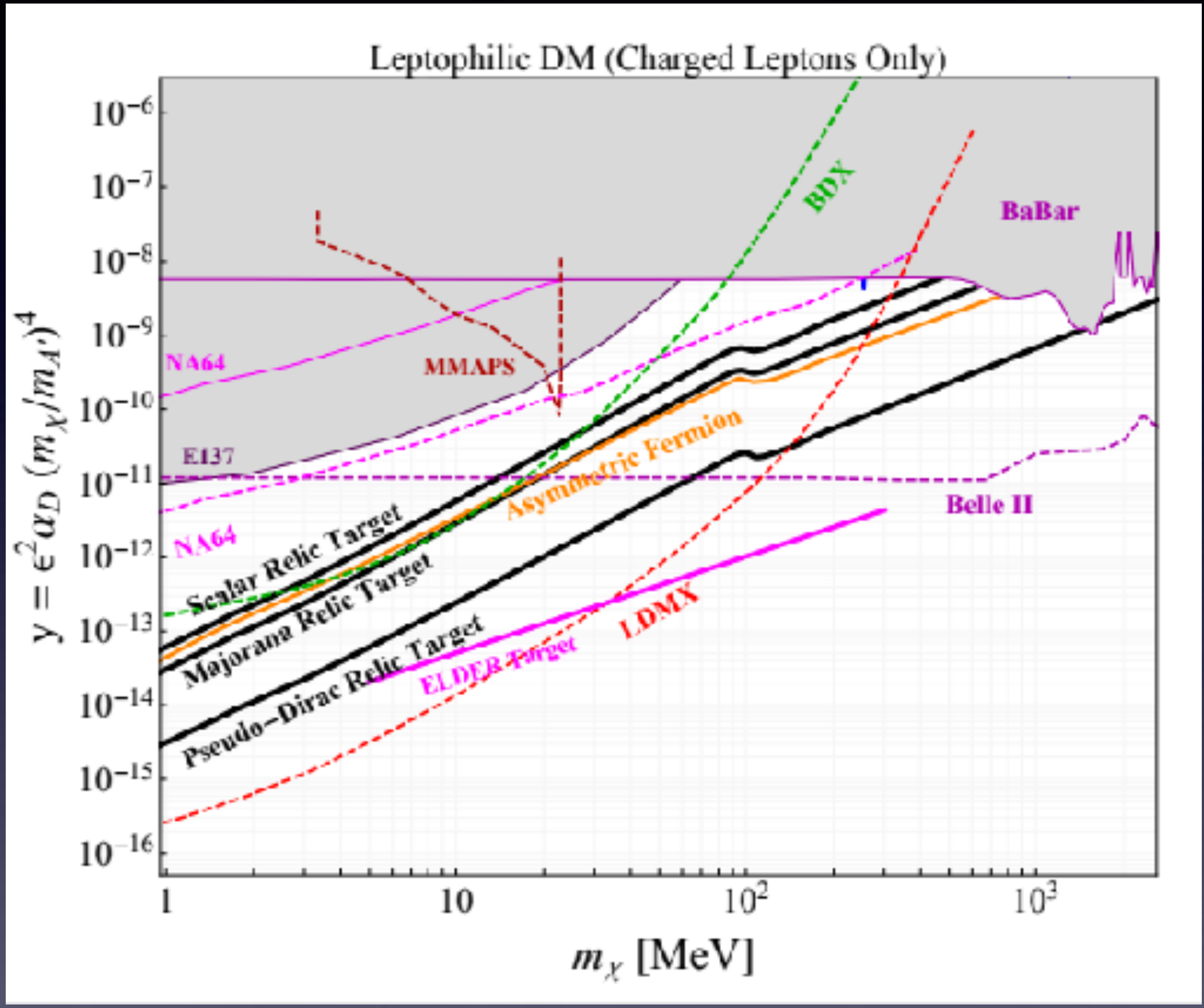
if thermal, generally not pointlike (unitarity)

…

$>10^{19}$ GeV
Primordial black holes?

The low-mass thermal region

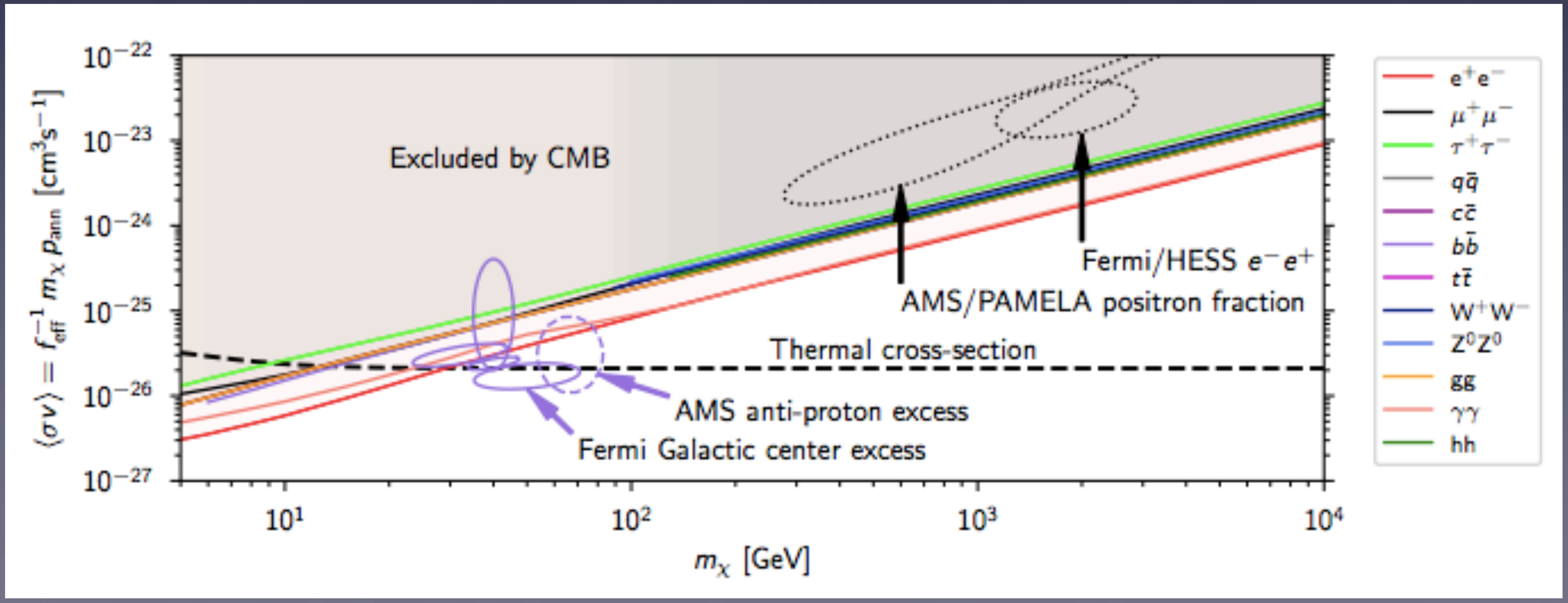
- Consider the sub-GeV mass range for DM with thermal freezeout.
- Traditional direct detection much more challenging here, due to energy thresholds - scattering off electrons (vs nuclei) can help.
- Consider simplified models of scalar/ Majorana fermion/pseudo-Dirac fermion DM, coupled to SM through light mediator (often a dark photon) - simple “dark sector”.
- Fix coupling to annihilation products via thermal relic calculation,
  - if DM directly coupled to Standard Model, allows well-defined thermal relic targets for different simplified models,
  - if DM annihilates within dark sector, search for mediators between dark and visible sectors, invisible decays, etc.
- re-examine complementarity between direct/ indirect/accelerator searches.



Example for thermal relic DM annihilating through a leptophilic mediator
Battaglieri et al ’17, Cosmic Visions report

Challenges for light thermal dark matter

- Many new ideas for experimental dark matter searches in the keV-GeV mass range - direct detection, beam dumps, fixed-target experiments, MeV-GeV gamma-ray telescopes, etc.
- But also many existing constraints! Most model-independent bounds on thermal relic annihilation rate come from indirect detection.
- Example: too large an annihilation rate producing photons/electrons during the cosmic dark ages leads to extra ionization - perturbs the CMB
- Thermal annihilation cross section during this epoch is ruled out for DM masses below ~10 GeV, unless DM annihilates mostly/entirely to neutrinos. Favors models with suppressed annihilation at late times.



Planck Collaboration '18 1807.06209 based on results of TRS '16

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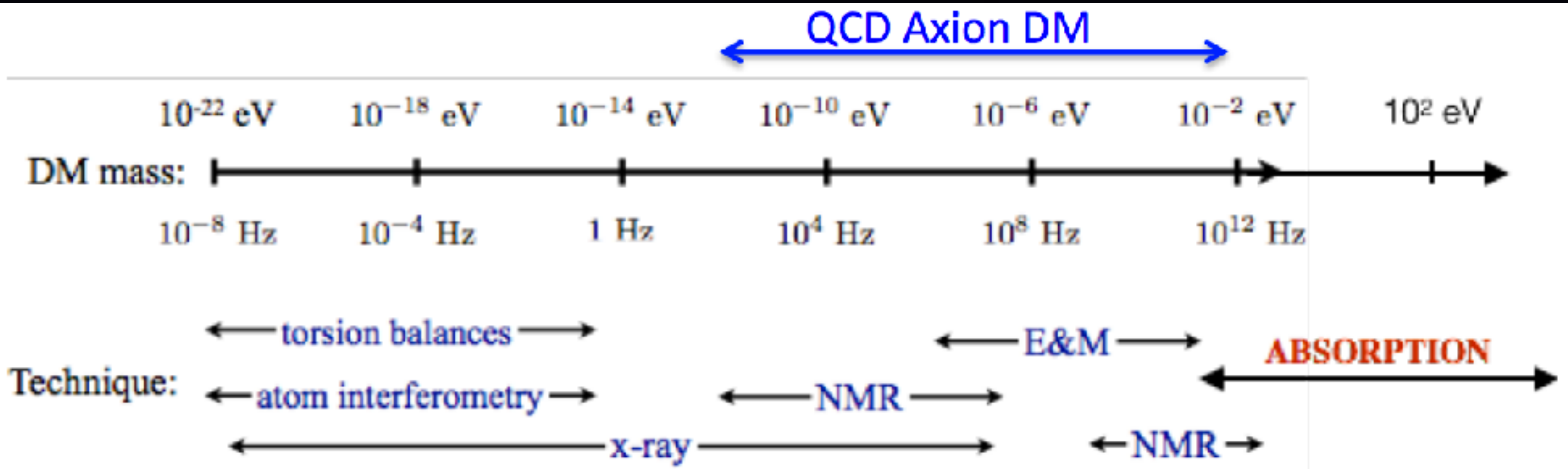
Light bosonic dark matter



Cosmic Visions '17

- Two main parameter regions for sub-keV bosonic dark matter
  - meV-keV: DM can be absorbed onto target electrons in semiconductors or superconductors via phonon emission [Hochberg, Lin & Zurek '16-'17, Bloch et al '16]
  - 10^{-21} eV - meV: DM can be regarded as a coherently oscillating classical field, opens up a range of new detection methods targeting continuous wave signals (rather than individual particles).

Classic example: QCD axion

- The Standard Model Lagrangian, describing all known particle interactions, in principle should have a term of the form:

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$ gluon field strength

- A term like this can be generated by CP violation elsewhere in the Standard Model, in the terms describing the quarks - no reason for it to vanish.

- But this term induces a neutron electric dipole moment:

$$d_n = 5.2 \times 10^{-16} \mathrm{e\,cm}$$

- Experimentally, we know that:

$$d_n < 3 \times 10^{-26} \mathrm{e\,cm} \qquad \Rightarrow \theta \lesssim 10^{-10}$$

- Why is this value so small?

The axion proposal

- Replace the parameter θ by a dynamical field, call it (by convention) a/f_a where a is the field and $1/f_a$ a coupling.
- Now we just need to explain why a would evolve toward a very small value.
- But the energy stored in this field depends on the value of a - potential energy changes as a evolves.
- We can work out this effective potential (I won't give the calculation here - see e.g. Dine's TASI lectures hep-ph/0011376 for much more detail on the strong CP problem) and find:

$$V(a) = -m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \cos(a/f_a)$$

$$f_\pi \approx 93\mathrm{MeV}$$

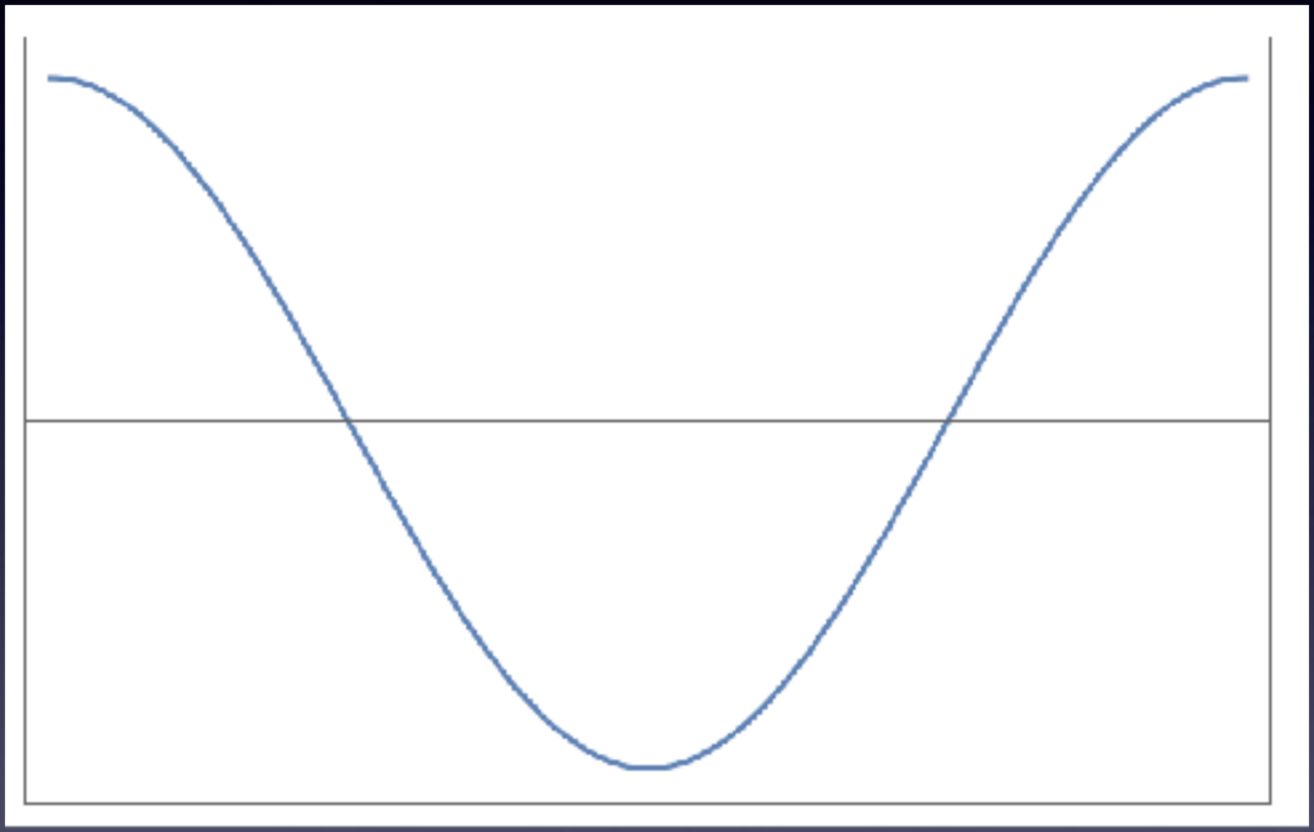
pion decay constant

$$m_\pi \approx 135\mathrm{MeV}$$

pion mass

The axion potential

- Field should evolve toward small values of this potential.
- Minima occur at $a/f_a = 2n\pi$; let's look at n=0.
- The potential is parabolic - coefficient of a^2 term gives axion mass.



$$V(a) = m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + \frac{1}{2} a^2 \left(\frac{f_\pi}{f_a}\right)^2 m_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + \mathcal{O}(a^4)$$

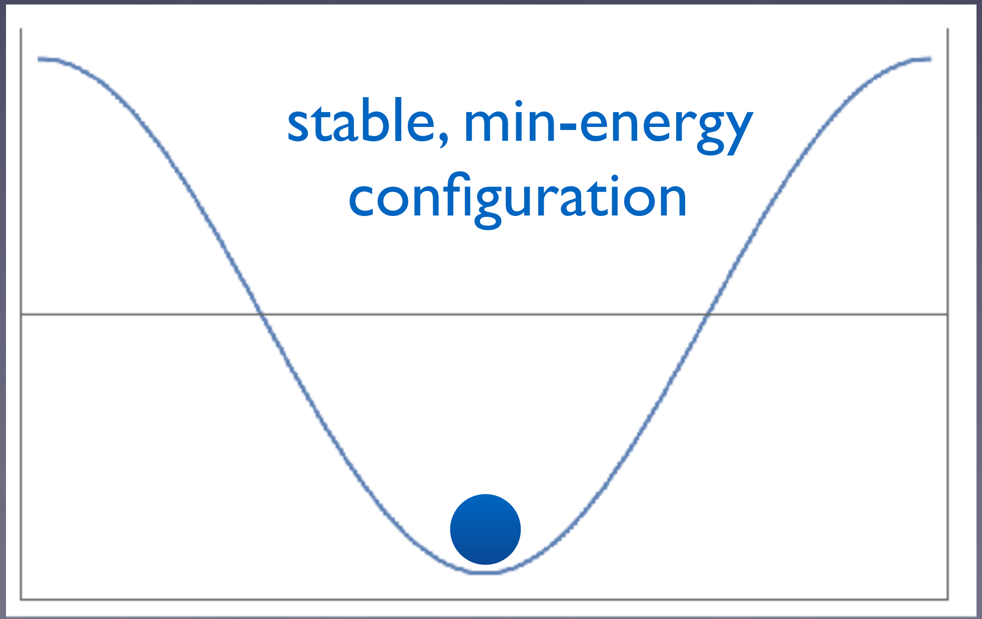
$$m_a = \frac{f_\pi m_\pi}{f_a} \left(\frac{m_u m_d}{(m_u + m_d)^2}\right)^{1/4} \approx 0.6\mathrm{meV} \left(\frac{10^{10}\mathrm{GeV}}{f_a}\right)$$

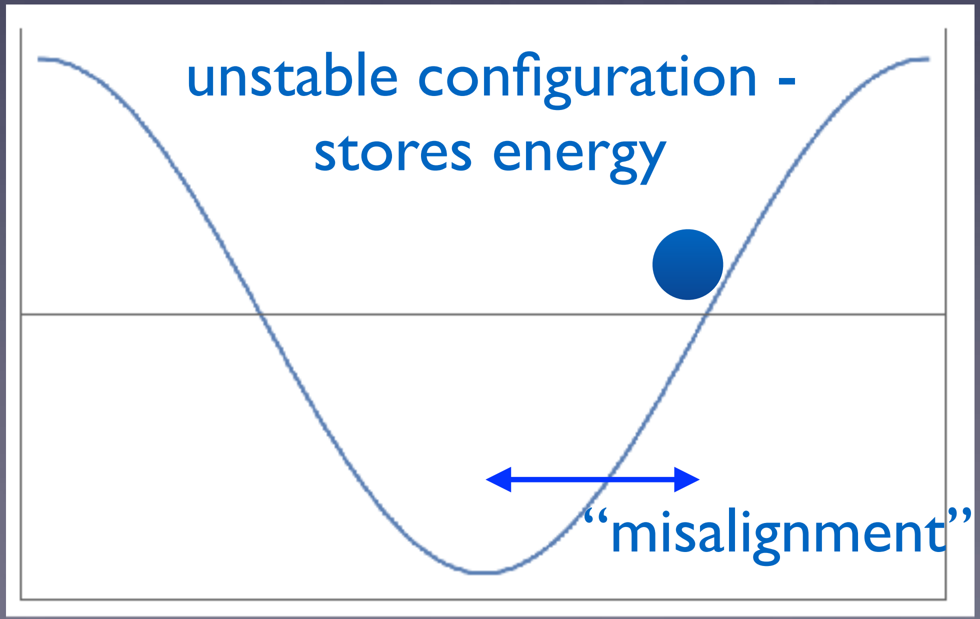
Axions as dark matter

- Strength of axion coupling to SM set by axion mass, light axions = weakly coupled
- Axions with mass > 20 eV decay rapidly, meV-20 eV axions thermalize and could be a hot DM subcomponent, $\Omega_{\rm axions} \sim \mathcal{O}\left(\frac{m_a}{100{\rm eV}}\right)$
- Lighter axions never thermalize, can act as cold DM - behavior dominated by bulk classical scalar field, evolving in potential, not excitations

Q: How does the field evolve?

A: If initially displaced from minimum of potential (by some "misalignment angle"), must "roll" toward that minimum





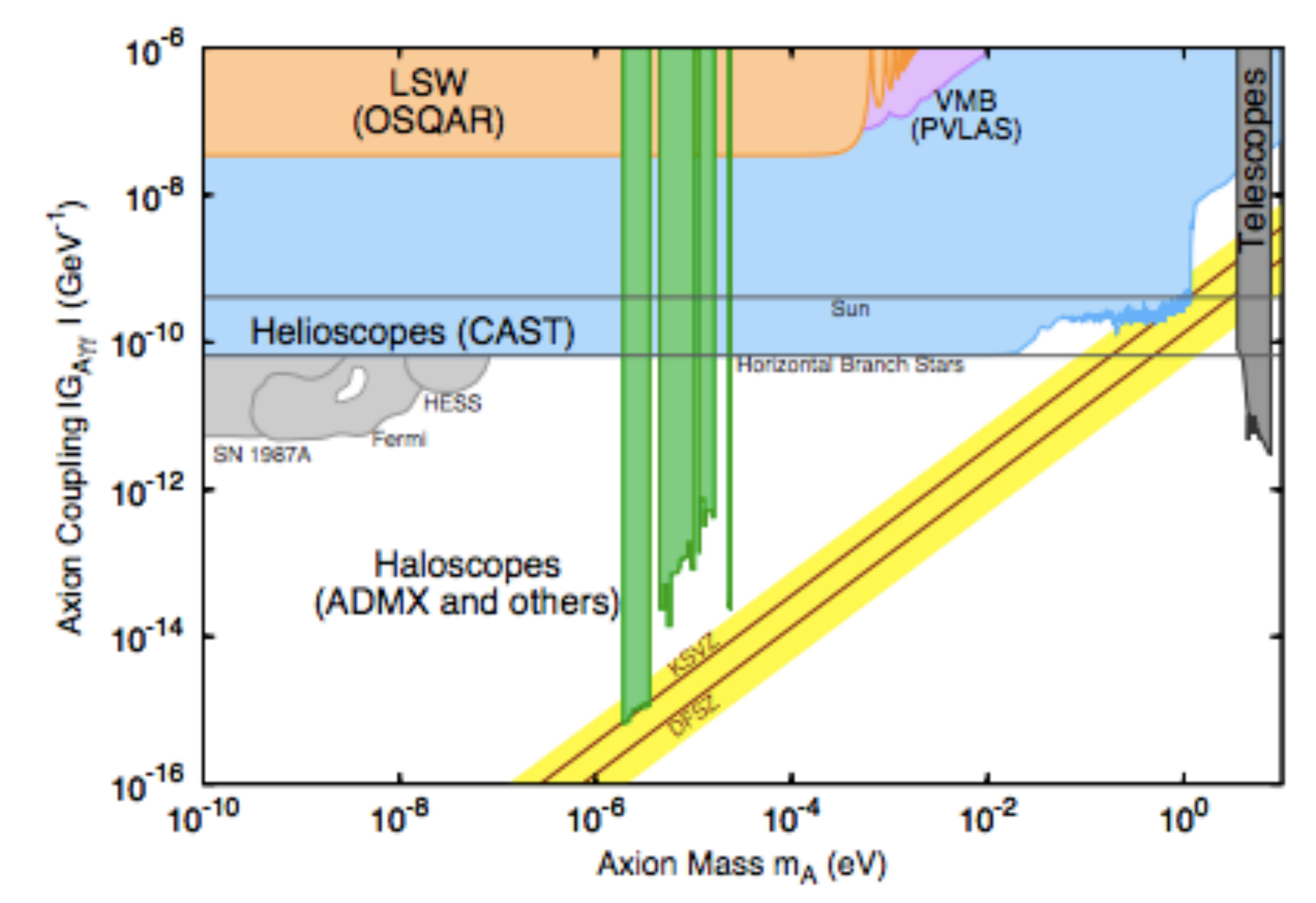
Axion density

- Axion density set by initial condition ("misalignment angle"),

$$\Omega_{\rm axions} \approx \Omega_{\rm DM}\Theta_0^2 \left(\frac{f_a}{5\times 10^{11}{\rm GeV}}\right)^{1.184}$$

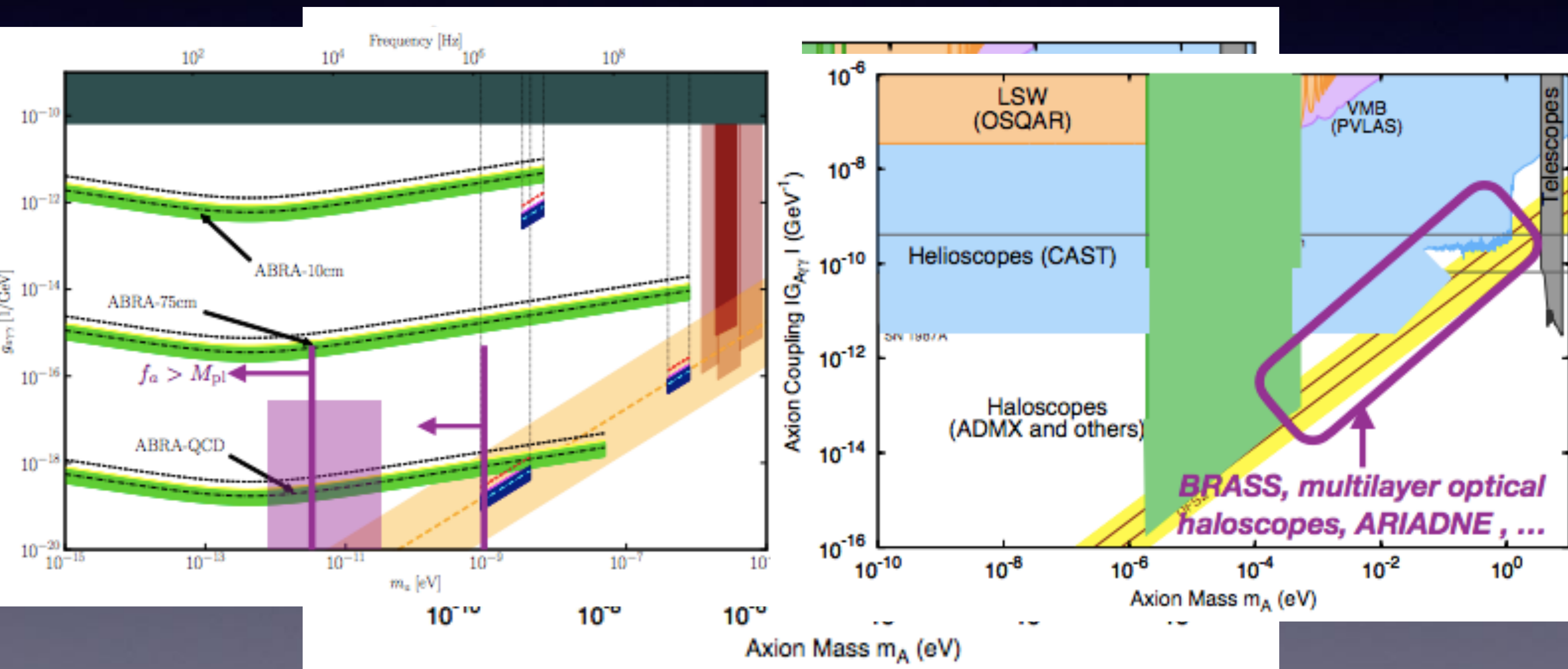
- Lighter axions = higher f_a = larger relic density, although relic density can always be reduced by small initial misalignment angle
- But if axions are produced / misalignment angle is set only after inflation, i.e. $H_I >> f_a$, different patches of cosmos likely have different misalignment angles - take average of random sample
- If misalignment angle is set (in patches) before inflation, each such patch gets blown up at inflation - everywhere in our Hubble volume should have same angle
  - "anthropic axion"?

Limits on axion(like) parameter space



Talk by Ben Safdi, IDM 2018

Limits on axion(like) parameter space



Talk by Ben Safdi, IDM 2018

Taking stock

- Huge diversity of reasonable models for dark matter - crucial to have a broad search strategy that probes many possibilities.
- Lightest massive particle we know: neutrino - DM could be 20 orders of magnitude lighter.
- Heaviest fundamental particle we know: top quark - DM could be 17 orders of magnitude heavier (or not even a particle!)
- There are many theoretical frameworks + creative experimental searches for interactions between dark matter and ordinary matter, for scenarios mapping out large parts of this range.
- What if DM doesn't interact with ordinary matter? We can also look at gravitational probes of DM, seek to improve our understanding of its distribution - could hold clues to DM microphysics.

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