Dark Matter

Tracy Slatyer

1st Workshop on High Energy Theory and Gender
CERN
27 September 2018

U.S. DEPARTMENT OF ENERGY | Office of Science

What is dark matter?

We know it:

What is dark matter?

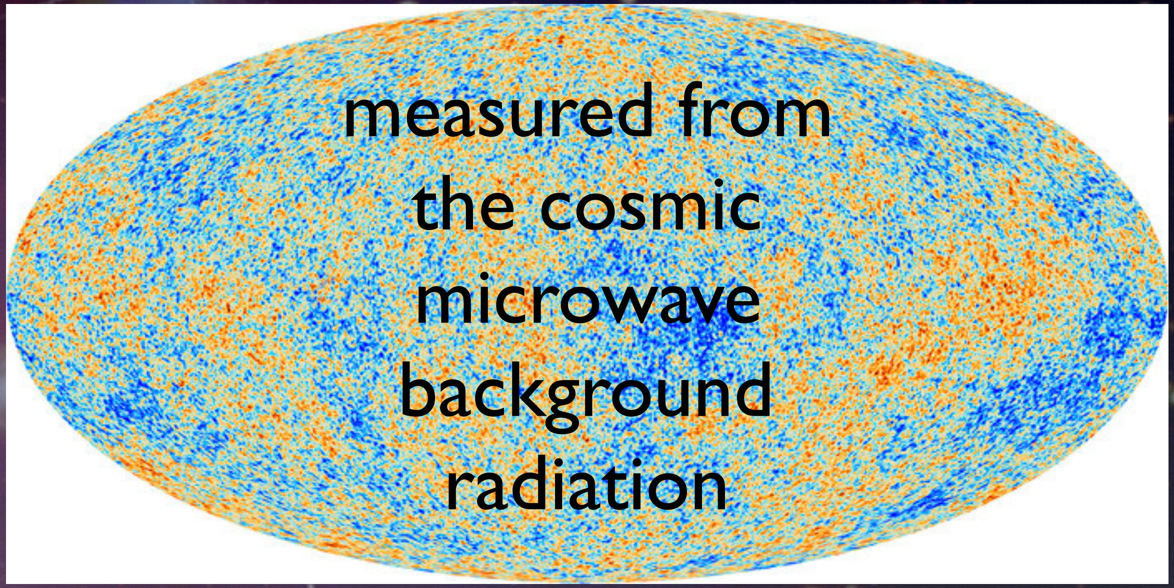
We know it:

- Doesn’t scatter/emit/absorb light (really “transparent matter”!) but does have mass (and hence gravity).

What is dark matter?

We know it:

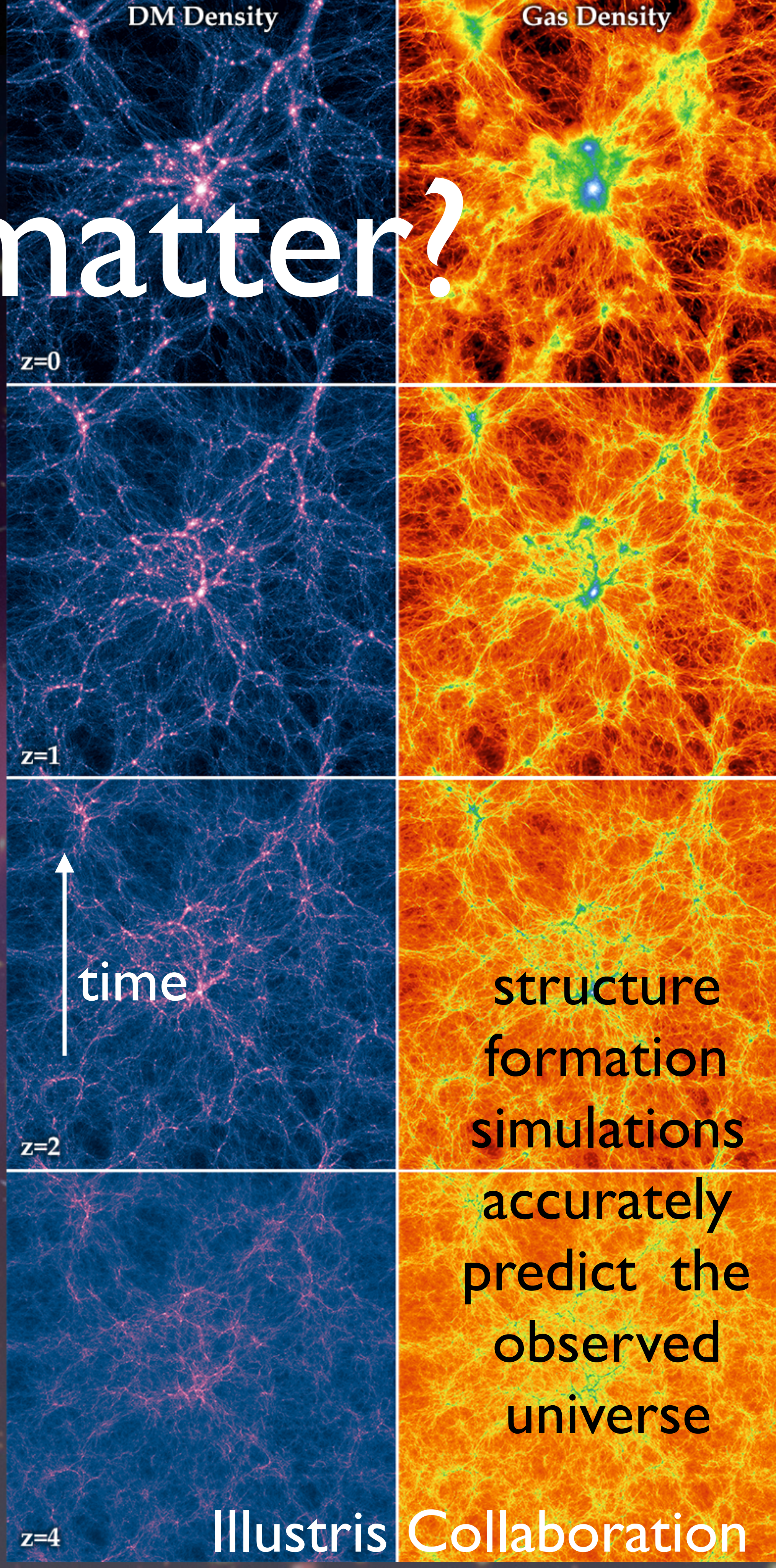
- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.



What is dark matter?

We know it:

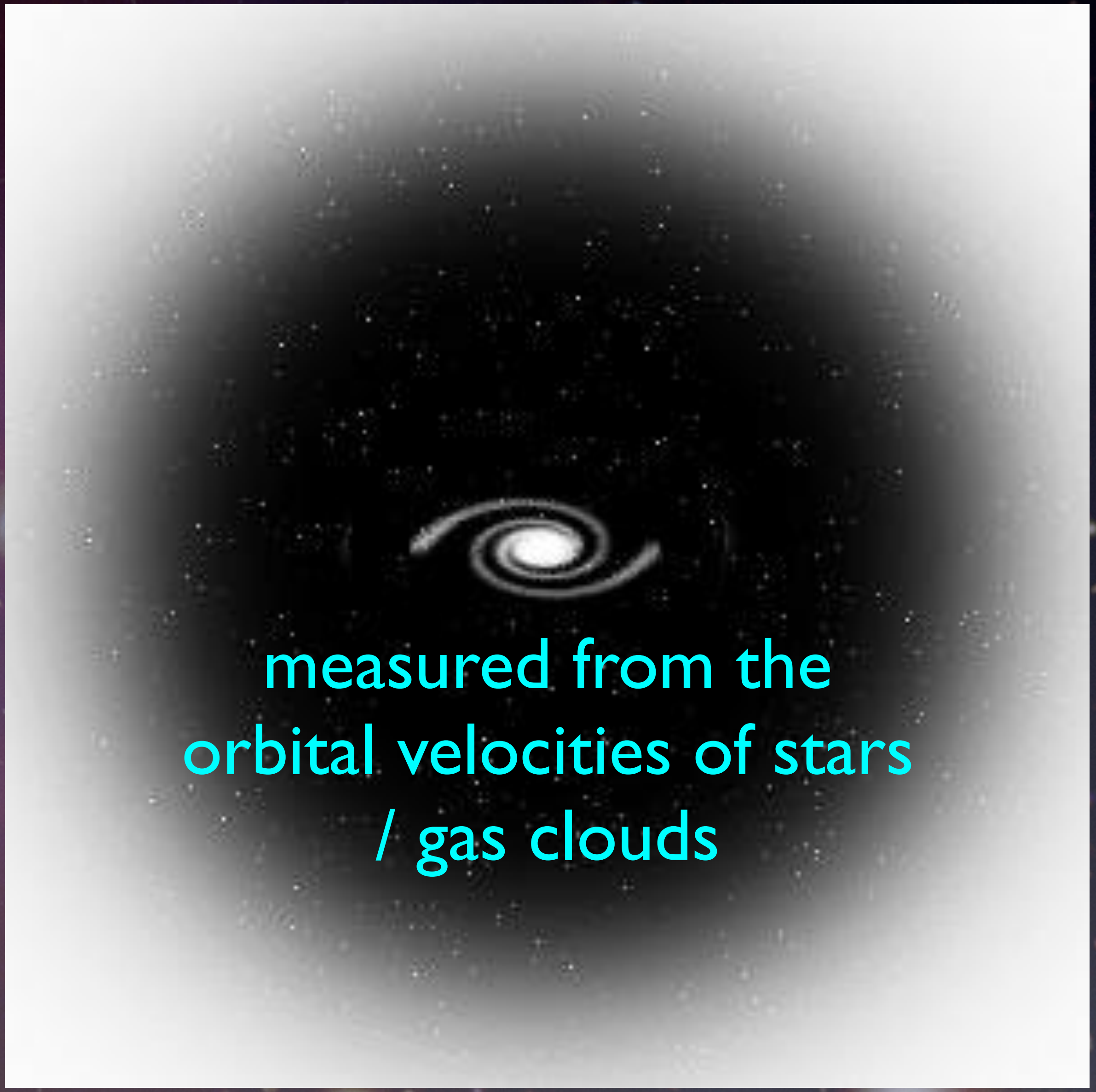
- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe, and consequently must be cold / slow-moving.



What is dark matter?

We know it:

- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe, and consequently must be cold / slow-moving.
- Forms large clouds or "halos" around galaxies.



What is dark matter?

We know it:

- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe, and consequently must be cold / slow-moving.
- Forms large clouds or "halos" around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches

What is dark matter?

We know it:

- Consequently, CANNOT be explained by any known particles

Open questions:

What is dark matter?

<u>We know it:</u>

- Consequently, CANNOT be explained by any known particles

<u>Open questions:</u>

- WHAT IS IT?

What is dark matter?

We know it:

- Consequently, CANNOT be explained by any known particles

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?

What is dark matter?

We know it:

- Consequently, CANNOT be explained by any known particles

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
- Where did it come from?

What is dark matter?

<u>We know it:</u>

- Consequently, CANNOT be explained by any known particles

<u>Open questions:</u>

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
- Where did it come from?
- Does it interact with ordinary particles? If so how?

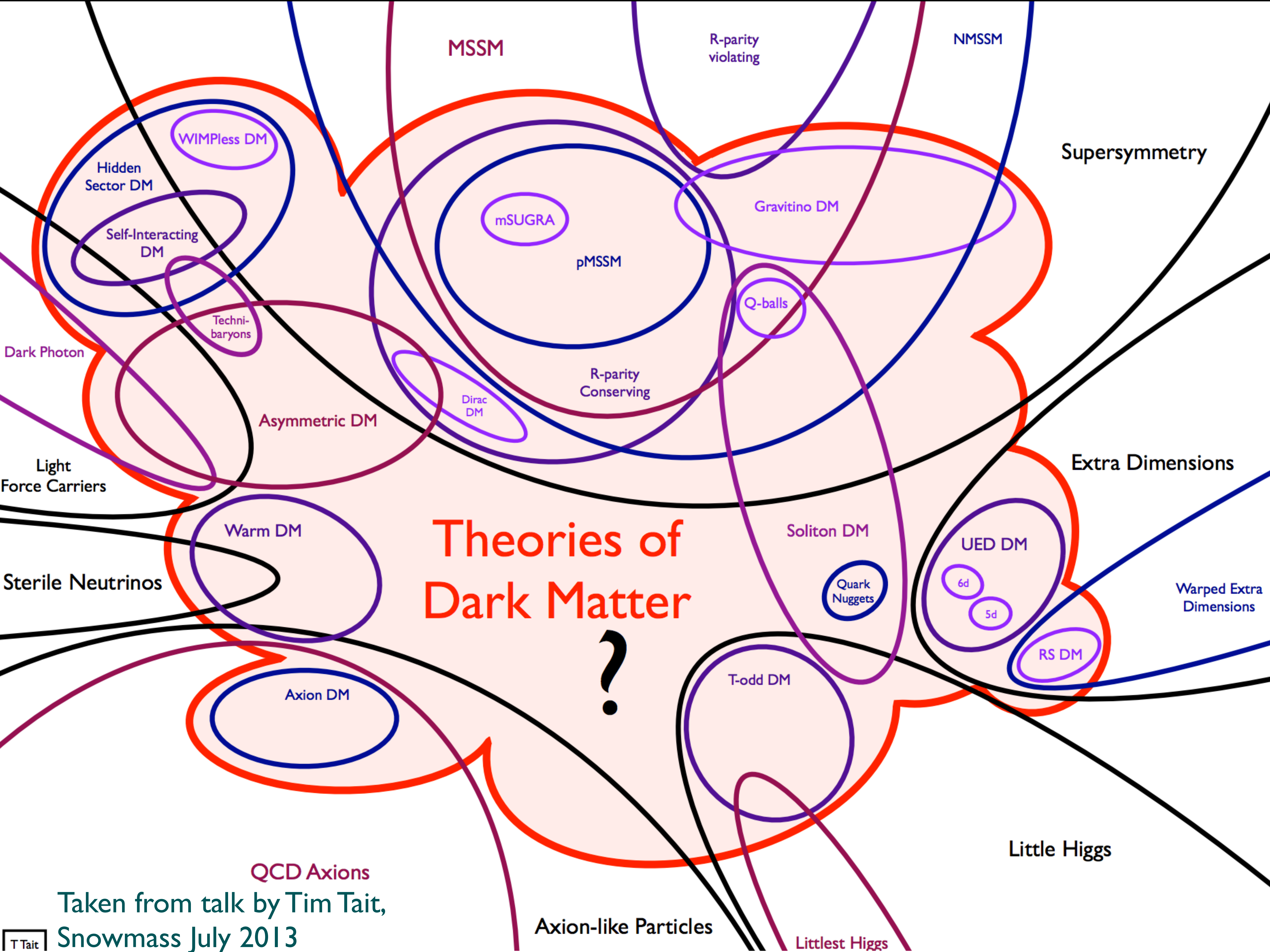
What is dark matter?

We know it:

- Consequently, CANNOT be explained by any known particles

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
- Where did it come from?
- Does it interact with ordinary particles? If so how?
- and many more…



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

Dark matter models by mass

neutrinos | electrons | protons, neutrons | Higgs boson

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

…

Down to 10^{-21} eV
Cold condensates

…

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

Dark matter models by mass

neutrinos

electrons

protons, neutrons

Higgs boson

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

bosonic

…

Down to 10^{-21} eV
Cold condensates

…

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

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

…

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

Dark matter models by mass

neutrinos

electrons

protons, neutrons

Higgs boson

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

generally nonthermal

bosonic

…

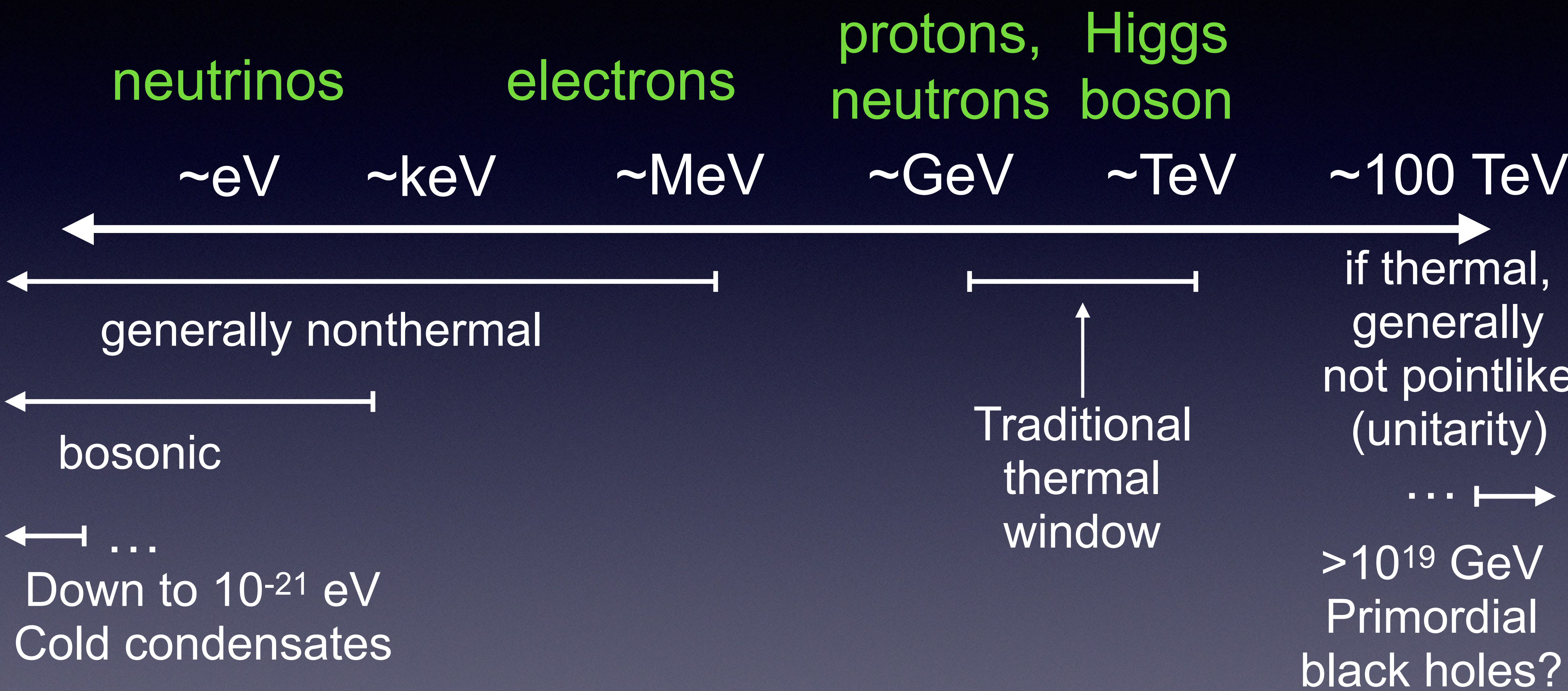
Down to 10^{-21} eV
Cold condensates

if thermal,
generally
not pointlike
(unitarity)

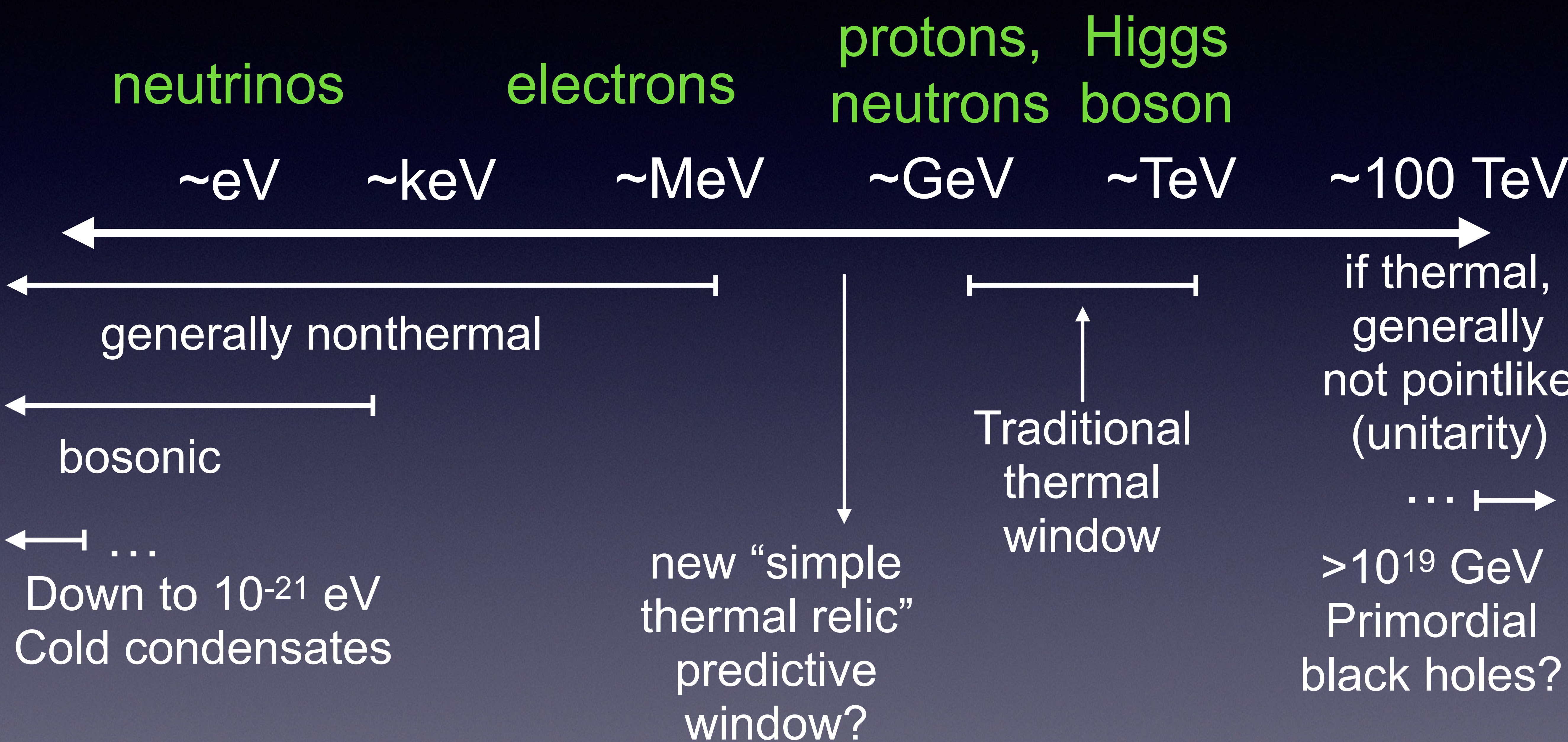
…

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

Dark matter models by mass



Dark matter models by mass



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?

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)

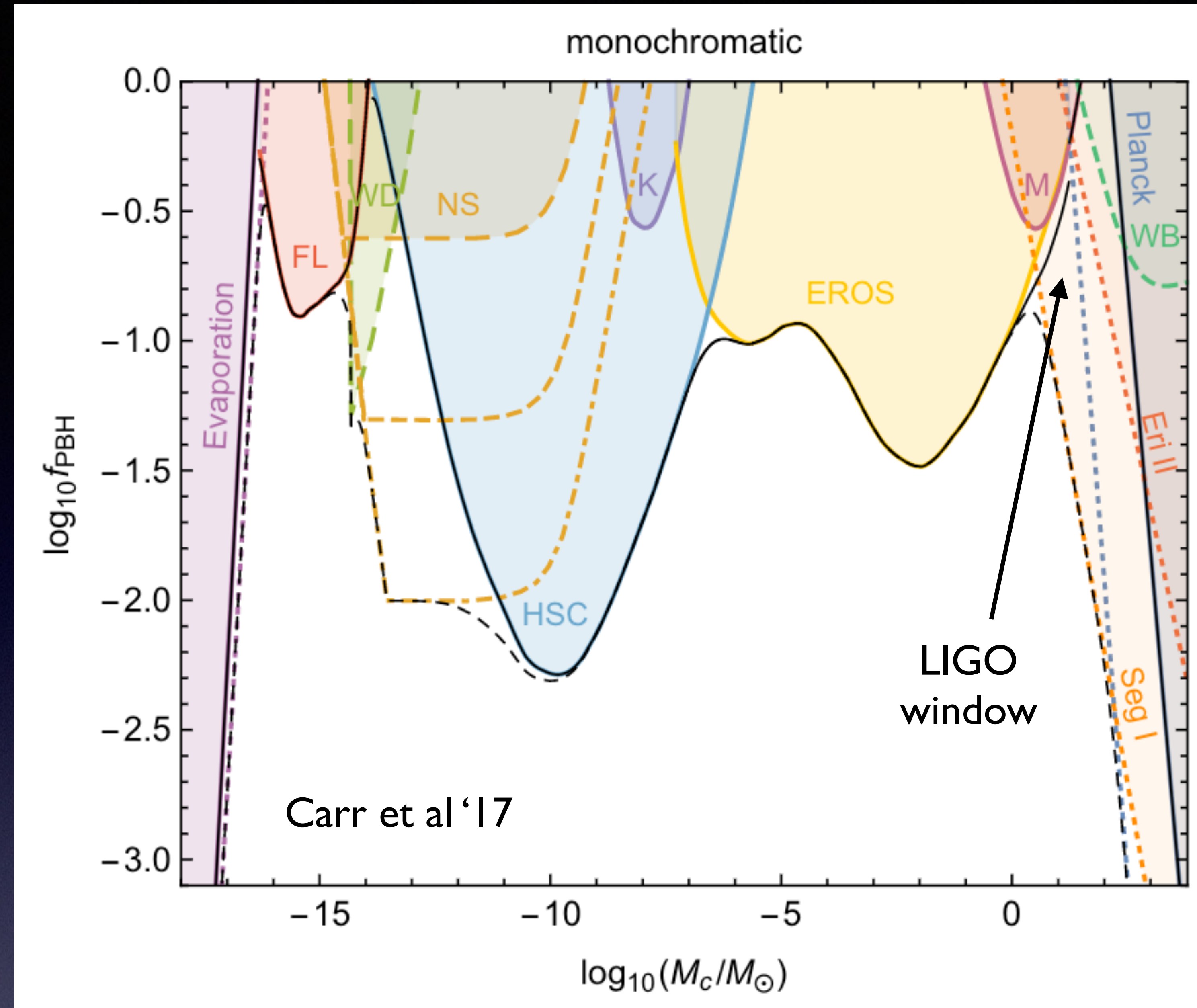
…

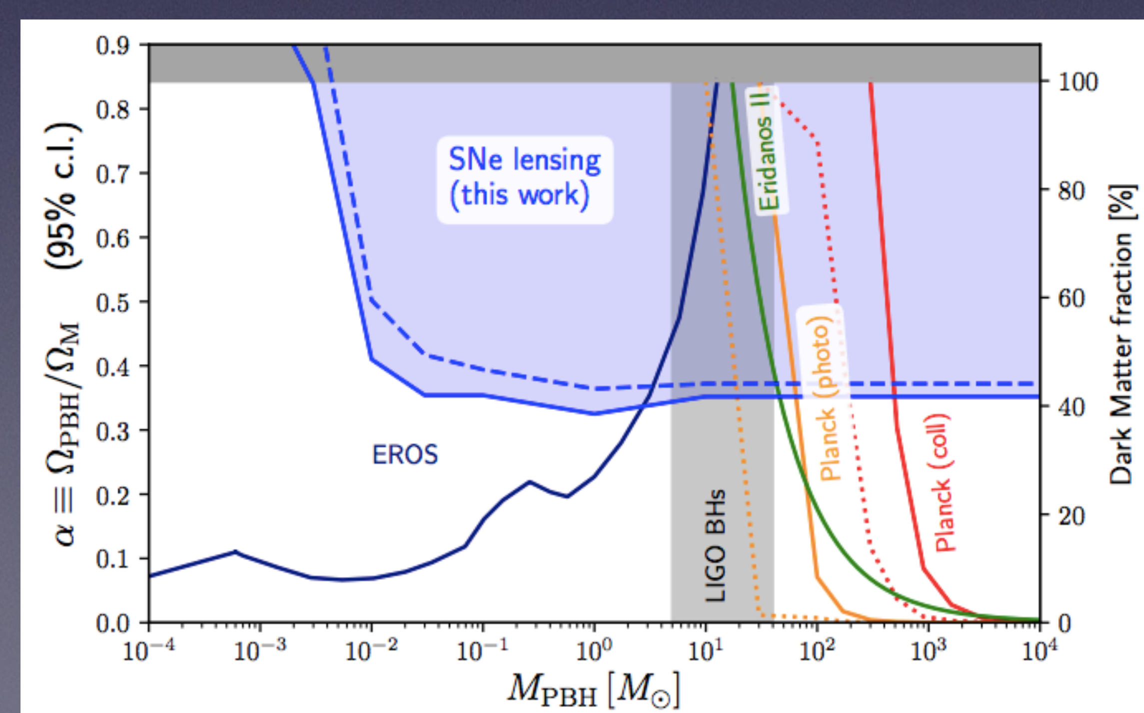
>10^{19} GeV
Primordial black holes?

MACHOs

(MAssive Compact Halo Objects)

- Dark matter could be composed of macroscopic objects, e.g. stars or black holes.
- Approximately 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, and very difficult to explain 100%.
- Production mechanism also an open research question.





Zumalacarregui & Seljak '18

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

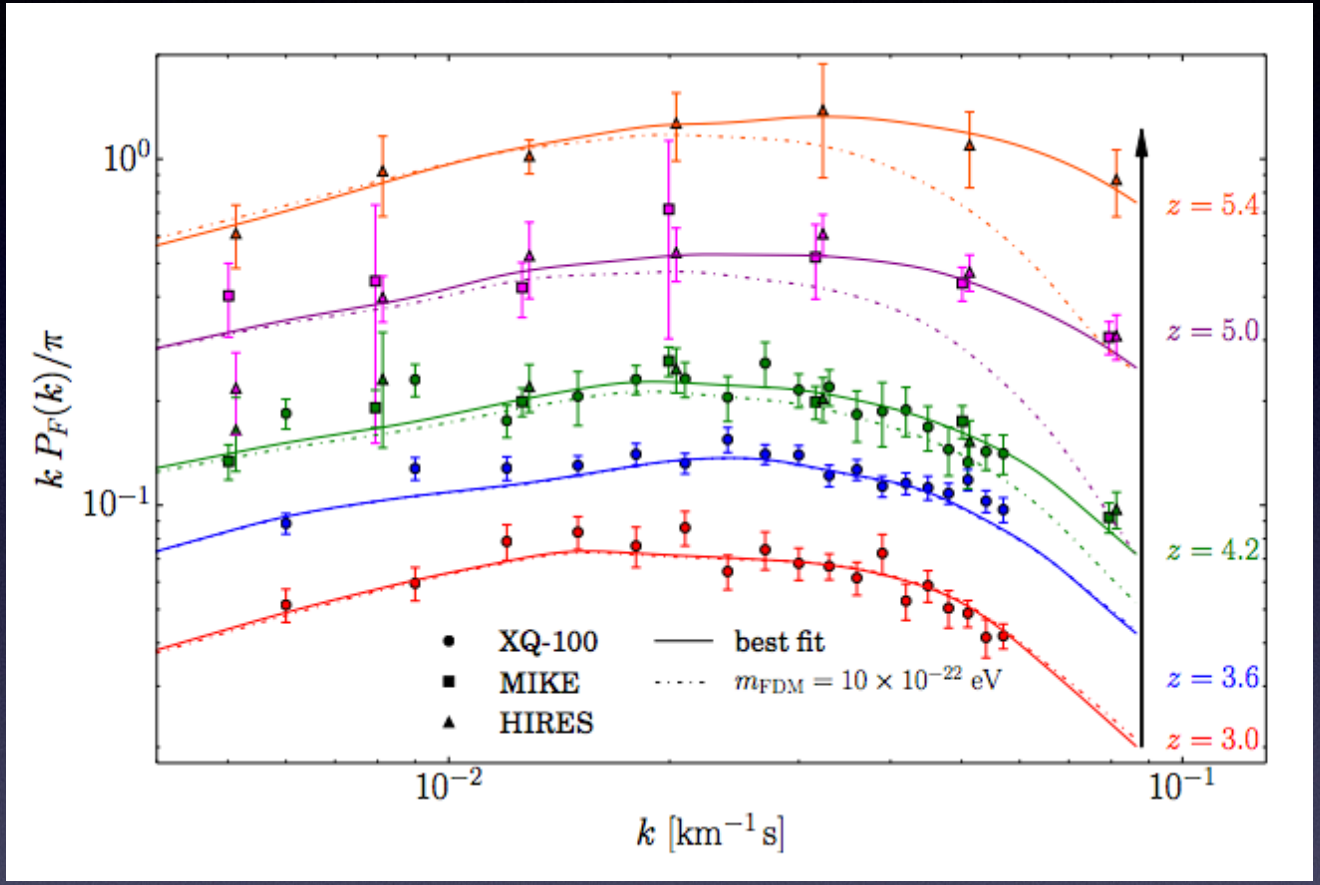
if thermal, generally not pointlike (unitarity)

…

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

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 (e.g. for fermionic DM the Pauli exclusion principle + observed dwarf galaxies requires mass > 400 eV).

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

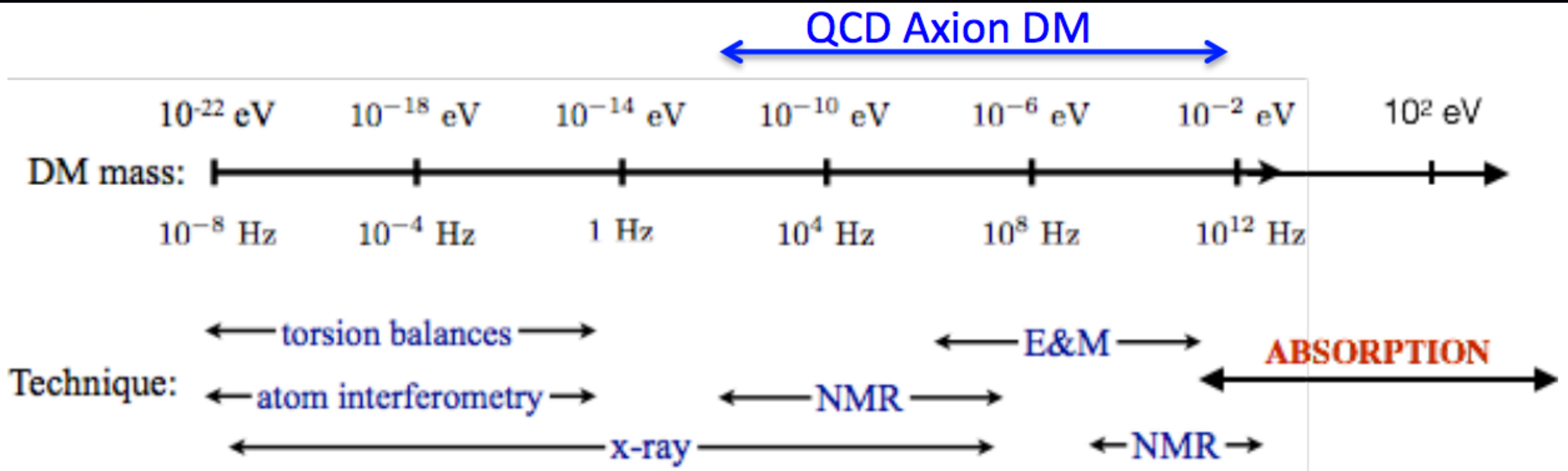
WIMPS

if thermal,
generally
not pointlike
(unitarity)

…

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

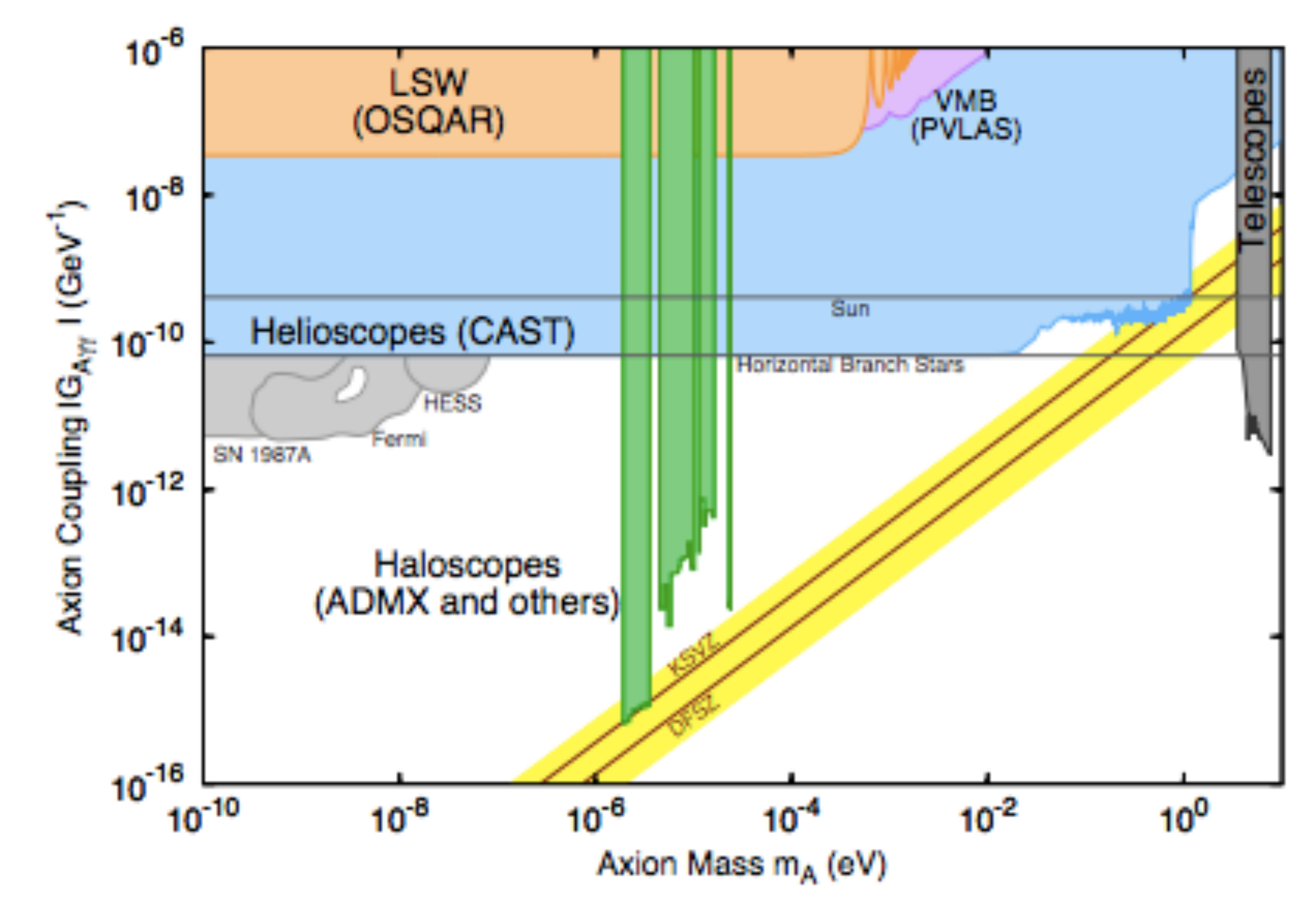
Light bosonic dark matter



Cosmic Visions '17

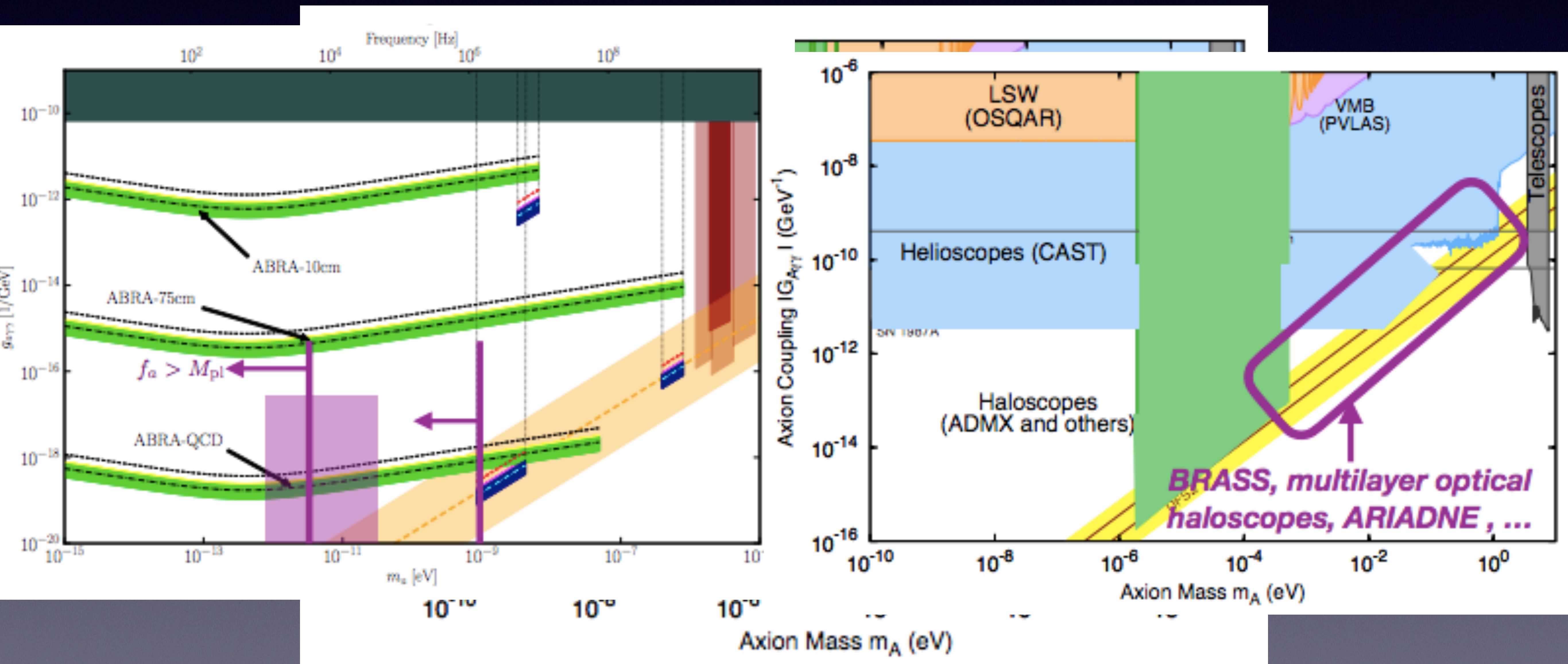
- Two main parameter regions for sub-keV bosonic dark matter
  - meV-keV: DM can be absorbed onto target electrons in semiconductors or superconductors via phonon emission [Hochberg, Lin & Zurek '16-'17, Bloch et al '16]
  - 10^{-21} eV - meV: DM can be regarded as a coherently oscillating classical field, opens up a range of new detection methods targeting continuous wave signals (rather than individual particles).
  - Classic example of this latter regime: axions/axion-like particles (ALPs), with tiny mass and tiny couplings. Never in thermal equilibrium with Standard Model - cold despite tiny mass.

Limits on axion(like) parameter space



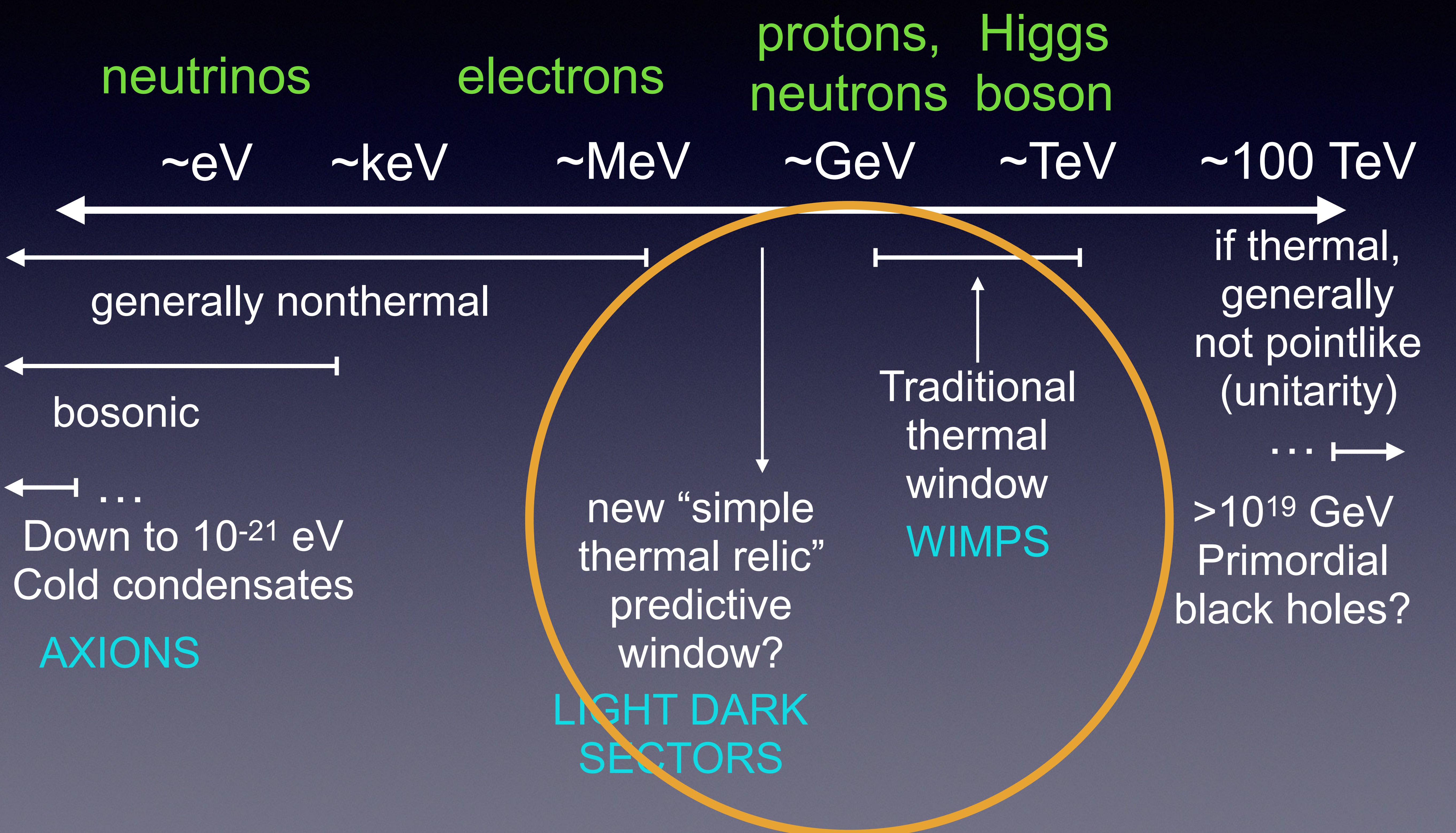
Talk by Ben Safdi, IDM 2018

Limits on axion(like) parameter space

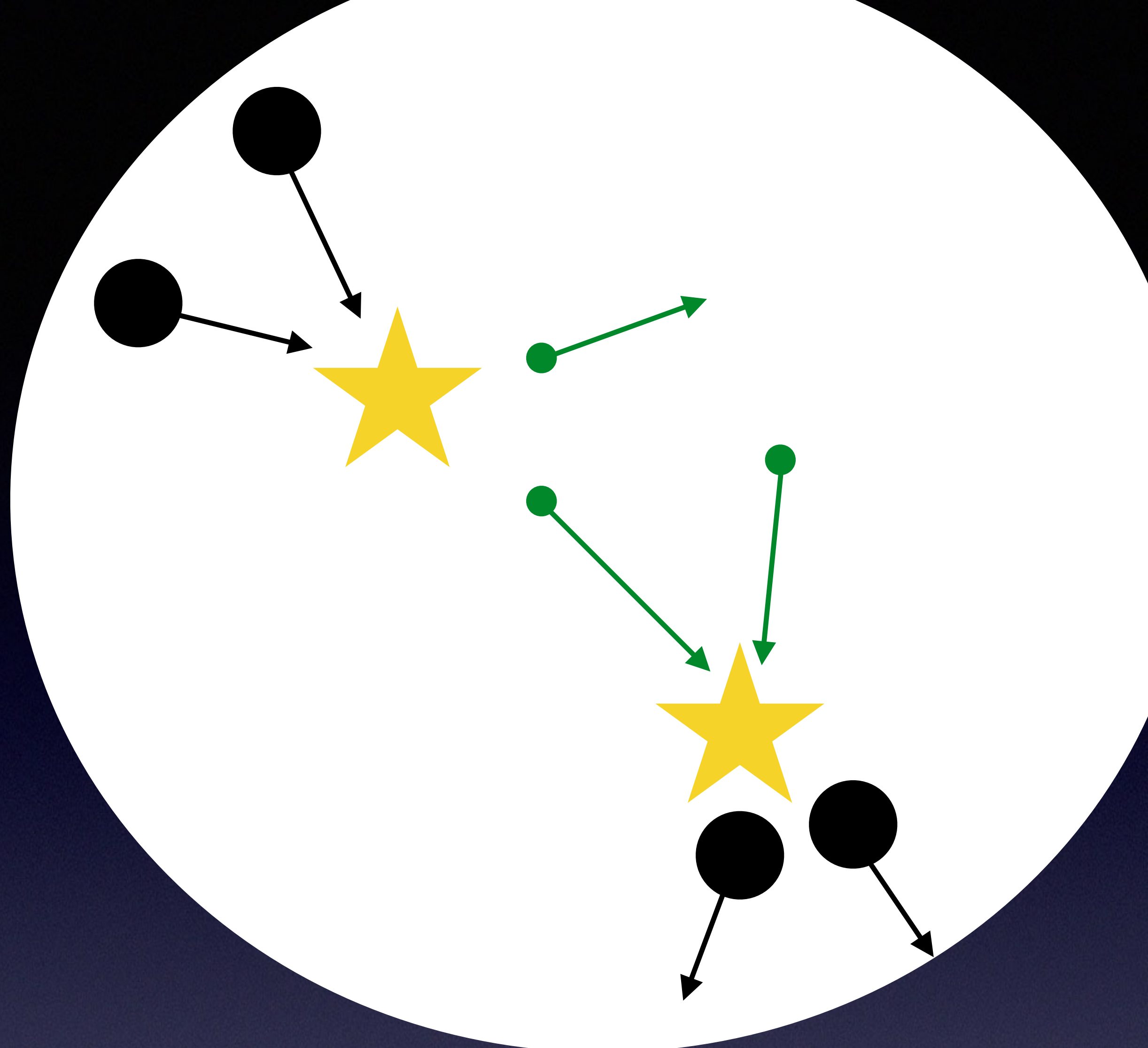


Talk by Ben Safdi, IDM 2018

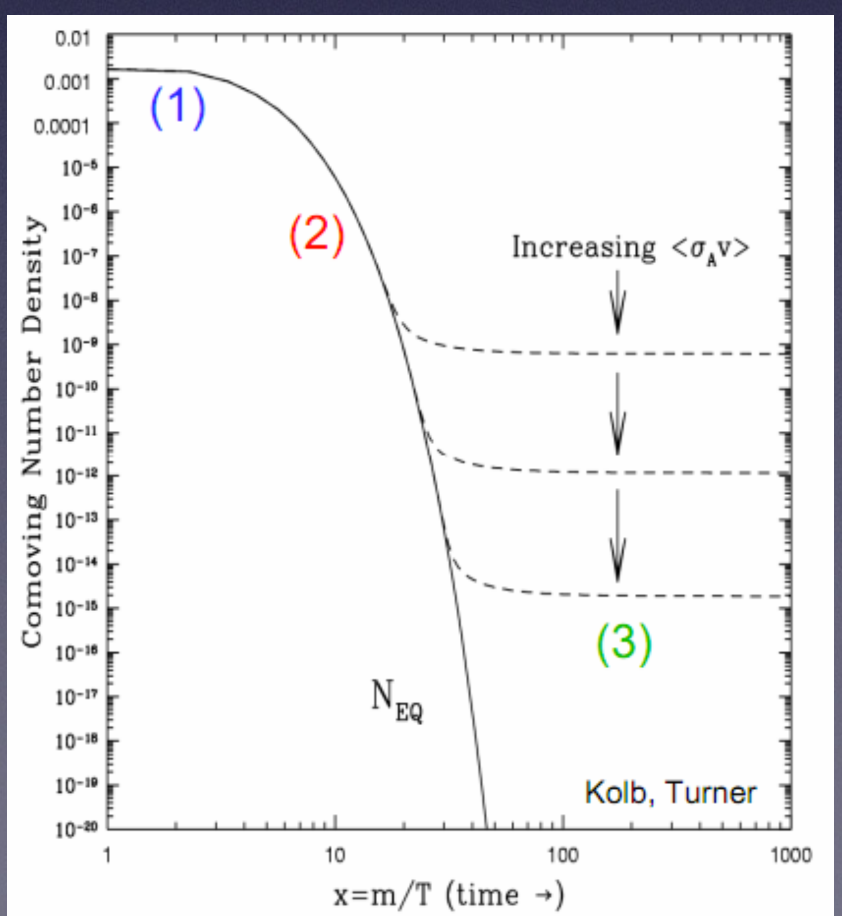
Dark matter models by mass



Thermal DM

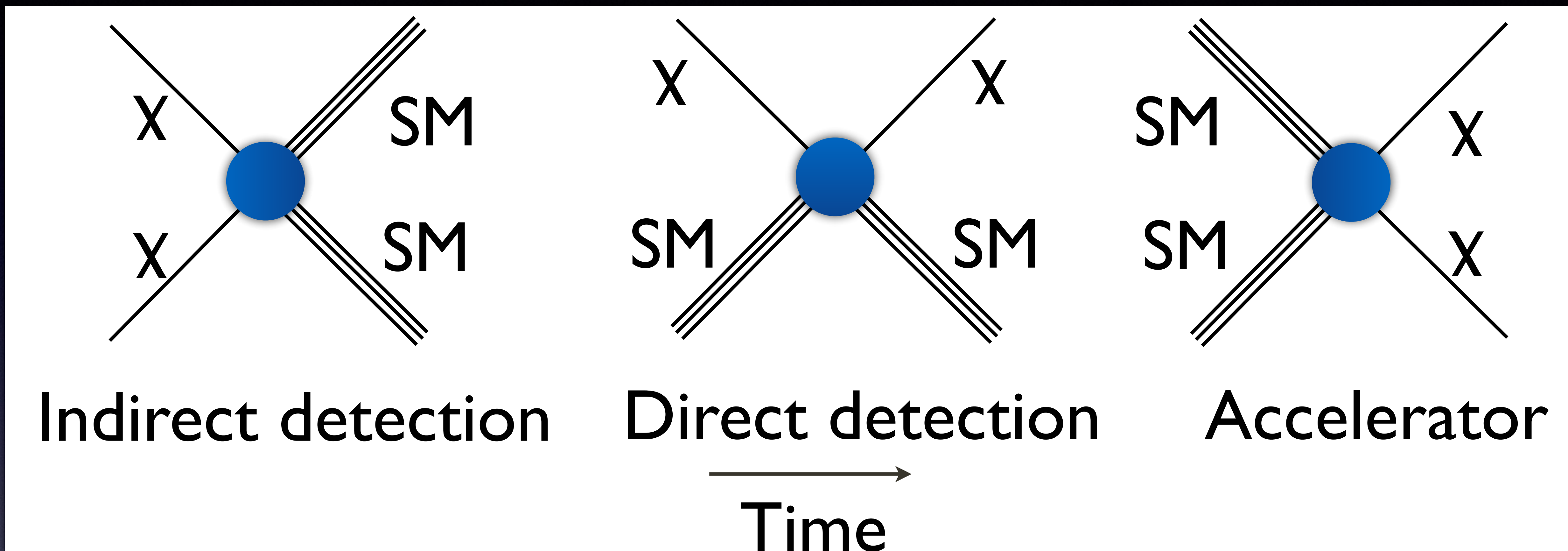


- Posits rapid interconversion between dark matter and ordinary matter in the early universe - keeps abundances similar.
- Dark matter abundance is depleted rapidly once temperature reaches a certain point (not enough energy to make more DM).
- Degree of depletion set by speed of dark-matter-destroying reaction - “dark matter annihilation”.
- There are variations on this scenario, but still true that interactions between DM and visible particles set eventual DM abundance.
- Thus can infer strength of dark matter interactions from measurements of abundance - predict present-day signals.
- Required annihilation rate (“thermal relic cross section”) consistent with electroweak-scale masses and couplings - “WIMP miracle” (WIMP = Weakly Interacting Massive Particle).



Classic WIMP searches

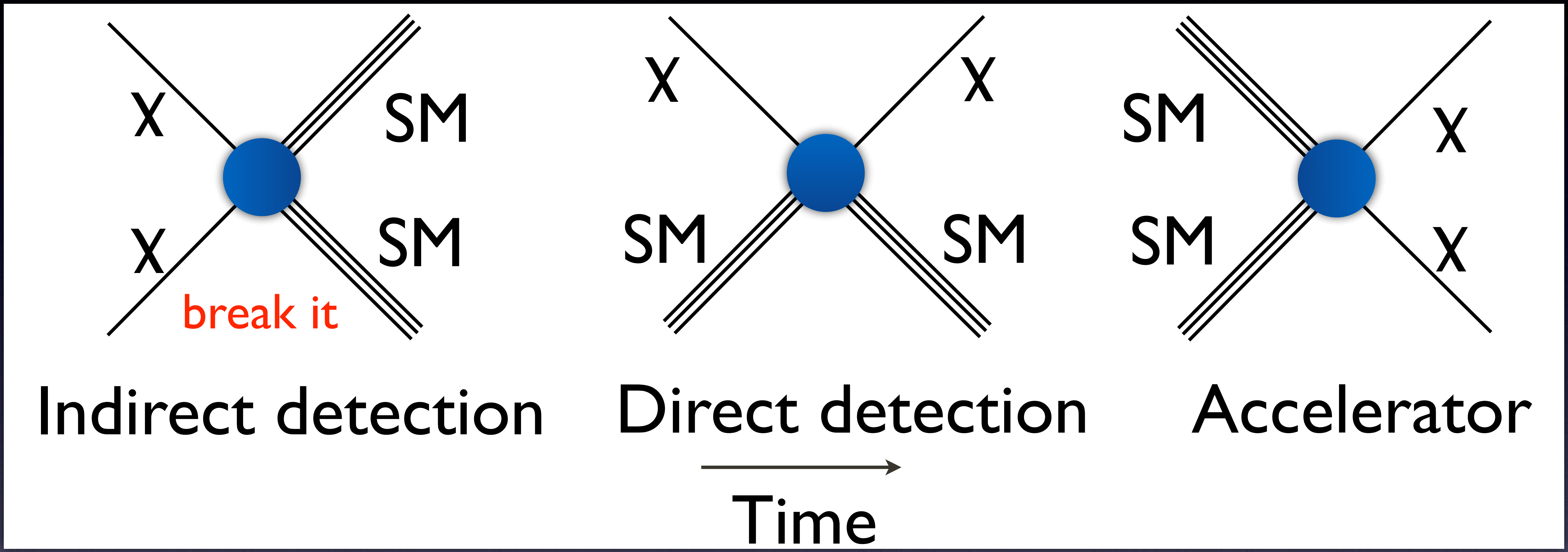
(GeV-TeV mass range)



- 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.

Classic WIMP searches

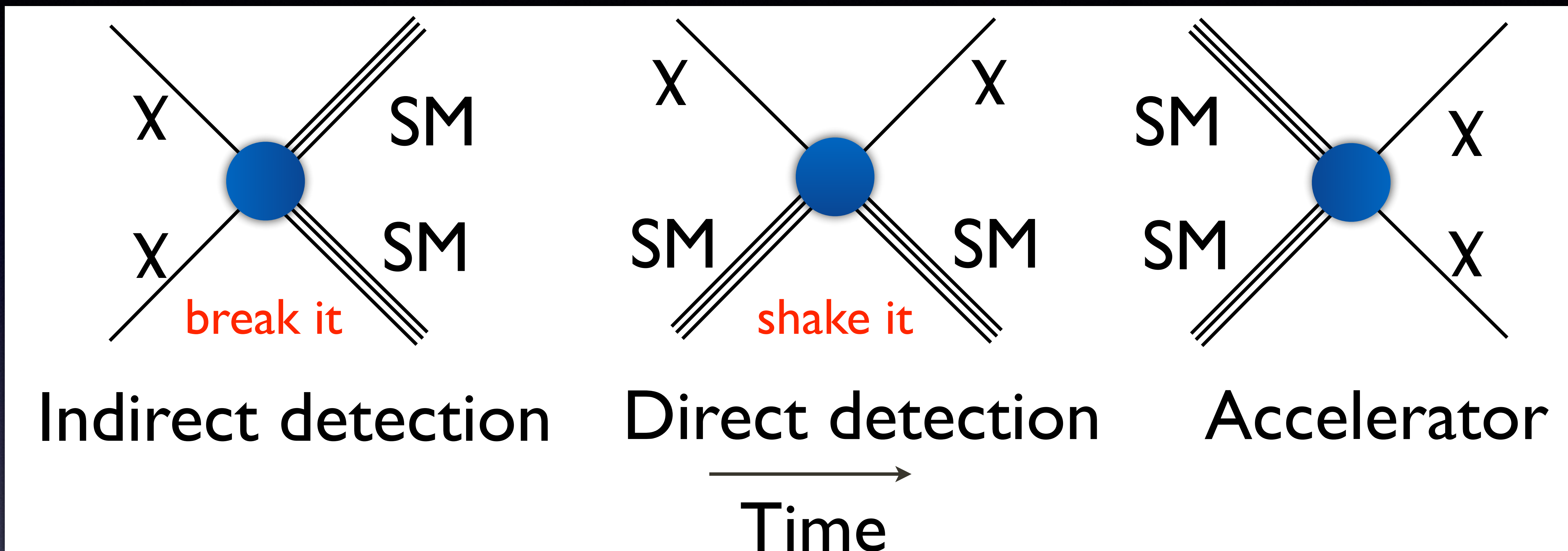
(GeV-TeV mass range)



- 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.

Classic WIMP searches

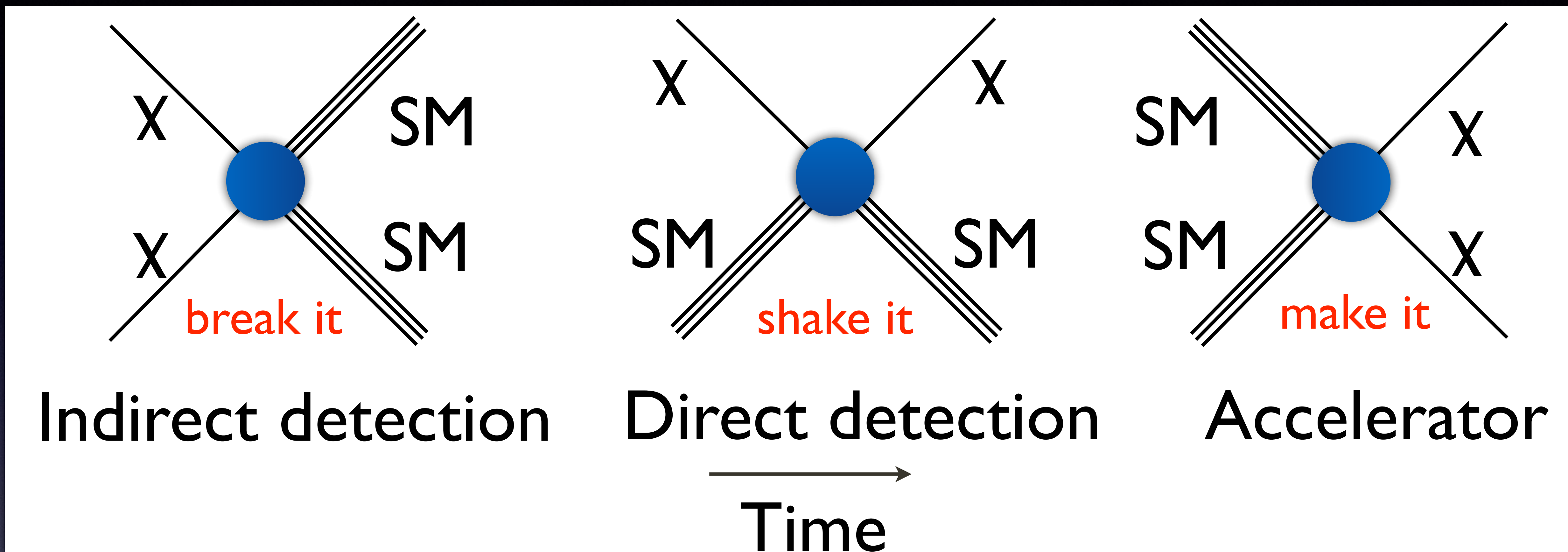
(GeV-TeV mass range)



- 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.

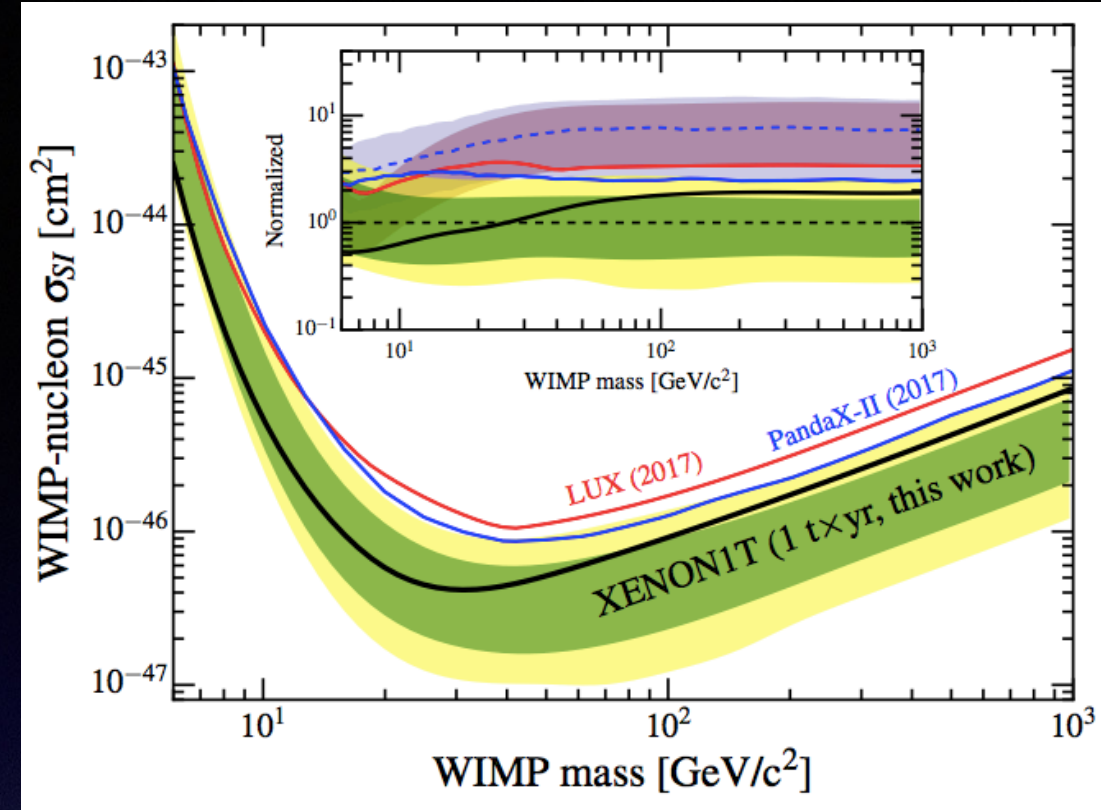
Classic WIMP searches

(GeV-TeV mass range)



- 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.

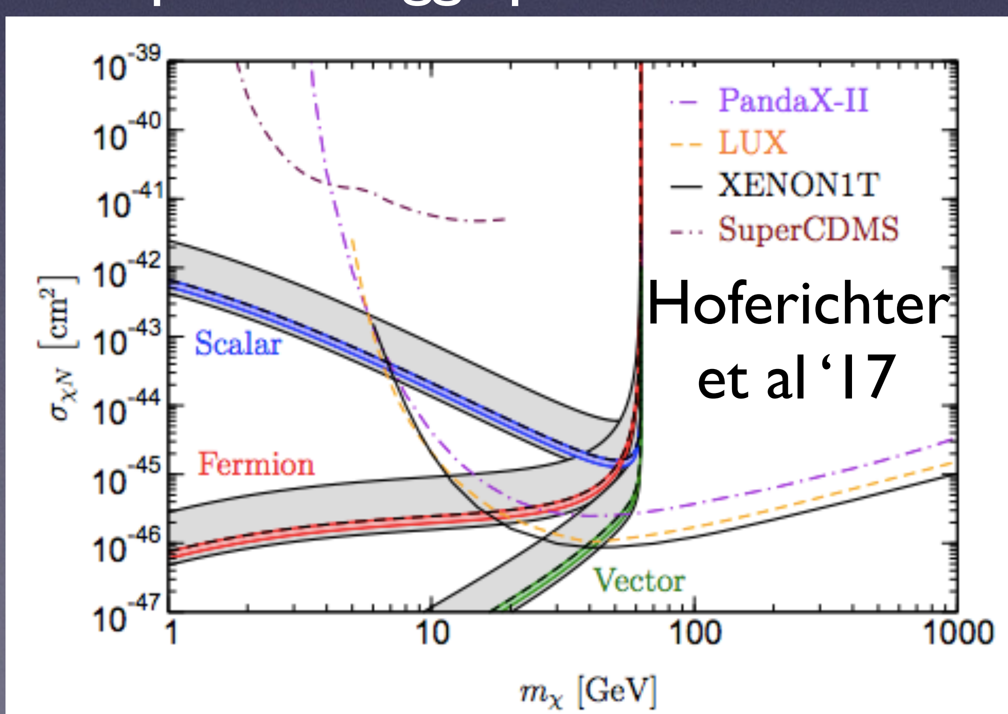
Terrestrial WIMP searches



Aprile et al (XENON1T Collaboration) '18

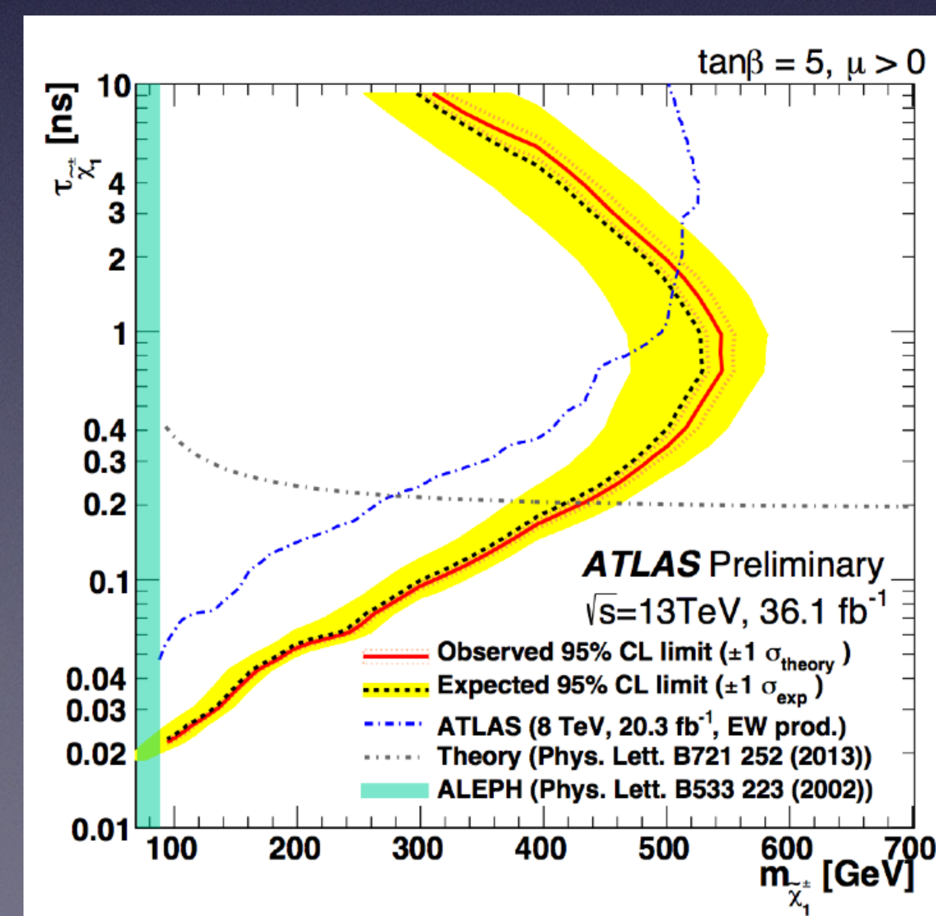
- Direct detection constrains low-energy scattering rate between DM and protons/neutrons - strongest limits at 10+ GeV masses from large xenon experiments (LUX & XENON1T)
- Colliders constrain DM interactions at a much higher center-of-mass energy - can express results in terms of complete models, simplified models, or limits on effective-field-theory operators.

Example 1: "Higgs portal" DM from invisible Higgs decays



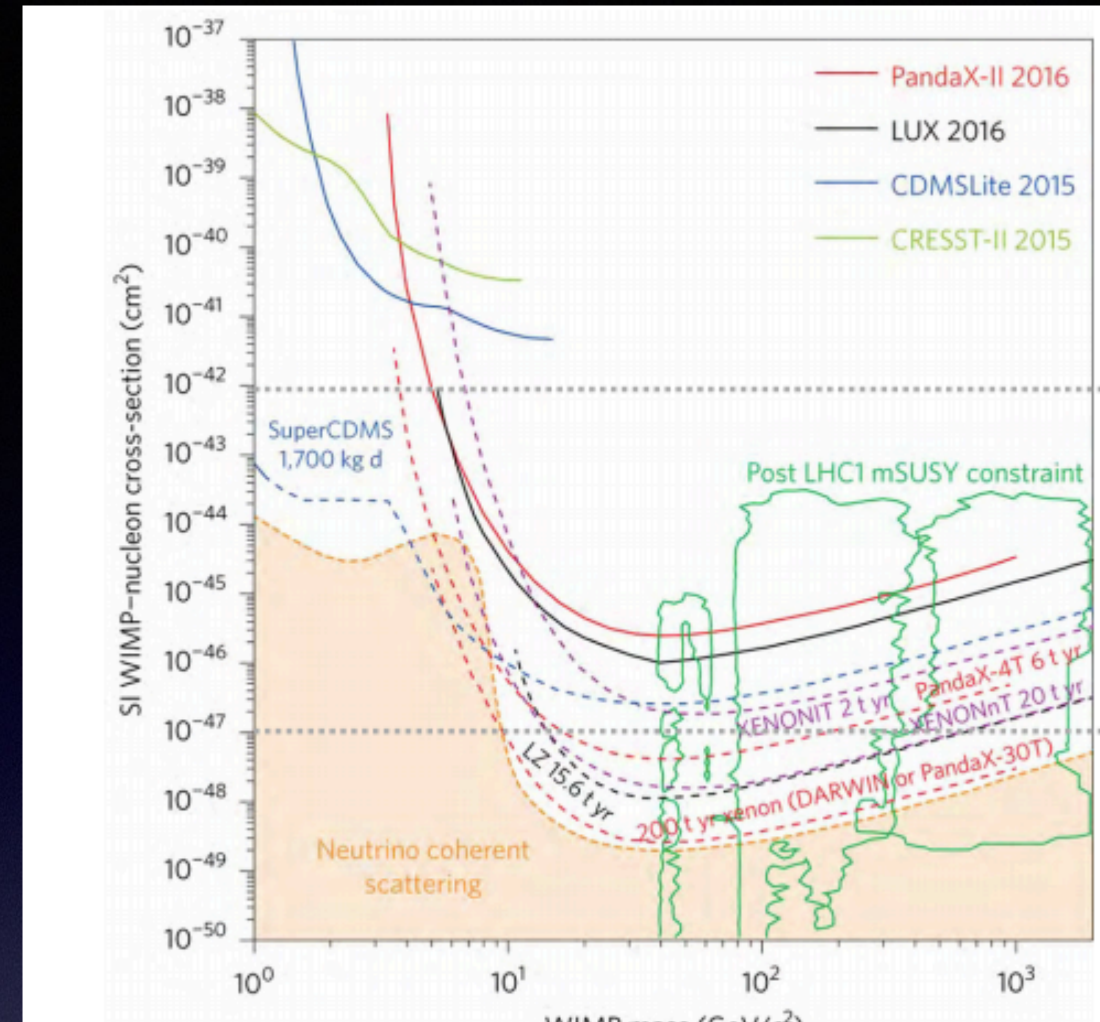
Hoferichter et al '17

Example 2: limits on wino DM from disappearing track searches, ATLAS-CONF-2017-017



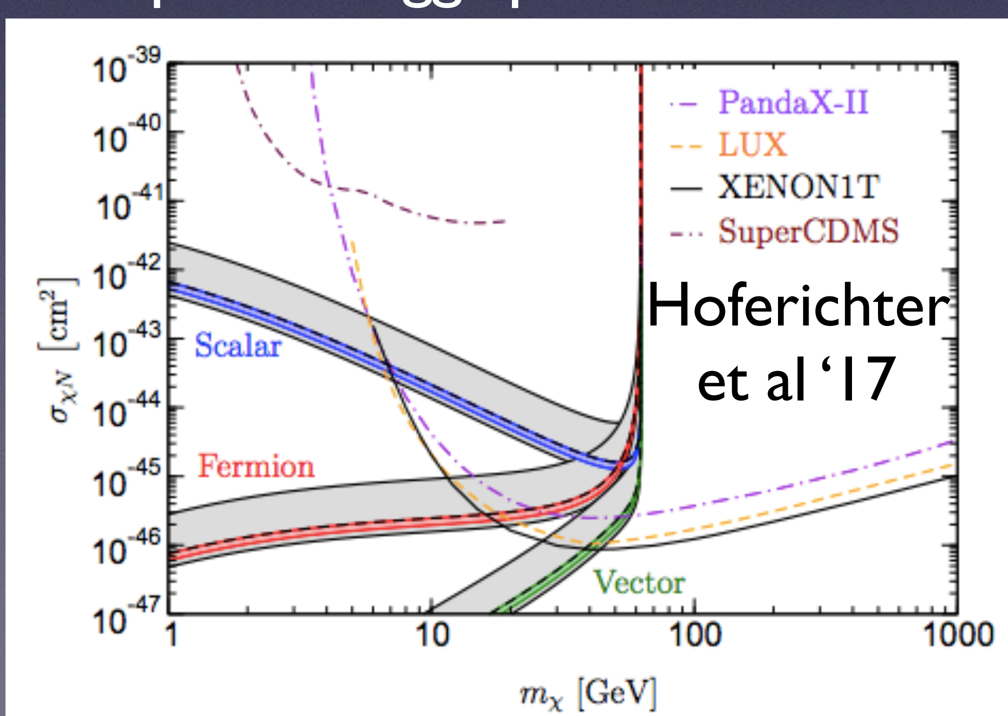
Terrestrial WIMP searches

- Direct detection constrains low-energy scattering rate between DM and protons/neutrons - strongest limits at 10+ GeV masses from large xenon experiments (LUX & XENON1T)
- Colliders constrain DM interactions at a much higher center-of-mass energy - can express results in terms of complete models, simplified models, or limits on effective-field-theory operators.



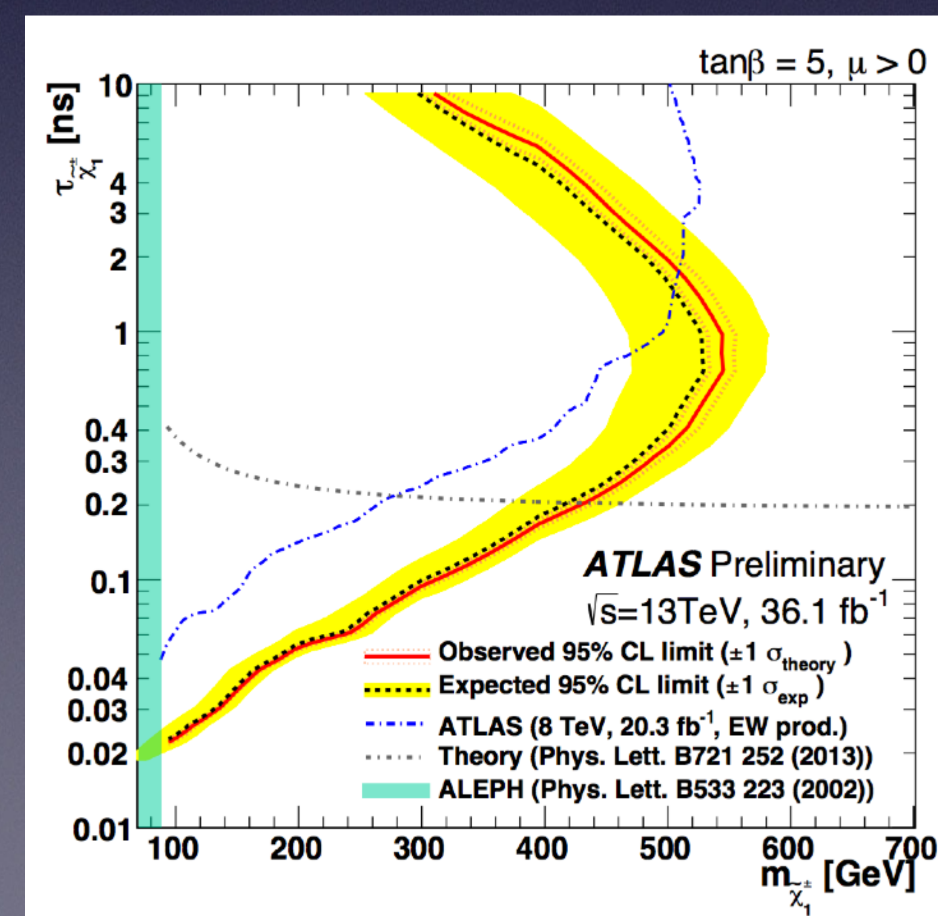
Nature physics, March 2017

Example 1: "Higgs portal" DM from invisible Higgs decays



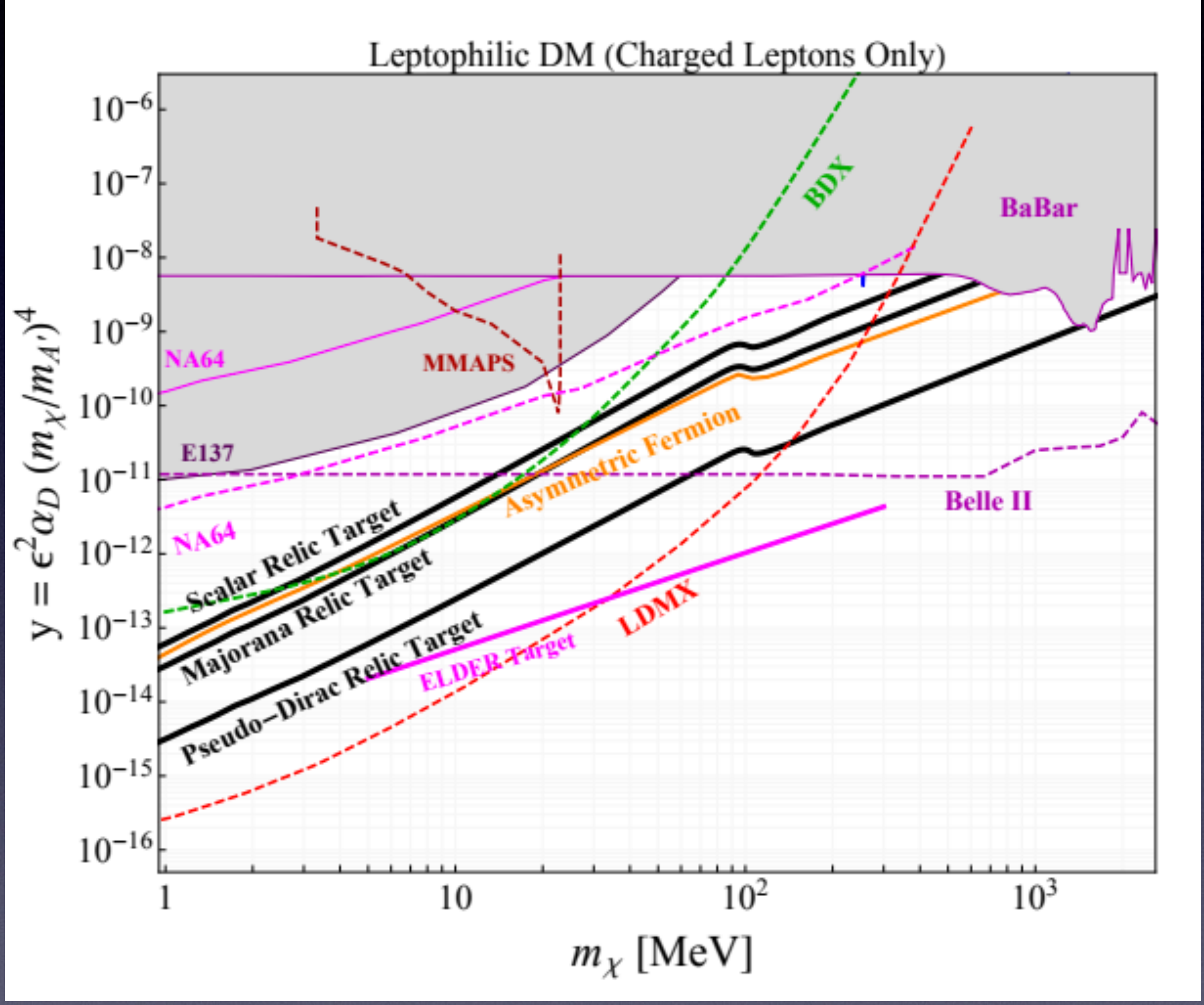
Hoferichter et al '17

Example 2: limits on wino DM from disappearing track searches, ATLAS-CONF-2017-017



Light thermal dark matter

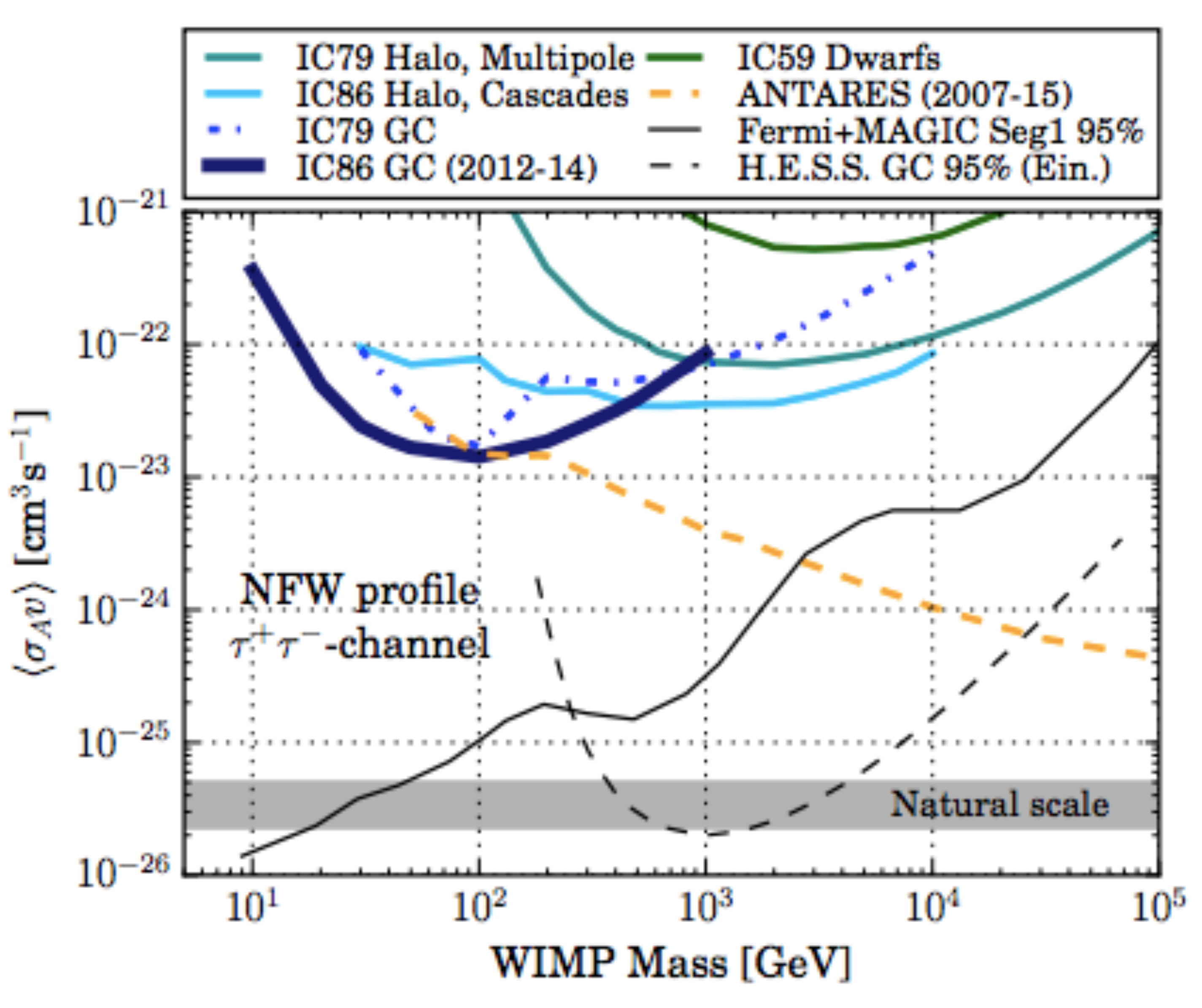
- Traditional direct detection much more challenging for DM masses below ~GeV, due to energy thresholds - scattering off electrons (vs nuclei) can help [e.g. Essig, Volansky & Yu '17, SENSEI Collaboration '18].
- Also many new ideas for accelerator searches in this region - looking for light but very-weakly-coupled particles, luminosity can matter more than center-of-mass energy.
- Most studies so far have focused on simplified model approach - if DM couples directly to SM through a mediator, relic density sets the coupling strength, provides clear target.



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

WIMP searches in the sky

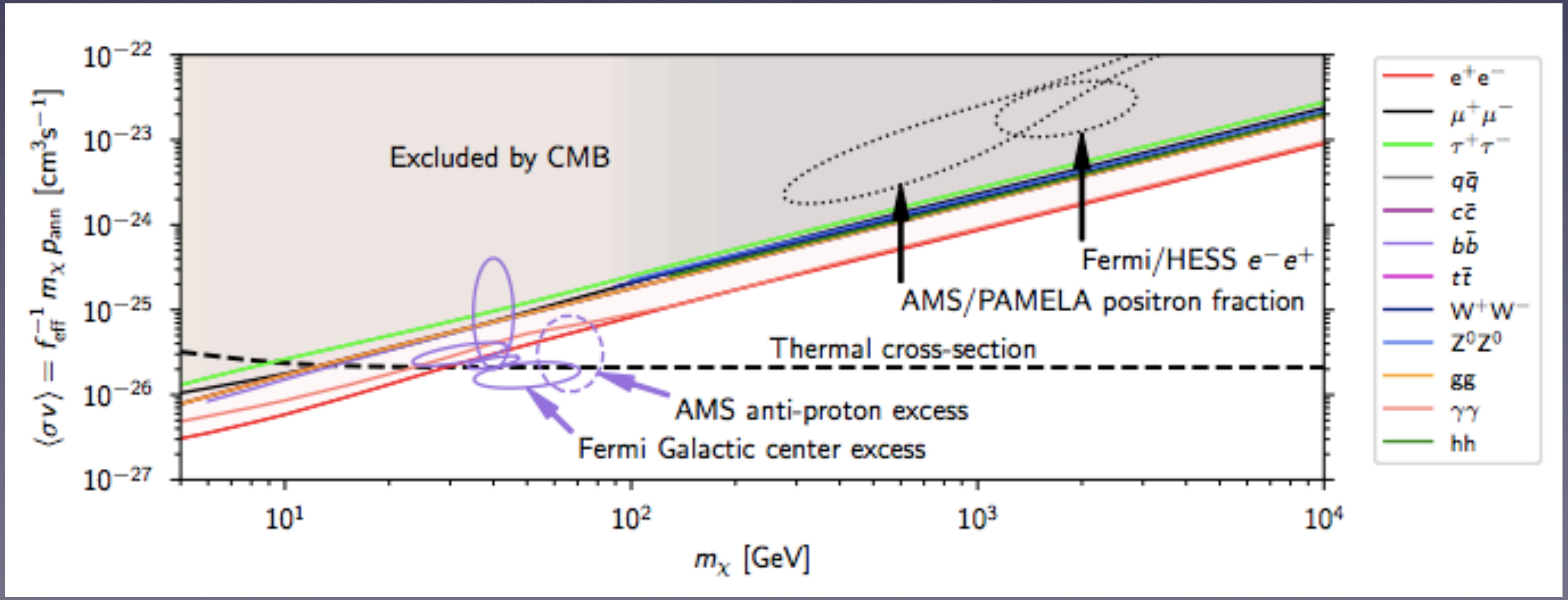
- Neutrino and photon telescopes can set limits on particle fluxes from Milky Way dark matter halo, Galactic Center, dwarf galaxies (dark matter clumps).
- AMS-02 experiment measures cosmic-ray fluxes in the neighborhood of the Earth.
- Possible to robustly probe "thermal relic" cross section (yields correct abundance) for DM masses up to ~100 GeV, depending on channel (up to ~1 TeV with generous assumptions).
- Different experiments test different annihilation final states (see e.g. Leane, TRS et al '18 for combined analysis).



IceCube Collaboration '17 (1705.08103)

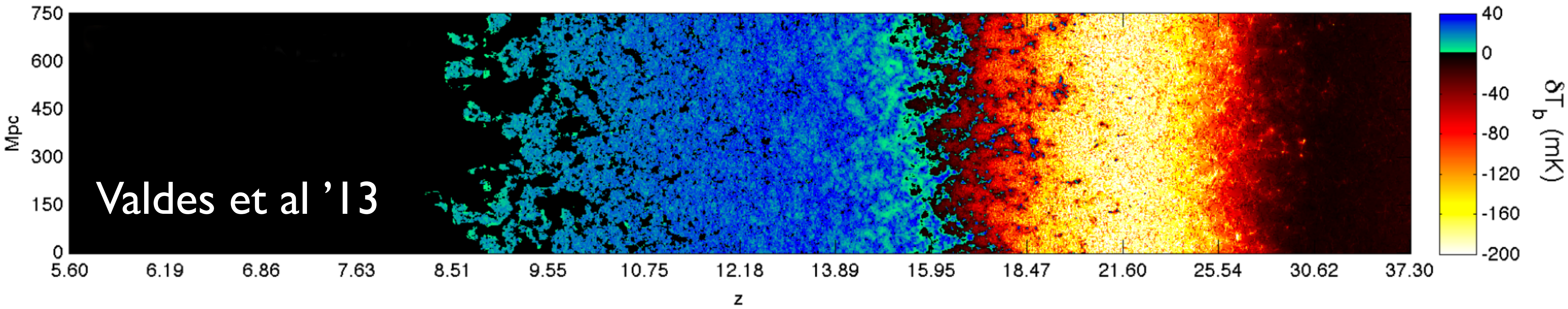
Light thermal DM and the early universe

- When the universe was a few hundred thousand years old, it went from being almost fully ionized to almost completely neutral.
- Optical depth to low-energy photons abruptly became small - those photons free-stream to our telescopes in the present day, cosmic microwave background (CMB) radiation. Gives a snapshot of the universe at very early times, can be precisely described by standard cosmological model.
- Ionizing the universe, even slightly, after the release of the CMB photons acts to "blur" this snapshot - extra free electrons act as scatterers for CMB.
- DM annihilation injects high-energy particles that generically decay and scatter to produce ionizing secondaries.
- Detailed analysis finds that effect on CMB is nearly model-independent [TRS '16] - model dependence encapsulated in overall normalization factor. One analysis simultaneously tests all annihilation channels, huge mass range. For all but neutrinos, excludes thermal relic cross section for masses below ~10 GeV.



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

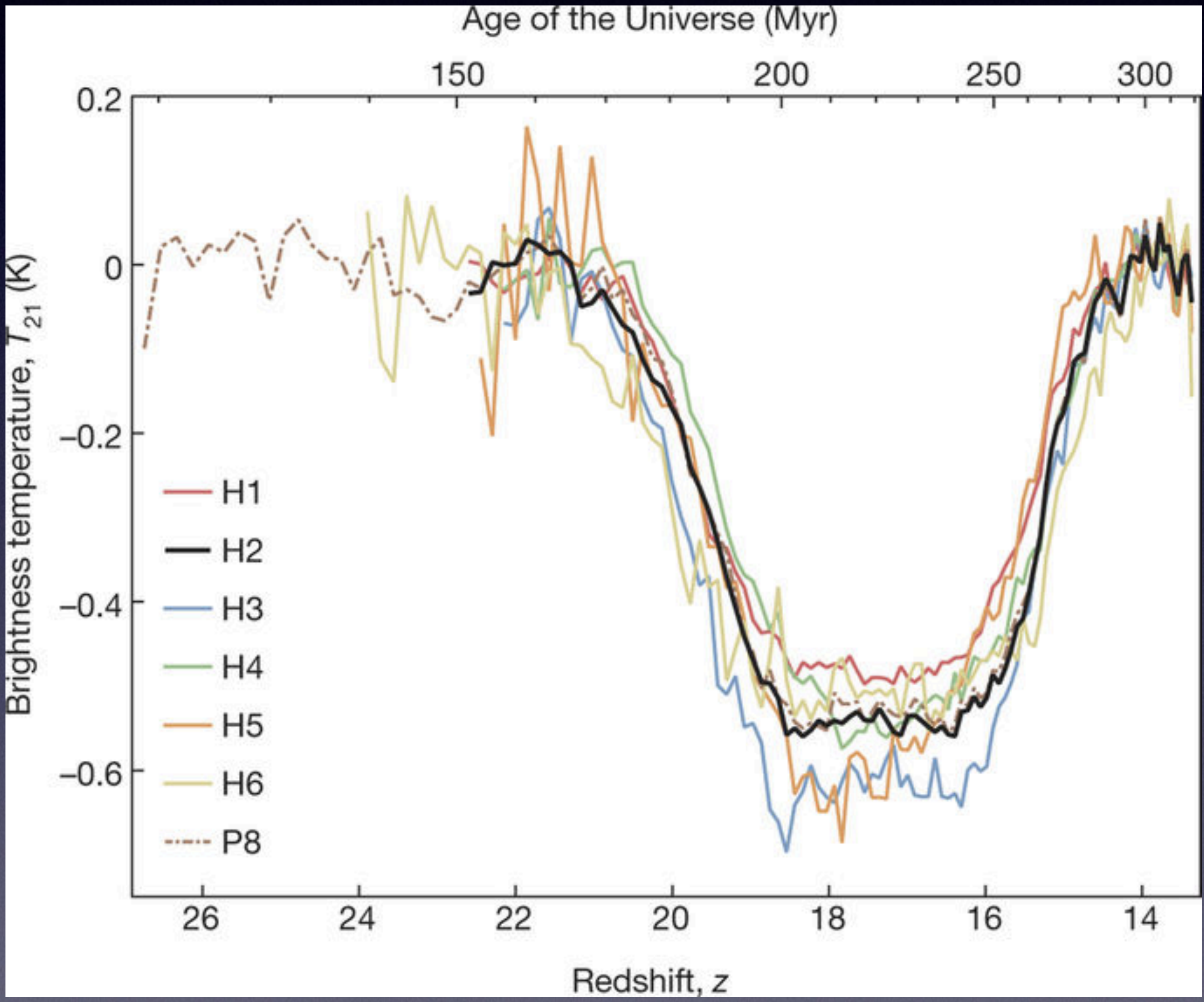
Beyond the CMB: 21cm



- As well as ionization, DM annihilation/decay could substantially heat up the intergalactic gas at redshifts < 200 [e.g. Liu, TRS & Zavala '16].
- The spin-flip transition of neutral hydrogen (wavelength 21cm) is sensitive to the "spin temperature" T_S, which measures the fraction of H in the upper vs lower levels. We expect that T_S should lie between T_{gas} and $T_{radiation}$.
- Net absorption occurs when $T_S < T_{radiation}$ (expected at early times), net emission when $T_S > T_{radiation}$ (expected at late times, due to stellar heating of gas).
- There are current (e.g. EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, HERA, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization (the universe becomes ionized again around z~10).
- Could vastly improve constraints on the temperature and ionization history.

A measurement of 21cm absorption in the dark ages?

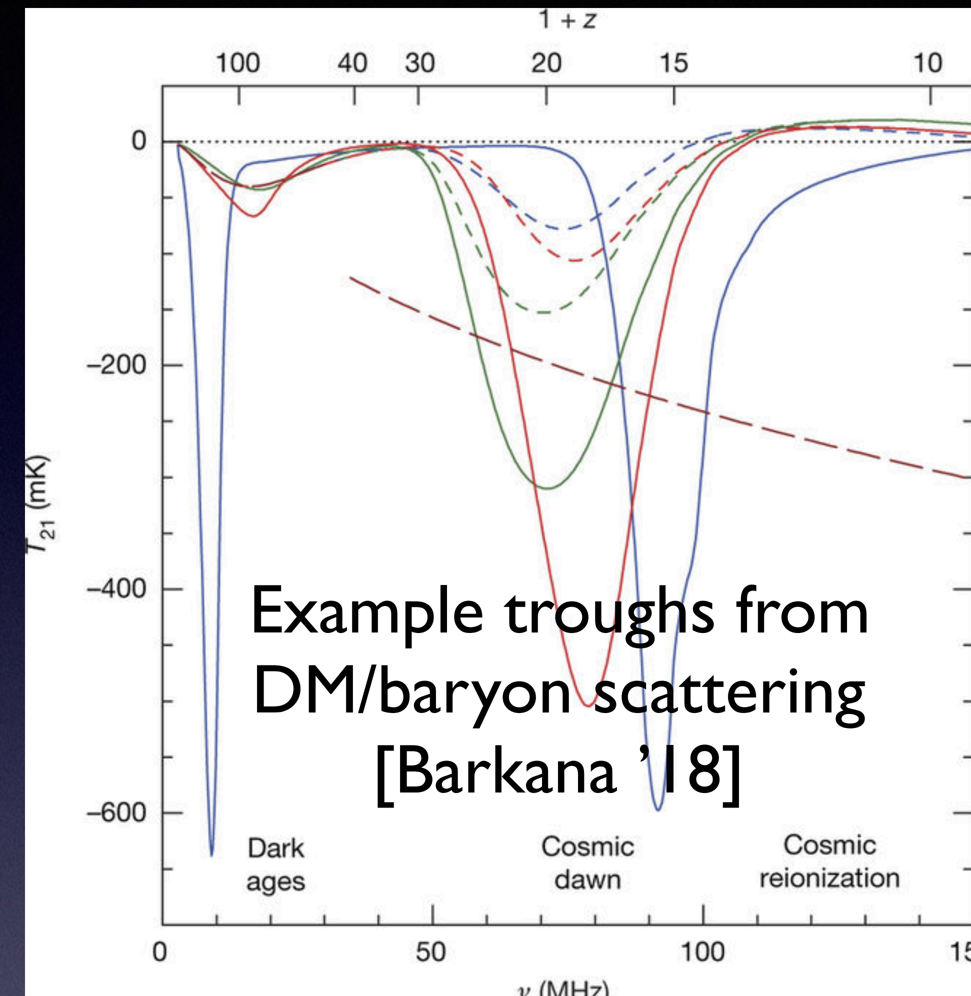
- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March '18].
- Claimed signal is a very deep absorption trough corresponding to z~15-20.
- Not consistent with standard picture! <u>If</u> confirmed, implies either (1) relevant radiation temperature is much larger than expected, or (2) gas temperature is lower than expected.



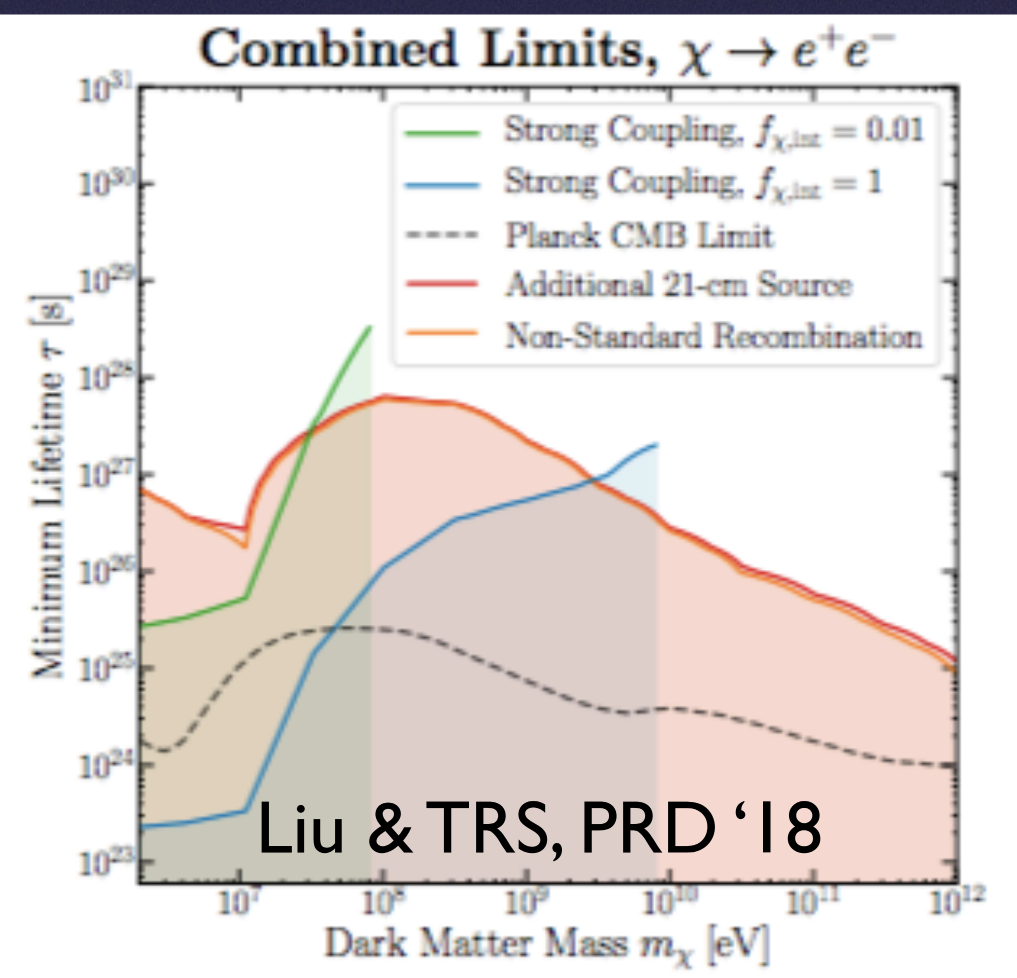
- Opposite to expected effect of DM decay/annihilation - allows for strong limits.
- Possible in principle that DM-baryon scattering could cool gas [e.g. Munoz et al '15, Barkana '18], since DM generally expected to be colder than visible matter.

Dark matter and EDGES

- Several authors [e.g. Barkana et al '18, Berlin et al '18, Munoz et al '18] have suggested that if ~1% of (10-100 MeV) DM carries a tiny electric charge, this could explain the signal, through Rutherford scattering to cool the gas.
- Recent work by Kovetz et al '18 shows that existing constraints can only be evaded if this component is 0.1-0.4% of DM, with 0.5-35 MeV mass.



Example troughs from DM/baryon scattering [Barkana '18]



Liu & TRS, PRD '18

- DM annihilation and decay: constraints on decaying DM could improve by up to 2 orders of magnitude.
- Strong constraints can still be set in the presence of scattering or other absorption-enhancing effects.

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 (current and planned) experimental searches for interactions between dark matter and ordinary matter, for scenarios mapping out large parts of this range:
    - axions and axion-like particles at very low masses
    - light thermal dark sectors in the keV-GeV range
    - WIMP-like dark matter at 1 GeV+
- Across many search strategies, it is possible for upcoming/planned experiments to improve sensitivity to couplings / cross sections by orders of magnitude.
- What if DM doesn't interact with ordinary matter? We can also turn to gravitational probes of DM, seek to improve our understanding of its distribution - could hold clues to DM microphysics.