*Review on Dark Matter**

* or at least an hint of it…

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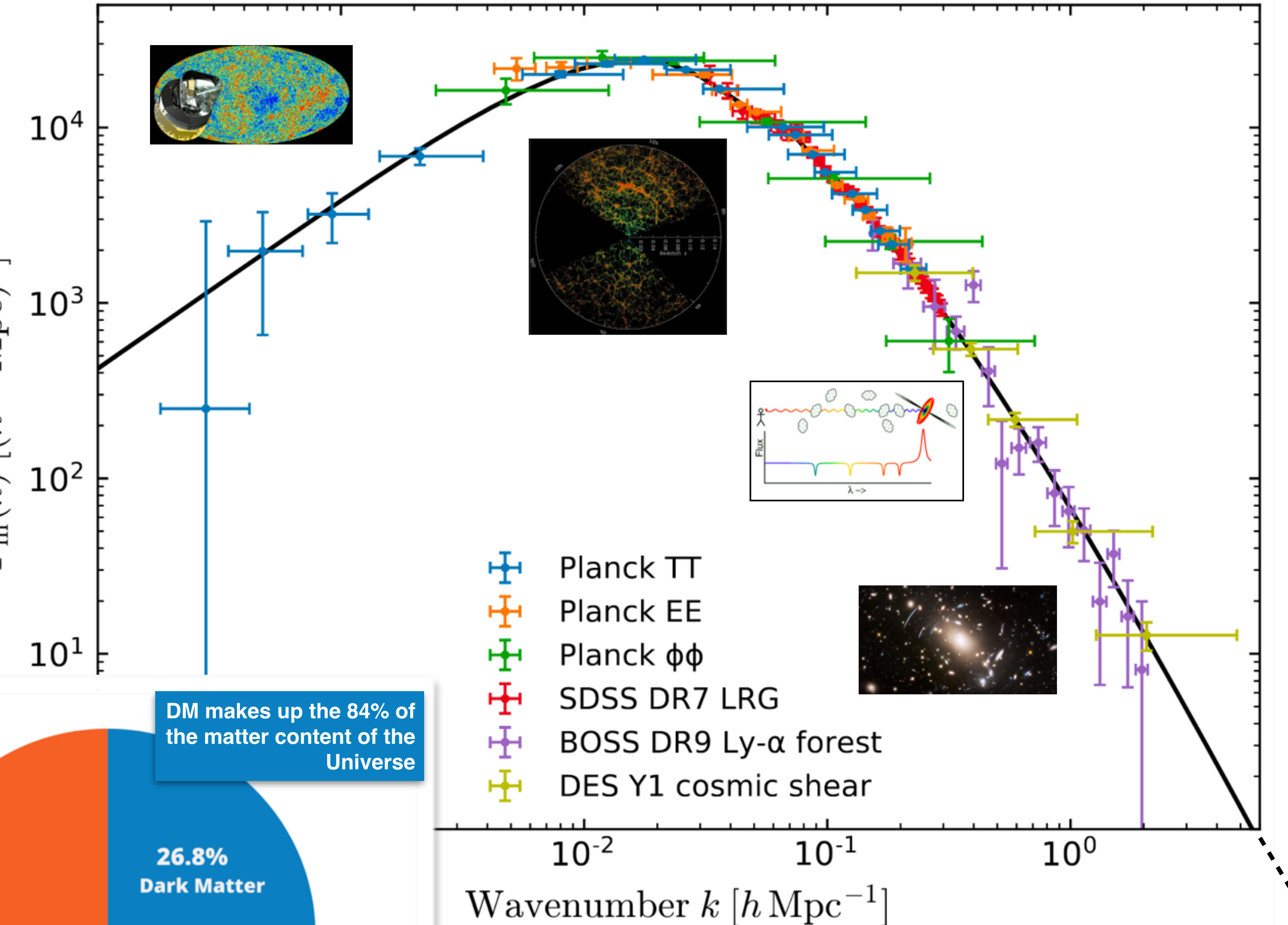
IRMP

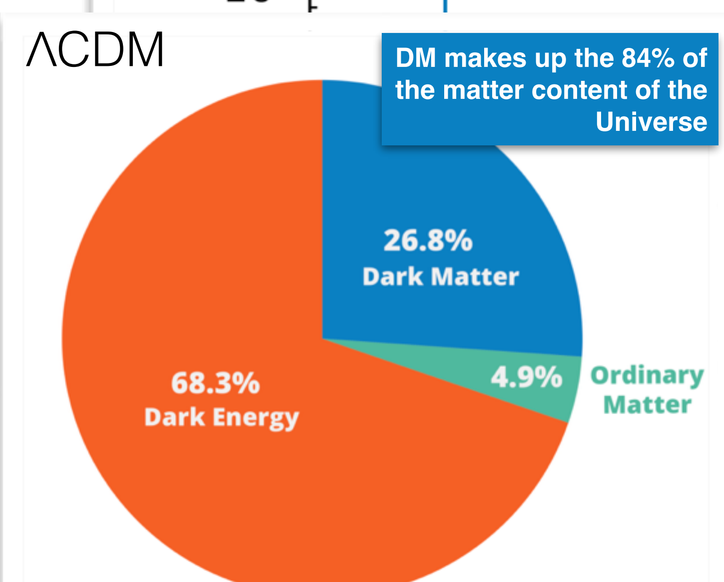
UCLouvain

What do we know so far?

- In 2021 our knowledge of DM is based on the ΛCDM cosmological model + astrophysics

Planck (arXiv:1807.06209)





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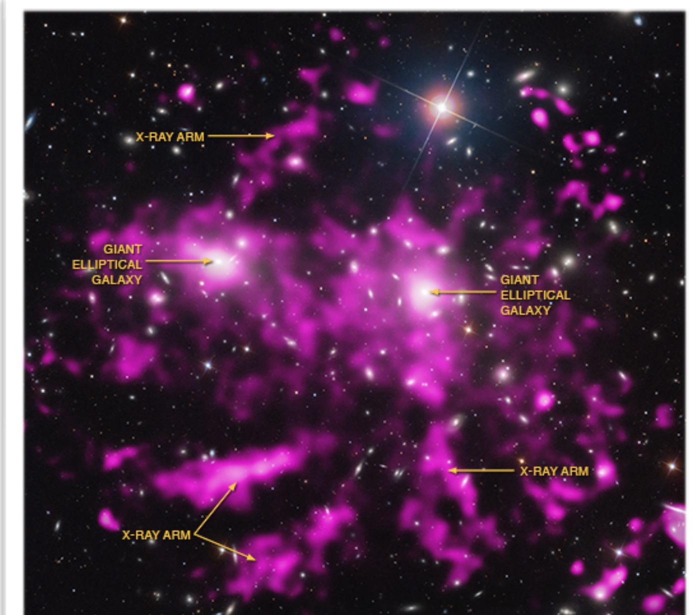
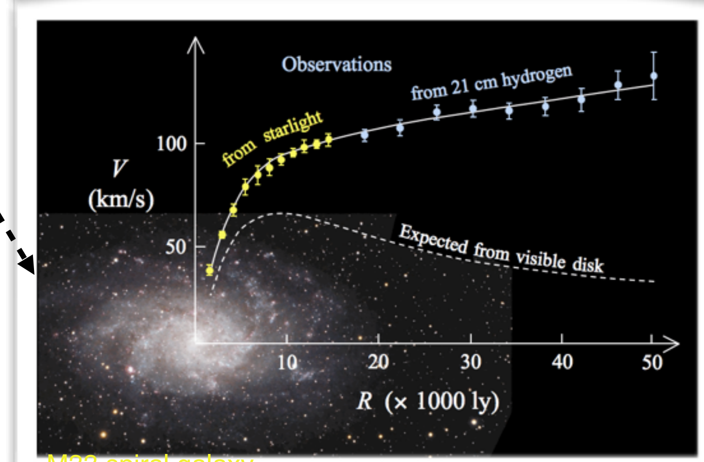


Come Cluster, X Rays, Chandra X-ray observatory



M33 spiral galaxy

Only GRAVITATIONAL evidence for DM

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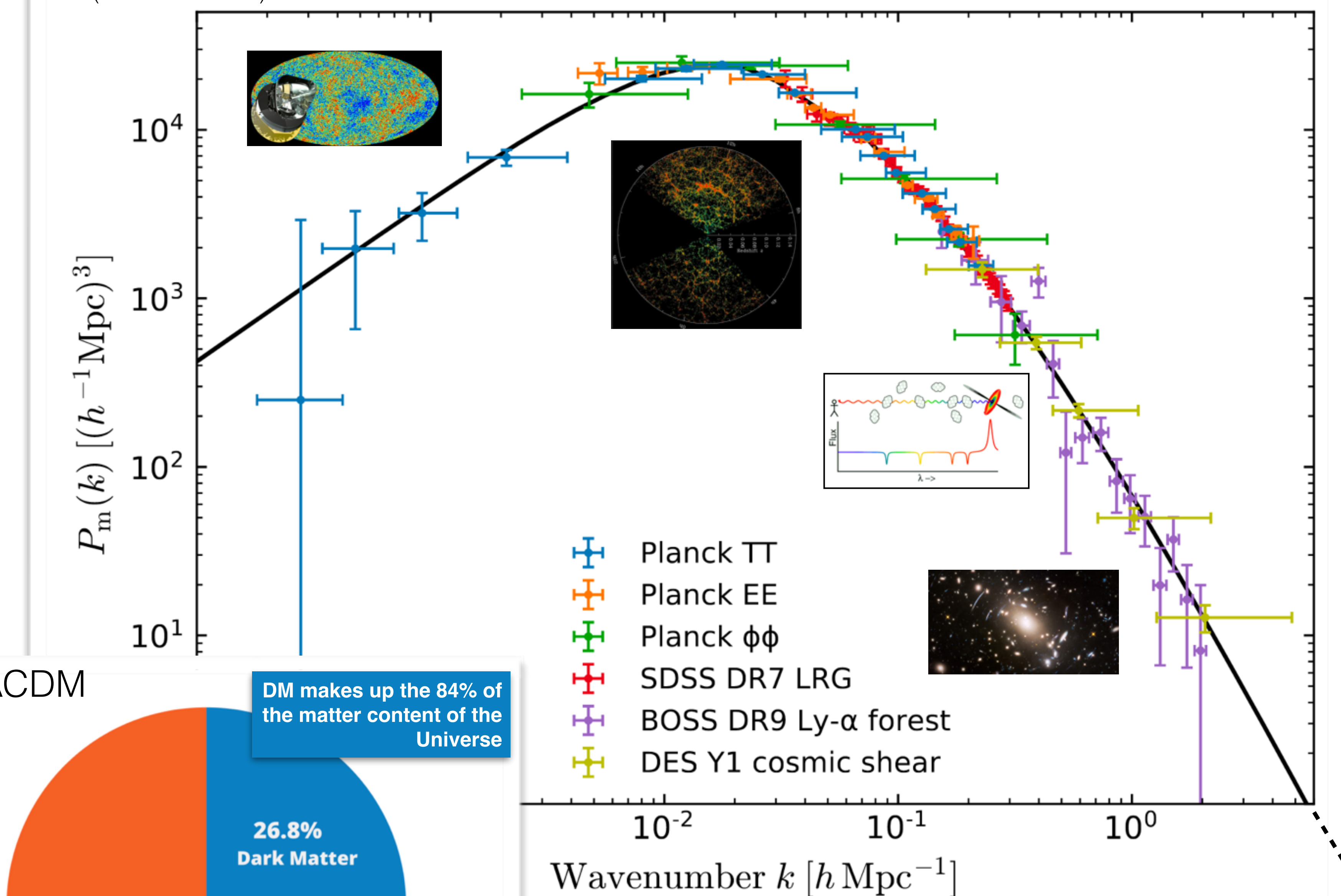

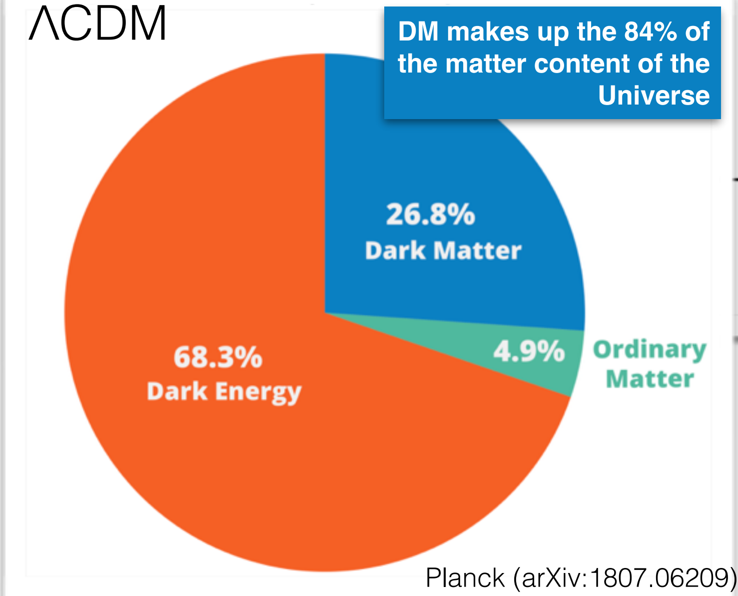

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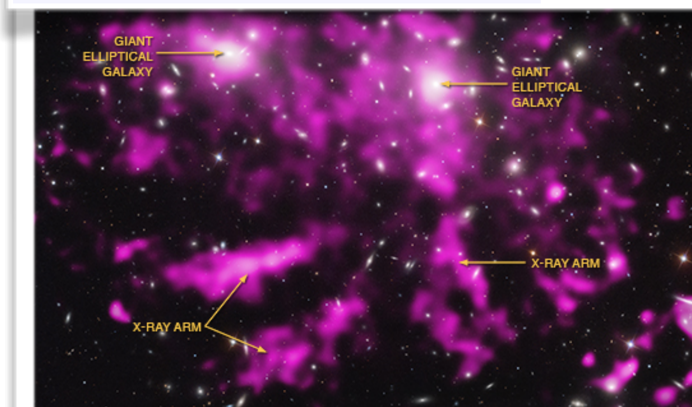

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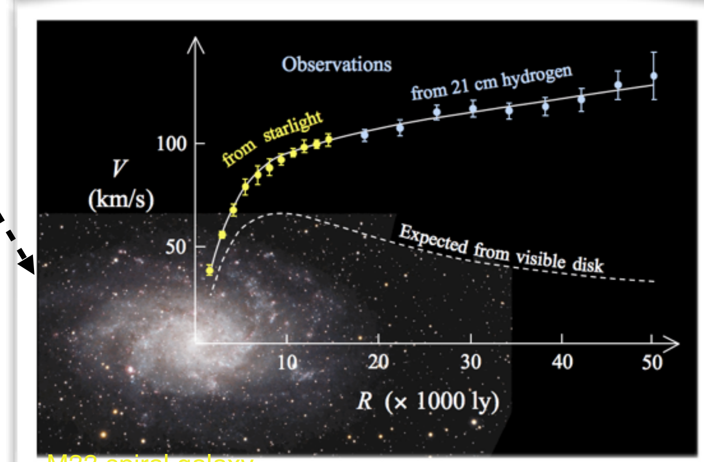

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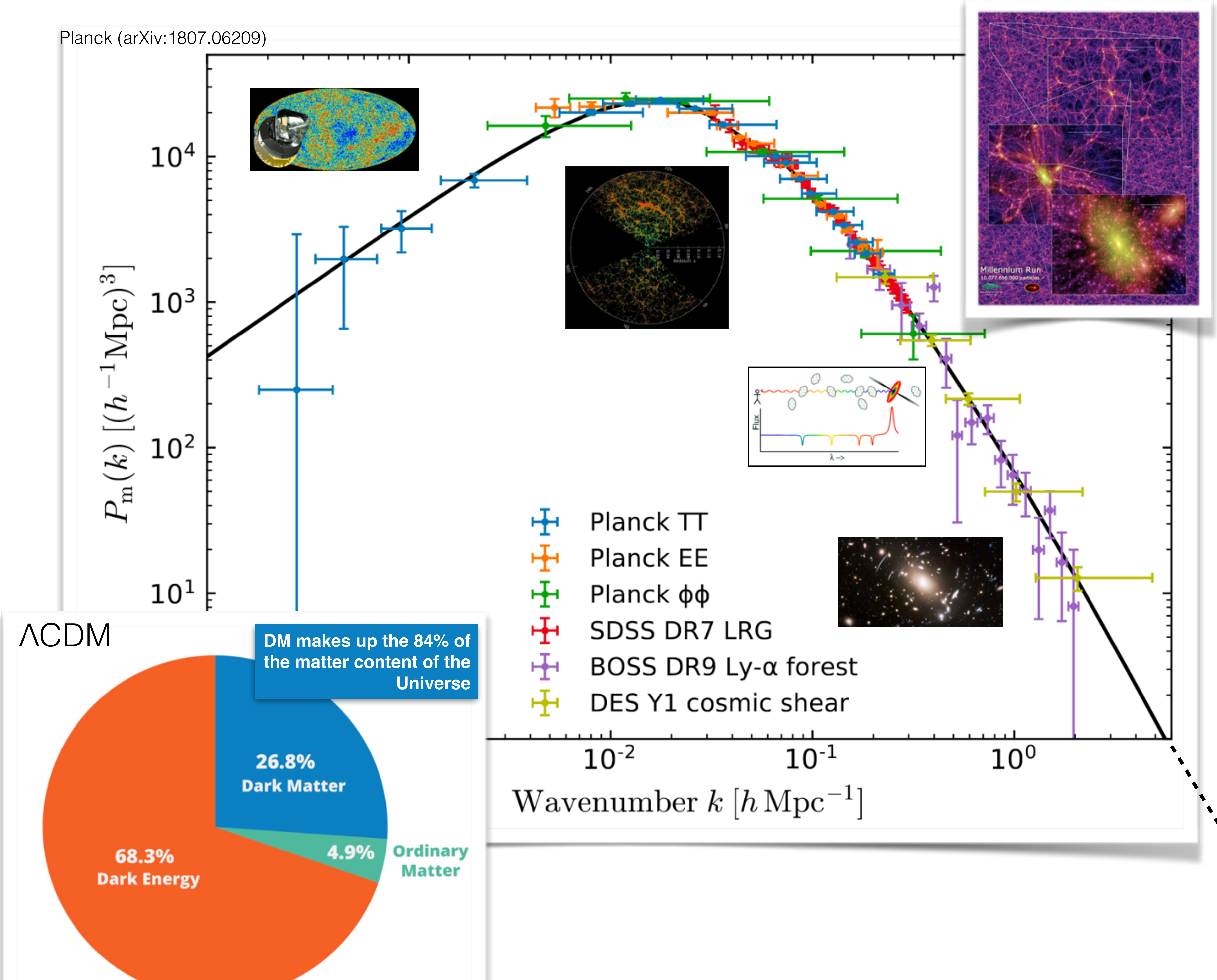

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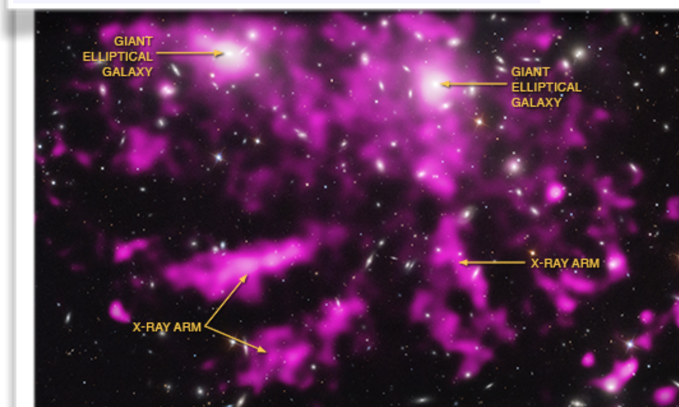
Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;



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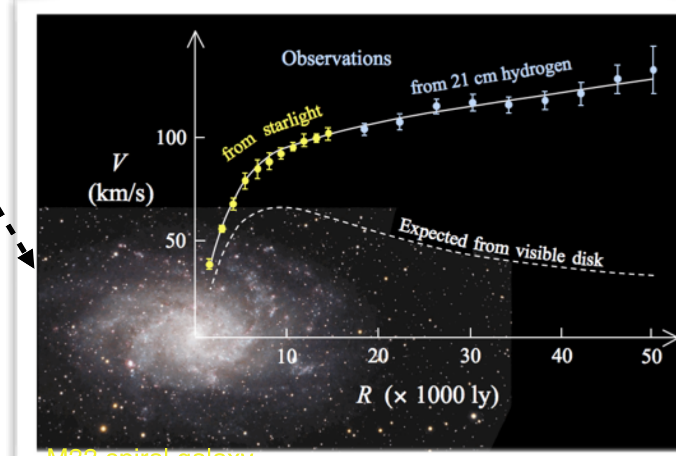
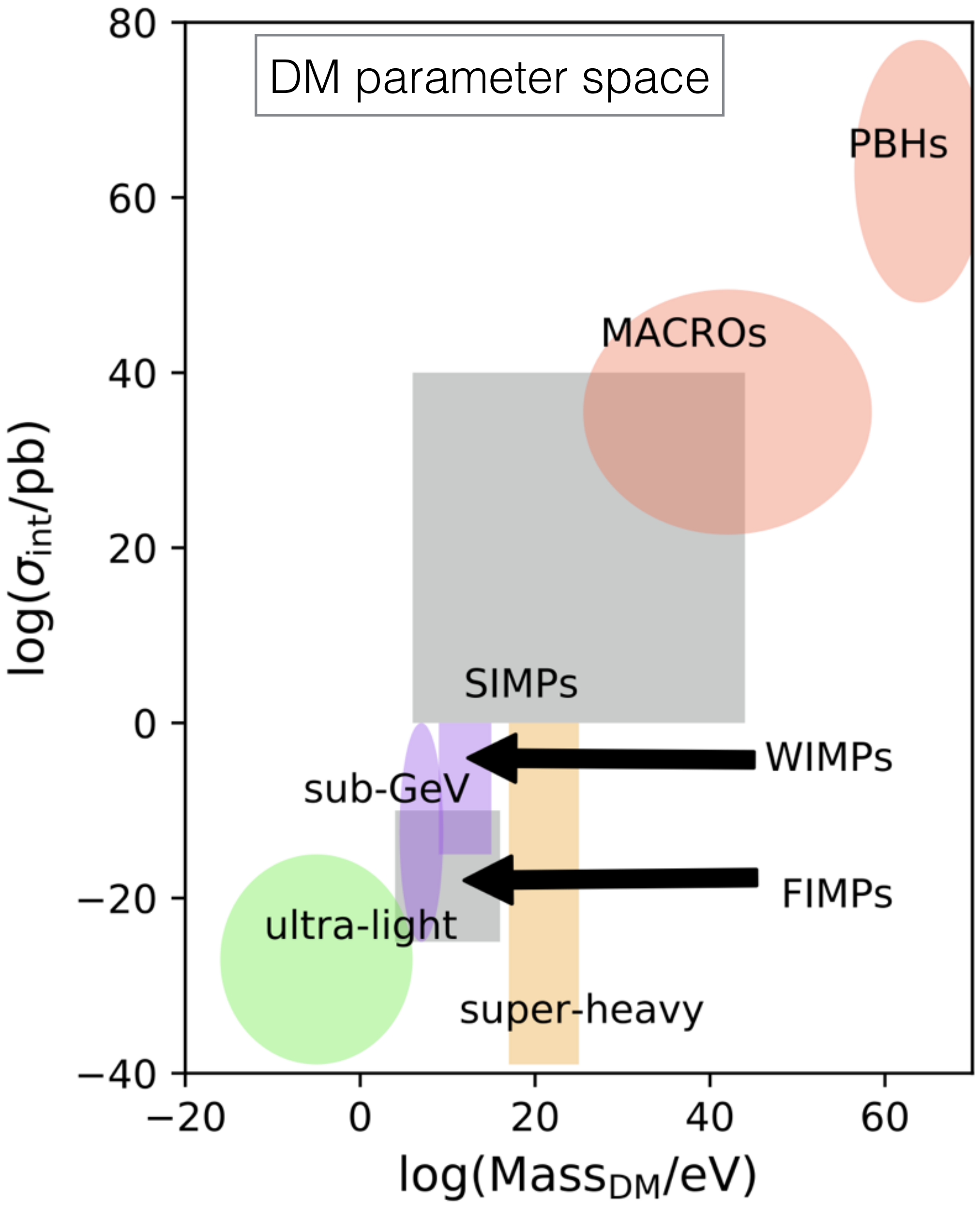


M33 spiral galaxy

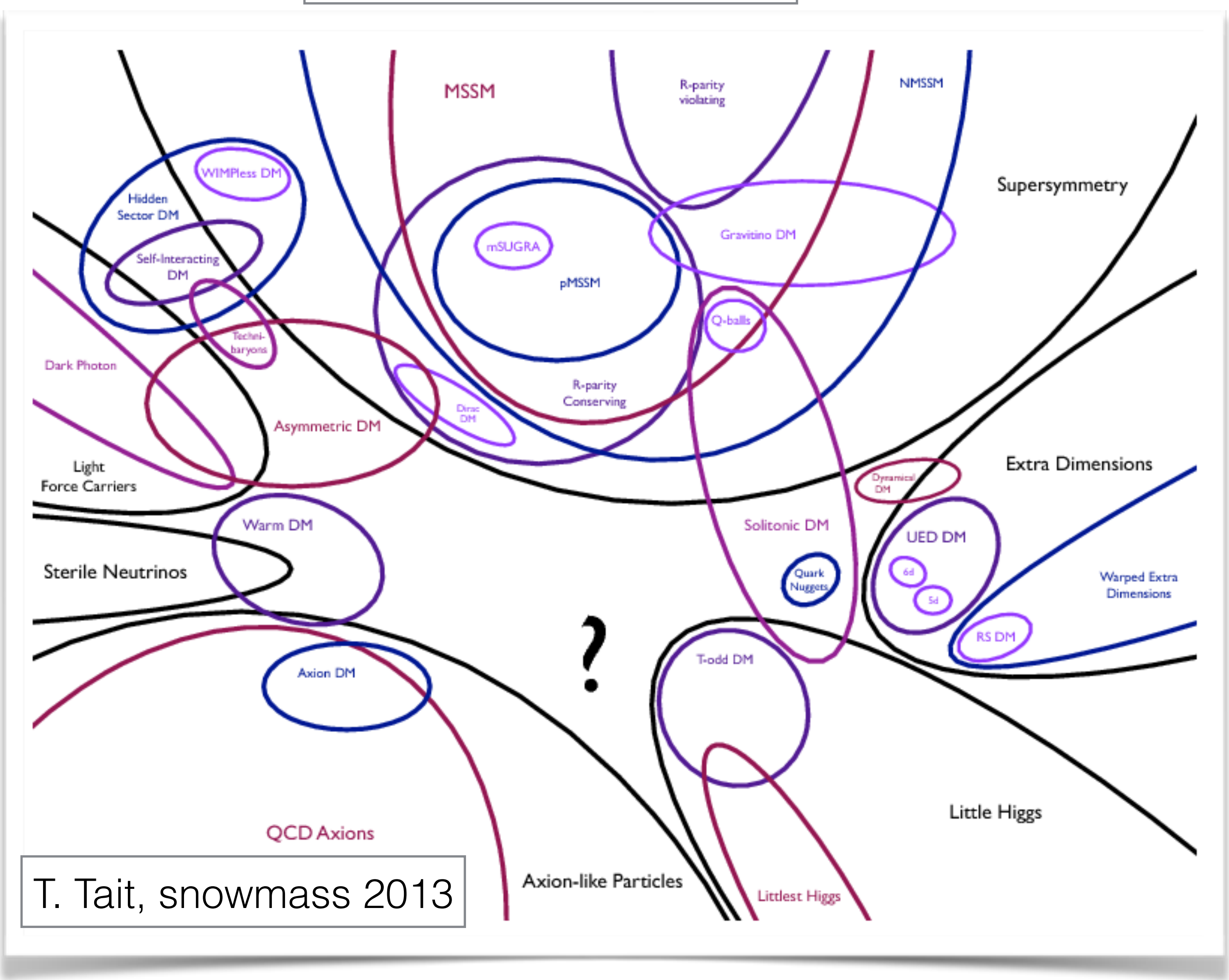
Only GRAVITATIONAL evidence for DM

The DM landscape

- We do not know of what the DM is made of
- Mainstream believe is that DM is a particle: what is its MASS ?? —> 90 orders of magnitude
- We do not know how or if DM interacts with SM particles other than gravitationally: what is its interaction “CROSS-SECTION” ?? —-> even more uncertain than the mass range



DM theoretical landscape



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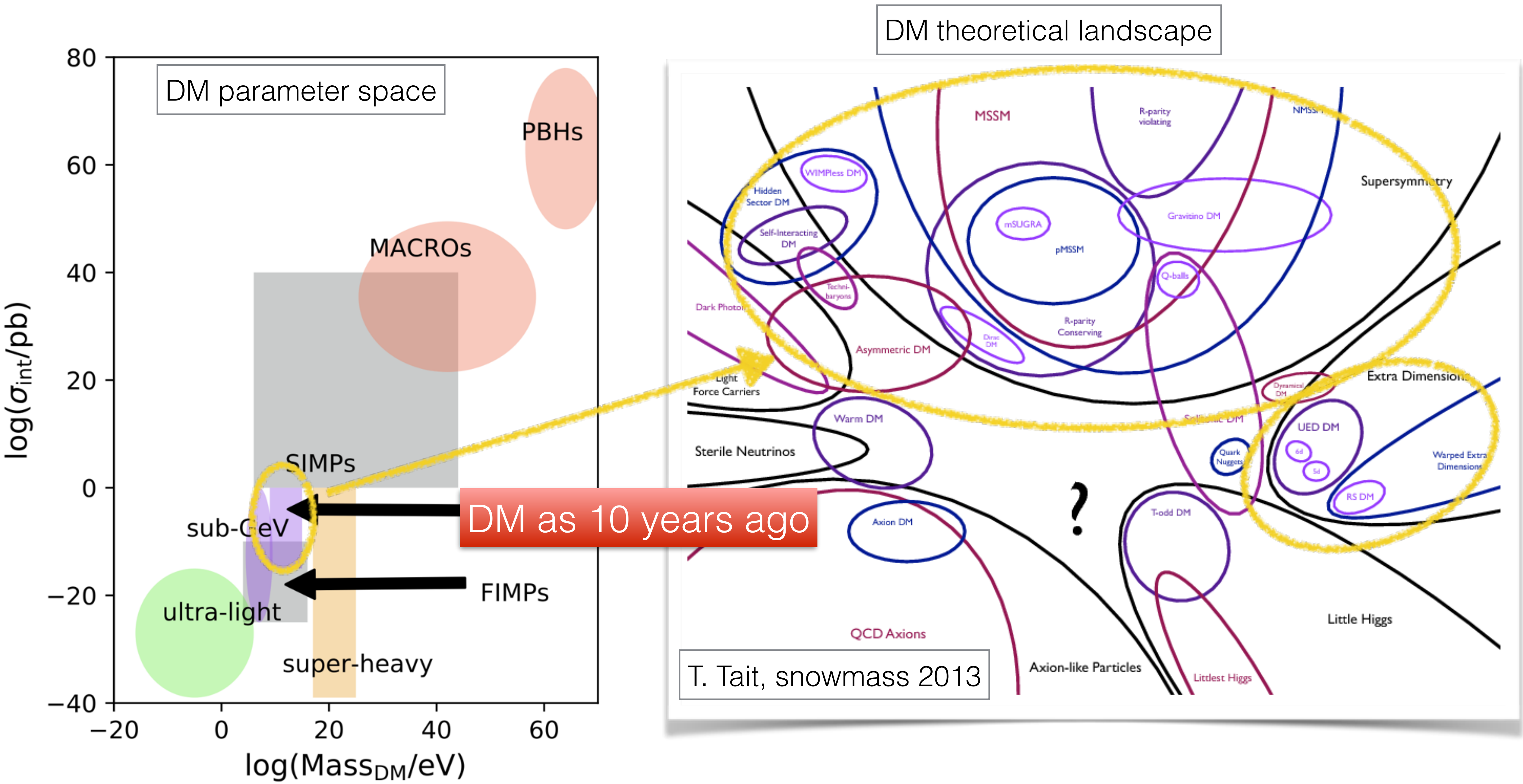

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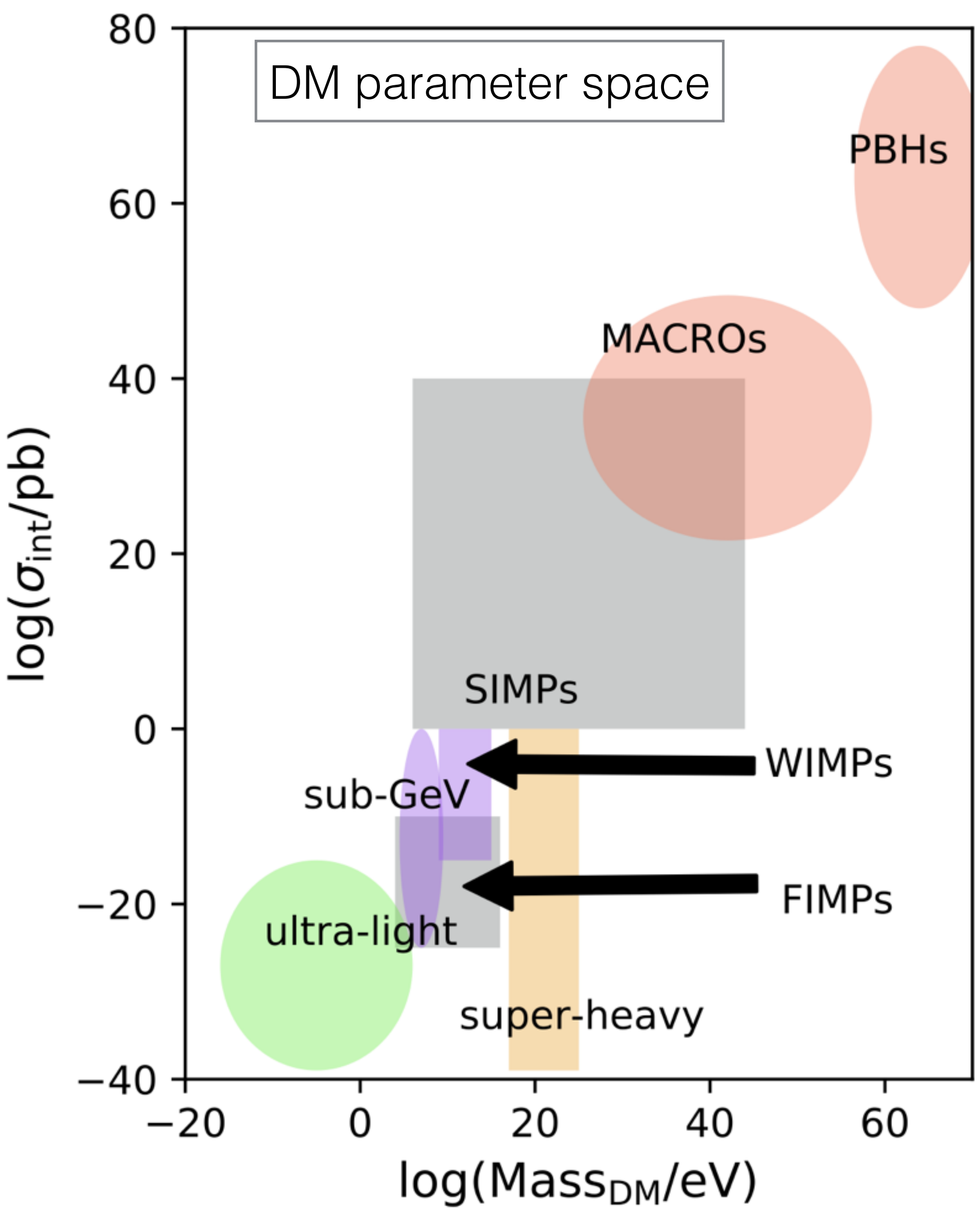

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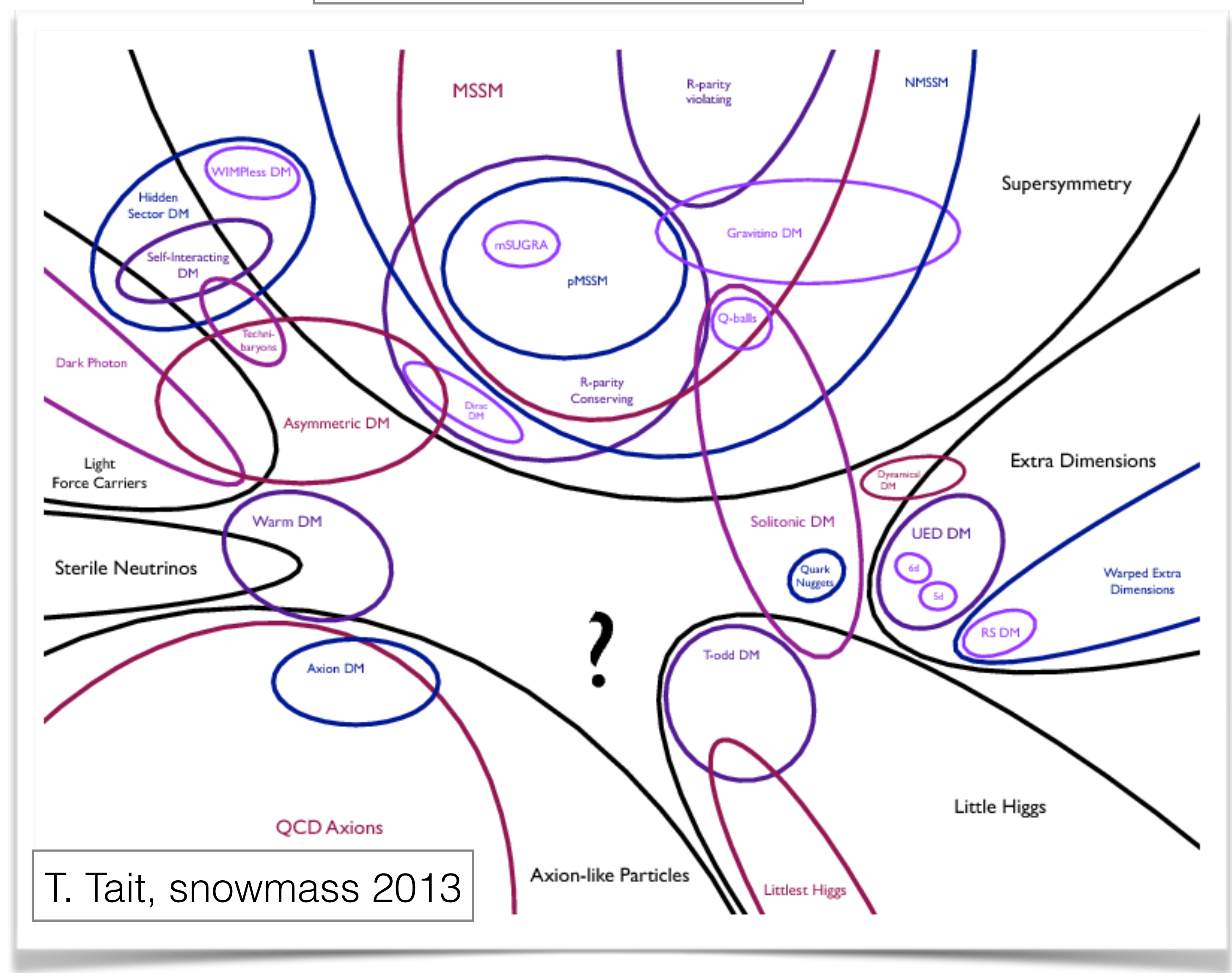

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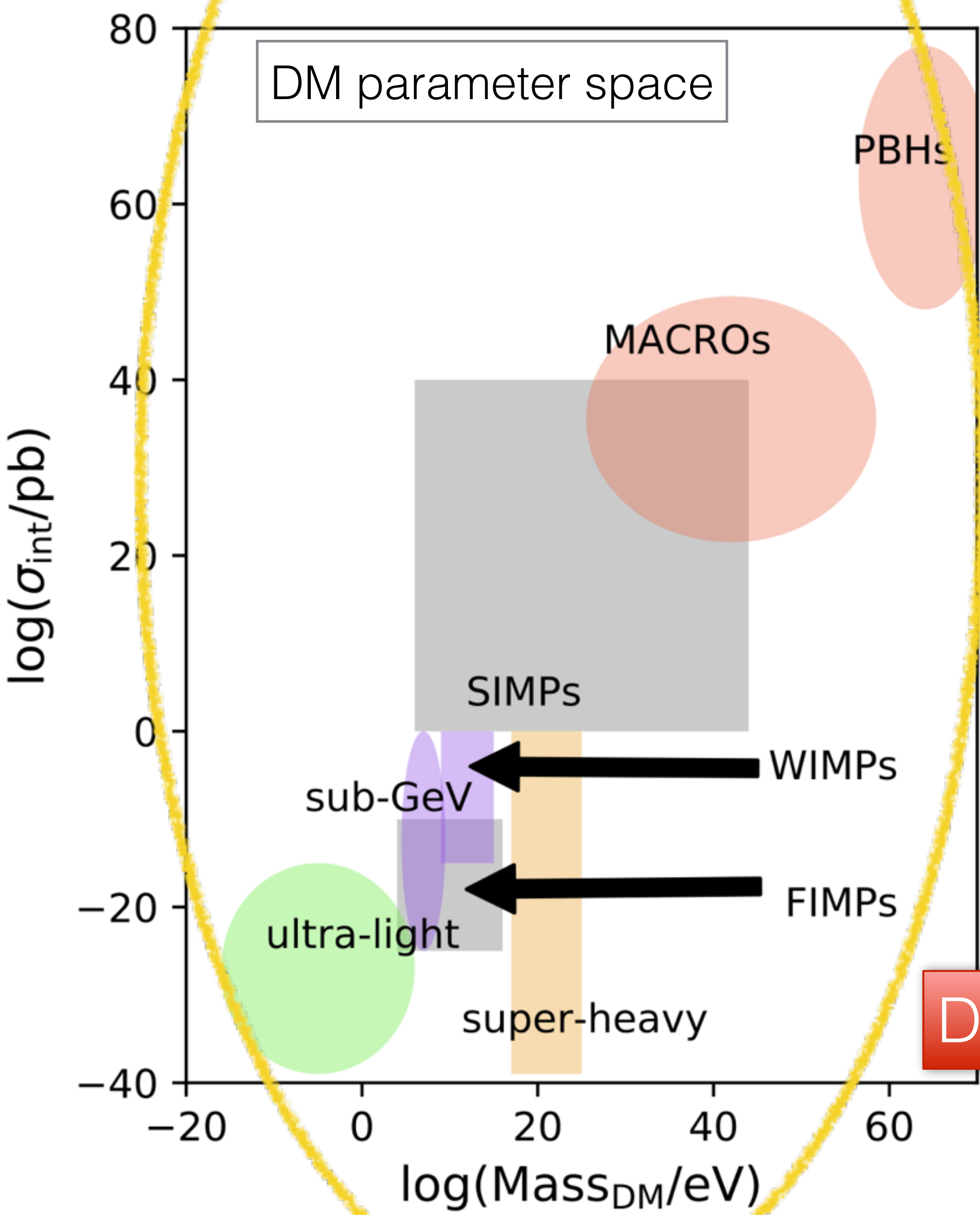
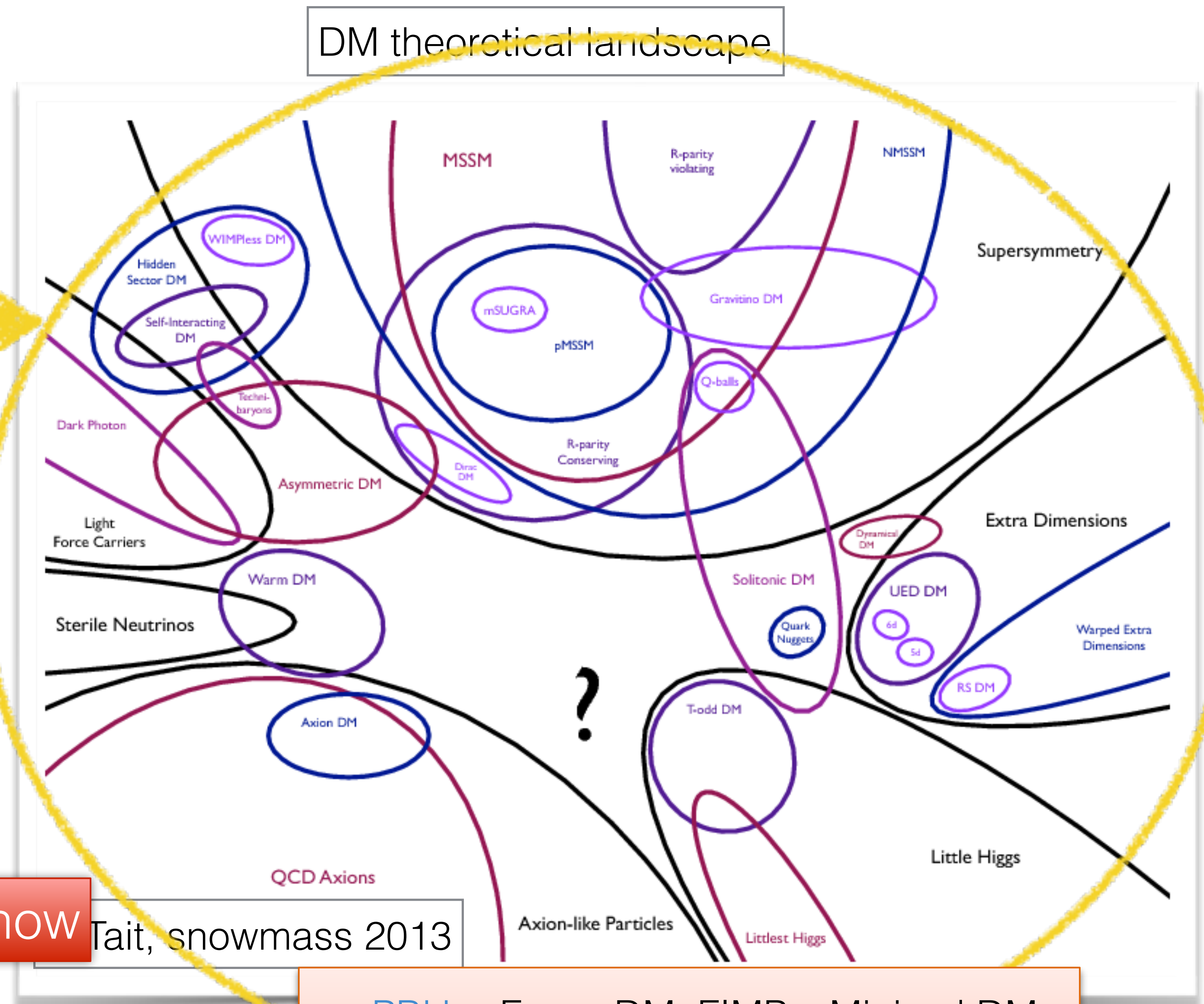


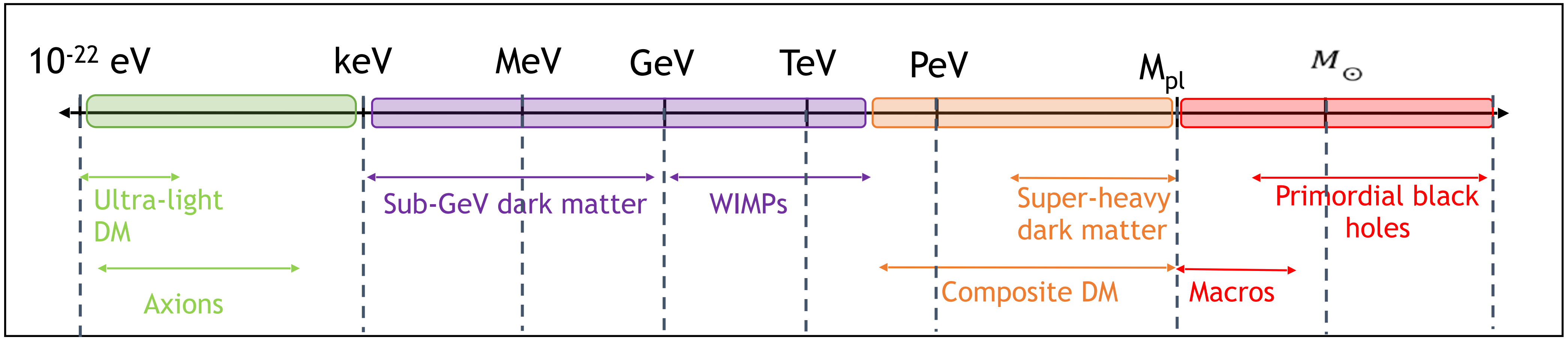
DM now



+ PBHs, Fuzzy DM, FIMPs, Minimal DM, Cannibal DM, Scalar Singlet, Magnetic Inelastic DM, Dipolar DM, WISPy DM, ….

Characterizing the DM landscape

- To have an overview of the DM landscape it is convenient to consider mass regions
- For each mass region, identify the typical signals expected to be detected, which can be related to the strength of the interaction cross-section
- Activity in the DM theory is now a days mostly data/experiment driven



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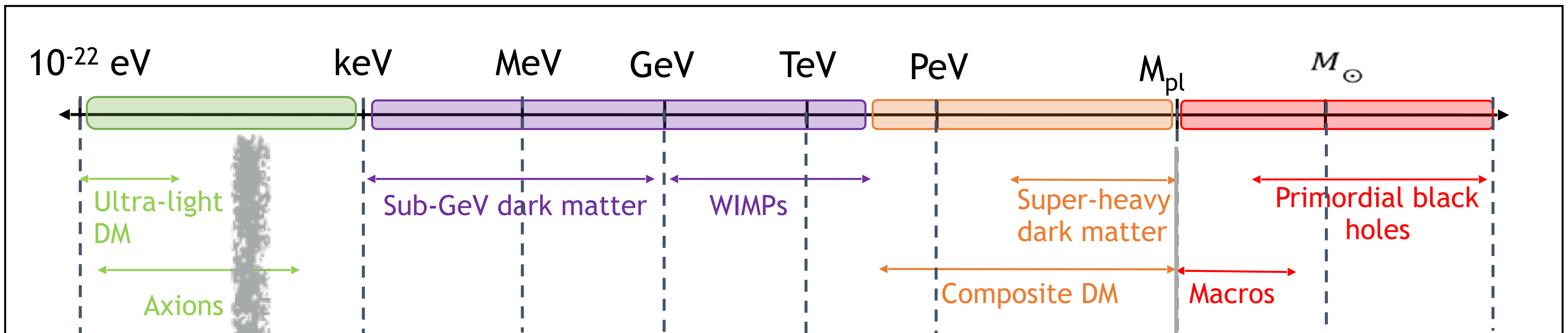

DM is a wave

DM is of particle nature (can be multi-component or composite)

DM is composite

3

1

2

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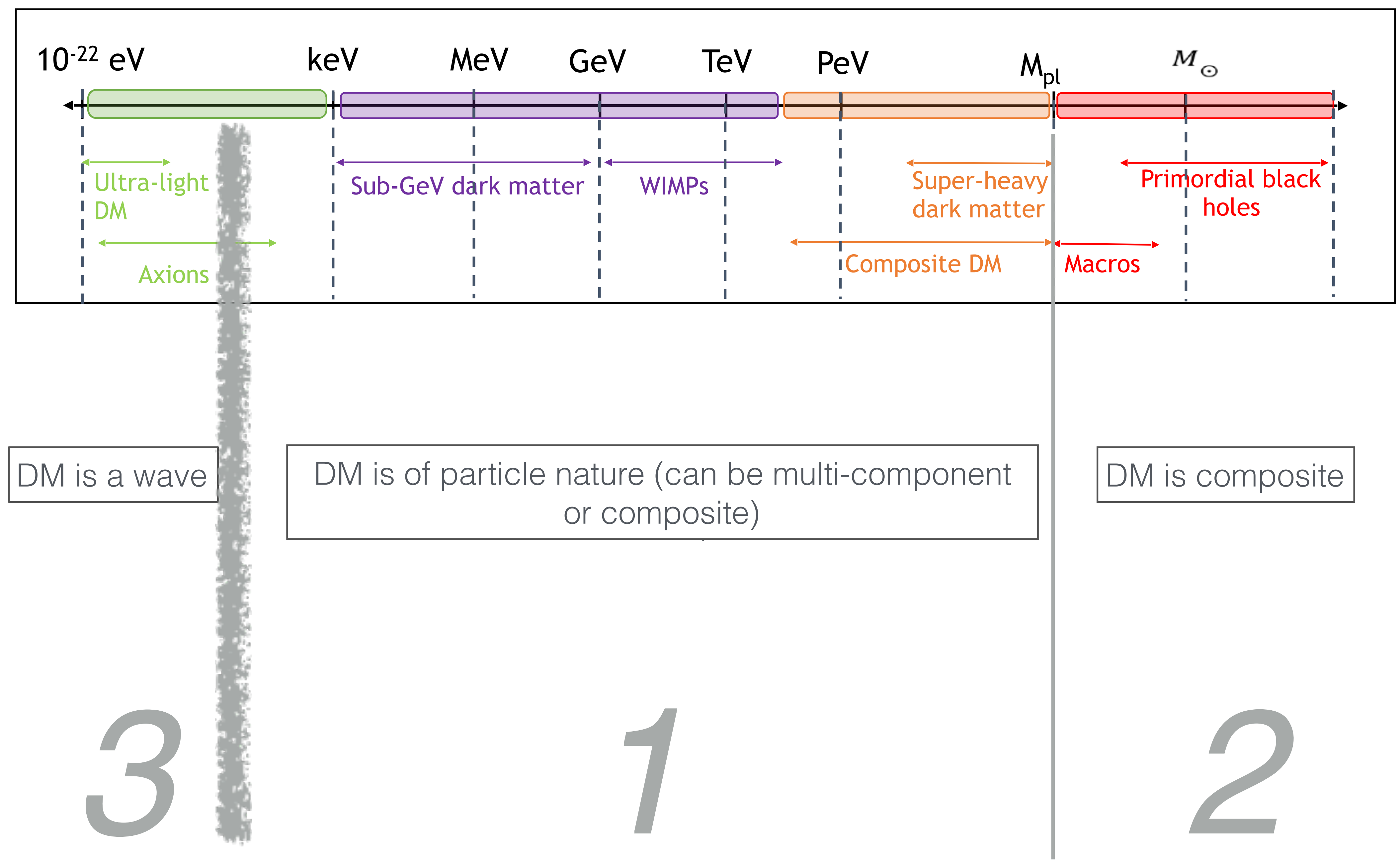

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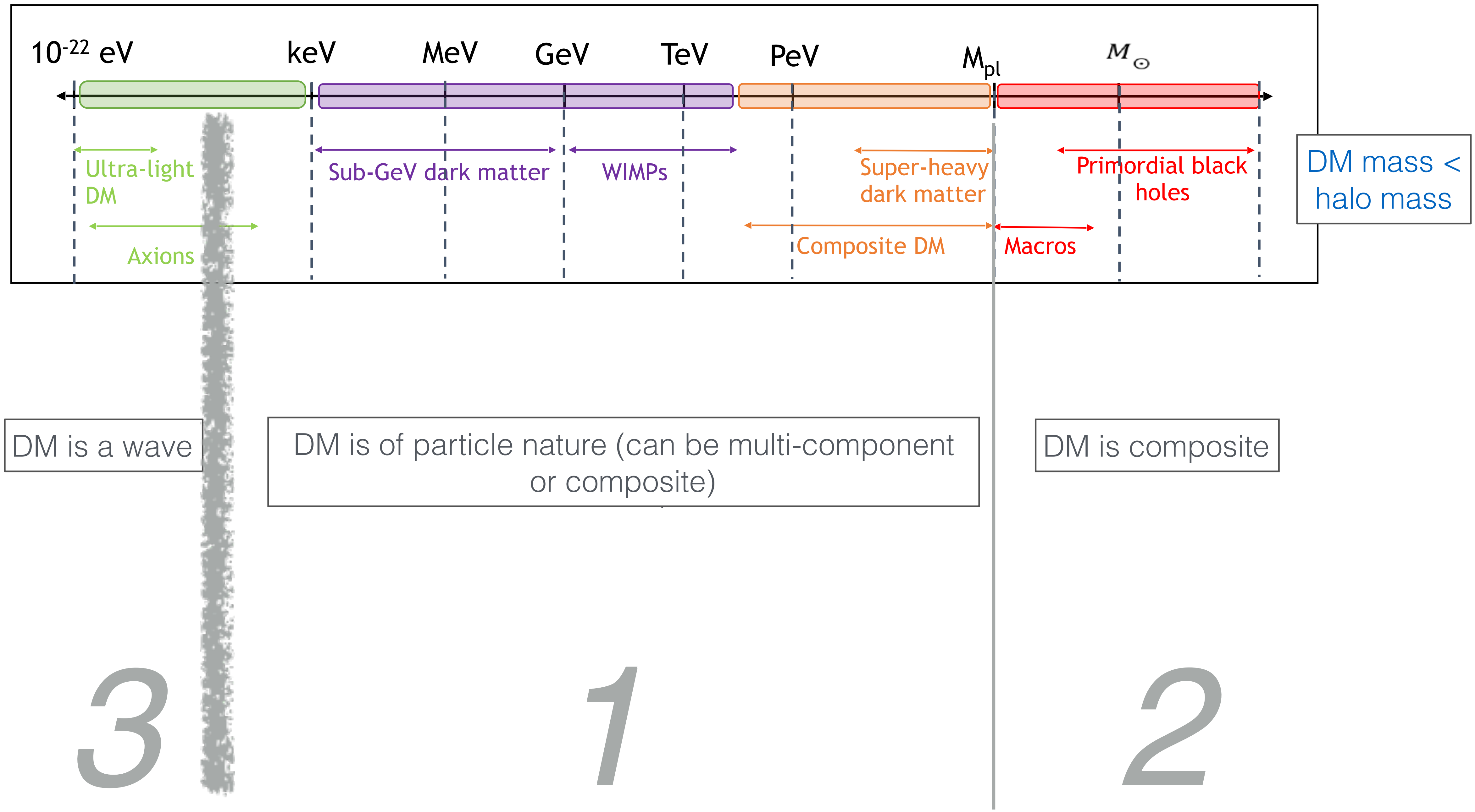

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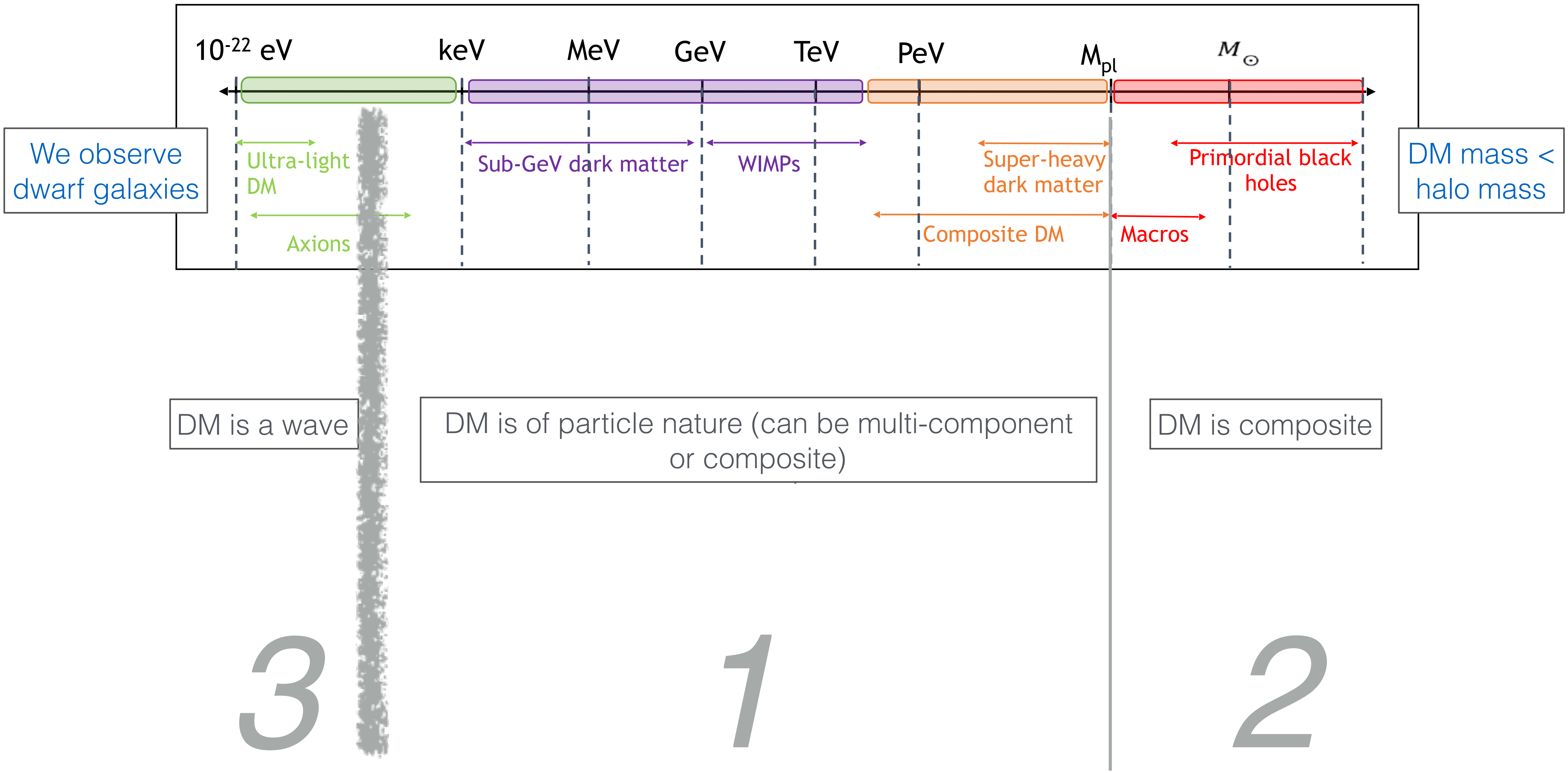

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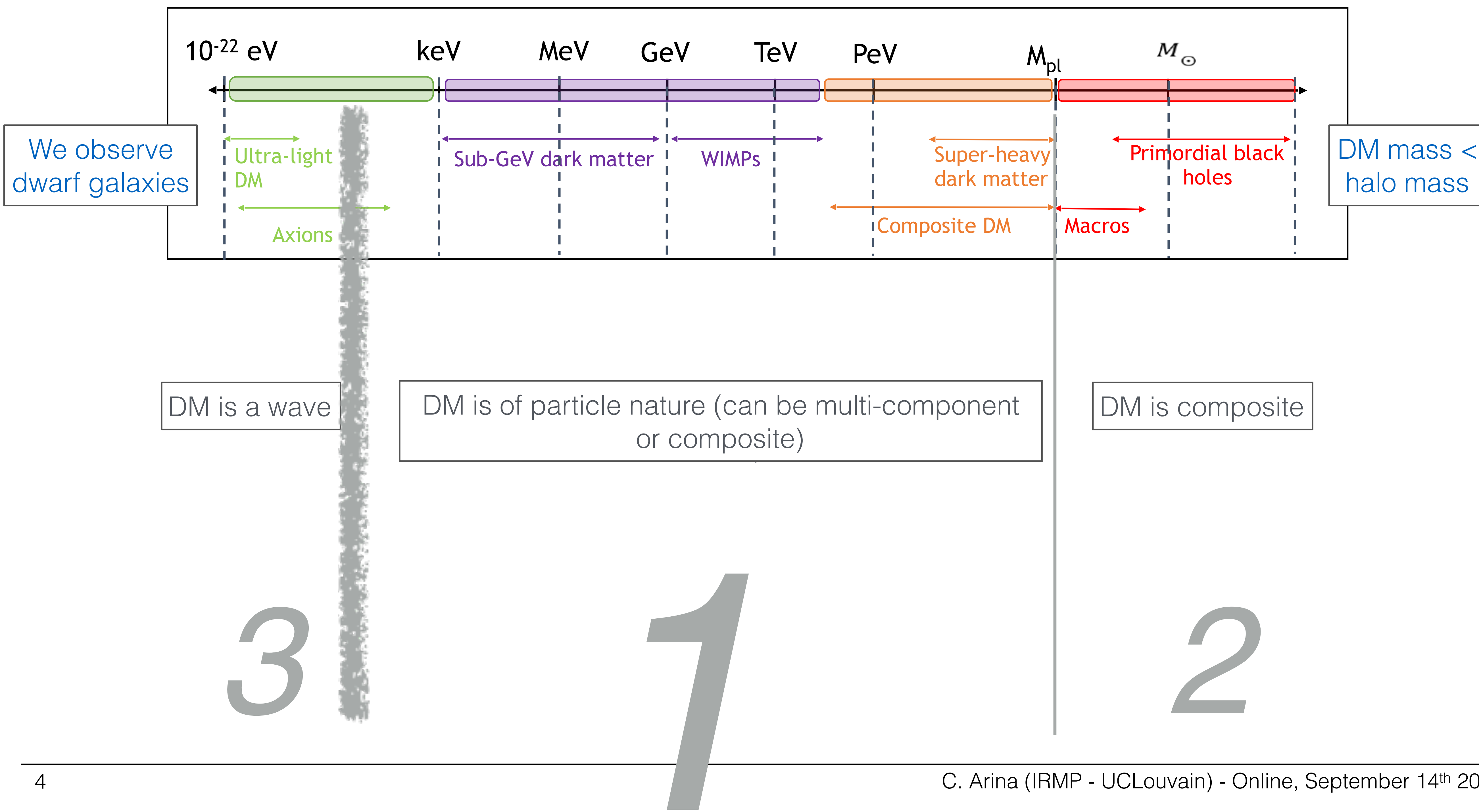
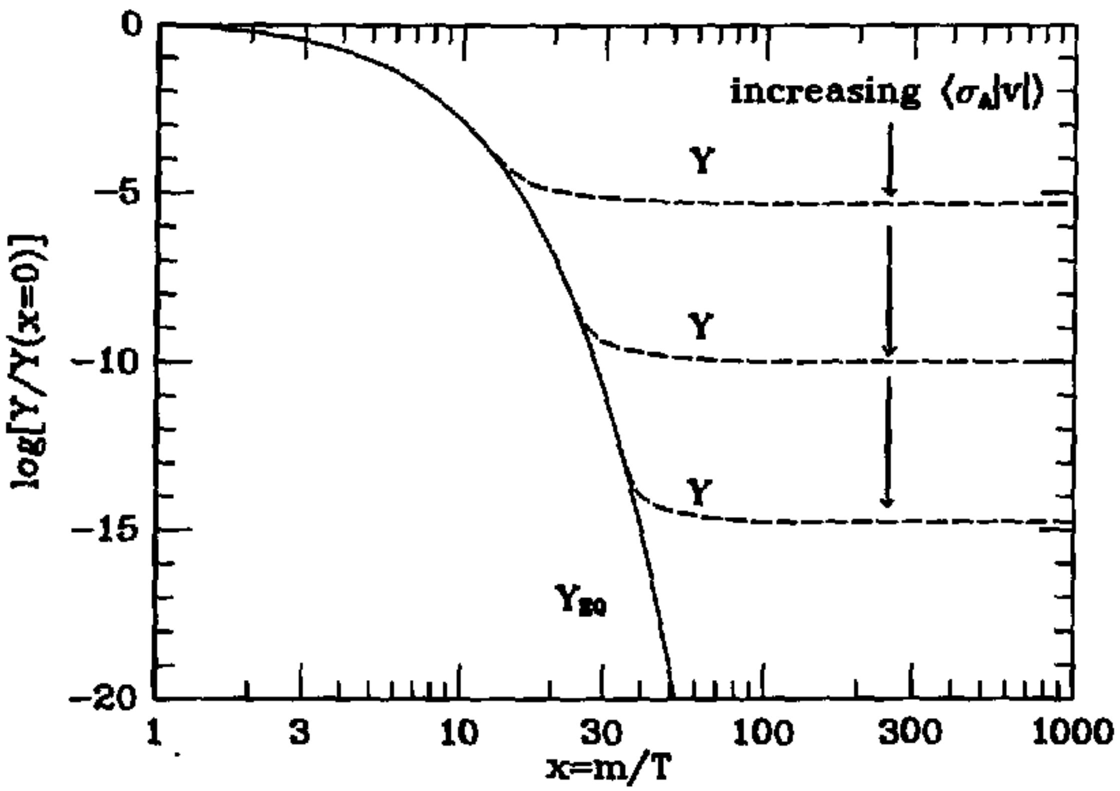


1. Longstanding Weakly Interacting Massive Particles

Lee & Weinberg '77, Gunn et al. '78, Steigman et al. '78, Kolb & Turner '81, Ellis et al. '84, Scherrer & Turner '85, Griest & Seckel '91

- Early universe WIMPs are produced via the freeze-out mechanism, based on 2 -> 2 processes $\chi + \overline{\chi} \leftrightarrow \mathrm{SM} + \overline{\mathrm{SM}}$

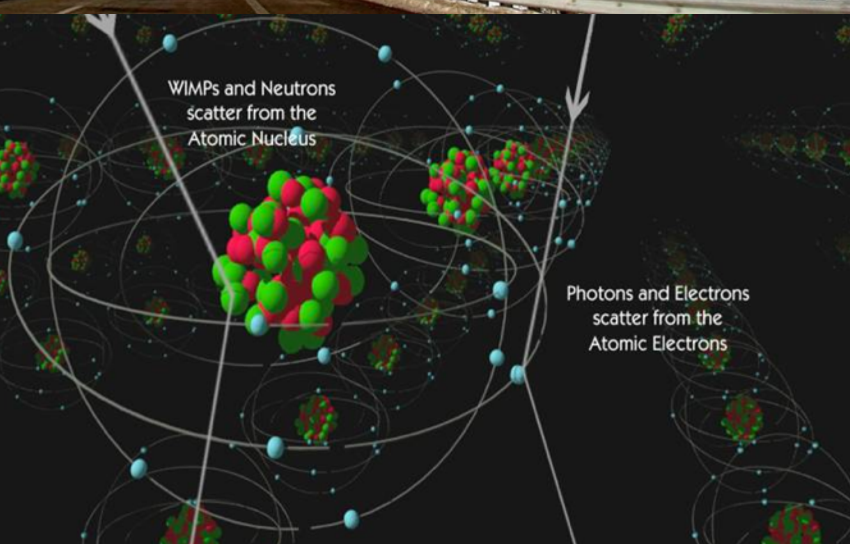


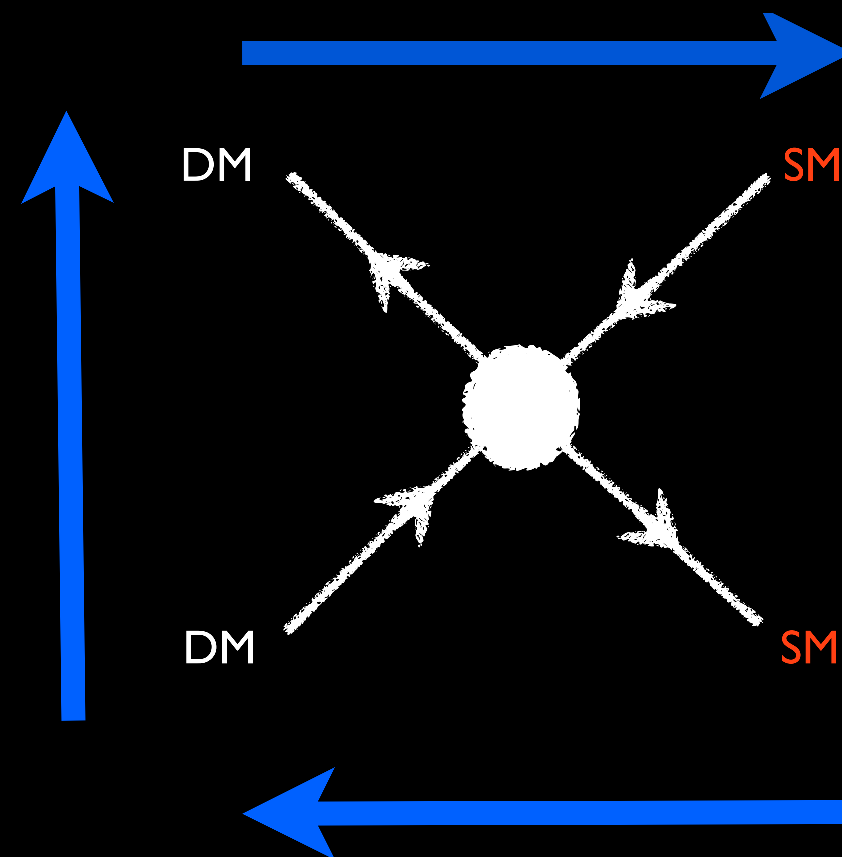
$$\Omega_{\mathrm{DM}}\mathrm{h}^2 \sim 0.3\left(\frac{10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma_A v>}\right)$$

$$<\sigma_A v> \sim \frac{g^2}{m_\chi^2} \sim \frac{0.01^2}{(100\ \mathrm{GeV})^2} \sim 8\times 10^{-25}\mathrm{cm}^3\mathrm{s}^{-1}$$

Many BSM models predict particles in the WIMP ballpark of mass and annihilation cross-section (SUSY, Kaluza-Klein, …)

1. WIMPs are expected to provide a (multitude of) signal(s)





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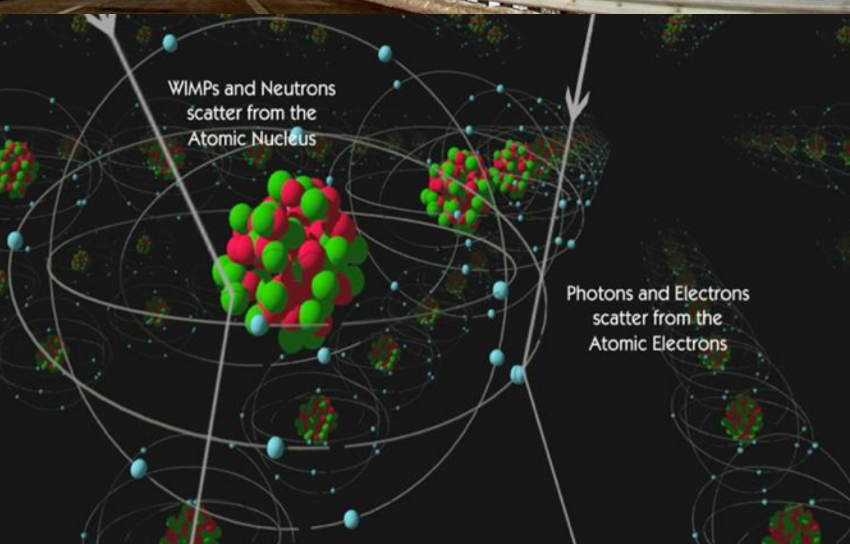
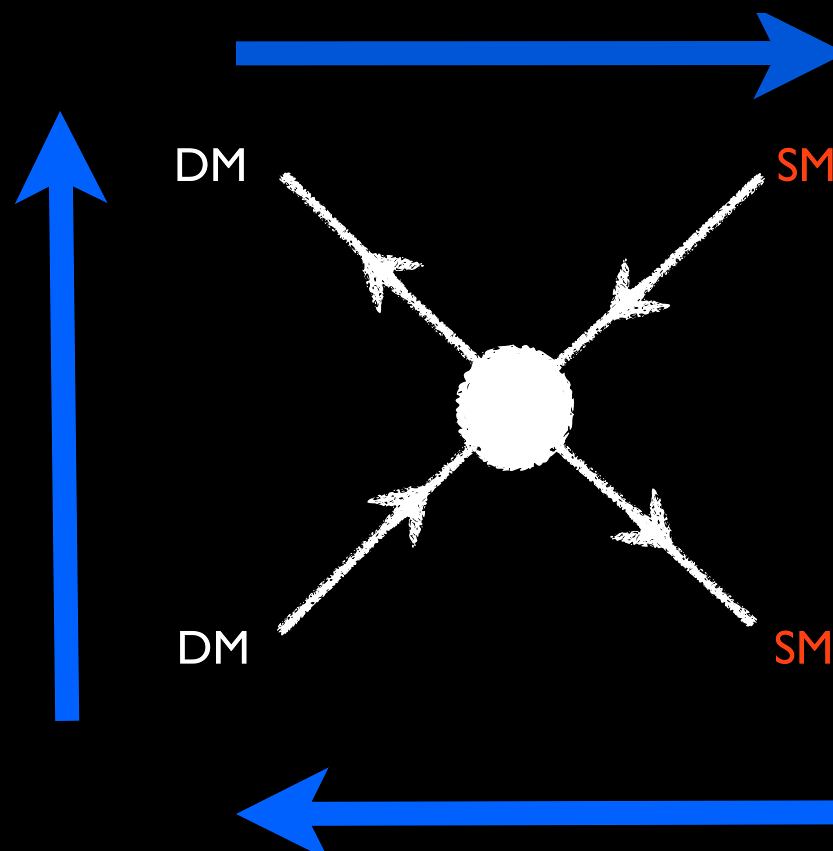


Indirect detection
(Freeze-out early Universe)



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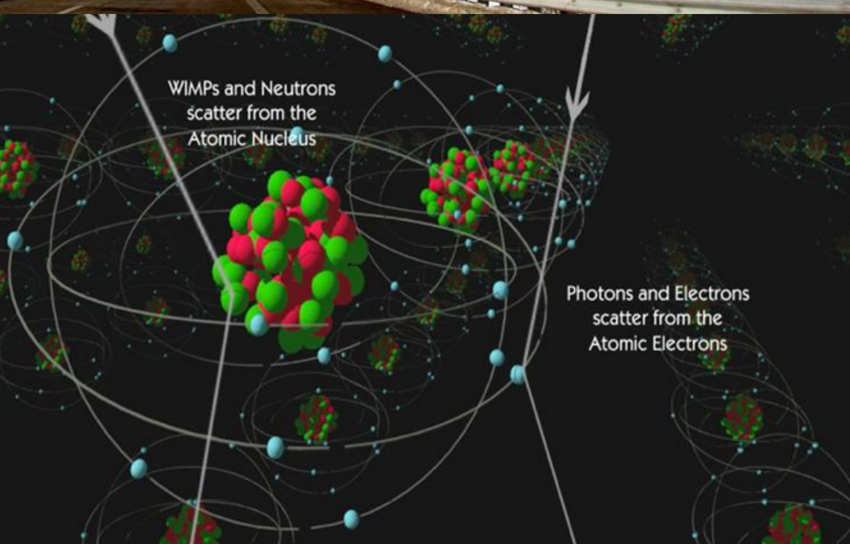

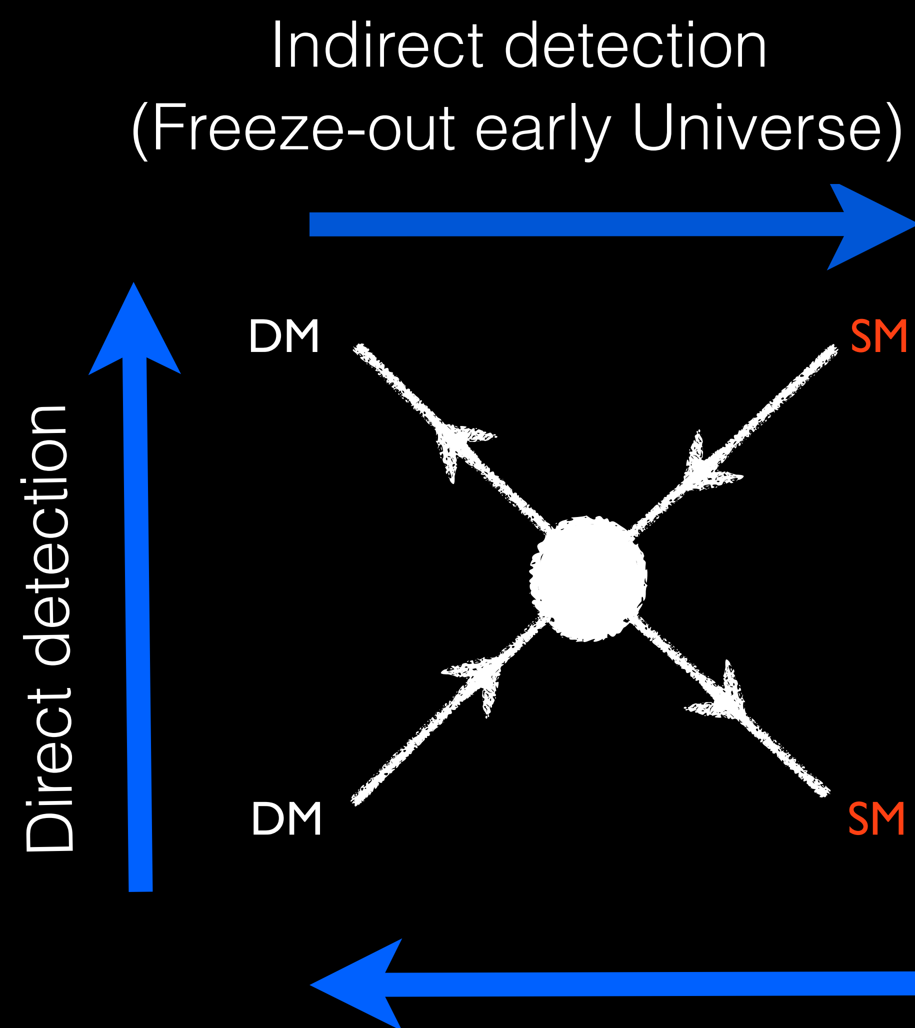

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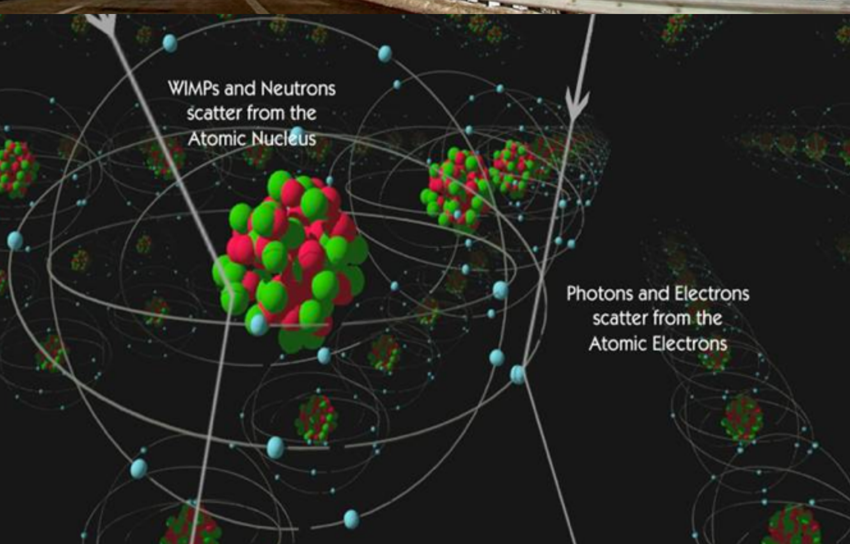

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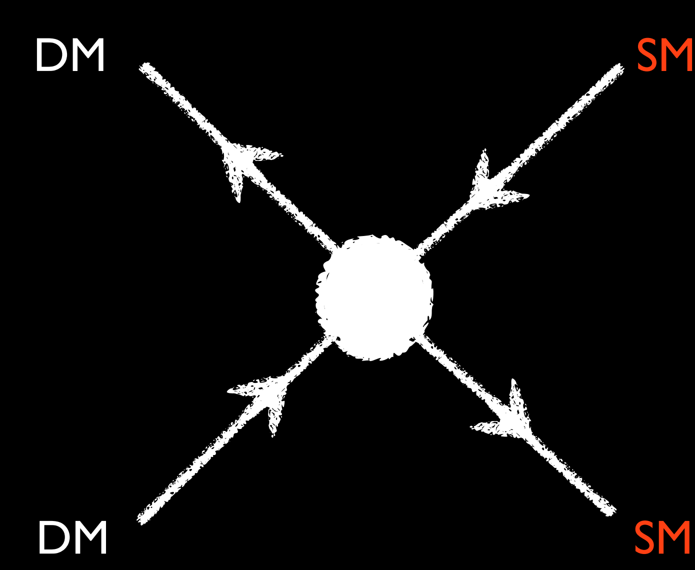
Direct detection



Production at colliders

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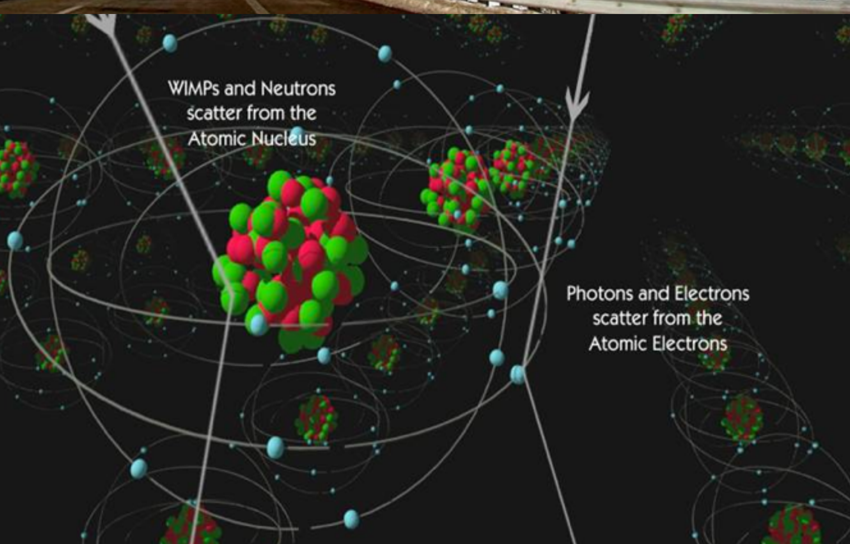

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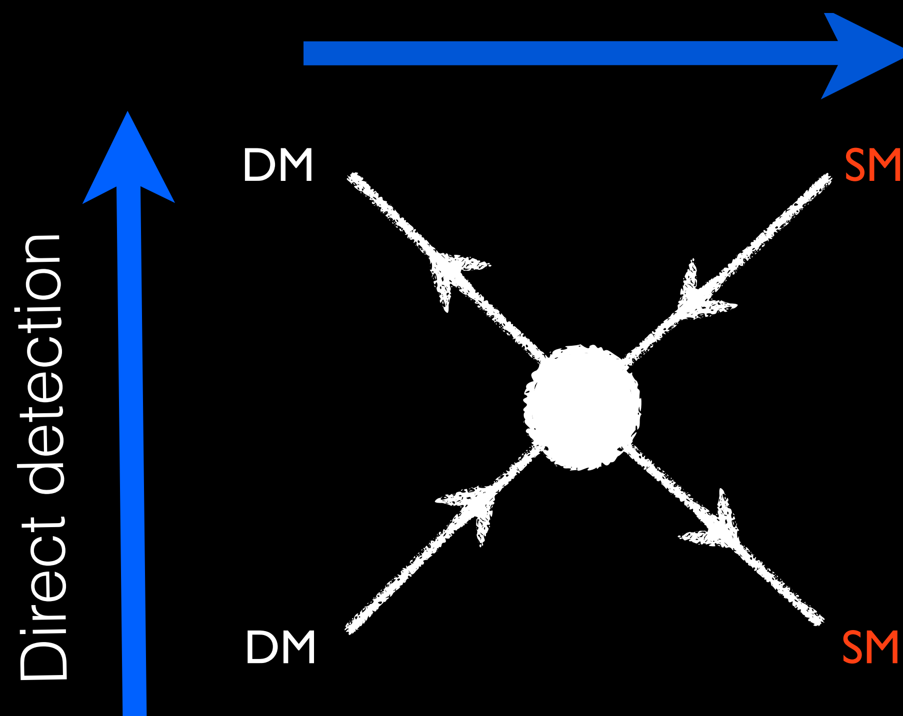


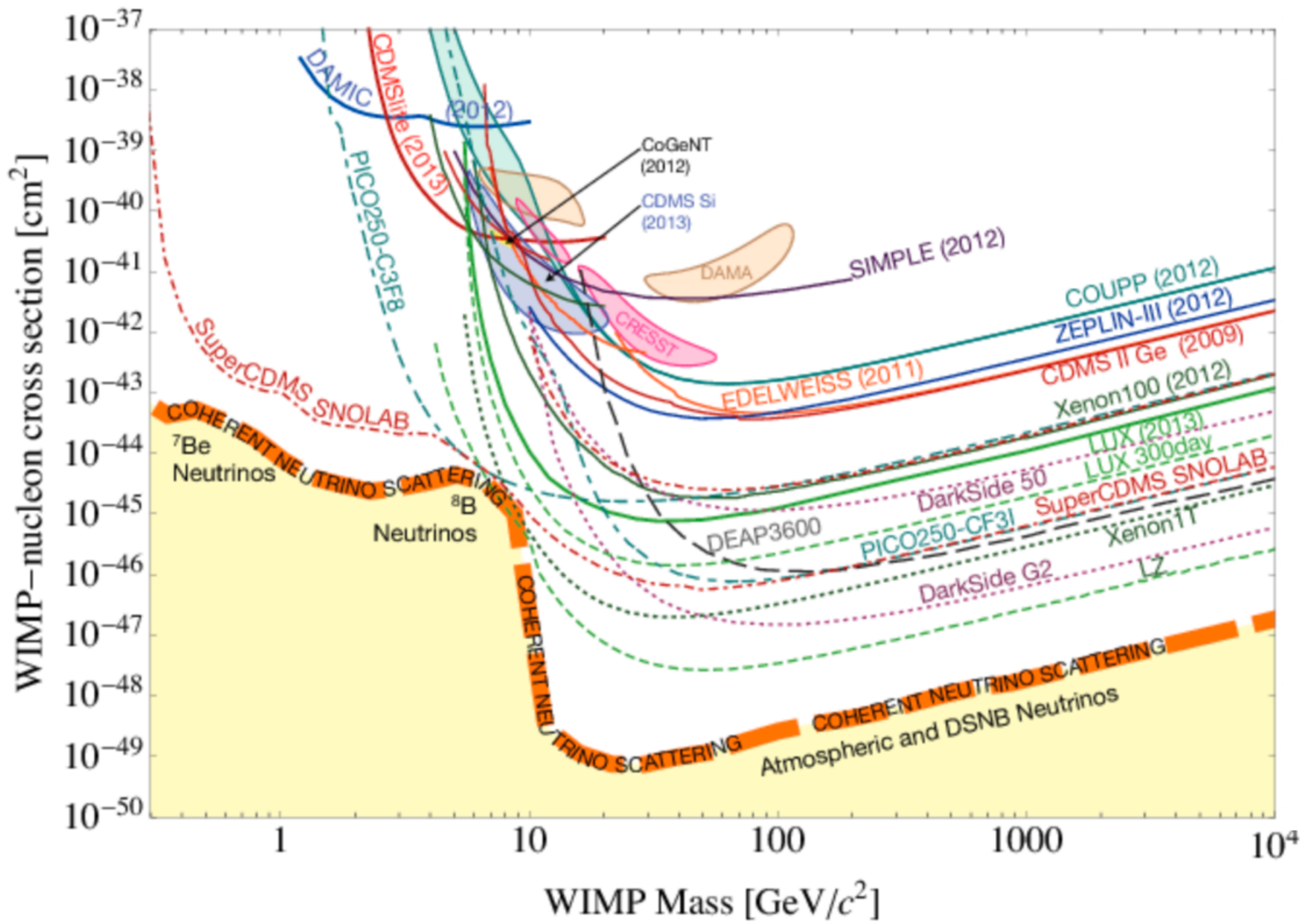
Production at colliders

Lot of activity in terms of Simplified Models (scalar or vector mediators, t-channel searches…)

See talks by P. Pani and M. Colucci

1. WIMPs: direct detection (dd)

Direct detection experiments, see talk by Di Gengi (XENON) and Suvorov (DarkSIDE)



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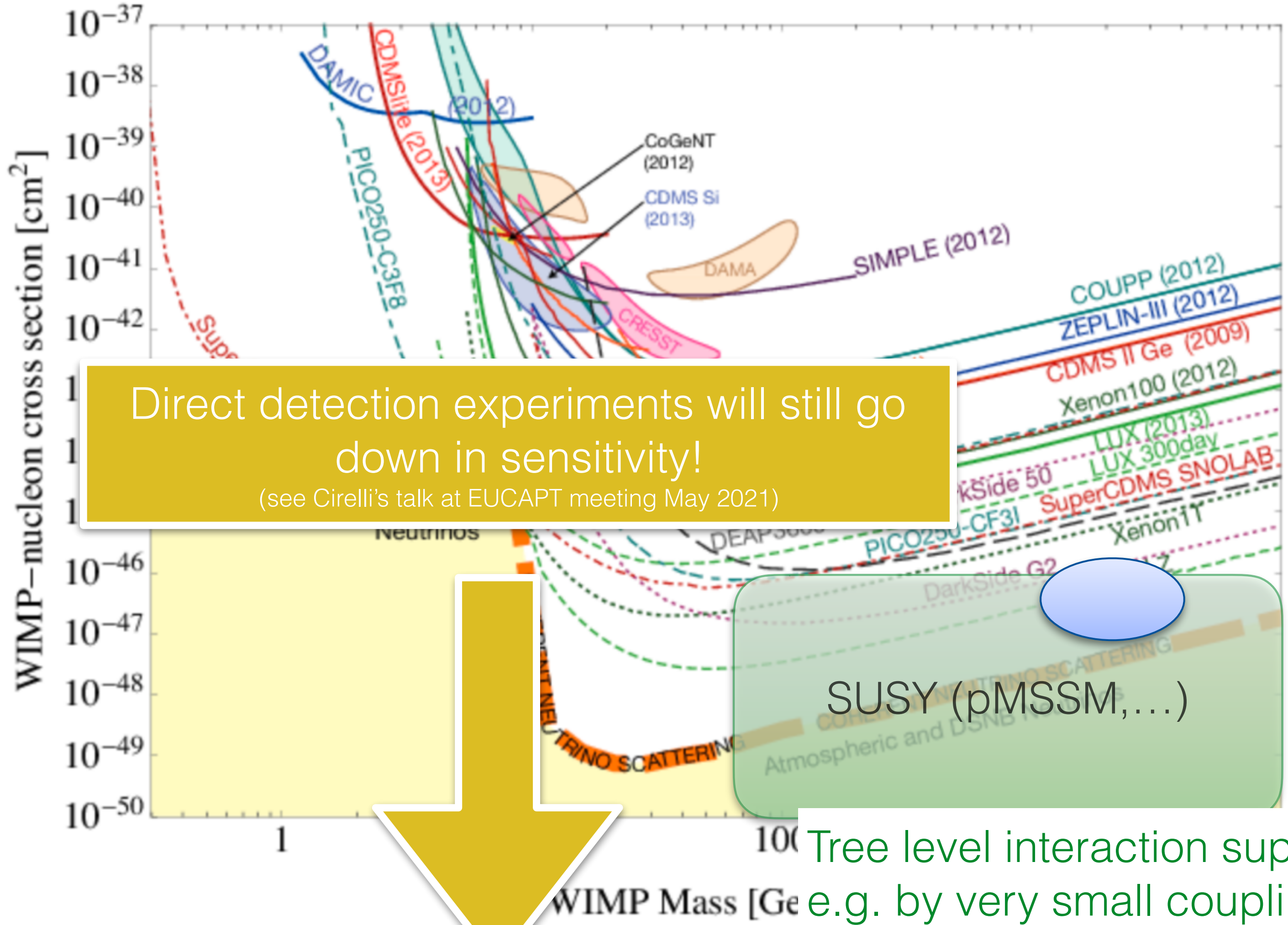
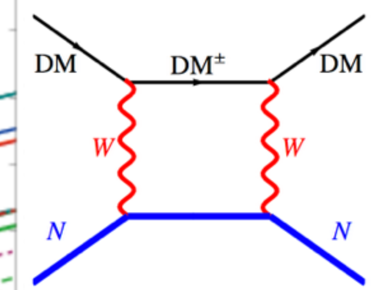


Direct detection experiments will still go down in sensitivity!

(see Cirelli's talk at EUCAPT meeting May 2021)

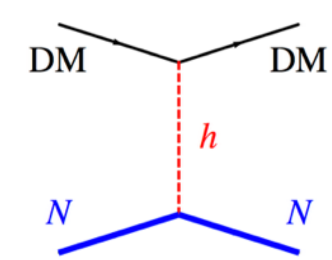
SUSY (pMSSM,…)



Minimal DM, one-loop interaction

(Cirelli, Fornengo, Strumia 2005)

Tree level interaction suppressed e.g. by very small coupling or by heavy mediator mass



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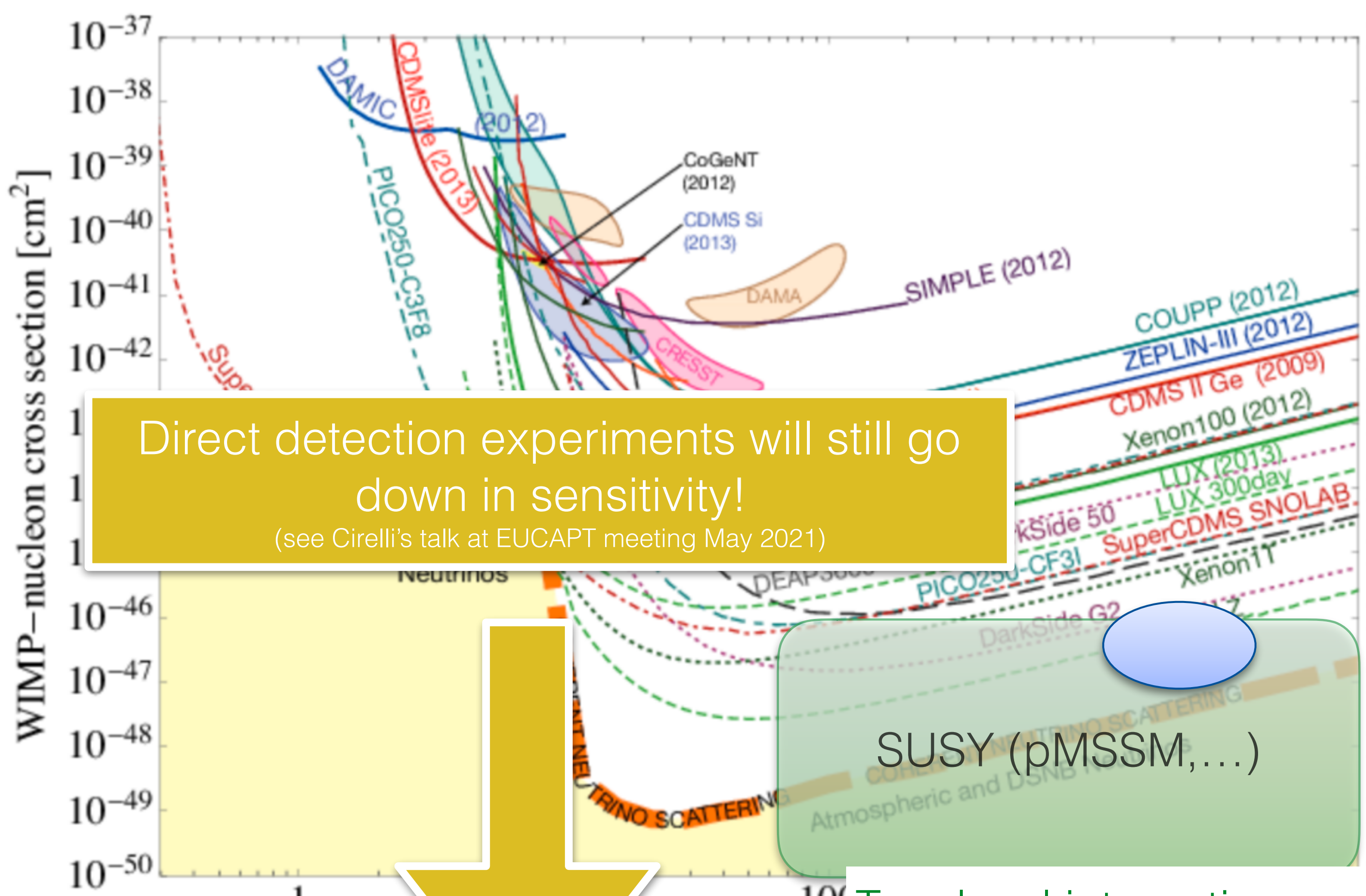

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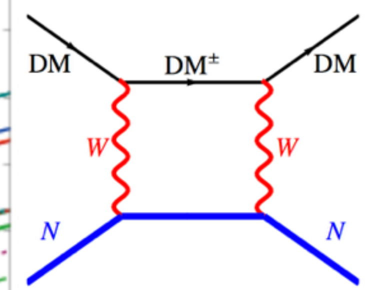

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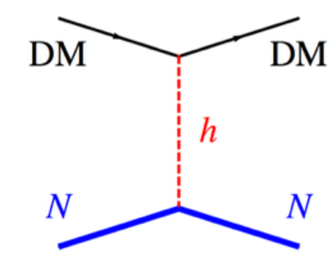

Standard SI interaction still many viable models e.g. SUSY, leptophilic models, minimal DM, …
Great potential for discovery in the next few years

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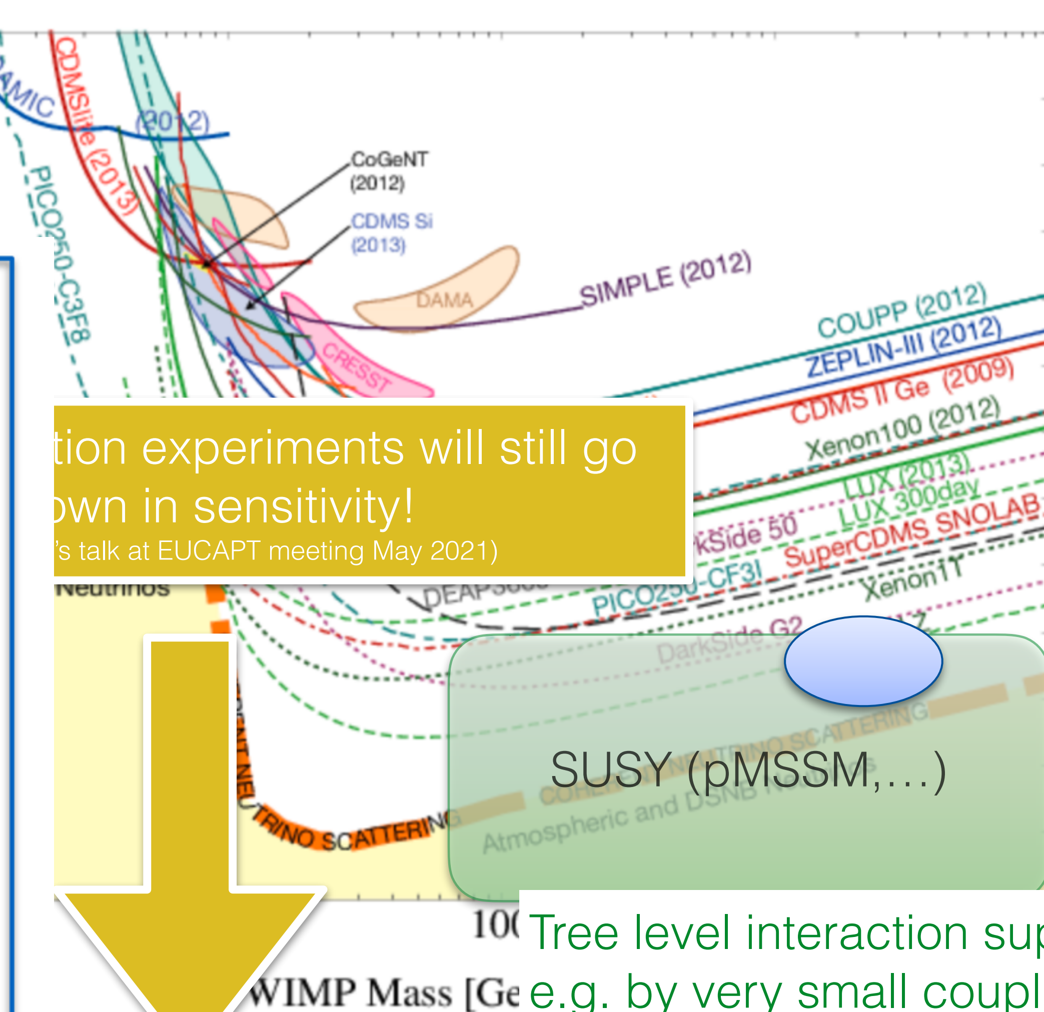

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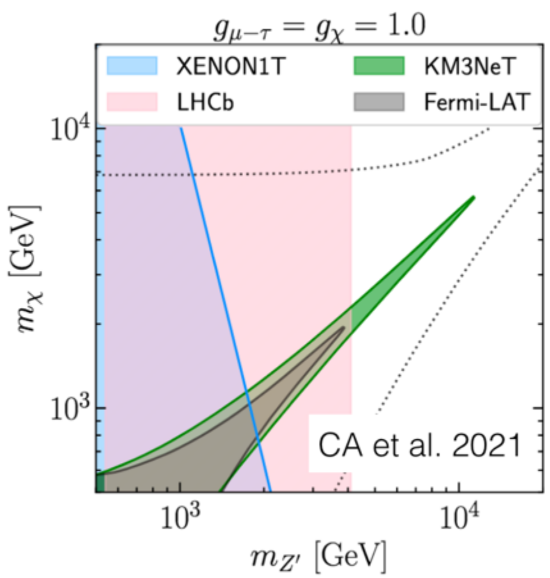

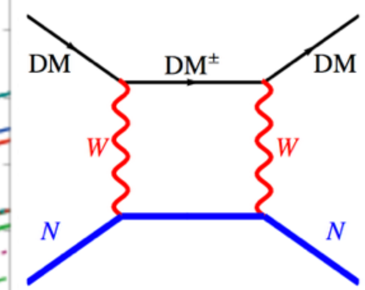

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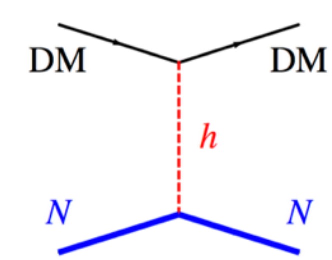

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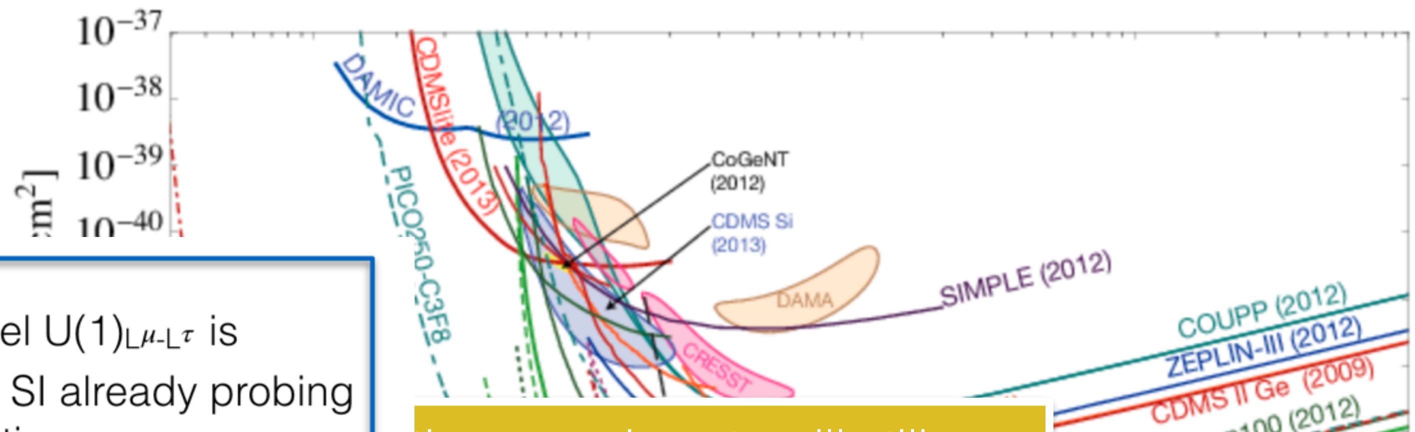

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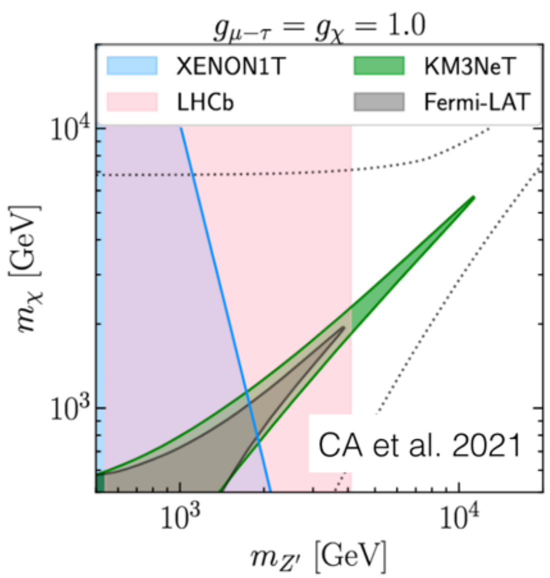

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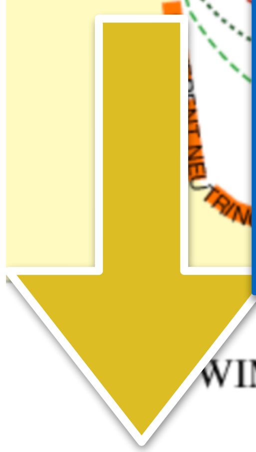
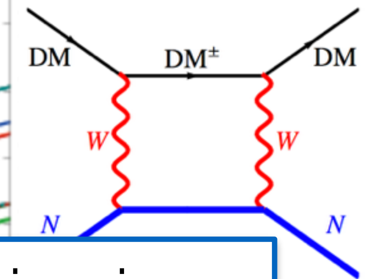


CAVEAT: If DM scattering is suppressed by its velocity (10^{-3}) it can not be seen in dd

(Coy dark matter, Boehm et al. 2013; CA, Panci, Del Nobile 2014; Secluded DM CA et al 2017, Pseudo Goldstone Boson DM CA et al. 2019)



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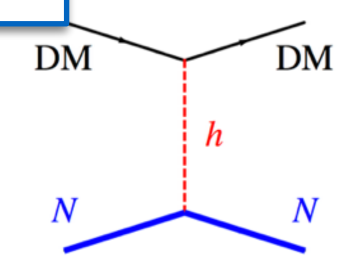

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1. Light DM

WIMP
from galactic halo

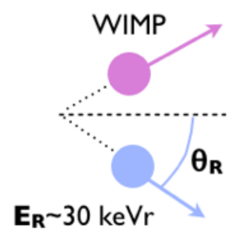
v ~ 230 km/s

Target Nucleus
in laboratory

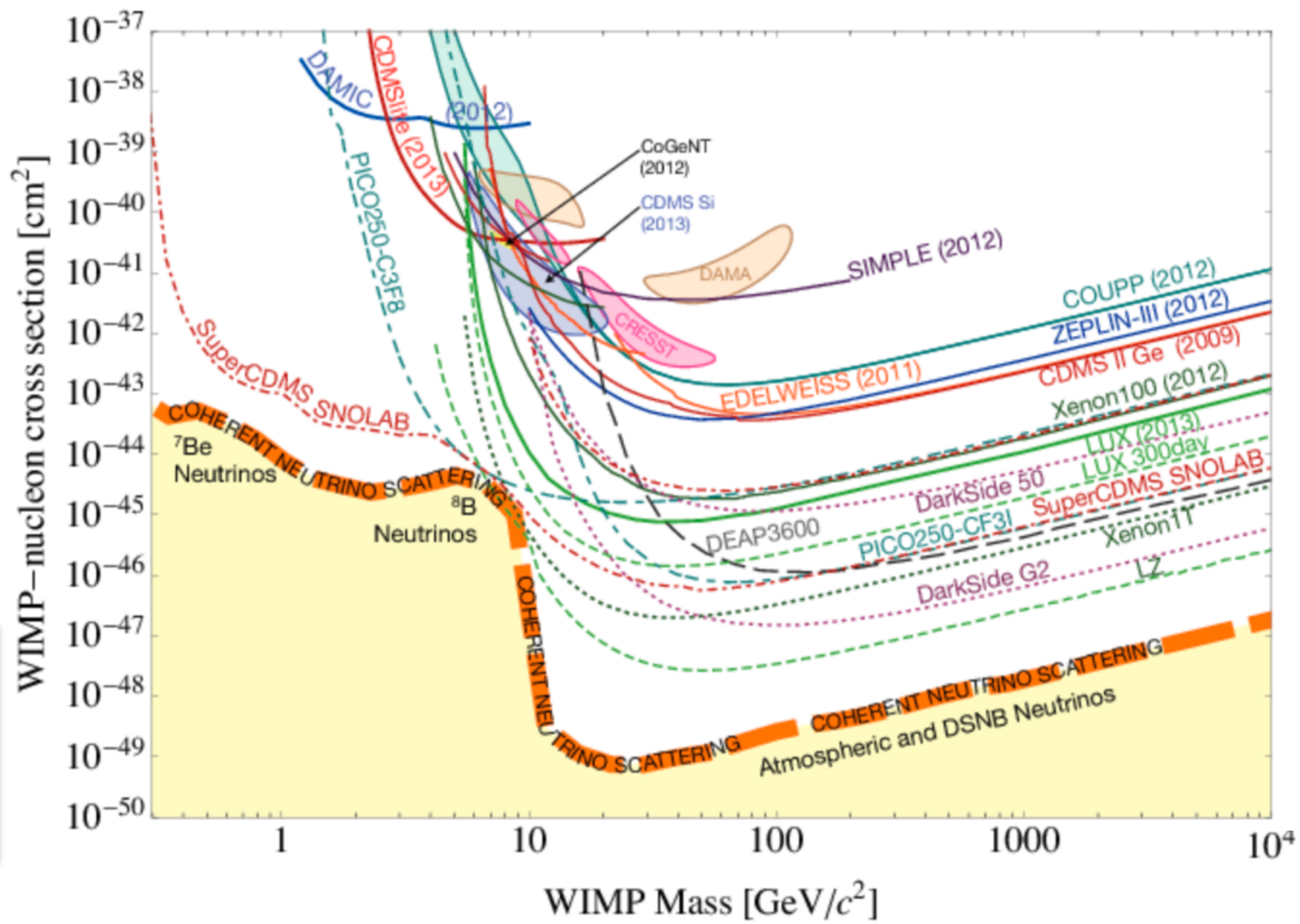
v_T ~ 0 km/s

Elastic collision

$$E_R = \frac{\mu^2 v^2}{m_T}(1 - \cos\theta)$$



DM-nucleus scattering limited in sensitivity for light DM, signal below threshold



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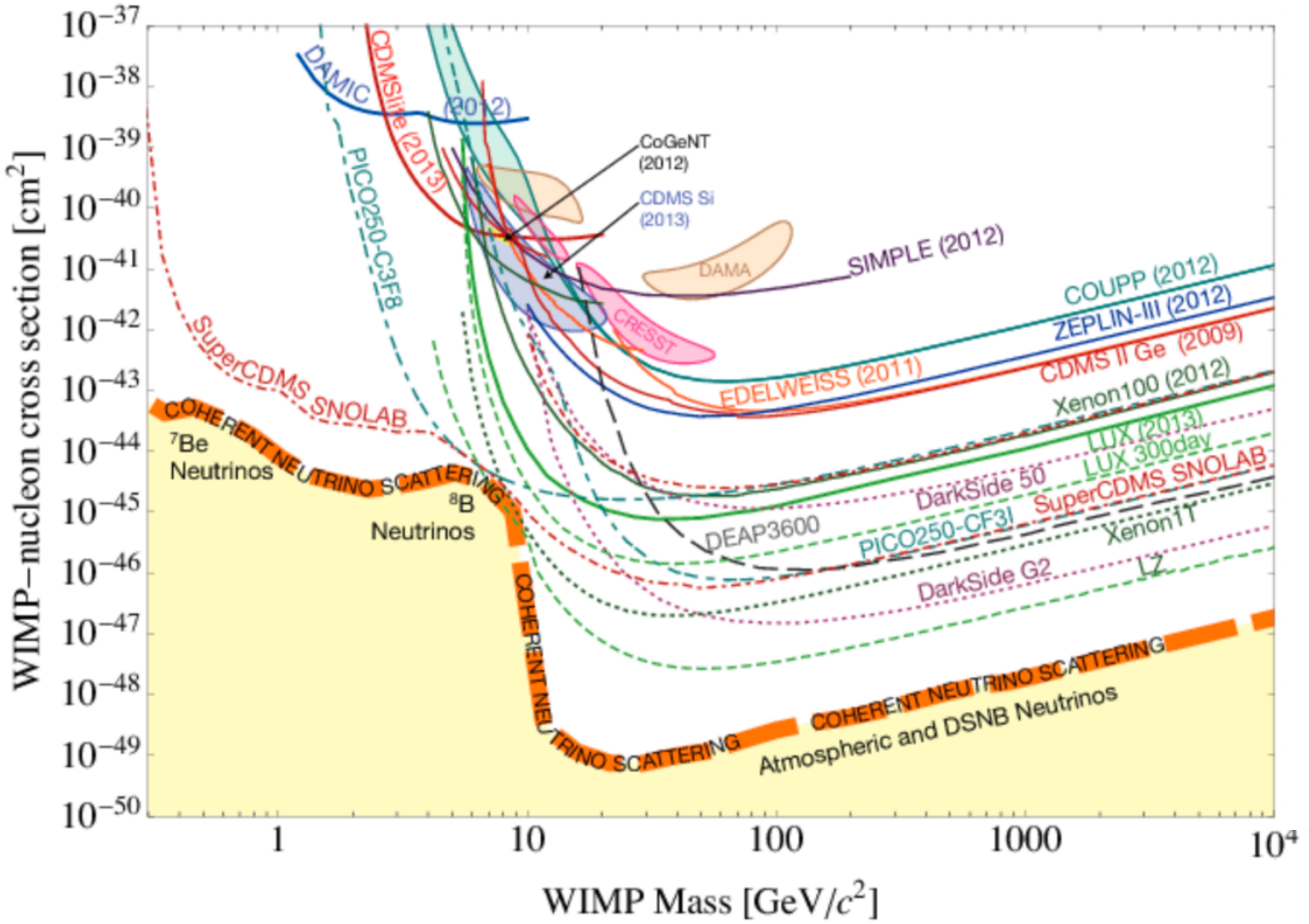
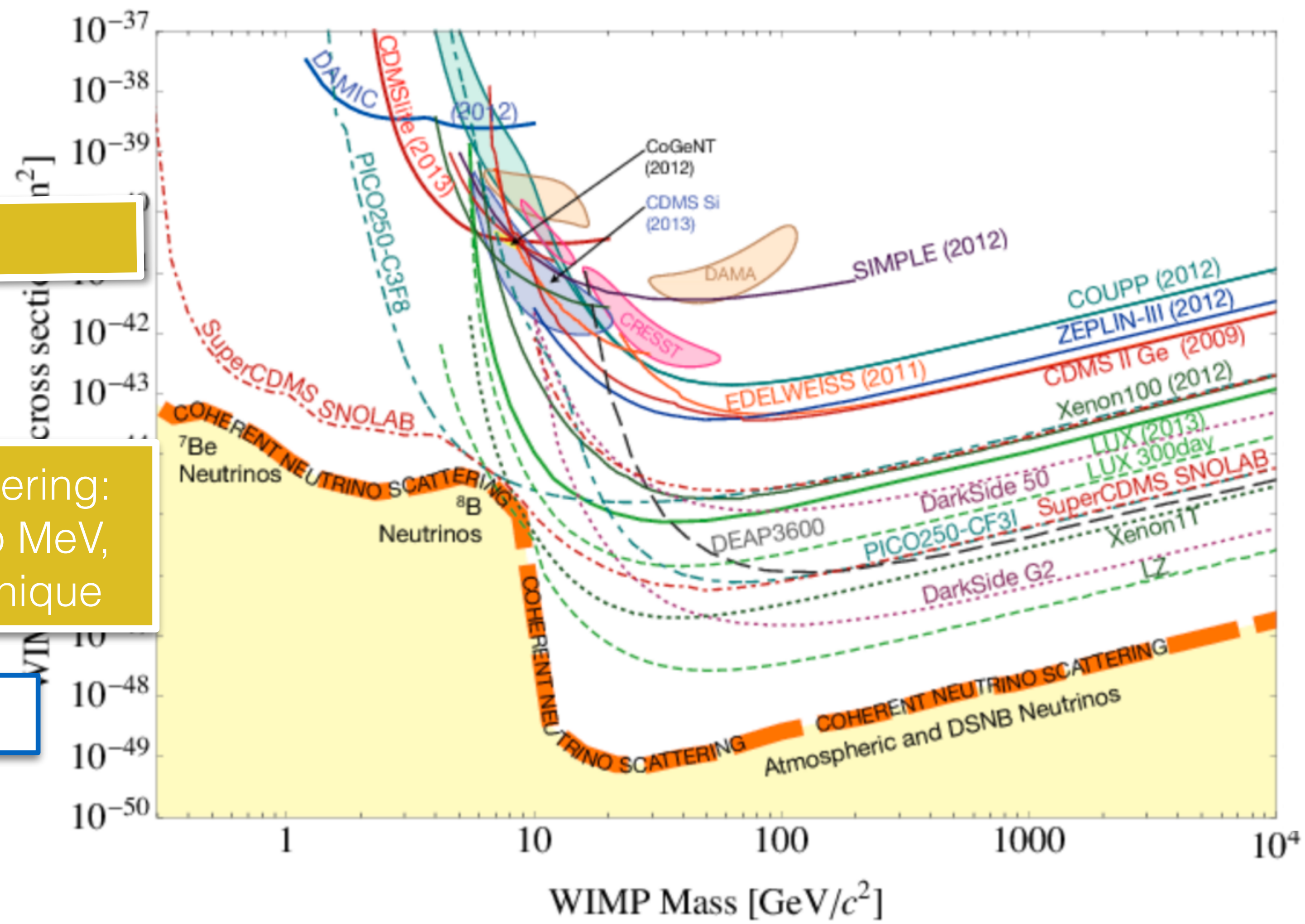


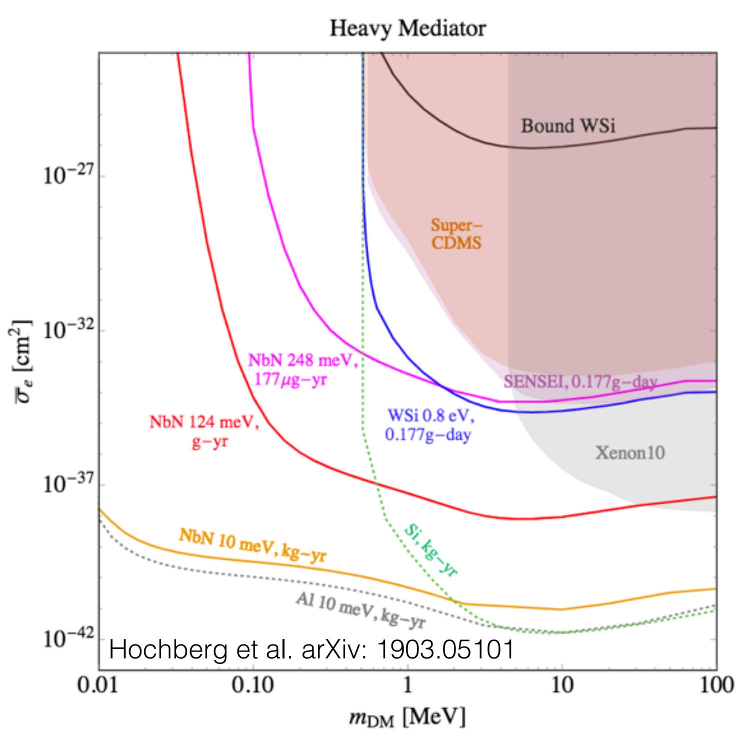
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
DAMIC
(2012)
CDMSlite (2013)
PICO250-C3F8
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
LUX 300day
DarkSide 50
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos

1. Light DM



The next step is DM-electron scattering: able to probe DM masses down to MeV, KeV or eV depending on the technique

Y. Hochberg e al., K. Zurek et al.



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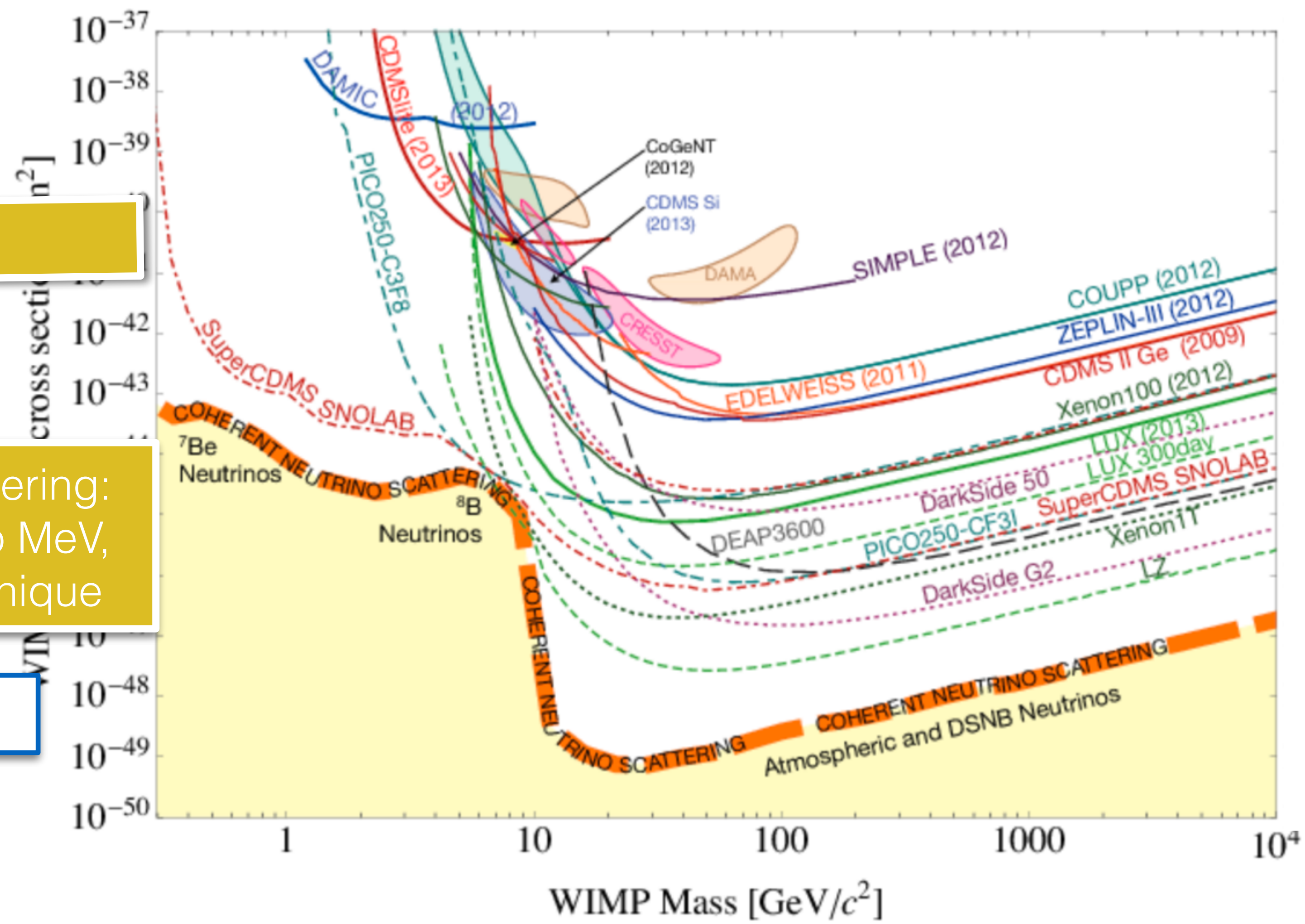

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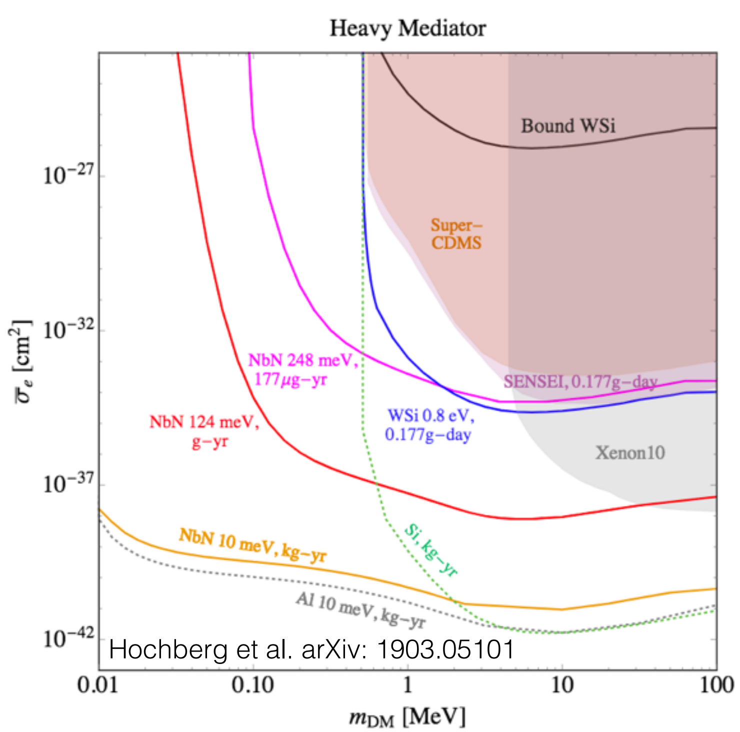
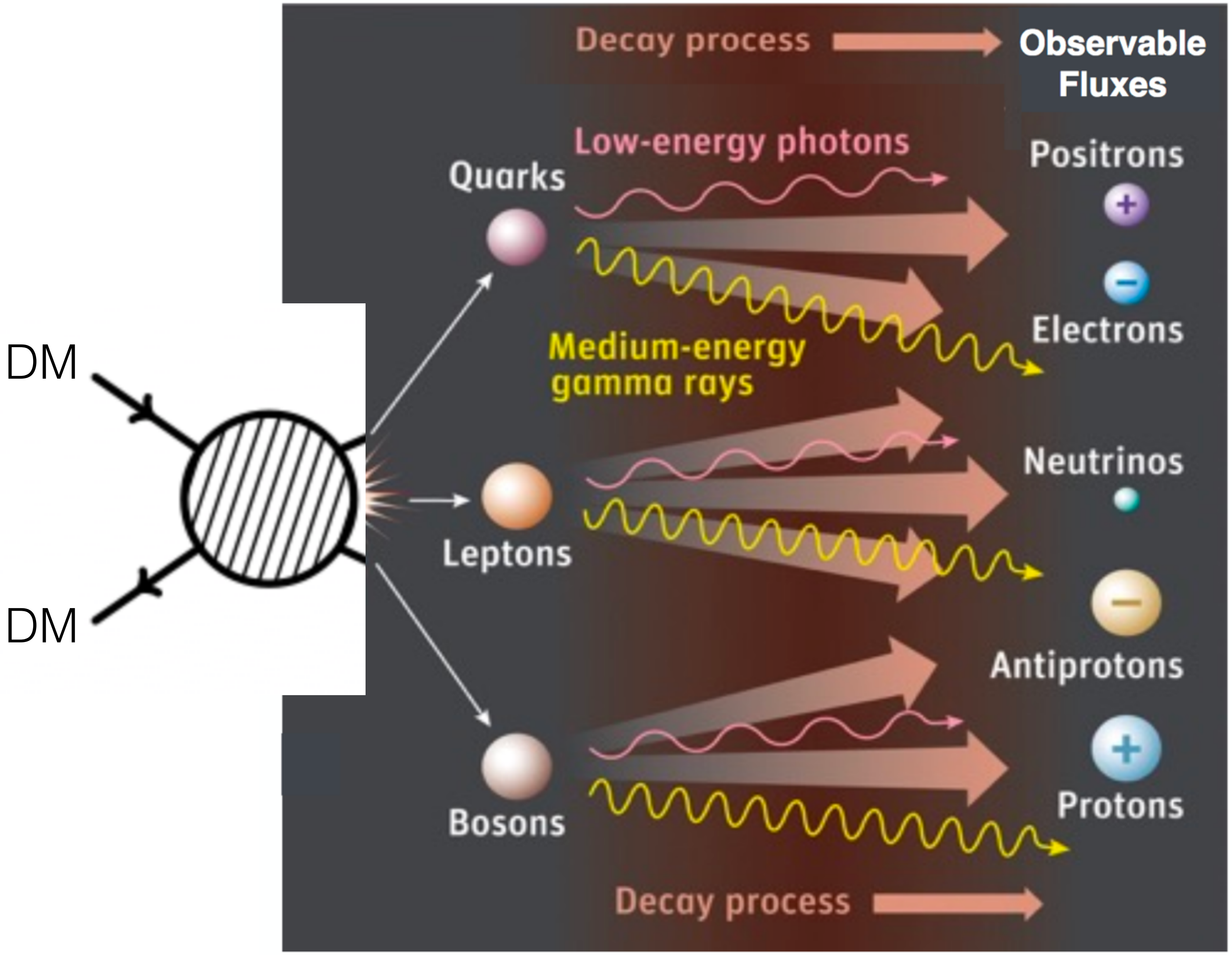


Models of sub-GeV DM:

- Boehm & Fayet 2003, light scalar DM to explain the 511 KeV integral signal
- WIMPless dark matter (or hidden sector DM) Feng, Kumar 2008
- SIMPs, something like dark-QCD (Hochberg et al. 2014)
- …

1. WIMPs: Indirect detection (id)

Prompt flux



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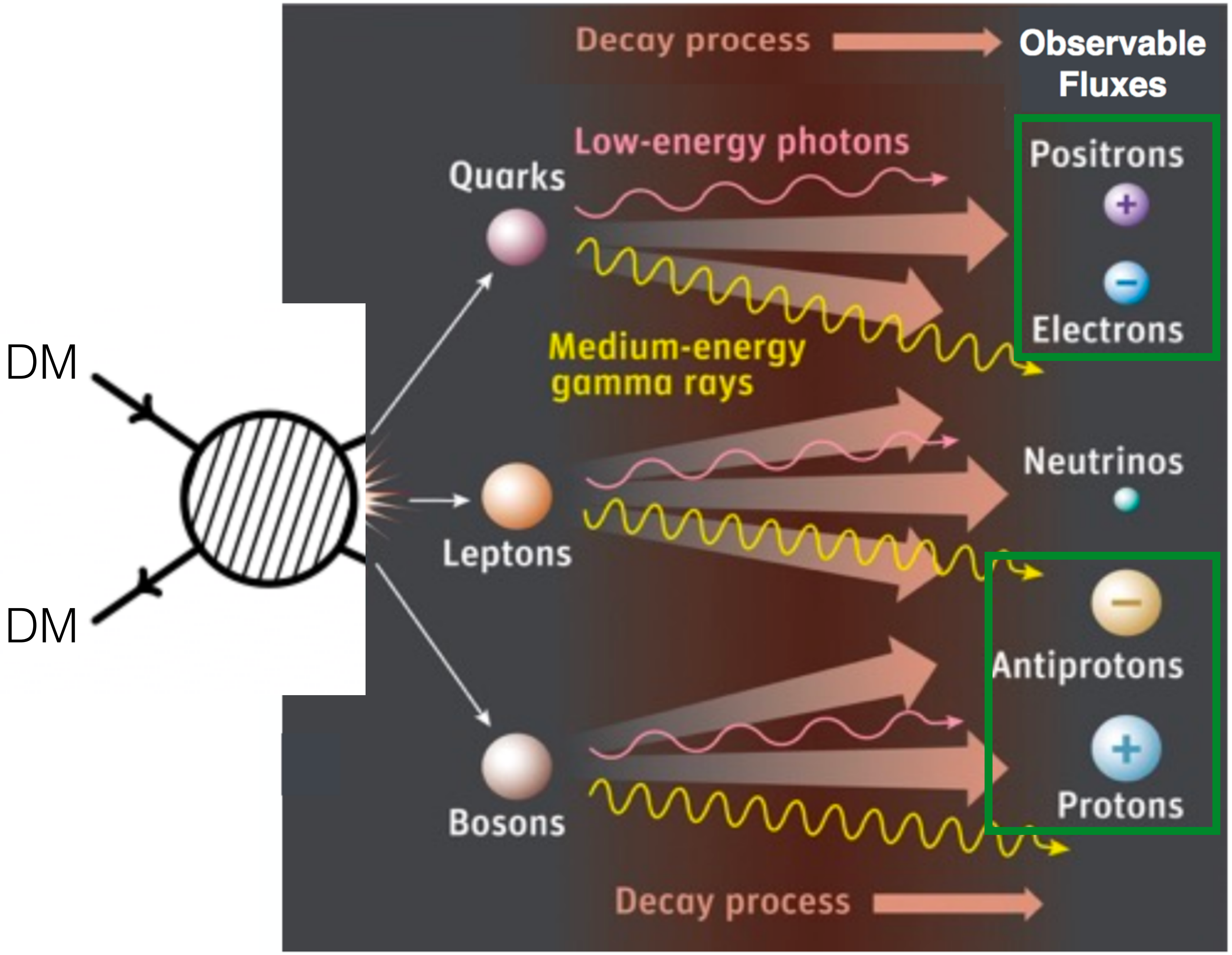

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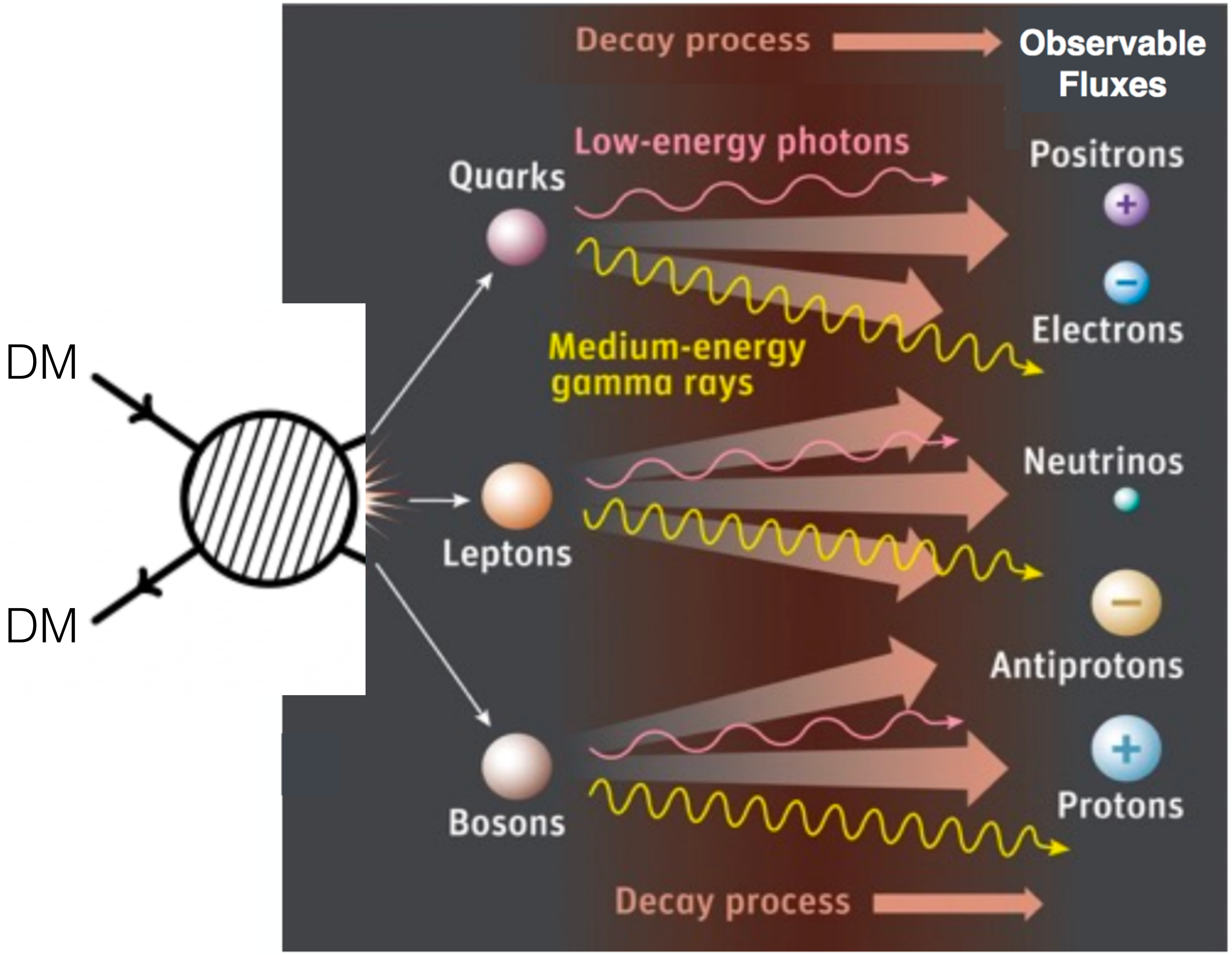

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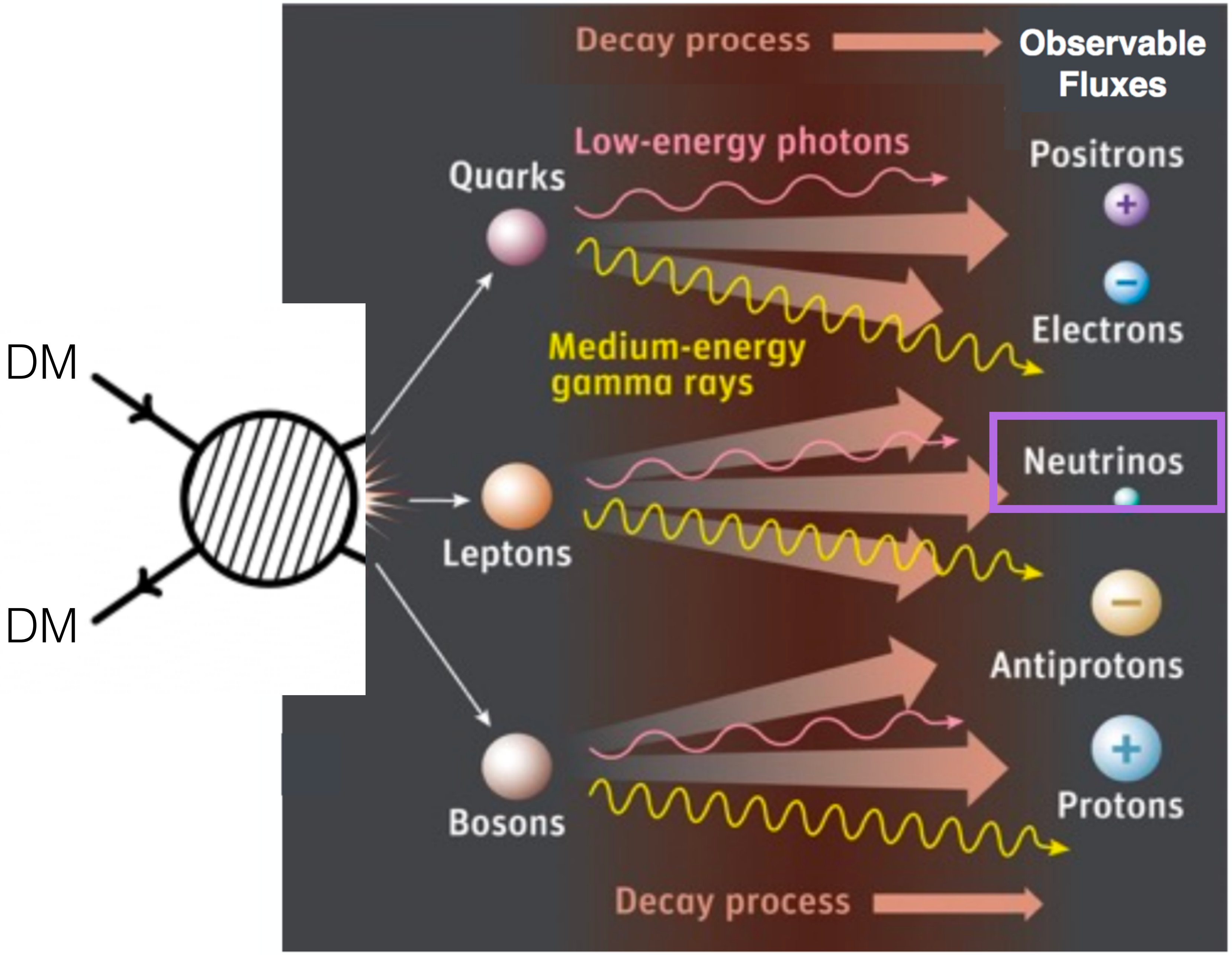

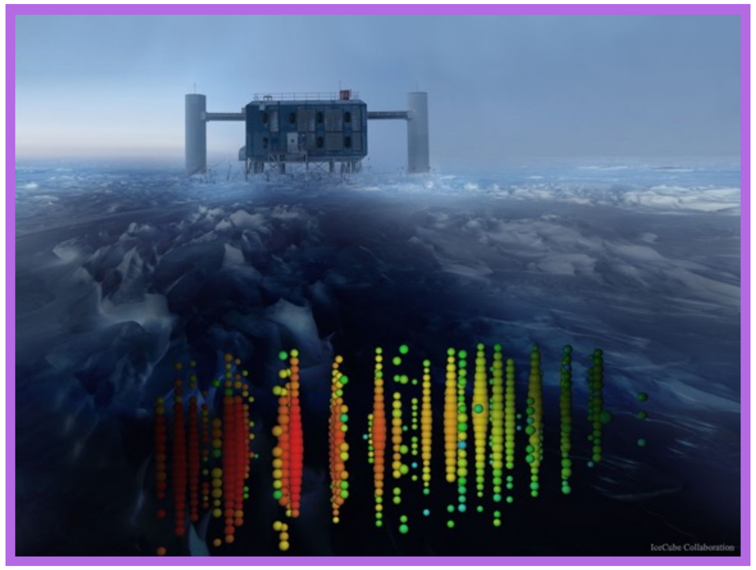

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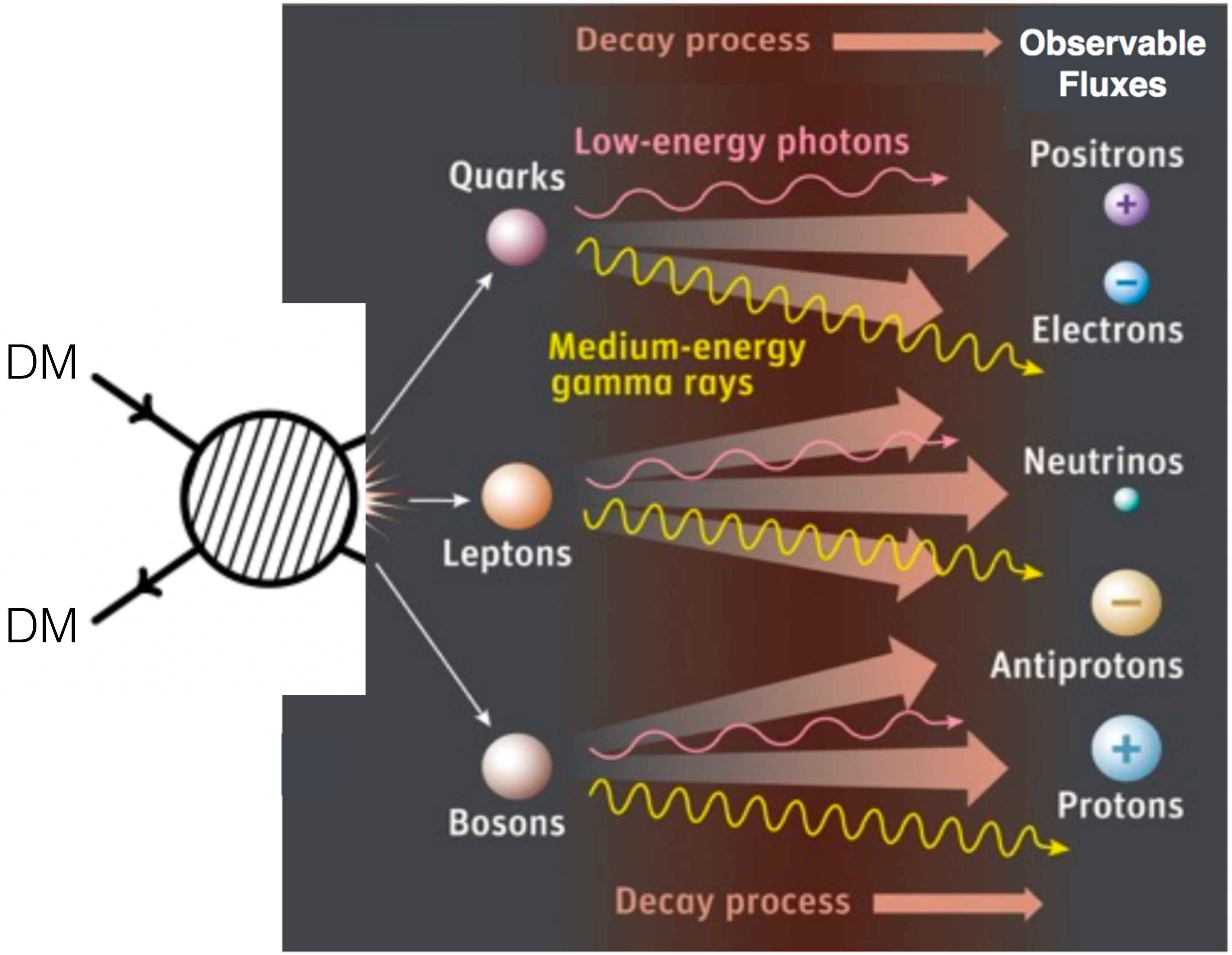

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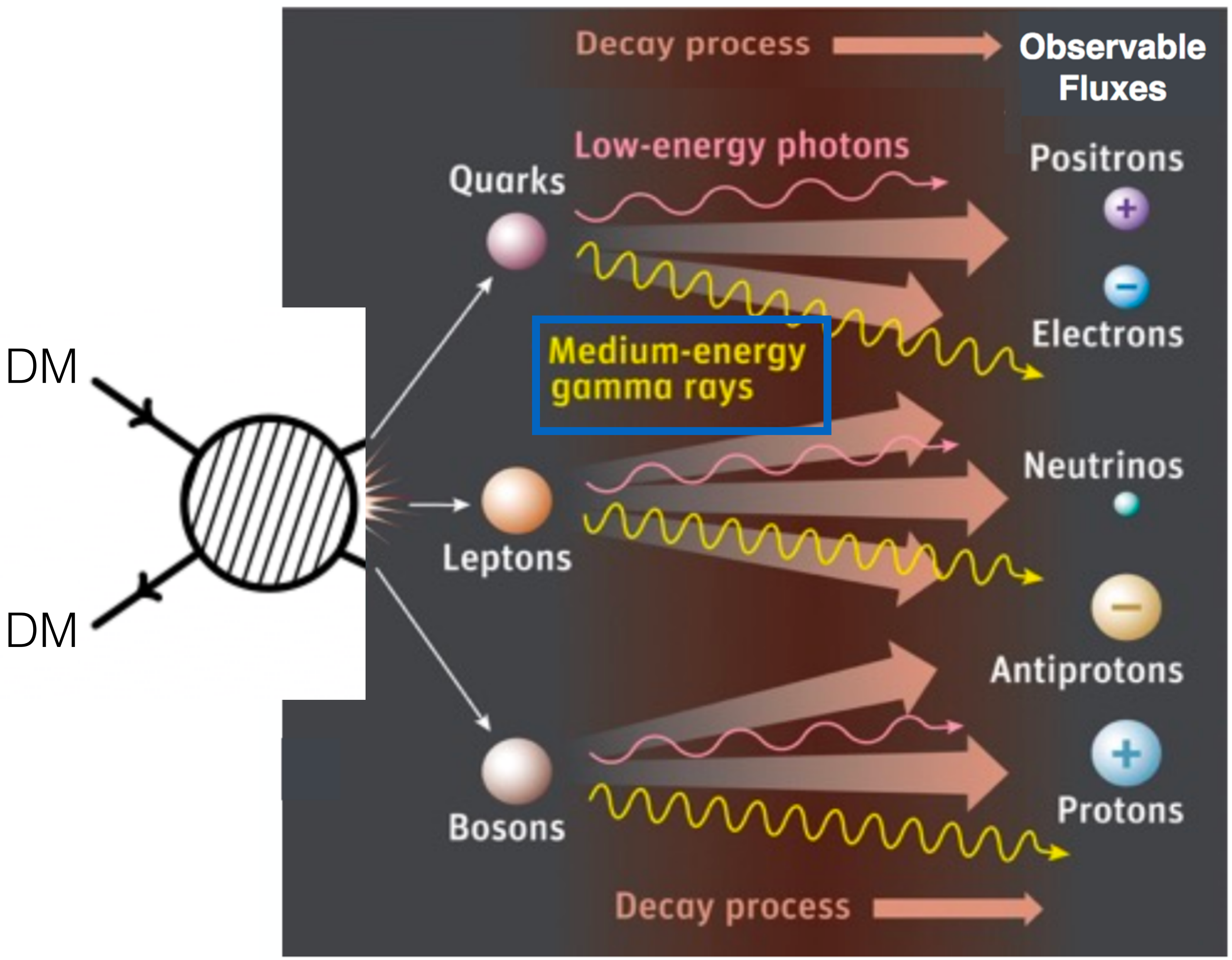

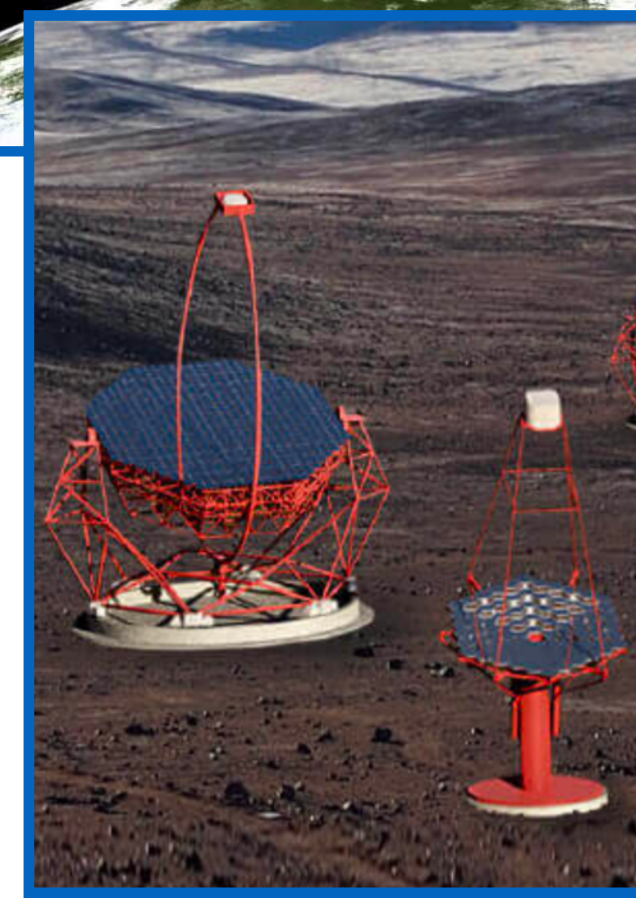

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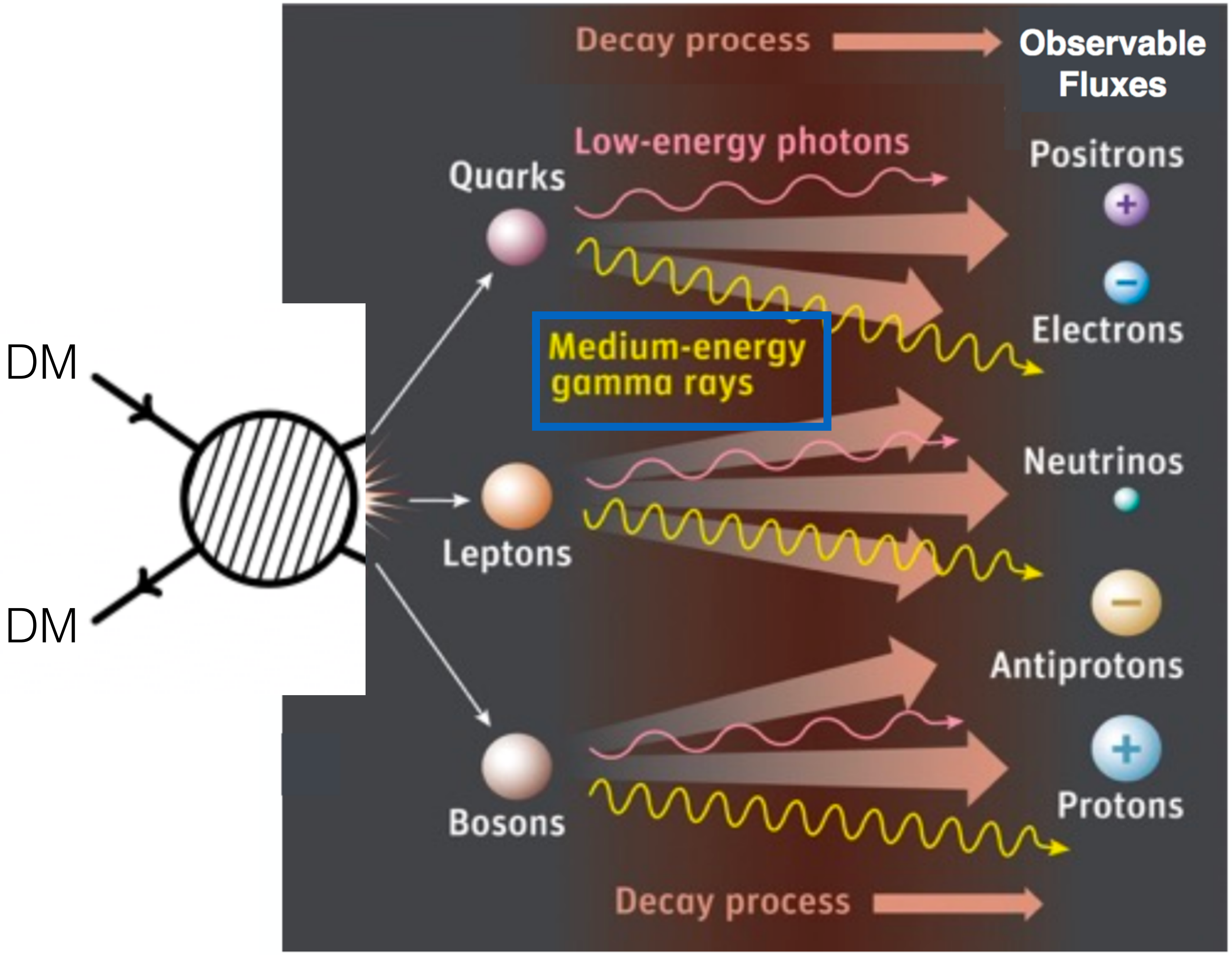

Focus on gamma rays an neutrinos (anti-protons from AMS give similar results, see also talk by R. Munin on cosmic-ray detectors)

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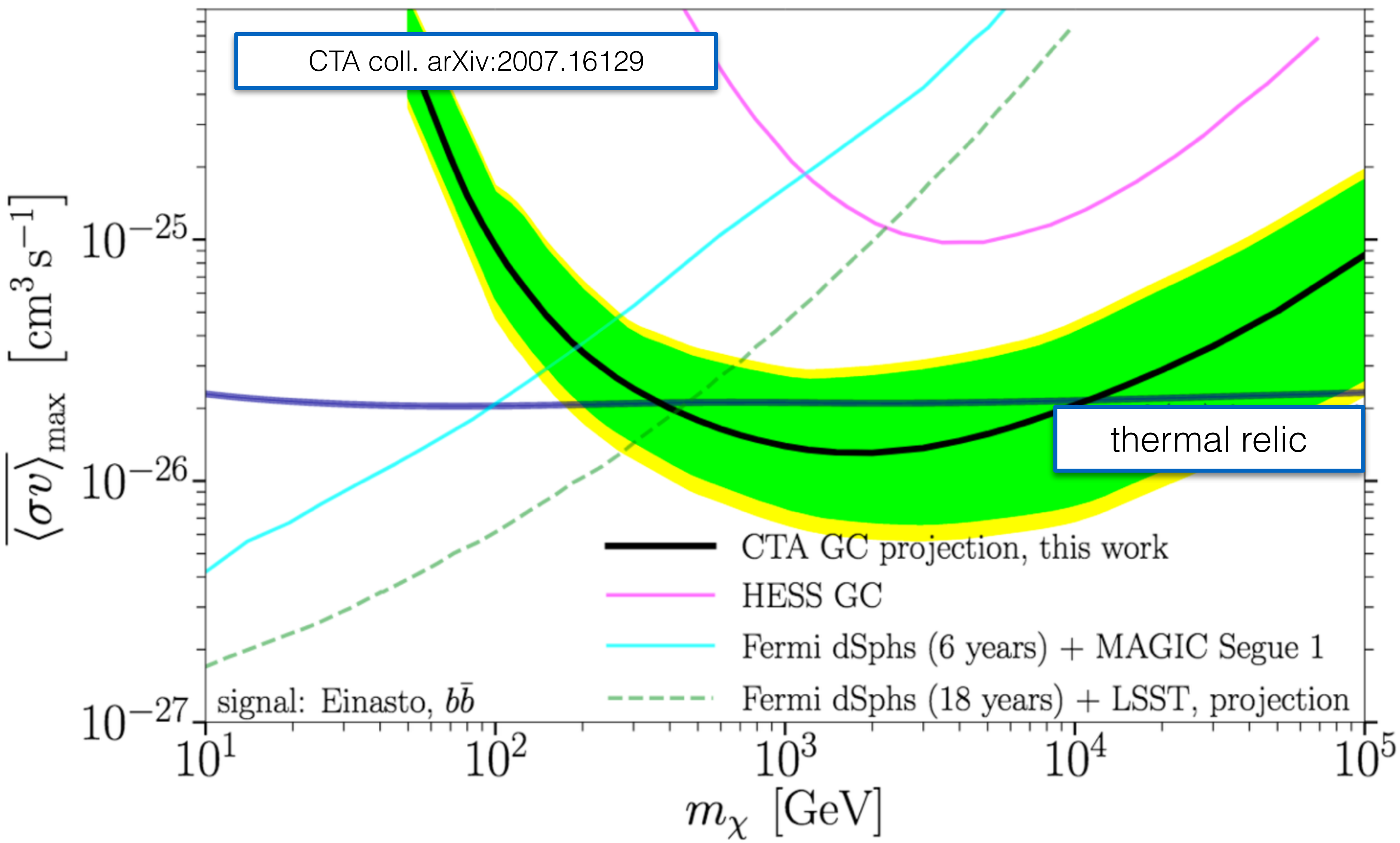

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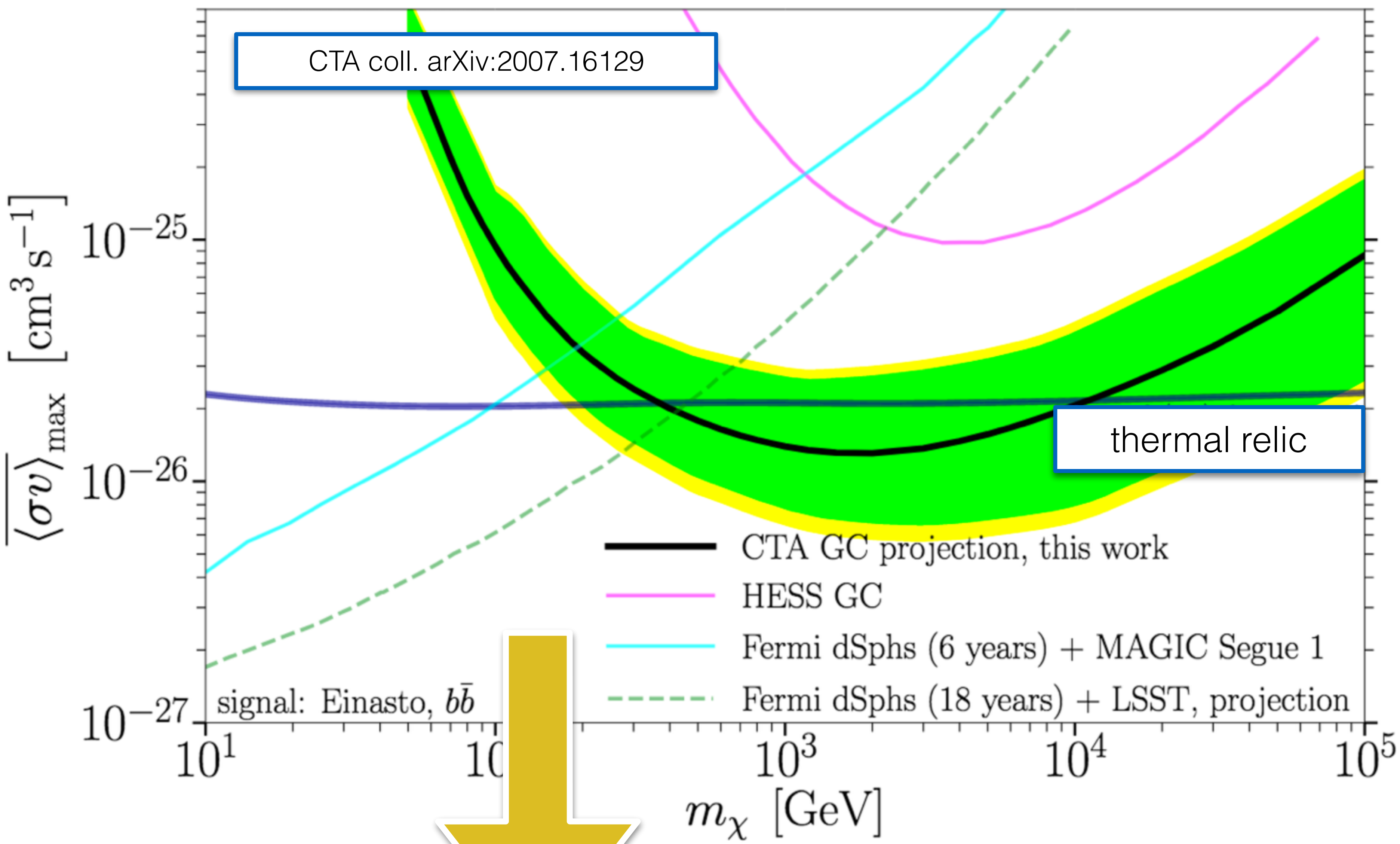

Indirect detection of gamma rays will increase its sensitivity

- Fermi-LAT dwarf spheroidal limits probe thermal DM below 100 GeV roughly
- Fermi-LAT will continue increase its sensitivity stacking more and more data
- There is however a lot of freedom to hide from current searches in the GeV range
- The game here is to lower the coupling with the SM as much as possible but keeping the relic density
- E.g. Freeze-in mechanism (McDonald 2002; Hall et al. 2009), hidden sectors, secluded DM (Pospelov et al. 2008), …

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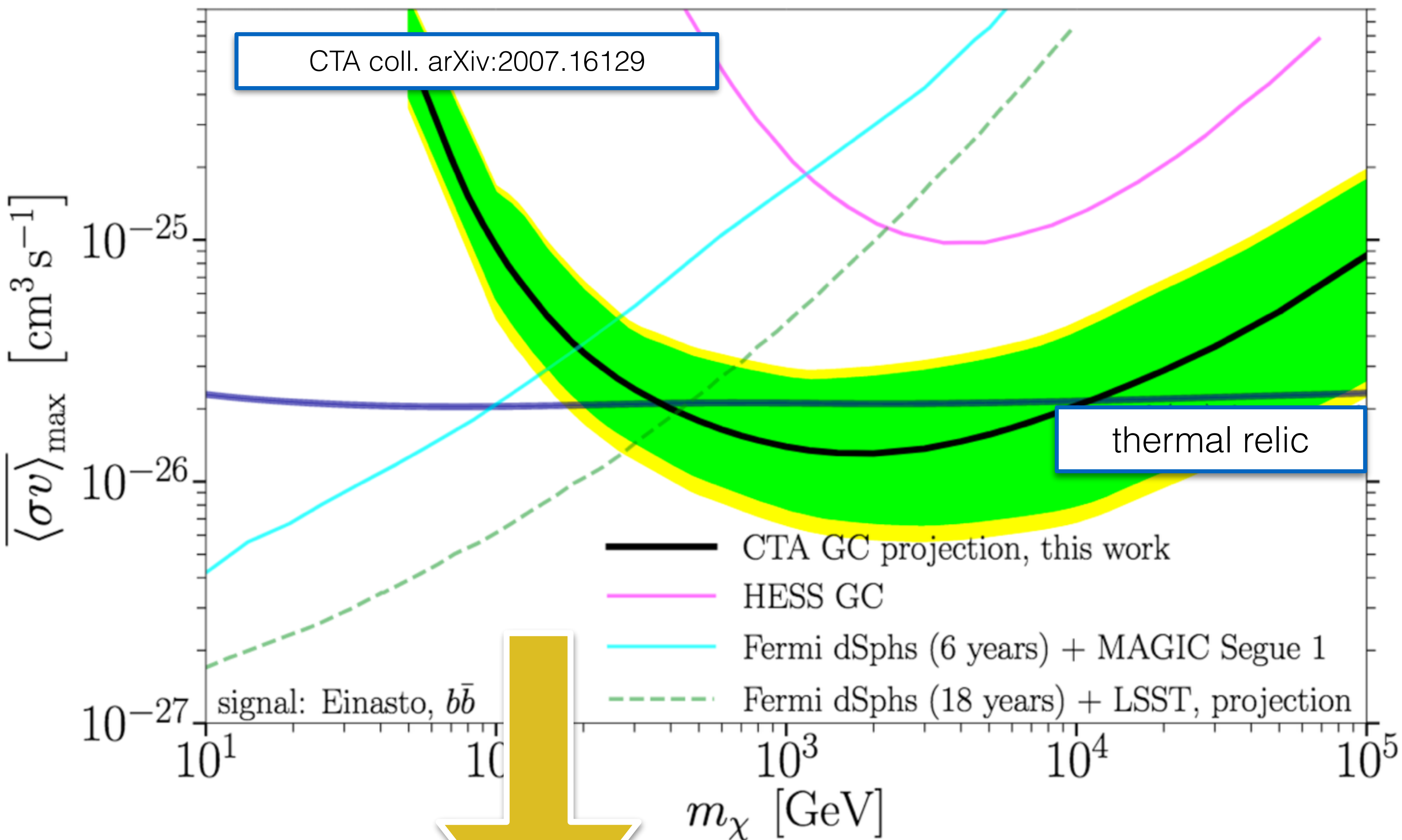

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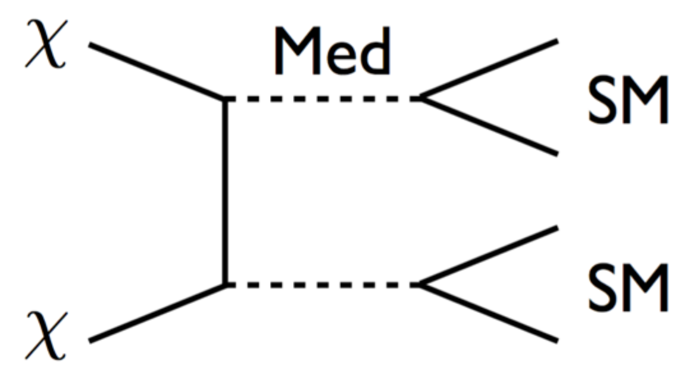
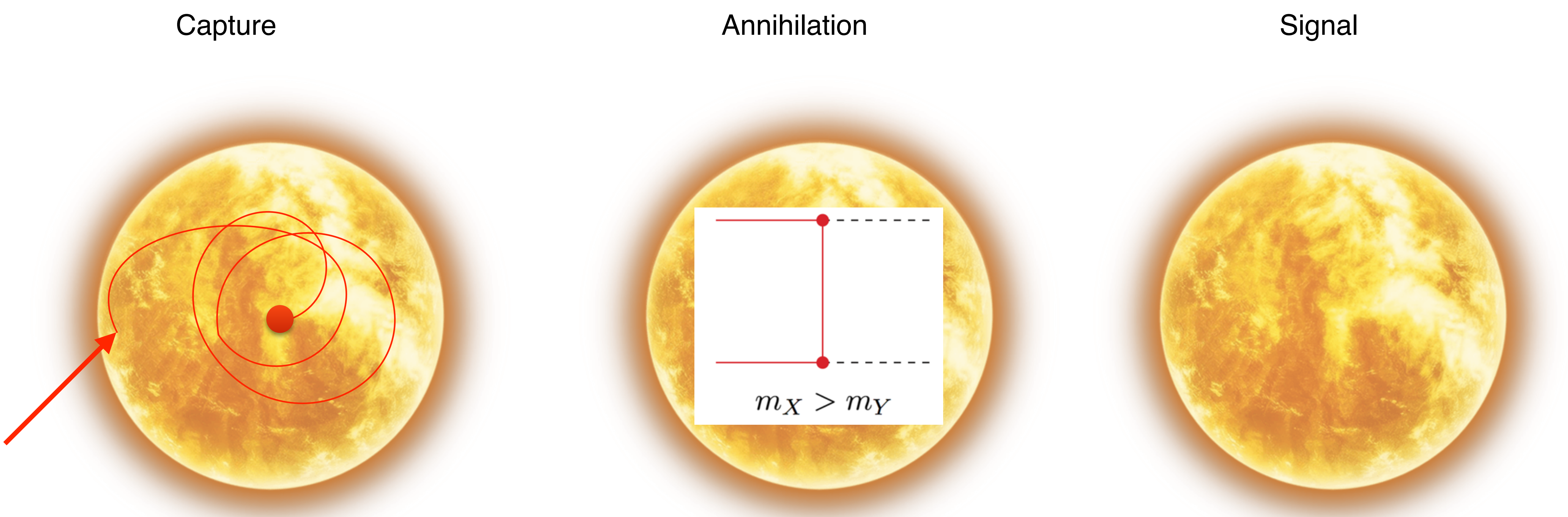
1. Secluded DM and pheno in compact object

[Batell,Pospelov, Ritz, Shang 2009, CA et al. 2017]

$$\mathcal{L} = g_q y_q \bar{q}\,[\cos\theta + i\sin\theta\,\gamma_5]\,q\,Y_0 + g_X\,\bar{X}_d\,[\cos\theta + i\sin\theta\,\gamma_5]\,X_d\,Y_0$$



- Avoids direct detection and collider bounds
- Mixed pseudo-scalar mediator annihilates s-wave —> long lived mediator can hide easily, one way to search for it:



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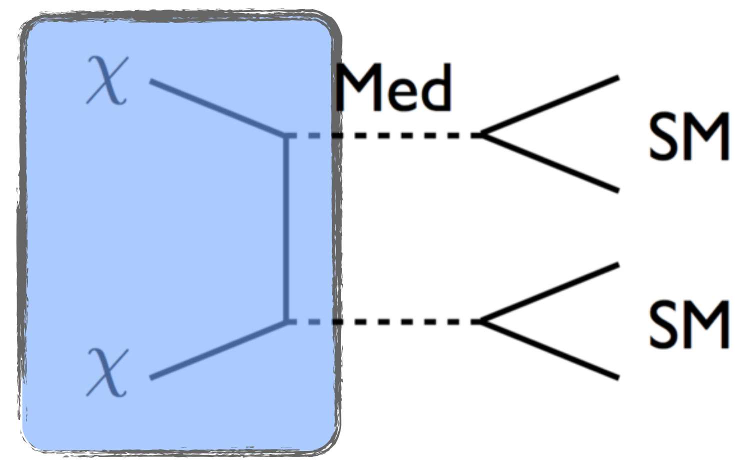

Annihilation into mediator fixes relic density

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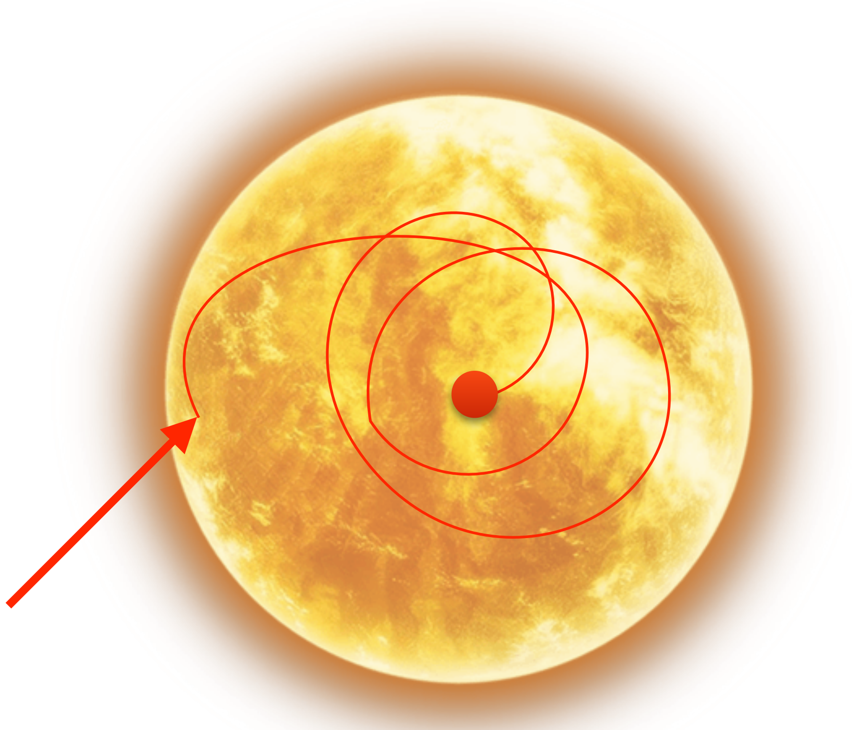
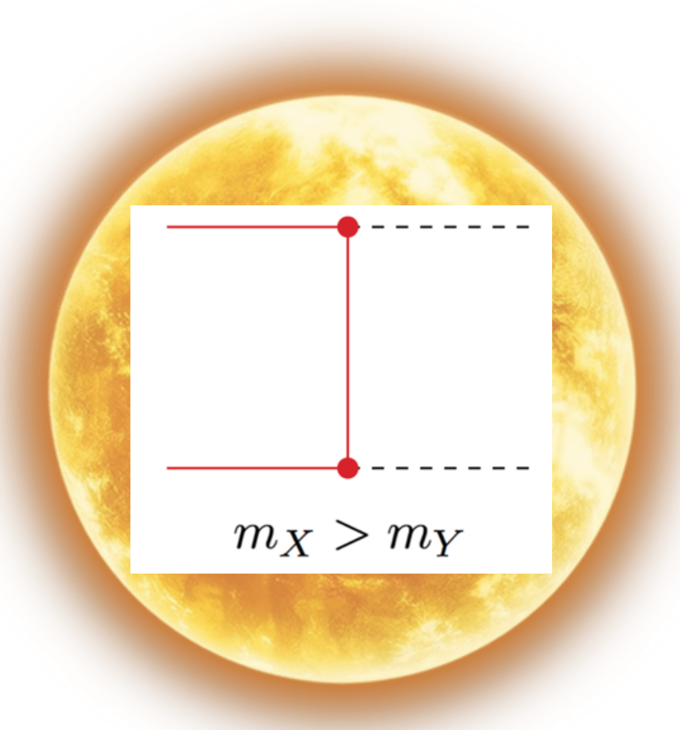
Capture



Annihilation



Signal

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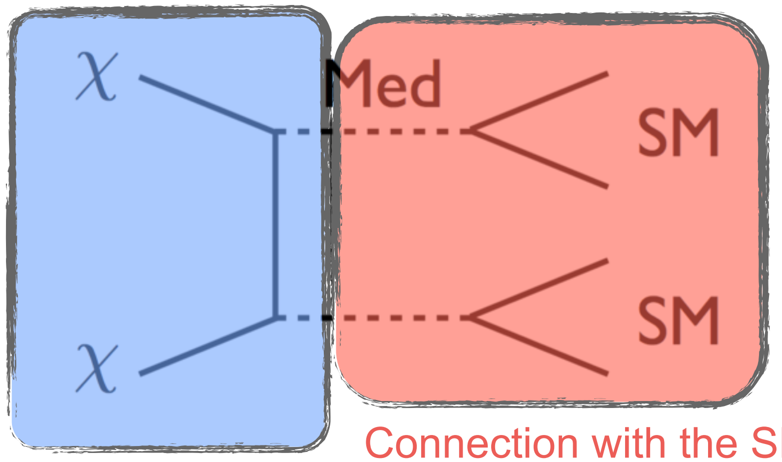

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Connection with the SM independent of the relic density, can be very small

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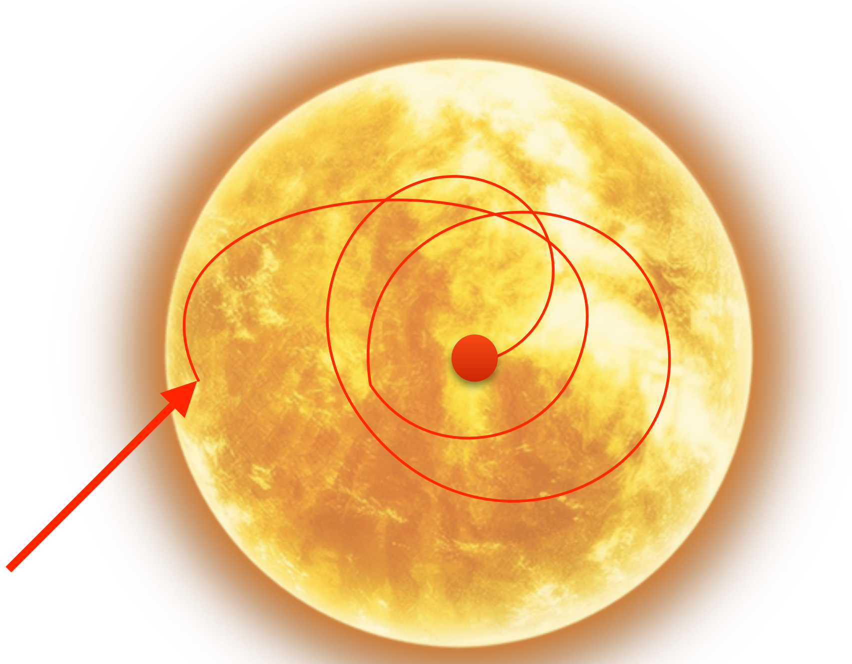

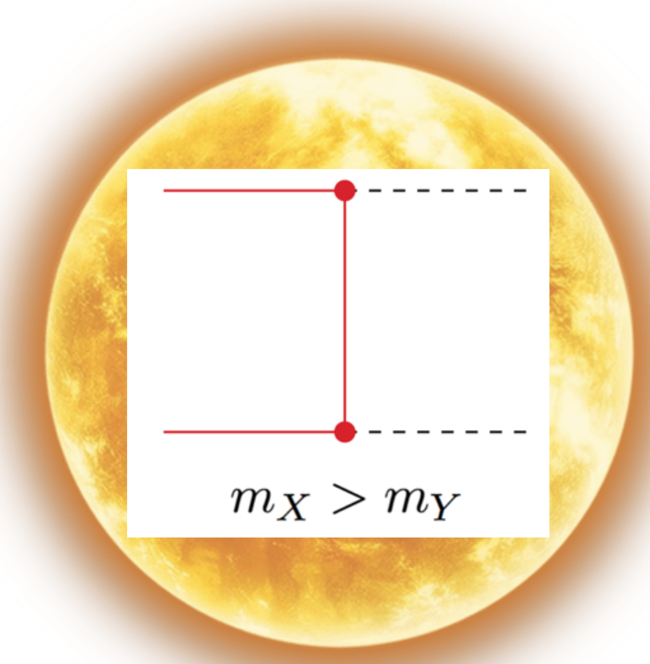

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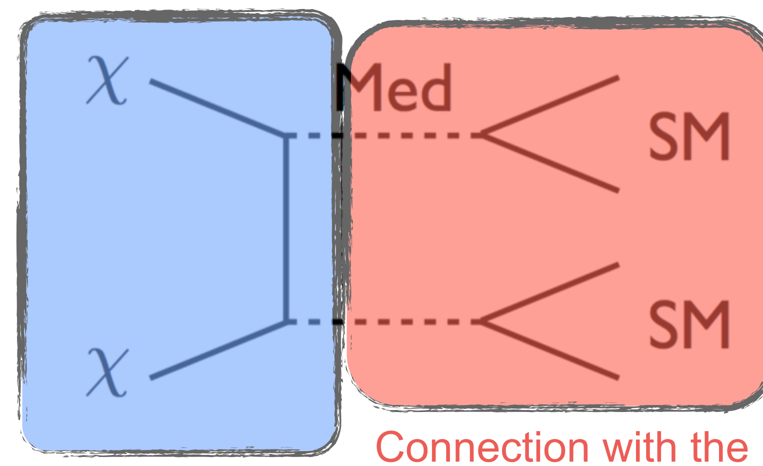

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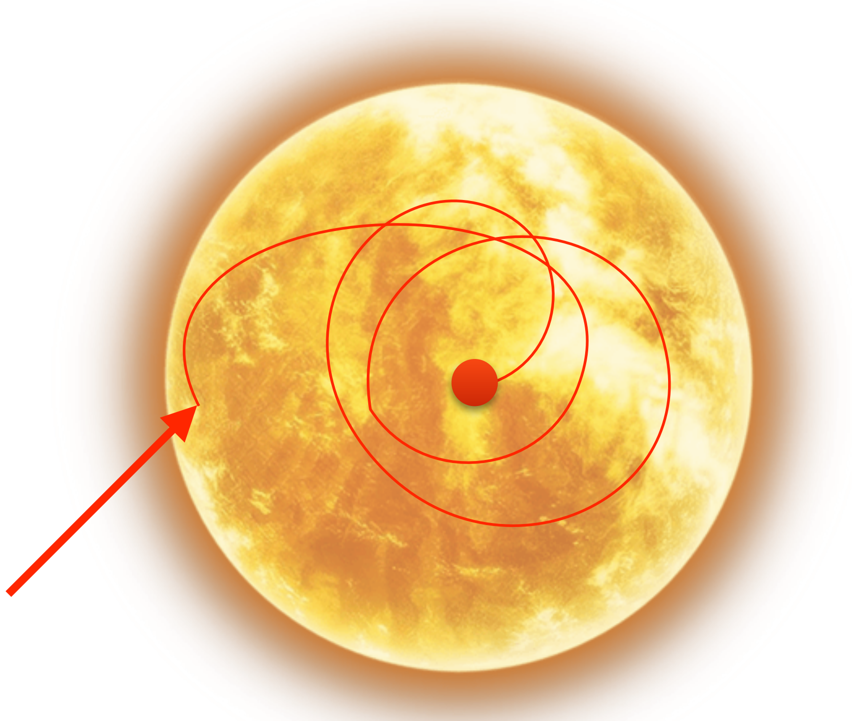
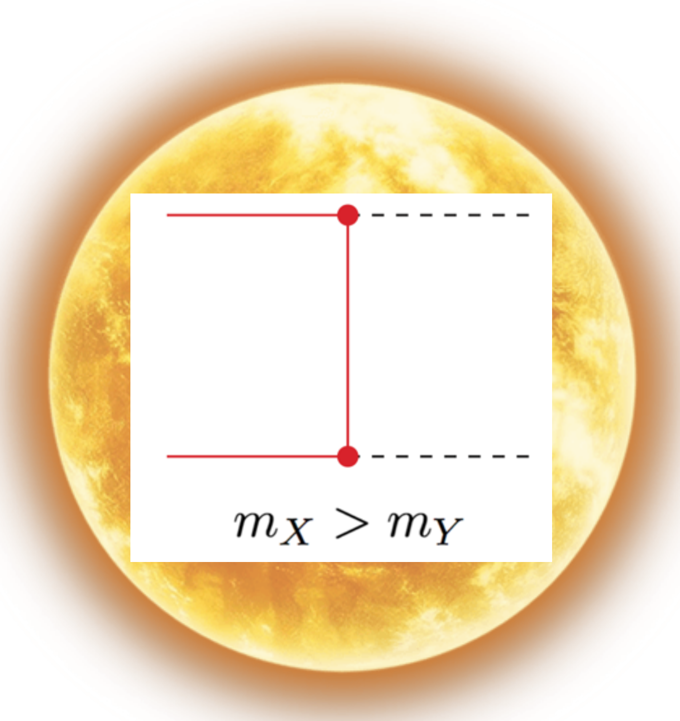
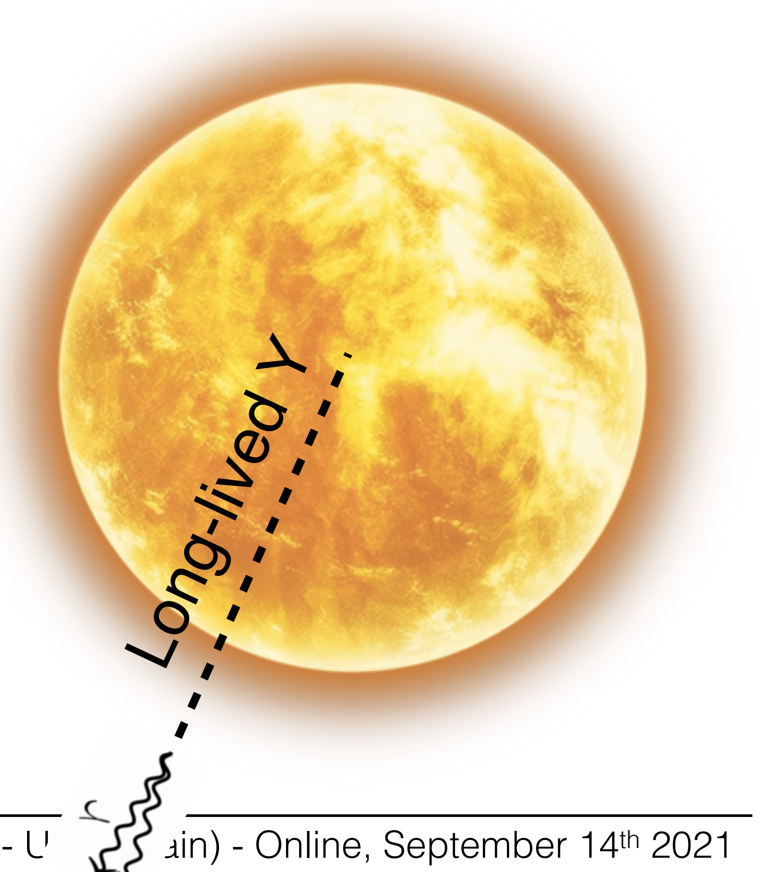


Annihilation



Signal



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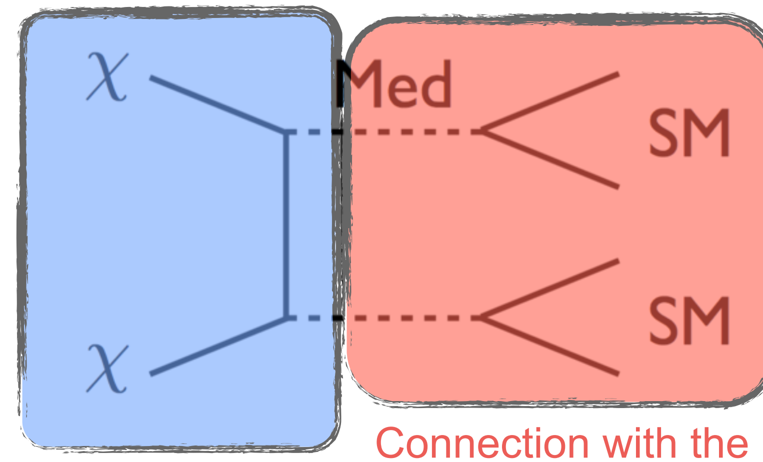

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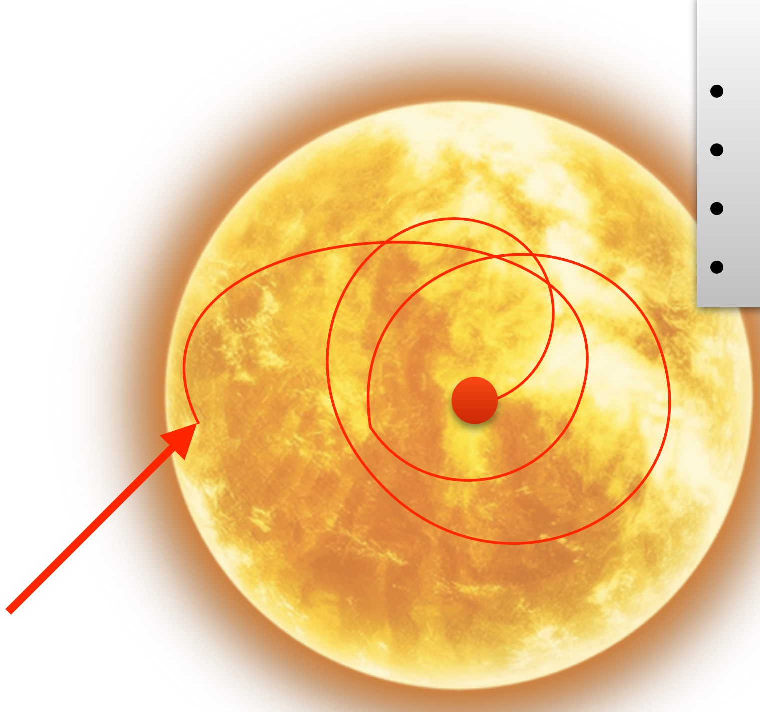
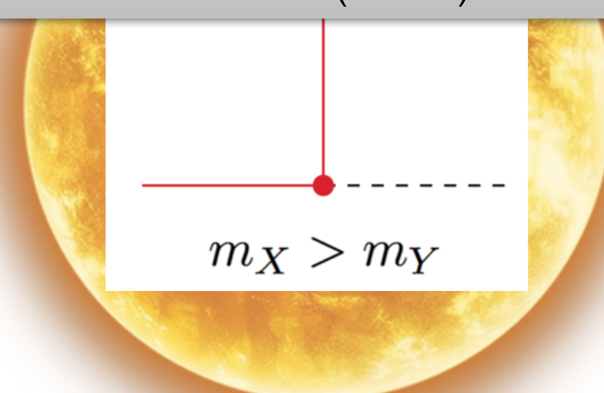
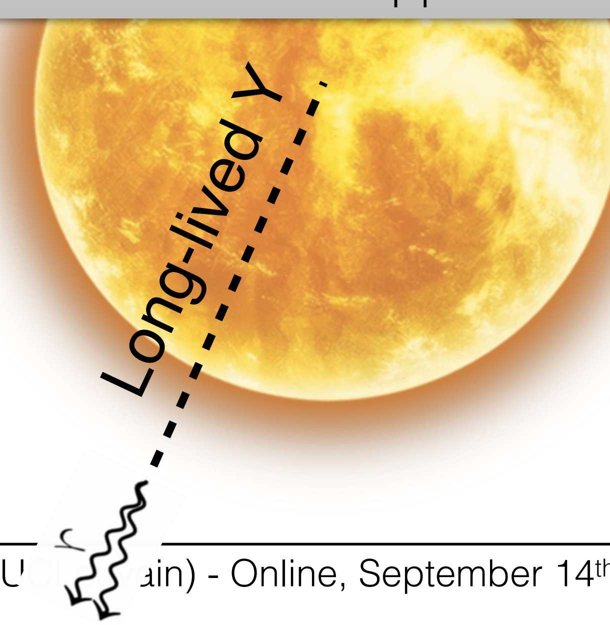
Capture | Annihilation | Signal

Gamma-rays from the Sun !

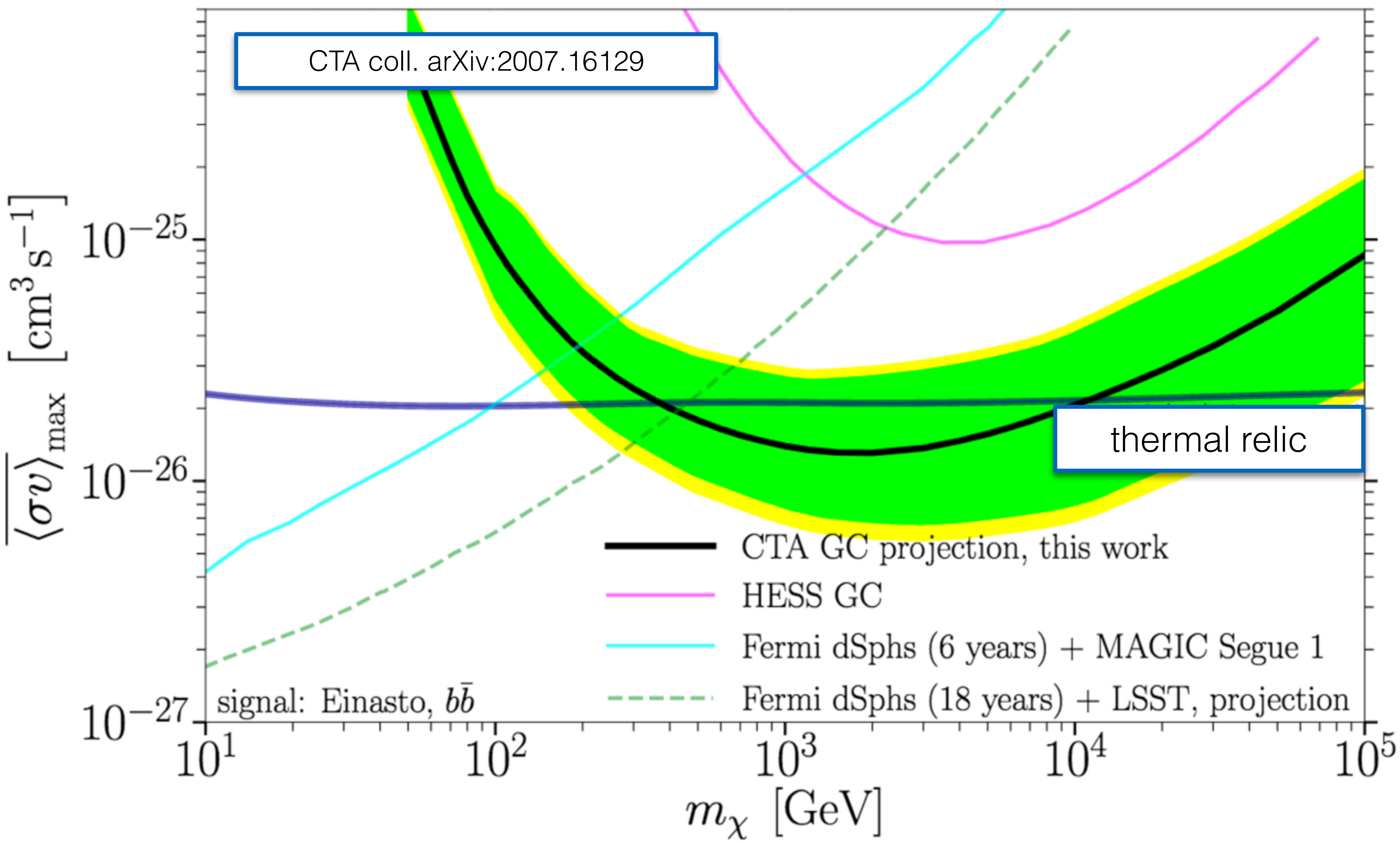
- Typically expected neutrinos from the Sun from DM annihilation
- Unique way to probe nature of long-lived mediators
- First proposed by our team and by R. Leane and collaborators
- HAWC (2018) and Fermi-LAT (2020) have performed searches and set upper limits







1. Heavy WIMP-like particles



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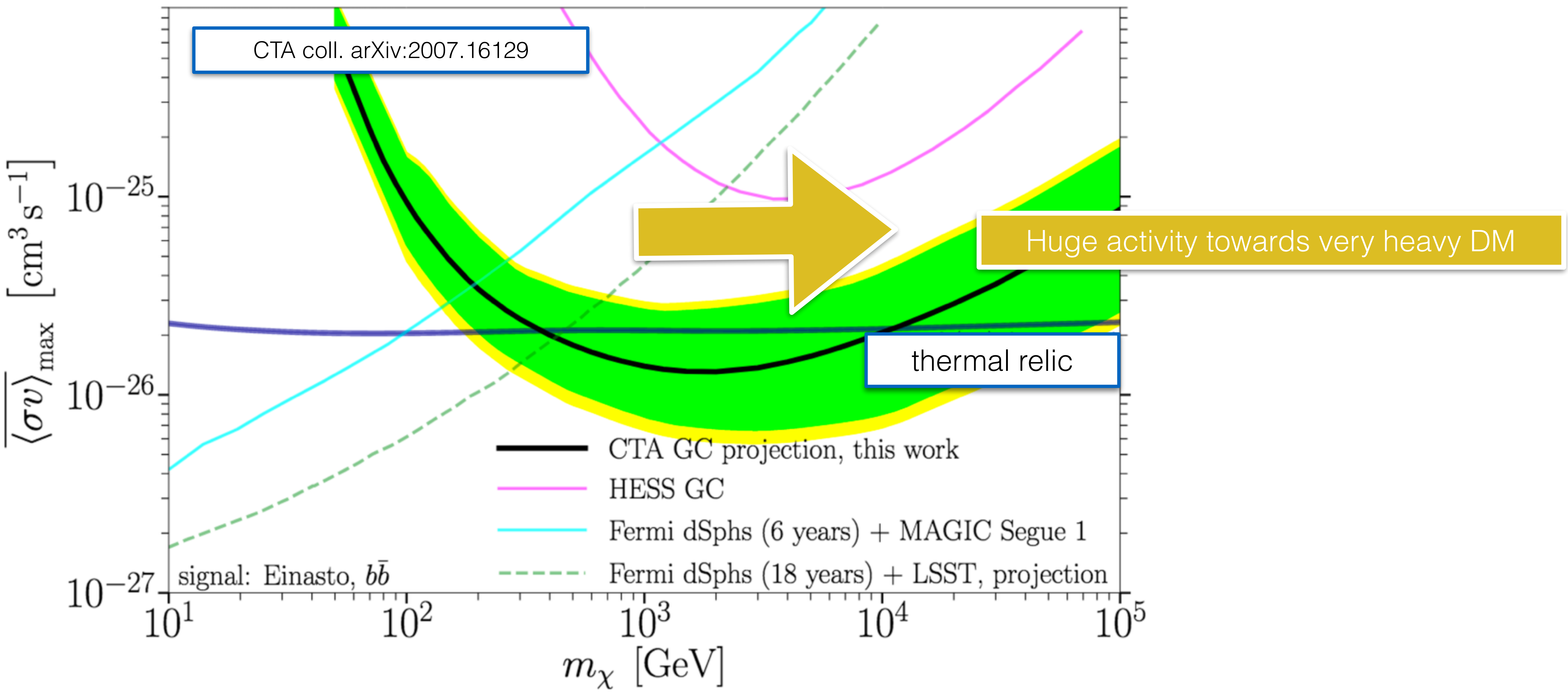

- Gamma-ray instruments are being actively developed or are already performant for high energy signals, good for heavy DM masses (CTA, LHAASO, …)
- Next decade will see the advent of neutrino telescopes and radio telescopes
- Dark matter can be annihilating (up to ~ 100 TeV or so) or decaying
- Heavy DM models are motivated in the framework of string theory (e.g. Cicoli et al. 2020), minimal DM, extra-dimensions …
- Heavy DM has nice phenomenology involving EW corrections, cohannihilation, Sommerfeld enhancement, bound state formations…

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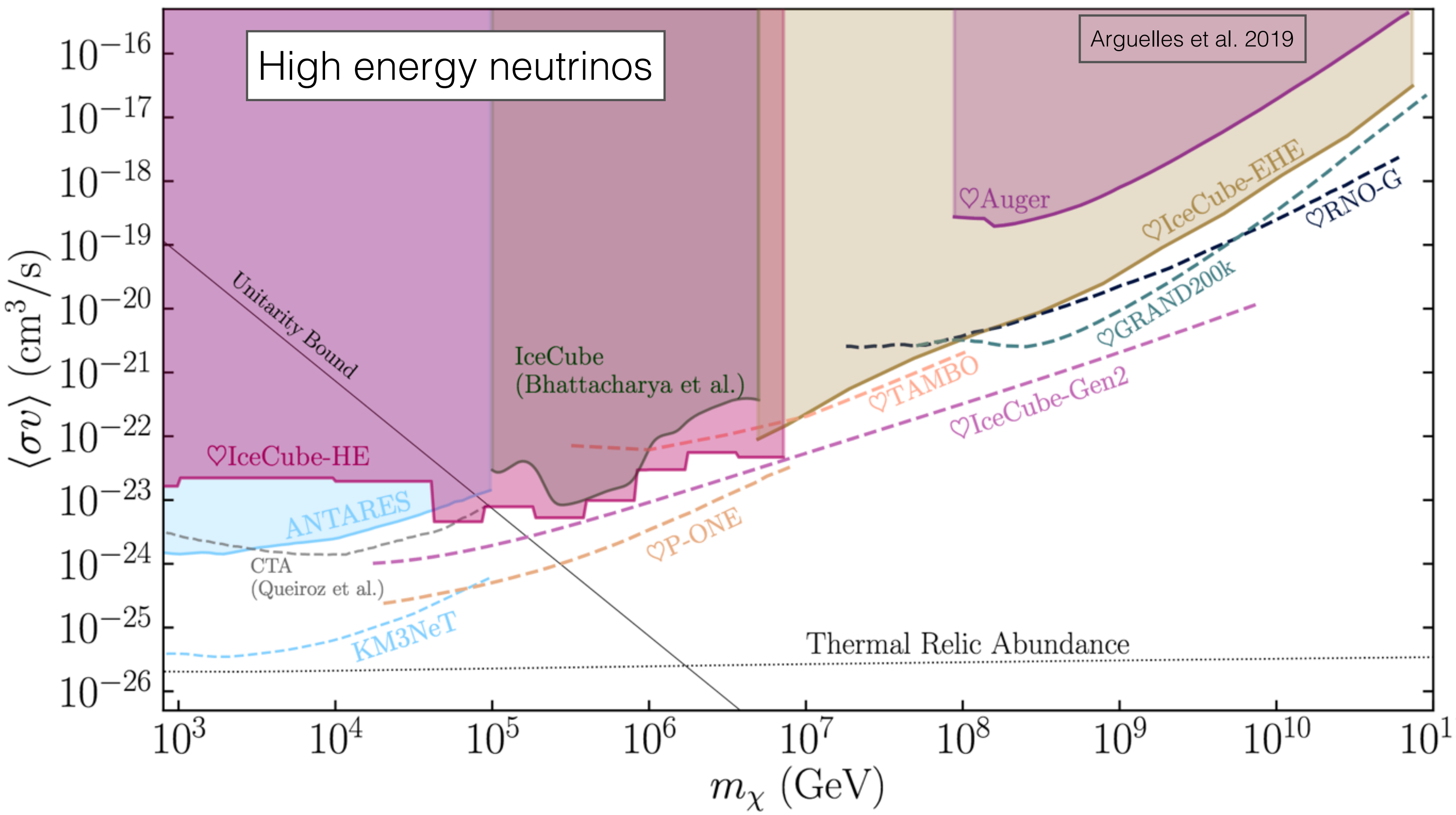

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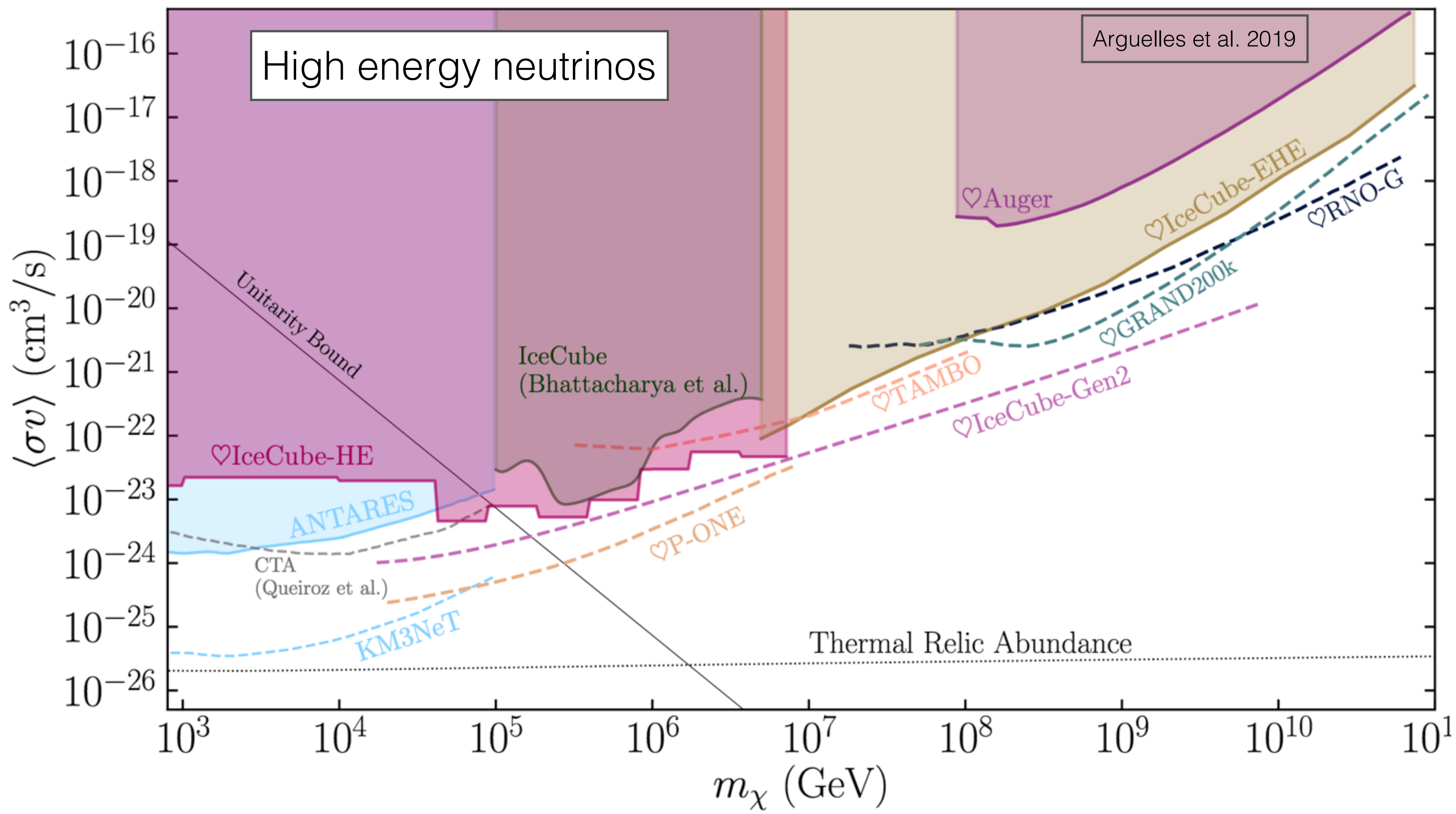
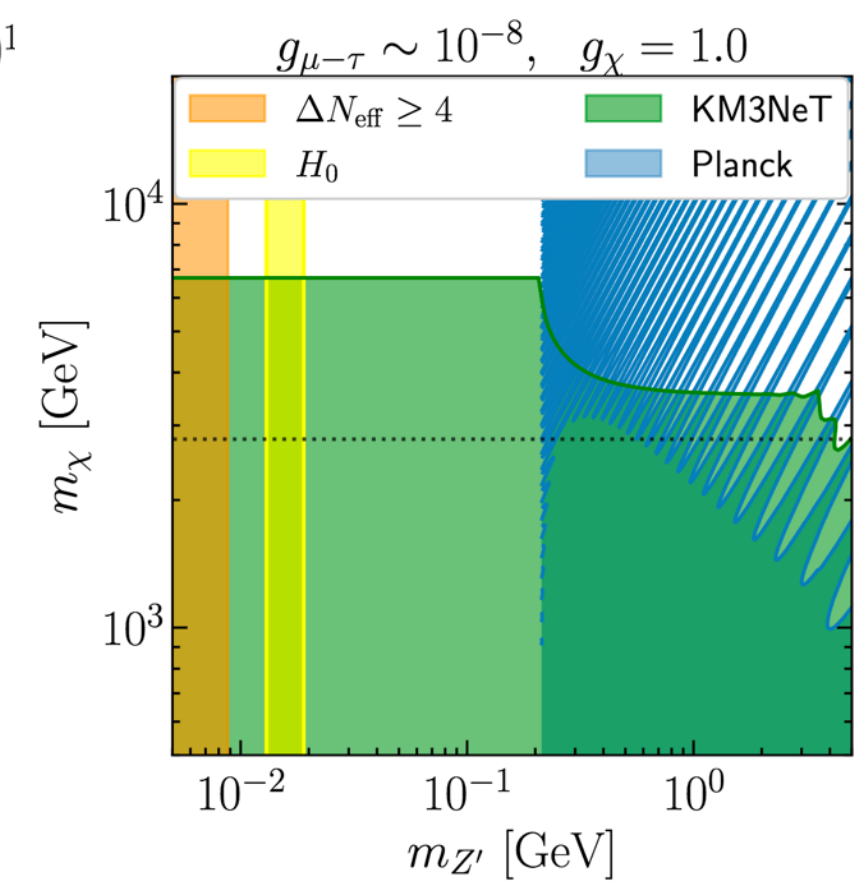




Secluded leptophilic Z' model can be probed actually only by KM3NeT Arca (CA et al. arXiv:2103.01237)

1. Sterile neutrinos

parts adapted from M. Drewes

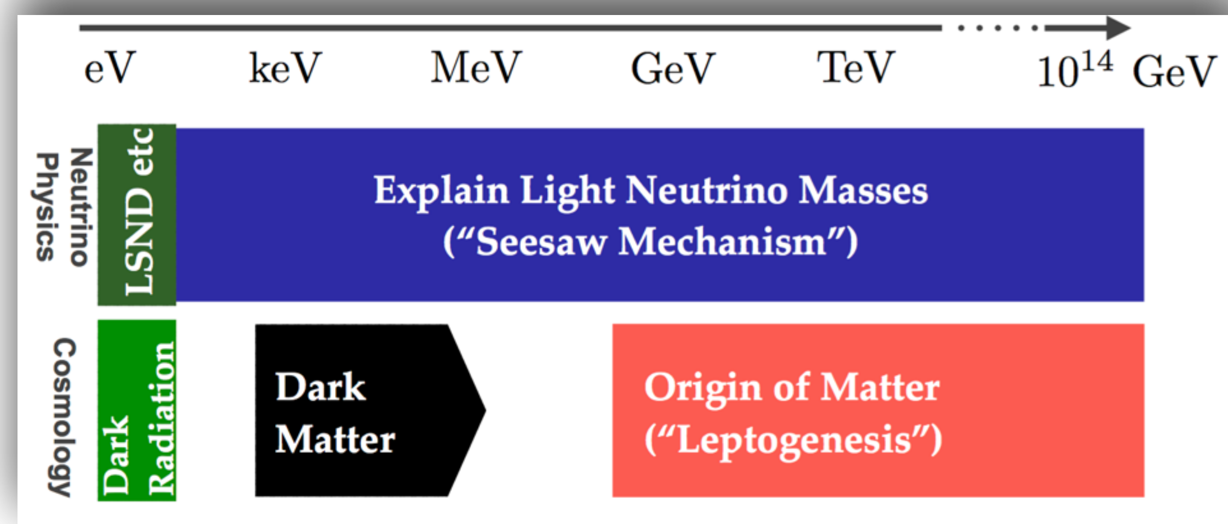
$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L - \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

Minkowski 1979, Gell-Mann/Ramond/Slansky 1979, Mohapatra/Senjanovic 1979, Yanagida 1980, Schechter/Valle 1980

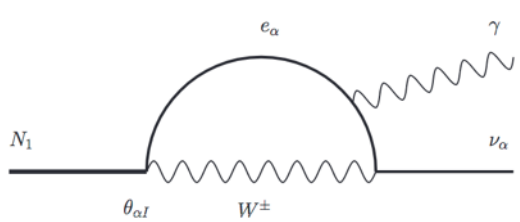
$$\Rightarrow \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

two sets of Majorana mass states with mixing $\theta = m_D M_M^{-1} = vFM_M^{-1}$

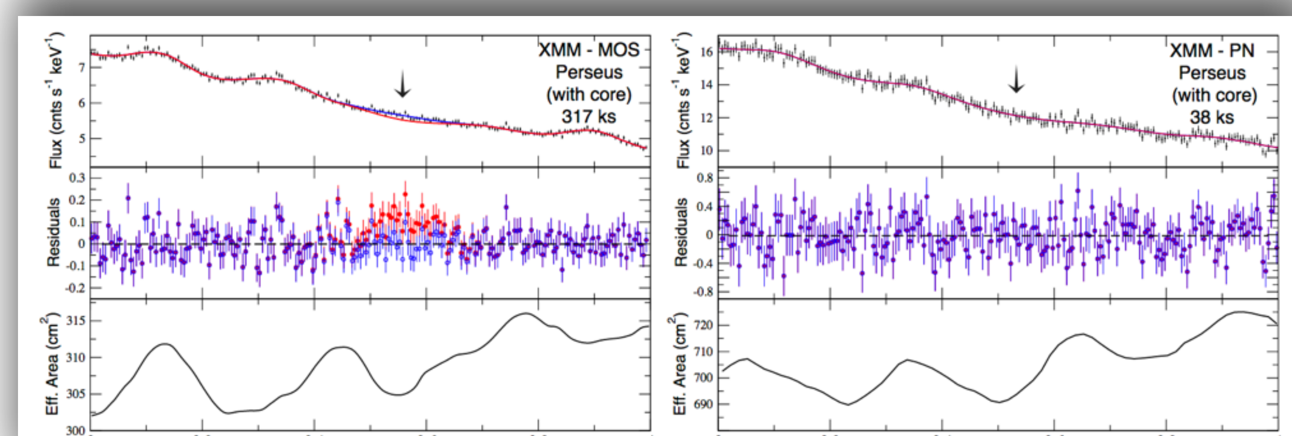
- Neutrino have masses
- BSM physics required to generate it
- One possibility is the seesaw mechanism



- Right-handed neutrinos can solve several SM issues depending on their mass scale
- The keV mass range: viable non-thermal (thermal) decaying warm DM



- Can explain X-ray excess seen in galaxy clusters
- Signal: XMM-Newton + Chandra, stack of 73 galaxy clusters, significance > 3σ
  E_γ = (3.55-3.57)±0.03 keV
- Best-fit: sterile neutrino with m=7.1 keV and mixing angle $\sin^2(\theta) \sim 7\times10^{-11}$

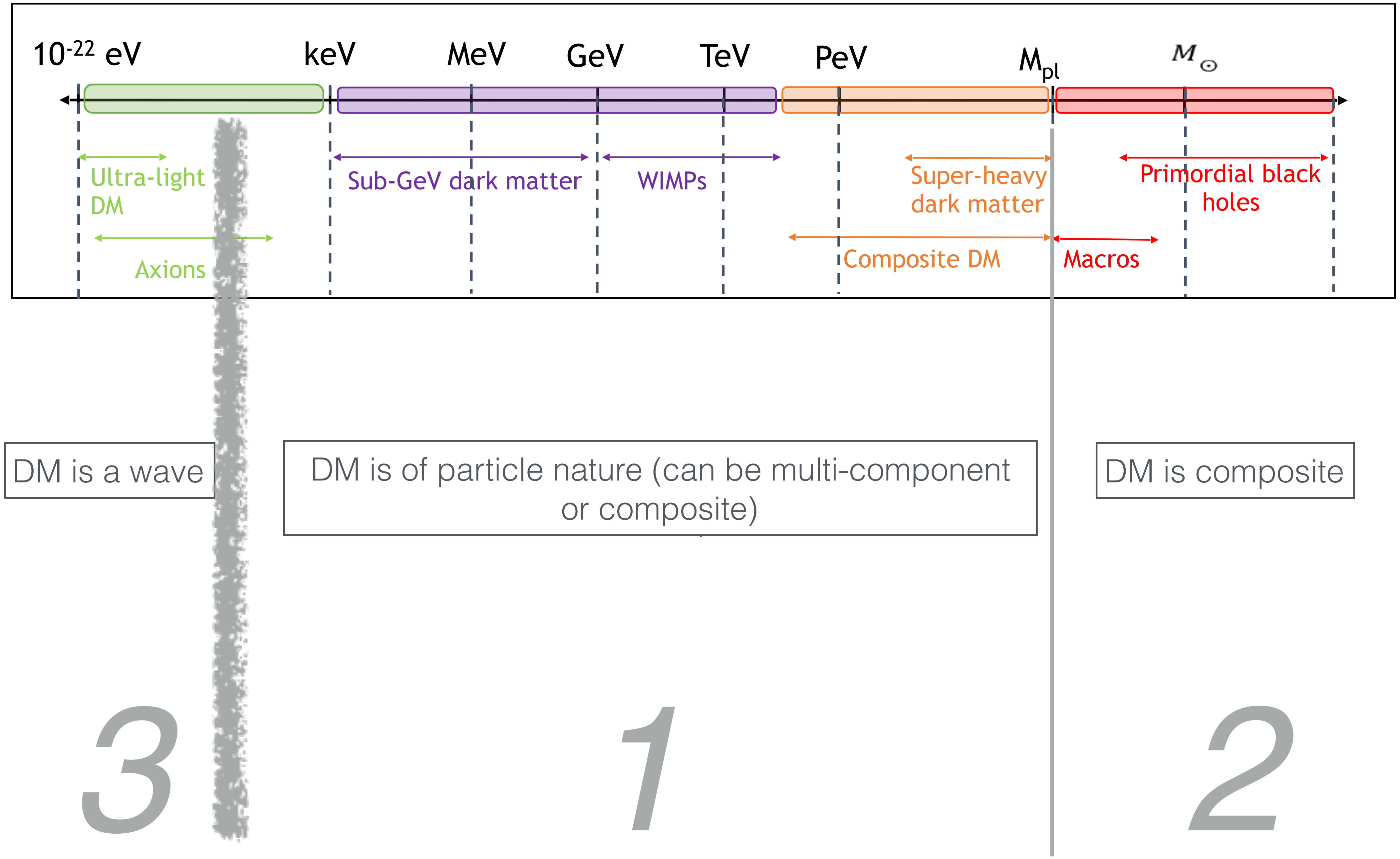


arXiv:1402.2301

See also talk on CMB and neutrinos (Gerbino)

Characterizing the DM landscape

- To have an overview of the DM landscape it is convenient to consider mass regions
- For each mass region, identify the typical signals expected to be detected, which can be related to the strength of the interaction cross-section
- Activity in the DM theory is now a days mostly data/experiment driven



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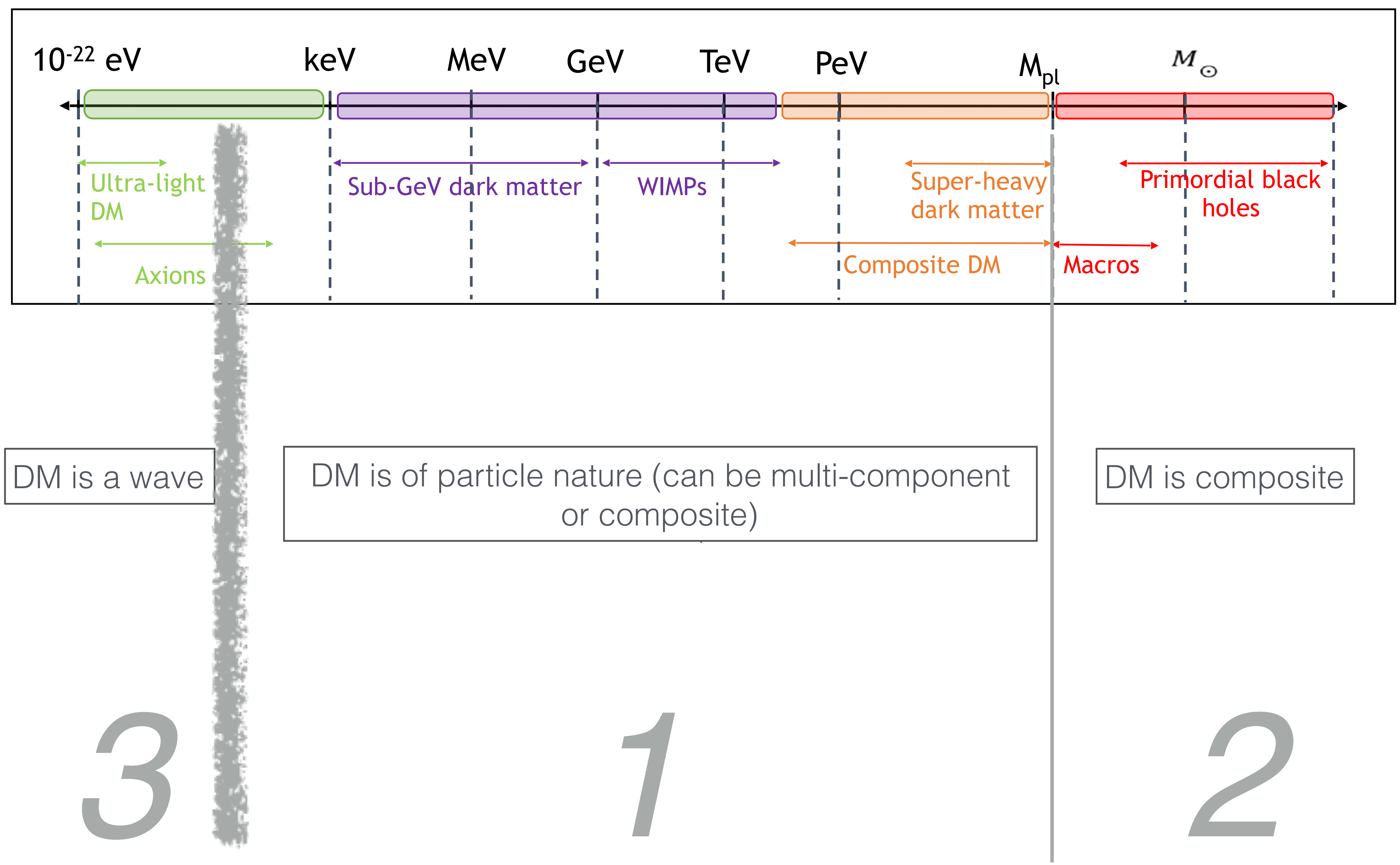

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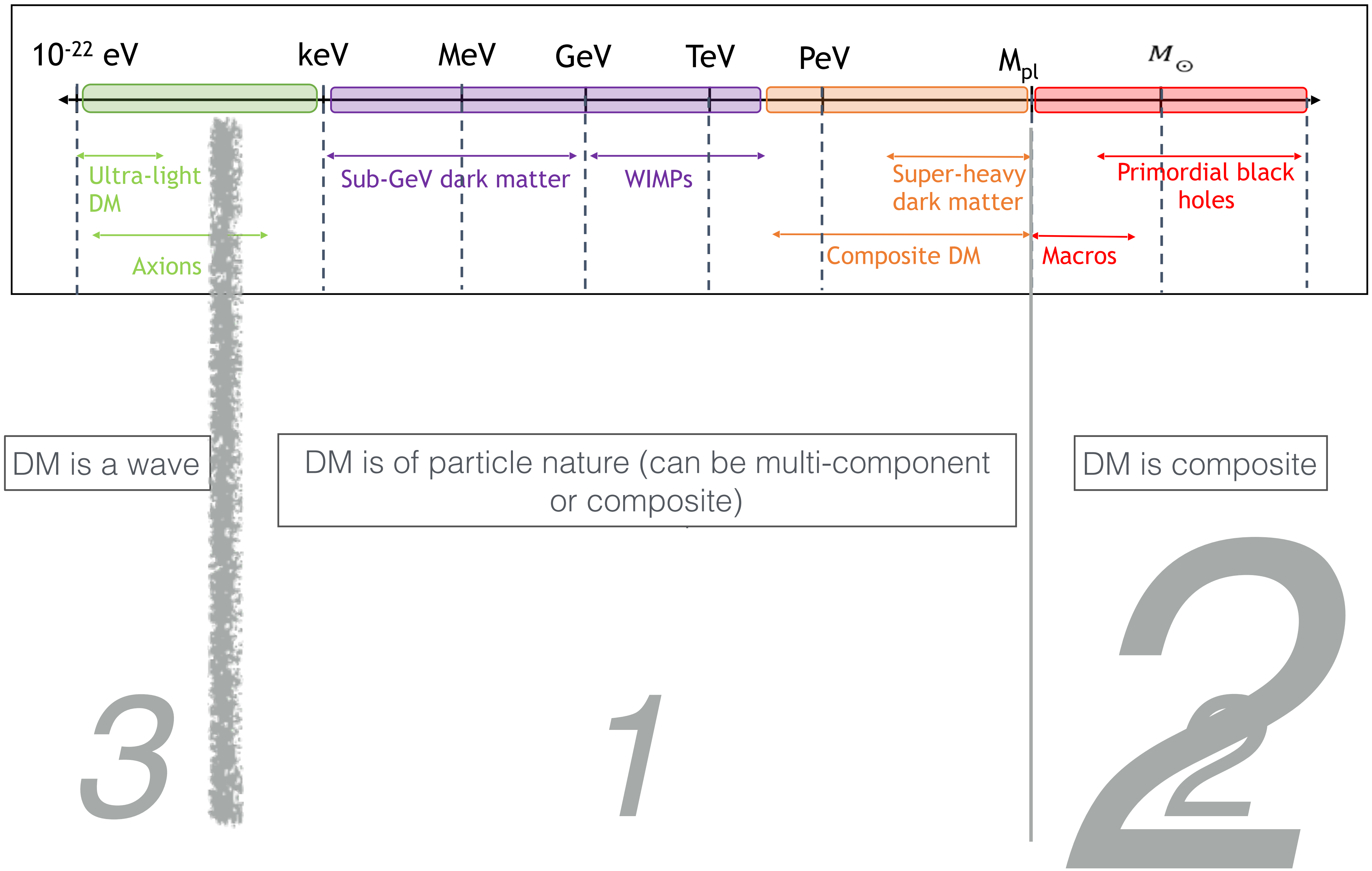

2. Primordial Black Holes

- Typically DM is believed to be a BSM particle because of the firm predictions of Big Bang Nucleosynthesis (BBN)
- MACHOs are constituted by astronomical bodies that emit very few or no light (hence very difficult to be detected) and are massive

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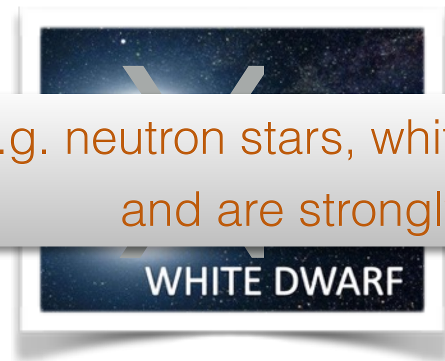
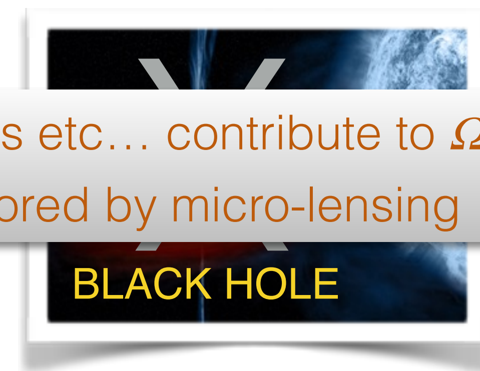


Machos, e.g. neutron stars, white dwarfs etc… contribute to Ω_b and not to Ω_m and are strongly disfavored by micro-lensing



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- What IF at the epoch of BBN and CMB formation the DM “composite objects” were already decoupled from the plasma such that they do not contribute to Ω_b ?

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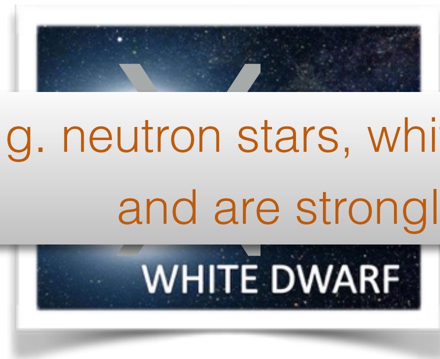
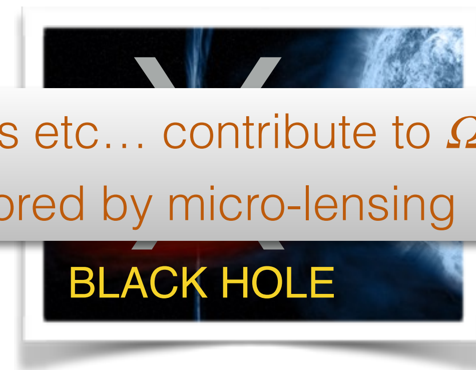


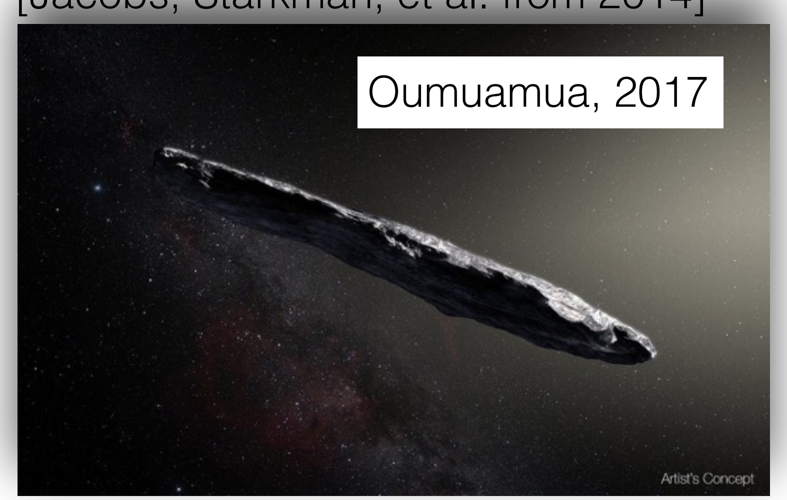


Machos, e.g. neutron stars, white dwarfs etc… contribute to Ω_b and not to Ω_m and are strongly disfavored by micro-lensing

- What IF at the epoch of BBN and CMB formation the DM “composite objects” were already decoupled from the plasma such that they do not contribute to Ω_b ?

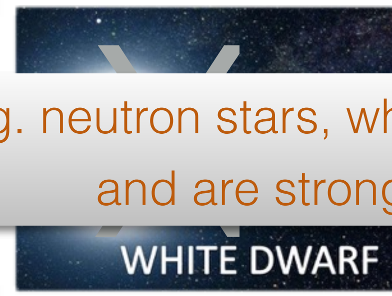
MACROs (asteroid-like bodies, aggregate of SM particles, …)

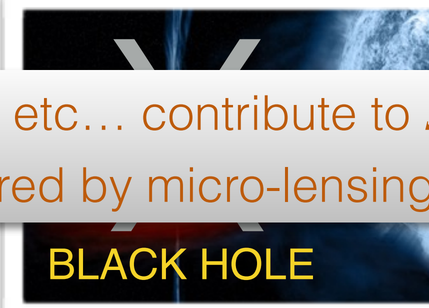
[Jacobs, Starkman, et al. from 2014]



2. Primordial Black Holes

- Typically DM is believed to be a BSM particle because of the firm predictions of Big Bang Nucleosynthesis (BBN)
- MACHOs are constituted by astronomical bodies that emit very few or no light (hence very difficult to be detected) and are massive





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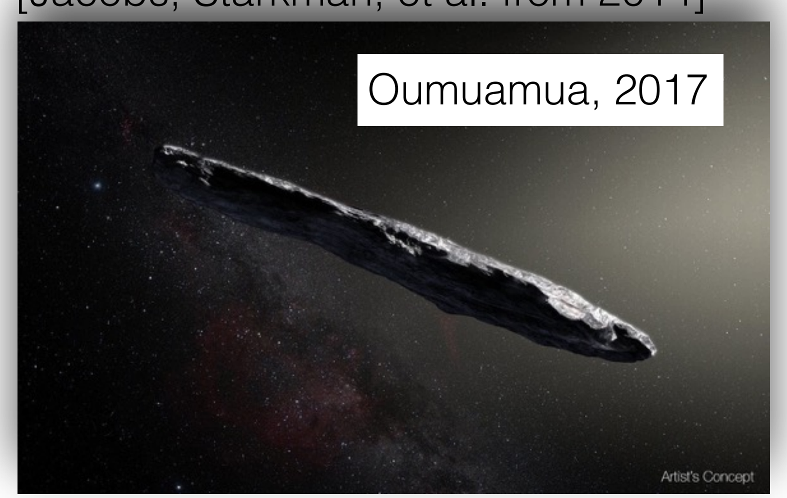

PHB can be DM and are constituted of ordinary baryonic visible matter

2. Primordial Black Holes

- PBHs are old DM candidates (and not only) [Zel'dovich & Novikov 1967,Hawking 1971,Carr 1975, Ivanov 1994]
- PBHs as DM got again a lot of excitements from 2016, after the first LIGO detection of gravitational waves (GWs) from a BH merger

For details about GWs see talks: aVirgo (Bersanetti), ET (Greco), LISA (Vetrugno)

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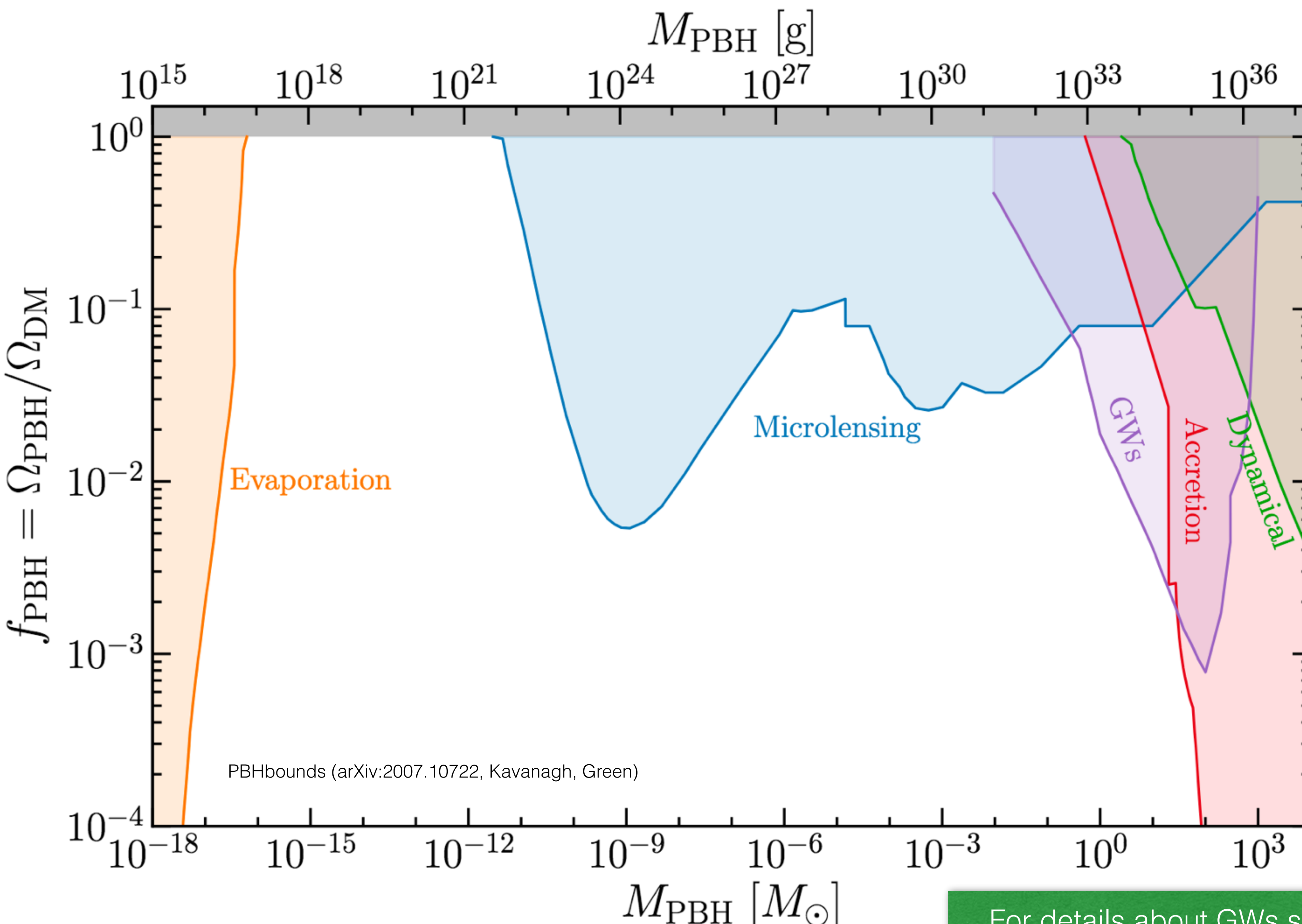

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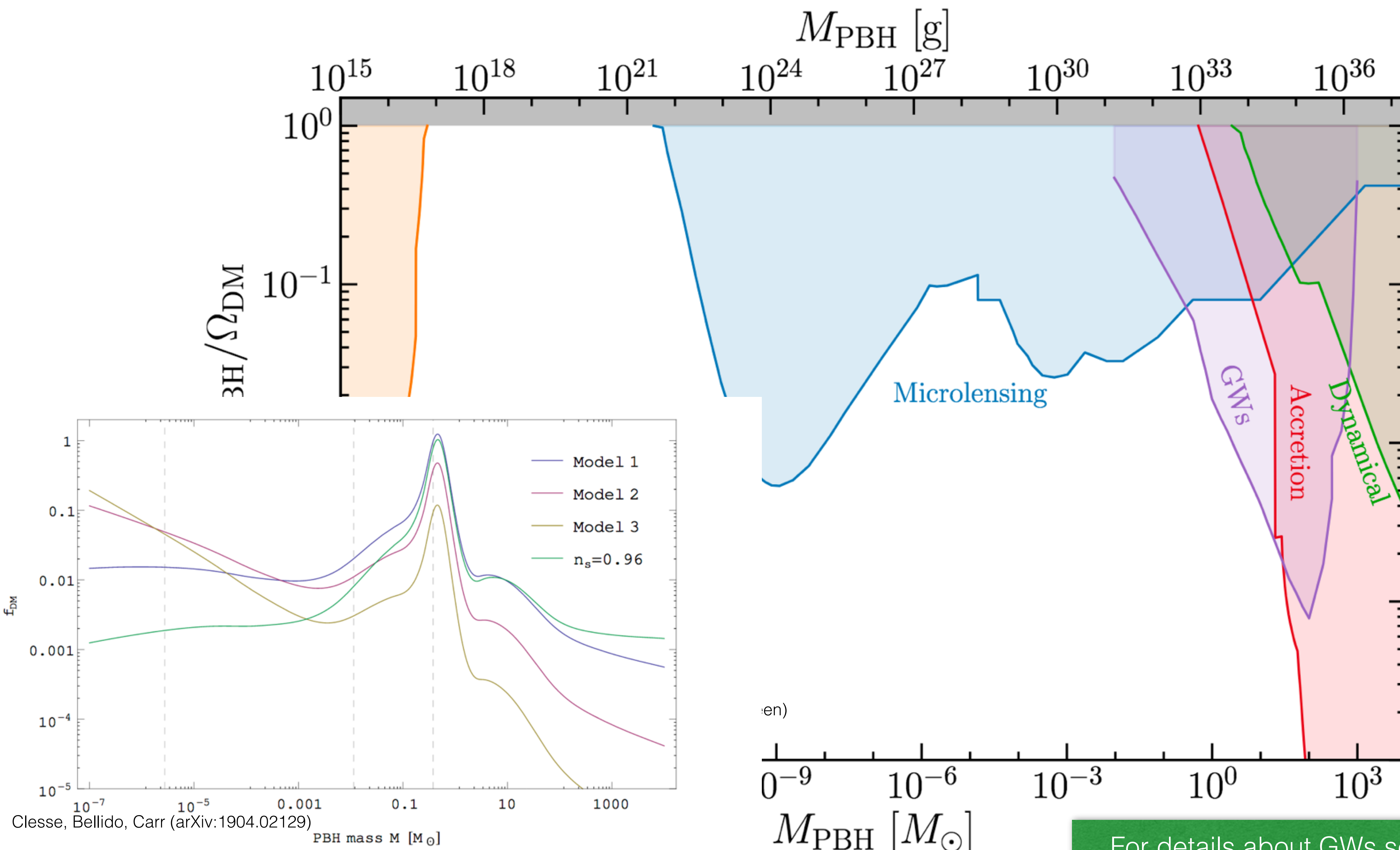
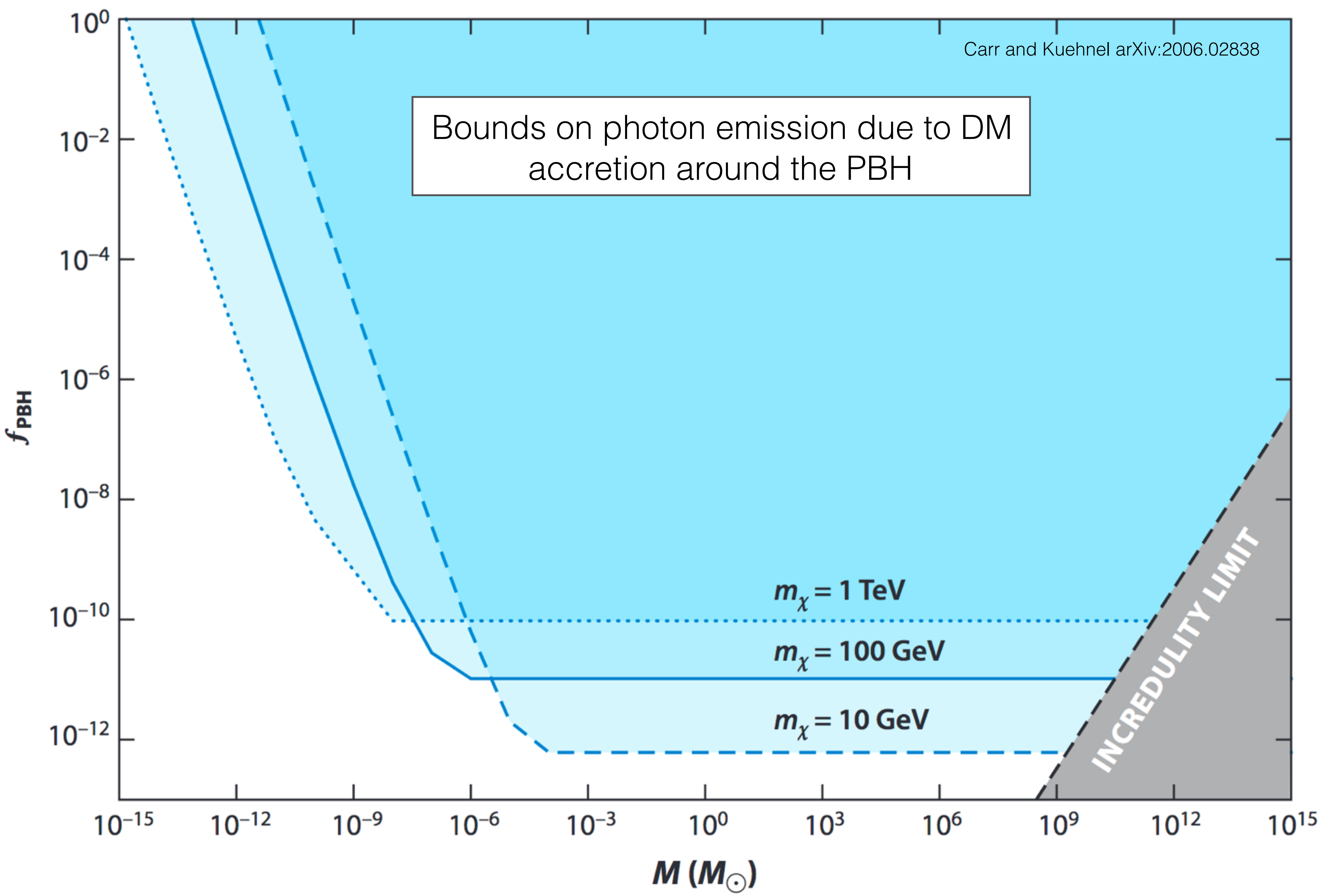


Clesse, Bellido, Carr (arXiv:1904.02129)

For details about GWs see talks: aVirgo (Bersanetti), ET (Greco), LISA (Vetrugno)

Multi-component DM: WIMPs and PBHs?

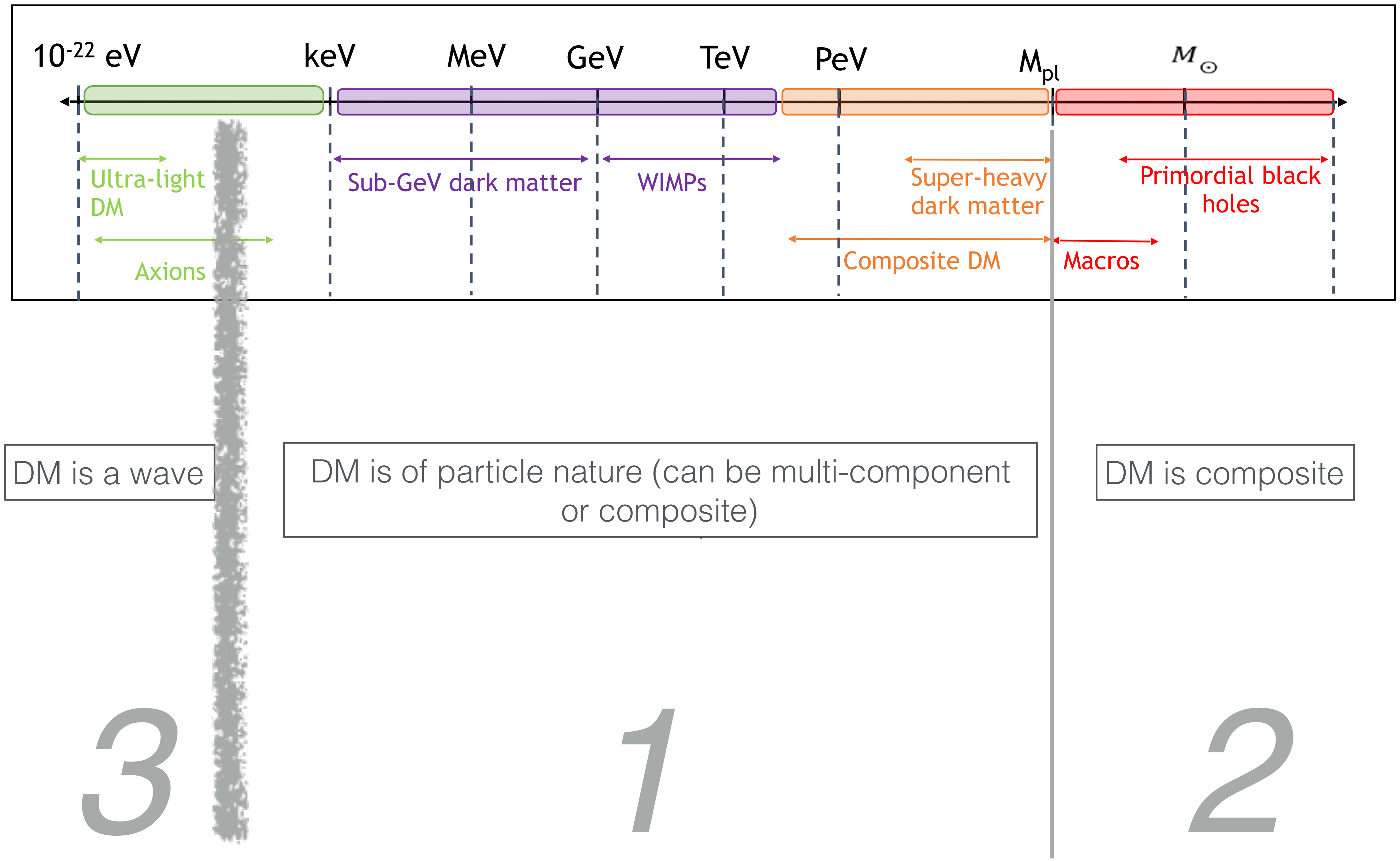
Carr, Kuehnel, Byrnes, Boucenna et al.



In the most probable scenarios, these two DM candidates are mutually exclusive, indication that one can rule out presence of the other

Characterizing the DM landscape

- To have an overview of the DM landscape it is convenient to consider mass regions
- For each mass region, identify the typical signals expected to be detected, which can be related to the strength of the interaction cross-section
- Activity in the DM theory is now a days mostly data/experiment driven



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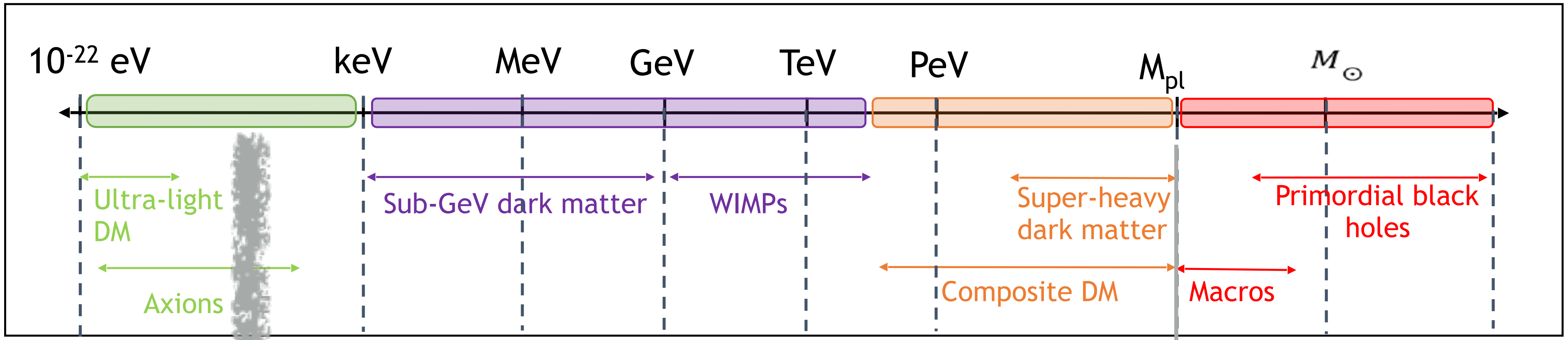

DM is a wave

DM is of particle nature (can be multi-component or composite)

DM is composite

3

1

2

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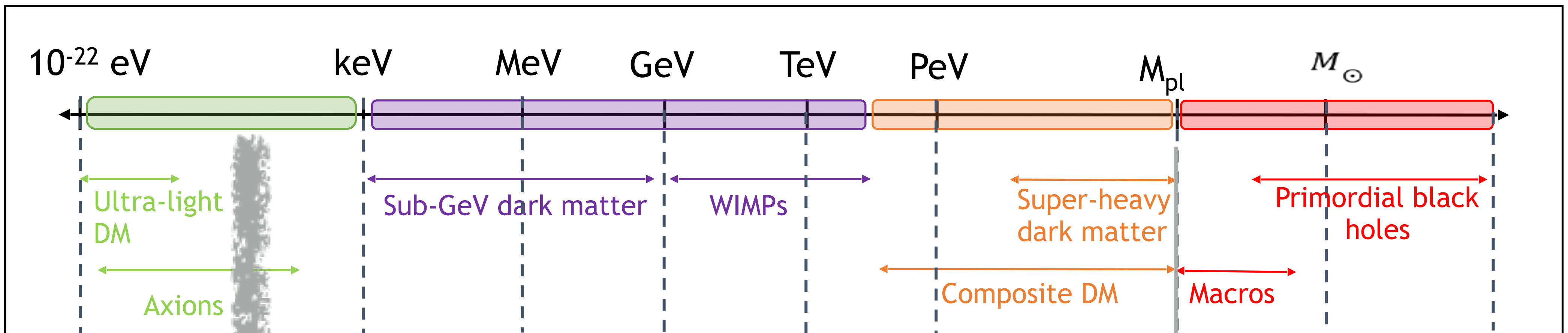

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3. Wave DM

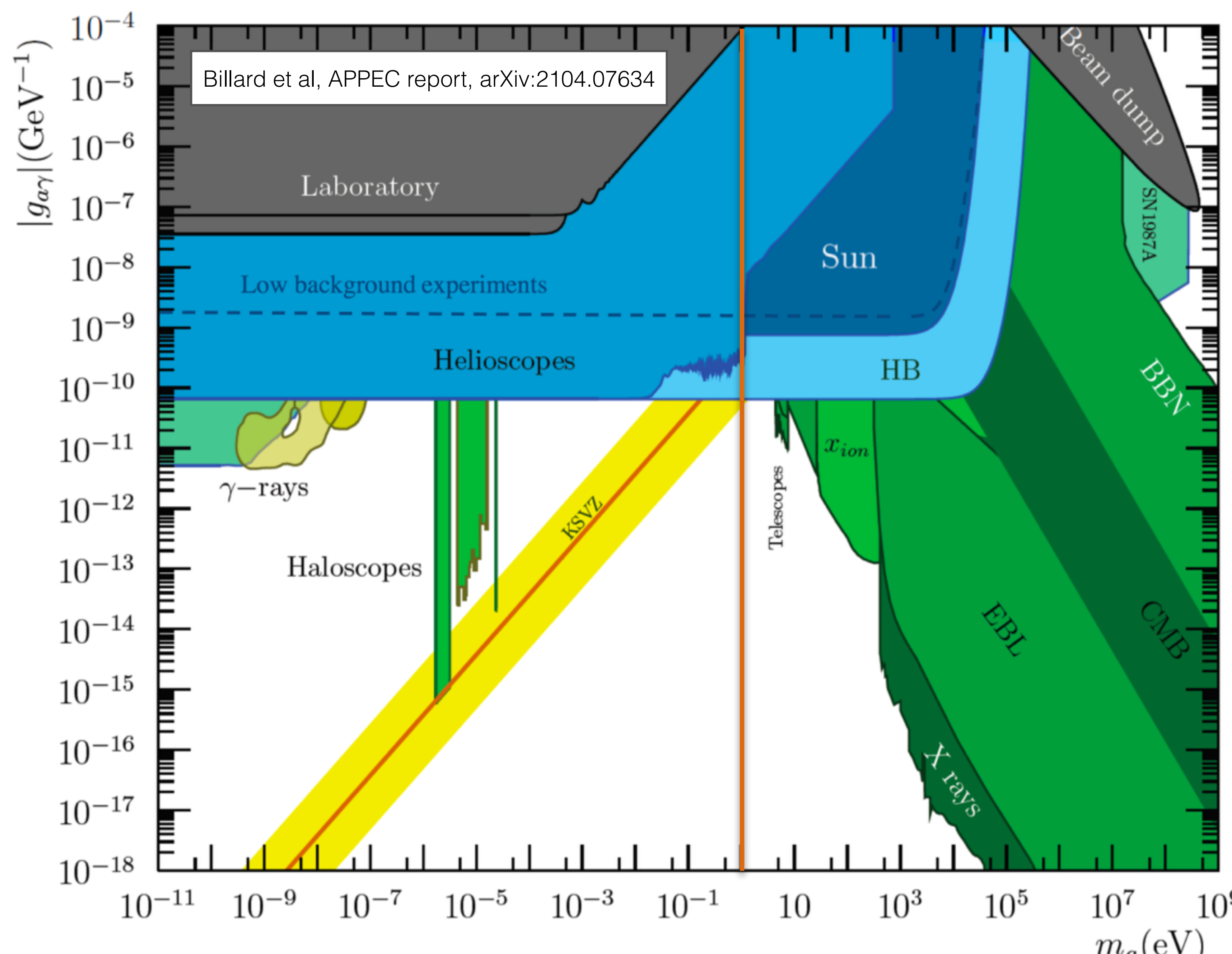
- For $m_{DM} < 1$ eV, DM should be thought as a wave and is bosonic

$$\text{Occupation number} \sim \frac{\rho_{\rm DM}}{m_{\rm DM}} \lambda^3_{\rm deBroglie} > 1$$

- One of the first candidates: QCD axion with definite predictions for the mass m_a and the decay constant f_a (very narrow target) [Peccei-QUinn 1977, Winberg 1978, Wilczek 1978].
- Spin 0 Axion-like candidates (ALPs) are pseudo Nambu Goldstone bosons with a broad parameter space for m_a, f_a (clockwork mechanism, misalignment, instantons, fuzzy DM…)
- Spin 1 Dark photons

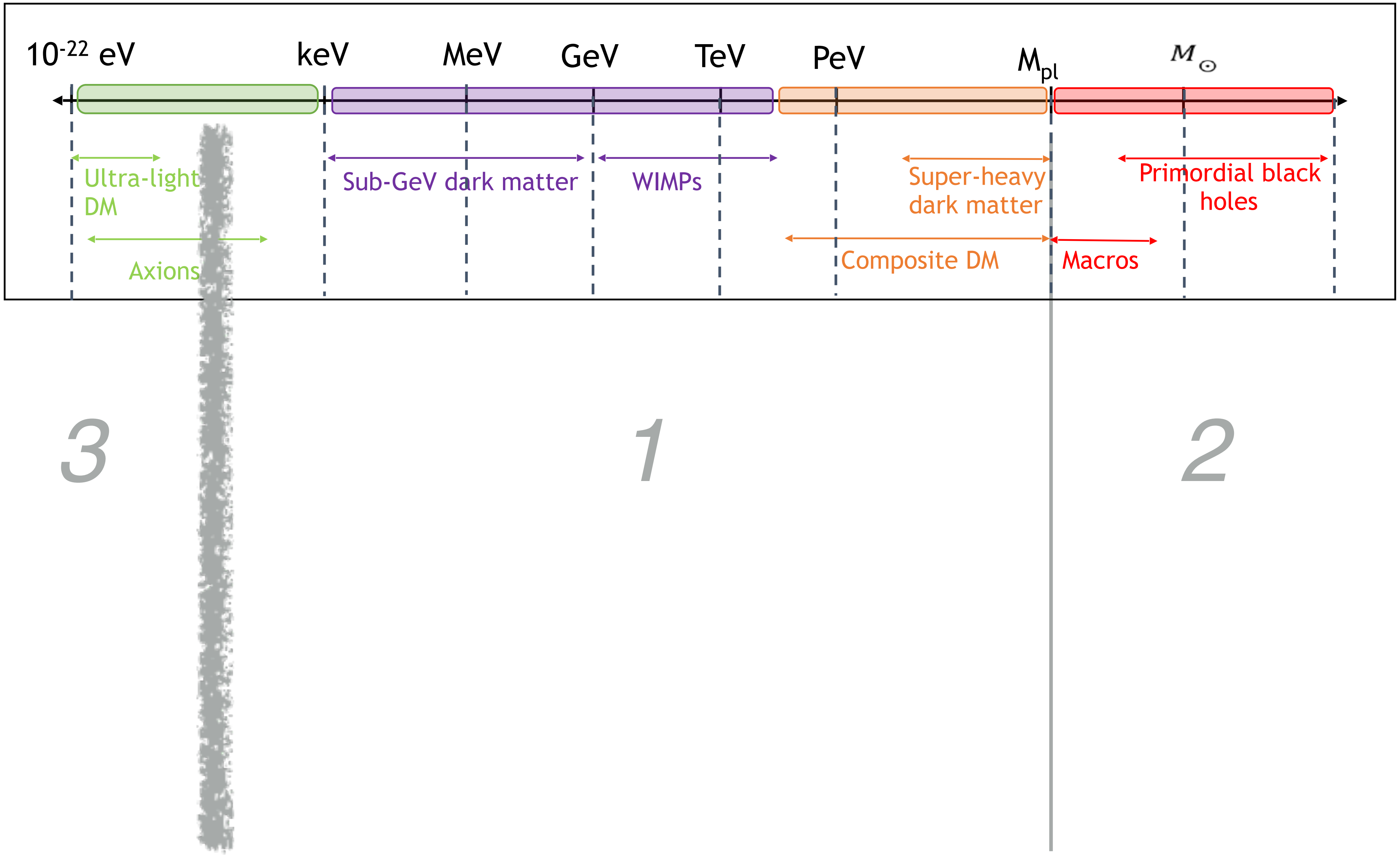
$$g_{a\gamma} \propto \frac{1}{f_a}$$

Alps: clockwork, Farina et al. 2016;
Instantons, Agrawal et al. 2017.
Dark photons: Agrawal et al. 2018; Co et al. 2018; Bastero-Gil et al. 2018; Dror et al. 2018; Long & Wang 2019.
Fuzzy DM: Hu,Barkana,Gruzinov 2000; Hui, Ostriker,Tremaine,Witten 2016.



For details about dark-photons and axion-like particles see talk by I. Oceano

Summary and Prospects



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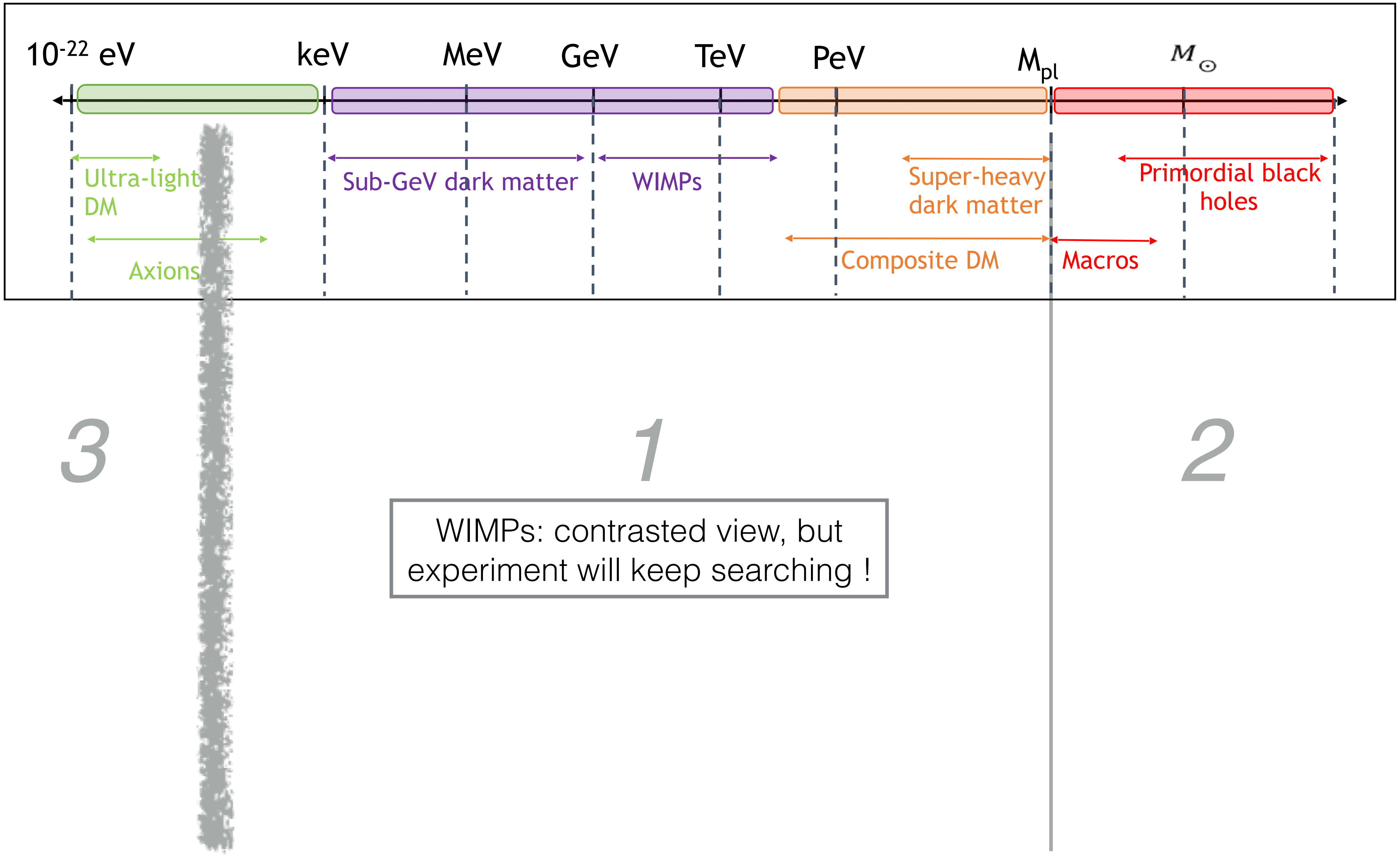

WIMPs: contrasted view, but experiment will keep searching !

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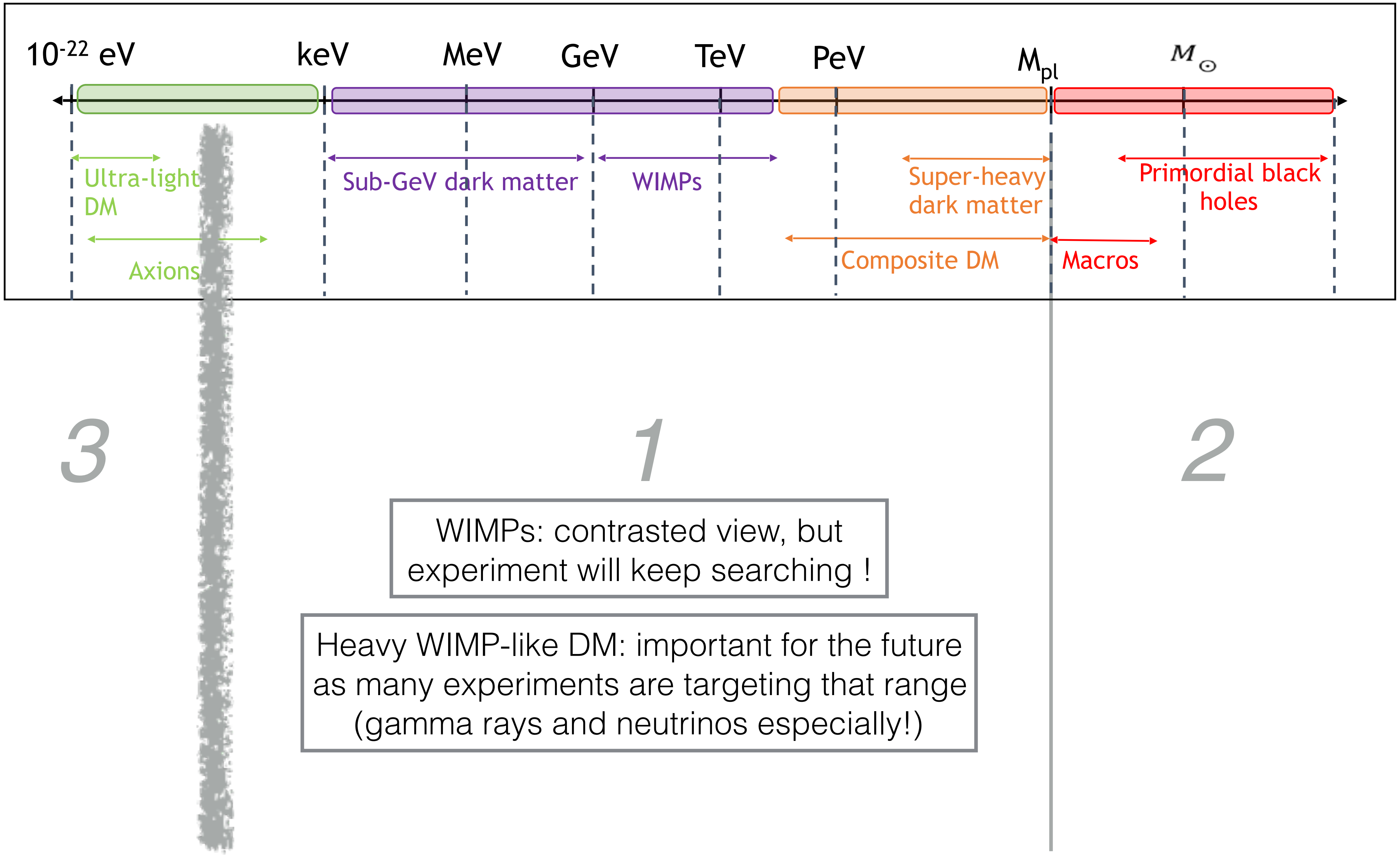

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Heavy WIMP-like DM: important for the future as many experiments are targeting that range (gamma rays and neutrinos especially!)

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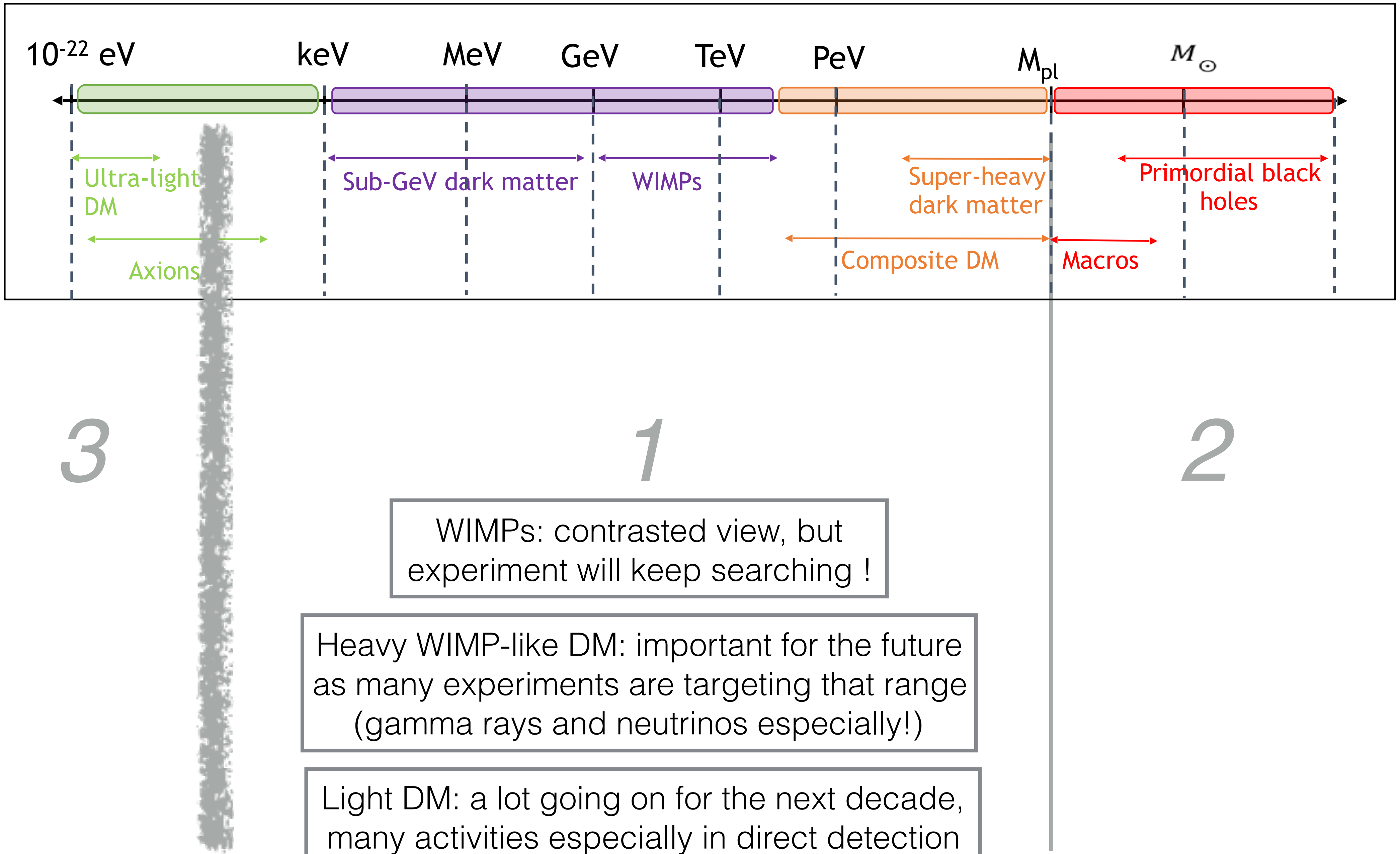

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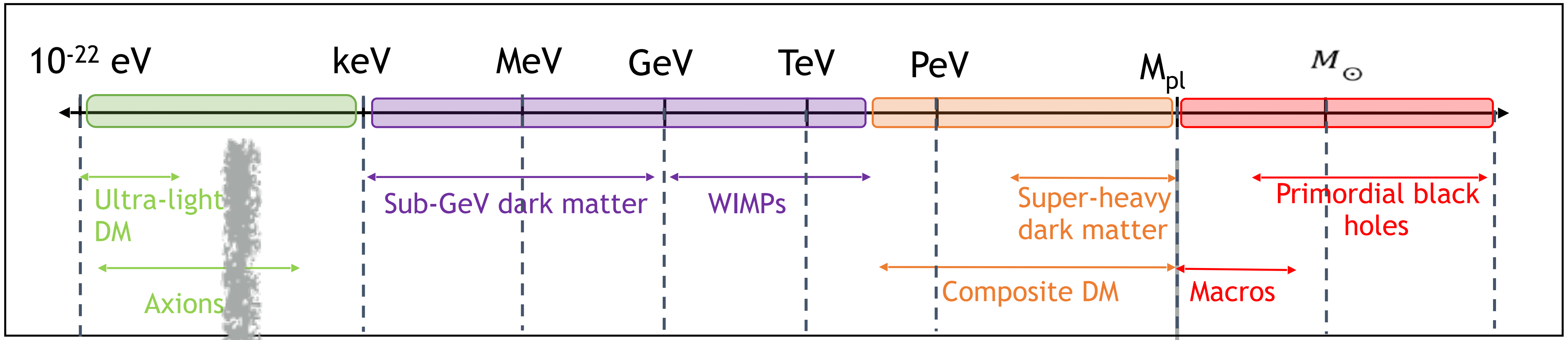

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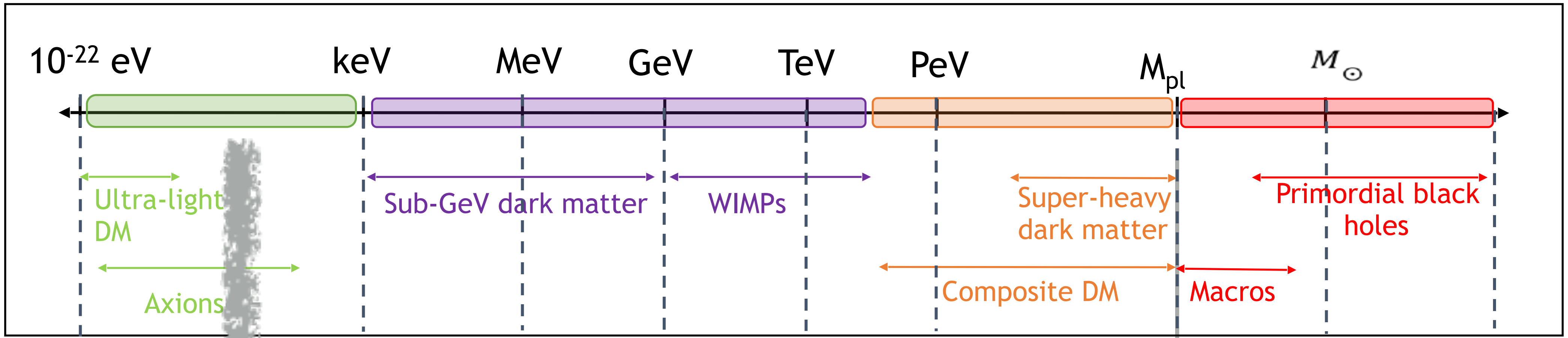

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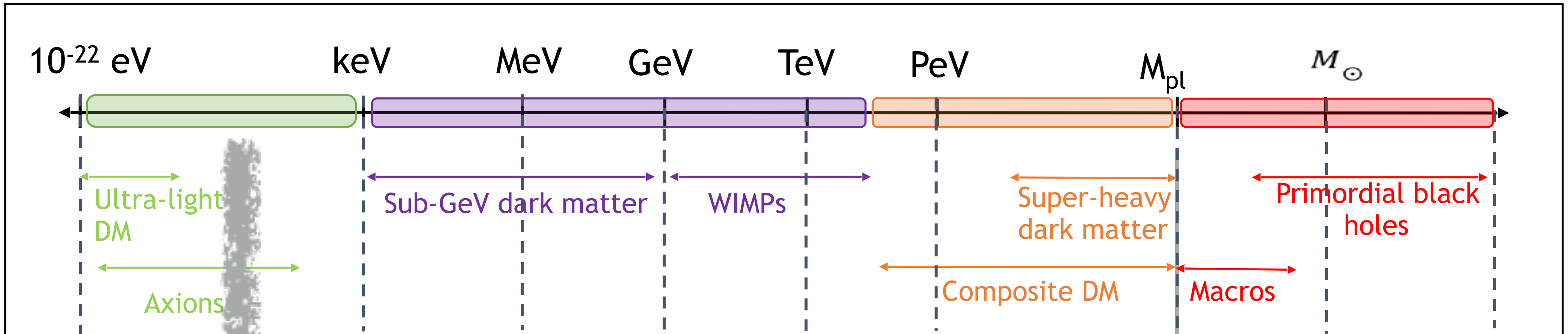

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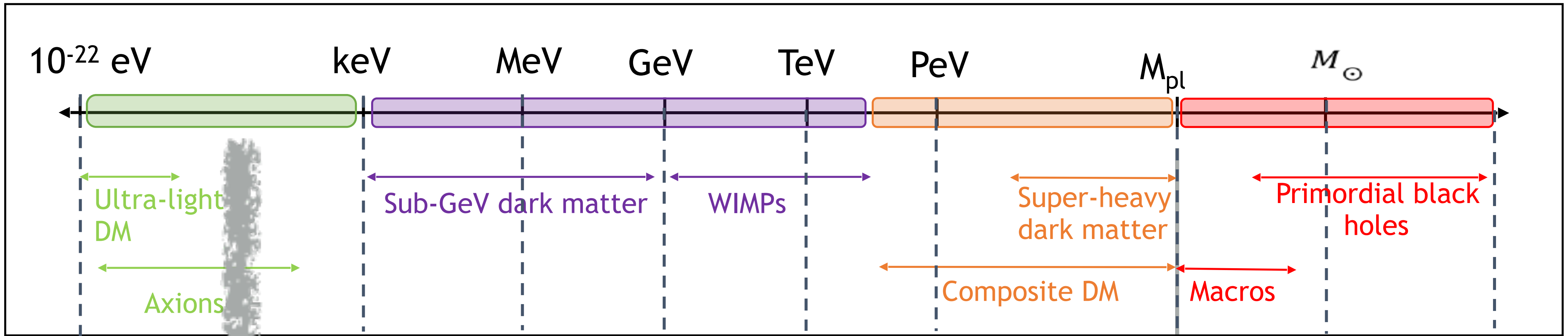

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The ability to sample efficiently the parameter space of DM models requires numerical and statistical tools: huge activity for the near future

Numerical tools development

Generic BSM model:

- MicrOMEGAs [Belanger, Pukhov et al., 2001]
- DarkSUSY [Bringmann, Edsjo et al., 2004]
- **MadDM [CA et al., 2013]**
- GAMBIT coll. [2017]

WIMP-like Model independent

- PPPC4DM, NREFT [Cirelli et al. 2010]
- Direct detection: DirectDM, RAPIDD, RunDM, DAMASCUS, DM-e … [Bishara, Cheek, Kavanagh, Kouvaris, Catena et al.]
- Indirect detection: USINE, DRAGON, GALPROP, CLUMPY, … [Hütten, Evoli, Maurin, Moskalenko, et al.
- CMB [Slatyer et al.]

PBHs, ALPs, etc…

- Private codes: I. Musco, S. Clesse, …
- PBHbounds [Kavanagh, Green 2020]
- gammaALPs [Meyer, Davies, Kehlmann 2021]

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- standard freeze-out, freeze-in and all pheno are fully covered
- Taken into account fancy hidden sectors
- Taken into account fancy phenomenology

- Developments needed for heavy DM related to neutrinos and gamma-rays (Chianese et al., Arguelles et al., …)
- Wider portability is heavily work in progress: e.g. python modules (gammapy, fermitools….)

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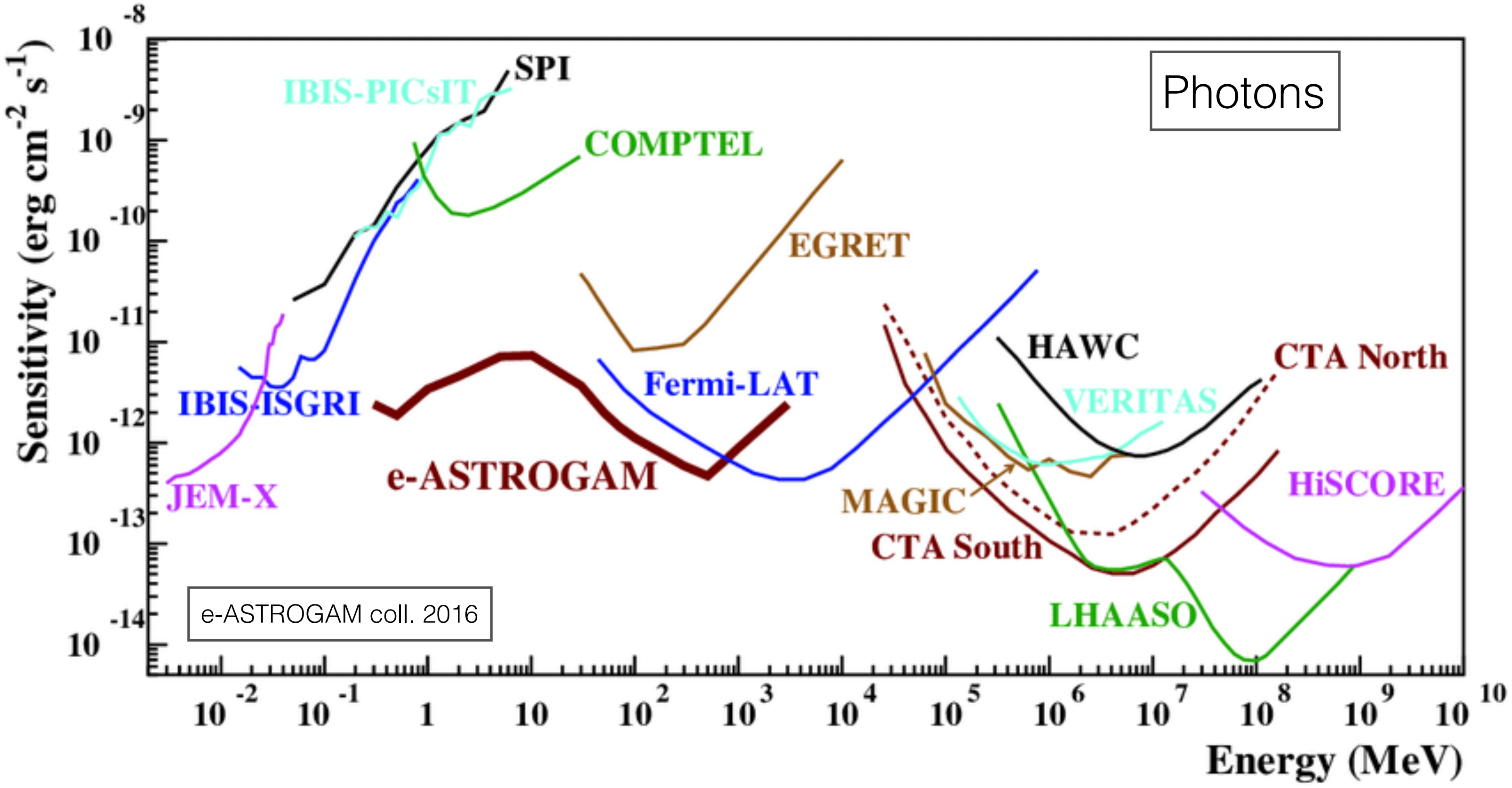
Thank you for your attention!

Back up slides

Full characterization of DM-nucleus scattering: NREFT description of DM for DD
(operators in a non-relativistic basis, see e.g. Cirelli,Panci,Del Nobile 2013)



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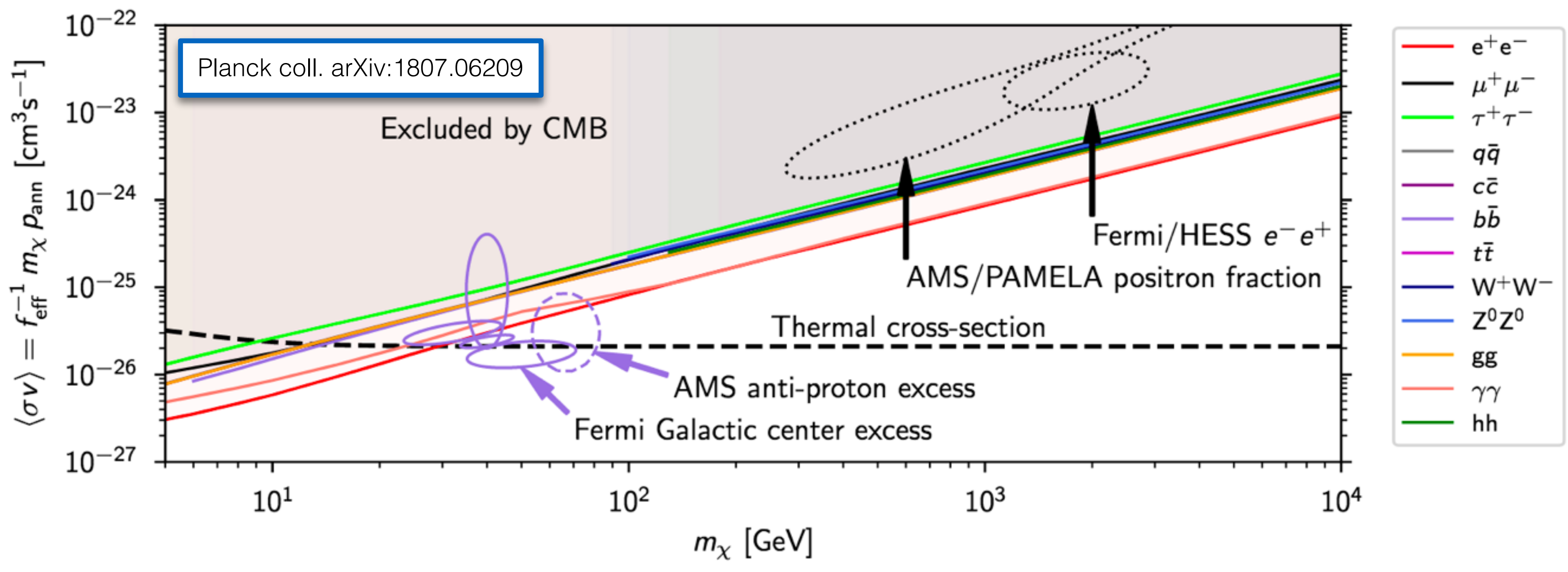

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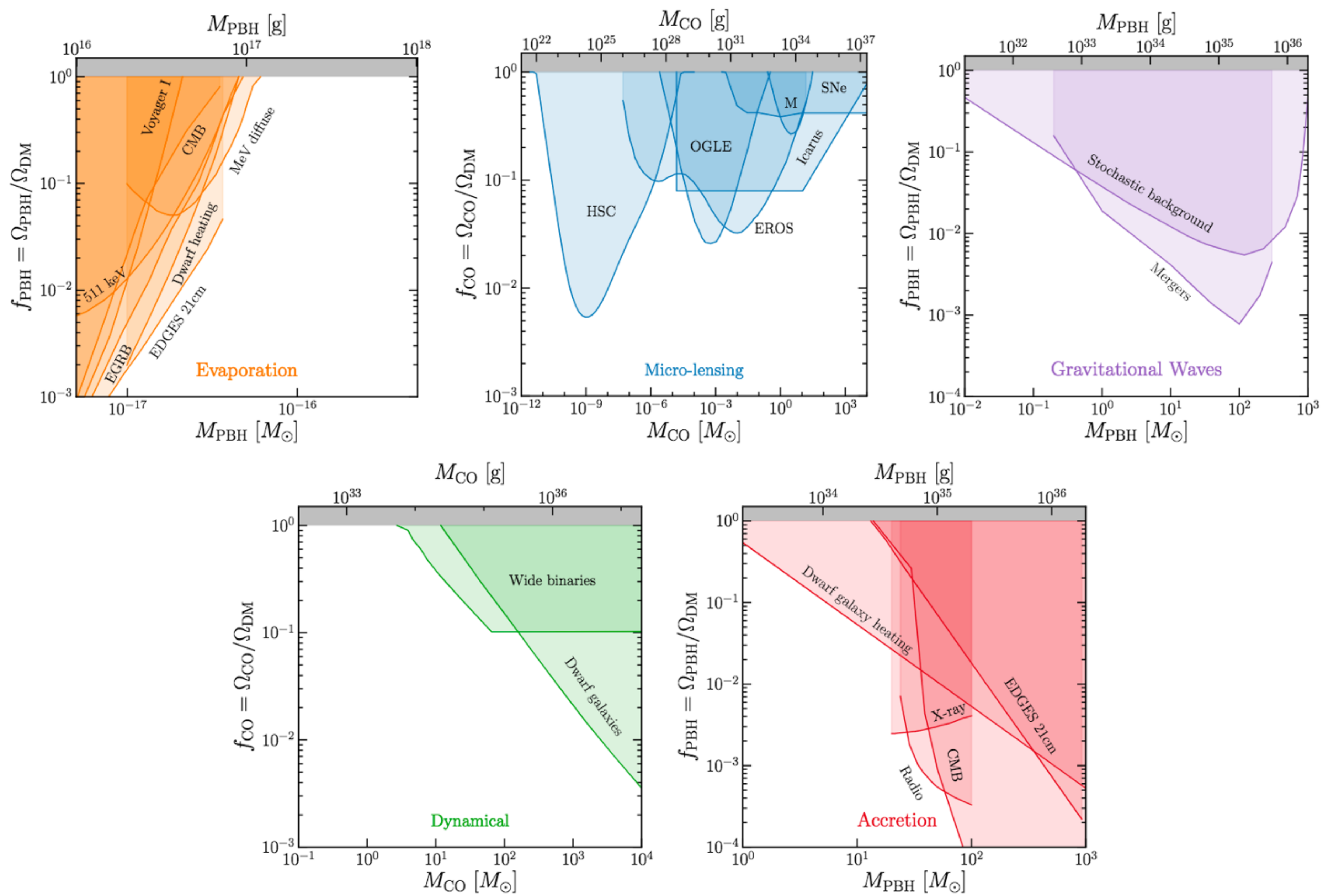
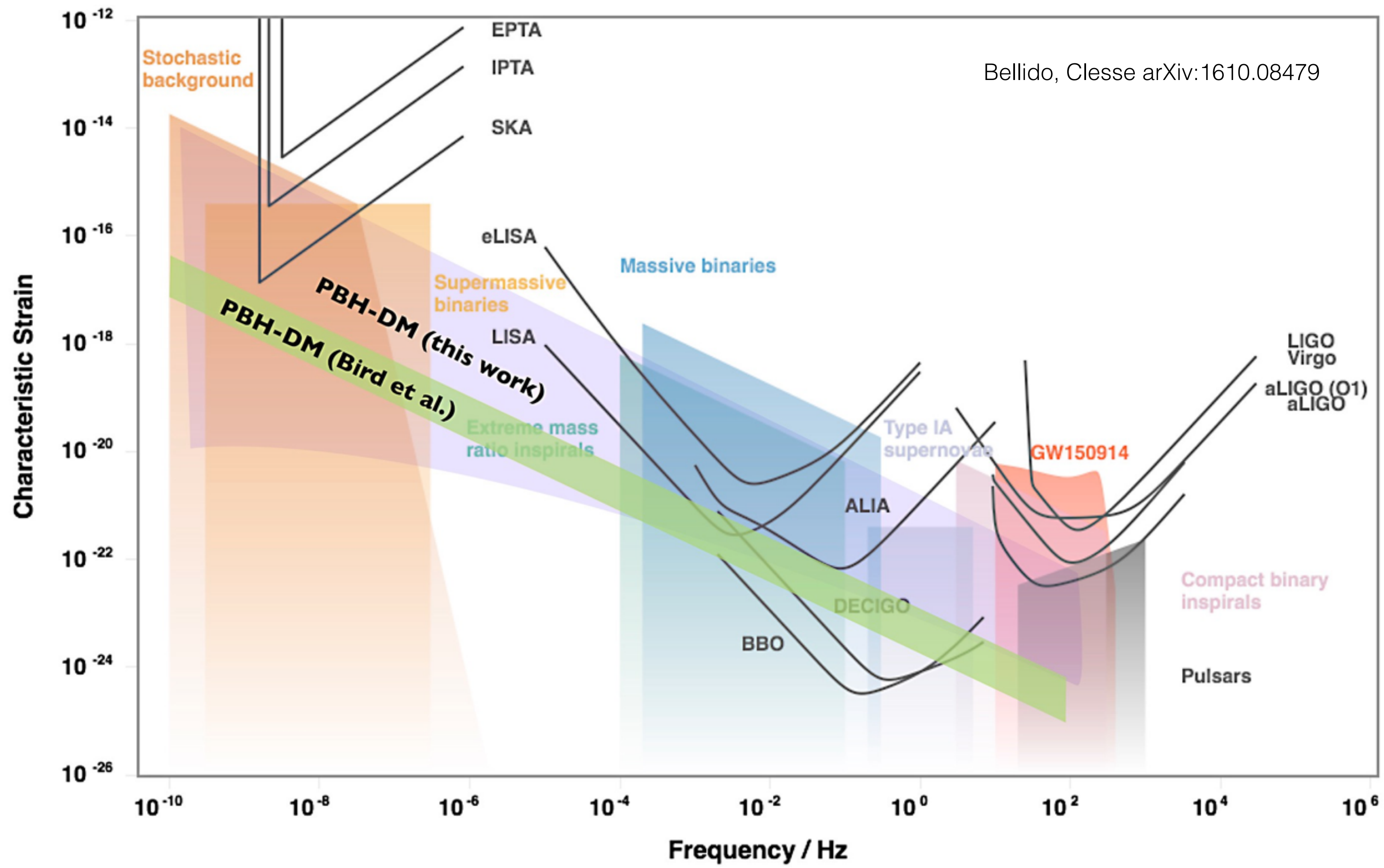
PBH constraints



PBHbounds (arXiv:2007.10722, Kavanagh, Green)

Multi-messengers approach: DM prospects from GWs

ET science case (Maggiore et al. arXiv:1912.02622), LISA science case (E. Barausse et al. arXiv:2001.09793)



- Accretion of DM in compact object can be studied during the merger phase
- Dark-photons (e.g. LIGO-Virgo)
- Bosonic clouds (e.g. LIGO-Virgo)
- Bound formation of spikes around BHs and WIMP annihilation/decay (Gondolo & Silk 1999; Banados et al, Silk et al.; CA, Silk, Kulkarni 2015; Silk, Lacroix, Bhoem 2015; Kavanagh et al 2020; …)

For details about GWs see talks: aVirgo (Bersanetti), ET (Greco), LISA (Vetrugno)

Outline

- What do we know so far about the dark matter (DM)
- What DM has been believed to be until recently
- Vast landscape of DM new (or old but revisited) candidates
- Theoretical or phenomenological motivations
- Expected DM signals depending on how DM interacts with its environment