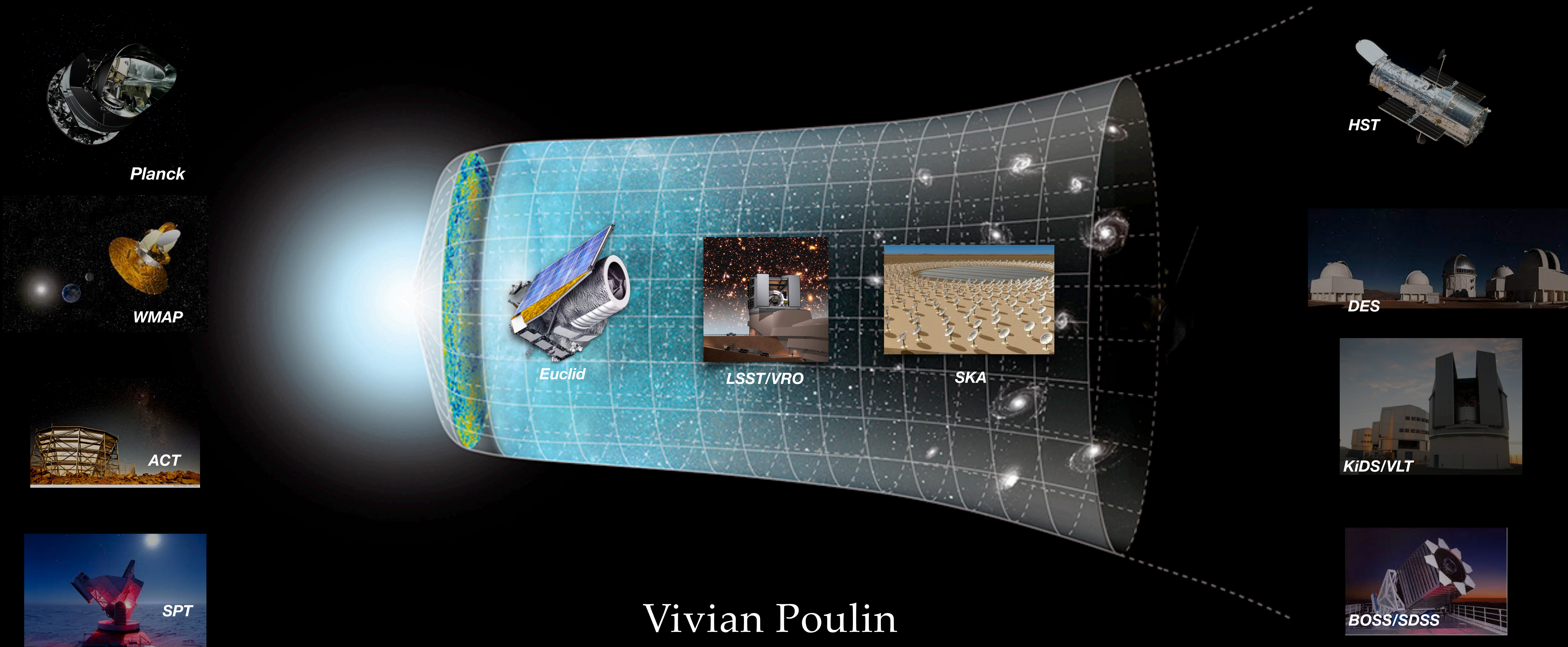
Dark Matter in Cosmology



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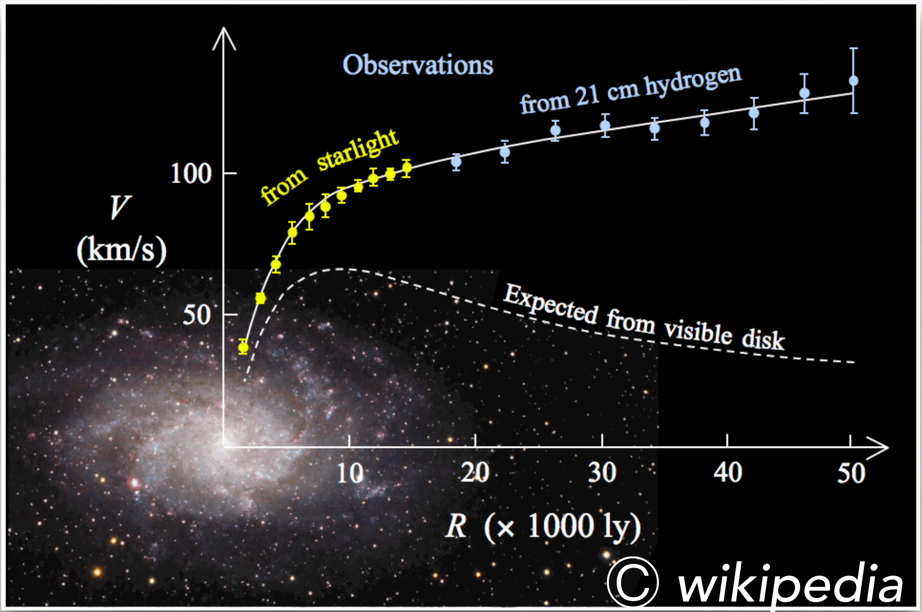
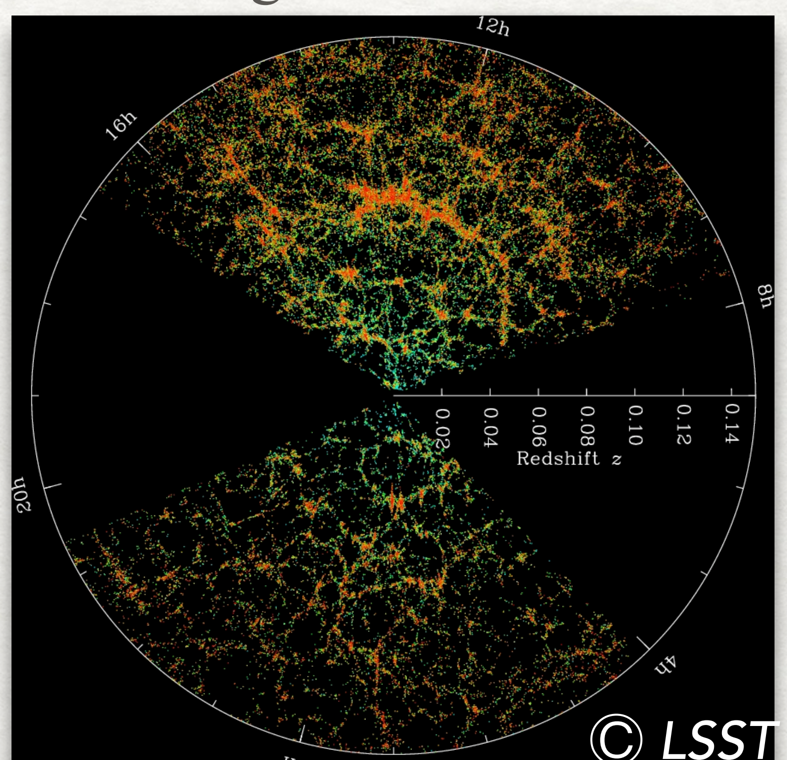
Atelier "Physique Théorique des deux infinis"
June, 08th 2021

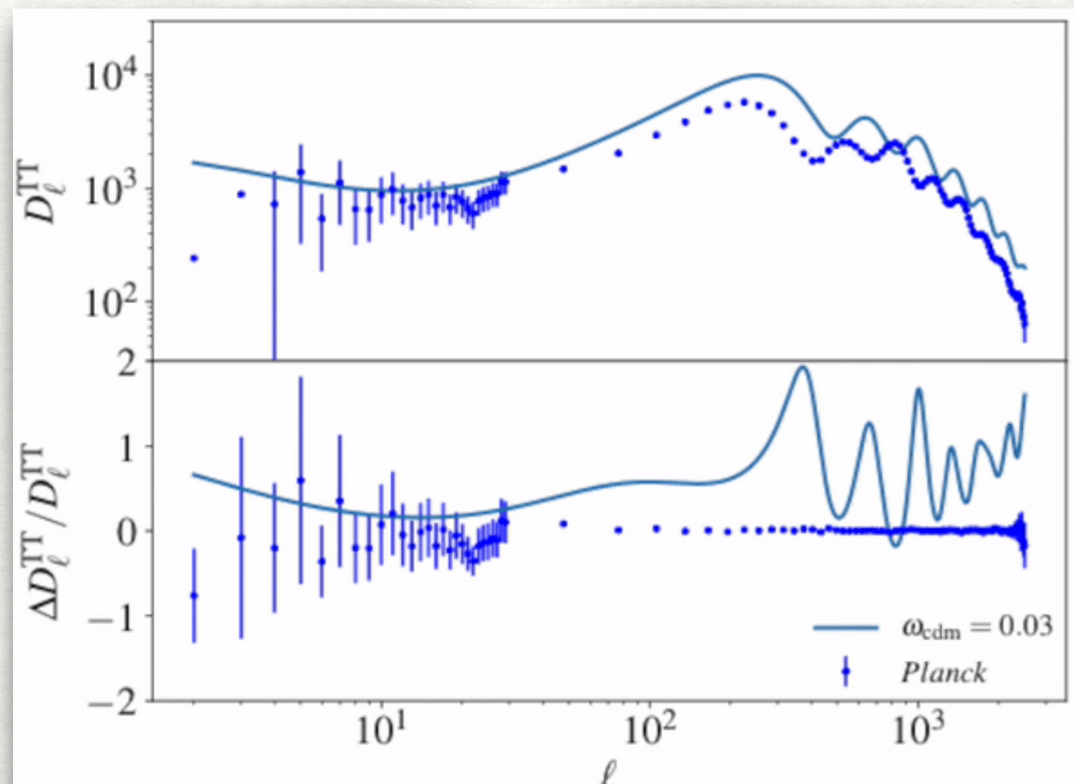
Dark Matter: many clues on many scales

From galactic scales…



… to cosmological scales.



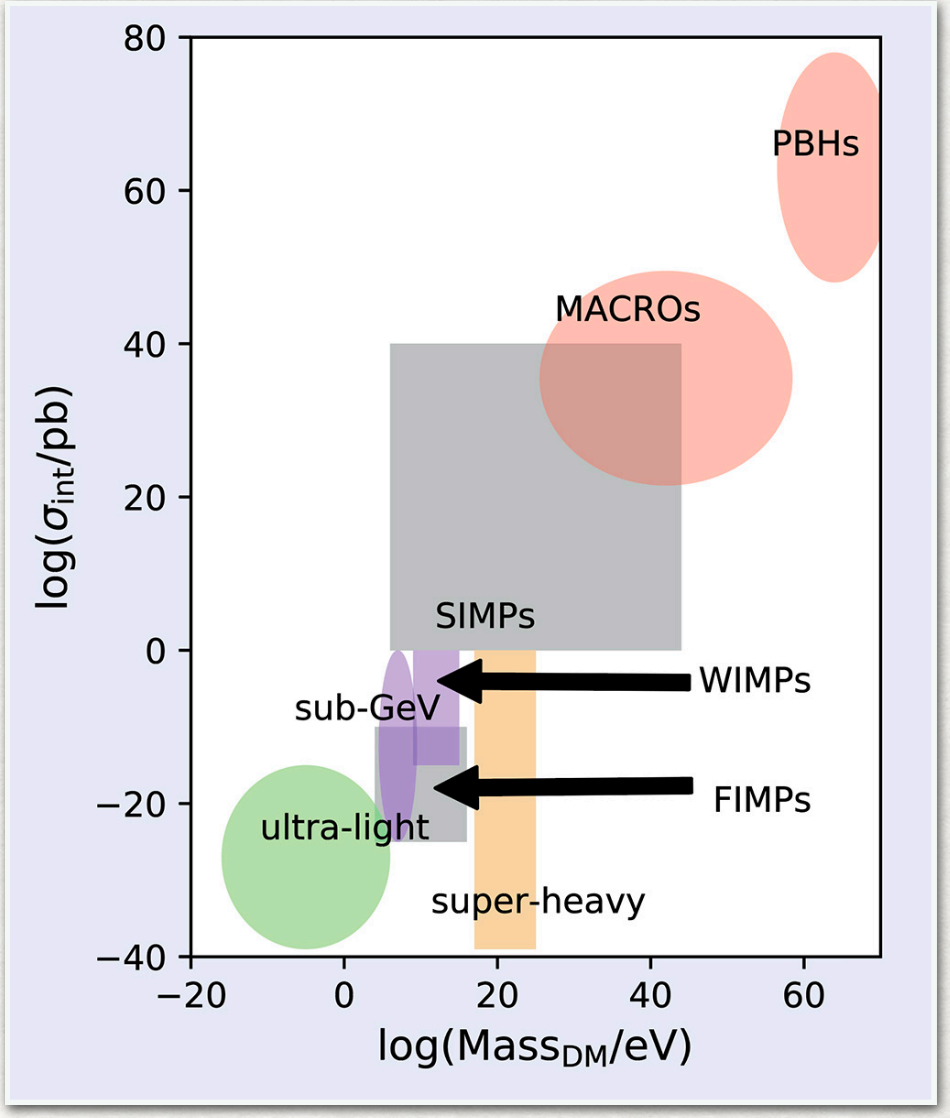


What we do **not** know about Dark Matter

In the ΛCDM model, Dark Matter is a cold, collision-less, matter component, which interacts only through gravity with other species.

Most of its basic properties are unknown

- Is it made of a single species?
- Is it a particle? A fermion? A boson?
- If it is a particle, what is its lifetime?
- Does it have non-gravitational interaction?
- How was it produced?
- Is it the same "dark matter" from cosmological to galactic scales?
- and many more…

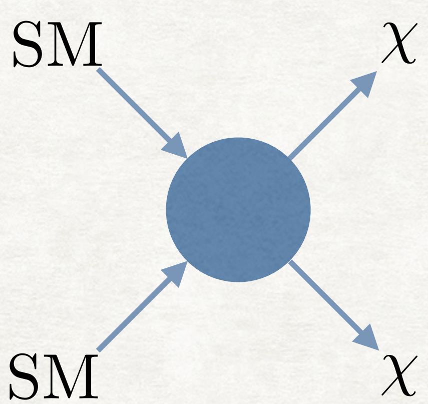


A sketch of the Theoretical DM landscape
Credit: C Arina (cern courier)

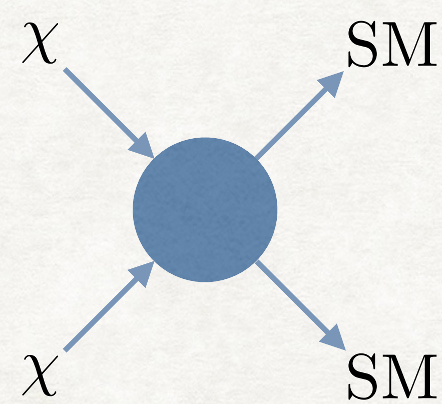
Searching for Dark Matter in cosmology

An analogy with the WIMP

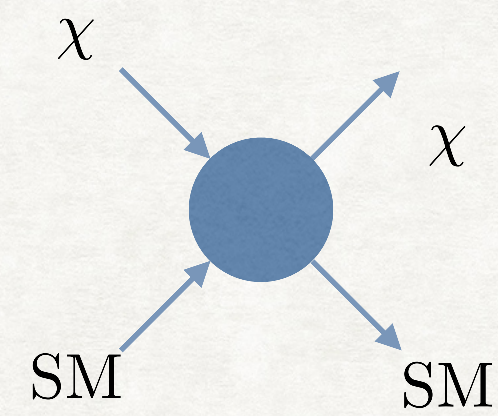
Production



Annihilation



Scattering



in particle physics

Collider | Indirect detection | Direct detection

in cosmology

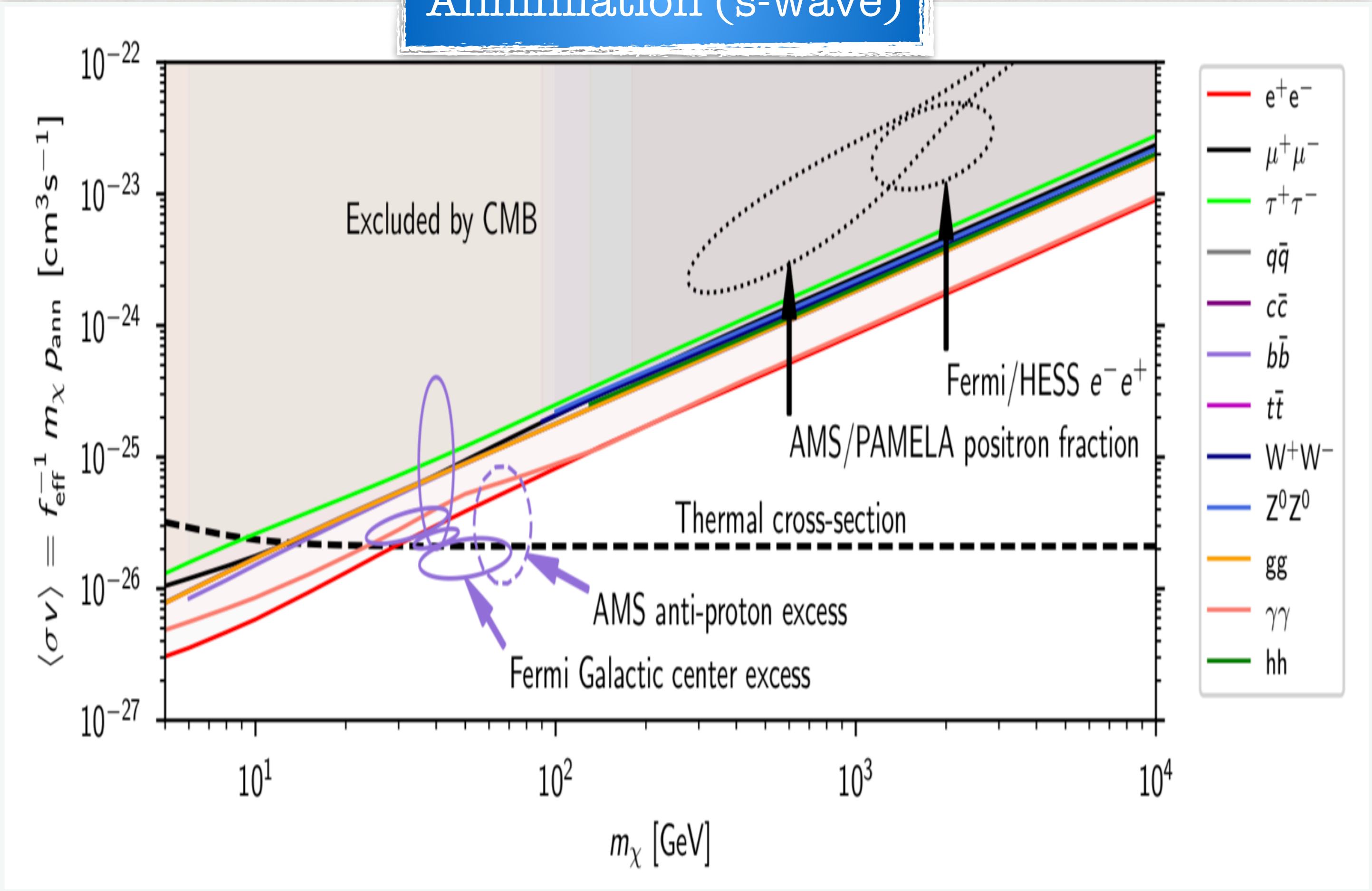
Relic abundance | Energy injection | Momentum transfer

The strength of cosmology is its ability to constrain many different scenarios via the complementarity of various probes
(WIMP, axions, sterile neutrinos, Primordial Black holes…)

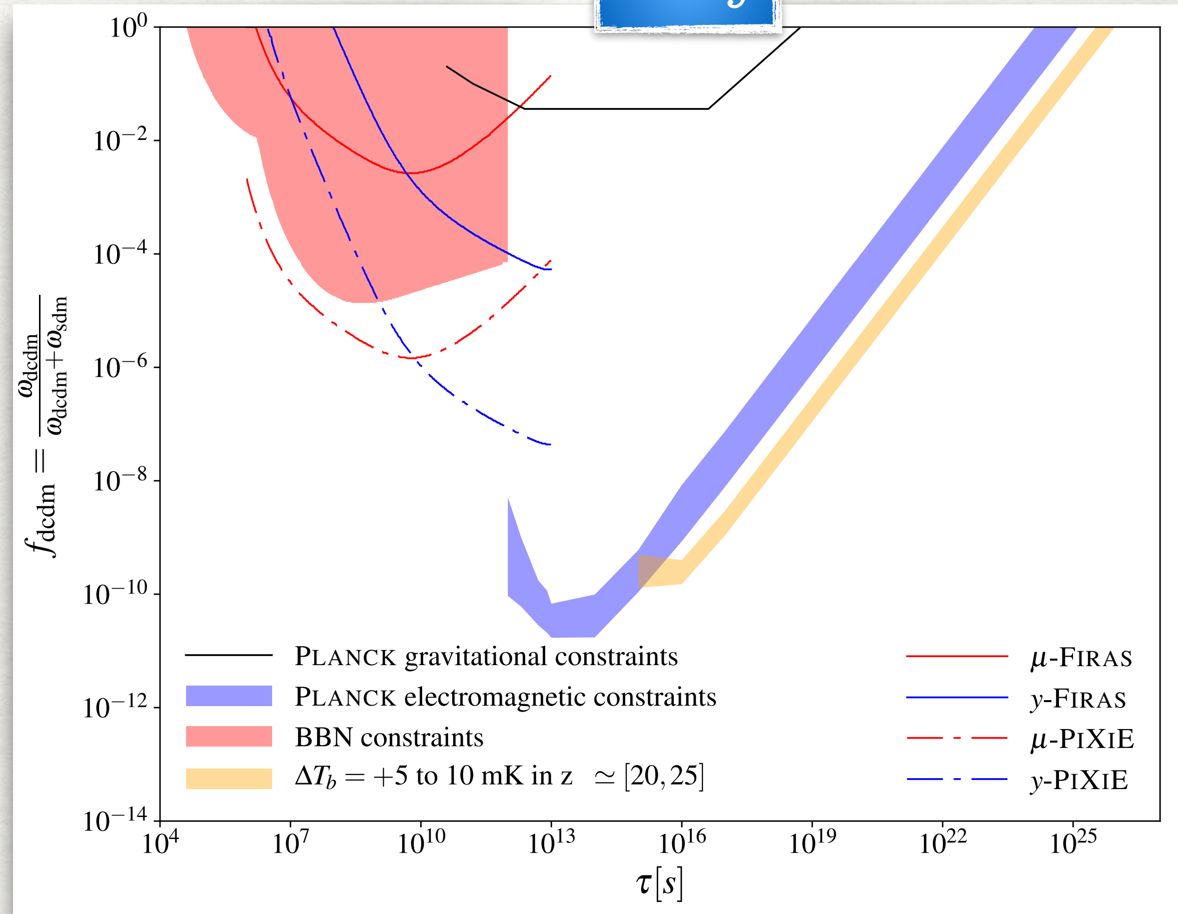
"Cosmic complementarity" over times

Electromagnetic energy injection of Dark Matter is strongly constrained by CMB and BBN.

Annihilation (s-wave)



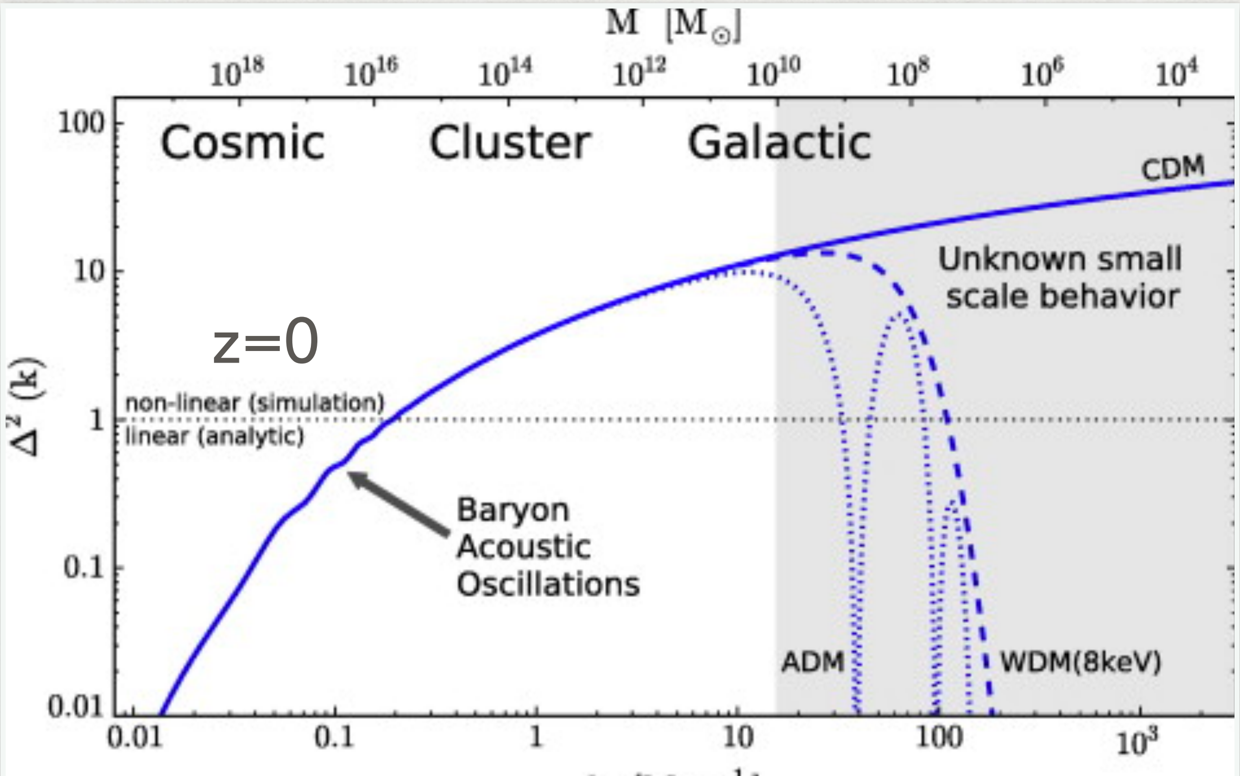
Decay



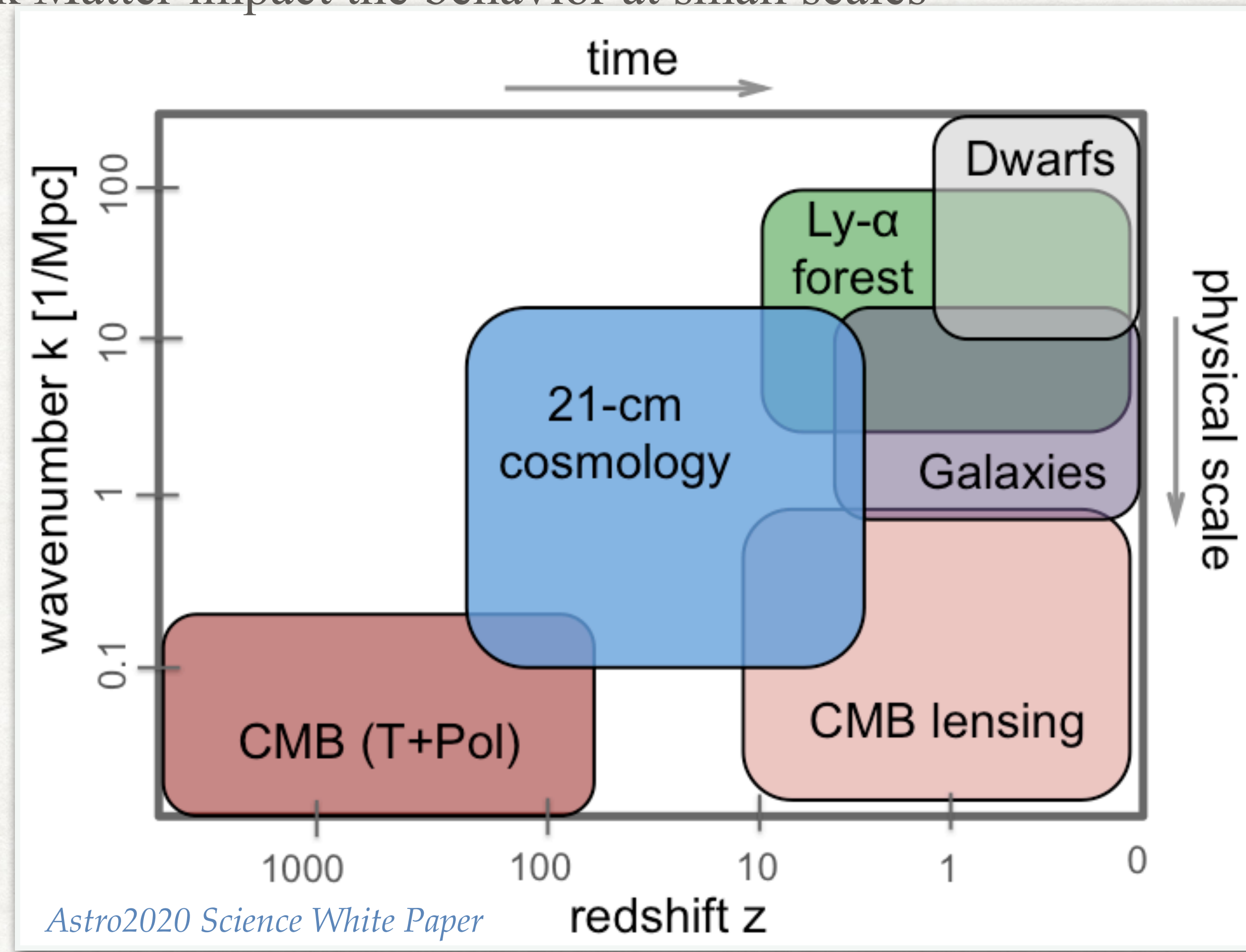
- WIMP Dark Matter: CMB excludes thermal relics below $m < 10 - 30$GeV. Competitive with Fermi, AMS constraints.
- Decaying Dark Matter: CMB can constrain $f_{\rm dcdm} \lesssim 10^{-10}$ at $z \sim 1000$! Complementarity with BBN $z < 2000$.
- Future: 21cm is an exquisite probe of DM thermal history. + CMB 'spectral distortions'.
- e.g. EDGES: exotic 21cm signal *orders of magnitude* stronger than CMB to constrain DM annihilations/decays.
- Theoretical challenges: efficient methods to extract 'cosmology' from large astrophysical uncertainties.

"Cosmic complementarity" over scales and times

Gravitational signature: the nature of Dark Matter impact the behavior at small scales



Kuhlen, Vogelsberger, Angulo 2012



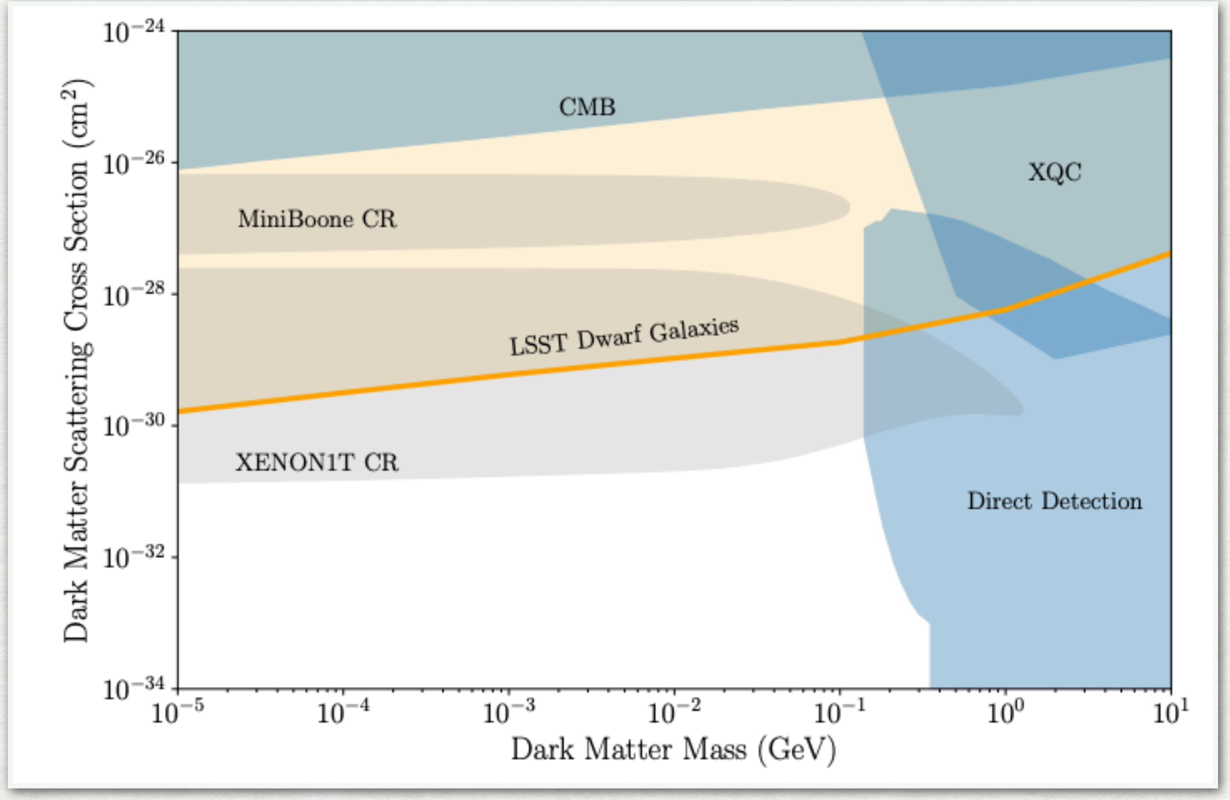
Astro2020 Science White Paper

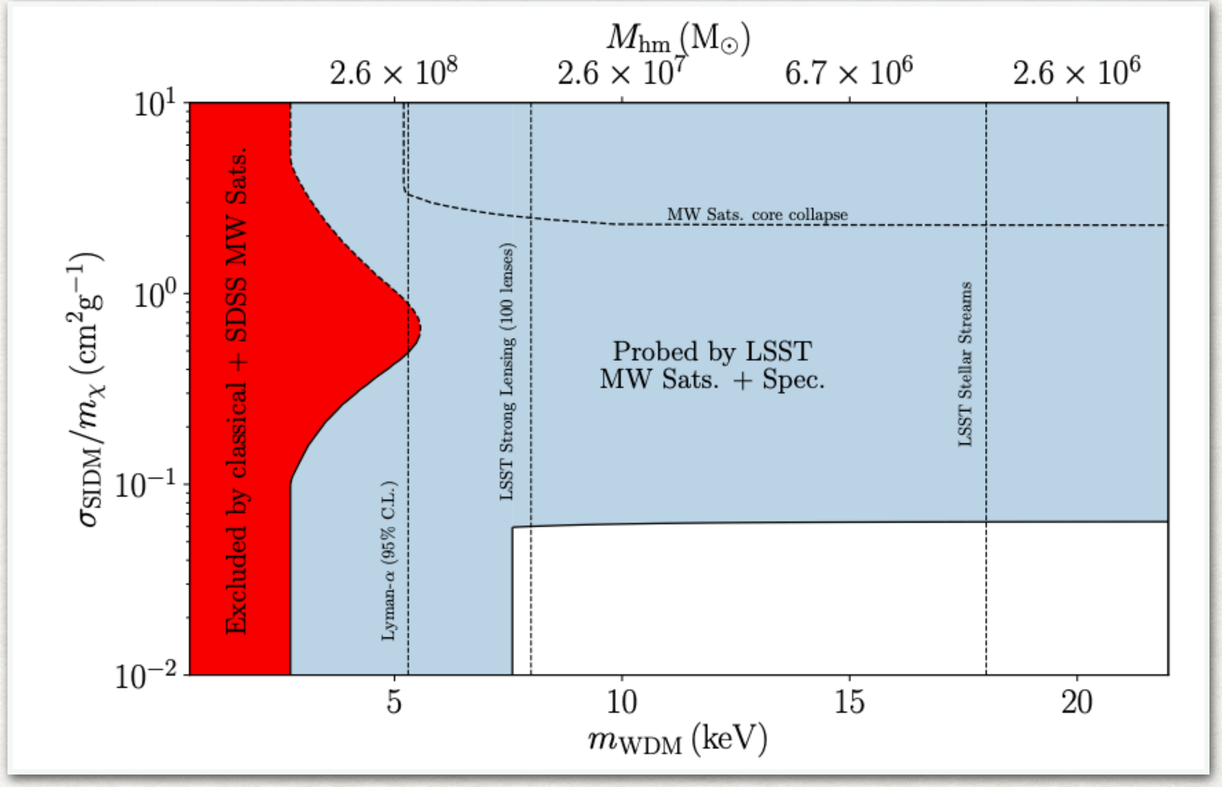
- Large scales: CMB measured to `cosmic-variance' until $\ell \lesssim 2500$ by Planck. (+ACT+SPT extend to 5000)
- Intermediate scales: CMB lensing, Galaxy clustering and weak lensing to few % precision.
- Small-scales: Dwarf satellite count and Lyα strongest at small scales.
- Canonical bounds from Lyα to date: $m_{\rm wdm} \gtrsim 3-5$ keV, $m_a > 2 \times 10^{-20}$ eV. Important for 'small-scale crisis'.
  Irsic++ 1702.01764, Rogers&Peiris 2007.12705
- Future: Great complementarity between CMB-S4 & Euclid / LSST (Vera Rubin Obs) & 21 cm probes (SKA).
- Theoretical challenges: accurate modeling of small-scale physics + statistical analysis. Nbody? EFT of LSS?

Complementarity with laboratory constraints

Direct detection: Dark Matter scattering also suppresses power at small-scales and the number of sub halos

LSST working group 1902.01055





- Direct DM detectors are shielded and insensitive to 'strongly' interacting dark matter; velocity-dependent interaction.
  Boddy & Gluscevic, 1712.07133, 1801.08609, Emken and Kouvaris 1802.04764
- Strong DM-baryon or DM-DM self interaction can impact the small-scale matter power spectrum and suppress the number of sub-halos.
  Nadler et al. 1904.10000
- LSST, Euclid: constrain on the minimal mass of sub halos (e.g. through gravitational lensing).
- EDGES *could* have detected the first hint of DM-b interaction (a fraction of milli-charged DM)
  Bowman et al, nature25792
- Future: Smoking gun signals? Refine understanding of astrophysics to extract cosmology and particle physics?

Many tentative discoveries of DM nature

(A very small sample)

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

Observational evidence for self-interacting cold dark matter

David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton NJ 08544 USA

NEWS **Space Experiment Sees Hints of Dark Matter Particles**

A Tale of Tails: Dark Matter Interpretations of the Fermi GeV Excess in Light of Background Model Systematics

Francesca Calore,[1,*] Ilias Cholis,[2,†] Christopher McCabe,[1,‡] and Christoph Weniger[1,§]
[1] *GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA*

LETTER

doi:10.1038/nature25791

Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana[1]

Evidence for dark matter interactions in cosmological precision data?

Julien Lesgourgues[a,*] Gustavo Marques-Tavares[bc,†] and Martin Schmaltz[b‡]

Dark Matter and the XENON1T electron recoil excess

Kristjan Kannike, Martti Raidal, and Hardi Veermäe
National Institute of Chemical Physics and Biophysics, Rävala 10, Tallinn 10143, E

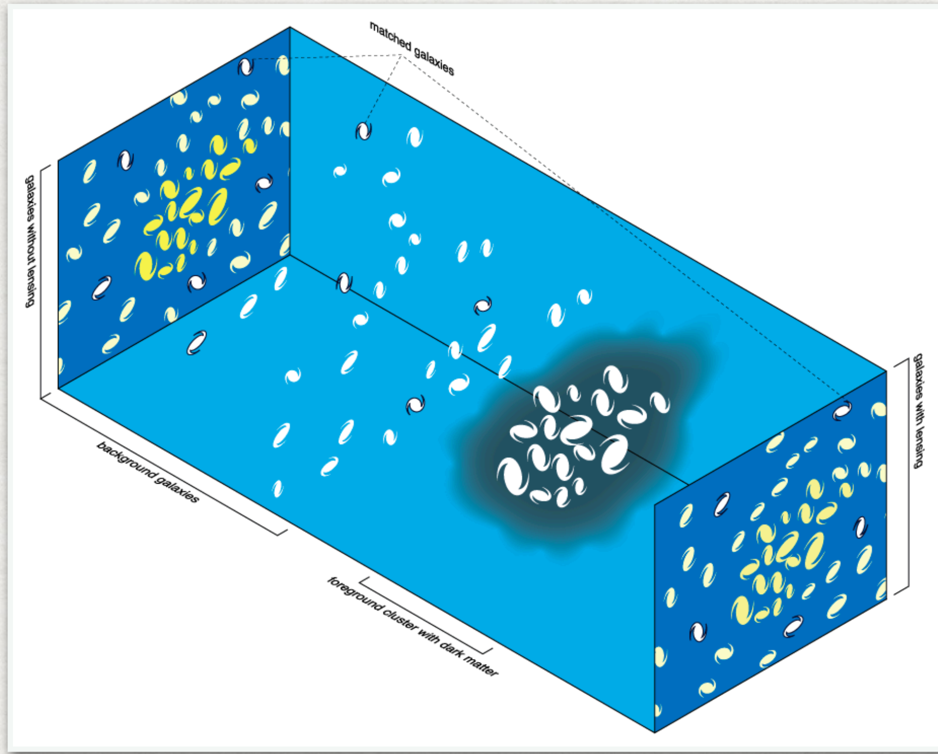
Hints for decaying dark matter from S_8 measurements

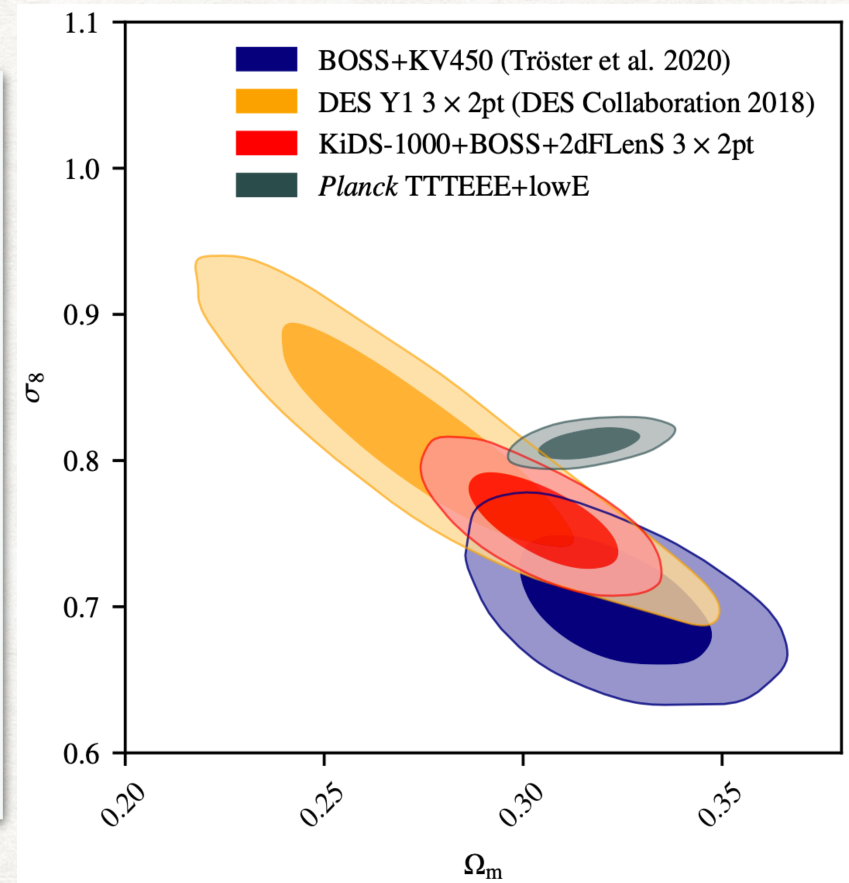
Guillermo F. Abellán,[1,*] Riccardo Murgia,[1,†] Vivian Poulin,[1,‡] and Julien Lavalle[1,§]
[1] *Laboratoire Univers & Particules de Montpellier (LUPM), Université de Montpellier (UMR-5299) Place Eugne Bataillon, F-34095 Montpellier Cedex 05, France*
(Dated: August 25, 2020)

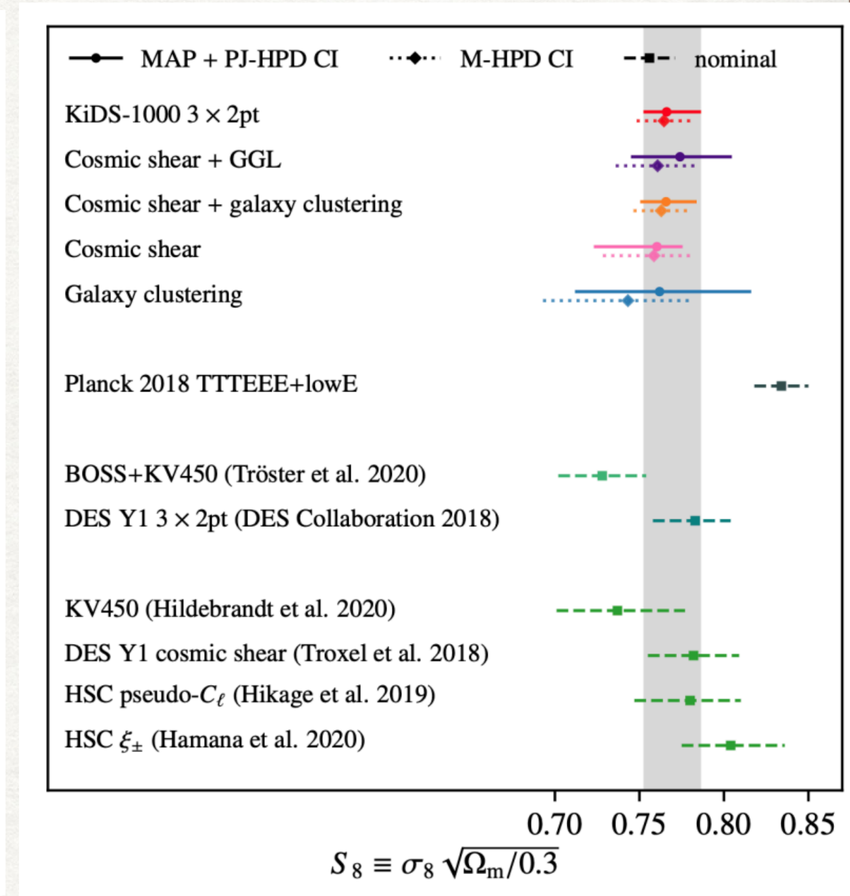
Unfortunately no coherent pictures emerge from these tentative detections…

The σ_8 tension

Figs. from Heymans++ 2007.15632







$$\sigma_8^2 \equiv \int_0^\infty dk \frac{k^2 P_L(k) W_R^2(k)}{2\pi^2},\ R = 8\text{Mpc}/h,\ k \sim 0.1 - 1h/\text{Mpc}$$

- $\sim 2-3\sigma$ tension between CFHTLenS/HSC/KiDS/DES and *Planck*. (Potentially also Planck SZ clusters).

  CFHTLenS MNRAS 2013, HSC PASJ 2019, DES PRD 2018, Salvati++ PoS 1901.05289

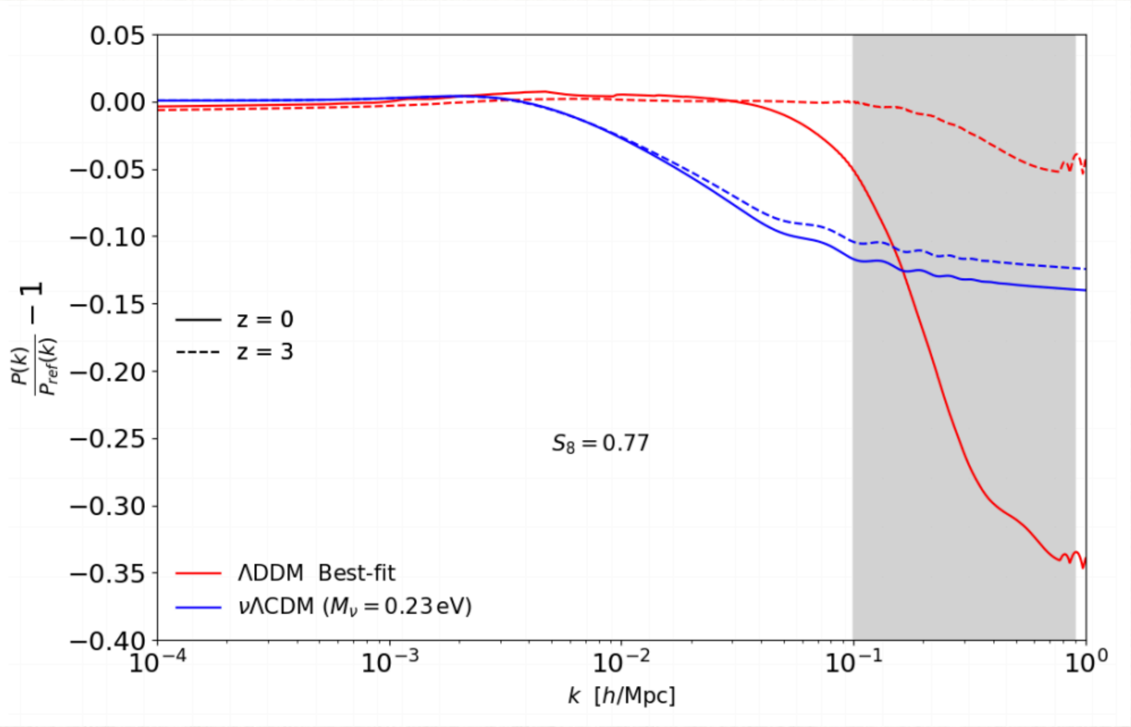
- To resolve the tension: reduce power at scales $k \sim 0.1 - 1$ h/Mpc. DM interactions or decays, fraction of fuzzy dark matter, hot dark matter.

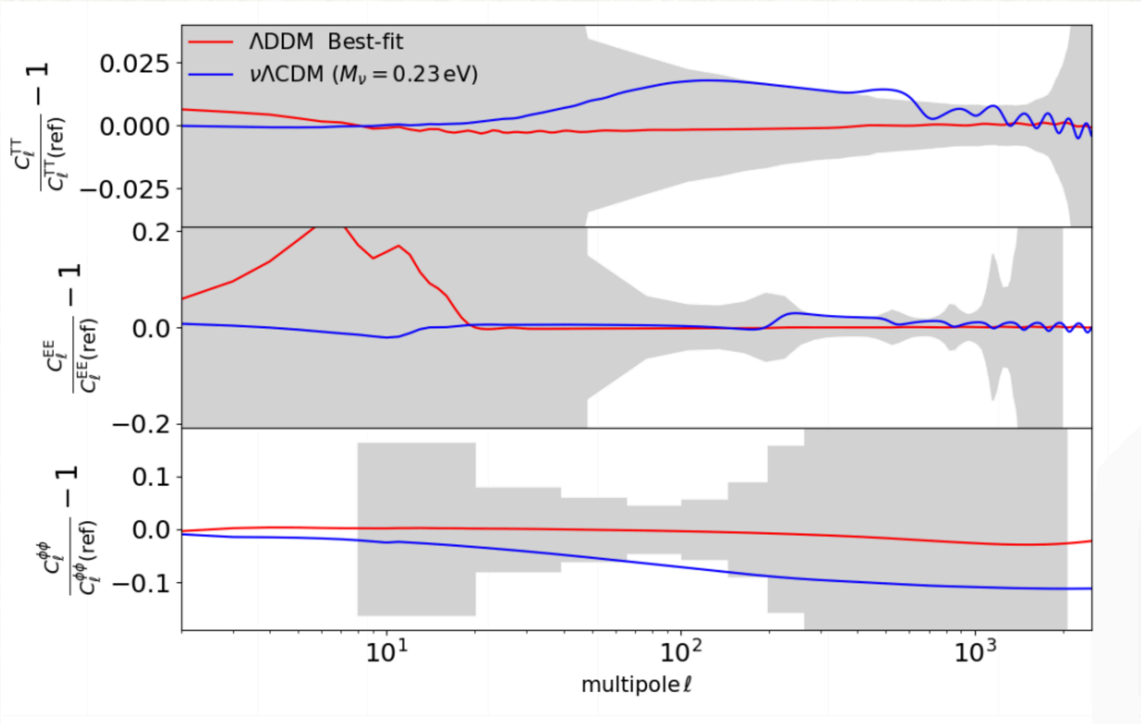
  See `cosmology intertwined' white paper Di Valentino++ 2008.11285

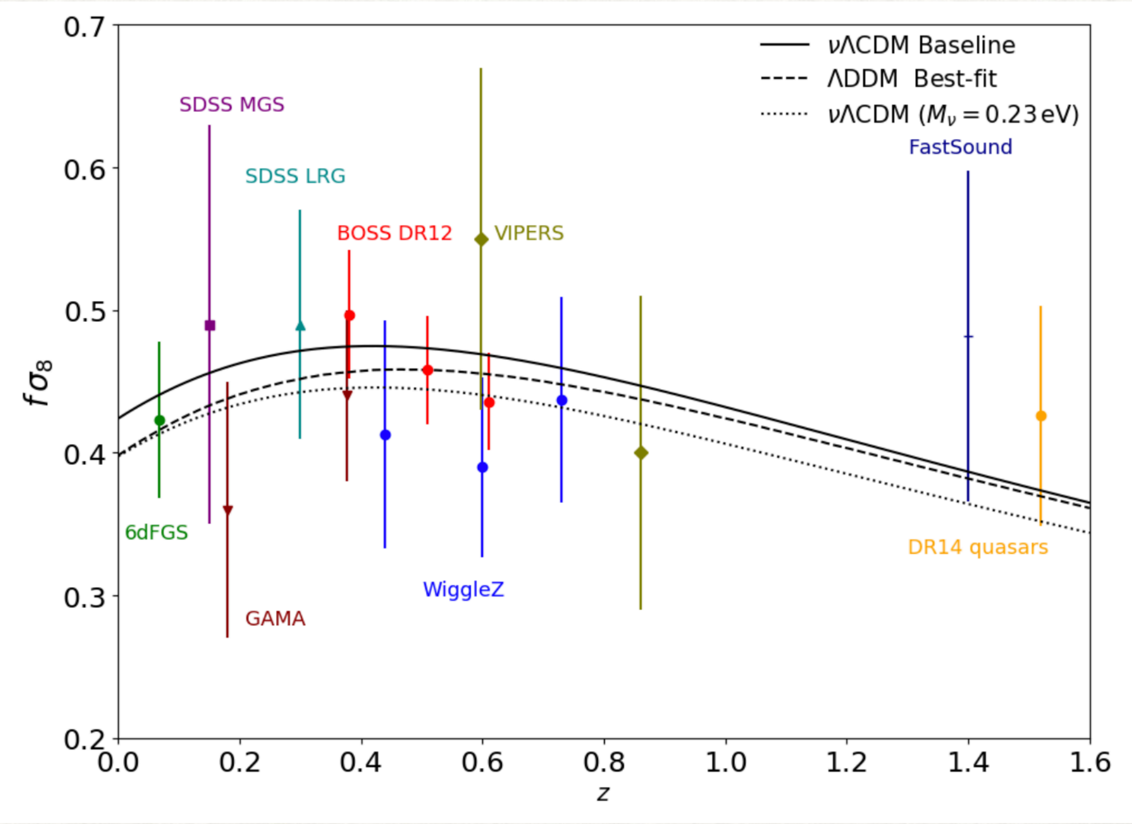
Decaying Dark Matter and the S_8 tension

Abellan, Murgia++ 2008.09615, 2104.03329

See also Vattis++ 1903.06220







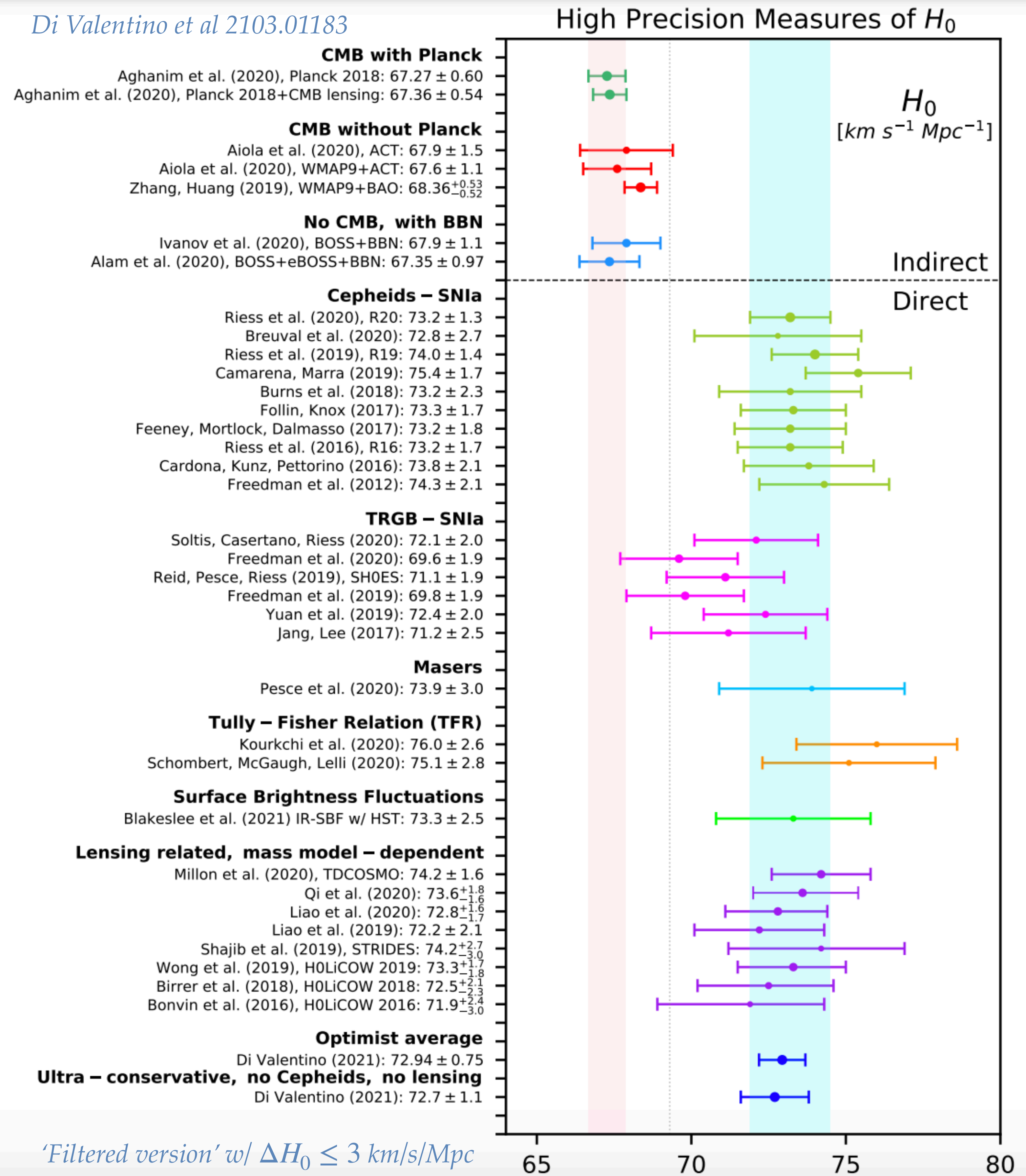
- DM with $\Gamma^{-1} \simeq 55(\epsilon/0.007)^{1.4}$ Gyrs with $\epsilon \simeq v_{\rm wdm}/c$ can explain low S_8.
- The warm daughter induces a power suppression similar to hot DM or non-zero m_ν but different time evolution.
- Future LSS measurements (EUCLID, VRO/LSST, DESI) will test the scenario.
- (Fraction of) HDM disfavored *Das++ 2104.03329*
- (Fraction of) Fuzzy DM seems to work *Laguë++ 2104.07802*

The Hubble tension

As of 2021, over 20 measurements and 800 papers!!

- Indirect: H_0 is a prediction from the ΛCDM model constrained with high-z data
- Direct: H_0 is measured at low-z in different ways
- Direct measurements are higher than predictions, not all are in strong tension.
- Average: tension between 4-6σ
- Systematics? New Physics?

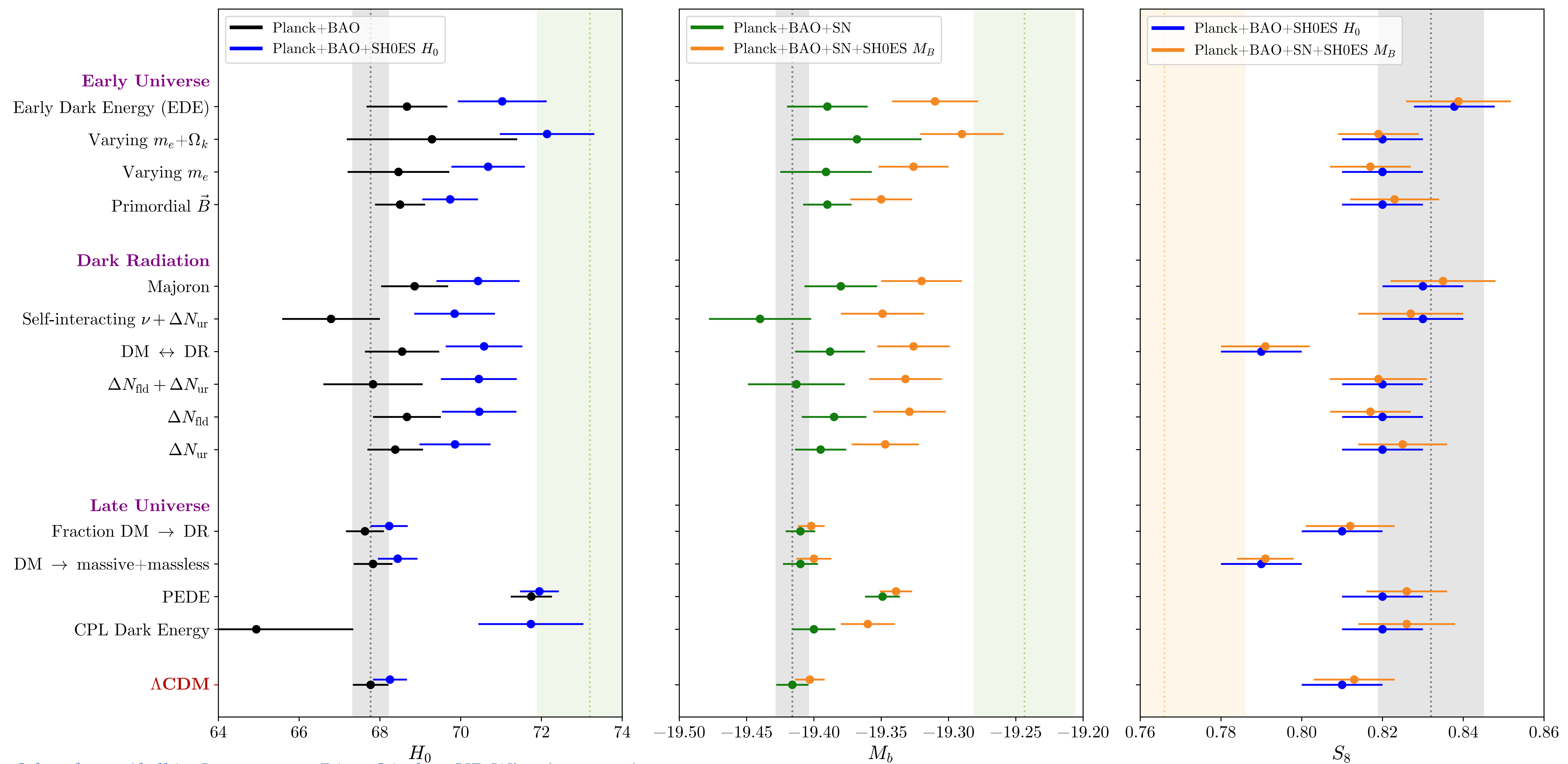
Di Valentino et al 2103.01183



'Filtered version' w/ $\Delta H_0 \leq 3$ km/s/Mpc

Barring systematic errors: no ‘concordance cosmology’ just yet

- What extension(s) could resolve these tensions? Many involve dark matter! None can fully resolve both tensions.



Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte (to appear)

- H_0: measure the background expansion rate. S_8: measure the amplitude of perturbations.
- Background: reduce the sound horizon at early times. Perturbations: reduce power at scales $k \sim 0.1 - 1$ h/Mpc.

Cosmology provides many powerful DM probes

- Many gravitational clues for the existence of Dark Matter on a variety of scales. Description "CDM" is purely parametric: are we seeing signs of the nature of DM?

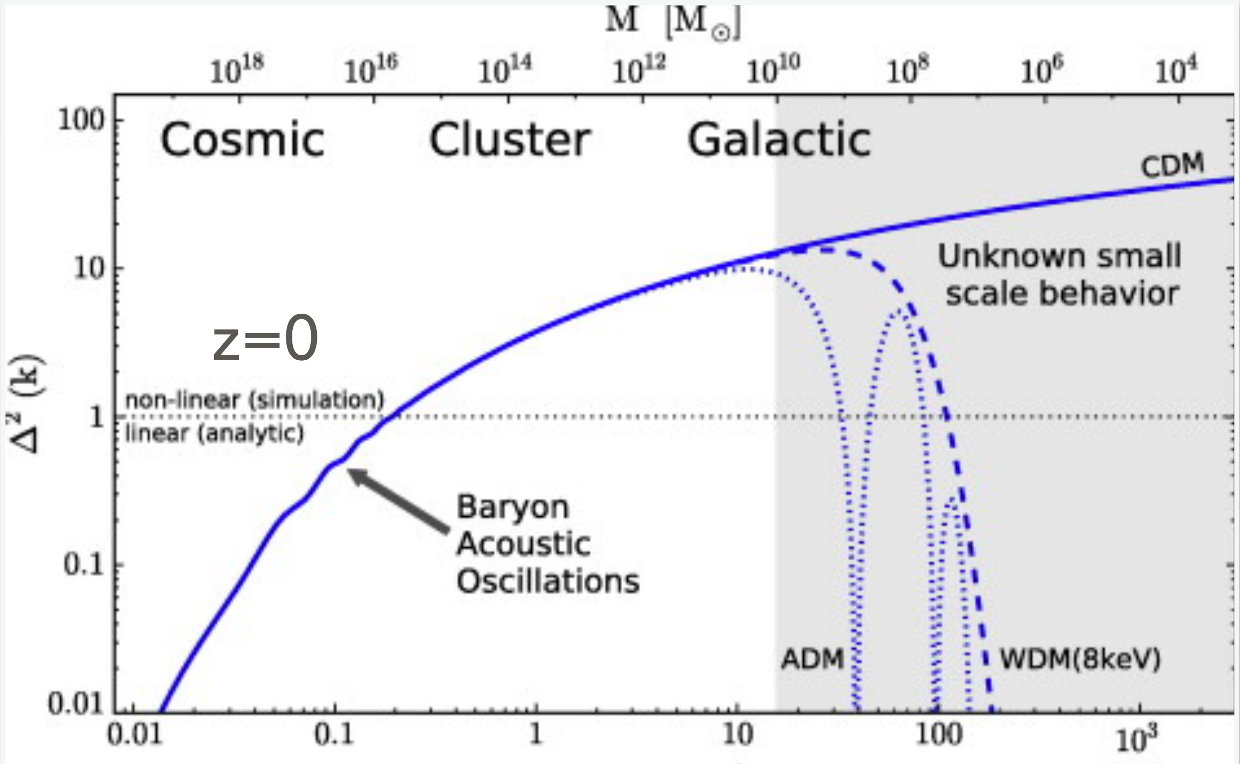
- Broad phenomenology: complementarity of probes over a wide-variety of scales and times.
- CMB & BBN: strong constraints on electromagnetic energy injection
- Weak lensing and galaxy clustering: few-% precision. Some tension with LCDM?
- Lyman-alpha and dwarf galaxies: constrains $m_{\rm wdm}$, m_a. Implications for 'Small-scale crisis'?

- S_8 and H_0 tension have received a lot of attention: they could point to Dark Matter interactions (with Dark Energy, Dark radiation) or decay.
- Signatures of these models in the scale and time-dependence of P(k,z)!

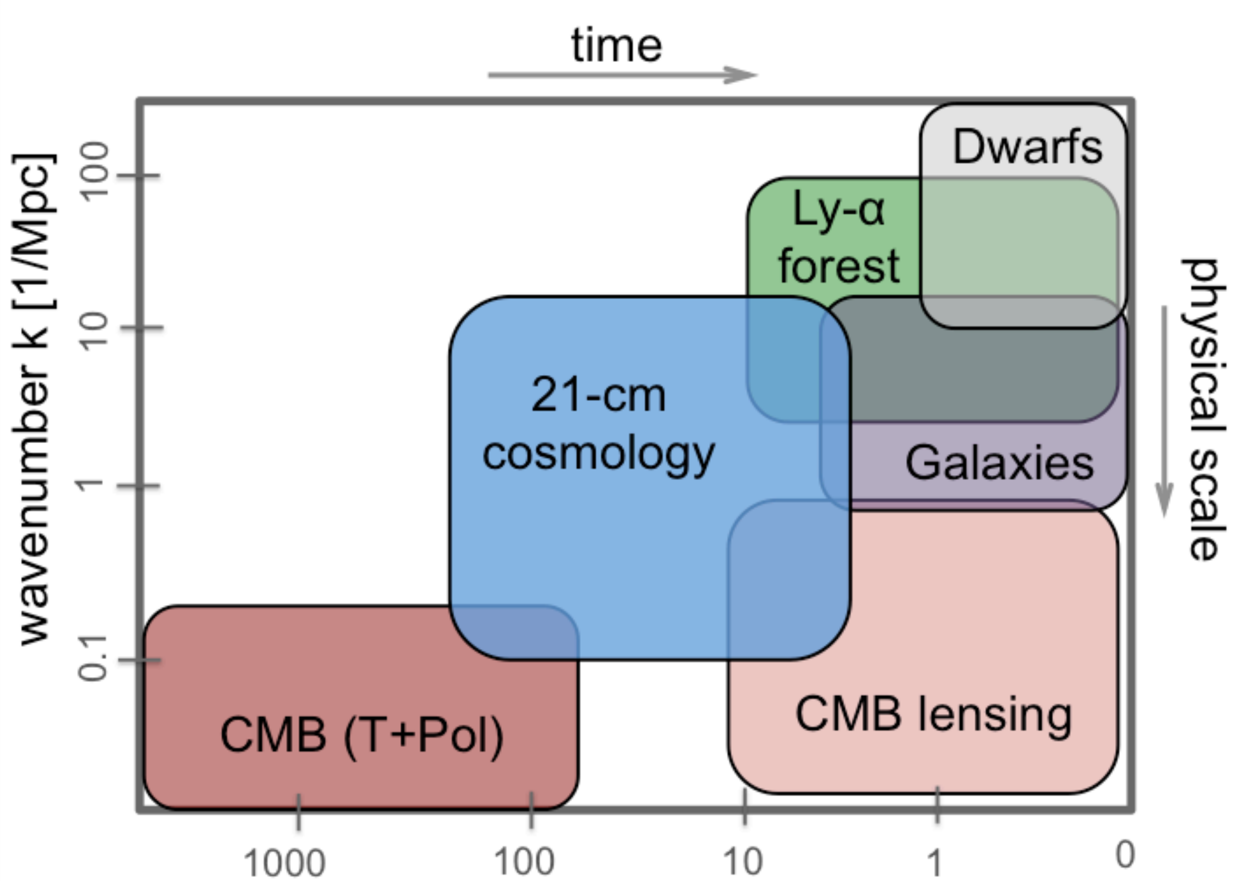
- Theoretical challenge: extract "cosmological" & "particle physics" information from large surveys with large astrophysical uncertainties.

Future of Dark Matter searches in Cosmology

The future is bright: 21cm experiments, Simons Observatory, LSST, EUCLID…
If these tensions exist/are due to new physics in the dark sectors, we will know!



Kuhlen, Vogelsberger, Angulo 2012



Astro2020 Science White Paper

- Strength of the French community: Strong expertise in early universe / CMB / BBN. Important experimental involvement in Planck, Euclid, LSST. (INSU / IN2P3 / INP / CEA). Large astro / cosmology / particle physics communities.
- Weaknesses / Risks: DM is a “multi-messenger quest”. Need for a coordinate effort between particle physicists and astro/cosmologists. 21 cm cosmology will be huge in ~5 to 10 years.