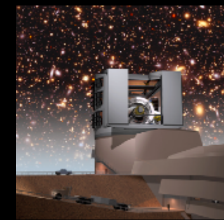
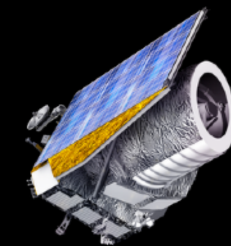

SKA


LSST/VRO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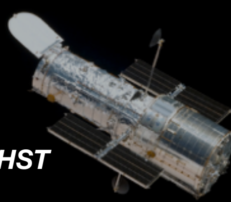
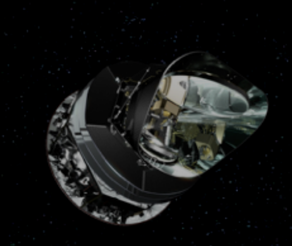
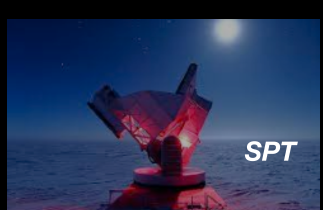

HST


Planck

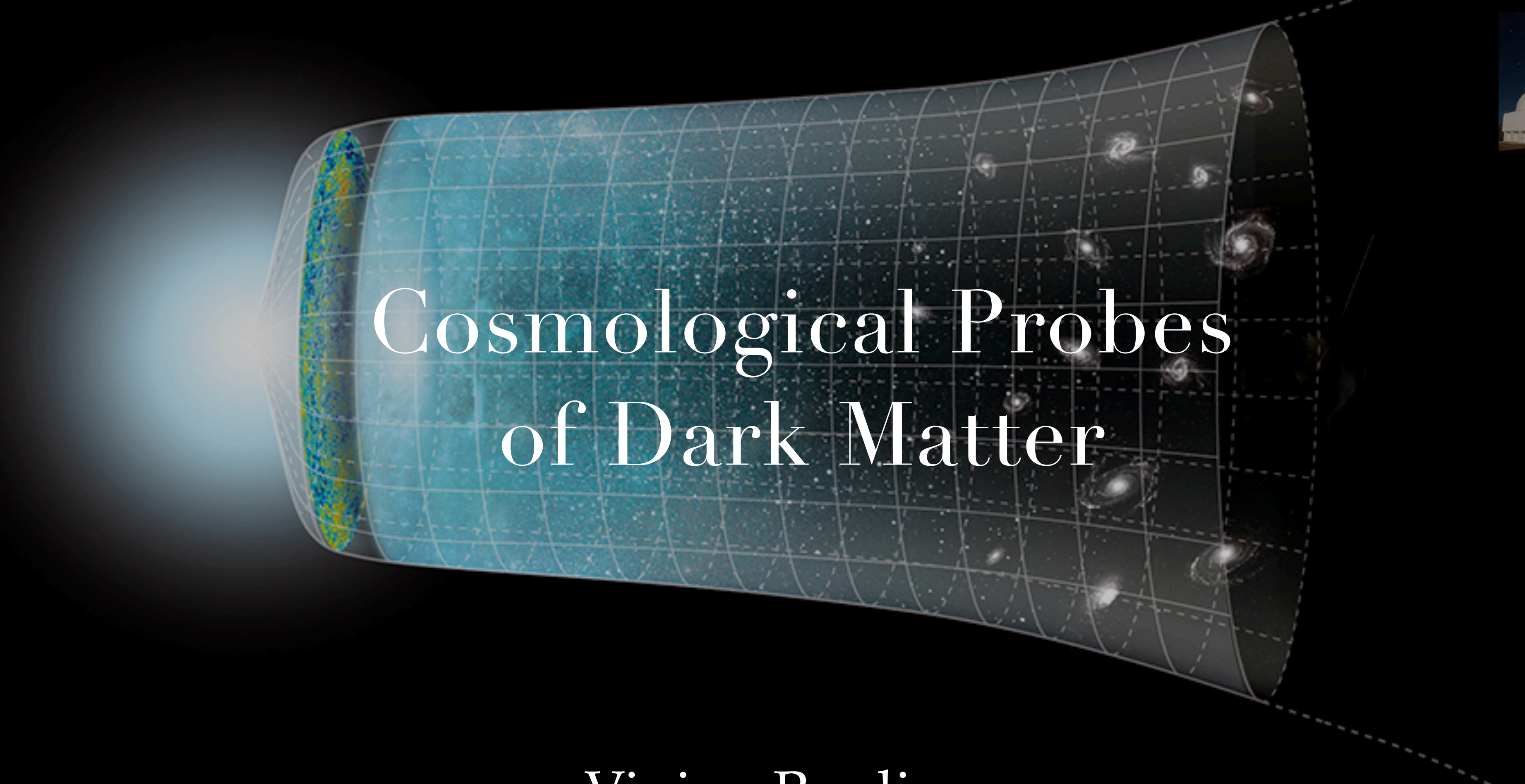

ACT


SPT


DES


KiDS/VLT


BOSS/SDSS



Cosmological Probes of Dark Matter

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26/09/23

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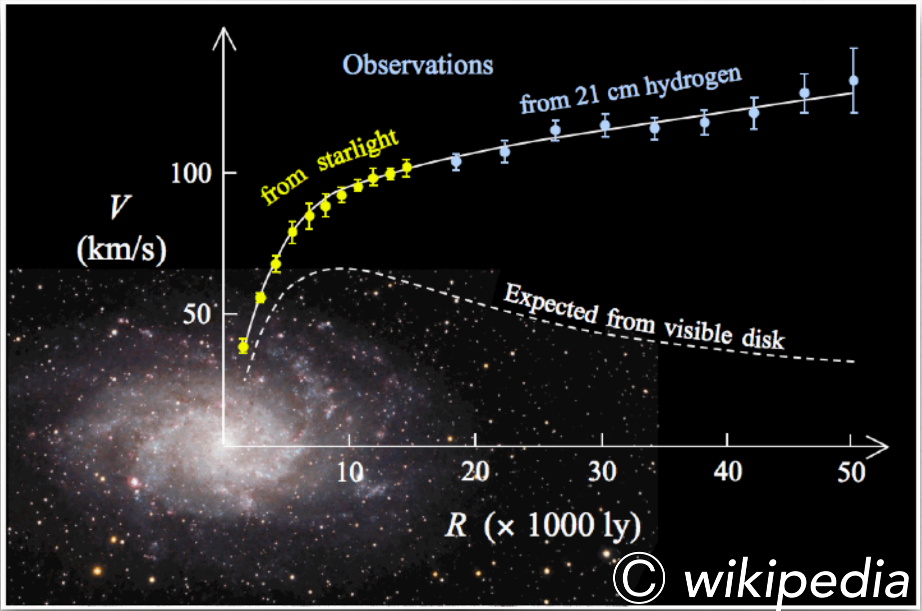
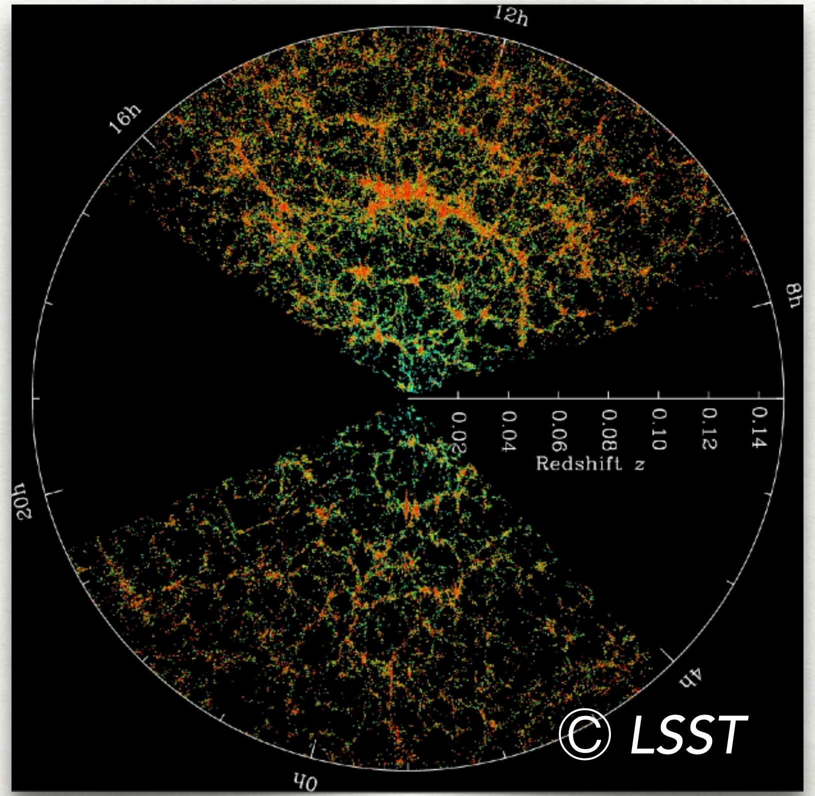
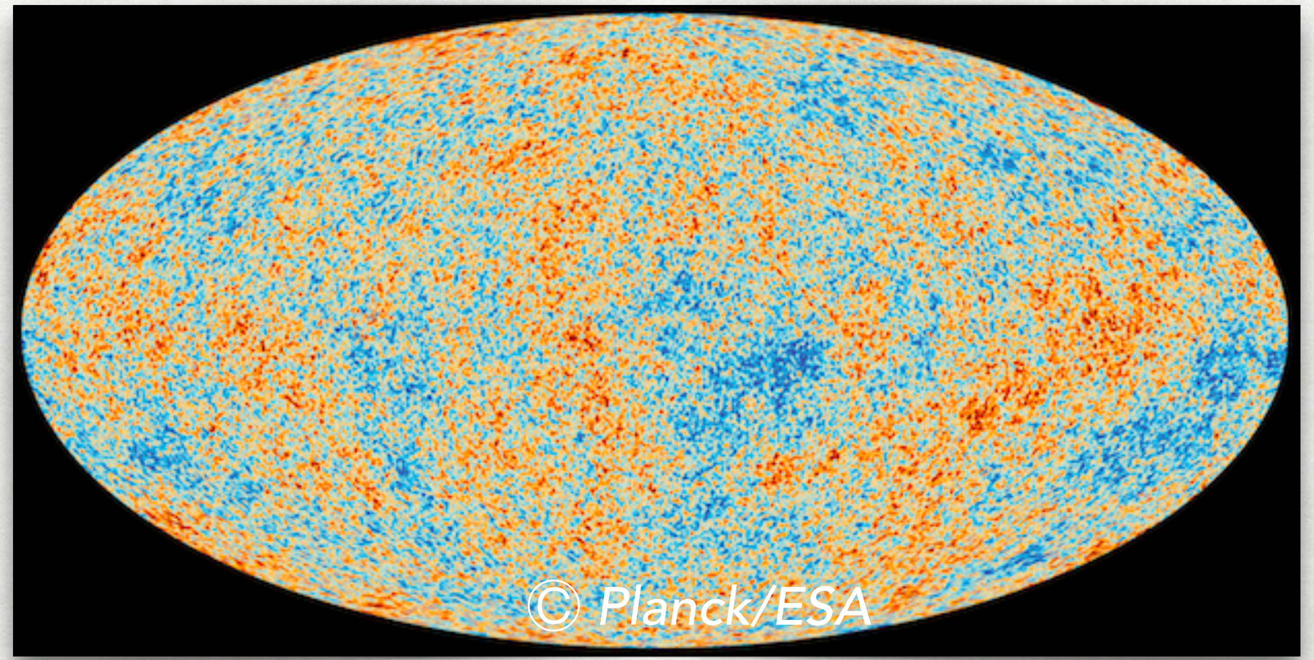
Dark Matter: many clues on many scales

From galactic scales…



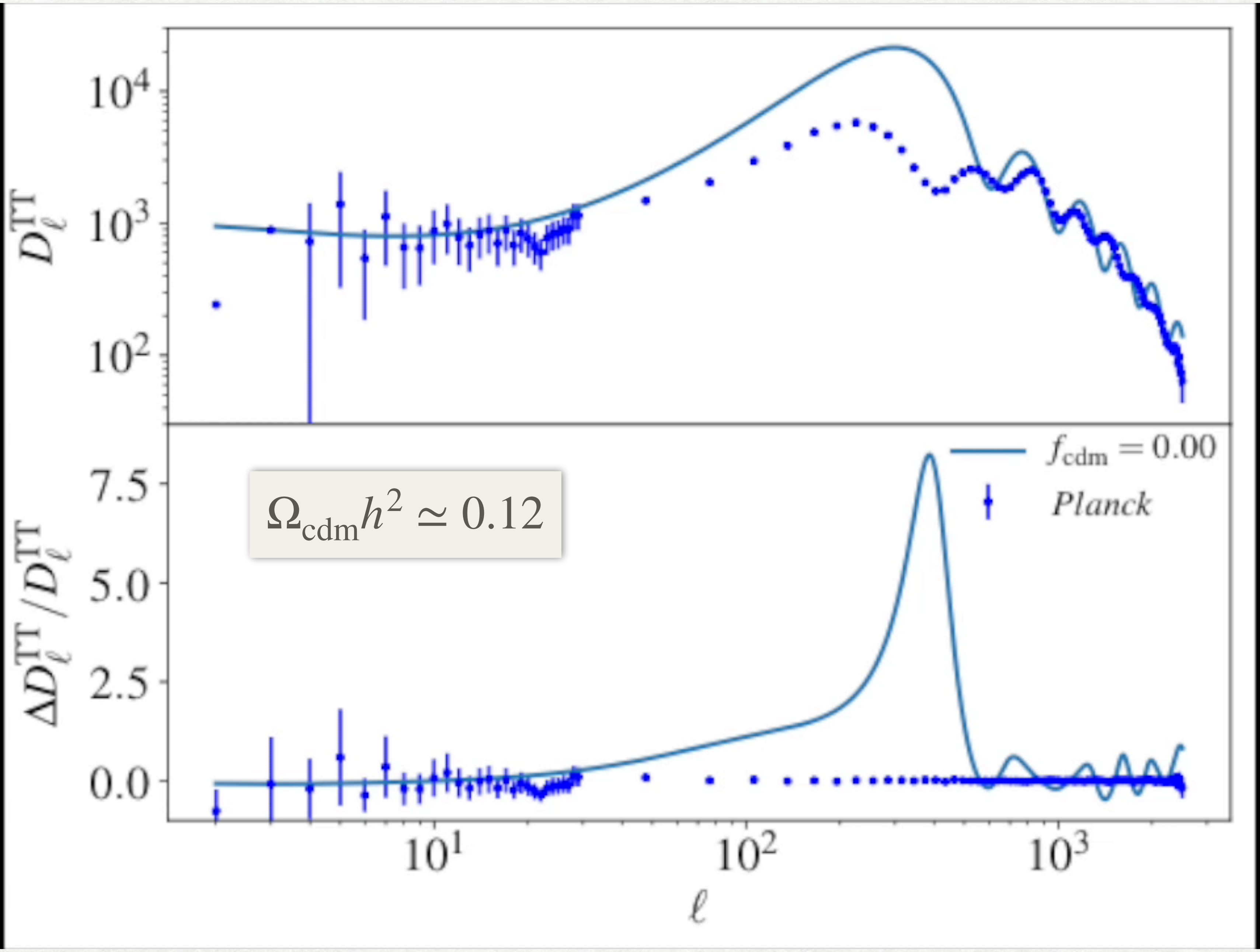
… to cosmological scales.





Cosmological detection of Dark Matter

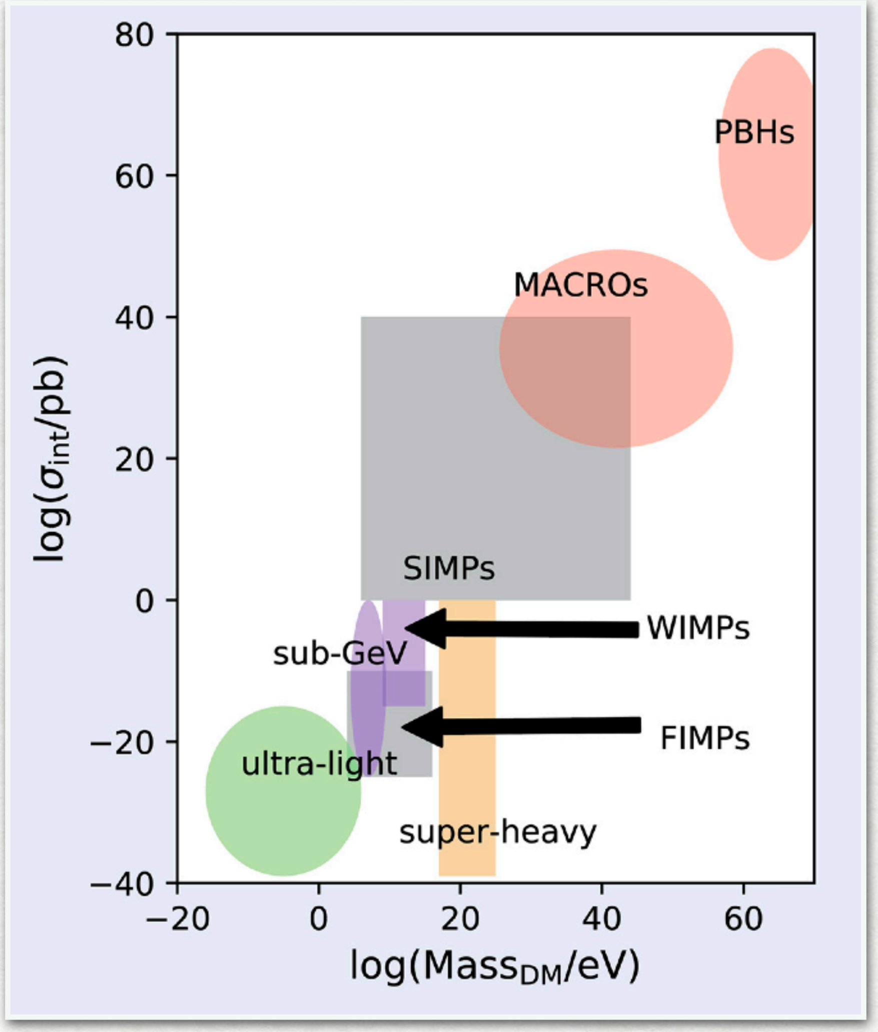
In the ΛCDM model, Dark Matter is a cold, collision-less, matter component, which interacts only through gravity with other species.



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

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…



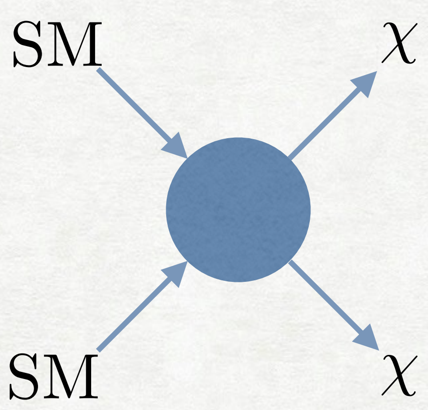
A sketch of the Theoretical DM landscape
Credit: C Arina (cern courier)

Searching for Dark Matter in cosmology

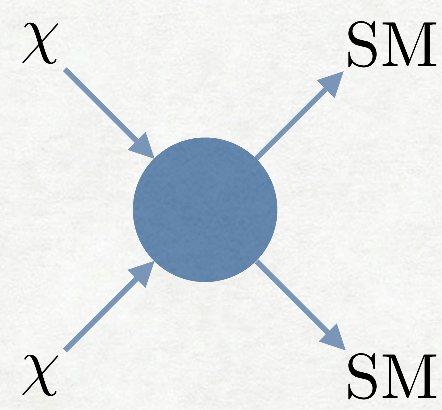
Based on K. Boddy (UT Austin)'s slide

An analogy with the WIMP

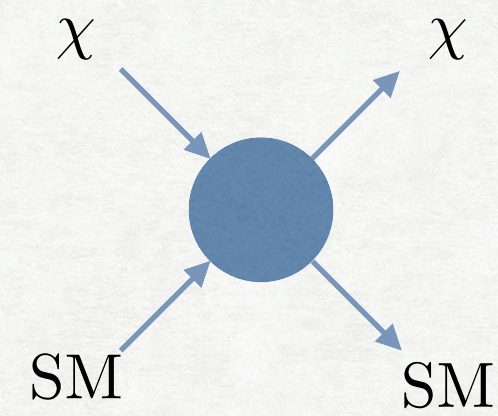
Production



Annihilation



Scattering



in particle physics

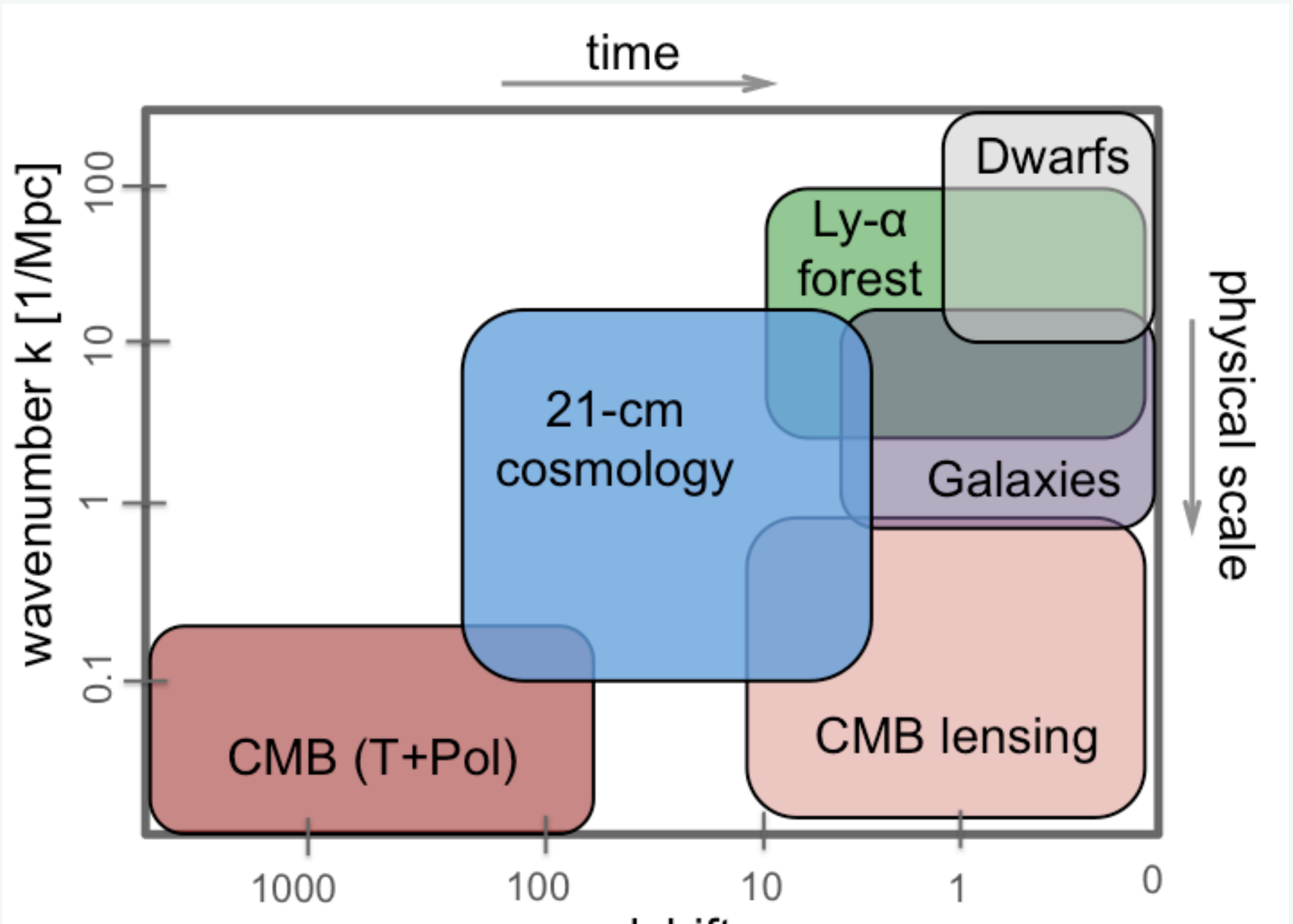
Collider | **Indirect detection** | **Direct detection**

in cosmology

Relic abundance +free-streaming | **Energy injection** | **Momentum transfer**

Great complementarity between probes to constrain many different DM models (WIMP, axions, sterile neutrinos, Primordial Black holes…)

“Cosmic complementarity” over scales and times



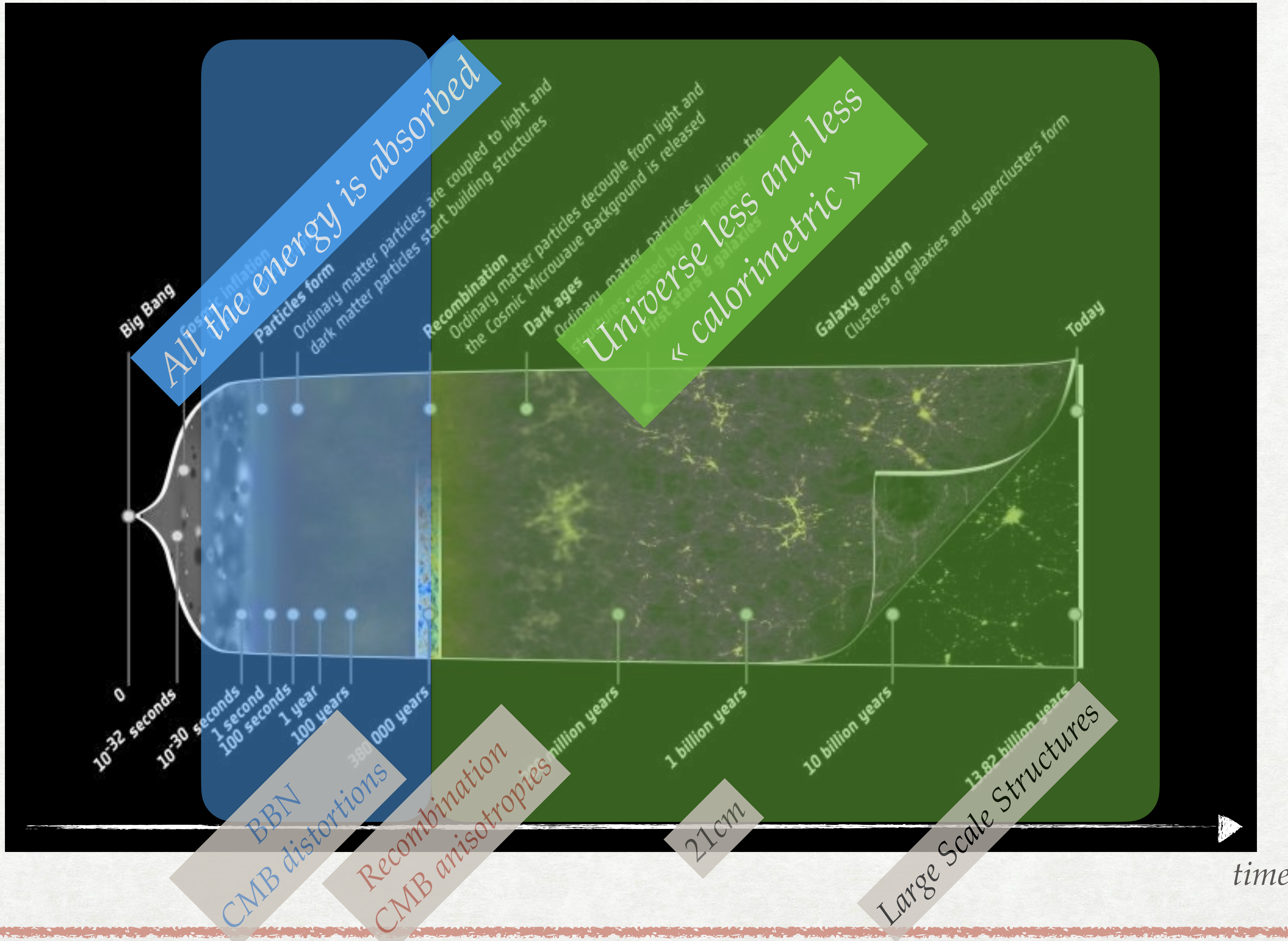
Gluscevic ++ 1903.05140

- Large scales & Early times: CMB at $\ell \lesssim 2500$ by Planck. (+ACT+SPT extend to 5000)
- Intermediate scales & Late times: CMB lensing, Galaxy clustering and weak lensing to few % precision.
- Small-scales: Dwarf satellite number counts and Lyman-α forest at small scales.
- Intermediate scales & intermediate redshift : 21cm cosmology to come soon.

Part I
Indirect detection in Cosmology

The universe as a calorimeter

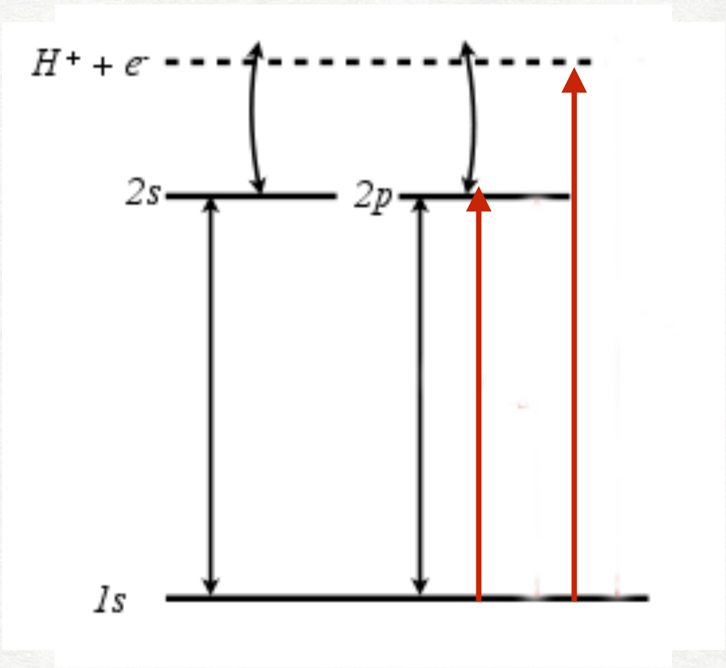
- Energy injection (e.g. from WIMP annihilations) can affect various probes



Impact of energy injection

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}[R_s(z) - I_s(z) - I_X(z)]$$

$$\frac{dT_{\rm M}}{dz} = \frac{1}{1+z}\left[2T_{\rm M} + \gamma(T_{\rm M} - T_{\rm CMB}) + K_h\right]$$



$$I_X(z) \text{ and } K_h(z) \propto \left.\frac{dE}{dV\,dt}\right|_{\rm dep,c} = f_c(z)\left.\frac{dE}{dV\,dt}\right|_{\rm inj}$$

Plasma Properties Particle Physics/Astrophysics

Computing the impact of energy injection requires:

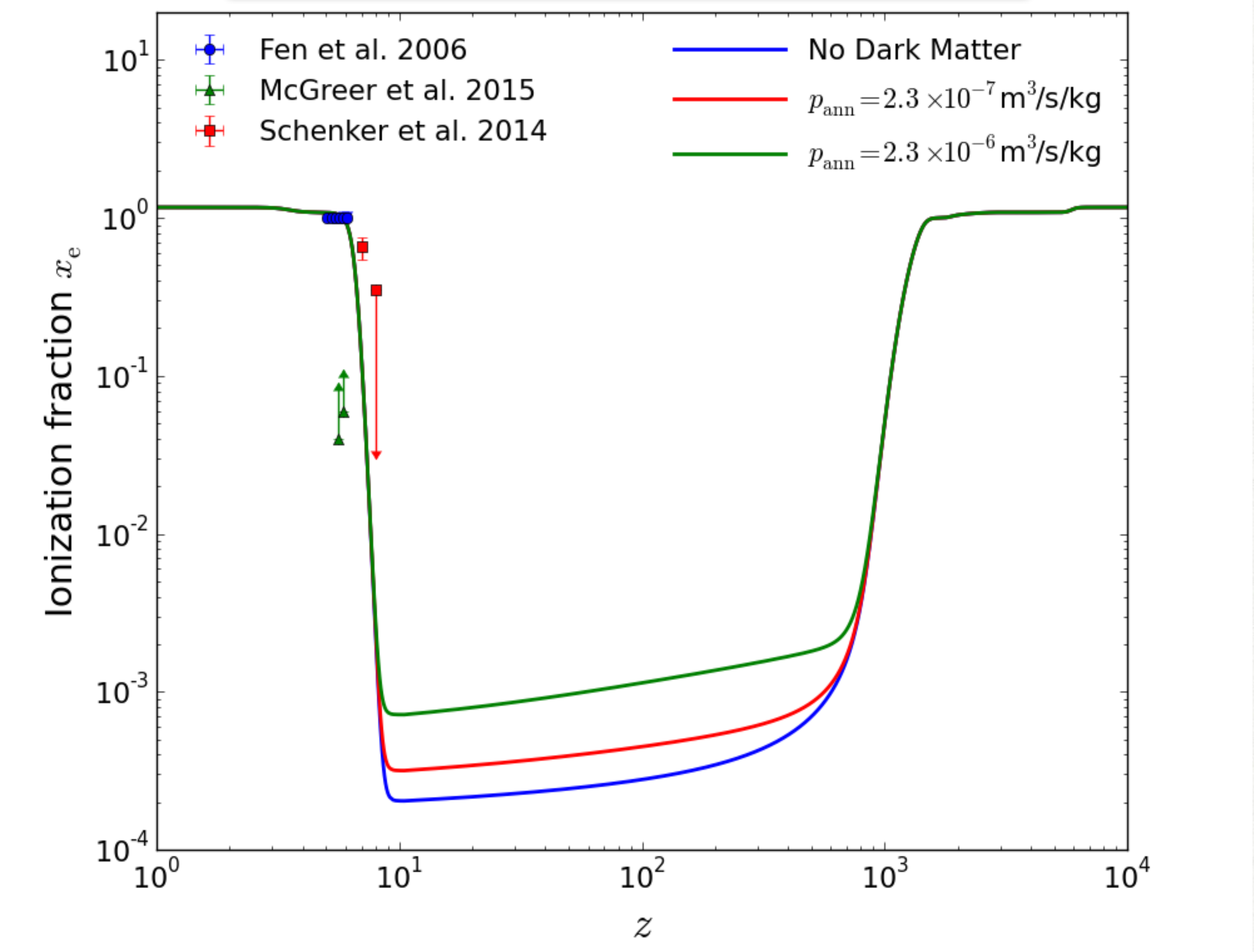
- an energy injection history $dE/dVdt_{inj}$
- The "energy deposition function per channel" $f_c(z)$: ionizing, exciting or heating the gas

Slatyer 1506.03811; Stoecker, Lesgourgues, Kramer, VP 1801.01871; Liu++ 1904.09296

Dark Matter annihilations

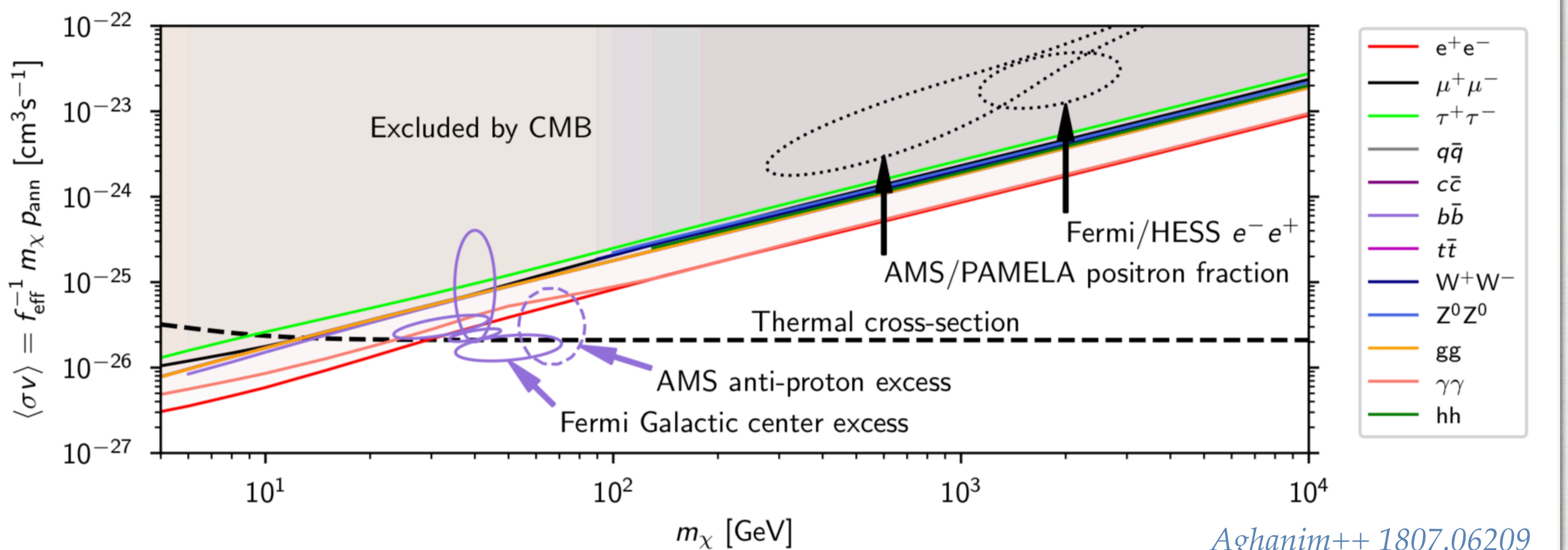
e.g. Slatyer, 1506.03811; VP, Lesgourgues, Serpico; 1508.01370

$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj,smooth}(z) = \kappa \rho_c^2 c^2 \Omega_{\rm DM}^2 (1+z)^6 \frac{\langle \sigma_{\rm ann} v\rangle}{m_{\rm DM}}$$



- DM annihilations delay the recombination and increase the freeze-out plateau

Planck 2018 results

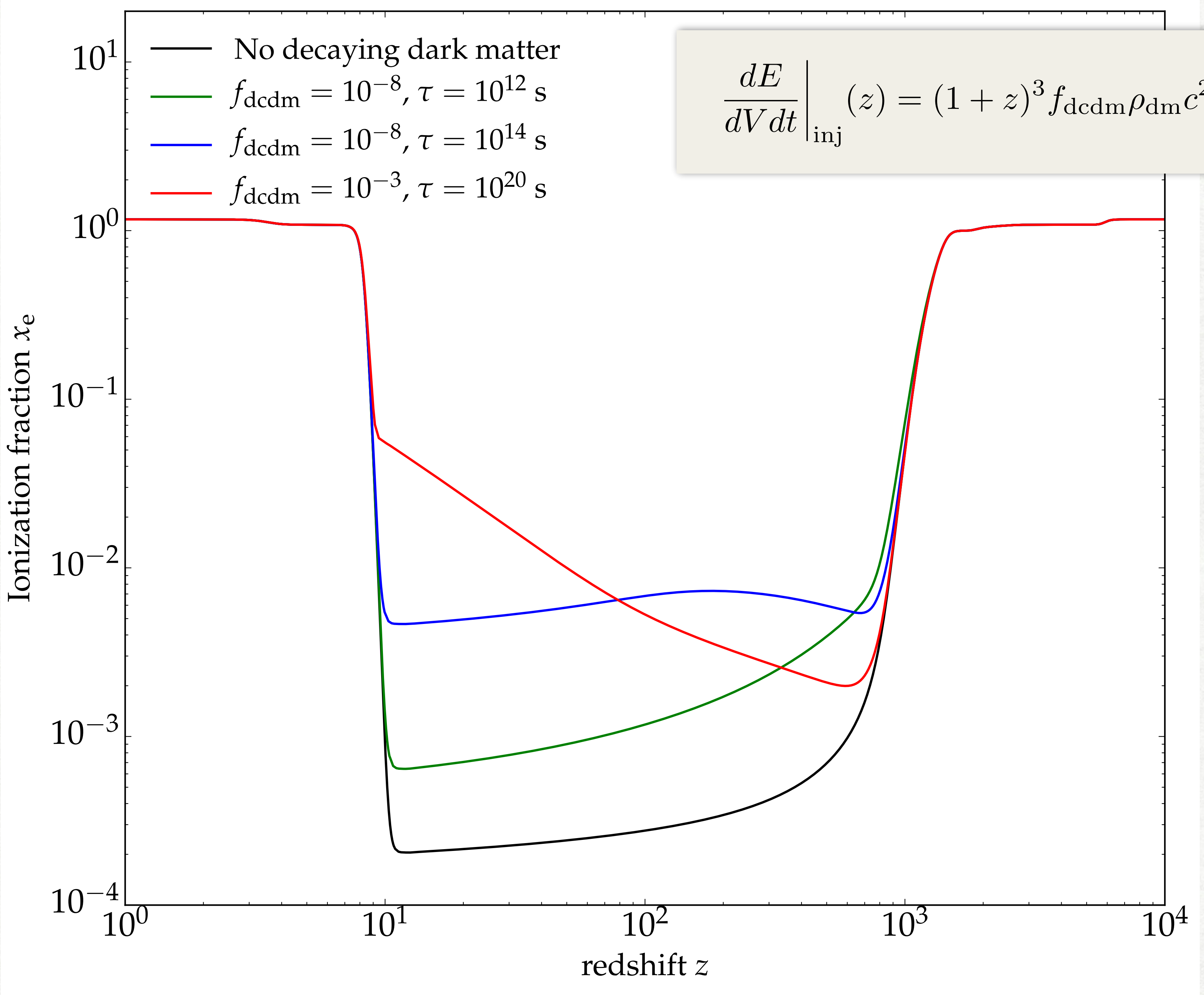


Aghanim++ 1807.06209

- Exclude thermal relics (s-wave) with m_χ < 10-30 GeV.
- Do not suffer from local astrophysical uncertainties (DM profile, density…).
- CMB complements cosmic/γ-rays for pure electronic channel/low masses (keV-MeV).

Dark Matter decay (electromagnetic)

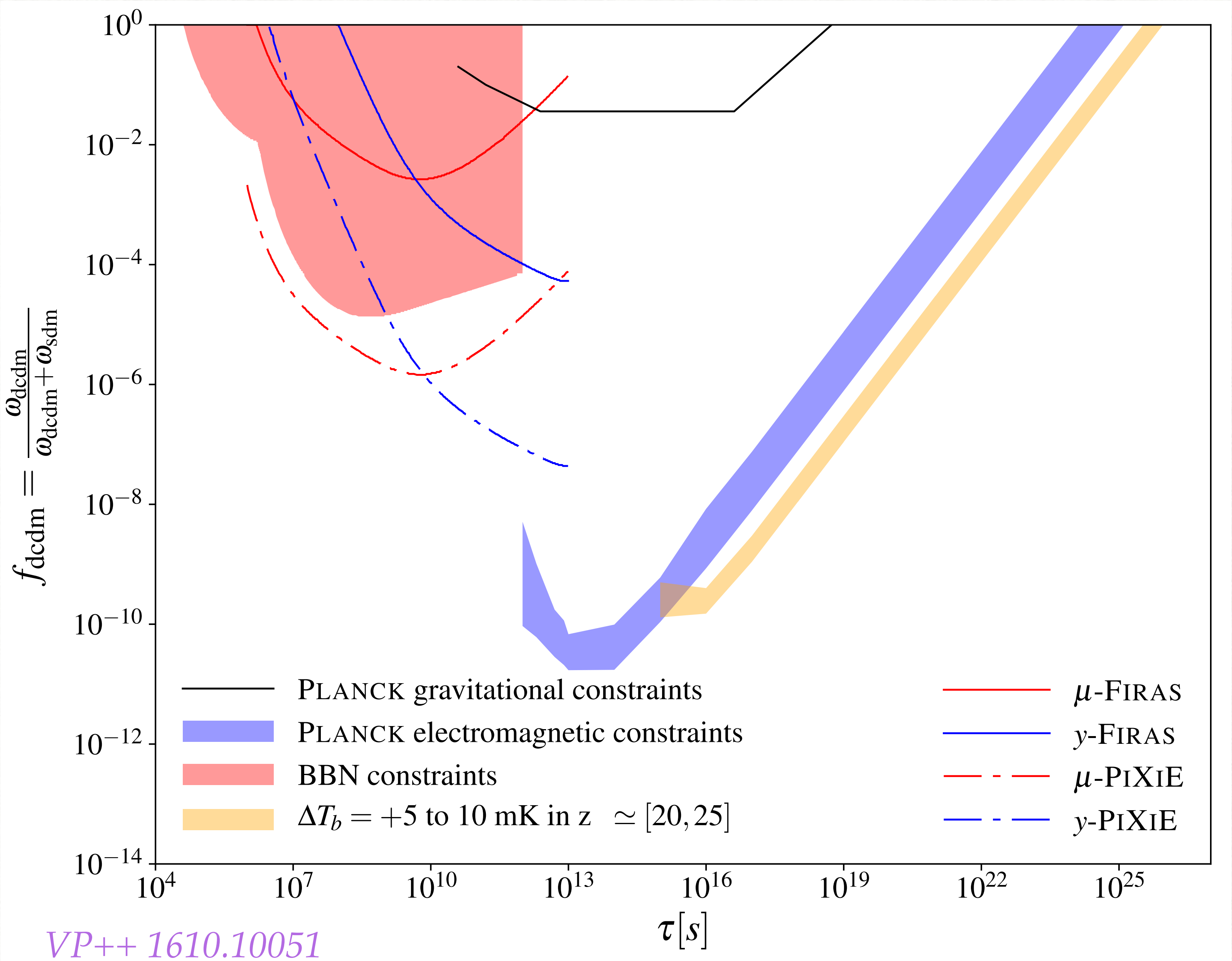
VP, Lesgourgues, Serpico; 1610.10051



$$\frac{dE}{dV\,dt}\bigg|_{\rm inj}(z) = (1+z)^3 f_{\rm dcdm}\rho_{\rm dm}c^2 \times \Delta_{\rm em} \times \frac{e^{-t/\tau}}{\tau}$$

see also Slatyer&Wu, 1610.06933

Constraints from various cosmological probes

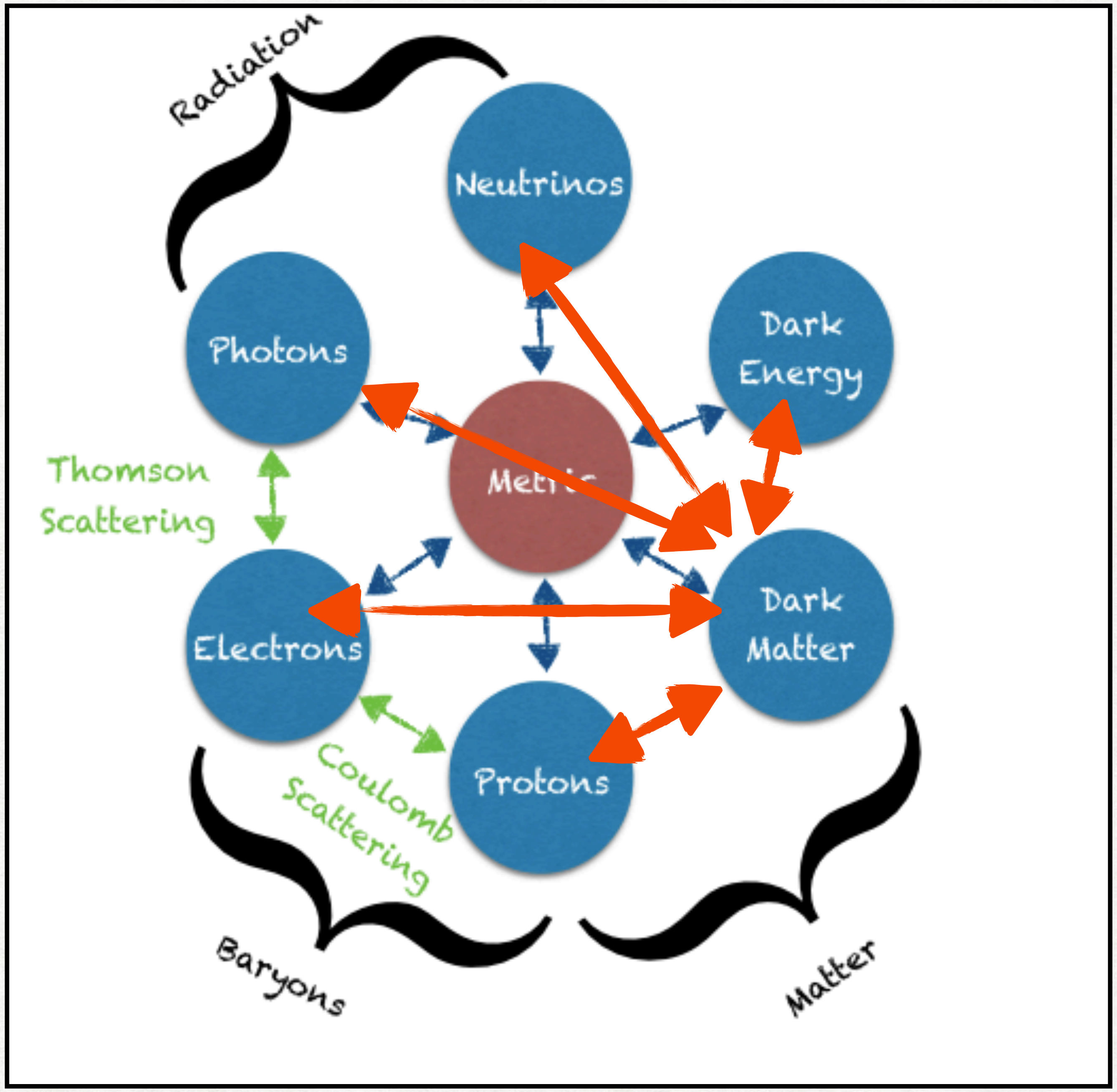


VP++ 1610.10051

- Big Bang Nucleosynthesis dominates at low-lifetime ($\tau < 10^{13}$ s); spectral distortions?
- 21cm will become a major probe of late-time energy injection. *Facchinetti++ 2308.16656*
- CMB/21cm can also constrain PBH, DM mini halos and more! *Stoecker (VP)++ 1801.01871*

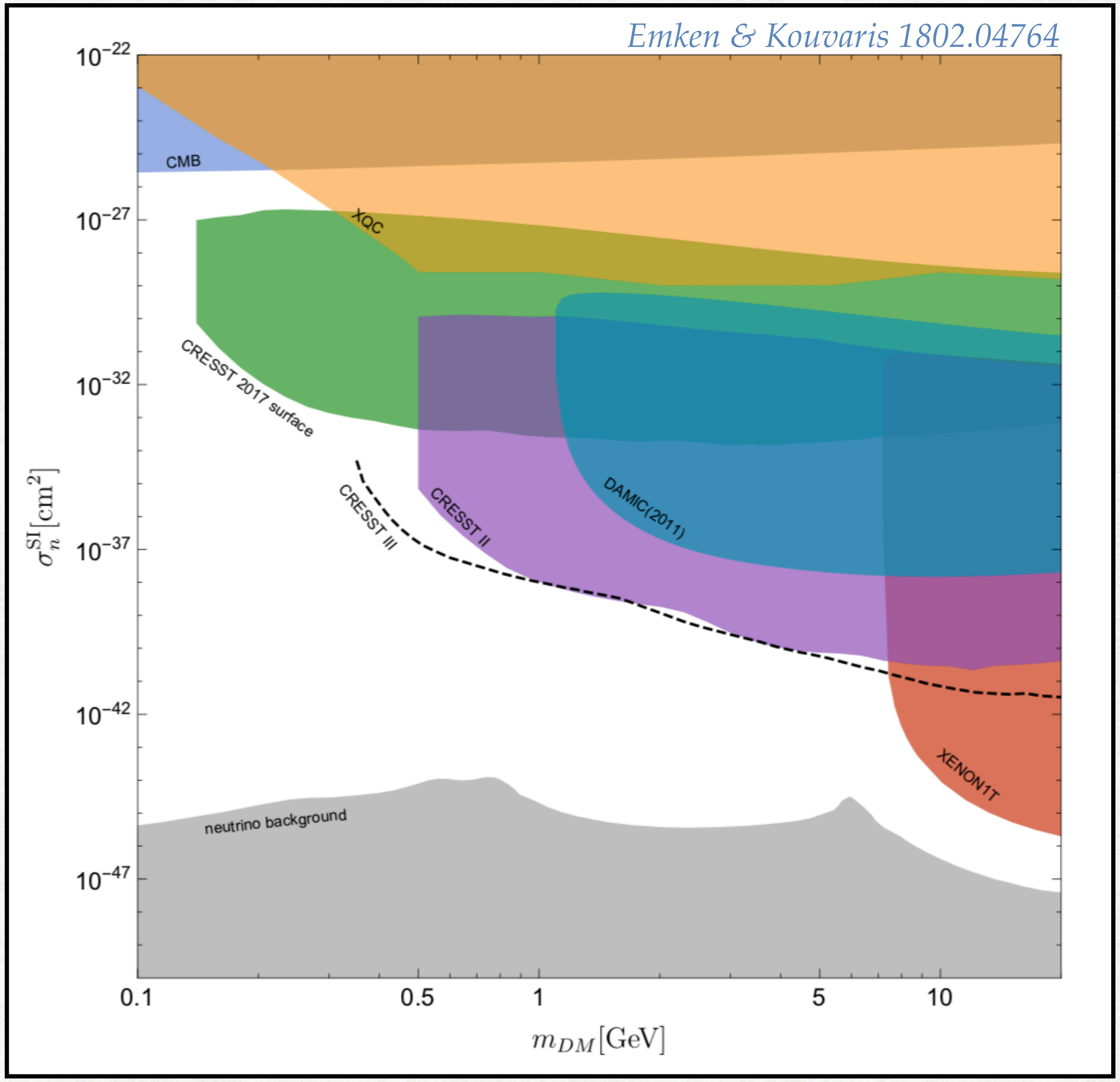
Part II
Direct detection in Cosmology

Dark Matter “direct detection” in Cosmology



- One can test for “exotic” interactions between DM (a dark sector) and the standard model

Why do direct detection with the CMB?



- Underground detectors are shielded and insensitive to strongly interacting DM!
- The CMB extends constraints down to the KeV scale.

Direct detection with the CMB

Boddy & Gluscevic, 1712.07133, 1801.08609

- Temperature evolution

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$

$$\dot{T}_b = -2\frac{\dot{a}}{a}T_b + \frac{2\mu_b}{m_\chi}\frac{\rho_\chi}{\rho_b}R'_\chi(T_\chi - T_b) + \frac{2\mu_b}{m_e}R_\gamma(T_\gamma - T_b)\ ,$$

Rate of heat transfer

- Evolution of density and velocity perturbations

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2} \qquad \dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

$$\dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2} \qquad \dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b}R_\chi(\theta_\chi - \theta_b)$$

$$\theta = i\vec{k}\cdot\vec{V}$$

Rate of momentum transfer

- Drag force due to scattering:

momentum-transfer cross section

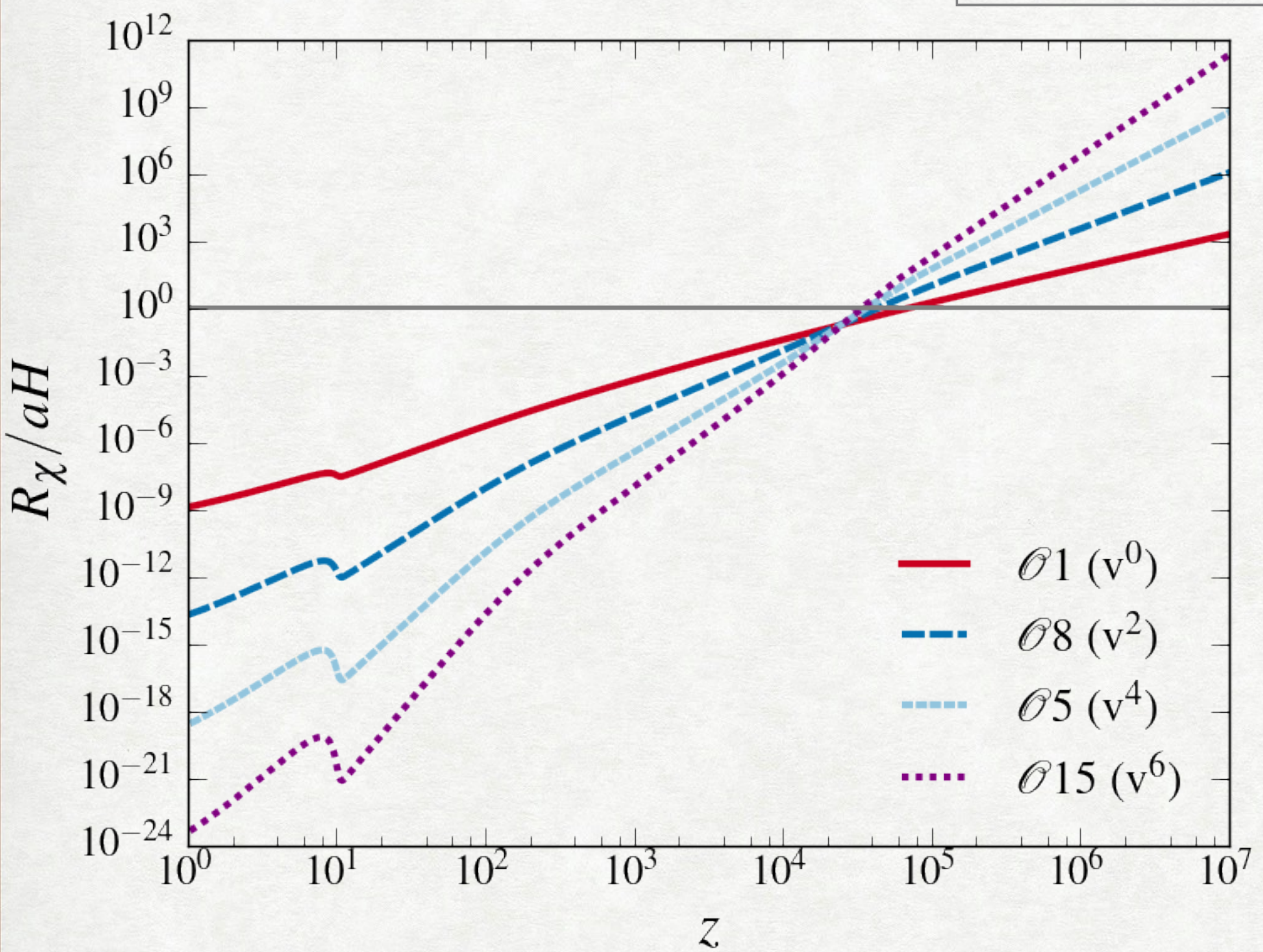
$$\frac{d\vec{V}_\chi}{dt} = (1+z)R_\chi(\vec{V}_b - \vec{V}_\chi) = -\rho_b \sum_B \frac{Y_B}{m_\chi + m_B}\int d^3v\,\vec{v}[\sigma_{\mathrm{MT},B}(v)v]f(\vec{v})$$

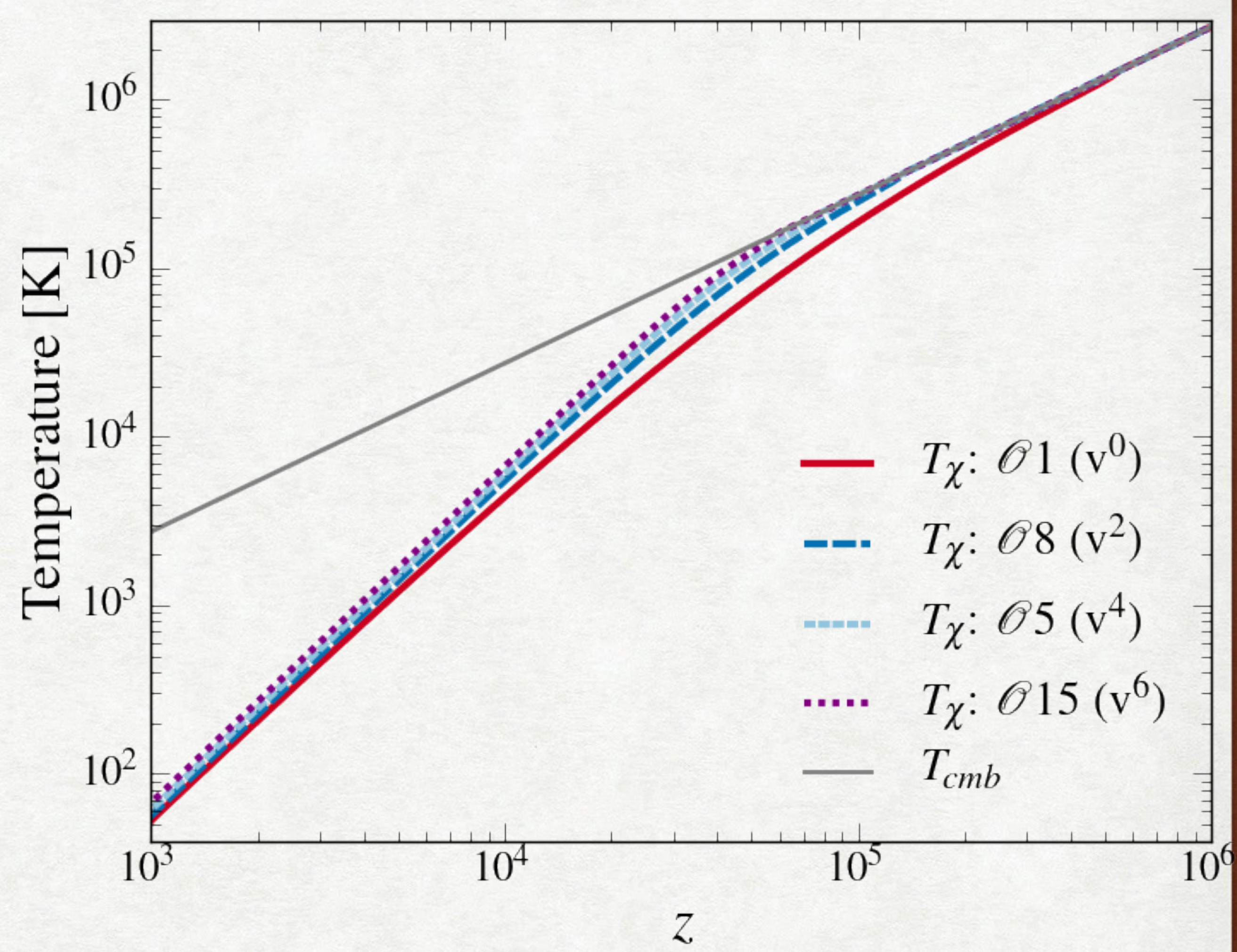
- The rates can be linked to the direct detection formalism with EFT operators

Different velocity scaling

Boddy & Gluscevic, 1712.07133, 1801.08609

$$R_\chi = a\rho_b \frac{Y_H \sigma_0}{m_\chi + m_p} \mathcal{N}_n \bar{v}_{\rm th}^{(n+1)}$$

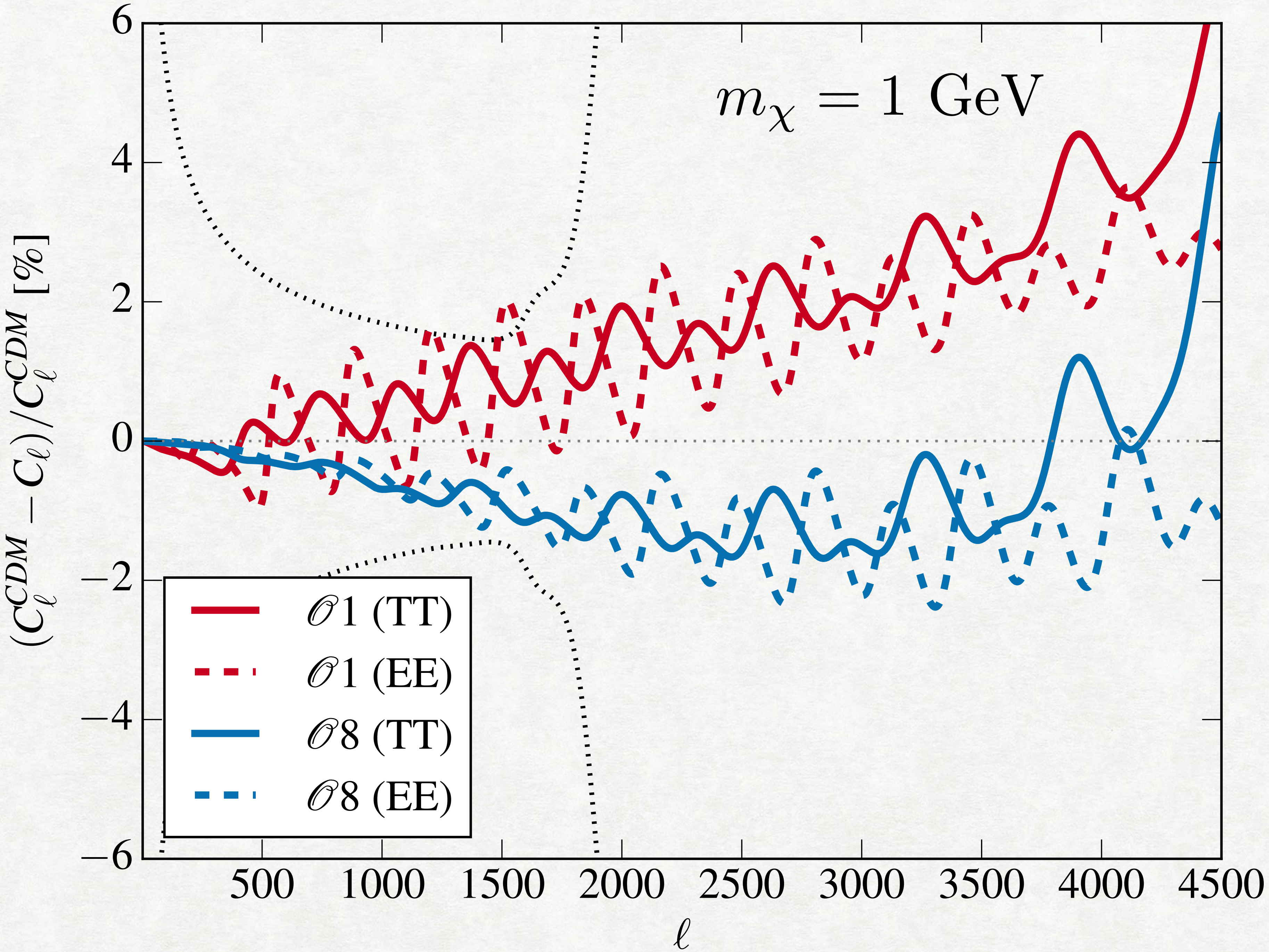




- The CMB enforces $R_\chi/aH \lesssim 1\,\%$ at $z \simeq 20000$

CMB power spectra

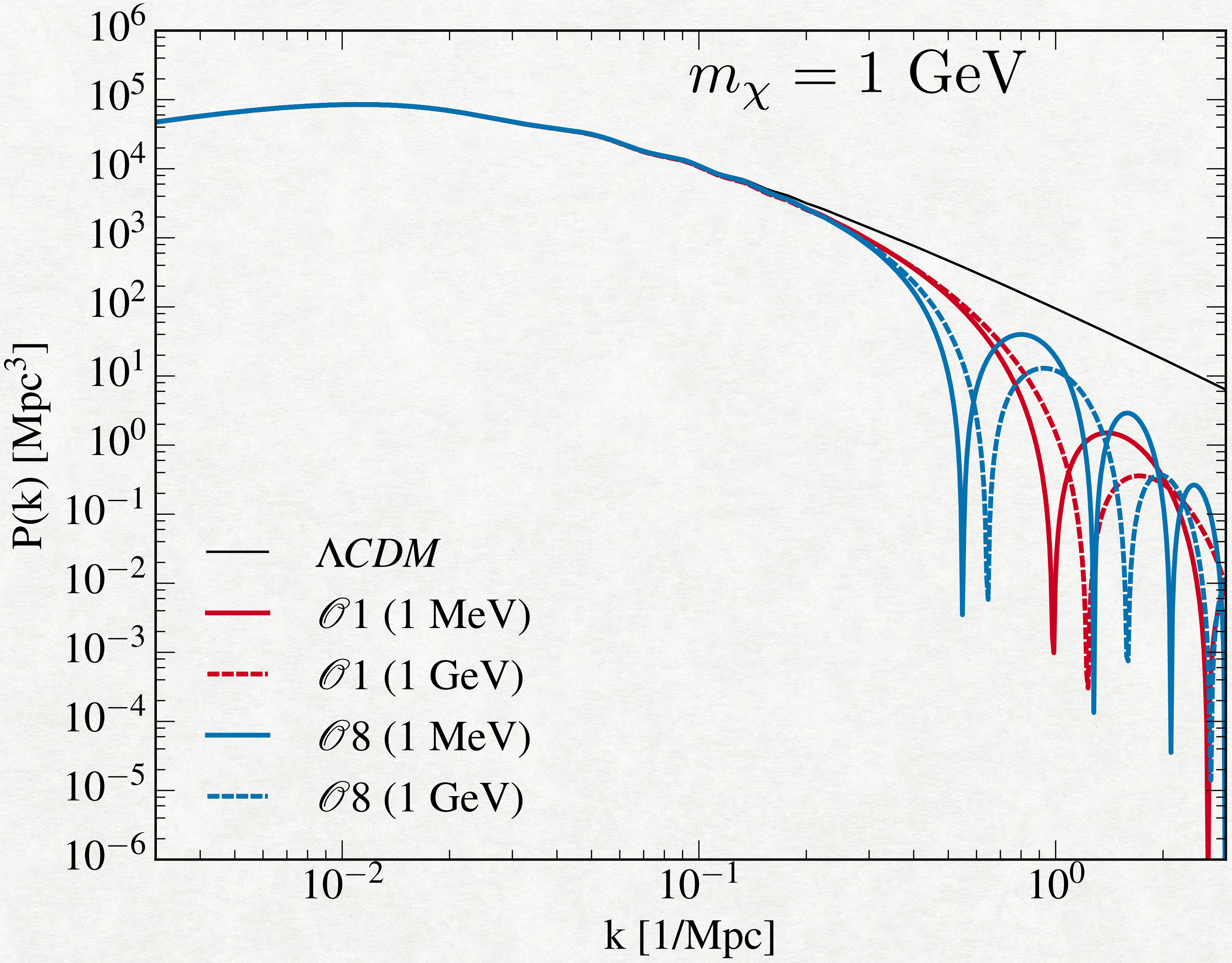
Boddy & Gluscevic, 1712.07133, 1801.08609



More damping + baryons loading (i.e. DM acts as baryons)

Linear matter power spectrum

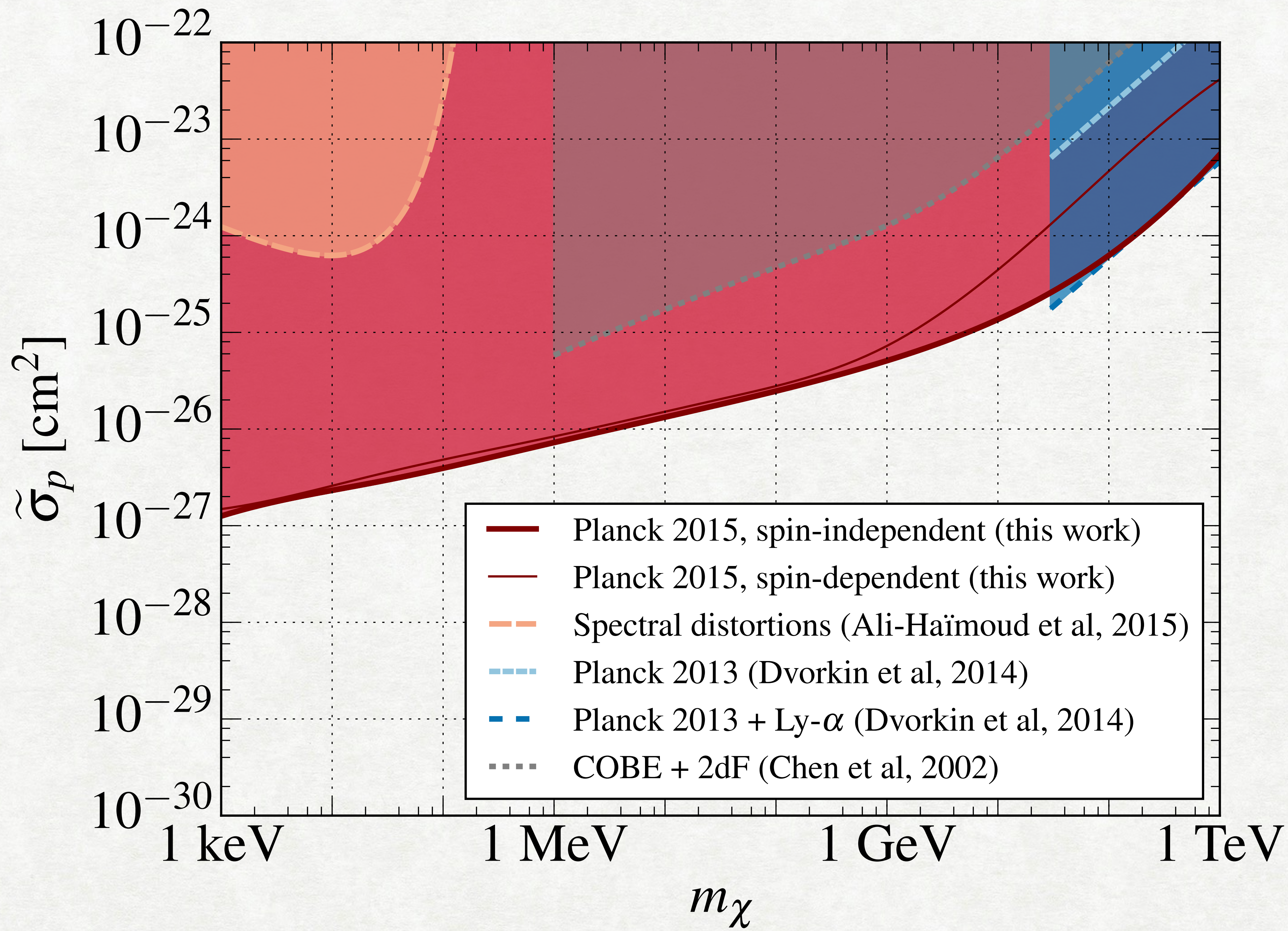
Boddy & Gluscevic, 1712.07133, 1801.08609



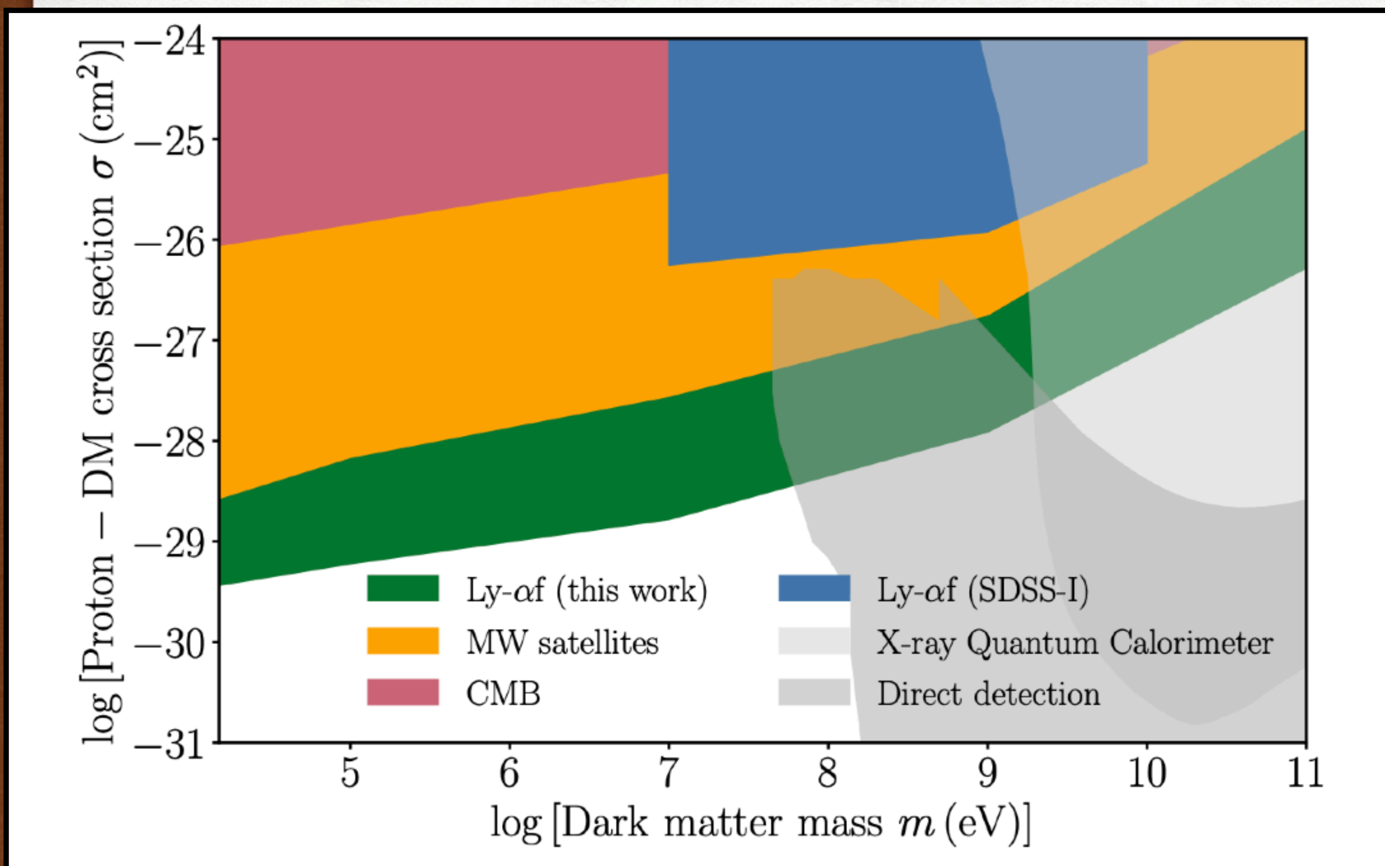
Power suppression + dark acoustic oscillations

Spin-dependent and independent scattering

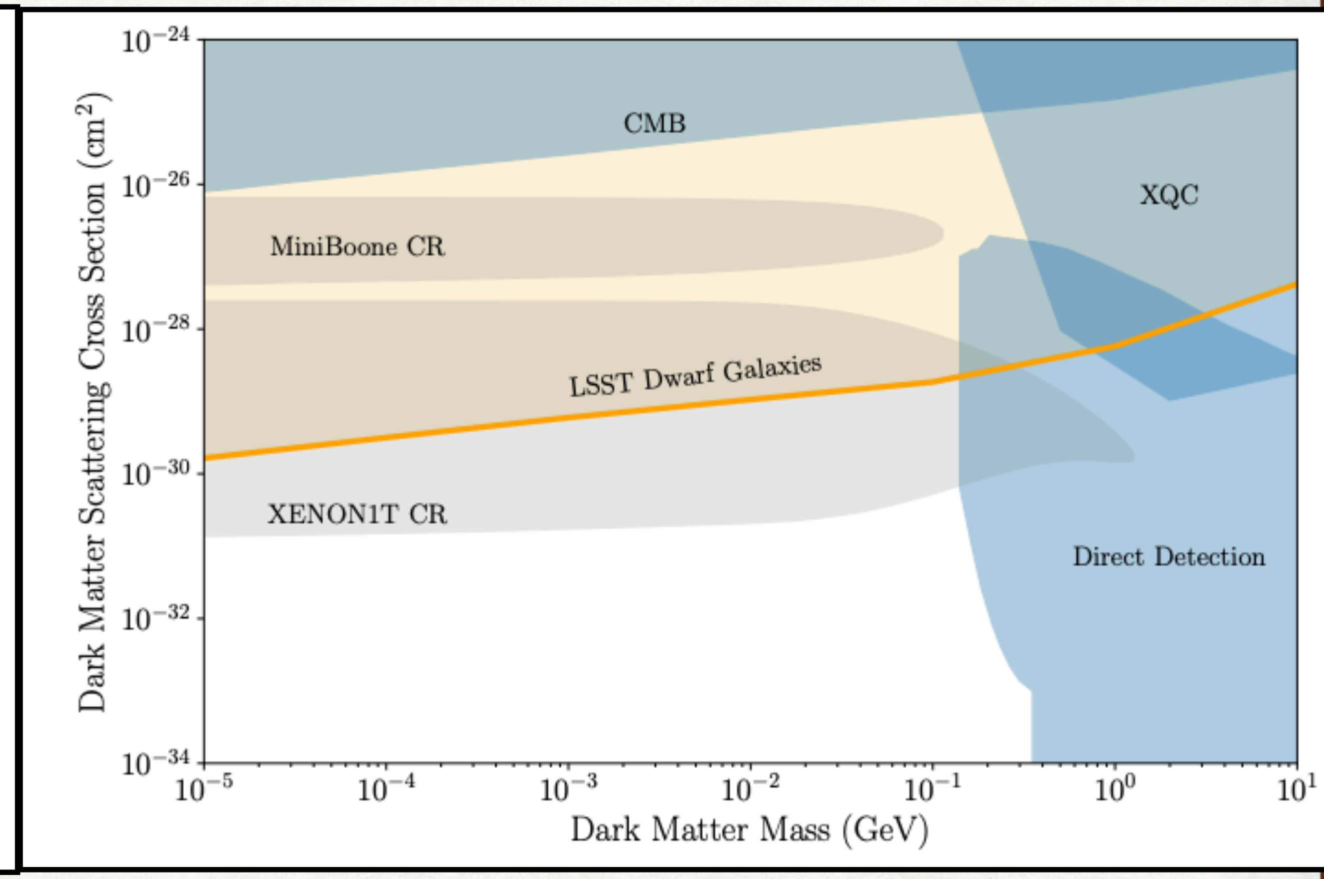
Boddy & Gluscevic, 1712.07133, 1801.08609



Comparison with other probes



Rogers++ 2111.10386



LSST working group 1902.01055

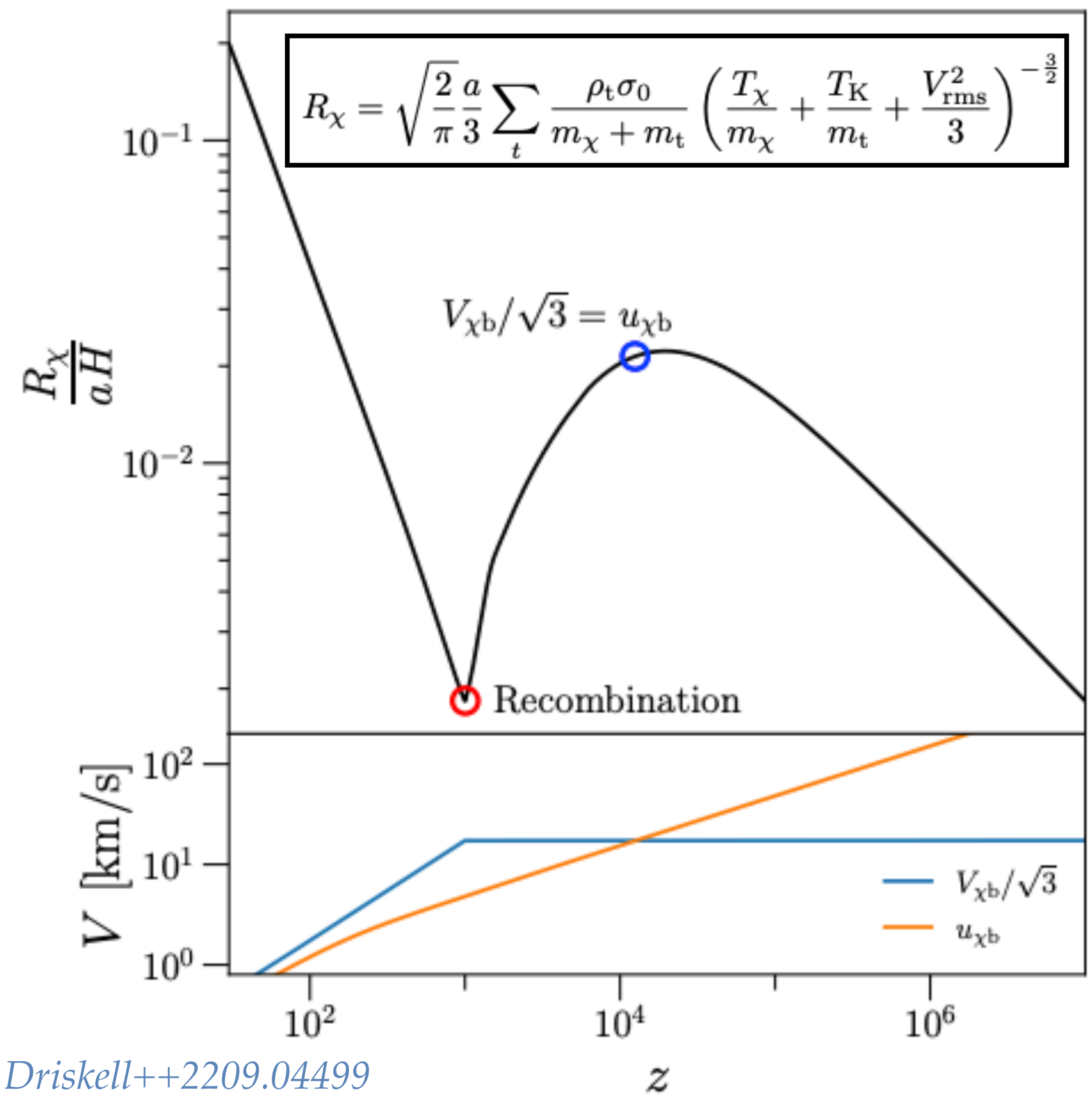
- MW satellites (no more missing-satellites) & Ly-α dominate constraints
- Future surveys like CMB-S4 or VRO/LSST will improve by orders of magnitude
- Also constraining DM-e^- interactions

Nguyen++ 2107.12380

Testing for coulomb-like DM interactions

- Interest for v^{-4} scattering with p^+/e^- (coulomb-like & millicharged models) with EDGES
- DM cools down the baryons.

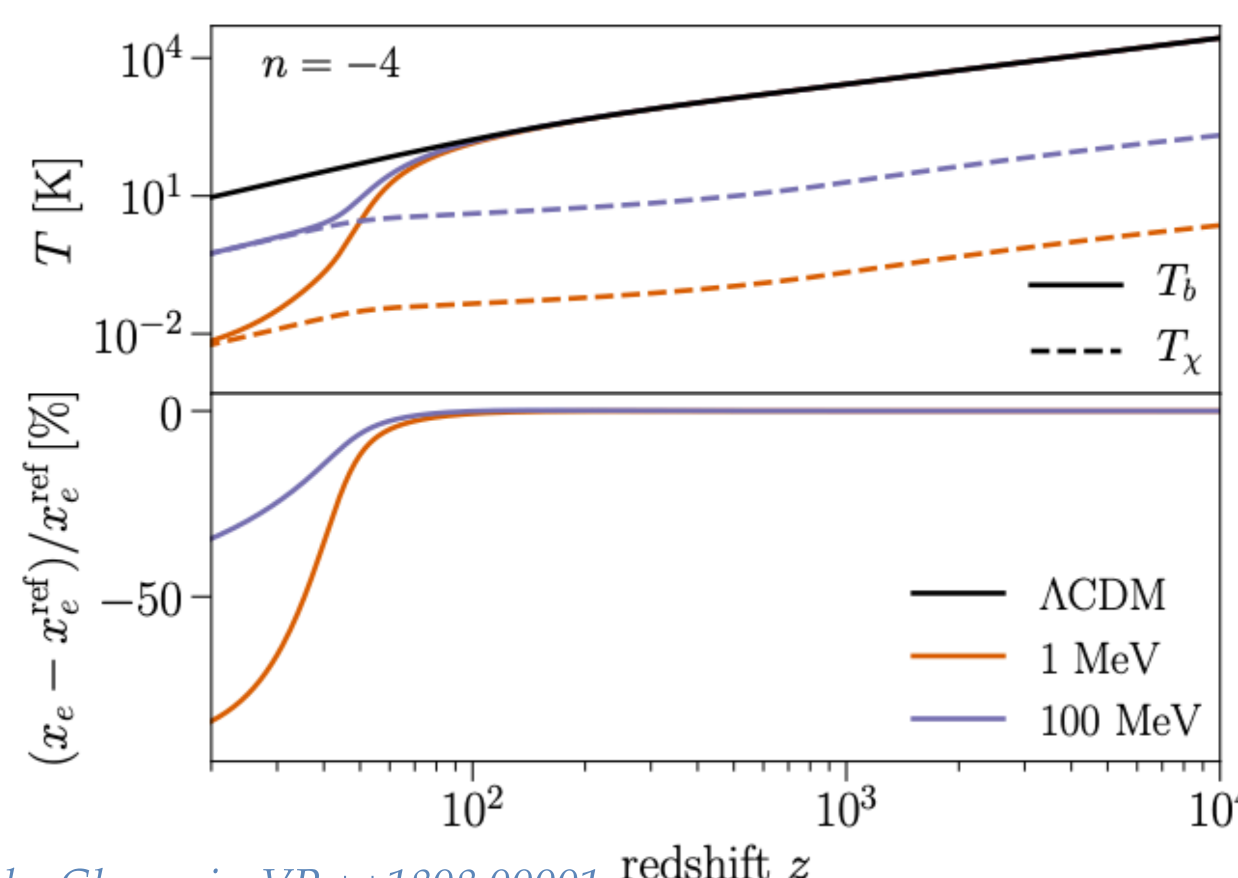
Bowman++ nature25792, Barkana nature25791



$$R_\chi = \sqrt{\frac{2}{\pi}}\frac{a}{3}\sum_t \frac{\rho_t\sigma_0}{m_\chi + m_t}\left(\frac{T_\chi}{m_\chi} + \frac{T_K}{m_t} + \frac{V_{rms}^2}{3}\right)^{-\frac{3}{2}}$$

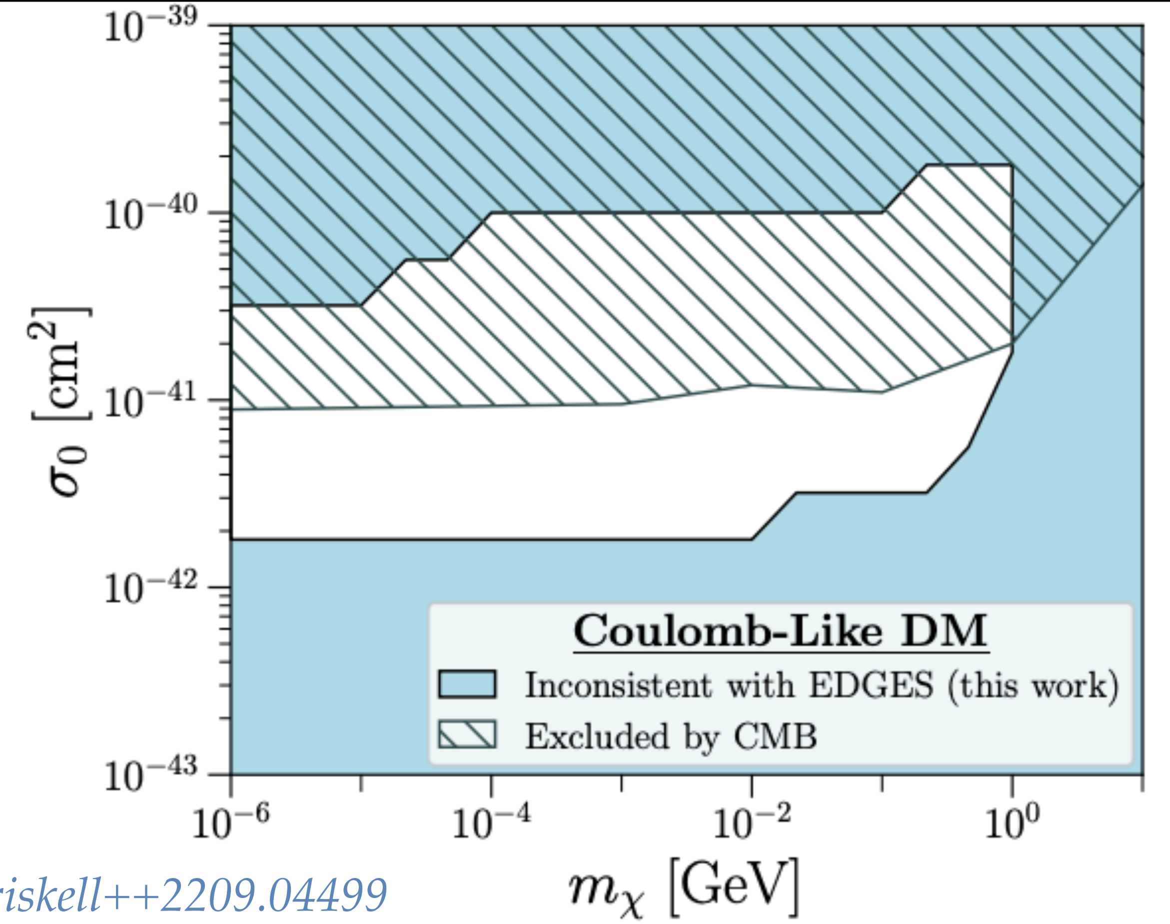
Driskell++2209.04499

$$\dot{T}_b = -2\frac{\dot{a}}{a}T_b + \sum_t \frac{2}{3}\frac{f_\chi \rho_t \rho_{DM}\sigma_{0,t}}{u_{\chi t}^3(1+f_{H_e}+x_e)n_H(m_\chi+m_t)^2} \times \left\{\sqrt{\frac{2}{\pi}}(T_\chi - T_b)e^{-r_t^2/2} + m_\chi\frac{V_{\chi b}^2}{r_t^3}F(r_t)\right\} + \Gamma_C(T_{CMB} - T_b), \quad (3)$$

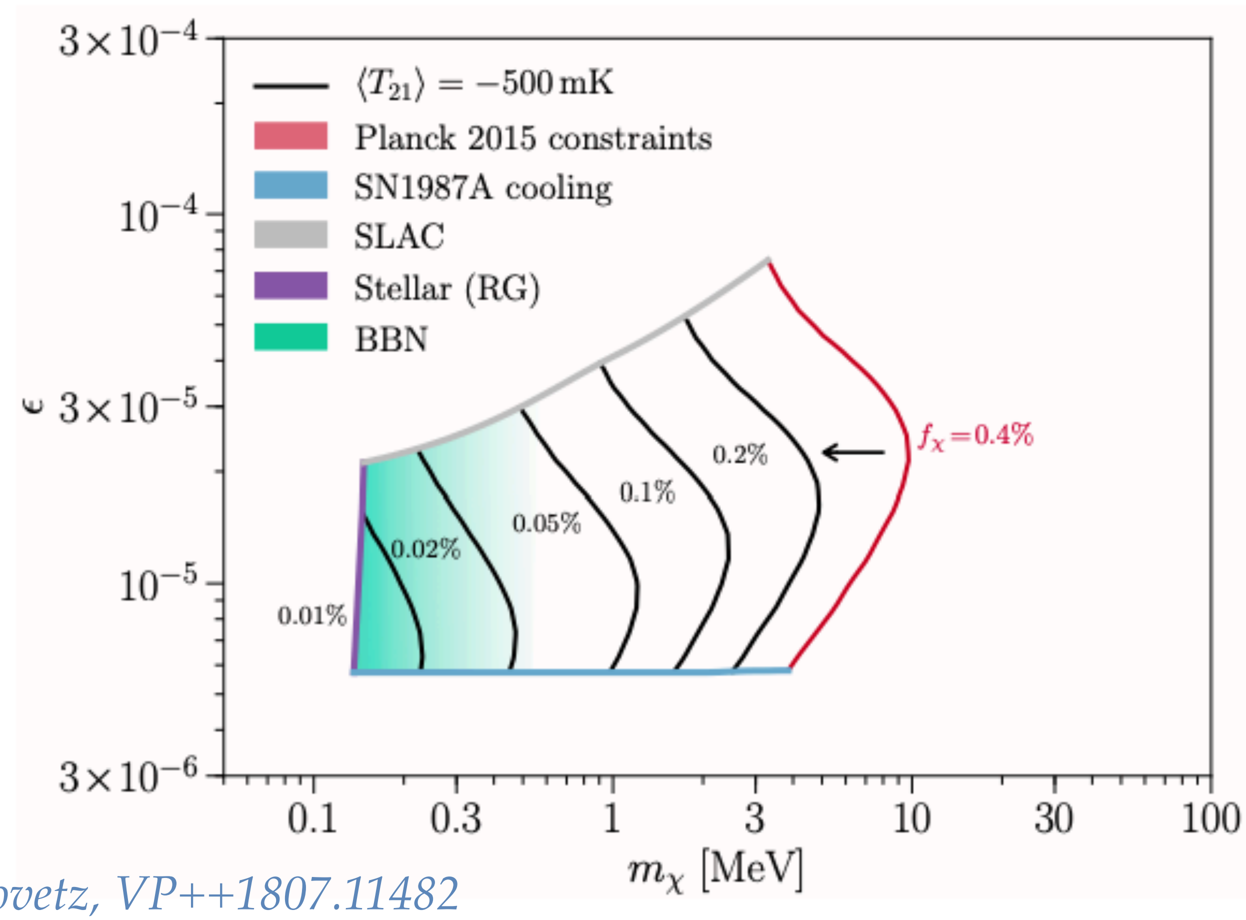


Boddy, Gluscevic, VP ++1808.00001

Constraints on coulomb-like scattering



Driskell++2209.04499



Kovetz, VP++1807.11482

- EDGES most likely systematic *Hills++ 1805.01421, Bradley++ 1810.09015, Singh++ 2112.06778*
- Parameter space for DM-b scattering explanations is very narrow
  Barkana, nature25791, Munoz&Loeb, 1802.10094, Berlin++1803.02804, Barkana++ 1803.03091

Part III
Gravitational constraints & the S_8 tension

The growth of CDM density perturbations

- For a non-relativistic pressure-less particles: 2 degrees of freedom $\delta \equiv \delta\rho/\rho \quad \phi$

- Continuity & Poisson equations: $\delta''_{\rm cdm} + \frac{a'}{a}\delta'_{\rm cdm} = -k^2\phi$ $\quad k^2\phi = -4\pi G a^2 \sum \delta\rho$

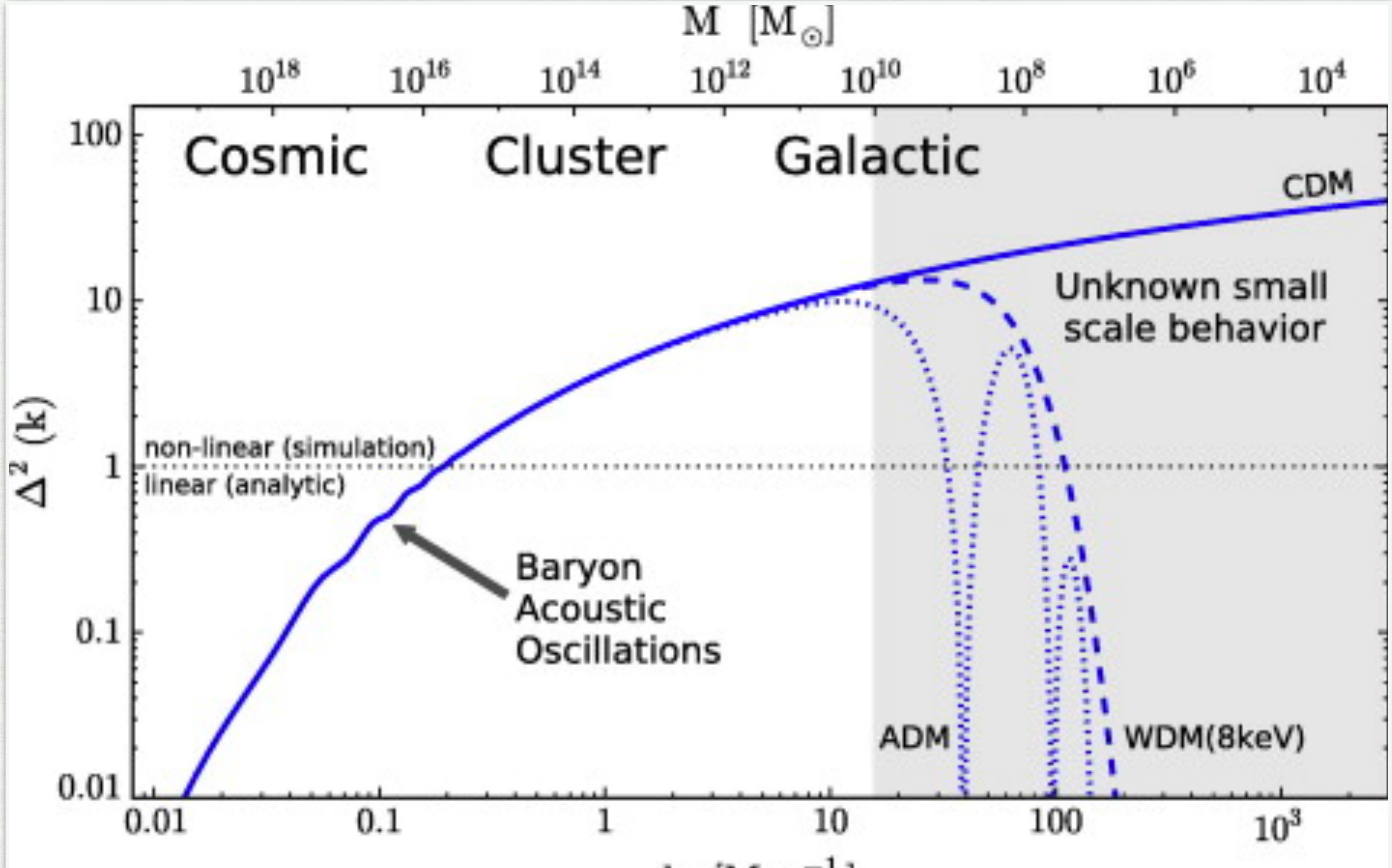
- For pressure-less, collision-less fluid: scale-independent growth $\delta(k) \propto a$

- If non-zero pressure: $w = \frac{p}{\rho}, c_a^2 = \frac{p'}{\rho'}, c_s^2 = \frac{\delta p}{\delta\rho}$ new degrees of freedom

$$\delta'_{\rm ncdm} = -(1+w)\left(\theta_{\rm ncdm} - \frac{1}{2}h'\right) - 3\frac{a'}{a}(c_s^2 - w)\delta_{\rm ncdm}, \quad \theta'_{\rm ncdm} = -\frac{a'}{a}(1-3c_a^2)\theta_{\rm ncdm} + \frac{c_s^2}{1+w} - k^2\sigma_{\rm ncdm}$$

- Neutrinos, warm dark matter, ultra-light axions… can lead to scale-dependent behavior.

Small-scale structures as a probe of DM

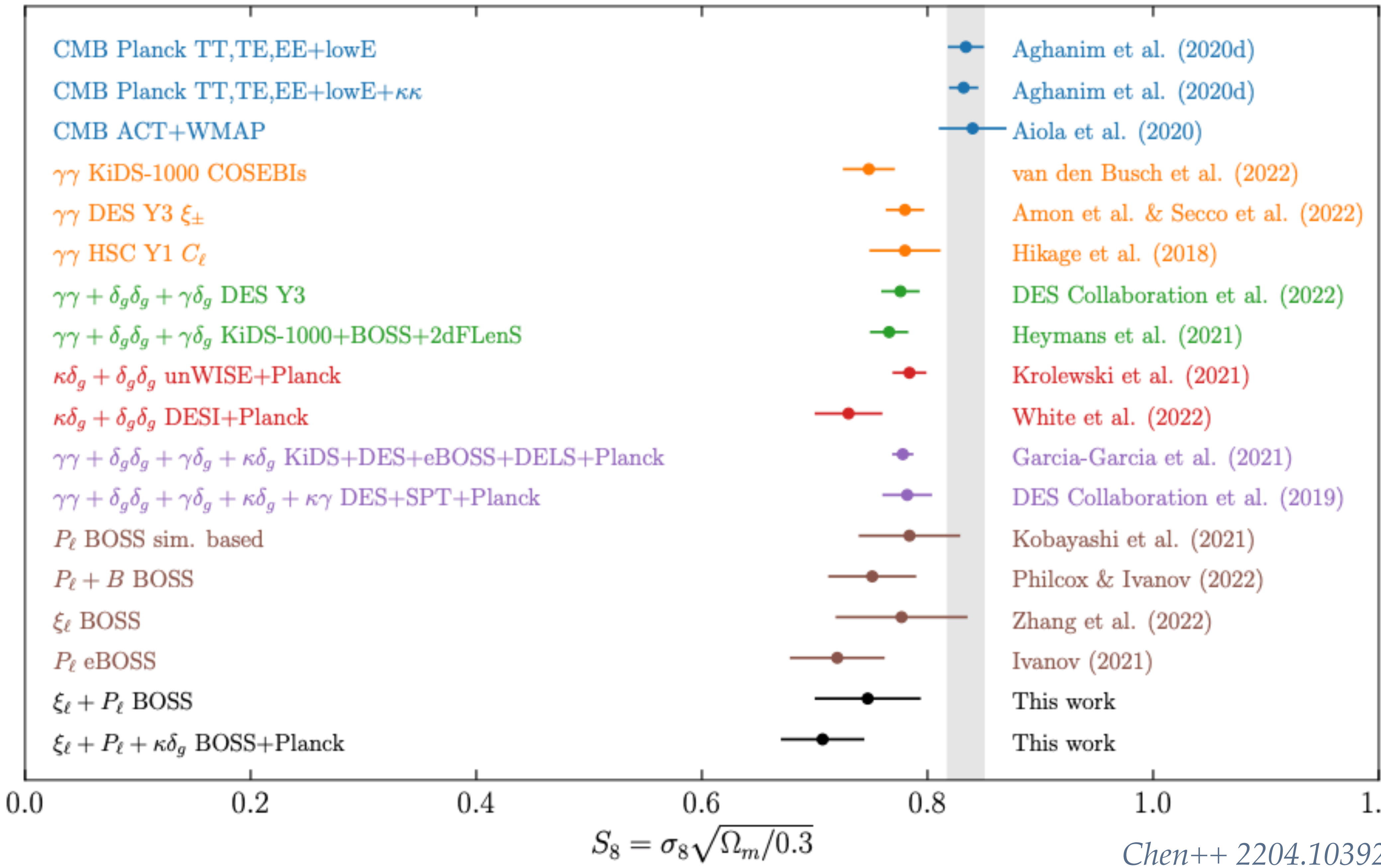


Kuhlen, Vogelsberger, Angulo 2012

- Canonical bounds from Lyα to date: $m_{\rm wdm} \gtrsim 5.7$ keV, $m_a > 2 \times 10^{-20}$ eV.
- Important for 'small-scale crisis'.

Rogers ++ 2007.12705, Irsic++ 2309.04533

The S_8 tension

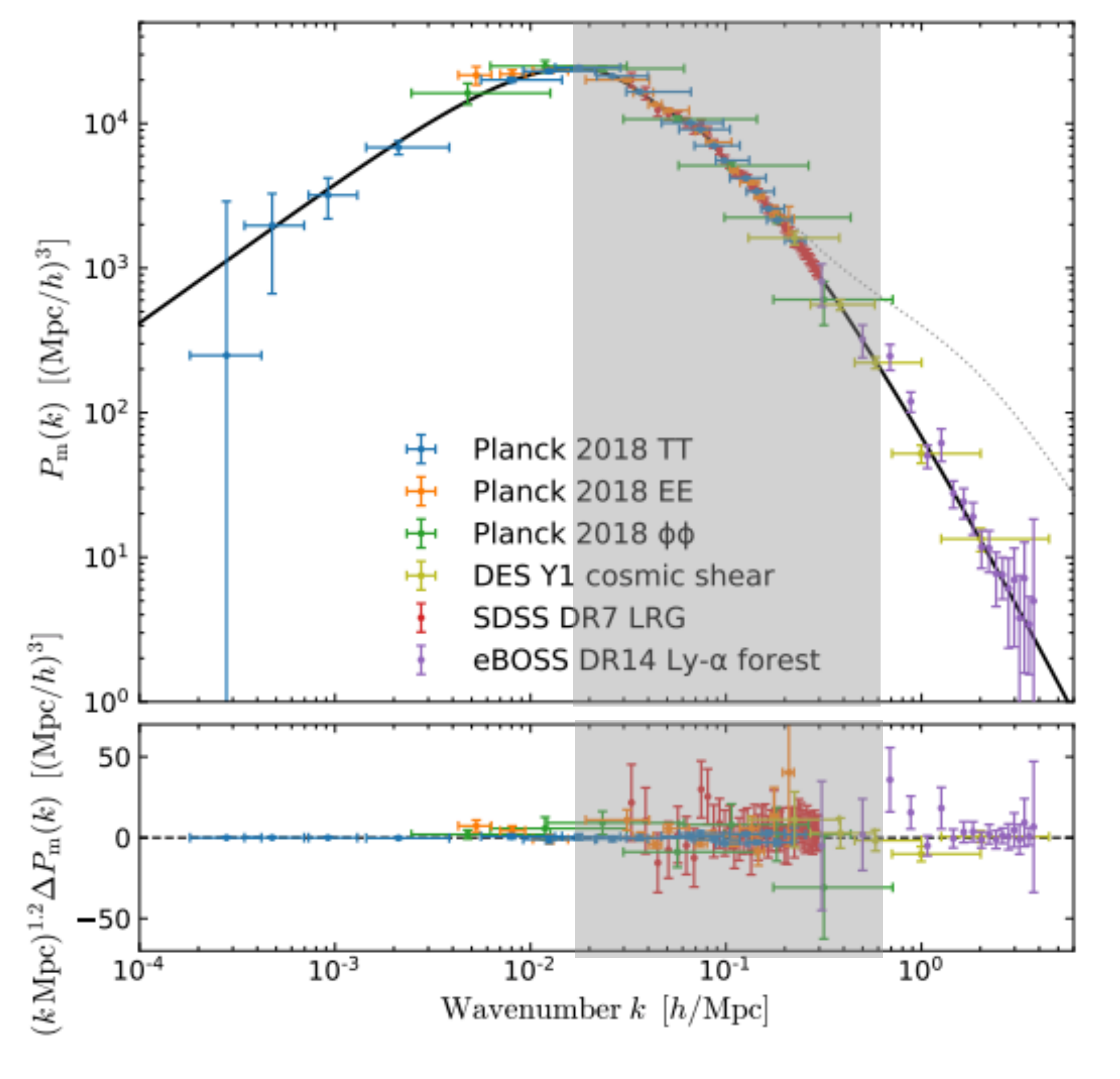


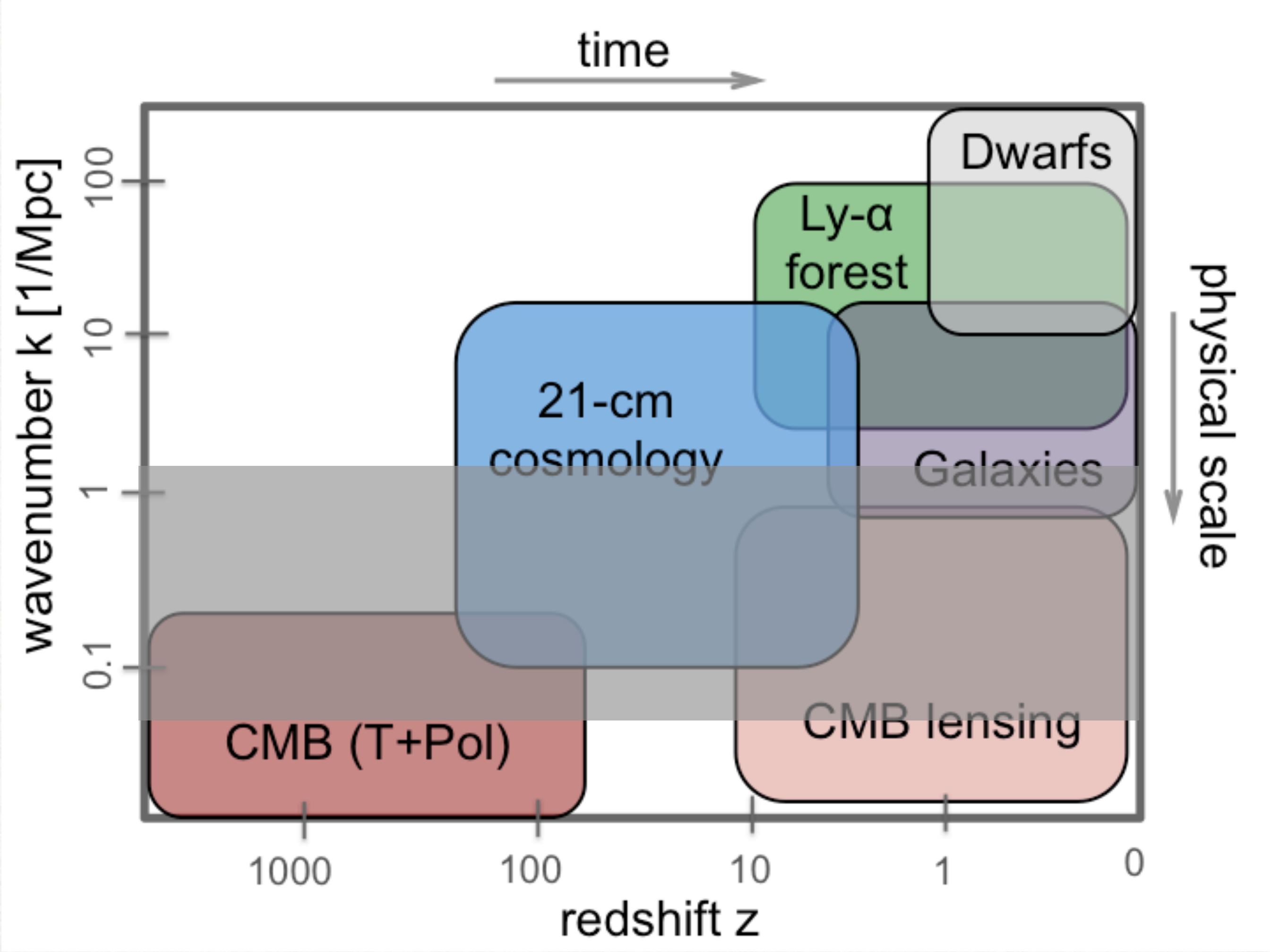
Chen++ 2204.10392

There is a 2-3σ tension between S_8 from WL x GC measurements and *Planck*

Latest DES and KIDS: Abbott++ 2305.17173, Li++ 2306.11124

How to resolve the S_8 tension



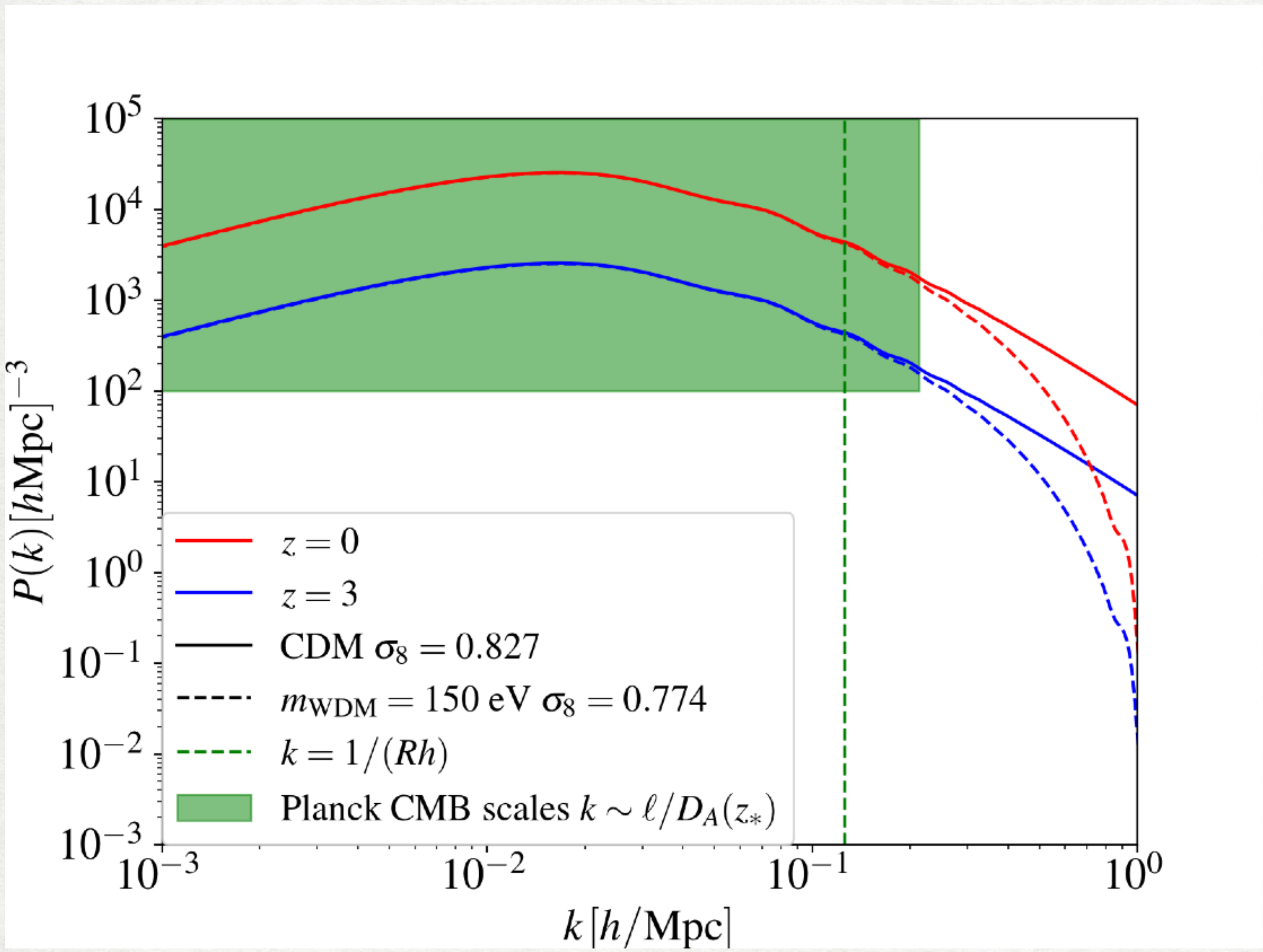


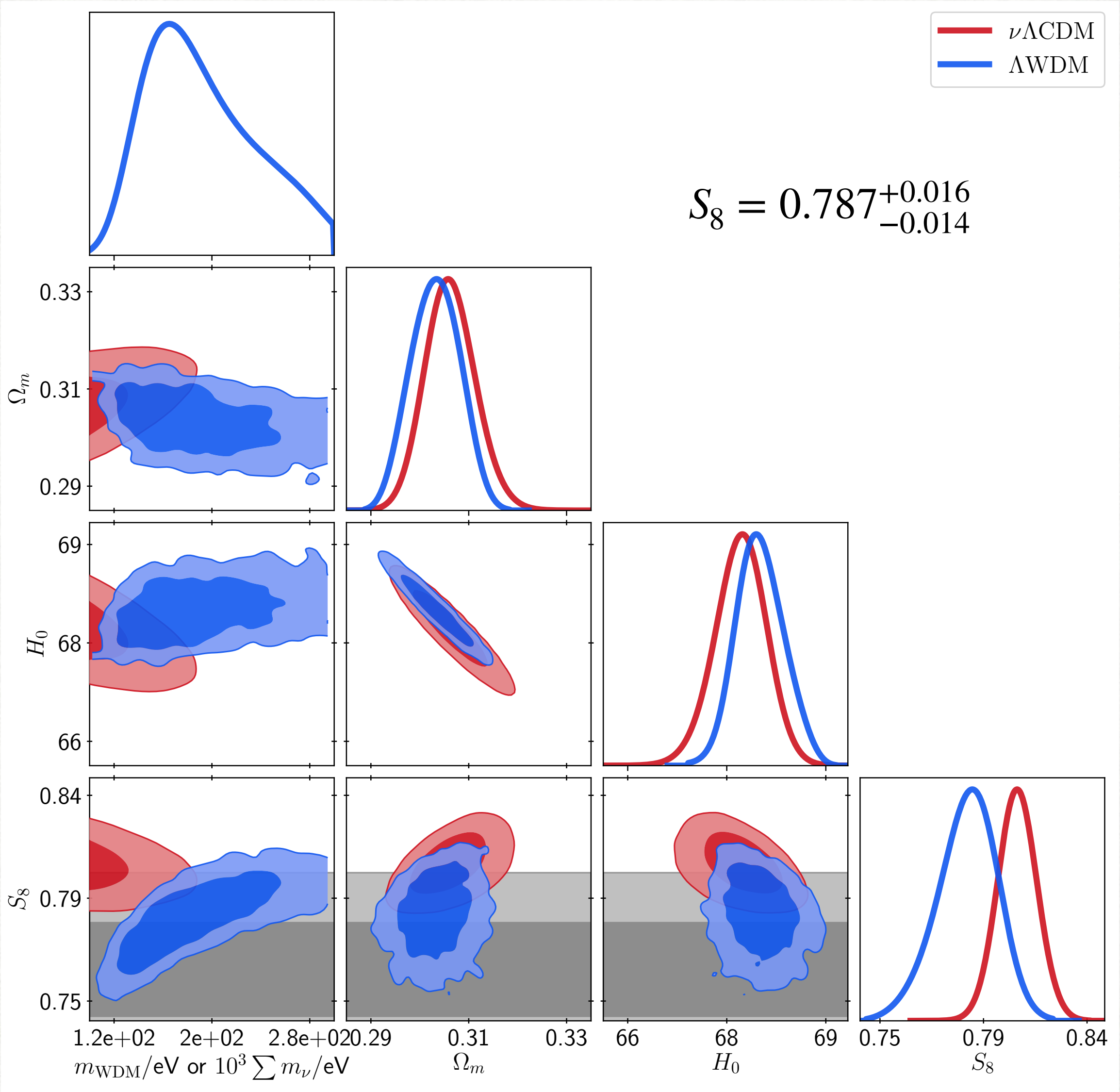
- σ_8 is a derived parameter measuring scales $k \sim 0.1$ h/Mpc. Fit the CMB at $z \sim 1100$ and predict $\sigma_8(z=0)$.
- To resolve the tension: Either suppress scales $k \gtrsim 0.2$ h/Mpc or change late-time evolution.
- Dark Sector physics: Ultra-light axions, Decaying DM, Interacting DM-DR, Interacting DM-DE…

Abdalla++ 2203.06142

Warm Dark Matter and S_8

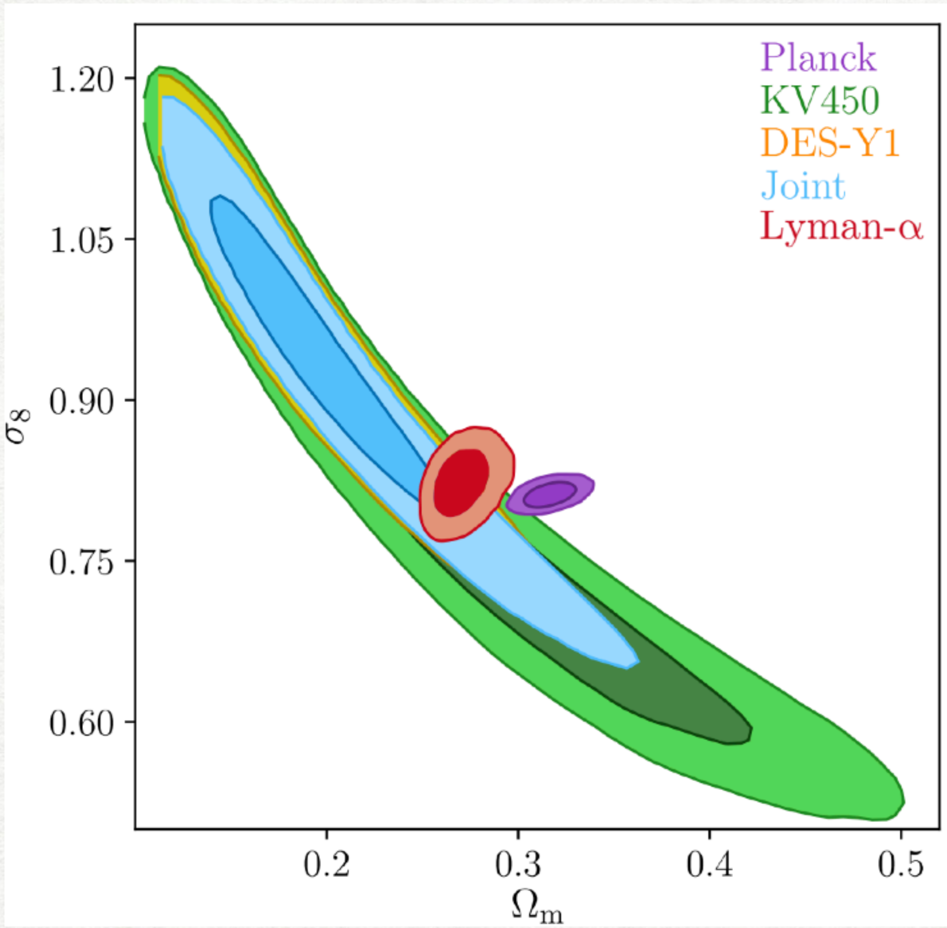
- For WDM: suppression at $k \geq k_{\rm FS} \sim 5\ {\rm Mpc}^{-1}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)\left(\frac{T_\nu}{T_{\rm WDM}}\right)$ *Viel++ astro-ph/0501562*
- Requiring $k_{\rm FS} \geq 0.1h/{\rm Mpc}$ and $\omega_{\rm ncdm} = \omega_{\rm cdm}$ leads to $m_{\rm WDM} \sim 100{\rm eV}$.

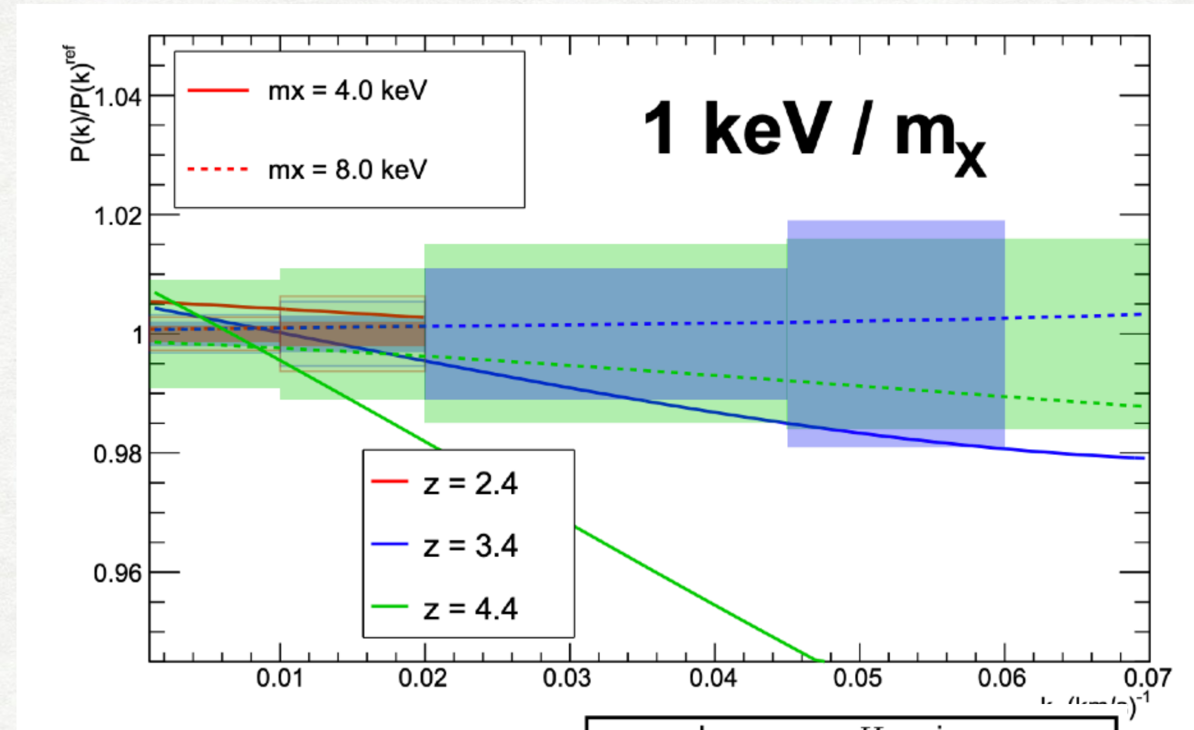


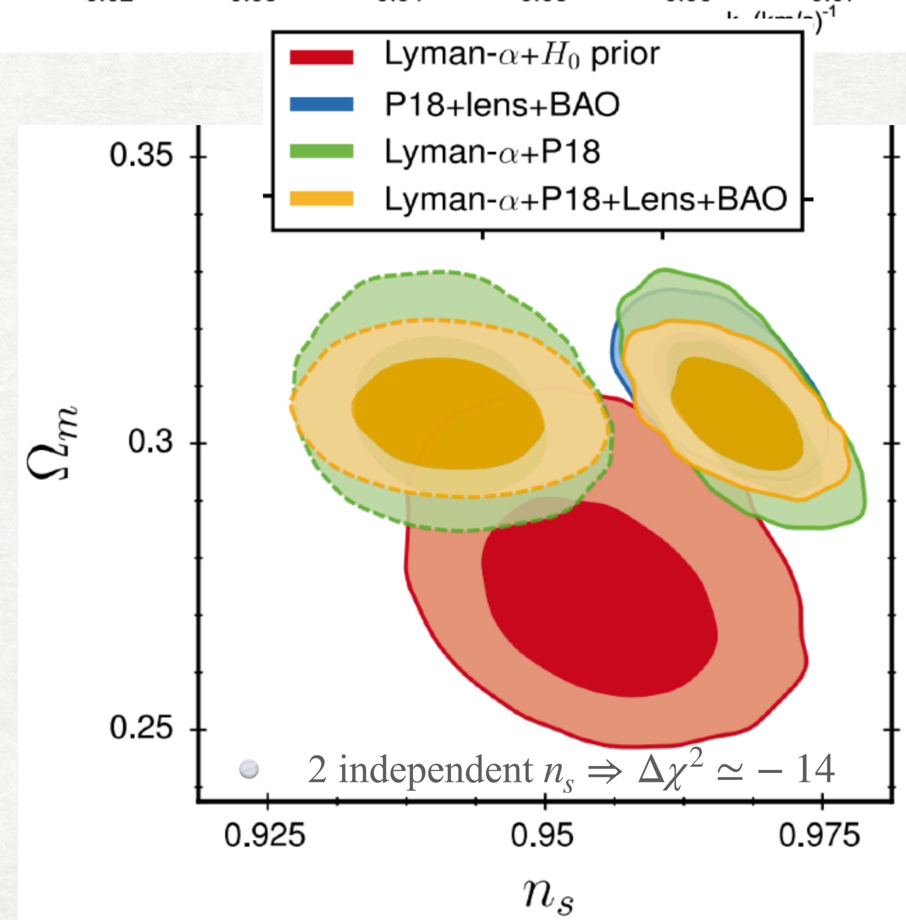


- CMB + BAO + S_8 $m_{\rm WDM} \simeq 192.2^{+31}_{-60}$ eV. Is that the end of the S_8 story?! Beware the Ly-α!

Ly-α and the S_8 tension



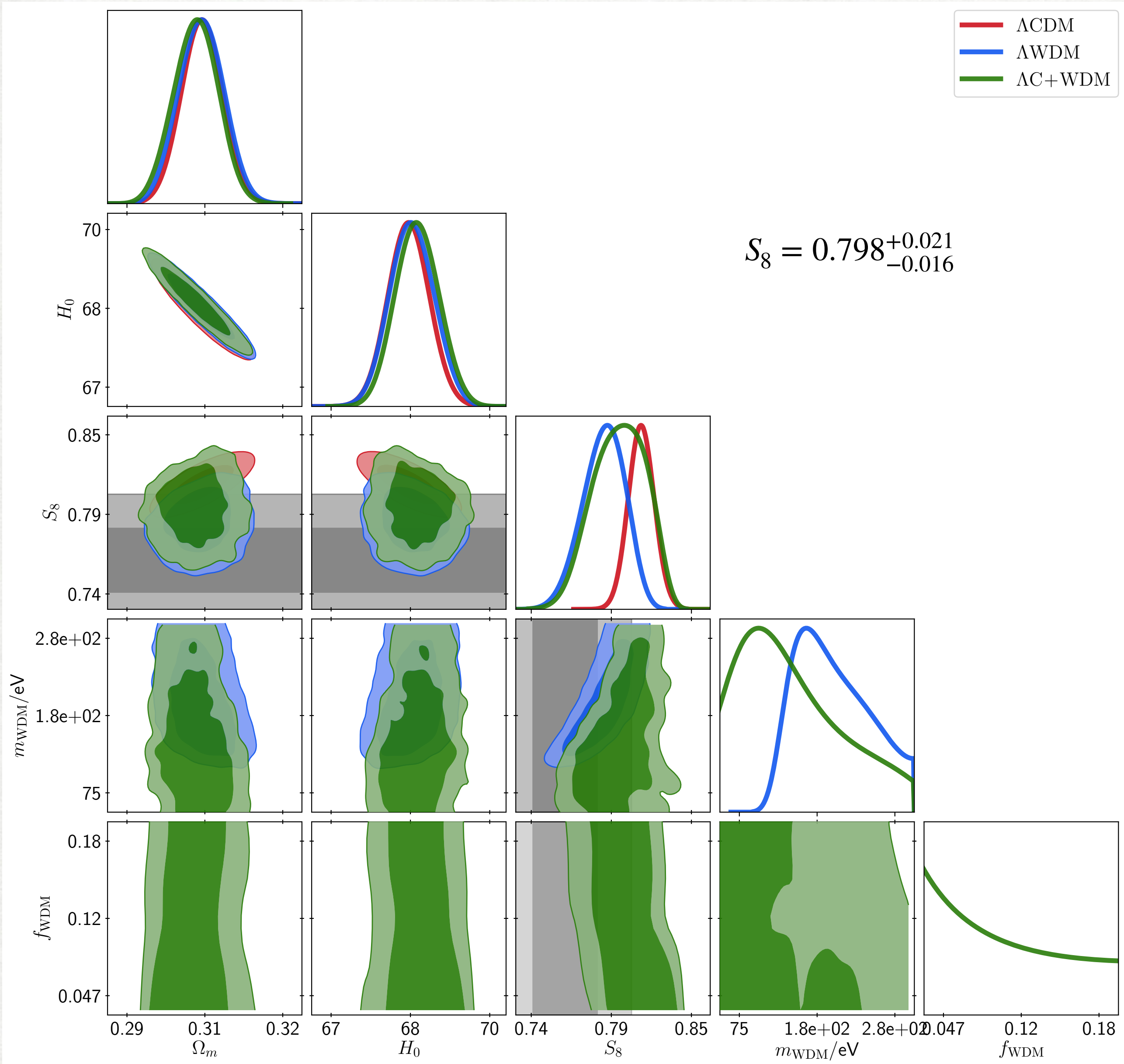




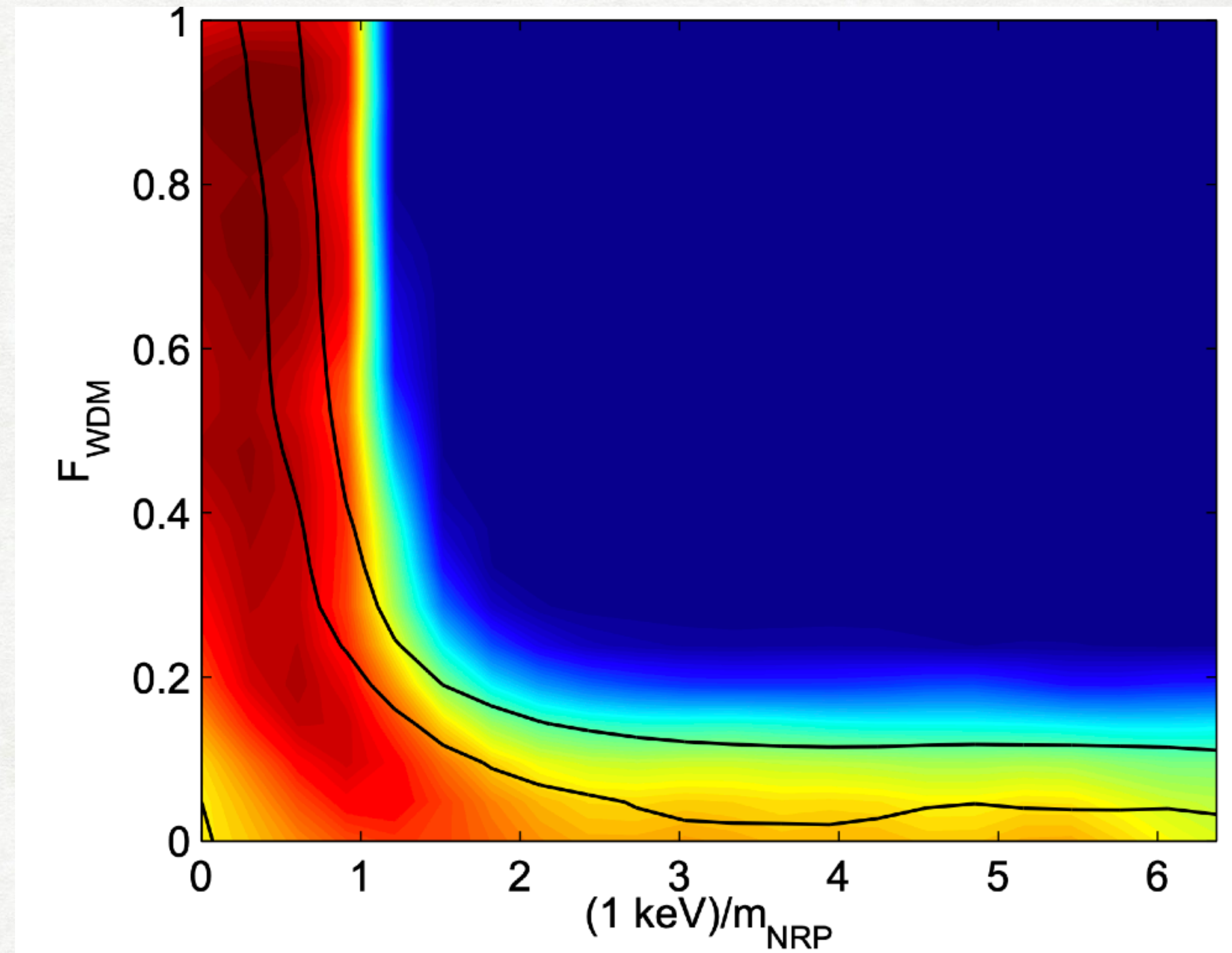
- Ly-α at $z \sim 3-5$ in 2.5σ tension with ΛCDM! Hints for smaller Ω_m!
- However, fixing Ω_m through Planck + BAO: n_s drives the tension!
- Ly-α hints for a (small) scale-dependent suppression of power.
- Yet, exponential cutoff 'a la WDM' are excluded: $m_{\rm WDM} > 5.7$ keV.

Palanque-Delabrouille++ 1911.09073, Irsic++ 2309.04533

Fraction of Warm Dark Matter and S_8



Boyarski, Lesgourgues ++ 0812.0010

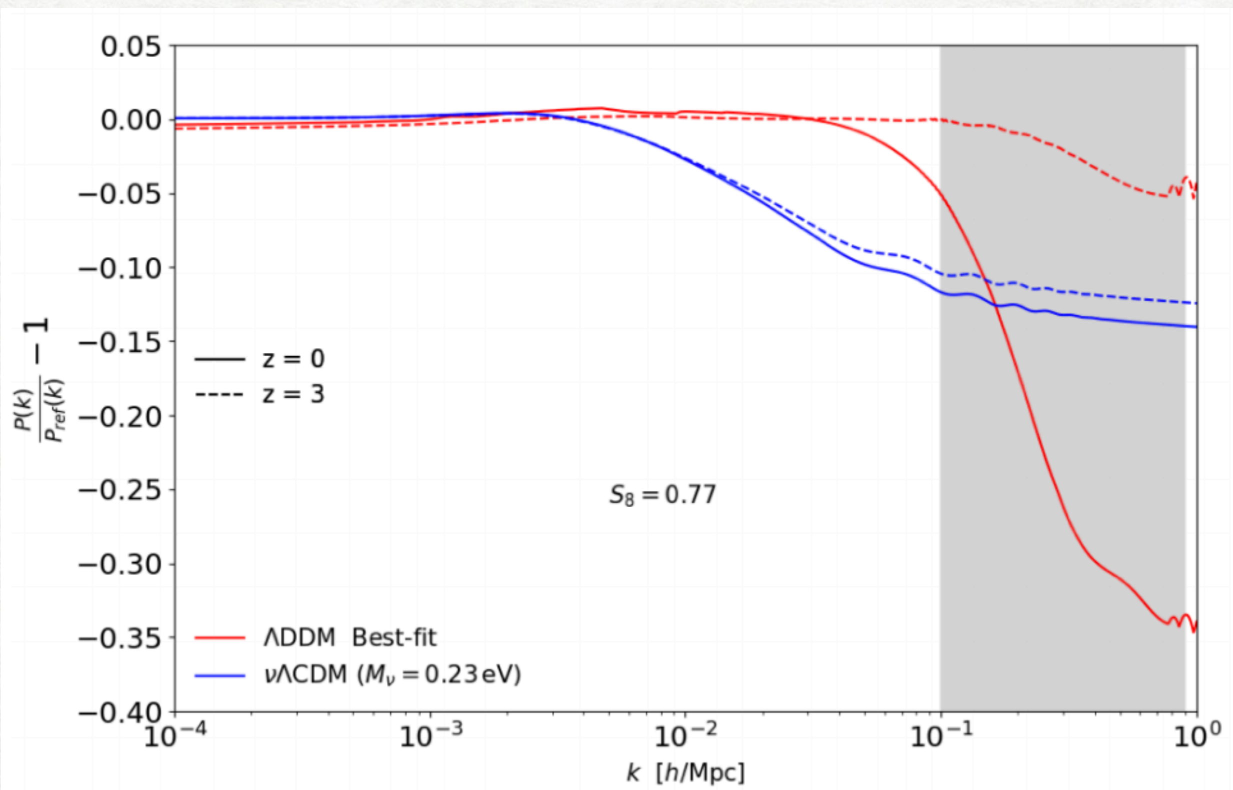


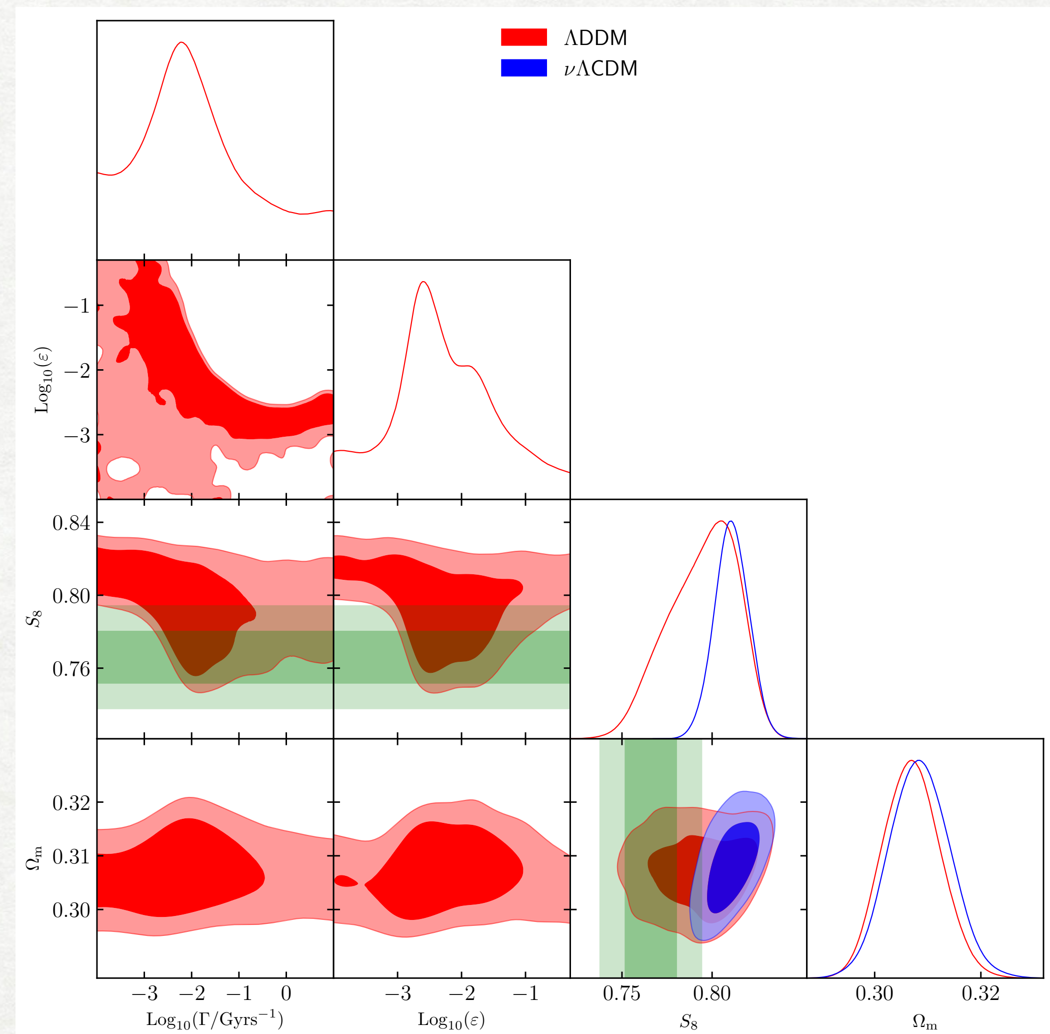
- A fraction of thermal WDM with $m \sim \mathcal{O}(100\text{eV})$ could explain low S_8: Ly-α restricts $f_{\rm WDM} \lesssim 0.2$
- How to generate a fraction of WDM? *See also Gariazzo++ 1704.02991*
- Nb: similar results apply to fraction of fuzzy dark matter *Allali++ 2104.12798, Laguë++ 2104.07802*

DM decays generate a late-time suppression

- ΛCDM + two free parameters: the CDM decay rate Γ and the branching ratio to DR $\varepsilon \equiv \left(\frac{1}{2} - \frac{m^2_{\rm WDM}}{m^2_{\rm DCDM}}\right) \simeq v_{\rm wdm}/c$

$$\dot{\bar{\rho}}_{\rm dcdm} = -3\mathcal{H}\bar{\rho}_{\rm dcdm} - a\Gamma\bar{\rho}_{\rm dcdm},$$
$$\dot{\bar{\rho}}_{\rm dr} = -4\mathcal{H}\bar{\rho}_{\rm dr} + \varepsilon a\Gamma\bar{\rho}_{\rm dcdm},$$
$$\dot{\bar{\rho}}_{\rm wdm} = -3(1+w)\mathcal{H}\bar{\rho}_{\rm wdm} + (1-\varepsilon)a\Gamma\bar{\rho}_{\rm dcdm}.$$





- DM with $\Gamma^{-1} \simeq 55(\varepsilon/0.007)^{1.4}$ Gyrs can explain low S_8 (1.3σ agreement) *Abellan, Murgia, VP++ 2008.09615 & 2104.03329*

See also Davari&khosravi 2203.09439, Clark++ 2110.09562

New interactions in the dark sector?

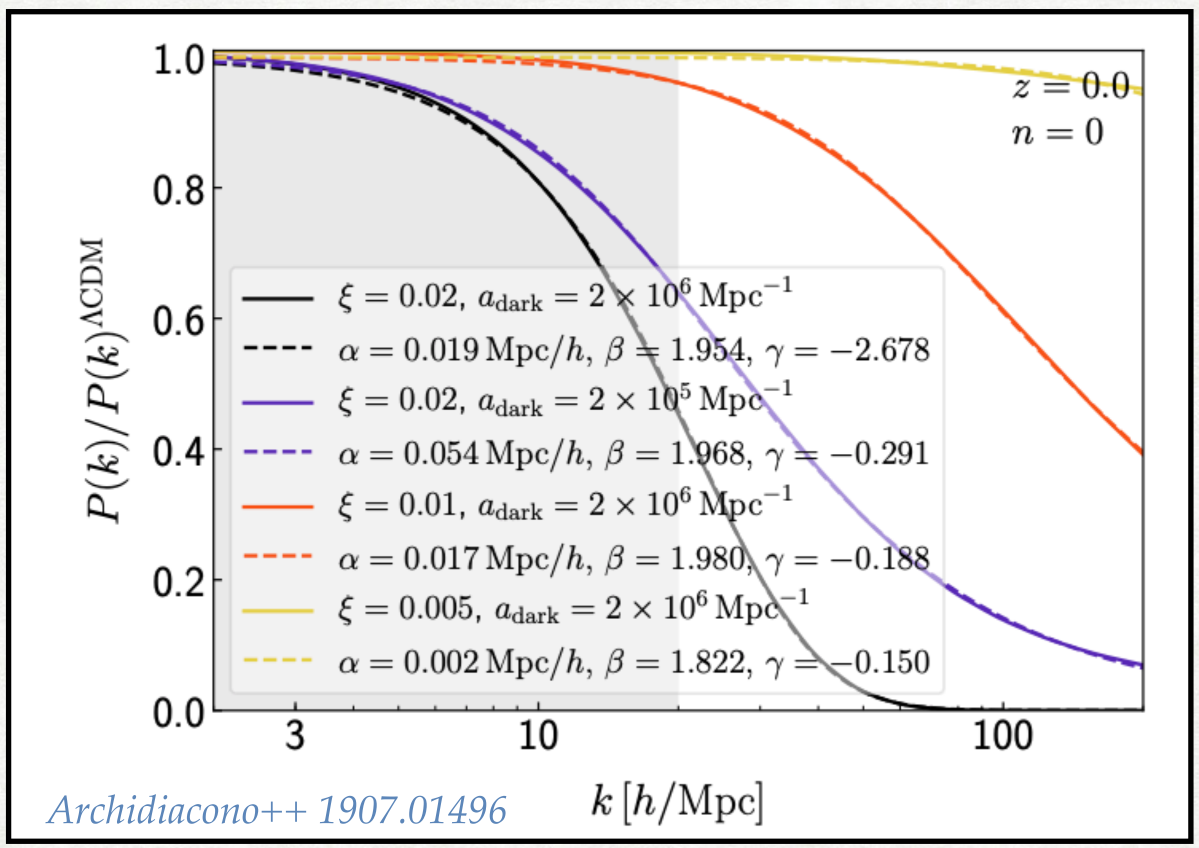
- DM-DR interactions can suppress power: Non-Abelian dark matter model, Cannibal dark matter, Stepped Dark Radiation, ETHOS…

Cyr-Racine++ 1512.05344, Buen-Abad++1505.03542, Lesgourgues++1507.04351, Heimersheim++ 2008.08486, Joseph++ 2207.03500

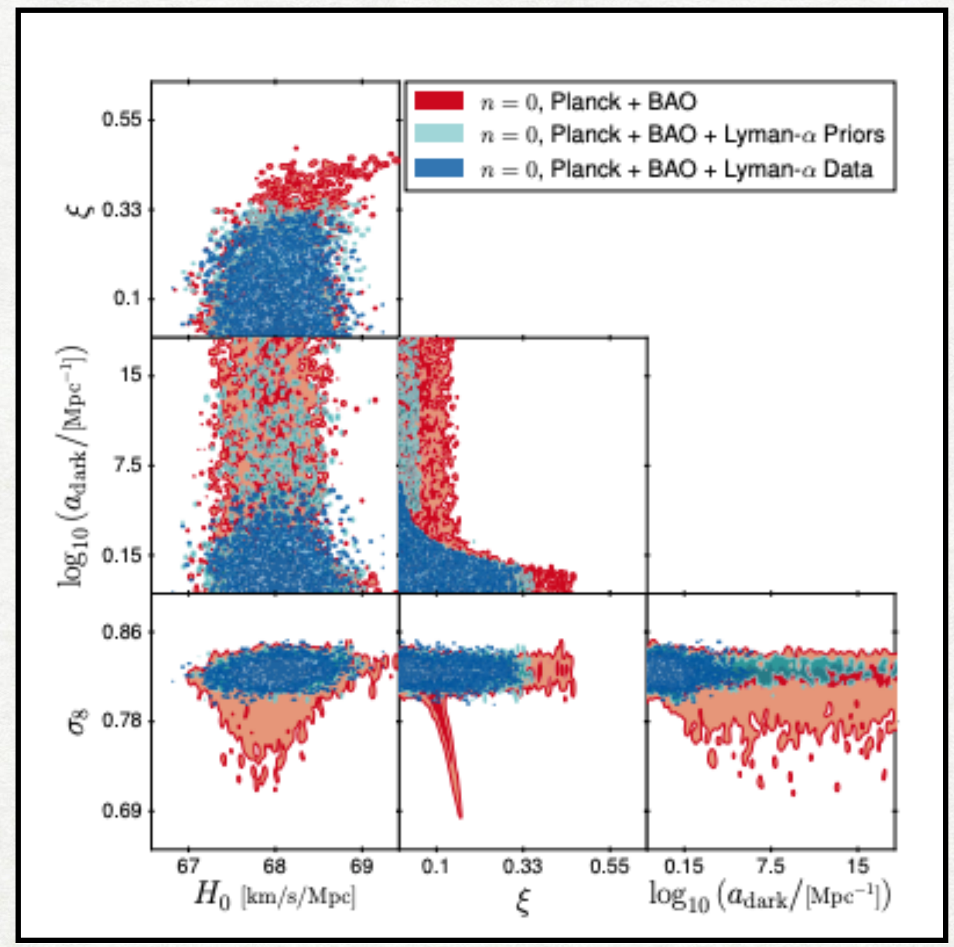
$$\dot{\delta}_{\rm DM} + \theta_{\rm DM} - 3\dot{\phi} = 0,$$
$$\dot{\theta}_{\rm DM} - k^2 c^2_{\rm DM}\delta_{\rm DM} + \mathcal{H}\theta_{\rm DM} - k^2\psi = \Gamma_{\rm DM-DR}\left(\theta_{\rm DM} - \theta_{\rm DR}\right),$$

$$\Gamma_{\rm DR-DM} = -\Omega_{\rm DM}h^2 a_{\rm dark}\left(\frac{1+z}{1+z_d}\right)^n,$$

$$\xi = T_{\rm DR}/T_\gamma$$



Archidiacono++ 1907.01496



- Models with early-times interactions such as DM-DR interactions are disfavored by Lyman-α data

A step in understanding the S_8 tension?

Aloni++ 2111.00014, Diamond++ 2207.03500

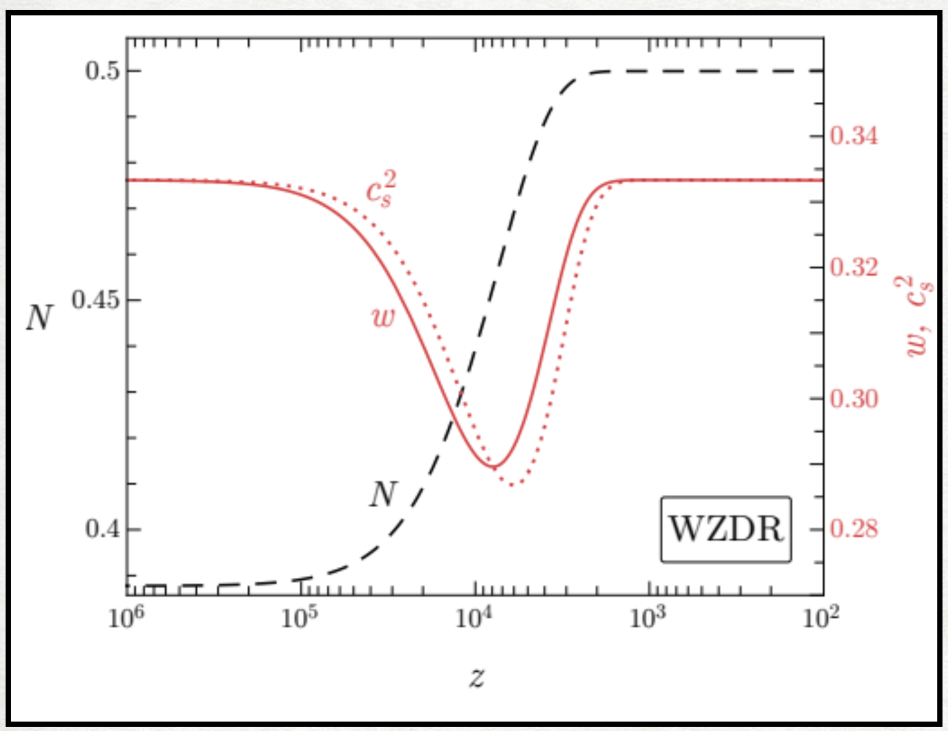
- If $N_{\rm eff}$ has a step around $z \sim 10^4$ from decoupling of a scalar ϕ with $m \sim 1$eV reheating a bath of DR fermions ψ.

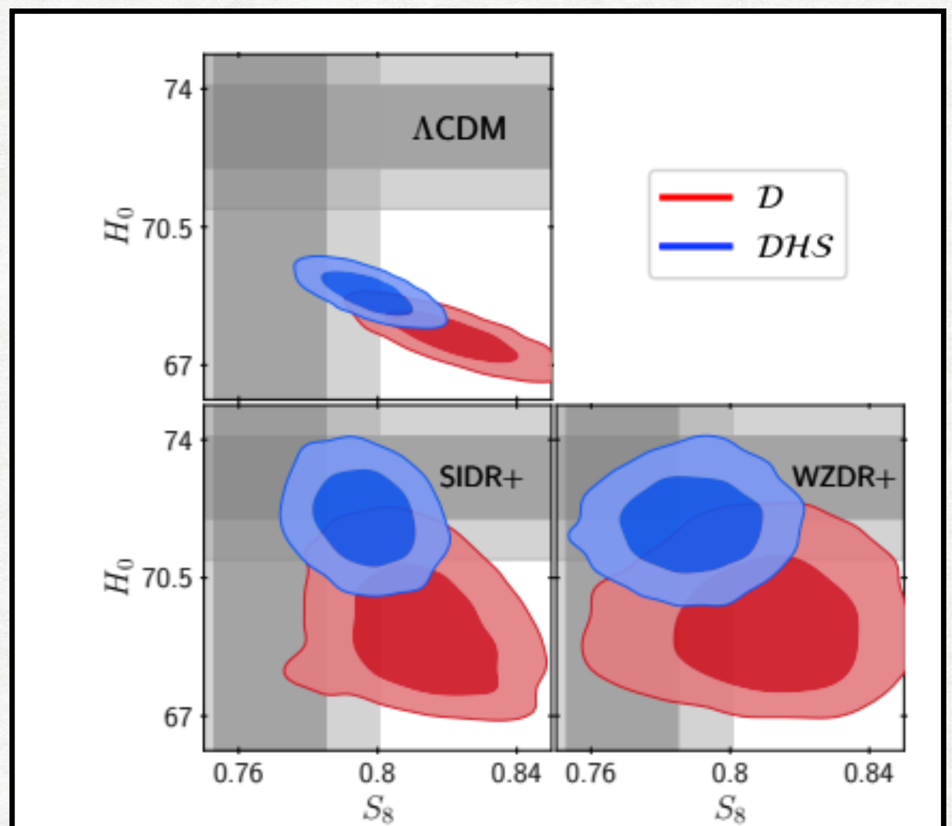
$$\frac{N_{\rm IR}}{N_{\rm UV}} = \left(\frac{g_*^\phi + g_*^\psi}{g_*^\psi}\right)^{1/3} = \left(\frac{15}{7}\right)^{1/3} \simeq 1.29$$

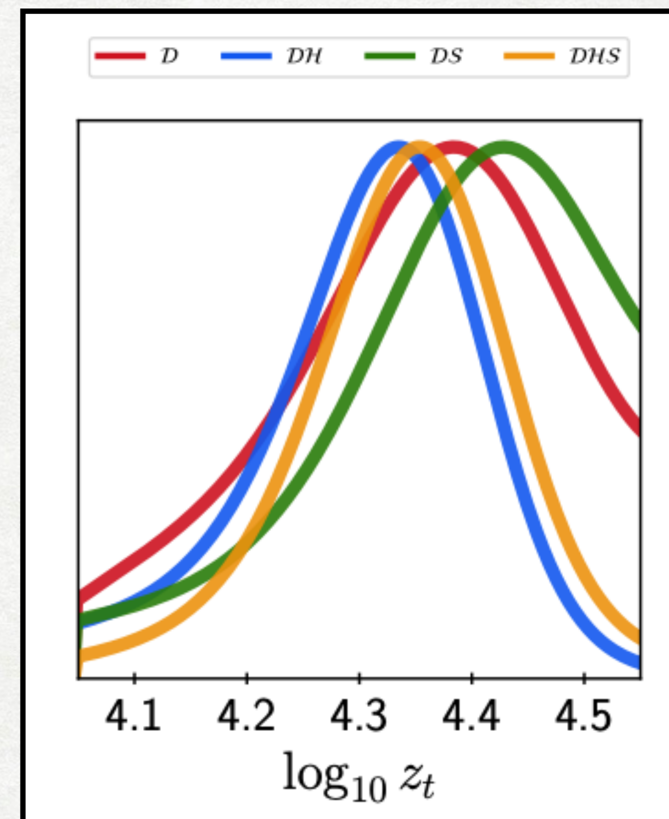
- Augments the model by allowing for interactions between DM and DR ψ mediated by ϕ : helps for both H_0 and S_8

$$\Gamma \propto \frac{T_d^2}{M_\chi} \qquad \text{for } T_d \gtrsim m_\phi$$

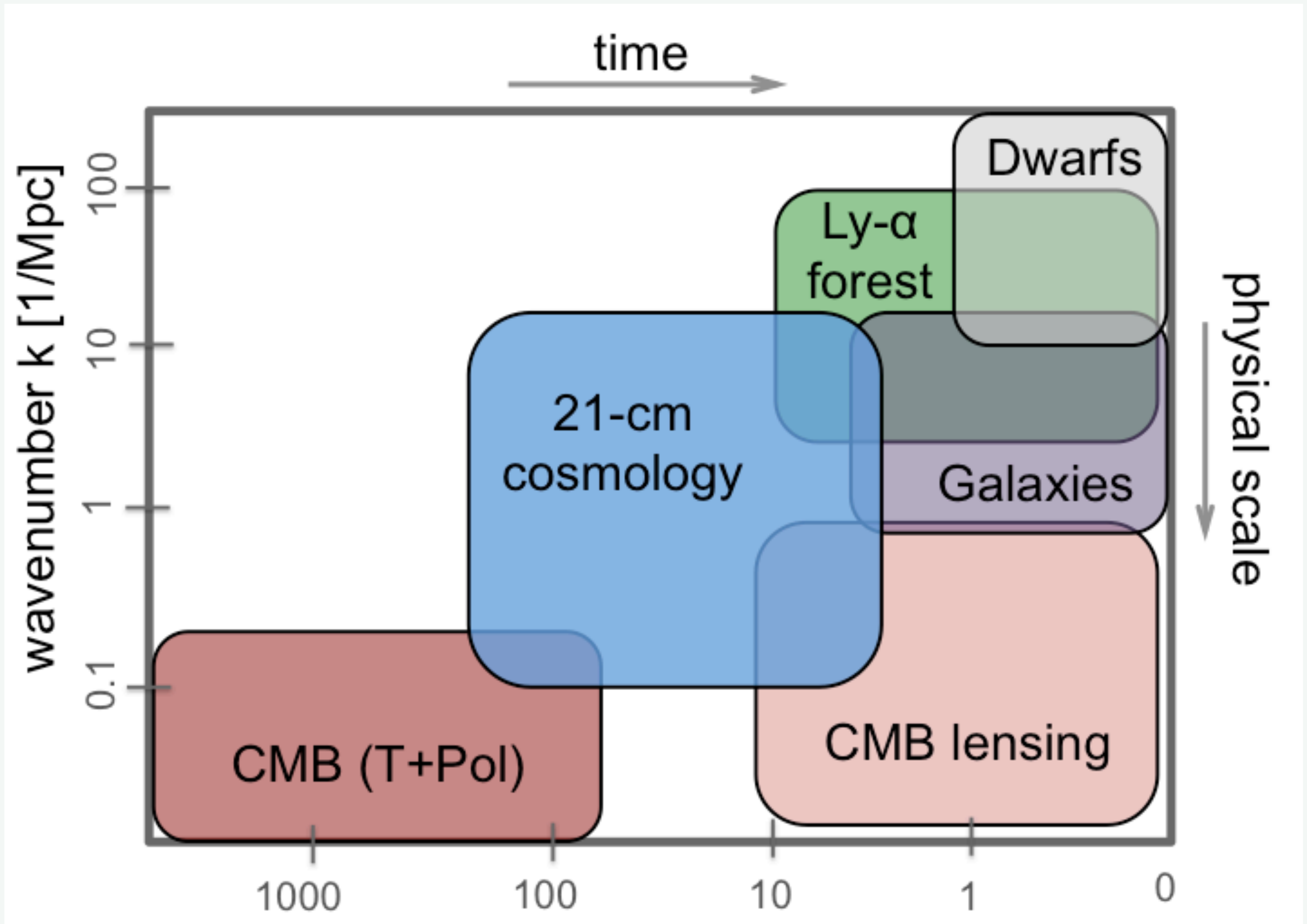
$$\Gamma \propto \frac{T_d^2}{M_\chi}\left(\frac{T_d}{m_\phi}\right)^4 \qquad \text{for } T_d \lesssim m_\phi$$







Cosmology provides powerful probes of DM



Gluscevic ++ 1903.05140

- 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?
- Future is bright: DESI, Euclid, VRO/LSST, SKA, Simons Observatory… all within the decade!