JOHNS HOPKINS UNIVERSITY

Shedding light on Dark Matter with the CMB: Implications for EDGES

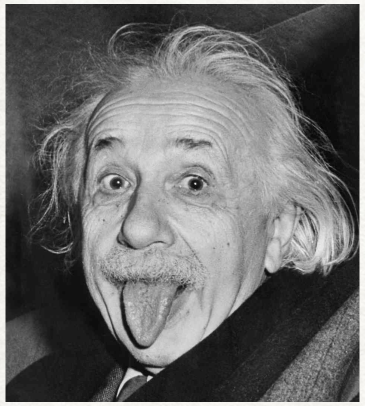
Vivian Poulin - Johns Hopkins University

- *based mostly on:* ***VP**, Serpico, Lesgourgues, JCAP 1703 (2017) no.03, 043*
  *Stöcker, Krämer, Lesgourgues, **VP**, JCAP 1803 (2018) no.03, 018*
  *Kovetz, **VP**, Gluscevic, Boddy, Kamionkowski, Barkana, 1807.11482*
  *Boddy, Gluscevic, **VP**, Boddy, Kamionkowski, Barkana, 1808.00001*

Lawrence Berkeley National Lab, RPM seminar
01 November 2018

ΛCDM is a big success!

From GR

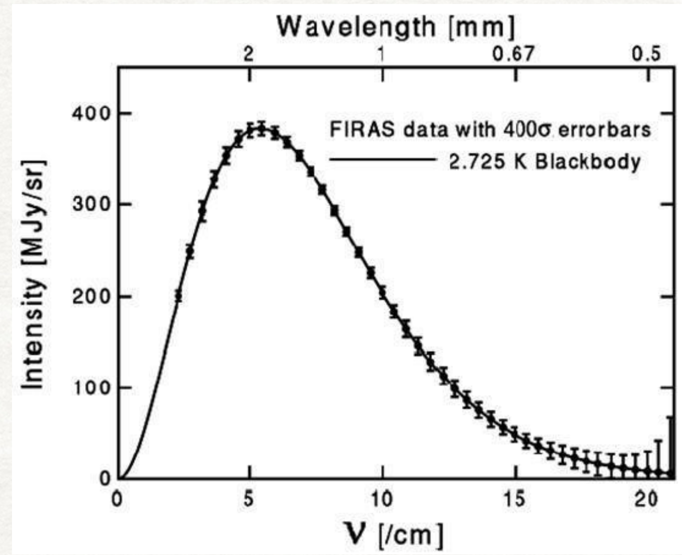


Homogeneous

& isotropic

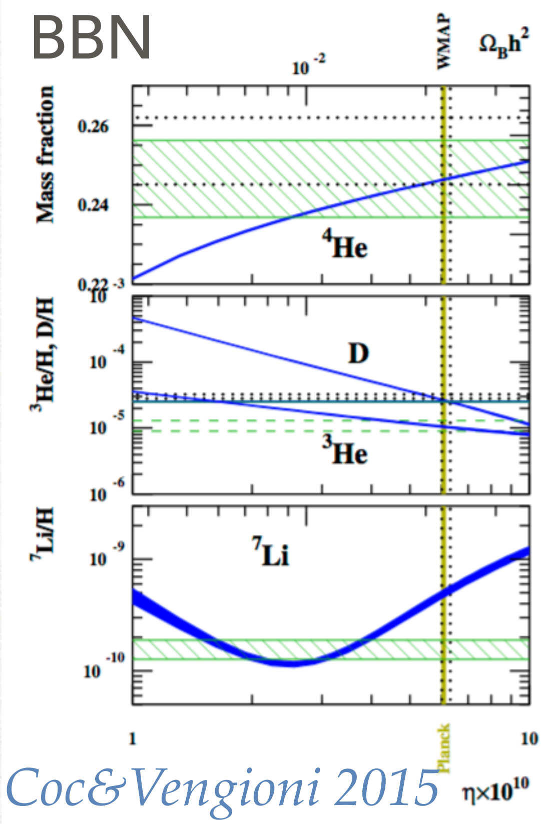
Perturbed

CMB blackbody distribution

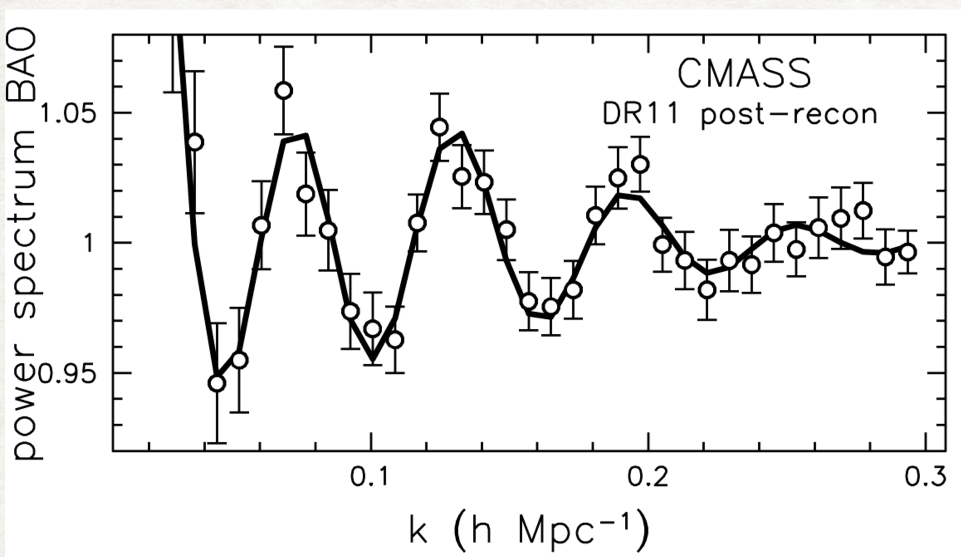


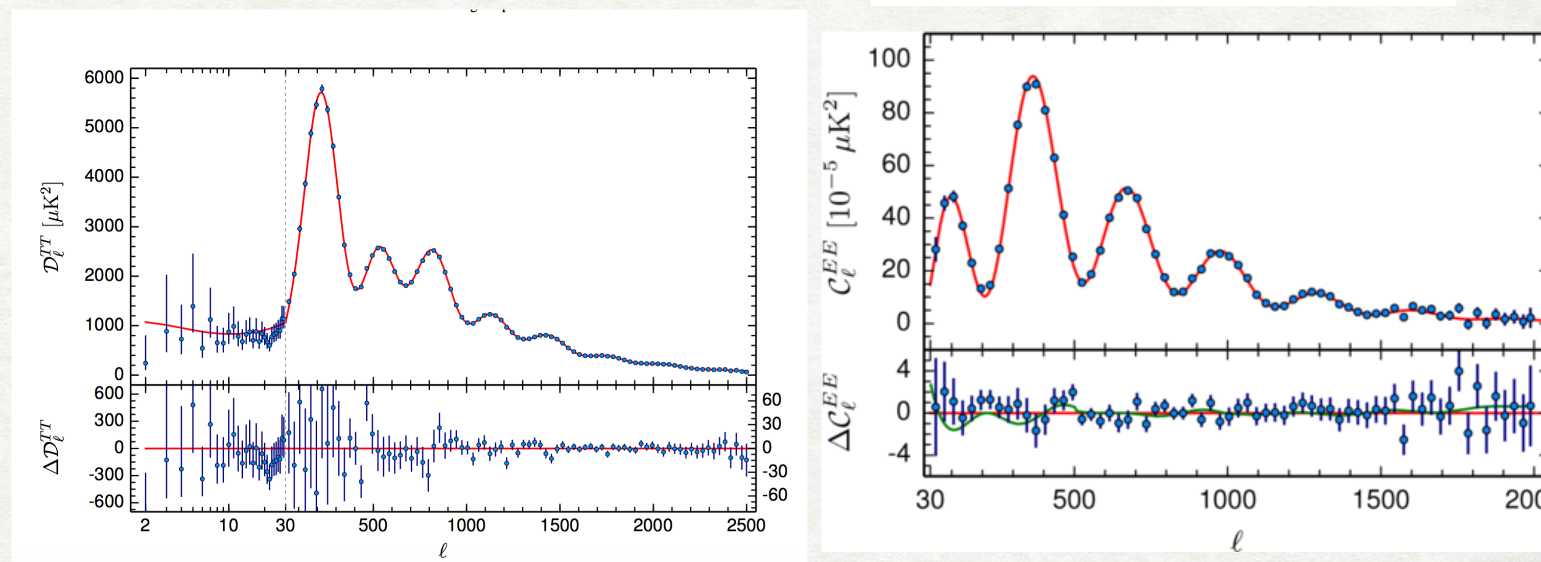
Firas [astro-ph/9605054]

BBN



Coc&Vengioni 2015





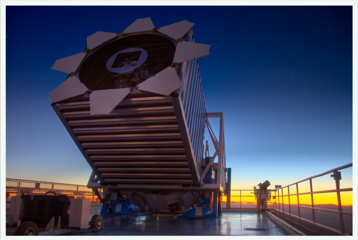
P(k) and BAO measurements

Andersen et al. 2012 [arXiv:1203.6594]

CMB power spectra

Planck 2015 [arXiv:1502.01589]

The Universe composition is Unknown!!

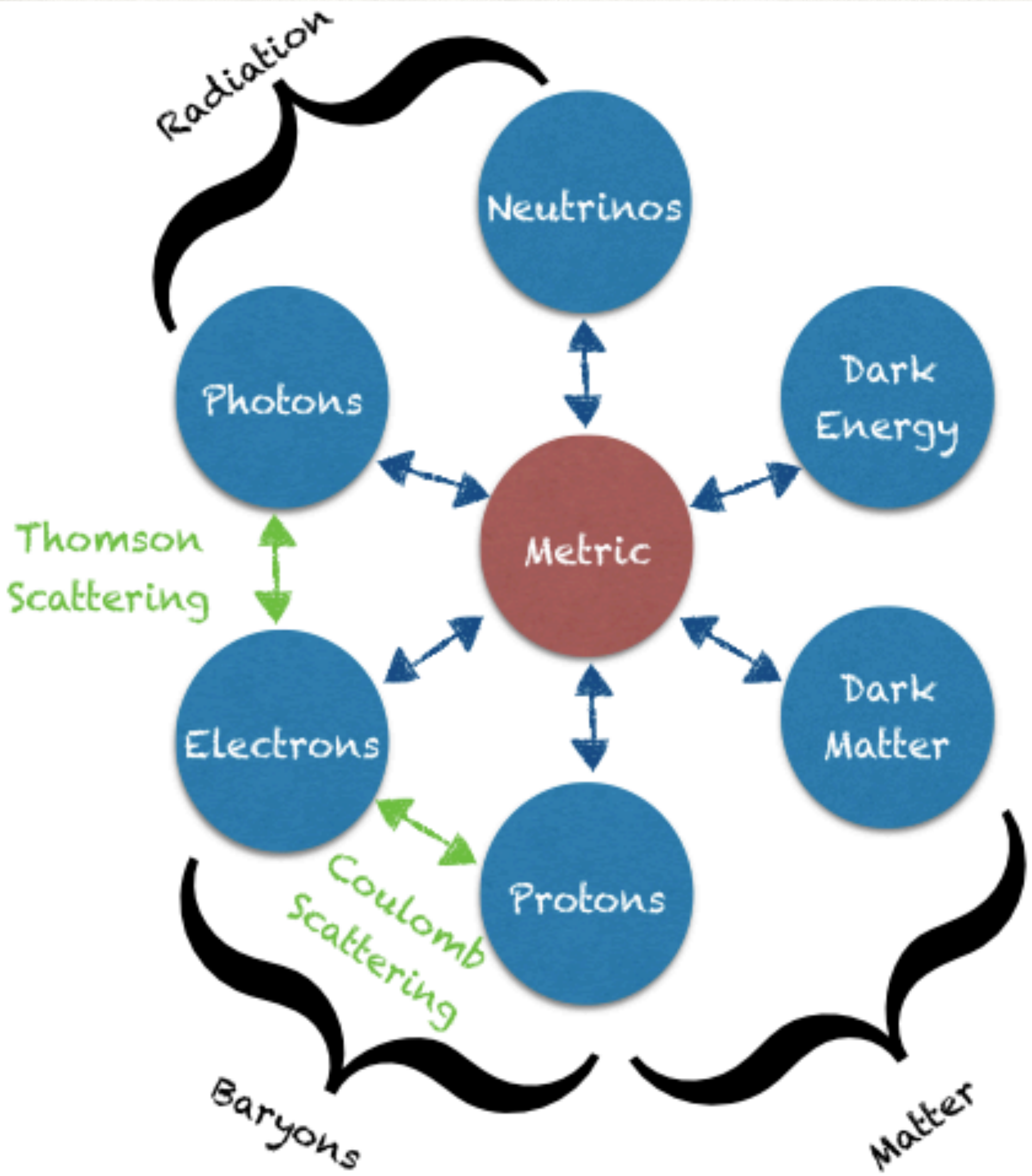


SDSS

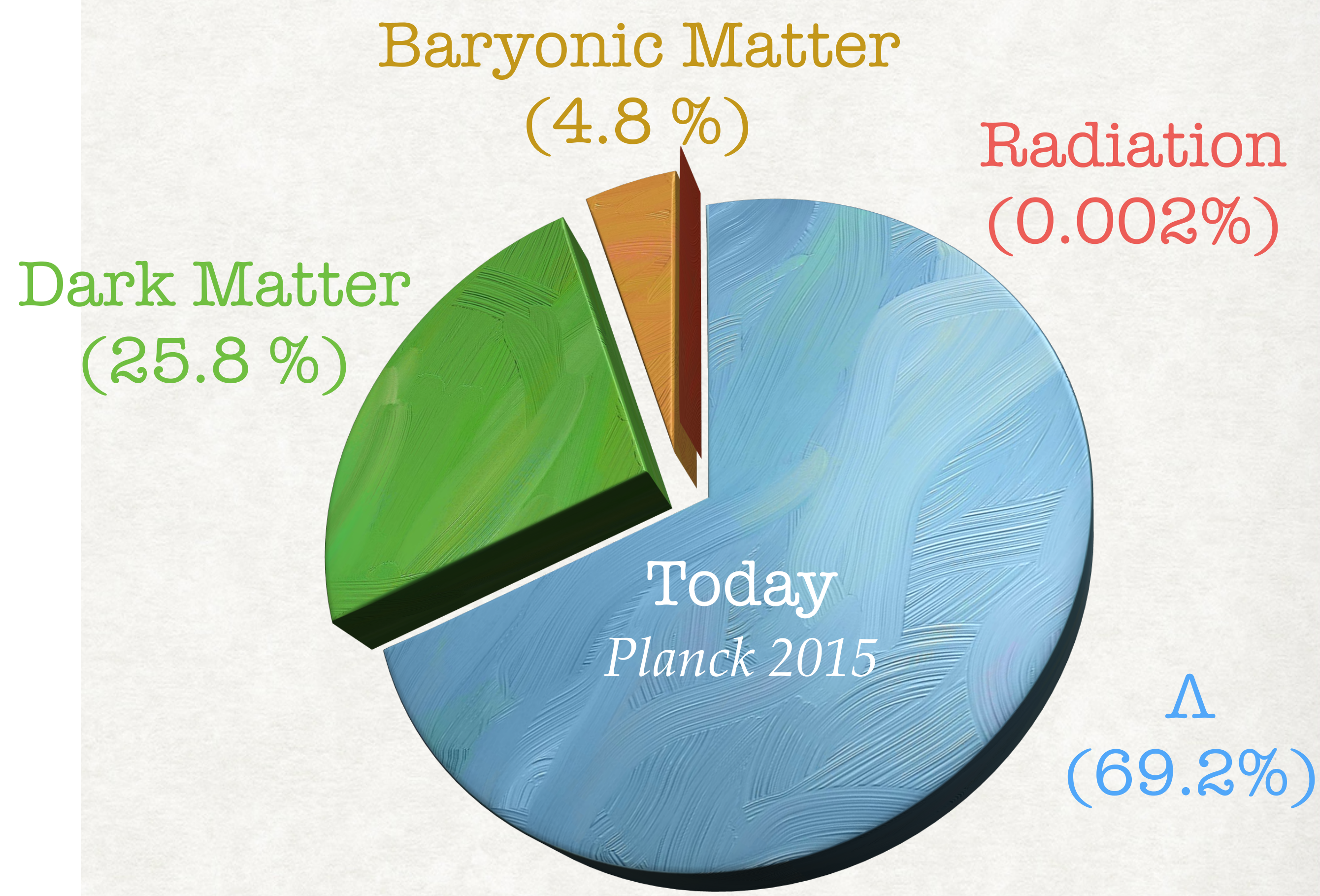
Minimal ΛCDM: $\{\omega_b,\ \omega_{cdm},\ h,\ A_s,\ n_s,\ z_{reio}\}$

Matter content   Inflation   Stars

Planck



Reproduced from Dodelson



DM is a pressure-less (cold) matter component, which interacts only via gravity.

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

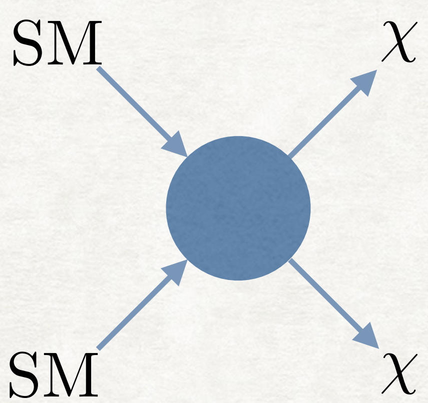
Most of its basic properties are unknown

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

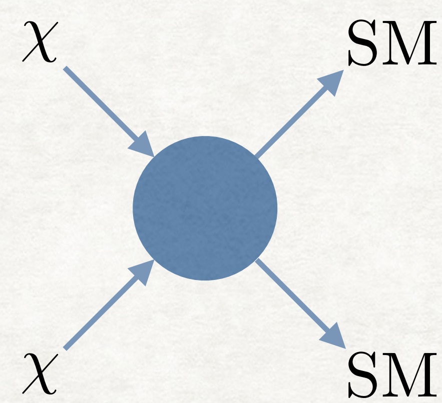
Searching for non-gravitational DM interaction

Most of our searches are motivated by the WIMP miracle

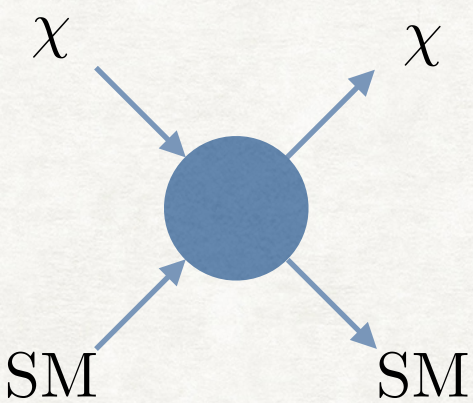
Production



Annihilation



Scattering



in particle physics

Collider | Indirect detection | Direct detection

in cosmology

Relic abundance | Energy injection | Momentum transfer

There are many other models that can be probed via cosmological observables!!
e.g. sterile neutrinos, Axions, Primordial Black Holes…

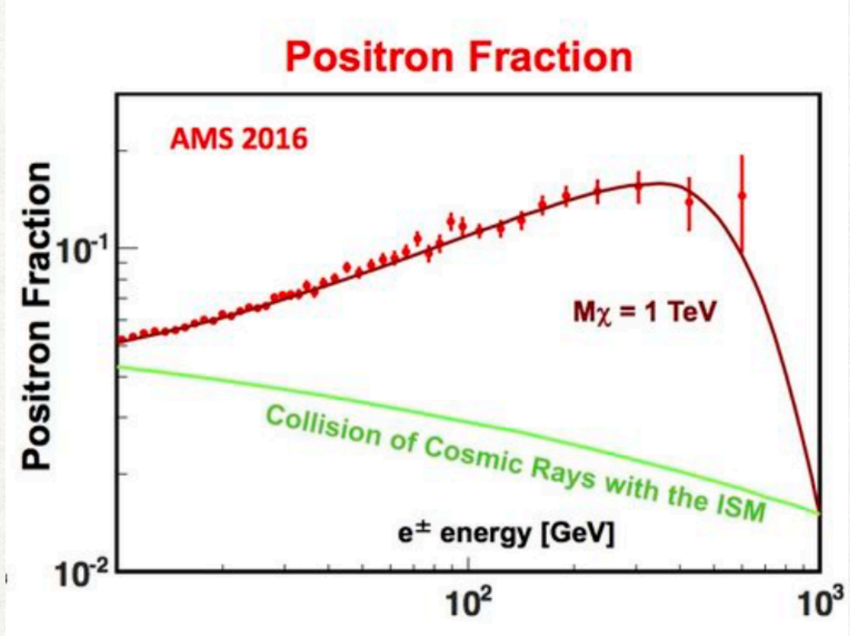
There have been many DM "discoveries"…

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*

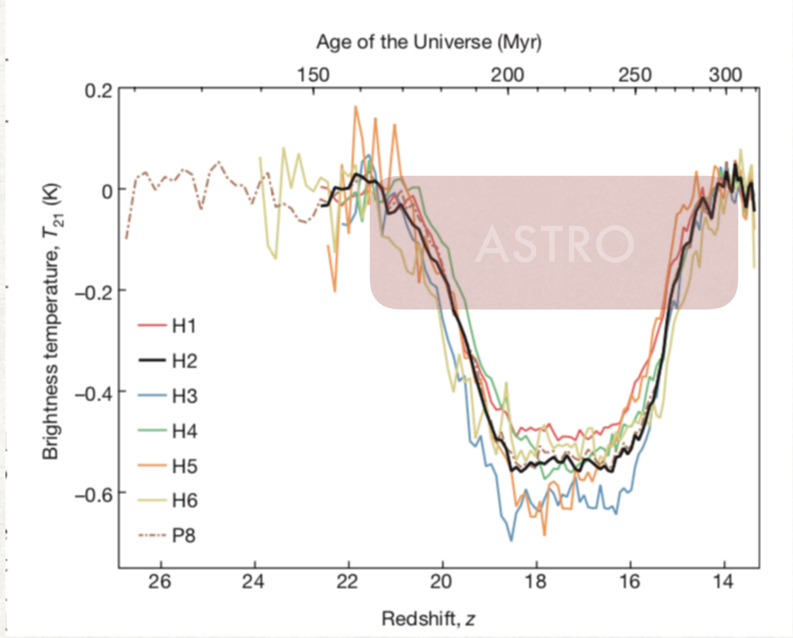
NEWS

AMS 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

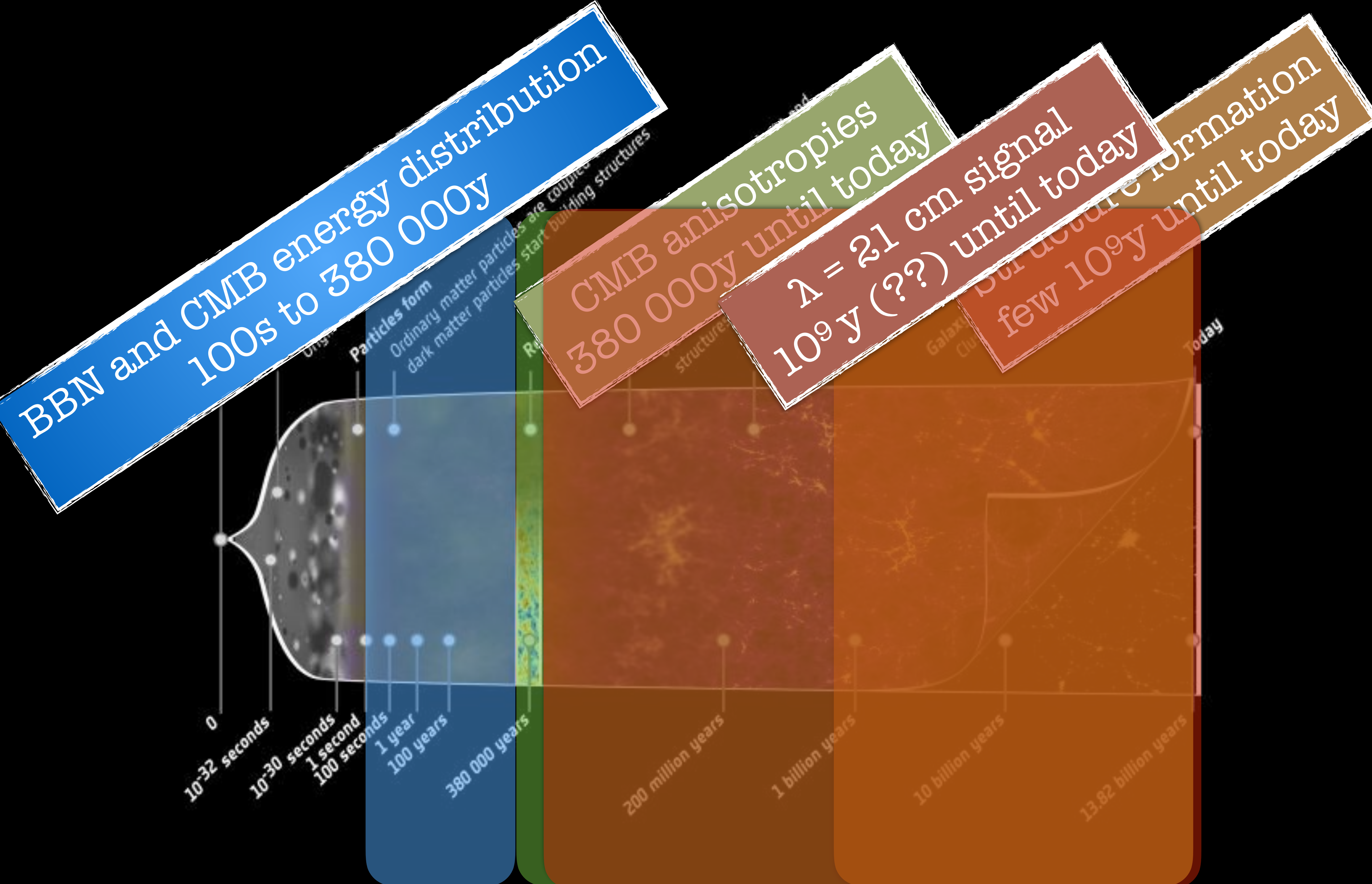
doi:10.1038/nature25791

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

Rennan Barkana[1]

These models can be constrained by cosmological observables

DM properties can be probed by many different observables



Summary

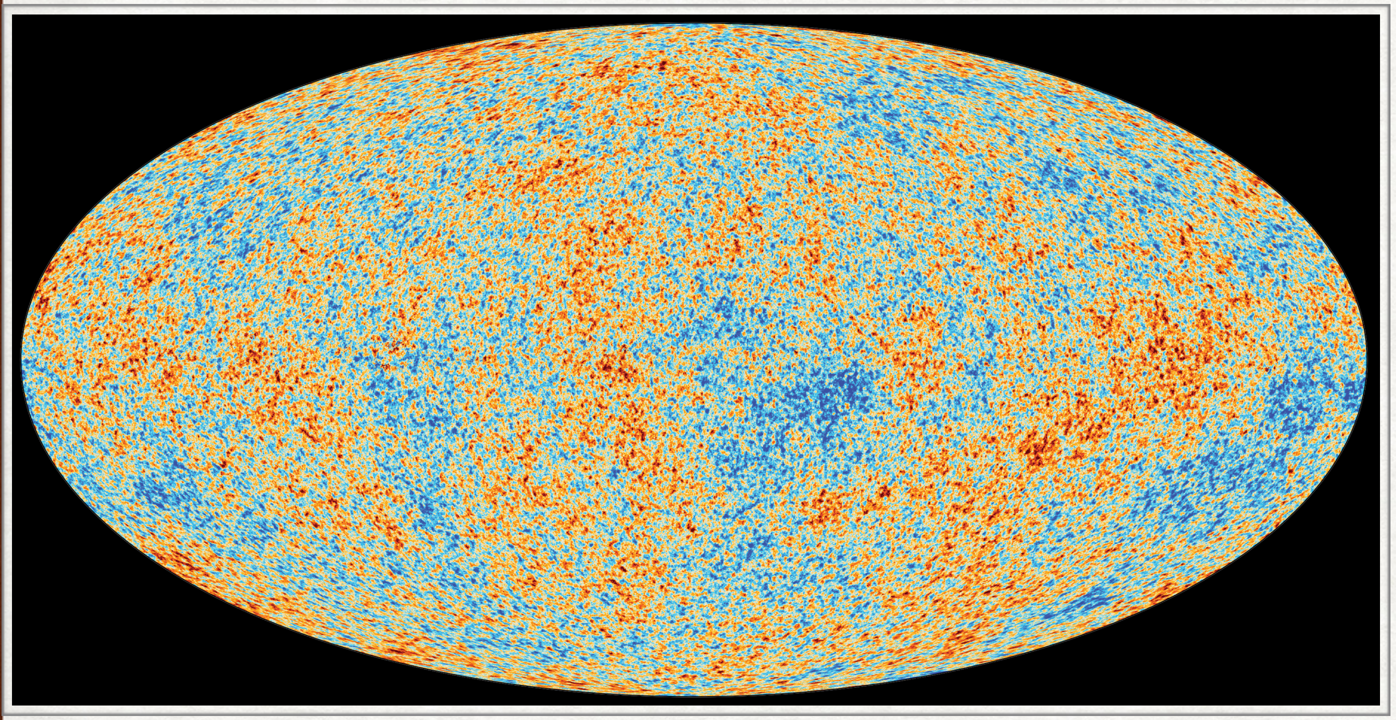
Today, I will discuss

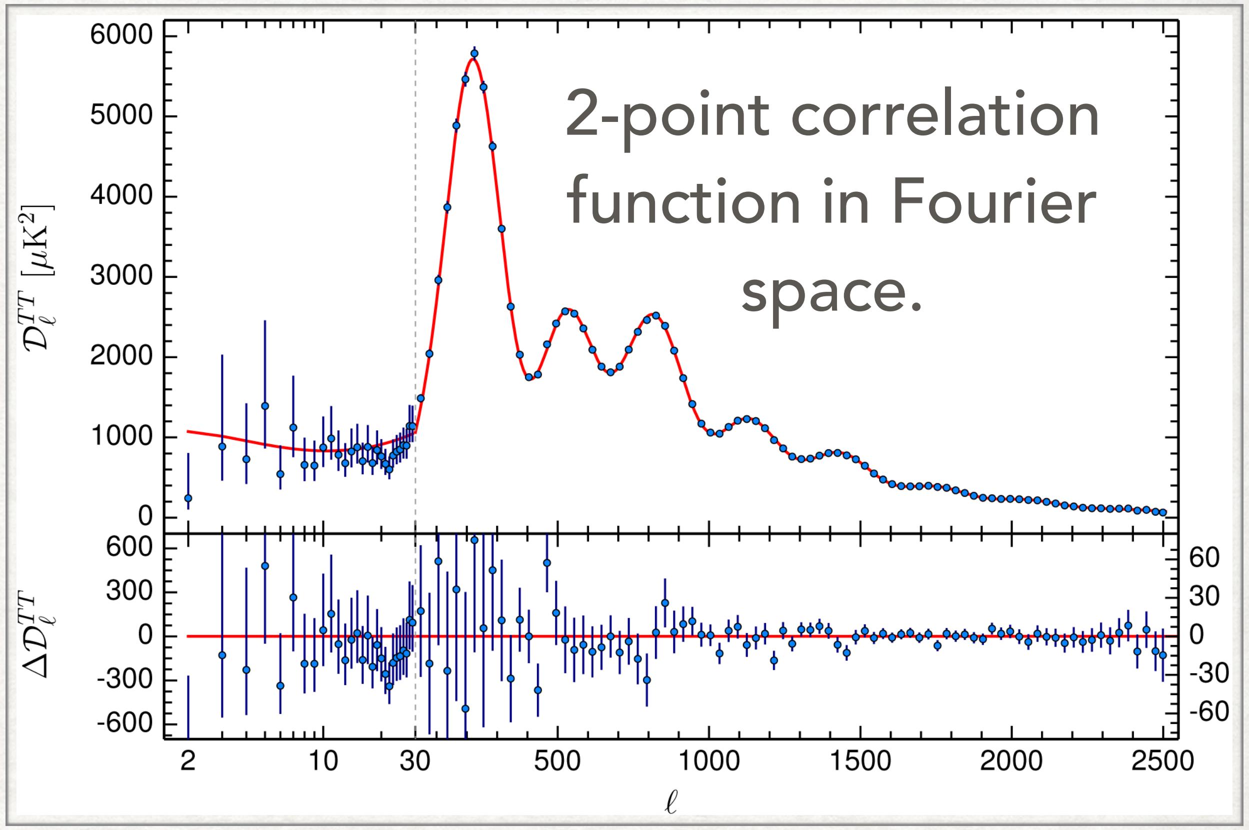
- Indirect Detection of Dark Matter with the CMB;
  - Comparison to other cosmological probes: BBN, SD.
  - Implications for cosmic and γ-ray excesses.

- DM-baryon scattering in cosmology:
  - Is there Dark Matter in EDGES data?
  - Constraints from the CMB.

Part I
Indirect detection in Cosmology

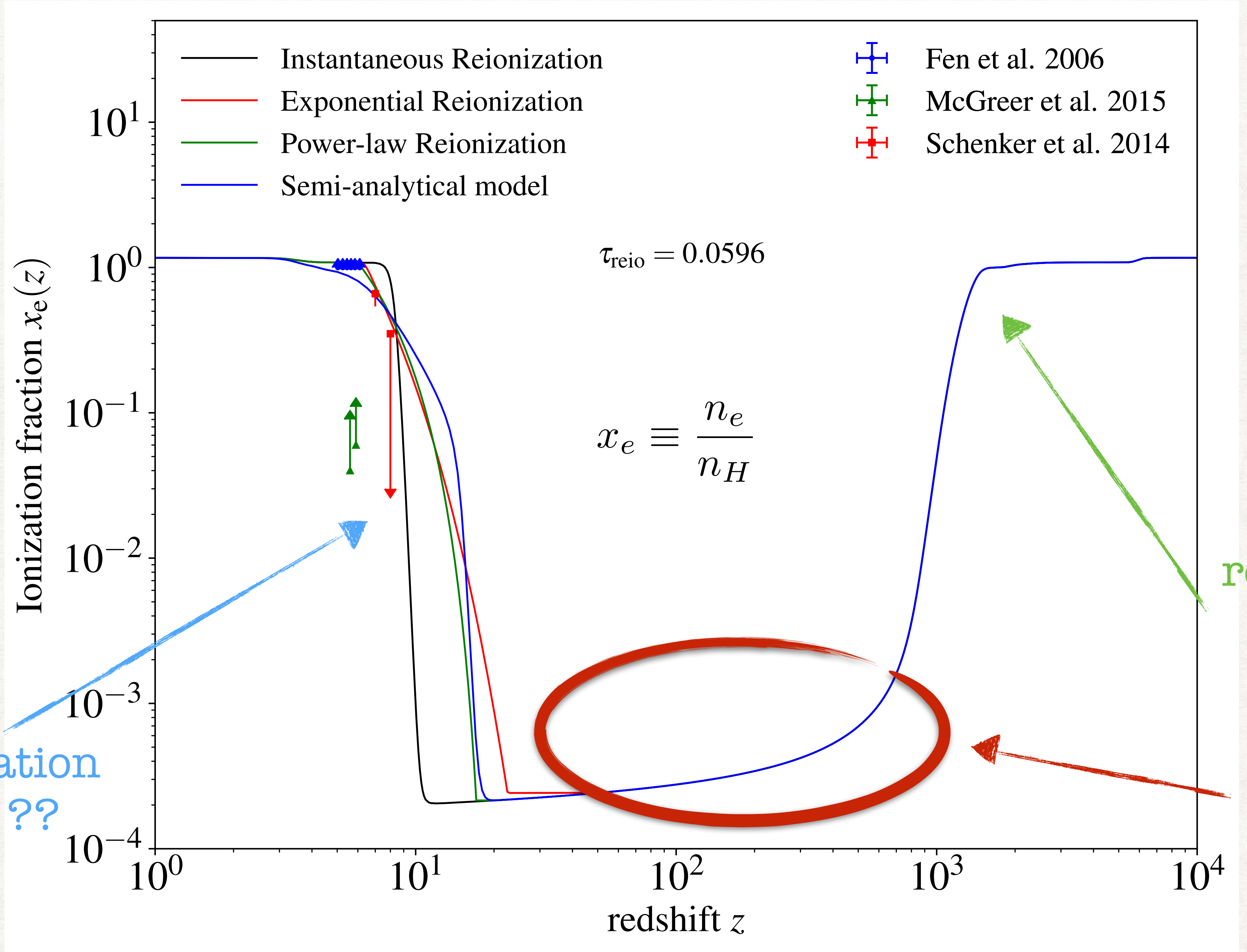
DM and the CMB in a nutshell





- Snapshot of inhomogeneities at photons last scattering around z ~ 1000, when free electrons and proton (re)combine.
- Most precise probe of the DM density — a **matter** component sensitive to gravity, , i.e. its energy density dilutes like $(1+z)^3$, but insensitive to the radiation pressure.
- The CMB is highly sensitive to the free electron density through Thomson scattering, which dictates the visibility function and the optical depth.
- Energy injection from DM affect the free electron density around/below recombination. This can change the thickness/time of last scattering and residual scattering.

The recombination history



recombination at z ≈ 1100

relic fraction of free e-

reionization at z ≈ ??

Back of the envelope estimate of constraints

- Energy injection can ionize (or heat) the medium, but x_e at z~1000 measured at % level.
- Consider annihilation of m_{DM}=1 GeV - what is the constraint on the number density of annihilated/decayed CMB?
- i) how many ionizations per photon:1 GeV / 13.6 eV ~ 10^{8}.
- ii) how many DM compared to baryons: $n_{DM} = 5 * n_b$ for m_{DM} = 1 GeV.

  ==> if 1/5th* 10^{-8} of the DM decays ALL of the baryons would be re-ionized…
- iii) fraction of annihilating/decaying particles can reach f<~ 0.01/5/10^8~10^{-11}!
- Complication: Electromagnetic cascade in an "optically thin" plasma. Most of the photons propagate freely and could be visible as extra-galactic background light.

Slatyer, PRD93 2016

Numerical tool: ExoCLASS

https://github.com/lesgourg/class_public/

*Stoecker, Lesgourgues, Kramer, **VP**, JCAP 0318*

- Key quantity to estimate: the energy deposited into ionization/heat

$$\left.\frac{dE}{dVdt}\right|_{\mathrm{dep,c}} = f_c(z)\left.\frac{dE}{dVdt}\right|_{\mathrm{inj}}$$

Plasma Properties Particle/Astro-Physics

- an energy injection history $dE/dVdt_{inj}$. currently implemented: DM s-wave annihilations, decay, Primordial Black Hole evaporation and matter accretion.

- "energy deposition function per channel" $f_c(z)$: From a spectra of injected electrons and photons, compute the response of the plasma.

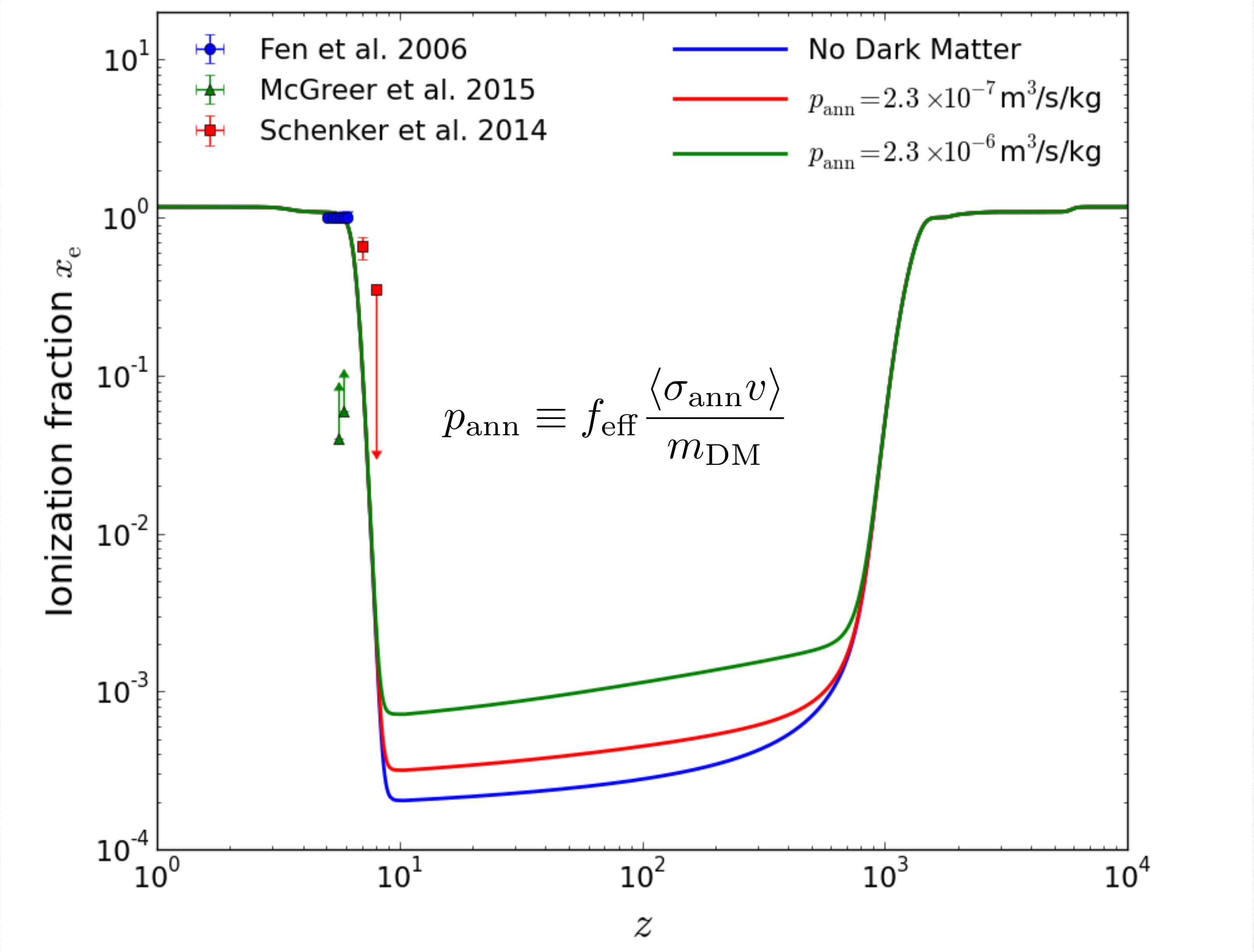
Slatyer, PRD93 2016

- Soon: DarkHistory developed by H. Liu, G. Rigdway and T. Slatyer (MIT);
  Global 21cm with E. Kovetz and B. Wang (JHU);
  DM-b scattering by K. Boddy (JHU);

DM annihilations

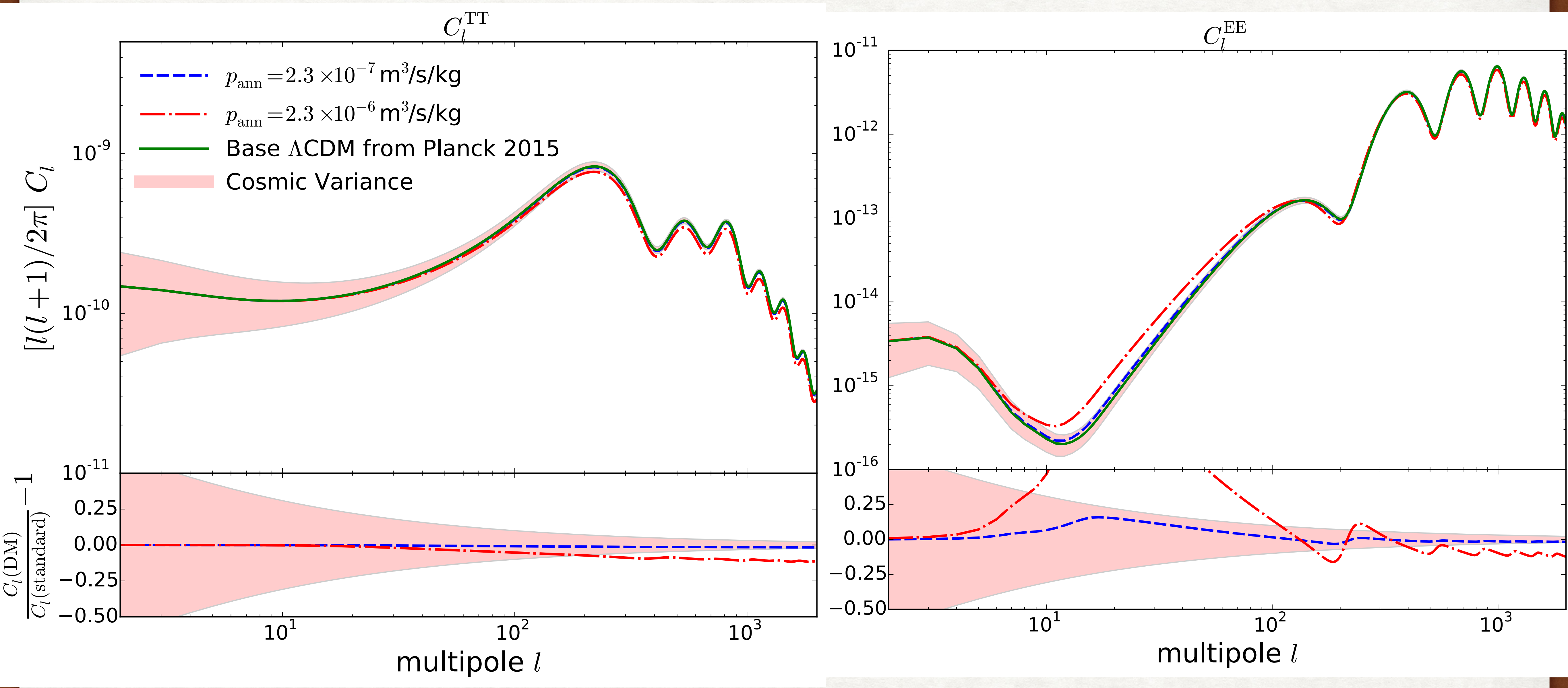
*e.g. Belikov++ PRD80 (2009), Cirelli++ JCAP (2009), Slatyer, PRD 2015; **VP**, Lesgourgues, Serpico JCAP 2015*

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



CMB power spectra

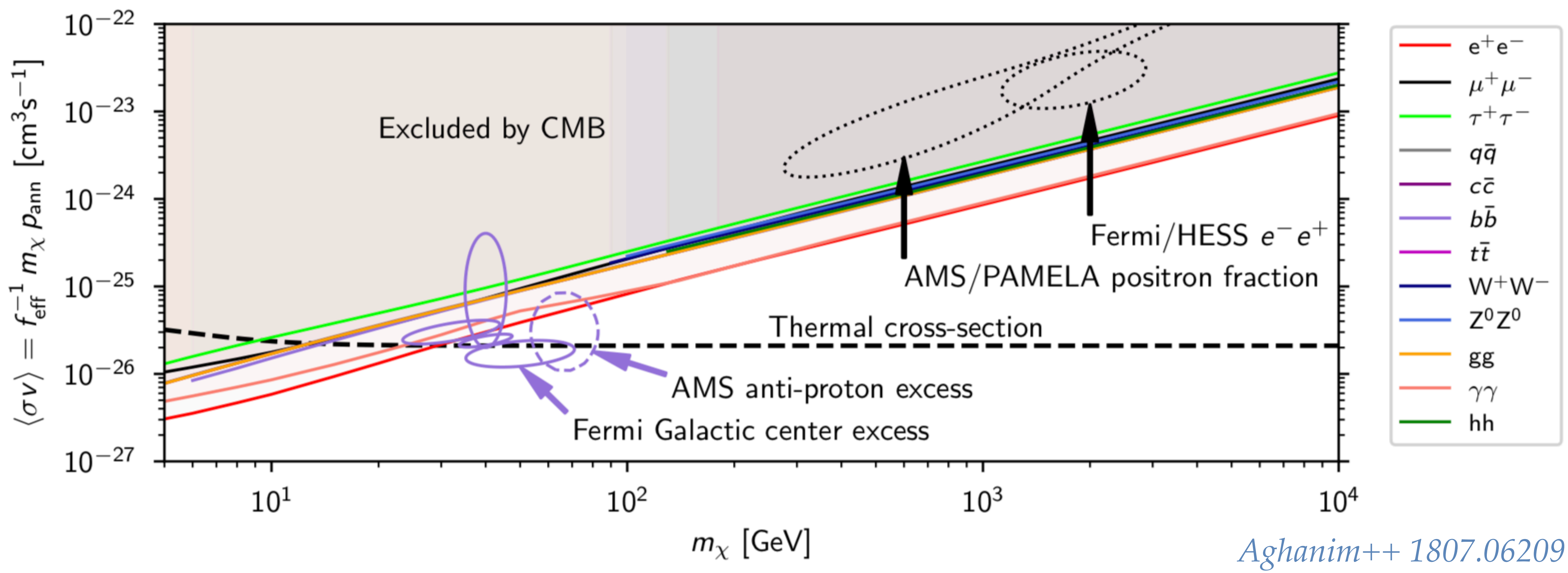
VP, Lesgourgues, Serpico JCAP 2015



- Recombination delay: shifts of the peak, more diffusion damping.
- Higher freeze-out plateau: reionization bump higher, higher optical depth.

Planck 2018 results

Computed by J. Lesgourgues for Planck 2018 data release using ExoCLASS



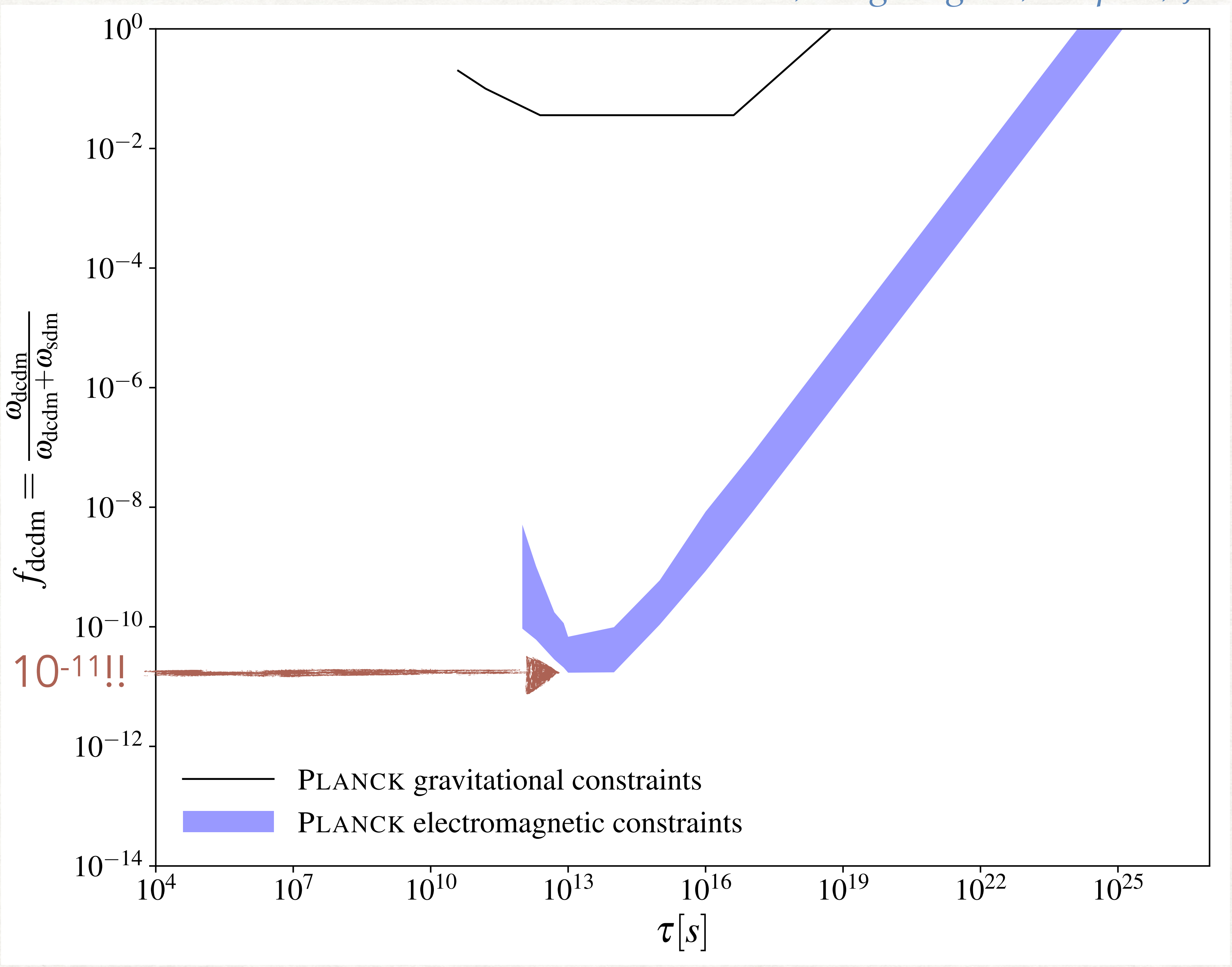
Aghanim++ 1807.06209

- 17% improvement since 2015 essentially thanks to polarization.
- Exclude thermal relics 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).

Constraints on decaying particles

DM = 1 stable + 1 unstable particle

VP, Lesgourgues, Serpico; JCAP (2016 & 2017)

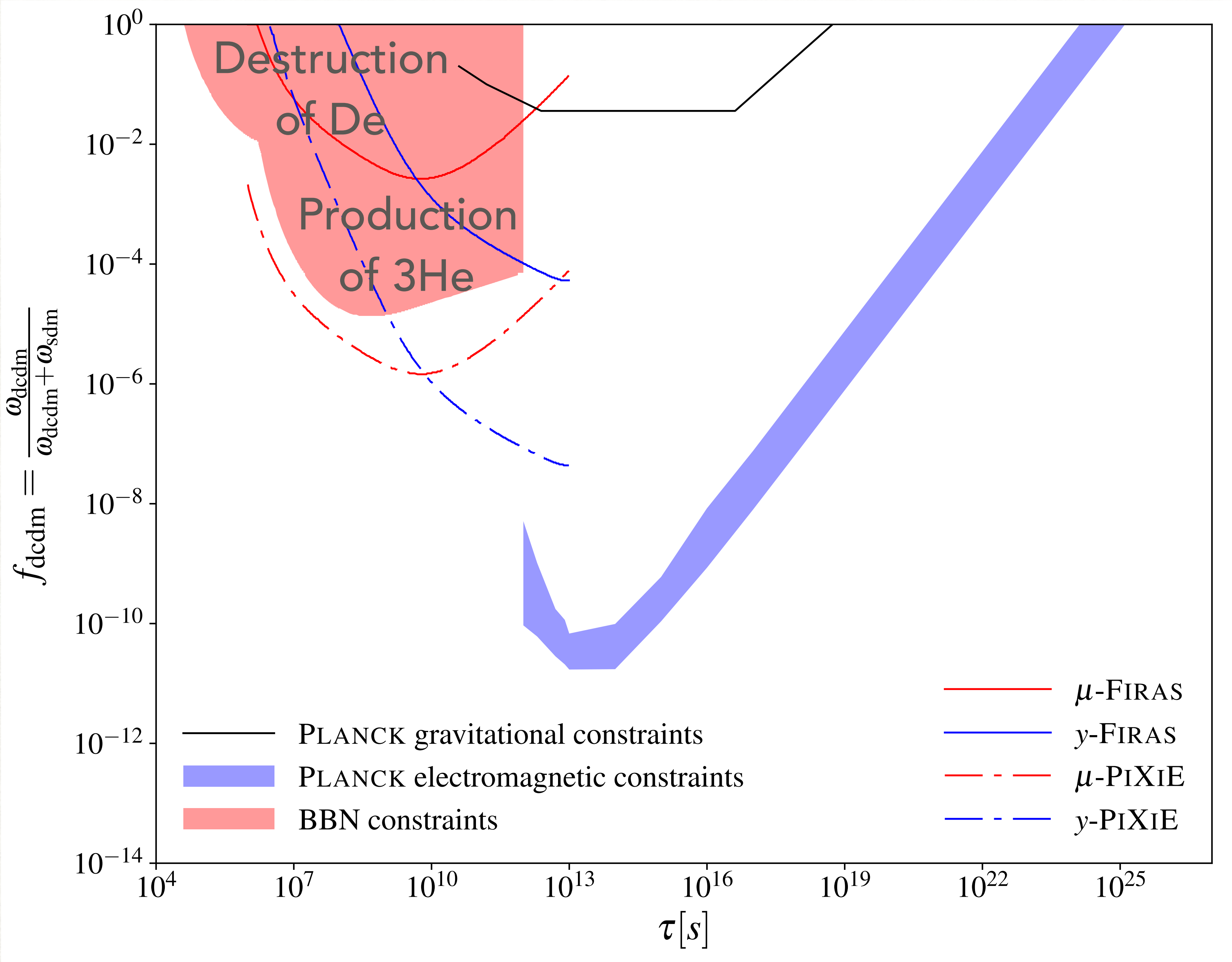


- Blue band: reflects difference between energy deposition efficiency.
- Results are reliable for m_χ in $[10^3, 10^{12}]$ eV whatever decay channel !

Constraints on decaying particles

DM = 1 stable + 1 unstable particle

VP&Serpico; PRD (2016)



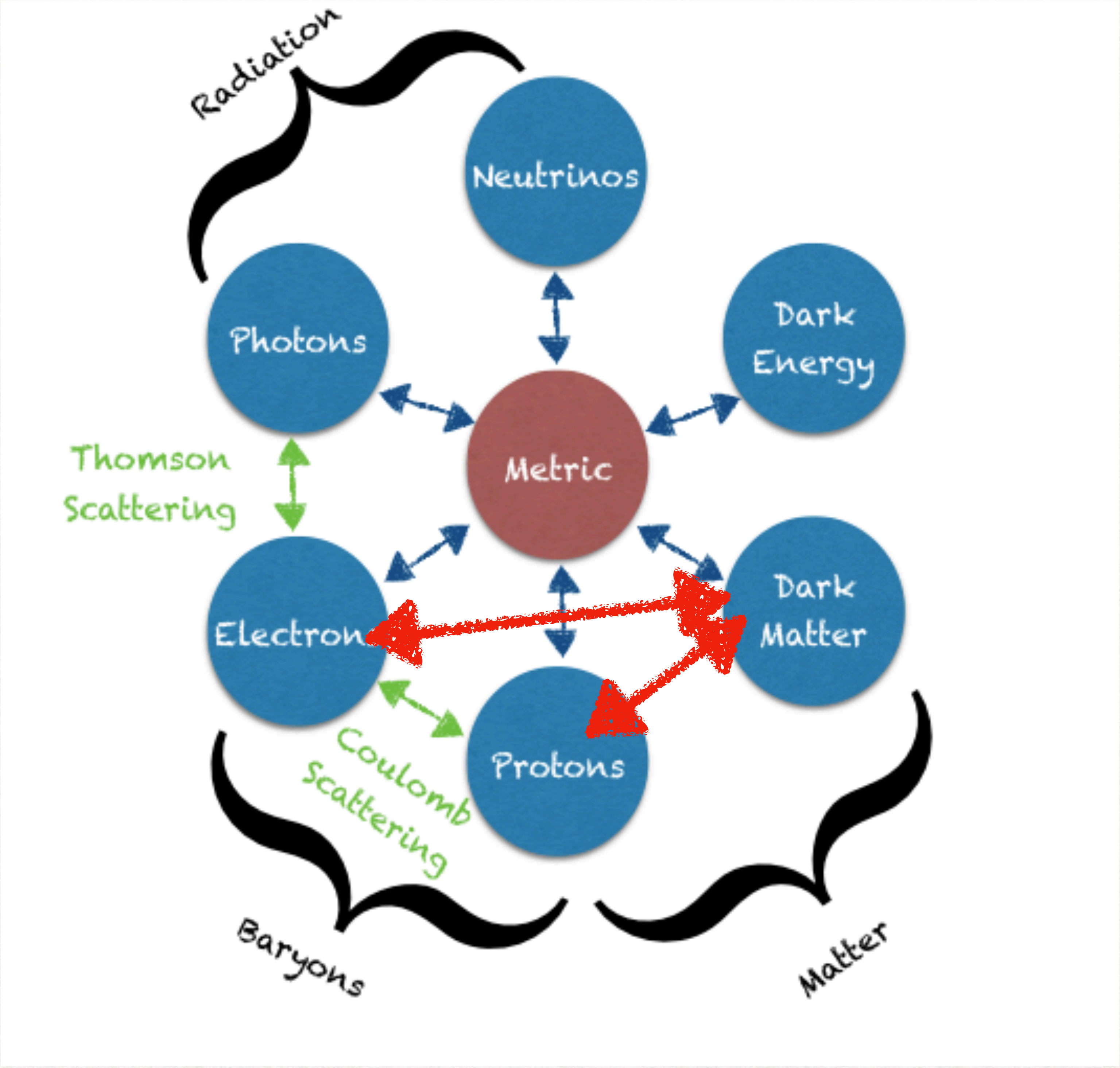
- At short lifetimes: BBN provides the strongest constraints.
- Spectral distortions could be a major probe in the future.

PART II

DIRECT DETECTION WITH THE CMB: IMPLICATIONS FOR EDGES

Direct Detection in Cosmology

- CMB/21cm is sensitive to momentum and heat transfer between DM and baryons.



Why care about the CMB?

Boddy & Gluscevic, 1712.07133, 1801.08609

Studying DM-baryon scattering in the early universe is complementary to standard Direct Detection.

- CMB can be used to study the most common non-relativistic EFT operators
- CMB bounds extend (at least) down to keV mass-scale (typical bound for a thermal, warm DM).
- CMB can probe "hadronic" cross-sections for which DD experiment are insensitive due to earth shielding. *e.g. Hooper&McDermott 2018*
- CMB bounds do not rely on knowledge of local halo properties.

We study DM-p interaction and parametrize $\sigma(v) = \sigma_0(v/c)^n$

Consider $\sigma(v) = \sigma_0(v/c)^n$

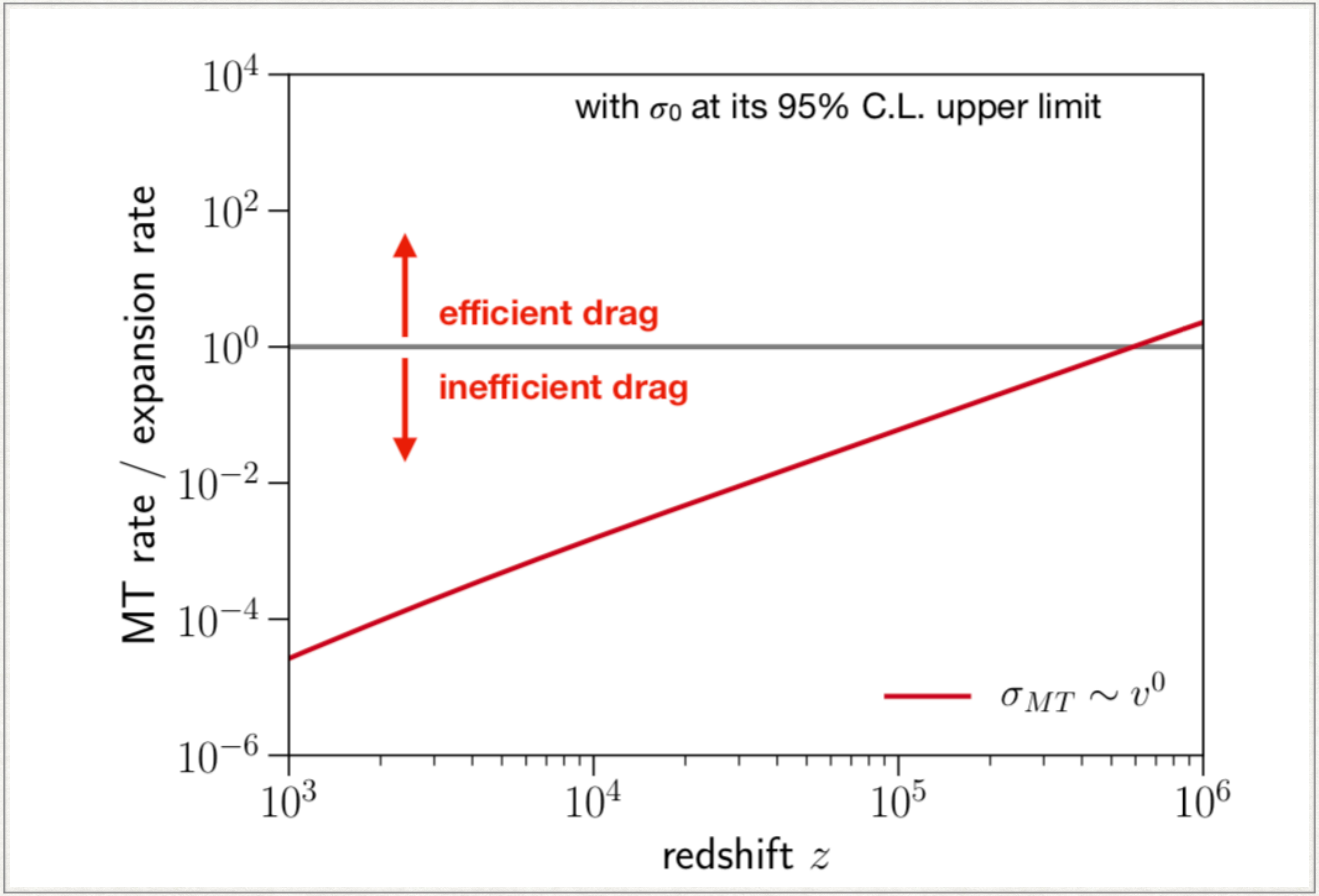


Figure by K. Boddy (JHU)

Consider $\sigma(v) = \sigma_0(v/c)^n$

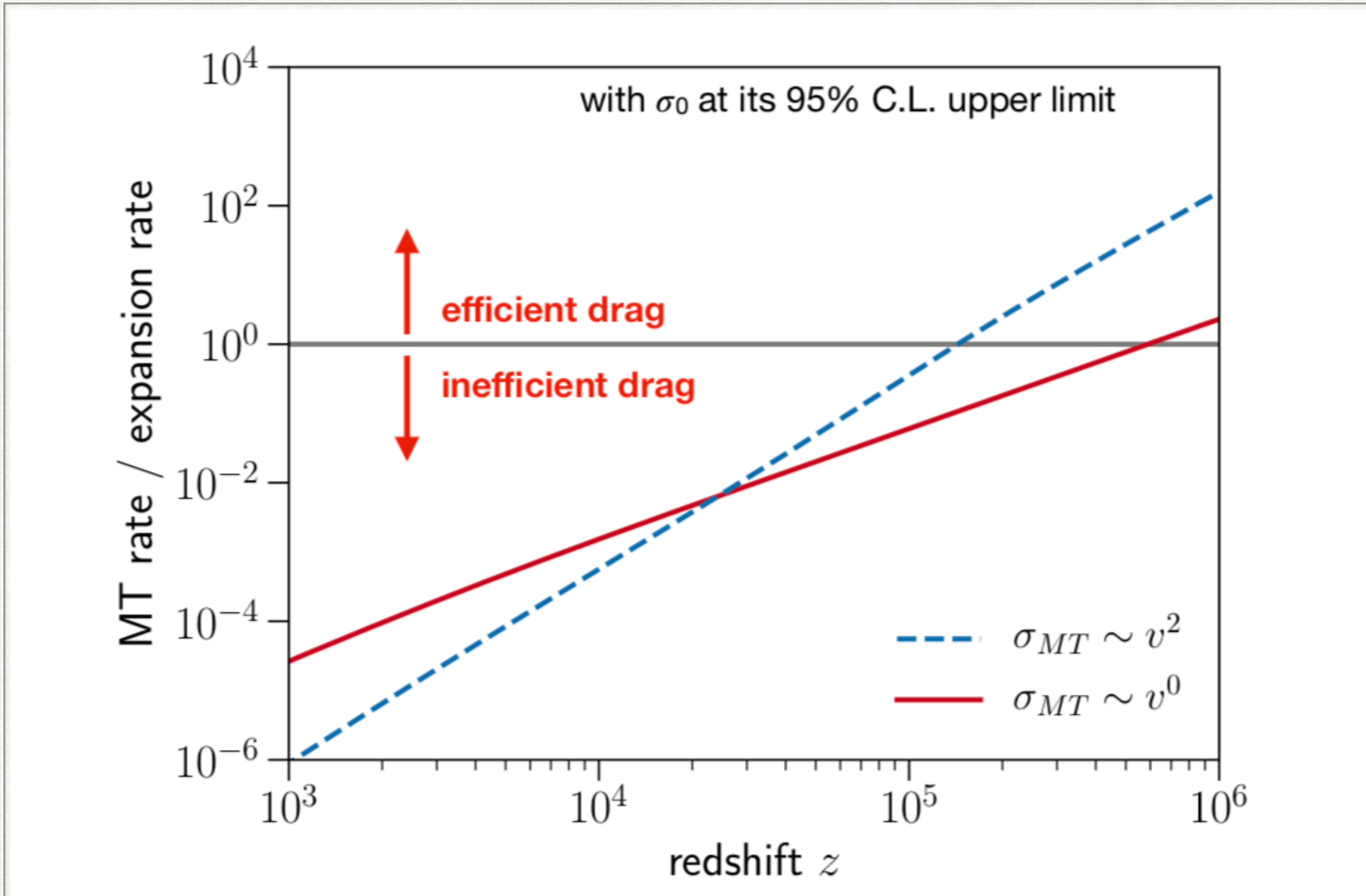


Figure by K. Boddy (JHU)

Consider $\sigma(v) = \sigma_0(v/c)^n$

What have we learned? MT is constrained to be < 1% at z = 30000!

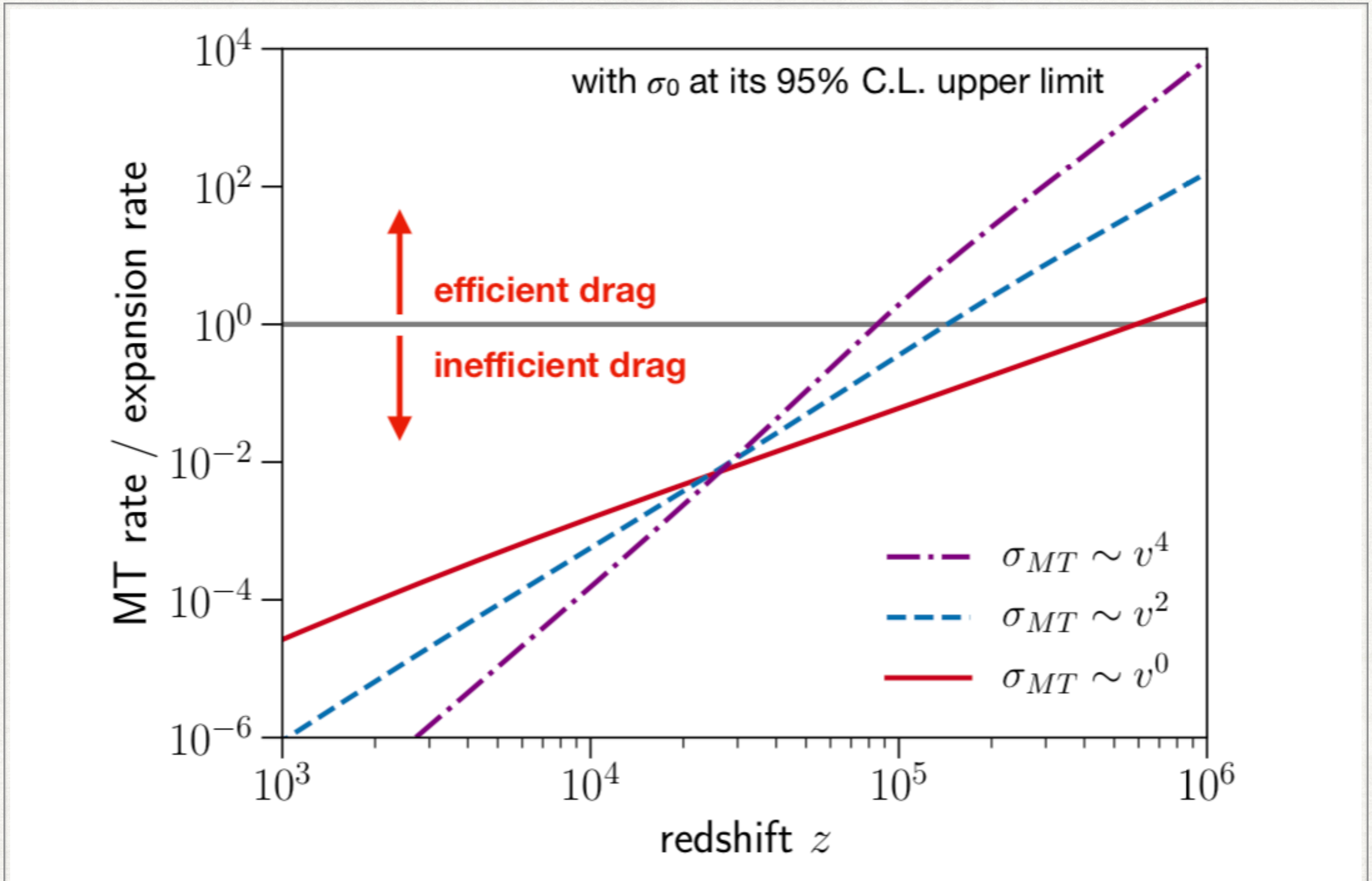
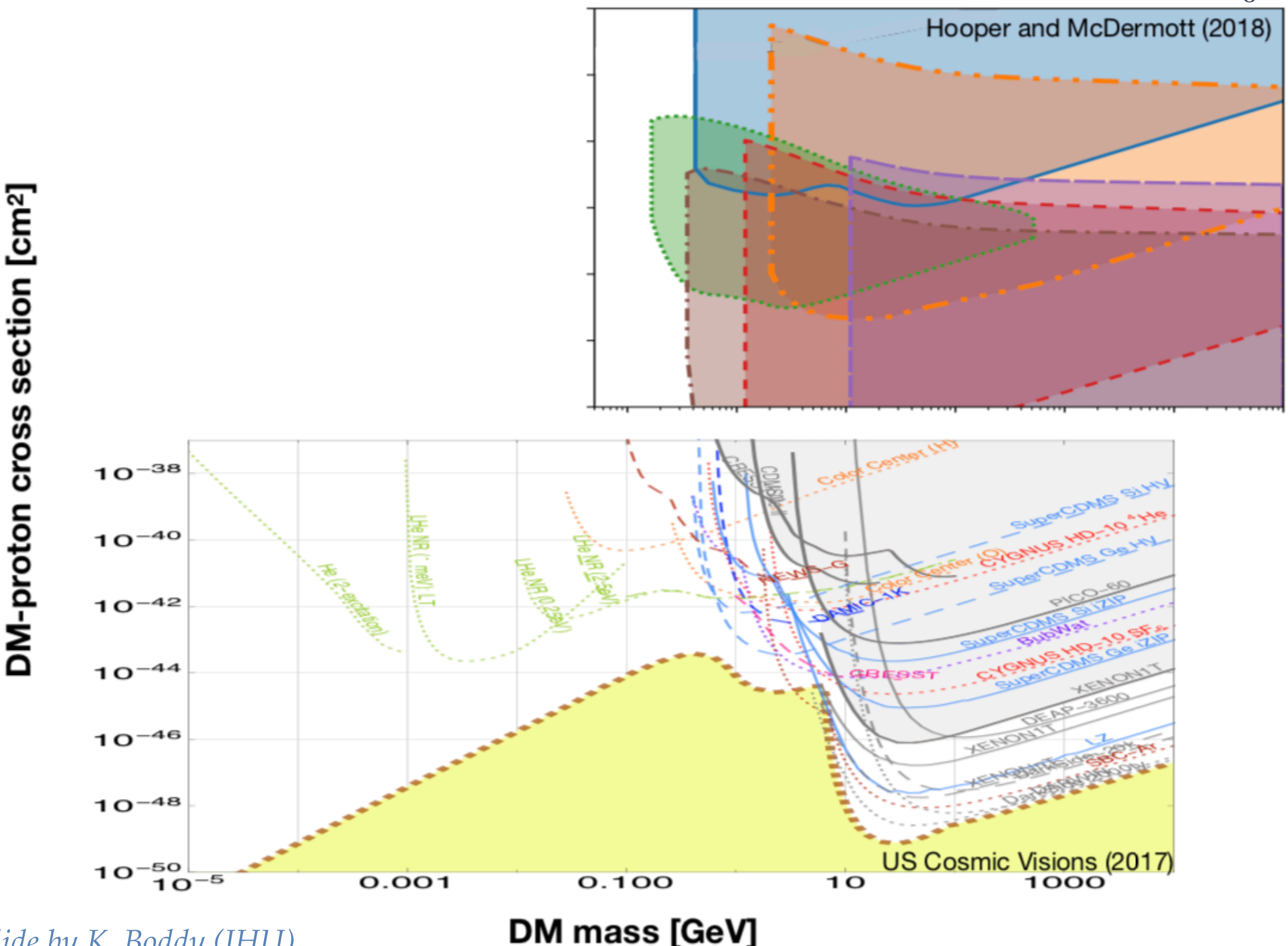
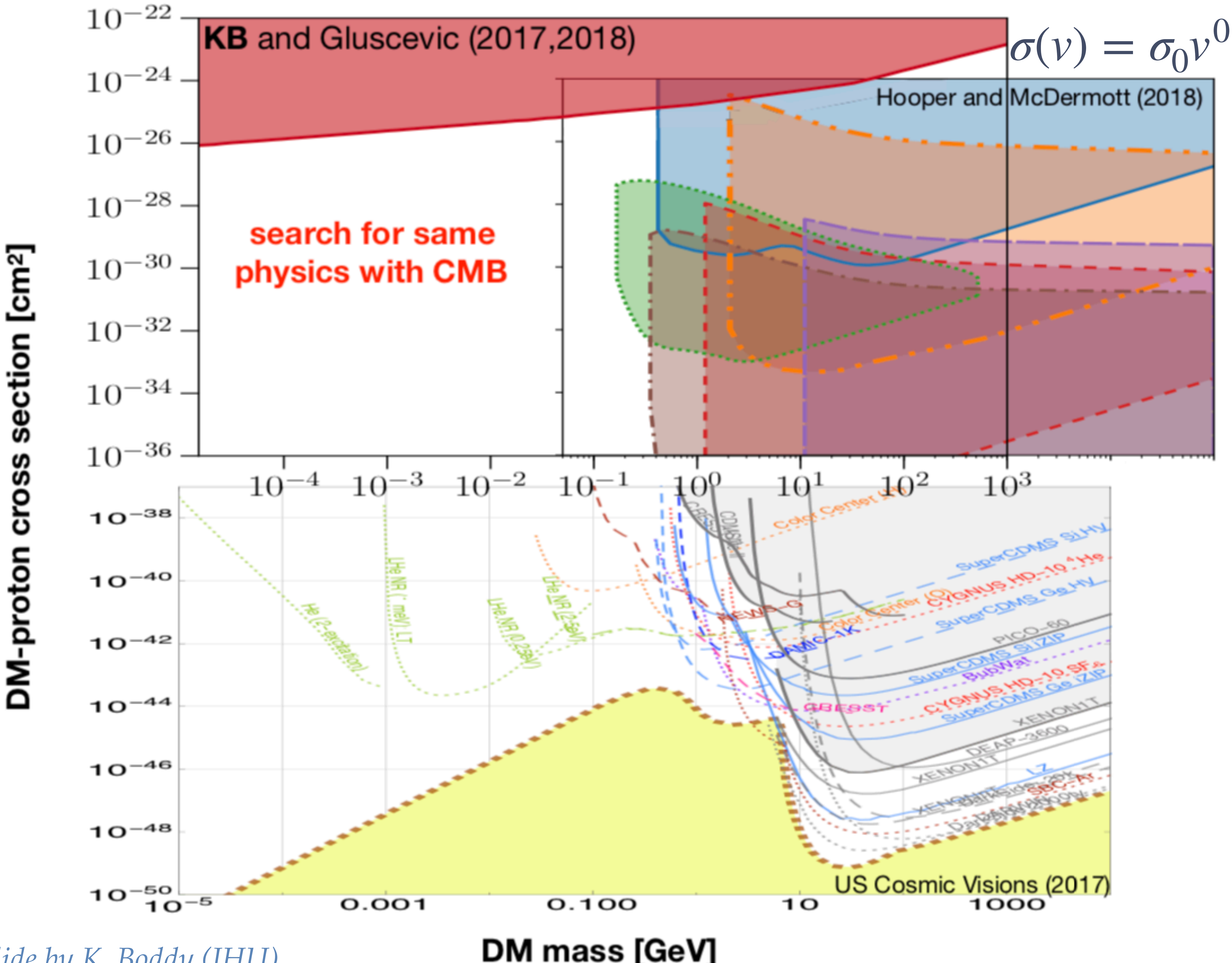


Figure by K. Boddy (JHU)

$$\sigma(v) = \sigma_0 v^0$$



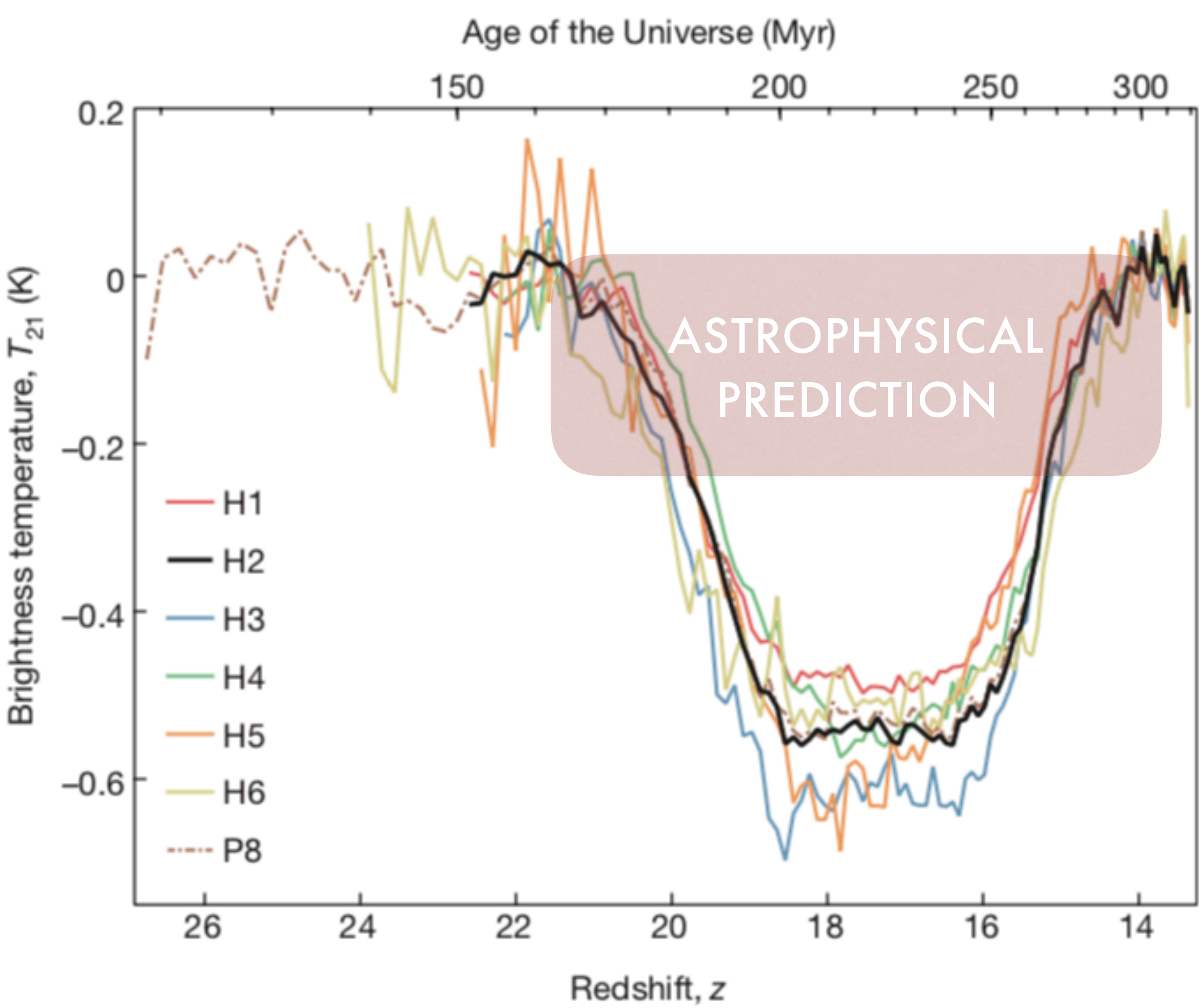
Slide by K. Boddy (JHU)



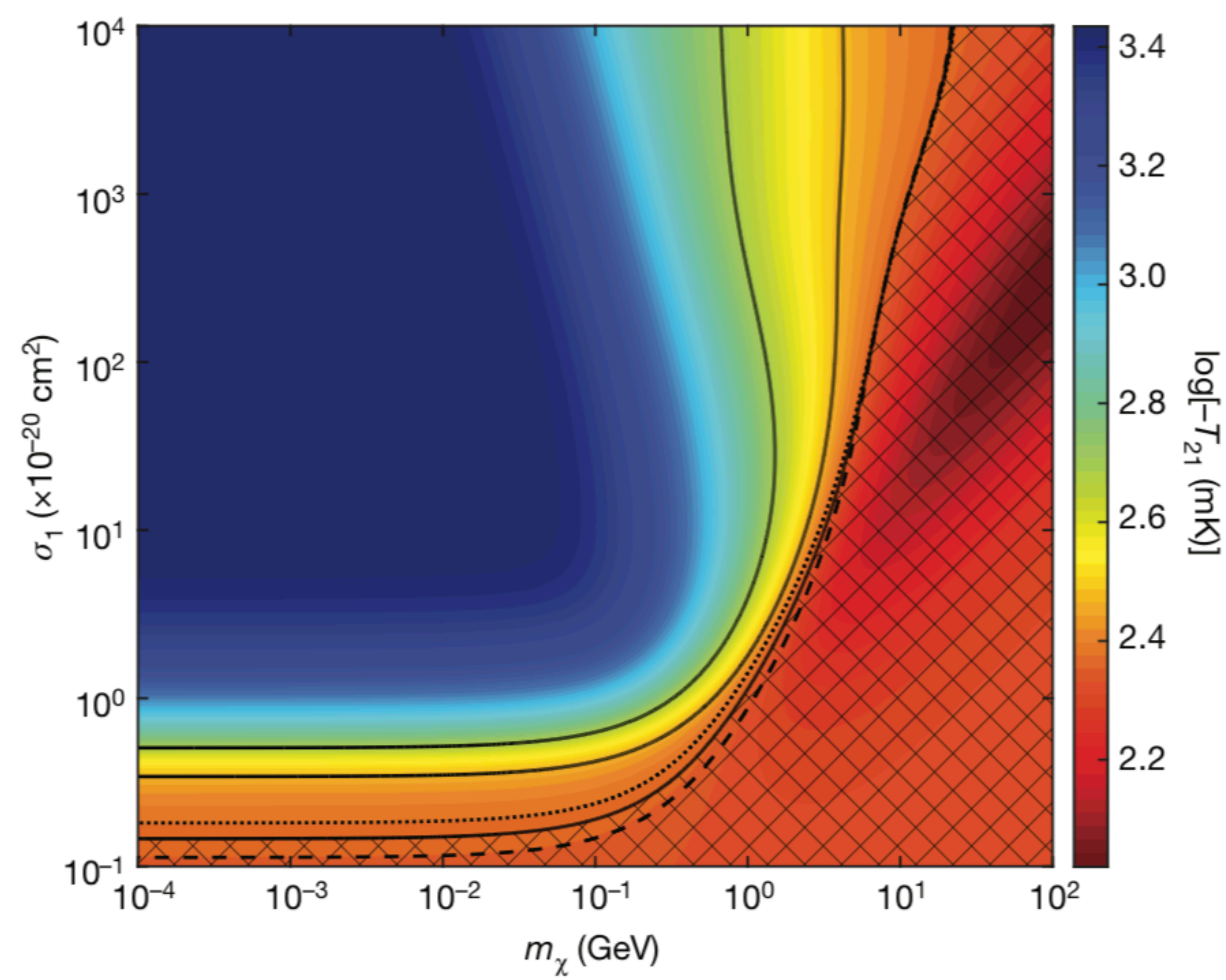
Slide by K. Boddy (JHU)

Is there Dark Matter in EDGES data?

Bowman++, nature25792



Barkana, nature25791



- EDGES has discovered an anomalous global 21cm absorption signal.
- Dark Matter cooling down baryons might be an explanation.
- Strong constraints on such models in particular from the CMB!

Global 21cm in a Nutshell

Spin Temperature

$$\frac{n_1}{n_0} = 3e^{-E_{10}/k_B T_S}$$

$$T_S^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

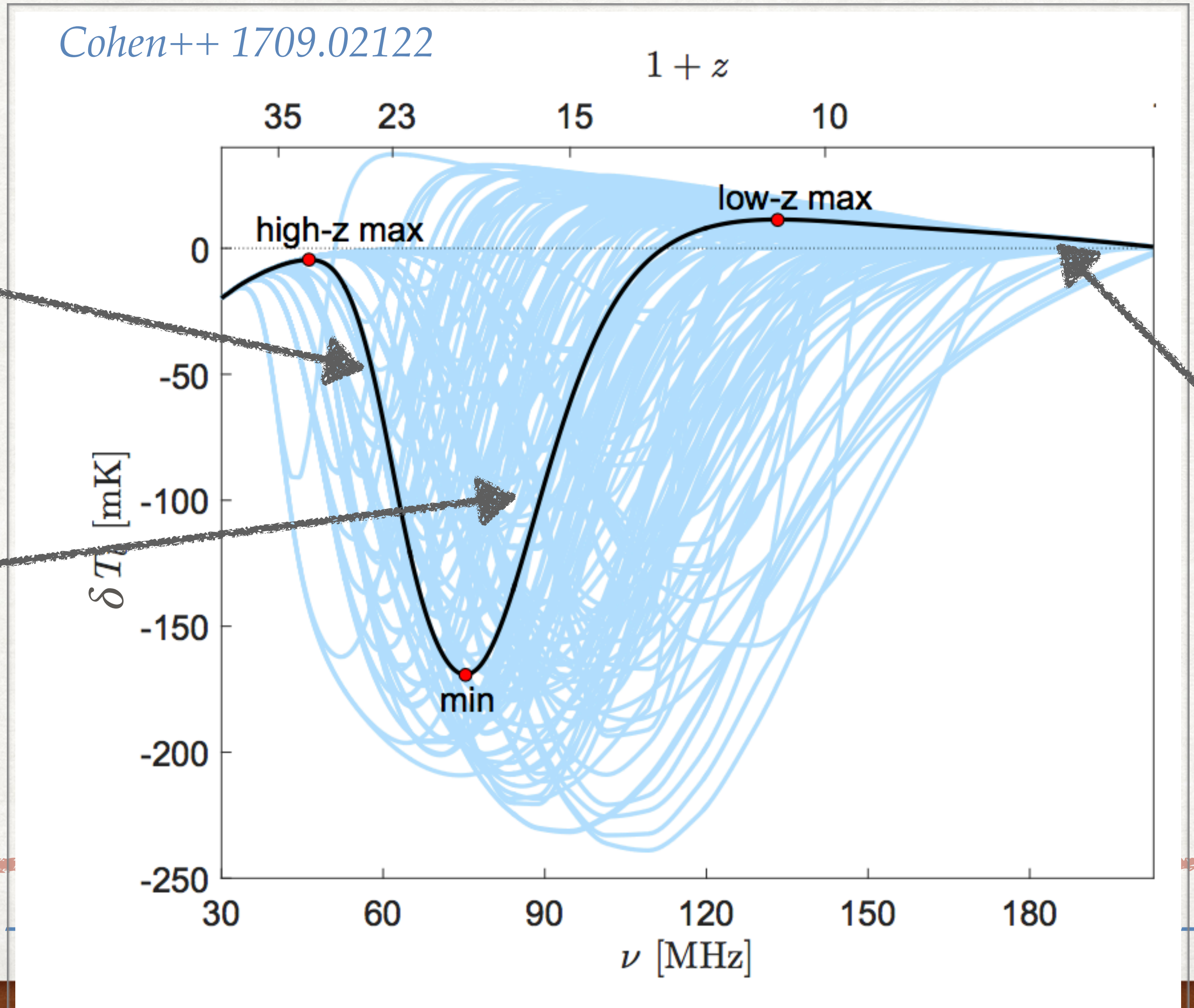
$$\delta T_b \propto n_H \left(1 - \frac{T_\gamma}{T_s}\right)$$

scattering with CMB   collision within the gas   interaction with UV from stars

- 21cm theoretically "easy" from z~1000 to 30; then huge astrophysical uncertainty.

First stars
Lyman-∝

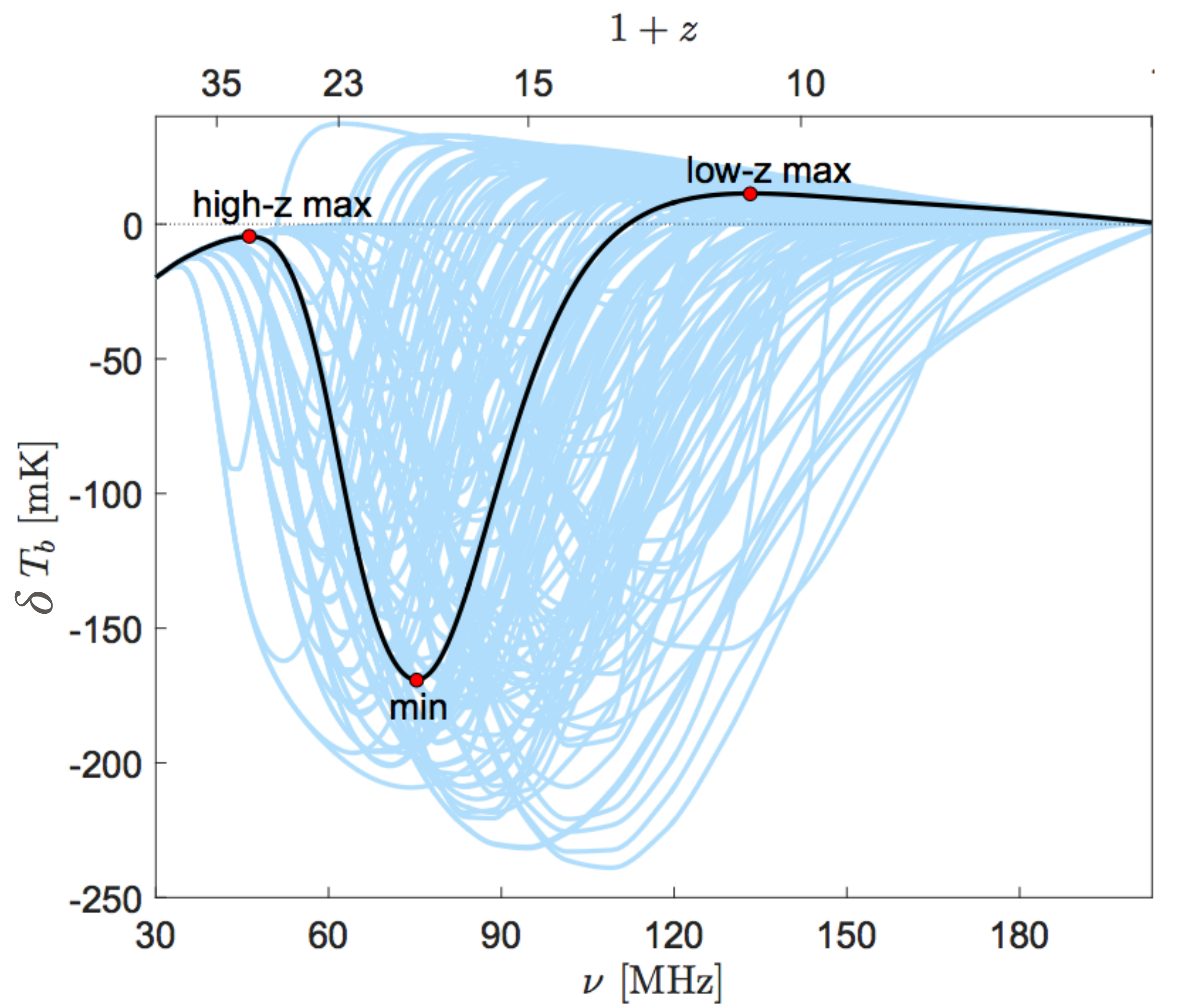
X-ray
(SN, X-ray binary,
quasars?)



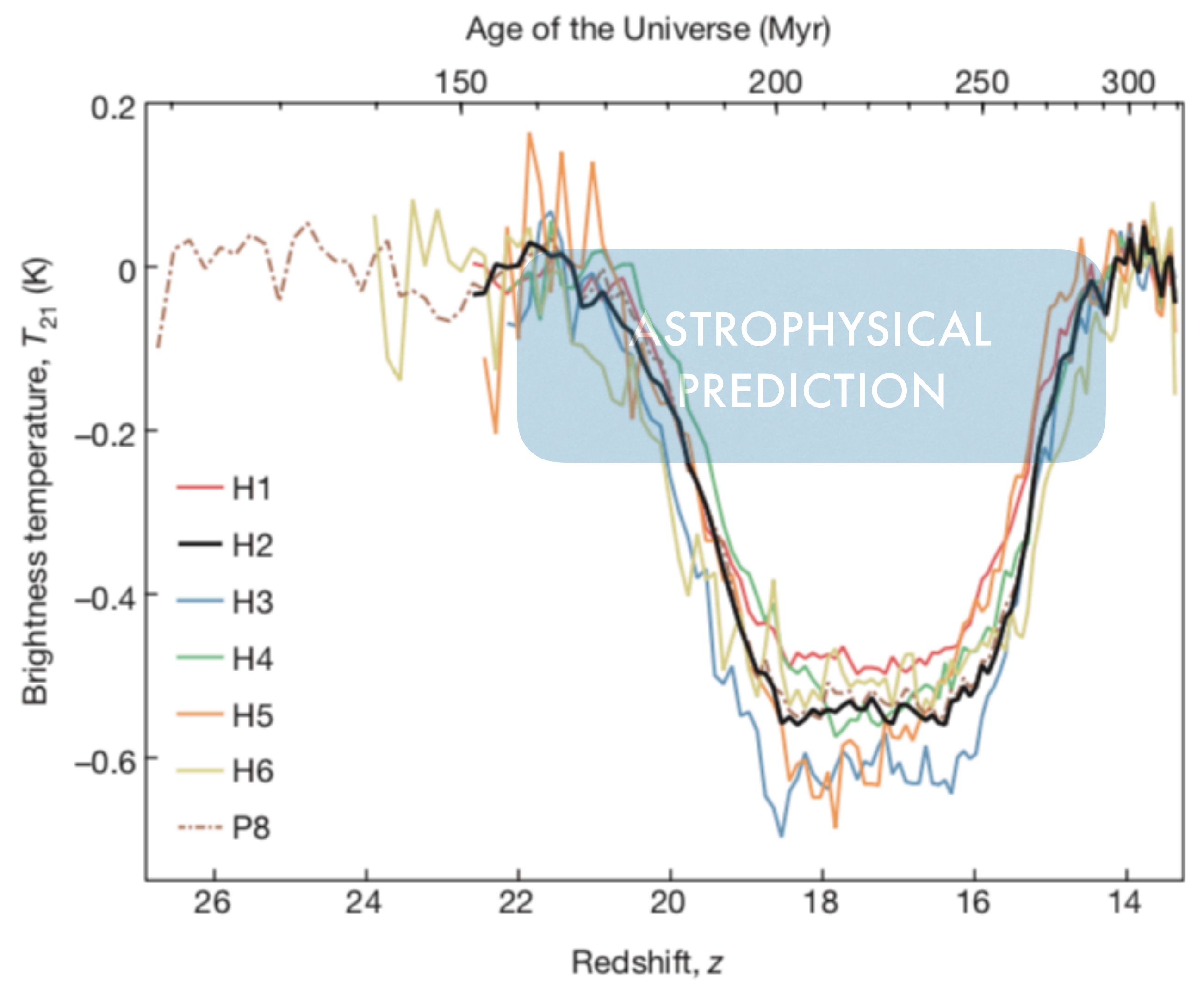
Ionization
(stars? quasars?
DM?)

Is everything "wrong" about EDGES?

Cohen++ 1709.02122



Bowman++, nature25792



1. Too strong absorption
2. Too sharp downward transition
3. Flat (?!)

If true, explaining EDGES might require both weird DM and Astrophysics!

How can we explain the signal?

- First, it could be a "false" signal:

i) Foreground: to extract the signal (~mK level) need to remove synchrotron (1000 K level)

ii) Instrument: systematics associated to the beam/data taking could affect the signal.

Hills++ 1805.01421, Bradley++ 1810.09015

- If we assume the signal to be real, what could it tell us:

$$\delta T_b \propto \left(1 - \frac{T_\gamma}{T_s}\right)$$

i) $T_\gamma \neq T_{cmb}$ could be higher: i.e. higher number of photons in the frequency range measured by EDGES. Potential link with the ARCADE2 excess.

Feng ++ 1802.07432, Fraser++1803.03245, Pospelov++ 1803.07048

ii) T_s could be smaller: minimal Ts=Tb, hence it would indicate a lower Tb.
Early decoupling? e.g. early dark energy (excluded by CMB).
DM-b scattering?

Barkana, nature25791, Munoz&Loeb 1802.10094, Hill&Baxter 1803.07555

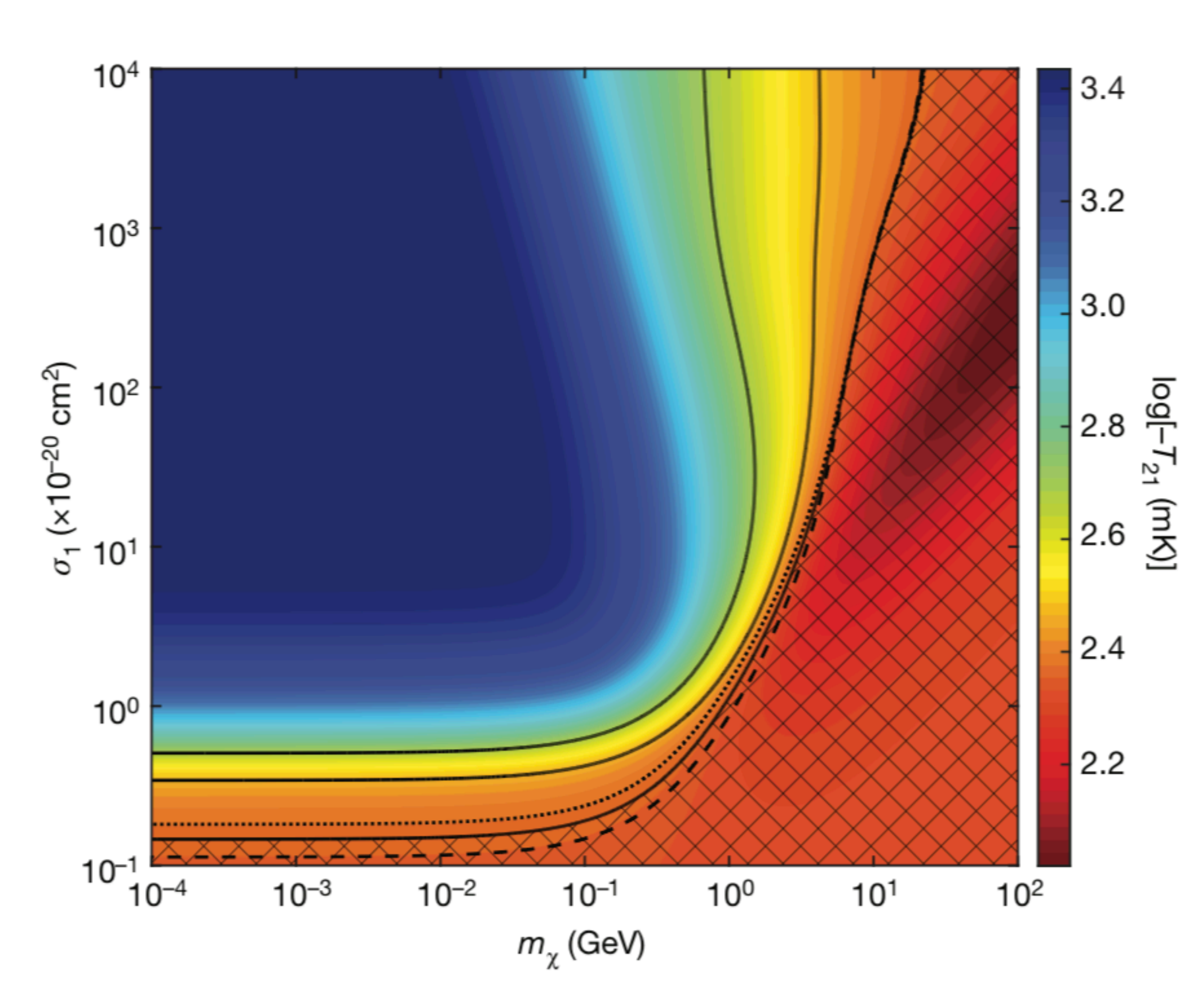
If true, many interesting consequences for astrophysics, dark matter, axions…!

Ewall-Wice++ 1803.01815, Kaurov++1805.03254, Slatyer&Liu 1803.09739

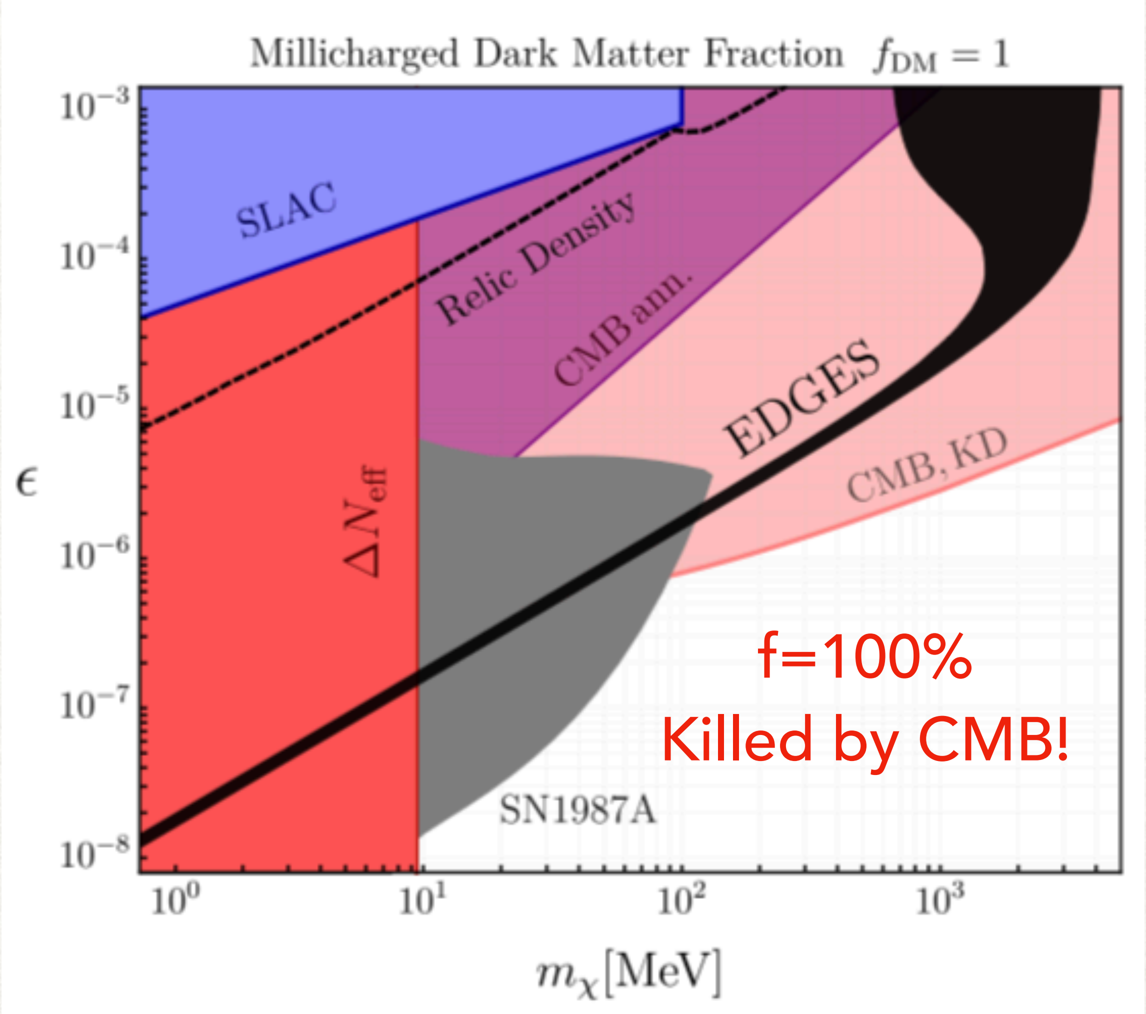
Have we (re-)discovered Dark Matter ?

Barkana, nature25791, Munoz&Loeb, 1802.10094, Berlin++1803.02804, Barkana++ 1803.03091

- cross-section must scale like $(v/c)^{-4}$ to avoid CMB constraints, i.e. light/massless mediator.
- Interaction with neutral hydrogen: $\sigma_0 \sim 4*10^{-43}$ cm^2; M < 1GeV respects CMB constraints!
- Long-range force excluded by 5th force experiment: milli-charged DM only survivor.
- Problem: at cosmic dawn, only 10^{-4} of the gas is charged…

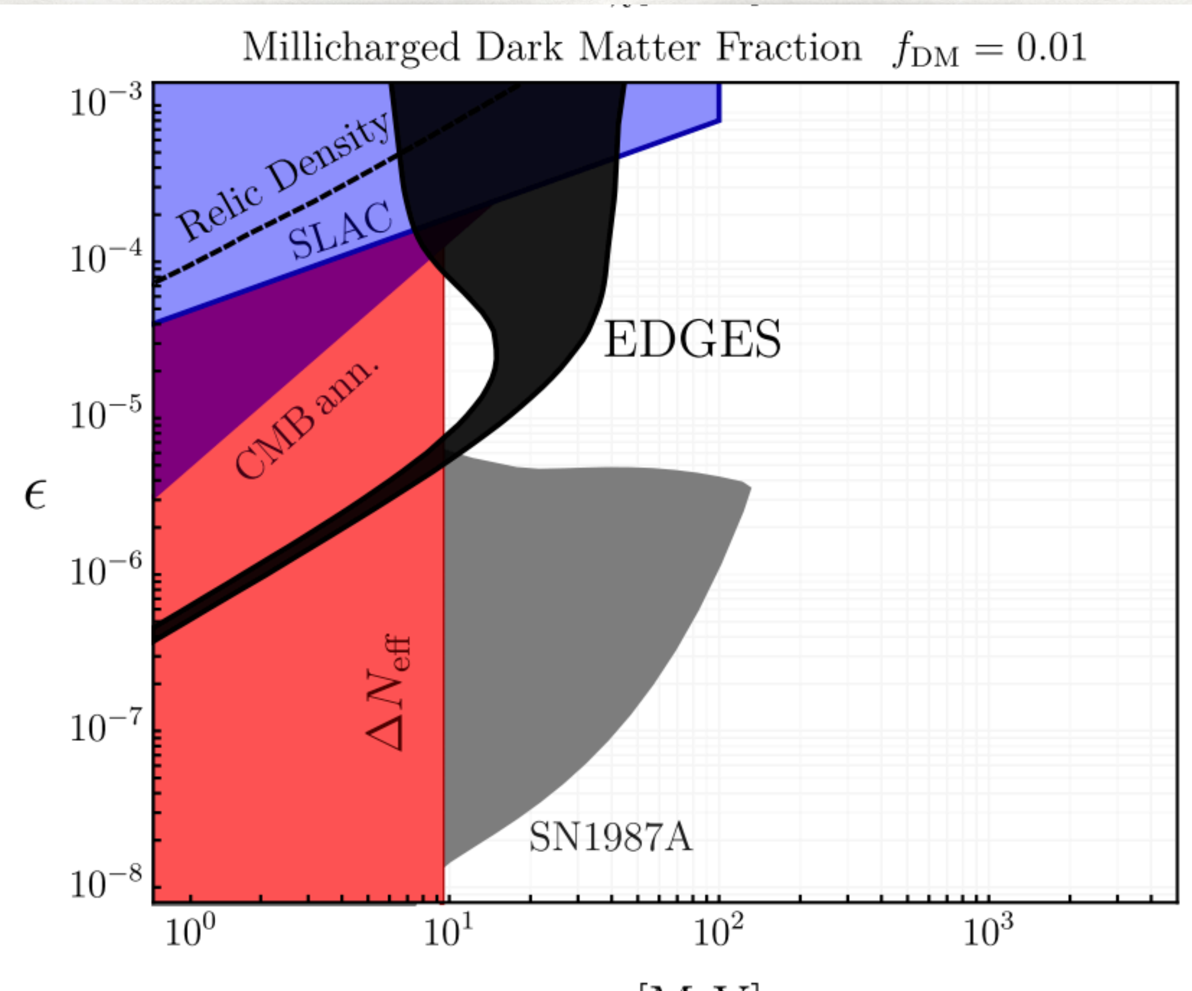


Barkana, nature25791

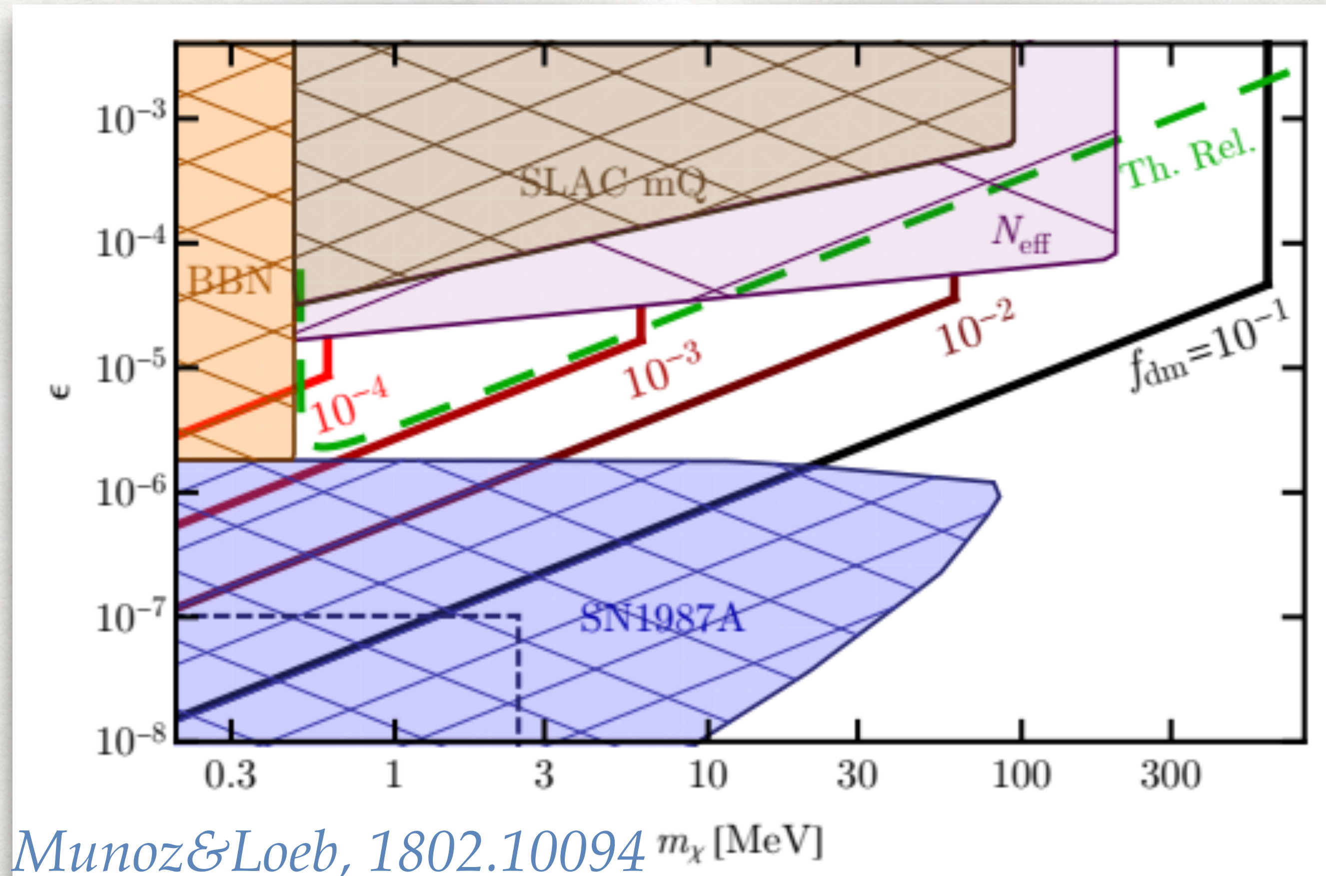


Berlin++1803.02804

Signs of "fractional" Dark Matter?



Berlin++1803.02804



Munoz&Loeb, 1802.10094

- It has been claimed that f~1% could avoid the constraints.
- nb: what if there was a "dark recombination" at z > 30000? TBD…
- $\Gamma_{b\to\chi} = \sigma v n_\chi$ but $\Gamma_{\chi\to b} = \sigma v n_b$: can fractional DM avoid CMB constraints?

Fractional Dark Matter is non linear

- There exists a supersonic bulk relative velocity between baryons and DM!
  Tseliakhovich&Hirata PRD (2010)
- This leads to non-linear equations that cannot be solved trivially in Fourier space.
- In the past, studies focused on f = 100% and assumed $V_{rel} = V_{LCDM}$
  Dvorkin++1311.2937, Xu++ 1802.06788, Slatyer++ 1803.09734

Temperature evolution

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

Heat exchange rate

$R'_\chi \propto \sigma(V_{rel}) * V_{rel} * n_b$

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

Bulk velocity evolution

Momentum exchange rate

$$\frac{\partial \vec{V}_\chi}{\partial \tau} - c_\chi^2\vec{\nabla}\delta_\chi + \frac{\dot{a}}{a}\vec{V}_\chi = R_\chi(\vec{V}_b - \vec{V}_\chi)$$

$$\frac{\partial \vec{V}_b}{\partial \tau} - c_b^2\vec{\nabla}\delta_b + \frac{\dot{a}}{a}\vec{V}_b = R_\gamma(\vec{V}_\gamma - \vec{V}_b) + \frac{\rho_\chi}{\rho_b}R_\chi(\vec{V}_\chi - \vec{V}_b)$$

Fractional Dark Matter is non linear

- for small f this approximation is *not* valid!!
- We devised several prescriptions to deal with these equations, all give similar results, in good agreement with former studies for f = 100%.

Boddy, Gluscevic, VP++ ,1808.00001

Temperature evolution

$$\dot{T}_\chi + 2\frac{\dot{a}}{a}T_\chi = 2R'_\chi \Bigg\{(T_b - T_\chi) \times \left[{}_1F_1\left(-\frac{n+3}{2}, \frac{3}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right) - \frac{V_{\chi b}^2}{3v_{\rm th}^2}\,{}_1F_1\left(-\frac{n+1}{2}, \frac{5}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right)\right] + \frac{m_p}{3}V_{\chi b}^2\,{}_1F_1\left(-\frac{n+1}{2}, \frac{5}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right)\Bigg\}$$

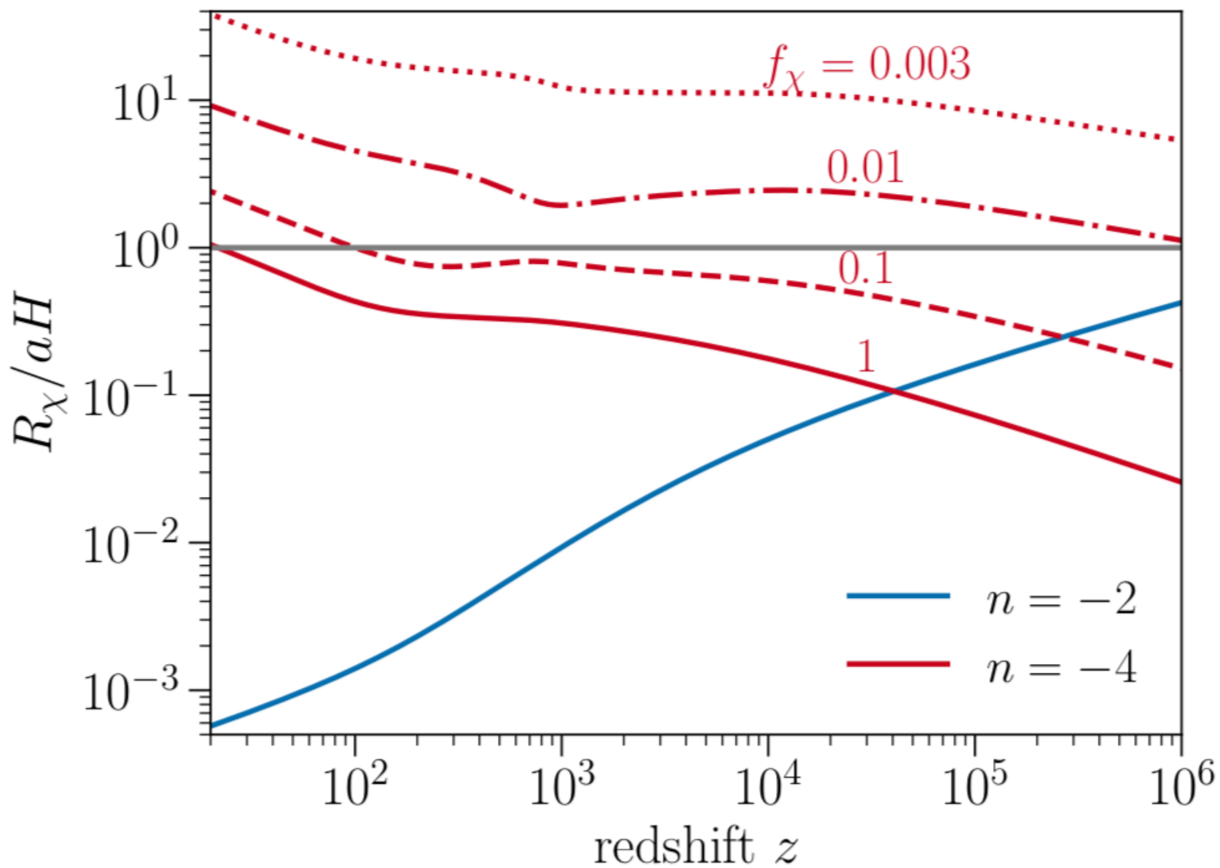
$$\dot{T}_b + 2\frac{\dot{a}}{a}T_b = 2\frac{\mu_b}{m_e}R_\gamma(T_\gamma - T_b) + 2\frac{\mu_b}{m_\chi}\frac{\rho_\chi}{\rho_b}R'_\chi \Bigg\{(T_\chi - T_b) \times \left[{}_1F_1\left(-\frac{n+3}{2}, \frac{3}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right) - \frac{V_{\chi b}^2}{3v_{\rm th}^2}\,{}_1F_1\left(-\frac{n+1}{2}, \frac{5}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right)\right] + \frac{m_\chi}{3}V_{\chi b}^2\,{}_1F_1\left(-\frac{n+1}{2}, \frac{5}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right)\Bigg\}$$

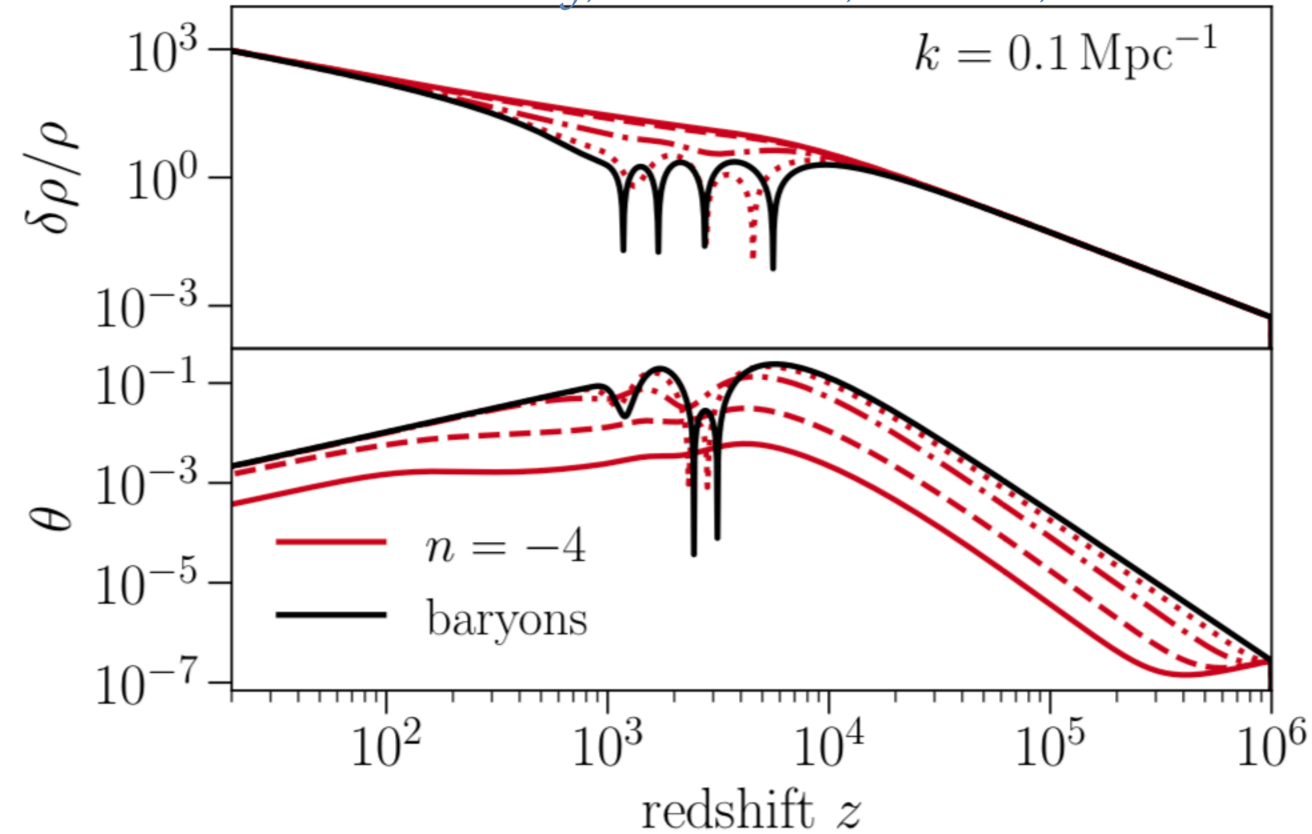
Bulk velocity evolution

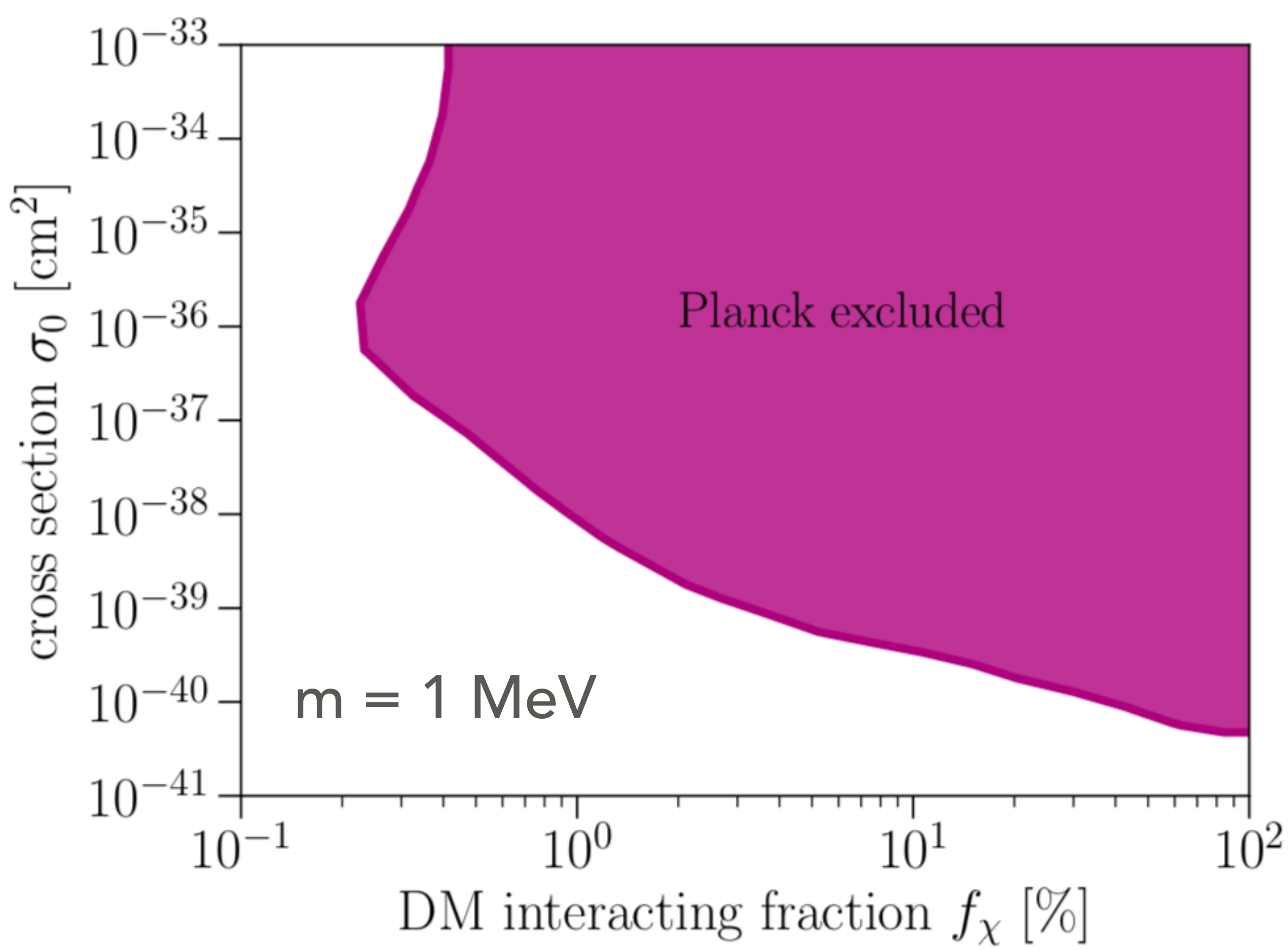
$$\frac{\partial \vec{V}_\chi}{\partial \tau} - c_\chi^2 \vec{\nabla}\delta_\chi + \frac{\dot{a}}{a}\vec{V}_\chi = R_\chi(\vec{V}_b - \vec{V}_\chi)\,{}_1F_1\left(-\frac{n+1}{2}, \frac{5}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right)$$

$$\frac{\partial \vec{V}_b}{\partial \tau} - c_b^2 \vec{\nabla}\delta_b + \frac{\dot{a}}{a}\vec{V}_b = R_\gamma(\vec{V}_\gamma - \vec{V}_b) + \frac{\rho_\chi}{\rho_b}R_\chi(\vec{V}_\chi - \vec{V}_b)\,{}_1F_1\left(-\frac{n+1}{2}, \frac{5}{2}, -\frac{V_{\chi b}^2}{2v_{\rm th}^2}\right)$$

Boddy, Gluscevic, VP++ ,1808.00001





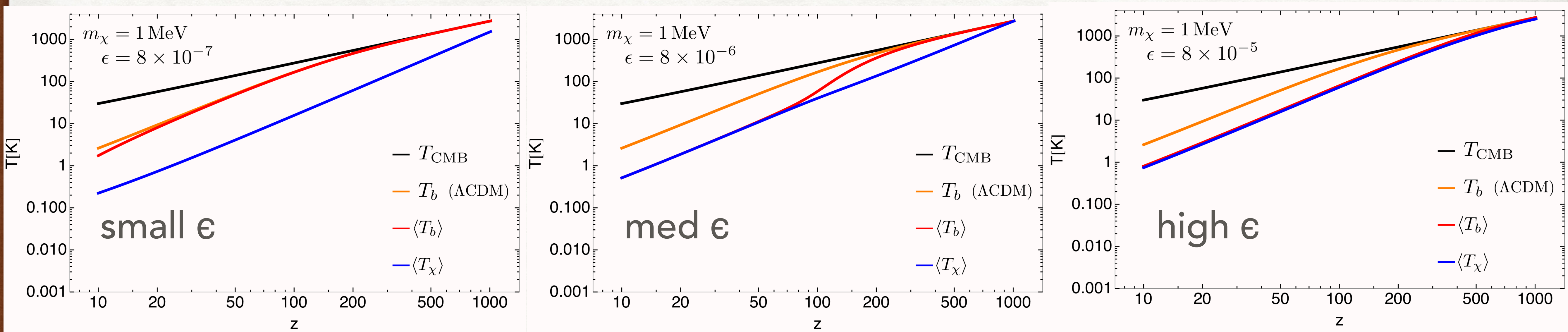


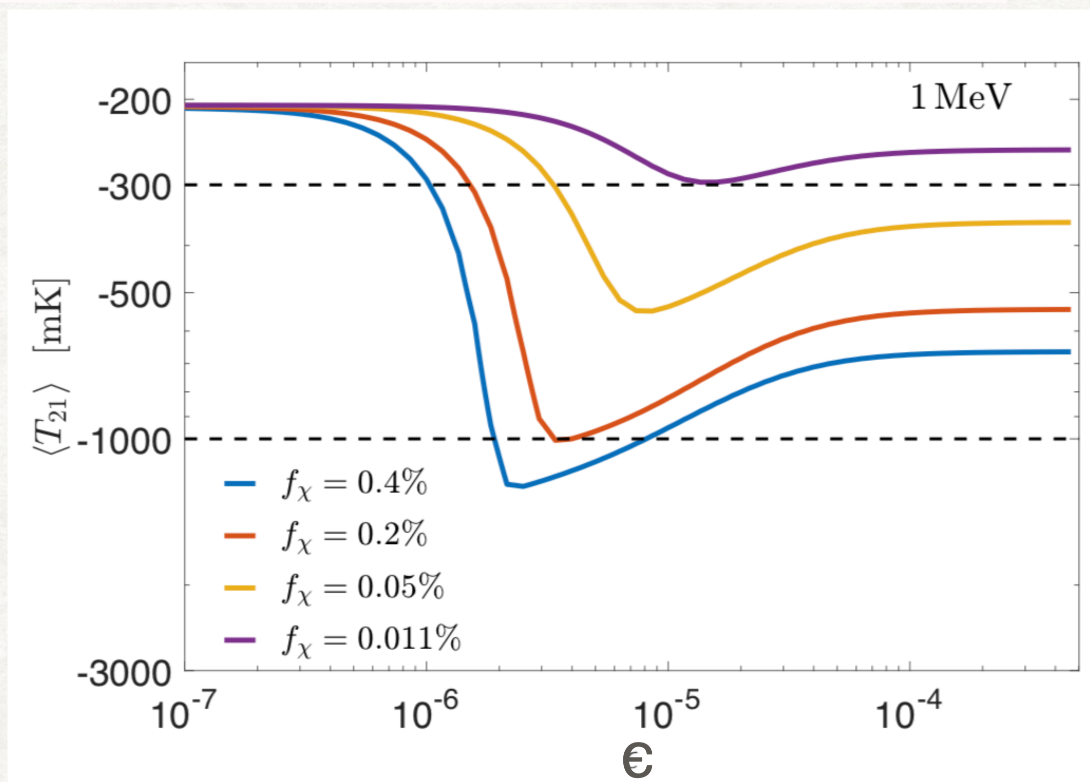
For small fraction, the CMB constraint vanishes! the interaction saturates (tight-coupling) and DM act (almost) like baryons.

f < 0.4%

see also De Putter++ 1805.11616

The cooling saturates for very high ϵ



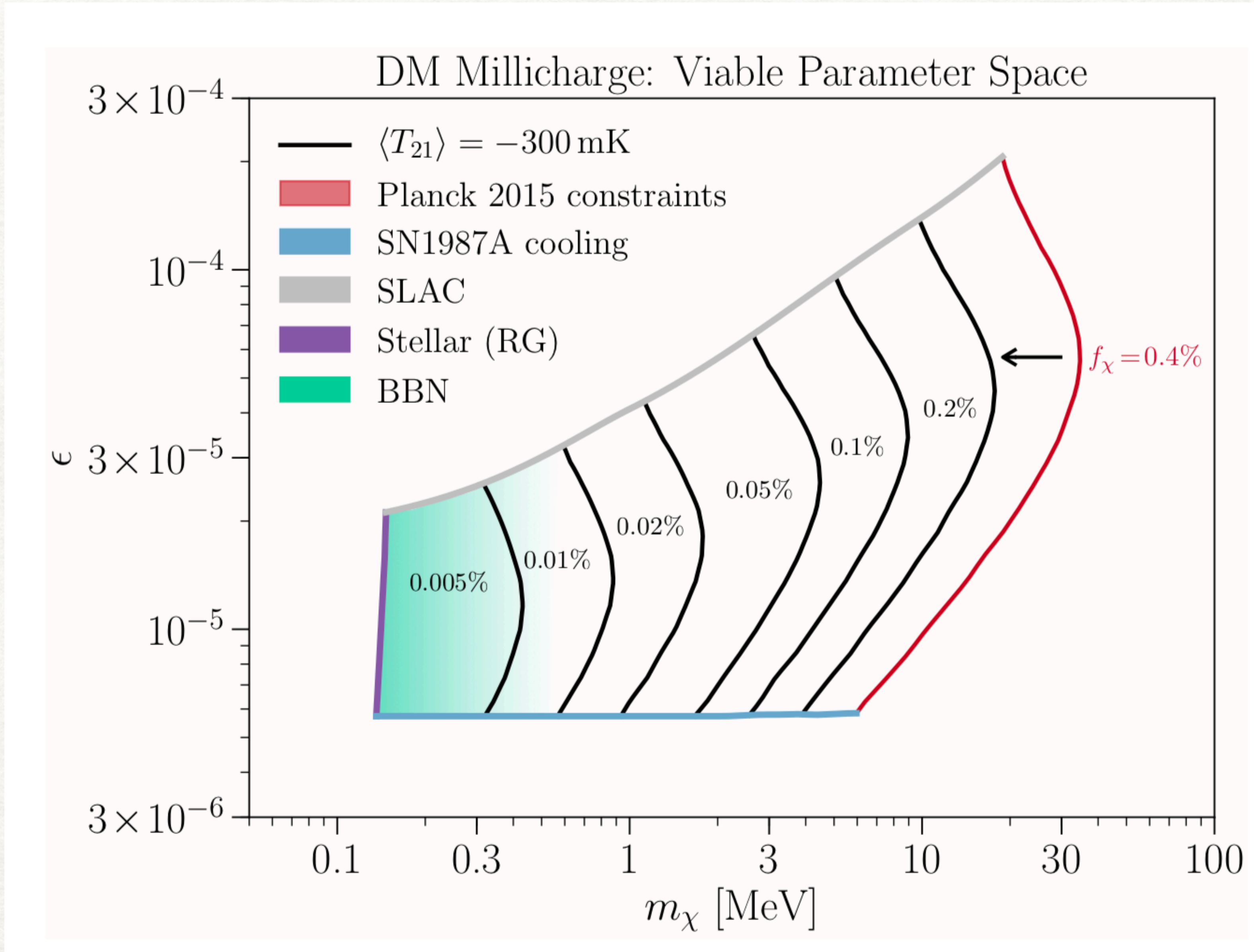


fχ > 0.015%; otherwise cooling inefficient.

Kovetz, VP,++1807.11482

Constraints on the DM milli-charged model

Kovetz, VP,++1807.11482



A small part of the parameter space still survives!

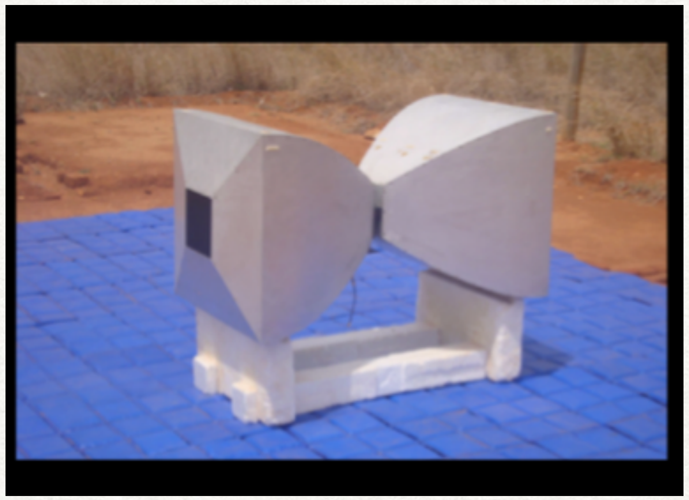
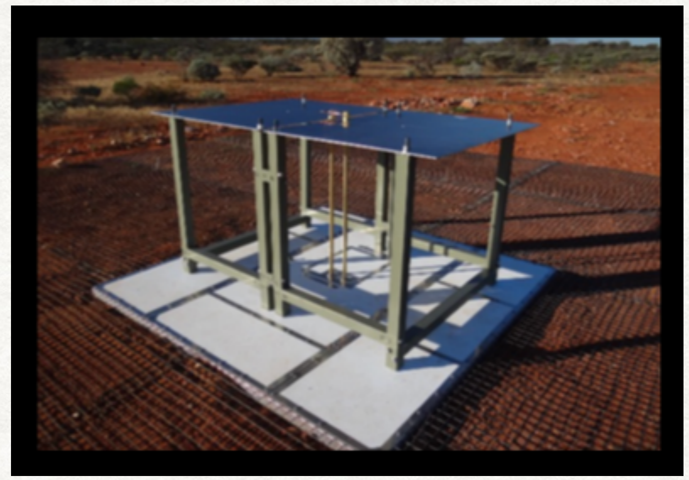
$\epsilon = [10^{-6}, 2*10^{-4}]e$, m = [0.2,30] GeV, f = [0.01%,0.4%]

nb: $\omega_b^{BBN} < \omega_b^{CMB}$ at 2sigma ~ 0.5%ω_{cdm}

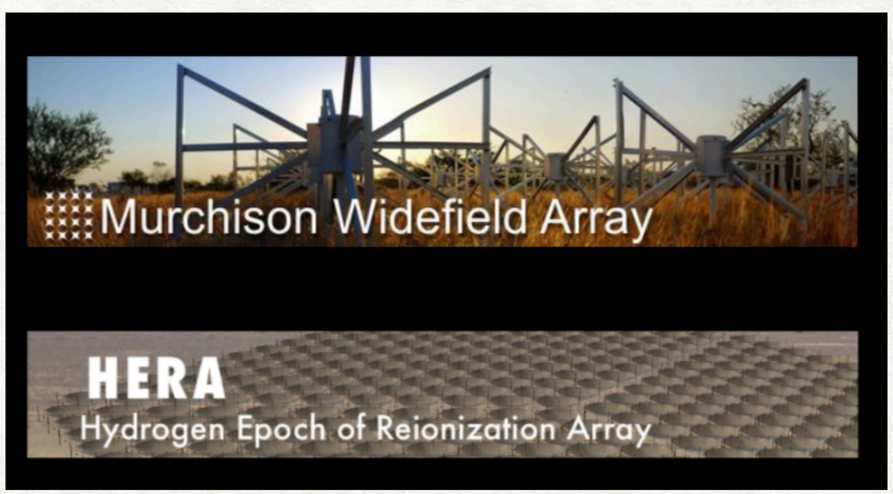
The future of 21cm is bright!

EDGES is the first of many experiments

- **Global Signal:** EDGES, SARAS2, PRIZM,


- **Power Spectrum:** MWA, HERA, SKA…



SKA
SQUARE KILOMETRE ARRAY

Even if CMB starts being exhausted, 21 cm will allow us to learn on astrophysics, cosmology and dark matter properties!

Conclusions

I have presented a (biased) overview of what Cosmology teaches us about DM.

- We can perform both direct and indirect detection: constraints are competitive and/or complementary to galactic searches.
- We can constrain tiny fractions of decaying particles at many different epochs.
- The EDGES 21cm signal could hold information on properties of (part of the) DM: the CMB provides strong constraints on this scenario.
- Even if EDGES signal is due to unknown systematic, 21cm (global and power spectrum) will be a major probe for cosmology and DM in the future.

Thank you!