Cosmic microwave background as a probe of dark relics

Corfu Summer Institute - Workshop on the SM and beyond, 08/09/2018

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RATIONALE AND OUTLINE

What if new physics is very weakly coupled?
E.g. what if DM does little more than its job of "gravitating"?
Is this type of **BSM undetectable**?

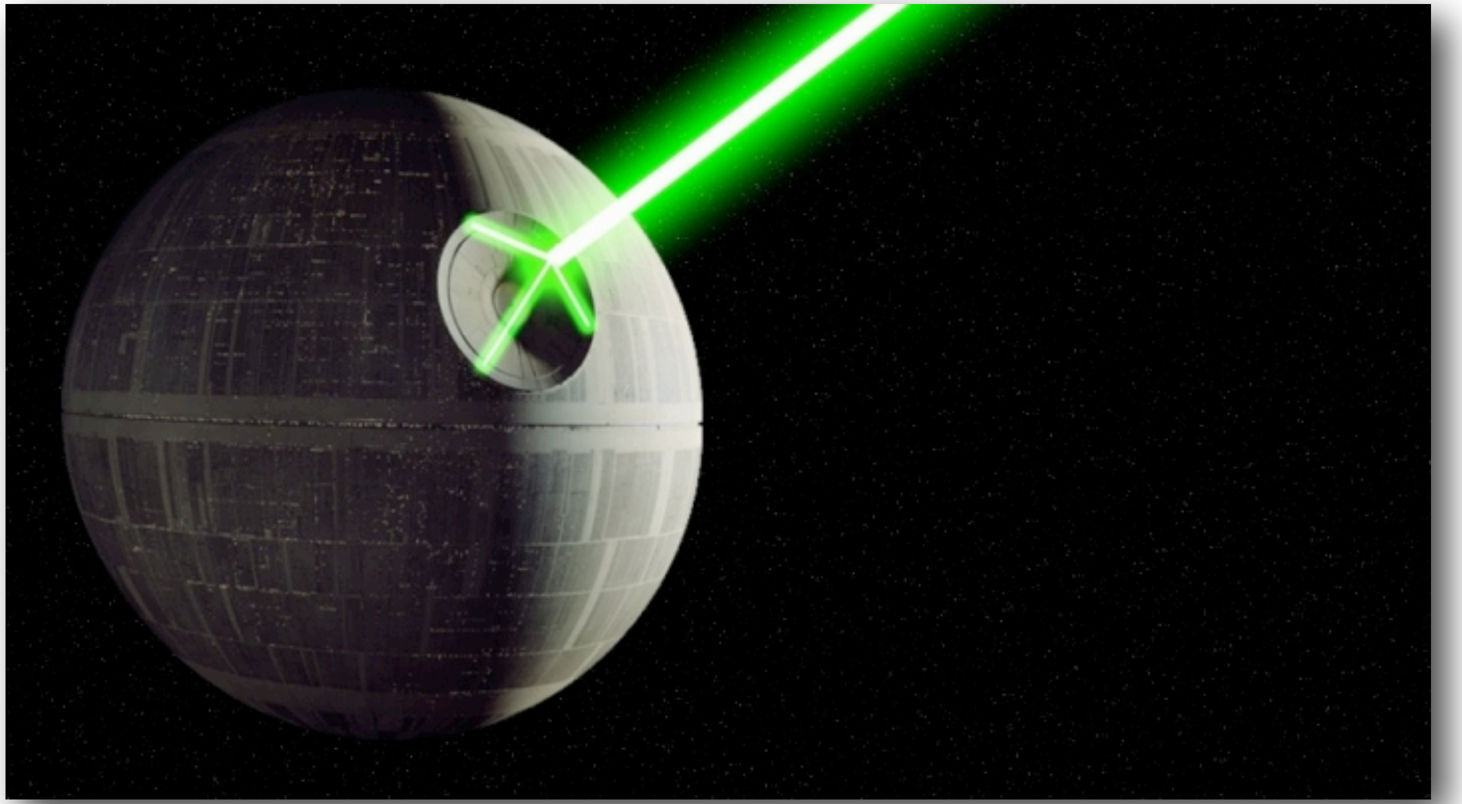
Not quite, there's still hope!
Notably from **cosmology**, where indirect techniques offer interesting **probes even** of **"almost invisible" relics**

- **"Dark matter" (part or all) conversion into *dark radiation***
  - Purely gravitational effects! Rationale of the argument & applications
- **Massive relics injecting some electromagnetic energy**
  - Principles & expected sensitivity
  - Application to annihilating WIMPs, decaying relics
  - Bonus (time permitting), applications to primordial BHs
- **Sensitivity to dark radiation & conclusions**

Episode I

possibly the next-to-closest thing to an "undiscoverable" DM candidate...

"Dark Matter" conversion into "Dark Radiation": Gravitational effects



On a decaying DM fraction

Assume a stable component in DM, plus an unstable relic, whose fraction of the initial total is *f*, decaying into "dark" relativistic species (DR).

$$\Omega_{\rm dm} = \Omega_{\rm sdm} + \Omega_{\rm dcdm}$$
$$= (1 - f_{\rm dcdm})\Omega_{\rm dm}^{\rm ini} + f_{\rm dcdm}\exp(-\Gamma_{\rm dcdm} t)\Omega_{\rm dm}^{\rm ini}$$

To some extent also describes DM' → "lighter" DM, which has however additional constraints

The smooth background equations can be easily derived, e.g. from $\nabla_\mu T^{\mu\nu} = 0$

homogeneous equations given by
(prime=derivative with respect to conformal time)

$$\rho'_{\rm dcdm} = -3\frac{a'}{a}\rho_{\rm dcdm} - a\Gamma_{\rm dcdm}\rho_{\rm dcdm}$$

$$\rho'_{\rm dr} = -4\frac{a'}{a}\rho_{\rm dr} + a\Gamma_{\rm dcdm}\rho_{\rm dcdm}$$

dilution factors for energy density of
matter
radiation

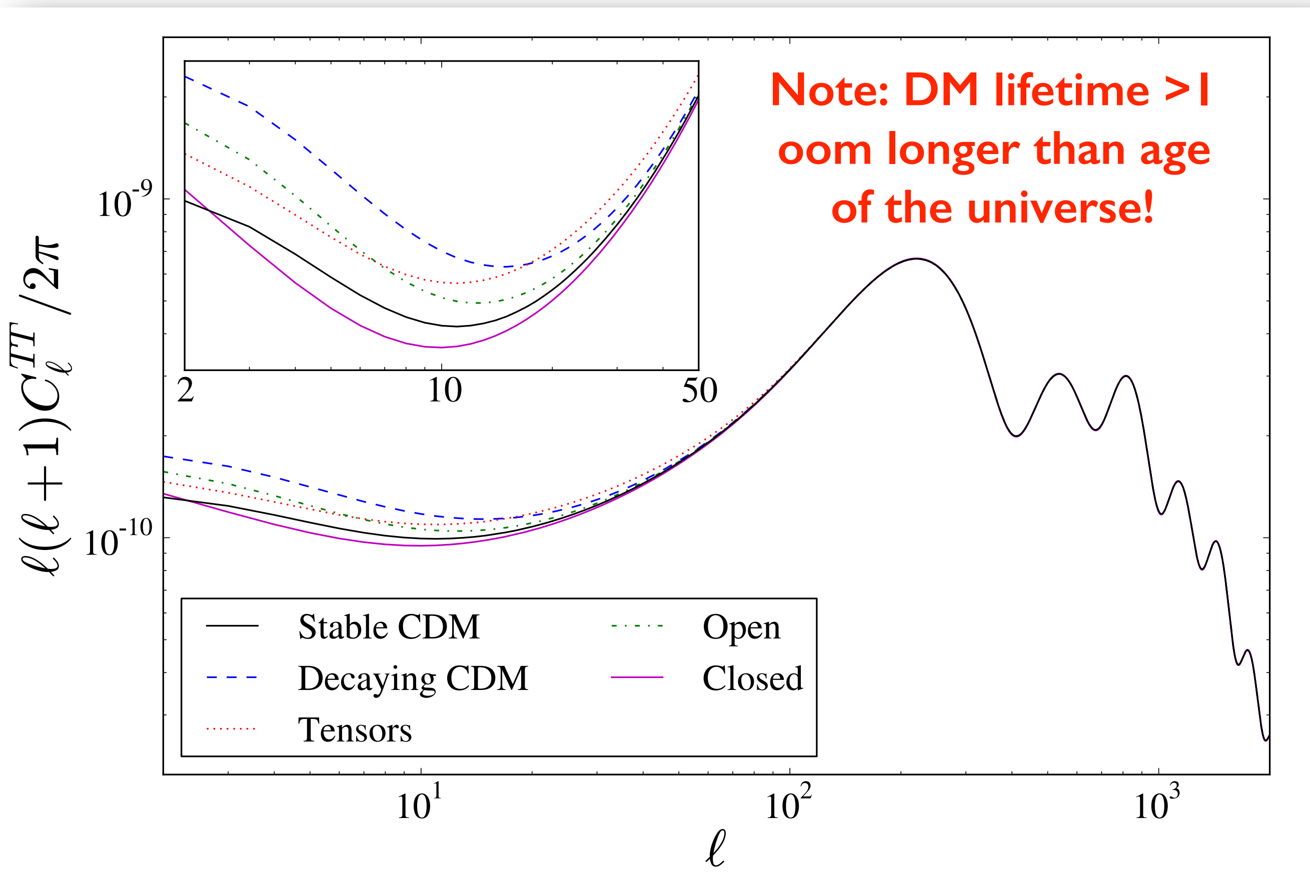
$$\frac{a'}{a} = a\,H = \mathcal{H}$$

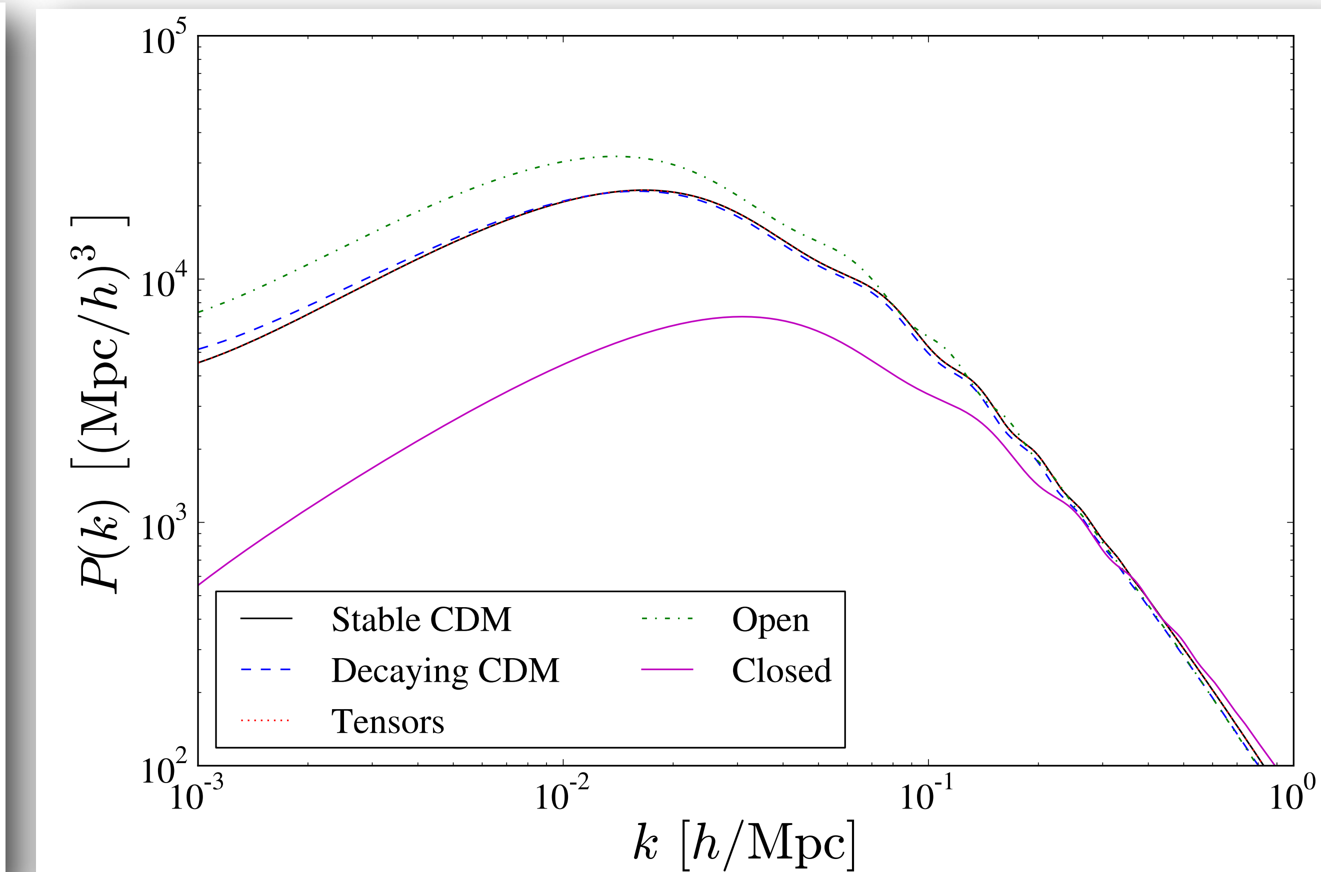
For perturbations, must be careful about gauge choice/fixing… I won't enter in details, if interested see *V. Poulin, P.D.S. and J. Lesgourgues, JCAP 1608, 036 (2016) [1606.02073]*

Effects of decaying DM (f_{dcdm}=1, first)

CMB affected (mostly) by late integrated Sachs-Wolfe effect (modification of homogeneous & perturbed DM density at late times affects evolution of metric fluctuation) LSS helps in breaking partial degeneracy with curvature & tensor modes

Model implemented in CLASS, http://class-code.net/





Case for f_{dcdm}=1, from

B. Audren et al. JCAP 1412, 028 (2014) [1407.2418]

Current bounds: τ≳160 Gyr (CMB only)

τ≳170 Gyr (with other consistent data)

V. Poulin, P.D.S. and J. Lesgourgues, JCAP 1608, 036 (2016) [1606.02073]

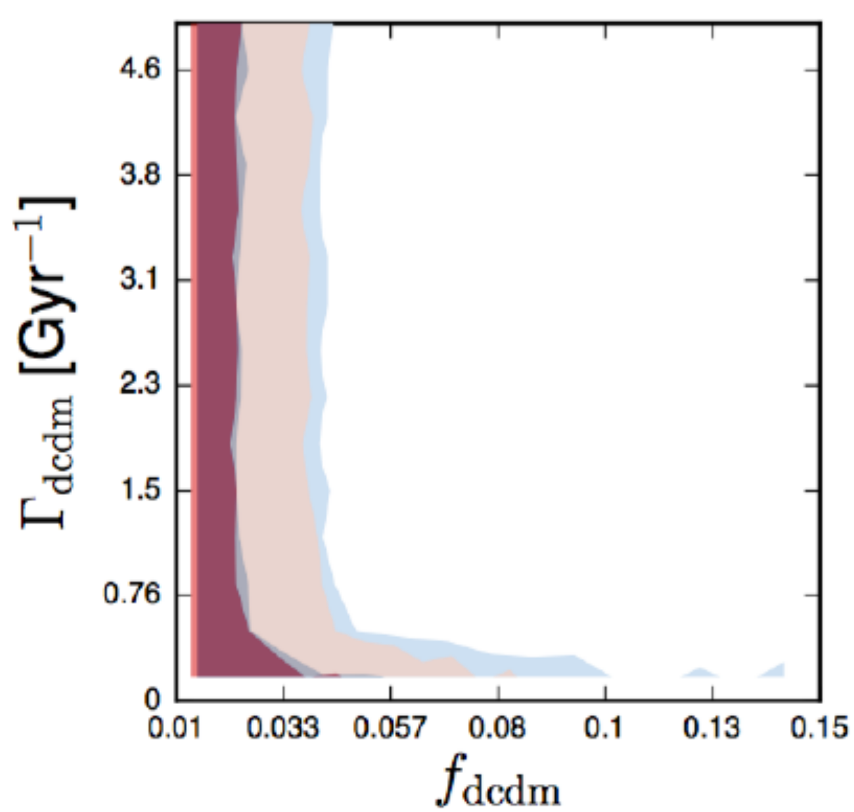
Bounds: 3 timescale regimes

If the lifetime is very long, to first order data are only sensitive to the product Γf

Γf< 0.0063 (0.0059) Gyr^{-1} CMB only (+consistent data)

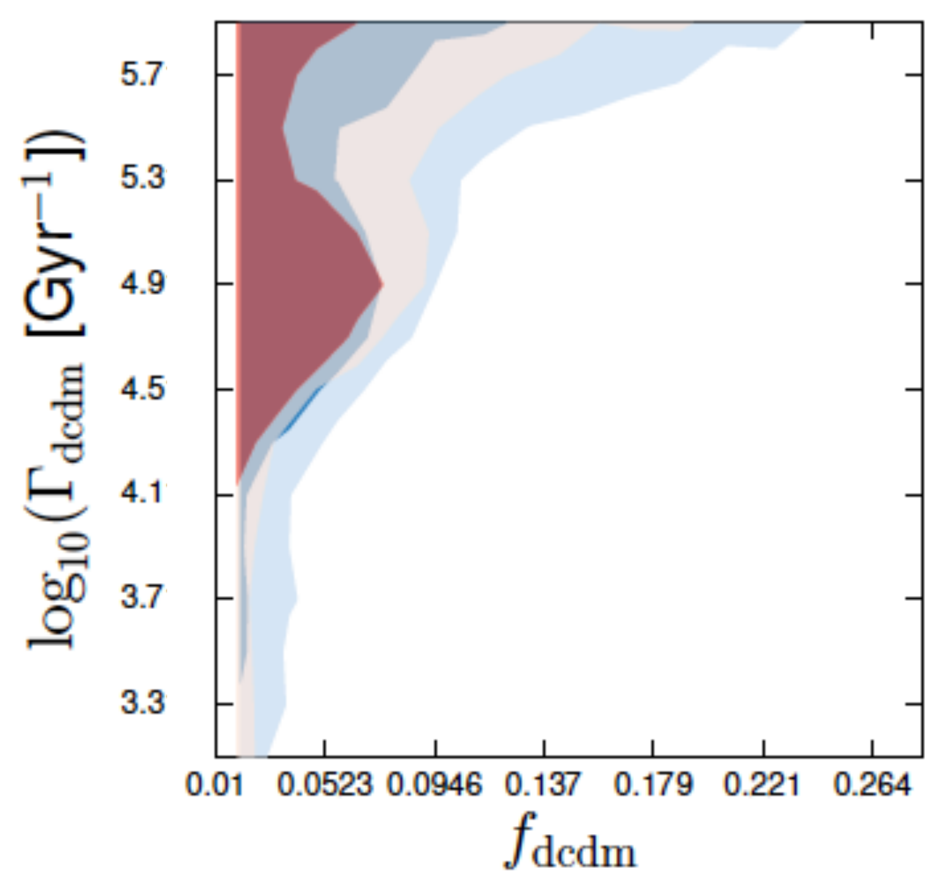
$$\begin{aligned}\Omega_{\rm dm} &= \Omega_{\rm sdm} + \Omega_{\rm dcdm} \\ &= (1 - f_{\rm dcdm})\Omega_{\rm dm}^{\rm ini} + f_{\rm dcdm}\exp(-\Gamma_{\rm dcdm} t)\Omega_{\rm dm}^{\rm ini} \\ &= (1 - f_{\rm dcdm})\Omega_{\rm dm}^{\rm ini} + f_{\rm dcdm}[1 - \Gamma_{\rm dcdm} t + \mathcal{O}((\Gamma_{\rm dcdm} t)^2)]\Omega_{\rm dm}^{\rm ini} \\ &= [1 - f_{\rm dcdm}\Gamma_{\rm dcdm} t + \mathcal{O}((\Gamma_{\rm dcdm} t)^2)]\Omega_{\rm dm}^{\rm ini} \ .\end{aligned}$$

bounds ~ independent of lifetime between recombination and recent times (bounds apply also to complicated, non-decaying DM)



Less than 3.8% of DM has converted into any invisible radiation from recombination to now!

bounds on *fdcdm* relax for very short lifetimes, accompanied by an increase in the value of $\Omega^{\rm ini}$



…but for a "sweet spot" where "the produced DR" alters N_{eff} appreciably

Numerous applications

Examples in the literature:

within SUSY, if the LSP and NLSP are gravitinos, axions/axinos, RH sneutrinos…

for a recent ex. see e.g. R. Allahverdi et al. "Dark Matter from Late Invisible Decays to/of Gravitinos," Phys. Rev D 91, 055033 (2015)

BSM models (including **string-inspired**) accompanied by dark sectors; generically the lightest particle expected in the dark sector and the **lightest "visible" SUSY partner is metastable**

B. S. Acharya, S. Ellis, G. Kane, B. Nelson & M. Perry, "The lightest visible-sector supersymmetric particle is likely to be unstable," Phys. Rev. Lett.. 117, 181802 (2016)

non SUSY examples: keV-scale majoron, decaying into neutrinos

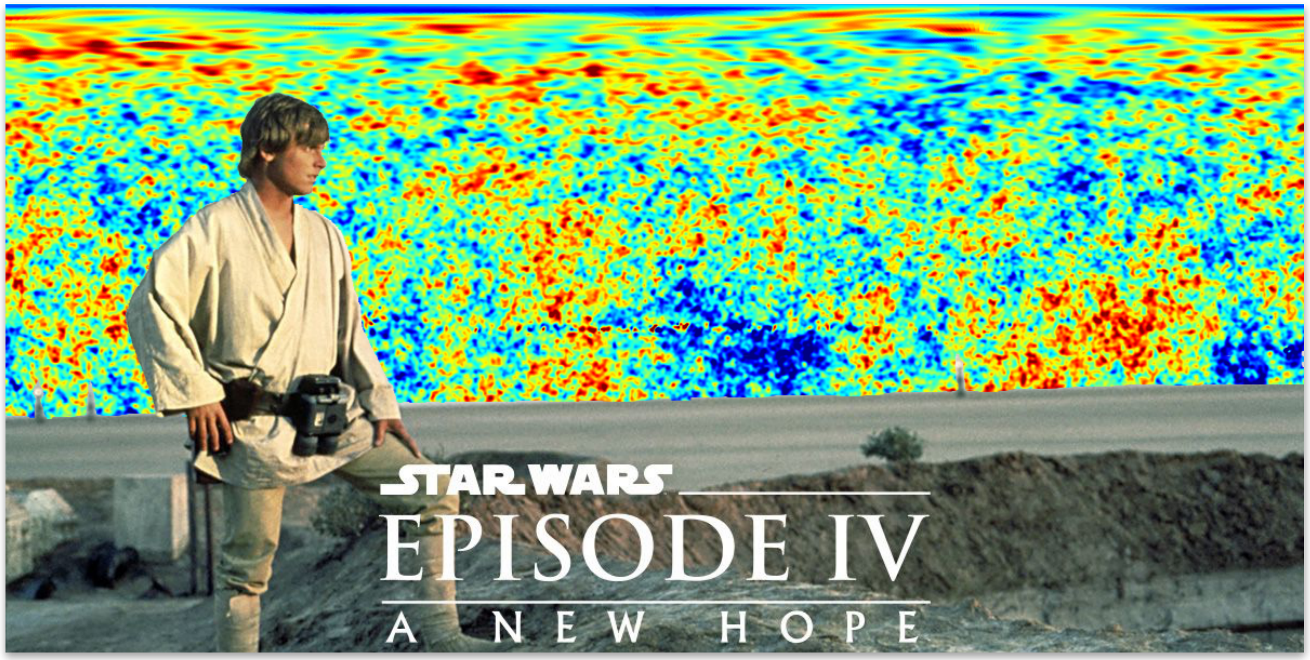
e.g. M. Lattanzi and J.W. F. Valle, "Decaying warm dark matter and neutrino masses," Phys. Rev.Lett., vol. 99, p. 121301, 2007

"non-particle" **example:** Primordial Black Holes (DR = GW due to merging)

➥ **either PBH do not make a sizable fraction of the DM or their mass function evolution should be negligible**

Episode II (or IV?)

Slightly less invisible relics:
rays of hope



What if a relic injects interacting SM particles?

associated to a number of processes, like

- Annihilating relics (like WIMP DM)
- Decaying relics such as sterile ν's, Super-WIMP progenitors
- Evaporating (hence "light") primordial black holes
- Accreting (hence "stellar mass or heavier") primordial black holes

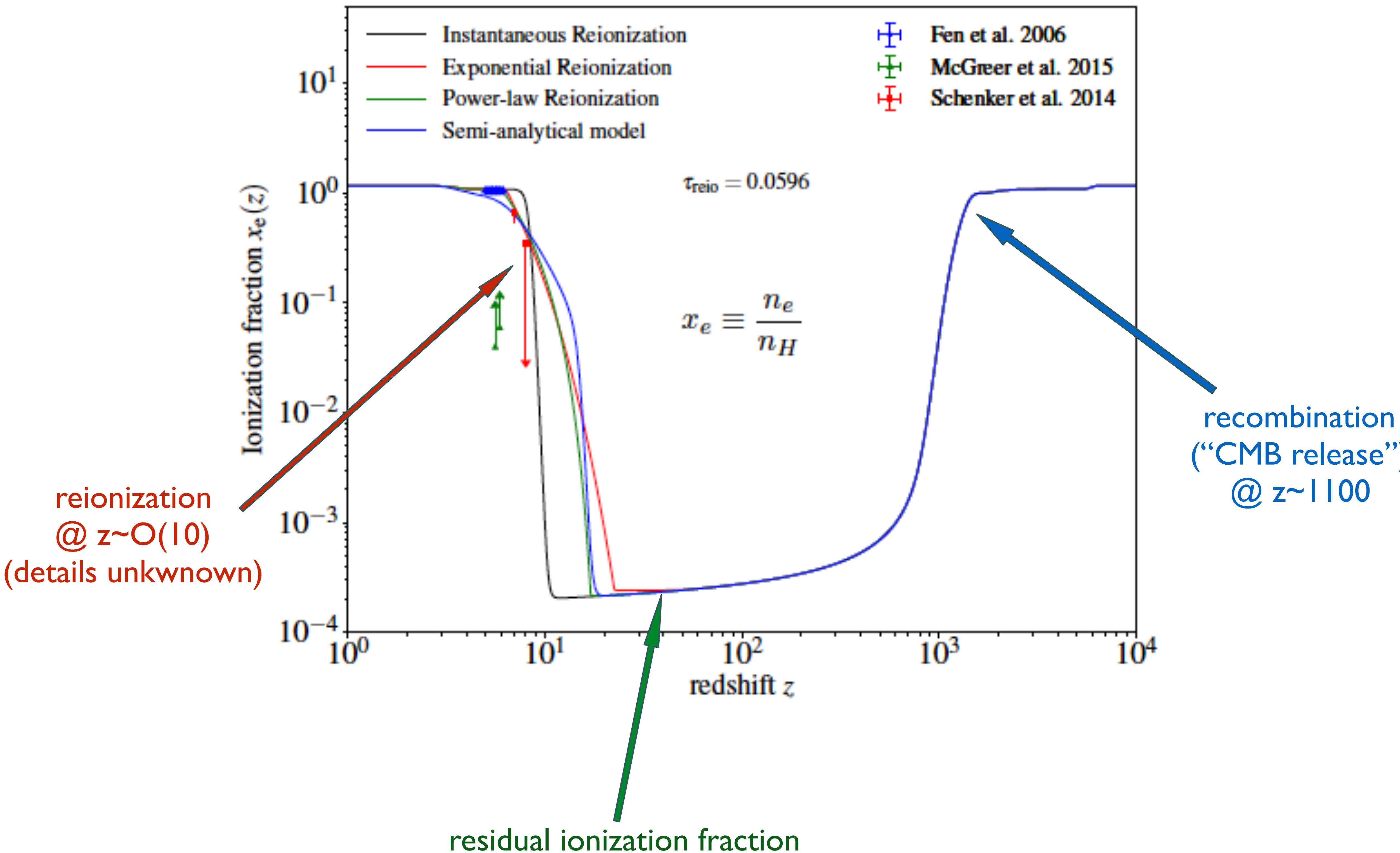
What happens e.g. to CMB observables?

the energy of the injected non-thermal particles is **not negligible wrt the kinetic energy of the baryonic gas.**
The e.m. interacting part of the injection can eventually **heat up** (alter T_M) and especially **ionize the gas** (alter x_e)**!** (hence alteration in the optical depth experienced by the CMB photons)

CMB is very sensitive to that!

Basic estimates

Have a look at the standard **ionization** and gas temperature evolution



Basic estimates

Have a look at the standard ionization and gas temperature evolution

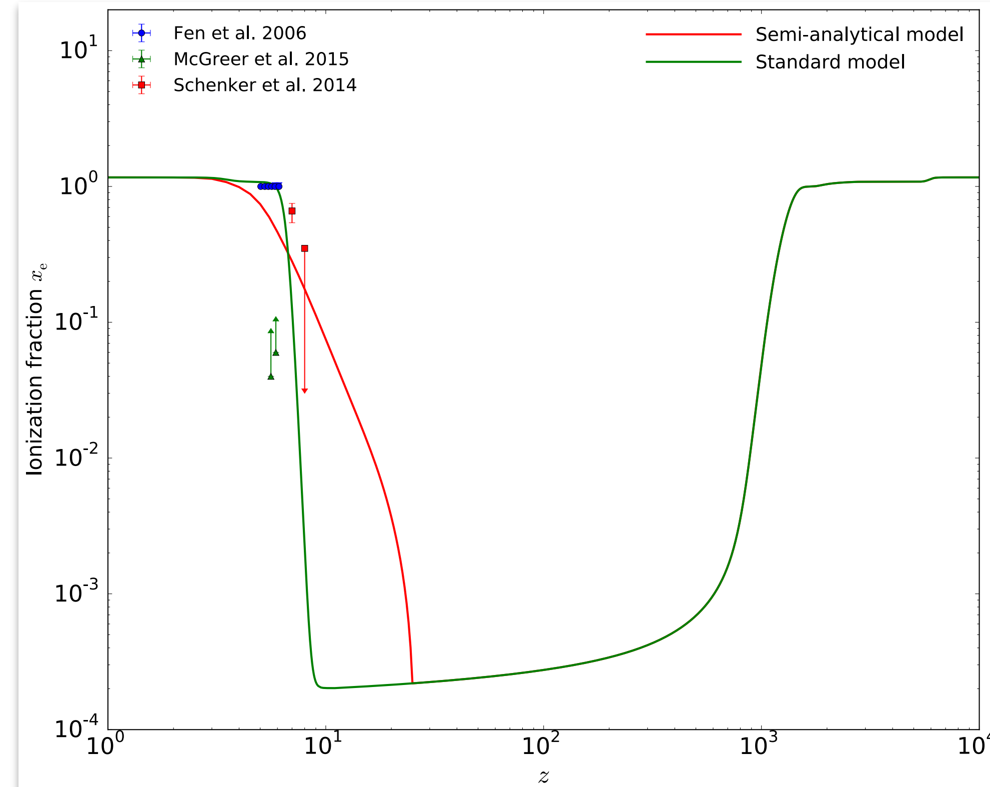
Note:

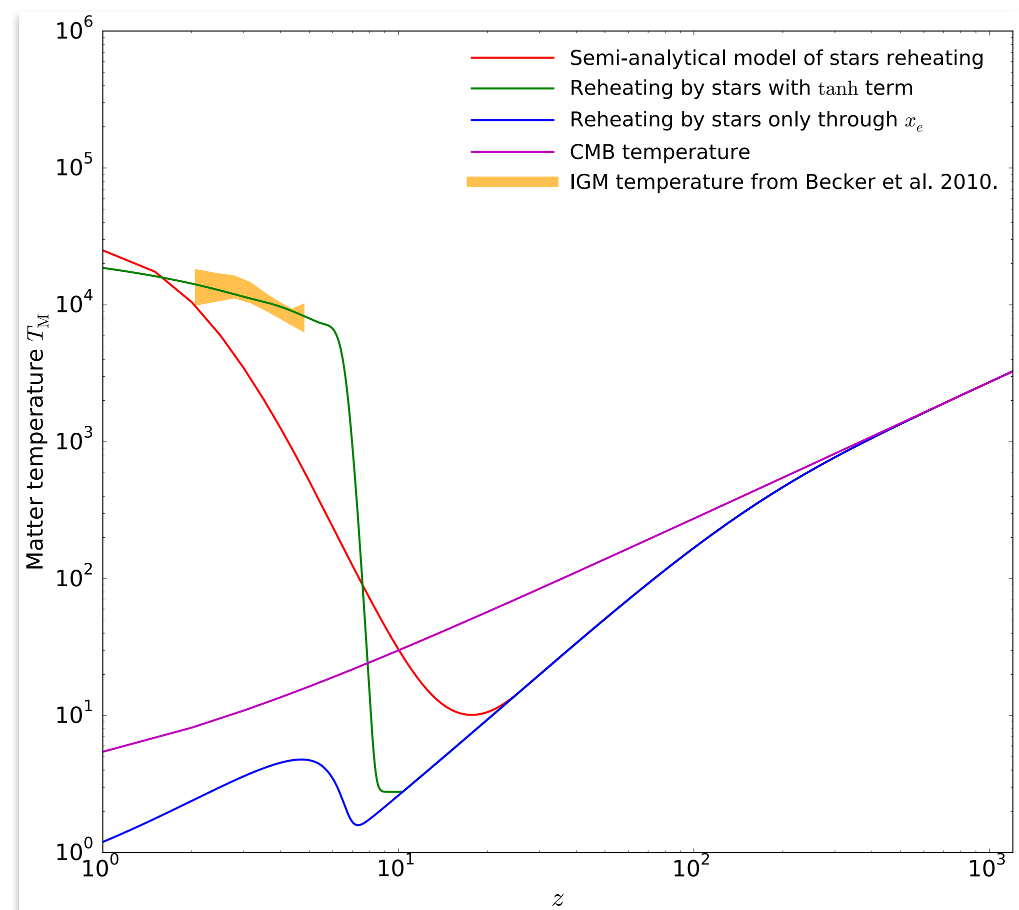
O(100) eV/baryons more than enough to ionize all atoms!

In the DM, in principle ~5 GeV/baryon "stored"

The reionization fraction in the standard expectation drops to ~ $5\ 10^{-4}$

a "visible" b.r. of **$O(10^{-11})$** may be sufficient to induce major alterations in x_e or T_M!





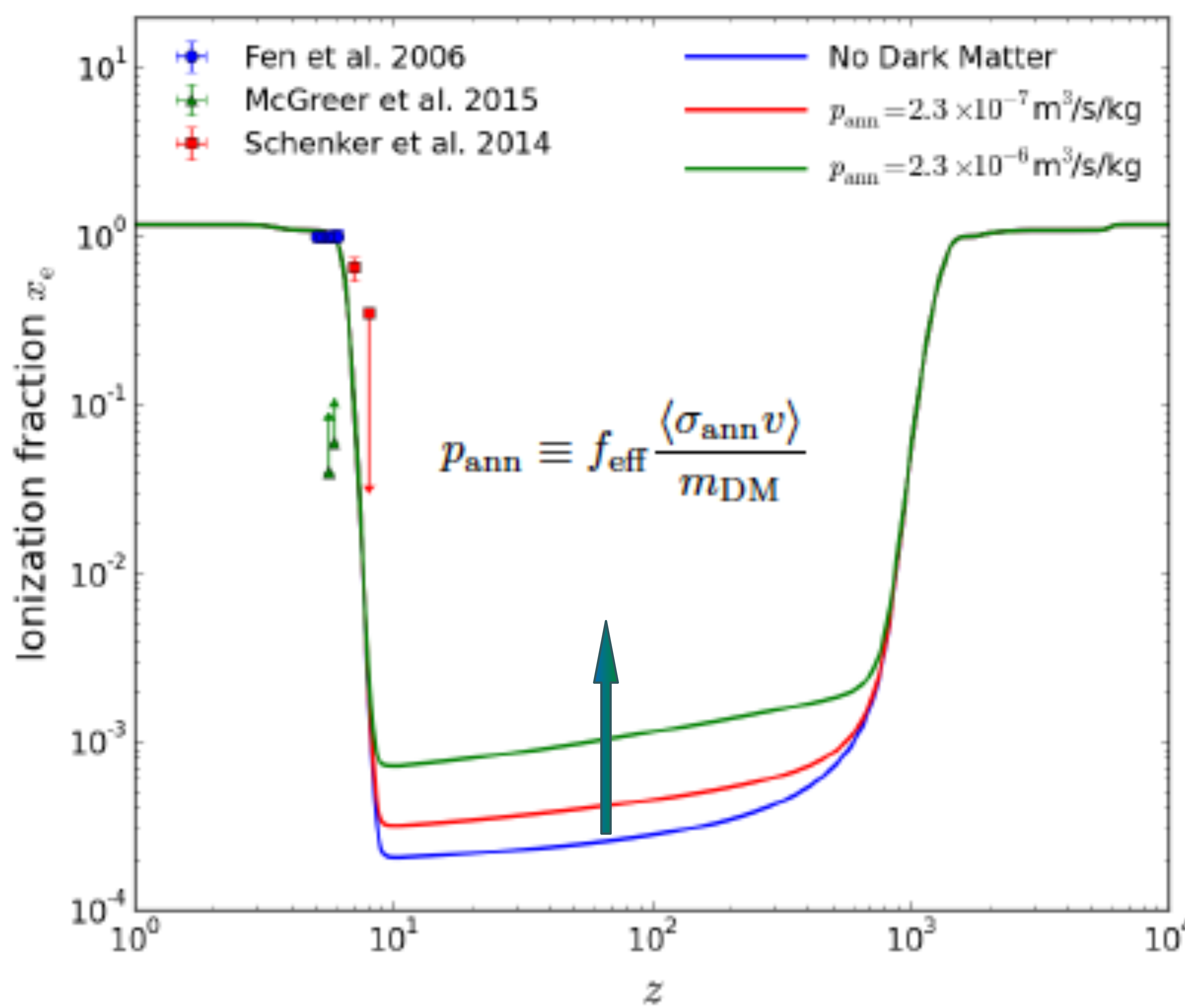
For instance, what do WIMPs do on CMB?

Via annihilation byproducts, they inject energy in the medium

$$\frac{dE}{dV\,dt} = \rho_c^2(1+z)^6\Omega_{\rm DM}^2\, p_{\rm ann}$$

key-parameter linked to particle physics

$$p_{\rm ann} = \frac{\langle\sigma v\rangle}{8\pi m_X^2}[4\pi][2m_X]f(z) = f(z)\frac{\langle\sigma v\rangle}{m_X}$$



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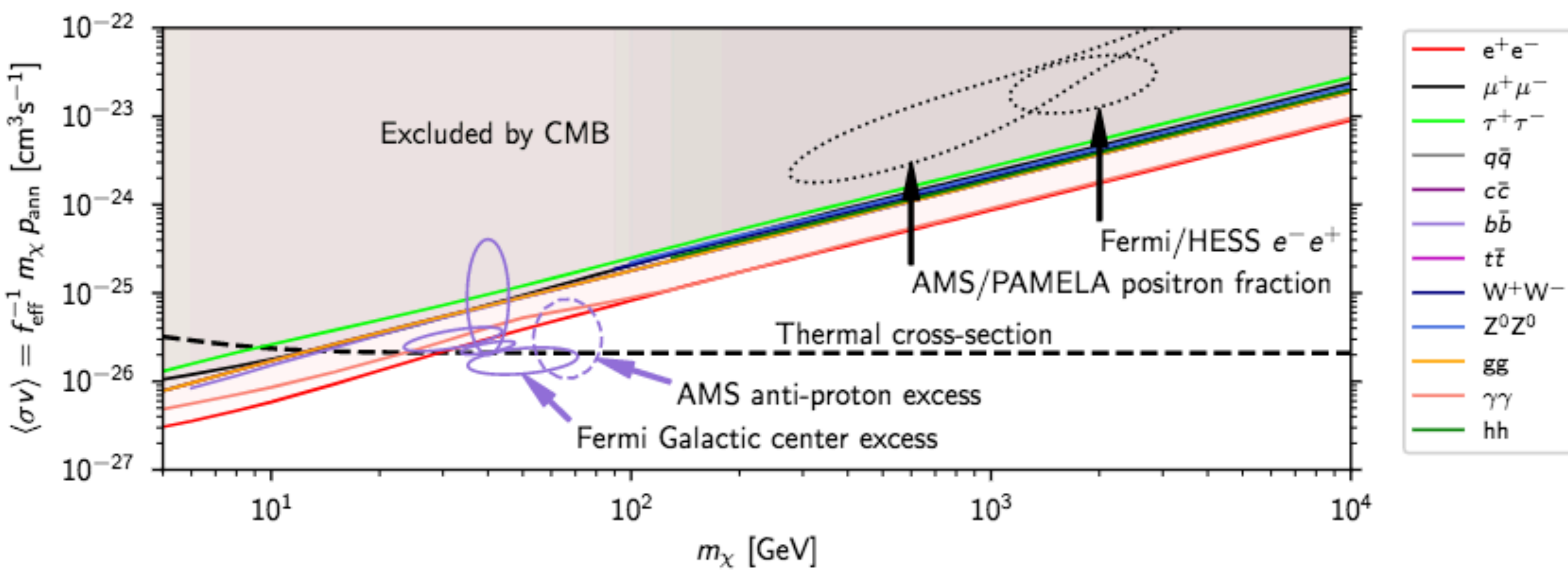
$$p_{\rm ann} < 3.2\times10^{-28}\frac{\rm cm^3}{\rm s\,GeV}$$

(Planck VI, 2018, 1807.06209)

computed with ExoCLASS module, P. Stöcker, M. Krämer, J. Lesgourgues and V. Poulin, JCAP1803 (2018)



Same ballpark of "low-z", astrophysical constraints but *calorimetric* and independent of astro details

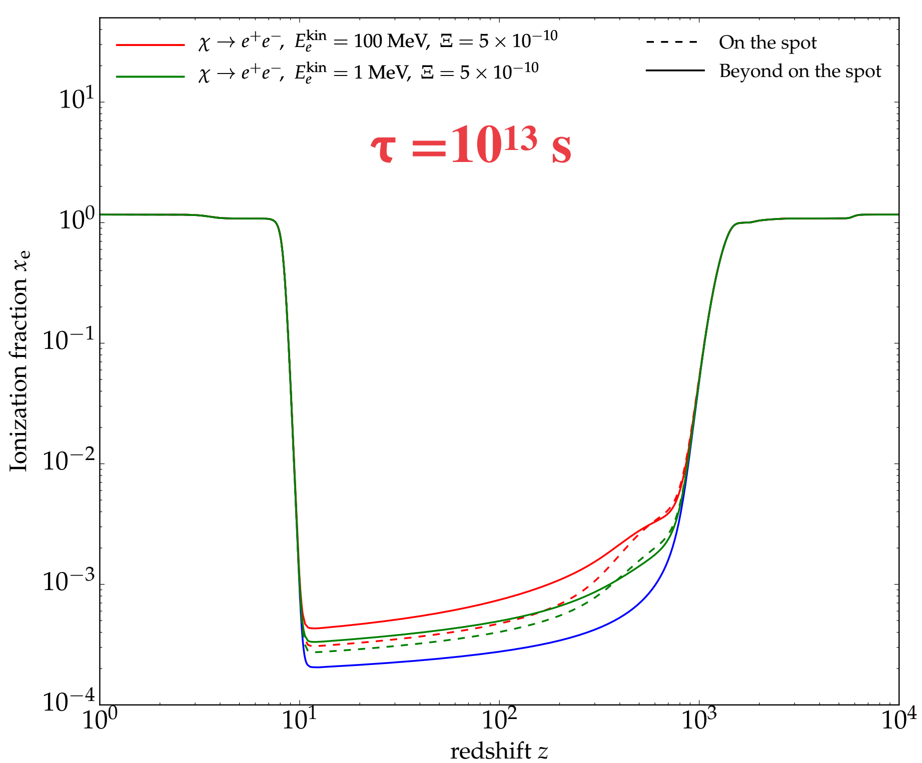
Example of application: relic decay (superWIMP, sterile ν…)

$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj} = (1+z)^3\,\Xi\,\Omega_{\rm DM}\rho_c c^2\,\Gamma\, e^{-\Gamma\, t}\,,$$

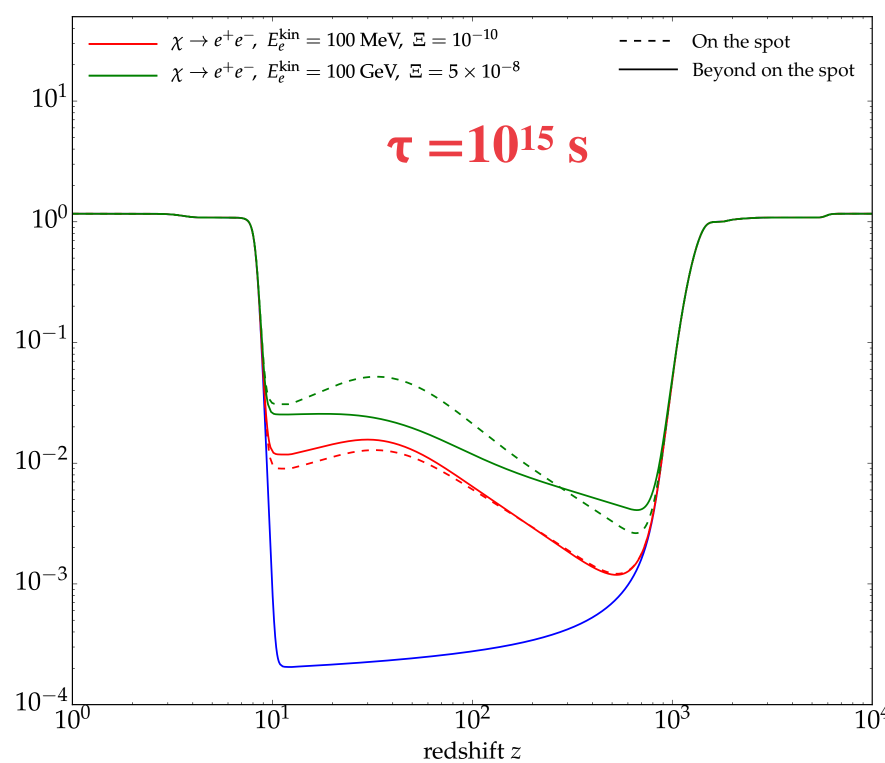
Ξ is the relative amount of energy released into e.m. for a single decay. For instance, a species constituting 1% of the total DM abundance decaying into ν γ corresponds to Ξ=1/200.

We can define the efficiency *f*-functions, and compute the corresponding evolution of x_e and T_M which show a certain variety, notably due to the large range of Γ allowed

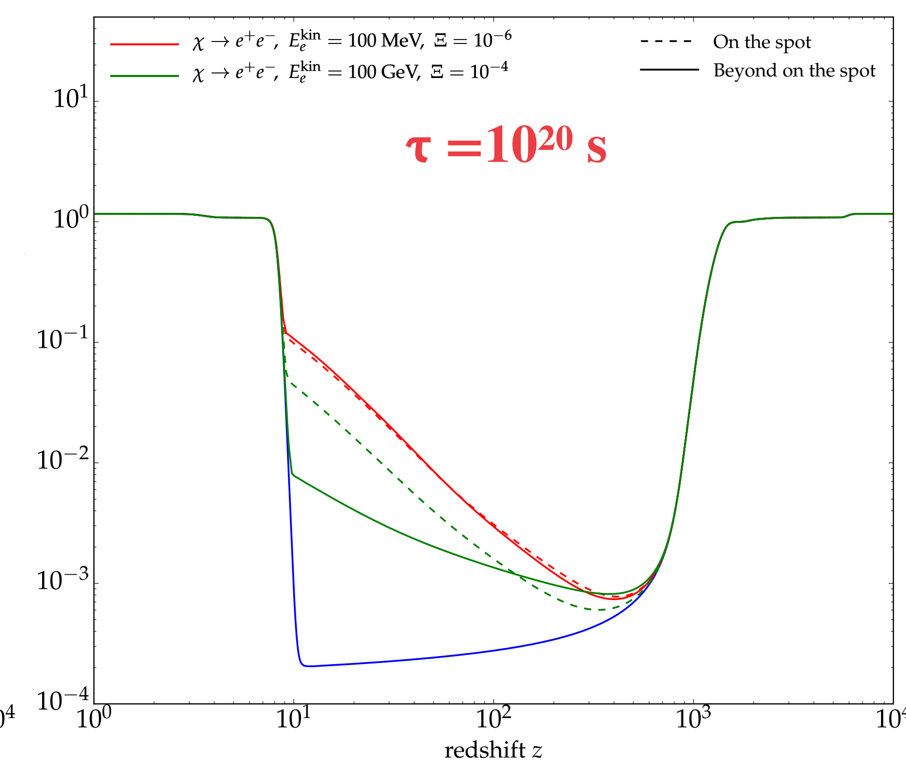
similar to WIMP annihilation



peculiarly bumpy!



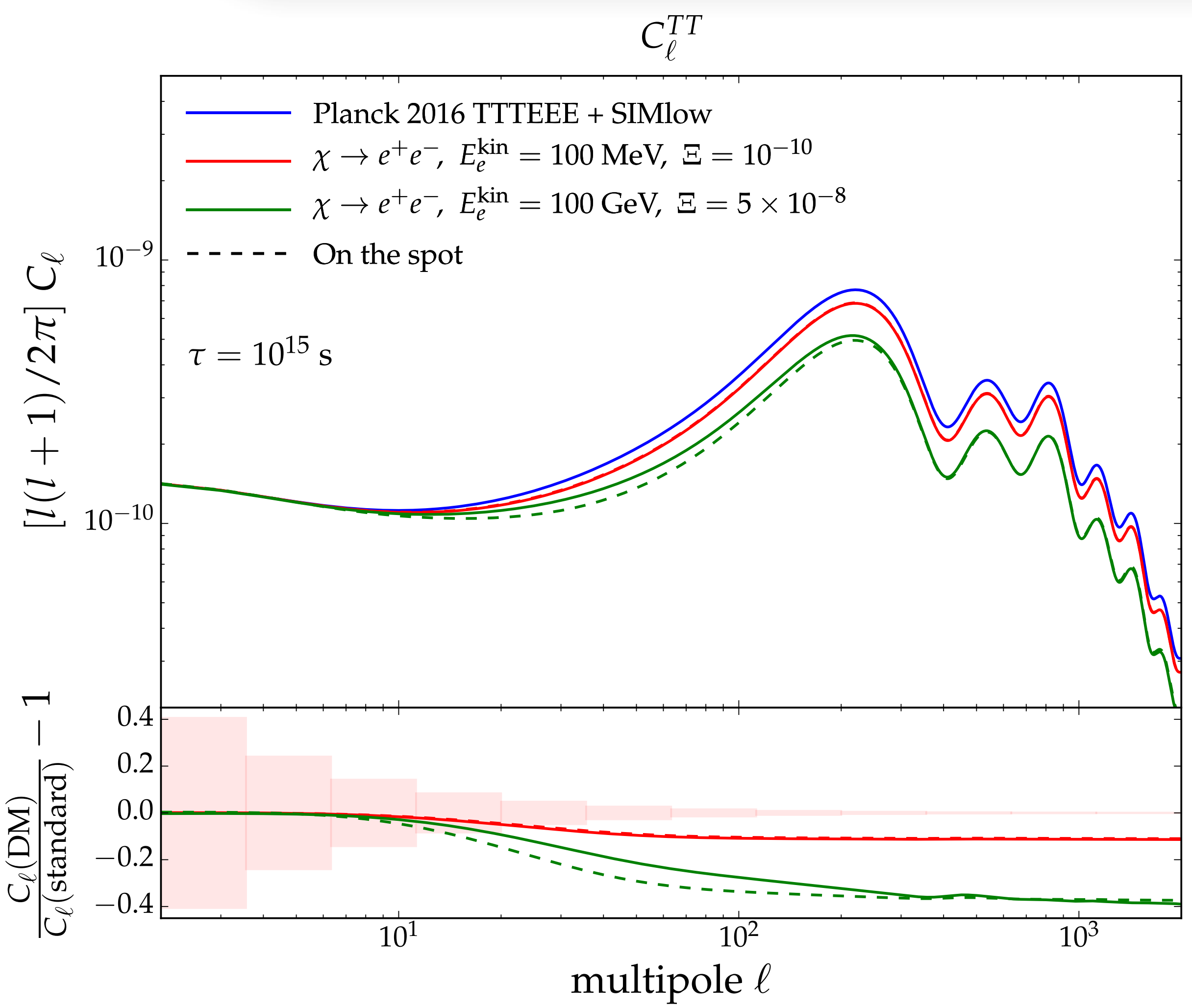
similar to early star formation

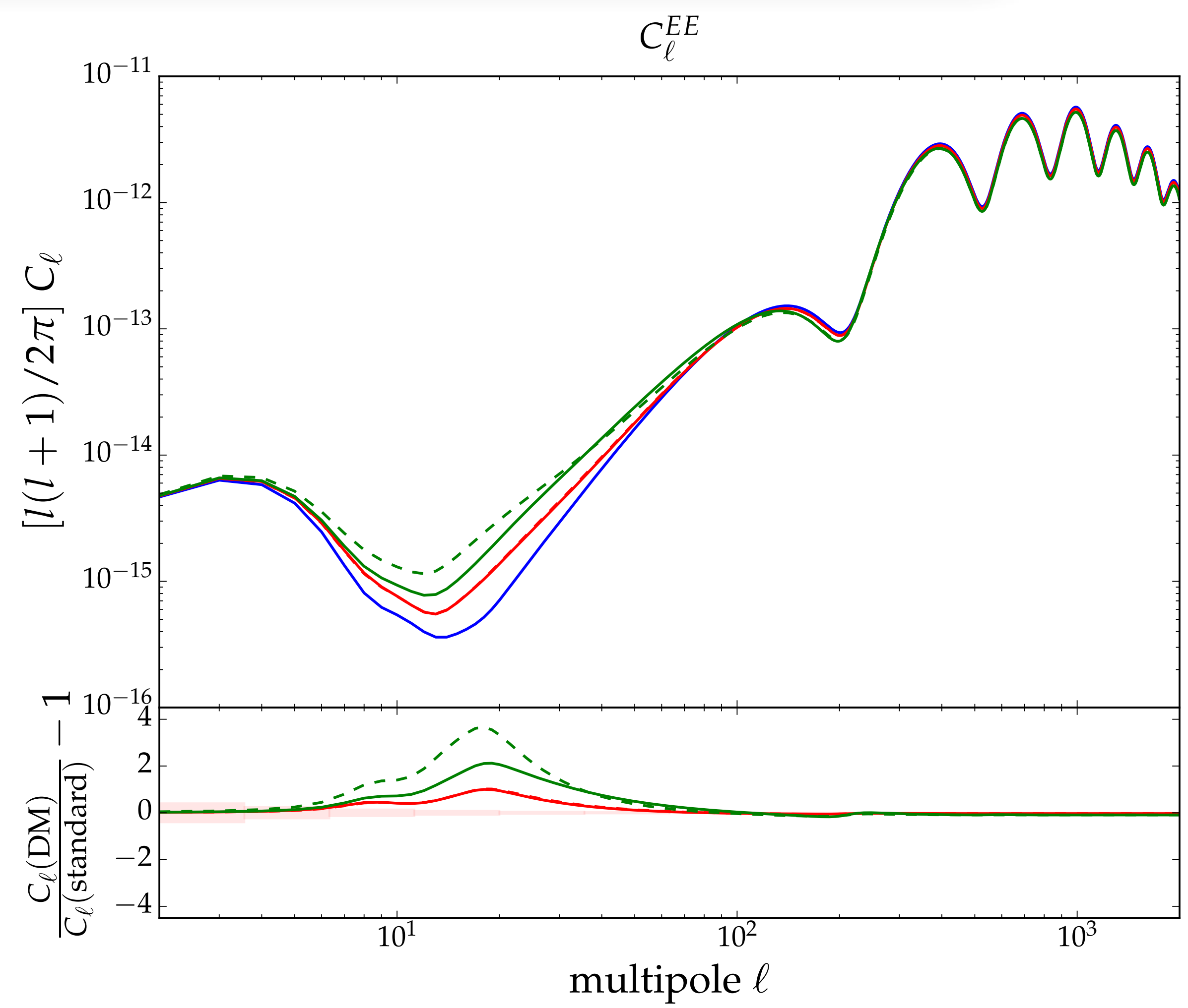


relic decay, C_l's

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

Major physical change is to reionization, since we keep $\exp(-2\tau_{reio})A_s$ fixed (i.e. same suppression at large scales)



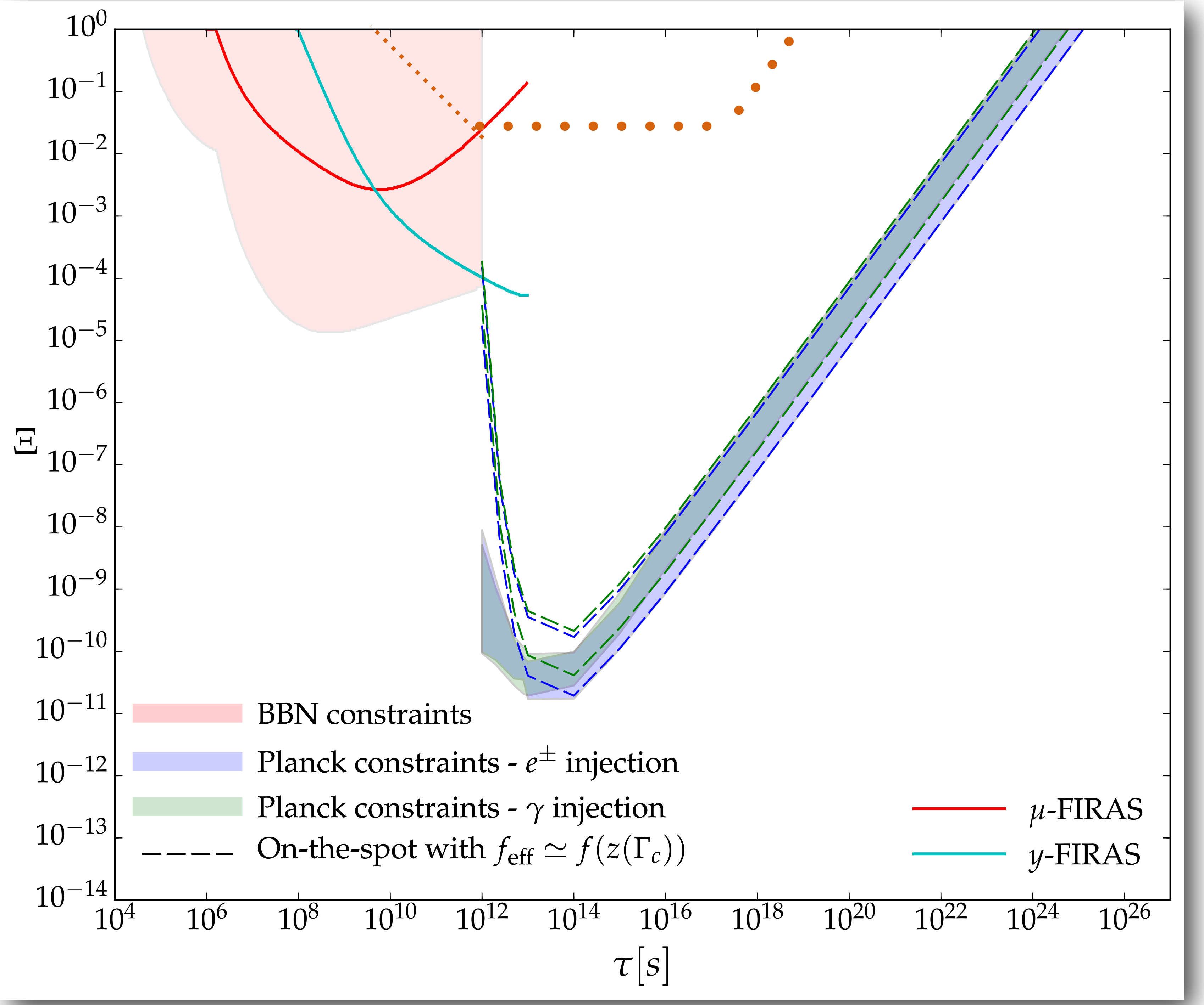


On TT the main effect is visible on the small-scale normalization.

As for EE, effect at relatively large scales (known to be good probe of reionization)

Results

& Complementarity of different probes



Notes:

1) we do reach the 10^{-11} level maximal sensitivity estimated at the beginning, for stuff decaying around recombination time
2) Much better than purely gravitational!
3) Complementarity (timescales and actually energies, too!) with other probes

Bonus Episode

Application to primordial black holes

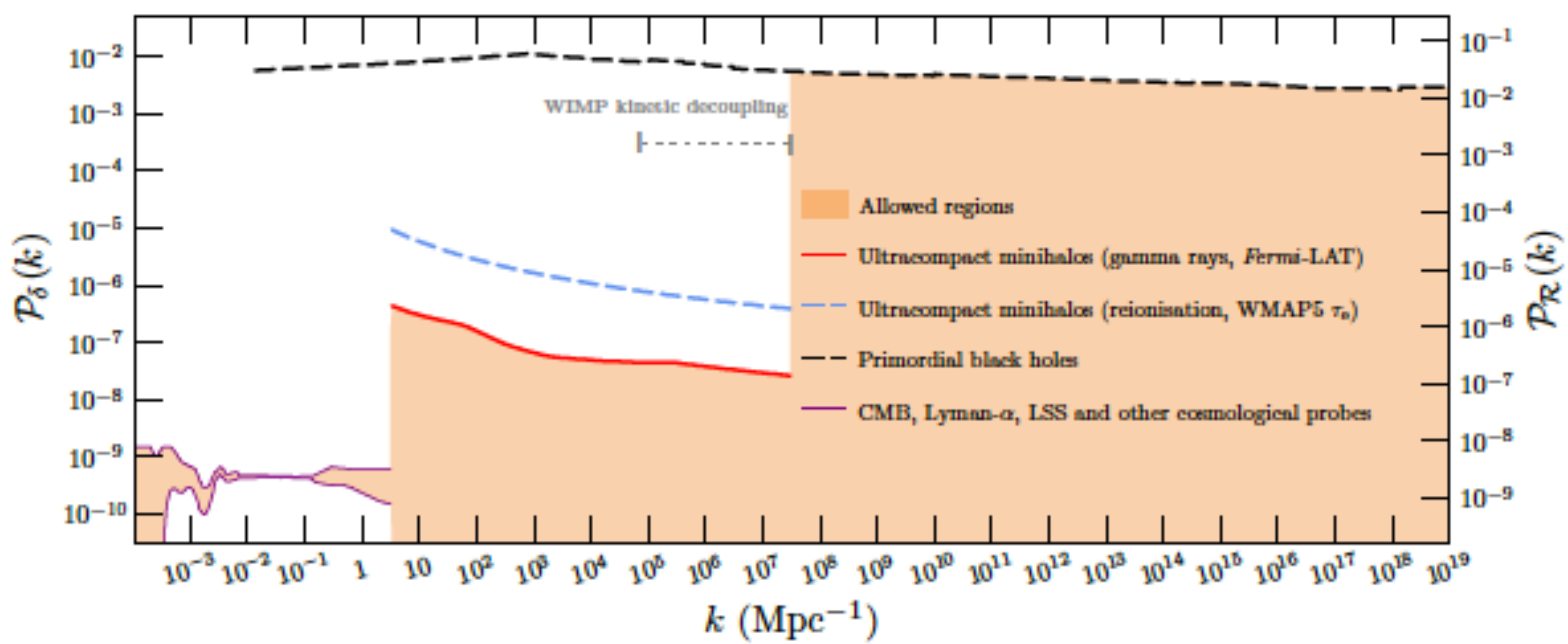
Since I mentioned Primordial Black Holes (PBH):

When thinking of "**early universe relics**" (like CMB photons) we usually think of ***particles***

Yet, PBH (*Zeldovich, Hawking*…) are possibly macroscopic relics which can originate from gravitational collapse of sufficiently large density fluctuations, at scales much smaller ($k \gg$ Mpc^{-1}) than the CMB ones, typically associated to *non-trivial inflationary dynamics or phase transitions* *(the kind of ingredients seen in the previous discussion!)*

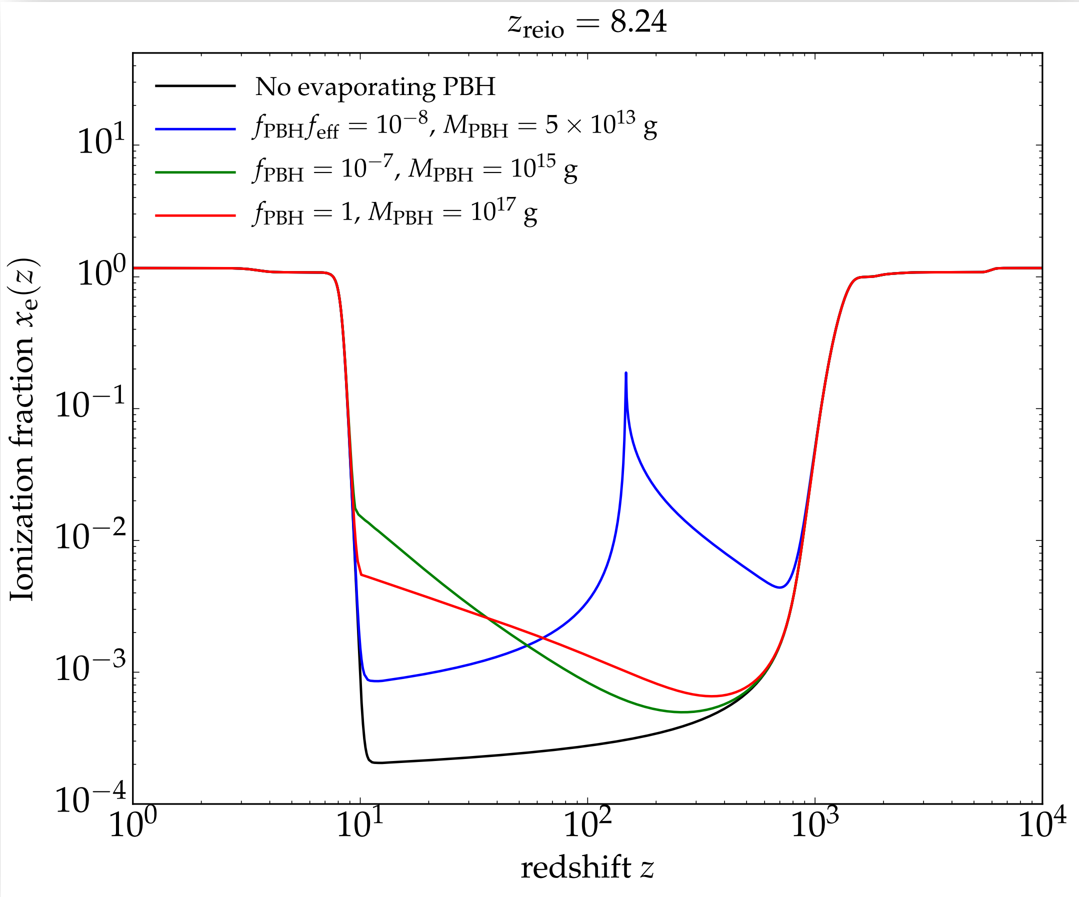
Such scales are almost unconstrained

(avoiding PBH overproduction which would over close the Universe is one of the few bounds)



T. Bringmann, P. Scott and Y. Akrami, Phys. Rev. D 85, 125027 (2012) [1110.2484]

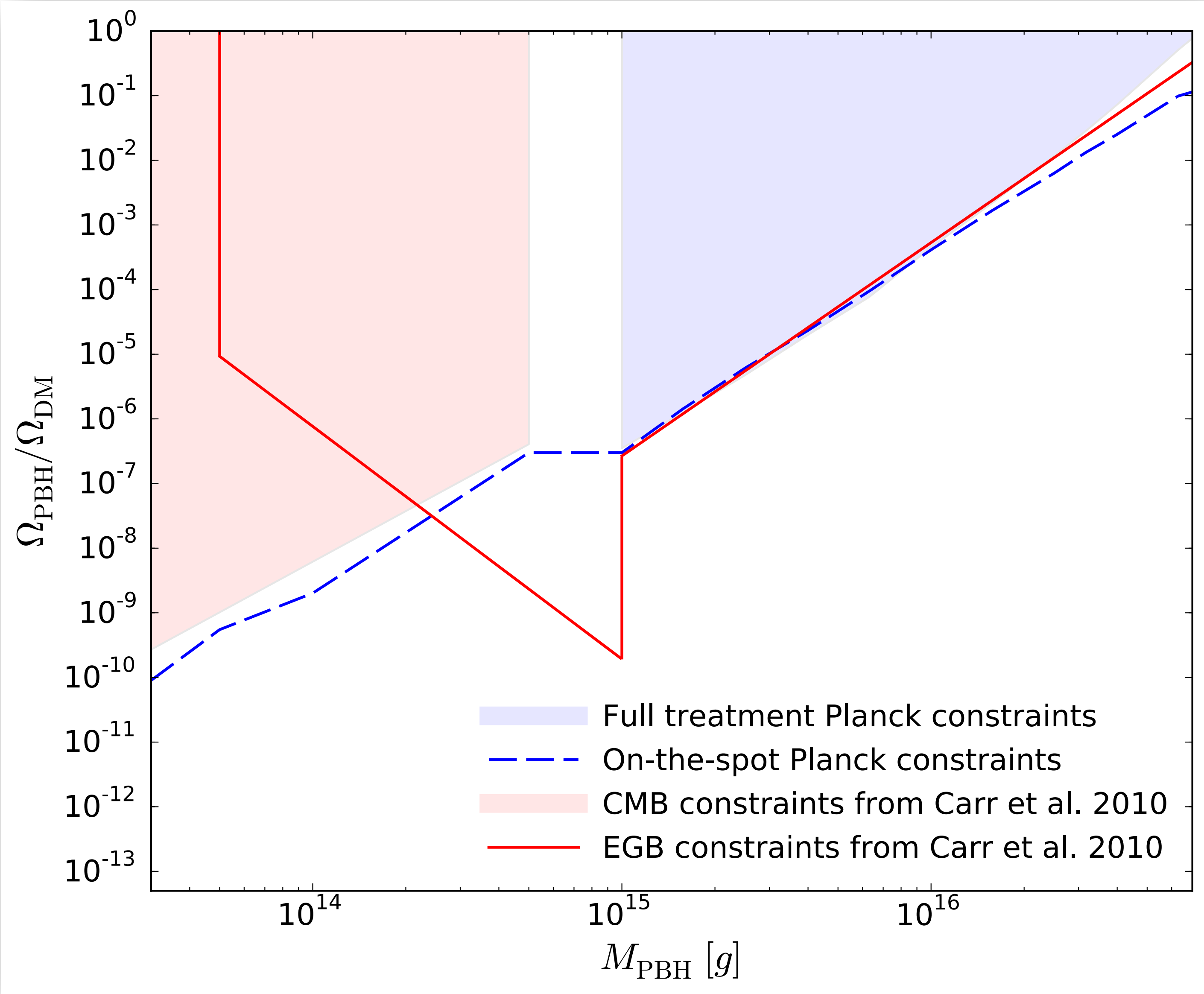
Evaporating PBH effects on x_e & CMB bounds



In particular,"light" PBH evaporation injects e^+e^-, γ… at a rate

$$\frac{dE}{dVdt} = \frac{\Omega_{\rm DM}\rho_c c^2 (1+z)^3 f_{\rm PBH}}{M_{\rm PBH}^{\rm ini}} \left.\frac{dM}{dt}\right|_{\rm e.m.}$$

Peculiar modification of x_e possible



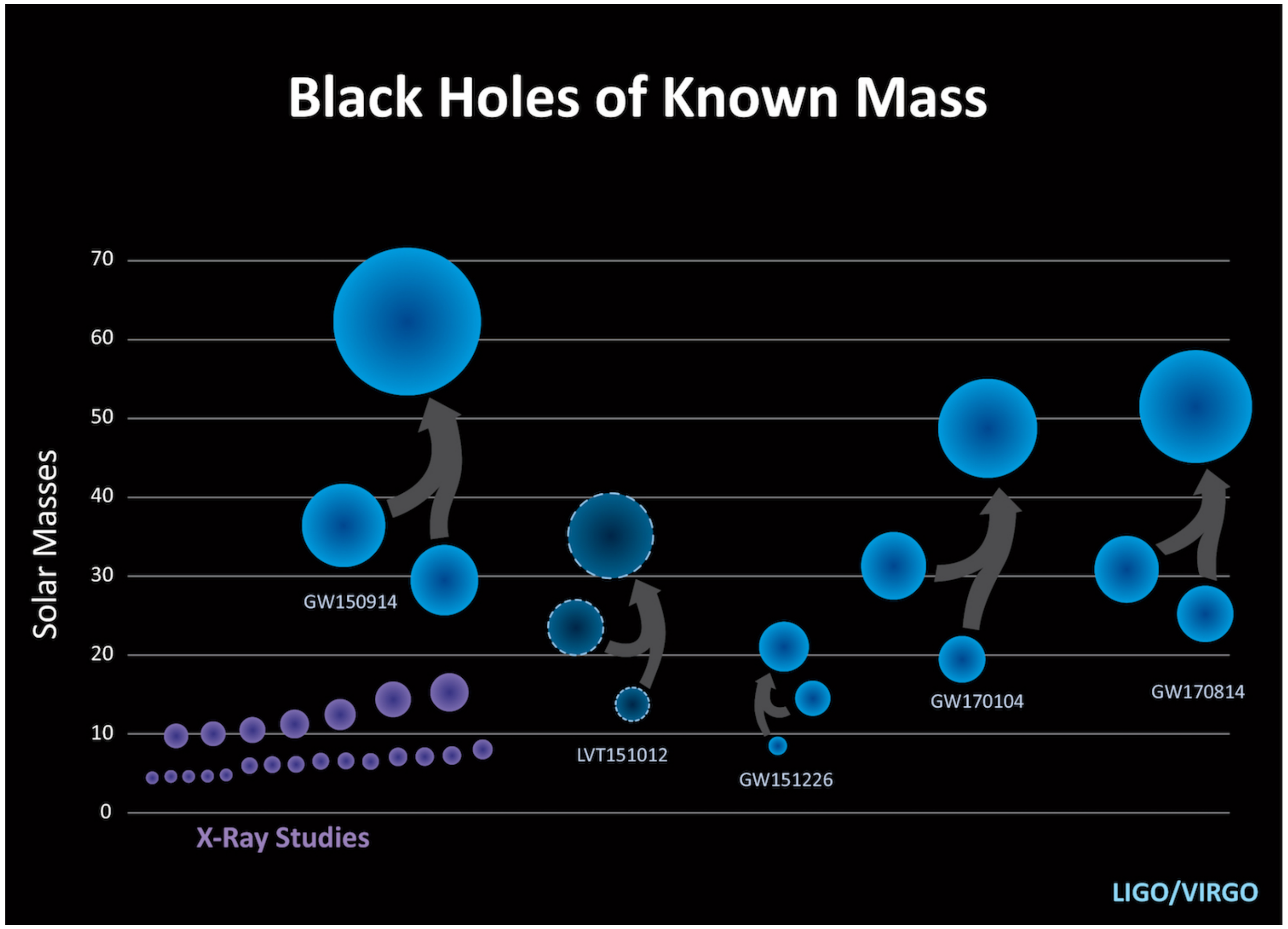
Bounds comparable or better than existing ones from diffuse gamma-ray background, for a certain range of masses

V. Poulin, J. Lesgourgues and P.D.S., "Cosmological constraints on exotic injection of electromagnetic energy," JCAP 1703, 043 (2017) [1610.10051]

Did LIGO detect PBH dark matter?

LIGO/Virgo has detected **relatively massive** BH mergers, starting from the seminal (Nobel-prize worth!)

B.P. Abbott et al. [LIGO & Virgo], PRL 116, 061102 (2016) [1602.03837]



Hypothesis that they are primordial & explain (part of) the DM considered in several papers:

S. Bird et al. "Did LIGO detect dark matter?," PRL 116, 201301 (2016) [1603.00464]
S. Clesse and J. García-Bellido, Phys. Dark Univ. 10, 002 (2016) [1603.05234]
M. Sasaki, T. Suyama, T. Tanaka, S. Yokoyama, PRL 117, 061101 (2016) [1603.08338]
K. Inomata, M. Kawasaki, K. Mukaida, Y. Tada, T.T. Yanagida, PRD 96, 043504 (2017) [1701.02544]
...

If true, this has consequences for the Cosmic Microwave Background!

Accreting PBH & CMB

Mass falling from "infinity to the BH" converts a sizable part of its potential energy into radiative emission, mostly X-rays: Up to 6%-40% of its mass energy, depending on BH spin, most efficient mechanism known in astrophysics! Invoked for powering Quasars, UHECRs, etc.

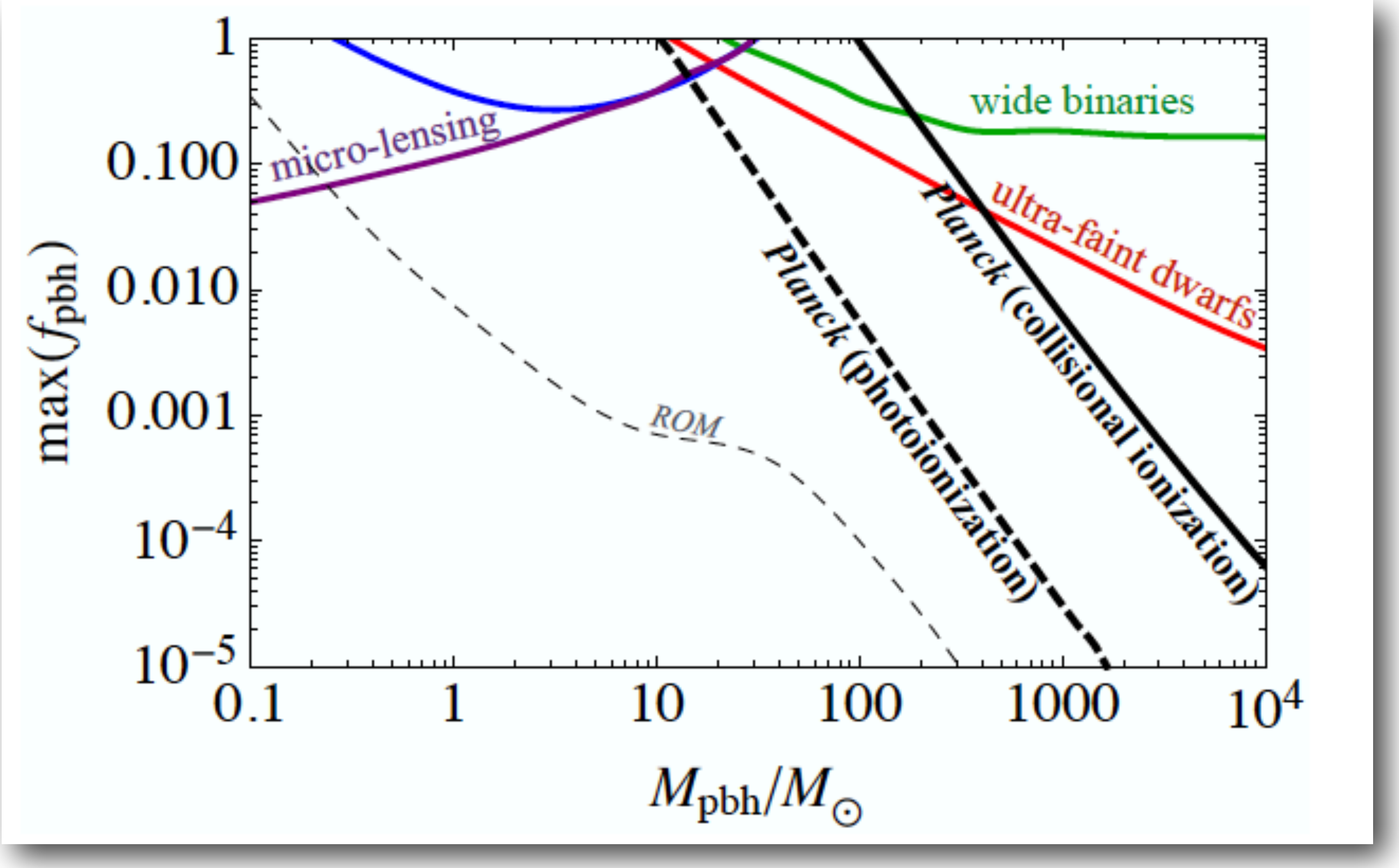
For stellar mass PBH, cosmological gas accreting onto PBH radiates, affecting CMB

Pioneering & stringent bounds obtained a decade ago (*Ricotti et al. 2008*) have been shown to be incorrect & inconsistent.

Y. Ali-Haïmoud and M. Kamionkowski, "Cosmic microwave background limits on accreting primordial black holes," PRD 95, 043534 (2017) [1612.05644]

Conservative bounds for a *spherical accretion* flow yield

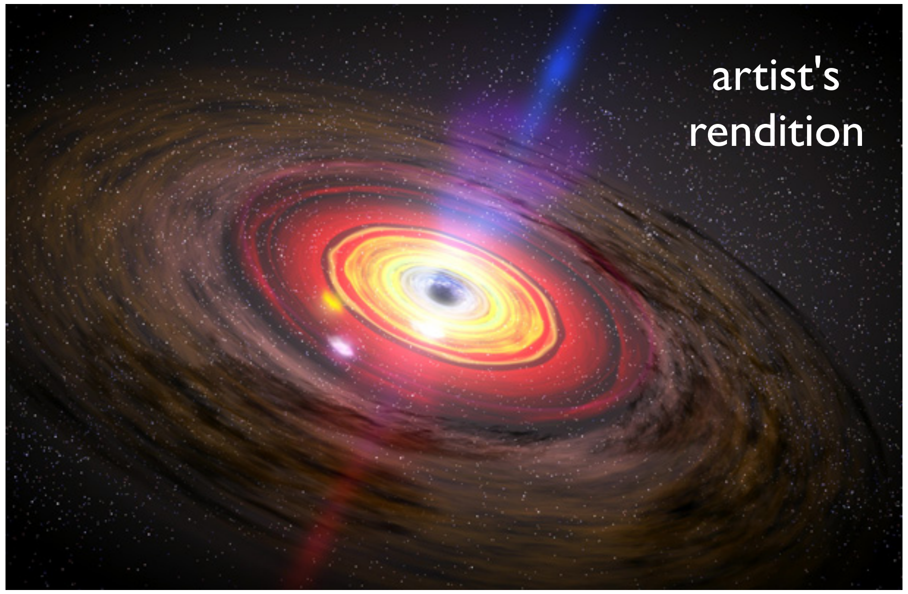
f_{PBH}<1 for M>10-100 $M_{\odot}$



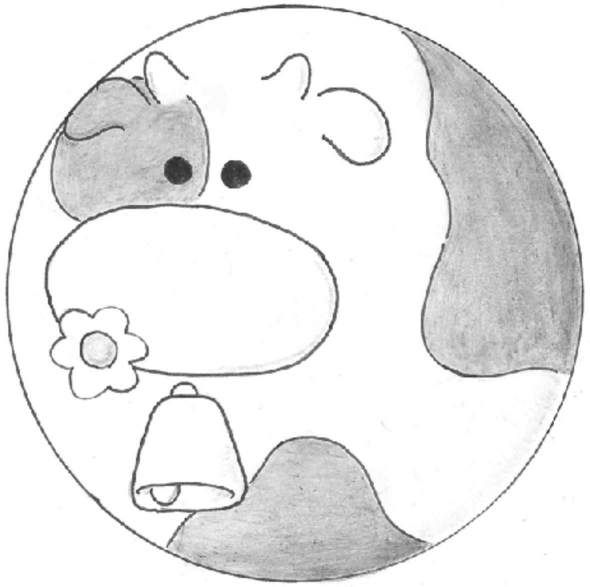
Our Contribution

Little problem:
Nobody has ever seen a BH emission associated to a **spherical** accretion!

Only disks!
Why? Is cosmology different?
Or it's a ***spherical cow*** approximation?



NASA/Dana Berry, SkyWorks Digital



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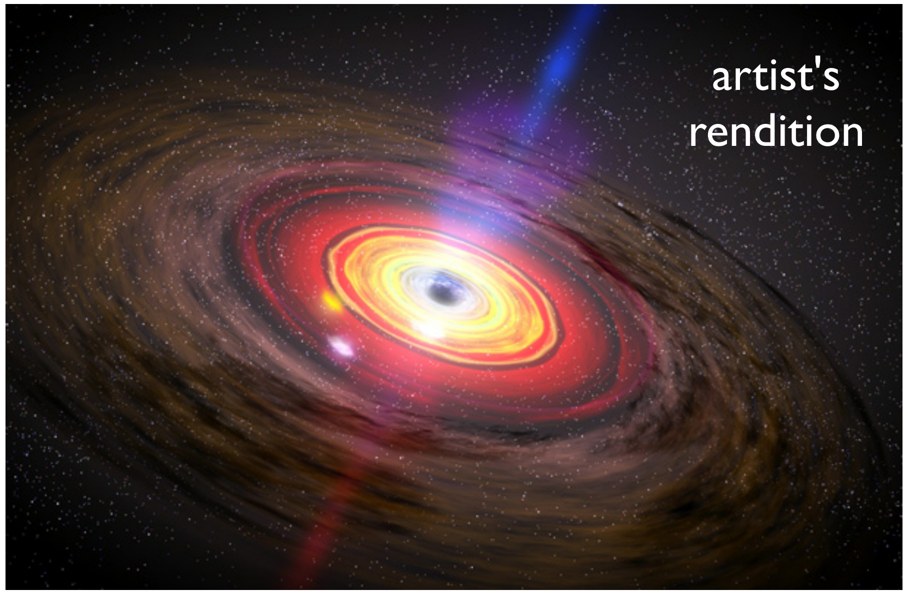

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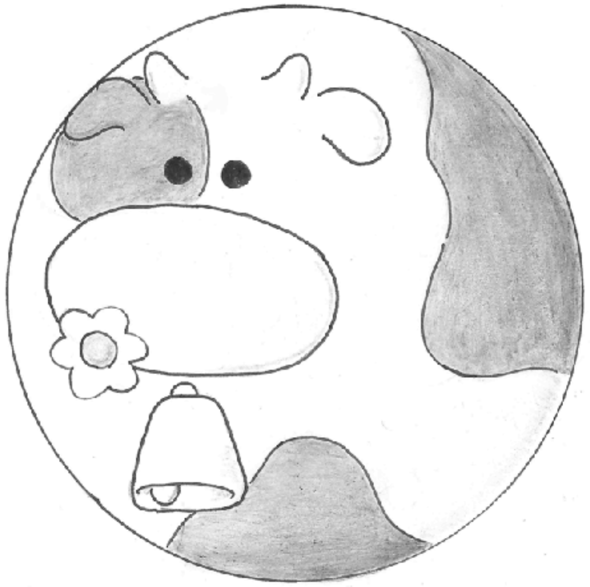

by Christopher Berry

Disk criterion:

If the accreted material has sufficient angular momentum wrt the BH to settle in Keplerian orbit at distance >>3 R_{Schw} then emission is disk-dominated (inner radii dominate the flux)

Criterion going back to *Shapiro & Lightman, ApJ 1976, Agol & Kamionkowski MNRAS 2002…*

The gas-PBH angular momentum cannot be computed exactly, since it depends upon non-linear physics. But several independent arguments (e.g. BH in binaries, supersonic motions) suggest that it is unavoidable to pass this threshold.

Also consistent with BH accretion *disks* being the only kind we've ever seen!

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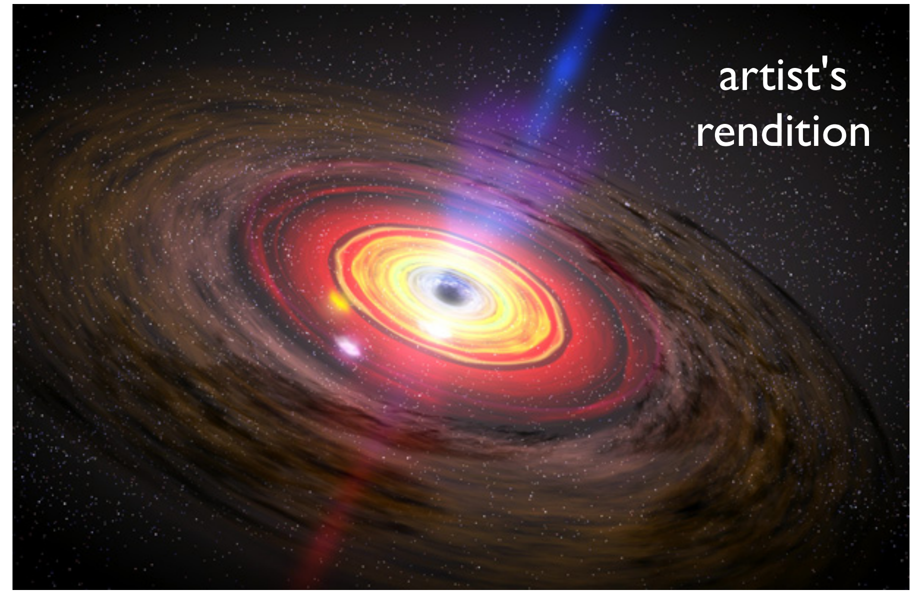

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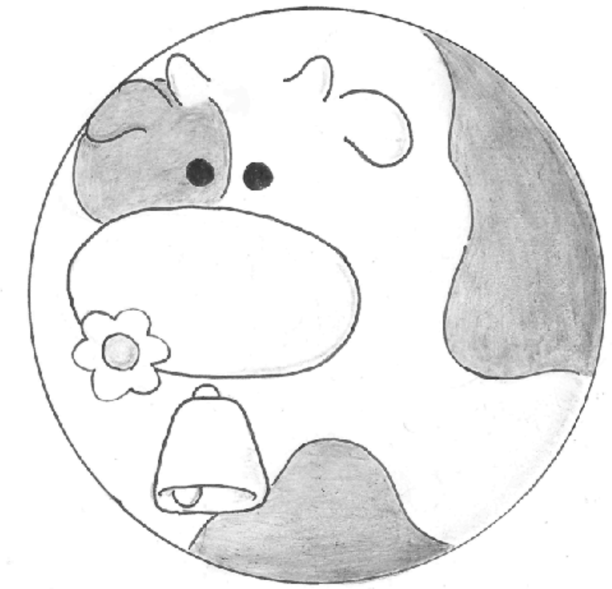

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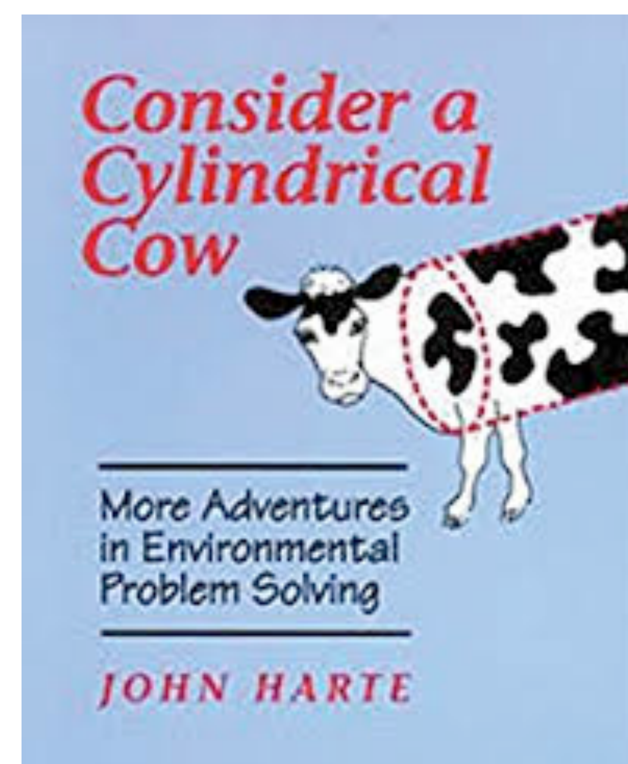
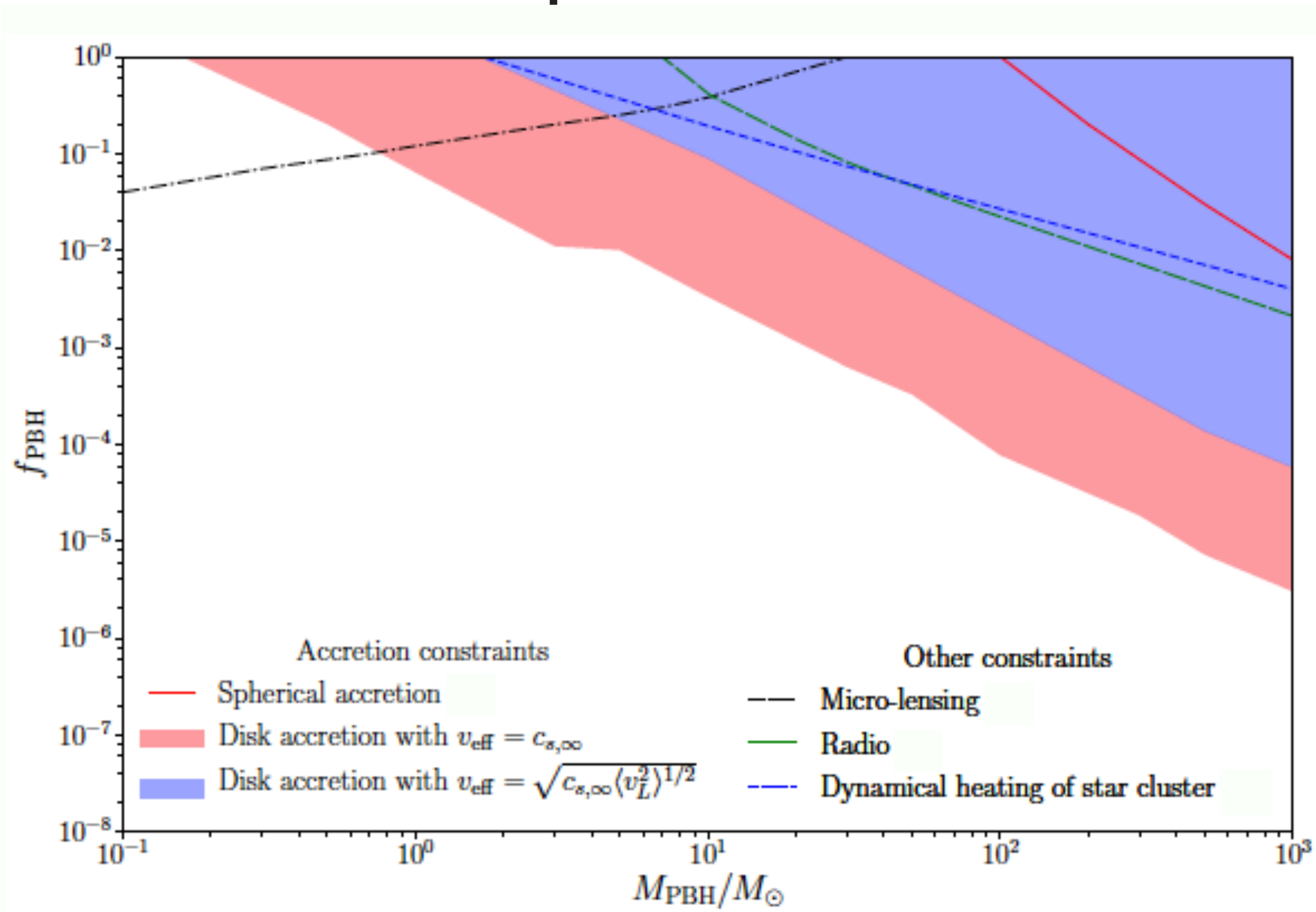
V. Poulin, P. D. Serpico, F. Calore, S. Clesse and K. Kohri, "CMB bounds on disk-accreting massive primordial black holes," Phys. Rev. D 96, 083524 (2017) [1707.04206]



Results: disk vs. spherical accretion results



Much stronger constraints

CMB excludes PBH as totality of DM down to solar masses, when eventually lensing constraints take over.

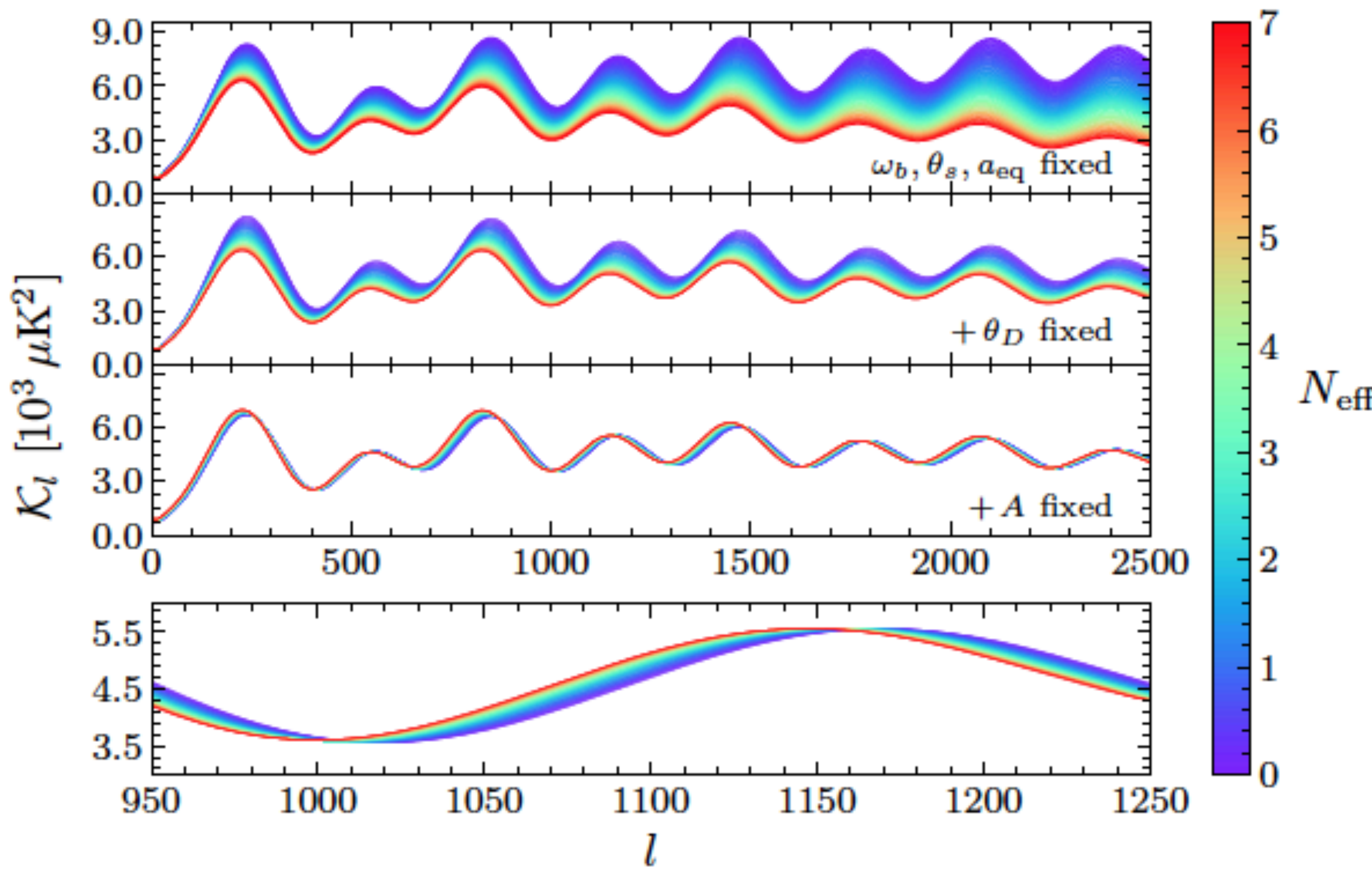
V. Poulin, P. D. Serpico, F. Calore, S. Clesse and K. Kohri, "CMB bounds on disk-accreting massive primordial black holes," Phys. Rev. D 96, 083524 (2017) [1707.04206]

Key message: analytical toy models fail. State of the art "recipes" suggest strong bounds. To check and improve over them, BH accretion in a cosmo context requires dedicated simulations

Episode III

on “dark radiation”: sensitivity and perspectives

Effects of "dark radiation" (neutrino-like) on CMB



D. Baumann, D. Green and B. Wallisch, JCAP1808, 08, 029 (2018) [1712.08067]

If holding the matter-radiation equality fixed, **more dark radiation → increased damping** (*1st panel*)

Partially degenerate with Yp, adjusting it one can fix the damping scale. Still, residual effect!

Dark radiation **free streaming causes anisotropic stress**, leading in turn to

- amplitude shift at small scales (visible in the *2nd panel*)
- Phase shift of acoustic peaks at small scales (visible in *3rd panel*, renormalized at 4th peak; zoomed in *4th panel*)

Standard model expectation and present sensitivity

$$\rho_{\rm DR} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\,\rho_\gamma$$

$$N_{\rm eff}^{\rm SM} = 3.045 - 3.046\;(\text{th. \& num. error} \sim \mathcal{O}(0.001))$$

Non-instantaneous, momentum-dependent decoupling, accounting for finite temperature QED corrections (effective electron and photon masses, that in turn modify the equation of state of the plasma) + neutrino oscillations (act on last digit at most)

G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti and PDS, "Relic neutrino decoupling including flavor oscillations," Nucl. Phys. B 729, 221 (2005) [hep-ph/0506164]

P. F. de Salas and S. Pastor, "Relic neutrino decoupling with flavour oscillations revisited," JCAP 1607, 051 (2016) [1606.06986]
(new code, plus improved treatment of off-diagonal dumping terms in density matrix evolution)

Planck+BAO only allow at 95% CL $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM} \lesssim 0.3$

(Planck I, 2018, 1807.06205)

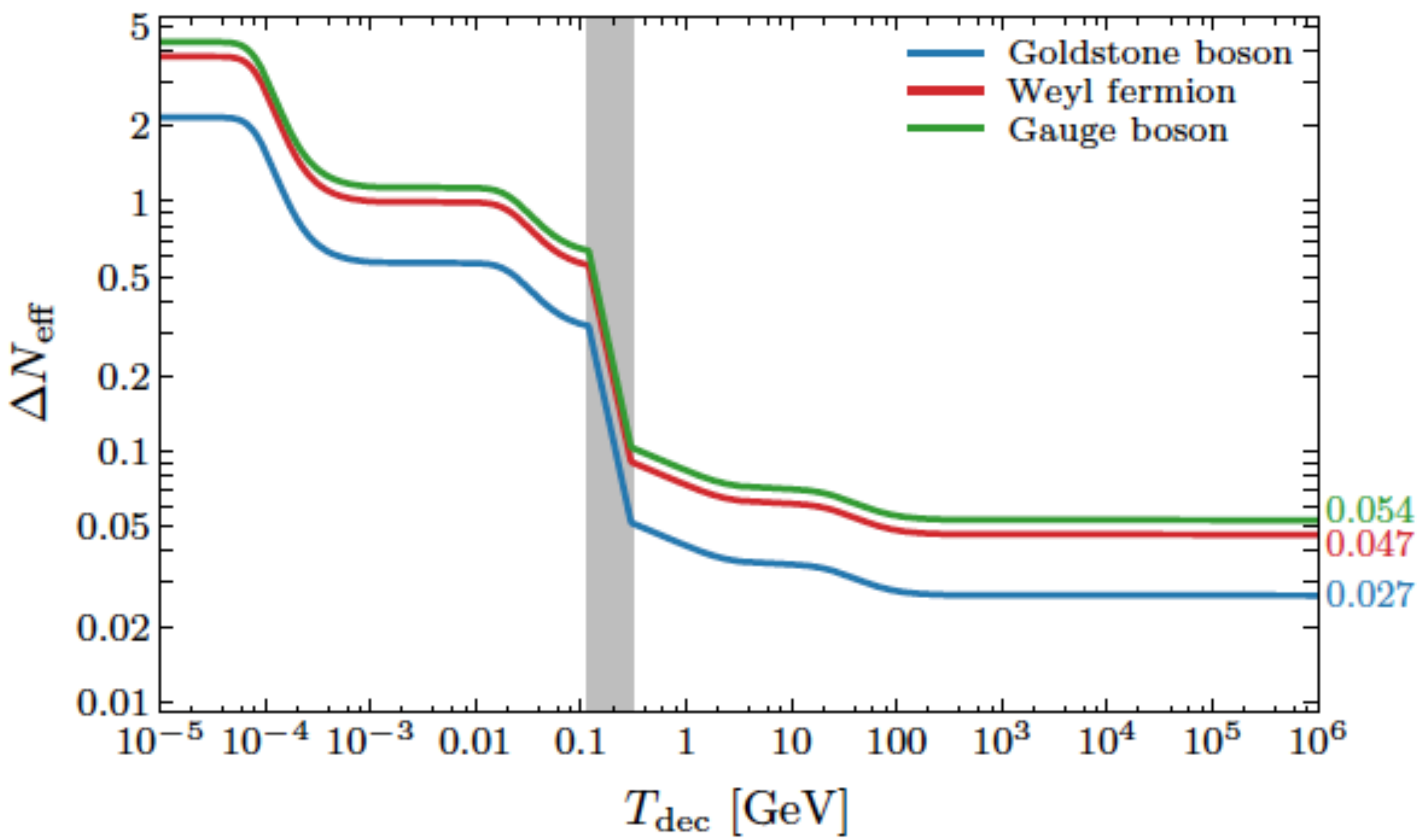
disfavours at 95%CL any light, thermal relics that froze out after the QCD phase transition

Future CMB sensitivity to "dark radiation"

The estimated sensitivity of future ground-based CMB-S4 surveys is about five times better: Should be marginally sensitive to the non-instantaneous ν decoupling & to the presence of any BSM relativistic thermal relic (no matter T_{dec} in the limit where the SM dofs are all there is…)

$$\sigma(N_{\rm eff}) \simeq 0.03$$

D. Baumann, D. Green and B. Wallisch, JCAP1808, 08, 029 (2018) [1712.08067]



summary and conclusions

- Cosmology (and CMB in particular) is sensitive to even extremely suppressed interaction rates of (meta)stable species present in the cosmic soup.

- The example of an **invisible** decay mode of (a fraction of) DM is noteworthy: For instance, it limits to <3.8% the conversion of DM mass into "dark" radiation (like GW, low-E ν's…)

- If even a tiny fraction of the energy stored in the DM mass is released into "visible" (e.m.) form, CMB constraints can be quite tight (due to gas ionization and heating phenomena). DM annihilation, DM decay, evaporating PBH, accreting PBH are examples to which this can be applied

- CMB is also sensitive directly to relic relativistic species (dark radiation): currently excluding any relic decoupling after QCD phase transition, in the future testing for any relativistic relic decoupling before EW phase transition is within reach!

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