CMB BOUNDS ON PRIMORDIAL BLACK HOLES

- *Introduction on PBH*
- *electromagnetic energy injection in CMB*
- *purely gravitational effects on CMB*

https://www.esa.int/gsp/ACT/phy/Projects/Blackholes/WebGL.html

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Primordial Black Holes (PBH)

When we think of "relics from the early universe", we usually think of *particles*

Yet, PBH are hypothetical (possibly macroscopic) relics which can originate from gravitational collapse of sufficiently large density fluctuations, at scales much smaller ($k \gg \mathrm{Mpc}^{-1}$) than the CMB & LSS ones, typically associated to *non-trivial inflationary dynamics or phase transitions*. Such scales are almost unconstrained (avoiding overproducing PBH is one of the few bounds)

The typical PBH mass is a fraction of the mass within the Hubble horizon at the time of production

$$M_{\rm PBH} \lesssim M_{\rm H} \simeq 5\times 10^4 M_\odot \frac{t}{1\,\rm s}$$

As all BH, they are subject to *Hawking evaporation*

$$T_{\rm BH} = \frac{1}{8\pi G M} \simeq \frac{10^{13}\,\rm g}{M}\,\rm GeV \qquad \Gamma^{-1}_{\rm PBH} \simeq 4\times 10^{11}\left(\frac{\mathcal{F}(M)}{15.35}\right)^{-1}\left(\frac{M}{10^{13}\rm g}\right)^3 \rm s$$

($\mathcal{F} \to 1$ at $M > 10^{17}$ g)

For $M > 10^{15}$ g, their lifetime exceeds the one of the universe, and PBH could make part or all of the DM (lighter PBH may still have a cosmological role, e.g. in altering BBN, being involved in baryogenesis, etc.)

The only "SM candidate" for DM

(perhaps with strangelets; both require however BSM in the early universe)

EM BOUNDS

What if a relic injects interacting SM particles?

What happens e.g. to CMB observables?

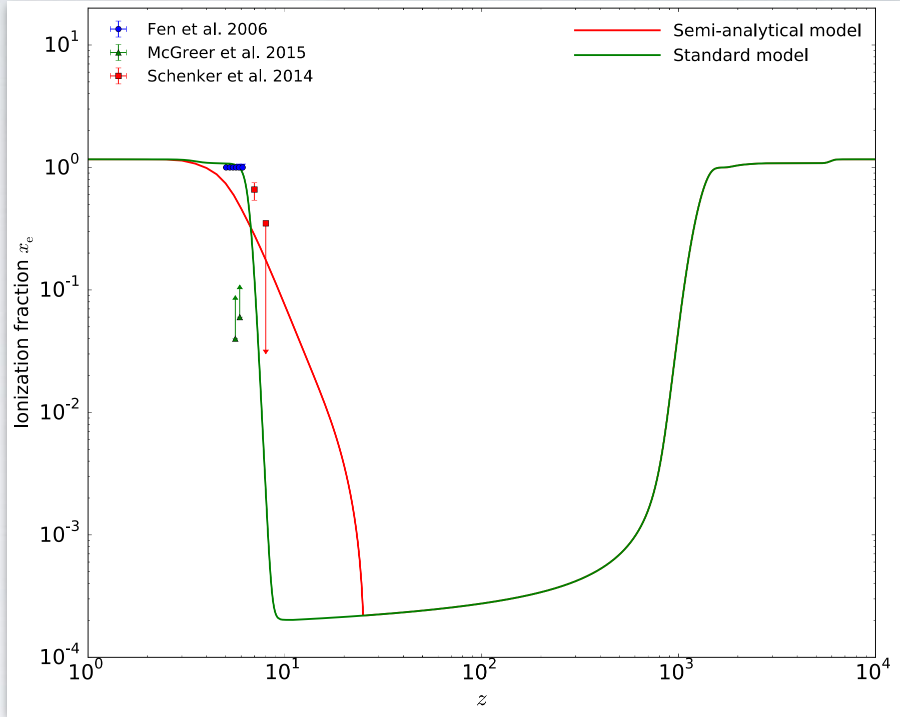
Usually the particles injected are too rarefied:

- to alter sizably the number of CMB photons
- to alter sizably the energy density budget of the universe.
- to induce a sizable probability for a CMB photon to interact with any of them.

But their energy might **not be negligible wrt kinetic energy in baryons** ☞ **heat up** & especially **ionize** the gas!

☞ Alteration in optical depth experienced by CMB photons

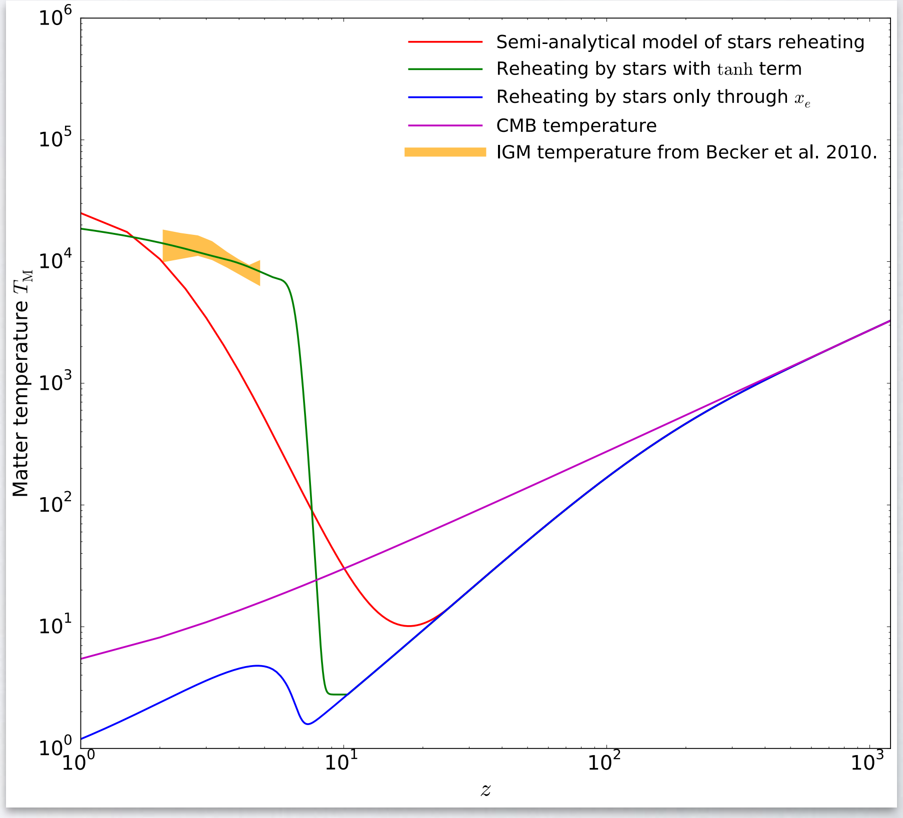
☞ CMB sensitive down to a "visible" DM b.r. of $O(10^{-11})$!



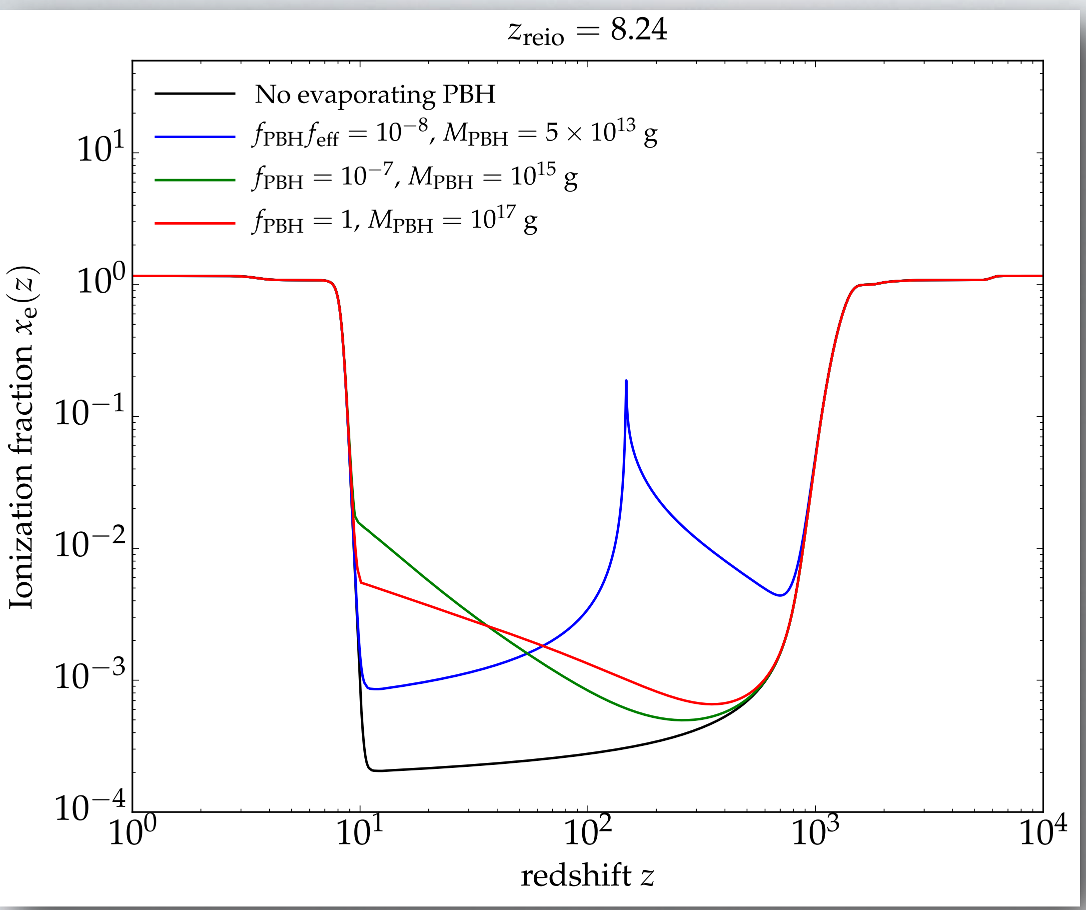
In particular,"light" PBH evaporation injects e^+e^-, γ… at a rate

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

normalized to the fraction of PBH making DM



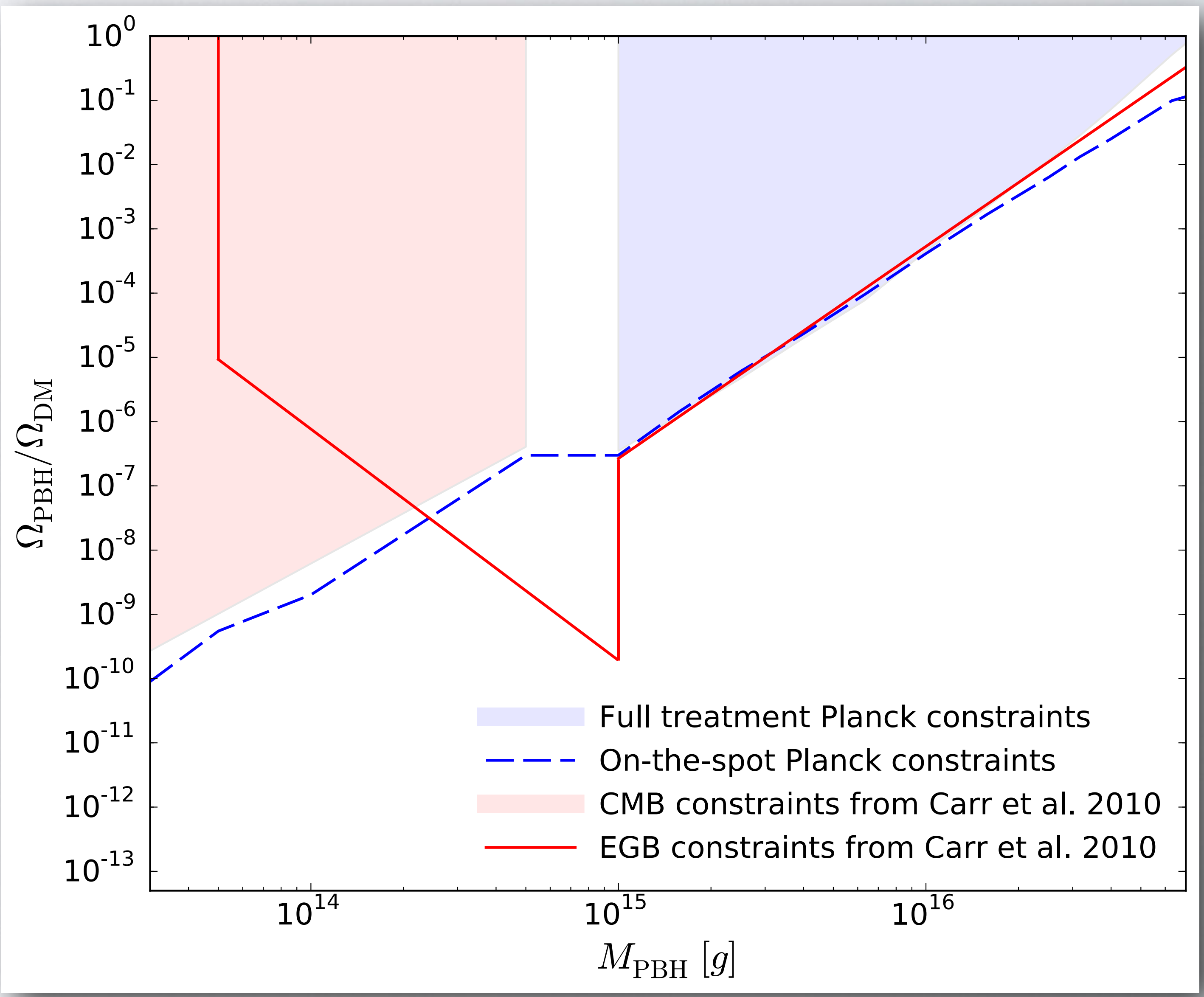
Evaporating PBH effects on x_e & CMB bounds



Peculiar modification of x_e possible, to which CMB is sensitive notably via the optical depth experienced by CMB photons (similar principle to CMB bounds to WIMP annihilation)

computations with suitable modification to the CLASS code

http://class-code.net/



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]

Accreting PBH

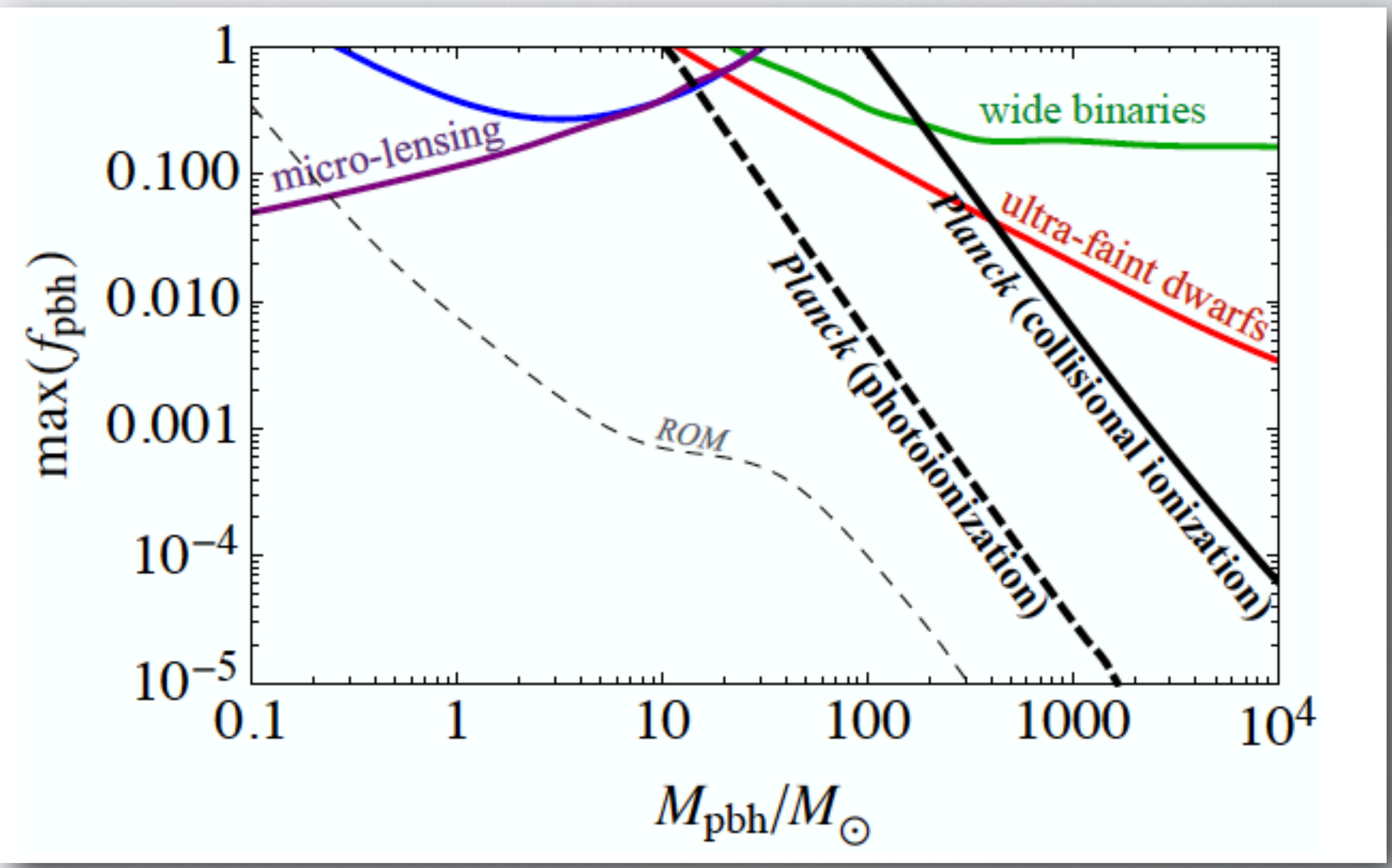
For stellar mass PBH, evaporation is negligible. Yet, a similar e.m. energy injection can happen due to the heating of cosmological, baryonic medium accreting onto PBH

Pioneering bounds obtained a decade ago (Ricotti et al. 2008) been shown to be incorrect and inconsistent.

Most conservative bounds for a spherical accretion flow (still depend if the accreting material has to "lose" some energy to ionize itself, or if this task is achieved by the emitted photons)

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

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



Dropping some assumptions (more realistic) the bounds can improve by up to one order of magnitude
Work in progress, with V. Poulin et al.

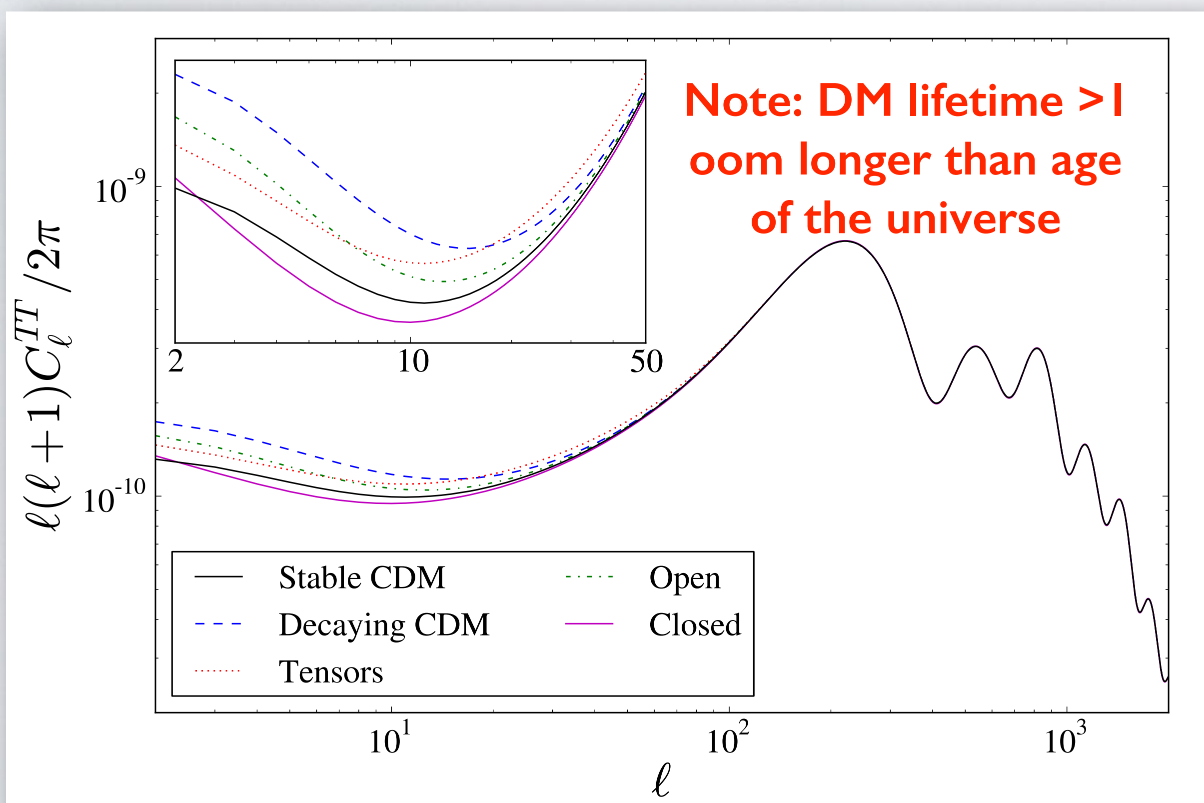
GRAVITATIONAL BOUNDS

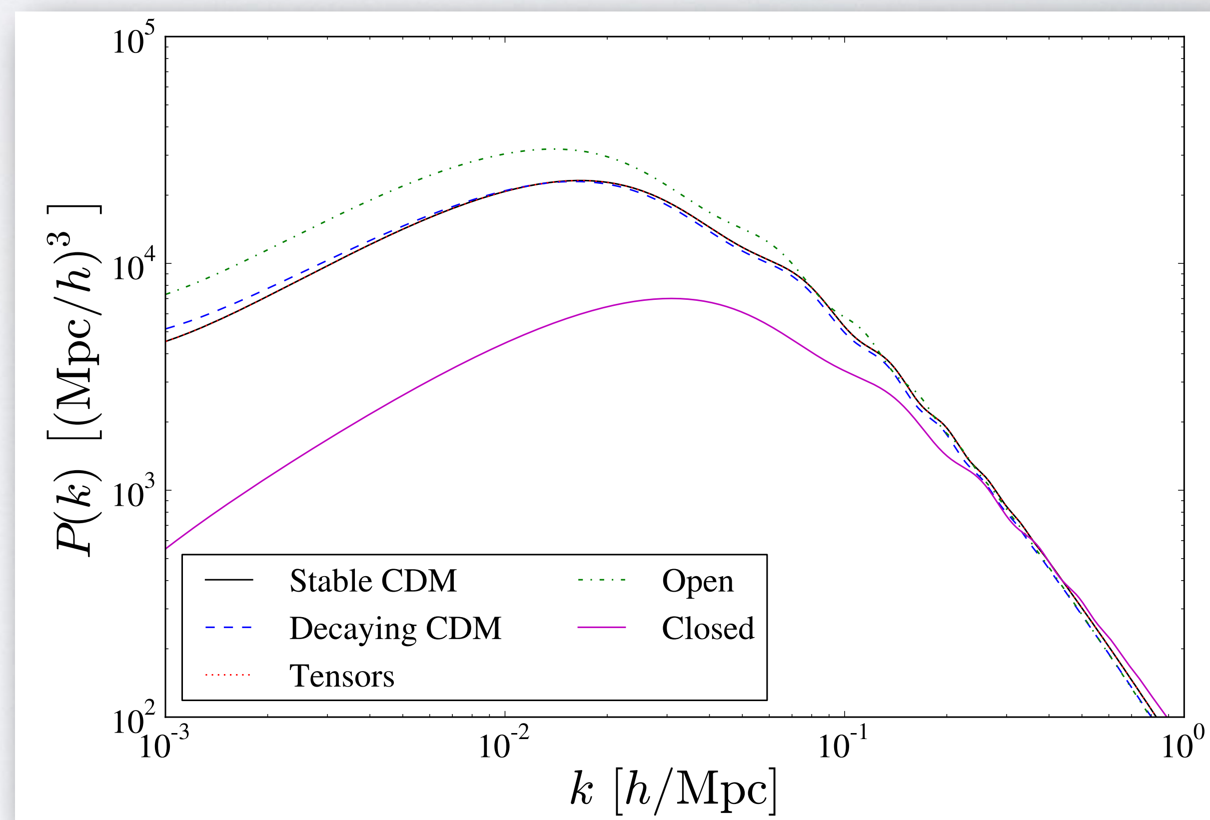
A detour: bound on decaying DM fraction

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

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

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





Case for $f_{\rm dcdm}$=1, from

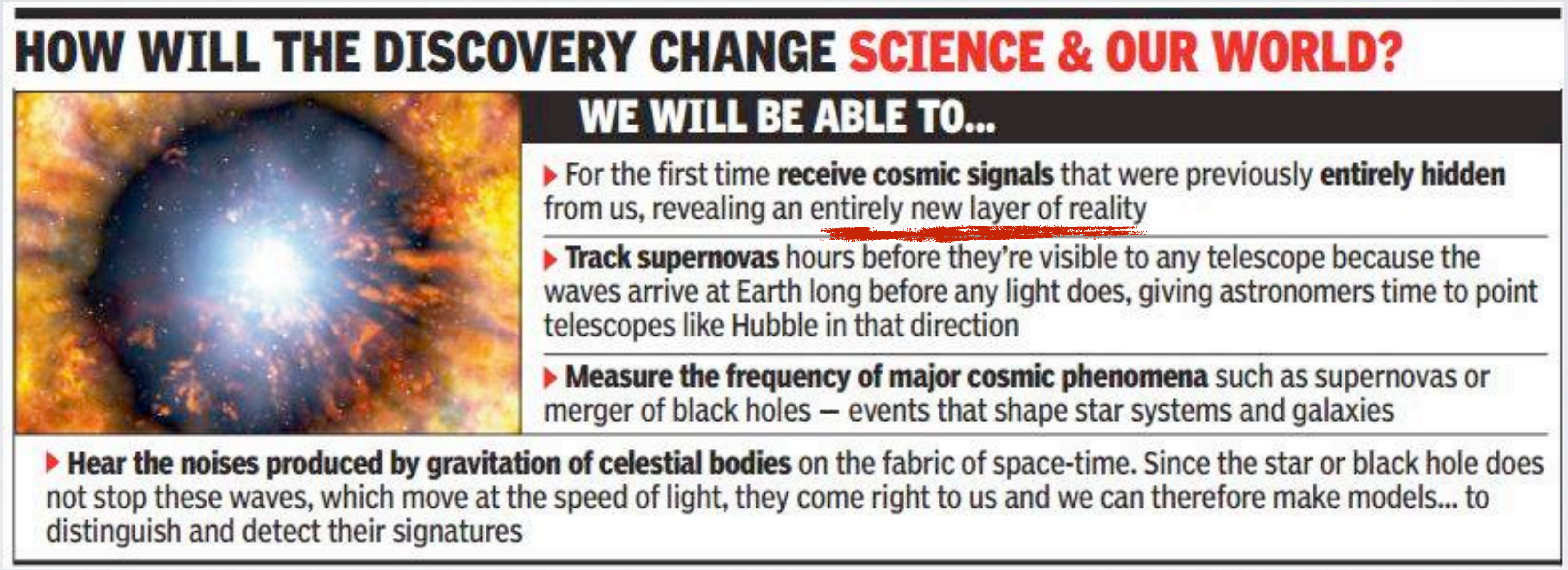
B. Audren et al. JCAP 1412, 028 (2014) [1407.2418]

Current bounds: τ≳160 Gyr (CMB only)

τ≳170 Gyr (with other consistent data)

Did LIGO detect PBH dark matter?

LIGO has detected 2 or 3 relatively massive BH mergers, with *4-5% conversion of mass into GW*



from *Times of India*

This conversion factor also turns out to be consistent with expectations, e.g.:

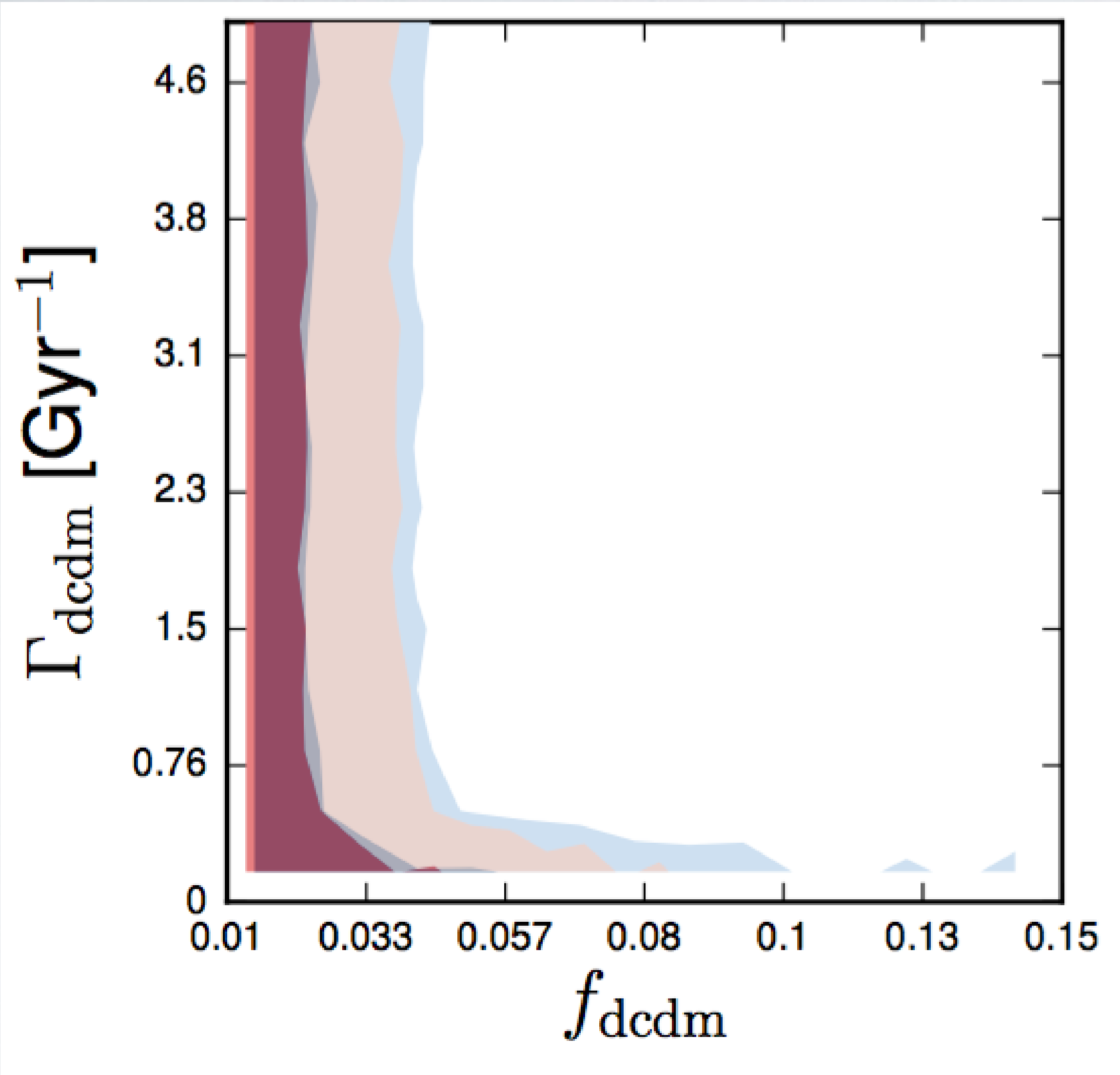
there is broad consensus that the merger of two equal mass Schwarzschild BHs produces a final remnant BH with spin a~0.7 M, and that the amount of energy radiated in the form of gravitational waves […] is ~0.04 M

J. M. Centrella, "The Final Merger of Comparable Mass Binary Black Holes," astro-ph/0609172

The hypothesis that these objects are of primordial origin & responsible for the DM of the universe has been considered, recently, in a number of 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 and S. Yokoyama, PRL 117, 061101 (2016) [1603.08338]
K. Inomata, M. Kawasaki, K. Mukaida, Y. Tada and T.T. Yanagida, 1701.02544
…

CMB also constrains PBH gravitationally!



CMB bounds ~ independent of lifetime between recombination and recent times, so also apply to a fraction of DM converting into "invisible radiation" with a complicated t-dependence in this period.

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

Application: one promising way to evade PBH DM bounds recently invoked is to assume that a sizable evolution of the mass function takes place (e.g. born sub-solar, thus evading CMB constraints from reionization, merging to tens of $M_\odot$, to evade lensing).

Alternatively, clustering of PBH could be used to increase their merger rate to match LIGO…

This bound excludes that >3.8% of DM (of any mass) has converted into any invisible radiation (thus including GW), over the whole history from recombination to now!

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

(essentially no more than 1 merger in a Hubble time in average)

Summary & conclusions

- DM has only been "discovered" gravitationally & cosmological observations are the only ones that provide evidence for its BSM nature. It is hence sensible to look for CMB (& other cosmo) signatures not only of "vanilla" WIMP models, but also of more exotic DM candidates, like PBH

- 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):

  – For "light" PBH (around 10^{15} g) whose lifetime via *evaporation* is within a few orders of magnitude of the Universe one, these are competitive with existing ones and sometimes stronger.

  – For Stellar mass PBH, similar bounds follow from the *accretion* phenomenon, and *exclude PBH DM at least for* $M>100\,M_\odot$. Actual bounds could be one order of magnitude stronger or more, depending on astrophysical and radiative physics details.

- CMB can also impose purely gravitational bounds:

  – For instance, it limits to <3.8% the conversion of DM mass into "dark" radiation (like GW) excluding scenarios where DM PBH (*of any mass*) have undergone more than ~1 merger in the lifetime of the Universe, on average

  – Other purely gravitational but model-dependent bounds exist, not discussed here

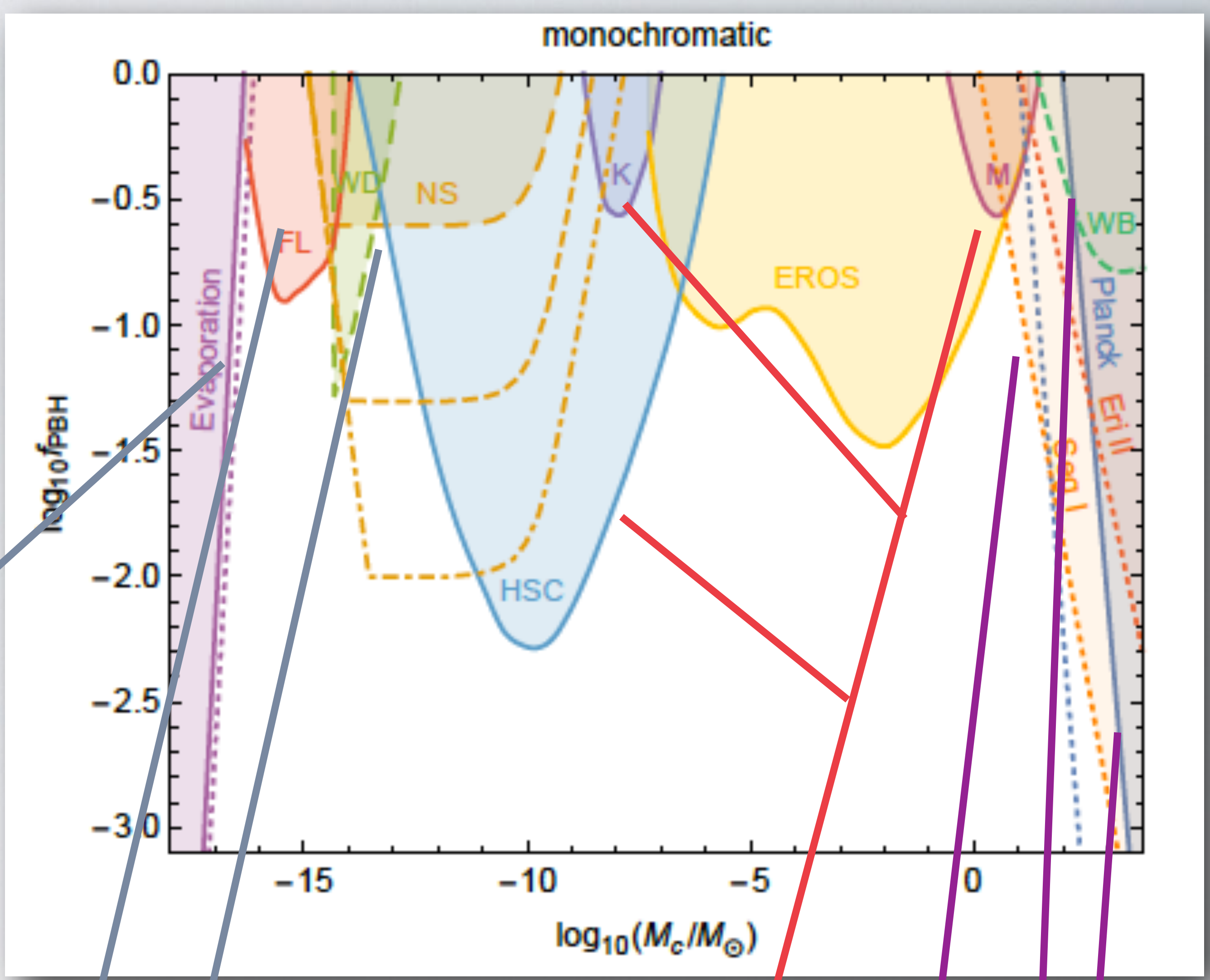
- Future CMB missions (Core-like) or 21 cm tomography (e.g. SKA) can further improve sensitivity

THANK YOU FOR YOUR ATTENTION!

BACKUP SLIDES

A number of bounds exist

Plot from B. Carr et al., 1705.05567



BH evaporate (emitting gamma-rays) on times comparable or shorter than lifetime of Universe

BH would induce "interferometry" pattern in the energy spectrum of lensed GRBs

PBH capture in stars catalyze fast conversion in BH, while "old" evolved objects like WD or NS are observed (DM-density dependent bound)

direct searches via micro-lensing in our Galaxy, M31… (do not strictly require them to be BHs)

other astrophysical and especially cosmological bounds

SETTINGS FOR COSMO BOUNDS

$$(\theta_s, \omega_b, \omega_{\rm cdm}^{\rm ini}, z_{\rm reio}, A_s e^{-2\tau}, n_s)$$

Planck 2015
TT,TE,EE+low-P

We keep fixed: abundance $\omega_b \equiv \Omega_b h^2$, the amplitude of primordial perturbation accounting for the late-time absorption $\exp(-2\tau_{\rm reio})A_s$, the index of the primordial perturbation spectrum n_s, the redshift of reionisation $z_{\rm reio}$ and the angular size of the sound horizon θ_s.