Cosmic microwave background bounds on PBH
(including dark matter halo accretion)

based on PDS, V. Poulin, D. Inman and K. Kohri, arXiv:2002.10771
(and V. Poulin et al. PRD 96, 083524 (2017))

On-line "**Newton 1665**" seminar, 23/03/2020

Pasquale Dario Serpico (LAPTh - Annecy, France)

Outline

- Introduction to PBH and generalities on impact on the CMB
- Parametrizing the impact of PBH: Accretion and luminosity efficiency
- The role of dark matter (DM) halos around PBH
- Results

About Primordial Black Holes (PBH)

PBH from gravitational collapse of sufficiently large density fluctuations,
at scales much smaller than the CMB ones (*Zeldovich & Novikov 67, Carr & Hawking 74, Carr 75…*)

Associated to non-trivial inflationary dynamics and/or phase transitions
(change of EOS, string loops, bubble collisions…)

Simple argument:
free-fall time of a density perturbation of Hubble size shorter than pressure counterbalance timescale

$$\tau_{\rm fall} < \tau_{\rm press} \Leftrightarrow \frac{\delta\rho}{\rho} \gtrsim \mathcal{O}(1) c_s^2 \simeq \frac{1}{3}\,(\mathrm{RD})$$

where

$$\tau_{\rm fall} \simeq (4\pi G\delta\rho)^{-1/2}$$

$$\tau_{\rm press} \simeq \frac{R_H}{c_s} \simeq \frac{\sqrt{3}}{c_s\sqrt{8\pi G\rho}}$$

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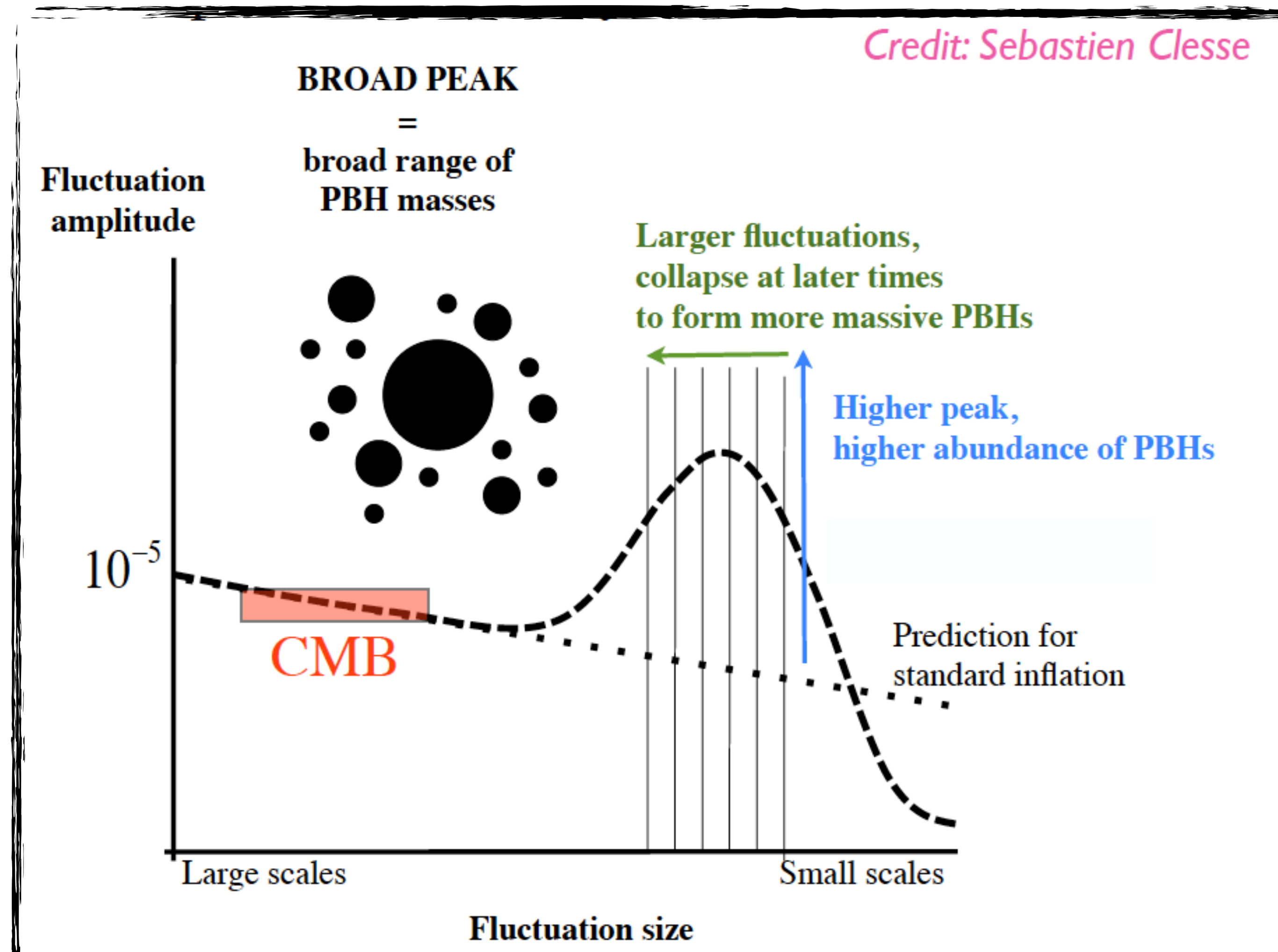
$$M_{\rm PBH} \sim M_H\Big|_{\rm cross} \sim \rho H^{-3}\Big|_{\rm cross} \propto H^{-1}\Big|_{\rm cross} \propto k_{\rm peak}^{-2}$$



Requires density contrast >> CMB-level ones!
(early matter phase would help, too!)

PBH & CMB

Bounds from the peculiar power spectrum at small scales

e.g. energy stored in small-scale density perturbations dissipated diffusively
→ ***spectral*** distortions of CMB (tight bounds for $10^4\, M_\odot \lesssim M \lesssim 10^{13}\, M_\odot$)

Chluba et al., ApJ. 758 (2012) 76; Kohri et al. PRD90 (2014), 083514

mode-mode coupling (non-Gaussianity) makes large (CMB) scales sensitive to
the small-scale *isocurvature* modes associated to PBH
(e.g. PBHs excluded as DM candidates even for very small local-type $|f_{NL}| \approx 0.001$)

Tada & Yokoyama, PRD 91, 123534 (2015)
Young & Byrnes, JCAP 1504 (2015), 034

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PBH-specific bounds

PBH of small masses can evaporate into SM particles
(phenomenologically relevant at $M \lesssim 10^{17}\,g \sim 10^{-16}\,M_\odot$)

Hawking, Nature 248 (1974) 30-31

PBH of stellar masses can accrete matter, leading to energetic photon emission

Ricotti et al., ApJ. 680 (2008) 829
Ali-Haïmoud & Kamionkowski, PRD 95 (2017), 043534

Impact on CMB anisotropies of energetic particles injected at high-z

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

Key notion

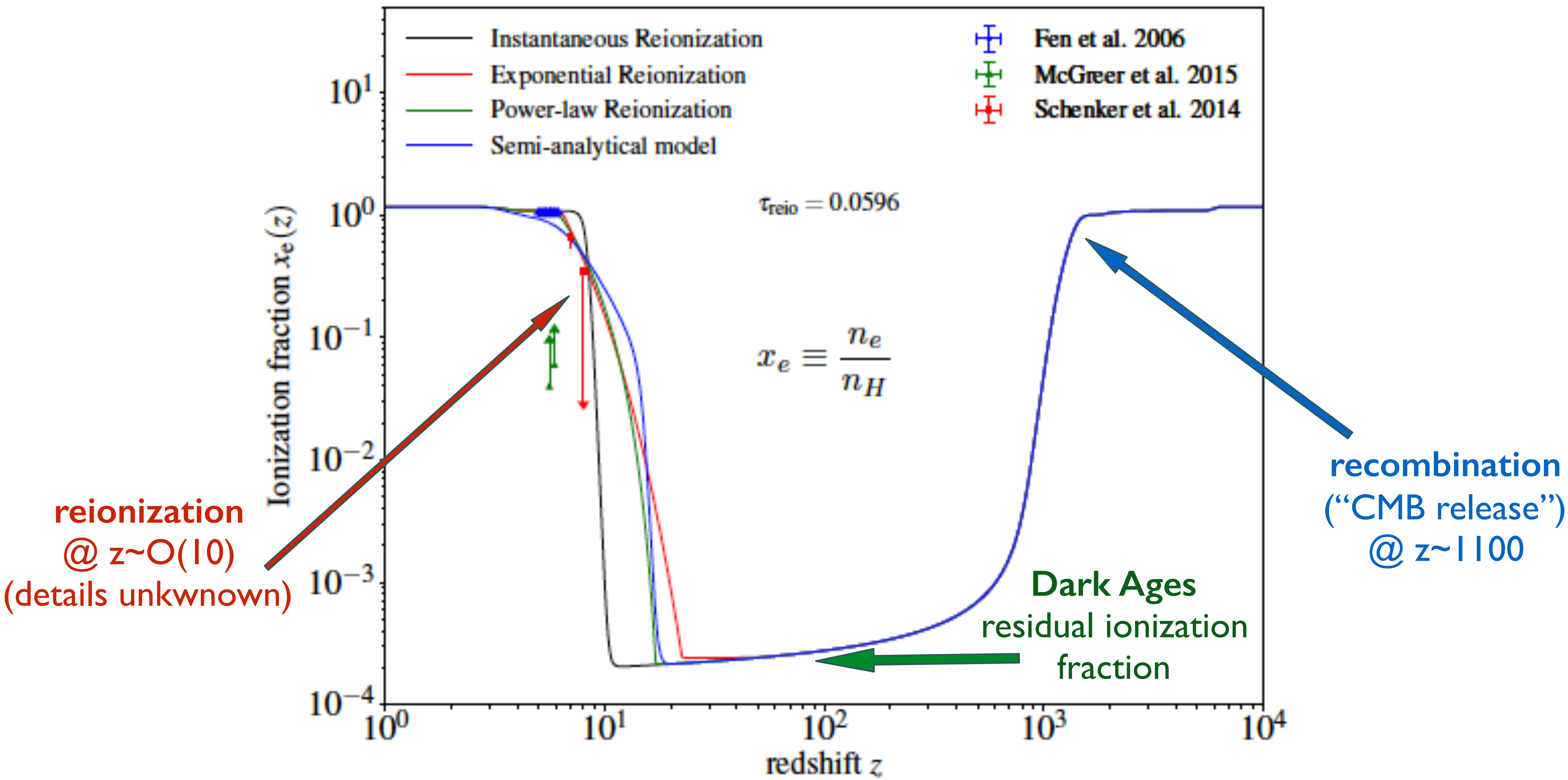
the energy of the injected non-thermal particles, even if negligible wrt ρ_γ, is **not negligible wrt the kinetic energy of the baryonic gas.** These particles can eventually **heat up** (alter T_M) and especially **ionize the gas** (alter x_e)

→ **CMB anisotropies very sensitive to that!**

(Technically, via alterations to optical depth and its time dependence/visibility function)

The three epochs affected

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

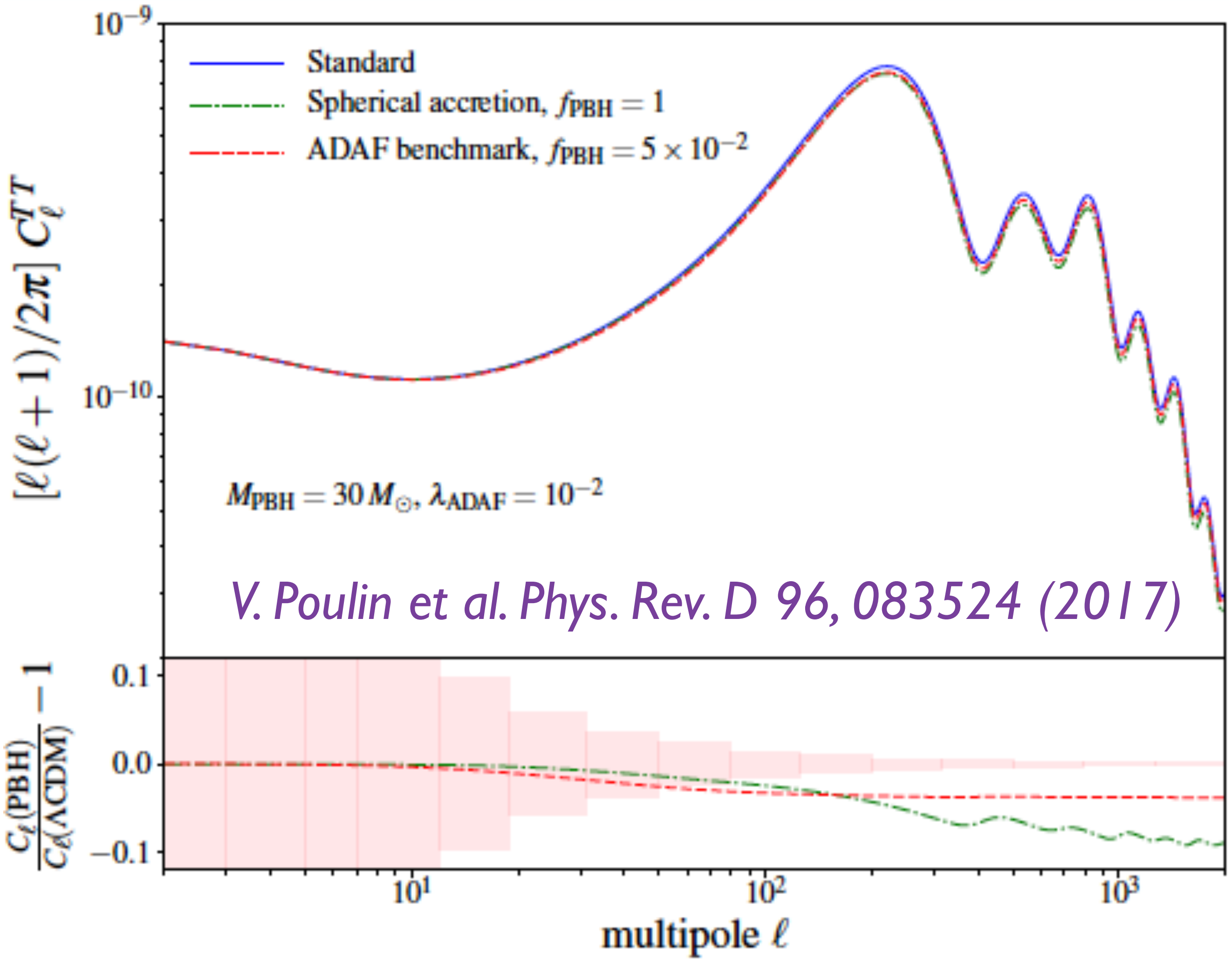


optical depth

$$\kappa(z) = \sigma_T n_{e,0} \int_0^z \mathrm{d}z' \frac{\mathrm{d}t}{\mathrm{d}z'} (1+z')^3 x_e(z')$$

E-deposition module interfaced via Boltzmann CMB solver dealt with via ExoCLASS *see 1801.01871*

Effect on CMB anisotropies



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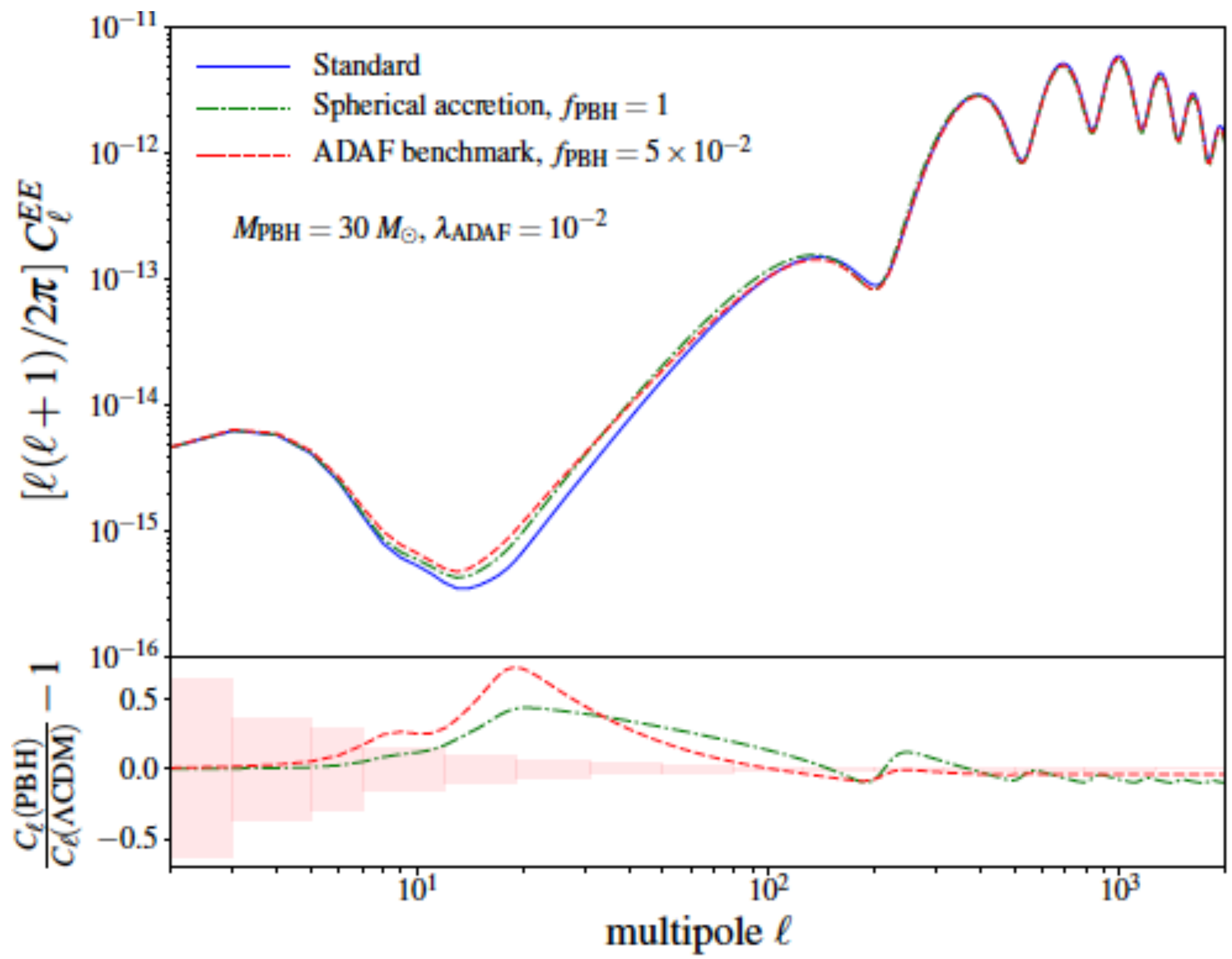

Delayed recombination: shift peaks and damping tail enhanced

Early reionization: step-like suppression and reionization bump enhanced

further details in *Poulin, Lesgourgues, PS JCAP 1703 (2017), 043*

Accretion, $\dot{M}$

Problem of accretion onto a point mass M is old (but no general solution!)

Steady state

Infinite & cold gas cloud, moving at v_{rel}

$$\dot{M}_{\rm HL} = 4\pi\rho_\infty \frac{(GM)^2}{v_{\rm rel}^3}$$

Hoyle & Littleton '39,'40

Up to a factor 2 smaller in presence of density inhomogeneities/wake account

Bondi & Hoyle '44

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accretion at rest, including pressure

$$\dot{M}_{\rm B} = 4\pi\lambda\rho_\infty \frac{(G\,M)^2}{c_{s,\infty}^3}$$

Bondi '52

$c_s^2=\delta P/\delta\rho$

λ~O(0.1-1) accretion eigenvalue comes from solving steady-state problem, depends on EOS & cooling/drag.

most recent solution in the cosmological setting

Ali-Haïmoud & Kamionkowski, PRD95 (2017), 043534

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Both can be parameterized as

$$\dot{M} = 4\pi\lambda_{\rm eff}\rho_\infty v_{\rm eff} r_{\rm B,eff}^2 \quad \text{where} \quad r_{\rm B,eff} = \frac{GM}{v_{\rm eff}^2}$$

key: to know what is v_{eff} (some function of c_s & v_{rel})

Mass accretion injects radiation in the surrounding medium!

Mass falling from "infinity to the BH" converts a sizable part of its potential energy into radiative emission/microscopic kinetic energy.

Most efficient mechanism known in astrophysics (efficiency can reach 40% for maximally rotating BH)! Invoked for powering Quasars, UHECRs, etc.

Efficiency parameterized as $L = \epsilon \dot{M}$

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Efficiency parameterized as $L = \epsilon \dot{M}$

Bulk of the emission falls in X-rays: bremsstrahlung & synchrotron emission from matter heated to $T \sim 10^9$-10^{11} K, subject to Comptonization

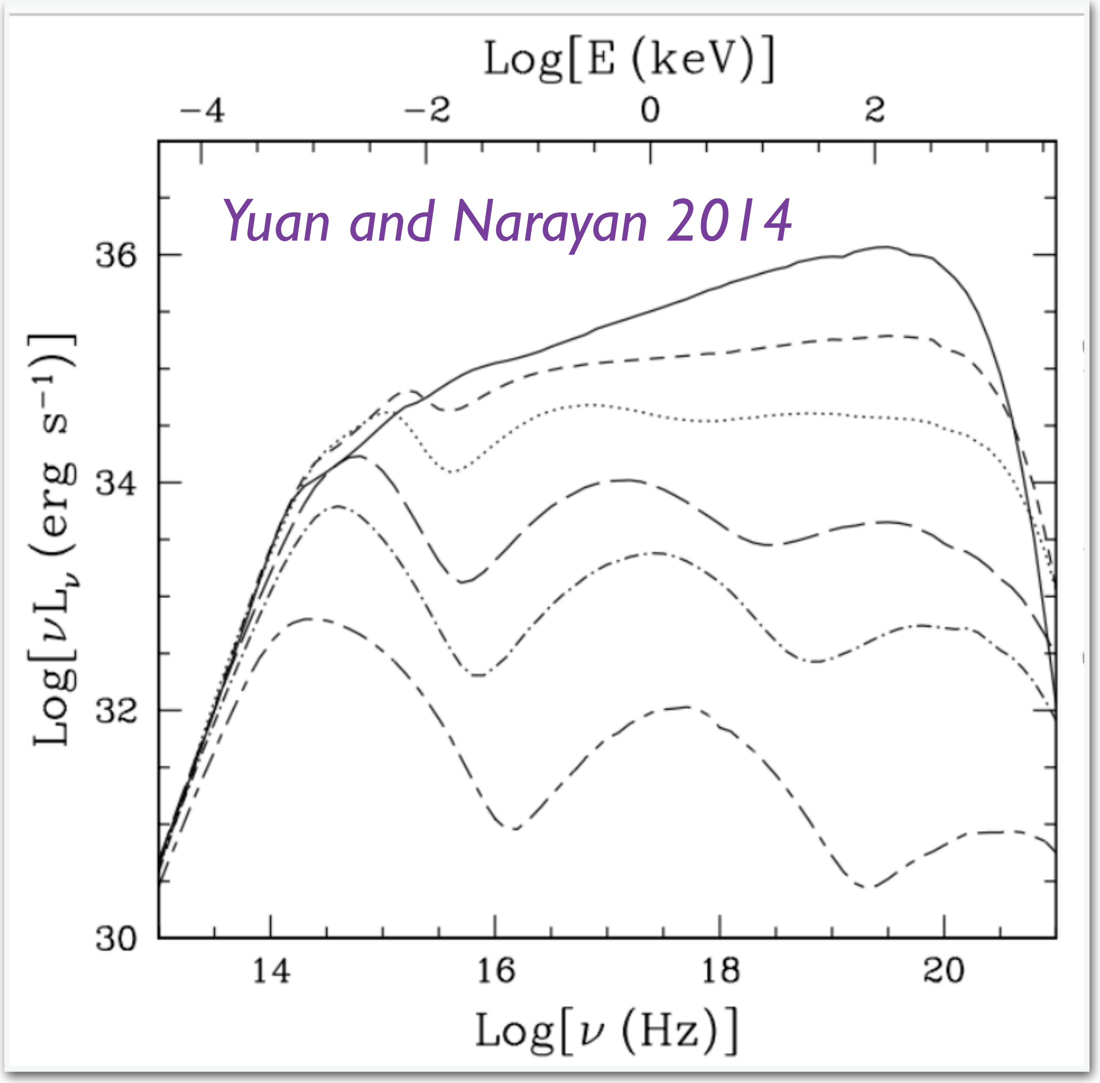
Shapiro 1973, 1974

we parameterize it as

$$L_\omega \propto \Theta(\omega - \omega_{\rm min})\omega^{-a}\exp(-\omega/T_s)$$

a~0-0.5 $\qquad$ $T_s \sim O(m_e)$

$\omega_{\rm min}$ accounts for 'useful fraction of the spectrum'



Effects on the CMB almost 'bolometric', do not depend much on E-distribution (factor ~2)

Key uncertainty: Bolometric efficiency ϵ

Can be computed semi-analytically for the **spherical Bondi case**, yielding

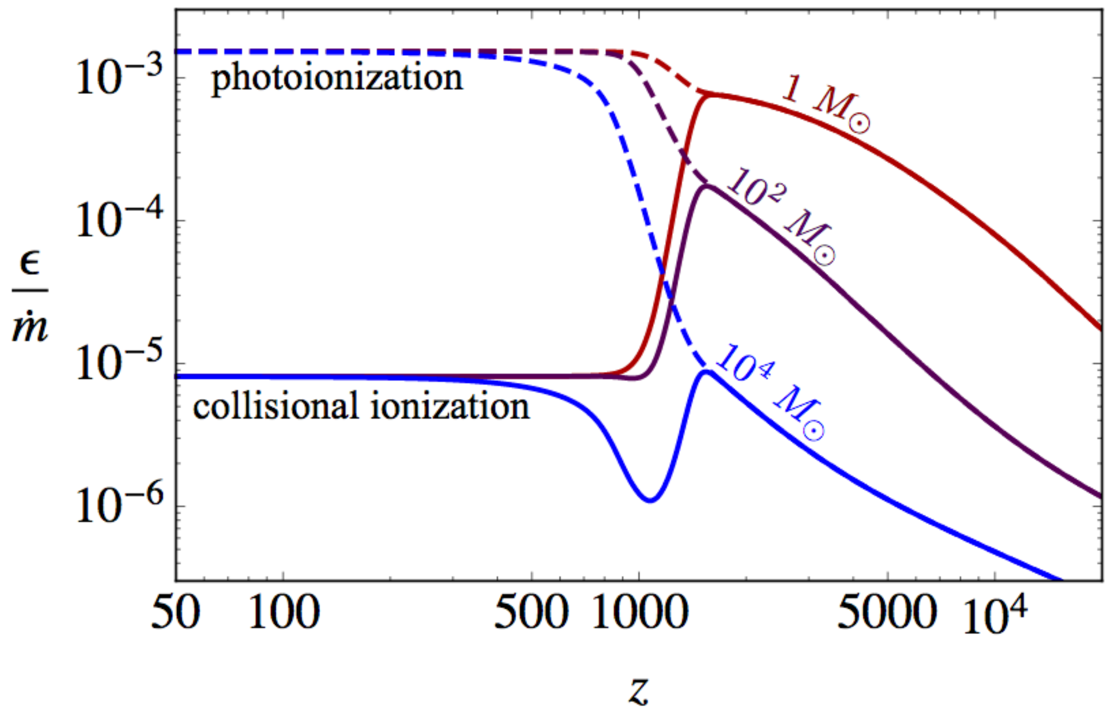
$$\epsilon \simeq 10^{-5} \div 10^{-3} \frac{\dot{M}}{L_{\rm Edd}}$$

where

$$L_{\rm Edd} = \frac{4\pi G\, M\, m_p}{\sigma_T} \simeq 1.3 \times 10^{38} \frac{M}{M_\odot} {\rm erg/s}$$

luminosity at which accretion is balanced by e.m. radiation pressure in a spherical system

Shapiro 1973, 1974
Ali-Haïmoud & Kamionkowski, PRD95 (2017), 043534



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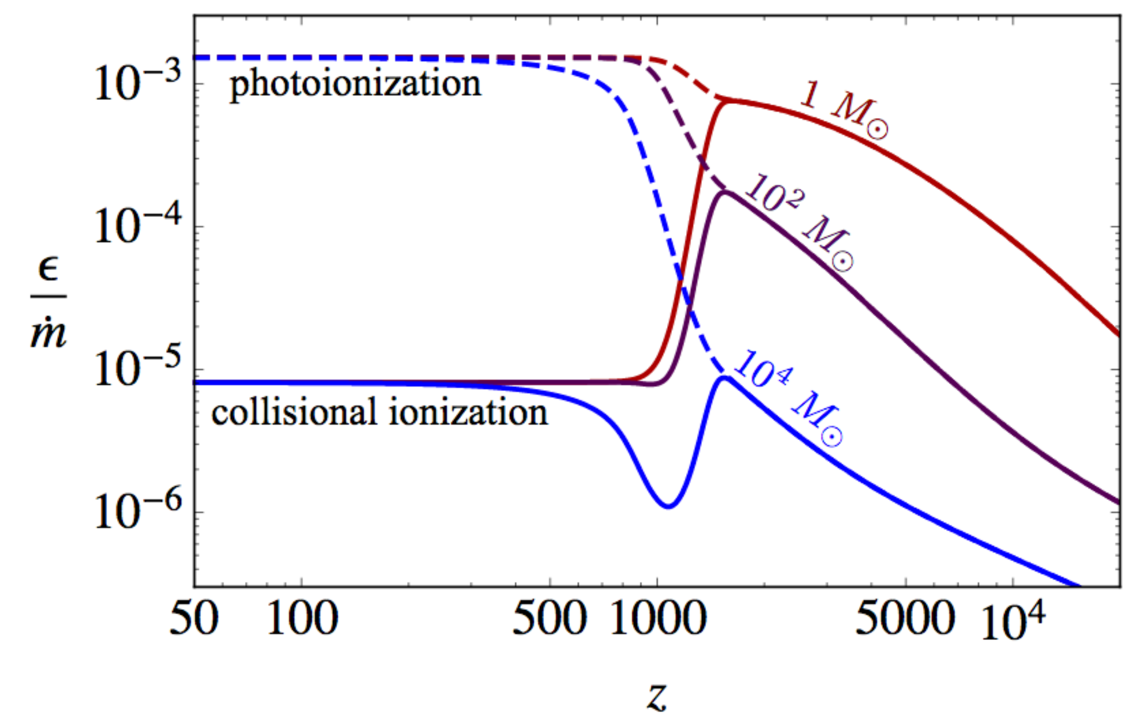


For a geometrically **thin, optically thick disk** $\epsilon \simeq 0.1$

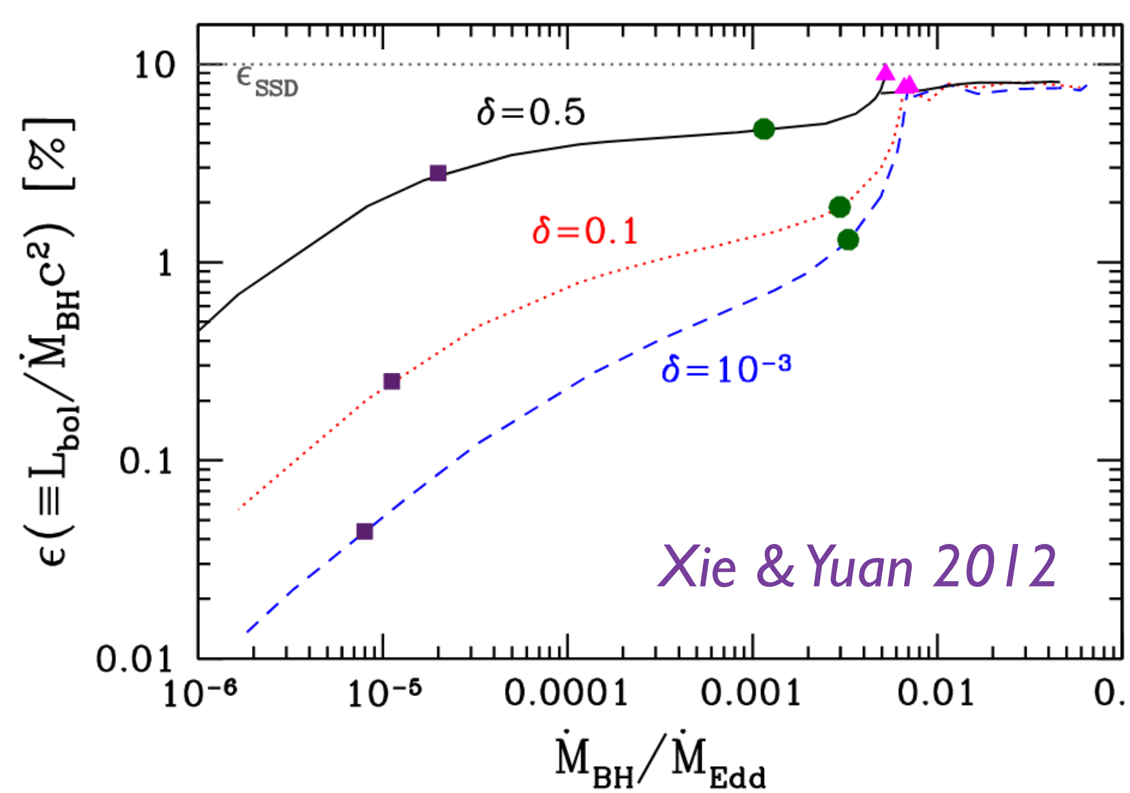
Shakura & Sunyaev '73

For radiative-inefficient disks ("ADAF") a 2-T thick torus forms, with **accreted mass & efficiency lower than S&S**

ϵ=ϵ(δ), δ=fraction of ion energy shared by electrons

Modern fits to data suggest 0.1<δ<0.5, we use δ=0.1

Yuan and Narayan 2014



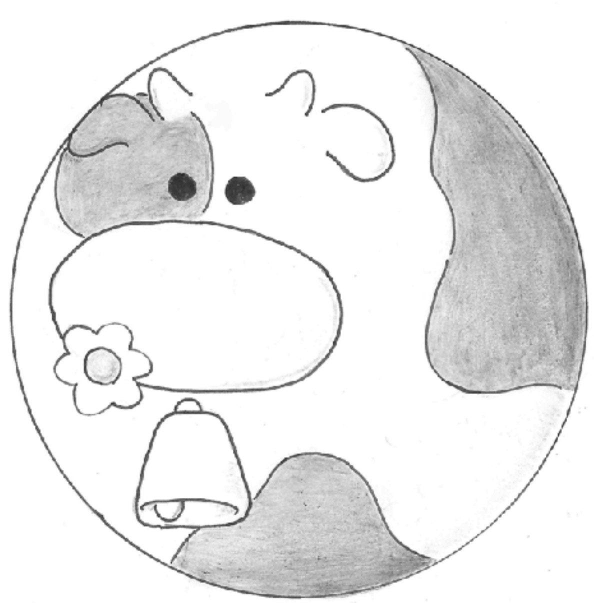
What are the ‘correct’ values of $\dot{M}$ and ϵ ?

A crucial quantity is the **relative velocity between baryons and PBH**

Naive expectation v_{bc}~c_s

In *the linear regime* we expect
spherical Bondi accretion

used in
Ricotti et al. 2008
as well as (in amended form!) in
Ali-Haïmoud & Kamionkowski 2017
(where it is also extended to $v_{eff}>>c_s$)



by Christopher Berry

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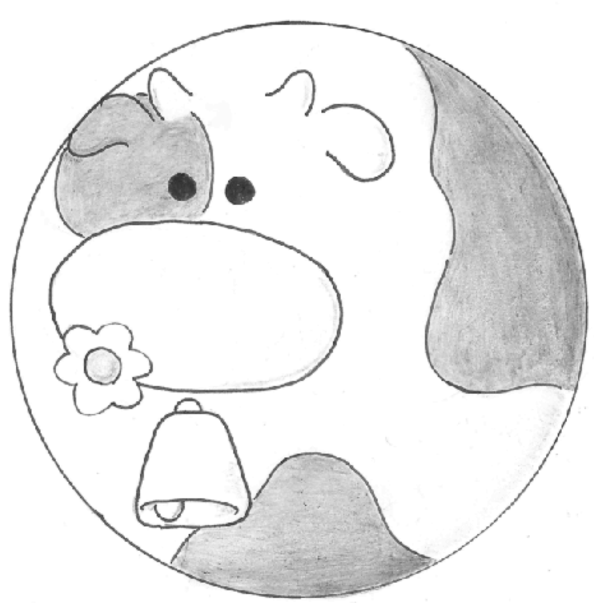

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Non-linear result $v_{bc} \sim 5\ c_s$ @ $z \sim 1000$

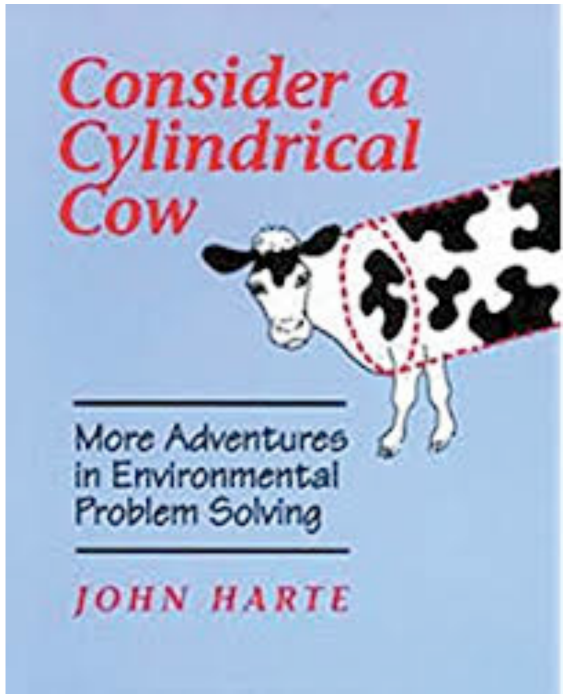
sound-speed in the baryonic gas drops from $c_s \sim c$ (tight coupling in radiation era) to $c_s \sim 10^{-5}c$, associated to supersonic coherent flows of the baryons relative to the underlying DM potential wells

Tseliakhovich & Hirata, Phys. Rev. D 82, 083520 (2010)

- Both papers assumed spherical accretion for radiative efficiency (as in ROM), but this is not consistent with PBHs moving supersonically at Mach ~5! An accretion disc will form.

M. Ricotti's lecture (2017)

Institute of Cosmos Sciences, University of Barcelona



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We consider both cases, with conservative collisional ionization for spherical case, and lowest (most conservative) value for δ from pheno fits of state-of-the-art RIAF disk models

Non-linear structure formation *could* be important & improve bounds!

- if DM fraction into PBH, f_{PBH}, is large, many PBH would form binaries/clusters early in the matter epoch & their orbital virial velocities become relevant ($\rightarrow$disk formation)
- Even for low f_{PBH}, PBH seed proto-halos much earlier than in ΛCDM, with typically low virial velocities (& higher accretion). Even if small fraction of gas involved, it could dominate the bounds…

What if PBH do not make all DM?

- A halo of gravitationally bound, collisionless DM will form around PBH
- Even if only a small fraction of the DM halo gets swallowed by the PBH, a baryon at infinity sees a stronger potential, "effectively attracted by a heavier BH"
- Hence we use the same master equation for accretion

$$\dot{M} = 4\pi\lambda_{\rm eff}\rho_\infty v_{\rm eff} r^2_{\rm B,eff}$$

But $r_{\rm B,eff}$ now comes from the solution of

$$\frac{G_N M_{\rm PBH}}{r_{\rm B,eff}} - \Phi_h\left(M_{\rm PBH}, r_{B,\rm eff}, t\right) = v^2_{\rm eff}(t)$$

K. Park, M. Ricotti, P. Natarajan, T. Bogdanovic, and J. H. Wise, ApJ 818, 184 (2016)

- Problem reduced to compute the DM halo potential (vs. time)

Note

The PBH mass remains essentially constant in time over the cosmological epochs of interest (100≲z≲1000), with the most relevant epoch being 300≲z≲600

Analytical expectations

PHB as point-attractor of cold DM moving radially with Hubble flow. A shell at distance *r* obeys

$$\frac{d^2 r}{dt^2} = -\frac{4G_N}{\pi} 3r \left[\frac{3\, M_{\rm PBH}}{4\pi\, r^3} + \sum_i \left(\rho_i + 3p_i\right) \right]$$

At any time, the mass of the halo is defined by the 'turn-around radius' satisfying

$$\frac{d r_{\rm t.a.}(t)}{dt} = 0$$

This leads to the prediction

$$M_{\rm halo} \simeq \left(\frac{3000}{1+z} \right) M_{\rm PBH}$$

which overshoots more accurate calculations by only a factor 1.6, but leads to a **too steep halo profile r^{-3} due to neglecting the angular momentum of DM**

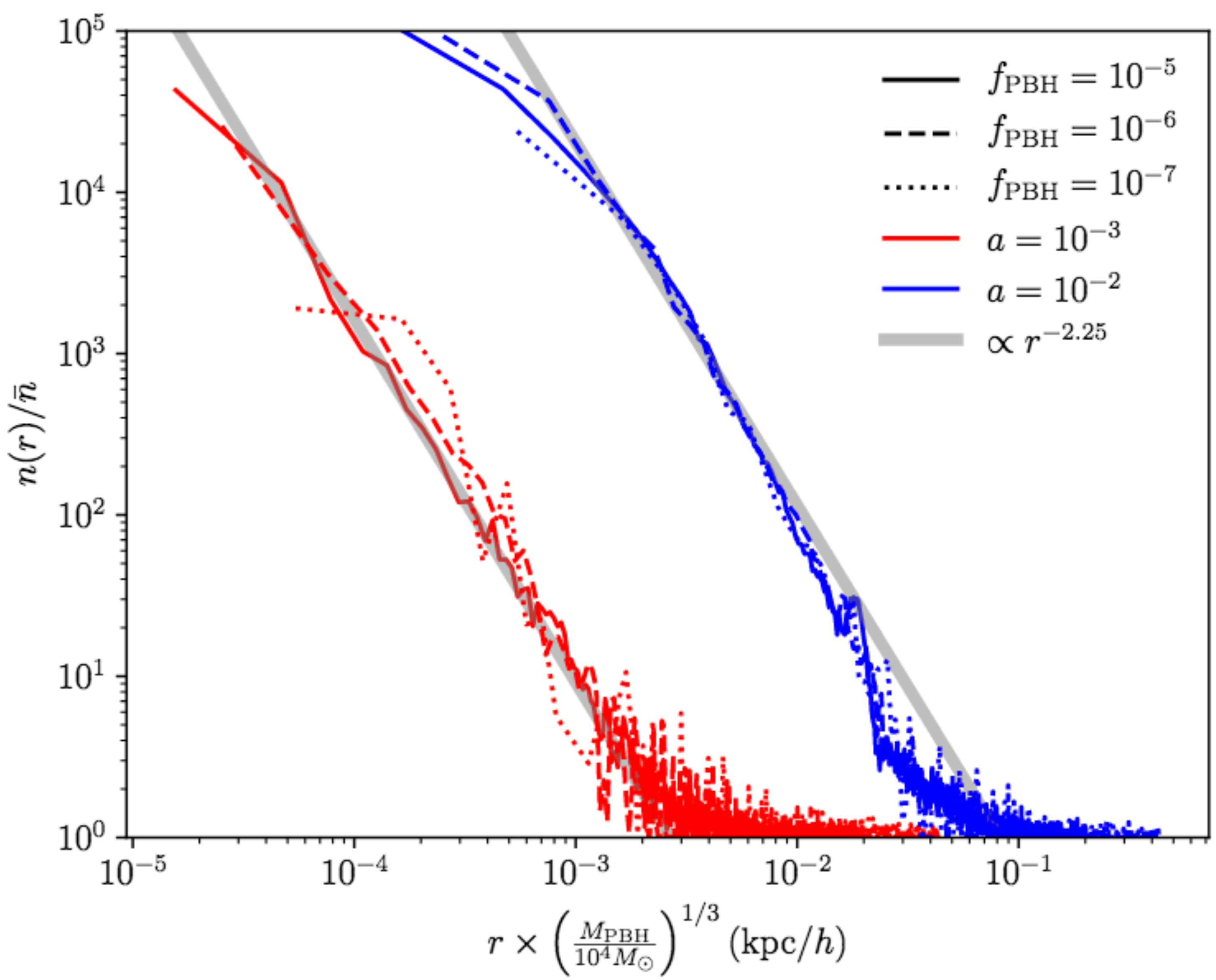
Numerical simulations

Self-similar solutions avoiding the free-fall boundary condition at the center and more appropriate for the case at hand suggest a profile $r^{-2.25}$

E. Bertschinger, Astrophys. J. Suppl.58, 39 (1985)

Our dedicated numerical simulations, with PBH and lighter DM particles, confirm expectations: power-law profile

r^{p-3}, with $p\sim0.75$



Semi-analytical model

(i.e. "calibrated" to numerical results)

In terms of the (maximal) halo Bondi radius $$r_{\mathrm{B},h} \equiv \frac{G_N M_h}{v_{\mathrm{eff}}^2}$$

we can find the analytical solution (if $M_h >> M_{PBH}$, as true in the range of interest)

If $r_{\mathrm{t.a.}}(z) < r_{\mathrm{B},h}(z)$

$$r_{\mathrm{B,eff}} \simeq r_{\mathrm{B},h}$$

All the halo matters, for the baryon accretion

If $r_{\mathrm{t.a.}}(z) \geq r_{\mathrm{B},h}(z)$

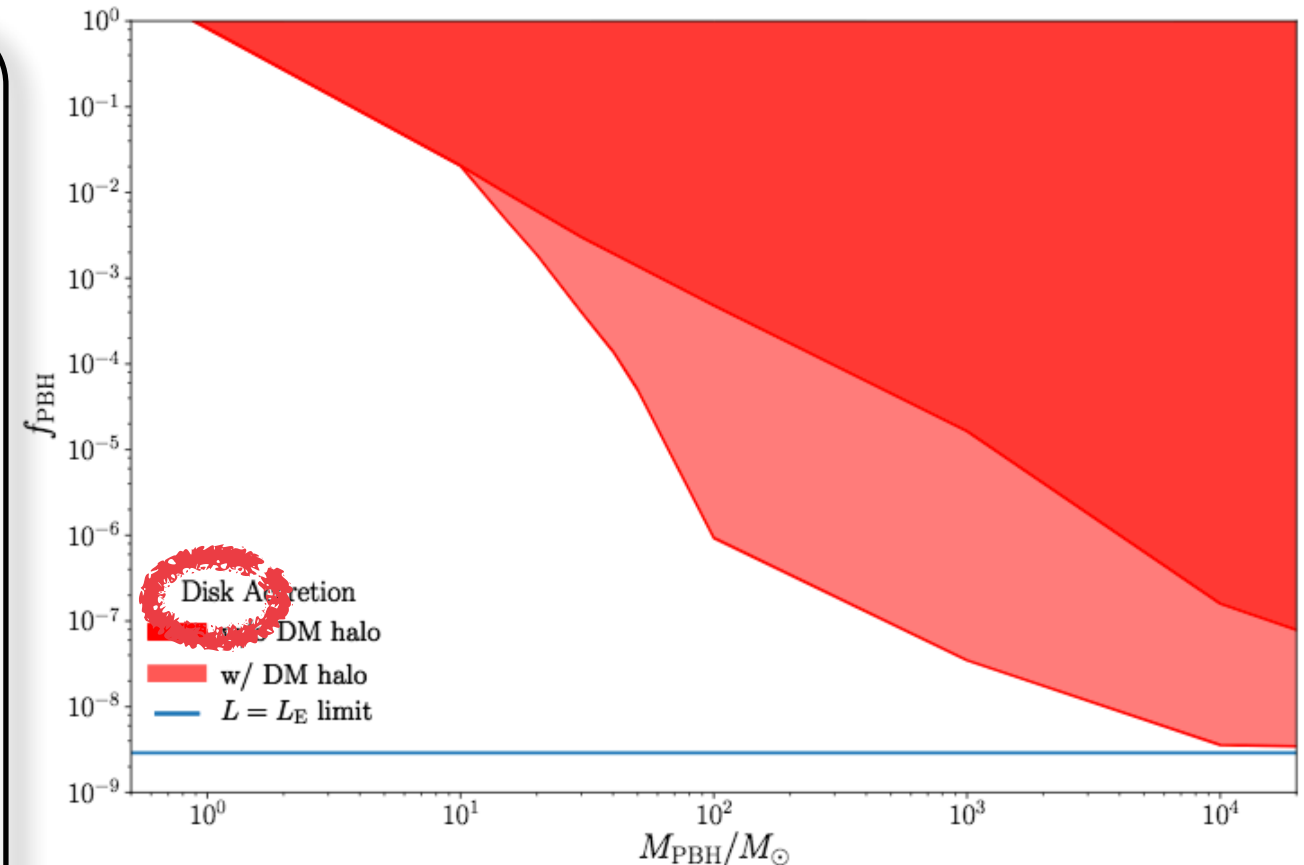
$$r_{\mathrm{B,eff}} \simeq r_{\mathrm{t.a.}} \left[(1-p)\frac{r_{\mathrm{t.a.}}}{r_{\mathrm{B},h}} + p\right]^{\frac{1}{p-1}} \leq r_{\mathrm{B},h}$$

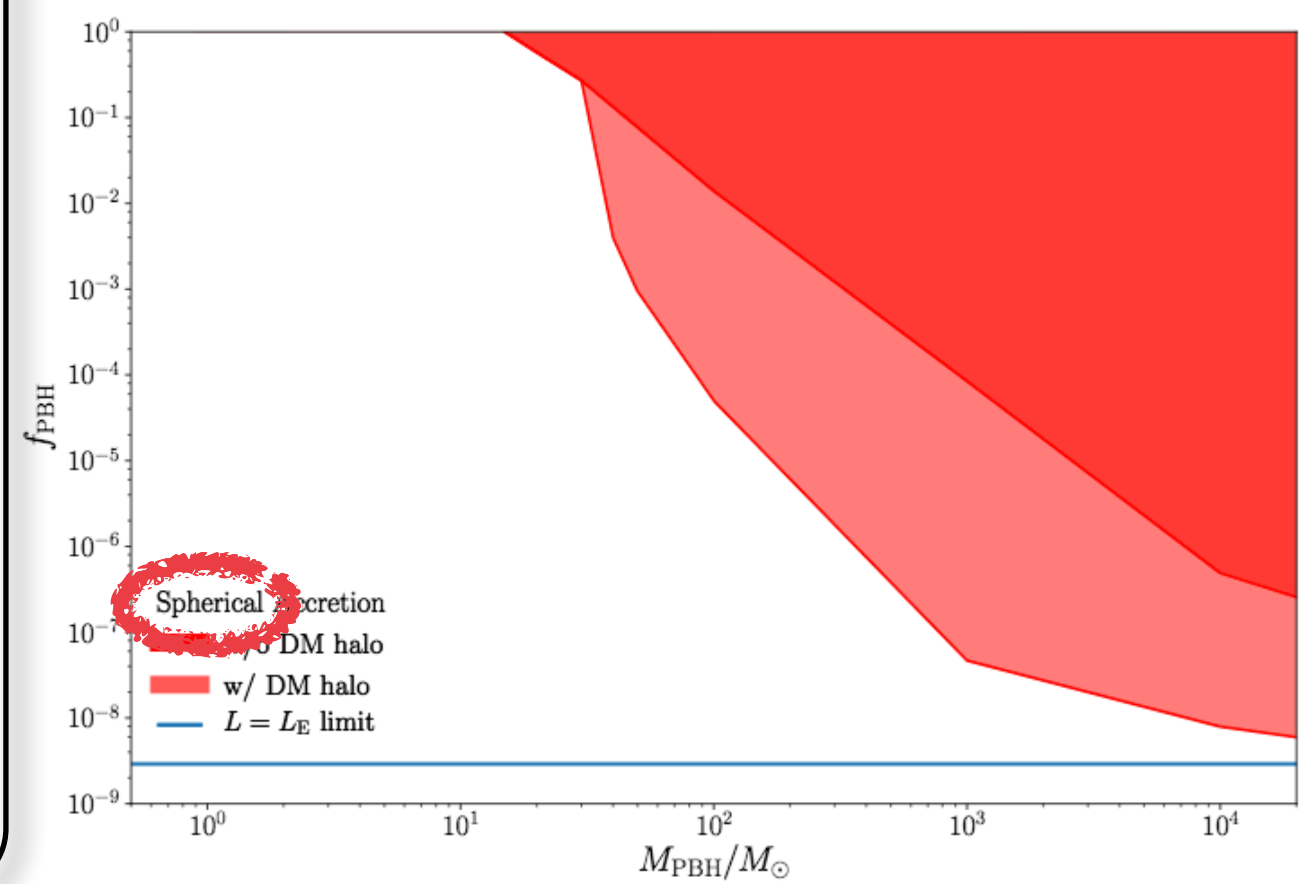
Only a fraction of the halo mass matters, the more the closer p is to 0

Results (monochromatic mass function)

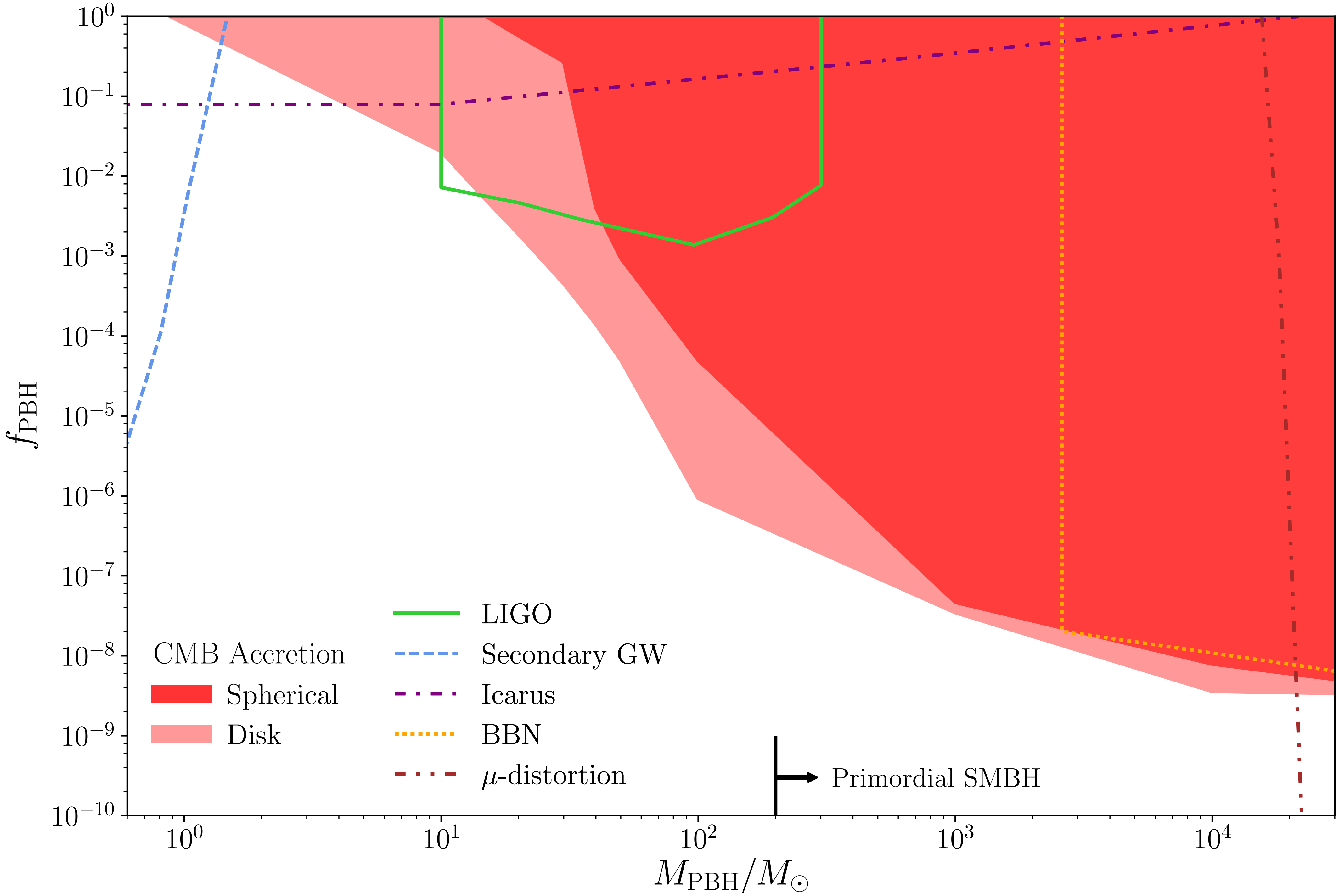
- PBH excluded as totality of DM if M>15 M⊙ even for spherical accretion under most conservative case of collisional ionization
- Compared to our results in 2017, factor ~4 improvement due to new & better cosmo data (notably Planck 2018 release with low-ℓ polarization) & better account of t-dependence of E-release/absorption (via ExoCLASS)
- The DM halos tighten the bound up to ~3 oom.
- Caveat for $0.01 \lesssim f_{PBH} \lesssim 0.1$ (unaccounted modifications of halo profile due to neighboring PBH)
- Spherical and disk case not so different especially at high-M, due to the lower velocity required for spherical case consistency
- Bounds flatten at $M \gtrsim 10^4$ M⊙ since approaching Eddington limit (at which we cap luminosity) for most of the cosmo relevant time

$$f_{\rm PBH} < 2.9 \times 10^{-9} \quad (L_{\rm acc} = L_E)$$





Comparison with best other bounds



- Compared to the best bounds available, CMB is competitive already at M≳10 M☉ and provides the best bounds for 50 M☉ ≲M≲2x10⁴ M☉
- At least for spherical accretion, compatible with hypothesis that the bulk of LIGO is due to PBH

Conclusions

- PBH may form in the early universe in a number of scenarios, with masses from microscopic to SMBH range.

- CMB can probe these objects, notably via the sensitivity of its anisotropy pattern to the ionization of the universe due to extra radiation injected by the hot plasma forming when matter accretes onto PBH

- The key unknown parameter is the luminosity of accreting PBH in the cosmo context, in turn crucially dependent from the relative velocity between PBH and the baryonic gas. We consider two limiting cases that should provide a conservative bracketing of this uncertainty.

- This argument **excludes PBH as the totality of DM for M>1-15 $M_\odot$** (This is **not** the most stringent constraint in that mass range, but it does add to the numerous arguments telling that stellar mass PBH cannot make the DM!)

- It also provides the **best bounds** on PBH (down to $f_{PBH} \lesssim 10^{-8}$!!!) for **50 $M_\odot$ $\lesssim$ M $\lesssim$ 2x10^4 $M_\odot$** .

  Accounting for the enhanced baryonic accretion due to the DM halos forming around PBH is crucial to infer such a bound.

- Despite such impressive bounds, within uncertainties PBH can however still account for

i) the bulk of LIGO-Virgo merger events
ii) seeding the SMBH observed at z>6

The consequences of PBH cosmologies have yet to be fully explored, notably in models where PBH only constitute a fraction (possibly very small!!!) of the DM