Cosmic microwave background bounds on PBH

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

LAPTh

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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
- On the validity of some approximations
- Implications for supermassive black holes (SMBH)

Bonus material

- Details on the physics of the CMB bounds
- More details on accretion
- More global view on PBH bounds

Introduction

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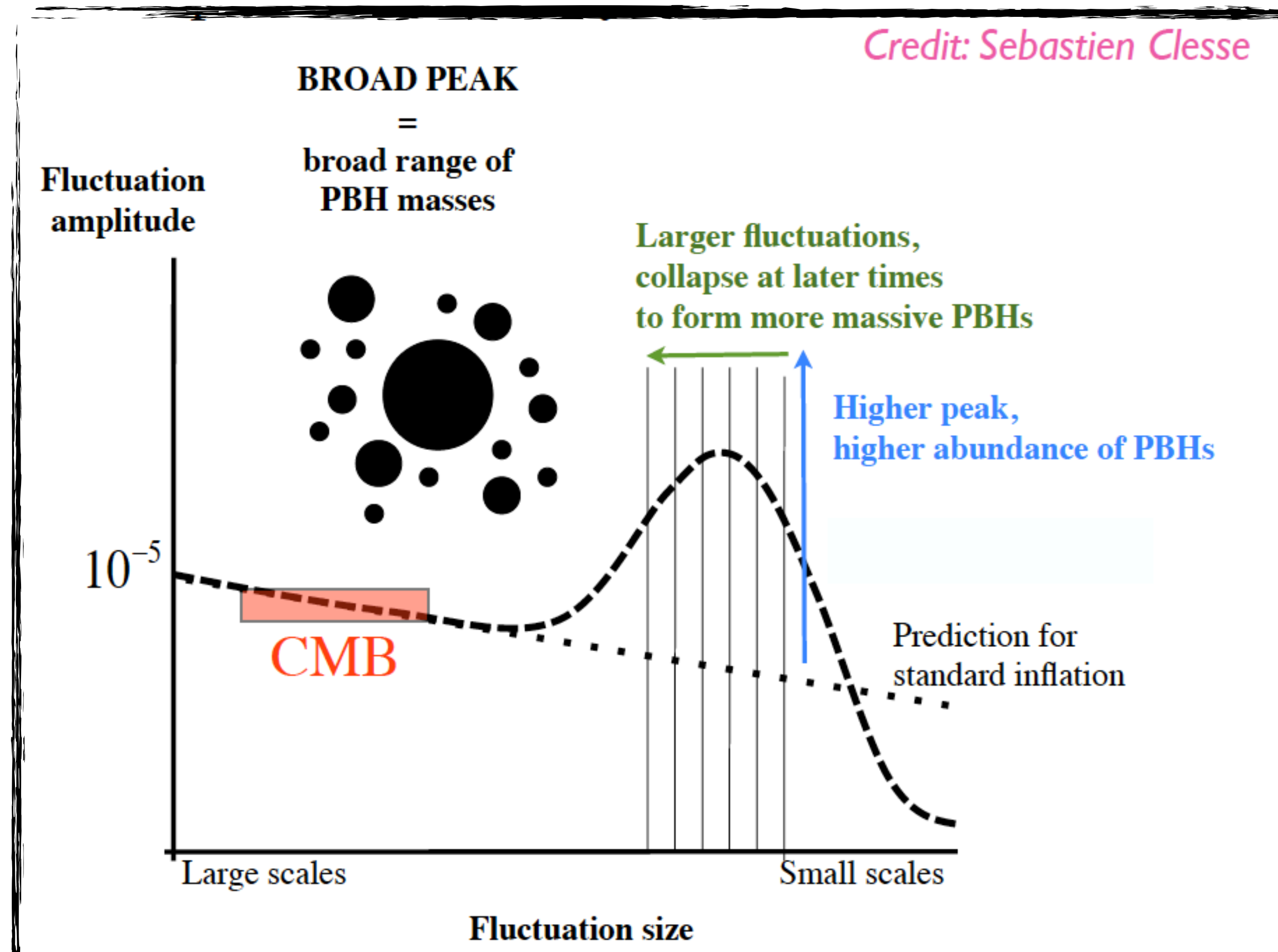
$$M_{\rm PBH} \sim M_H\Big|_{\rm cross} \sim \rho\, H^{-3}\Big|_{\rm cross} \propto H^{-1}\Big|_{\rm cross} \propto k_{\rm peak}^{-2}$$



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 $M \lesssim 2\times10^{17}\,g \sim 10^{-16}\,M_\odot$)

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

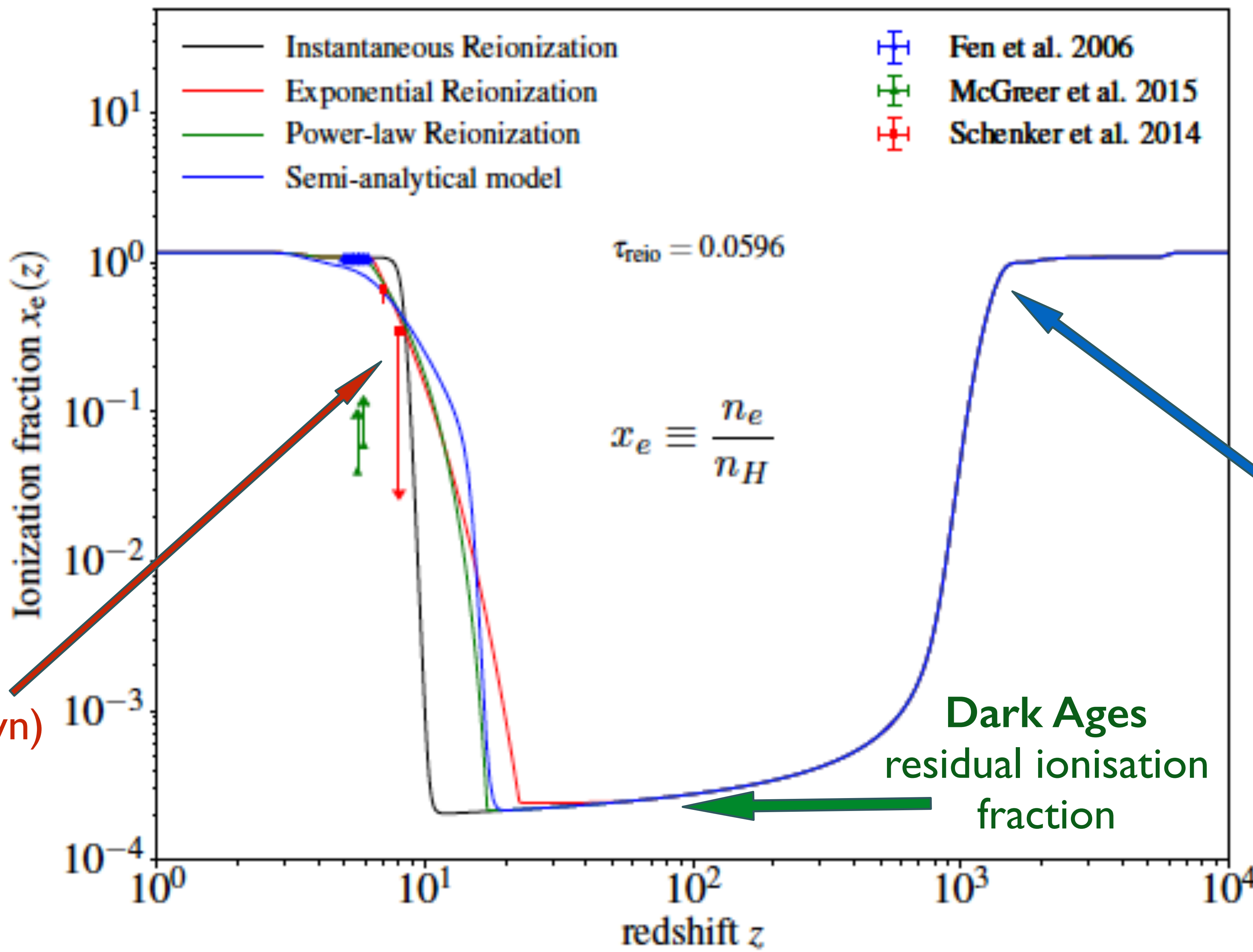
the energy of the injected non-thermal particles, even if negligible wrt ρ_γ, is **not negligible wrt the kinetic energy of the baryonic gas.** These particles can eventually **heat up** (alter T_M) and especially **ionise the gas** (alter x_e)

→ **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 **ionisation** and gas temperature evolution

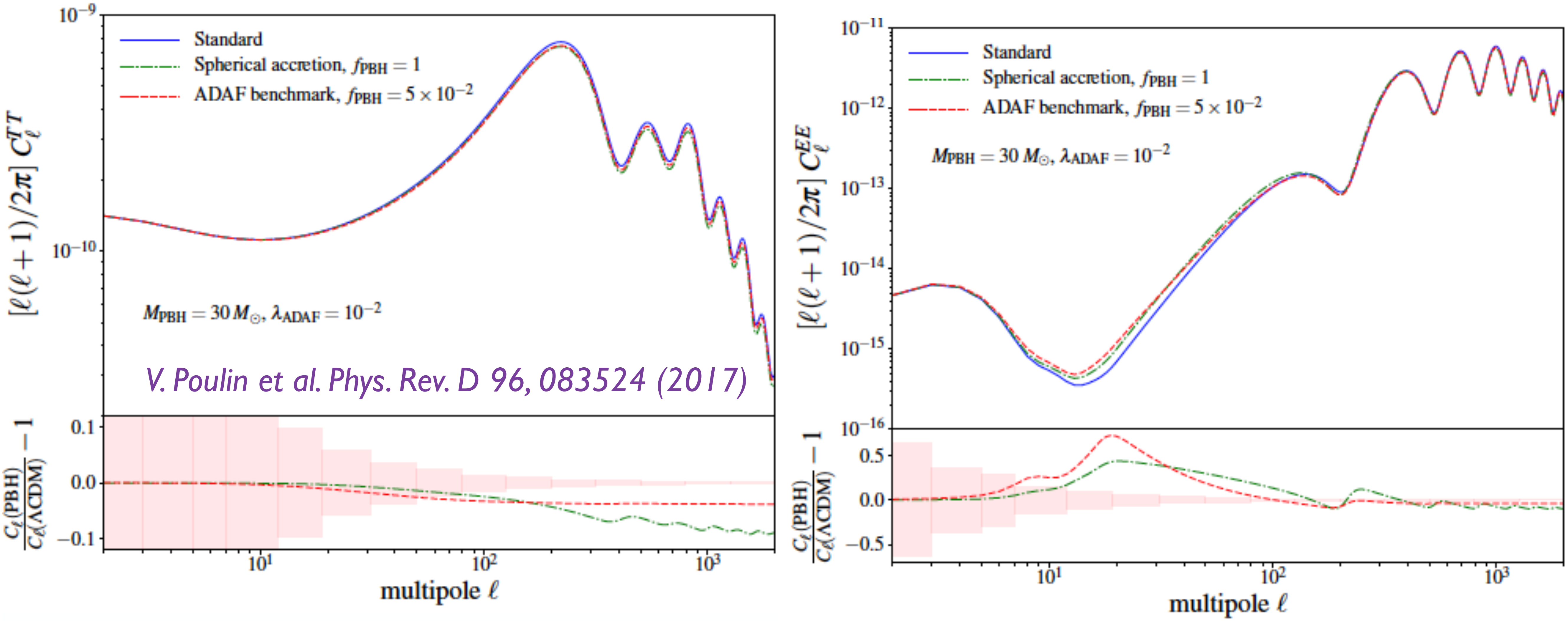


optical depth

$$\kappa(z) = \sigma_T n_{e,0} \int_0^z dz' \frac{dt}{dz'} (1+z')^3 x_e(z')$$

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

Generic effects of E-injection on CMB anisotropies



"Delayed recombination":
shift peaks and damping tail enhanced

"Early reionisation":
step-like suppression and reionisation bump enhanced

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

Key parameters

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

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

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

Both can be parameterised 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 sizeable 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 parameterised as $L = \epsilon \dot{M}$

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Efficiency parameterised 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

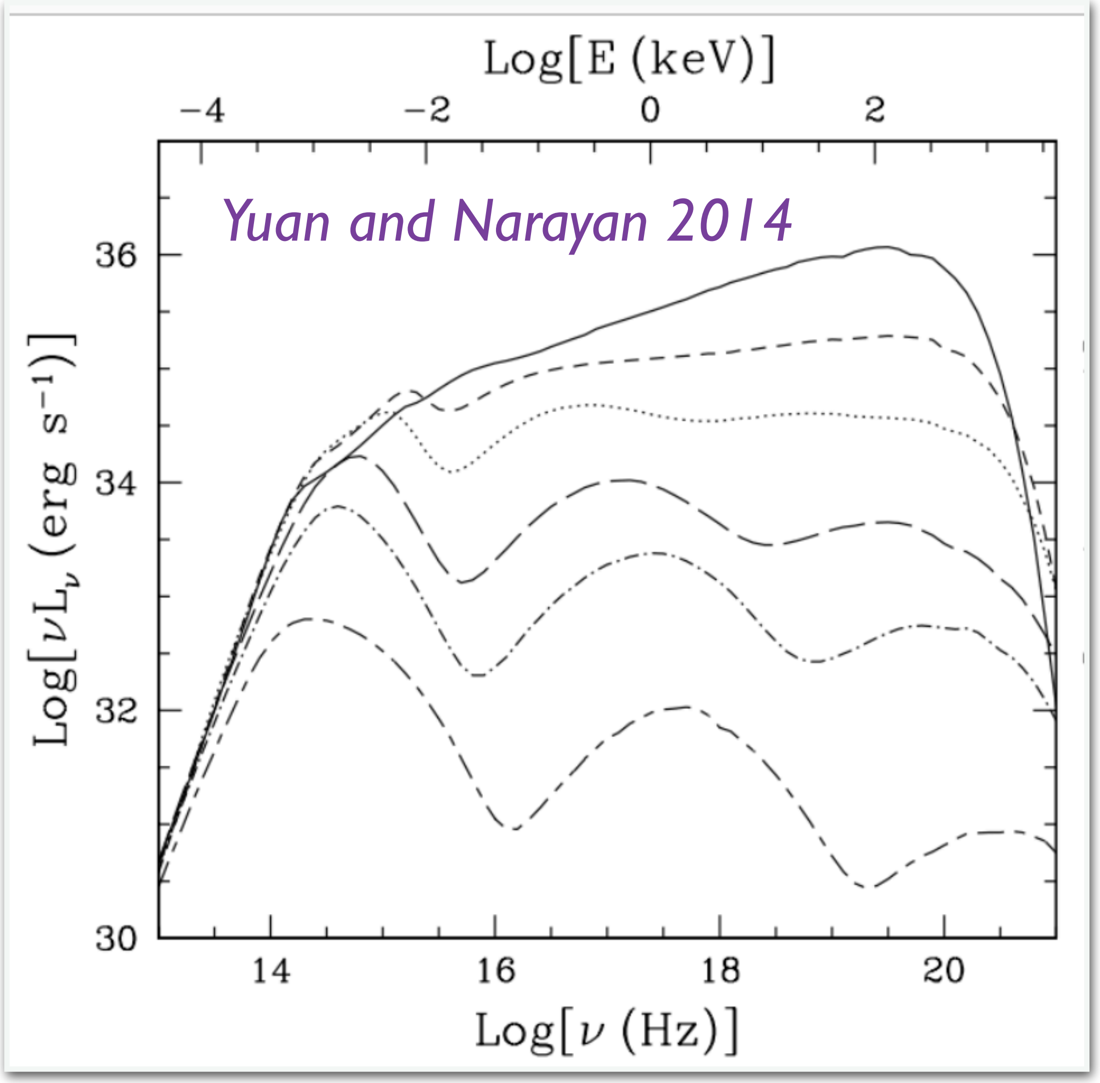
Shapiro 1973, 1974

we parameterise it as

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

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

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



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

Key uncertainty: Bolometric efficiency ϵ

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

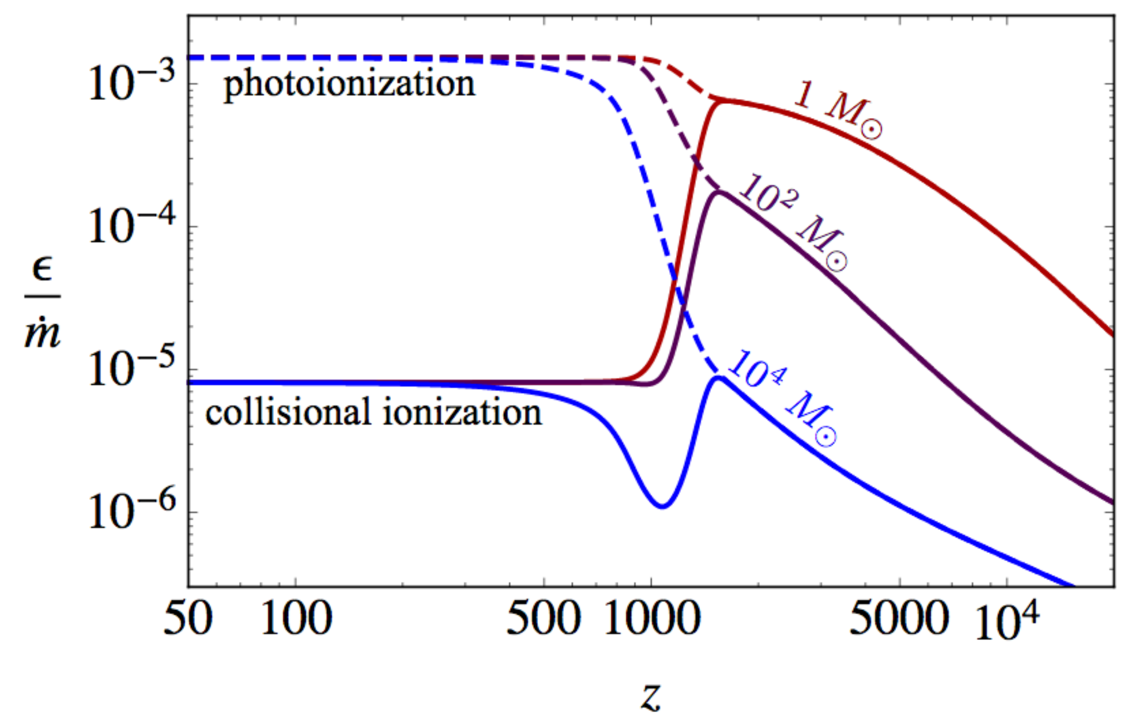
$$\epsilon \simeq 10^{-5} \div 10^{-3} \frac{\dot{M}}{L_{\rm Edd}}$$

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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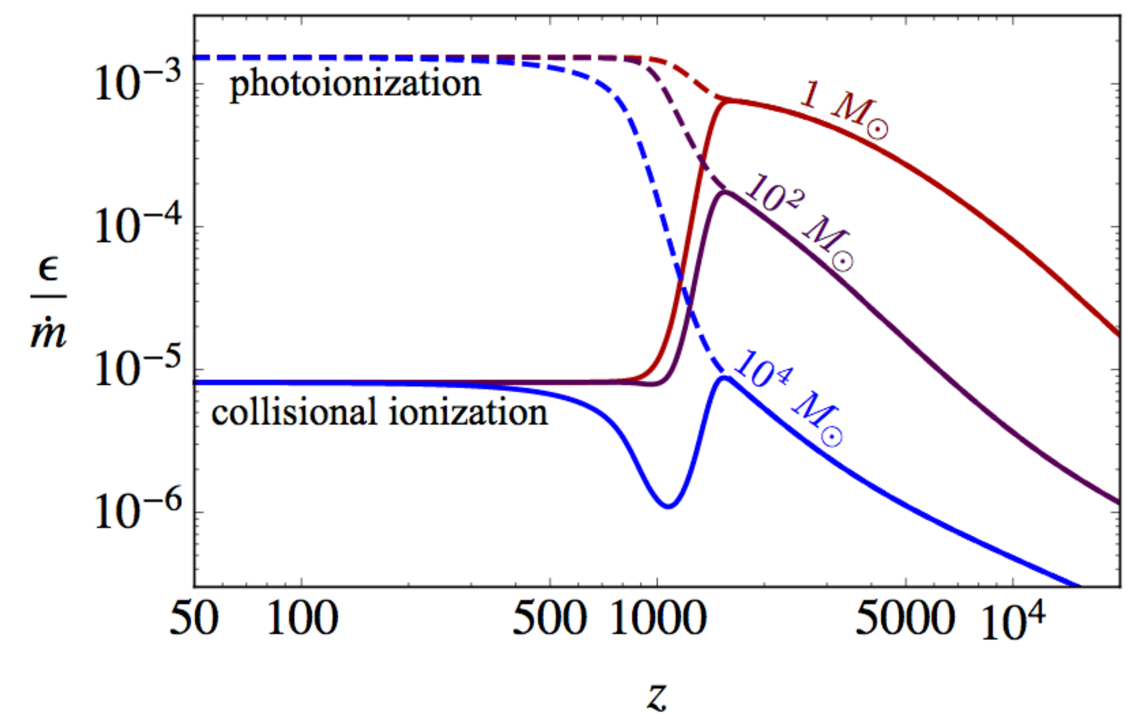


For a geometrically **thin, optically thick disk** $\epsilon \simeq 0.1$

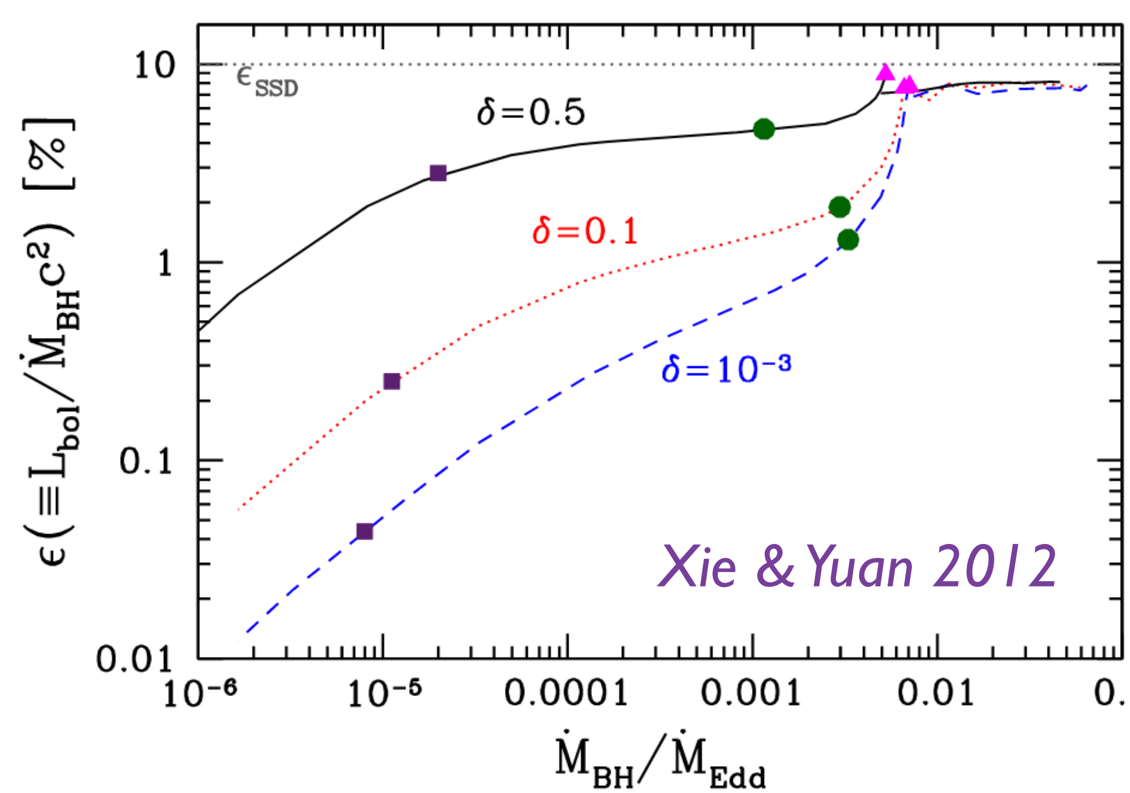
Shakura & Sunyaev '73

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 $v_{bc} \sim c_s$

In *the linear regime* we expect spherical Bondi accretion

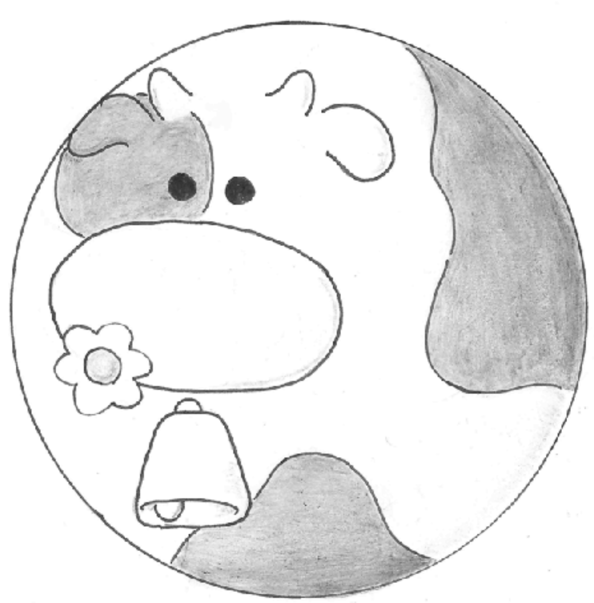
used in

Ricotti et al. 2008

as well as (in amended form!) in

Ali-Haïmoud & Kamionkowski 2017

(where it is also extended to $v_{eff} >> c_s$)



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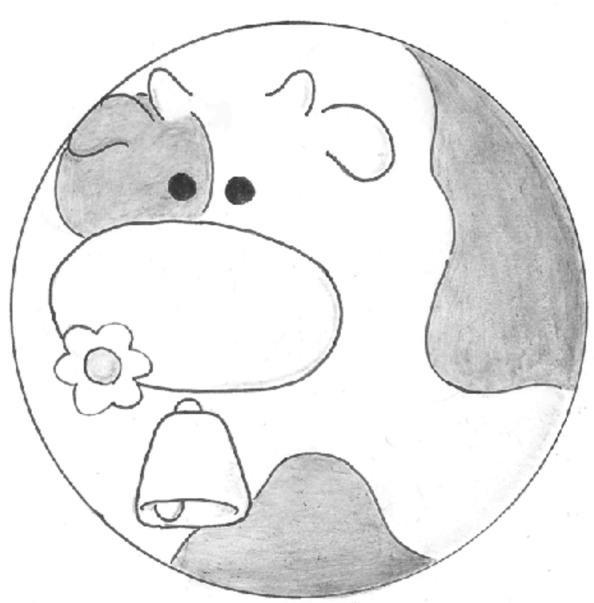

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Non-linear result $v_{bc} \sim 5\ c_s$ @ $z \sim 1000$

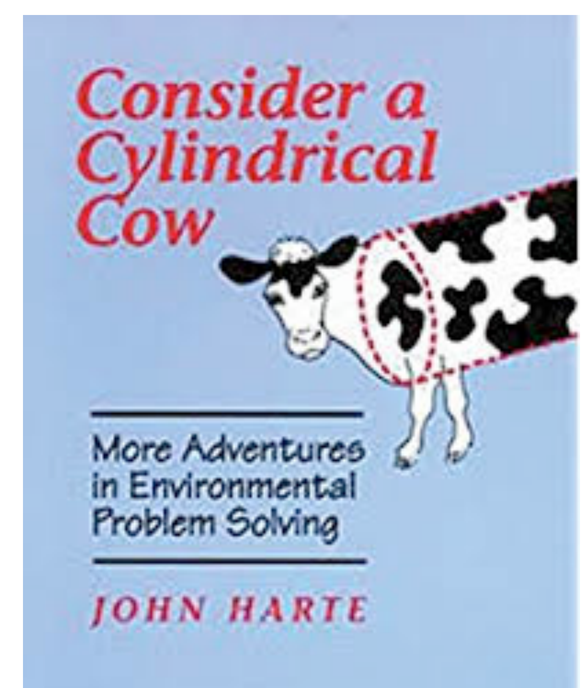
sound-speed in the baryonic gas drops from $c_s \sim c$ (tight coupling in radiation era) to $c_s \sim 10^{-5}c$, associated to supersonic coherent flows of the baryons relative to the underlying DM potential wells

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 (→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…

DM halos enter the scene

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

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

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**

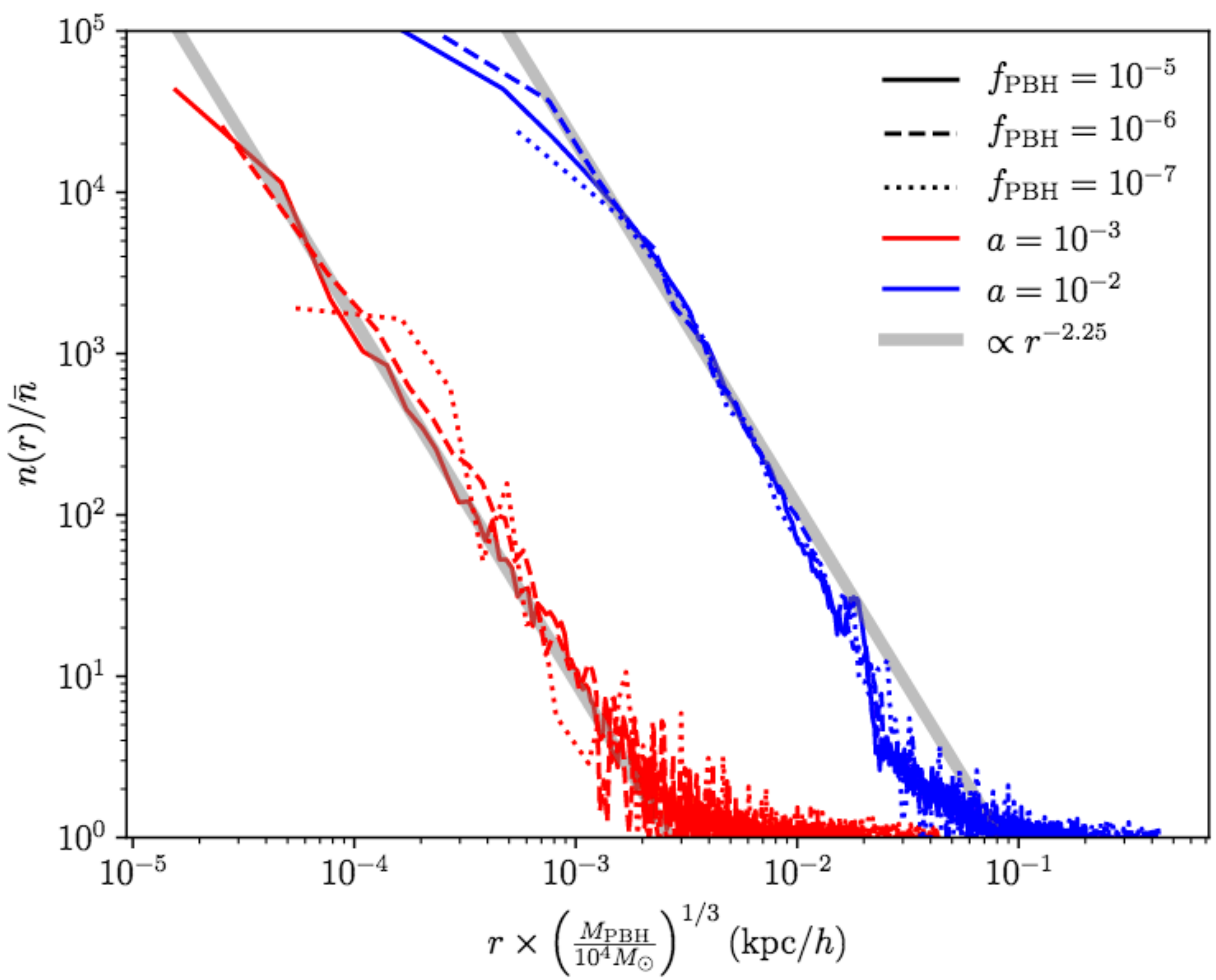
Numerical simulations

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 $p \sim 0.75$



Semi-analytical model

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

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

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

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

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

All the halo matters, for the baryon accretion

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

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

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

Results

Results (monochromatic mass function)

- PBH excluded as totality of DM if $M > 15\ M_\odot$ 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 2-3 oom.

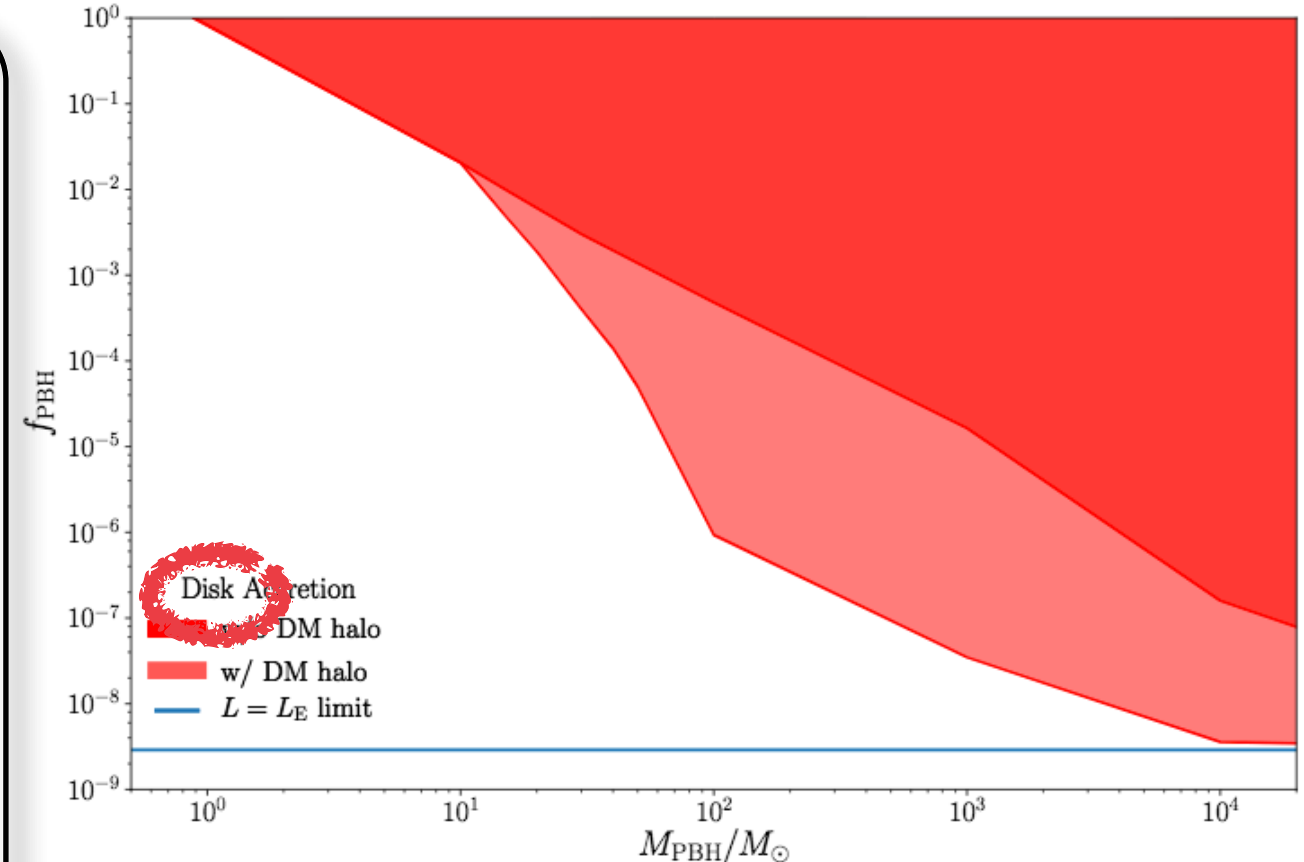
- Caveat for $0.01 \lesssim f_{PBH} \lesssim 0.1$ (unaccounted modifications of halo profile due to neighboring PBH)

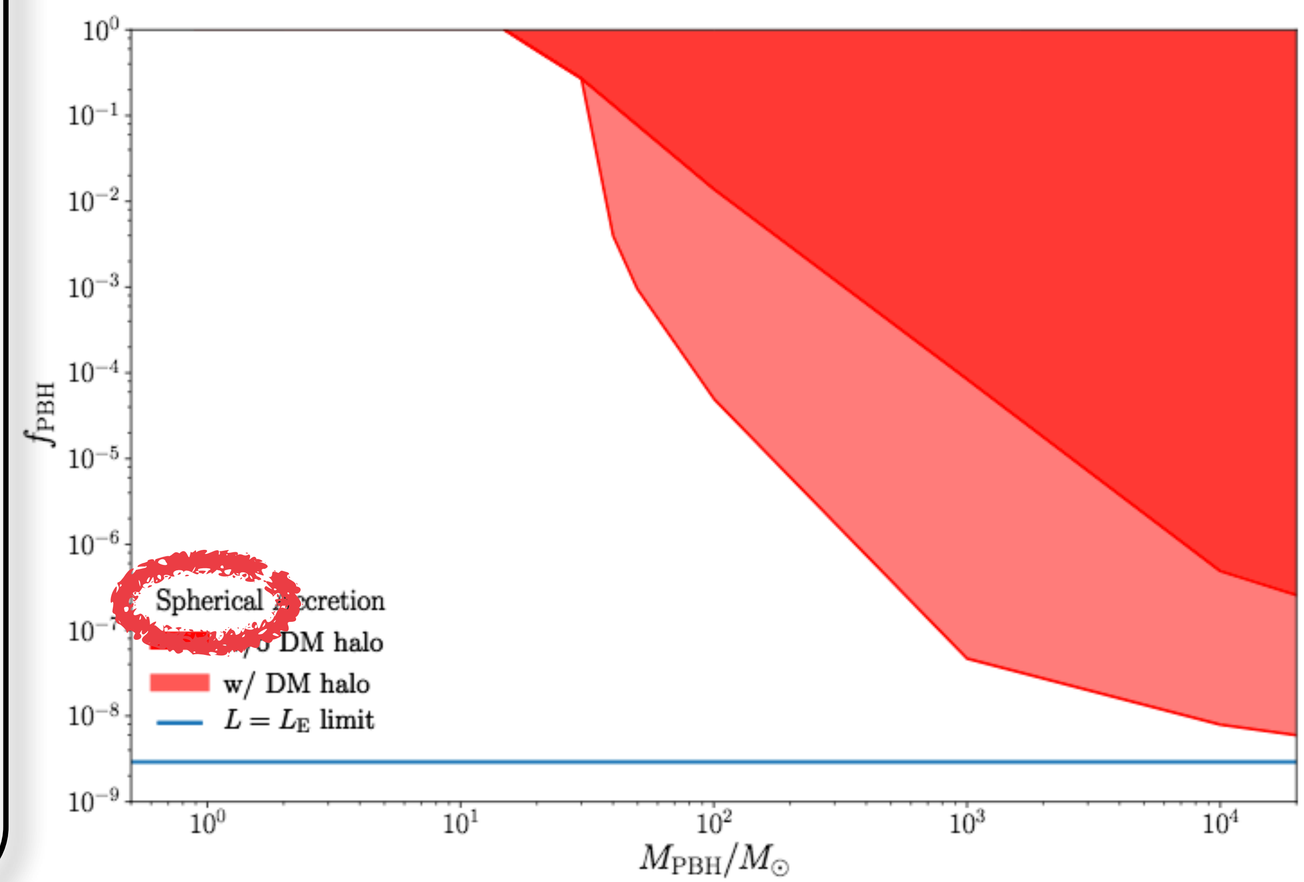
- Spherical and disk case not so different especially at high-M, due to the lower velocity required for spherical case consistency

- Bounds flatten at $M \gtrsim 10^4\ M_\odot$ since approaching

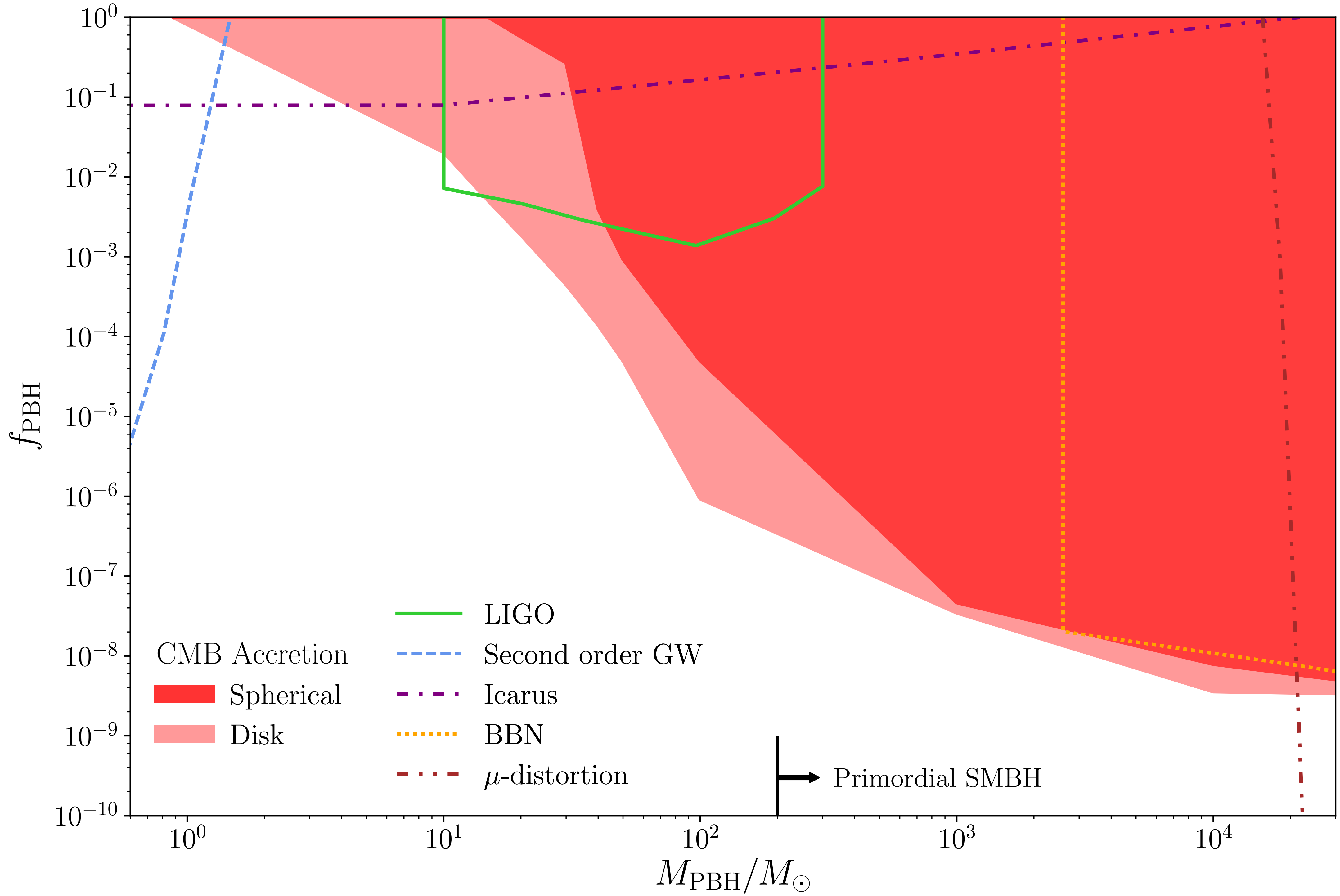
  Eddington limit (at which we cap luminosity) for most of the cosmo relevant time

$$f_{\rm PBH} < 2.9\times10^{-9} \quad (L_{\rm acc} = L_E)$$





Comparison with best other bounds



- Compared to the best bounds available, CMB is competitive already at $M \gtrsim 10\ M_{\odot}$ and provides the best bounds for $50\ M_{\odot} \lesssim M \lesssim 2 \times 10^{4}\ M_{\odot}$
- For spherical accretion, still compatible with hypothesis that bulk of LIGO events due to PBH

Discussion of approximations

Checking approximations

Is the steady state approximation verified?

For consistency, the system must settle down in the (~Bondi) steady-state fast compared to the cosmological expansion

$$\frac{r_B}{v_{\rm eff}} H(z) < 1 \quad \rightarrow \; M \lesssim 10^{4.5}\, M_\odot$$

Can we neglect dynamical friction?

A massive PBH moving supersonically in the cosmological baryonic gas slows down in a timescale

$$\tau_{\rm loss}(z) H(z) \simeq 1.8 \times 10^4 \frac{M_\odot}{M} \left(\frac{1+z}{100}\right)^{3/2} \frac{10}{\ln \Lambda}$$

Ok for us to neglect if limiting to $M \lesssim 10^{4.5}\, M_\odot$, but important for the physics of these PBH in dark ages

Is the homogeneous approx. ok?

A PBH can ionize all of the region separating it from the nearest PBH if

$$f_{\rm PBH} > 10^{-15} x_e^3 \frac{M_\odot}{M}$$

(always satisfied in our range of parameters)

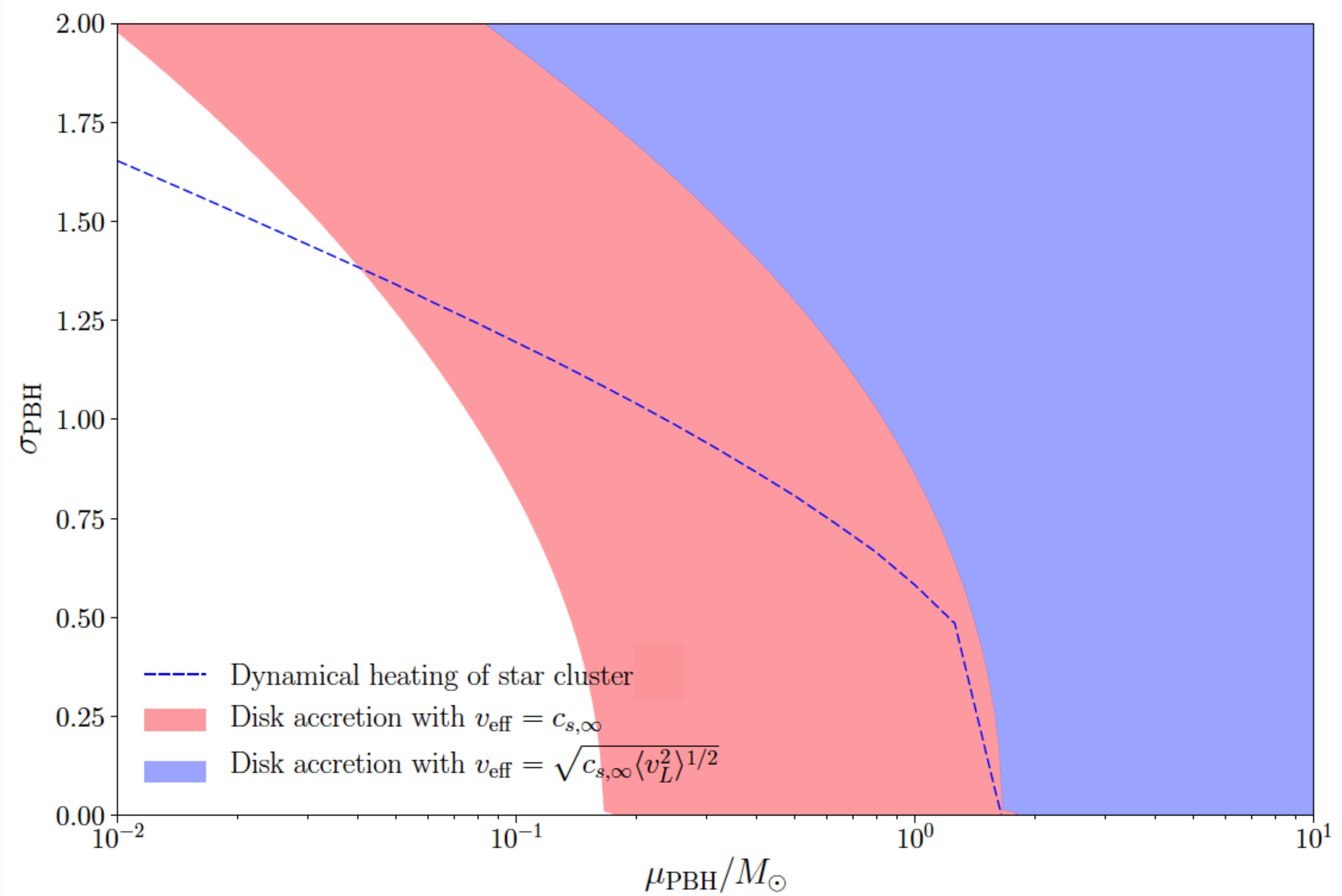
Up to the maximum multipole used (ℓ~2000), there is more than a PBH in each patch of the CMB

$$N_{\rm PBH} \simeq 5 \times 10^7 \ell^{-1} \left(\frac{f_{\rm PBH} M_\odot}{M}\right)^{1/3} > 1$$

What about broad mass functions?

Typically the bounds become stronger for broad mass functions

B. Carr et al. PRD 96, 023514 (2017)
F. Kühnel and K. Freese, PRD 95, 083508 (2017)



We checked explicitly that this is the case for the CMB bound and a gaussian mass distribution in our previous article

V. Poulin et al. Phys. Rev. D 96, 083524 (2017)

Implication for supermassive black holes

Implications for SMBH

- Supermassive BH with $M \lesssim 10^9\, M_\odot$ have been observed at $z \gtrsim 6$.

- **Can they form from stellar BH** ($M \lesssim 10^2\, M_\odot$) **seeded at z~15** (PopIII star collapse?)

PBH mass (growing via accretion) obeys the bound

$$M(t) \lesssim M_i \times \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t-t_i}{\tau_E}\right) \qquad \tau_E = \frac{c^2 M}{L_E} = 0.4\,\mathrm{Gyr}$$

Barely so if accreting at Eddington luminosity for a benchmark ϵ=0.1

Several hypotheses around:

- Super-Eddington accretion?
- (close to) Eddington luminosity with a very small ϵ?
- Important role of 'runaway' mergers?
- Direct collapse of very massive clouds (rather than seeded via stellar BH)?
- Primordial origin?
- …

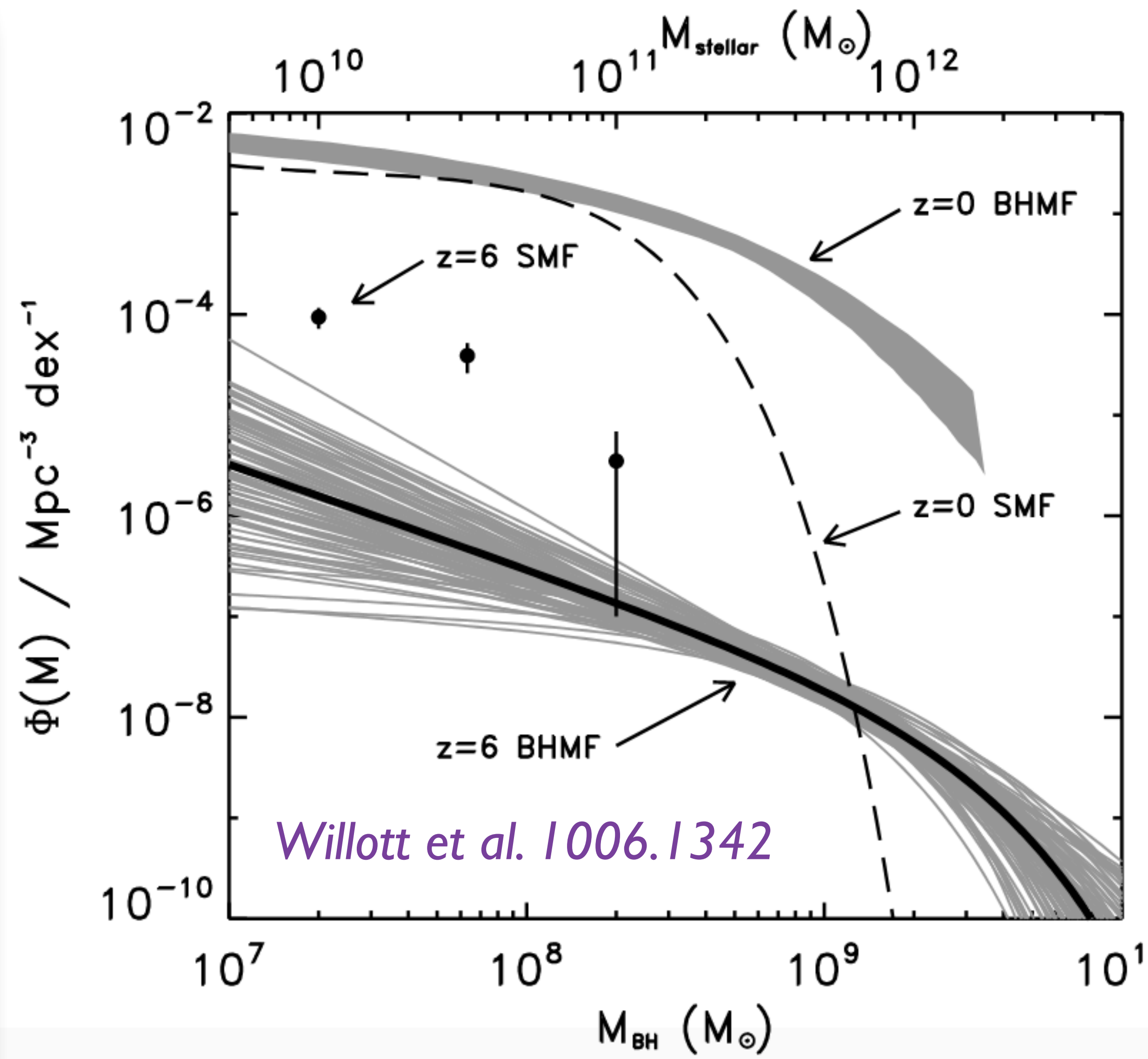
For a review, see e.g. M.Volonteri, 1003.4404

Some not-so-well-know facts about SMBH

- SMBH currently account for ~10^{-5} of the DM density.
- Based on observations, SMBH have undergone significant evolution between z~6 and z~0, cumulatively growing in mass by a factor ~$10^{3.5}$ *(much more than stars!)*
- Even if SMBH underwent no mass growth before z~6, in cosmological epochs they would fulfill the CMB bound, which is *less stringent* that

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

- In case of PBH origin, unlikely that SMBH seen at z~6-7 already in place as such at much earlier epochs:
  i) Hard to see why they would grow in mass by o.o.m. at z<6, but not at z>6.
  ii) Competing and strong bounds exist from CMB spectral distortions.
  iii) Such massive PBH require formation after BBN epoch, since M~10^5 M$_\odot$(t/s): harder for model-building



Conclusions:
despite strong bounds, CMB is compatible with the hypothesis that SMBH @ z>6 are ***seeded*** e.g. by M~O(10^3) M$_\odot$

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 $M_\odot \lesssim M \lesssim 2\times10^4$ $M_\odot$** .

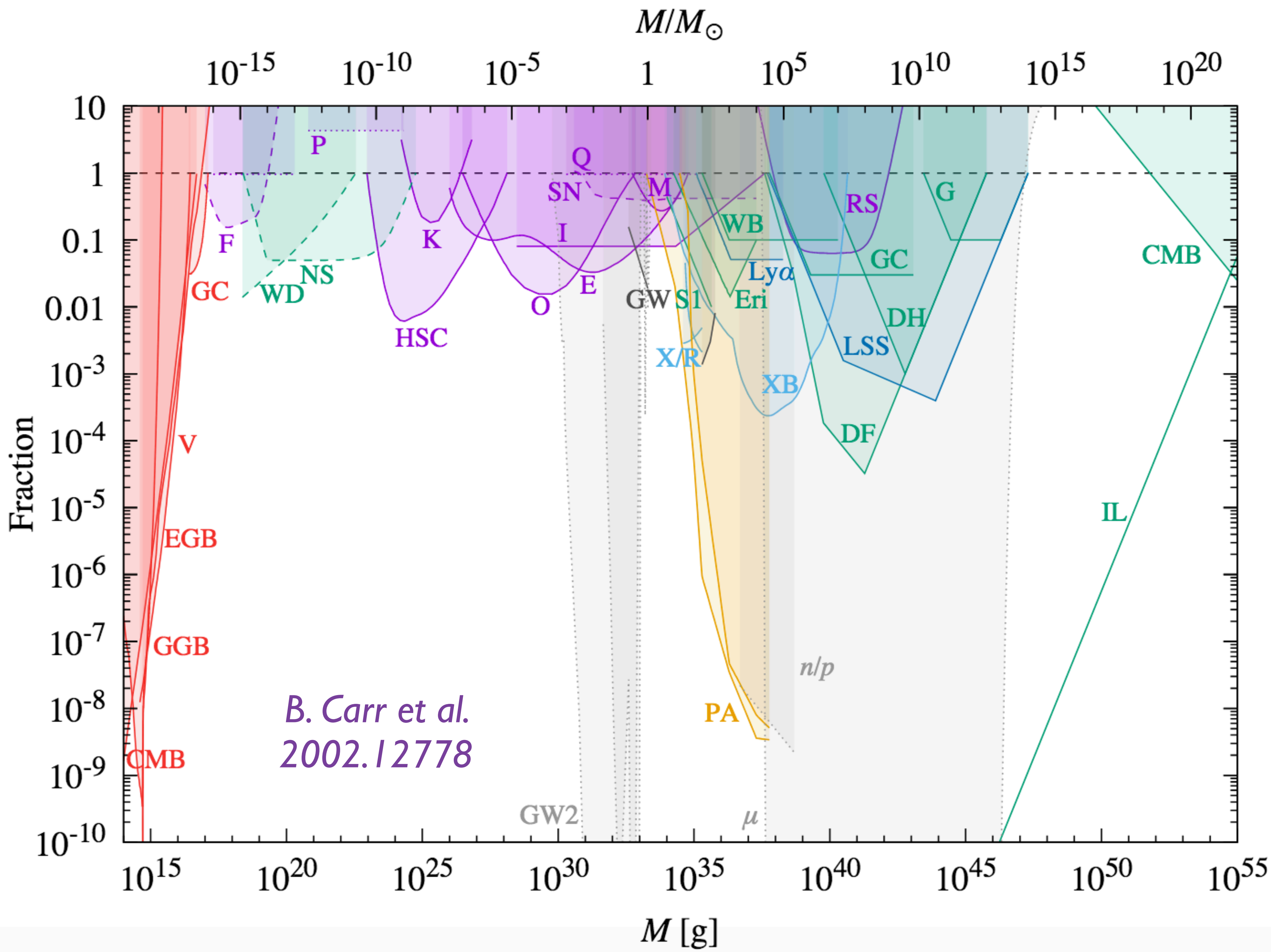
  Accounting for the enhanced baryonic accretion due to the DM halos forming around PBH is crucial to infer such a bound.
- Despite such impressive bounds, within uncertainties PBH can however still account for

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

Backup

Overall bounds: current situation



Constraints on f(M) from evaporation (red), lensing (magenta), dynamical effects (green), accretion (light blue), CMB distortions (orange), large-scale structure (dark blue) and background effects (grey). Evaporation limits come from the extragalactic gamma-ray background (EGB), the Galactic gamma-ray background (GGB) and Voyager e± limits (V). Lensing effects come from femtolensing (F) and picolensing (P) of gamma-ray bursts, microlensing of stars in M31 by Subaru (HSC),in the Magellanic Clouds by MACHO (M) and EROS (E), in the local neighbourhood by Kepler (K), in the Galactic bulge by OGLE (O) and the Icarus event in a cluster of galaxies (I), microlensing of supernova (SN) and quasars (Q), and millilensing of compact radio sources (RS). Dynamical limits come from disruption of wide binaries (WB) and globular clusters (GC), heating of stars in the Galactic disk (DH), survival of star clusters in Eridanus II (Eri) and Segue 1 (S1), infalling of halo objects due to dynamical friction (DF), tidal disruption of galaxies (G), and the CMB dipole (CMB). Accretion limits come from X-ray and radio (X/R) observations, CMB anisotropies measured by Planck (PA) and gravitational waves from binary coalescences (GW). Background constraints come from CMB spectral distortion (μ), 2nd order gravitational waves (GW2) and the neutron-to-proton ratio (n/p). The incredulity limit (IL) corresponds to one hole per Hubble volume.

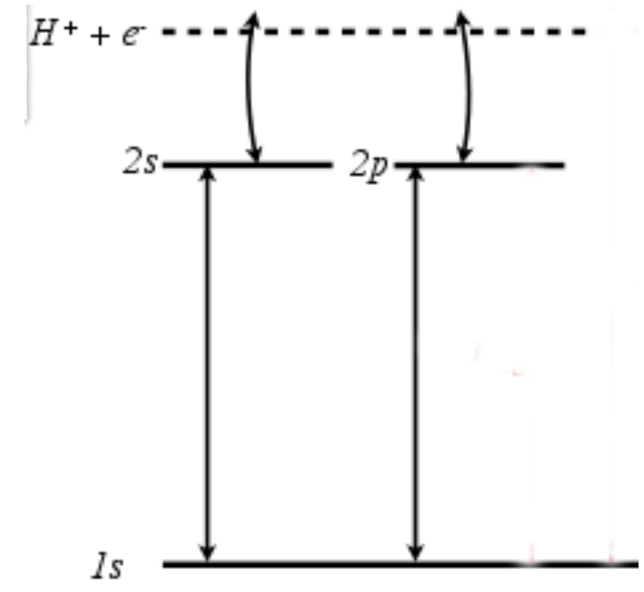
A quick (& simplified!) look at the relevant Eqs.

$$\frac{dx_e(z)}{dz} = \frac{1}{(1+z)H(z)}(R(z) - I(z))$$

ionization fraction Eq.

$$R(z) = C\,\alpha_H x_e^2 n_H \qquad I(z) = C\,\beta_H (1 - x_e) e^{-\frac{h\nu_\alpha}{k_b T_\mathrm{M}}}$$

recombination rate *ionization rate*



The « three levels atom »

$$\gamma \equiv \frac{8\sigma_T a_r T_\mathrm{CMB}^4}{3Hm_e c}\frac{x_e}{1 + f_{He} + x_e}$$

Compton "drag" (note that x_e enters into this coefficient)

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

Eq. for gas temperature

Peebles, P. J. E., "Recombination of the Primeval Plasma", Astrophysical Journal, vol. 153, p. 1, 1968
Zeldovich, Y. B.; Kurt, V. G.; Syunyaev, R. A., "Recombination of Hydrogen in the Hot Model of the Universe", Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, V.55, N. 1, P. 278-286, 1968

Adding exotic terms

$$\frac{dx_e(z)}{dz} = \frac{1}{(1+z)\,H(z)}\left(R(z) - I(z) - I_X(z)\right)$$

Interface via Boltzmann CMB solver dealt with via ExoCLASS

see 1801.01871

$$I_{Xi} = -\frac{1}{n_H(z)E_i}\frac{dE}{dVdt}\bigg|_{\mathrm{dep},i} \qquad I_{X\alpha} = -\frac{(1-C)}{n_H(z)E_\alpha}\frac{dE}{dVdt}\bigg|_{\mathrm{dep},\alpha}$$

These terms encode the model-dependence!

For each channel c, a particle of type/energy P in the cosmological medium with x_e at epoch z only deposits a fraction of the overall energy injected

$$\frac{dE}{dVdt}\bigg|_{\mathrm{dep},c} = f_c^{(P)}(z,x_e)\frac{dE}{dVdt}\bigg|_{\mathrm{inj}}$$

$$K_X = -\frac{2}{H(z)(1+z)3k_b n_H(z)(1+f_{He}+x_e)}\frac{dE}{dVdt}\bigg|_{\mathrm{dep},h}$$

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

The crucial parameters entering the eqs. are the energy deposited by the new source in the plasma

Where does λ come from?

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

Bondi '52

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

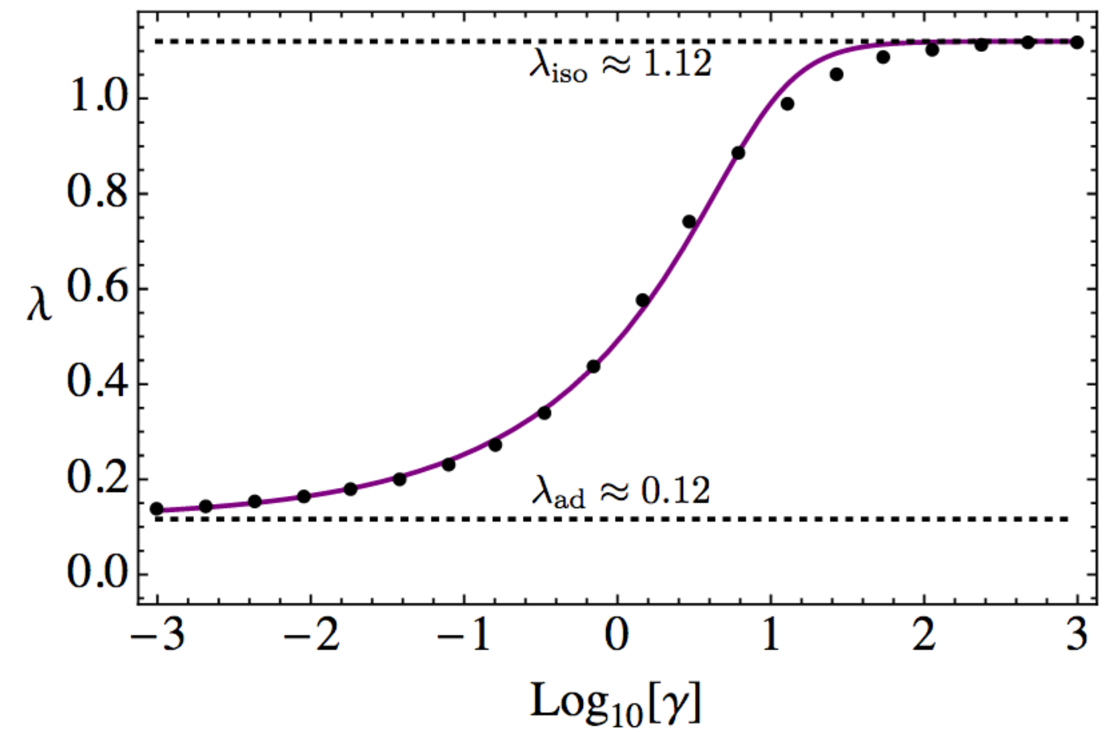
λ~O(0.1-1) accretion eigenvalue comes from solving steady-state problem

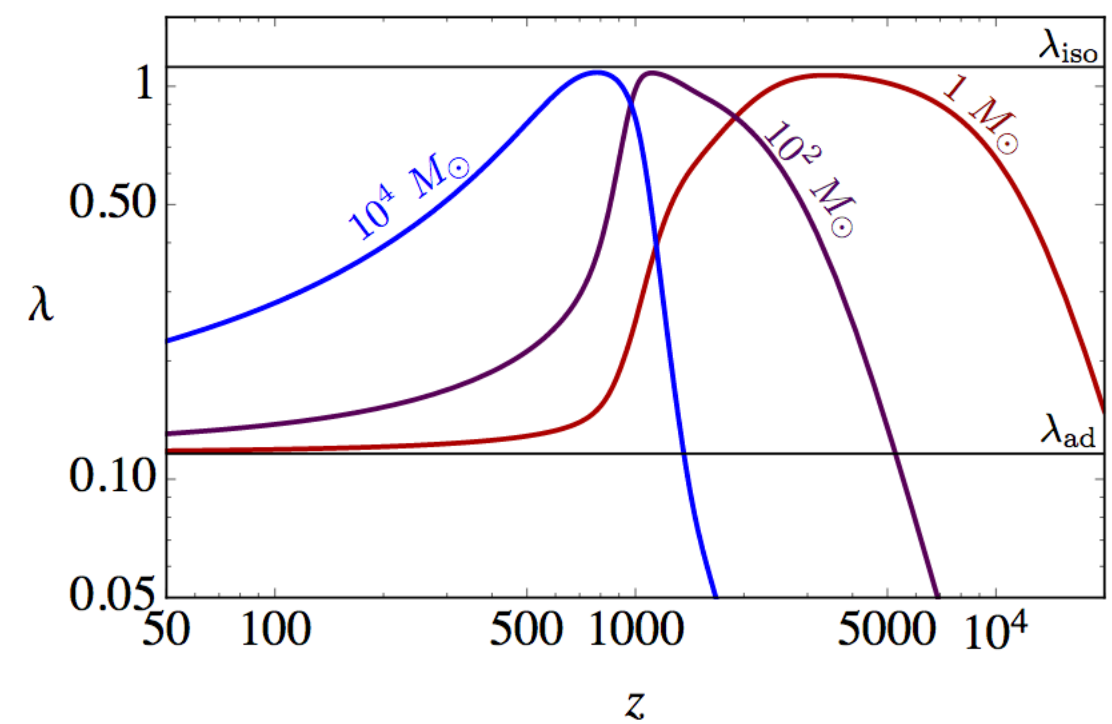
$$4\pi r^2 \rho |v| = \dot{M} = \text{const}$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{GM}{r^2} - \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} - \beta_{\rm drag} v$$

$$P = P(\rho, T)$$

$$\mathscr{D}(T) = \mathscr{F}(T, \beta_{\rm cool})$$





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

On disk formation

If the accreted gas has specific angular momentum l, it cannot fall straight onto the BH, but sets in Keplerian motion at distance $r_D(l)$ given by

$$l \simeq r_D v_{Kep}(r_D) \simeq \sqrt{GMr_D}$$

If $\mathbf{r_D >> 3\, r_{Schw}}$ a disk will form (emission dominated by innermost stable orbits)

Shapiro&Lightman 1976; Ipser&Price 1977; Ruffert 1999; Agol&Kamionkowski 2002

In our case

$$l \simeq \left(\frac{\delta\rho}{\rho} + \frac{\delta v}{v_{\rm eff}} \right) v_{\rm eff} r_{\rm HB} \qquad r_{\rm HB} \simeq \frac{GM}{v_{\rm eff}^2}$$

V. Poulin et al. PRD 96, 083524 (2017)

Density gradients perp. to the BH motion

$$\left.\frac{\delta\rho}{\rho}\right|_{k\sim r_{BH}^{-1}} \gg 10^{-4}$$

easy to satisfy because of the enhanced power spectrum on small scales!

Typical velocity dispersion on small scales

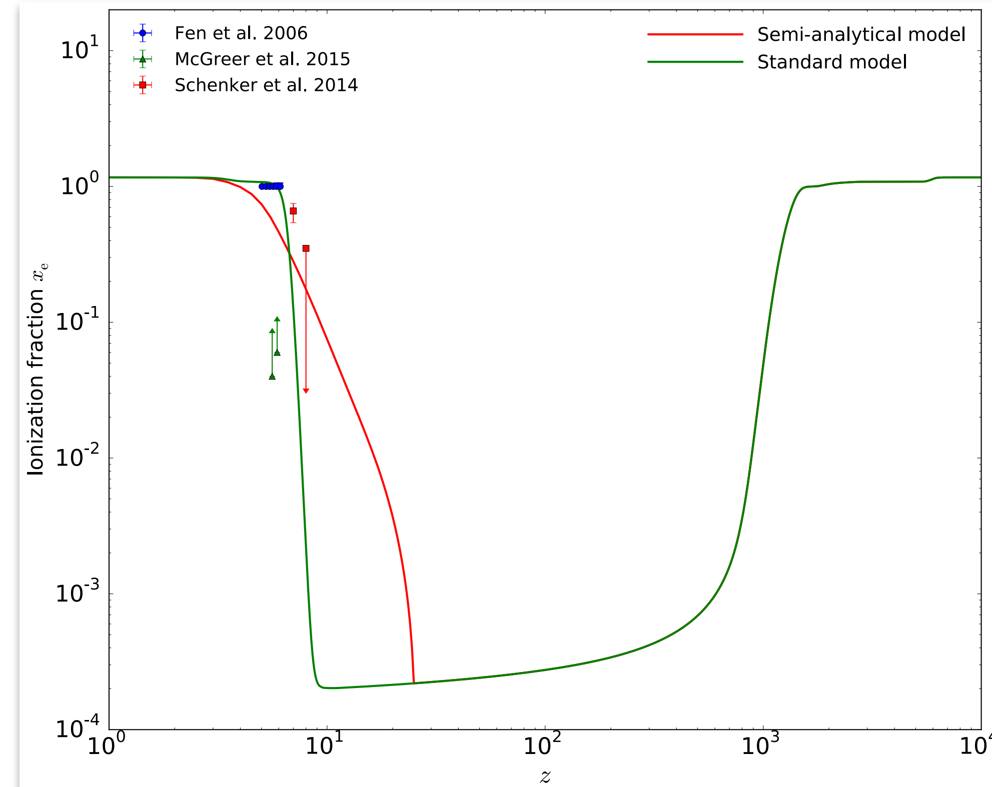
$$\delta v \gg 1.5 \left(\frac{1+z}{1000}\right)^{3/2} \text{m/s}$$

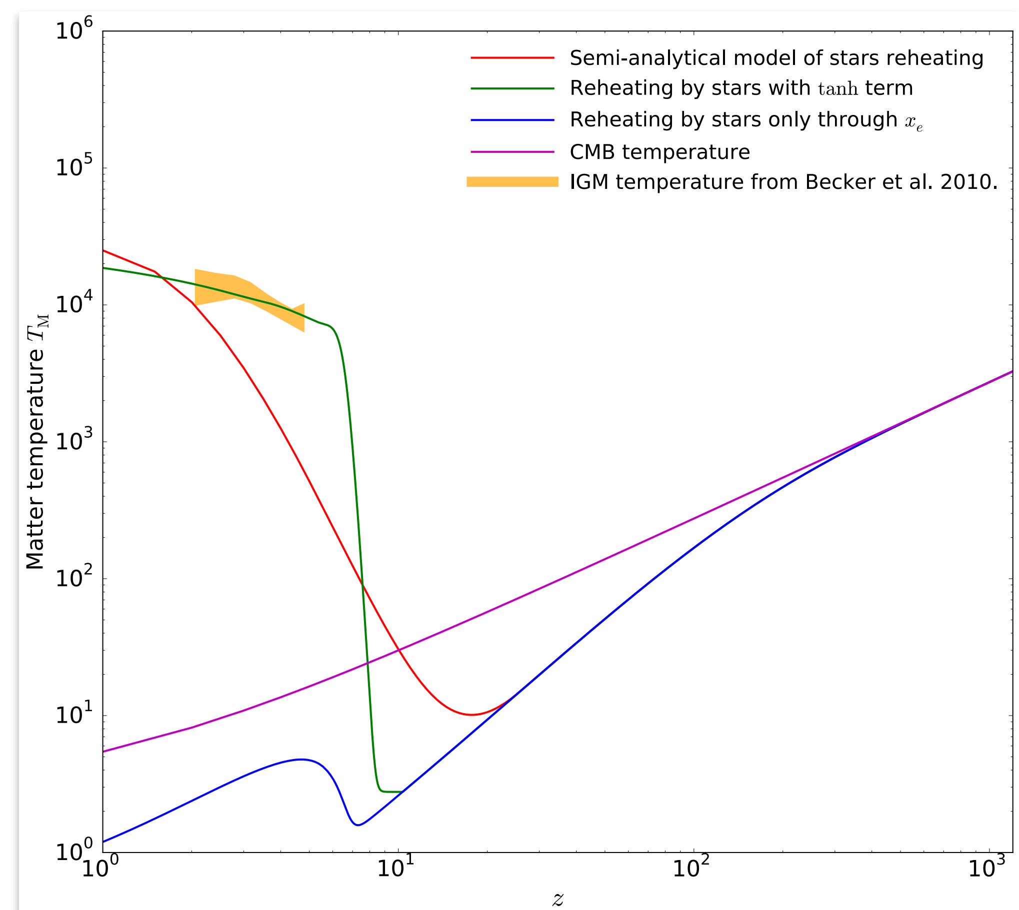
Always true e.g. for typical binary PBH

But these effects are not necessarily sizable if $f_{PBH} \rightarrow 0$

How sensitive is CMB to an alteration in x_e ?

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!