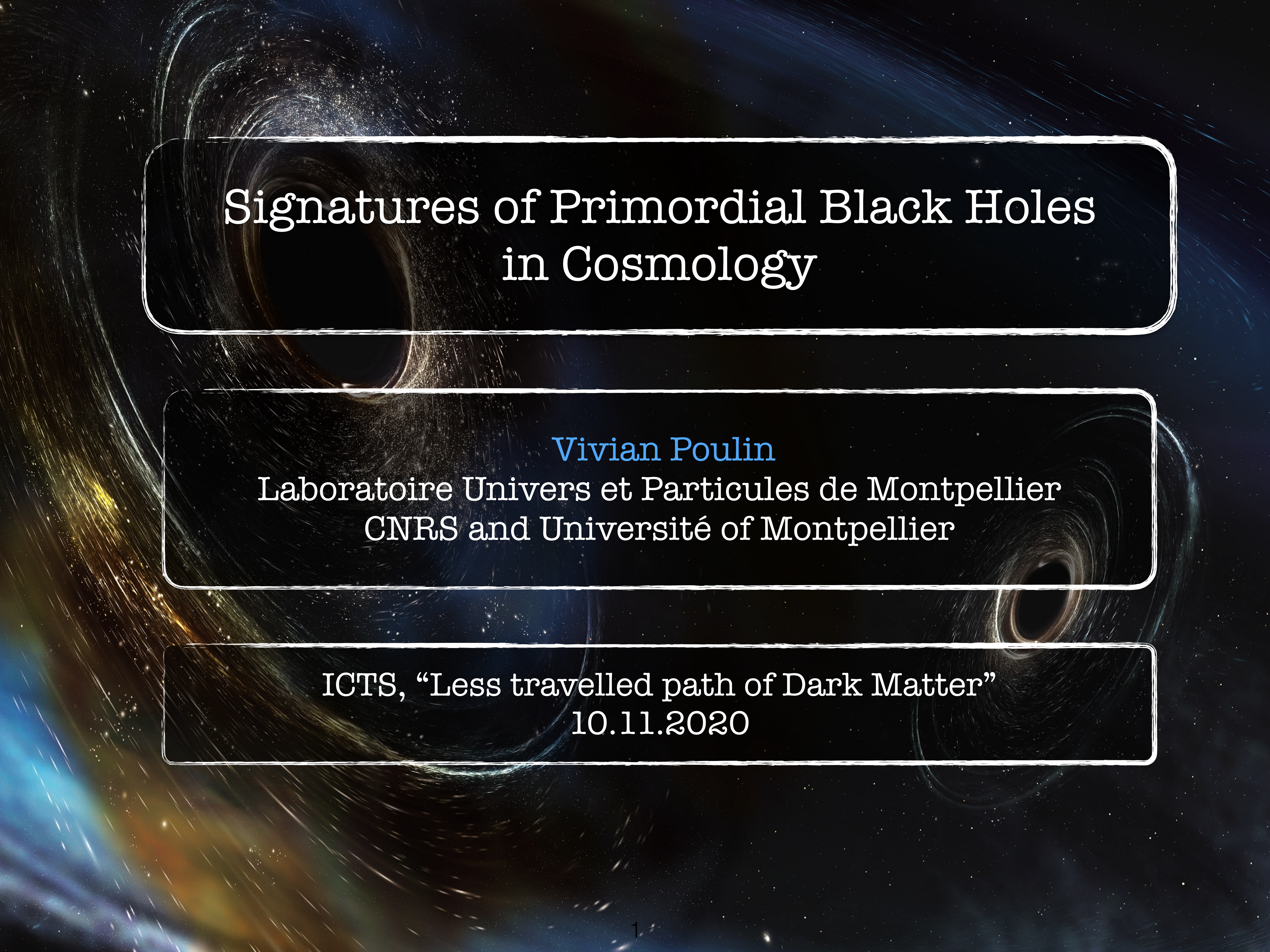

Signatures of Primordial Black Holes in Cosmology

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CNRS and Université of Montpellier

ICTS, “Less travelled path of Dark Matter”
10.11.2020

PBHs are great Dark Matter candidates

- Postulated 40 years ago, they can be created by large density contrast in the early universe;

  Carr&Hawking, MNRAS, vol. 168, pp. 399–415, 1974
  Carr, ApJ., vol. 201, pp. 1–19, 1975
- Do not emit light; Non-relativistic; Nearly collisionless; Formed before BBN;
- Solve small scales issues of DM! *S. Clesse, J. Garcia-Bellido, Phys. Rev. D 92, 023524 (2015)*
- Can be the seeds of SMBH at the center of galaxies; *Carr&Silk, 1801.00672*
- They can be probed in many ways, hence subject to many observational constraints … *Sasaki++, 1801.05235*

Today I will discuss (some of the) cosmological constraints.

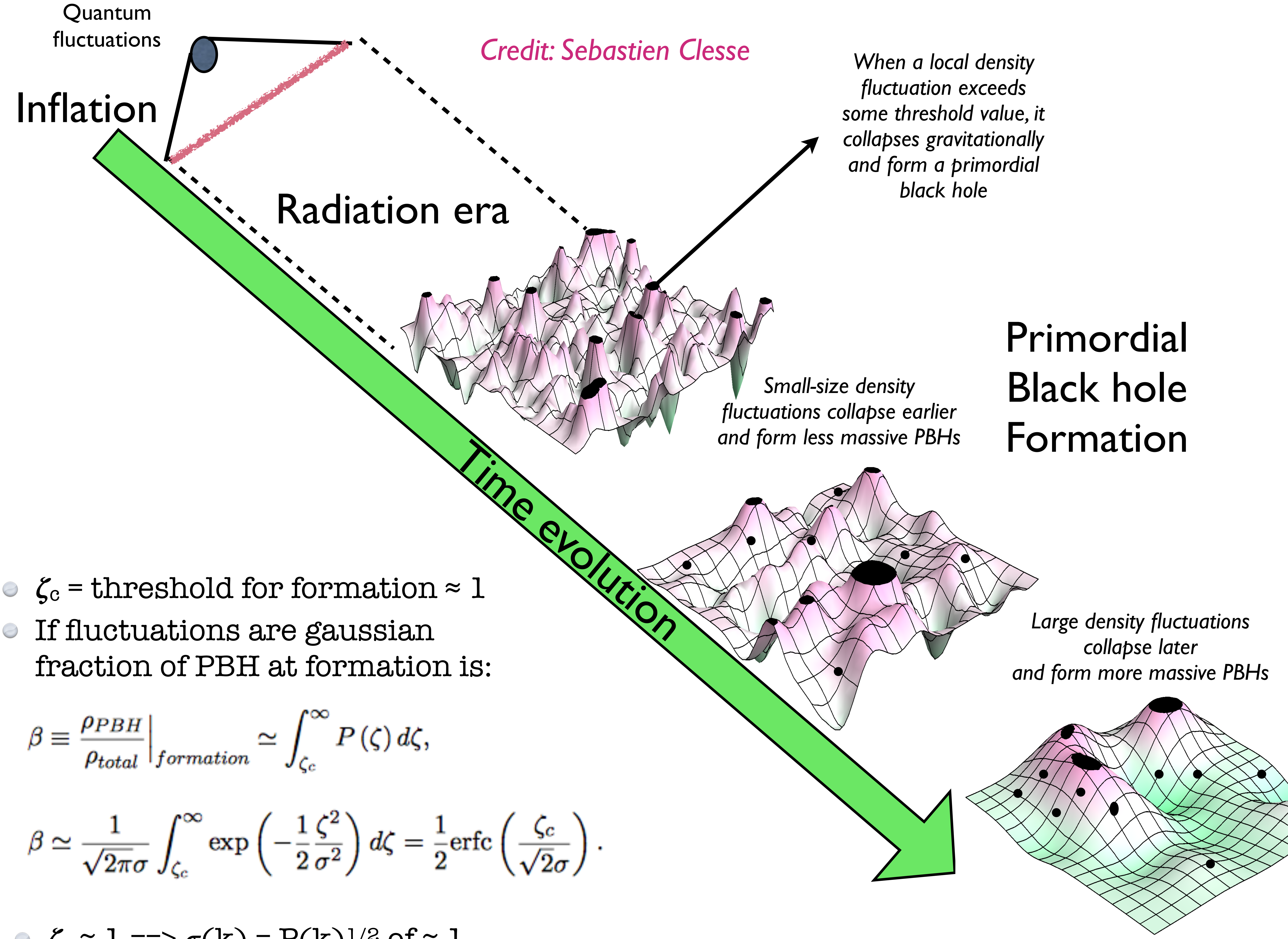
Table of content

- Briefly: constraints on PBH formation and the primordial power spectrum
- Constraints on disk accreting PBH ($1 < M/Msun < 10^{xxx}$)
- A new hope: the 21cm signal
- Constraints on mixed (PBH+else) DM models
- Constraints on evaporating PBH ($3 * 10^{13} < M/g < 10^{17}$)

For more details

- B. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, 2002.12778
- B. Carr and F. Kuhnel, 2006.02838
- M. Sasaki, T. Suyama, T. Tanaka, and S. Yokoyama, 1801.05235
- Green and Kavanagh 2007.10722

Primordial Black hole Formation



Quantum fluctuations

Inflation

Radiation era

Time evolution

Credit: Sebastien Clesse

When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole

Small-size density fluctuations collapse earlier and form less massive PBHs

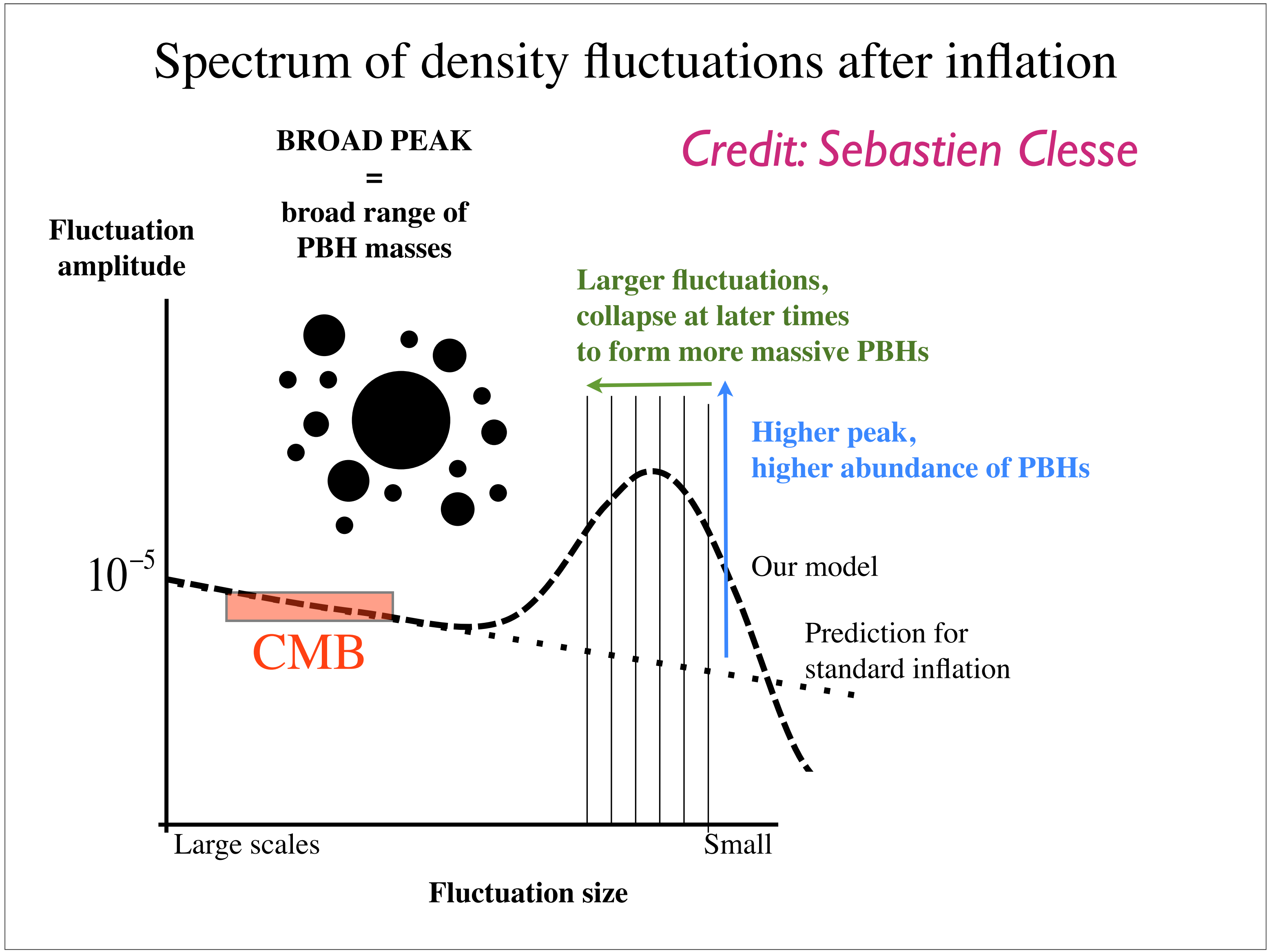
Large density fluctuations collapse later and form more massive PBHs

- ζ_c = threshold for formation ≈ 1
- If fluctuations are gaussian fraction of PBH at formation is:

$$\beta \equiv \frac{\rho_{PBH}}{\rho_{total}}\Big|_{formation} \simeq \int_{\zeta_c}^{\infty} P(\zeta)\, d\zeta,$$

$$\beta \simeq \frac{1}{\sqrt{2\pi}\sigma}\int_{\zeta_c}^{\infty} \exp\left(-\frac{1}{2}\frac{\zeta^2}{\sigma^2}\right) d\zeta = \frac{1}{2}\mathrm{erfc}\left(\frac{\zeta_c}{\sqrt{2}\sigma}\right).$$

- $\zeta_c \approx 1 \Longrightarrow \sigma(k) = P(k)^{1/2}$ of ≈ 1



Many more models in the literature, e.g.

- From extended inflation models (Hybrid, curvaton, multi-fields ...): Typically the field driving inflation needs to slow down to create a peak in $P(k) \propto H^2/\epsilon$. ($\epsilon$ = slow-roll parameter).

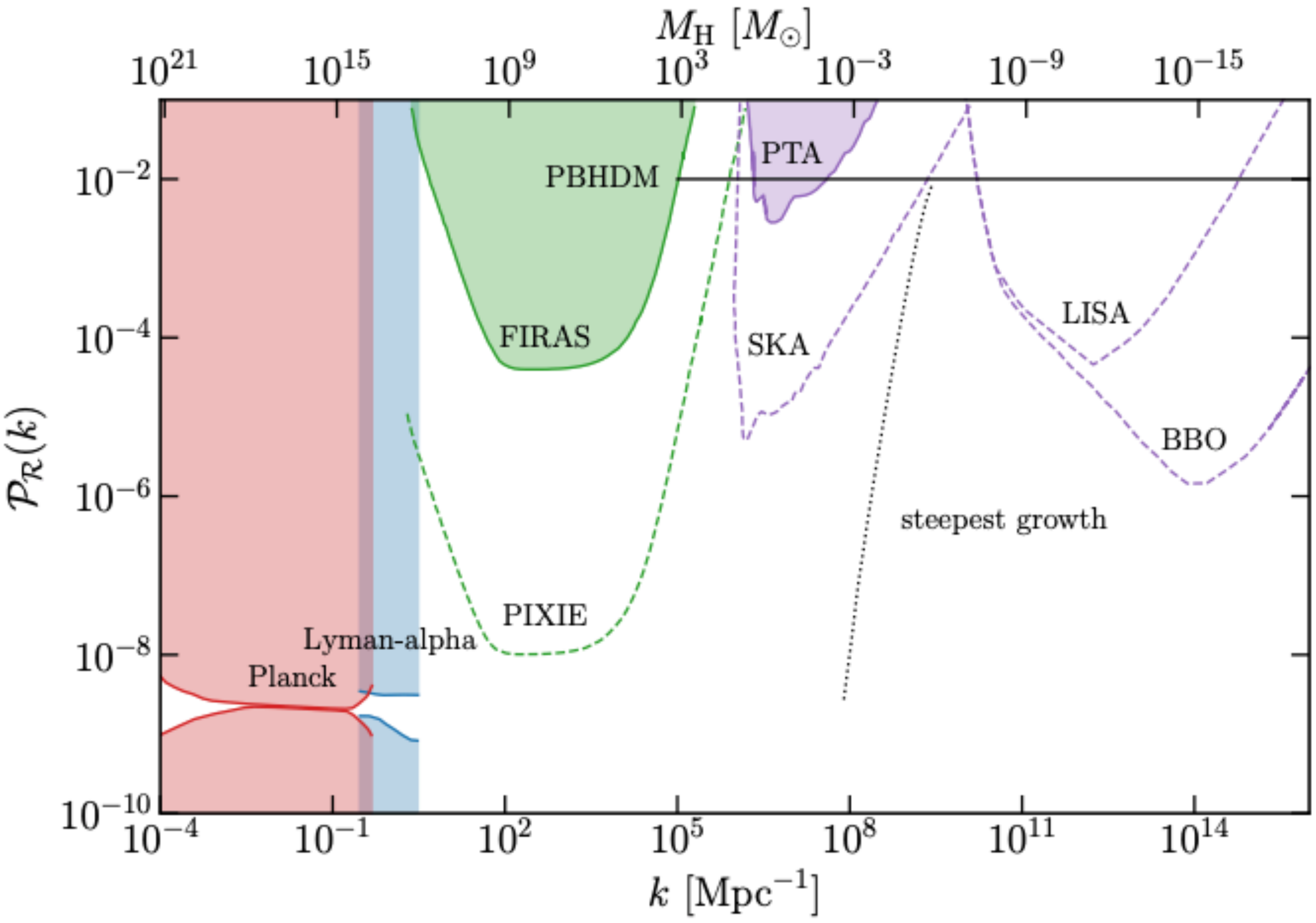
See very complete review by Sasaki++ 1801.05235

- 1st and 2nd order phase transitions: lowers the threshold

Jedamzik& Nemeyer, PRD59, p. 124014, 1999; Rubin et al., JETP, vol. 91, pp. 921–929, 2001

Green and Kavanagh 2007.10722

Constraints on the (primordial) amplitude of density fluctuations



Relic density
(Assuming Gaussian)

- These constraints can affect specific scenarios of PBH formation
- They can be sensitive to the `statistics' of the fluctuation

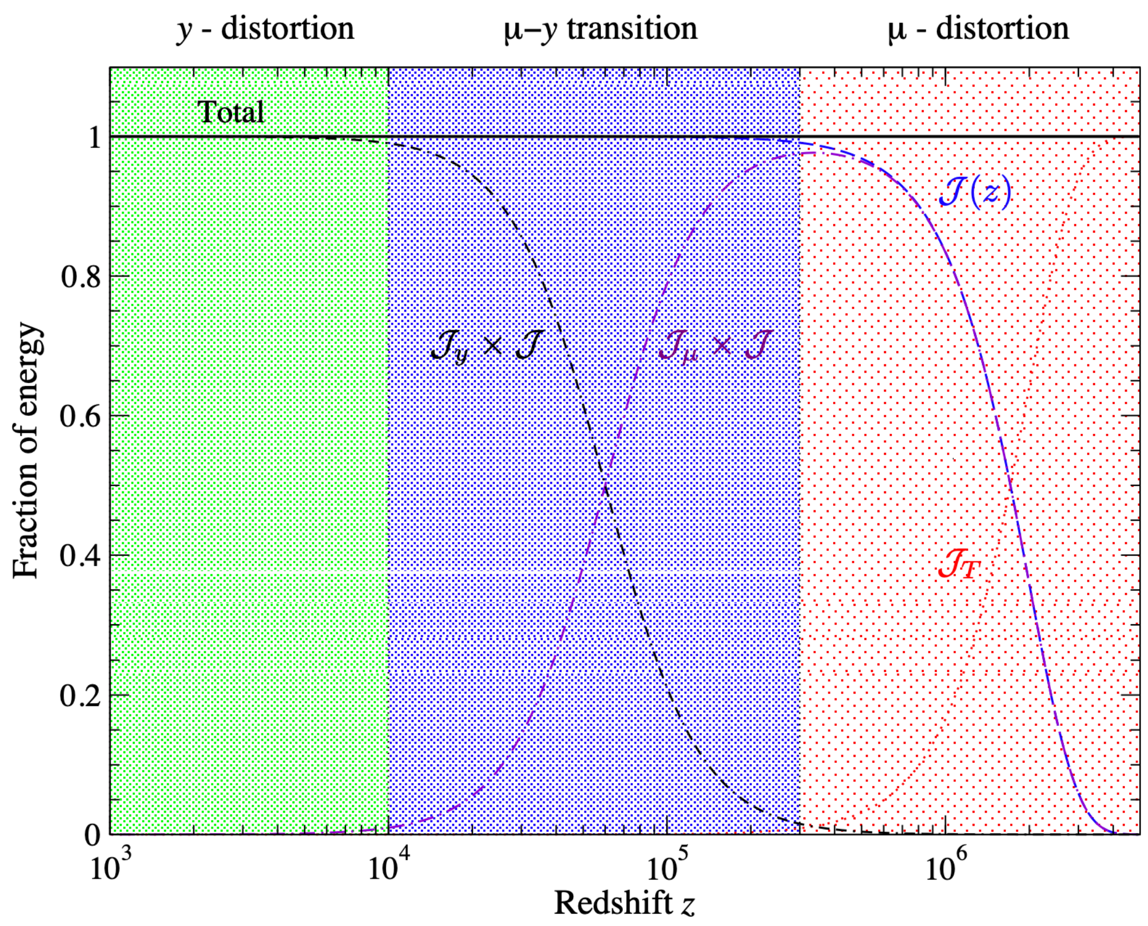
Spectral Distortions

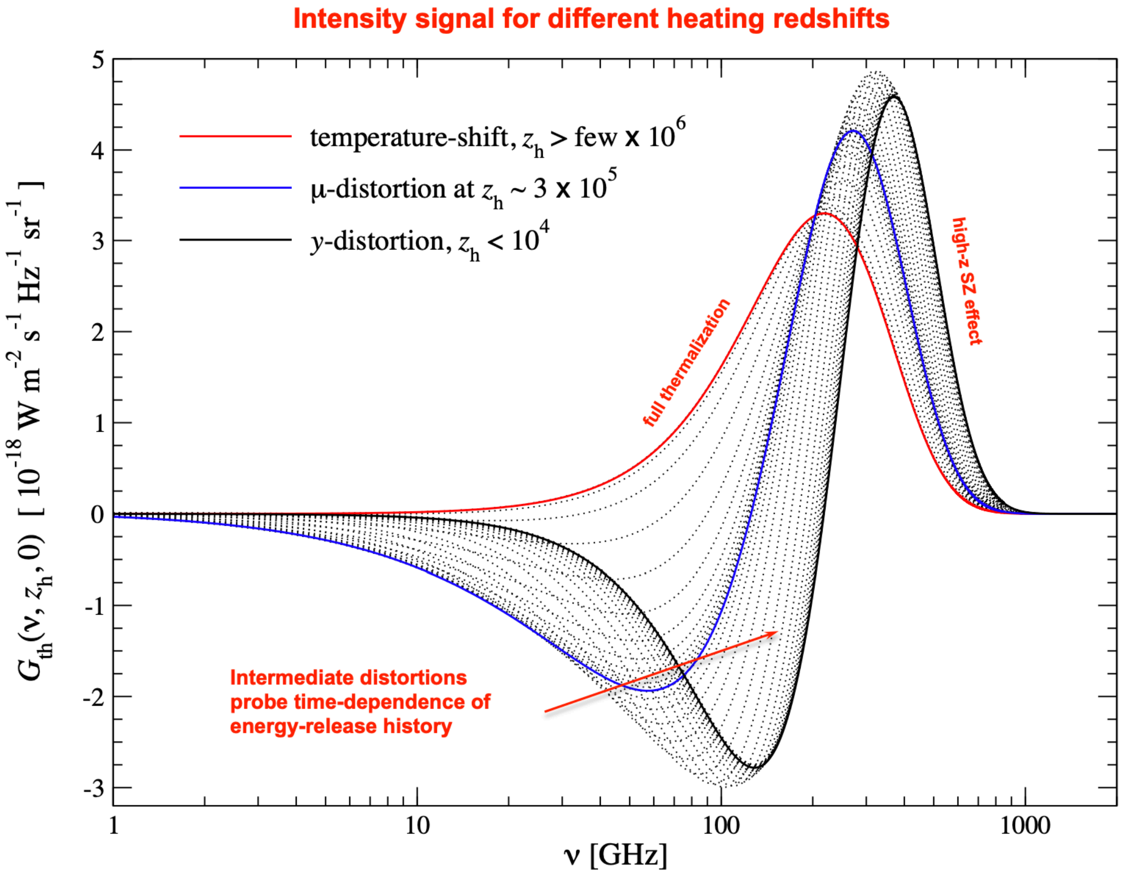
Chluba++ 1505.01834

- Power at small scales is damped via Compton scattering- the so-called "Silk Damping": this `thermalization' affect the black-body distribution
- Most important processes to thermalise any energy injection are Bremsstrahlung, Compton and Double-Compton scattering.
- If those processes go out of equilibrium, SD can occur.

$$\Delta I(\nu) = I_{\rm true}(\nu) - I_{\rm bb}(\nu)$$

$$\Delta I_\nu \approx \int G_{\rm th}(\nu, z') \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$$





Chluba++ 1505.01834

Firas: $\mu < 9 \times 10^{-5},\ y < 1.5 \times 10^{-5}$

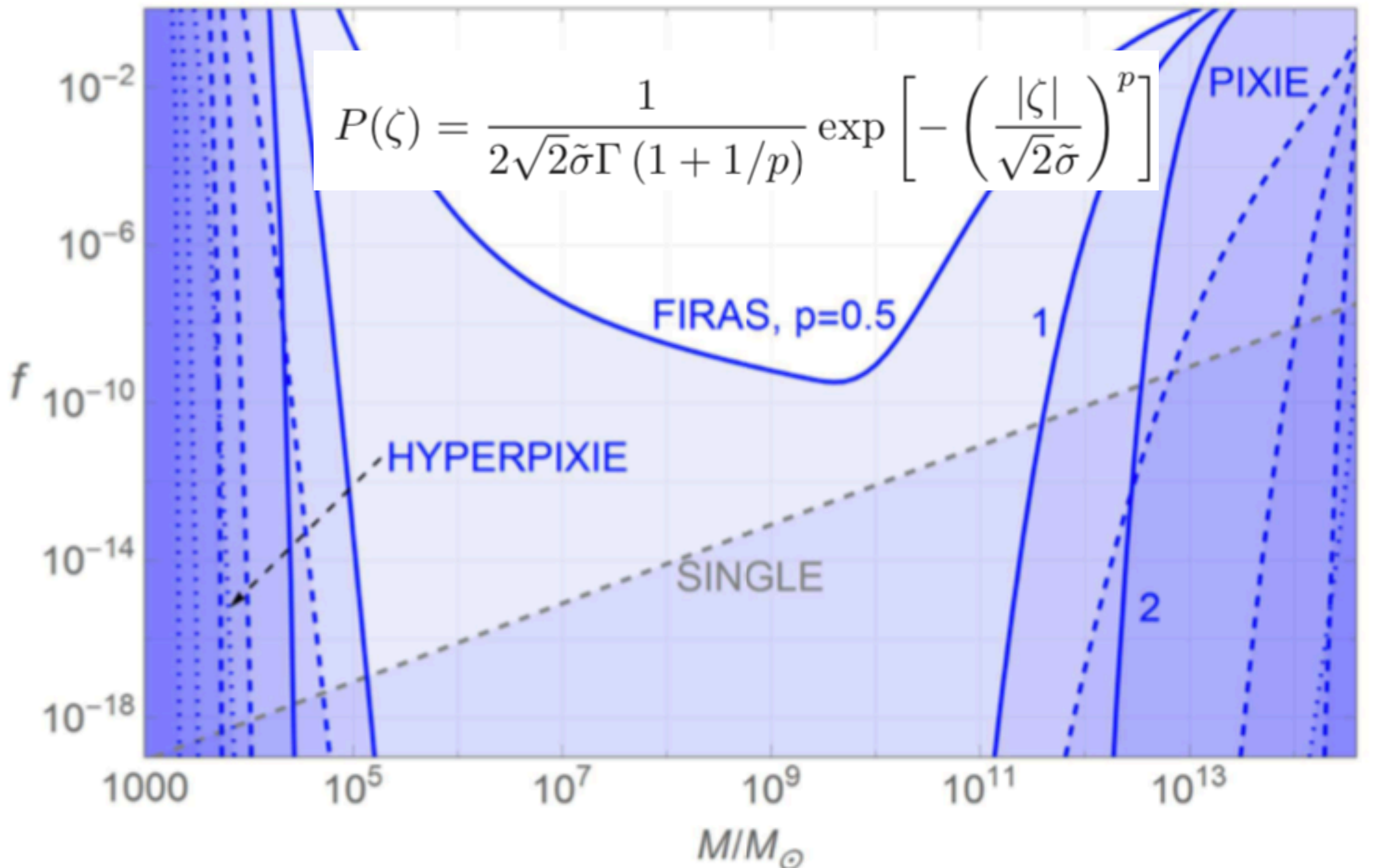
Fixsen++ ApJ 1996

Spectral Distortions

$$\frac{\mathrm{d}(Q_{\mathrm{ac}}/\rho_\gamma)}{\mathrm{d}z} \approx -2A^2 \frac{\mathrm{d}}{\mathrm{d}z} \int \frac{k^2\,\mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k)\, \mathrm{e}^{-2k^2/k_{\mathrm{D}}^2}$$

$$r_d^2(\tau) \equiv \left(\frac{2\pi}{k_d}\right)^2 \sim \int_{\tau_{\mathrm{ini}}}^{\tau} \frac{d\tau}{a n_e \sigma_T}$$

- Range probe: 30 Mpc^{-1} < k < 5000 Mpc^{-1}, which corresponds to the PBH mass range of $10^5 M_\odot < M < 10^{10} M_\odot$
- Caveat: the constraints depend on the statistics. It relaxes largely for non-gaussian $(p \neq 2)$ distribution.



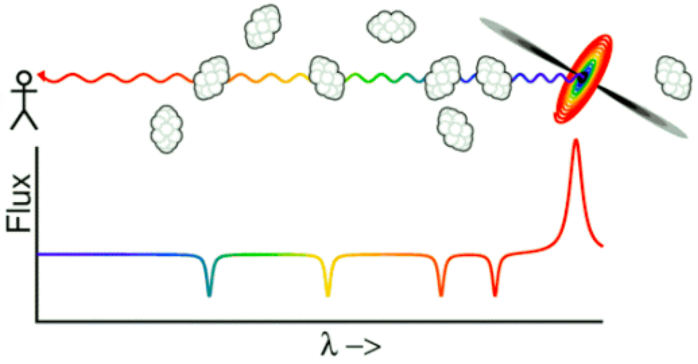
$$P(\zeta) = \frac{1}{2\sqrt{2}\tilde{\sigma}\Gamma\left(1+1/p\right)} \exp\left[-\left(\frac{|\zeta|}{\sqrt{2}\tilde{\sigma}}\right)^p\right]$$

Kohri++ 1405.5999
Nakama++ 1710.06945

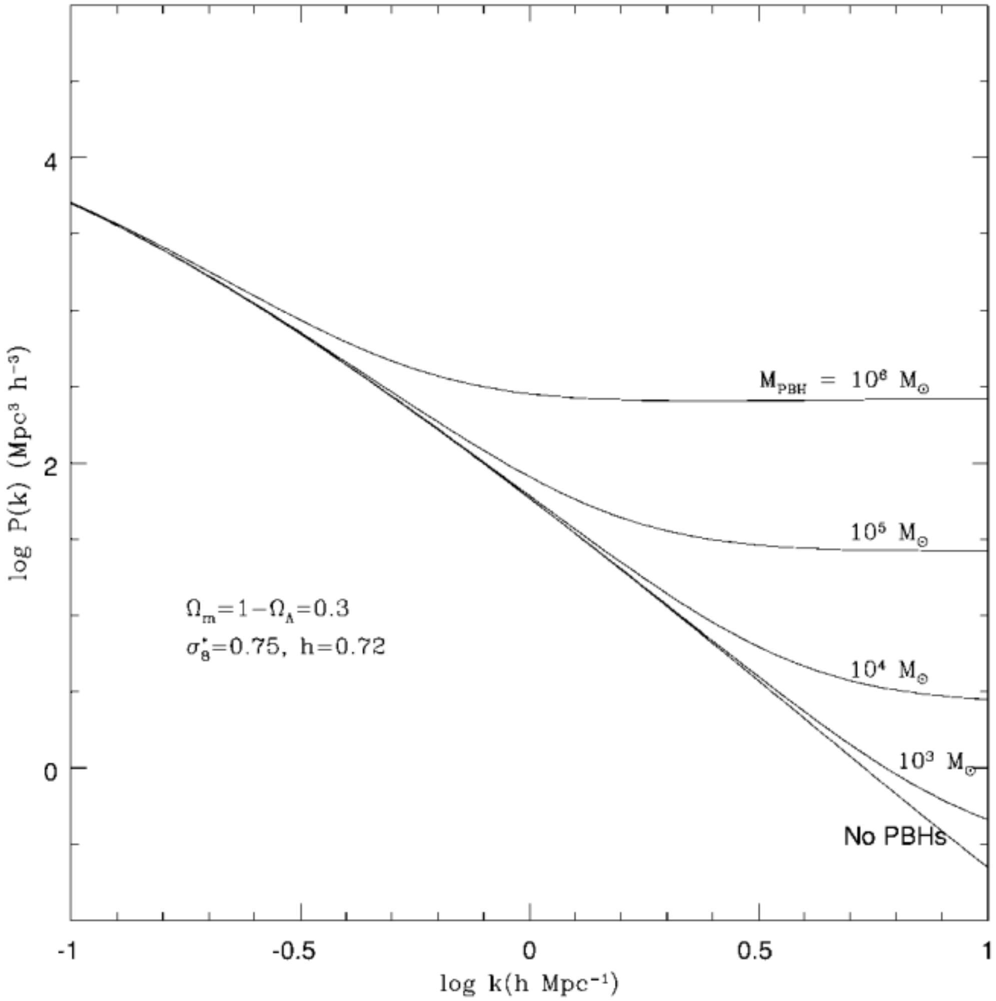
Constraints from Ly-α

- Poisson-fluctuation in the density field leads to power enhancement

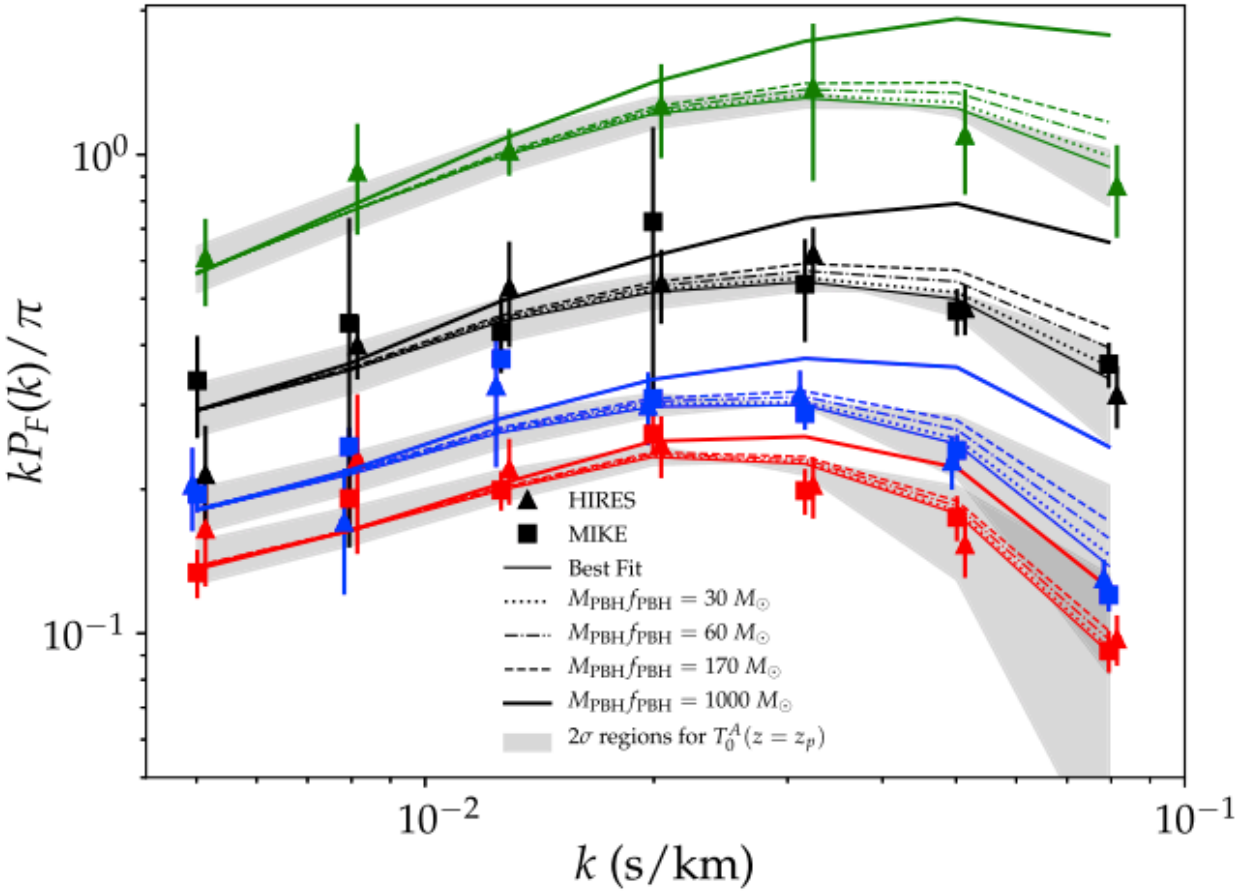
$$P_{\rm PBH}(k) = \langle|\delta_{\rm PBH}(k)|^2\rangle = \frac{1}{n_{\rm PBH}}$$



- Ly-α constrains the fraction of PBH to satisfy: $f_{\rm PBH}M_{\rm PBH} \lesssim 60 M_\odot\ (2\sigma)$.

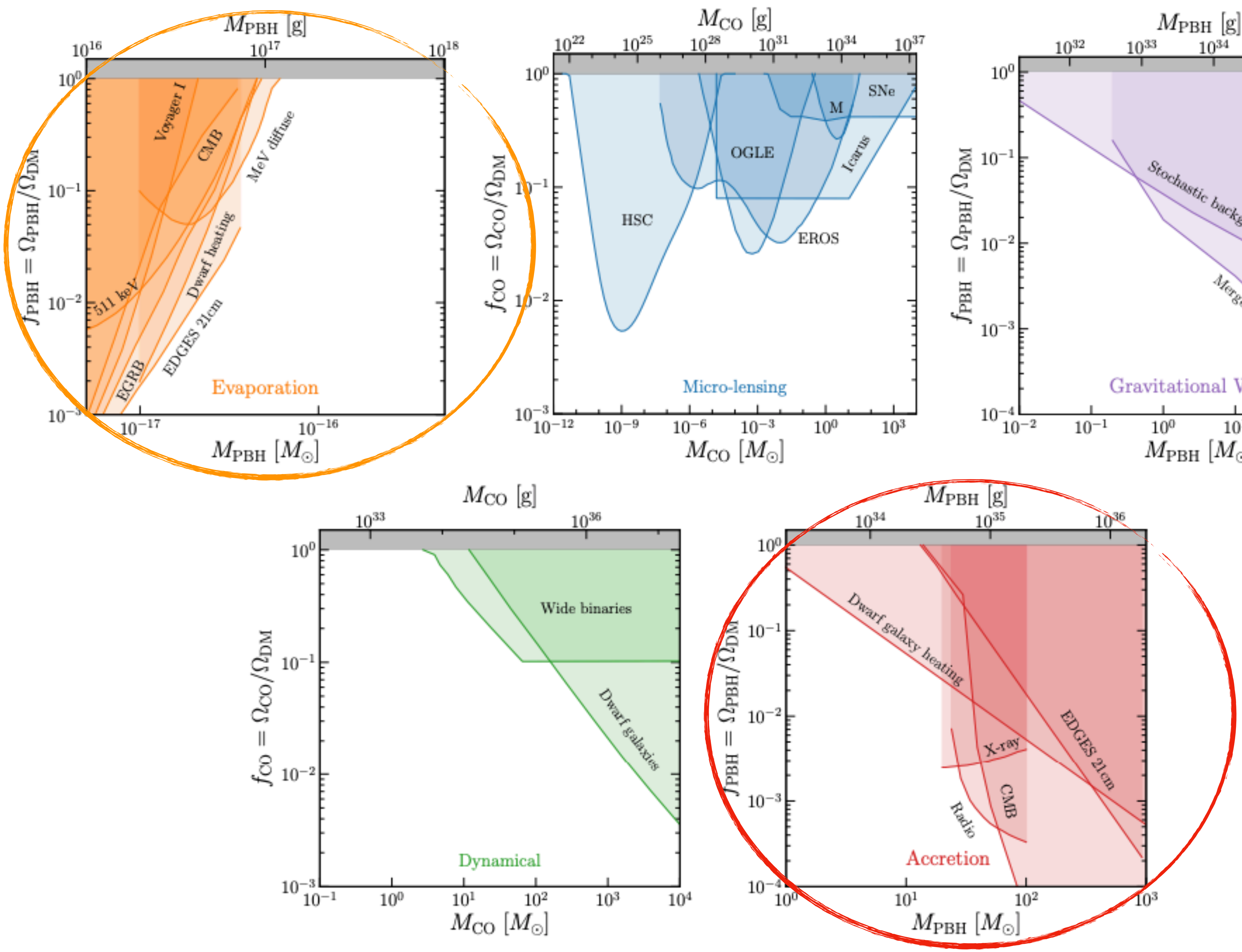


Ashfordi, McDonald, Spergel, JCAP 2003



Murgia++ 1903.10509

Green and Kavanagh 2007.10722



- Today: Accretion and Evaporation with the CMB and 21 cm signal

How do e.m. energy injection affect the CMB?

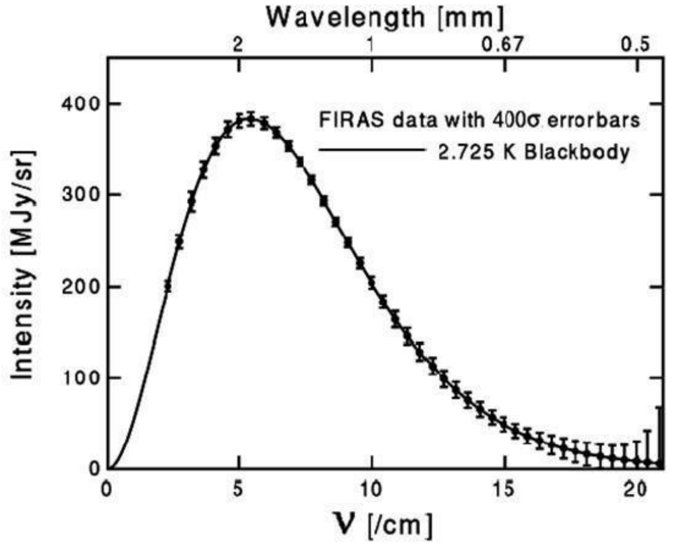
I) Generate spectral distortions $\approx \dfrac{\Delta\rho_\gamma}{\rho_{\gamma,\mathrm{cmb}}} < 10^{-5}$.

Problem: $\rho_{\gamma,\mathrm{cmb}}$ is huge when interactions are switched on (z >1000).

see e.g. Chluba & Sunyaev, MNRAS 419 (2012) 1294-1314

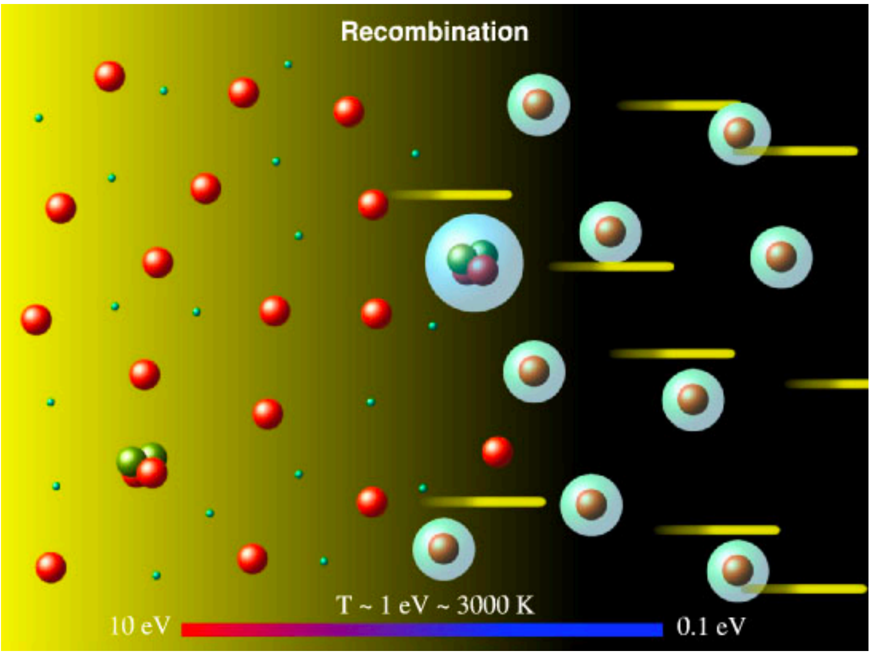
SD distortions from the PBH are weak.

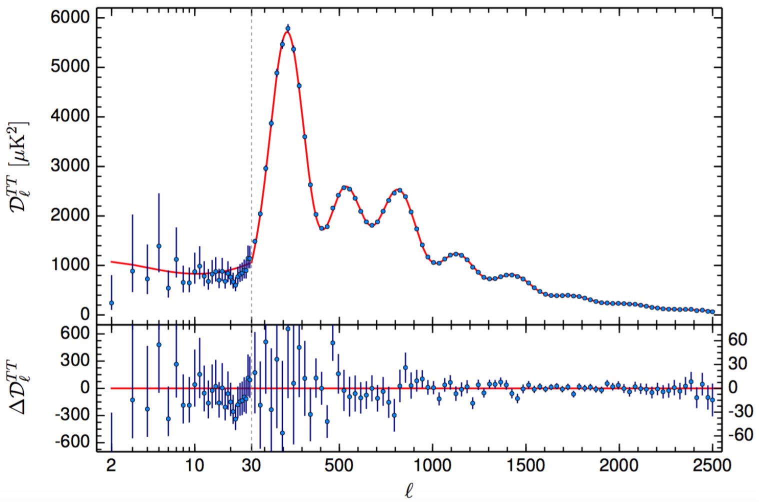
Ali-Haimoud&Kamionkowski, PRD95, no. 4, p. 043534, 2017.

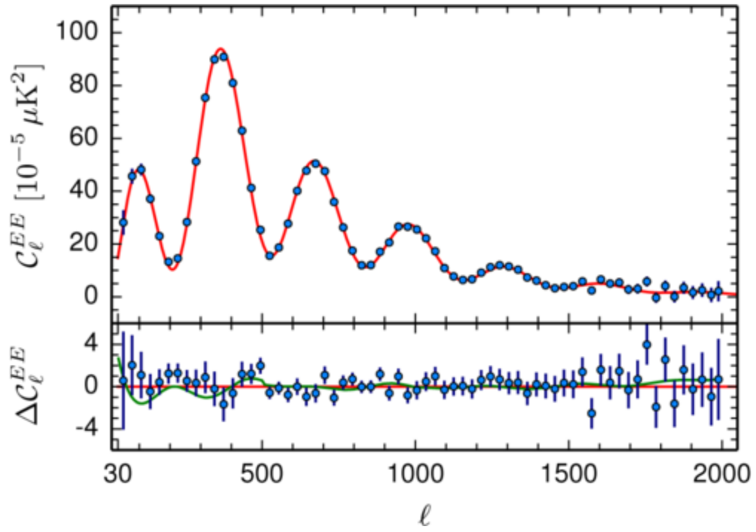


(COBE/Firas 1990)

II) Affect baryons, which in turn affects CMB decoupling and CMB anisotropies

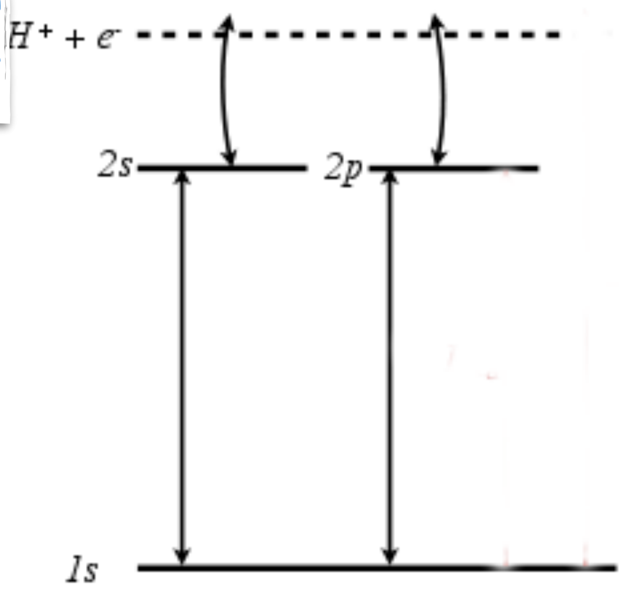






Main impact of e.m. energy injection: modification of recombination era

The recombination era at T ≈ 0.2 eV



The « three levels atom »
Zeldovich Kurt Sunyaev 1968
Peebles 1968

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}[R_s(z) - I_s(z)]$$

$$[R_s(z) - I_s(z)] = C \times \left[x_e^2(n_H + n_p)\alpha_\beta - \beta_B(1-x_e)e^{-\frac{h\nu_\alpha}{k_b T}}\right]$$

e–p recombination term

$\gamma_{\rm CMB}$H ionization term

$$x_e = \frac{n_e}{n_e + n_H}$$

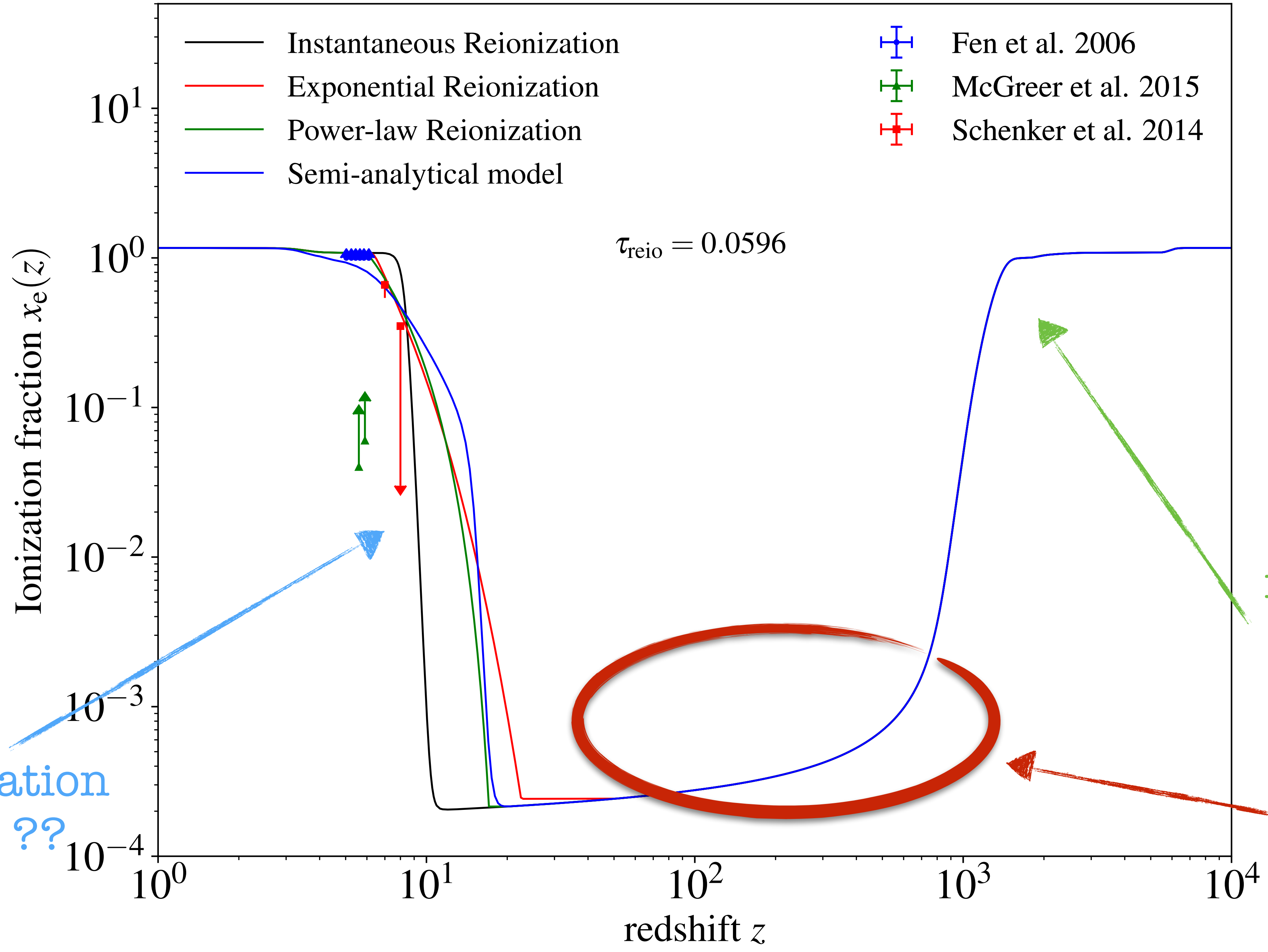
$$\frac{dT_{\rm M}}{dz} = \frac{1}{1+z}\left[2T_{\rm M} + \gamma(T_{\rm M} - T_{\rm CMB})\right]$$

For cosmology, sub % precision is needed!

- multilevel atoms in non-equilibrium
- radiative transfer effects
- H and He feedbacks

Numerical codes used: **CosmoRec, HyRec and « fudged » Recfast**

Standard ionization history



$$x_e = \frac{n_e}{n_e + n_H}$$

recombination
at z ≈ 1100

relic fraction
of free e-

reionization
at z ≈ ??

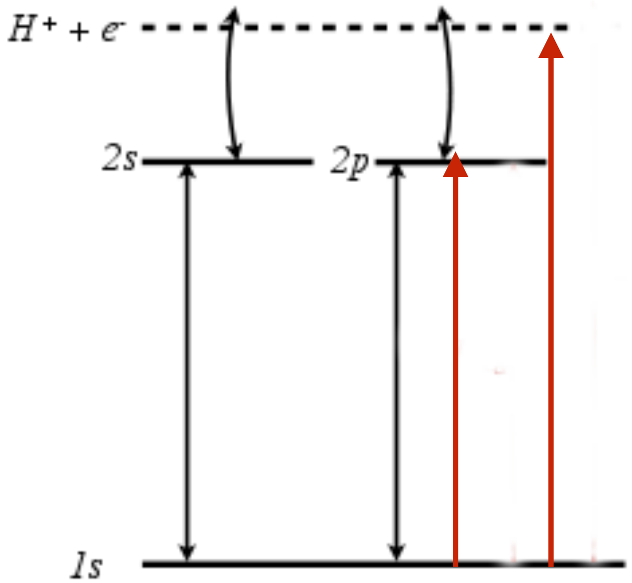
Huge uncertainty in the reionization modelling!
Does not matter that much for CMB analysis. 21cm!!

E.m. energy injection can modify the ionization and temperature history

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}\left[R_s(z) - I_s(z) - I_X(z)\right]$$

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

$$I_X(z) \text{ and } K_h(z) \;\propto\; \left.\frac{dE}{dV\,dt}\right|_{\rm dep,c}$$



The « three levels atom »

Typical parametrization through the $f_c(z, x_e)$ functions :

$$\left.\frac{dE}{dV\,dt}\right|_{\rm dep,c}(z) = f_c(z, x_e)\left.\frac{dE}{dV\,dt}\right|_{\rm inj}(z)$$

Plasma Properties

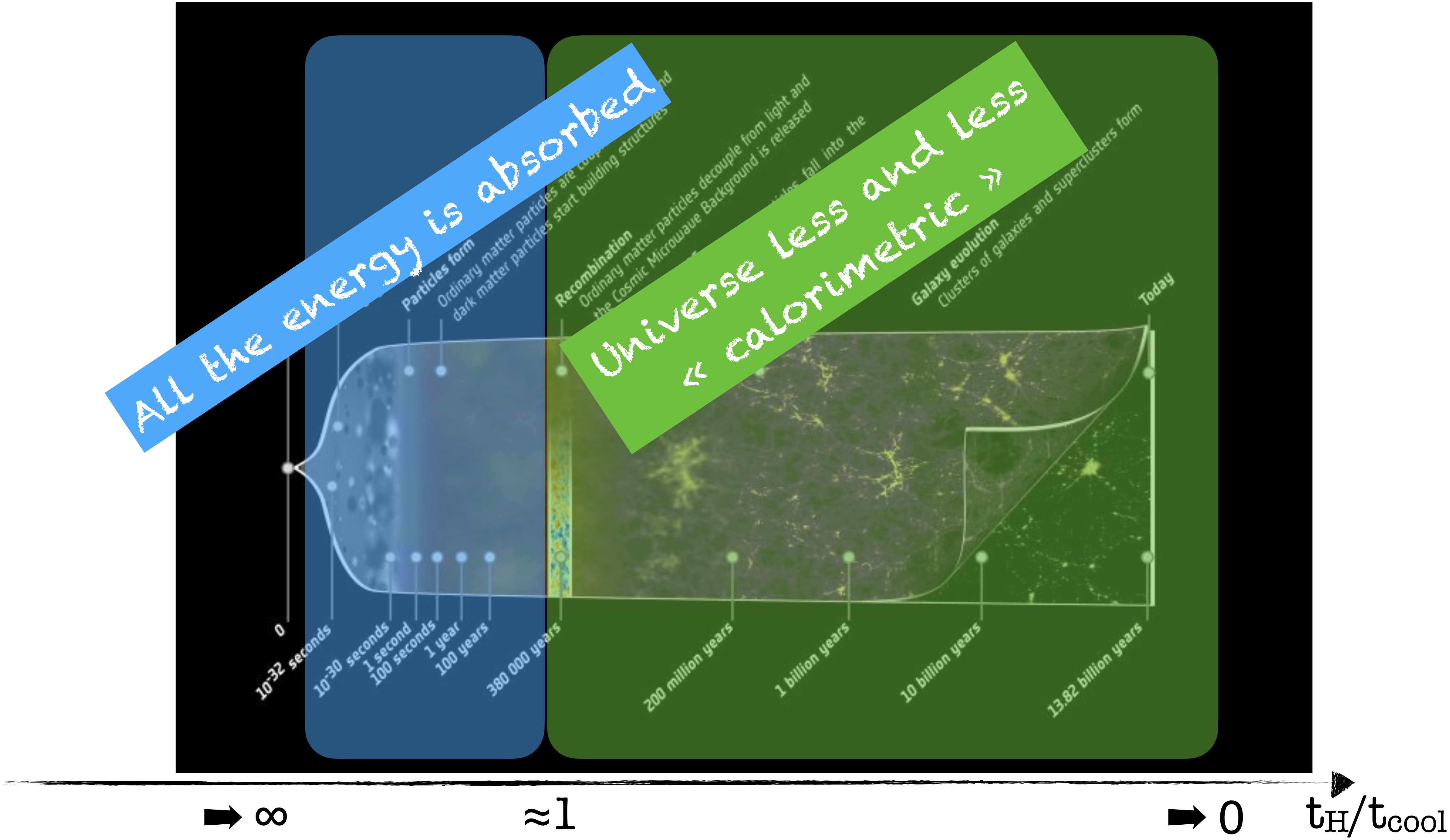
Particle/Astro-Physics

$f_c(z, x_e)$ is the key quantity, it encodes:

- What fraction of the injected energy is left to interact with the IGM
- How this is energy is distributed among each channel: ’heat’, ‘ionization’, ‘excitation’

We inject γ in a plasma with $n_\gamma >> n_b$

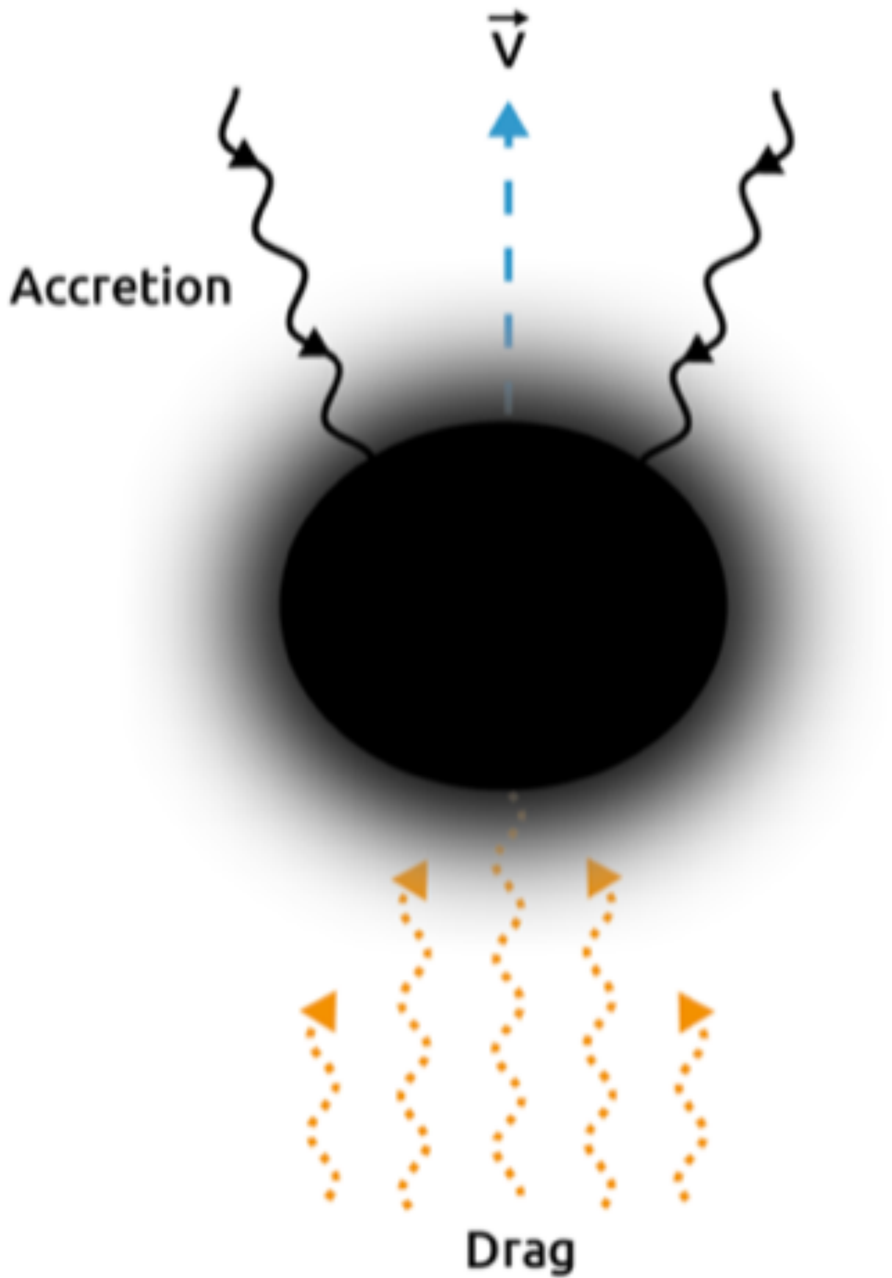
Q : What happens to the photon distribution?



Slatyer, PRD93 2016, Liu++ PRD 2020

High mass BH accrete the surrounding medium

This heats the gas and leads to the emission of x-ray emission that can affect the CMB.



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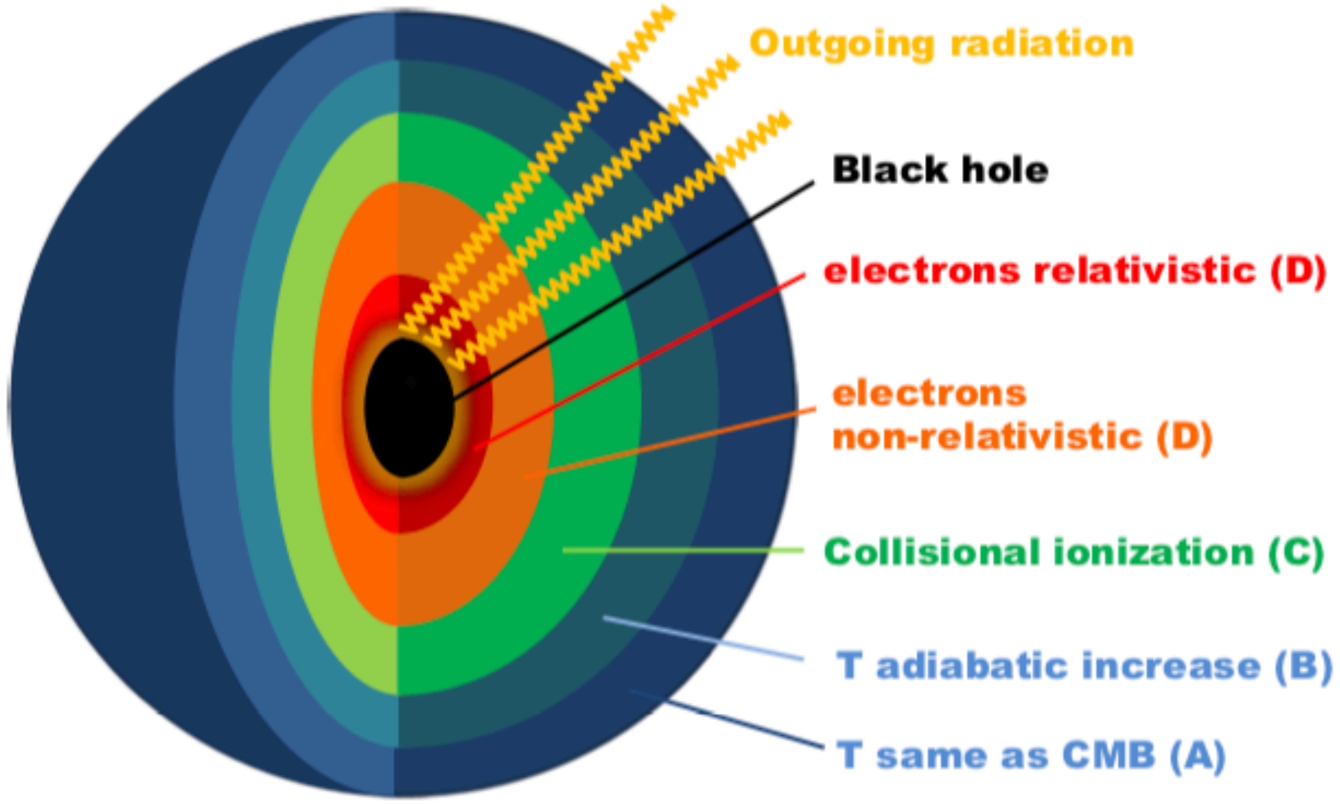


Sasaki++, 1801.05235

Essential on PBH accretion

See Yacine Ali-Haimoud's lecture

- Problematic of accretion onto a point mass M is old: seminal papers focused on accretion by star in an infinite gas cloud.

Hoyle & Lyttleton, 1939, 1940; Bondy & Hoyle 1944; Bondi 1952

- Famous result by Bondi derived in the context of spherical accretion

$$\dot{M}_{\rm HB} \equiv 4\pi\lambda\rho_\infty v_{\rm eff} r_{\rm HB}^2 \equiv 4\pi\lambda\rho_\infty \frac{(GM)^2}{v_{\rm eff}^3}$$

- This is a « geometrical » result: Mass passing through a sphere of radius $r_{\rm HB} = GM/v_{\rm eff}^2$
- what is $v_{\rm eff}$? No exact calculation exists... Proxy: $v_{\rm eff}^2 = c_{s,\infty}^2 + v_{\rm rel}^2$

Sound speed in the gas Relative velocity between gas & BH

- $\lambda \approx 1$: accretion eigenvalue. Take into account gas pressure, interaction with CMB...
- The accreted matter gets heated $T_S \approx 10^9$-10^{11}K: bremsstrahlung emission.

$$L = \epsilon \dot{M}_{HB} c^2 \qquad \epsilon \simeq 10^{-3} - 10^{-5} \dot{M}/\dot{M}_{\rm edd} \qquad L_\nu \propto \nu^{-0.5} \exp(-\nu/T_s)$$

Shapiro 1973, 1974

- This formalism is applied to disk accretion with appropriate values:

$$\lambda \simeq 10^{-1} - 10^{-2} \qquad \epsilon \simeq 10^{-1} - 10^{-3} \dot{M}/\dot{M}_{\rm edd}$$

Review: Narayan&Yuan 2014

A major unknown: the geometry of the accretion

- CMB constraints strongly depend on the geometry of the accretion: spherical or disk?
- This will then set the typical values required for λ and ϵ.
- Spherical accretion: Ricotti et al, 2007, Ali-Haimoud & Kamionkowski: $M > 100 M_\odot$ (conservative case).

Ricotti et al., ApJ., vol. 680, p. 829, 2008.

Ali-Haimoud&Kamionkowski, PRD95, no. 4, p. 043534, 2017.

Is spherical accretion a good approximation ??

- If the accreted gas has a high angular momentum, it cannot fall straight onto the BH.
- Energy is dissipated but angular momentum is conserved ==> Accretion disk forms.
- How high should be the angular momentum?
  => Keplerian angular momentum for a rotation around the BH at a distance r_D.

$$l_D \simeq r_D v_{\rm Kep}(r_D) \simeq \sqrt{G M r_D}$$

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

A criterion for disk accretion

- Now the angular momentum is simply

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

Density gradients perp. to the BH motion Typical velocity dispersion on small scales

- Hypothesis: a disk forms if the radius of the disk $r_D >> r_S=2GM$

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

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

Agol&Kamionkowski 2002, VP++ 1707.04206

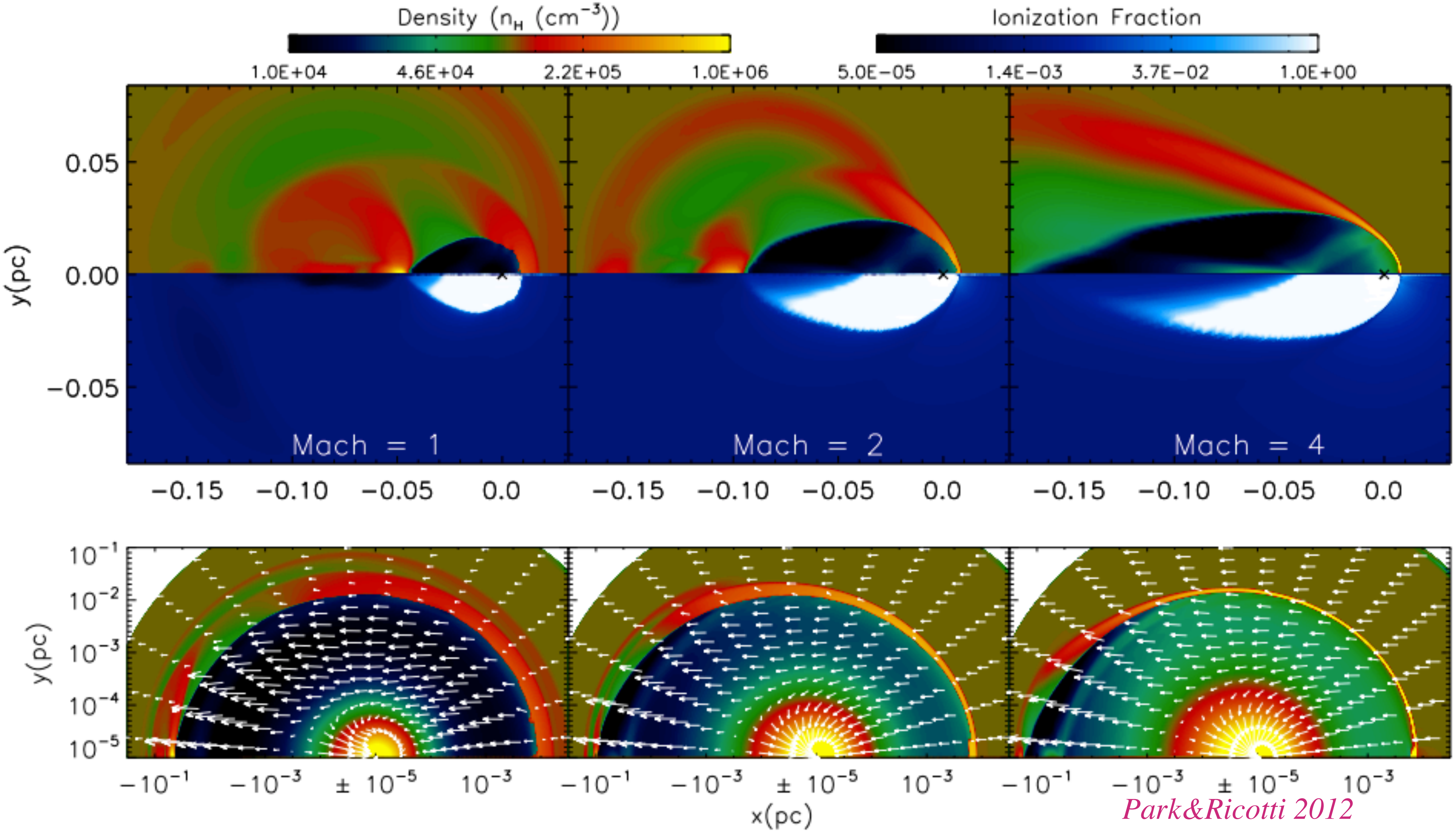
- This is easily satisfied because of the enhanced power spectrum on small scales! At z=1000, $k_{NL} \approx 10^3 \text{Mpc}^{-1} << k_{BH} \approx 10^5 \text{Mpc}^{-1}$

Afshordi et al., ApJ. 594 (2003) L71-L74
Gong&Kitajima, 1704.04132

- No exact computation possible because of non-linearity, but this is always true for binary BH: $\delta v = \omega r_{\rm HB} = \sqrt{2GM/a^3}$ with $a \simeq d/2 \simeq (3M/(4\pi\rho_{\rm PBH}))^{1/3} \Rightarrow M/M_\odot \gg ((1+z)/730)^3$

- Spherical accretion leads to conservative constraints but in the early universe, it is possible that a disk forms!

- This is also favored by numerical simulations of supersonic moving black holes.
- Accretion transitions from spherical to “bow-shaped”.
- At $z \lesssim 1000$: $v_{\rm rel} \simeq 5c_s\sqrt{(1+z)/1000}$.



Park&Ricotti 2012

What disk forms?

Review: Yuan&Narayan 1401.0586

- Optimistic: Cold, Thin Disk, high radiative efficiency $\epsilon \sim 0.1$, leads to the strongest constraints.

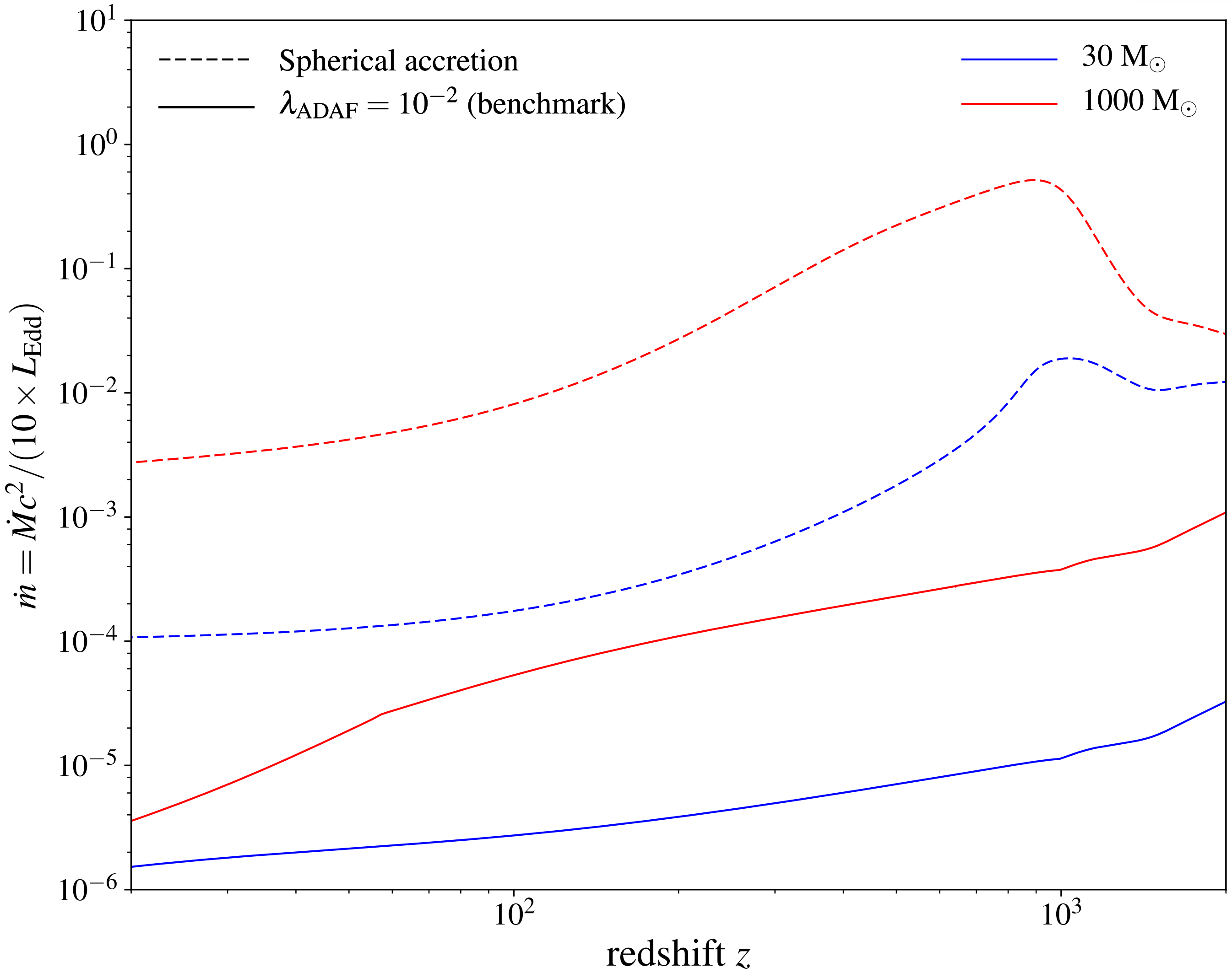
Shakura & Sunyaev 1973

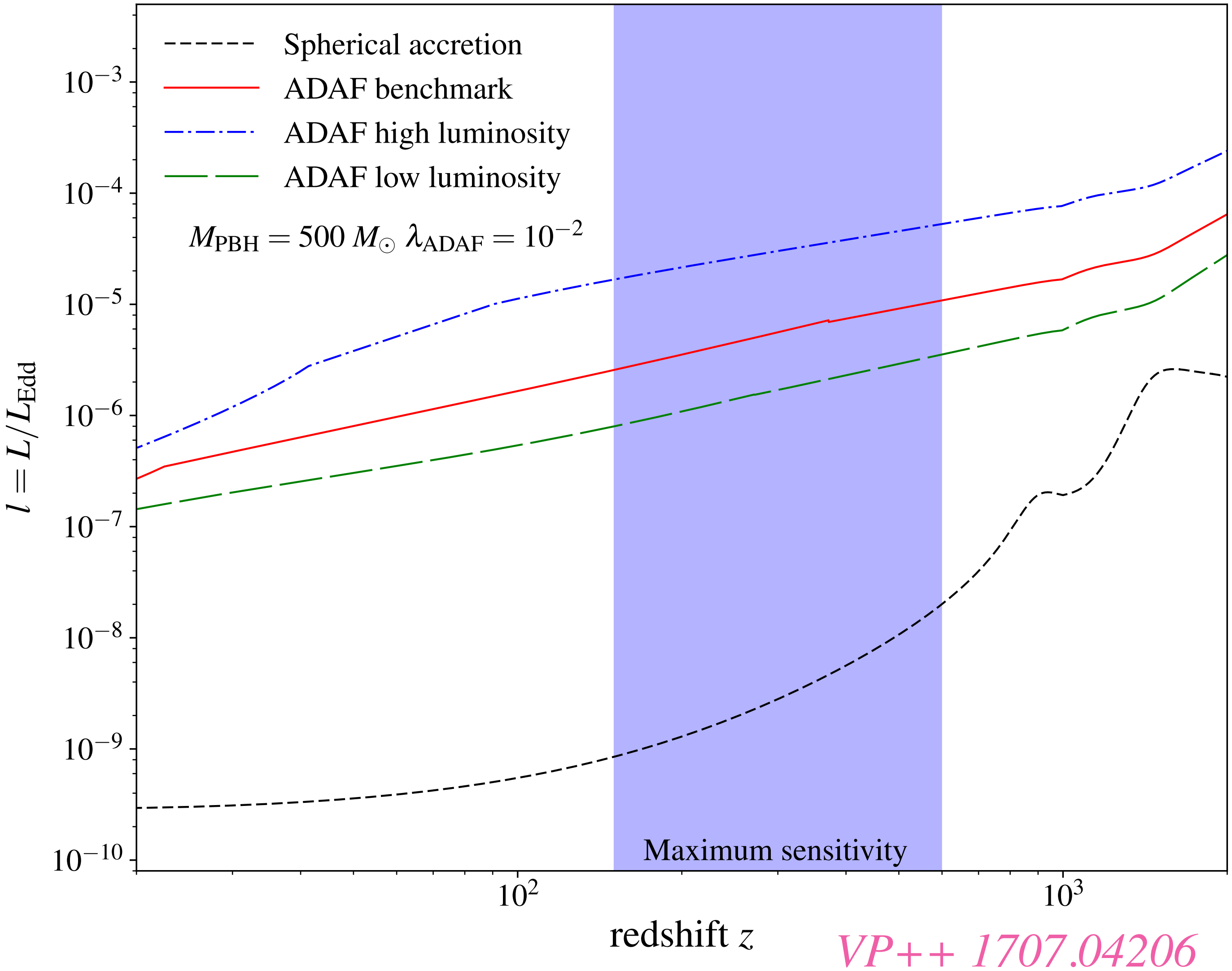
- More realistic and conservative: Hot, Thick disk with inefficient cooling — ADAF (Advection Dominated Accretion Flow).

Ichimaru 1977, Narayan&Yi 1994

- Results of numerical simulations confirmed by observations (e.g. Sgr A*).
- Relatively low radiative efficiency and accretion rate.

Xie&Yuan 2012





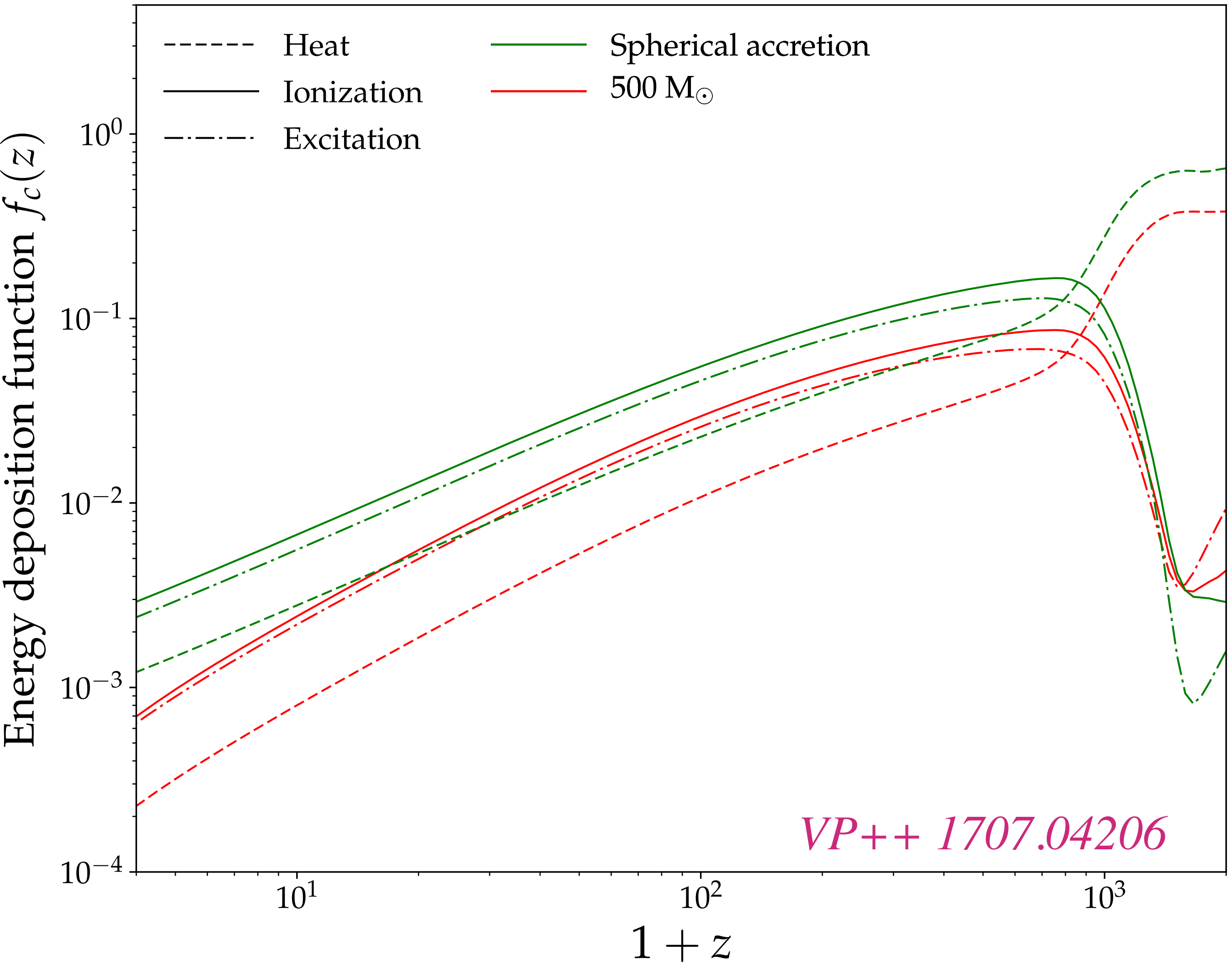
VP++ 1707.04206

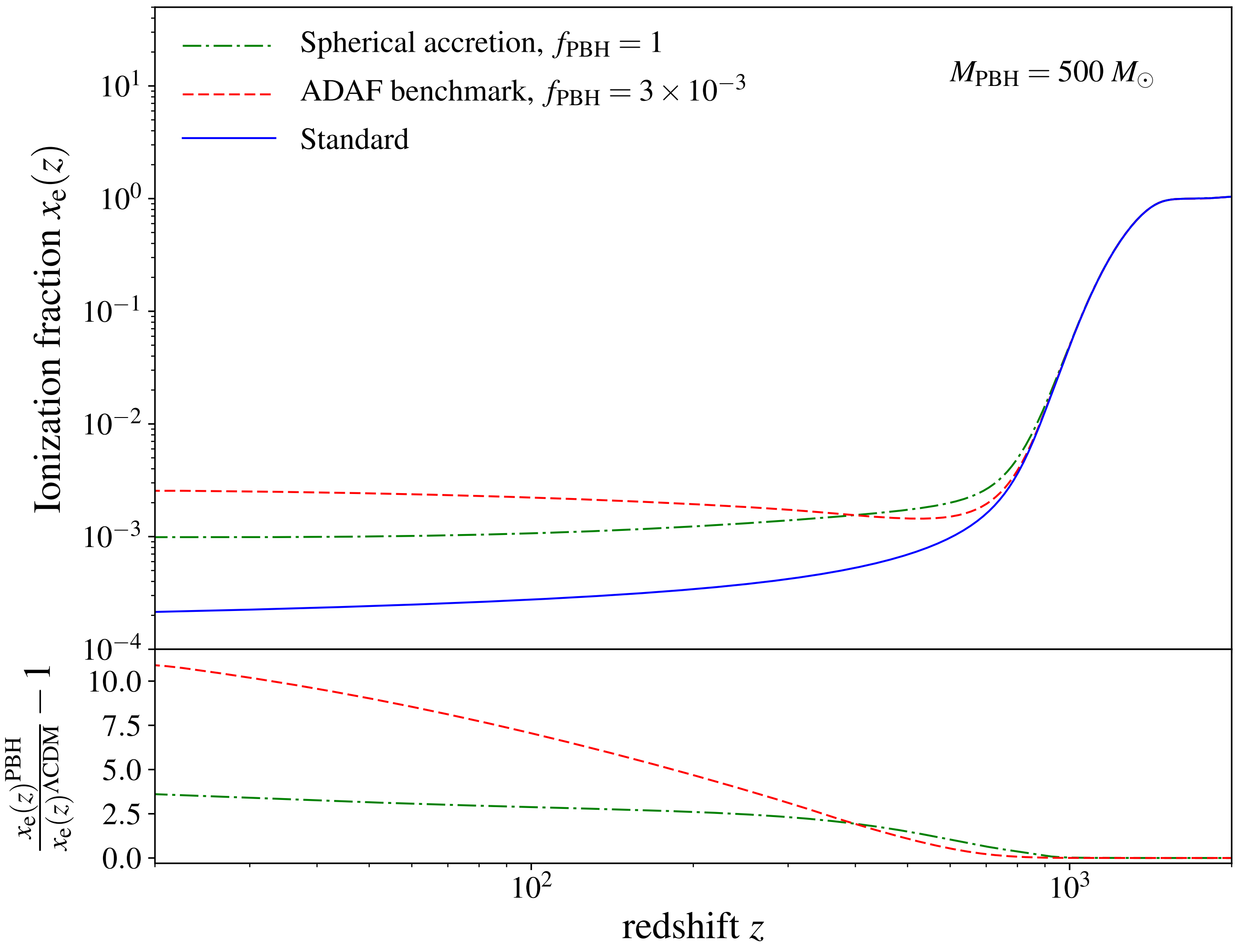
Energy deposition function

- Power law shape up to 100 keV energies from synchrotron and bremsstrahlung.
- Depend on PBH mass and accretion rate.

Review: Narayan&Yuan 2014

$$L_\omega \propto \omega^{-a} \exp(-\omega/T_s) \qquad T_s \sim m_e,\ a \in [-1.3, -0.7]$$

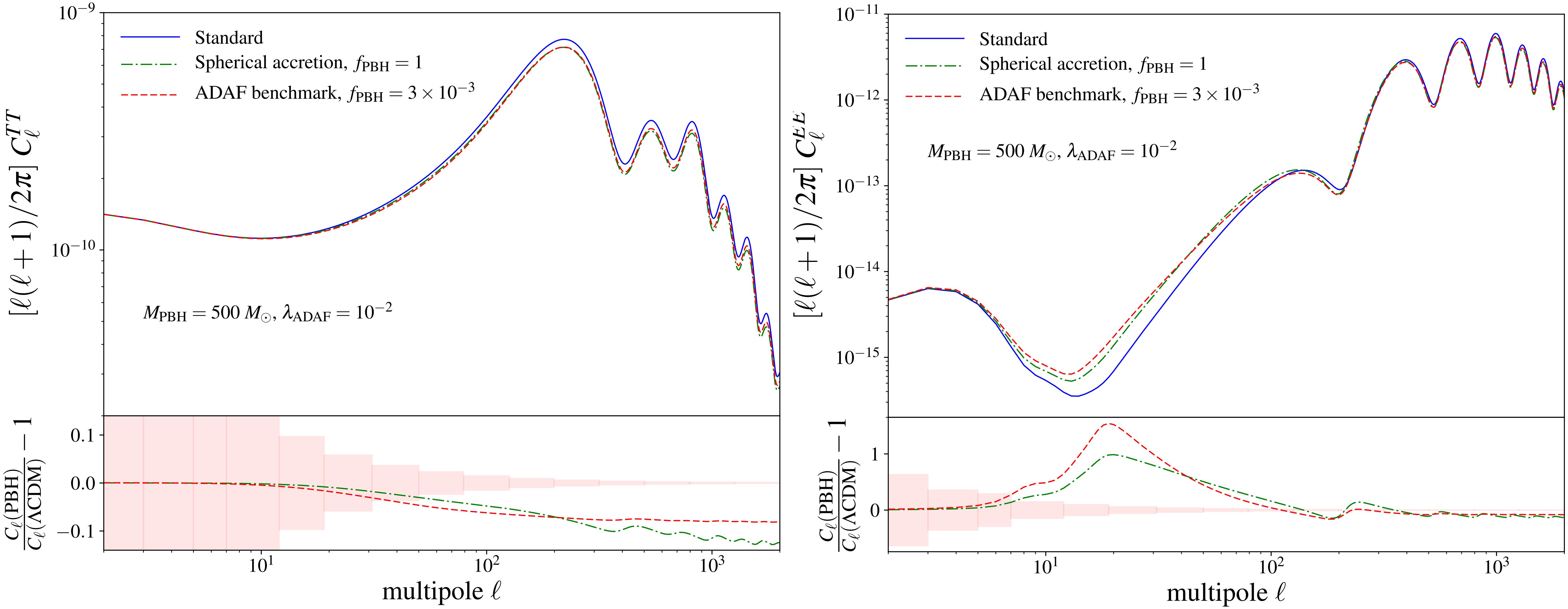




- Delayed recombination, higher freeze-out plateau, early reionization

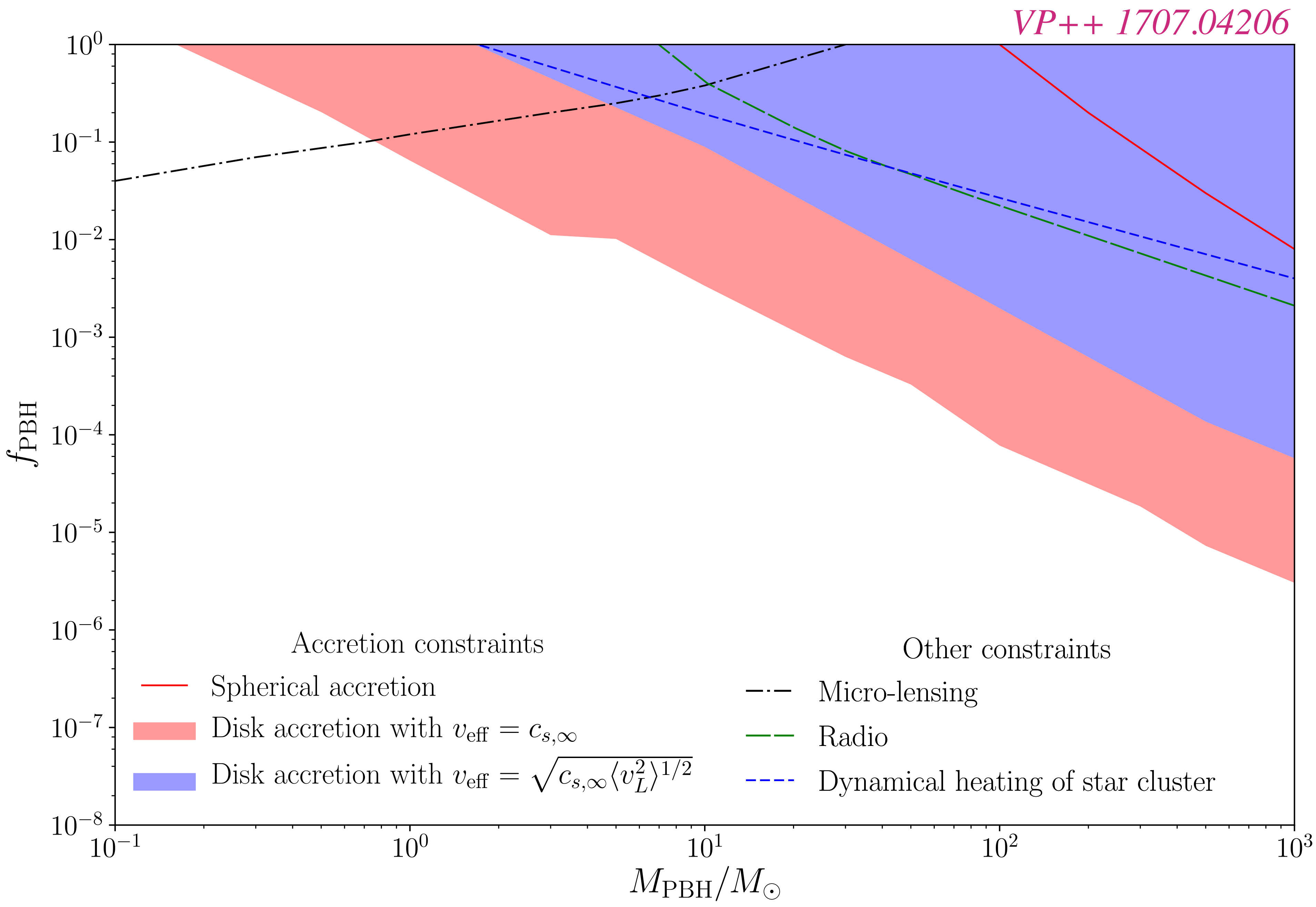
Impact on the CMB power spectra

VP++ 1707.04206



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

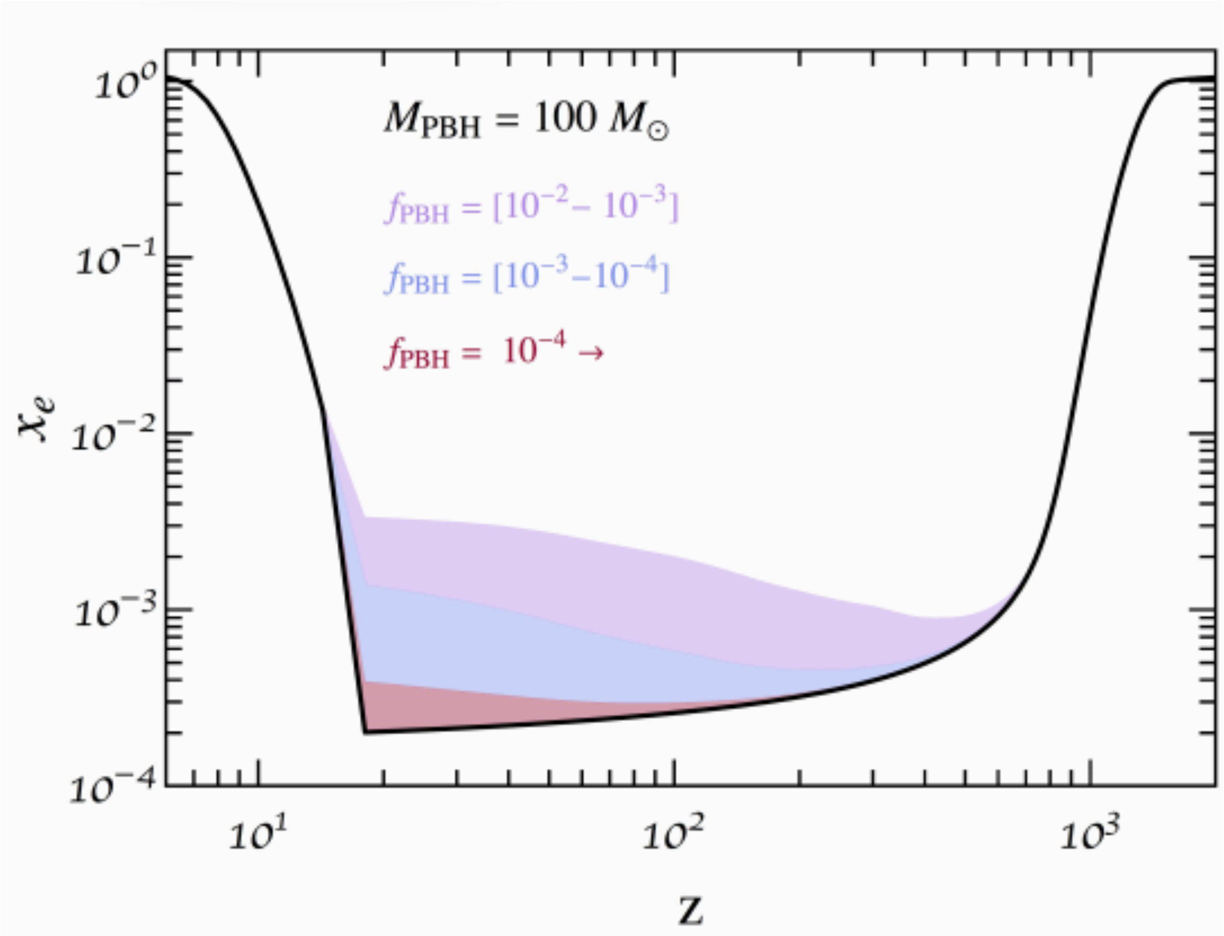
Constraints on disk-accreting PBH

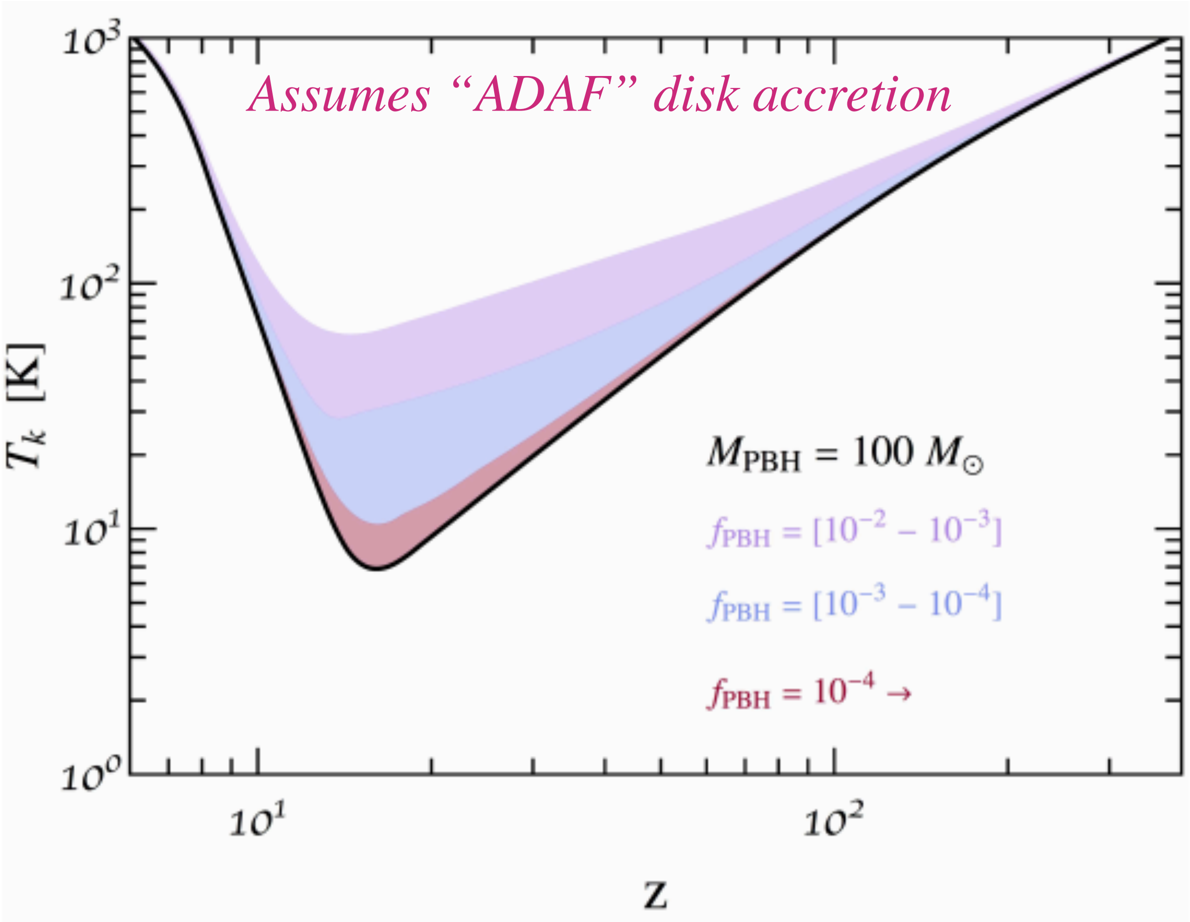


- Disk accretion constraints are two to three orders of magnitude stronger.
- Main uncertainty: relative velocities between PBH and baryons.
- Could be improved thanks to better understanding of PBH/baryons structures.

21 cm as a probe of PBH

- PBH accretion leads to increase in the ionization fraction and temperature of the IGM at late times



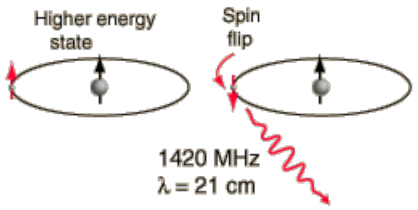


Assumes “ADAF” disk accretion

Mena++ 1906.07735

- The effect on x_e and T_k is much stronger at late times.
- This is particularly interesting for 21cm experiments!

21 cm as a probe of PBH



Spin Temperature

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

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

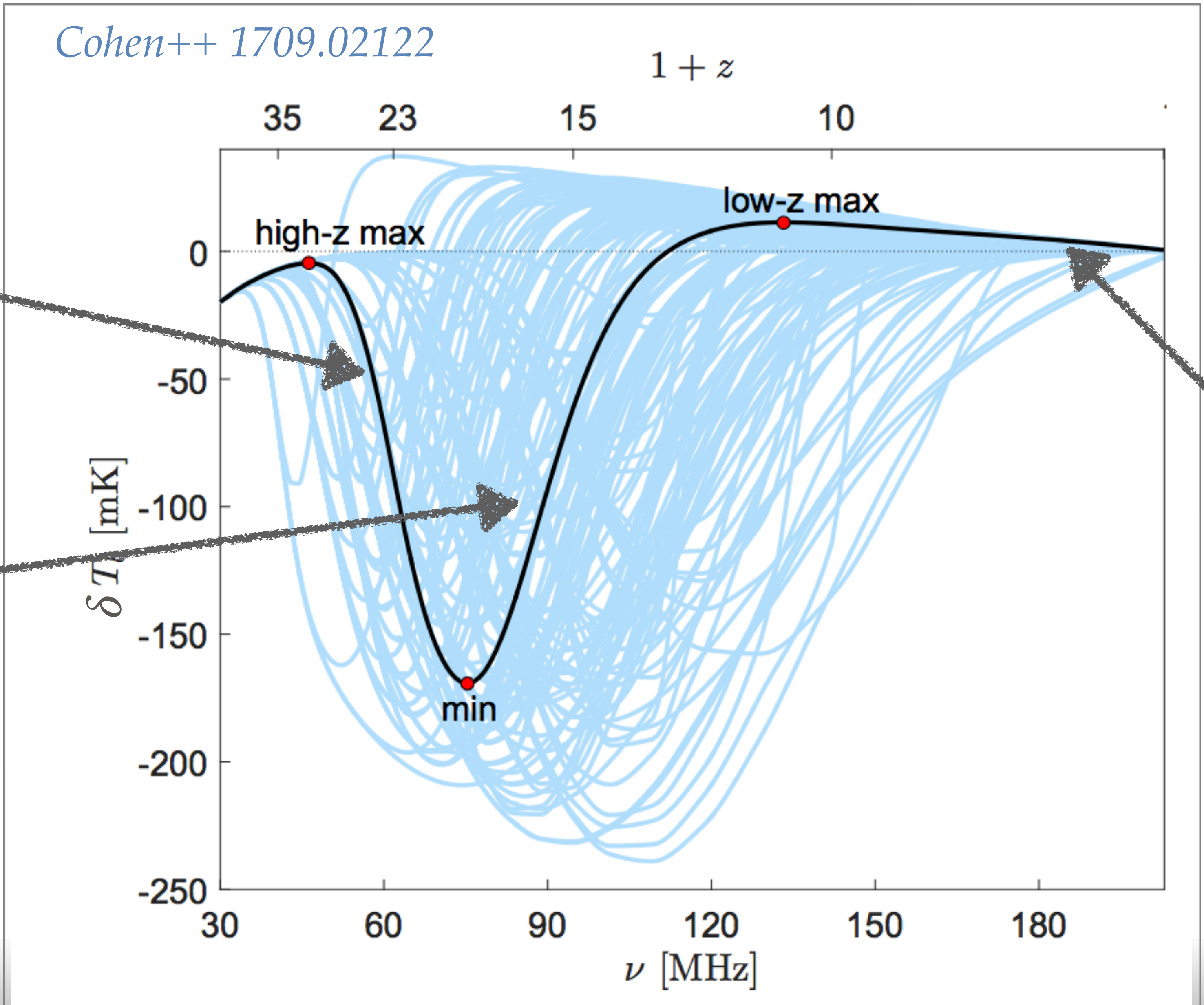
$$\delta T_b \propto n_H\left(1 - \frac{T_\gamma}{T_s}\right)$$

scattering with CMB

collision within the gas

interaction with UV from stars

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



Cohen++ 1709.02122

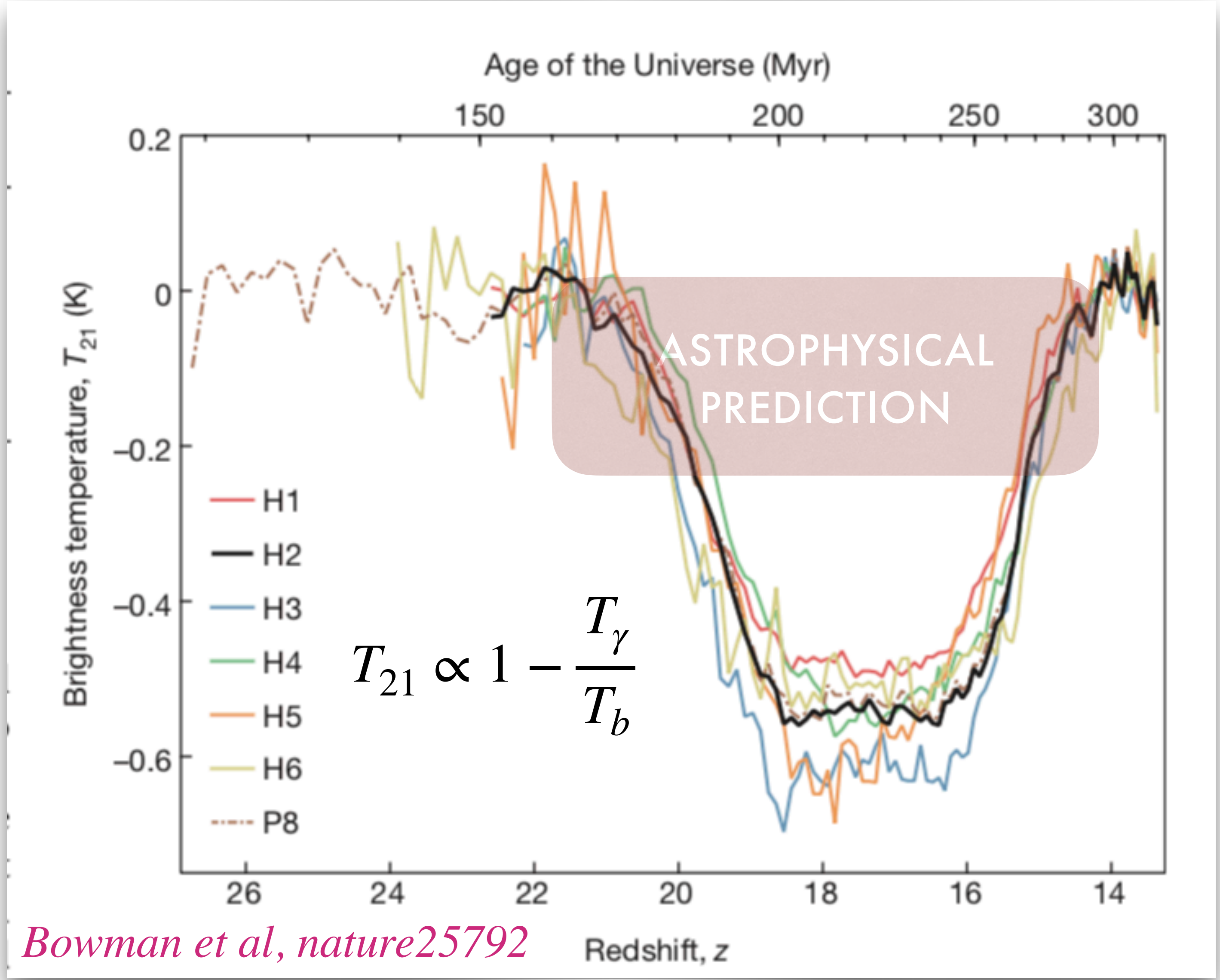
First stars Ly-α

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

Ionization
(stars? quasars?
DM?)

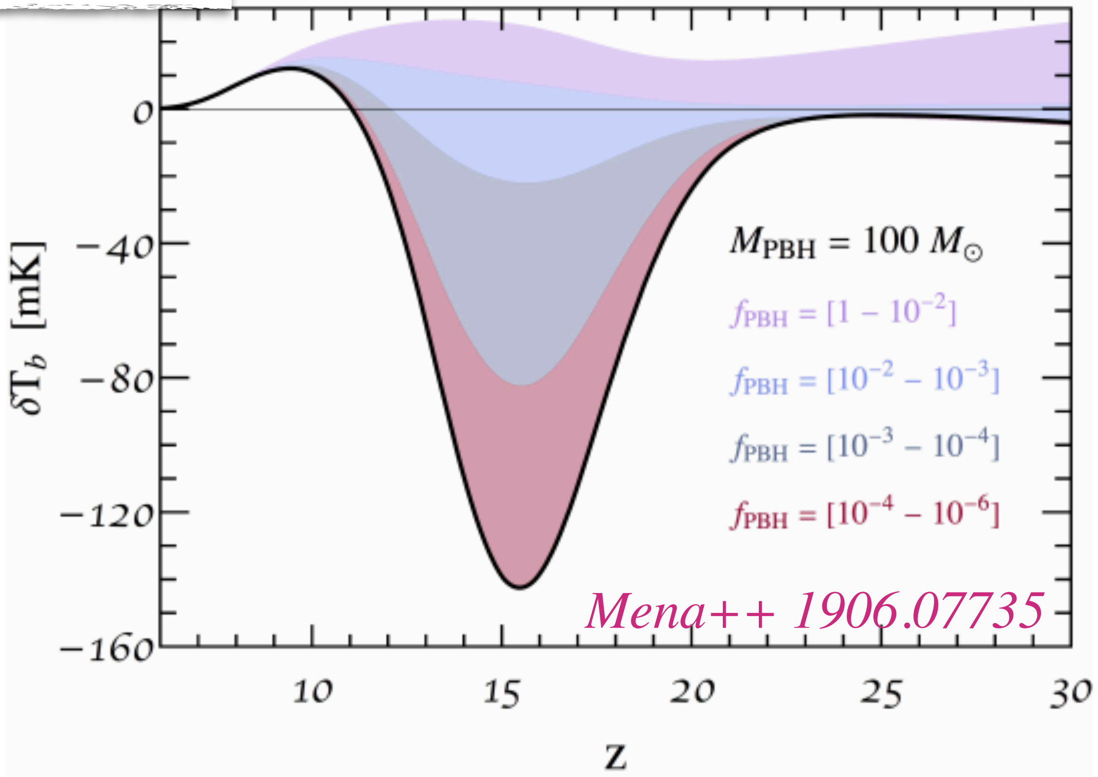
21 cm as a probe of PBH

- From the global signal: energy injection increase the baryon temperature and thus reduce the amplitude of the global signal.

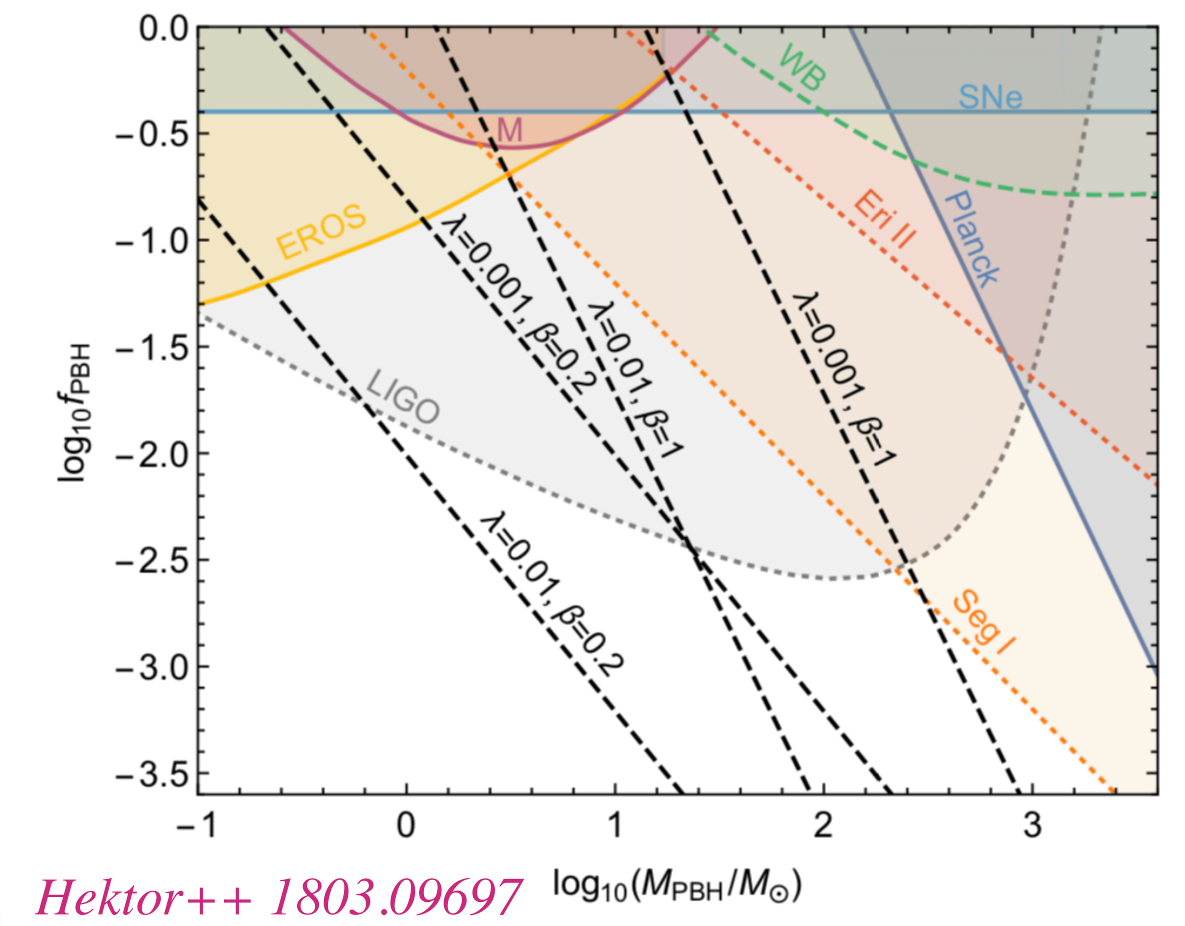


$$T_{21} \propto 1 - \frac{T_\gamma}{T_b}$$

Bowman et al, nature25792



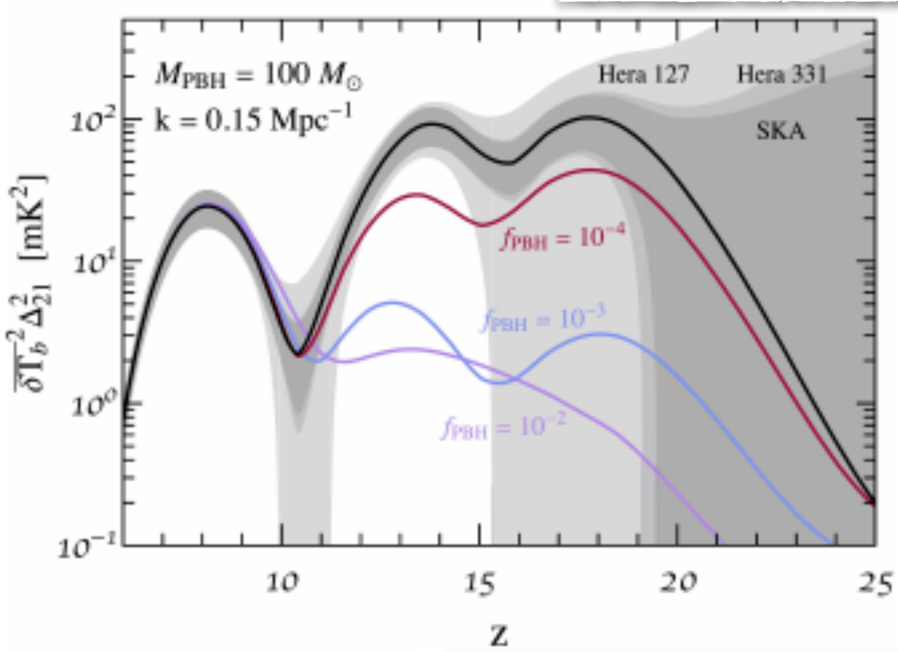
Mena++ 1906.07735

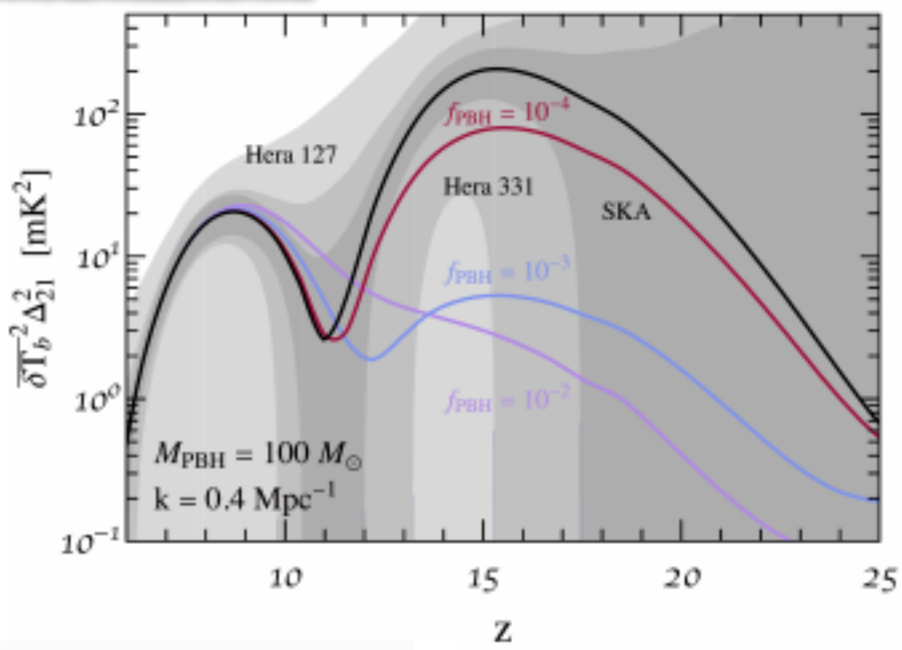


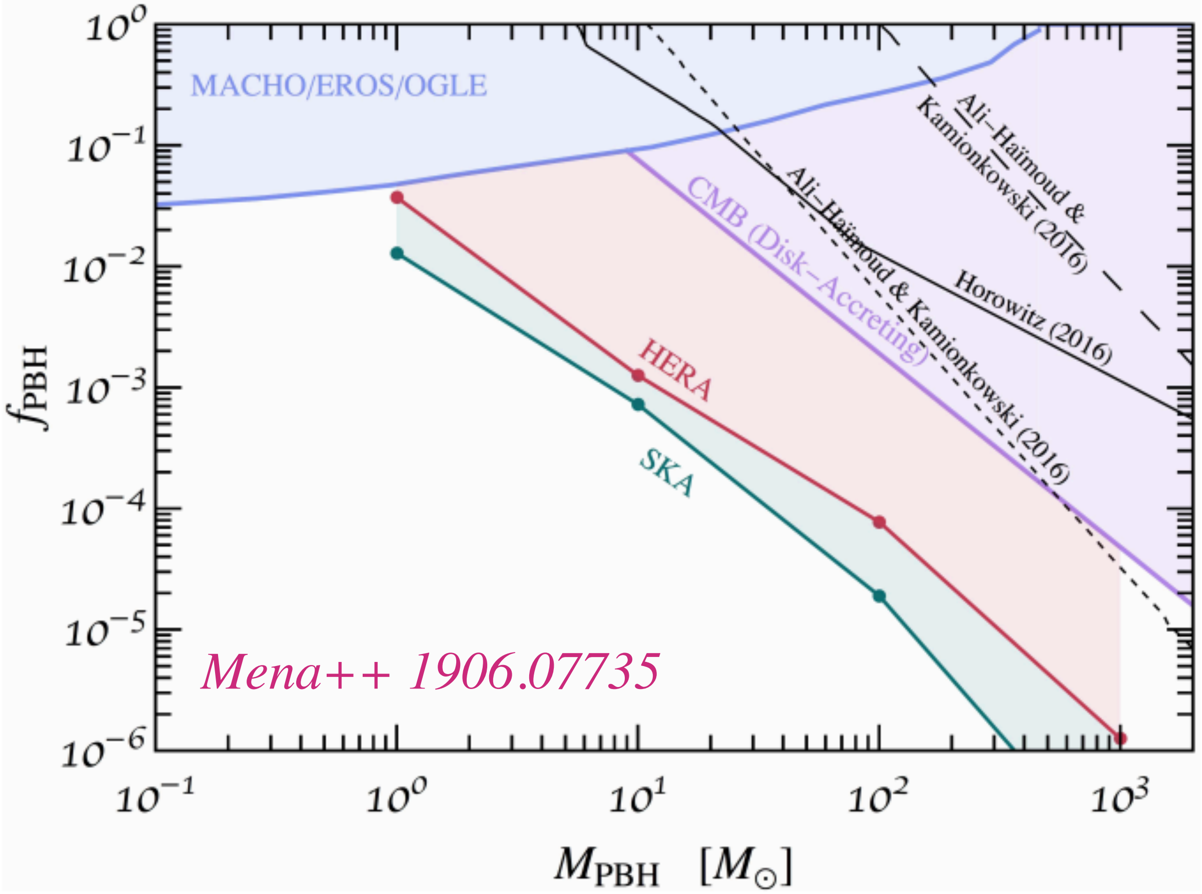
Hektor++ 1803.09697

If true, the EDGES measurement would strongly constrain PBH in the universe

21 cm as a probe of PBH



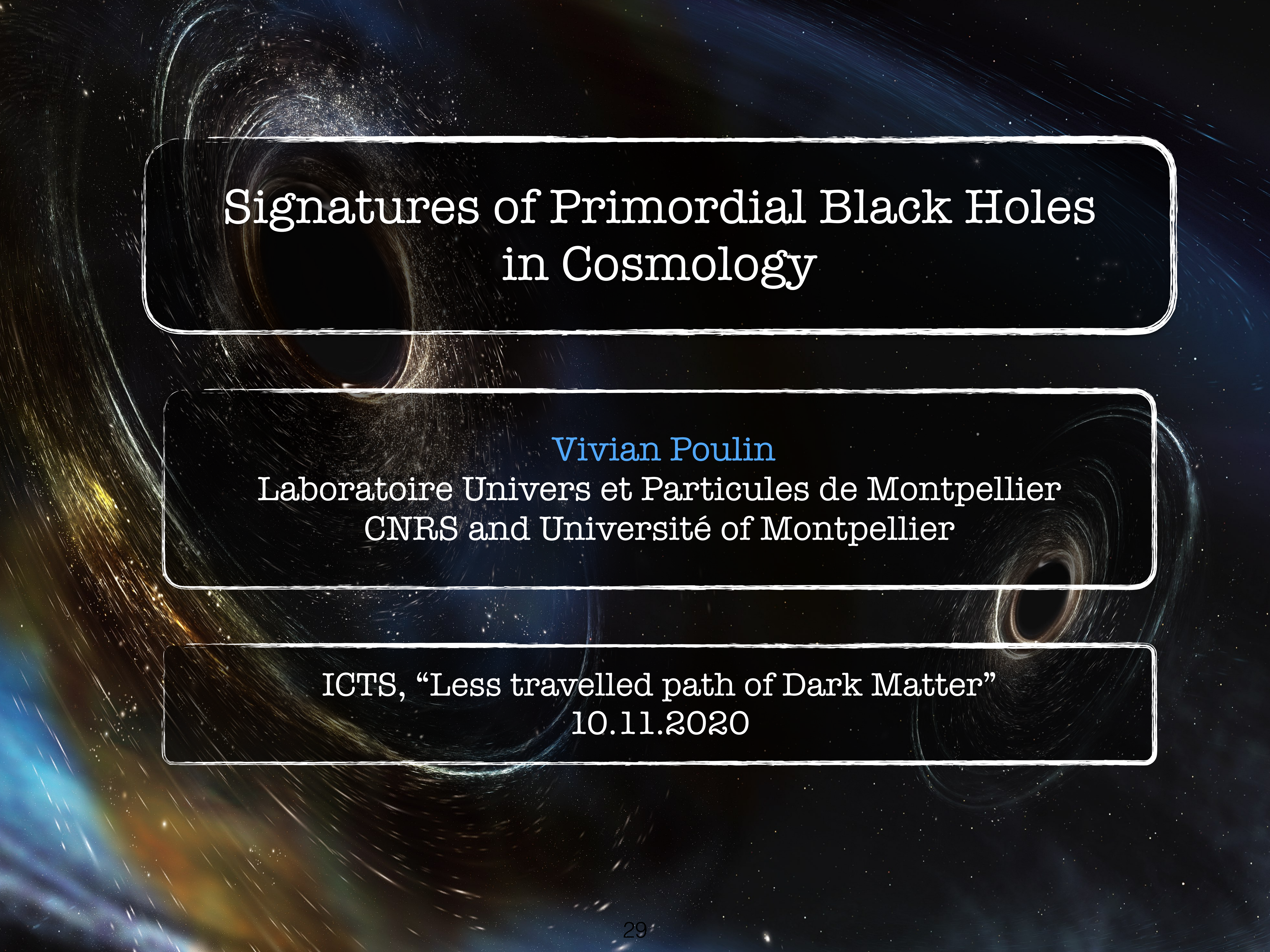




Mena++ 1906.07735

- PBH can also suppress the amplitude of fluctuations in the 21cm power spectrum
- Huge discovery potential for future experiments (HERA, SKA)!

See also Bernal++ 1712.01311



Signatures of Primordial Black Holes in Cosmology

Vivian Poulin
Laboratoire Univers et Particules de Montpellier
CNRS and Université of Montpellier

ICTS, “Less travelled path of Dark Matter”
10.11.2020

The SMBH problem

- SMBH have masses $M_{\rm BH} > 10^5 M_\odot$. They sit at the center of almost every galaxies.

Marloni 1505.04940

- Their accretion disk emission is known to saturate the X-ray background.
- SMBH with masses $M_{\rm BH} > 10^9$ have been observed at $z \gtrsim 6$.

Banados++ 2017

- The mass accretion rate is limited to $M \lesssim M_i \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t-t_i}{\tau_E}\right)$ with $\epsilon \sim 0.1$ and $\tau_E \sim 400$ Myrs
- Hence there is barely enough time for a stellar BH formed at $z \sim 15$ with $M \sim 100 M_\odot$ to grow to $10^9 M_\odot$ by $z \sim 6$.

Volonteri 1003.4404

- Several possibilities: super-Eddington accretion, mergers, direct collapse for heavy gas cloud… and SMBH from PBH!

Begelman++ astro-ph/0602363

- Even if it seems complicated for PBH to form all of the Dark Matter, f_PBH ≈ 10^{-8} with M_PBH ≈ 10^5 Msun to explain SMBH at the center of galaxies.

Carr & Silk 1801.00672

The existence of a DM halo increases the accretion rate

- Extend bound to sub-fraction of the population: if DM is a particle, what about the DM halo?

- The presence of a DM halo can act as to increase the effective mass of the BH and hence the accretion rate.

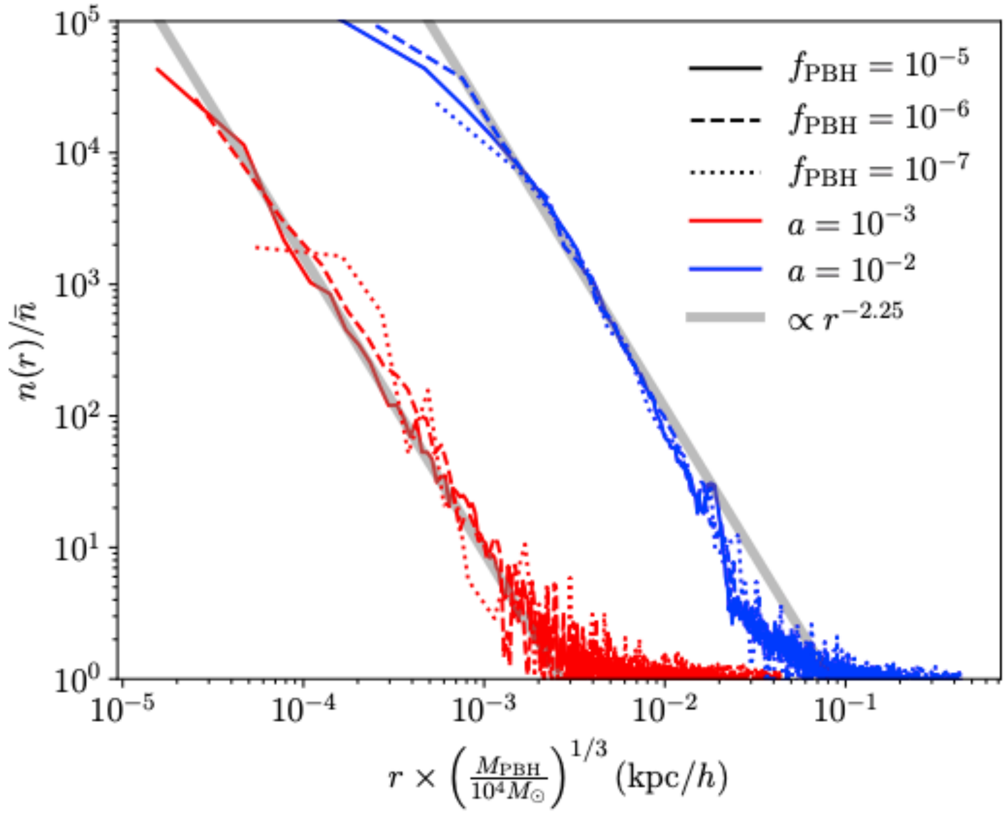
Ricotti++ ApJ 2008, Park++ 1512.03434

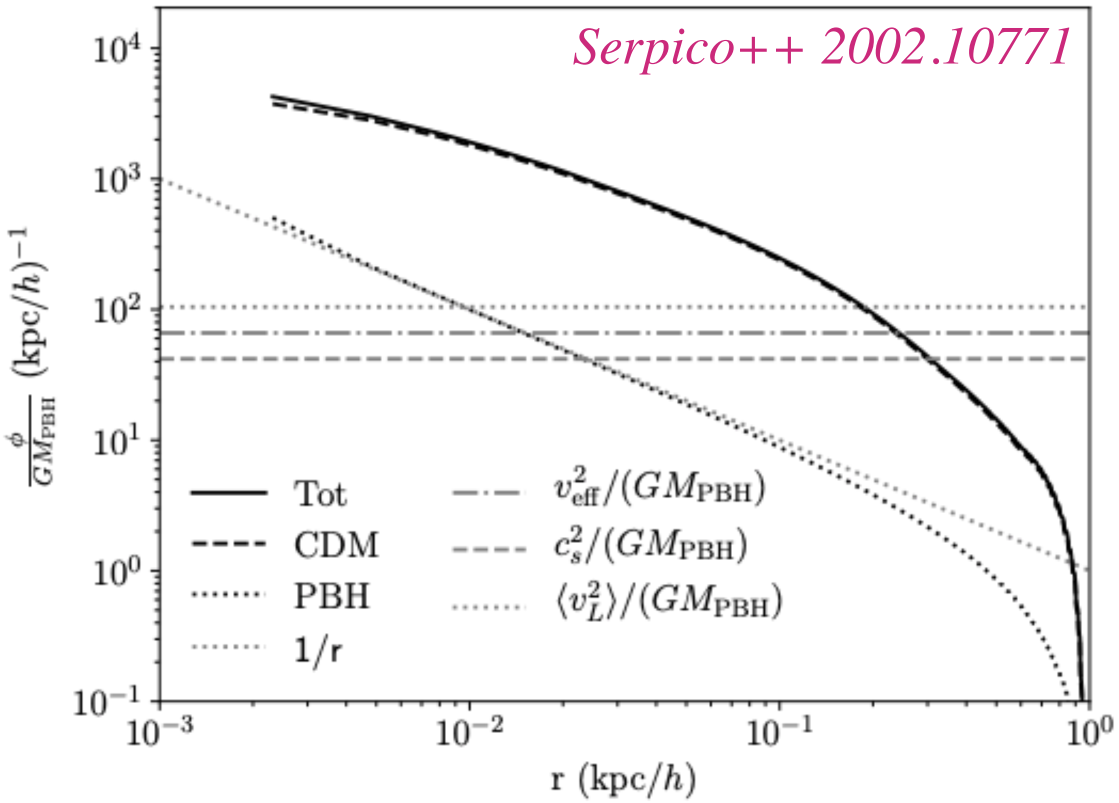
- First assuming that the DM particles cannot annihilate: what is the $r_{b,\mathrm{eff}}$?

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

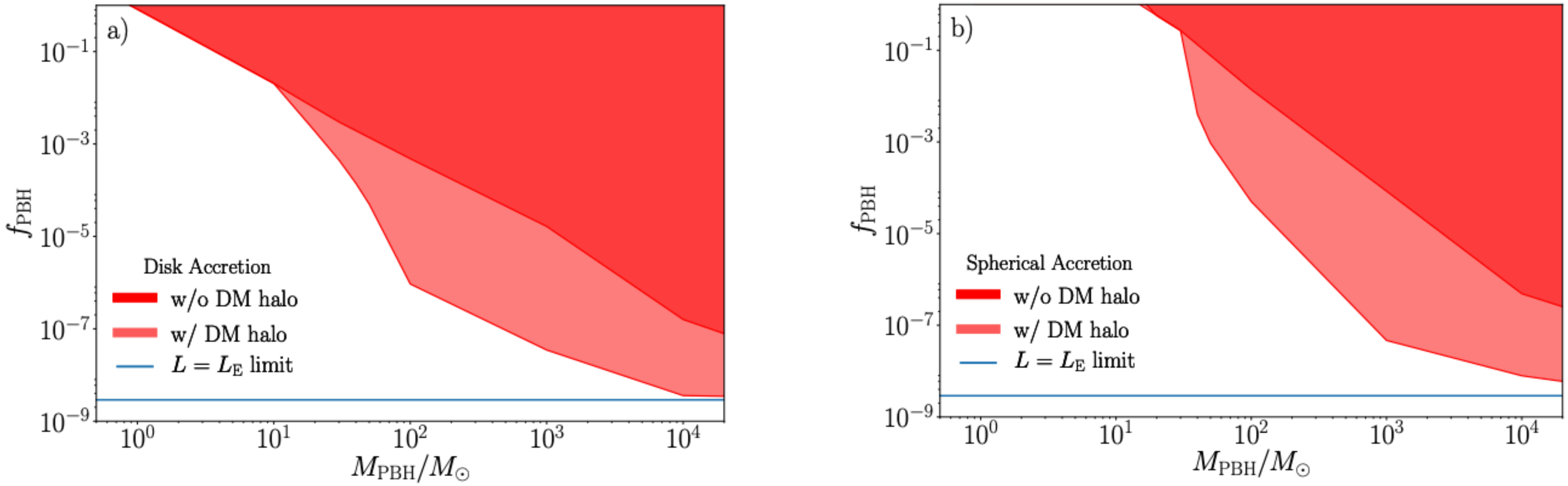
$$\begin{cases} \rho \propto r^{-9/4},\ r \lesssim r_{BH} \\ \rho \propto r^{-3},\ r \gg r_{BH} \end{cases}$$

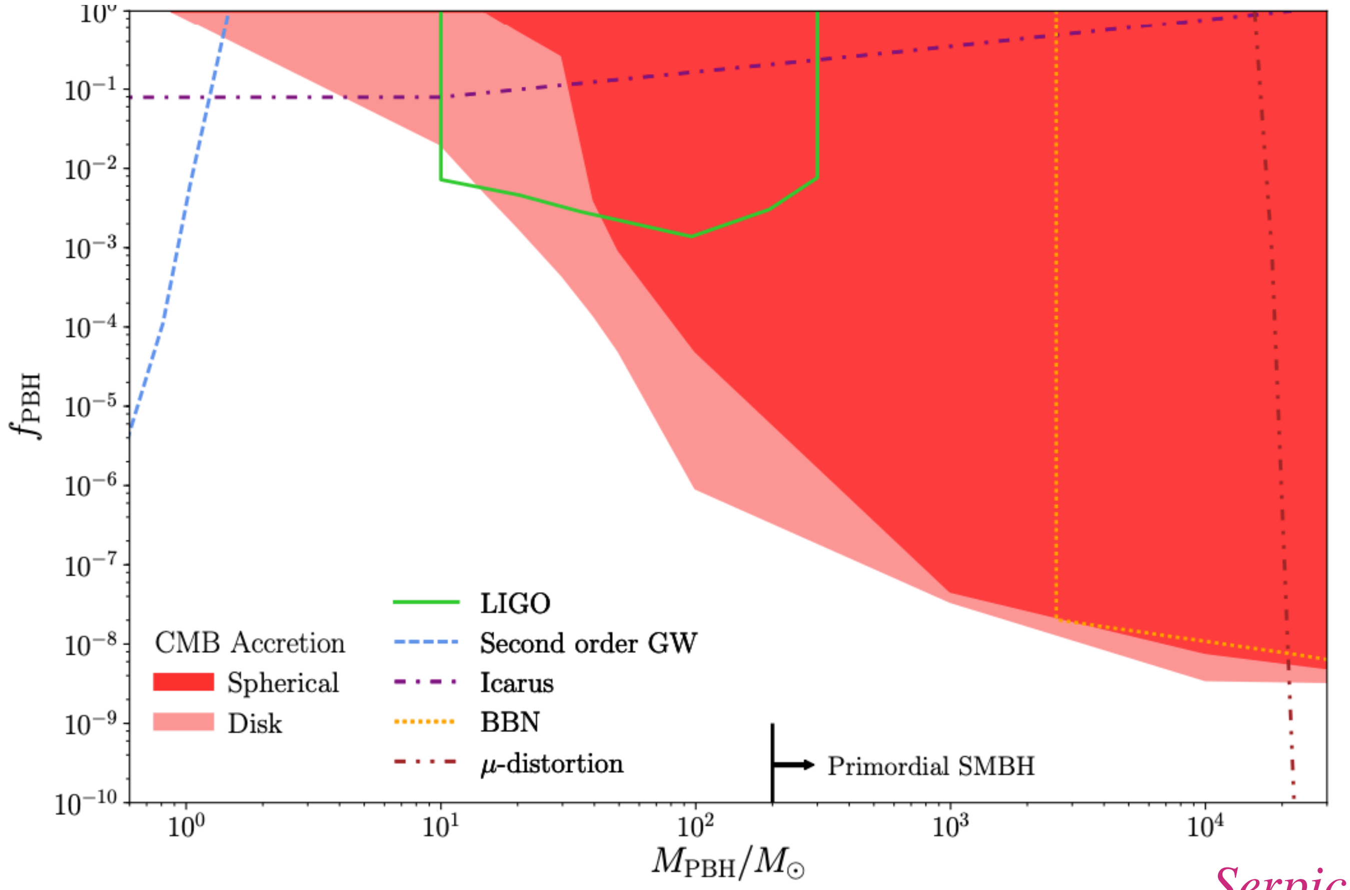
Bertshinger 1985





A halo of DM can strongly increase bounds on PBH



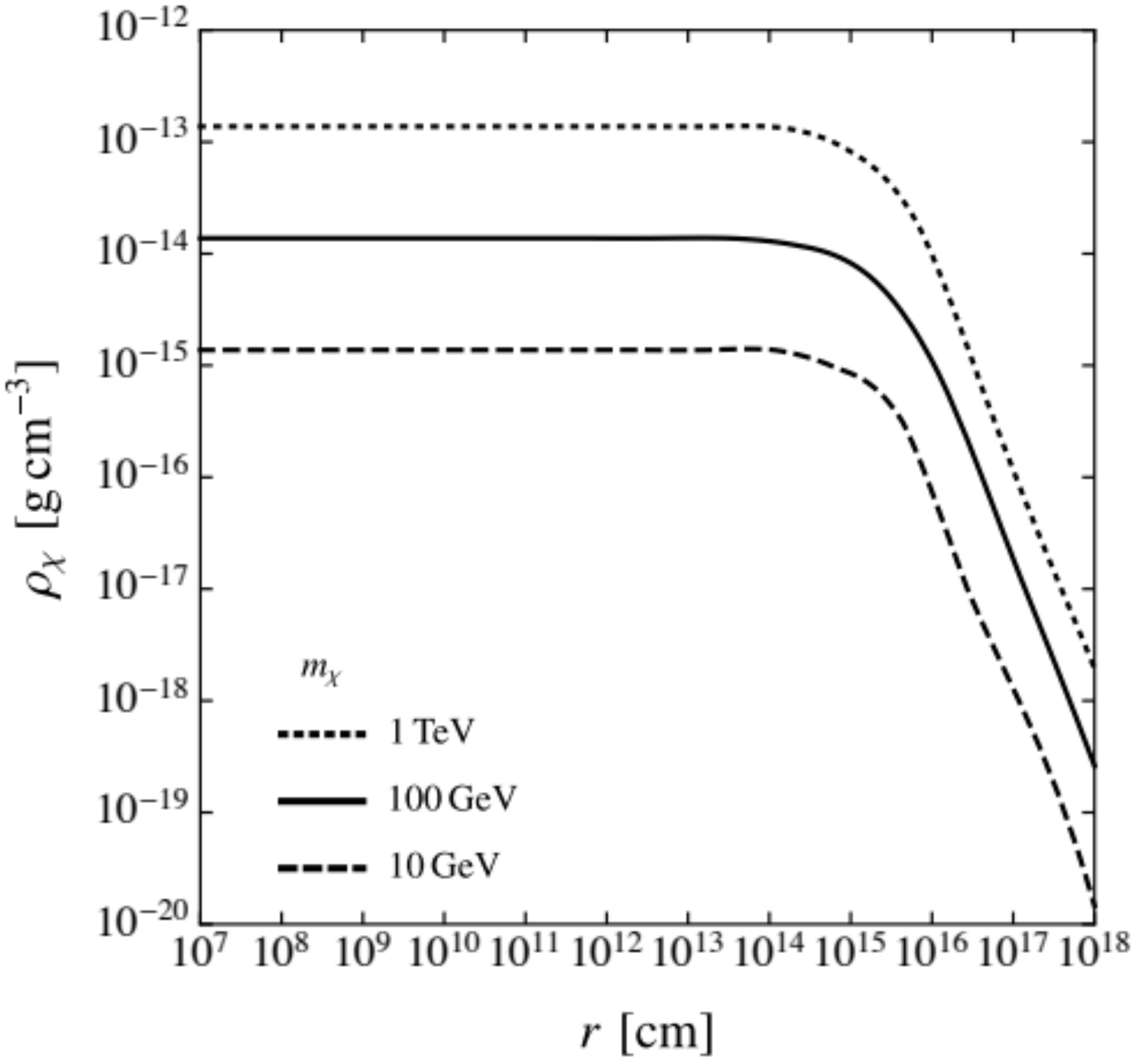


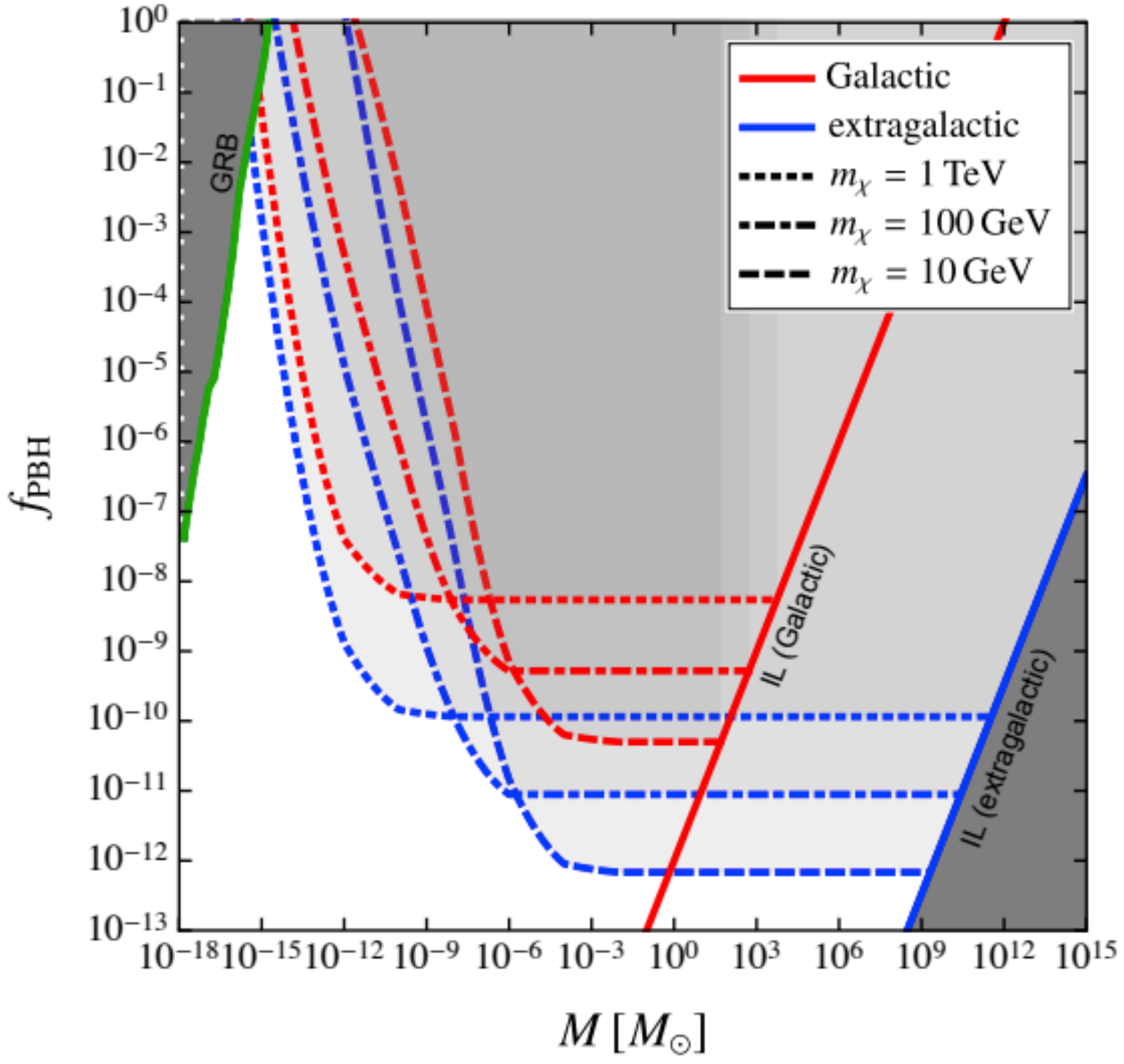
Serpico++ 2002.10771

DM or WIMP: All or nothing

Carr++ 2011.01930

$$\rho_{\chi,\,\mathrm{max}}(z) = f_\chi \frac{m_\chi H(z)}{\langle \sigma v \rangle_{\mathrm{H}}} \qquad \frac{r_{\mathrm{cut}}}{\bar{r}} = \left[\alpha_{\mathrm{E}} \frac{\rho_{\mathrm{eq}}}{2} \left(\frac{M}{M_\odot} \right)^{3/4} \frac{\langle \sigma v \rangle_{\mathrm{H}}}{m_\chi H(z)} \right]^{4/9} \qquad \Gamma_0 = \frac{\langle \sigma v \rangle_{\mathrm{H}}}{m_\chi^2} \int \mathrm{d}V \, \rho_\chi^2$$





See also Lacki&Beacom 1003.3466, Adamek++ 1901.08528

- Alternatively, detecting PBH would strongly constrain WIMP

Bertone++ 1905.01238

Energy injection by evaporating PBH

- BHs emit SM particles with a black body spectrum at a temperature *Hawking, Nat. (1974)*

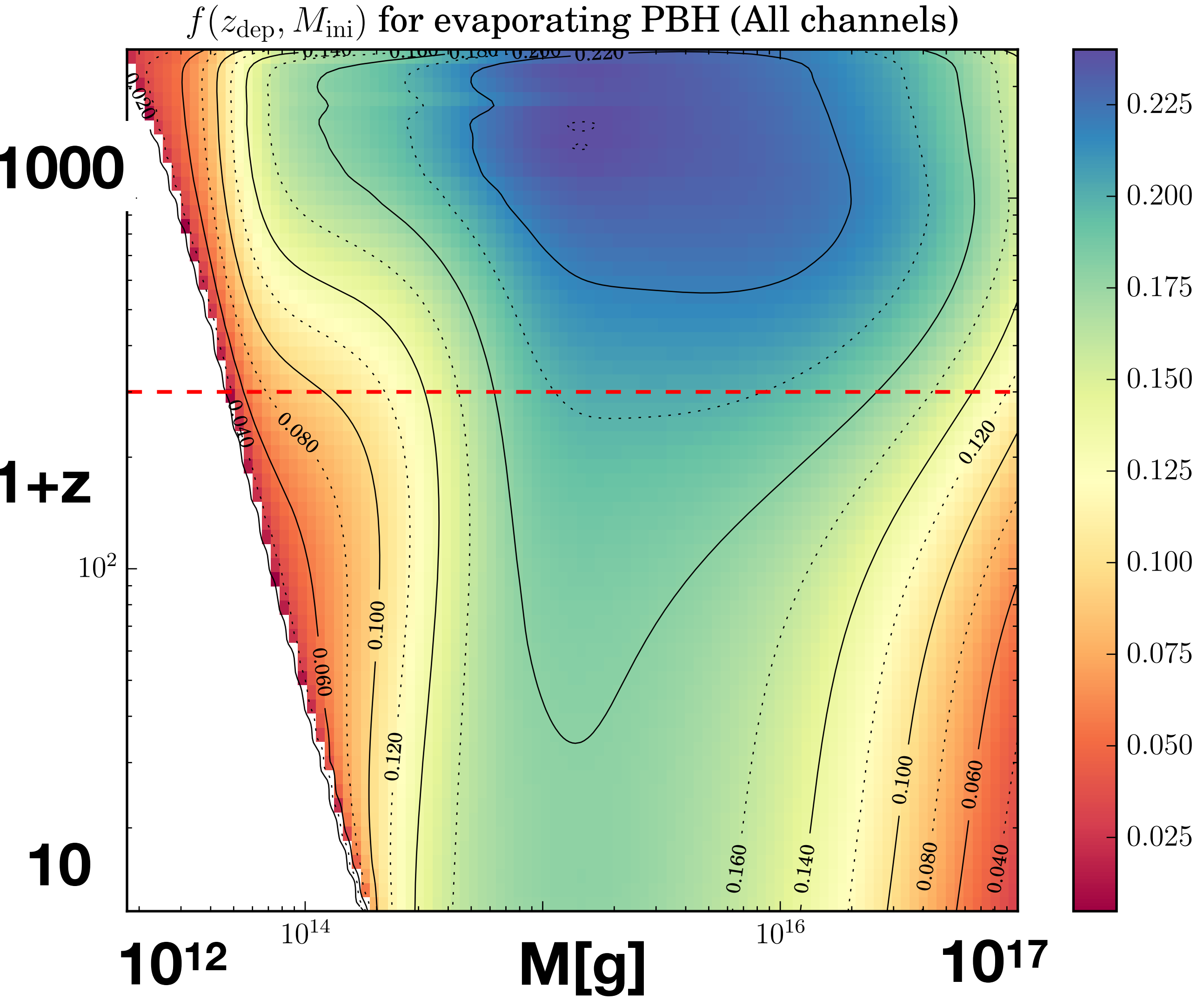
$$T_{\rm BH} = \frac{1}{8\pi GM} \simeq 1.06\left(\frac{10^{10}\,{\rm g}}{M}\right)\ {\rm TeV}$$

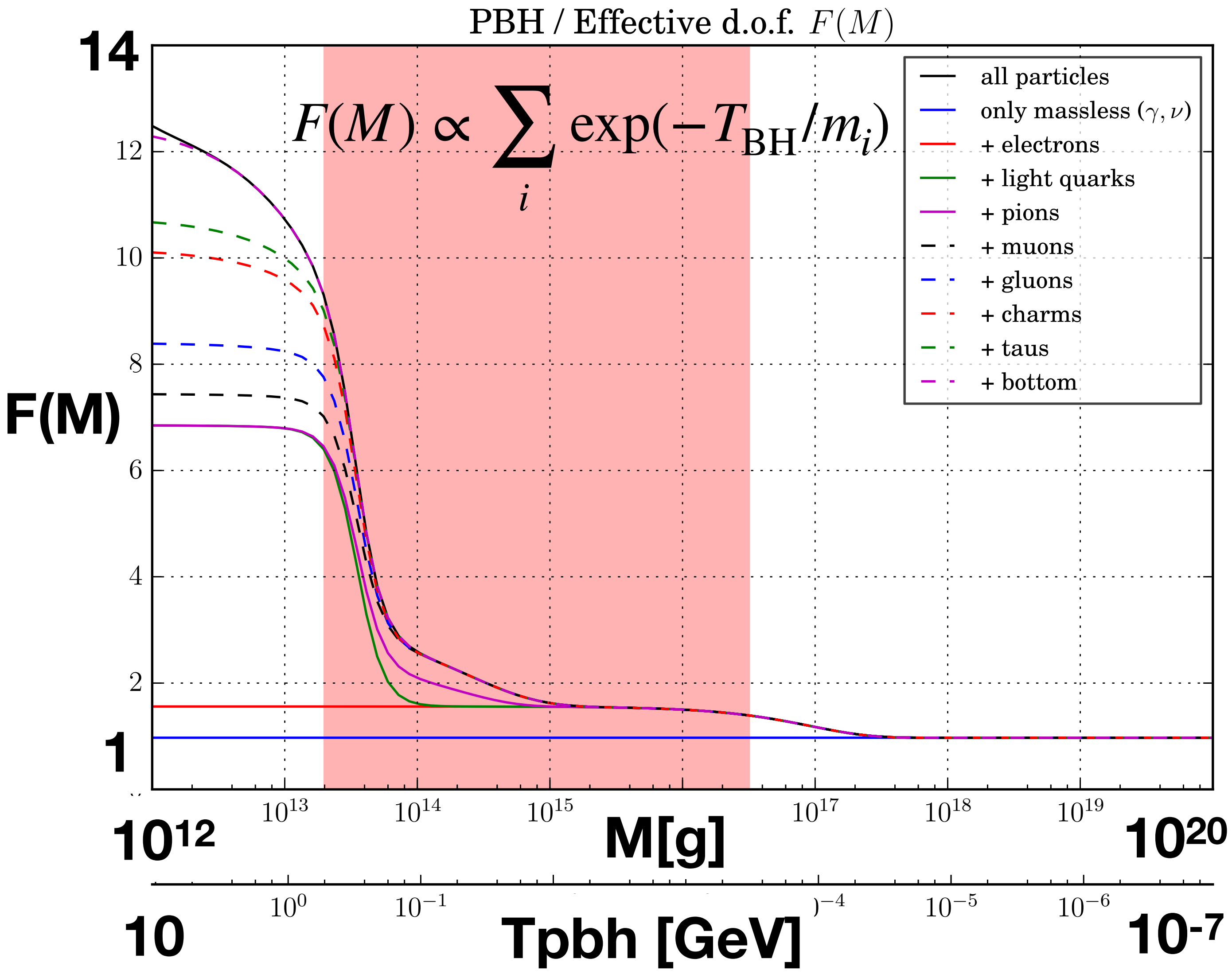
$$\tau_{\rm BH} \simeq 13.8\left(\frac{1.6}{\mathscr{F}(M)}\right)\left(\frac{M}{2\times 10^{14}\,{\rm g}}\right)^{3}\ {\rm Gyrs}$$

- Energy injection rate is proportional to the mass-loss rate

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

$$\frac{dM}{dt} = -\,5.34\times 10^{25}\mathscr{F}(M)\left(\frac{\rm g}{M}\right){\rm g/s}$$

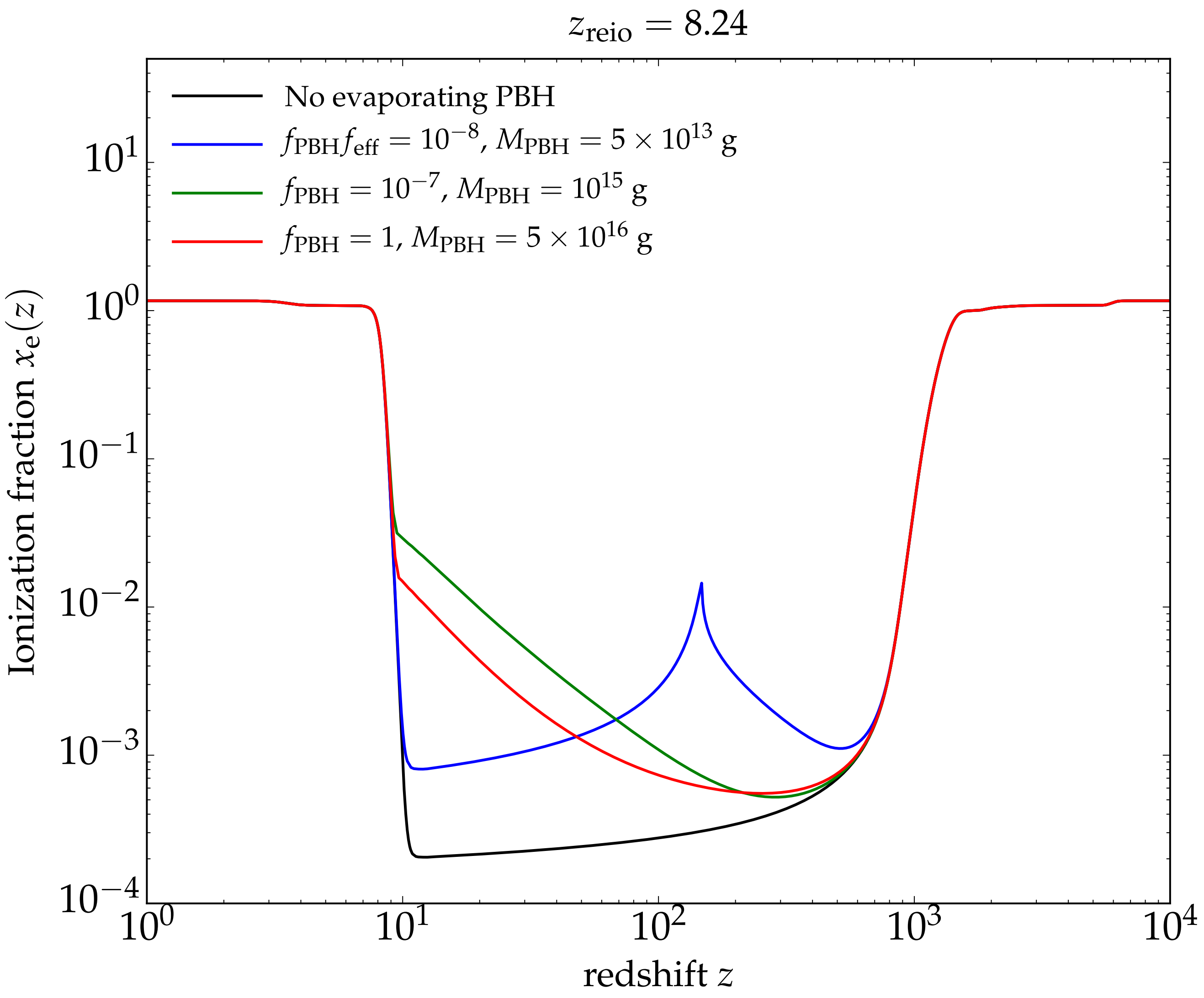


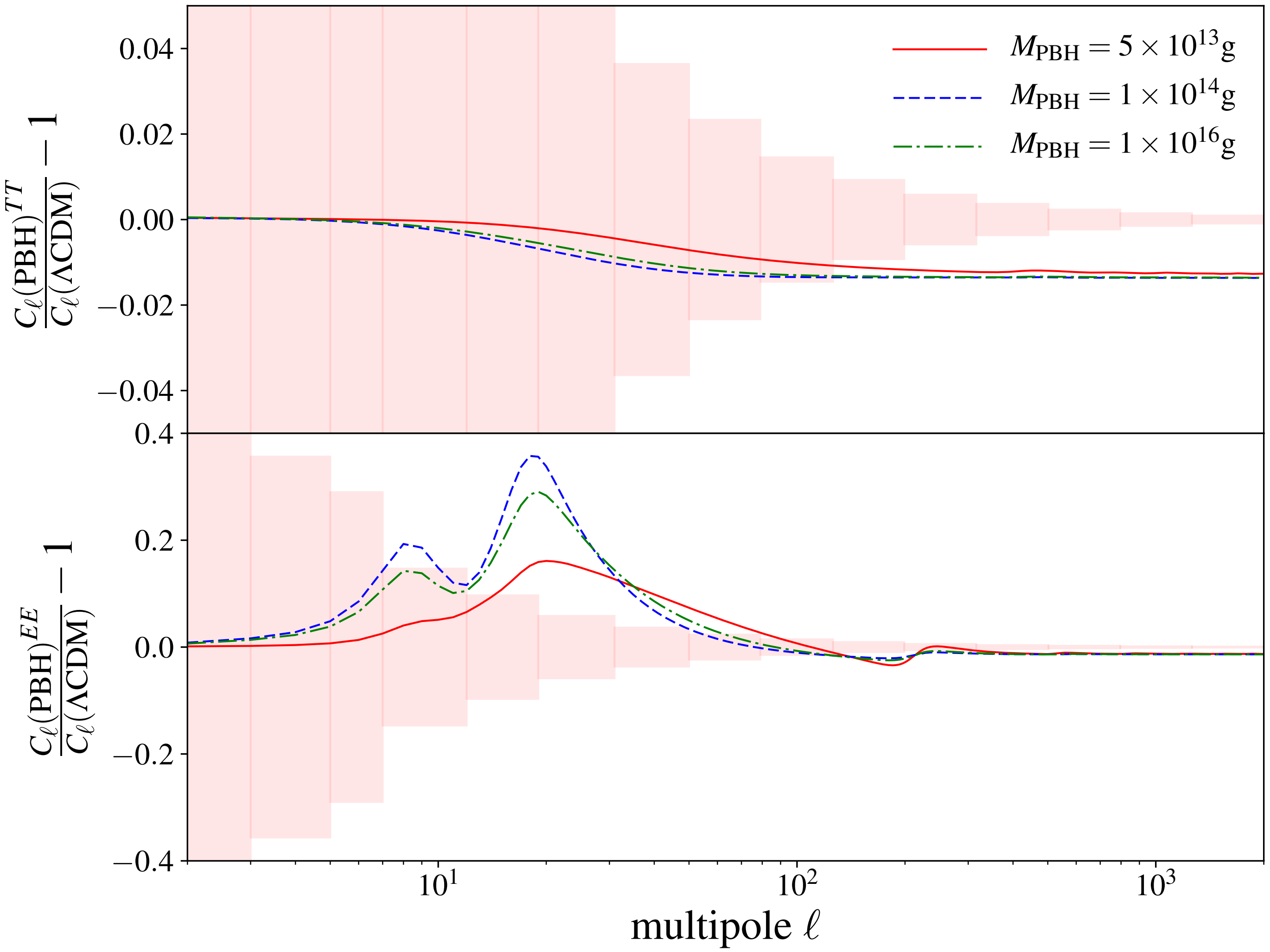


Stöcker++JCAP 1803 (2018) no.03, 018

Impact of evaporating PBH on the CMB

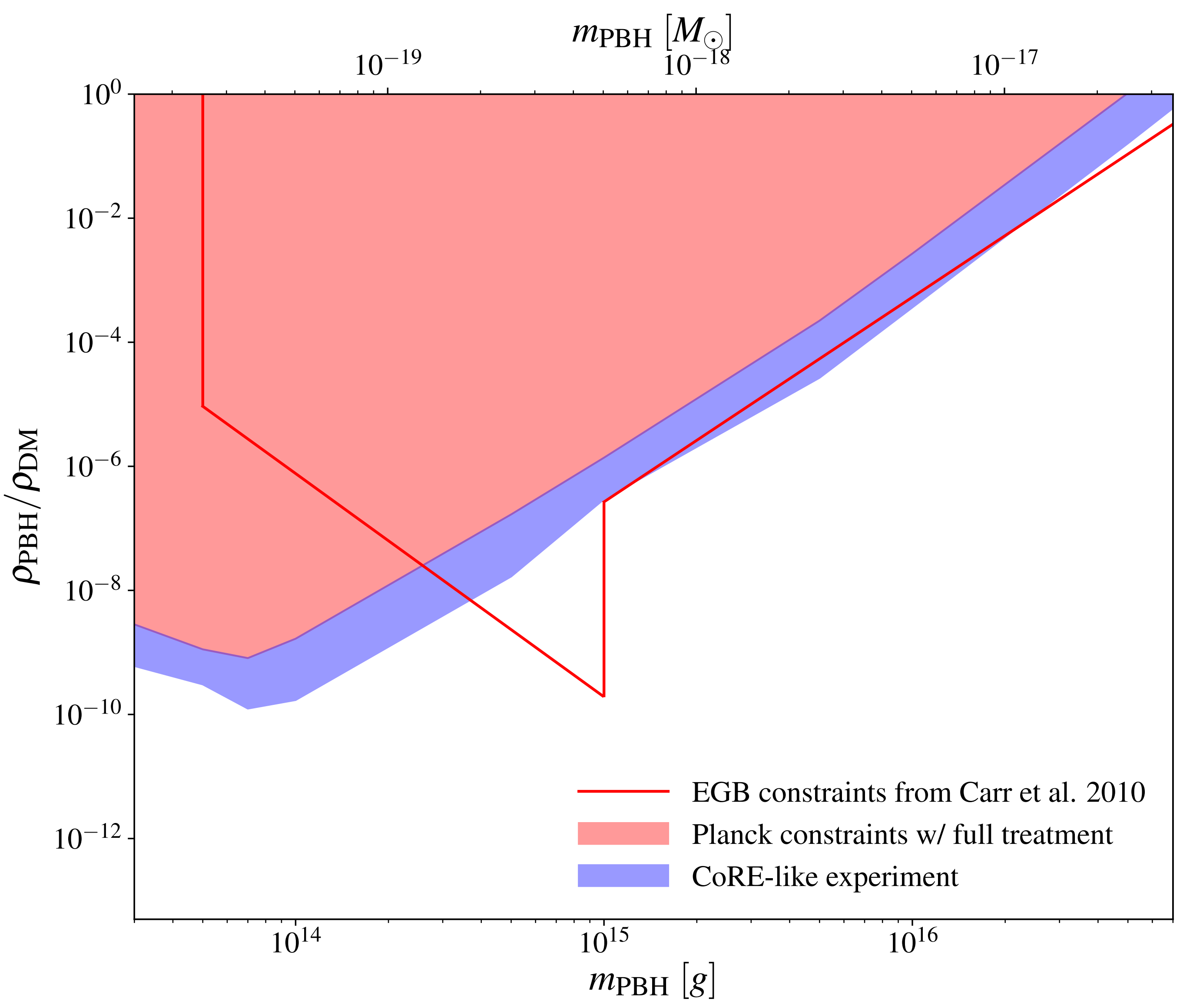
VP++2017
Stöcker++ 2018
Poulter++ 1907.06485



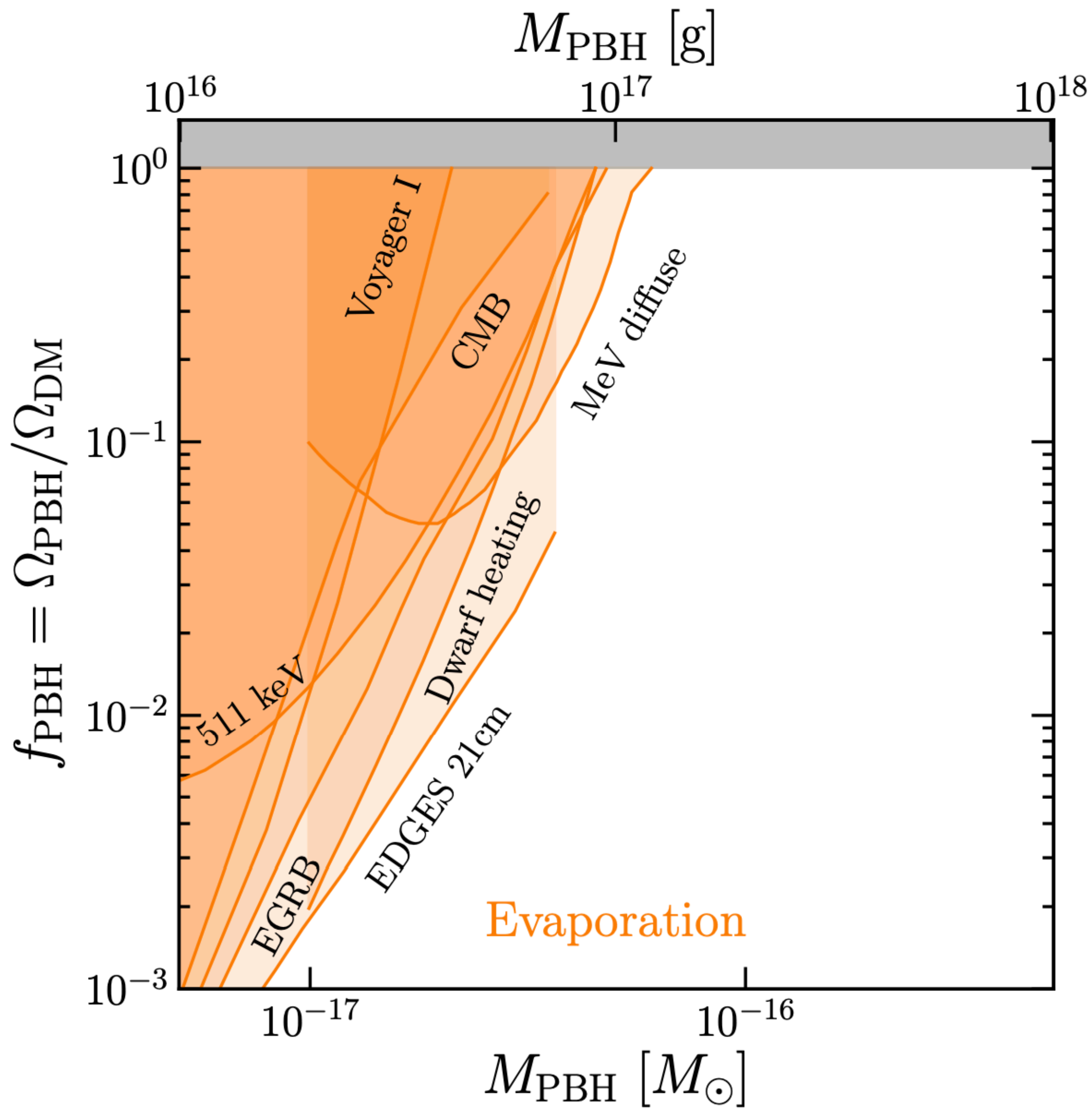


- Effect is quite similar to that of accreting PBH unless mass is < 10^{15}g.

Constraints on evaporating PBH



Stocker++ 1801.01871



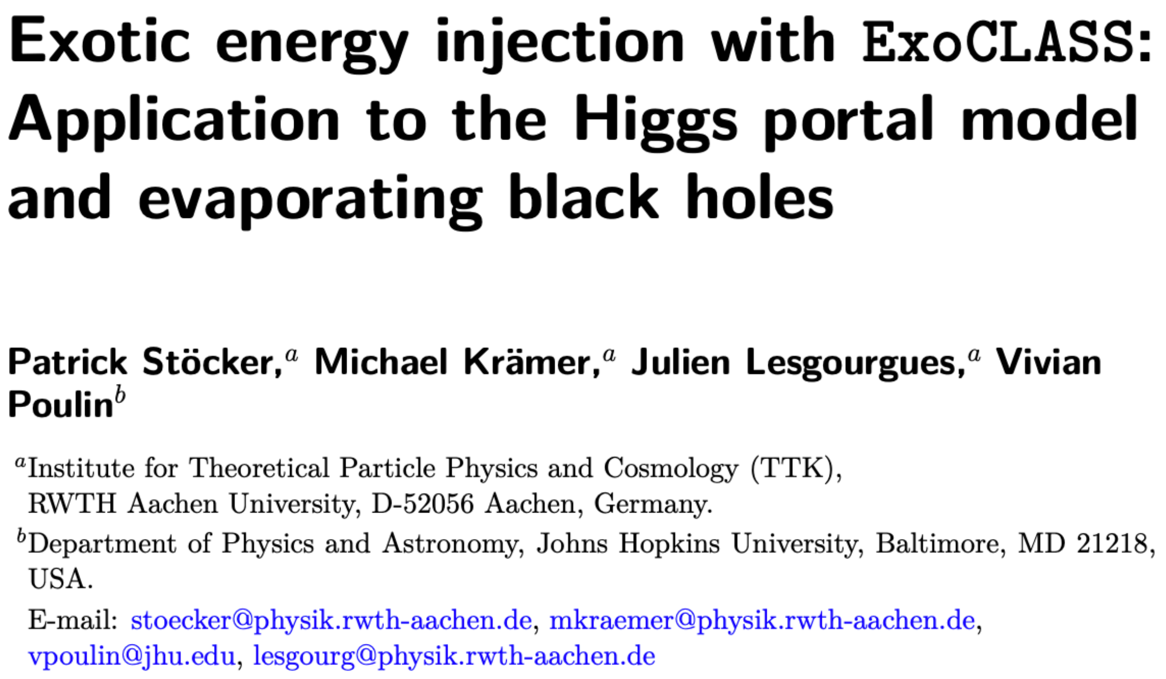
Green and Kavanagh 2007.10722

- CMB largely dominates at low masses and can improve constraints in the future !

Exercices!

- The numerical code is public: ExoCLASS

Stocker++ 1801.01871



Exotic energy injection with ExoCLASS: Application to the Higgs portal model and evaporating black holes

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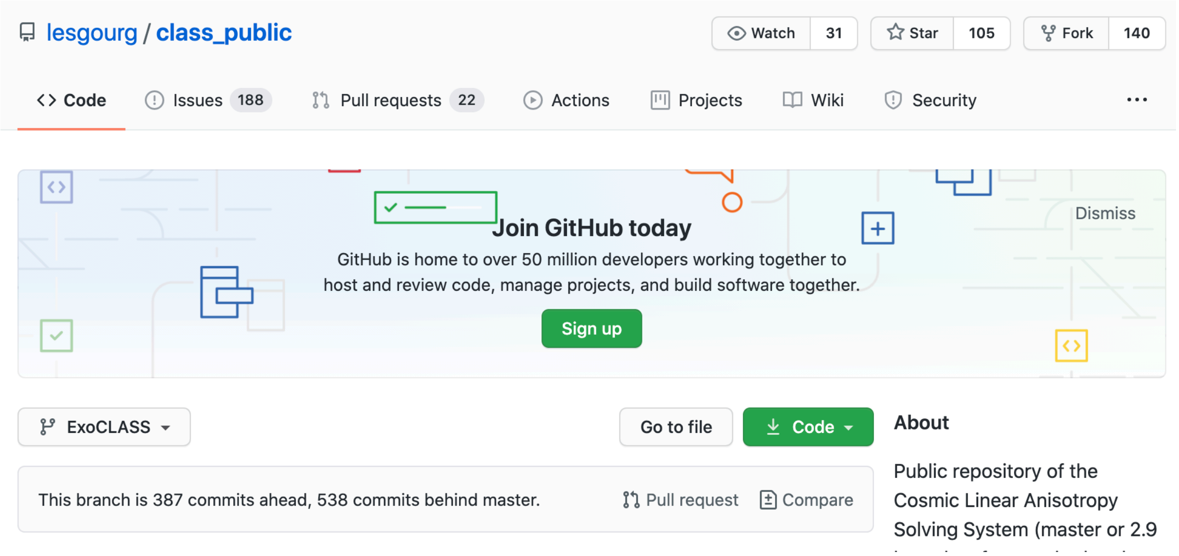
vpoulin@jhu.edu, lesgourg@physik.rwth-aachen.de



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GitHub is home to over 50 million developers working together to host and review code, manage projects, and build software together.

This branch is 387 commits ahead, 538 commits behind master.

About

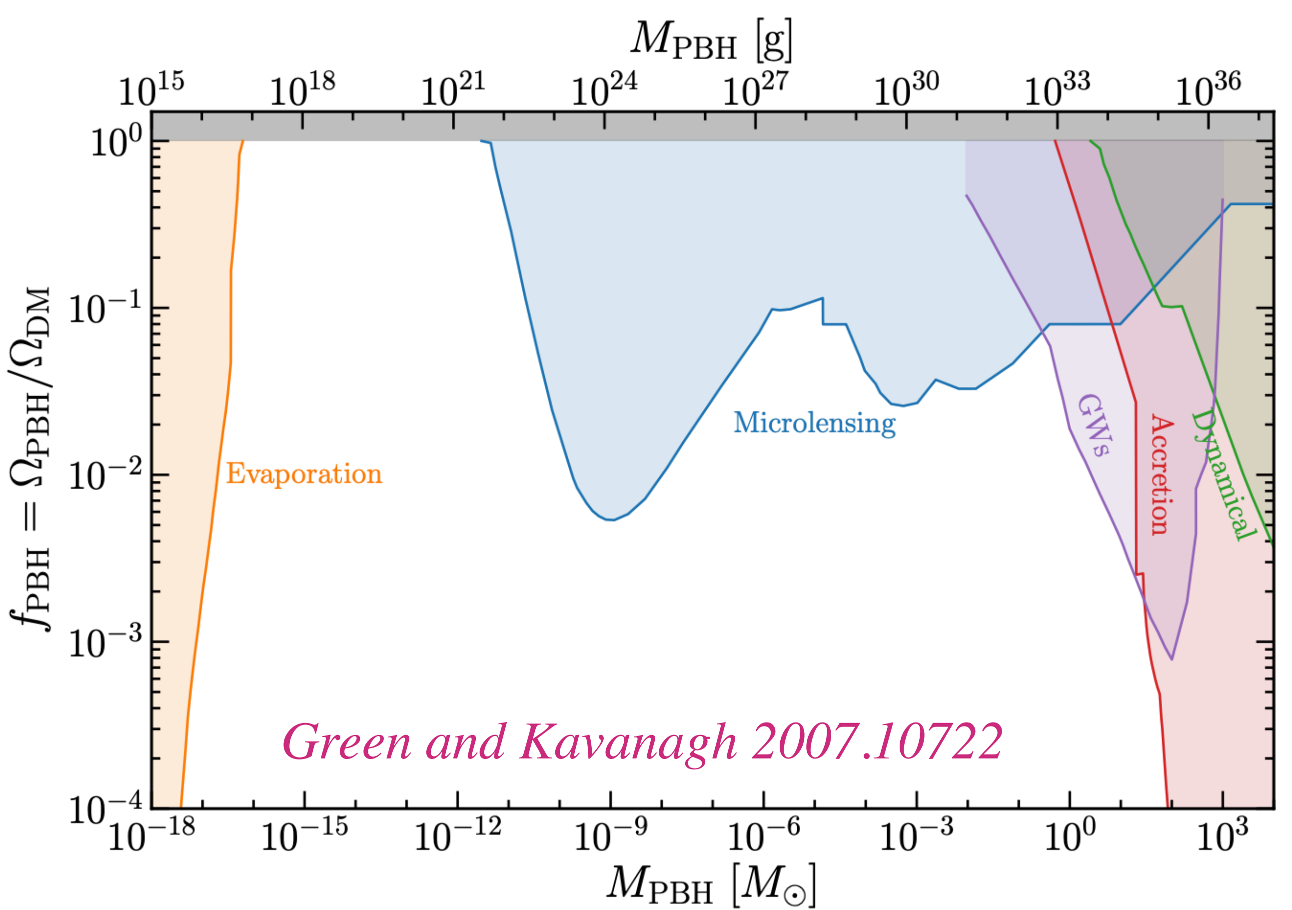
Public repository of the Cosmic Linear Anisotropy Solving System (master or 2.9

- Try to reproduce some of the figures presented previously.
- You can also study the effect of DM annihilations & decays.

Take-Home message

PBH is a great DM candidate that can be probed in many ways:

- Cosmological probes are very powerful to look for electromagnetic signatures of PBH
- Accretion excludes PBH as 100 % DM for $M_{\rm PBH} \gtrsim 30\ M_\odot$ (spherical) or $M_{\rm PBH} \gtrsim 1\ M_\odot$ (disk)
- Evaporation excludes PBH as 100 % DM for $M_{\rm PBH} \lesssim 10^{17} g$
- Future 21 cm experiments increase tremendously the discovery potential
- Discovery of even a fraction of PBH as DM (SMBH?) could be the 'silver bullet' for WIMPs.
- There exists also model-dependent constraints depending PBH formation mechanism (e.g. GW background, spectral distortions…) not treated here.



Green and Kavanagh 2007.10722

Thanks for your attention!