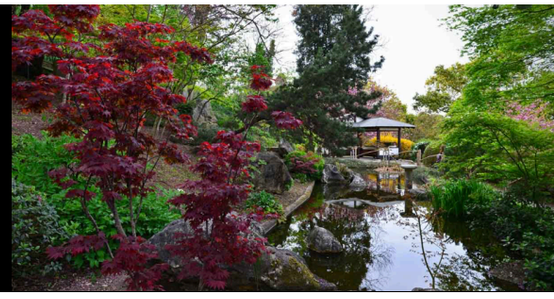
Future Perspectives on Primordial Black Holes

Rome — 12 December 2023



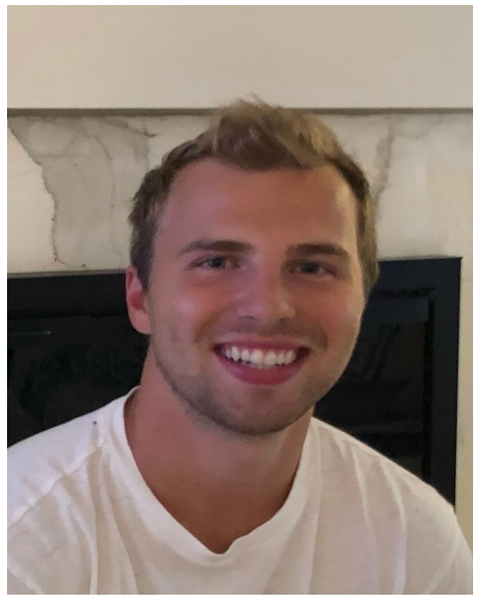
On the Cosmological Bound on Primordial Black Holes

MAURO VALLI

INFN Rome

Réddite quae sunt Caésaris Caésari

Team up!



Dominic Agius
IFIC / U. Valencia

Gregory Suczewski
YITP / Stony Brook U.

+ Francesca Scarcella (U. Montpellier, NEXT SPEAKER)

+ Daniele Gaggero (INFN Pisa) & **Rouven Essig** (YITP)

PBHs & Cosmo

Model of Inflation / Phase Transition such that:

$$\tau_{\rm fall} \sim 1/\sqrt{4\pi G_N \delta\rho} < \tau_{\rm press} \sim 1/(c_s H)$$

i.e., overdense region locally revert expansion & collapse

Non-standard power spectrum @ small scales!

— Ann. Rev. Nucl. Part. Sci. 70 (2020) 355-394 —

- COBE/FIRAS bound on CMB distortions —> $M_{\rm PBH}/M_\odot \lesssim 10^5$

  — APJ 758 (2012) 76 / PRD 90 (2014) 083514 —

- $P(\zeta)$ non-gaussian, PBHs induce DM isocurvature —> $|f_{\rm NL}| \lesssim 10^{-3}$

  — PRD 91 123534 (2015) / JCAP 1504 (2015) 034 —

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PBHs expected to evaporate due to Hawking radiation

$$T_{\rm BH} = (8\pi G_N M_{\rm BH})^{-1} \sim \left(\frac{10^{-10} M_\odot}{M_{\rm BH}}\right) T_{\rm rec}$$

- BBN & CMB constrain injection of high-energy particles in the plasma

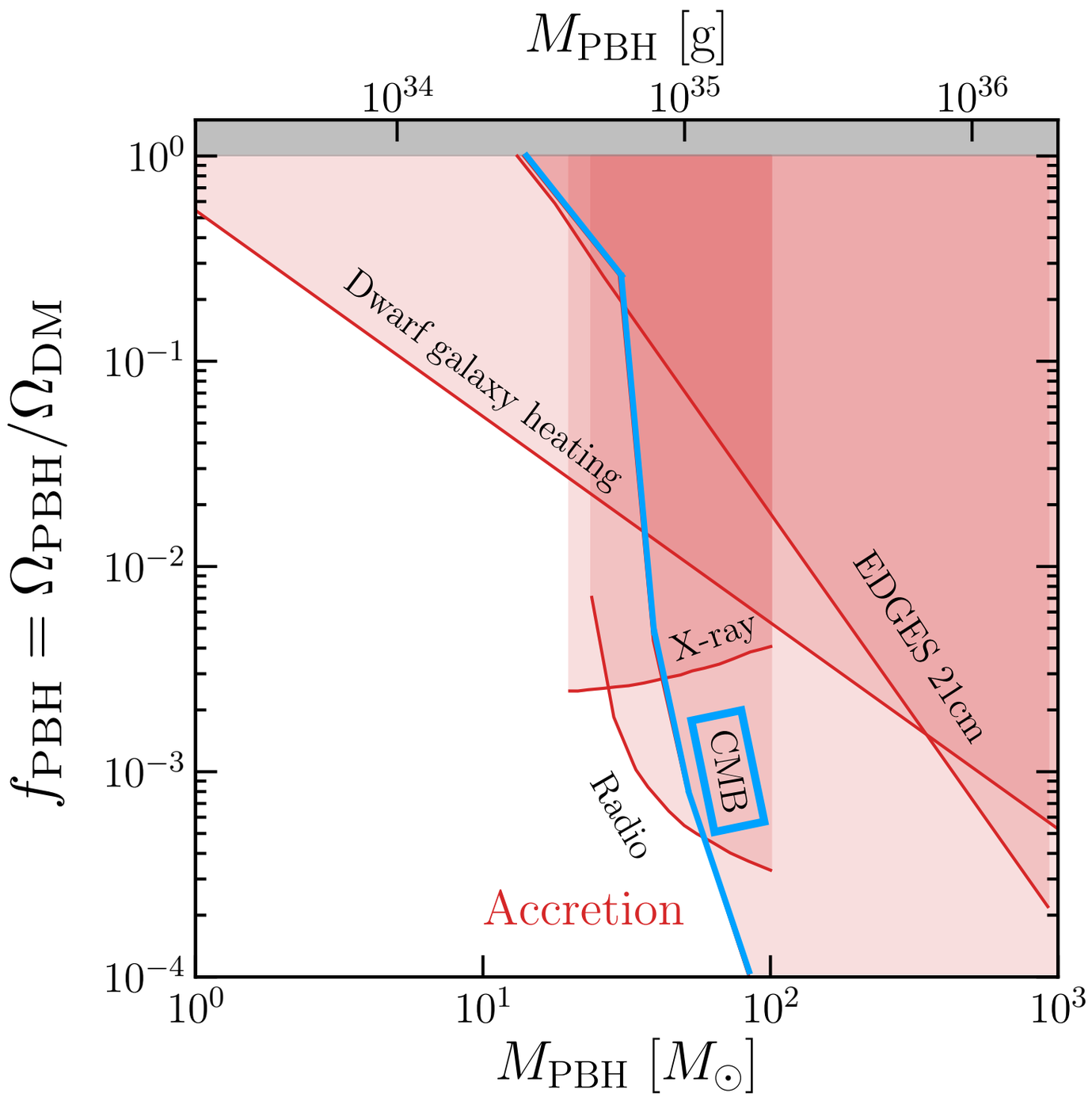
  — PRD 81 (2010) 104019 / PRD 102 (2020) 103512 —

- If $M_{\rm PBH} \gtrsim 10^{-18} M_\odot$, $\tau_{\rm PBH} \gtrsim$ 13.8 billion yrs —> $f_{\rm PBH} \equiv \dfrac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} > 0$

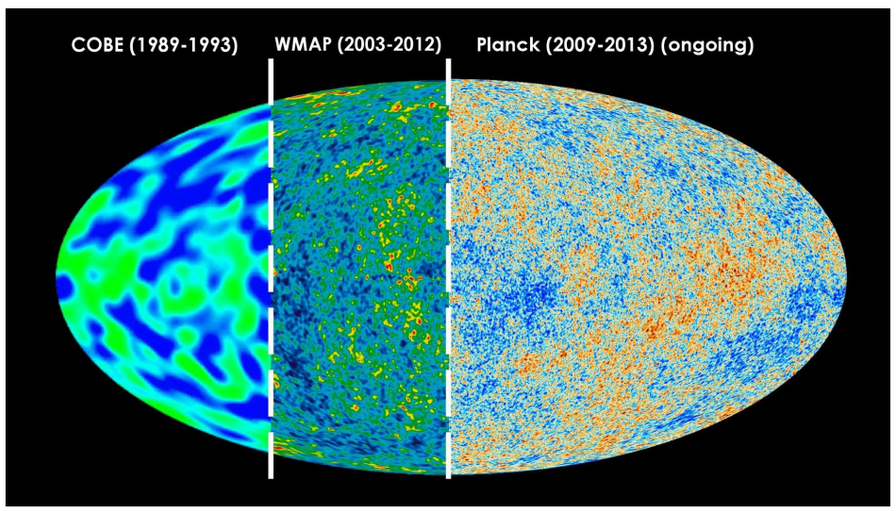
Focus of this Talk

PBHs of stellar masses can accrete matter —> energetic photon emission !

— ApJ. 680 (2008) 829 —



Cosmological bound on *heavy* PBHs largely dominated by



Q: CARVED IN STONE?

Physics of the Bound

Energy injection from exotica (PBHs)

$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj.}(z) \neq 0$$

Effective 3-level atom model

$$\begin{cases} \dfrac{dx_e}{dz} = \mathcal{C}_e[x_e, T_M] \\ \dfrac{dT_M}{dz} = \mathcal{C}_M[x_e, T_M] \end{cases}$$

Line-of-sight sol. of Boltzmann hierarchy affected mainly via alteration of:

$$\tau(z) = \int_0^z n_H(z')x_e(z')\sigma_T \frac{dt}{dz'}dz' \qquad \textit{Thompson Optical Depth}$$

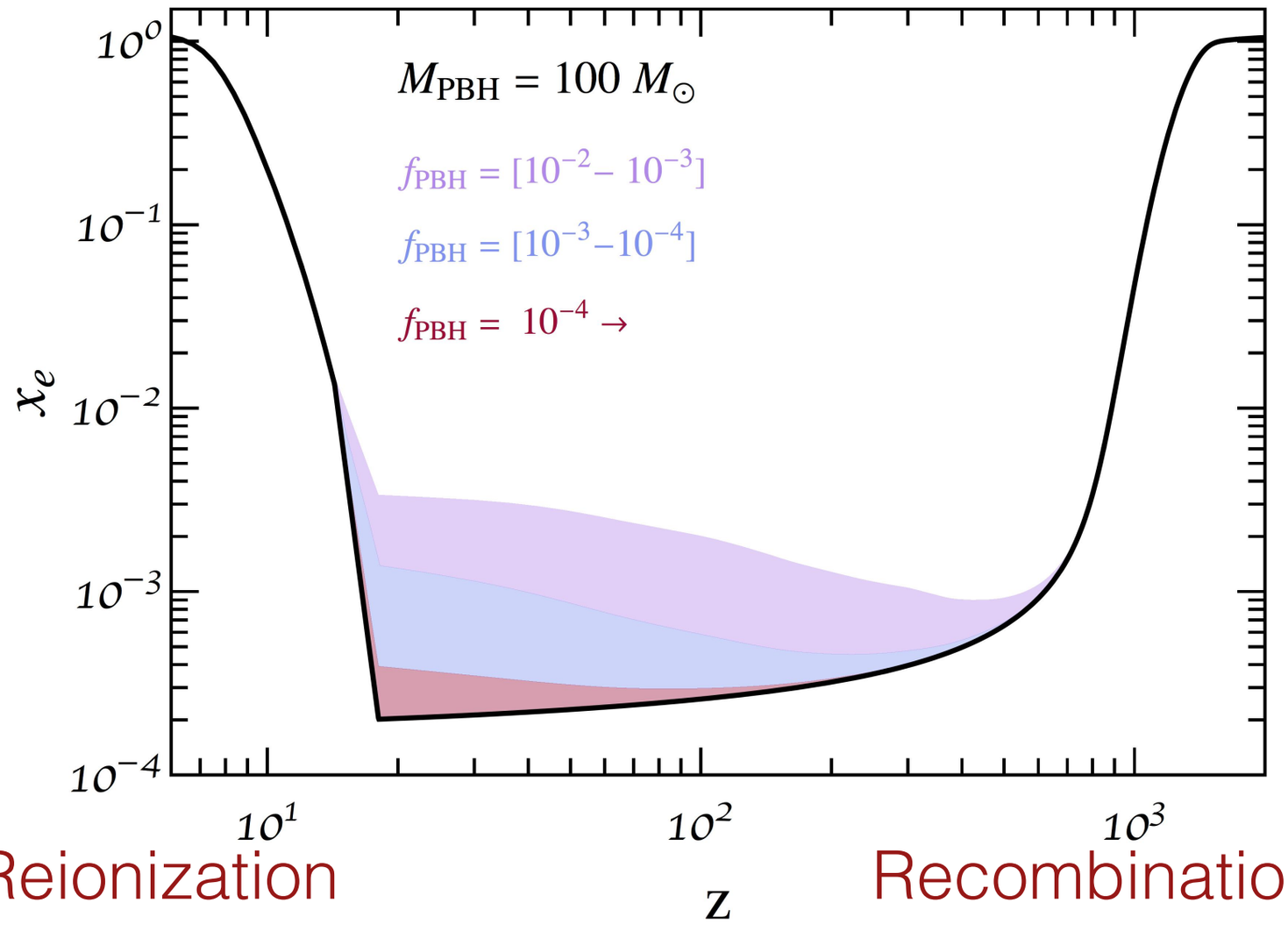
$$v(z) = \left|\frac{d\tau}{dz}\right| \exp(-\tau) \qquad \textit{Visibility Function}$$

— JCAP 03 (2018) 018 / PRD 99 (2019) 043537 —

CMB vs PBHs

PBHs messing up $X_e = n_e/n_H$ from "rec" to "rein" (effects also on T_M)

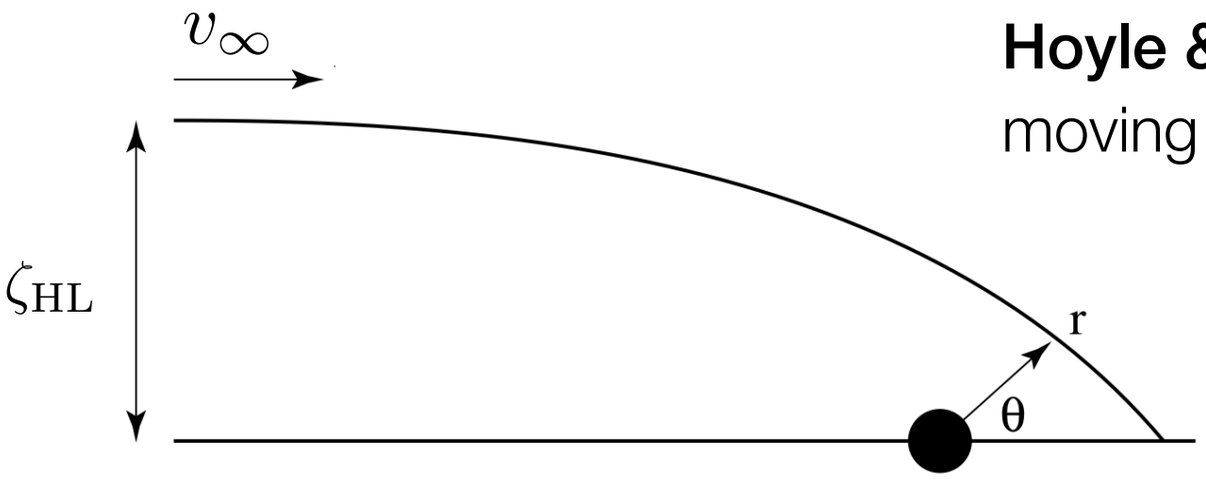
— *Phys.Rev.D 100 (2019) 043540* —



ON CMB: late "rec" (peaks shift in C_ℓ^{TT}) + early "rein" (extra bump in C_ℓ^{EE})

— *JCAP 1703 (2017) 043* —

Accretion 101



— *JCAP 1703 (2017) 043* —

Hoyle & Lyttleton: accretion by a point-like mass M moving at a steady speed through infinite gas cloud.

Material will be accreted if following satisfied:

$$\frac{1}{2}v_\infty^2 < \frac{G_N M}{r} \Leftrightarrow \zeta < \zeta_{\rm HL} \equiv \frac{2G_N M}{v_\infty^2}$$

ACCRETION RATE: $\dot{M}_{\rm HL} = \pi \zeta_{\rm HL}^2 v_\infty \rho_\infty = \dfrac{4\pi G_N^2 M^2 \rho_\infty}{v_\infty^3}$

Bondi generalization of **HL** result **(BHL)**:

which matches up to a fudge factor λ the original HL rate as sound speed c_s of medium becomes negligible.

$$\dot{M}_{\rm BHL} = \lambda \frac{4\pi G_N^2 M^2 \rho}{v_{\rm eff}^3}$$

OBS.

λ tuned to observations (neutron stars, SMBH, AGNs)

- $\rho =$ density of the medium
- $v_{\rm eff} = \sqrt{v_{\rm rel}^2 + c_s^2}$

Disc or Not Disc

$$L \lesssim \dot{M}$$

NOT ALL POTENTIAL ENERGY GOES INTO RADIATION!

IN 4π APPROX., SOME ANALYTIC RESULTS:

$$10^{-5} L_{\rm Edd}/\dot{M} \lesssim \epsilon \equiv L/\dot{M} \lesssim 10^{-3} L_{\rm Edd}/\dot{M}$$

— *PRD 95 (2017) 043534* —

VS

MORE REALISTICAL CASE, DISC ACCRETION …

— *PRD 96 (2017) 8 083524* —

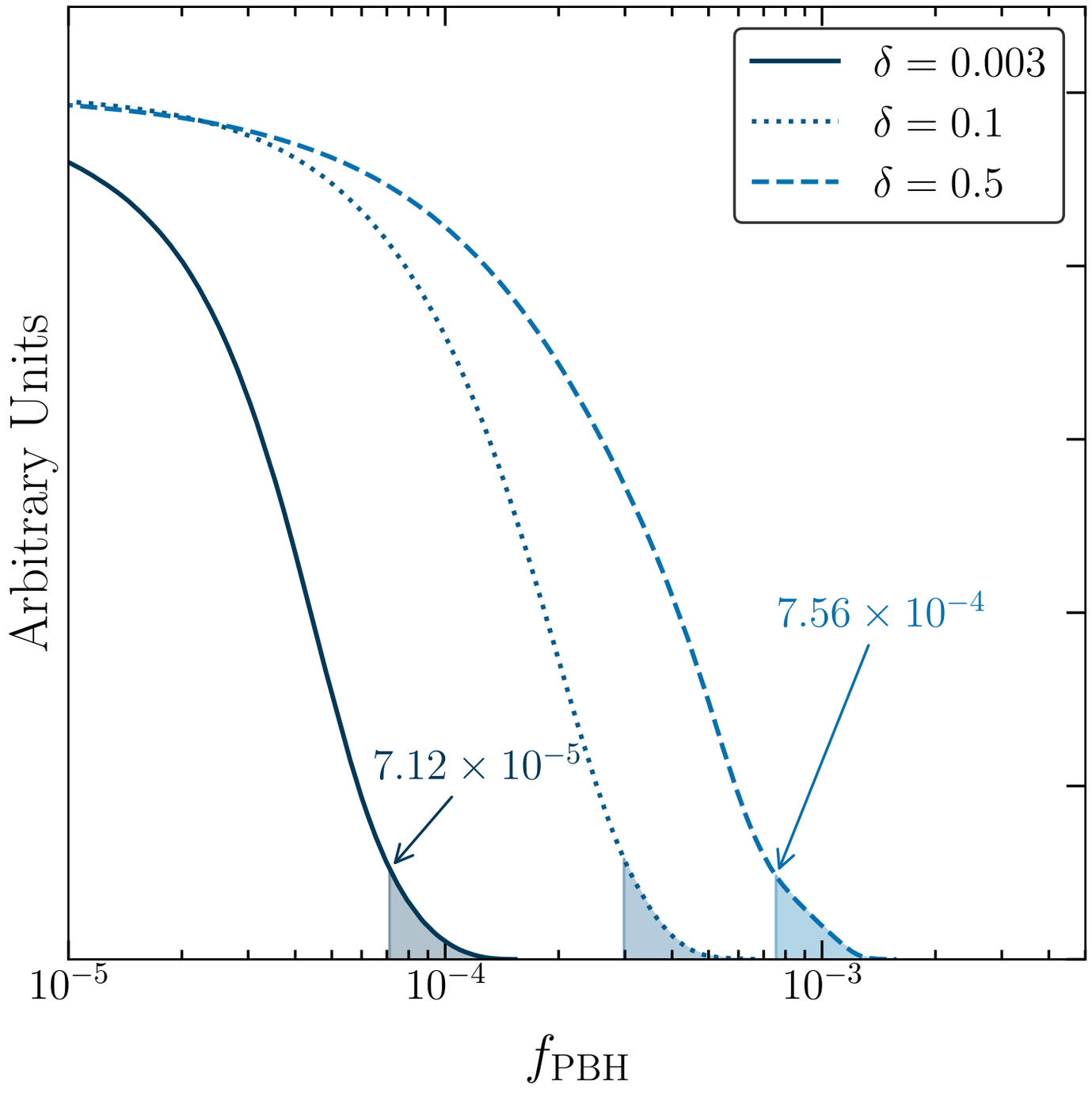
ADVECTION DOMINATED ACCRETION FLOW (ADAF)

BOLOMETRIC EFFICIENCY MAINLY SET BY

δ = % OF IONS INTERACTING W/ LEPTONS

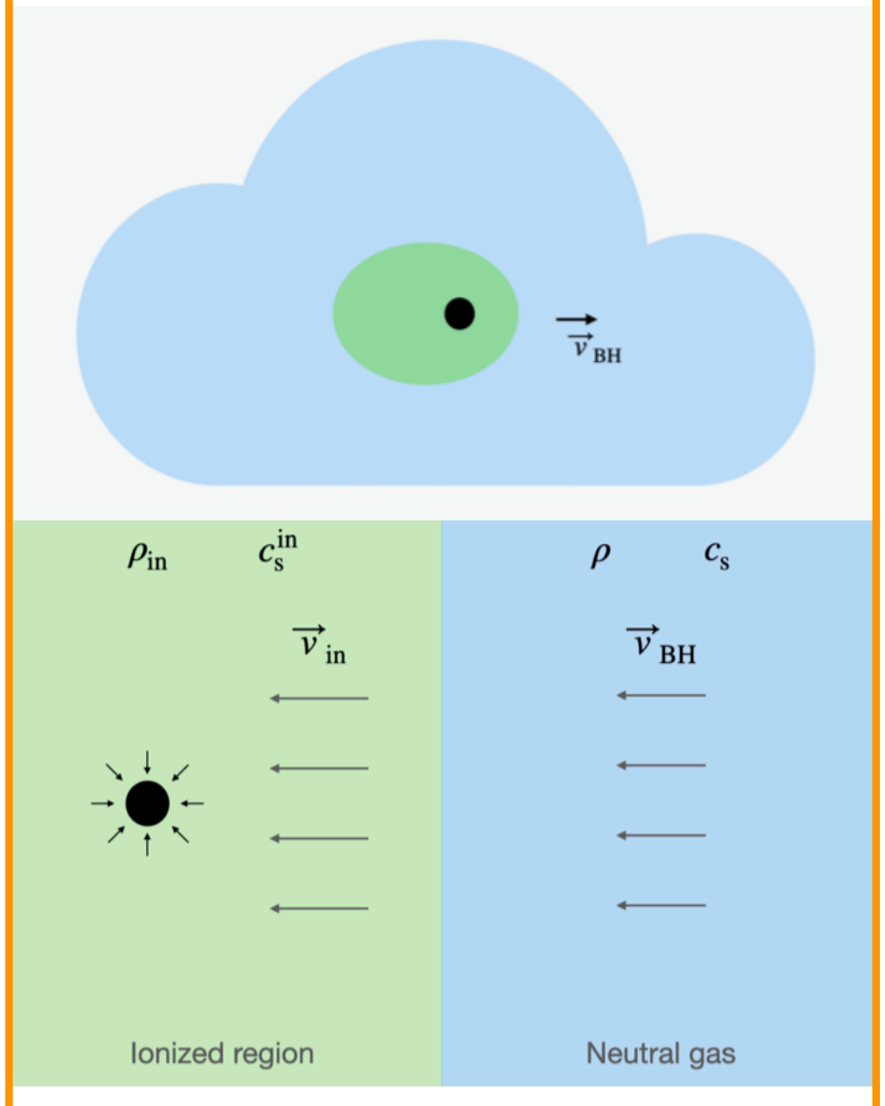
Focus #1

Role of the disc impacts accretion —> one order of magnitude on f_{PBH}!



Beyond BHL

F. Scarcella *— Ph.D. thesis*



— BHL holds within ionized bubble

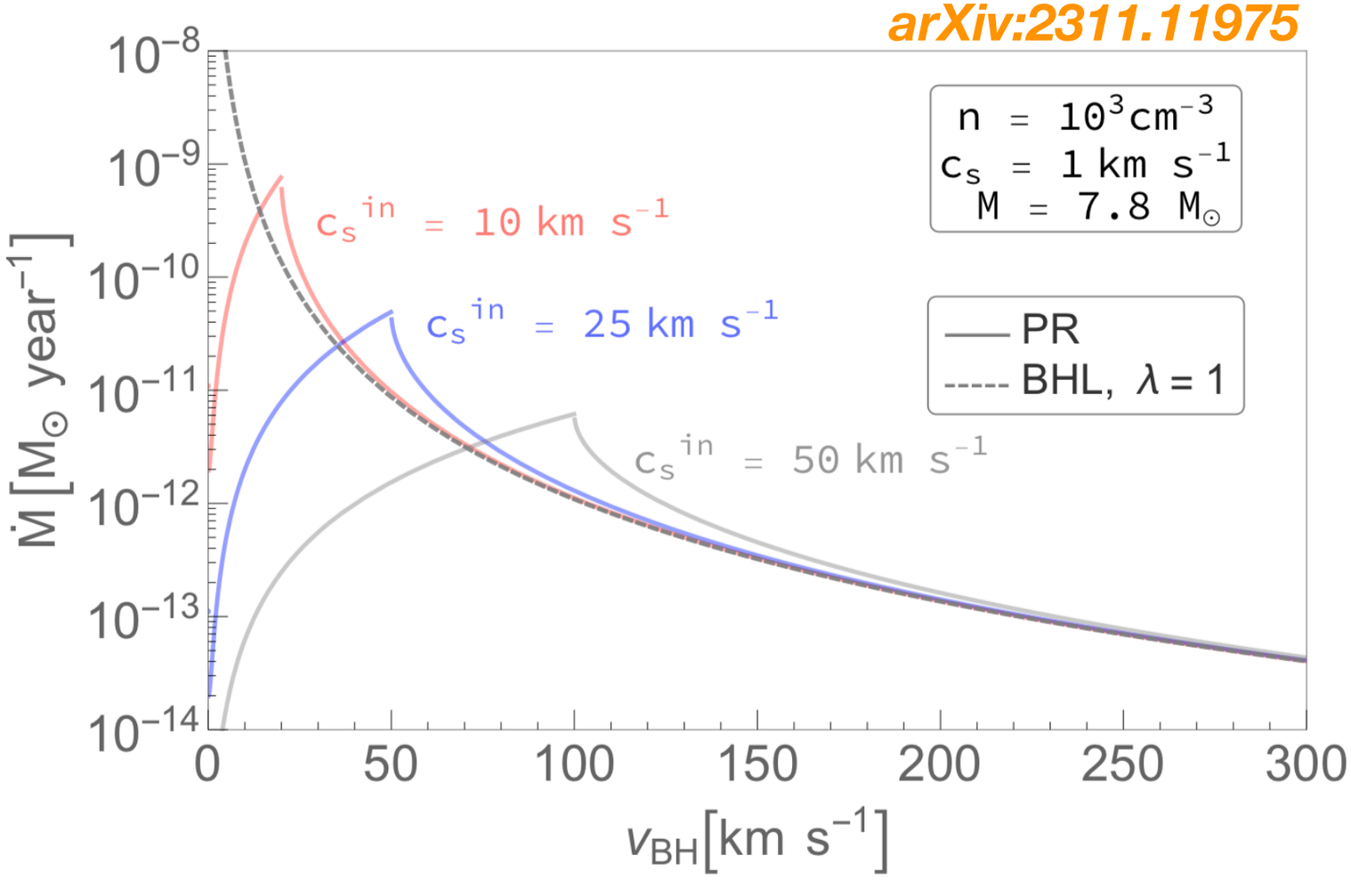
— Euler's eq.s link the two regions

Park & Ricotti (PR13): hydro sim.s show ionizing effect of radiation emitted during accretion process.

— APJ 767 163 (2013) —

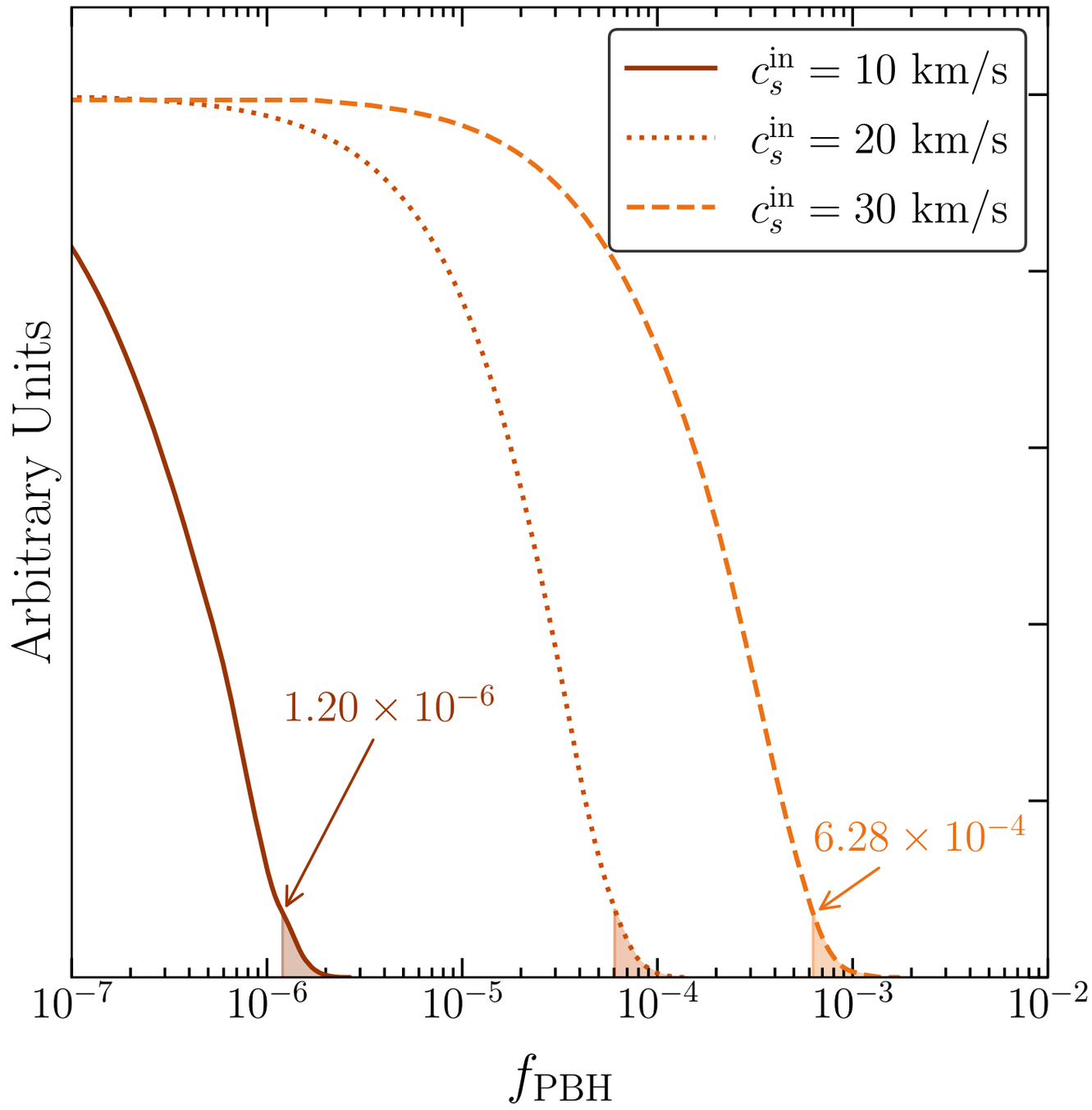
Non-negligible radiative feedback makes accretion rate less efficient at low $v_{\rm rel}$

arXiv:2311.11975



Focus #2

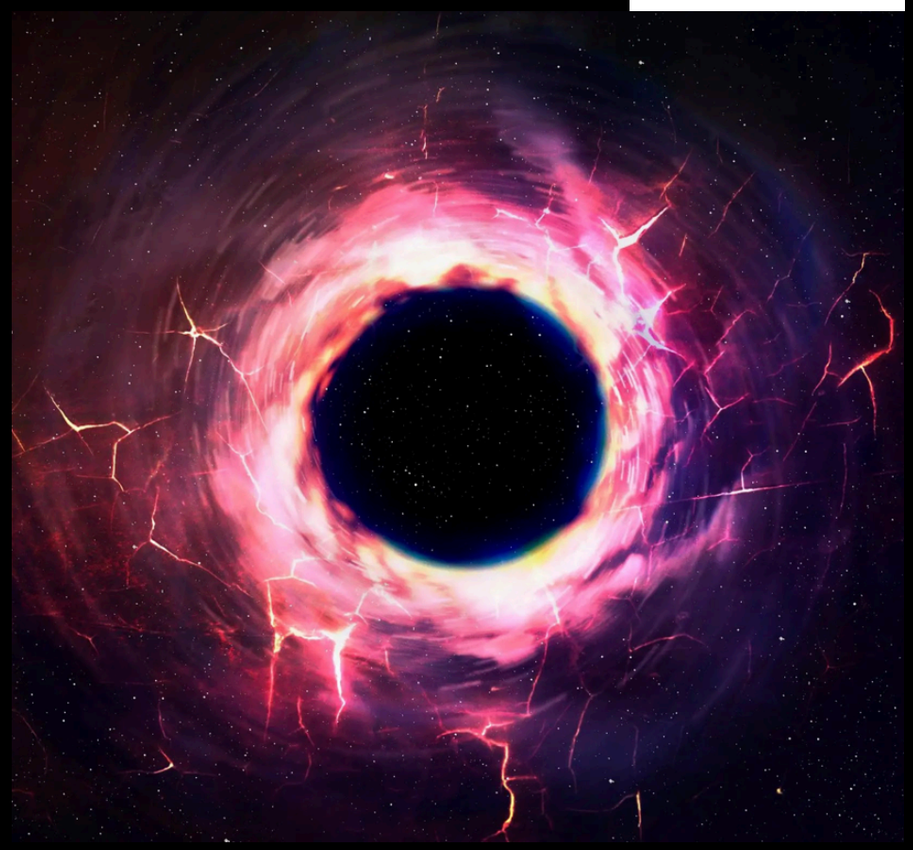
The inner speed of sound in PRI3 accretion model is a key parameter!



Do not forget about DM

Breakthrough Study Confirms Hypothesis of Density Spike of Dark Matter Near Black Holes

Guardian mag June 09, 2023 *Guardian Mag*



— APJL 943 (2023) L11 —

$f_{\rm PBH} \ll 1$ ⇨ DM ≠ PBH around!

A GRAVITATIONALLY BOUND DM HALO IS EXPECTED TO FORM AROUND PBHS

EDUCATED GUESS

FREE-FALLING BARYONIC MATTER INTO PBH FEELS A DEEPER POTENTIAL WELL

$$\dot{M} \sim \zeta_{\rm eff}^2 \, v_{\rm eff} \, \rho$$

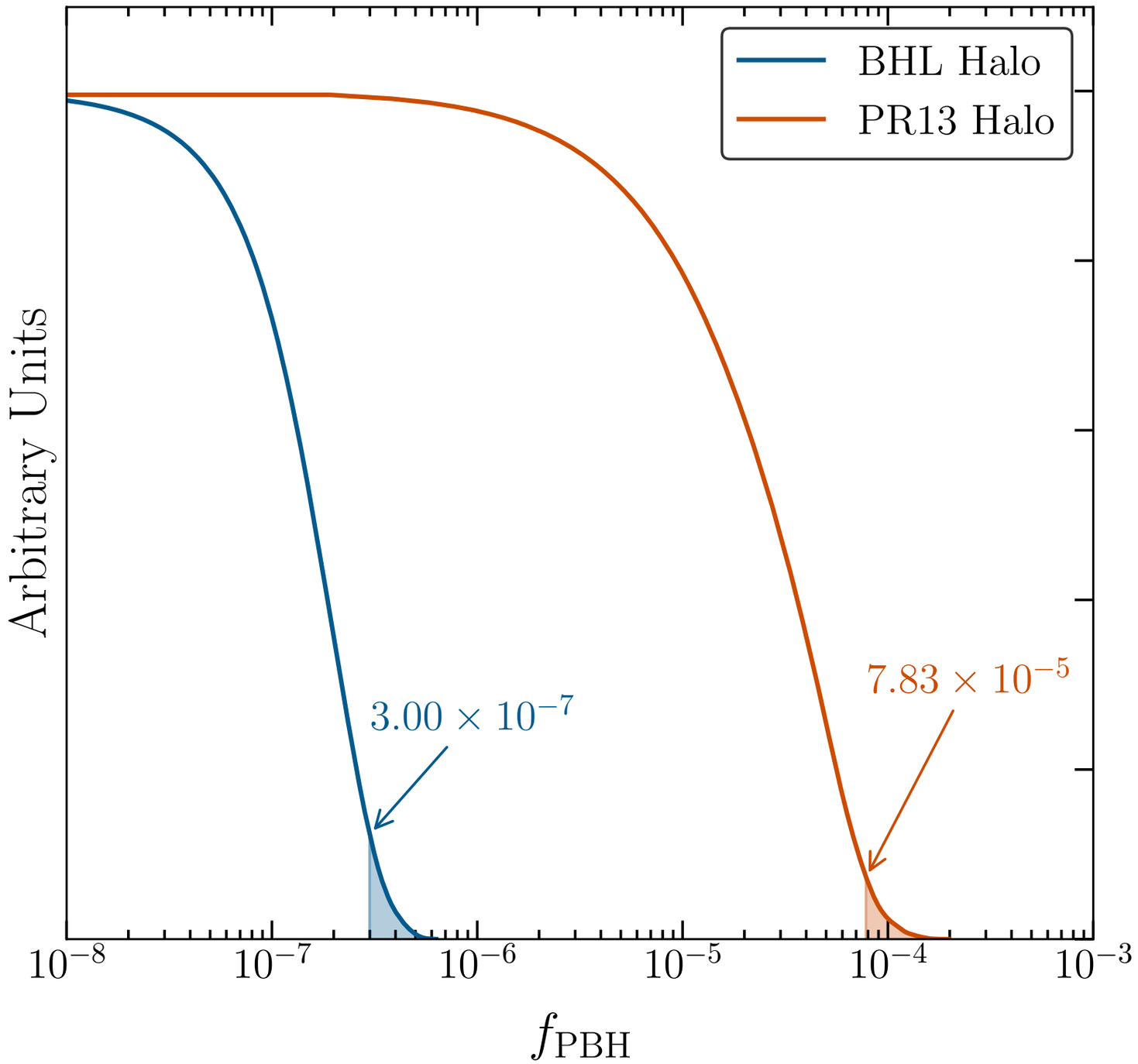
$$\frac{G_{\rm N} M_{\rm PBH}}{\zeta_{\rm eff}} - \Phi_{\rm DM} = v_{\rm eff}^2$$

EFFECT APPRECIABLE PHENOMENOLOGICALLY FOR BHL MODEL, NOT FOR PR13 ACCRETION

D.Agius, G.Suczewski, et al. — TO APPEAR SOON

Focus #3

The impact of DM halo is intimately related to the underlying accretion model !



A "standardized" recipe

- Modify your favorite Boltzmann solver to include extra energy injection

  CAMB / **CLASS** https://github.com/lesgourg/class_public

  1 — Implement a "realistic" accretion model for PBHs (i.e., also emitted spectrum)

  Ann.Rev.Astron.Astrophys. 52 (2014) 529

  2 — Model baryon - PBH relative vel. from "rec" to "rein" & average over it

  Linear theory usually assumed: $\langle v_{rel} \rangle = \min[1,(1+z)/10^3] \times 30\,\mathrm{km/s}$

  3 — Translate energy injection rate into energy deposition rate via:

  ✱ Semi-analytic approach — *PRD 95 (2017) 043534*

  ✱ Tabulated transfer functions — *PRD 87 (2013) 123513*

- Adopt << best dataset >> & your favorite sampler for Bayesian inference

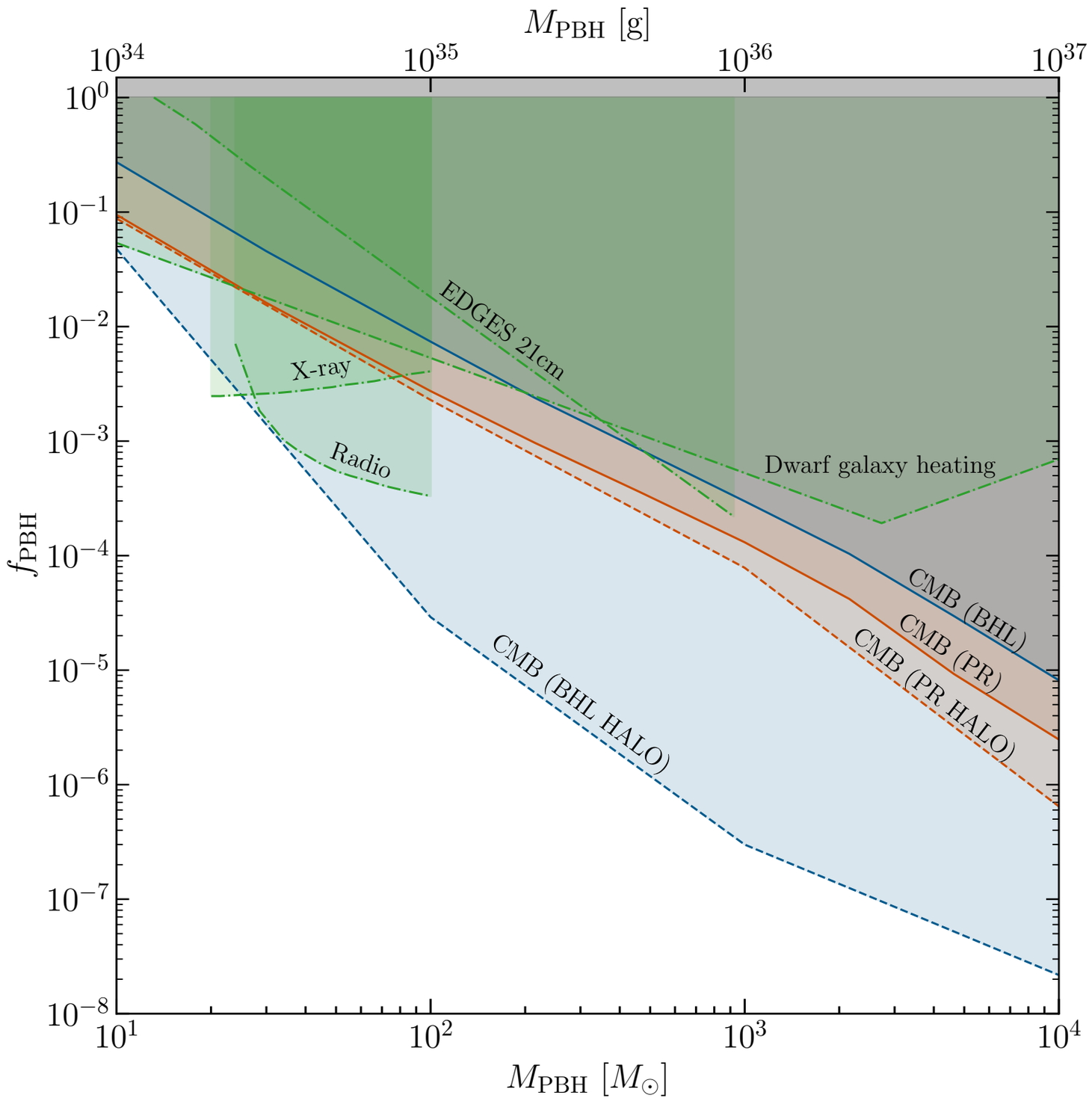
  ACT + SPT latest release
  BAO consensus likelihood
  Planck '18 TTTEEE + lens

  Cobaya / Monte Python

  https://github.com/CobayaSampler/cobaya

PLOT

PRELIMINARY



D.Agius, G.Suczewski, D.Gaggero, F.Scarcella, R.Essig & MV

CMB (PR13) IN AGREEMENT WITH WHAT RECENTLY DERIVED IN ***PRD 107 (2023) 043537***

Take Home

- CMB <—> sensitive probe of PBHs as (a fraction of) DM, f_{PBH}

— ACCRETION OF MATTER DOES MATTER —
ESPECIALLY W/ DARK MATTER

$f_{PBH} \lesssim 10^{-7}$ @ 95 % (BHL+DM halo)

$f_{PBH} \lesssim 10^{-4}$ @ 95 % (PR13+DM halo)

— from CMB + BAO for $M_{PBH}/M_\odot = 10^3$ —

- CMB ruling out $f_{PBH} > 1\%$ for $M_{PBH}/M_\odot > 10^2$ still very true

WHAT'S NEXT

* Baryon - PBH velocity beyond linear theory
* Role of PBH mass function & merger history