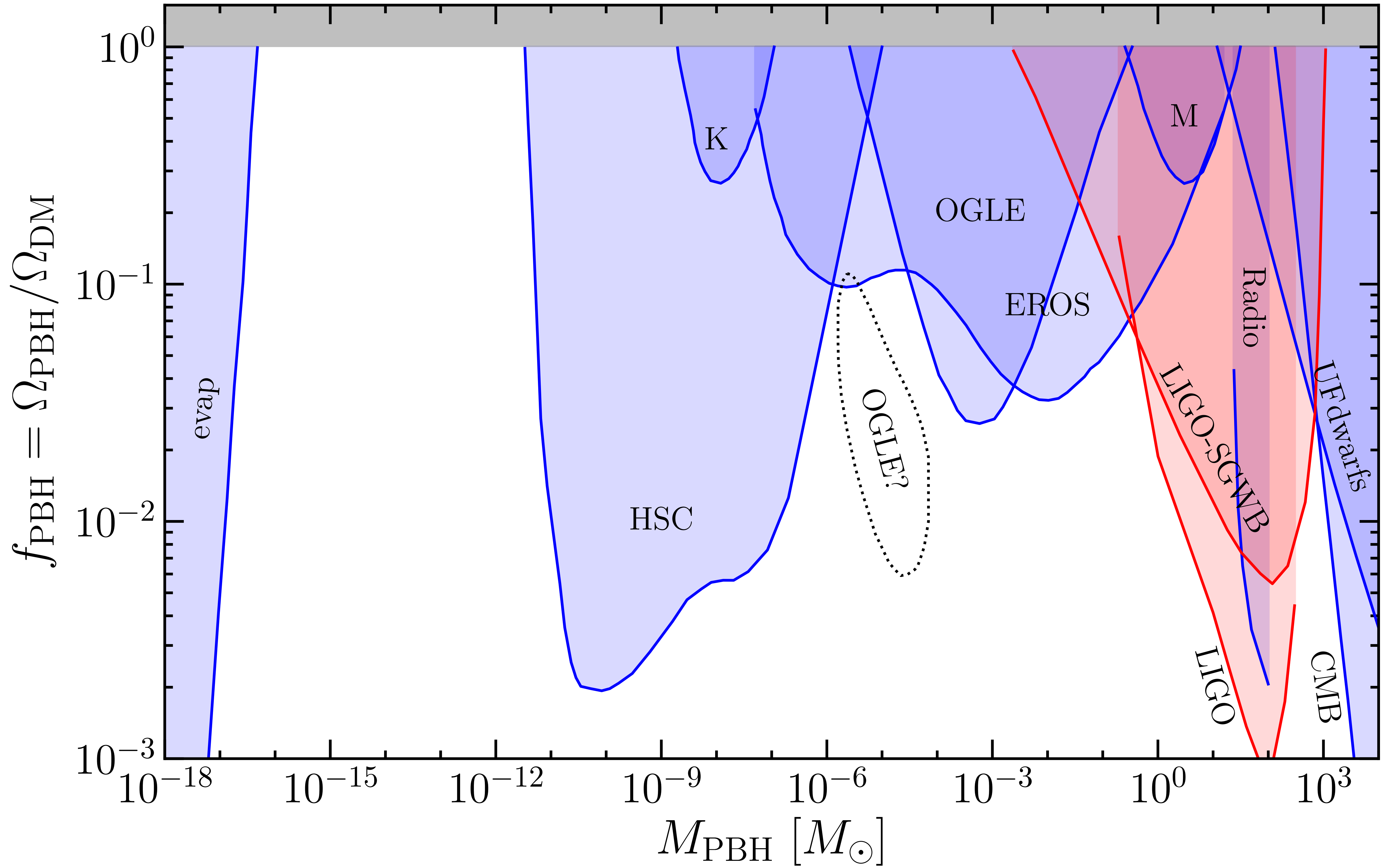
Feedback in the Dark: The CMB bound on the PBH abundance

Daniele Gaggero

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

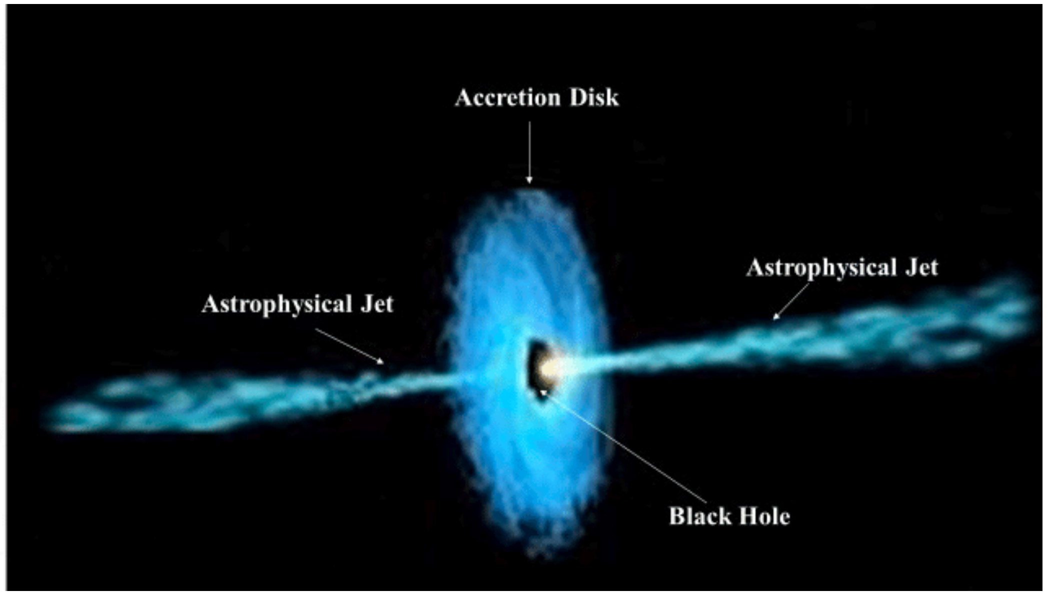
in collaboration with: Dominic Agius (IFIC Valencia), Rouven Essig (YITP), Francesca Scarcella (U. Montpellier), Gregory Suczewski (YITP / Stony Brook U.), Mauro Valli (INFN Rome)

Primordial Black Hole phenomenology



Credit: Bradley Kavanagh, https://github.com/bradkav/PBHbounds

Accretion bounds

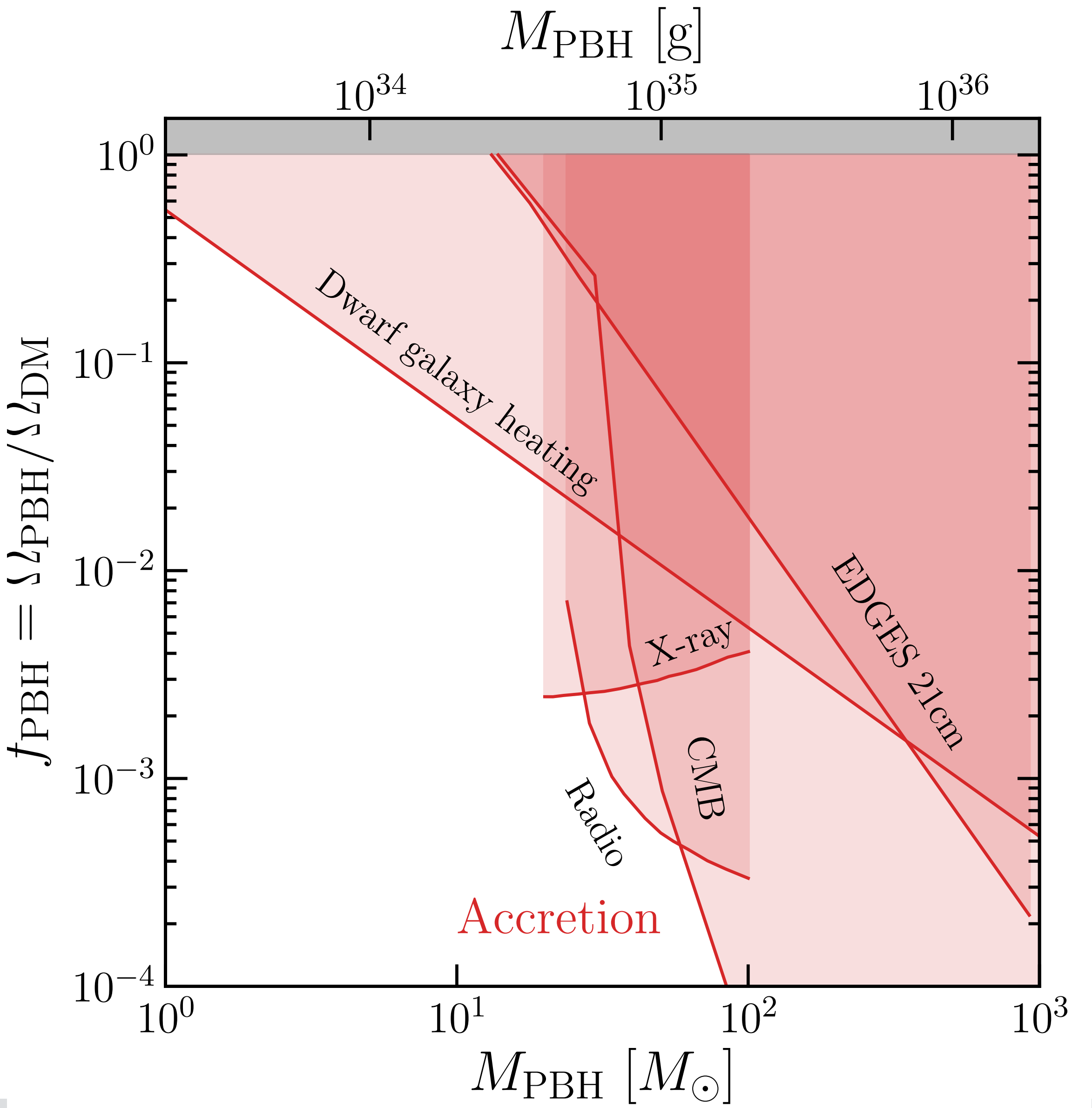


- **Primordial Black Holes can accrete baryonic matter**

- **Astronomical environments:** X-ray/radio bounds (focus on Galactic center)

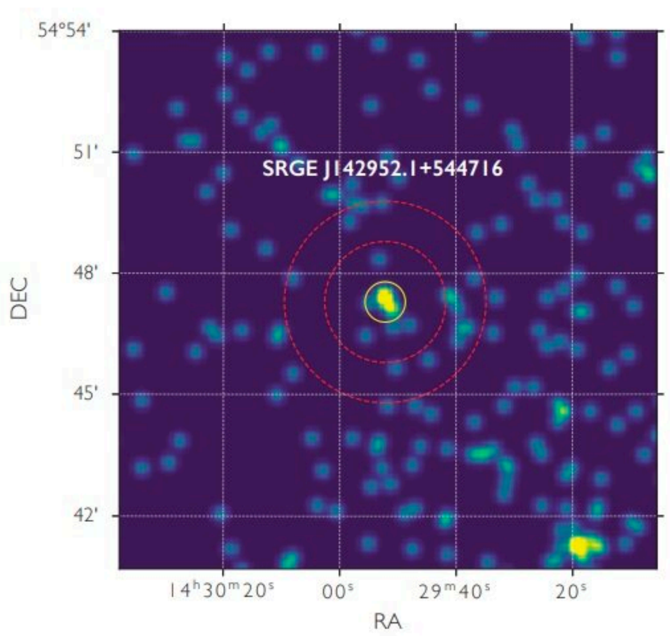
- **Cosmological bound:** for instance from Cosmic Microwave Background (focus on accretion during the Dark Ages)

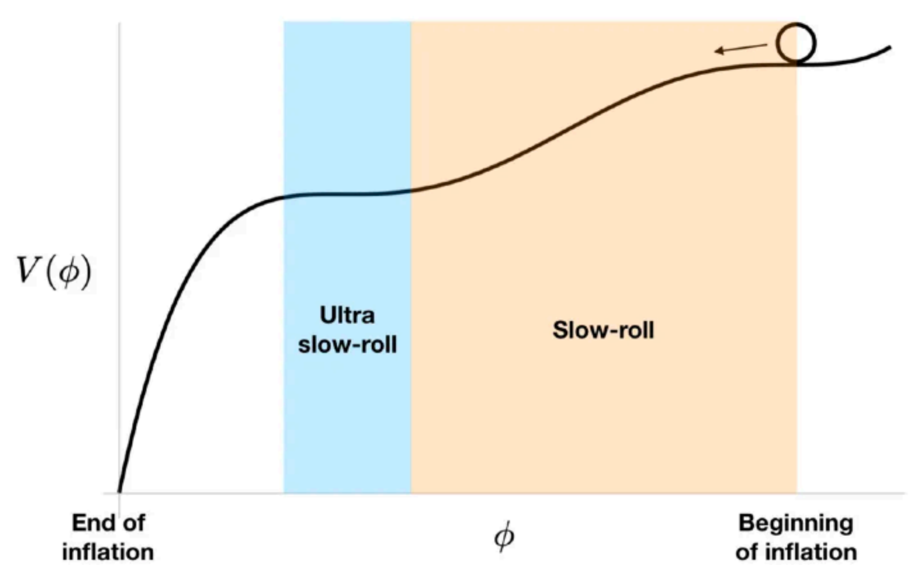
- They rely on complicated accretion physics
- Comprehensive assessment of the uncertainties is very much needed!

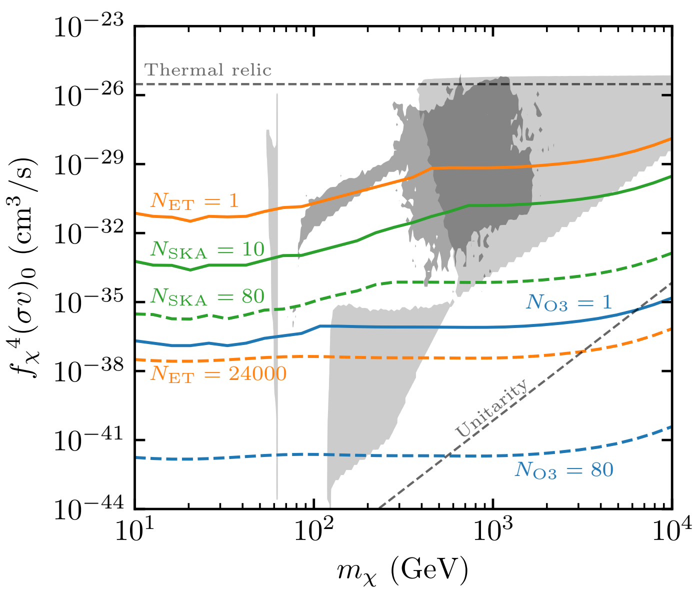


Why a sub-dominant population would matter?

- A discovery of a sub-dominant population of DM in the form of (massive) PBHs could:
  - Solve the problem of the **SMBH seed**?
  - Reveal non-trivial **early universe physics**
  - Help us set stringent **upper limits** on other DM candidates







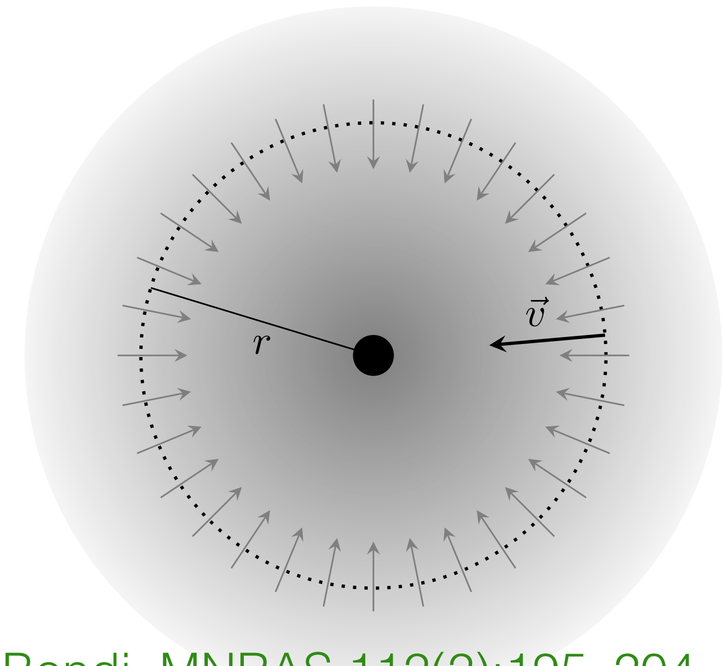
Accretion physics: Bondi formalism.

Continuity equation for steady-state flow

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho v\right) = 0$$

Euler equation

$$\rho v \frac{dv}{dr} = -\frac{dP}{dr} - \frac{GM\rho}{r^2}$$

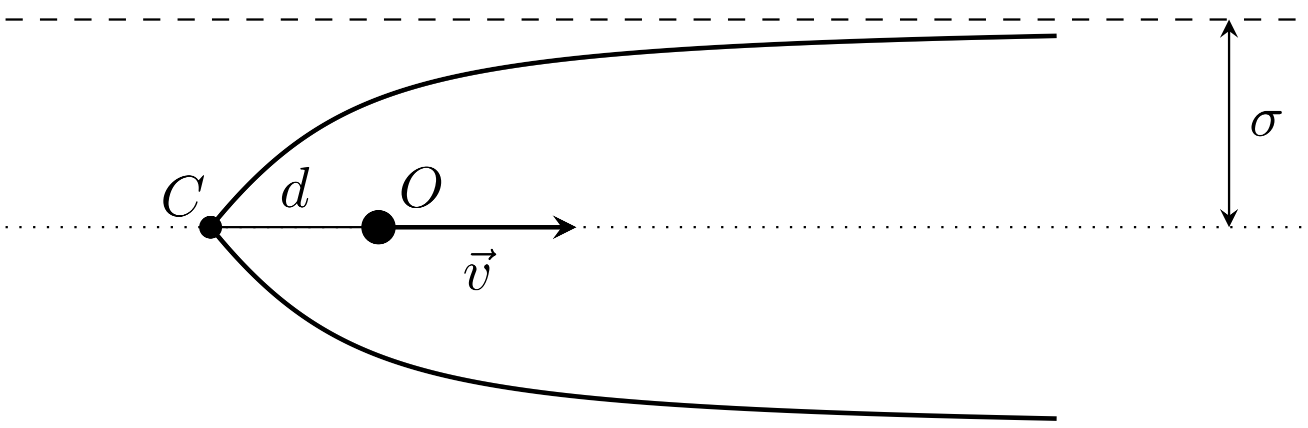


BH at rest: *Bondi* accretion rate

$$\dot{M} = 4\pi r_s^2 \rho(r_s) c_s(r_s) = \pi \frac{(GM)^2 \rho(\infty)}{c_s^3(\infty)} \left(\frac{2}{5-3\gamma}\right)^{\frac{5-3\gamma}{2(\gamma-1)}}$$

H. Bondi, MNRAS 112(2):195–204, 1952

H. Bondi and F. Hoyle, MNRAS 104(5):273–282, 1944



Moving BH: *Bondi-Hoyle-Littleton* accretion rate

$$\dot{M}_{\rm BHL} = 4\pi \frac{(GM)^2 \rho_\infty}{(v^2 + c_\infty^2)^{3/2}}$$

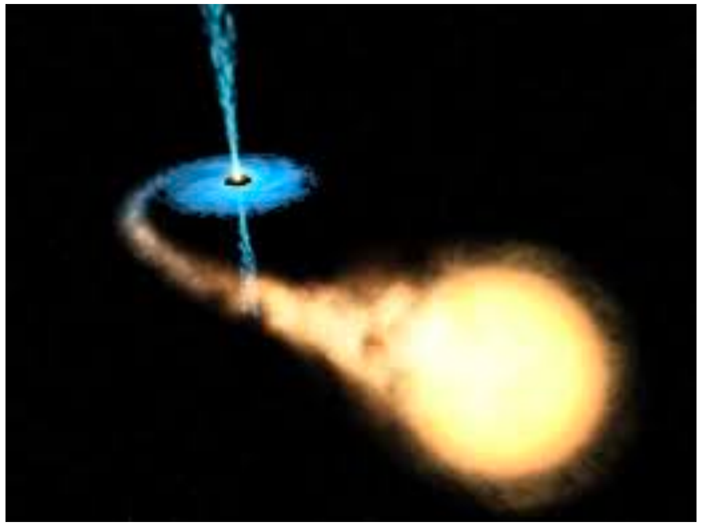
Accretion physics: Bondi formalism

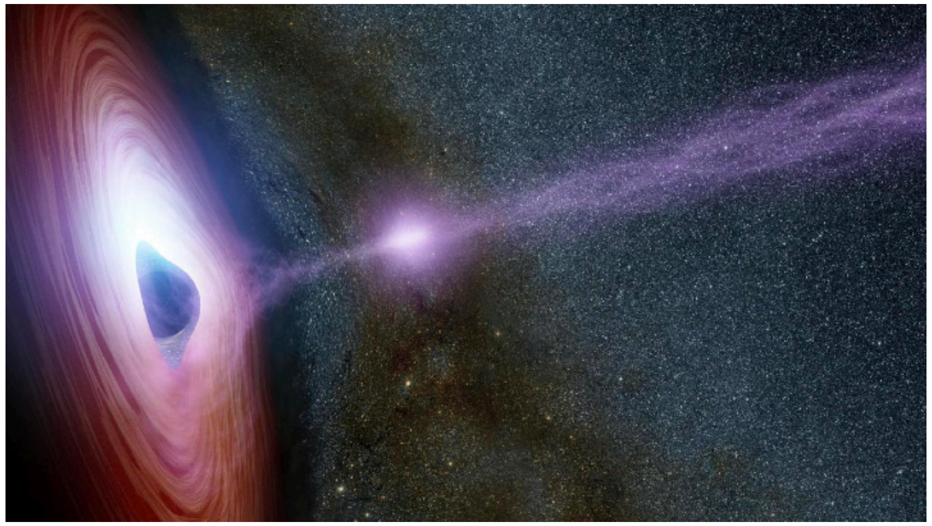
Bondi-Hoyle-Littleton formula needs to be "fudged" because of observational constraints related to local neutron stars, the SMBH at the center of the Galaxy, and AGNs.

$$\dot{M} = 4\pi\lambda(GM_{BH})^2\rho\left(v_{BH}^2 + c_s^2\right)^{-3/2}$$

- Perna et al. 2003, *"Bondi accretion and the problem of missing isolated neutron stars"*
- S. Pellegrini 2005, *"Nuclear Accretion in Galaxies of the Local Universe: Clues from Chandra Observations"* (explanation for the radiative quiescence of supermassive black holes in the local Universe)
- Wang et al. 2013, *"Dissecting X-ray-emitting Gas around the Center of our Galaxy"*

The fudge factor takes into account several effects, including the role of outflows





The physics behind the bound

- PBHs accrete baryonic matter during the *Dark Ages*.
  - The accretion rate depends on *ambient density* and PBH - baryon *relative speed*.
  - Ambient density dilutes with decreasing redshift

$$\rho_\infty = m_\mathrm{p}\, n_\infty \approx m_\mathrm{p}\, 200\,\mathrm{cm}^{-3} \left(\frac{1+z}{1000}\right)^3$$

  - PBH speed relative to baryons *decreases* according to linear theory *(DM does not suffer Thompson scattering)*

$$\sqrt{\langle v_\mathrm{L}^2 \rangle} \simeq \min\left[1, \frac{1+z}{1000}\right] \times 30\,\mathrm{km/s}\,.$$

Hu, Sugiyama 9407093
Tseliakhovich+ 1005.2416
Dvorkin+ 1311.2937

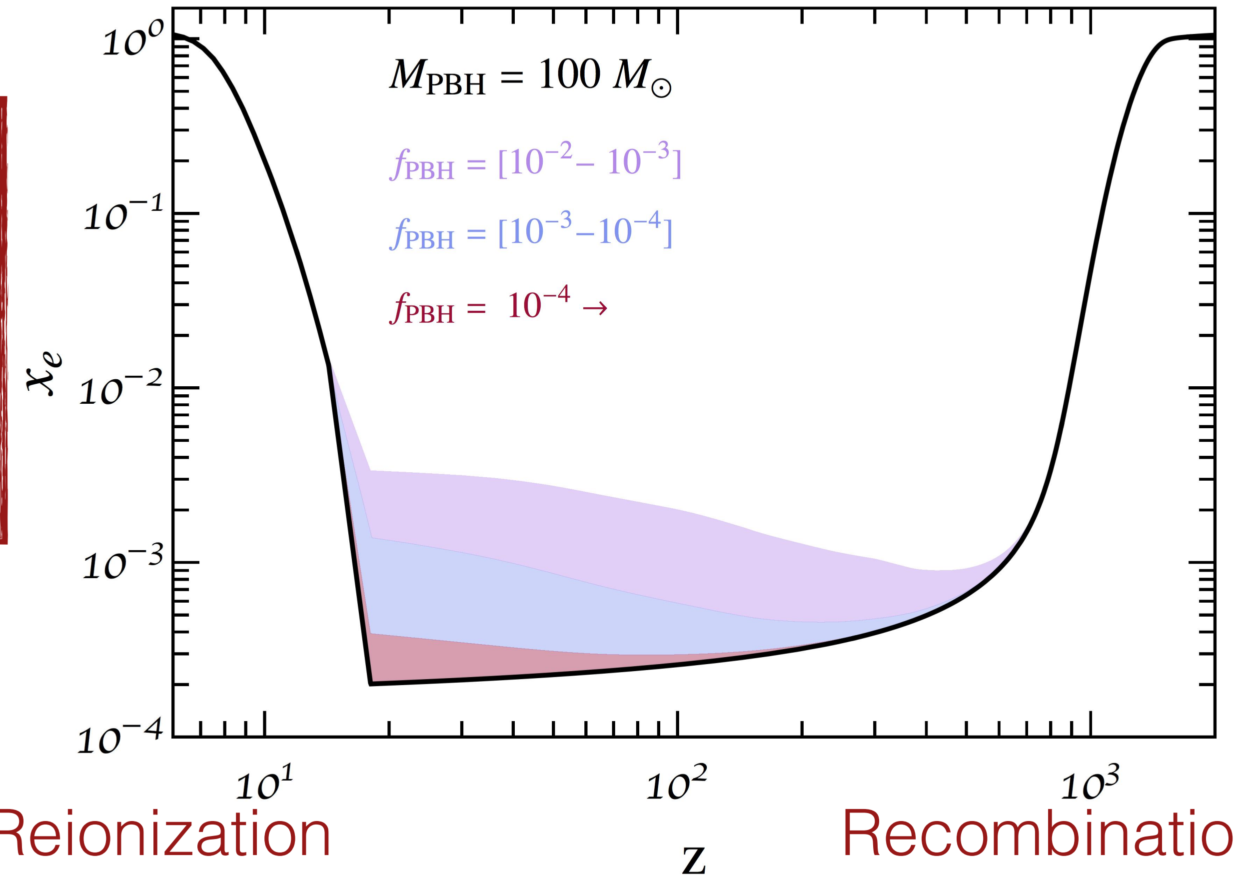
The physics behind the bound

- Accretion disks emits *ionizing radiation* during the Dark Ages (between Recombination and Reionization)*:*
  - IGM is heated up (alteration of T_M)
  - IGM is also partially ionized (alteration of the *free electron fraction* X_e)

Mena+ 1906.07735

$$\frac{dx_e(z)}{dz} = \frac{1}{(1+z)H(z)}\left(R(z) - I(z) - I_X(z)\right) ,$$
$$\frac{dT_{\rm M}}{dz} = \frac{1}{1+z}\left[2T_{\rm M} + \gamma(T_{\rm M} - T_{\rm CMB})\right] + K_h .$$

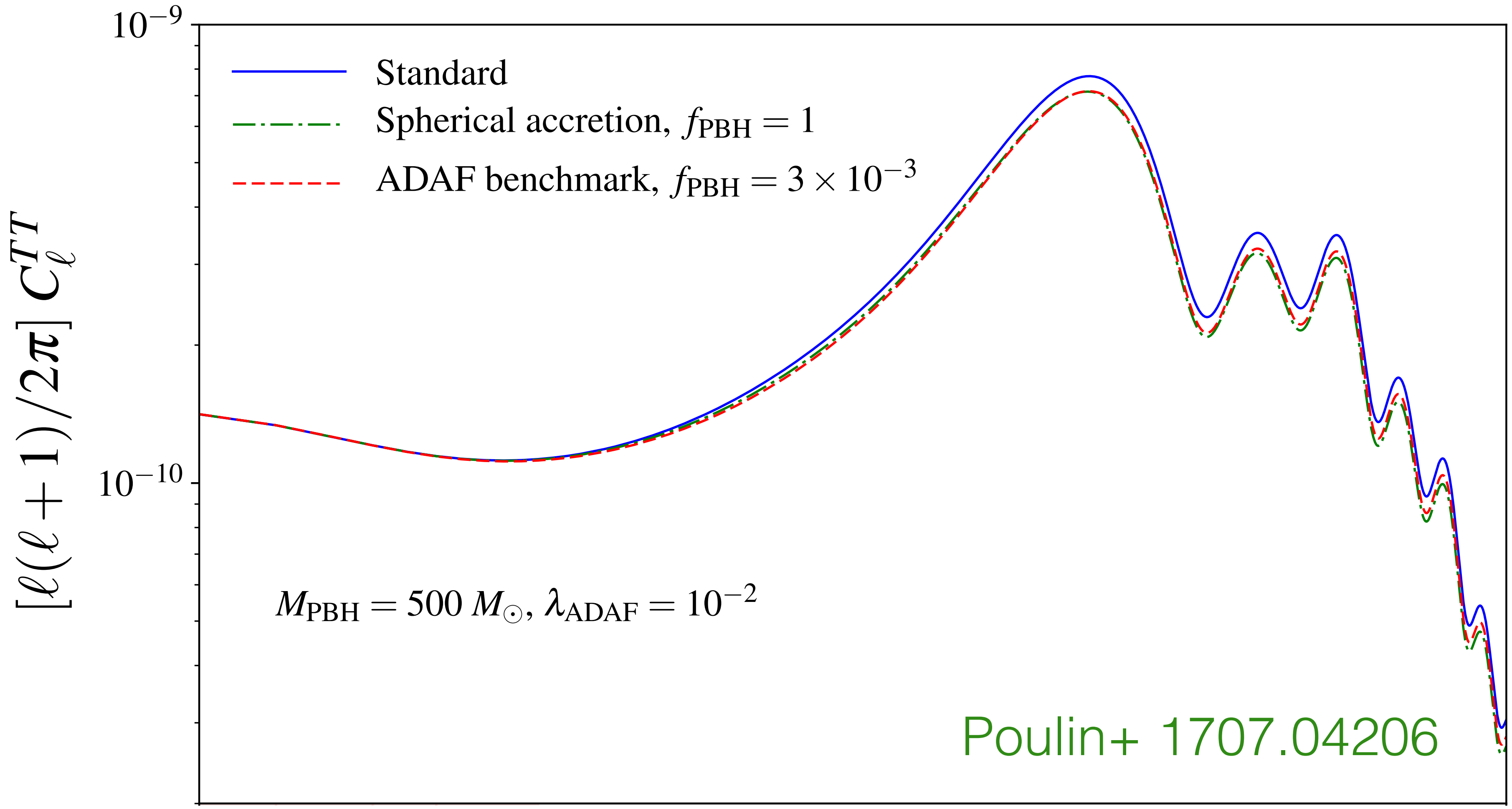
Stocker+ 1801.01871



Reionization Recombination

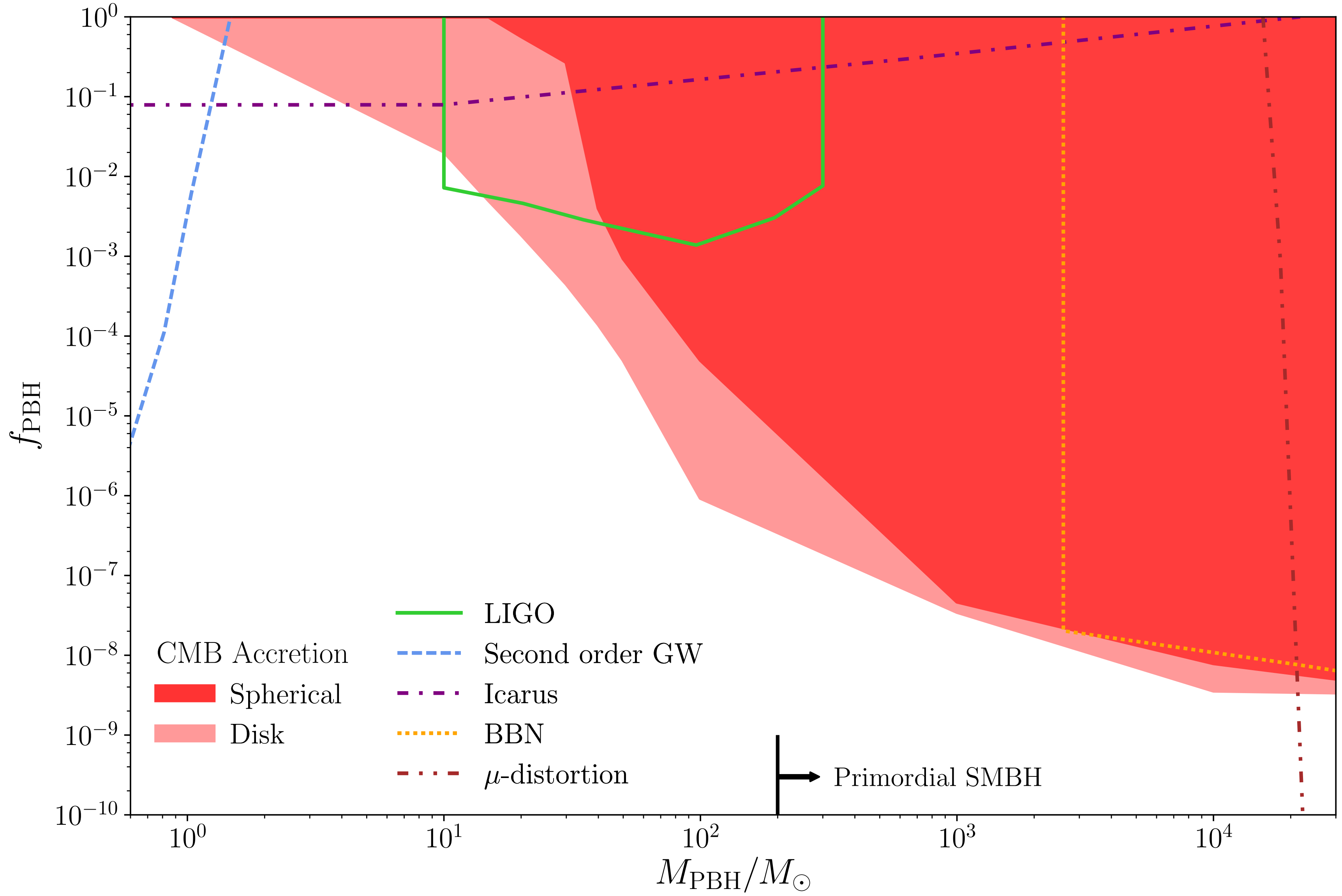
The physics behind the bound

- Impact on CMB anisotropy is due to the alteration of the *visibility function* and the recombination optical depth



The physics behind the bound

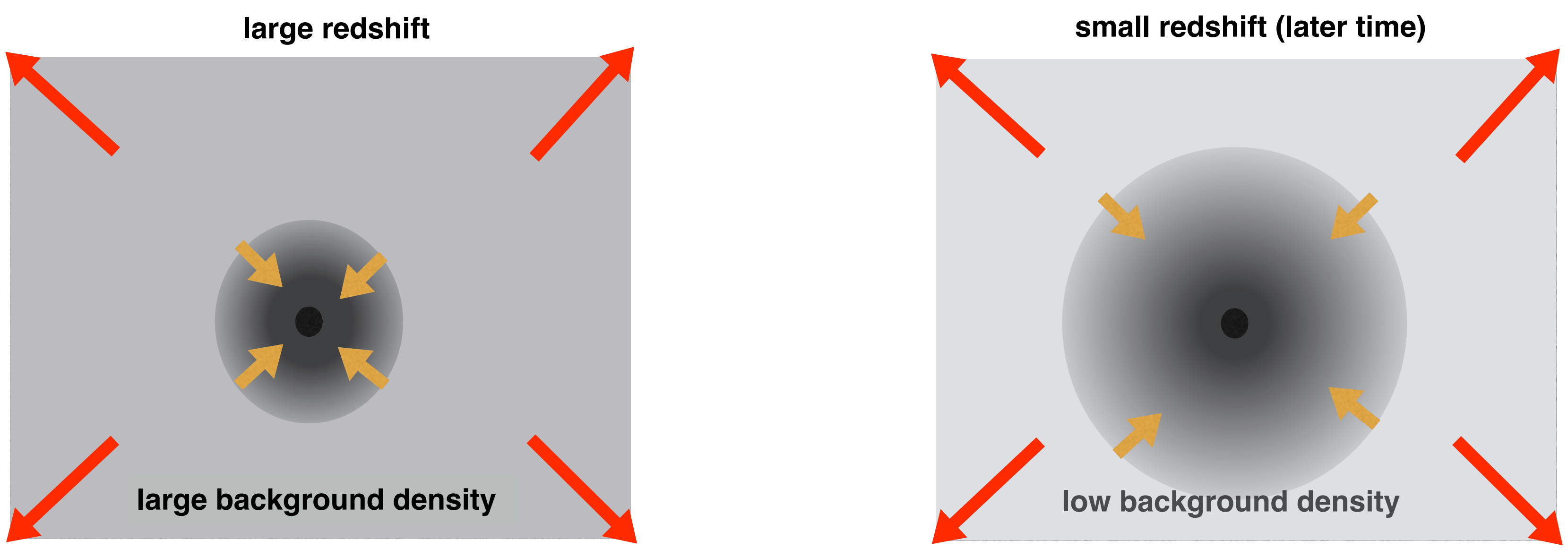
- Result: The **strongest bound** in the high-mass range!



Poulin+ 1707.04206
Serpico+ 2002.10771

The role of Dark Matter mini-halos

- **Sub-dominant population of PBHs** immersed in another form of DM, expanding and diluting
- Accretion of **DM mini-halos**: Balance between **gravitational pull** and **expansion of the universe**



Turn-around radius for a generic DM shell

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{GM_{\mathrm{PBH}}}{r^2} + (\dot{H} + H^2) r \,,$$

$$GM_{\mathrm{PBH}} = (1+3\omega)\frac{H^2}{2} r_{\mathrm{ta}}^3 .$$

A PBH can accrete a DM halo with $M_{Halo} = M_{PBH}$ at the end of the radiation era $(z = z_{eq})$

The role of Dark Matter mini-halos

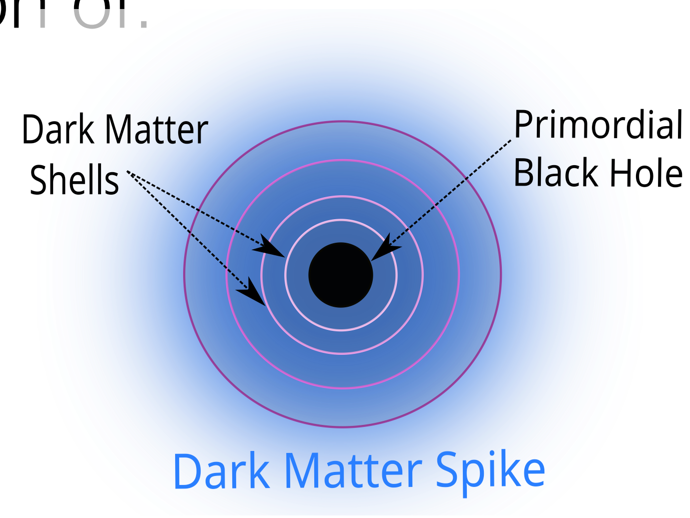
- Simple analytical computation (DM particles are frozen in at turn-around with their density matching the background density):

$$r_{\rm ta} \simeq \left(2\, G\, m_{\rm pbh}\, t_{\rm ta}^2\right)^{1/3}$$

$$\rho_{\rm sp}(r) \simeq \frac{\Omega_{\rm cdm}}{\Omega_{\rm m}} \frac{\rho_{\rm eq}}{2} \left(2\, G\, m_{\rm pbh} t_{\rm eq}^2\right)^{3/4} r^{-9/4}$$

Analytical and numerical computations in [Bertschinger, ApJS 1985; Sten Delos *et al.* 1712.05421; Gosenca *et al.* 1710.02055; Adamek et al. 1901.08528]

- *Recent developments:* Computation of profile as function of:
  - BH mass and DM particle mass,
  - Temperature of kinetic decoupling [Boudaud+ 2106.07480, Carr+ 2011.01930]



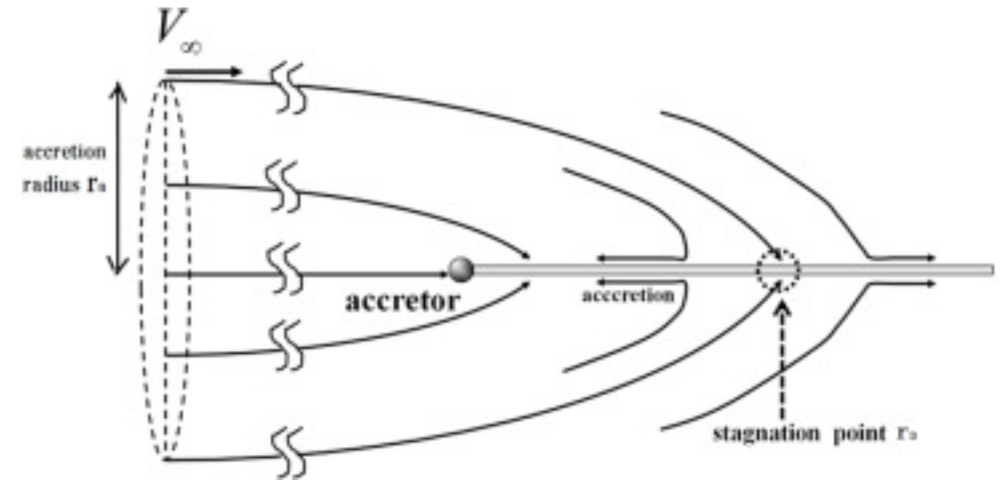
$$\dot{M}_{\rm BHL} = 4\pi\lambda\rho_{\rm b}\frac{G^2M^2}{v_{\rm eff}^3} = 4\pi\lambda\rho_{\rm b}\, v_{\rm eff}\, r_{\rm B}^2$$

$$v_{\rm eff}^{\rm BHL} = \left(c_{\rm s}^2 + v_{\rm rel}^2\right)^{1/2}$$

$$r_{\rm B} = \frac{GM}{v_{\rm eff}^2}$$

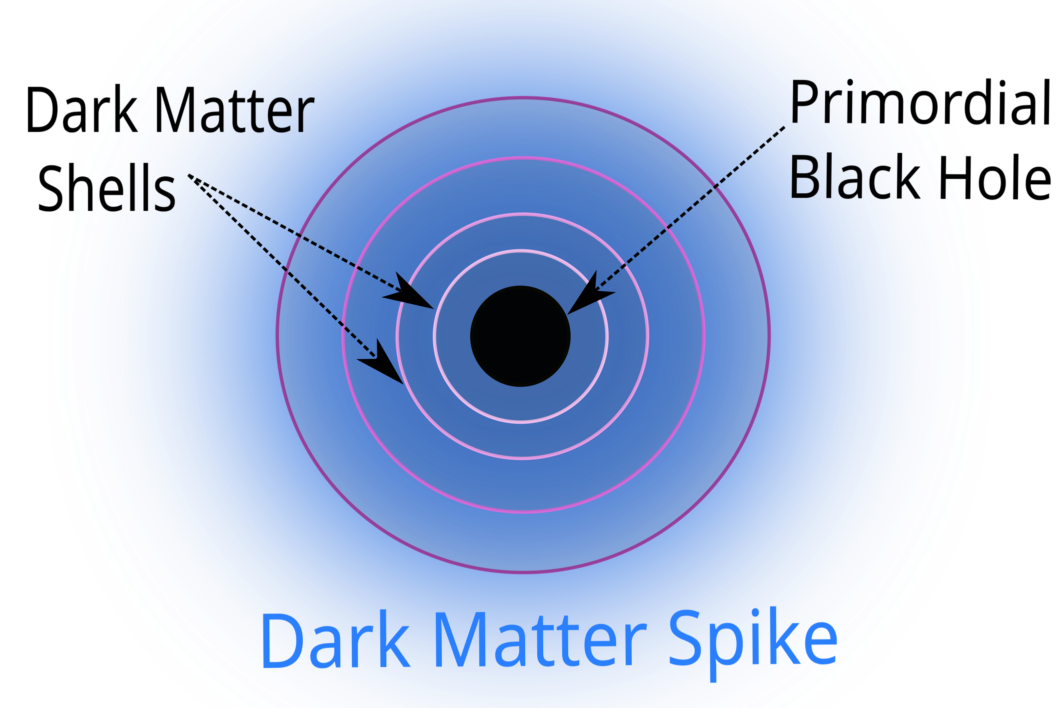
Generalized Bondi Radius

Within this radius, the object *effectively captures* and accretes material from the gas flow: **Sphere of influence**
(gravitational potential energy of the gas > thermal + kinetic energy)



DM mini halos impact the Bondi radius

$$\dot{M}_{\rm BHL} = 4\pi\lambda\rho_{\rm b}\frac{G^2 M^2}{v_{\rm eff}^3} = 4\pi\lambda\rho_{\rm b}\, v_{\rm eff}\, r_{\rm B}^2$$



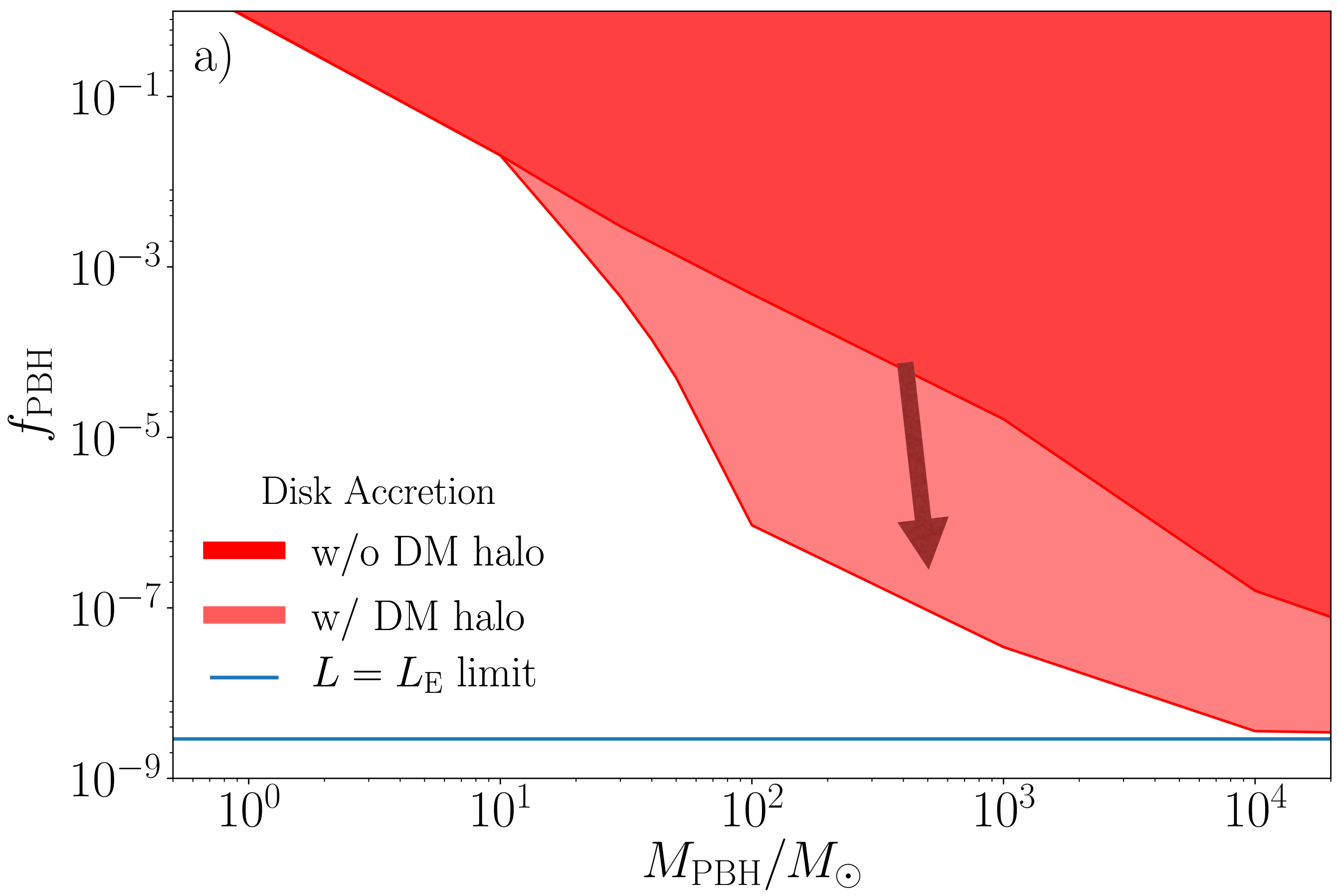
$$\frac{G_N\, M_{\rm PBH}}{r_{\rm B,eff}} - \Phi_h(M_{\rm PBH}, r_{B,\rm eff}, t) = v_{\rm eff}^2(t)$$

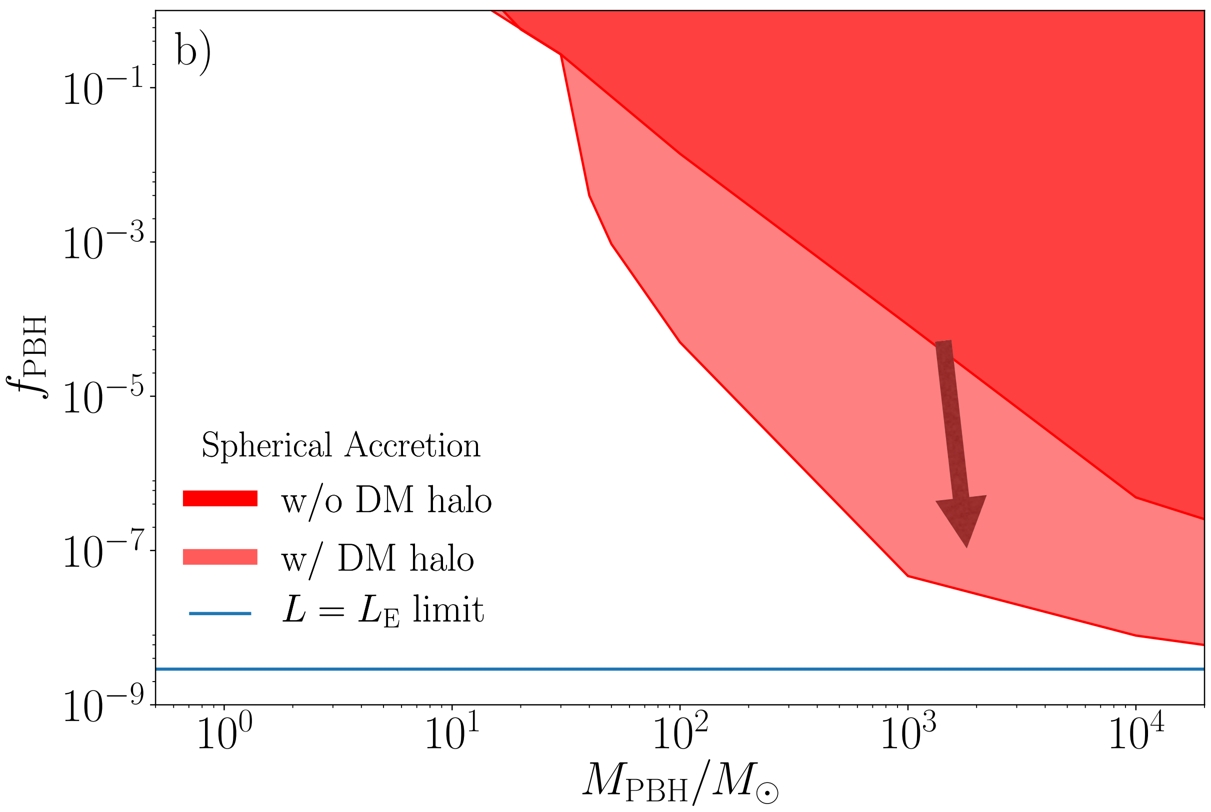
- We define an **Effective Bondi Radius** in presence of the DM mini halo (Potential energy of the gas *with halo* > thermal + kinetic energy)
- Potential due to DM mini-spike —> Effective Bondi radius is *larger* —> **"Accretion boost" —> Stronger bound**

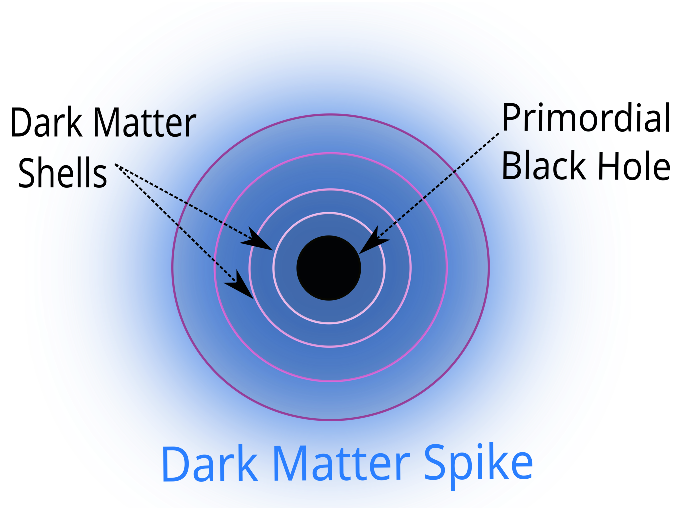
$$r_{\rm B,eff} = \frac{G_N(M_{\rm PBH} + M_h)}{v_{\rm eff}^2} \simeq \frac{G_N\, M_h}{v_{\rm eff}^2} \equiv r_{{\rm B},h} \qquad M_{\rm h} \simeq \frac{3000}{1+z} M$$

P. Serpico *et al.*, 2002.10771

Contribution to the Bound: Challenging the “SMBH” floor



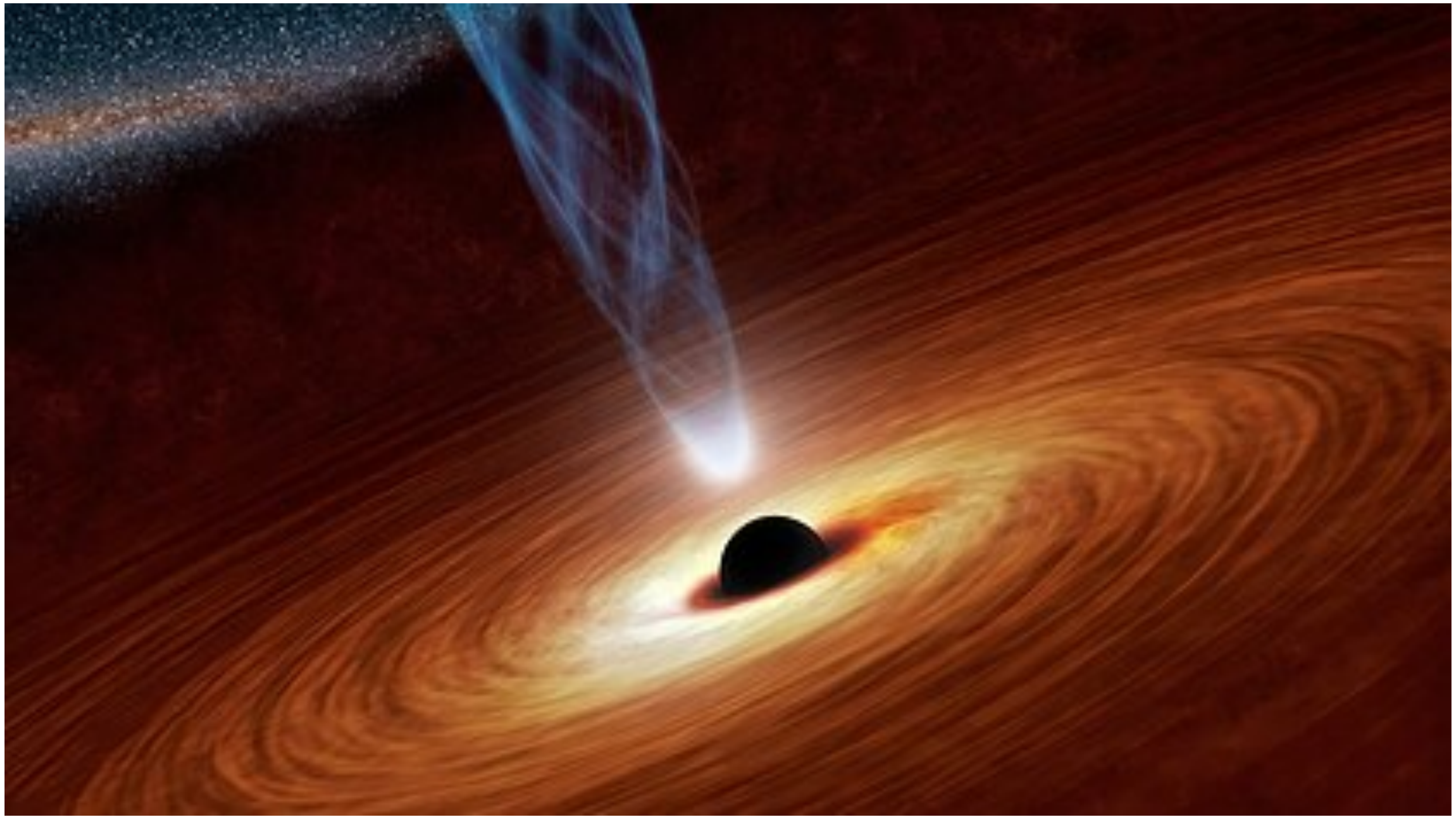




$$r_{\rm B,eff} = \frac{G_N(M_{\rm PBH} + M_h)}{v_{\rm eff}^2} \simeq \frac{G_N\, M_h}{v_{\rm eff}^2} \equiv r_{{\rm B},h}$$

P. Serpico *et al.*, 2002.10771

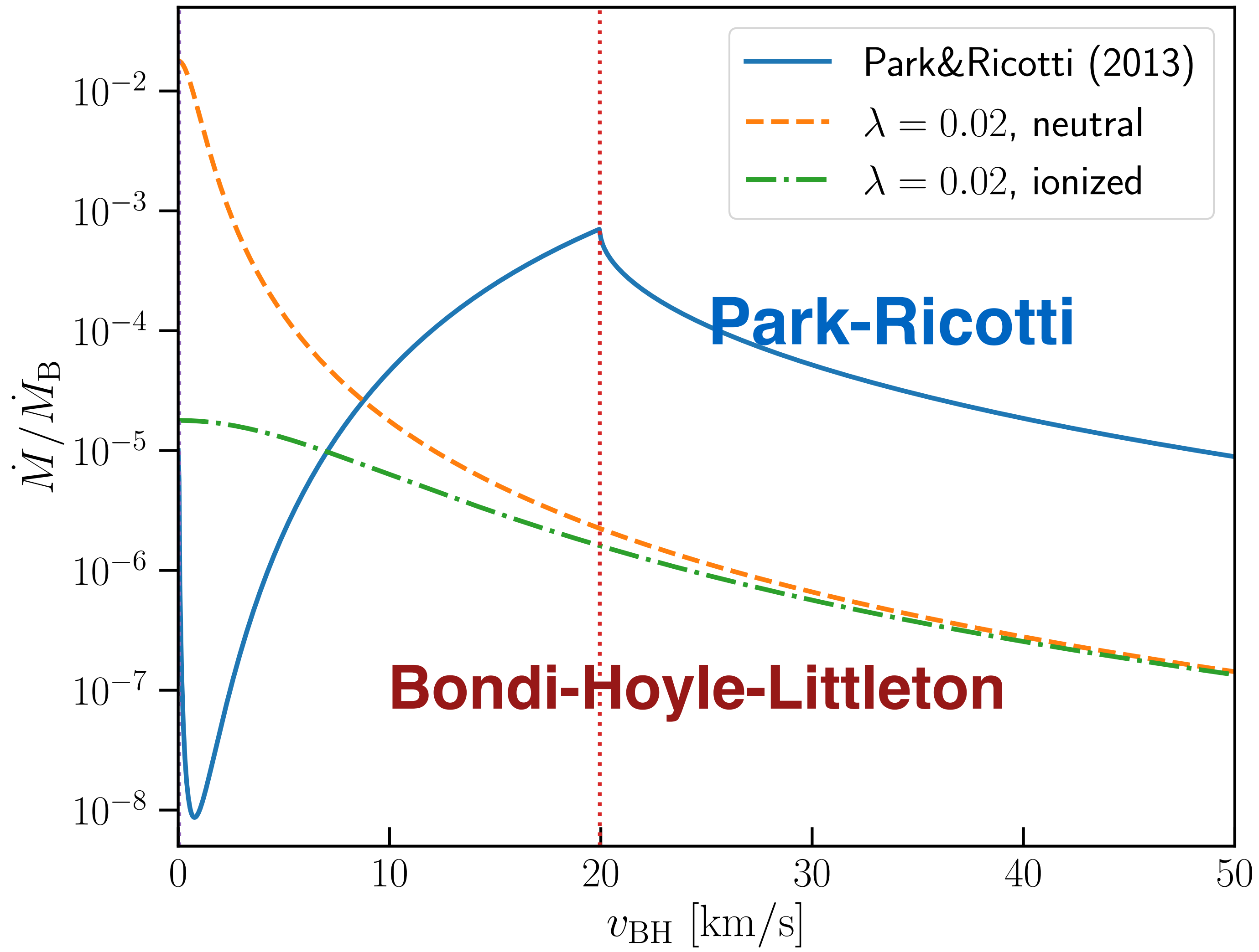
Radiation Feedback comes into play

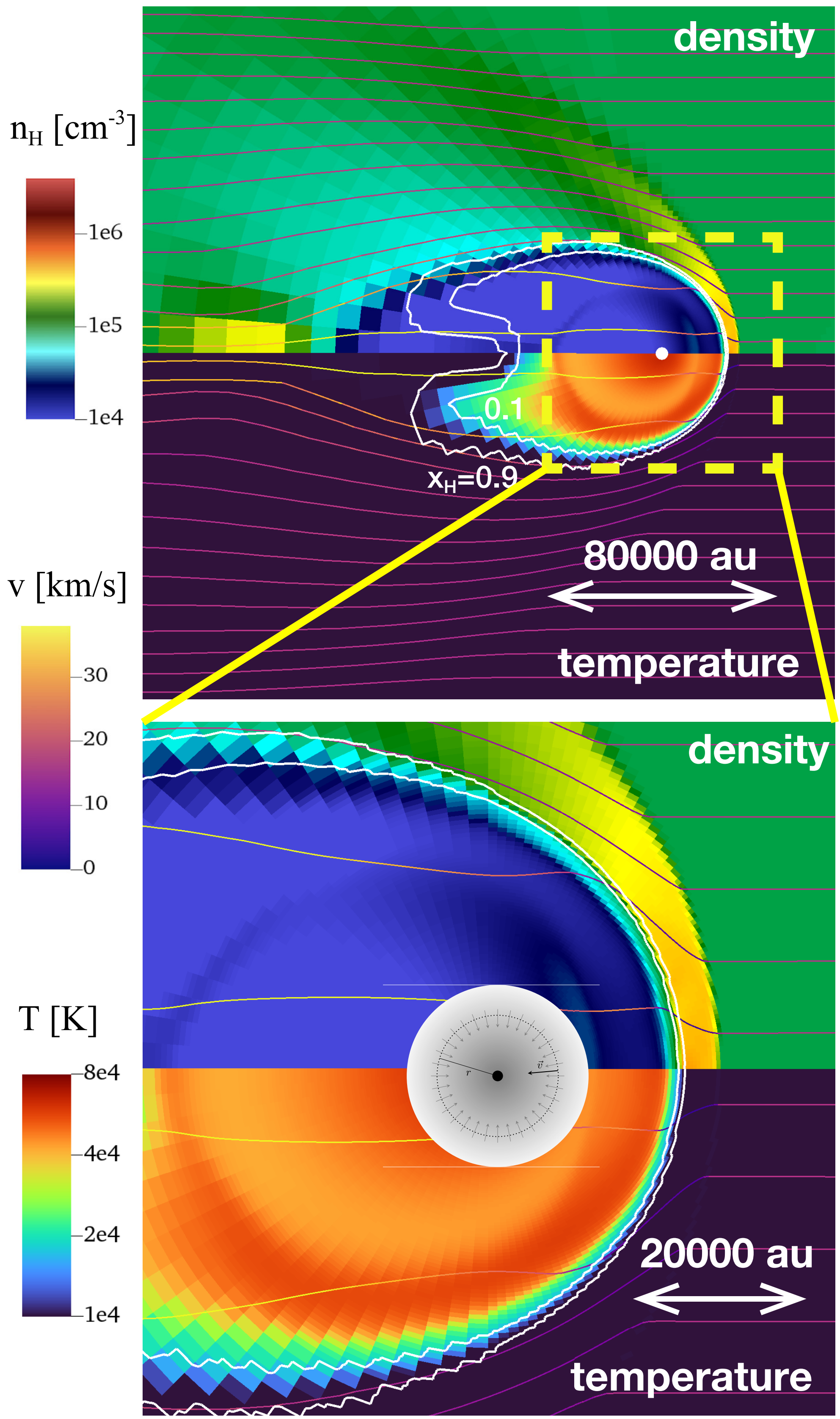


The Park-Ricotti model

- **Park-Ricotti model:** numerical simulations + semi-analytical parametrization in presence of radiative feedback.

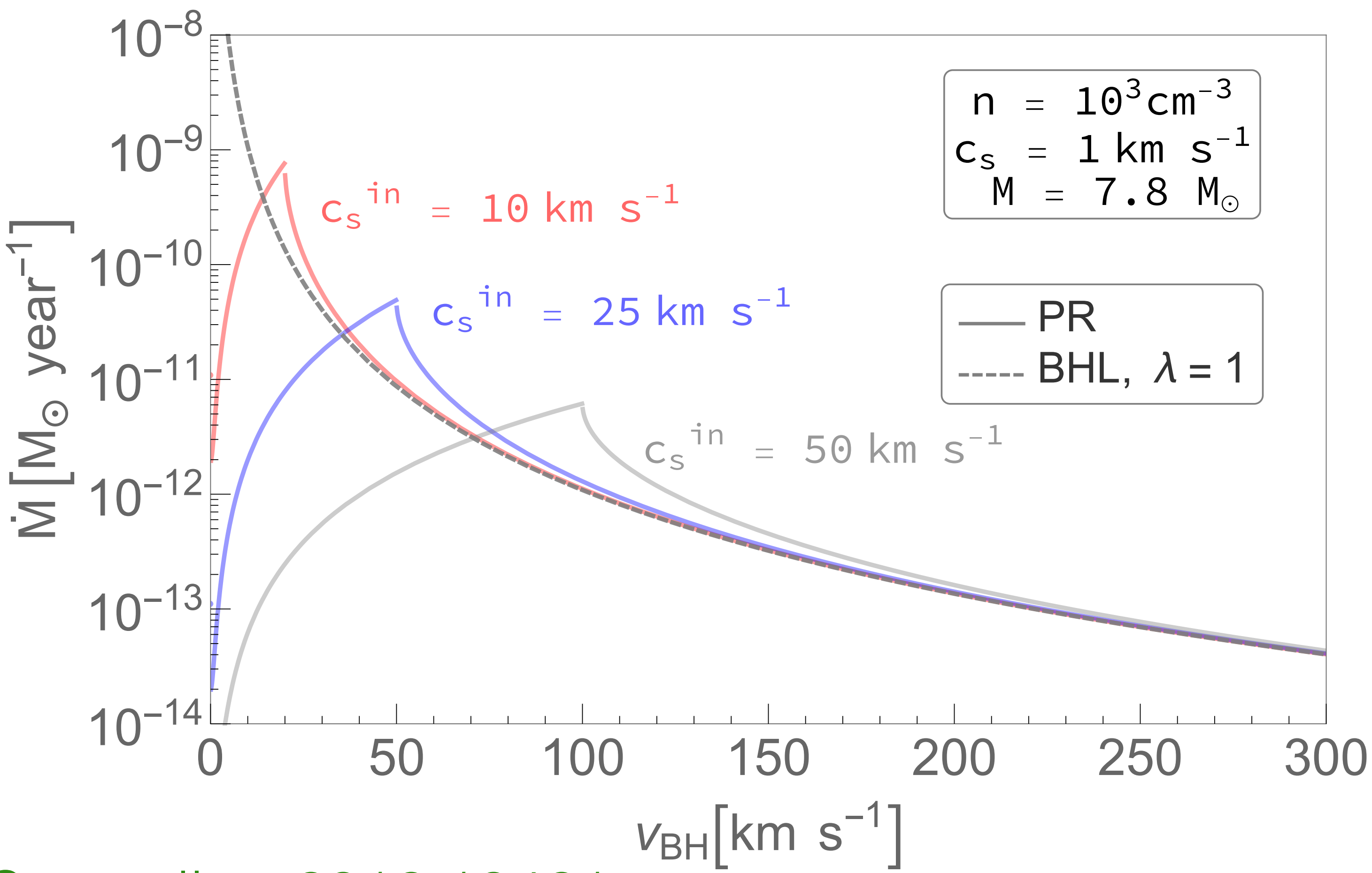
- Suppression of the accretion rate at low velocity, due to the formation of an ionized bubble

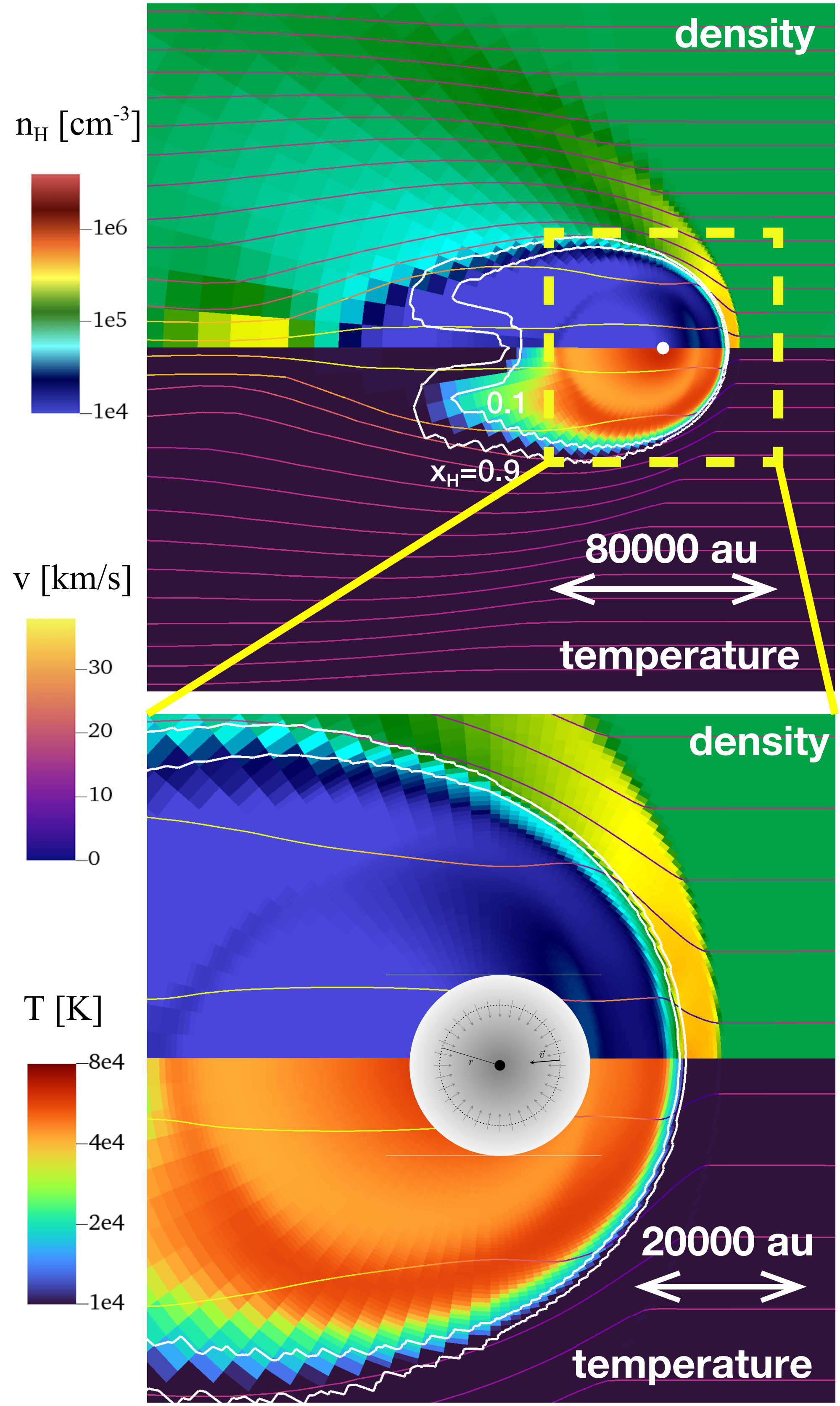




The Park-Ricotti model

- **Park-Ricotti model:** numerical simulations + semi-analytical parametrization in presence of radiative feedback.
- Peaks of accretion rate depends on ionized sound speed

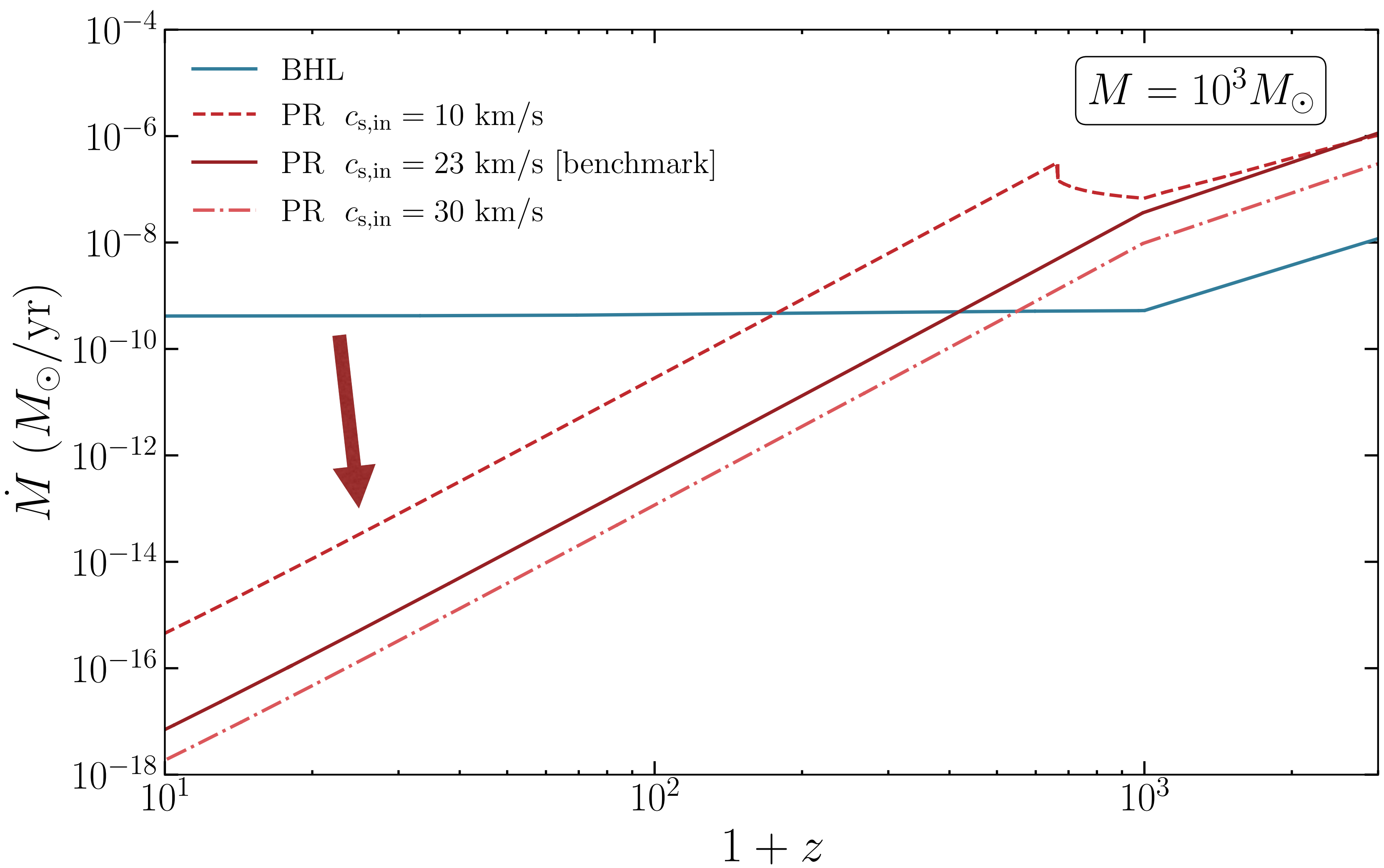


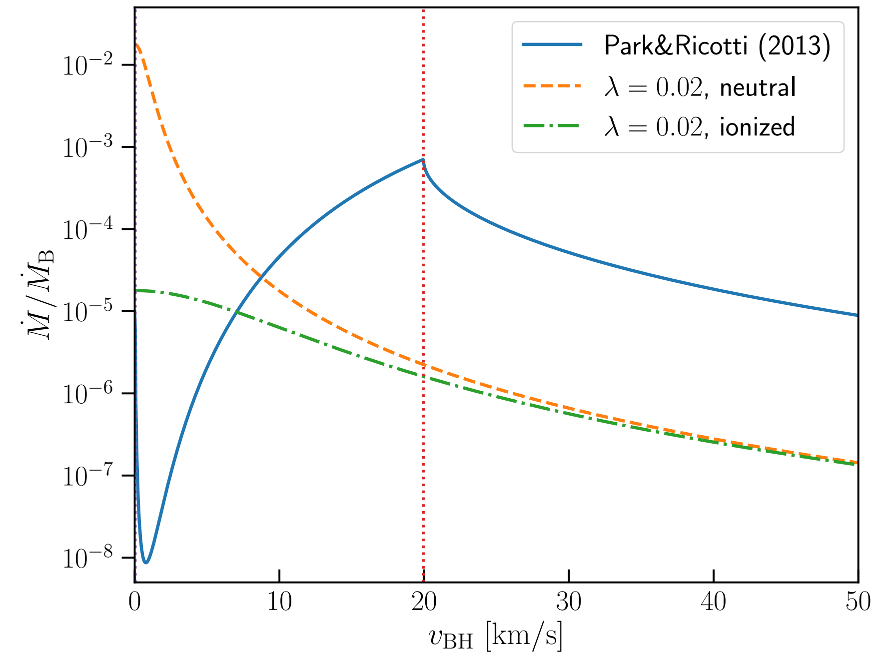


Scarcella+ 2012.10421

Revisiting the Cosmological constraint

- Accretion rate **suppression** around PBHs is very relevant
- Dependence on the ionized sound speed
- **May weaken the bound**



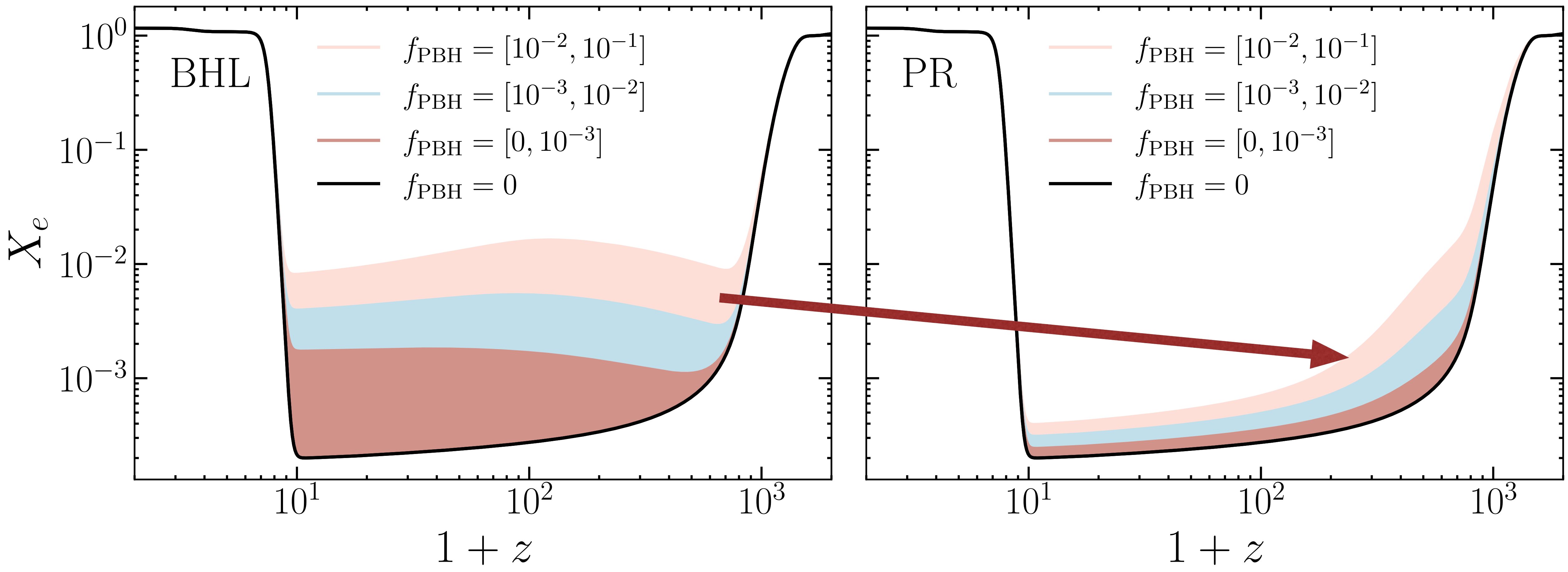


Dominic Agius, Rouven Essig, DG, Francesca Scarcella, Gregory Suczewski, Mauro Valli, *2403.18895*

Feedback vs Ionization History

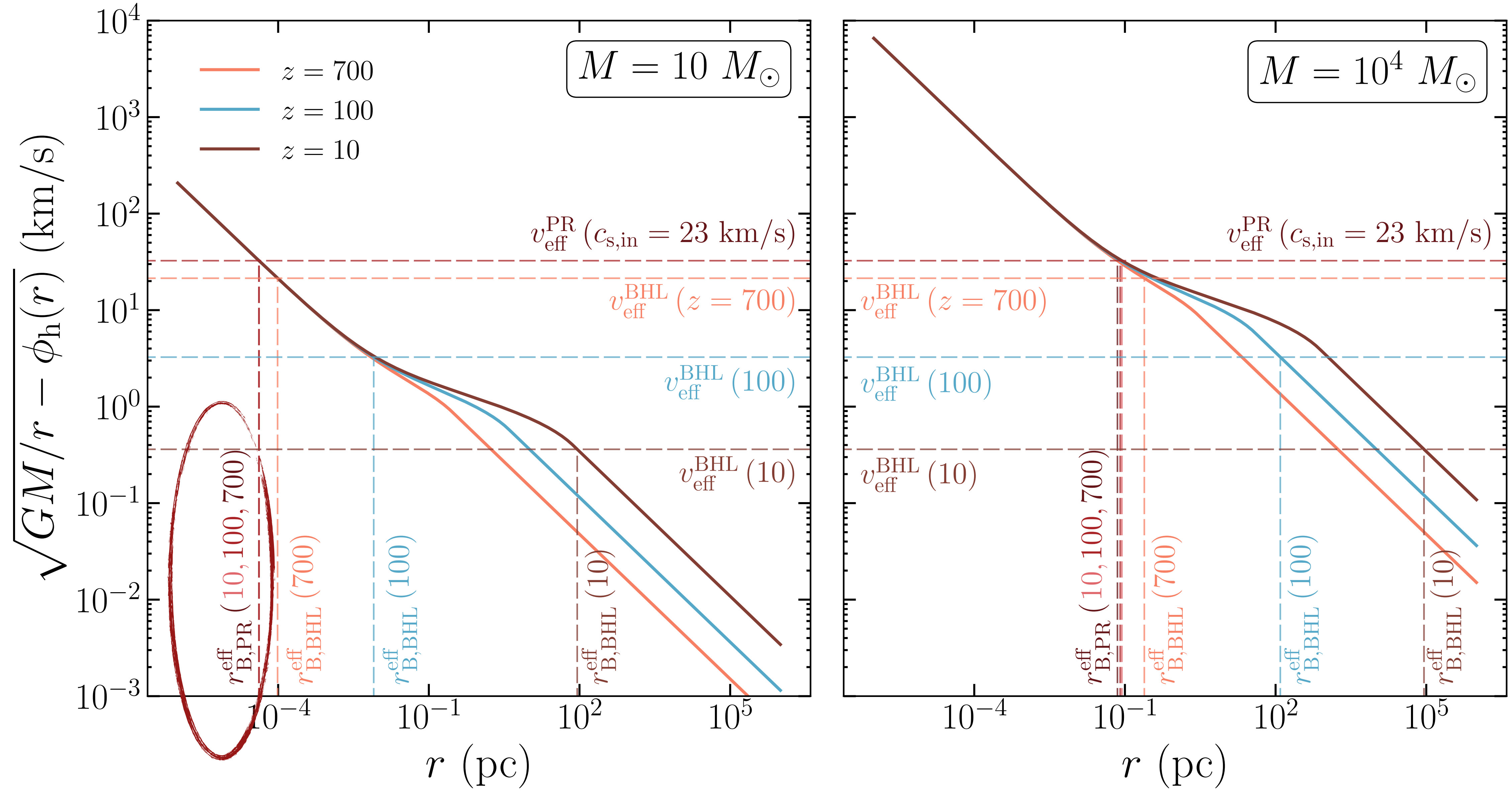
- Accretion rate **suppression** around PBHs is very relevant
- Dependence on the ionized sound speed
- **May weaken the bound**

Dominic Agius, Rouven Essig, DG, Francesca Scarcella, Gregory Suczewski, Mauro Valli, *2403.18895*

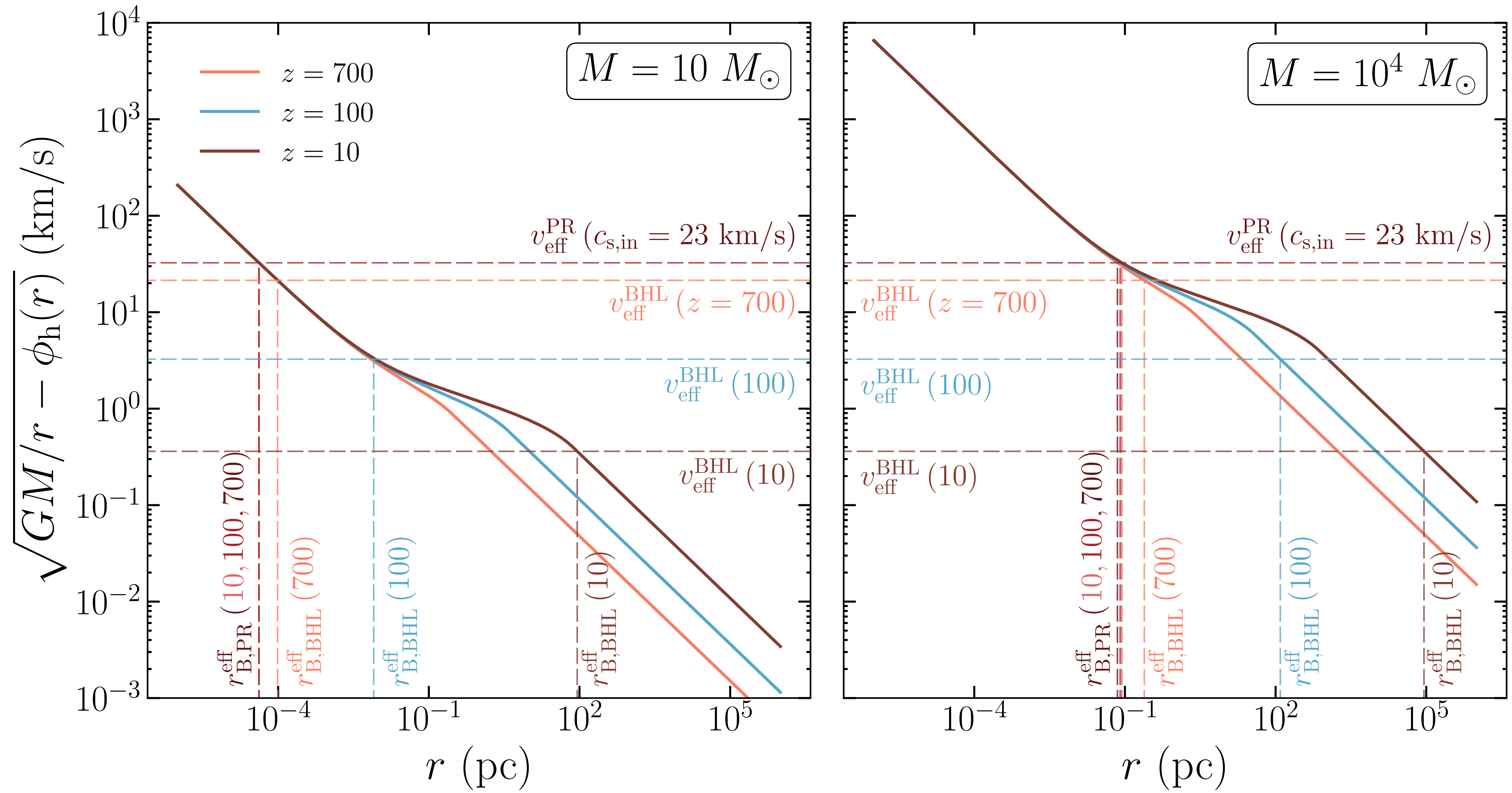


- The Park-Ricotti model can be recast into a **Bondi problem inside the ionized radius**

$$\dot{M} = 4\pi \rho_b \, v_{\rm eff} \, (r_B^{\rm eff})^2 \qquad v_{\rm eff}^{\rm PR} = (c_{\rm s,in}^2 + v_{\rm in}^2)^{1/2} \qquad v_{\rm eff}^2 = \frac{GM}{r} - \phi_h(r)$$



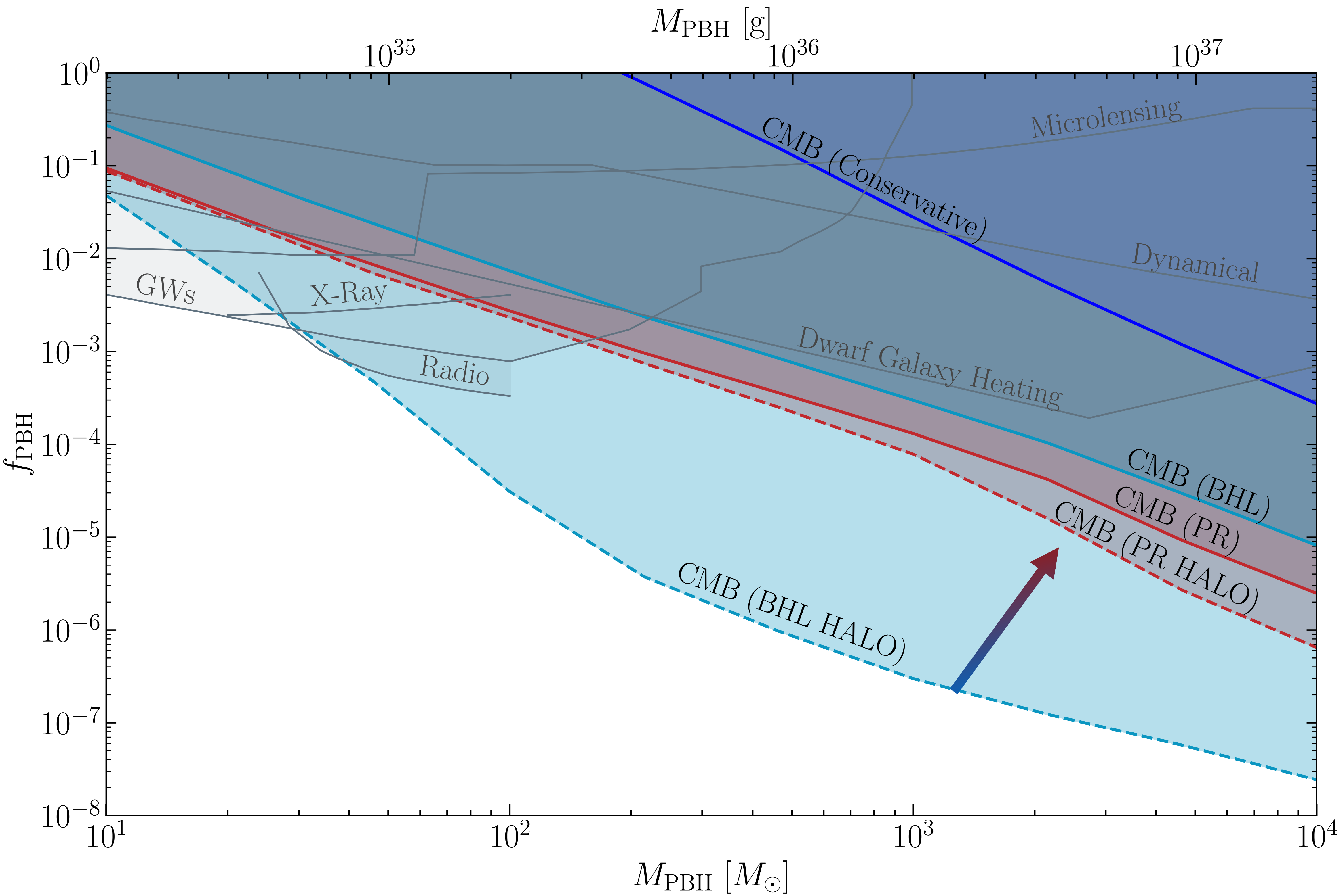
- The Park-Ricotti model can be recast into a **Bondi problem inside the ionized radius**



- The effective velocity of the PR model is larger (larger, constant sound speed within the ionized region)

- The **effective Bondi radius is smaller** —> **Less "accretion boost"**

Main Result: Radiation feedback weakens the bound



Made with `Cobaya+CLASS` (modified to account for energy injection)

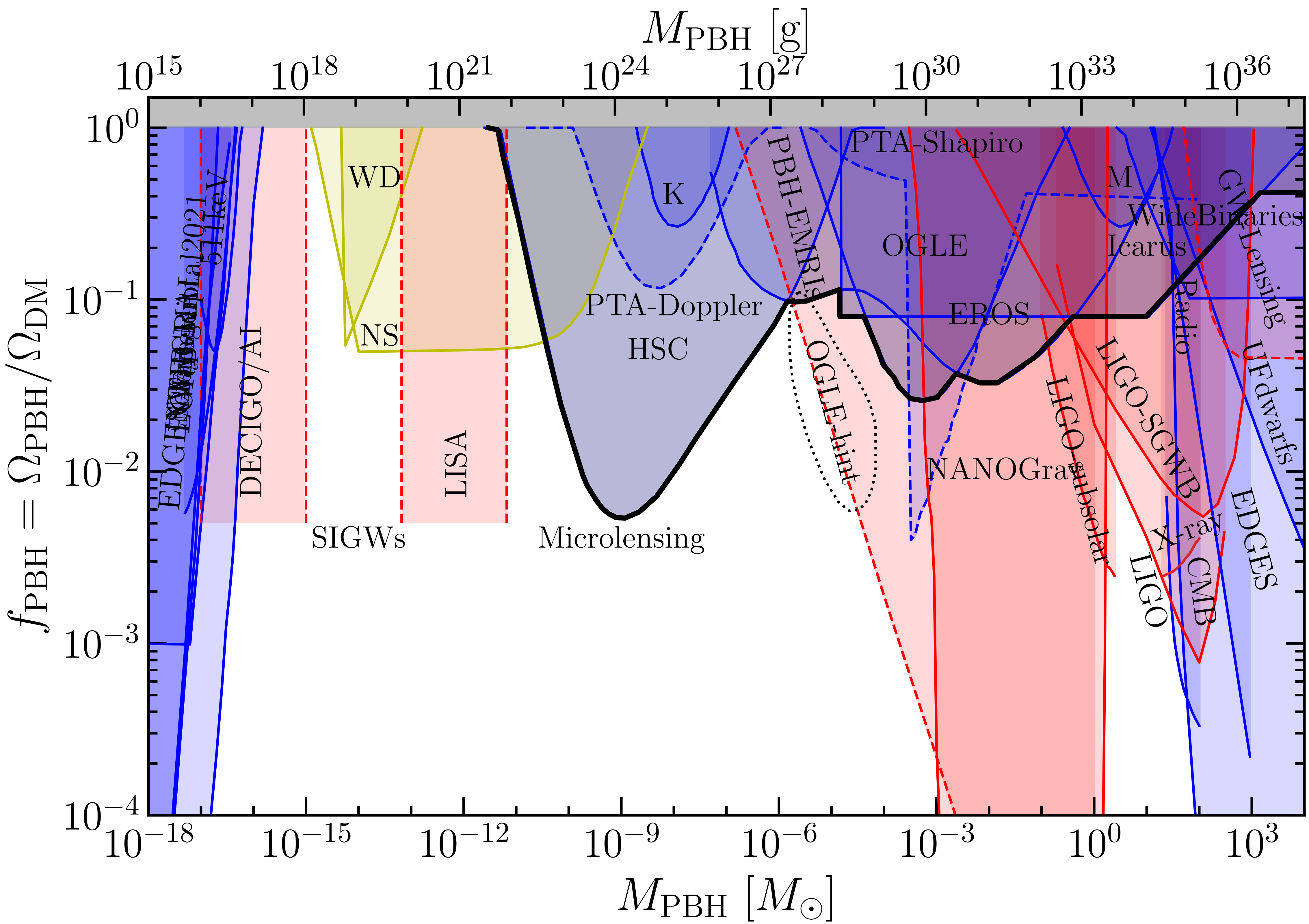
`2018 low-l Planck TT.EE, high-l Planck TT.TE.EE, lensing, ACT, BAO`

Conclusions

- **PBHs can be a portion of the DM.** Cosmological accretion bounds are the strongest in the high-mass domain.
- We presented a comprehensive assessment of the uncertainty on the **CMB bound**.
- **Crucial role of radiation feedback:** Modeling radiation feedback weakens the bound including mini-halos

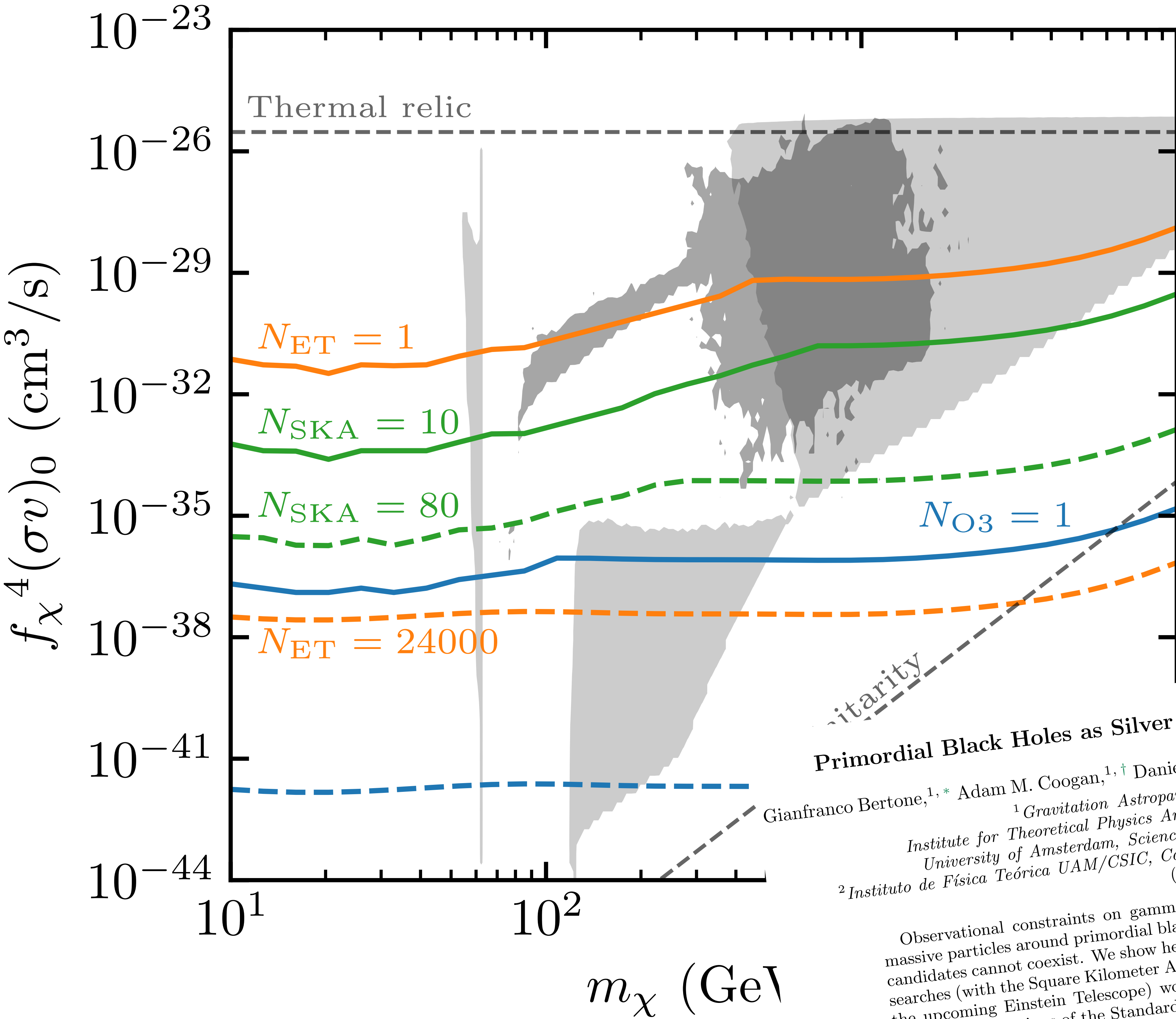
Backup slides

Primordial Black Hole phenomenology

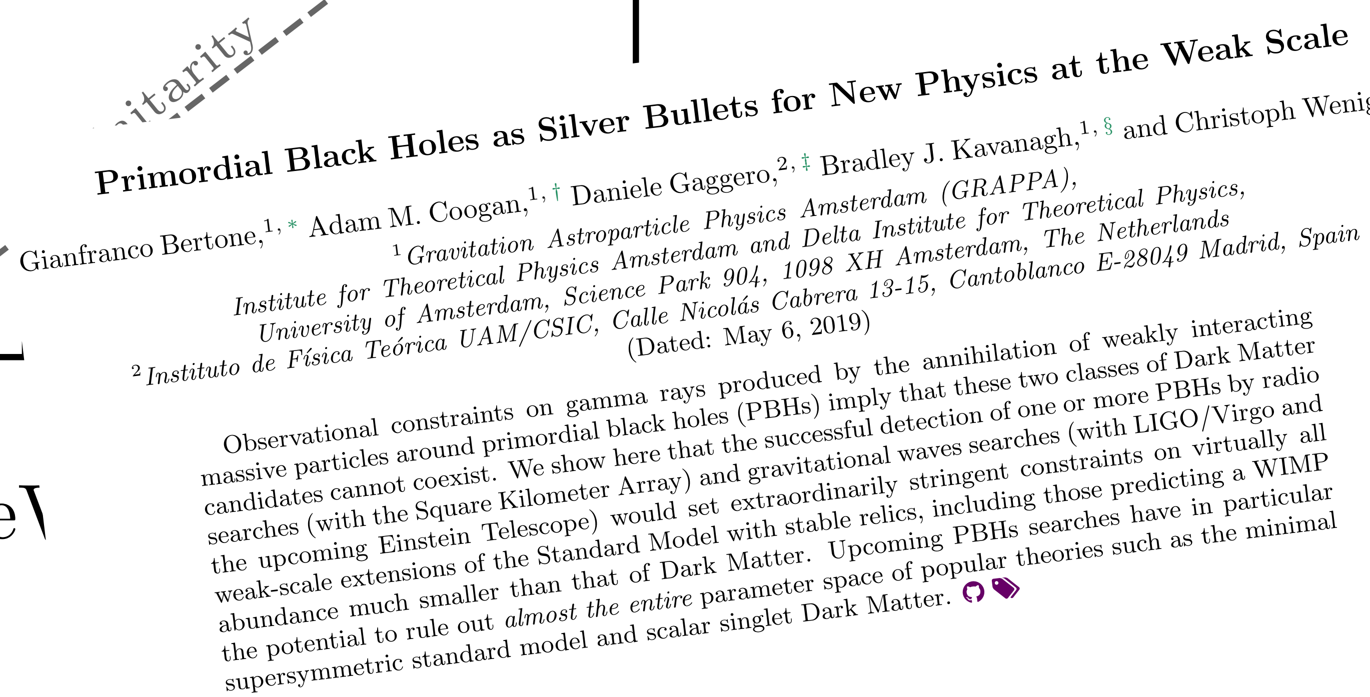


Credit: Bradley Kavanagh, https://github.com/bradkav/PBHbounds

Why a sub-dominant population would matter?



- G. Bertone, A. Coogan, **D. Gaggero**, B.J. Kavanagh, C. Weniger, arXiv:1905.01238



Primordial Black Holes as Silver Bullets for New Physics at the Weak Scale

Gianfranco Bertone,[1,*] Adam M. Coogan,[1,†] Daniele Gaggero,[2,‡] Bradley J. Kavanagh,[1,§] and Christoph Weniger[1,¶]

[1] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

[2] *Instituto de Física Teórica UAM/CSIC, Calle Nicolás Cabrera 13-15, Cantoblanco E-28049 Madrid, Spain*

(Dated: May 6, 2019)

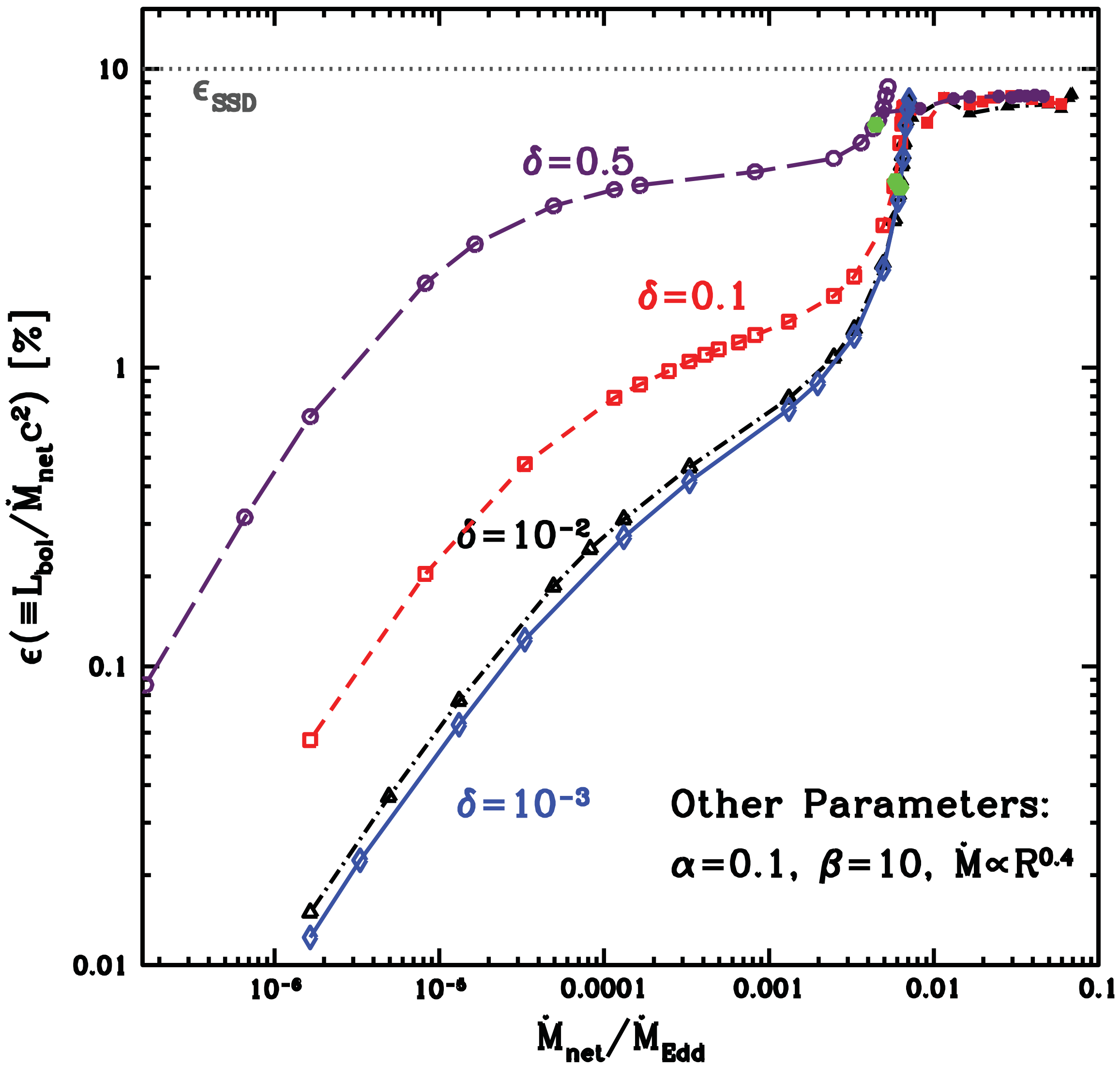
Observational constraints on gamma rays produced by the annihilation of weakly interacting massive particles around primordial black holes (PBHs) imply that these two classes of Dark Matter candidates cannot coexist. We show here that the successful detection of one or more PBHs by radio searches (with the Square Kilometer Array) and gravitational waves searches (with LIGO/Virgo and the upcoming Einstein Telescope) would set extraordinarily stringent constraints on virtually all weak-scale extensions of the Standard Model with stable relics, including those predicting a WIMP abundance much smaller than that of Dark Matter. Upcoming PBHs searches have in particular the potential to rule out *almost the entire* parameter space of popular theories such as the minimal supersymmetric standard model and scalar singlet Dark Matter.

Uncertainty: radiation efficiency

$$\left.\frac{\mathrm{d}^2 E}{\mathrm{d}V\ \mathrm{d}t}\right|_{\mathrm{inj}} = L n_{\mathrm{PBH}} = L f_{\mathrm{PBH}} \frac{\rho_{\mathrm{DM}}}{M}$$

$$L = \epsilon \dot{M} c^2 \qquad \epsilon(\dot{M}) = \epsilon_0 \left(\frac{\dot{M}}{0.01 \dot{M}_{\mathrm{edd}}} \right)^a$$

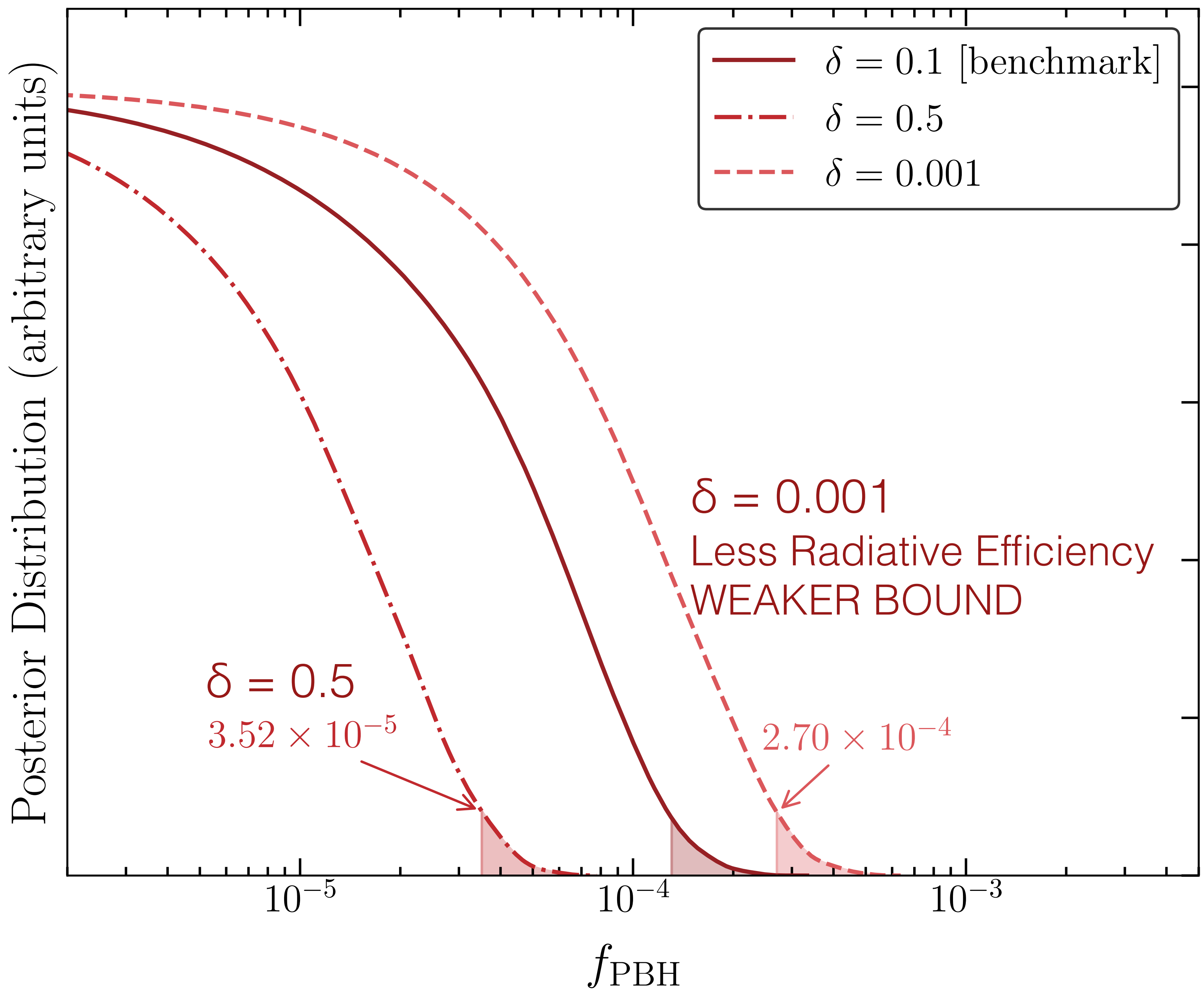
- Accretion disks form
- Radiative efficiency scales with accretion rate
- Low accretion rate: ADAF (thick) disks
- in ADAF disks, the functional form depends on δ: *fraction of rest-mass energy that is transferred to electrons and is radiated away*.

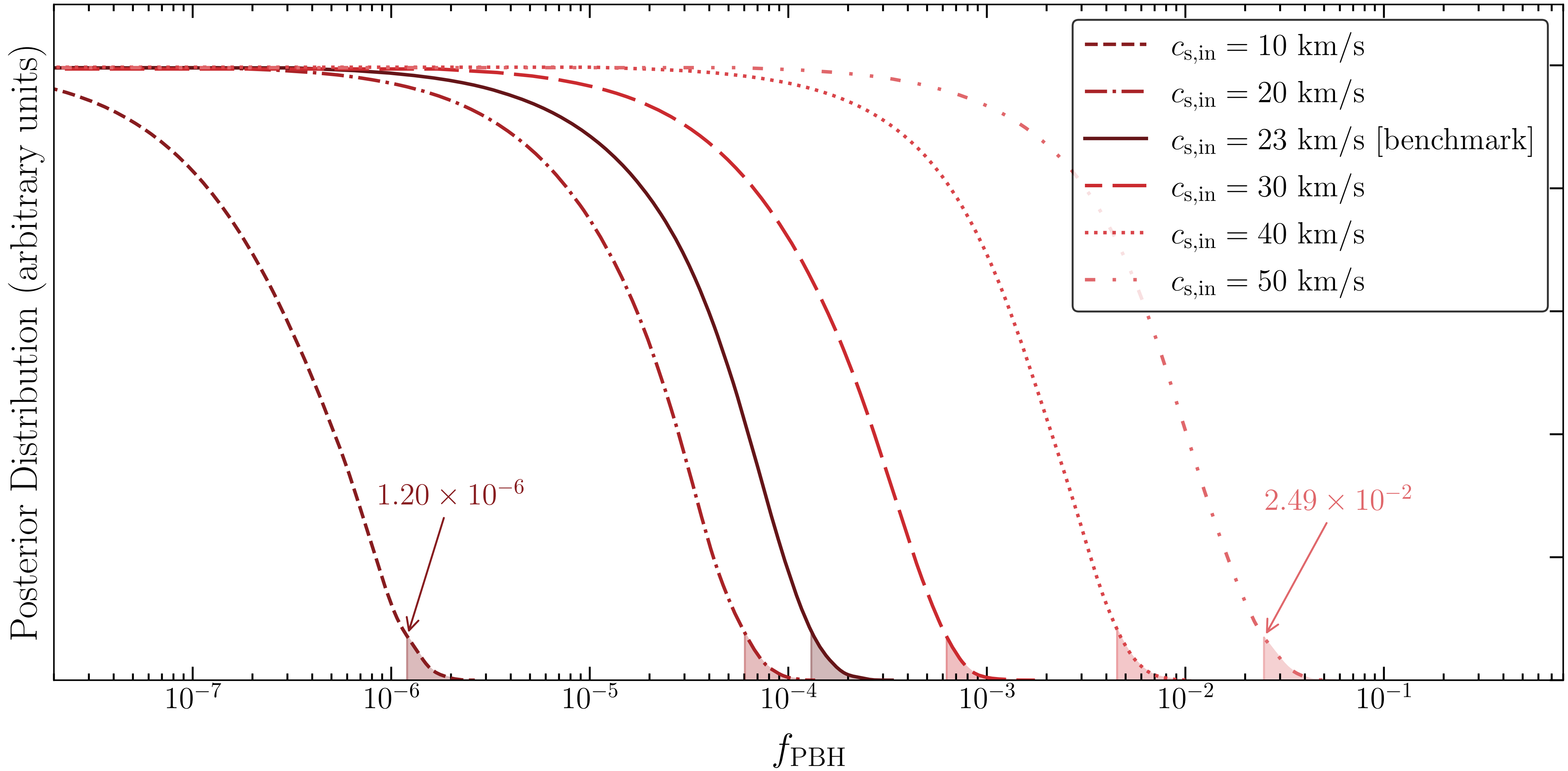


Xie, Yuan 1207.3113

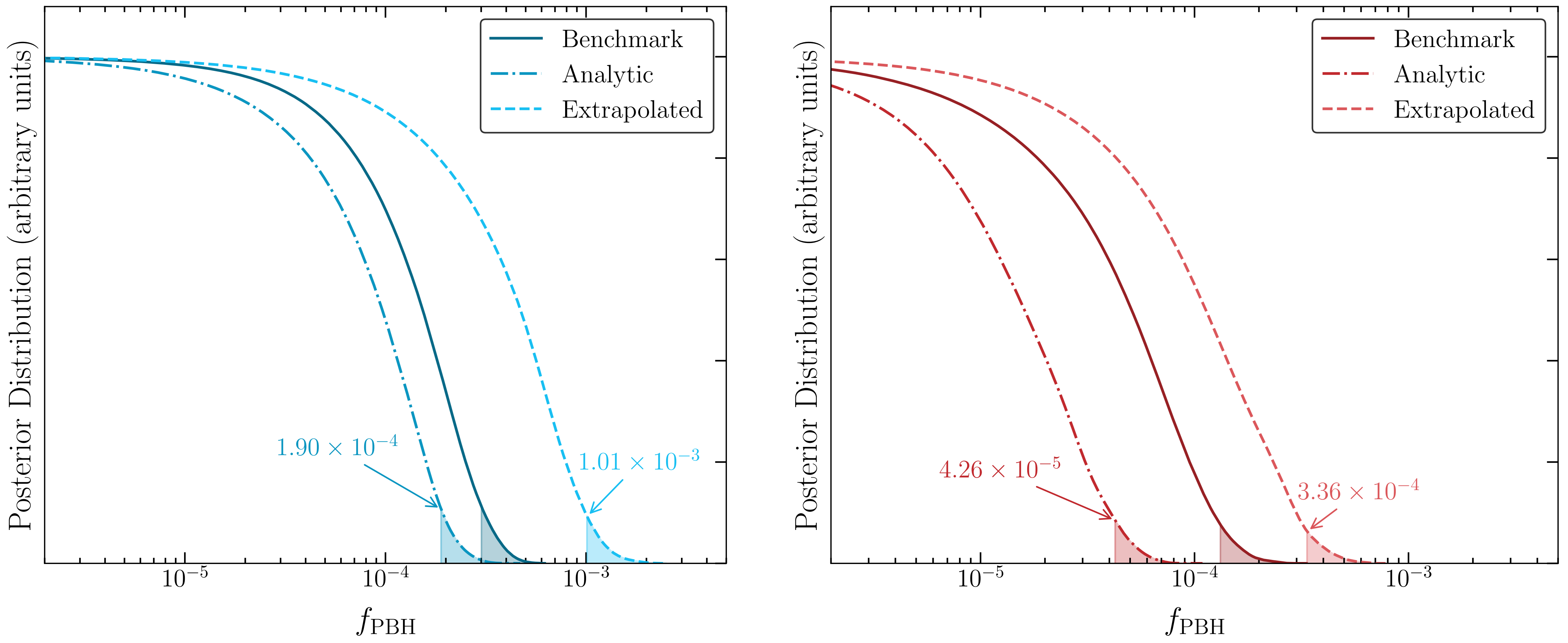
Uncertainty: radiation efficiency

$$L = \epsilon \dot{M} c^2 \qquad \epsilon(\dot{M}) = \epsilon_0 \left(\frac{\dot{M}}{0.01 \dot{M}_{\rm edd}} \right)^a$$

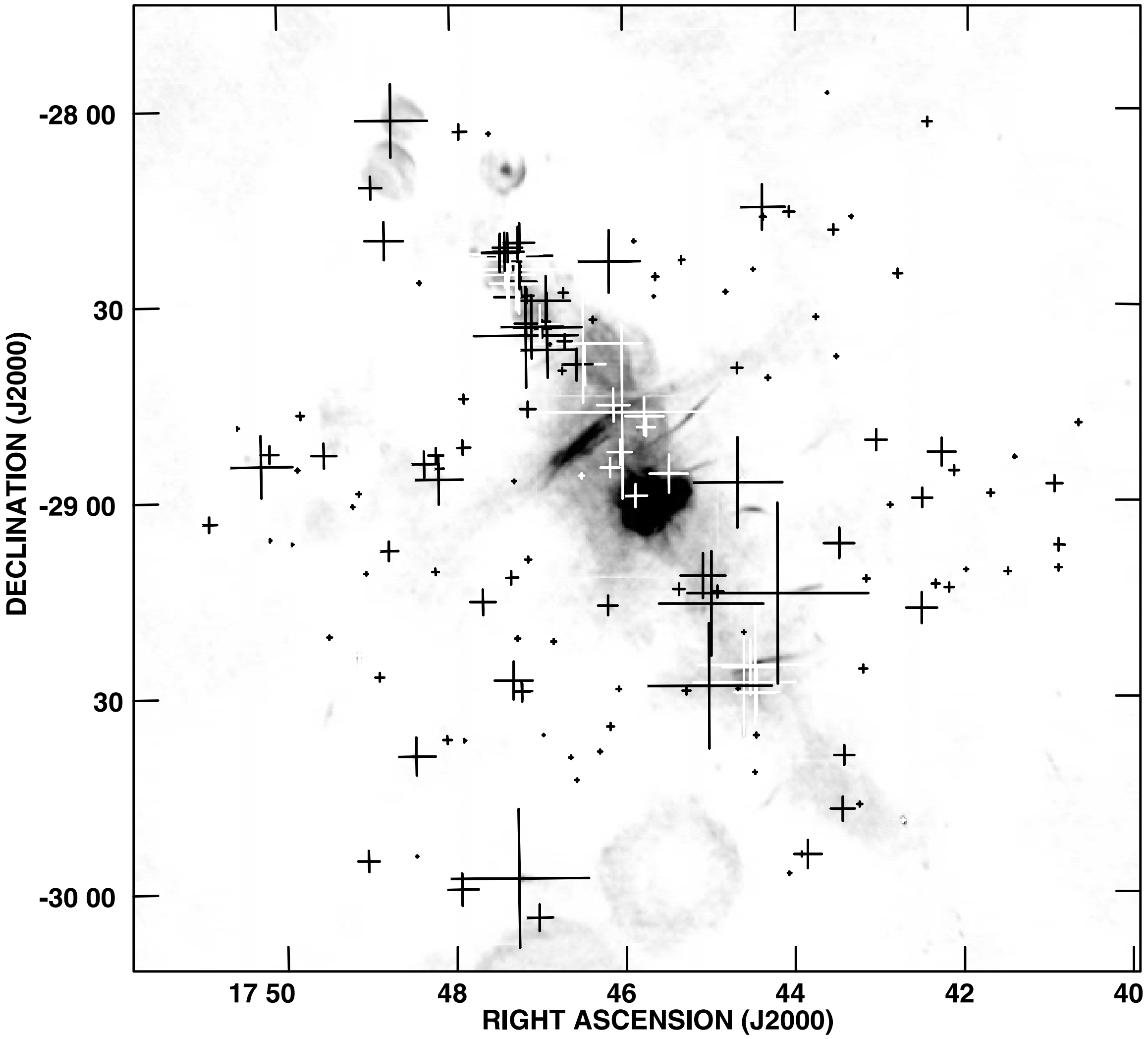




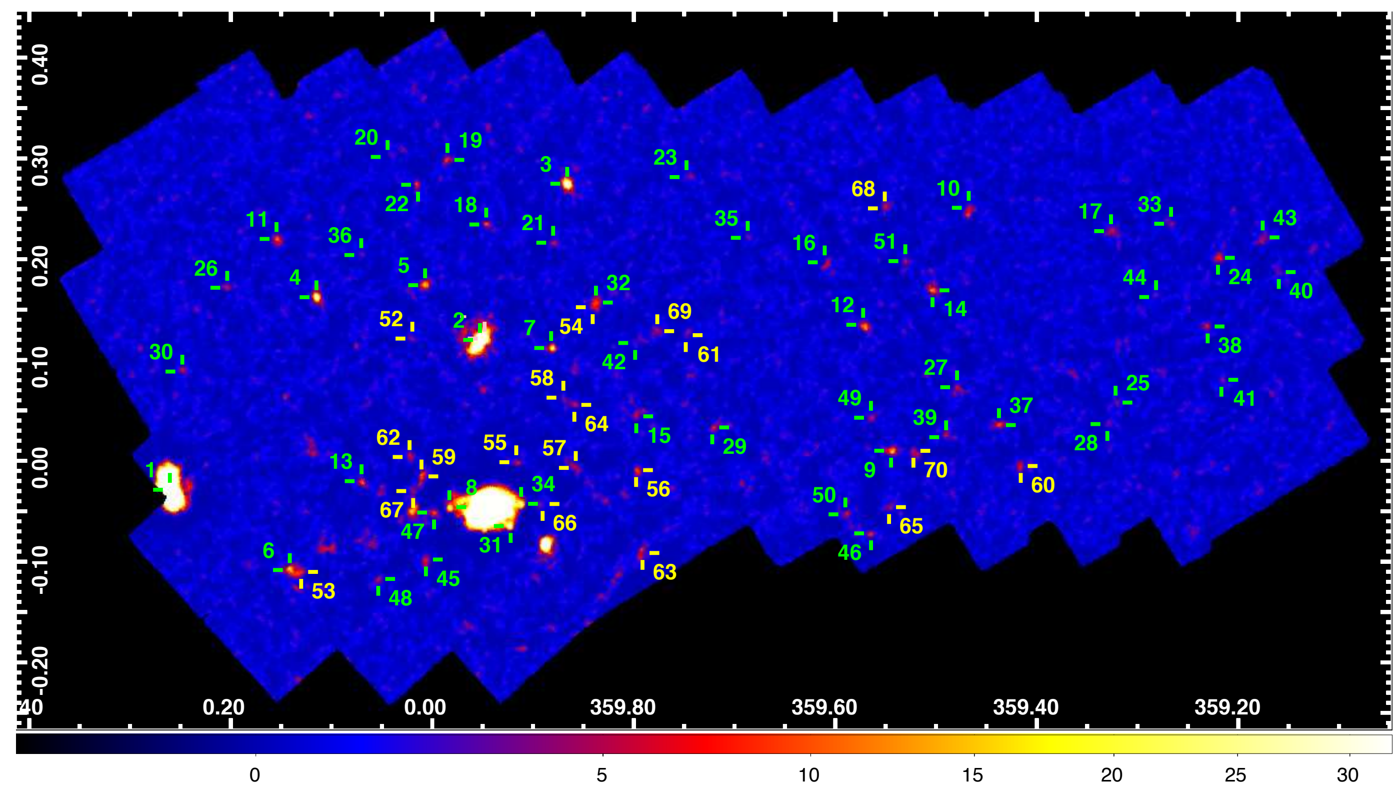
$c_{\mathrm{s,in}} = 10$ km/s
$c_{\mathrm{s,in}} = 20$ km/s
$c_{\mathrm{s,in}} = 23$ km/s [benchmark]
$c_{\mathrm{s,in}} = 30$ km/s
$c_{\mathrm{s,in}} = 40$ km/s
$c_{\mathrm{s,in}} = 50$ km/s
1.20×10^{-6}
2.49×10^{-2}
Posterior Distribution (arbitrary units)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
f_{PBH}


Benchmark
Analytic
Extrapolated
Posterior Distribution (arbitrary units)
1.90×10^{-4}
1.01×10^{-3}
10^{-5}
10^{-4}
10^{-3}
$f_{\rm PBH}$
Benchmark
Analytic
Extrapolated
Posterior Distribution (arbitrary units)
4.26×10^{-5}
3.36×10^{-4}
10^{-5}
10^{-4}
10^{-3}
$f_{\rm PBH}$

Good data from GC region



1.4 GHz, VLA, *Lazio & Cordes 2008*



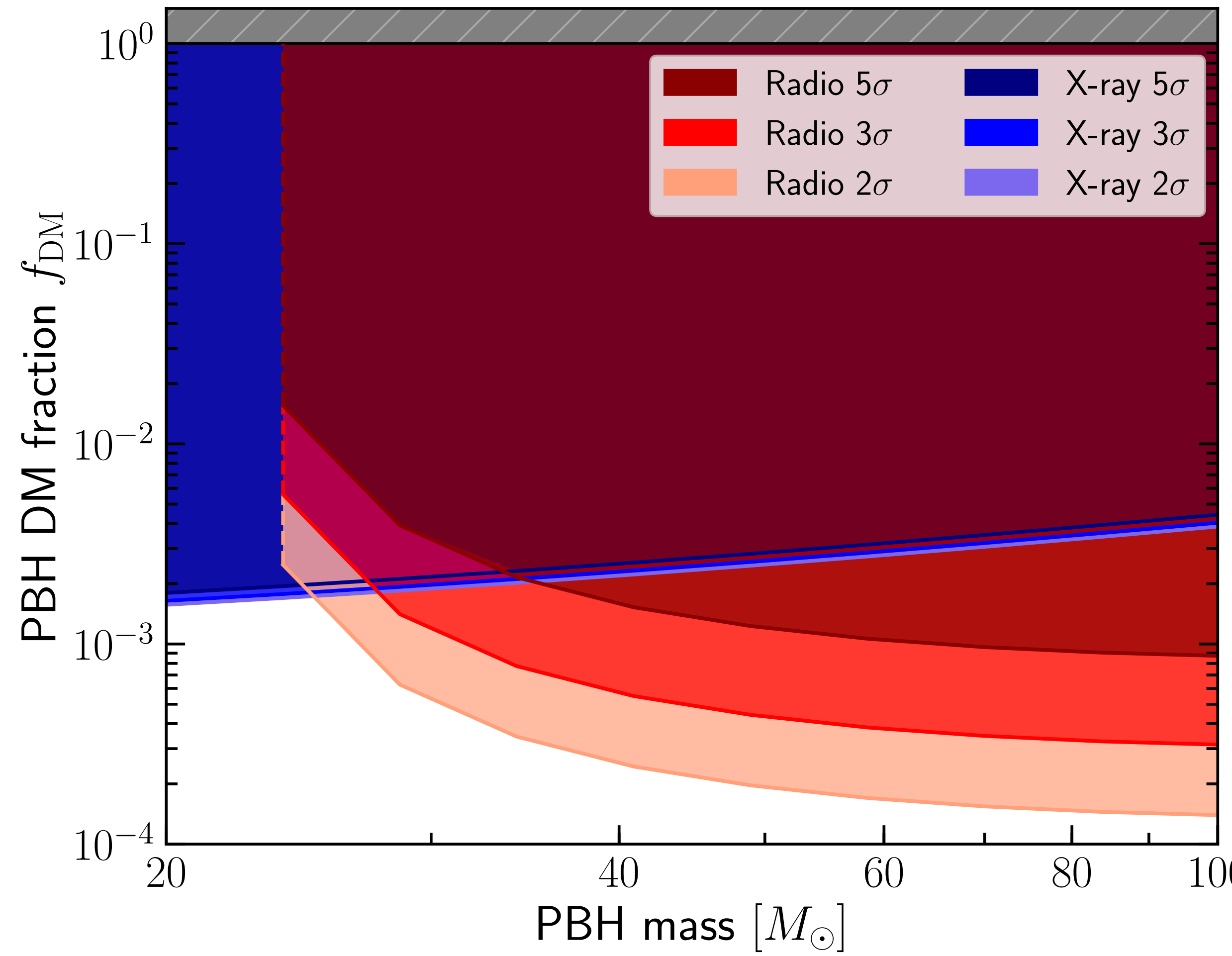
10-40 keV, NuStar catalog, *Hong et al. 2016*

Accretion Bounds in Astronomical Context

- **Monte-Carlo simulations** of the emission from BHs in the inner Galaxy

- **Simulated maps of the expected radio and X-ray sources** near the GC region associated to the PBH population

- **Conservative upper limits on the DM fraction** in PBHs

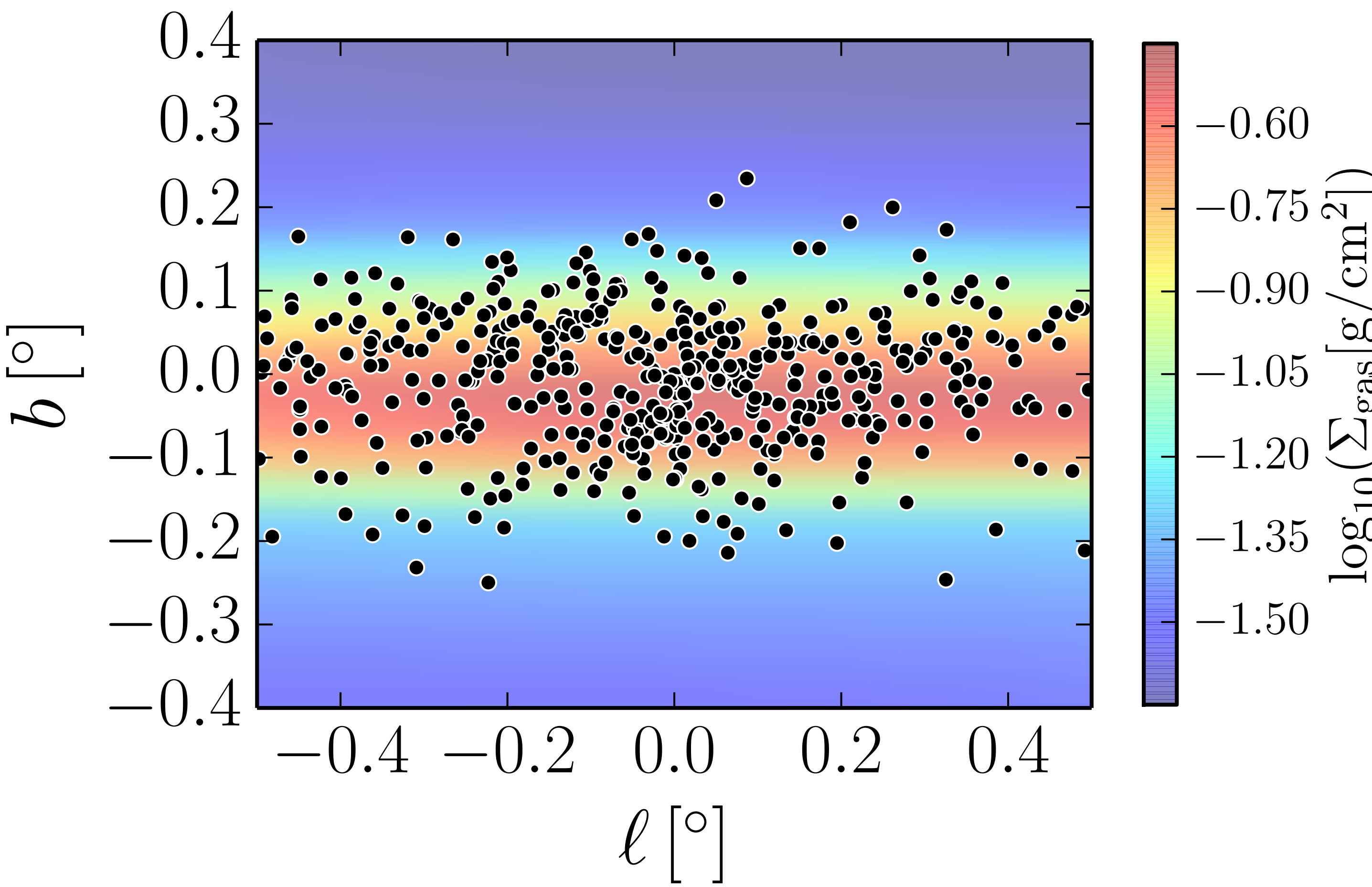


DG, Bertone, Calore, Connors, Lovell, Markoff, Storm, 1612.00457

Manshanden, **DG**, Connors, Bertone, Ricotti, 1812.07967

Accretion Bounds in Astronomical Context

A science case for SKA!



Weltman et al., *"Fundamental Physics with the Square Kilometre Array"* `1810.02680`

DG, Bertone, Calore, Connors, Lovell, Markoff, Storm, `1612.00457`

Manshanden**, DG**, Connors, Bertone, Ricotti, `1812.07967`