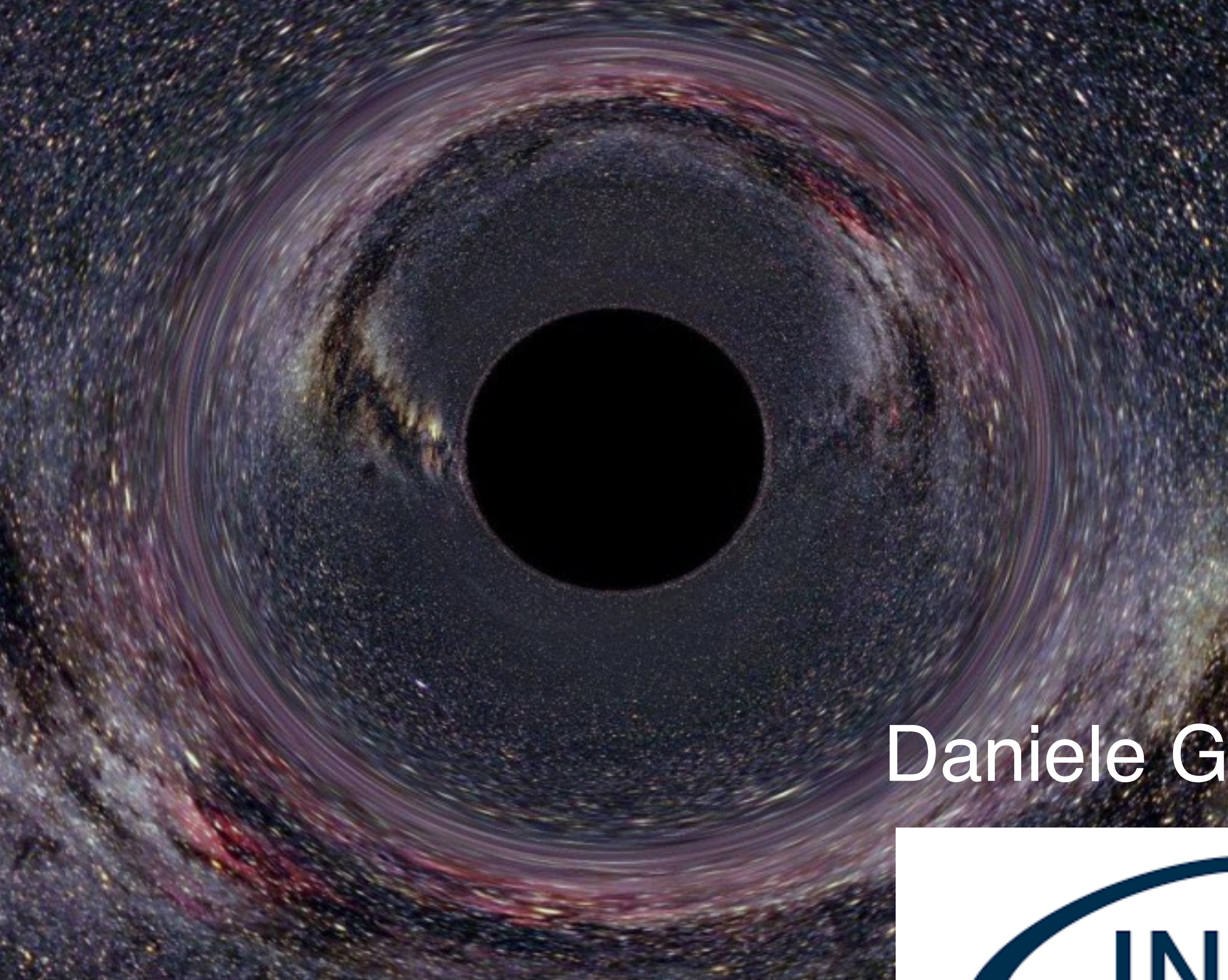
Black Holes and Dark Matter



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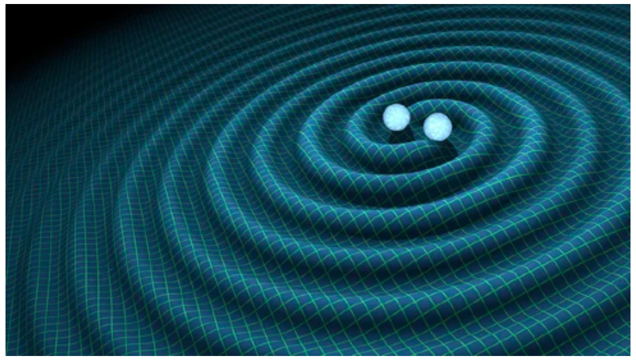
Part I - Black Holes and Dark Matter

Black Holes phenomenology:

- Study of Black Hole *inspirals*
- Accretion physics



Dark Matter searches

- *Can Black holes of primordial origin be a part of the Dark Matter?*
- *Can we learn something on the nature of the Dark Matter by studying Black Hole physics?*

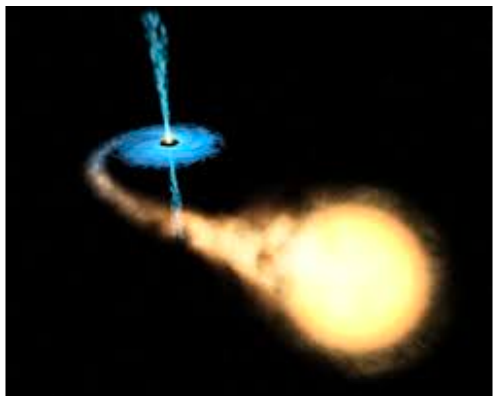
Multi-messenger astronomy

- Gravitational Waves
- Radio waves/ X-rays/ Gamma rays/ Neutrinos

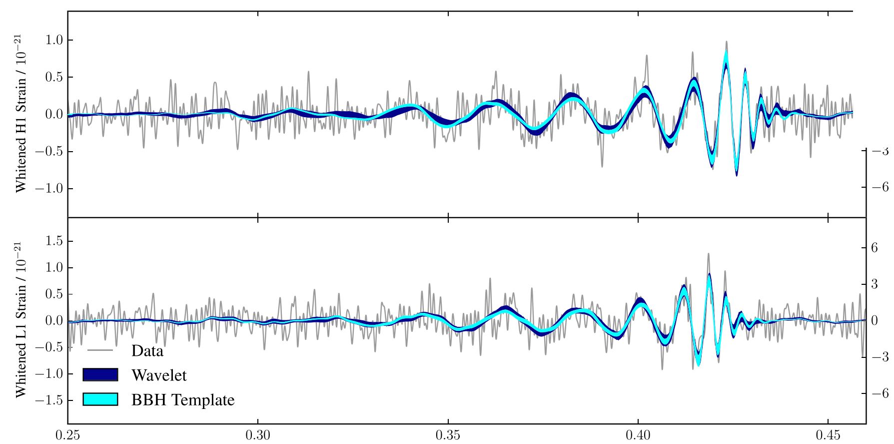
Black Holes in the Universe

Stellar-mass black holes

X-ray binaries



GW mergers

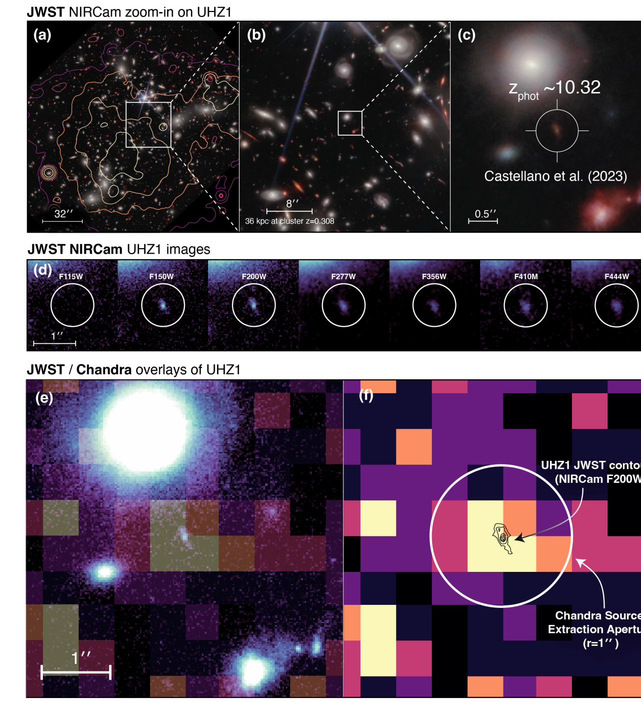


Supermassive black holes

Observed up to

z ~ 10

Seed problem

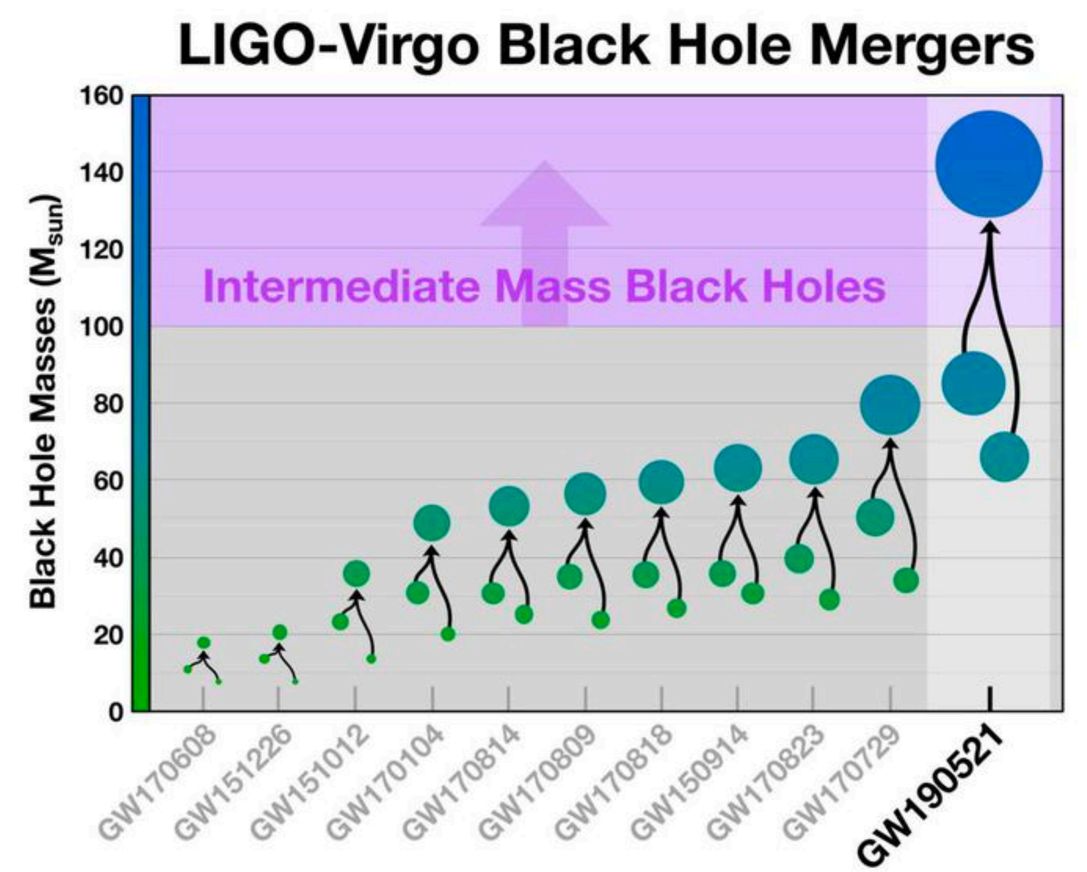


IMBHs?

100 < M < 10⁶ M_Sun

Hypothetical link between stellar-mass and SMBHs

- Originated by direct collapse of low-metallicity gas clouds? Primordial origin?
- Recent detection by LIGO/Virgo arXiv:2009.01190



Black Holes as Dark Matter

$\sqrt{\frac{hc}{G}}$

10^{-22} eV

Axion-like particles

1 GeV 1 TeV

10^{19} GeV (10^{-5} g)

10^{57} GeV (10^{33} g)

Sterile neutrinos

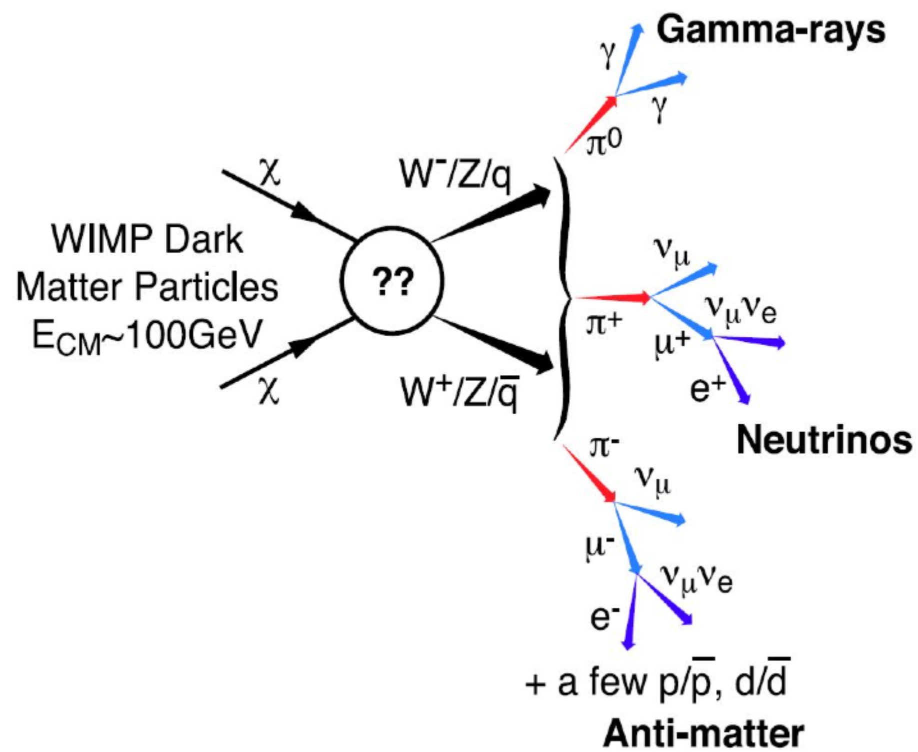
"Fuzzy" Dark Matter

λ_{dB} ~ 1 kpc ~ size of a dSph Galaxy

[Hui, Ostriker, Tremaine, Witten 2016]

Weakly interacting massive particles (WIMPS)

e.g. lightest neutralino state in MSSM



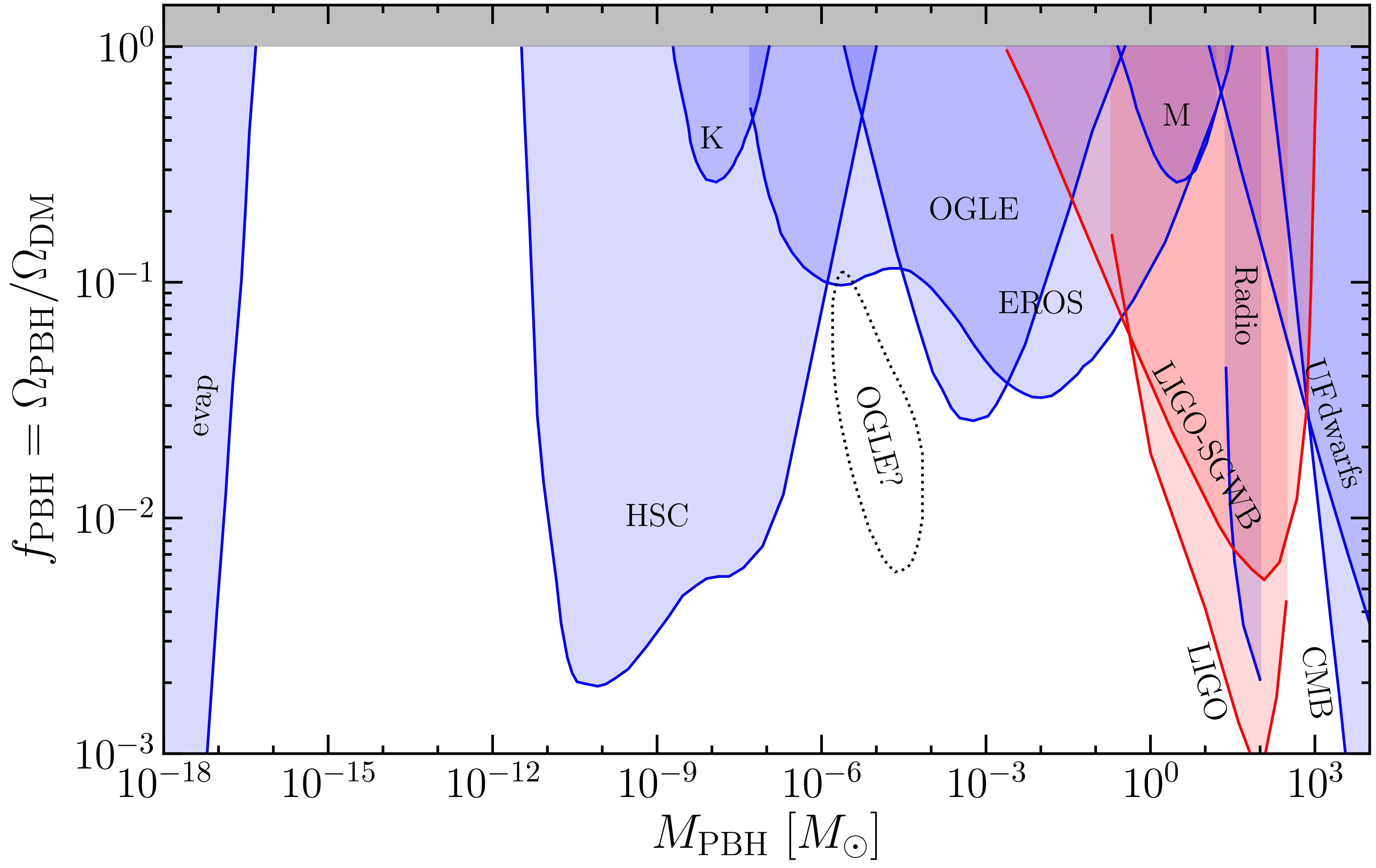
Primordial black holes (PBHs)

Proposed more than 40 years ago *[Zeld'ovich and Novikov 1966, Hawking 1971]*

1st wave of popularity following microlensing hints by MACHO collaboration *[Alcock et al. 1997]*

Recently **reconsidered in the DM community**

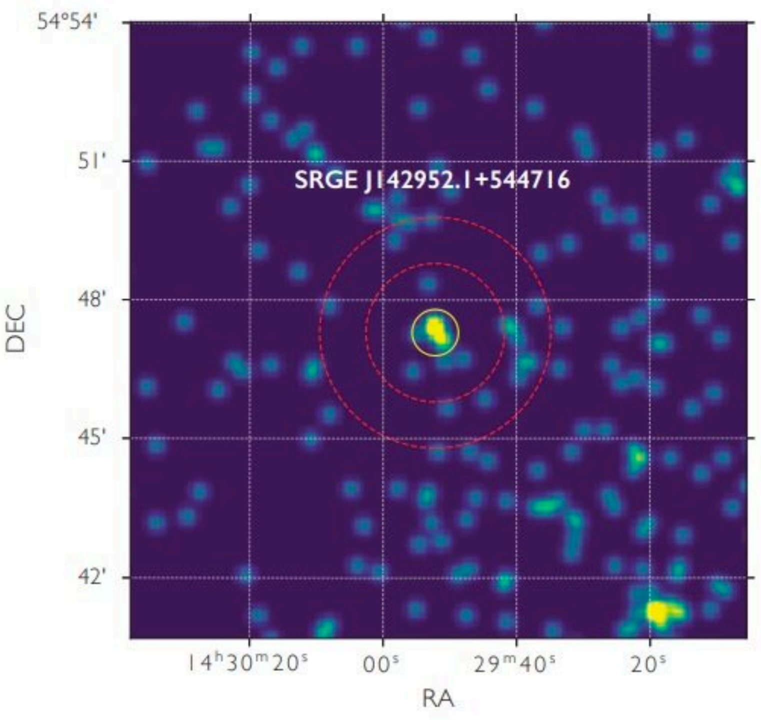
Primordial Black Hole phenomenology

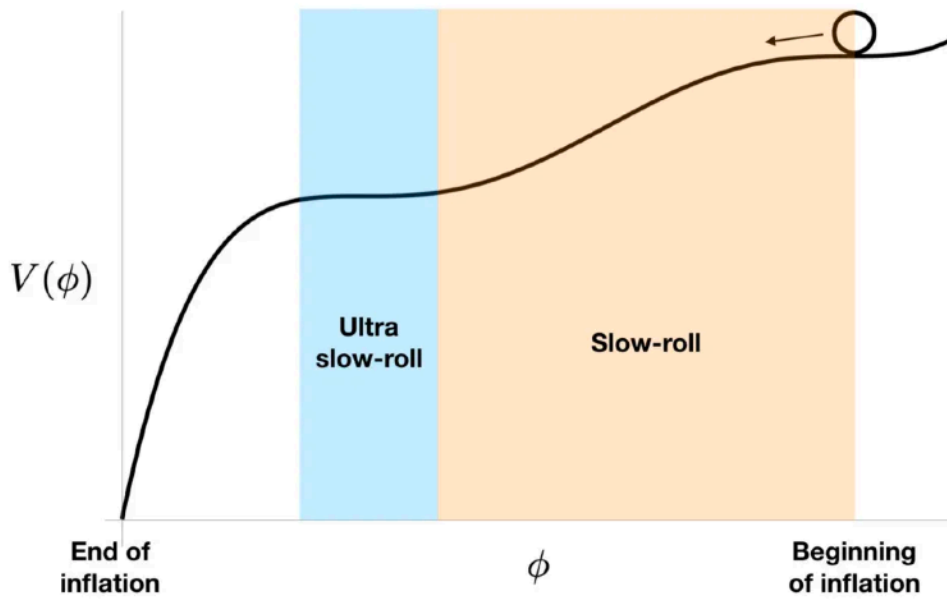


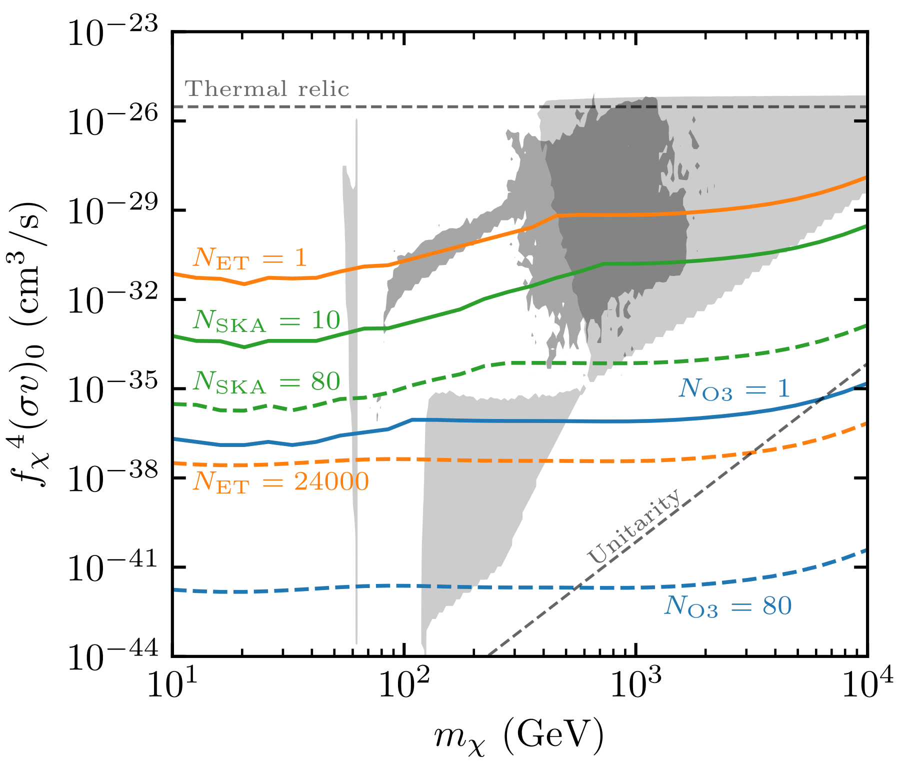
Credit: Bradley Kavanagh, https://github.com/bradkav/PBHbounds

Why a sub-dominant population would matter?

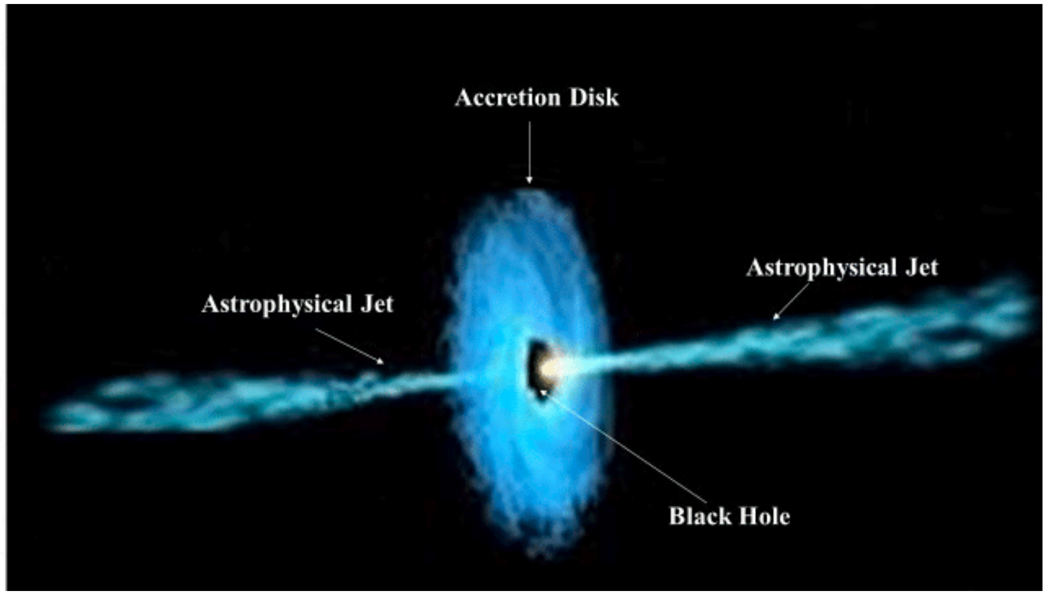
- A discovery of a sub-dominant population of DM in the form of (massive) PBHs could:
  - Solve the problem of the **SMBH seed**?
  - Reveal non-trivial **early universe physics**
  - Help us set stringent **upper limits** on other DM candidates

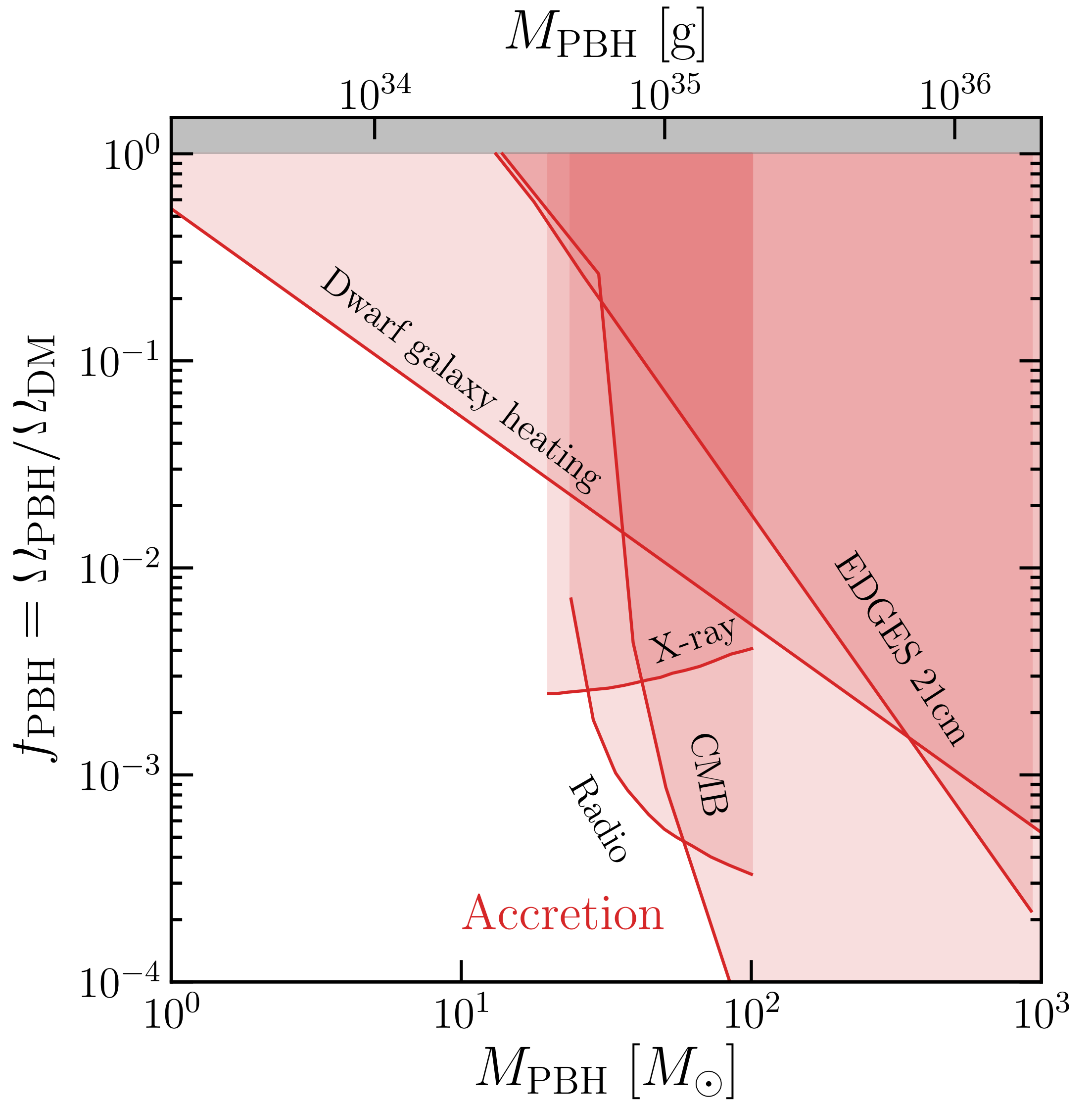






- **Primordial Black Holes can accrete baryonic matter**
- **Astronomical environments:** X-ray/ radio bounds (focus on Galactic center)
- **Cosmological bound:** for instance from Cosmic Microwave Background (focus on accretion during the Dark Ages)
- They rely on complicated accretion physics
- Comprehensive assessment of the uncertainties is very much needed!





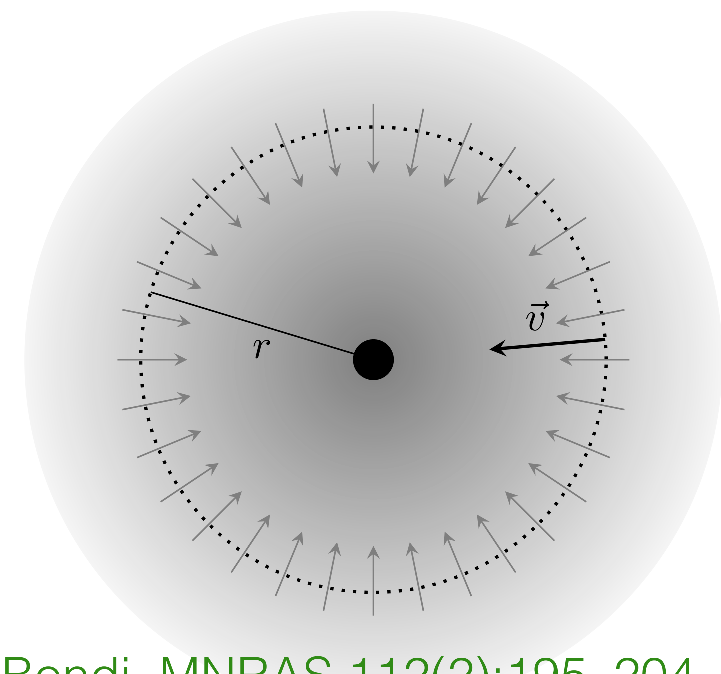
Accretion physics under the spotlight: BHL formalism.

Continuity equation for steady-state flow

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

Euler equation

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

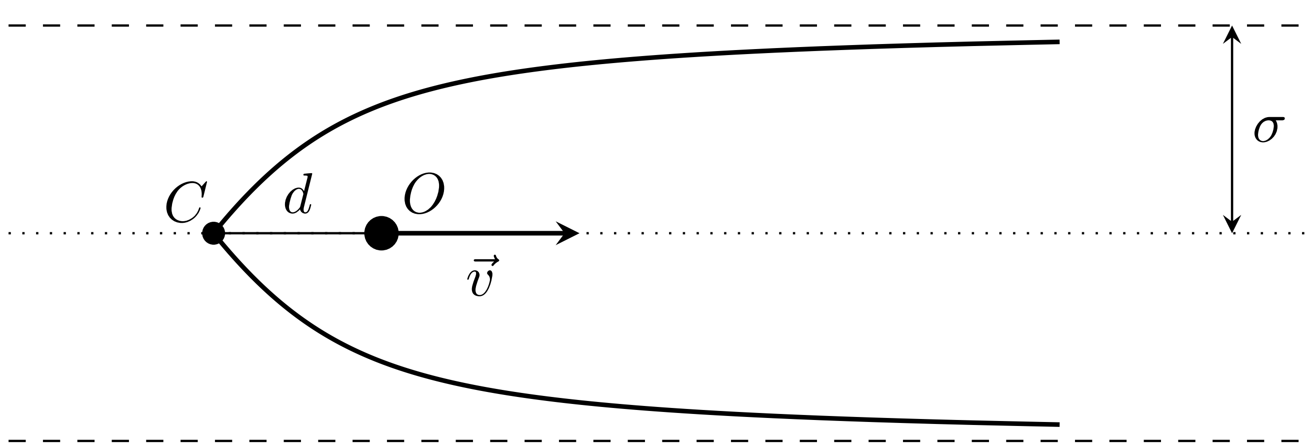


BH at rest: *Bondi* accretion rate

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

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

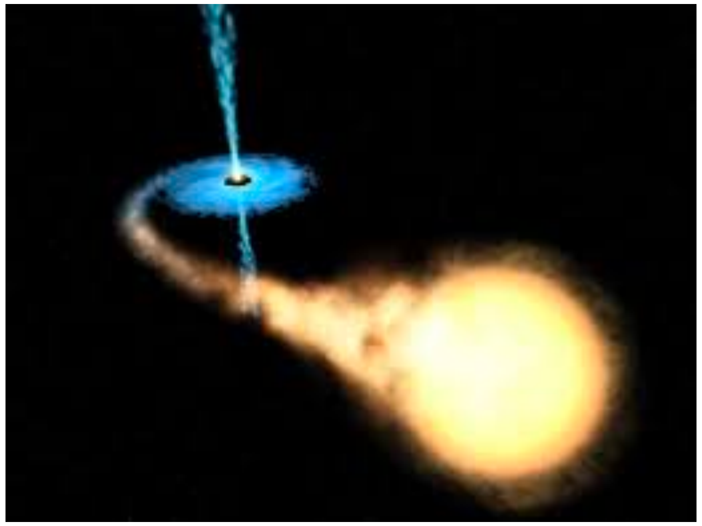
$$\dot{M}_{\rm BHL} = 4\pi \frac{(GM)^2 \rho_\infty}{(v^2 + c_\infty^2)^{3/2}}$$

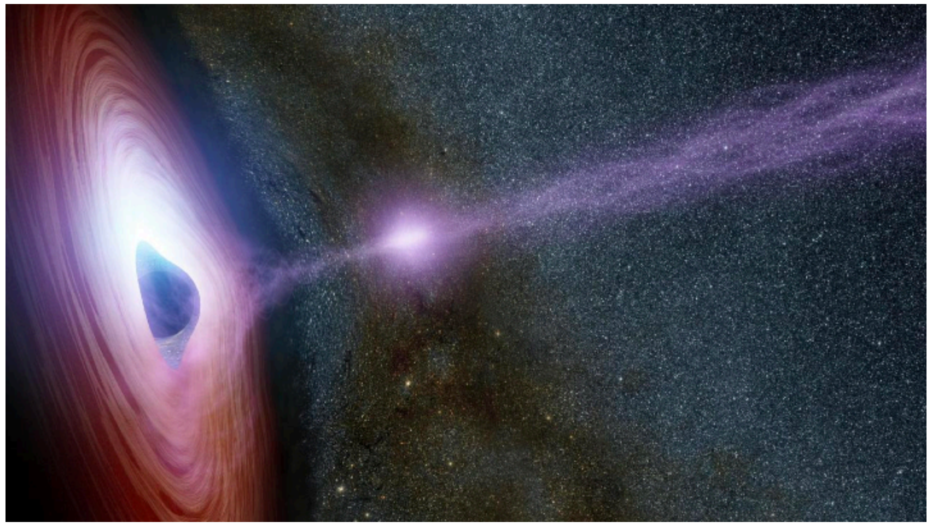
Bondi-Hoyle-Littleton formula needs to be "fudged" because of observational constraints related to local neutron stars, the SMBH at the center of the Galaxy, and AGNs.

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

- 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

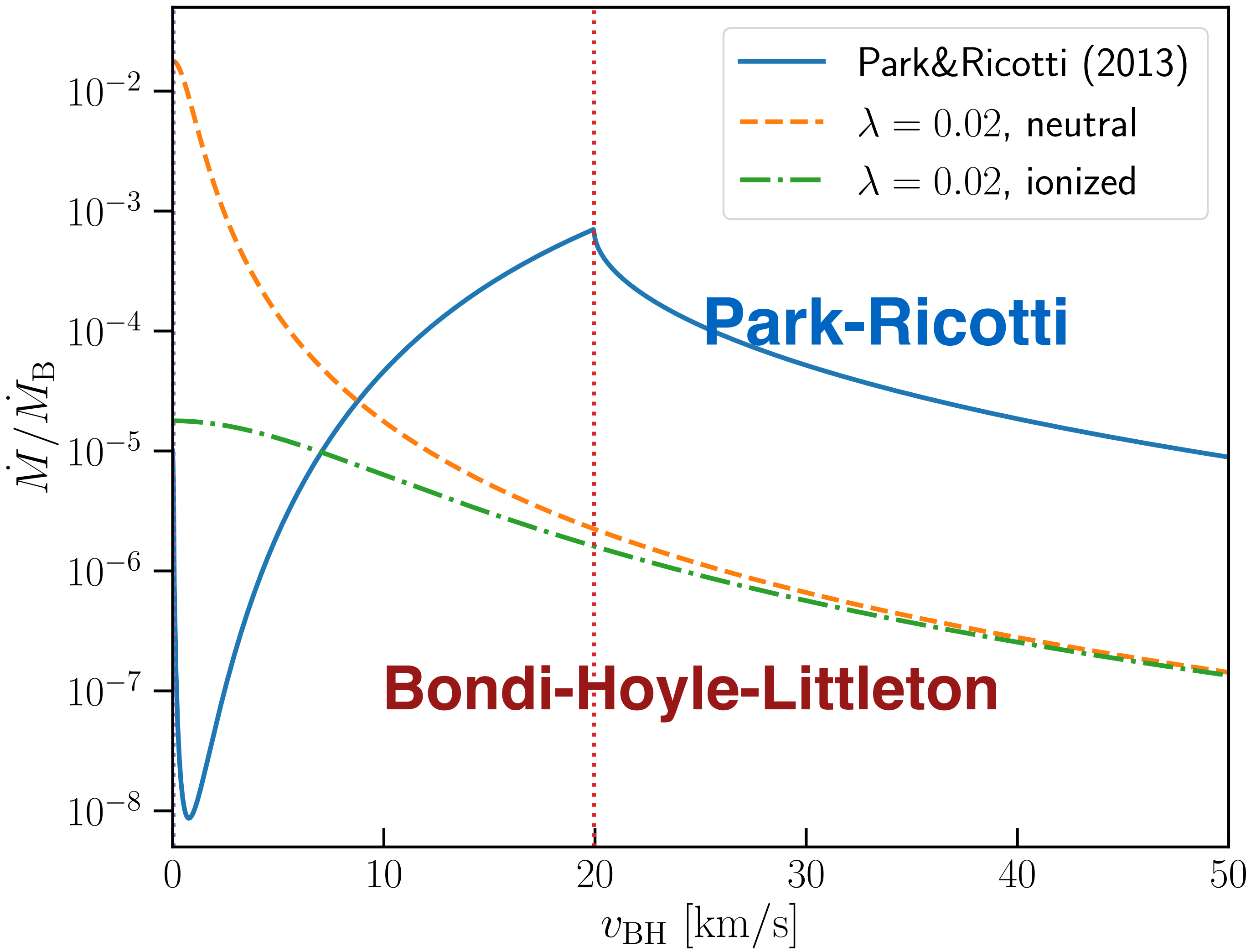


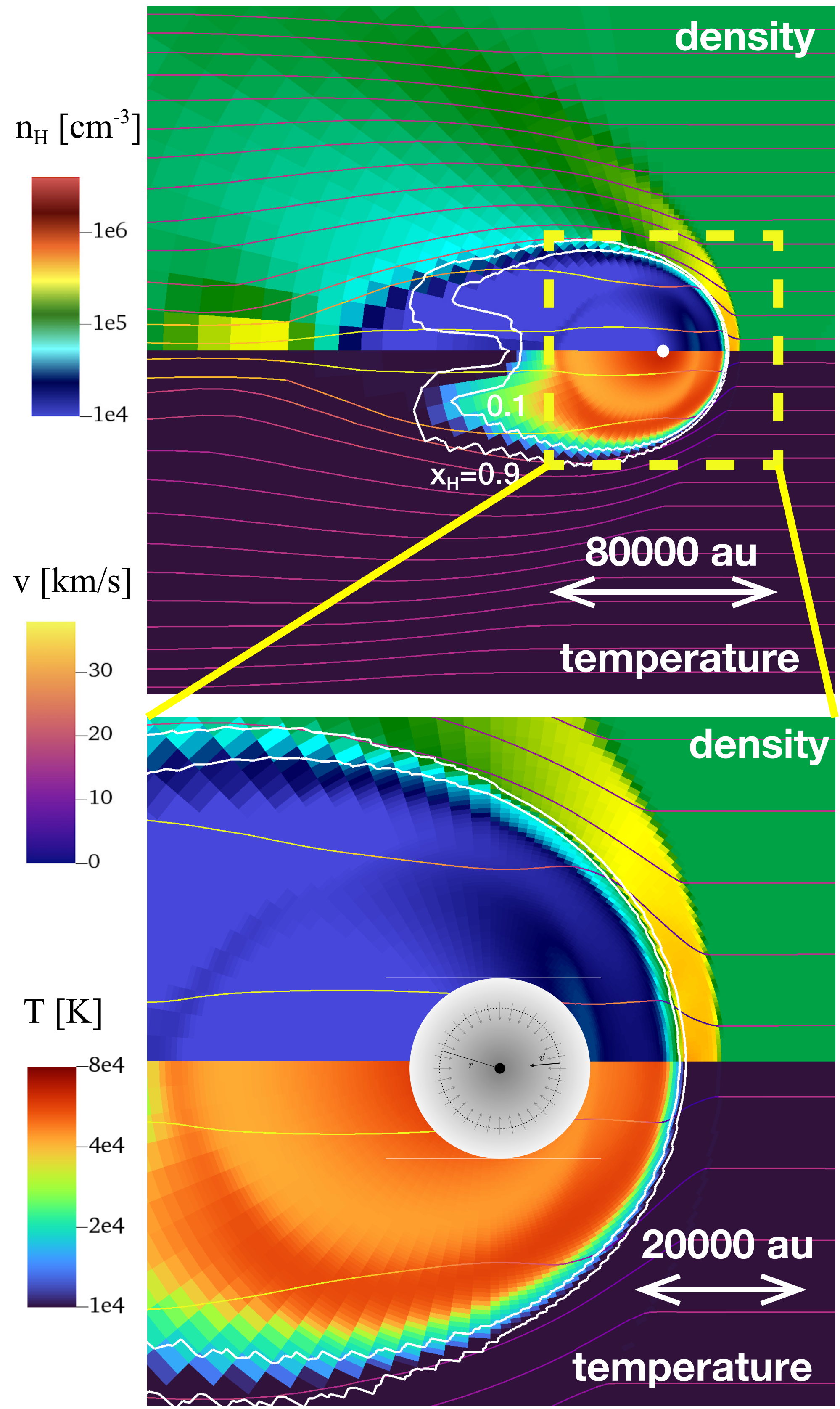


The Park-Ricotti model

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

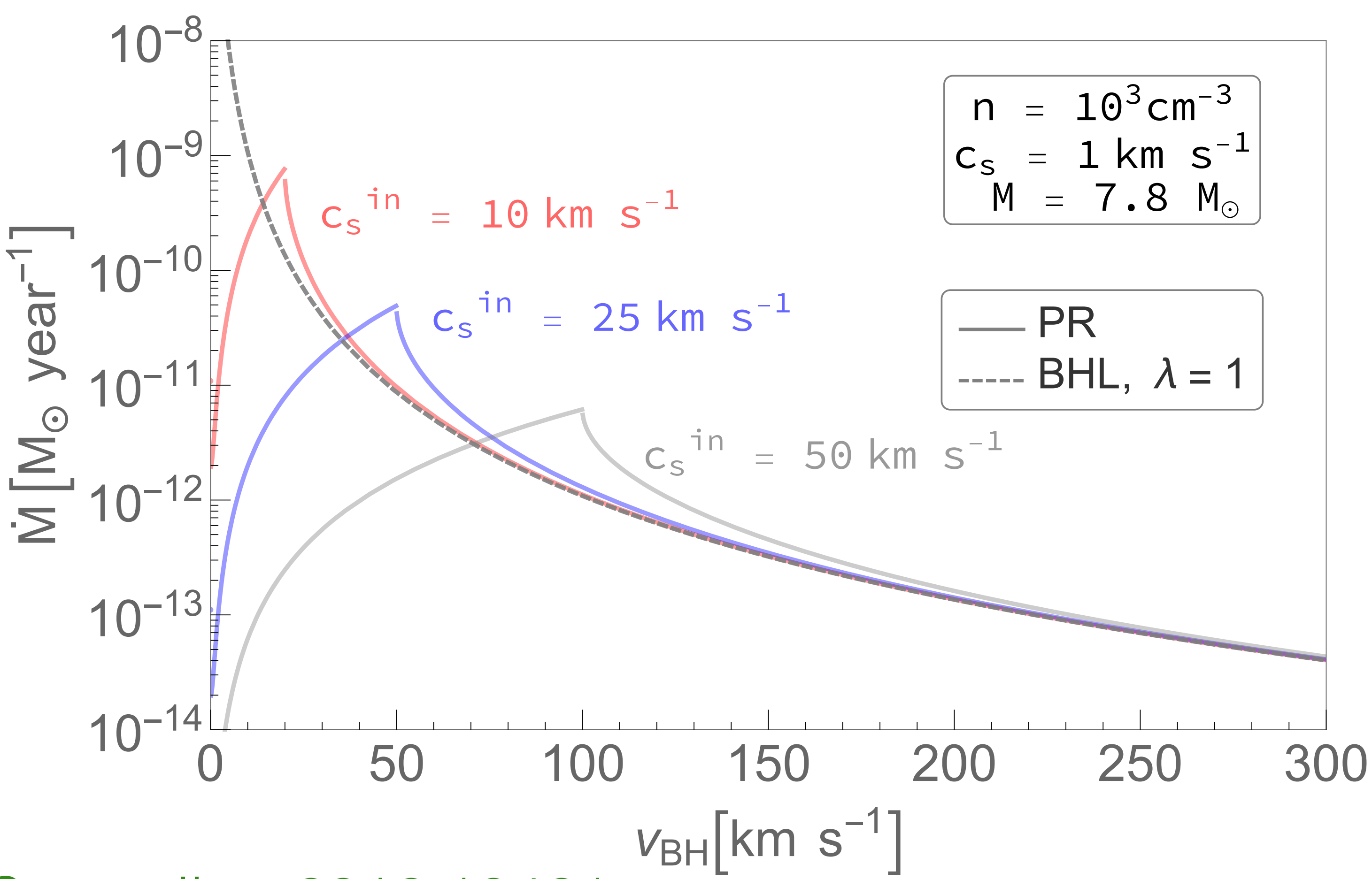
- Suppression of the accretion rate at low velocity, due to the formation of an ionized bubble



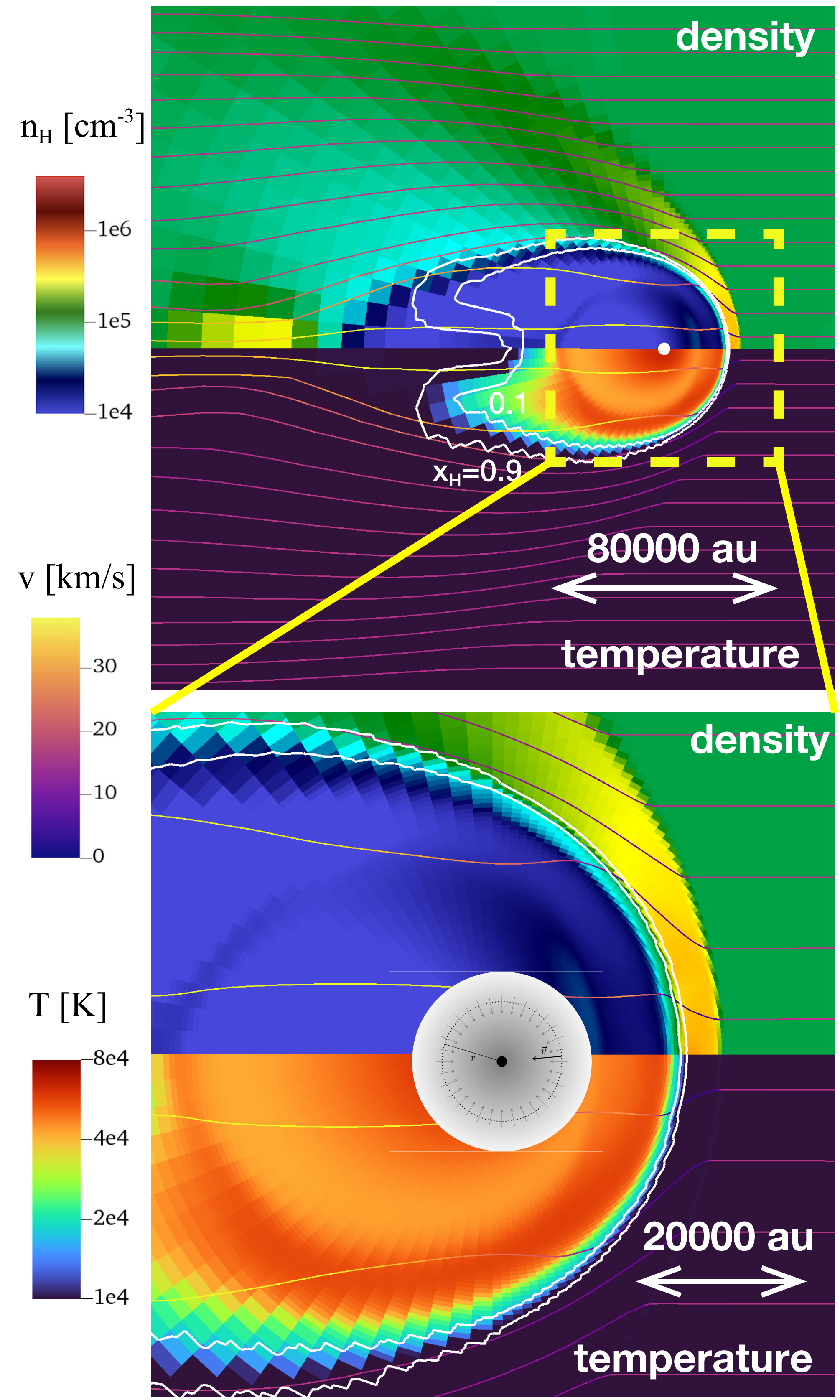


The Park-Ricotti model

- **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



The physics behind the bound

- PBHs accrete baryonic matter.

  - The accretion rate Mdot depends on ambient density and PBH - baryon relative speed. **BHL** and **PR** model.

  - Ambient density dilutes with decreasing redshift

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

Poulin+ 1707.04206

  - PBH speed relative to baryons also decreases according to linear theory:

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

The physics behind the bound

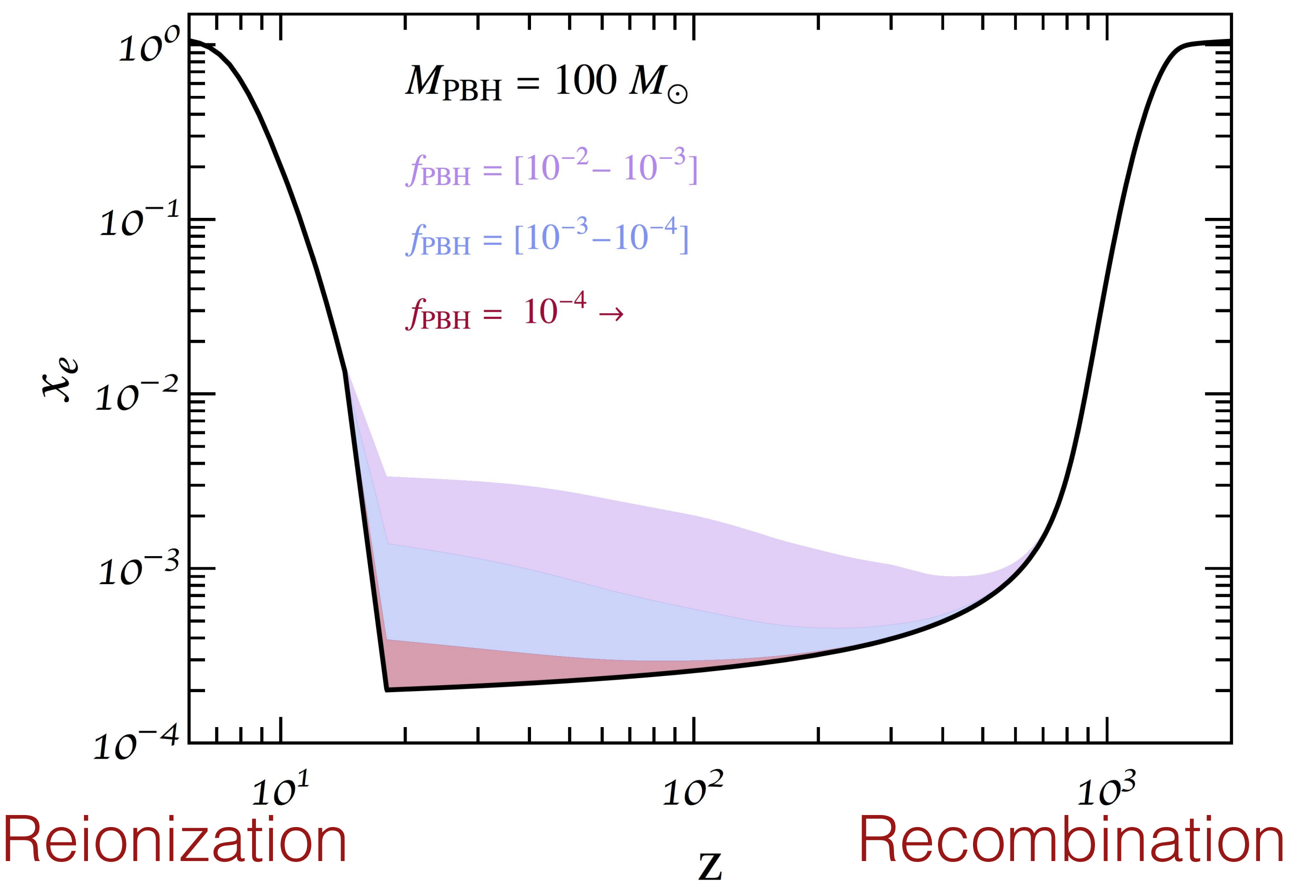
- Accretion disks emits *ionizing radiation* during the Dark Ages (between Recombination and Reionization)*:*
  - IGM is heated up (alteration of T_M)
  - IGM is also partially ionized (alteration of the *free electron fraction* X_e)

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

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

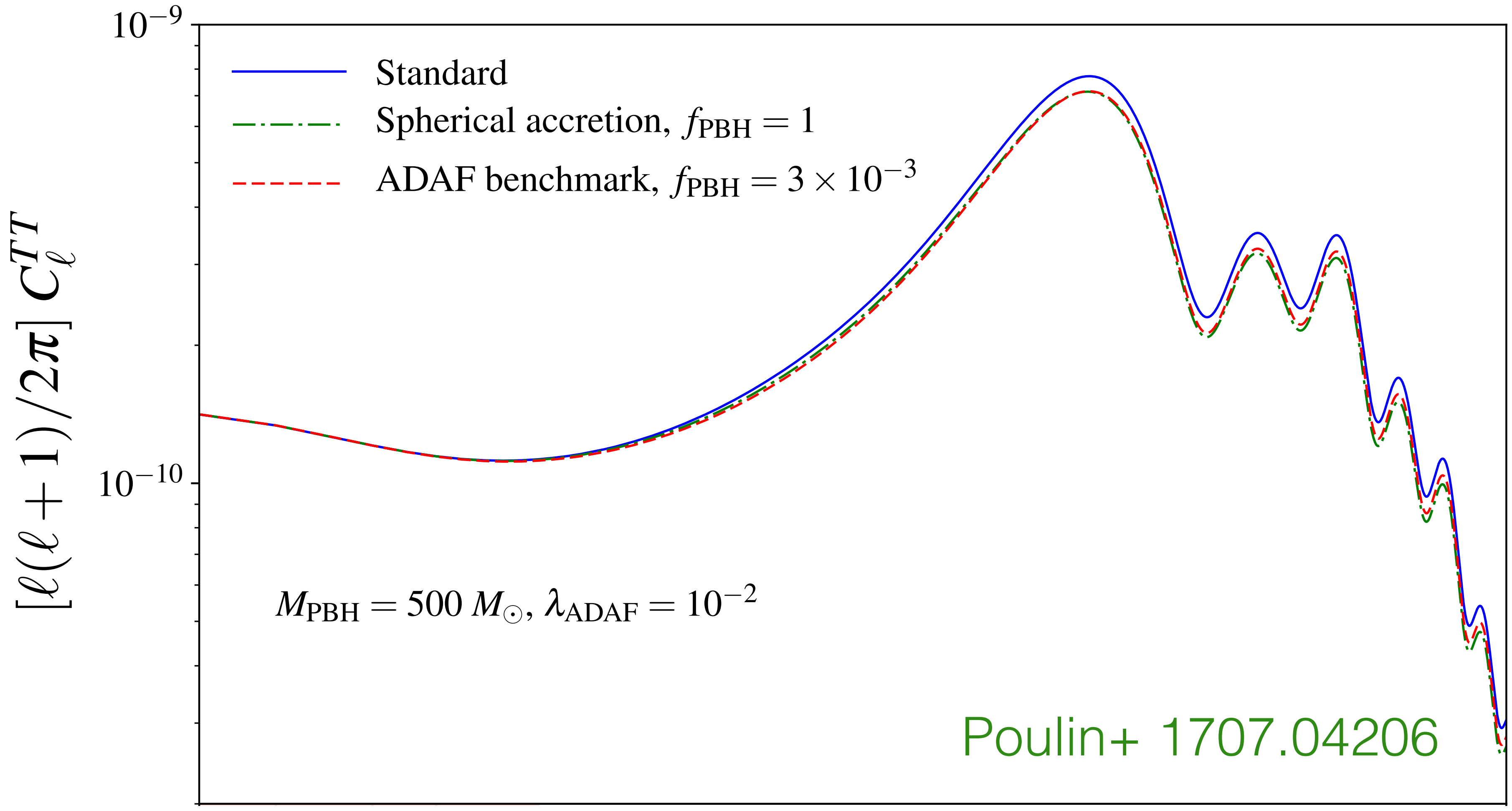
Stocker+ 1801.01871

Mena+ 1906.07735



The physics behind the bound

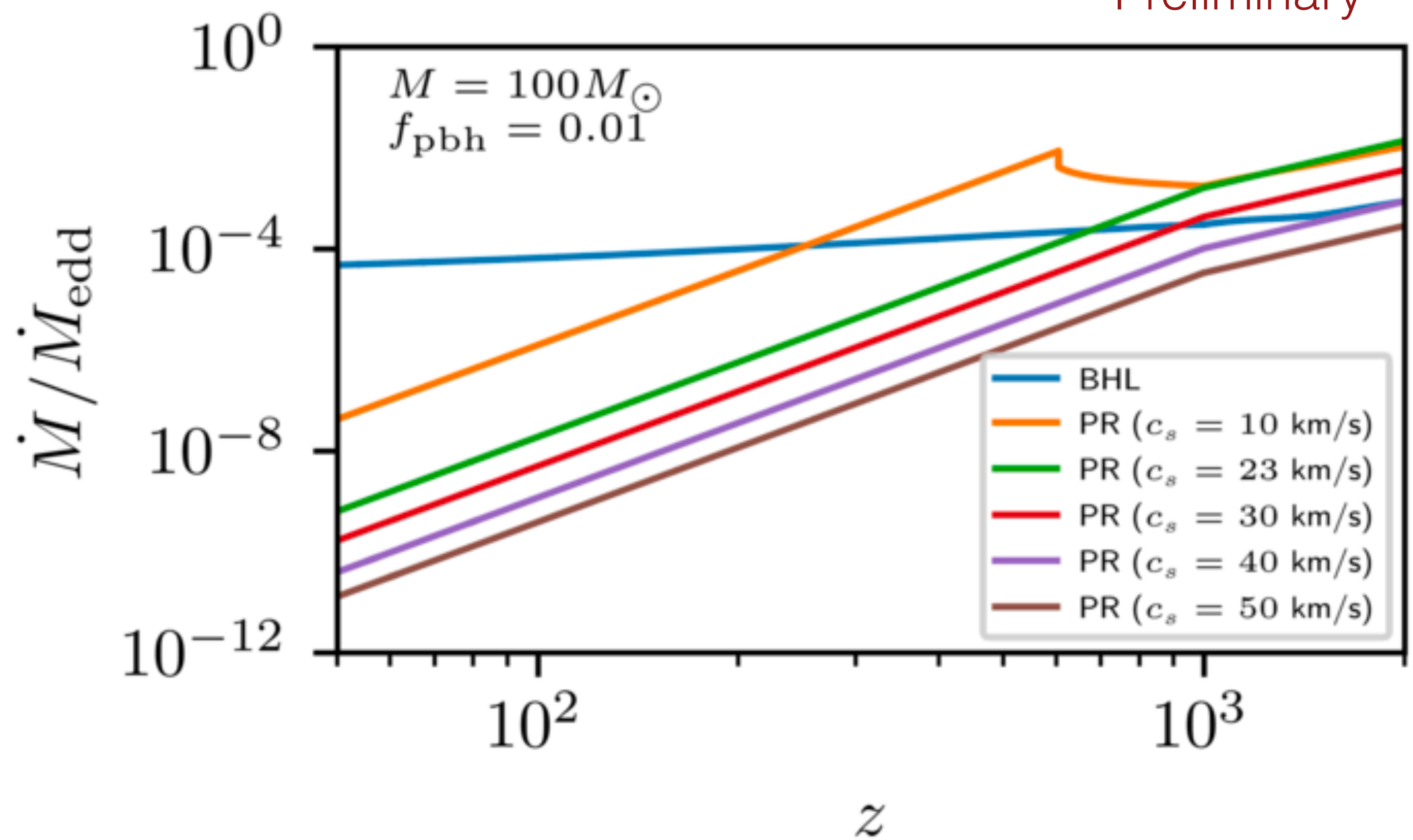
- Impact on CMB anisotropy is due to the alteration of the visibility function and the recombination optical depth

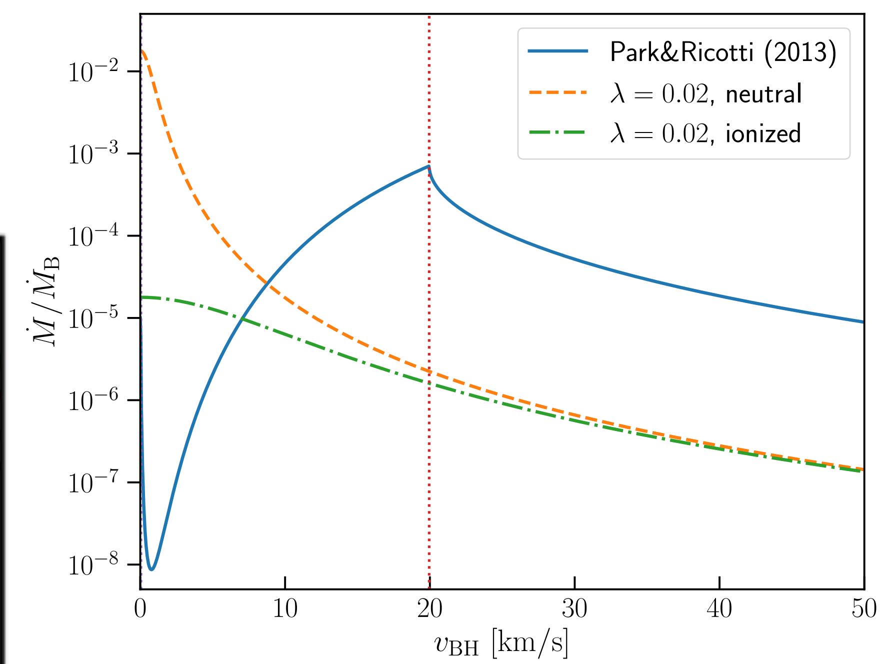


Revisiting the Cosmological constraint: Results

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

Preliminary

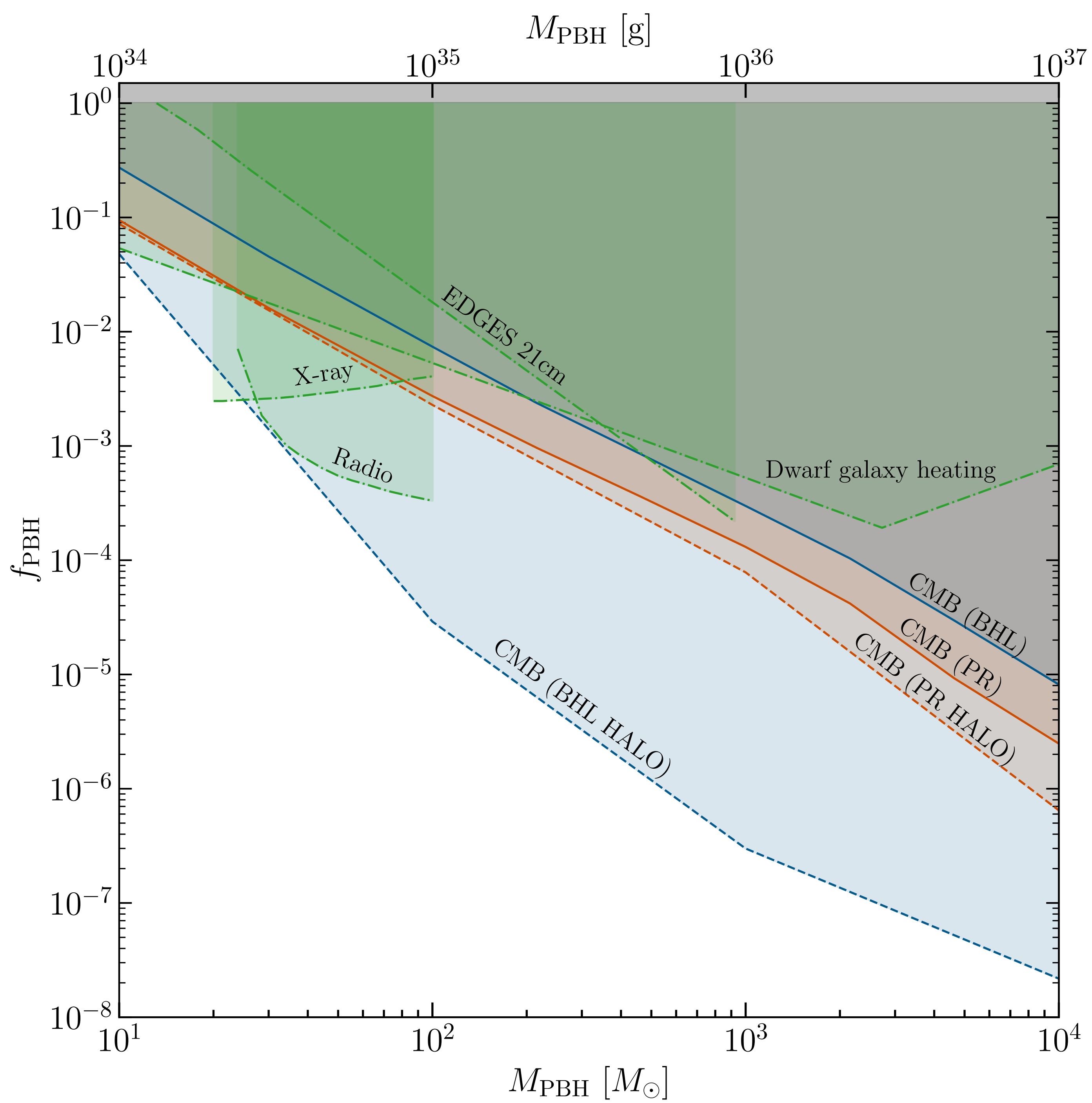




Dominic Agius, Gregory Suczewski, Rouven Essig, **DG**, Francesca Scarcella, Mauro Valli, *in preparation*

Revisiting the Cosmological constraint

BHL vs PR: the **“Unexpected robustness”** of the bound



Preliminary

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

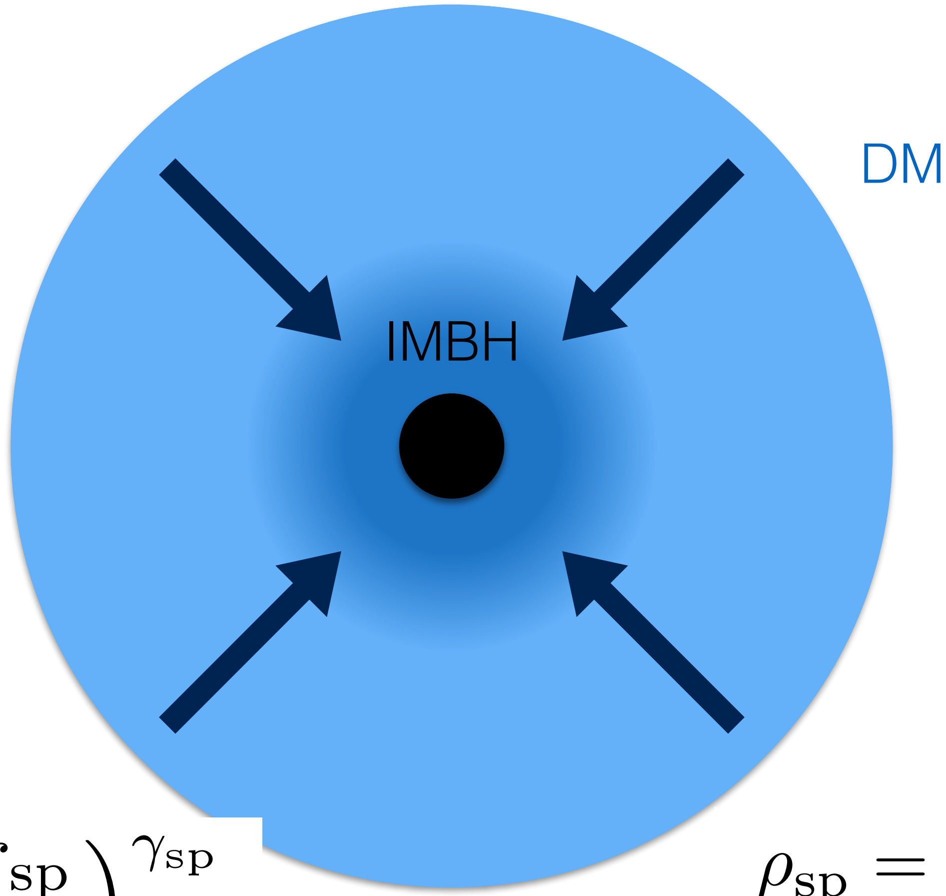
See also Facchinetti+ 2212.07969

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`

Black Holes as Portals to new Physics

- Intermediate-Mass Black Holes may exist in the Universe.
- Dark-Matter over-densities can form around them [Gondolo&Silk 9906391, Zhao&Silk 0501625, Hannuksela+ 1906.11845].

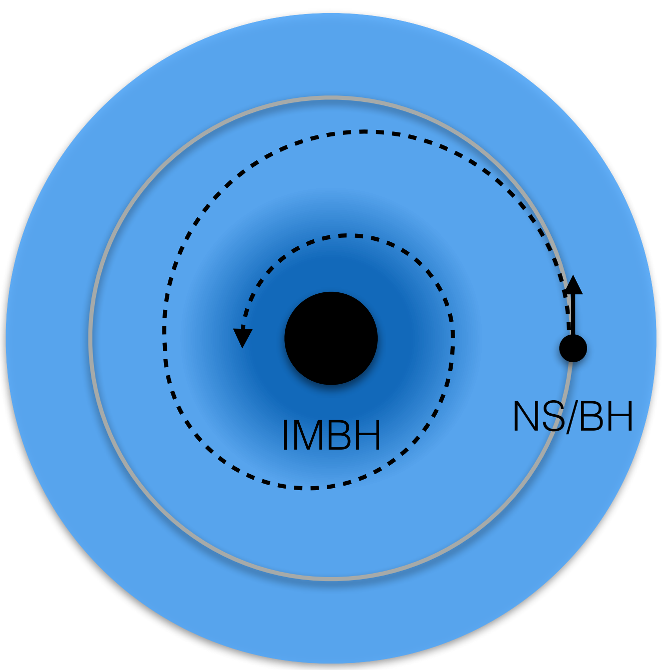
$M_{IMBH} = 1000\, M_{Sun}$

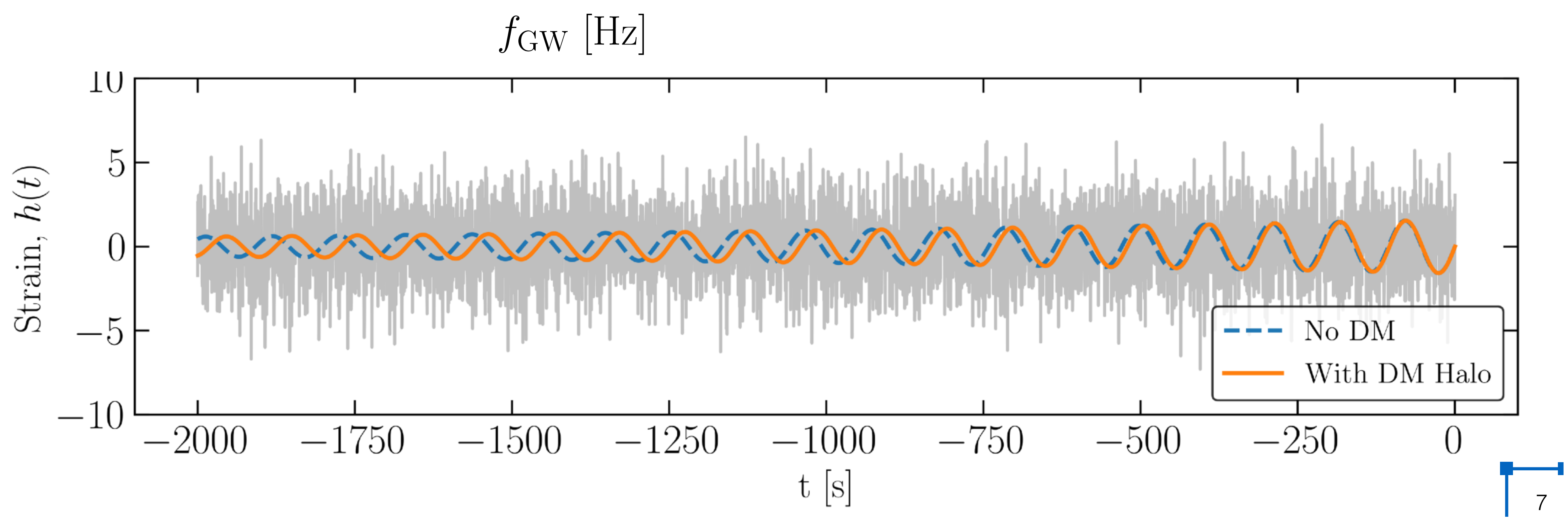


$$\rho_{\rm DM}(r) = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

$$\rho_{\rm sp} = 200\, M_\odot\, {\rm pc}^{-3}$$
$$r_{\rm sp} = 0.5\, {\rm pc}$$

- Stellar-mass black holes that inspiral around IMBHs can trace the presence of either accretion disks or Dark Matter overdensities (DM “dresses” or “spikes”)

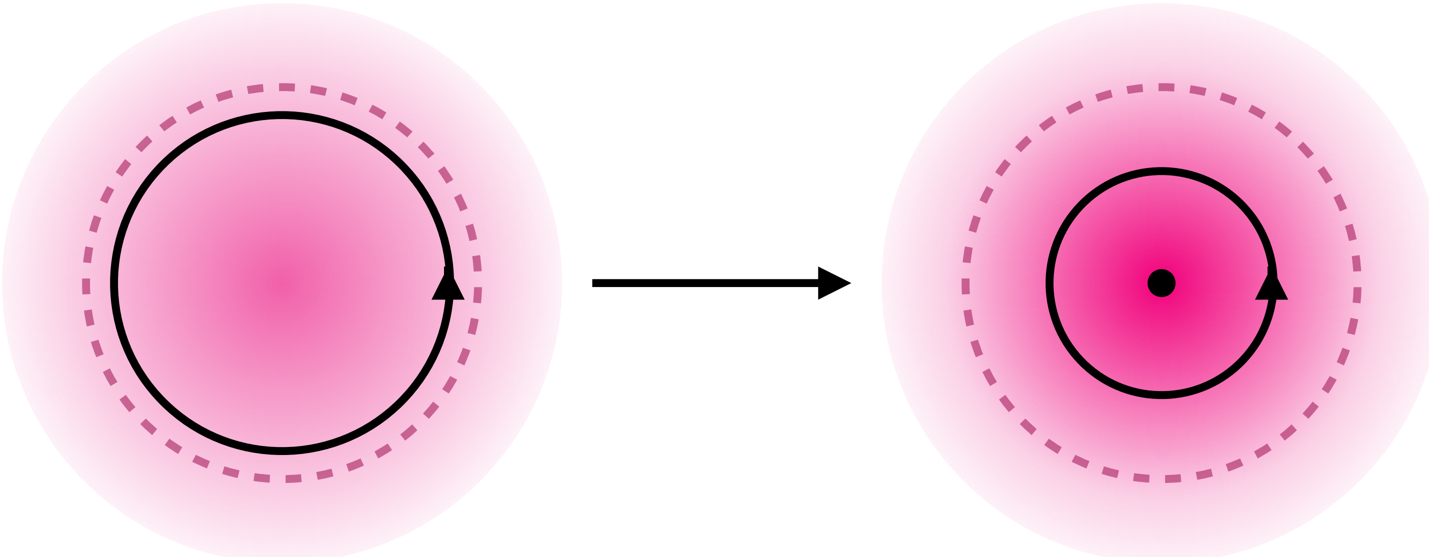




- Dephasing of the waveform w.r.t. GR in vacuum
- Physical process: Dynamical Friction

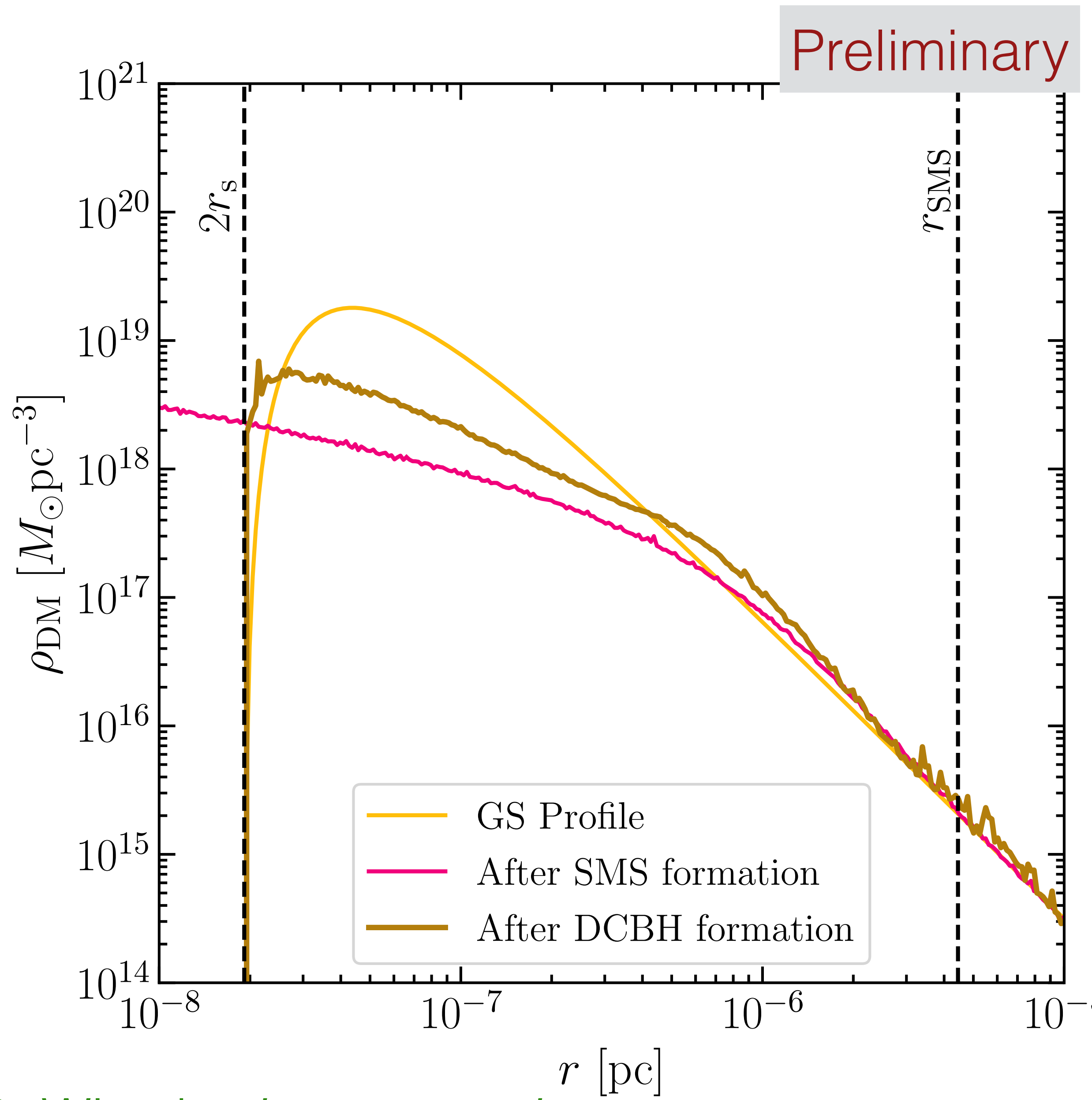
- Kavanagh+ 2002.12811 (PRD)
- Coogan+ 2108.04154 (PRD)
- Cole+ 2211.01362 (Nature Astronomy)

$$\frac{\mathrm{d}E_{\mathrm{DF}}}{\mathrm{d}t} = 4\pi (G m_2)^2 \rho_{\mathrm{DM}}(r_2)\, \xi(v)\, v^{-1} \log \Lambda$$



Adiabatic and non-adiabatic treatment, simplified scenario:
- Gondolo and Silk, 9906391
- Ullio et al. 0101481

$$\rho(r) = \int \mathrm{d}^3\mathbf{v}\, f(\mathcal{E}, L) = 4\pi \int \mathrm{d}v_r \mathrm{d}v_T\, v_T\, f(\mathcal{E}, L)\,,$$



- **Realistic scenario:** We follow the evolution of a small DM + baryon halo
  - **Supermassive star** forms
  - **Direct collapse** into BH
  - **BH grows** adiabatically

G. Bertone, **DG**, B. Kavanagh, R. Wierda, *in preparation*

Conclusions

- Multiple relevant interplay between BH phenomenology and DM searches

- **Accretion physics** is crucial to set upper limits on the PBH abundance
- Need to go beyond the textbook BHL approach
- **The CMB bound on PBH abundance seems robust** with respect to the uncertainties associated to the accretion model!

- **DM overdensities** around IMBHs provide a **discovery potential** thanks to GW dephasing
- Realistic models that describe the **formation of DM overdensities** are in progress

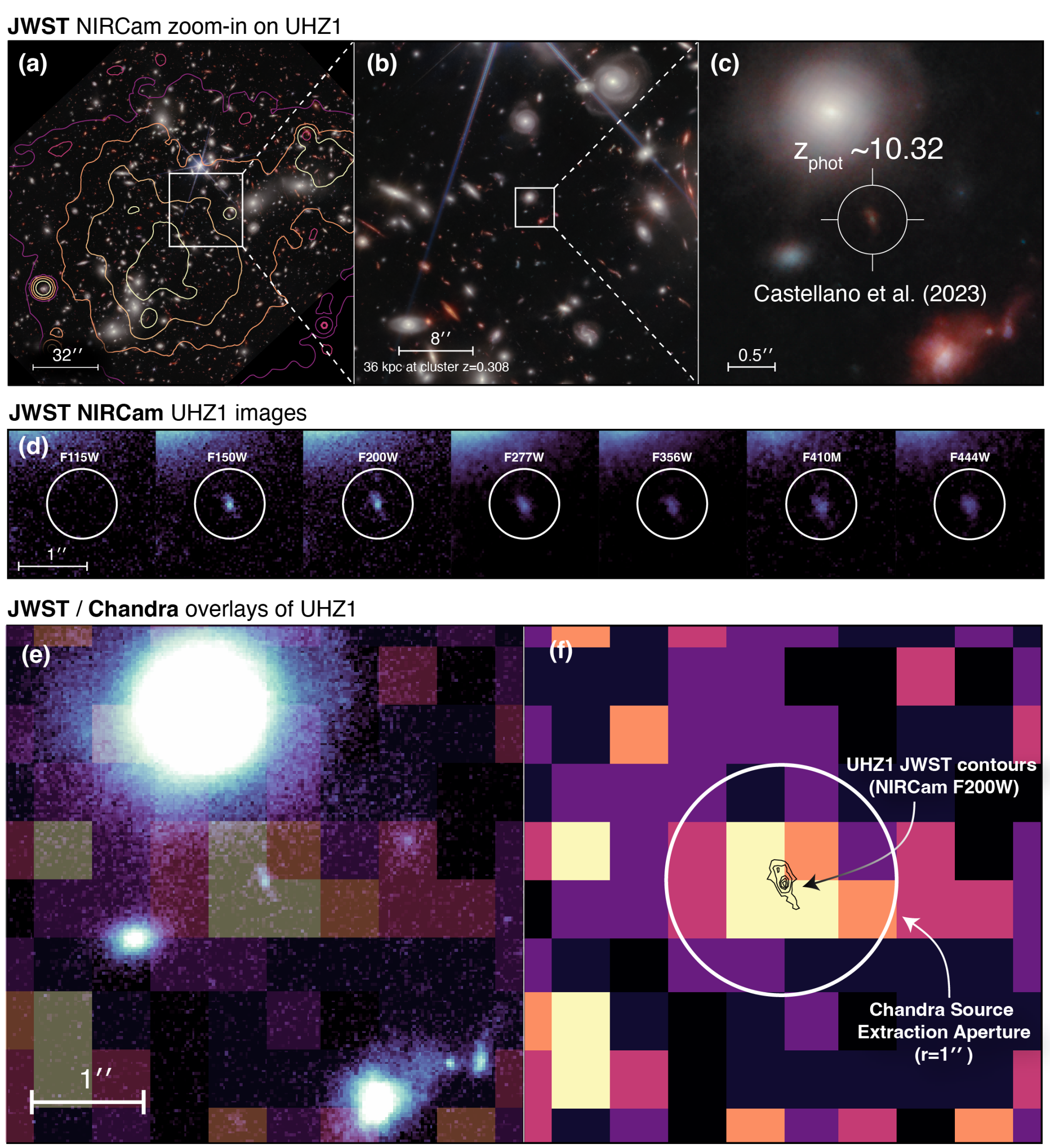
Thank you!

The most distant quasar

Supermassive black holes at the centre of Galaxies.

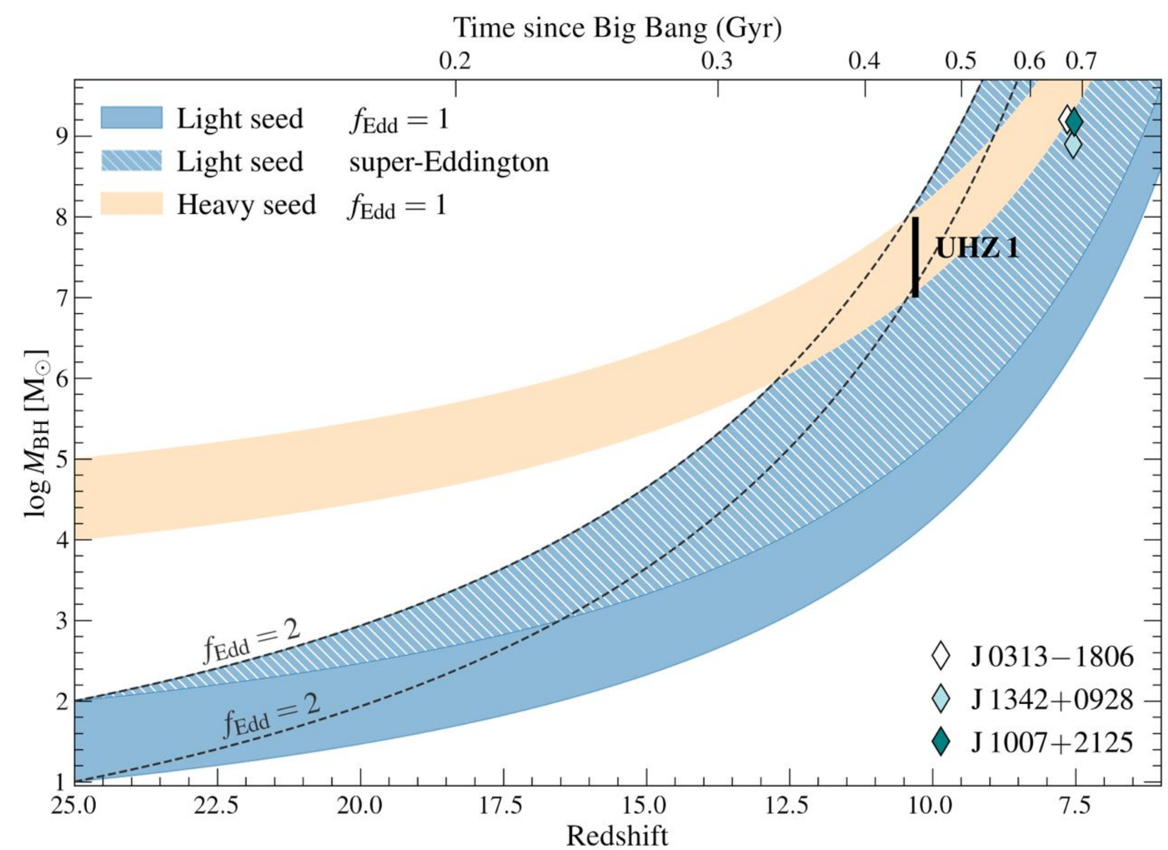
News: Observed up to ***z ~ 10***

Seeds? Probably Heavy



Evidence for heavy seed origin of early supermassive black holes from a $z \sim 10$ X-ray quasar

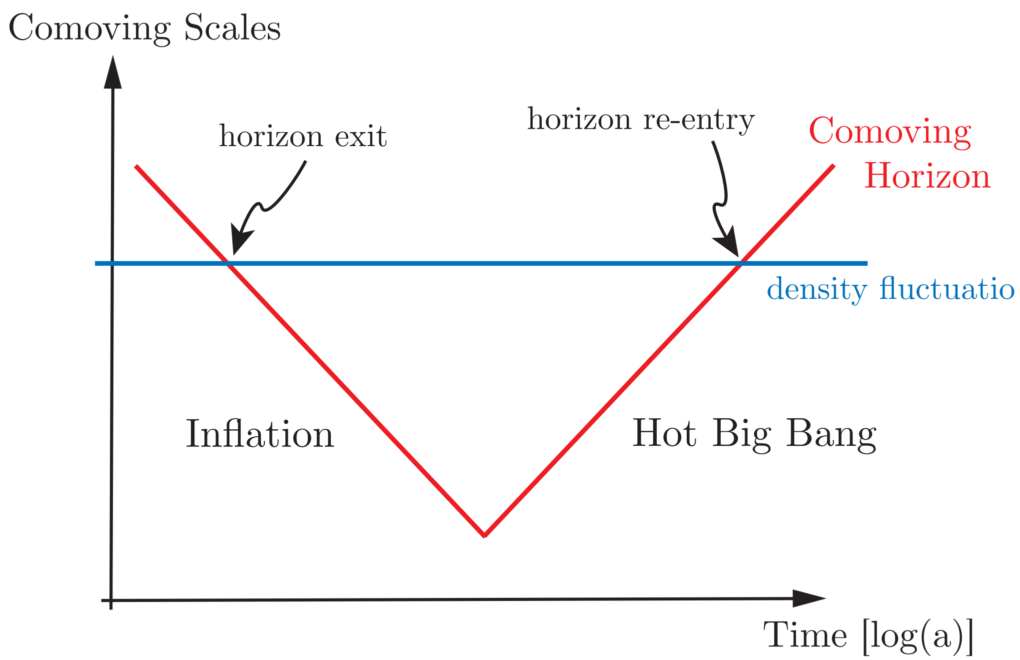
Ákos Bogdán[1*], Andy D. Goulding[2†], Priyamvada Natarajan[3,4,5†], Orsolya E. Kovács[6], Grant R. Tremblay[1], Urmila Chadayammuri[1], Marta Volonteri[7], Ralph P. Kraft[1], William R. Forman[1], Christine Jones[1], Eugene Churazov[8] and Irina Zhuravleva[9]



Black holes of primordial origin?

BHs formed in the **early Universe** (before BBN), out of *small-scale, large-amplitude density fluctuations* possibly **originated during inflation**

[S. Hawking, MNRAS 152 (1971); Carr and Hawking, MNRAS 168 (1974)]



"…it is tempting to suppose that the major part of the mass of the Universe is in the form of collapsed objects. This extra density could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound."

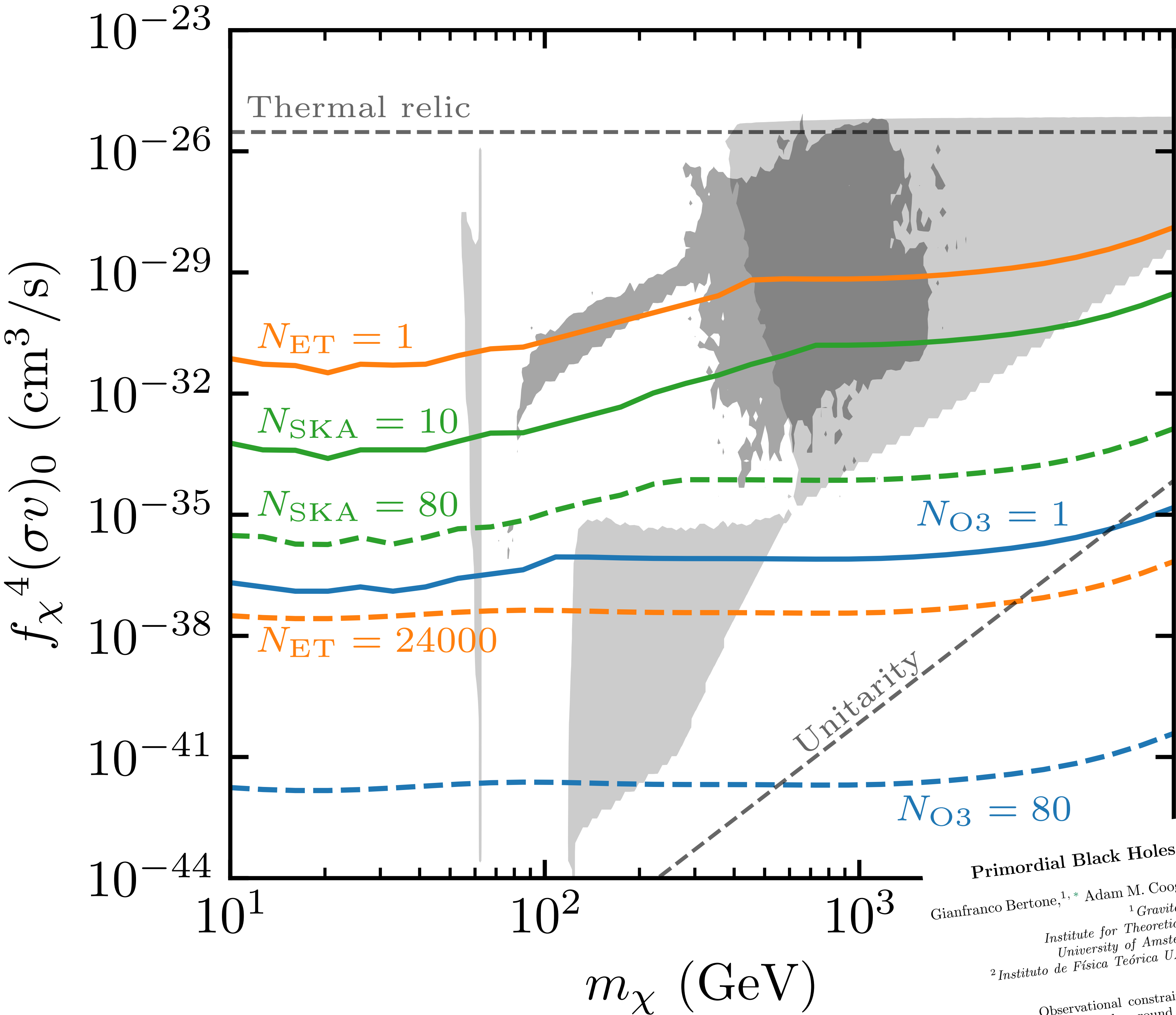
PBH mass ~ horizon mass at the time of formation

$$M_{\rm PBH} \sim M_{\rm H} \sim \frac{c^3 t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\,{\rm s}}\right) {\rm g}\,.$$

Wide mass range for PBHs as DM candidates

$M \sim 10^{16}\ g\ (10^{-17}\ M_\odot) - 10^{39}\ g\ (10^{5}\ M_\odot)$

WIMPs and PBHs



G. Bertone, A. Coogan, **DG**, B.J. Kavanagh, C. Weniger, 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*

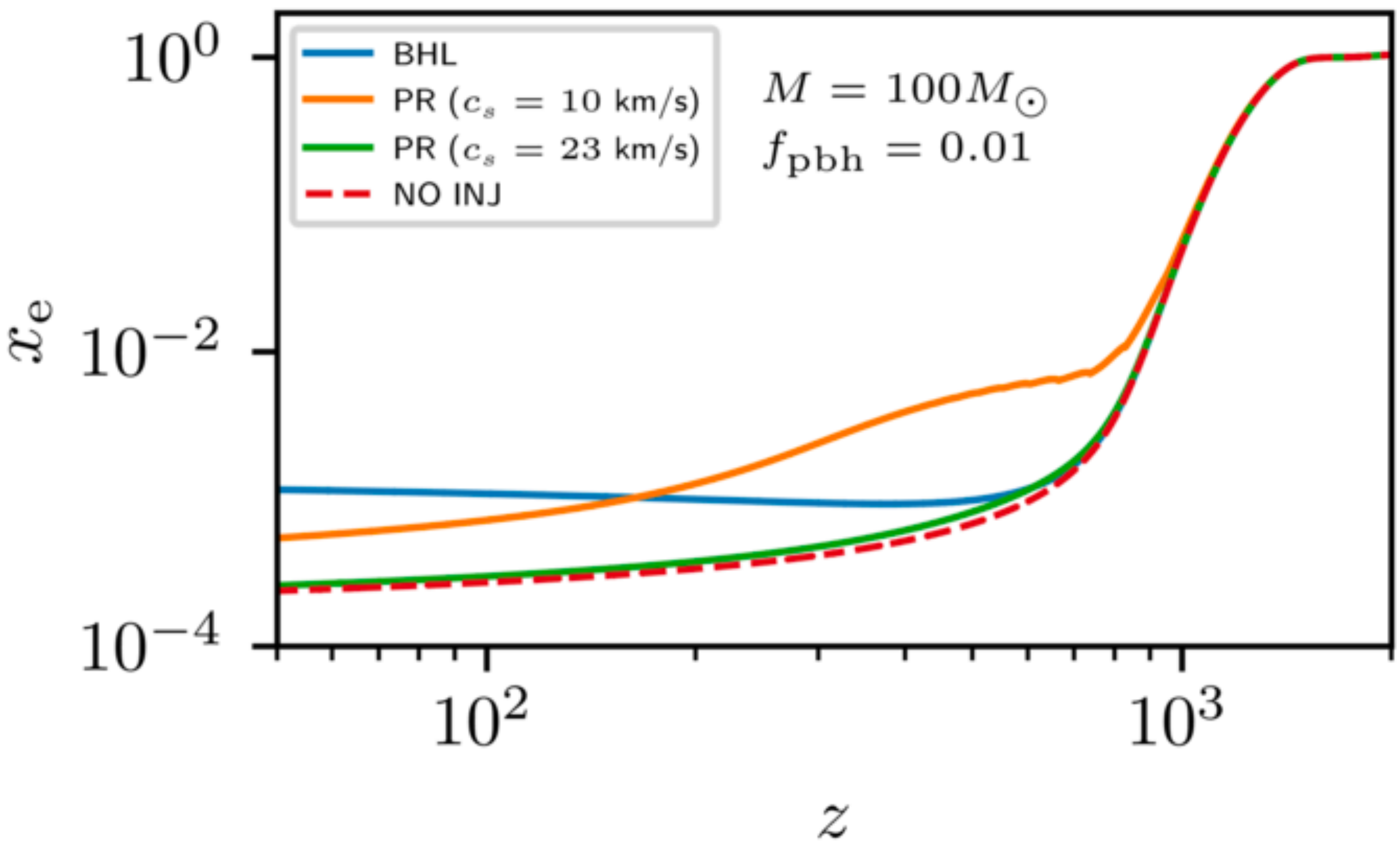
(Dated: May 6, 2019)

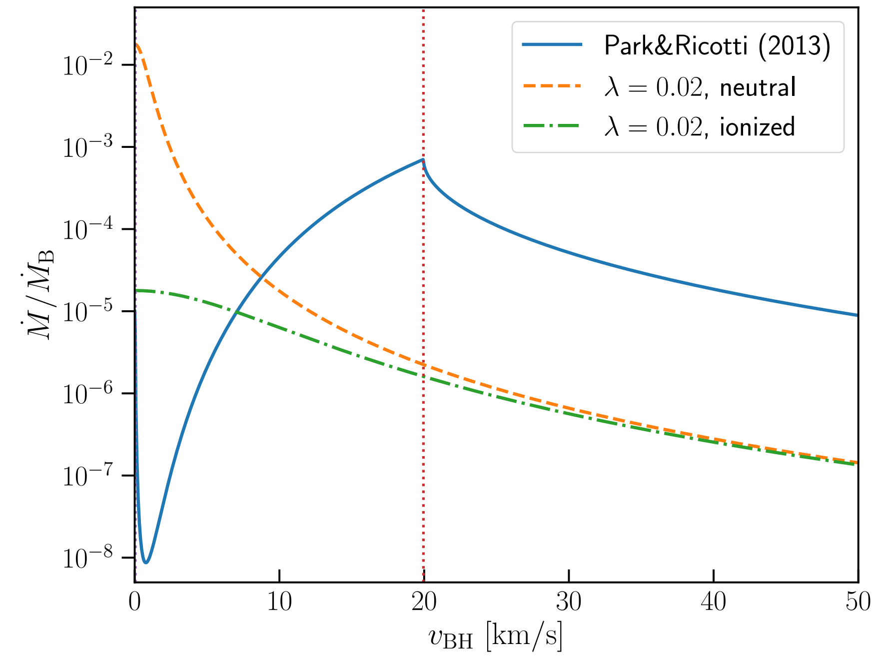
Observational constraints on gamma rays produced by the annihilation of weakly interacting massive particles around primordial black holes (PBHs) imply that these two classes of Dark Matter candidates cannot coexist. We show here that the successful detection of one or more PBHs by radio searches (with 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.

Revisiting the Cosmological constraint: Results

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

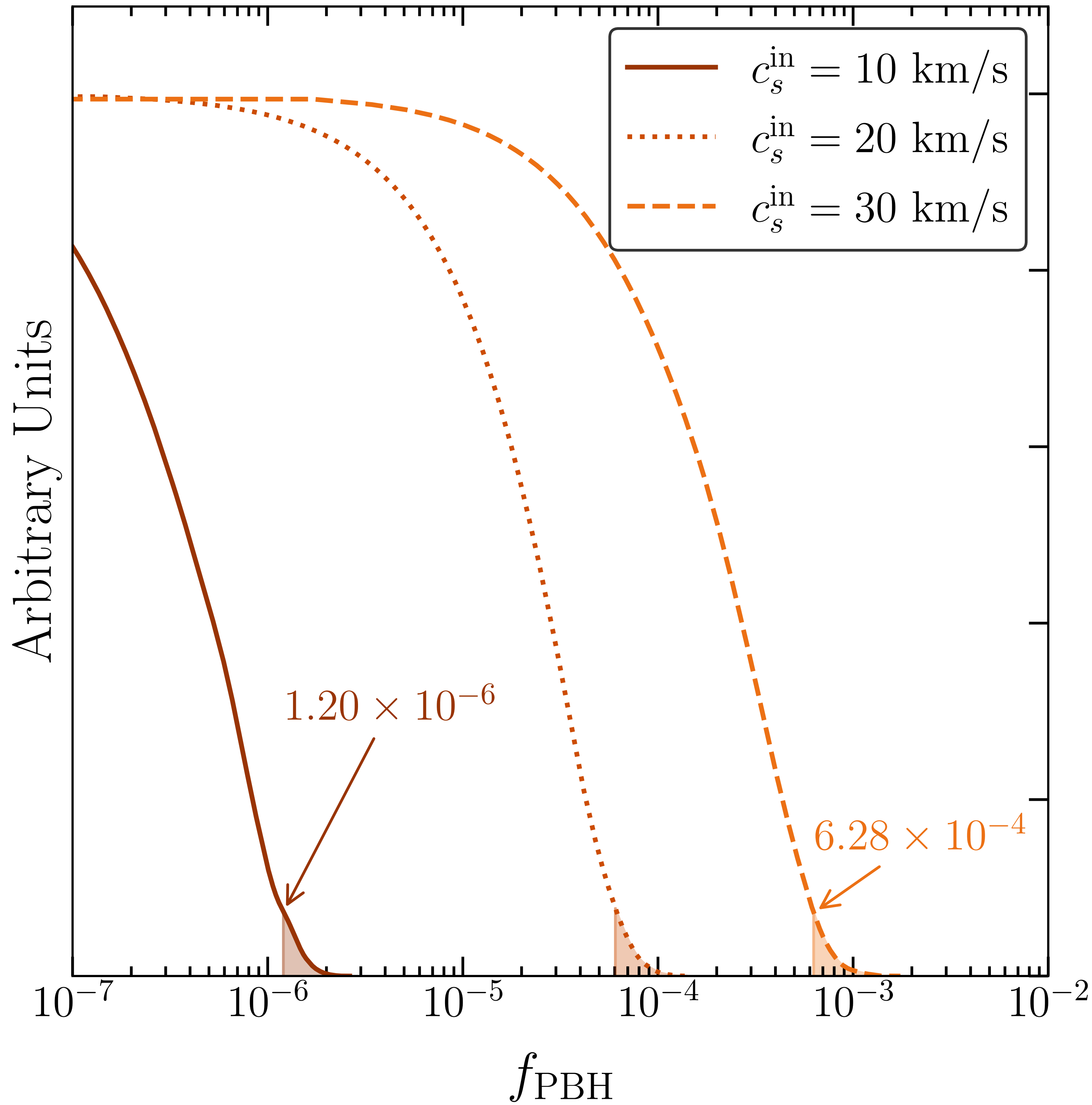
Preliminary



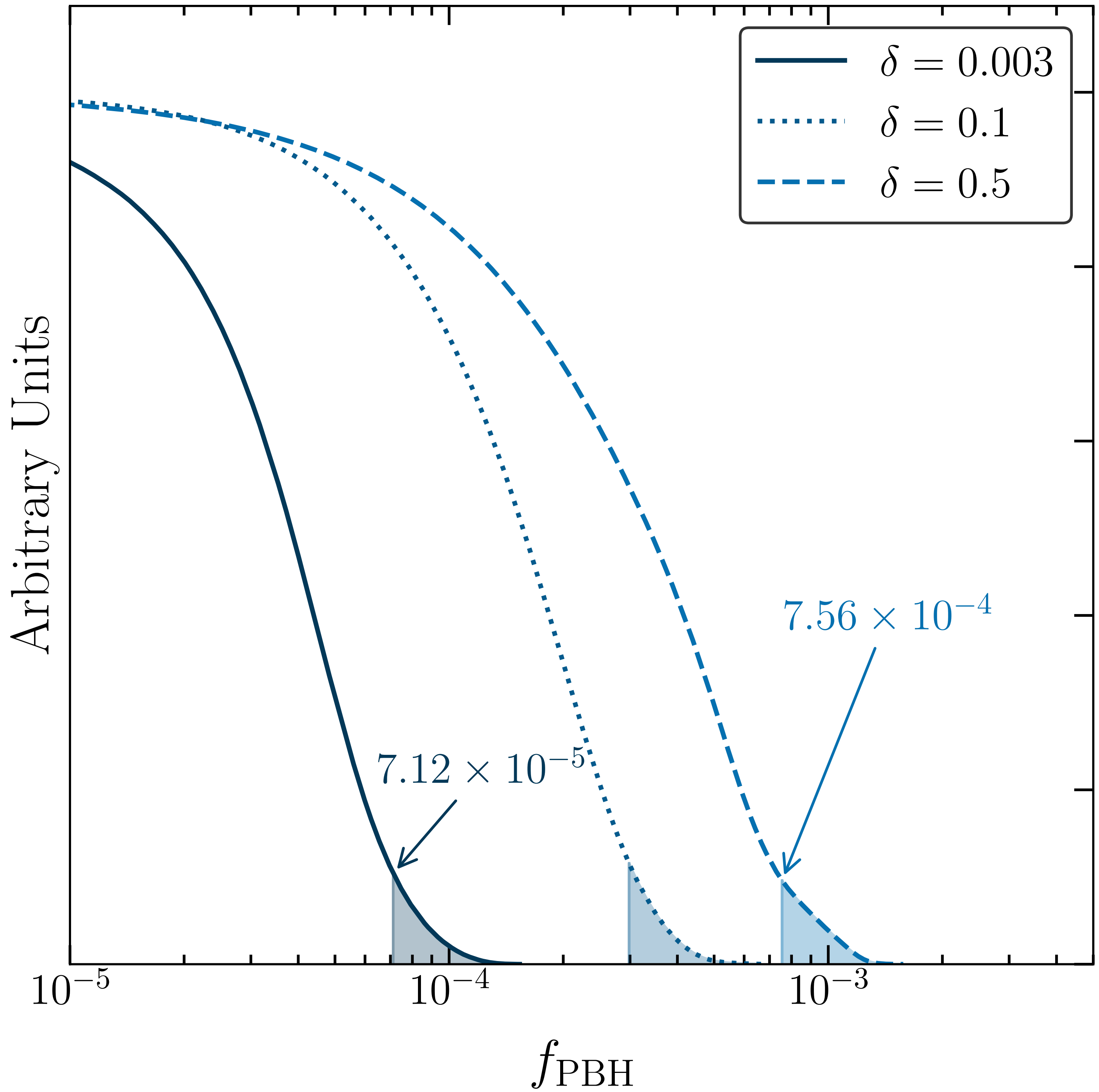


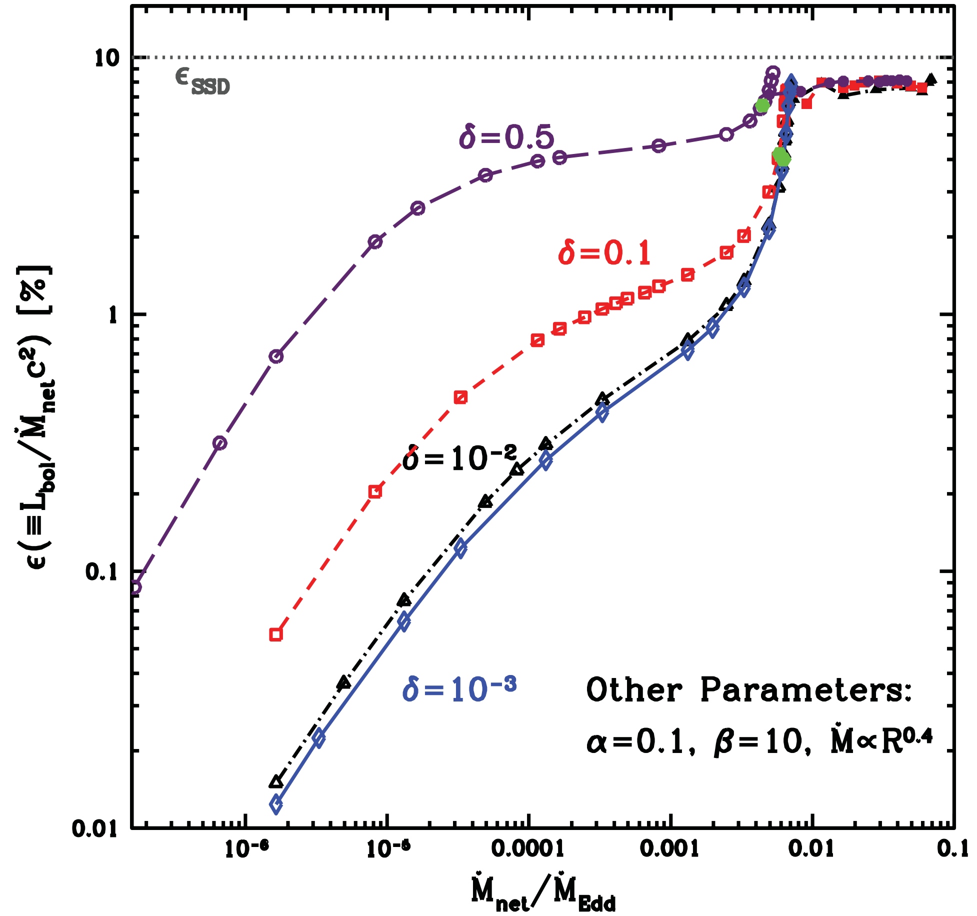
Dominic Agius, Gregory Suczewski, Rouven Essig, **DG**, Francesca Scarcella, Mauro Valli, *in preparation*

Uncertainties in the CMB bound



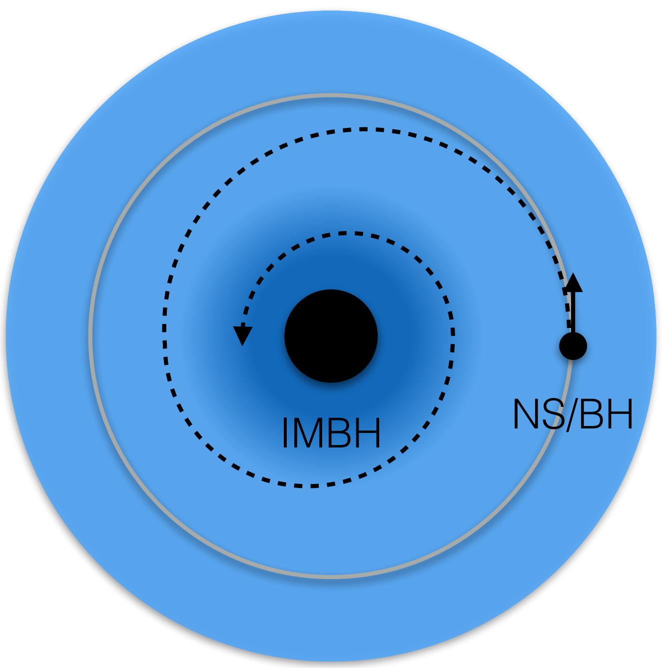
Uncertainties in the CMB bound

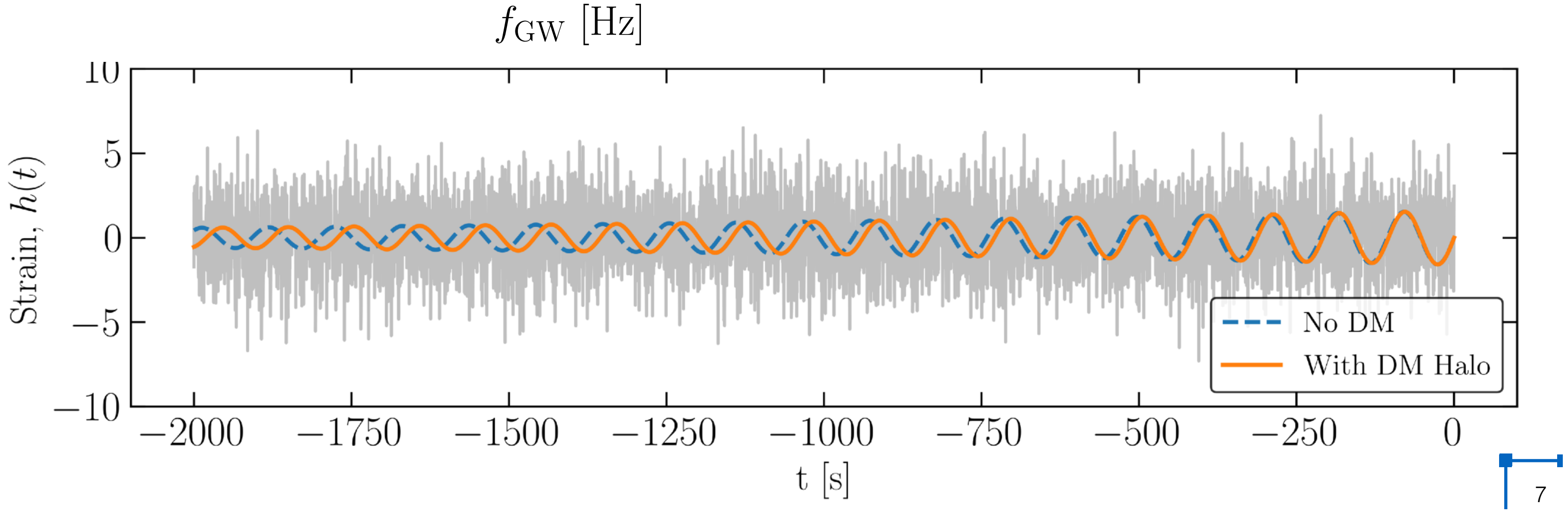




More gravitational energy is transferred to the electrons -> more radiative efficiency -> stronger bound!

- Stellar-mass black holes that inspiral around IMBHs can trace the presence of either accretion disks or Dark Matter overdensities (DM “dresses” or “spikes”)





$$M_{test}\,\ddot{\mathbf{r}} \;=\; \mathbf{F}_{grav}(r,v) + \mathbf{F}_{dyn}(r,v) + \mathbf{F}_{rad}(r,v)$$

$$\mathbf{F}_{grav}(r,v) = -M_{test}\frac{G(M_{IMBH} + M_{halo,enclosed})}{r^3}\mathbf{r}$$

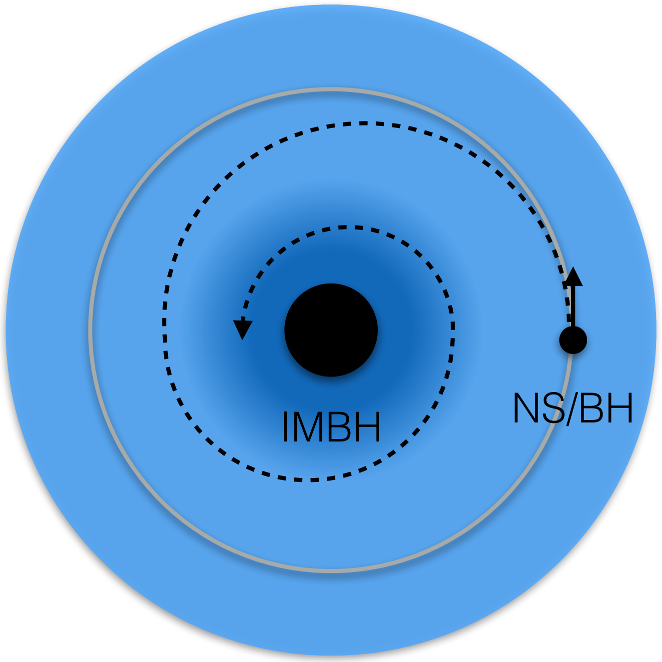
$$\mathbf{F}_{dyn}(r,v) = -M_{test}\,\frac{4\pi\, ln(\Lambda)\, G^2 M_{test}\,\rho(r)}{v^3}\,\mathbf{v},$$

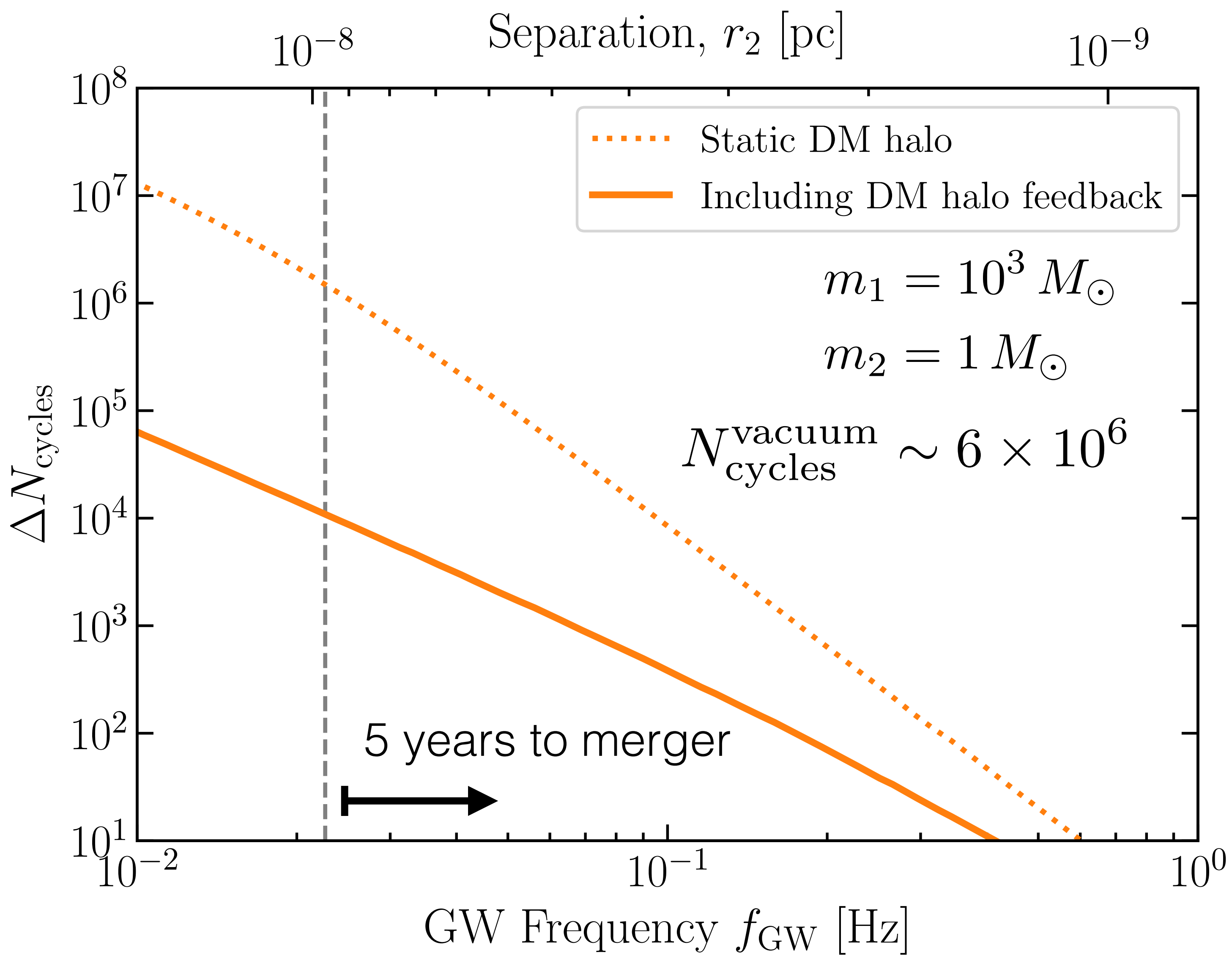
$$\mathbf{F}_{rad}(r,v) = -\frac{32}{5}M_{test}\frac{G^3\,M_{tot}^3\,\nu}{c^5 r^4}\left(1 + \gamma\left(-\frac{743}{336} - \frac{11}{4}\nu\right)\right)\,\mathbf{v}$$

- Kavanagh+ 2002.12811 (PRD)
- Coogan+ 2108.04154 (PRD)
- Cole+ 2211.01362 (Nature Astronomy)

Black Holes as Portals to new Physics

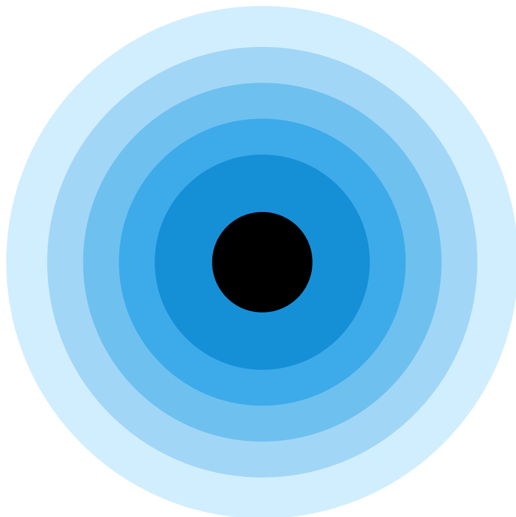
- Stellar-mass black holes that inspiral around IMBHs can trace the presence of either accretion disks or Dark Matter overdensities (DM “dresses” or “spikes”)





- Kavanagh+ 2002.12811 (PRD)
- Coogan+ 2108.04154 (PRD)
- Cole+ 2211.01362 (Nature Astronomy)

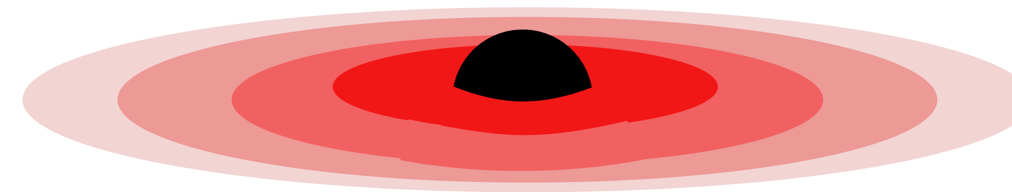
LISA can discriminate environmental effects



Particle Dark Matter
'**Spikes**' or '**Dresses**'

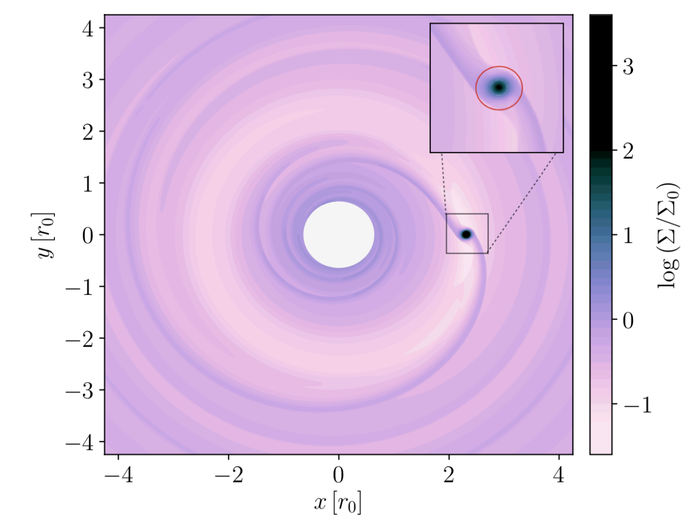
- **Collisionless** DM overdensity
- **Spherical** symmetry
- **Dynamical friction** at work
- **Feedback** on the halo is important

$$\frac{\mathrm{d}E}{\mathrm{d}t} = m_2 v_0 \frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{4\pi (G_N m_2)^2 \rho_{\mathrm{DM}}(r) \xi(v_0)}{v_0} \log \Lambda$$



Baryonic
Accretion Disks

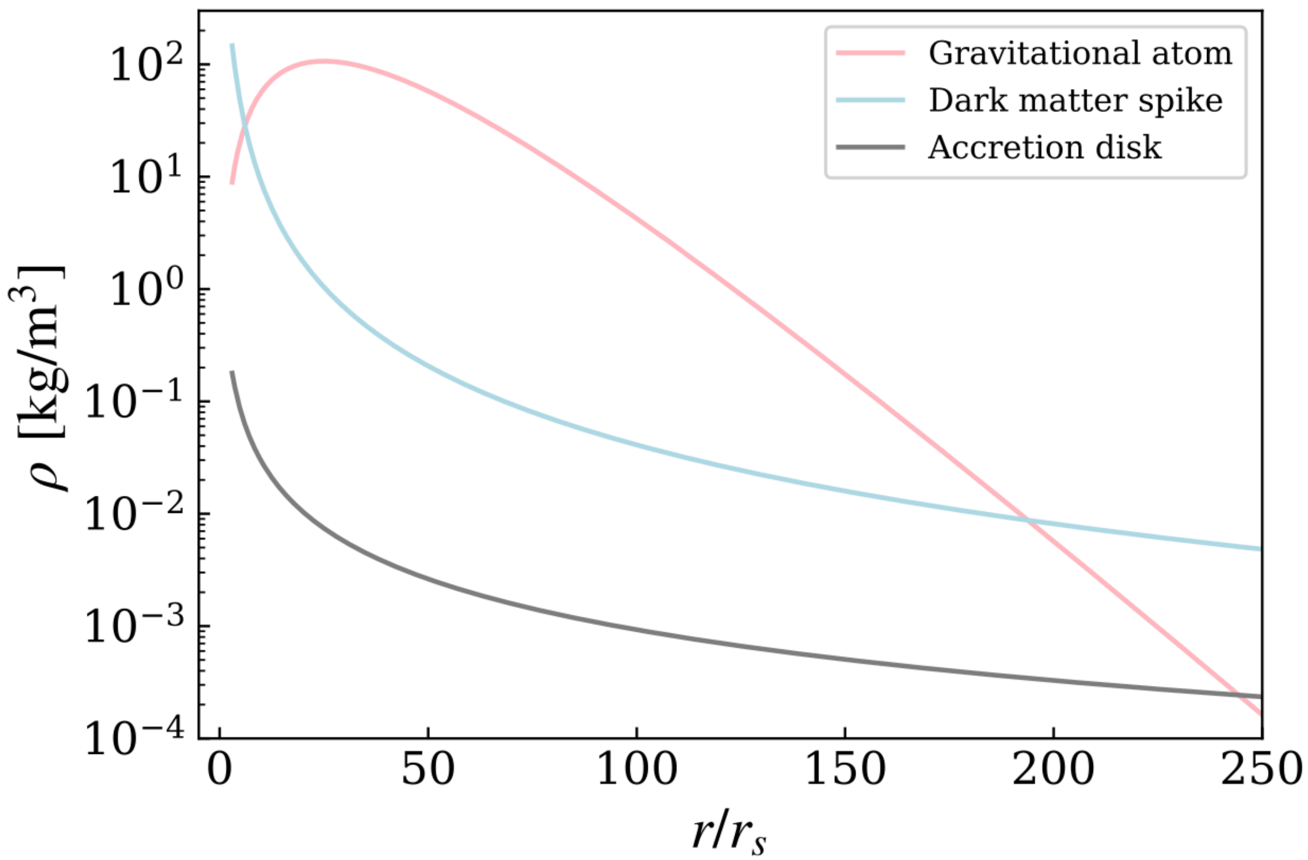
- Differentially rotating **baryonic** disk
- Disk is perturbed by the inspiralling object. Asymmetric "wake"
- Perturbation back-reacts and exerts **torques**

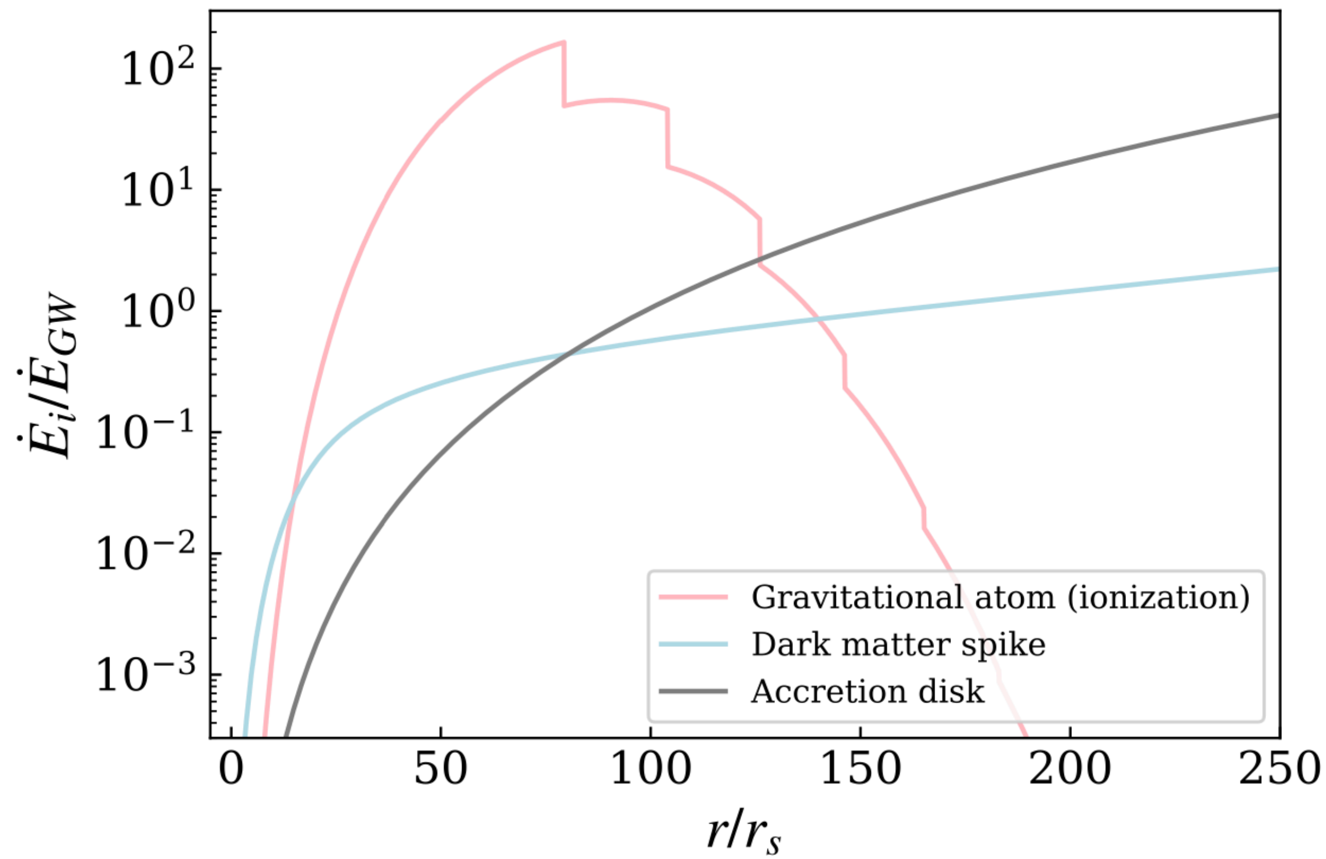


$$T_{\mathrm{I}} = -\Sigma(r) r^4 \Omega^2 q^2 \mathcal{M}^2$$

$$\frac{\mathrm{d}E_{\mathrm{torque}}}{\mathrm{d}t} = \frac{1}{4} m_1 T_{\mathrm{I}} \left(\frac{G_N}{r^3 M}\right)^{1/2}$$

LISA can discriminate environmental effects





Signals **very hard to confuse** in 1 year of LISA data (huge Bayes factors!)

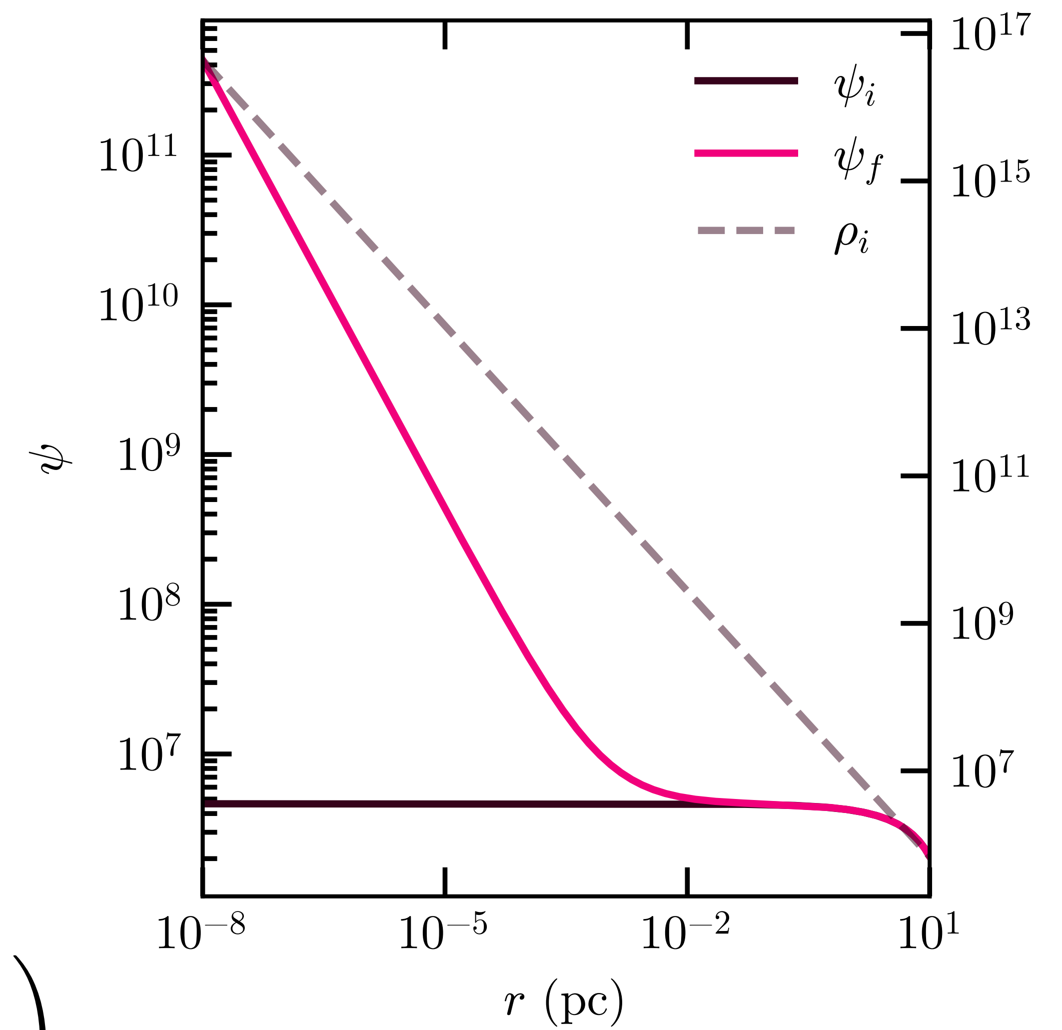
$\log_{10} \mathcal{B}$	Dark dress signal	Accretion disk signal	Gravitational atom signal
Vacuum template	34	6	39
Dark dress template	-	3	39
Accretion disk template	17	-	33
Gravitational atom template	24	6	-

P. Cole, G. Bertone, A. Coogan, **DG**, T. Karydas, B. Kavanagh, T. Spieksma, G. Tommaselli 2211.01362 (Nature Astronomy)

Dark Dresses around IMBH as well

Generalizing Gondolo and Silk, 9906391

- Adiabatic BH growth:
  - Initial density follows a *"cuspy"* profile
  - A BH forms and grows *adiabatically*
  - Eddington analysis
  - Conservation laws are applied
  - Final density is computed



$$\rho(r) = \int \mathrm{d}^3\mathbf{v}\, f(\mathcal{E}, L) = 4\pi \int \mathrm{d}v_r \mathrm{d}v_T\, v_T\, f(\mathcal{E}, L)\,,$$

$$f_k(\mathcal{E}) = \frac{1}{\pi^2\sqrt{8}}\left(\int_0^{\mathcal{E}} \frac{\mathrm{d}^2\rho_k}{\mathrm{d}\Psi^2}\frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}} + \frac{(\mathrm{d}\rho_k/\mathrm{d}\Psi)_{\Psi=0}}{\sqrt{\mathcal{E}}}\right)$$

$$\rho_f(r) = 4\pi \int_{\mathcal{E}_f^{\min}}^{\mathcal{E}_f^{\max}} \mathrm{d}E \int_{L_{\min}}^{L_{\max}} \mathrm{d}L\, \frac{L}{r^2 v_{r,f}} f_i(\mathcal{E}_i(\mathcal{E}_f, L_f), L_f)\,.$$

Radial Action is Conserved $I_{r,x}(\mathcal{E}_x, L) = \frac{1}{\pi}\int_{r_{\text{peri}}}^{r_{\text{apo}}} \mathrm{d}r\; v_{r,x}(r, \mathcal{E}_x, L)$