## PROBES OF PRIMORDIAL black holes as dark matter

# *Sergio Palomares-Ruiz*

IFIC, CSIC - U. Valencia





**RICAP-24 Roma International Conference on Astroparticle Physics**

> Frascati, September 26, 2024



Gravitational waves

Dark Matter

# Primordial Black Holes

Cosmic radiation backgrounds

Formation: Physics of the Early Universe



#### **The early Universe is very hot and dense: ideal environment for black hole formation**





**UCD/2010), which is completely negligible [45]. Therefore, in order to have a relevant population of PBHs, and PBHs, and** 

 $F_{\rm eff}$  in the fractions as low as  $F_{\rm eff}$  mass  $B_{\rm eff}$  mass  $B_{\rm eff}$  in  $P_{\rm eff}$  in  $P_{\rm eff}$ 

masses. In this review, we focus on monochromatic distributions for simplicity, although it is possible to translate

*<sup>s</sup>* enter the horizon, i.e., their wavelength = 2⇡*/k* (which characterizes the size of the

PBHs could form during radiation era from the gravitational collapse of large fluctuations (at horizon entry) with  $\|$ masses of the order of the horizon mass… or via collapse of cosmic string loops or a scalar field, bubble collisions…

$$
M_{\text{PBH}} \sim \frac{t}{G} \sim 10^{15} \left( \frac{t}{10^{-23} \text{ s}} \right) \text{g}
$$
  $t = 10^{-43} \text{ s} \rightarrow M_{\text{PBH}} \sim 10^{-5} \text{ g}$   
 $t = 1 \text{ s} \rightarrow M_{\text{PBH}} \sim 10^{5} M_{\odot}$ 

#### **The early Universe is very hot and dense: ideal environment for black hole formation**

Y. B. Zel'dovich and I. D. Novikov, Sov. Astron. 10:602, 1967 S. Hawking, Mon. Not. R. Astron. Soc. 152:75, 1971



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> $l = 10^{-43} \text{ s} \rightarrow M_{\text{PBH}} \sim 10^{-5} \text{ g}$  $M = 10^{-5}$  $\ell \ell l$ motific inflation models presenting and influence point  $2$ on the initial fraction and lead to a larger population, as well as  $\mathcal{C}$ non-universal nature of the threshold, the use of peak theory provides more accurate  $\mathcal{S}^{\text{max}}$ . Its validity,  $\mathcal{S}^{\text{max}}$  $M_{\rm{max}} \approx 10^5 M_{\rm{max}}$  $\mathbf{v}_1$  $\mathcal{L}$  initial fraction  $\mathcal{L}$  is a very small quantity, since matter and radiation density, since  $\mathcal{L}$  $M_{\rm PBH} \thicksim$ *t*  $\frac{V}{G} \sim 10^{15}$   $\bigg($ *t*  $\frac{1}{10^{-23} s}$  ) g  $t = 10^{-43}$  s  $\rightarrow M_{\text{PBH}} \sim 10^{-5}$  g  $t = 1 \text{ s} \rightarrow M_{\text{PBH}} \sim 10^5 M_{\odot}$

⌦PBH(*M*) = (*M*)(1 + *z<sup>f</sup>* )⌦ ' <sup>1</sup>*/*<sup>2</sup> ✓ (*M*) 1*.*15 ⇥ 10<sup>8</sup> ◆ ✓ *M* Black holes radiate thermally, so they eventually evaporate  $D N$  Page Phus Rev  $D13.198$  1976 D. N. Page, Phys. Rev. D13:198, 1976 S. W. Hawking, Commun. Math. Phys. 43:199, 1975

$$
T_{\text{BH}} \sim \frac{1}{8 \pi G M_{\text{BH}}} \sim 10 \left( \frac{10^{15} \text{ g}}{M_{\text{BH}}} \right) \text{MeV} \qquad \qquad \tau(M_{\text{BH}}) \sim G^2 M_{\text{BH}}^3 \sim 100 \left( \frac{M_{\text{BH}}}{10^{15} \text{ g}} \right)^3 \text{Gyr}
$$

 $O(n)$ , cricle would be proserve control For masses between 10 $^{-17}$  M $_{\odot}$  and 10 $^{5}$  M $_{\odot},$  they would be present today



#### **The early Universe is very hot and dense: ideal environment for black hole formation**

Y. B. Zel'dovich and I. D. Novikov, Sov. Astron. 10:602, 1967 S. Hawking, Mon. Not. R. Astron. Soc. 152:75, 1971



**UCD/2010), which is completely negligible [45]. Therefore, in order to have a relevant population of PBHs, and PBHs, and** 

*<sup>s</sup>* enter the horizon, i.e., their wavelength = 2⇡*/k* (which characterizes the size of the PBHs could form during radiation era from the gravitational collapse of large fluctuations (at horizon entry) with  $\|$ masses of the order of the horizon mass… or via collapse of cosmic string loops or a scalar field, bubble collisions…

> larger values of the initial power spectrum are needed. On the other hand, the assumption of a gaussian distribution  $M = 10^{-5}$  $\ell \ell l$ motific inflation models presenting and influence point  $\ell$  $t = 10^{-43}$  s → *M*<sub>PBH</sub> ∼ 10<sup>-5</sup> g non-universal nature of the threshold, the use of peak theory provides more accurate  $\mathcal{S}^{\text{max}}$ . Its validity,  $\mathcal{S}^{\text{max}}$  $M_{\rm{max}} \approx 10^5 M_{\rm{max}}$  $\mathbf{v}_1$  $t = 1 \text{ s} \rightarrow M_{\text{PBH}} \sim 10^5 M_{\odot}$  $M_{\rm PBH} \thicksim$ *t*  $\frac{V}{G} \sim 10^{15}$   $\bigg($ *t*  $\frac{1}{10^{-23} s}$  ) g

⌦PBH(*M*) = (*M*)(1 + *z<sup>f</sup>* )⌦ ' <sup>1</sup>*/*<sup>2</sup> ✓ (*M*) 1*.*15 ⇥ 10<sup>8</sup> ◆ ✓ *M* Black holes radiate thermally, so they eventually evaporate  $D N$  Page Phus Rev  $D13.198$  1976 D. N. Page, Phys. Rev. D13:198, 1976 power spectrum imply approximately *monochromatic* distributions. For instance, chaotic new inflation may give rise to relatively narrow peaks  $\overline{M}$ . However, inflation point in a plateau of the potential point in a plateau of [56, 57], or hybrid inflation [58], predict, instead, *extended* mass functions, which can span over a large range of PBHs  $\sum_{i=1}^N C_i^2 M_i^3$  on  $100$  monochromatic  $G_{\rm vir}$  $\mu_{\rm F}$  is the very stringent of  $\mu_{\rm BH}$  can be very string more parameters to fit having more pa  $\frac{1}{2}$  in the monochromatic case, the monochromatic case, the most or all of the monochromatic case, the  $\frac{1}{10^{15} \text{ g}}$ 4. ACCRETION ON A CONTRACTOR  $O(n)$ , cricle would be proserve control For masses between 10 $^{-17}$  M $_{\odot}$  and 10 $^{5}$  M $_{\odot},$  they would be present today  $T_{\rm BH} \sim \frac{1}{8 \pi G}$  $\frac{1}{8 \pi G M_{\rm BH}} \sim 10$  $10^{15}$  g  $\frac{E}{M_{\rm BH}}$  ) MeV S. W. Hawking, Commun. Math. Phys. 43:199, 1975  $\tau(M_{\rm BH}) \sim G^2 M_{\rm BH}^3 \sim 100$  (  $M_{\rm BH}$  $\sqrt{10^{15} g}$ 3 Gyr **PBHs would form before BBN, so they** 

3

**A DM candidate which is not a new particle (although its formation involves BSM physics)**



G. F. Chapline, Nature 253:251, 1975 PM candidate!

**would not count as baryonic matter**

### **Even if they cannot form all the dark matter… still of great interest**

#### **Recent detection of black hole mergers with gravitational waves**

B. P. Abbott et al. [LVC], Phys. Rev. Lett. 116:061102, 2016; Phys. Rev. Lett. 116:241103, 2016; Phys. Rev. Lett. 116:131102, 2016; Phys. Rev. X6:041015, 2016; Phys. Rev. Lett. 118:221101, 2017; Astrophys. J. 851:L35, 2017; Phys. Rev. Lett. 119:141101, 2017

#### **Did LIGO detect dark matter?**

S. Bird et al., Phys. Rev. Lett. 116:201301, 2016

**Insight into early Universe physics (inflation, phase transitions…)**



#### **WIMPs and PBHs relation: no go**

B. Lacki and J. F. Beacom, Astrophys. J. 720:L67, 2010 R. Saito and S. Shirai, Phys. Lett. B697:95, 2011 D. Zhang, Mon. Not. R. Astron. Soc. 418:1850, 2011

#### **PBHs as DM (or other exotics) generators**

**Timing problem: Could PBHs be connected to the origin of SMBHs?**

e.g., A. Smith and V. Bromm, Contemp. Phys. 60:111, 2019

### PBHS AS DM: ABUNDANCE CONSTRAINTS

### Evaporation Reversion

**Hawking radiation: Multi-messenger signals Heating and ionization of the IGM**



**Stellar and quasar micro-lensing Supernovae magnification distribution Strong lensing of FRBs Femtolensing of GRBs**

#### Gravitational Waves **Accretion**

**Binary PBHs merger rates Stochastic GW background From PBH production**

**Emission of a broad band spectrum: Heating and ionization of the IGM Contribution to the (X-ray, infrared, radio) astrophysical spectra**

#### Dynamical

**Disruption of bound systems: galaxies, globular clusters, stellar binaries… Galactic disk and dynamical friction Accretion by compact objects which might subsequently be destroyed**





P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Using

### **74** Chapter 3. Primordial Black Holes is the V bkgs; ionization and thermal history **Partial evaporation** Hawking radiation: cosmic-ray, γ-ray,



P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Using

#### **Partial evaporation**

#### Microlensing of stars, SN, QSO

**74 Cravitational Lensing Community Community Gravitational lensing**



P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Using







Sergio Palomares-Ruiz as DM as function of the Probes of PBHs as DM

**Gravitational waves**

**Partial evaporation**



### PBHS: EVAPORATION AND **ACCRETION**



A. M. Green and B. J. Kavanagh, J. Phys. G. 48:043001, 2021

Types of signals



**Figure 2.** Constraints on the fraction of DM in the form of PBHs *f*PBH, with mass *M*PBH, A. M. Green and B. J. Kavanagh, **ORGORIZE:** J. Phys. G. 48:043001, 2021 constraint. In each case the excluded regions are shaded. Top left: evaporation constraints

on PBHs (section 3.1): extragalactic gamma-ray background [55], CMB [153, 154], dwarf Galaxy heating [155], EDGES 21 cm [156], Voyager e*<sup>±</sup>* [157], 511 keV gammaray line [158, 159] and the MeV Galactic diffuse !ux [160]. Top middle: gravitational lensing constraints on compact objects (section 3.3): stellar microlensing (MACHO [161], EROS [12], OGLE [162], HSC [163]), Icarus lensing event [164], and supernovae magnituding the constraints on PBHs from GWs (section 3.4). Top right: constraints on PBHs from GWs (section 3.4) produced by individual mergers [166, 167] and the stochastic background of mergers [168]. Note that there are substantial uncertainties on GW constraints, arising from the possible disruption of PBH binaries. Bottom left: dynamical constraints on compact  $\blacksquare$ accretion constraints on  $P$ Hs (section 3.6): CMB  $\sim$  CMB  $\sim$  CMB  $\sim$  CMB  $\sim$  CMB  $\sim$  21 cm  $\sim$  $\mathcal{H}$  and dwarf  $\mathcal{H}$  and dwarf Galaxy heating  $\mathcal{H}$ . Digitised bounds and plotting codes and plot

We restrict our attention to PBHs with  $\mathcal{M}$ the DM halos of small dwarf Galaxies. The abundance of more various constraints on the abundance of more various massive PBHs, for an overview, see reference in the PBHs, for an overview, and the PBHs, for an overview, and have a delta-function MF and do not form clusters. We discuss the application of delta-function of delta-functio constraints to extended MFs in section 3.10. As discussed in section 3.4 understanding the late time columns is an outstanding challenge. In this section we use the section we use  $\mathcal{P}(P)$ limits which apply specifically to  $P$ Hs and 'Co' to denote limits which apply to any compact  $\mathcal{L}$ 

**Neutrinos Electrons Figure 2.** Constraints on the fraction of DM in the form of PBHs *f*PBH, with mass *M*PBH,

or in the form of compact objects, *f*CO, with mass *M*CO for each of the different types of

**21cm Lyman-α**

object.

**Messenger production Energy injection**  We restrict our attention to PBHs with *<sup>M</sup>*PBH ! <sup>10</sup><sup>7</sup>*M*" which could, in principle, constitute

**Photons**

constraint. In each case the excluded regions are shaded. Top left: evaporation constraints are shaded. Top left: evaporation constraints are shaded. Top left: evaporation constraints are shaded. The exclude of the exclude on PBHs (section 3.1): extragalactic gamma-ray background [55], CMB [153, 154], CMB [153, 154], CMB [153, 154], dwarf Galaxy heating [155], EDGES 21 cm [156], Voyager e*<sup>±</sup>* [157], 511 keV gammaray line [158, 159] and the MeV Galactic diffuse !ux [160]. Top middle: gravitational lensing constraints on compact objects (section 3.3): stellar microlensing (MACHO [161], EROS [12], OGLE [162], HSC [163]), Icarus lensing event [164], and supernovae magnituding the constraints on PBHs from GWs (section 3.4). Top right: constraints on PBHs from GWs (section 3 produced by individual mergers [166, 167] and the stochastic background of mergers [168]. Note that there are substantial uncertainties on GW constraints, arising from the possible disruption of PBH binaries. Bottom left: dynamical constraints on compact objects (section 3.5): from dwarf Galaxies [169] and wide binaries [170]. Bottom right: accretion constraints on PBHs (section 3.6): CMB [171], EDGES 21 cm [171], EDGES 21 cm [171], x-ray, x-ray, x-[173], radio [173], radio [173], radio [174]. Digitised bounds and plotting codes bounds and plotting codes and

 $H_{\text{H}}$  Antimatter  $T_{\rm{H}}$  in  $\sim$   $T_{\rm{V}}$  in section 3.10. As  $T_{\rm{V}}$ time clustering of PBHs is an outstanding challenge. In this section we use 'PBH' to denote

**PROPERTY PROPERTY SERGIO PALOMARES-RUIZ** 7 **PROPERTY SPECIES AS DM** 

 $\overline{\phantom{a}}$ 

are available online at PBHbounds.

 $\frac{1}{2}$  in the IGM *<u>Energy injection</u>* present day **in the IGM**  $\blacksquare$ 

**CMB**

are available online at PBHbounds.

#### MESSENGER PRODUCTION BY PBHS where ⇢*<sup>m</sup>* = R <sup>1</sup> <sup>0</sup> <sup>d</sup>*MM* <sup>d</sup>*n*(*M,z*) <sup>d</sup>*<sup>M</sup>* for normalization, and the mass function of DM halos is based

Evaporation

Many references…

**Extragalactic and galactic γ/X-ray backgrounds Local electron-positron flux Electron-induced near-UV, synchrotron and IC flux 511 keV electron-positron annihilation line Antiproton flux**

Extragalactic and galactic neutrino flux



X.-H. Tan and J.-Q. Xia,

on the model by ref.[38] commonly used. We show contributions from extragalactic and Galactic sources for all components at *<sup>M</sup>*PBH = 7 ⇥ <sup>10</sup><sup>16</sup> g in Fig.2, with the same



N. Bernal, V. Albornoz-Muñoz, SPR and  $\mathbf{b}$  and  $\mathbf{b}$  and  $\mathbf{b}$  and  $\mathbf{b}$  been verified to provide a good to provide a go AP 10:068. 2022 P. Villanueva-Domingo, JCAP 10:068, 2022 B.-Y. Su et al., Eur. Phys. J. C84:606, 2024



 $\delta$ u et al., Eur. Phys. J. C84:606,

#### Accretion

Galactic IR/X/radio backgrounds  $\frac{2}{3}$  10°



See also:

 $\overline{\mathsf{K}}$ & *E* e<br>shlín: *,* Kashlinsky, Astrophys. J. 823:L25, 2016 *D*. Gage<br>G. Hass & *E* 2 −1 D. Gaggero et al., Phys. Rev. Lett. 118:241101, 2017 *,* G. Hassinger, JCAP 07:022, 2020

Sergio Palomares-Ruiz 8 Probes of PBHs as DM

Assuming all DM in the Milky Way consists of PBHs with ΩPBH = ΩDM. Dashed, solid, and dotted curve corresponds to fDM,disk = 0.0, 0.25, and 1.0 accounting for all the ISM target gases. Dot-dashed curve takes into account radiation feedback for the case of

### ENERGY INJECTION FROM PBHS EVAPORATION

 $\sqrt{2}$ 

**Evaporation rate**



 $T_{\rm BH}$  ∼



D. Page, Phys. Rev. D13:198, 1976; Phys. Rev. D14:3260, 1976; Phys. Rev. D16:2402, 1977

**thermal body with temperature:**

Emission rate equal to that of a  
thermal body with temperature: 
$$
T_{BH} \sim \frac{1}{8\pi G M_{BH}} \sim 10 \left(\frac{10^{15} \text{ g}}{M_{BH}}\right) \text{MeV}
$$
  $\tau(M_{BH}) \sim G^2 M_{BH}^3 \sim 100 \left(\frac{M_{BH}}{10^{15} \text{ g}}\right)^3 \text{Gyr}$ 

$$
\sim G^2 M_{\text{BH}}^3 \sim 100 \left( \frac{M_{\text{BH}}}{10^{15} \text{ g}} \right)^3
$$

$$
\frac{dE}{dVdt}\bigg)_{inj} = n_{PBH} \int E\left(\frac{dN}{dt dE}\right)_{evap} dE = \frac{f_{PBH} \rho_{DM}}{M_{PBH}} \int E \frac{g}{2\pi} \frac{\Gamma(E, M_{PBH})}{e^{E/T_{PBH}} \pm 1} dE
$$

**Energy injection** Energy *deposition* from DM annihilations

#### **Emission of a thermal quasi-black-body spectrum**

J. H. McGibbon and B. R. Webber, Phys. Rev. D41:3052, 1990 J. H. McGibbon, Phys. Rev. D44:376, 1991

### **Energy deposition**



### Excitations, ionization and heating **Excitations, ionization and heating**

What does not do not an

![](_page_16_Figure_15.jpeg)

![](_page_16_Picture_17.jpeg)

T. R. Slatyer, Phys. Rev. D93:023521, 2016  $\mathbb{R}$  and  $\mathbb{R}$ . Vincent  $\mathbb{R}$ 

Rate of energy injection/deposition into *c* = heat, ionization, excitation

### ENERGY INJECTION FROM ACCRETION BY PBHS

**Acrettion rate**

**Energy injection**

![](_page_17_Picture_2.jpeg)

**Usually Bondi-Hoyle-Lyttleton model**

$$
\dot{M}_{\text{PBH}} = 4\pi \lambda \rho_{\infty} \frac{(GM_{\text{PBH}})^2}{\left(c_s^2 + v_{\text{rel}}^2\right)^{3/2}}
$$

F. Hoyle and R. A. Lyttleton, Mon. Not. R. Astron. Soc. 101:227, 1941 H. Bondi and F. Hoyle, Mon. Not. R. Astron. Soc. 104:273, 1944 H. Bondi, Mon. Not. R. Astron. Soc. 112:195, 1952

DM imprint

K. Park and M. Ricotti, Astrophys. J. 739:2, 2011;<br>Actualise 1 747.0.2012 Actualise 1 747.0.2012 Astrophys. J. 747:9, 2012; Astrophys. J. 767:163, 2013

 $= \perp_{\mathsf{acc}}$  n $_{\mathsf{PBH}} = \perp_{\mathsf{acc}}$ 

Luminosity:

inj

dE  $\frac{dE}{dv dt}$ 

$$
_{\rm acc} = \epsilon \dot{\rm M}_{\rm PBH}
$$

 $t_{\rm PBH}$   $\rho_{\rm DM}$ 

MPBH

if cooling is inefficient, a thick disk could form:  $\mathsf{ADAF} \qquad \epsilon = \epsilon_\mathsf{O}$  $\frac{1}{2}$ 

Energy *deposition* from DM annihilations

See, e.g., F.-G. Xie and F. Yuan, Mon. Not. R. Astron. Soc. 427:1580, 2012 *f*¯*f* , ,*W*<sup>+</sup>*W*, ... *e*<sup>+</sup> *, e,* using e.g. [ Pythia, Mardon'09, PPPC4DMID]

 $\sqrt{2}$ 

### **Energy deposition**

![](_page_17_Picture_14.jpeg)

Excitations, ionization and heating

![](_page_17_Figure_16.jpeg)

From A. C. Vincent

**Not on-the-spot**

 $(10 \text{ \AA}$ 

LEdd

 $\bigwedge^a$ 

![](_page_17_Figure_19.jpeg)

T. R. Slatyer, Phys. Rev. D93:023521, 2016

Sergio Palomares-Ruiz **10** Probes of PBHs as DM **Energy spectrum: synchrotron, IC and bremsstrahlung** 

#### EFFECTS OF ENERGY INJECTION FROM PBHS matic PBH population with mass *M*PBH = 10<sup>3</sup>*M*, for di↵erent PBH abundances, as labelled. The left figure is for the BHL accretion scenario, and the right figure shows the PR scenario, with

#### **cosmology (with parameters described in the caption of cosmology (with parameters described in the caption of** of Figure 1) is described by the solid black line. **Damping of CMB anisotropies**

#### **Evaporation**

- V. Poulin , J. Lesgourgues and P. D. Serpico, JCAP 03:043, 2017
- S. Clark et al., Phys. Rev. D95:083006, 2017
- P. Stöcker, M. Kramer, J. Lesgourgues and V. Poulin, JCAP 03:018, 2018
- H. Poulter et al., arXiv:1907.06485
- S. K. Acharya and R. Katri, JCAP 06:018, 2020

#### **Accretion**

- B. J. Carr, Mon. Not. R. Astron. Soc 194:639, 1981
- M. Ricotti, J. P. Ostriker and K. J. Mack, Astrophys. J. 680:829, 2008
- B. Horowitz, arXiv: 1612.07264
- Y. Ali-Haïmoud and M. Kamionkowski, Phys. Rev. D95:043534, 2017
- V. Poulin et al., Phys. Rev. D96:083524, 2017
- P. Serpico et al., Phys. Rev. Res. 2:023204, 2020
- L. Piga et al., JCAP 12:016, 2022
- G. Facchinetti, M. Lucca and S. Clesse, Phys. Rev. D107:043537, 2022
- D. Agius et al., JCAP 07:003, 2024

#### Heating of the 21cm temperature Broadening of  $\mathbf{c} \mathbf{r}$

![](_page_18_Picture_19.jpeg)

Sergio Palomares-Ruiz and the standard scenario (with fill black lines) are also depicted. See text for the standard scenario (with for the standard by the solid black lines) are also  $\mathbf{DM}$ O. Mena, SPR, P. Villanueva-Domingo and k ↓ 10.15 Mpc−1 (left panel) and k ∆ 14 mpc−1 (left panel) and k ∴ 14 Mpc−1 (left panel) and k ∞ 14 mpc−1 (left panel) and k ∞ 14 mpc + 2 mpc 0.4 Mitte−Phile\_Rev\_D100:043540\_2019 M.K.Saha, A. Sing S. J. Witte, Phys. Rev. D100:043540, 2019 P.R. K. Sana, A. Sing For a non-spin  $\alpha$   $\alpha$  above expectation  $\alpha$   $\alpha$  above  $\alpha$ 

![](_page_18_Figure_21.jpeg)

Figure 5: The impact of the accretion recipe on the CMB *T T* (left) and *EE* (right) power spectrum D. Agius et al., JCAP 07:003, 2024 for a monochromatic population of PBHs with masses *M* = 10<sup>3</sup> *M*, assuming the fixed ⇤CDM

#### Broadening of Lyman-a absorption features  $\sigma$  die Convo  $\overline{\phantom{a}}$  $N = 180$ nusur pu

![](_page_18_Figure_24.jpeg)

A. K. Saha, A. Singh, P. Parashari and R. Laha, arXiv:2409.10617 shift, in presence of non-spinning PBH DM (teal) and in the

10<sup>1</sup> 10<sup>2</sup> 10<sup>3</sup>

# Example of evaporation constraint: Neutrino flux

B. J. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, Phys. Rev. D81:104019, 2010 B. Dasgupta, R. Laha and A. Ray, Phys. Rev. Lett. 125:101101, 2020 S. Wang et al., Phys., Rev. D103:043010, 2021 V. De Romeri, P. Martínez-Miravé and M. Tórtola, JCAP 10:051, 2021 R. Calabrese et al., Phys. Lett. B829:137050, 2022 N. Bernal, V. Albornoz-Muñoz, SPR and P. Villanueva-Domingo, JCAP 10:068, 2022

Sergio Palomares-Ruiz 12 Probes of PBHs as DM

#### Neutrinos from PBHs evaporation

![](_page_20_Figure_1.jpeg)

![](_page_20_Figure_2.jpeg)

PBH signal invisible µ

![](_page_20_Figure_3.jpeg)

**…and prospects for HK, JUNO, DUNE, ARGO, DARWIN**

![](_page_20_Figure_5.jpeg)

reva-Domingo, JCAP 10:068, 2022  $\ddot{o}$  the detectors discussed in this work: HK (red solid curve),  $\ddot{o}$  and  $\ddot{o}$ 

DM<br>DM Probes of PBHs as DM

## Example of accretion constraint: 21cm signal

#### In the context of EDGES (accretion):

A. Hektor et al., Phys. Rev. D98:023503, 2018 Y. Yang, Phys. Rev. D104:063528, 2021

Forecasts (accretion): O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019

**For evaporation constraints, see also:** In the context of EDGES (evaporation): S. Clark et al., Phys. Rev. D98:043006, 2018 Y. Yang, Phys. Rev. D102:083538, 2020 A. Halder and M. Pandey, MNRAS 508:3446, 2021 A . Halder and S. Banerjee, Phys. Rev. D103:0530044, 2021 S. Mittal et al., JCAP 03:030, 2022 U. Mukhopadhyay, D. Majumdar and A. Halder, JCAP 10:099, 2022 A. K. Saha and R. Laha, Phys. Rev. D105:103026, 2022

#### Forecasts (evaporation):

P. K. Natwariya, A. C. Nayak and T. Srivastava, MNRAS 510, 4236, 2021 J. Cang, Y. Gao and Y.-Z. Ma, JCAP 03:012, 2022 Y. Yang, Phys. Rev. D106:123508, 2022

![](_page_22_Figure_0.jpeg)

### THE 21CM LINE

Predicted by H. van de Hulst in 1944 and first observed by H. I. Ewen and E. M.Purcell in 1951

**Hyperfine transition: ν = 1420 Mhz** 

**21cm photon from HI clouds during cosmic dawn: ν ~ 100 Mhz**

![](_page_22_Figure_5.jpeg)

**neutral hydrogen gas (intergalactic medium: IGM)**

**observer**

![](_page_22_Picture_8.jpeg)

![](_page_22_Picture_10.jpeg)

**CMB photons as backlight emission/absorption**

**Population of ground and excited states controlled by:** 

z~1000 population of ground and absorption and stimulated emission of background radiation z=**0 collisions of neutral hydrogen excitation/de-excitation by Lyman-α photons** 

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Sergio Palomares-Ruiz Probes of PBHs as DM

### THE 21CM SIGNAL

**Differential brightness temperature**

 $\delta T_b (v) \approx 27 x_{HI} (1+\delta) \left(1-\frac{T_{CMB}}{T}\right)$  $T_{S}$  $\sqrt{2}$  $\setminus$ ⎜  $\overline{a}$ ⎠ ⎟  $1 + z$ 10  $\sqrt{2}$  $\setminus$  $\left(\frac{1+z}{10}\right)$ ⎠ ⎟ 1/2

**Fraction of neutral H** Reionization suppresses the signal **Spin temperature:** 

**Baryon overdensity**

16

 $n_1$  $n<sub>O</sub>$  $= 3 e^{-T_{21}/T_{S}}$ 

**occupation of the two states**

 $\delta T_b \approx 0$  if  $T_S - T_{CMB}$  $\delta T_b > 0$  if  $T_s > T_{CMB}$  $\delta T_b < 0$  if  $T_s < T_{CMB}$ 

**no signal**

**signal in emission, can saturate**

**signal in absorption, limited by gas temperature**

Astrophysical processes decouple  $T_S$  from  $T_{CMB}$ 

Sergio Palomares-Ruiz Probes of PBHs as DM

### THE 21CM SIGNAL: TIME EVOLUTION

**Reionization: no neutral hydrogen**

> **X-ray heating: from absorption to emission**

 $T_{\rm CMB}$ 

 $T_{\rm K}$ 

Sergio Palomares-Ruiz<br>Bergio Palomares-Ruiz<br>Bergio Palomares-Ruiz<br>Bergio Palomares-Ruiz<br>Bergio Palomares-Ruiz<br>Render Probe<br>Palomares-Ruiz<br>Render Probes of Probes of Person Probes of Person Probes of Person Probes of Person **Dense medium: Spin temperature coupled to gas via collisions and gas coupled to CMB via Compton scattering** 

**CMB decouples: gas cools faster** 

**density decreases: collisions not effective**

**first stars: Lyman α coupling**

10 20 30 100 300

![](_page_24_Picture_10.jpeg)

#### **THE 21 CM SIGNAL** The 21cm signal: Time evolution

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![](_page_25_Figure_1.jpeg)

brightness temperature (medium panel) and 21 cm power spectrum (bottom panel) as a

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**Dense medium: Spin temperature coupled to gas via collisions and gas coupled to CMB via Compton scattering** 

**CMB decouples: gas cools faster** 

#### Dark Ages - sity decreases: <u>k=0.03 Mpc<sup>-1</sup></u> LOWS not effective

![](_page_25_Picture_6.jpeg)

#### **THE 21 CM SIGNAL** The 21cm signal: Time evolution

![](_page_26_Figure_1.jpeg)

#### **THE 21 CM SIGNAL** The 21cm signal: Time evolution

![](_page_27_Figure_1.jpeg)

on-site measurements of the reflection coefficients of the antennas.

#### PBHs: Brightness temperature

7 8 **Accretion: Injected energy goes into ionizing and heating the IGM**

![](_page_28_Figure_2.jpeg)

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Probes of PBHs as DM

#### PBHs: 21cm power spectrum

J. C. Pober et al., Astrophys. J. 145:65, 2013

We use 21cmSense

J. C. Pober et al., Astrophys. J. 782:66, 2014 **Four-parameter astrophysical model** 

![](_page_29_Figure_3.jpeg)

O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019 heating, and Lyman-α production by x-ray sourcess of the Lyman-α production by x-ray sourcess of the Lyman-a p<br>The Lyman-a production by x-ray sourcess of the Lyman-a production by x-ray sourcess of the Lyman-a production O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019

dependence on the total x-ray emission rate, which is pro-

Sergio Palomares-Ruiz are the same as in the same as in the same are the same as in Fig. 20. The same states  $19$ Probes of PBHs as DM

#### $\bf{I}$ PBHs abundance: Sensitivity

![](_page_30_Figure_1.jpeg)

G. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Kev. D100:045540, 2019 10<sup>3</sup>*M*. Results are compared to various limits derived from microlensing surveys and the CMB. O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019

Sergio Palomares-Ruiz Probes of PBHs as DM rise to an observable signal, we show here that these calculations had not self-consistently accounted for the global

Y. Ali-Haïmoud and M. Kamionkowski, Phys. Rev. D95:043534, 2017

B. Horowitz, arXiv: 1612.07264

V. Poulin et al., Phys. Rev. D96:083524, 2017

P. Serpico et al., Phys. Rev. Res. 2:023204, 2020

#### $\bf{I}$ PBHs abundance: Sensitivity

![](_page_31_Figure_1.jpeg)

G. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Kev. D100:045540, 2019 10<sup>3</sup>*M*. Results are compared to various limits derived from microlensing surveys and the CMB. O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019

Sergio Palomares-Ruiz Probes of PBHs as DM rise to an observable signal, we show here that these calculations had not self-consistently accounted for the global

P. Serpico et al.,

V. Poulin et al.,

arXiv: 1612.07264

Y. Ali-Haïmoud and

M. Kamionkowski,

B. Horowitz,

Phys. Rev. Res. 2:023204, 2020

Phys. Rev. D96:083524, 2017

Phys. Rev. D95:043534, 2017

#### $\bf{I}$ PBHs abundance: Sensitivity

![](_page_32_Figure_1.jpeg)

G. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Kev. D100:045540, 2019 10<sup>3</sup>*M*. Results are compared to various limits derived from microlensing surveys and the CMB. O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019

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M. Kamionkowski,

V. Poulin et al., Phys. Rev. D96:083524, 2017

P. Serpico et al., Phys. Rev. Res. 2:023204, 2020

![](_page_32_Picture_8.jpeg)

### Some final words of caution

**All constraints have caveats!**

**They all depend on the mass function! Extended mass functions are, in general, more constrained** 

**Uncertainties on estimates and observations can be very significant**

### Some final words of caution

### **All constraints have caveats!**

**They all depend on the mass function! Extended mass functions are, in general, more constrained** 

Just to name a few...

Evaporation

**Memory burden : slowing down of evaporation** 

![](_page_34_Picture_6.jpeg)

**Size of sources, wave optics, halo properties…**

Accretion

**Accretion modeling**

Gravitational Waves

**Uncertainties on estimates and** 

**observations can be very significant**

**Clustering and PBH binaries survival**

### Dynamical

**Assumed initial stellar distribution Are stellar binaries genuine or spurious?**