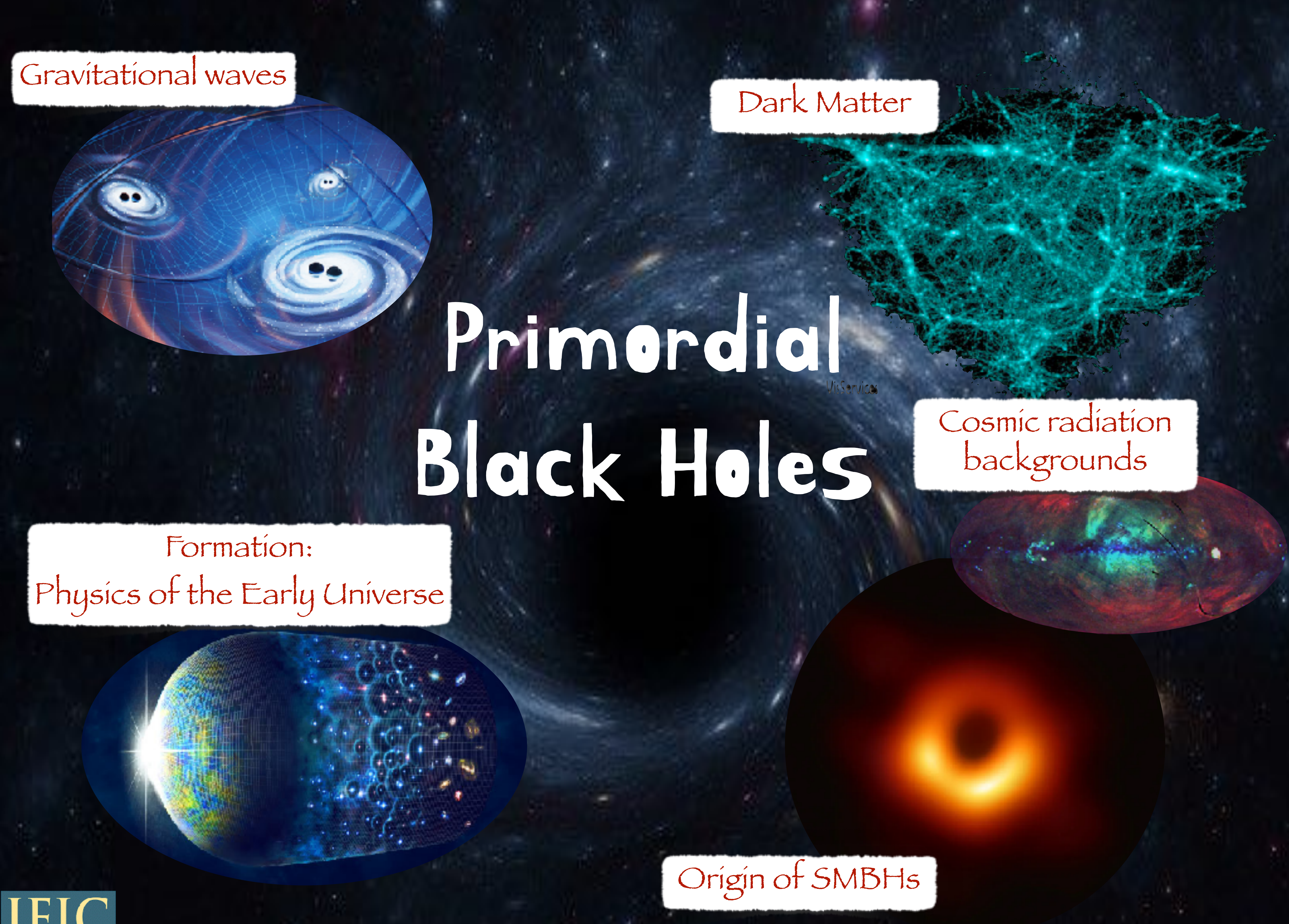
Probes of primordial black holes as dark matter

Sergio Palomares-Ruiz

IFIC, CSIC - U. Valencia

RICAP-24 Roma International Conference on Astroparticle Physics

Frascati,
September 26, 2024

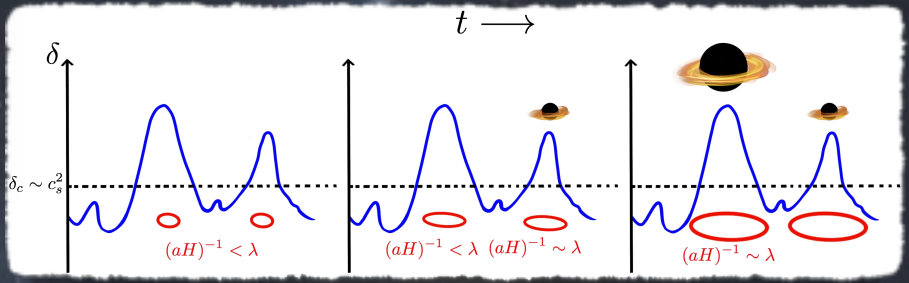

Gravitational waves
Dark Matter
Primordial
Black Holes
Cosmic radiation
backgrounds
Formation:
Physics of the Early Universe
Origin of SMBHs

Primordial black holes

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



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...

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

$$t = 10^{-43}\,{\rm s} \rightarrow M_{\rm PBH} \sim 10^{-5}\,{\rm g}$$

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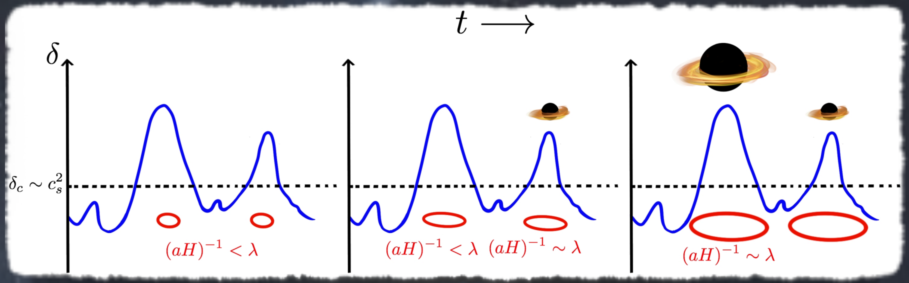
Primordial black holes



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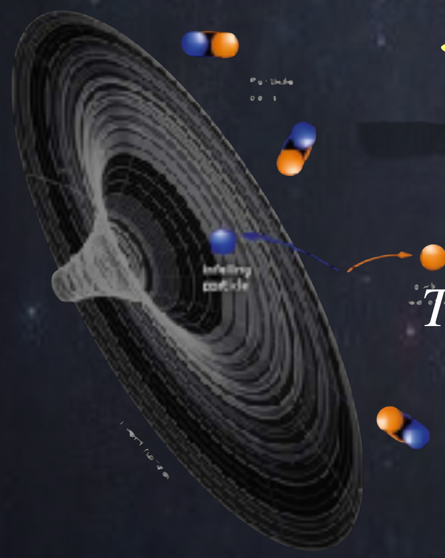


Black holes radiate thermally, so they eventually evaporate

S. W. Hawking, Commun. Math. Phys. 43:199, 1975

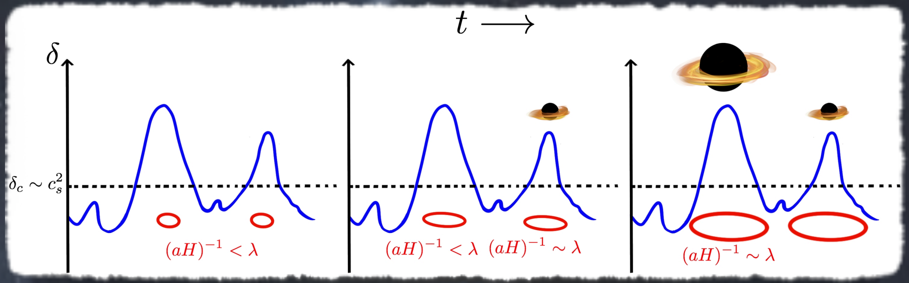
D. N. Page, Phys. Rev. D13:198, 1976

$$T_{\rm BH} \sim \frac{1}{8\,\pi\,G\,M_{\rm BH}} \sim 10 \left(\frac{10^{15}\,{\rm g}}{M_{\rm BH}}\right) {\rm MeV}$$

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

For masses between $10^{-17}\,M_\odot$ and $10^{5}\,M_\odot$, they would be present today

Primordial black holes



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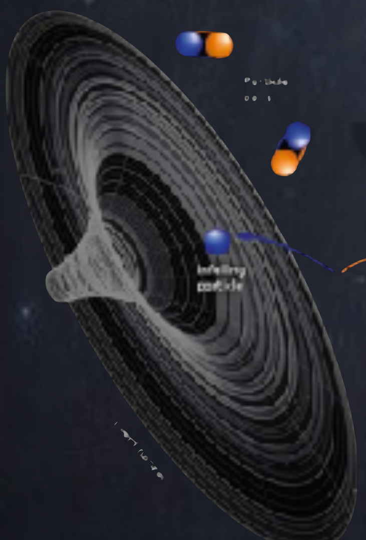

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For masses between $10^{-17}\,M_\odot$ and $10^{5}\,M_\odot$, they would be present today

PBHs would form before BBN, so they would not count as baryonic matter

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

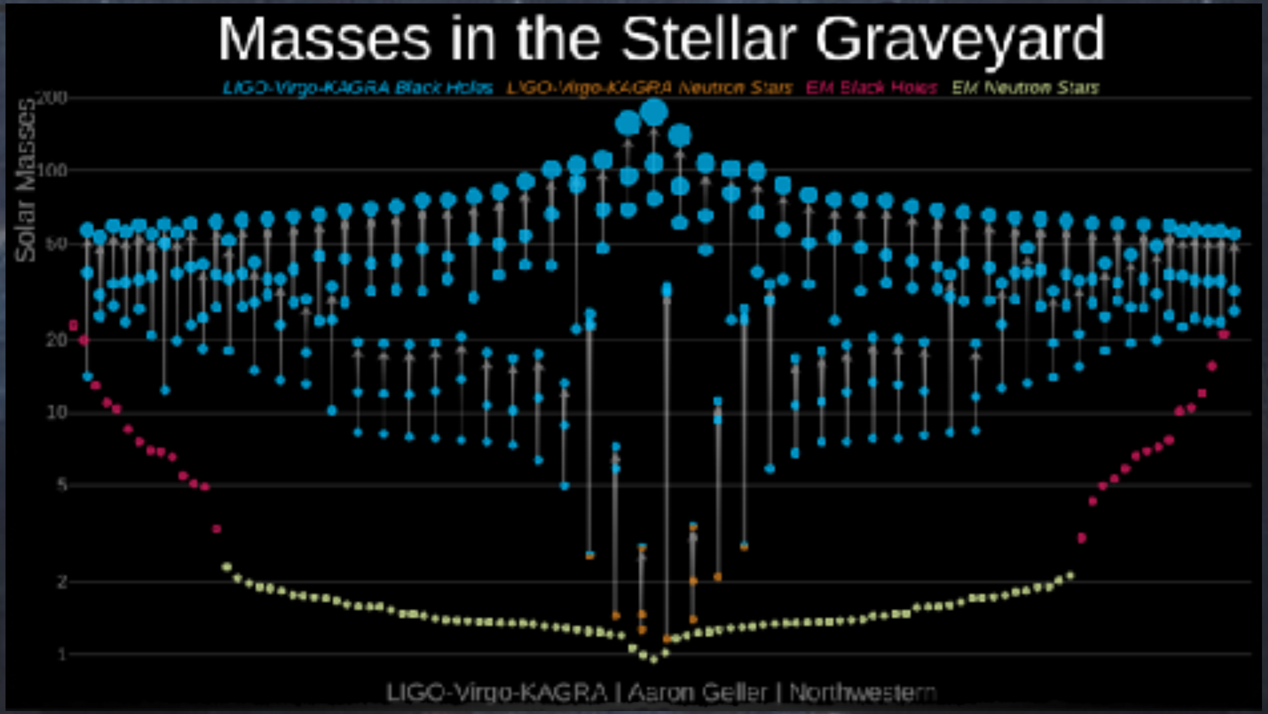
G. F. Chapline, Nature 253:251, 1975

Primordial black holes

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

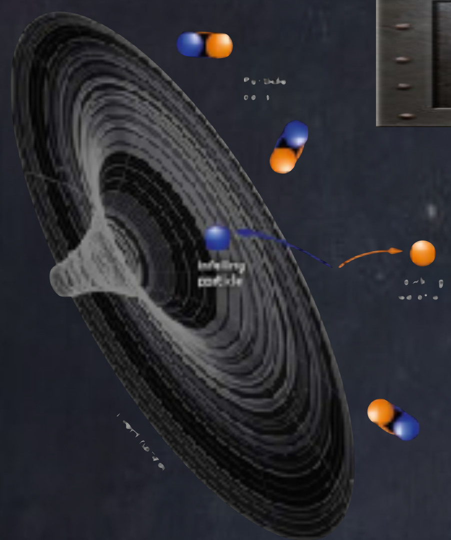
B. Lacki and J. F. Beacom, Astrophys. J. 720:L67, 2010
R. Saito and S. Shirai, Phys. Lett. B697:95, 2011
D. Zhang, Mon. Not. R. Astron. Soc. 418:1850, 2011

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

Hawking radiation:

Multi-messenger signals

Heating and ionization of the IGM

Lensing

Stellar and quasar micro-lensing

Supernovae magnification distribution

Strong lensing of FRBs

Femtolensing of GRBs

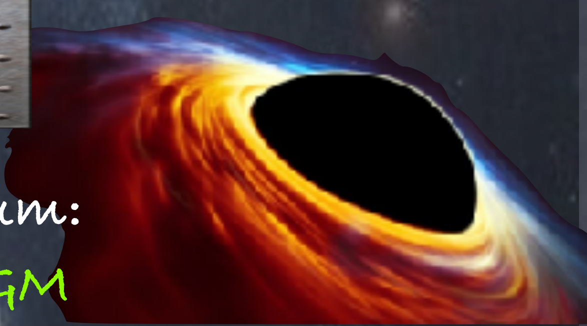
Gravitational Waves

Binary PBHs merger rates

Stochastic GW background

From PBH production

Accretion



Emission of a broad band spectrum:

Heating and ionization of the IGM

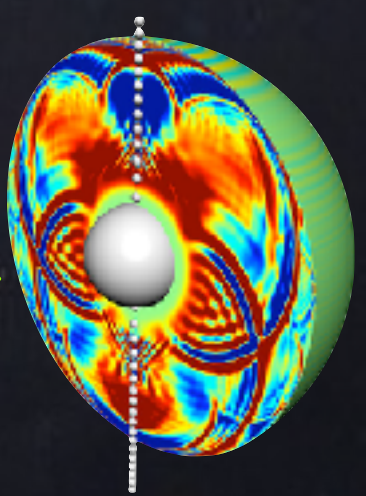
Contribution to the (X-ray, infrared, radio) astrophysical spectra

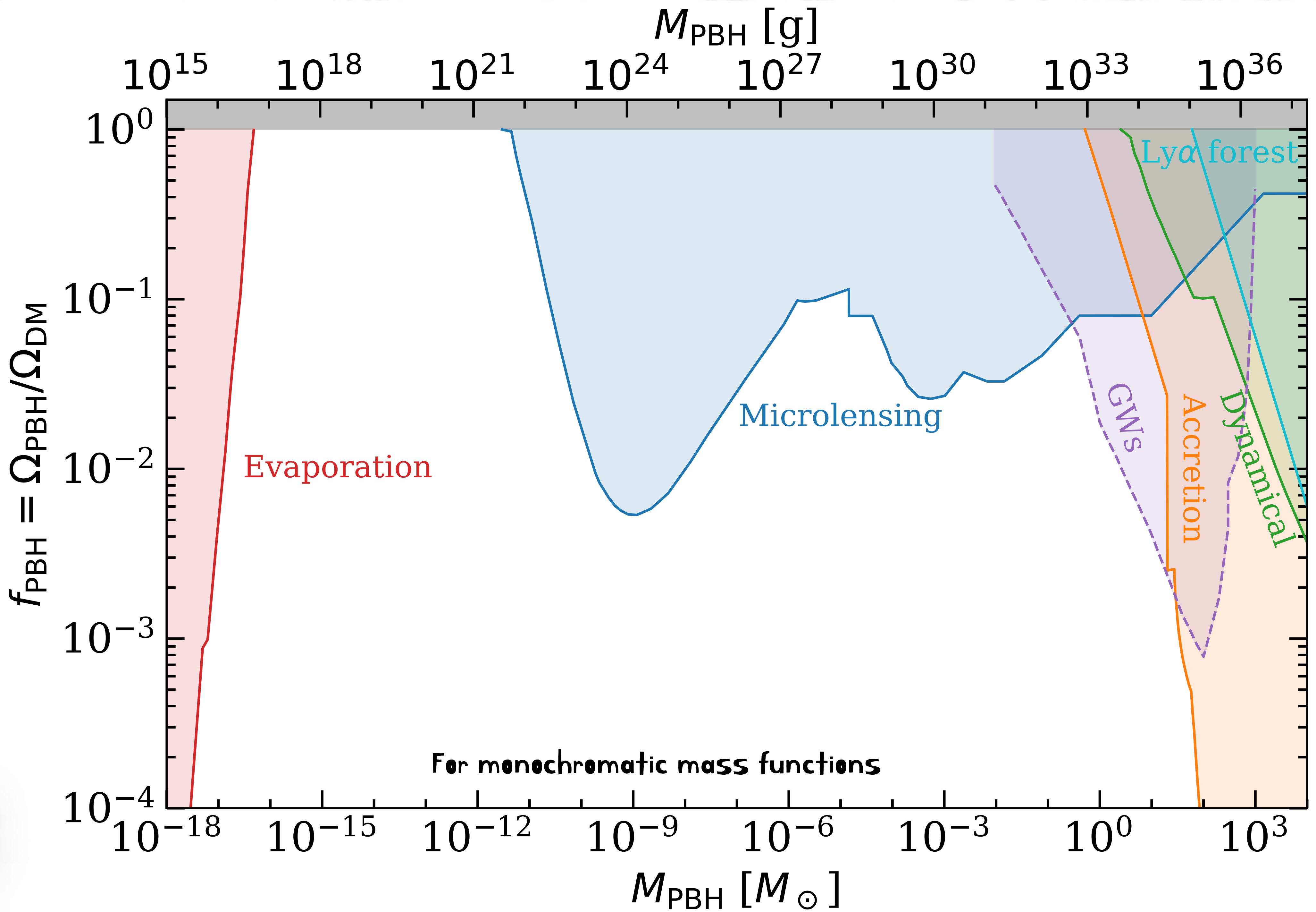
Dynamical

Disruption of bound systems: galaxies, globular clusters, stellar binaries…

Galactic disk and dynamical friction

Accretion by compact objects which might subsequently be destroyed



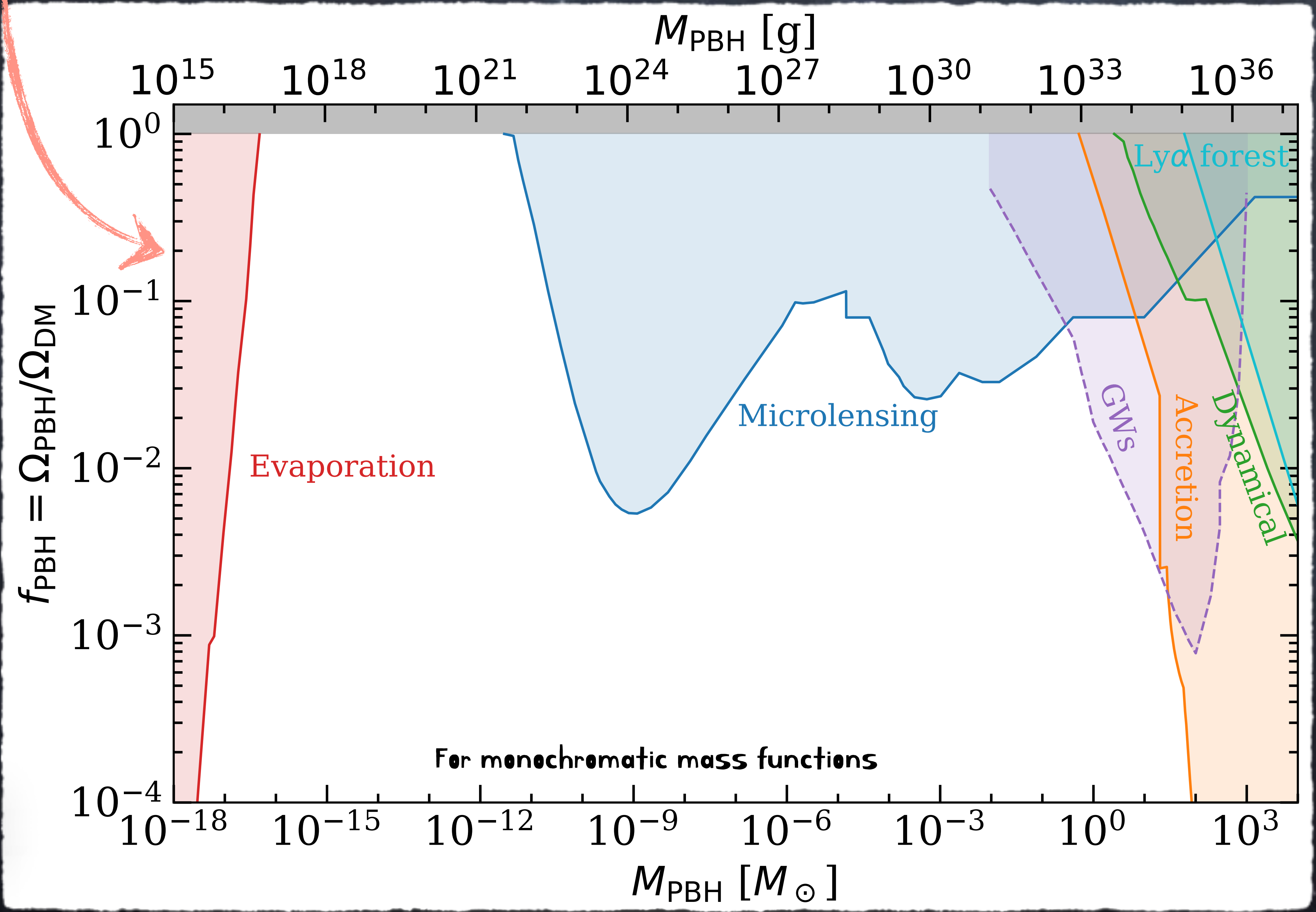


Using PBHbounds
B. J. Kavanagh

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

Partial evaporation

Hawking radiation: cosmic-ray, γ-ray, ν bkgs; ionization and thermal history



Using PBHbounds
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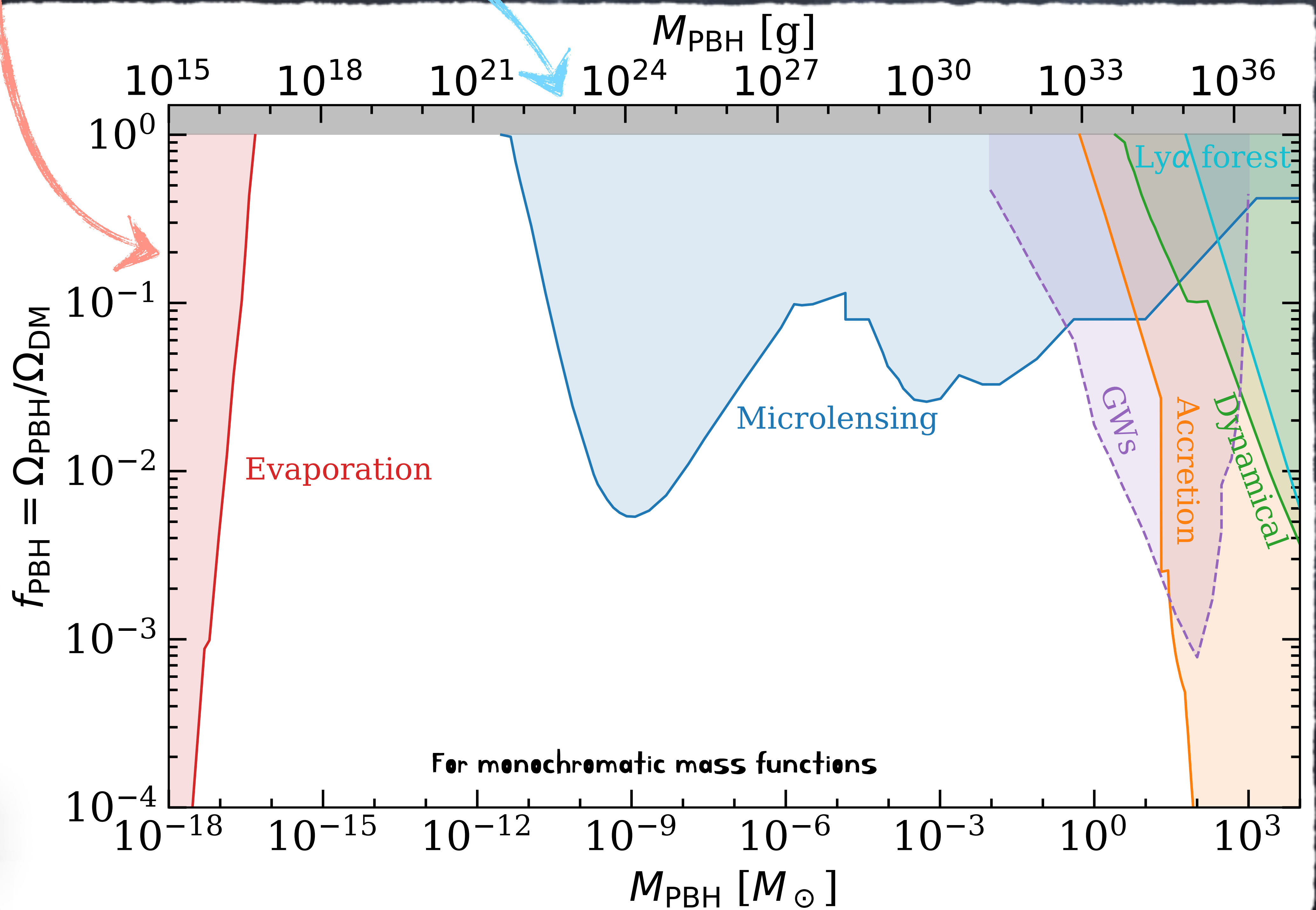
Partial evaporation

Gravitational lensing

Microlensing of stars, SN, QSO



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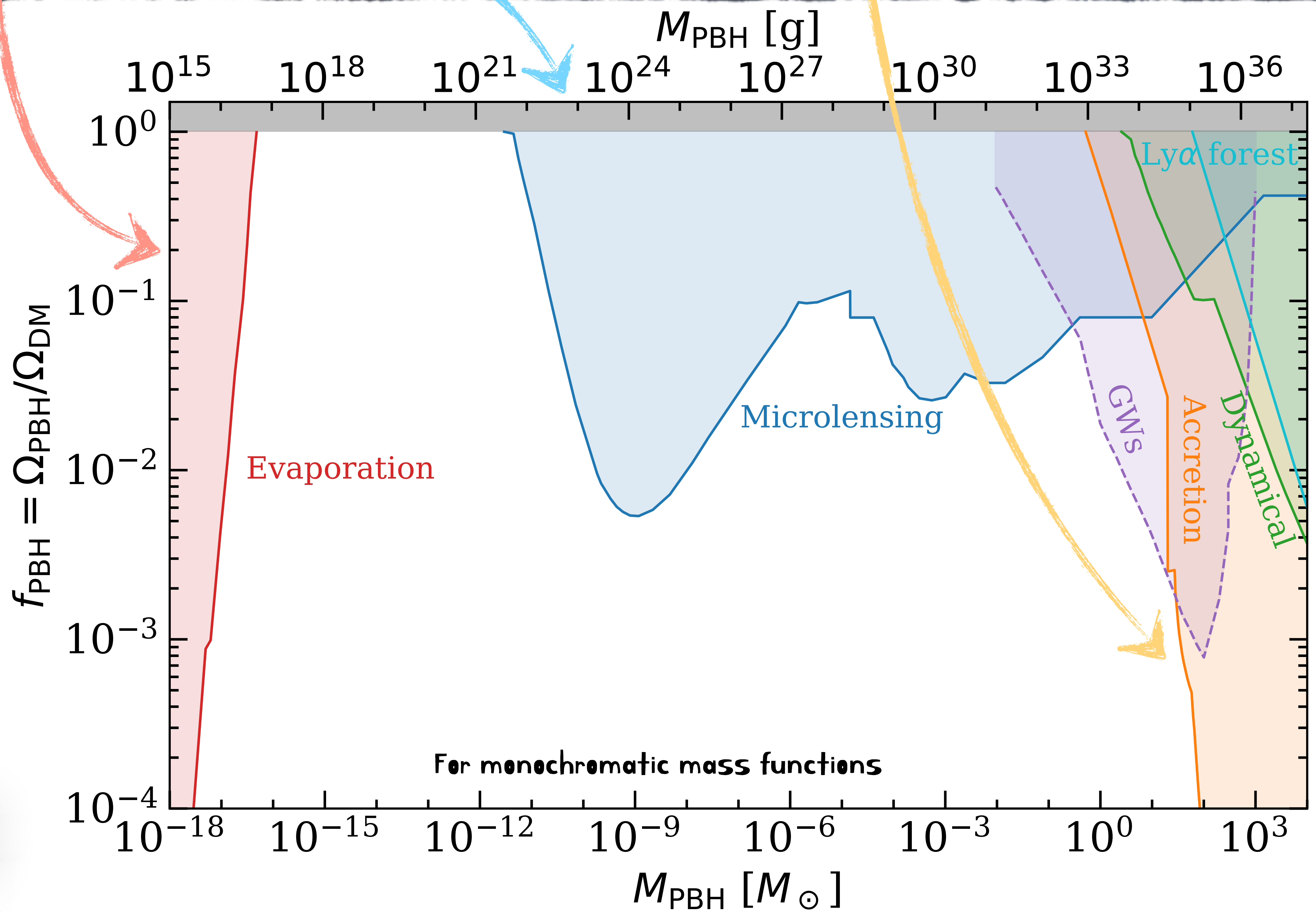
Partial evapo

Ionization and thermal history, radio and X-ray emission

Accretion



Using PBHbounds
B. J. Kavanagh

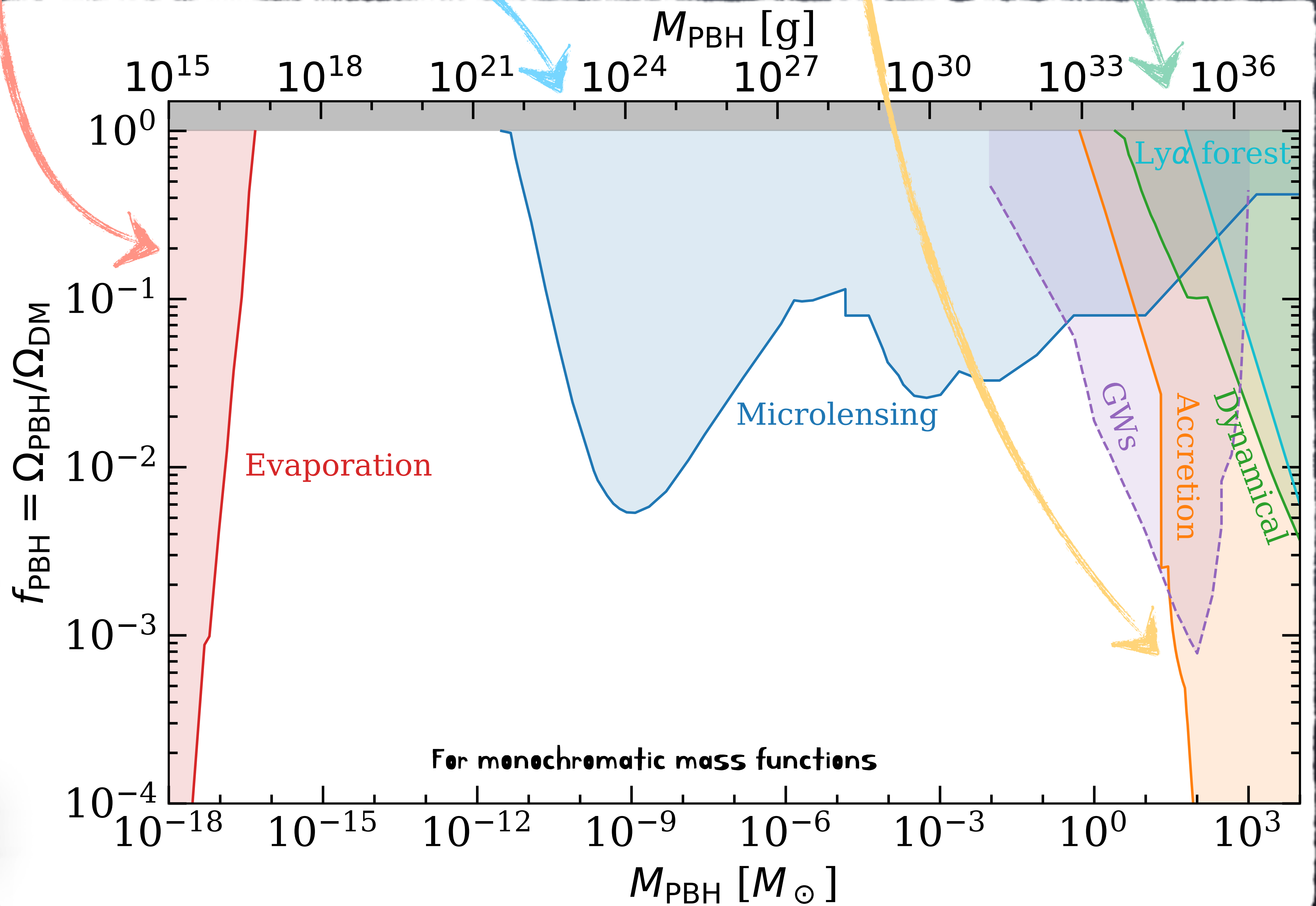
P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Partial evaporation

Gravitation

Destruction of astronomical systems by the passage of PBHs

Dynamical effects



Using PBHbounds

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

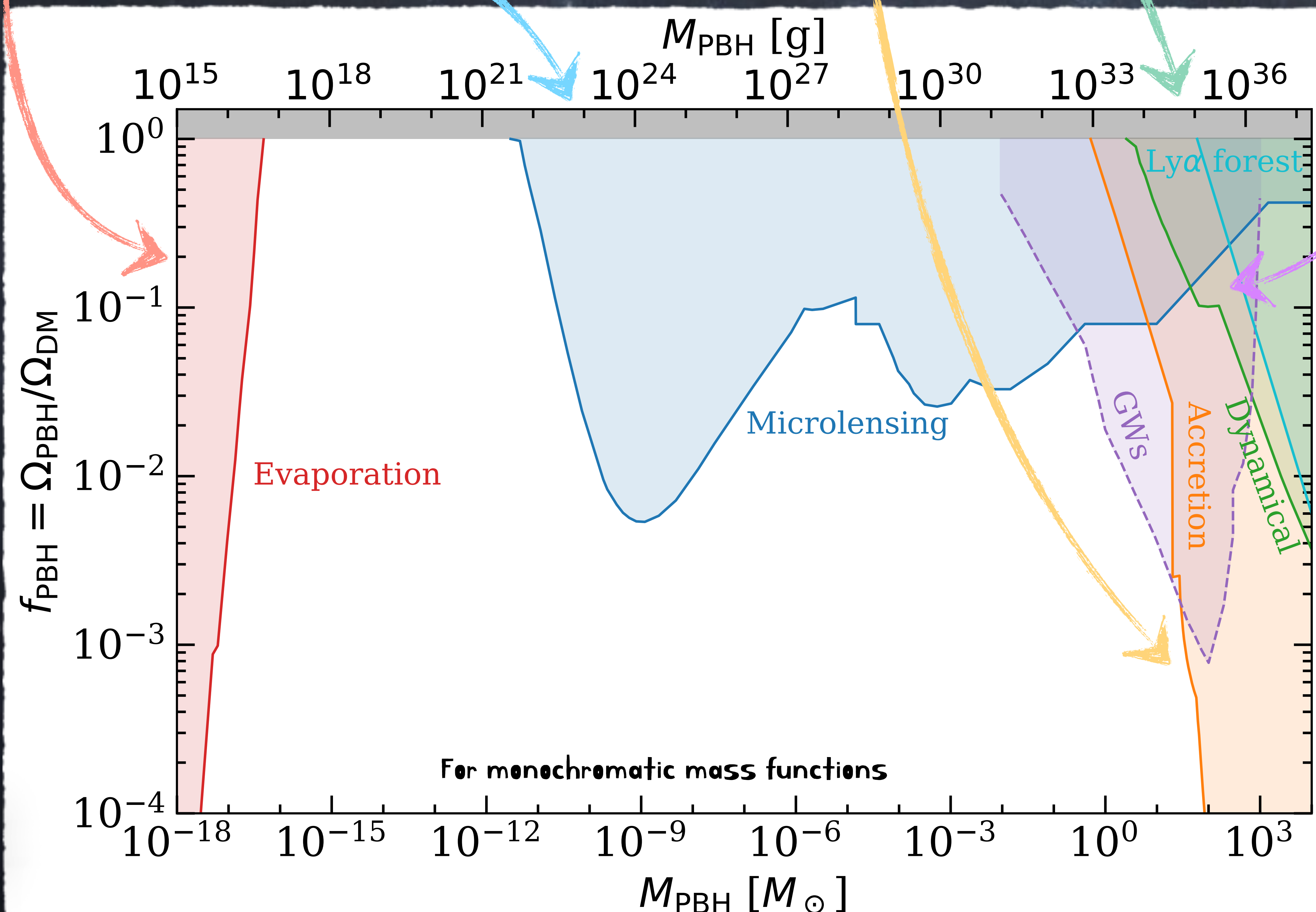
Partial evaporation

Gravitational lensing

LIGO/VIRGO events
stochastic background

Gravitational waves

...cal effects



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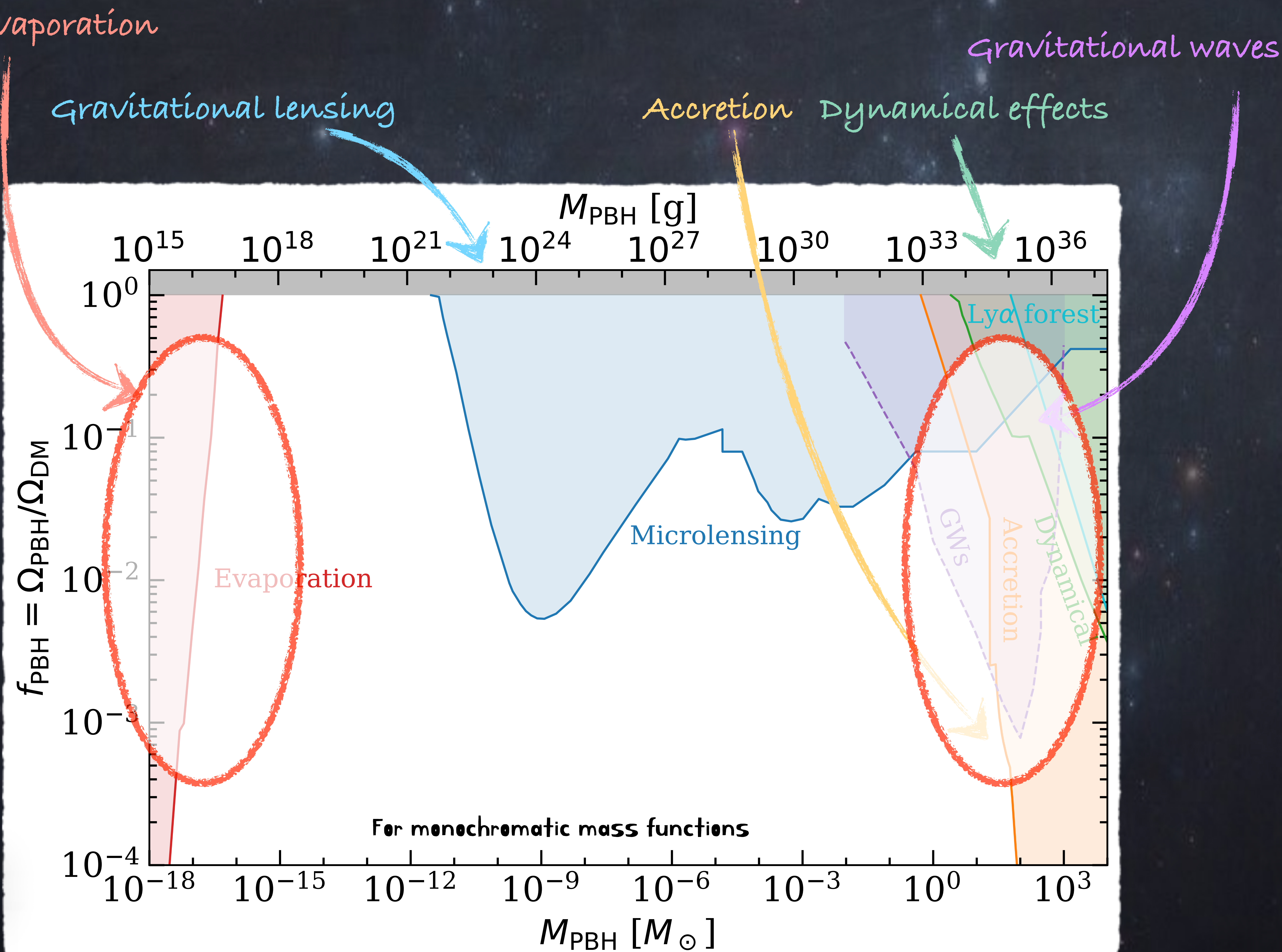
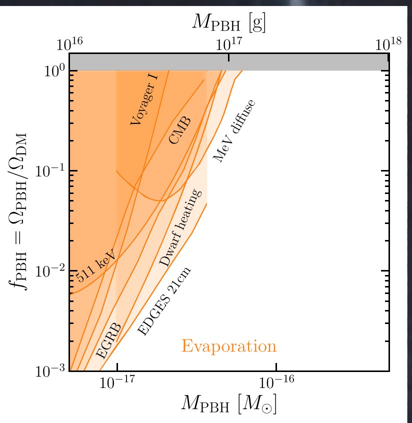


Using PBHbounds
B. J. Kavanagh

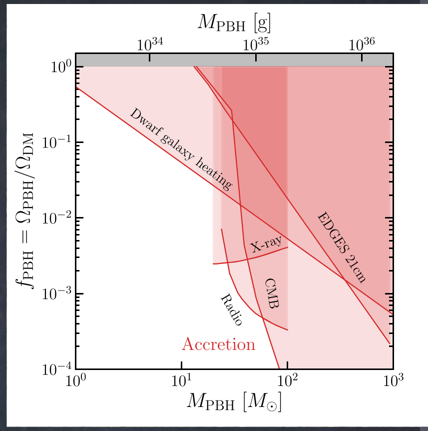
P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

PBHs: Evaporation and Accretion



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

Types of signals

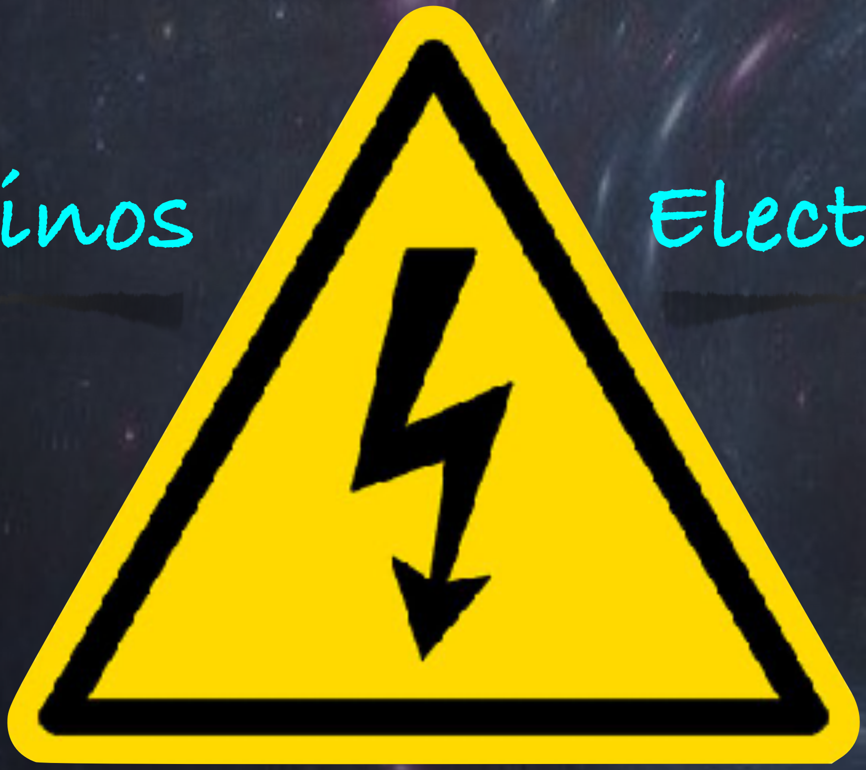


A. M. Green and B. J. Kavanagh, J. Phys. G. 48:043001, 2021

Photons

Neutrinos

Electrons



Messenger production

Antimatter

CMB

21cm

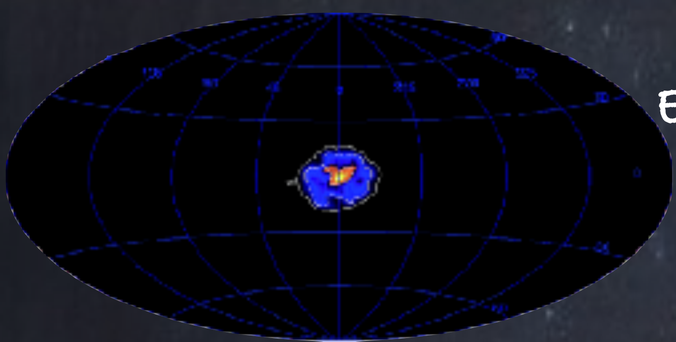
Lyman-α

Energy injection in the IGM

Messenger production by PBHs

Evaporation

Many references...



Extragalactic and galactic γ/X-ray backgrounds

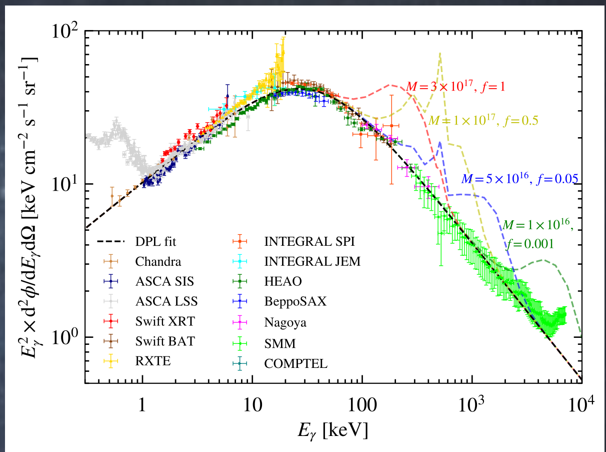
Local electron-positron flux

Electron-induced near-UV, synchrotron and IC flux

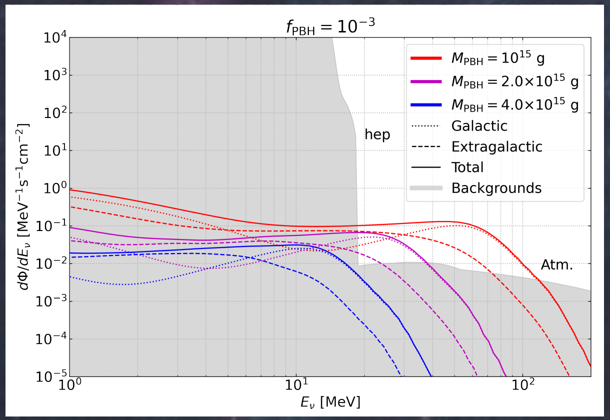
511 keV electron-positron annihilation line

Antiproton flux

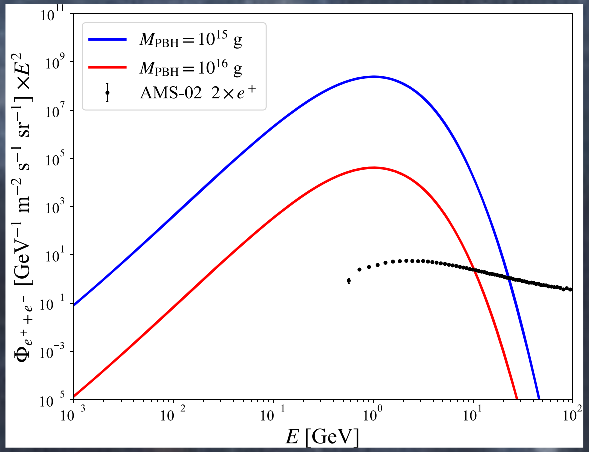
Extragalactic and galactic neutrino flux



X.-H. Tan and J.-Q. Xia, arXiv:2404.17119



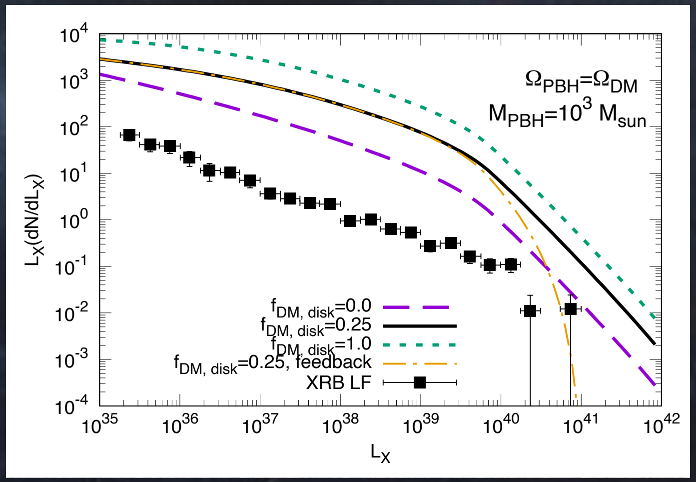
N. Bernal, V. Albornoz-Muñoz, SPR and P. Villanueva-Domingo, JCAP 10:068, 2022



B.-Y. Su et al., Eur. Phys. J. C84:606, 2024

Accretion

Galactic IR/X/radio backgrounds



Y. Inoue and A. Kusenko, JCAP 10:034, 2017

See also:

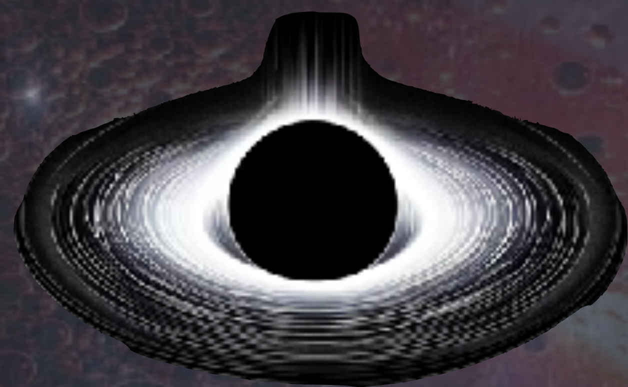
Kashlinsky, Astrophys. J. 823:L25, 2016

D. Gaggero et al., Phys. Rev. Lett. 118:241101, 2017

G. Hassinger, JCAP 07:022, 2020

Energy injection from PBHs evaporation

Evaporation rate



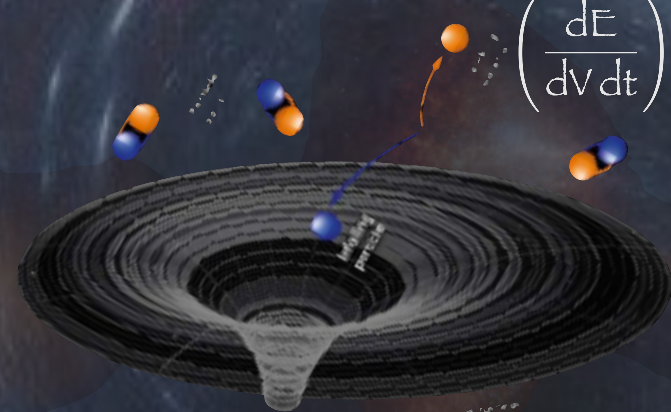
$$\frac{dM_{PBH}}{dt} = -\frac{f(M_{PBH})}{M_{PBH}^2}$$

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

Emission rate equal to that of a thermal body with temperature:

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

Energy injection



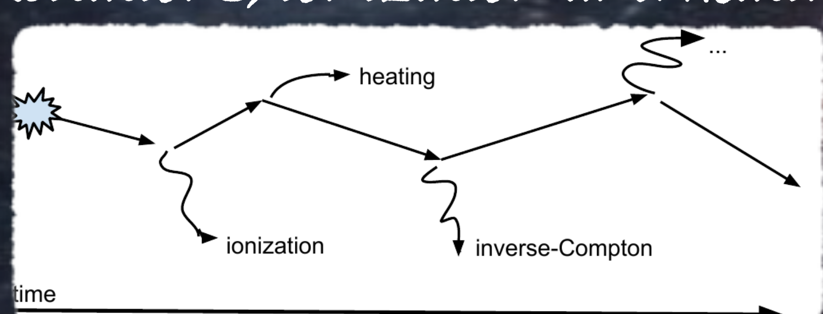
$$\left(\frac{dE}{dV\,dt}\right)_{inj} = n_{PBH} \int E \left(\frac{dN}{dt\,dE}\right)_{evap} dE = \frac{f_{PBH}\,\rho_{DM}}{M_{PBH}} \int E\, \frac{g}{2\pi} \frac{\Gamma(E, M_{PBH})}{e^{E/T_{PBH}} \pm 1} dE$$

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



From A. C. Vincent

Not on-the-spot

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

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

Energy injection from accretion by PBHs

Acrettion rate

Usually Bondi-Hoyle-Lyttleton model

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

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

...but also see Park-Ricotti accretion

K. Park and M. Ricotti, Astrophys. J. 739:2, 2011; Astrophys. J. 747:9, 2012; Astrophys. J. 767:163, 2013

Energy injection

Luminosity: $L_{acc} = \epsilon\, \dot{M}_{PBH}$

$$\left(\frac{dE}{dV\,dt}\right)_{inj} = L_{acc}\, n_{PBH} = L_{acc} \frac{f_{PBH}\,\rho_{DM}}{M_{PBH}}$$

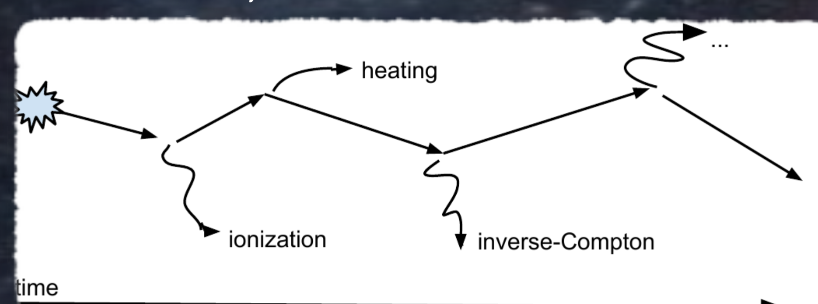
if cooling is inefficient, a thick disk could form: ADAF

$$\epsilon = \epsilon_0 \left(\frac{10\,\dot{M}_{PBH}}{L_{Edd}}\right)^a$$

See, e.g., F.-G. Xie and F. Yuan, Mon. Not. R. Astron. Soc. 427:1580, 2012

Energy deposition

Excitations, ionization and heating



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

Energy spectrum: synchrotron, IC and bremsstrahlung

R. Mahadevan, Astrophys. J. 477:585, 1997

Effects of energy injection from PBHs

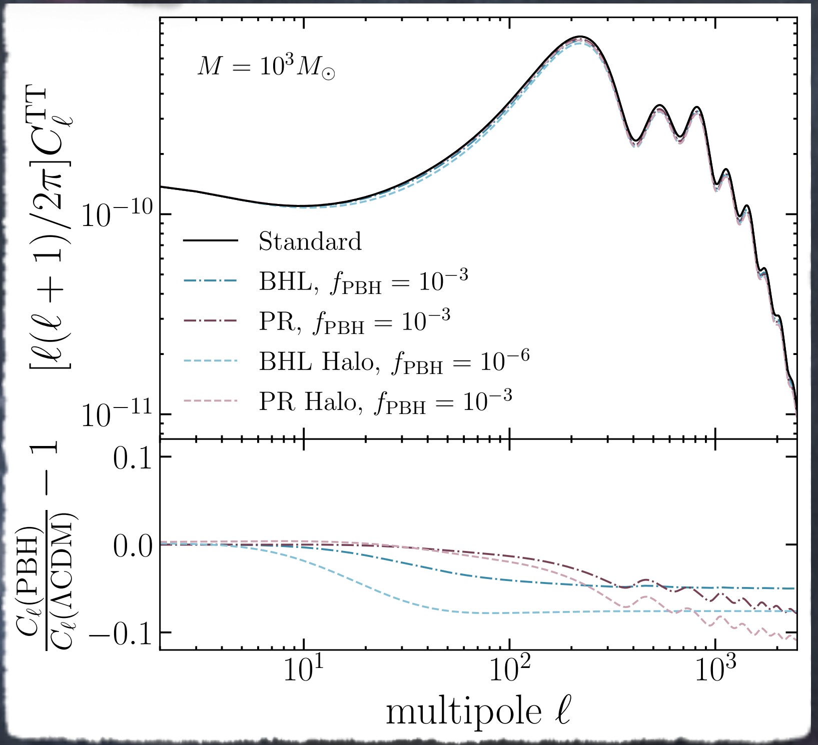
Damping of CMB anisotropies

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

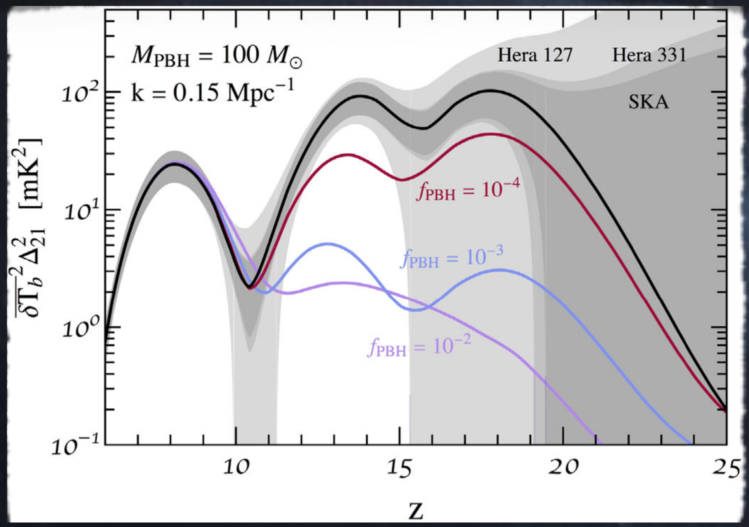
Accretion

- 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



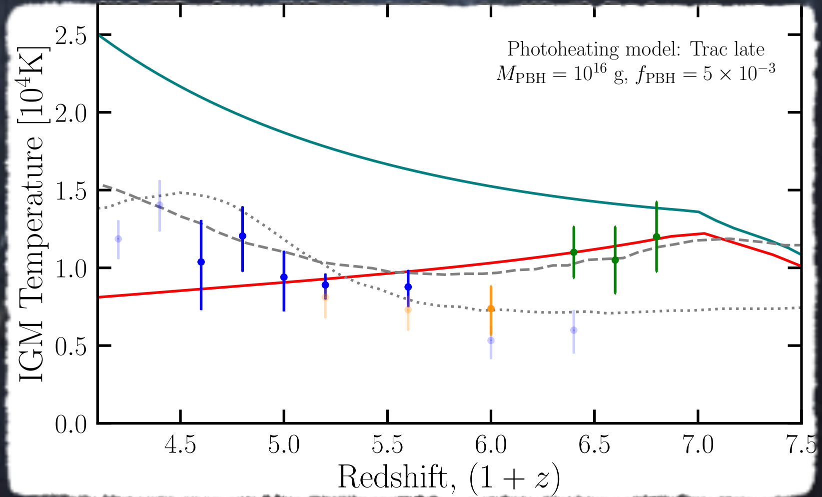
D. Agius et al., JCAP 07:003, 2024

Heating of the 21cm temperature



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

Broadening of Lyman-α absorption features



A. K. Saha, A. Singh, P. Parashari and R. Laha, arXiv:2409.10617

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

Neutrinos from PBHs evaporation

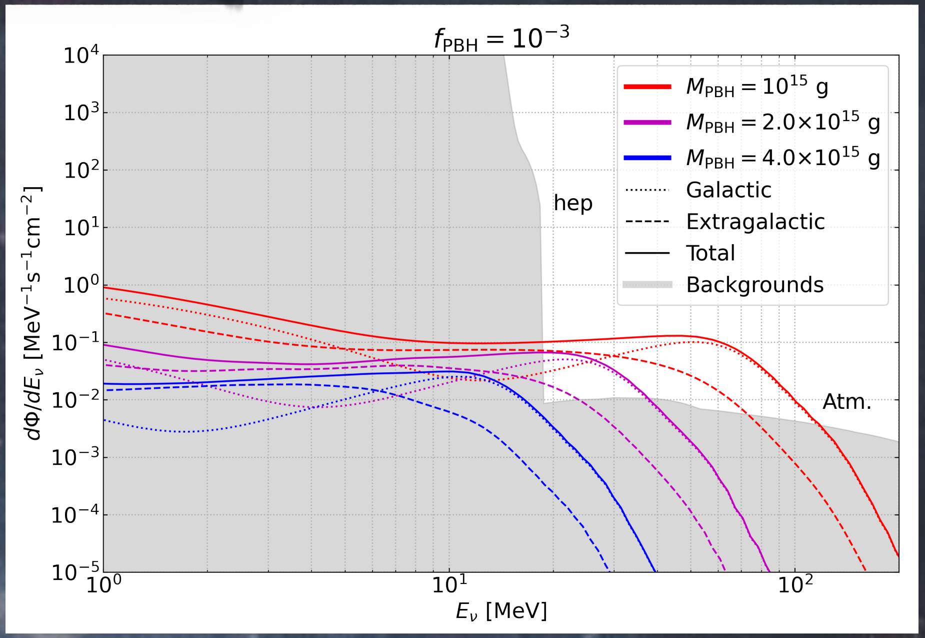
with BlackHawk A. Arbey and J. Auffinger, Eur. Phys. J. C79:693, 2019

Galactic contribution

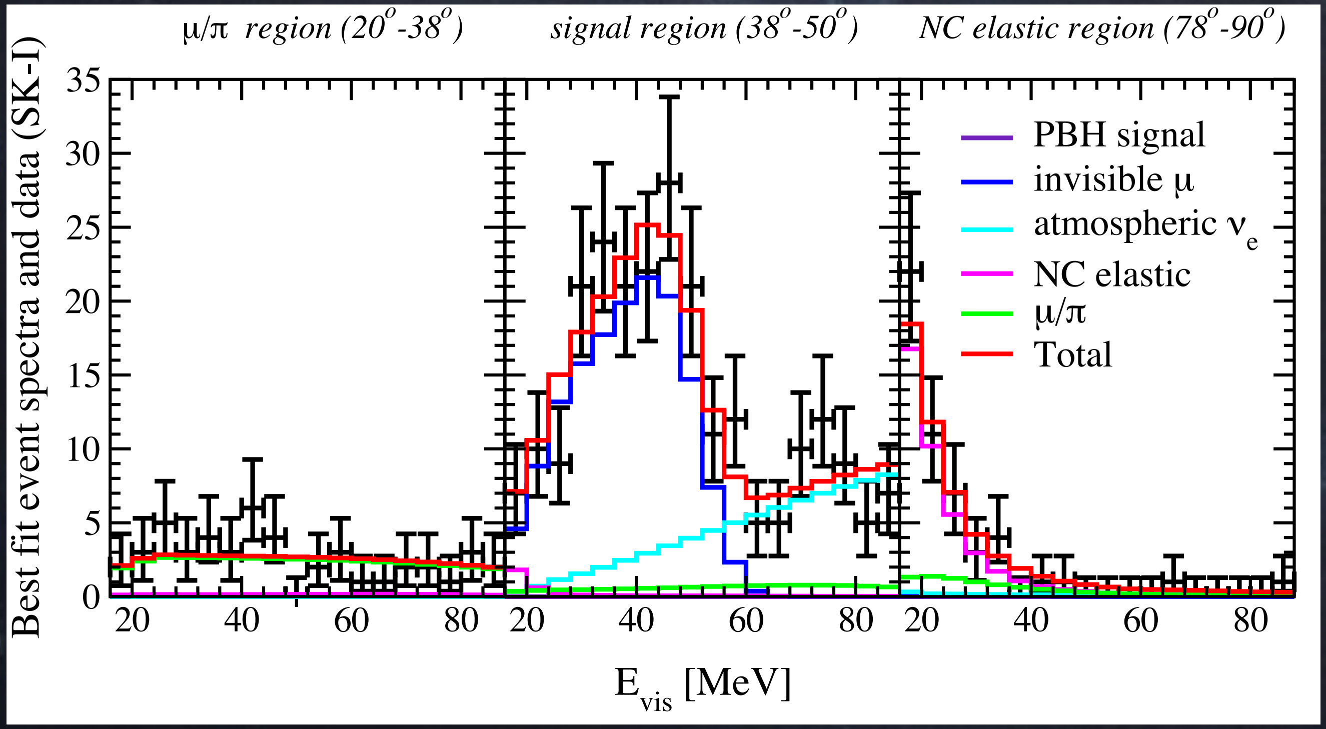
$$\frac{d\Phi_G(E_\nu)}{dE_\nu} = \frac{d^2N_\nu(E_\nu, t_0)}{dE_\nu dt} \frac{f_{PBH}}{\bar{M}} \int \frac{d\Omega}{4\pi} \int_0^{\ell_{max}} d\ell \, \rho_{DM}(r(\ell, \phi))$$

Extragalactic contribution

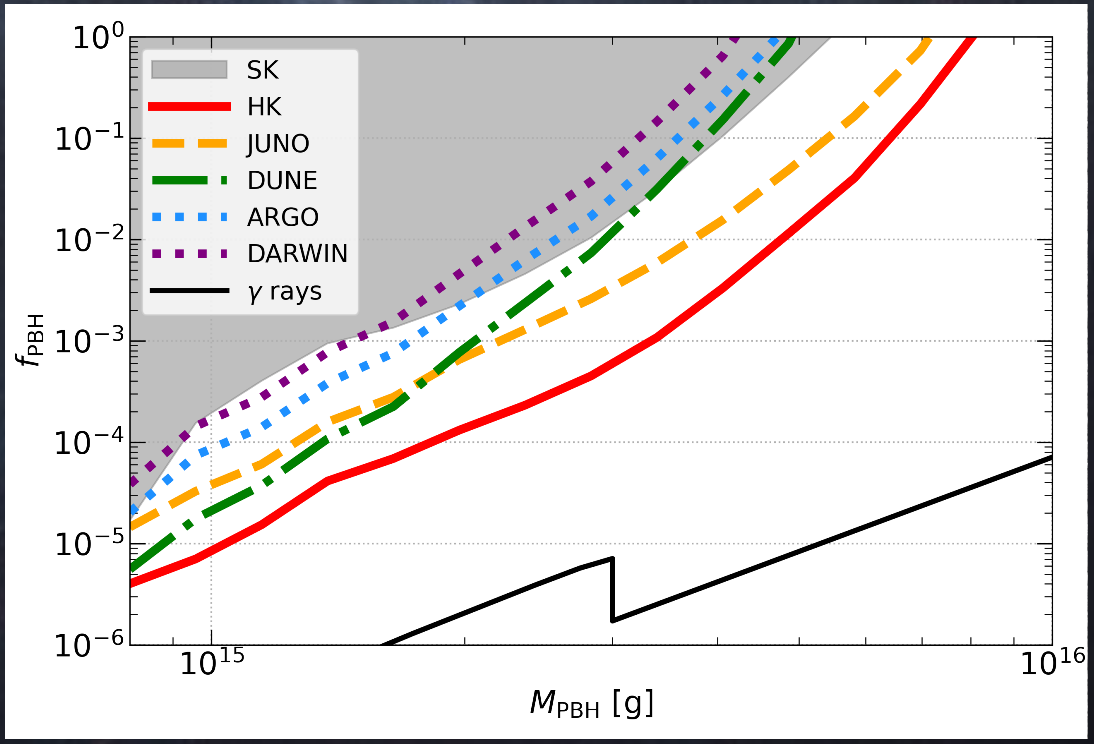
$$\frac{d\Phi_{EG}(E_\nu)}{dE_\nu} = n_{PBH}(t_0) \int_{z_{max}}^{z_{min}} dz \left| \frac{dt}{dz} \right| (1+z) \frac{d^2N_\nu(E_\nu(1+z), t)}{dE_\nu dt}$$



Analysis of SK DSNB data



...and prospects for HK, JUNO, DUNE, ARGO, DARWIN



N. Bernal, V. Albornoz-Muñoz, SPR and P. Villanueva-Domingo, JCAP 10:068, 2022

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):

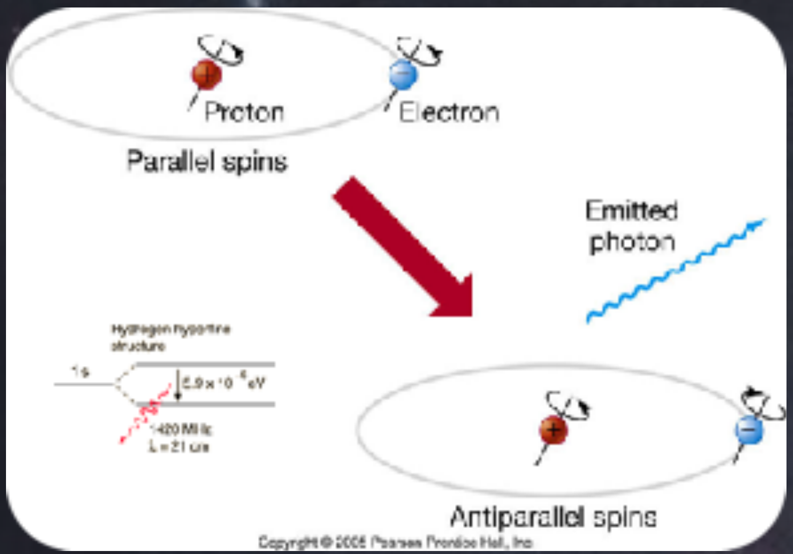
P. K. Natwariya, A. C. Nayak and T. Srivastava, MNRAS 510, 4236, 2021

J. Cang, Y. Gao and Y.-Z. Ma, JCAP 03:012, 2022

Y. Yang, Phys. Rev. D106:123508, 2022

The 21cm line

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

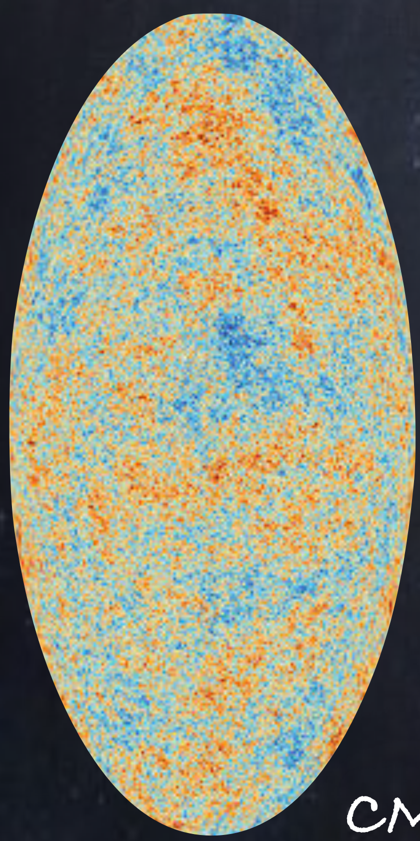


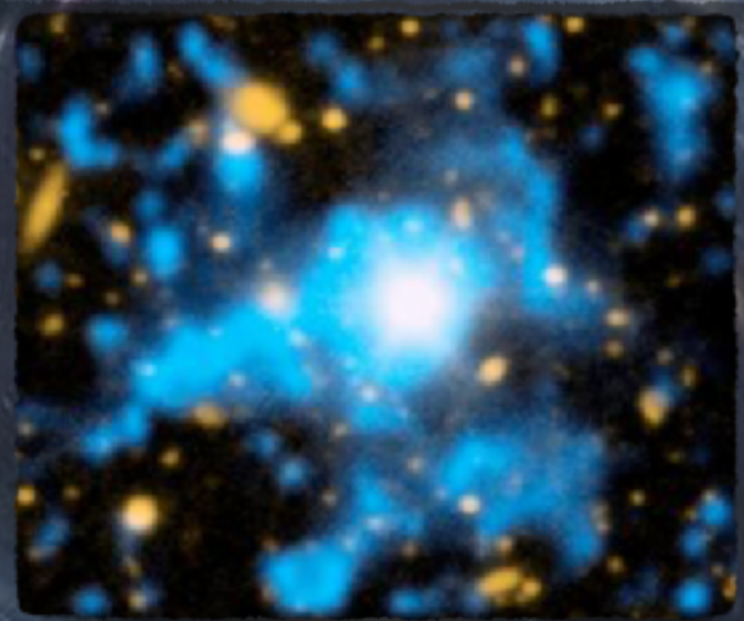
Hyperfine transition: ν = 1420 Mhz

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

$$\nu = \frac{\nu_0}{(1+z)}$$

neutral hydrogen gas (intergalactic medium: IGM)





observer

CMB photons as backlight

emission/absorption

z~1000

z=0

Population of ground and excited states controlled by:

absorption and stimulated emission of background radiation
collisions of neutral hydrogen
excitation/de-excitation by Lyman-α photons

The 21cm signal

Differential brightness temperature

$$\delta T_b(\nu) \simeq 27 x_{HI} (1+\delta)\left(1 - \frac{T_{CMB}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}$$

Fraction of neutral H

Reionization suppresses the signal

Baryon overdensity

$$\frac{n_1}{n_0} = 3 e^{-T_{21}/T_S}$$

Spin temperature: occupation of the two states

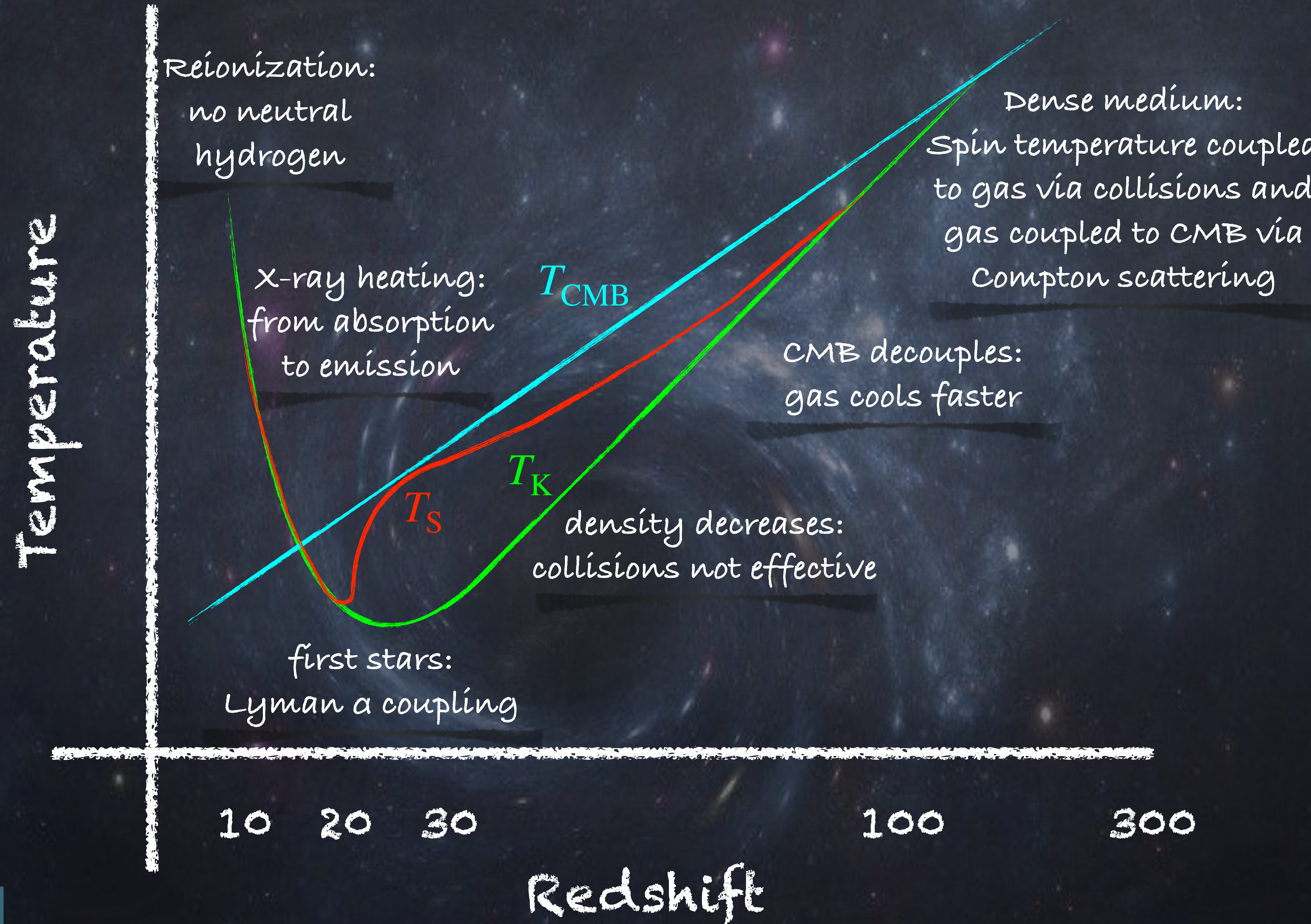
$\delta T_b \approx 0$ if $T_S \sim T_{CMB}$ — no signal

$\delta T_b > 0$ if $T_S > T_{CMB}$ — signal in emission, can saturate

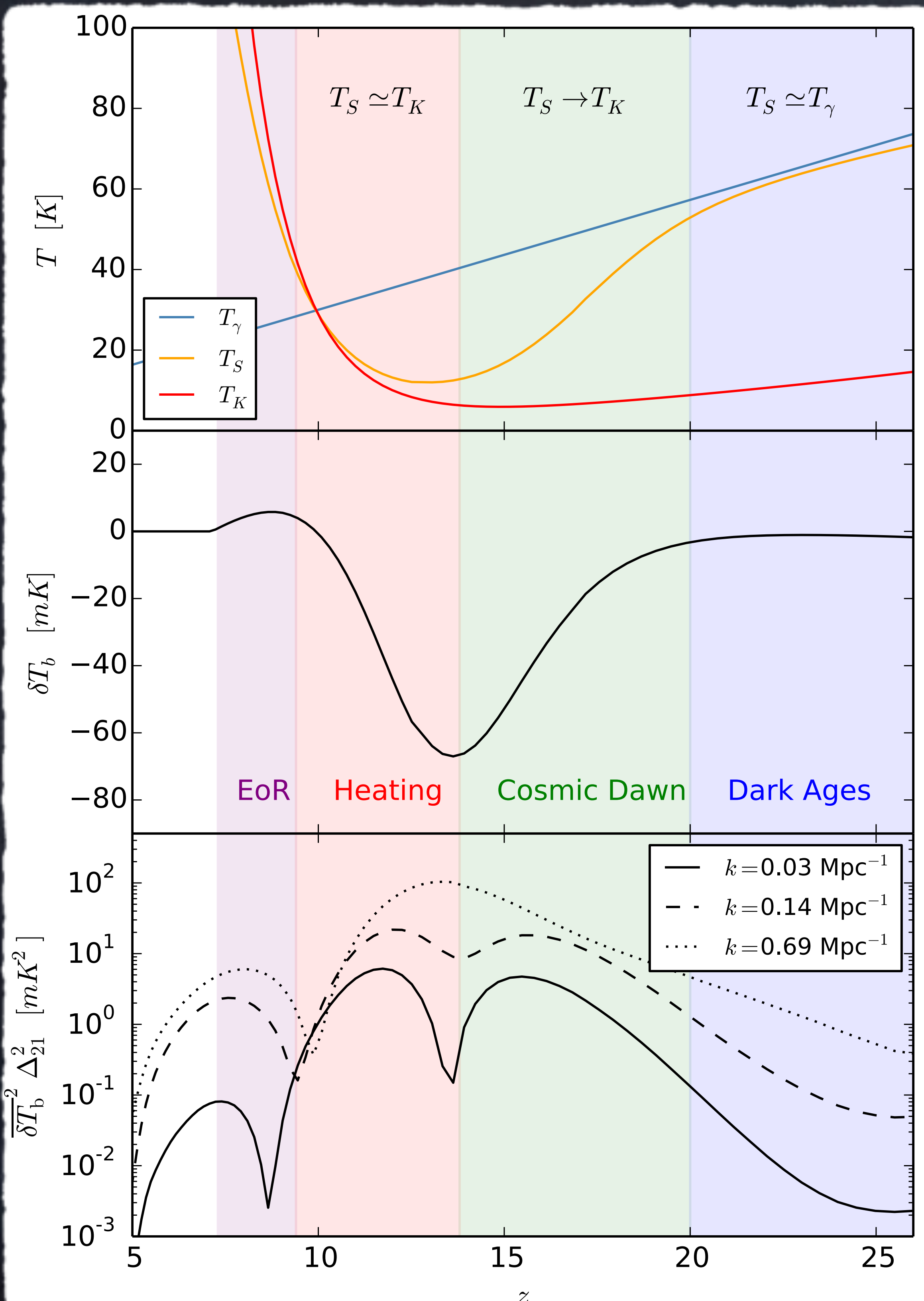
$\delta T_b < 0$ if $T_S < T_{CMB}$ — signal in absorption, limited by gas temperature

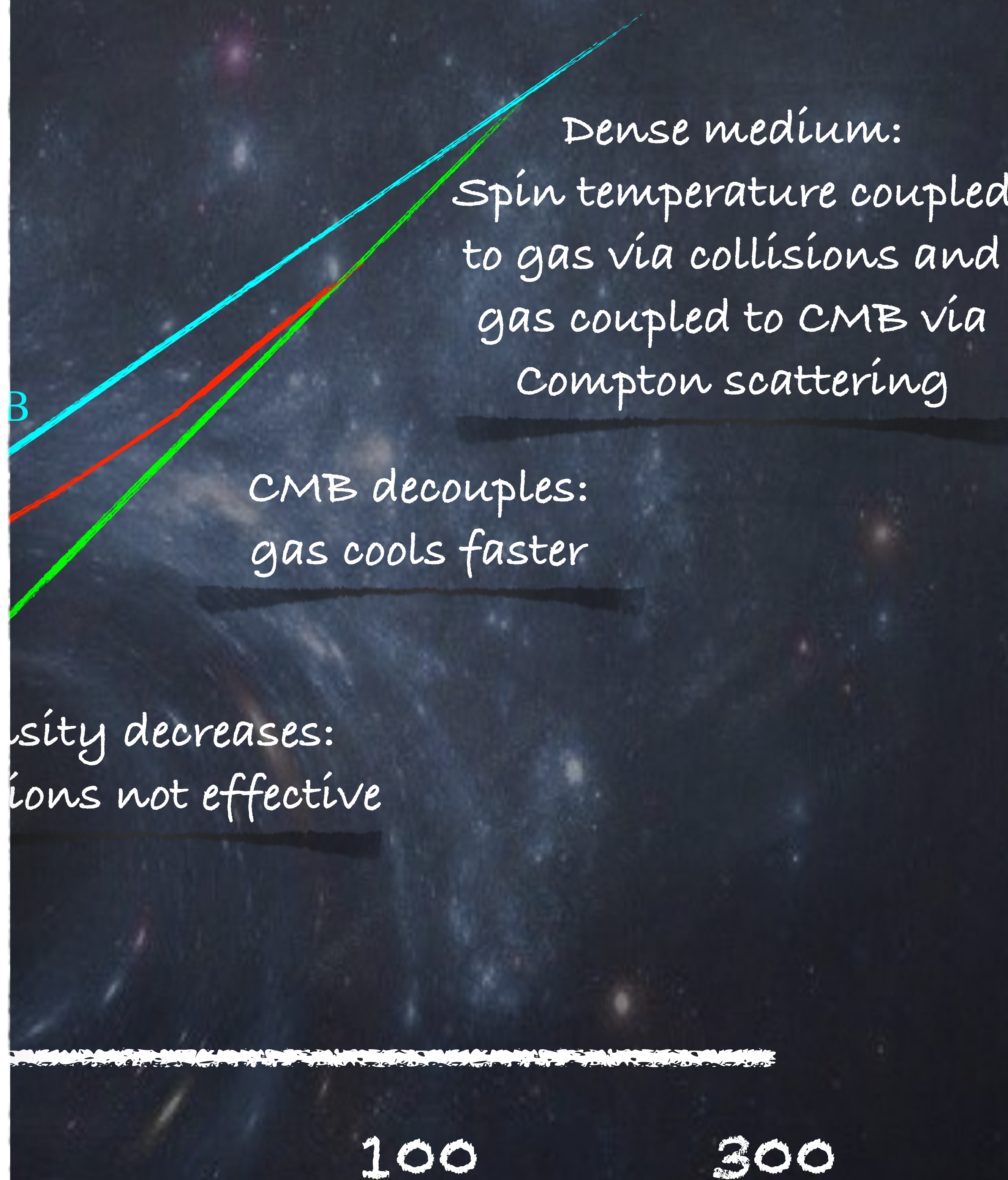
Astrophysical processes decouple T_S from T_{CMB}

THE 21CM SIGNAL: TIME EVOLUTION



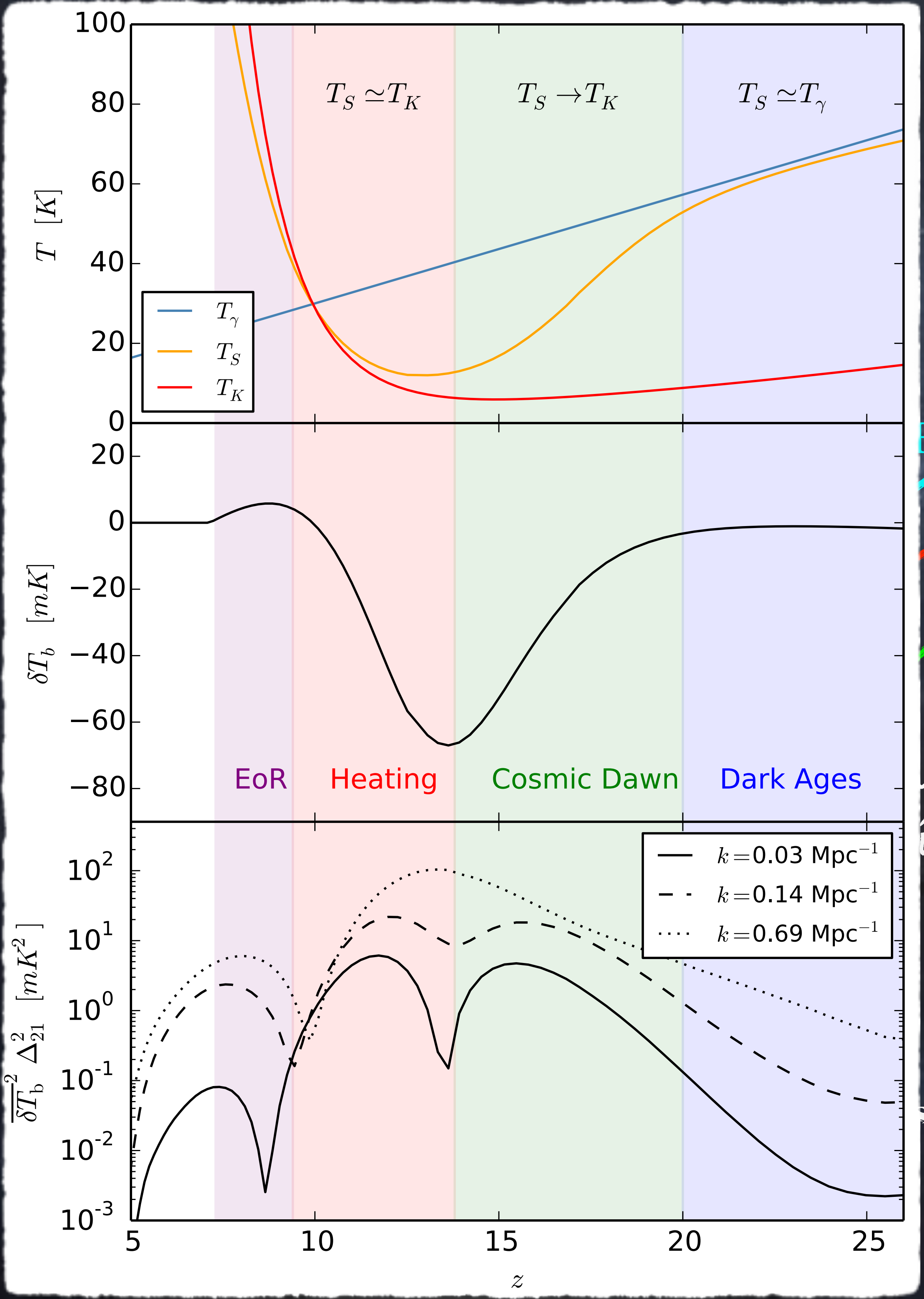
THE 21CM SIGNAL: TIME EVOLUTION





P. Villanueva-Domingo, PhD Thesis, 2021

The 21cm signal: Time evolution



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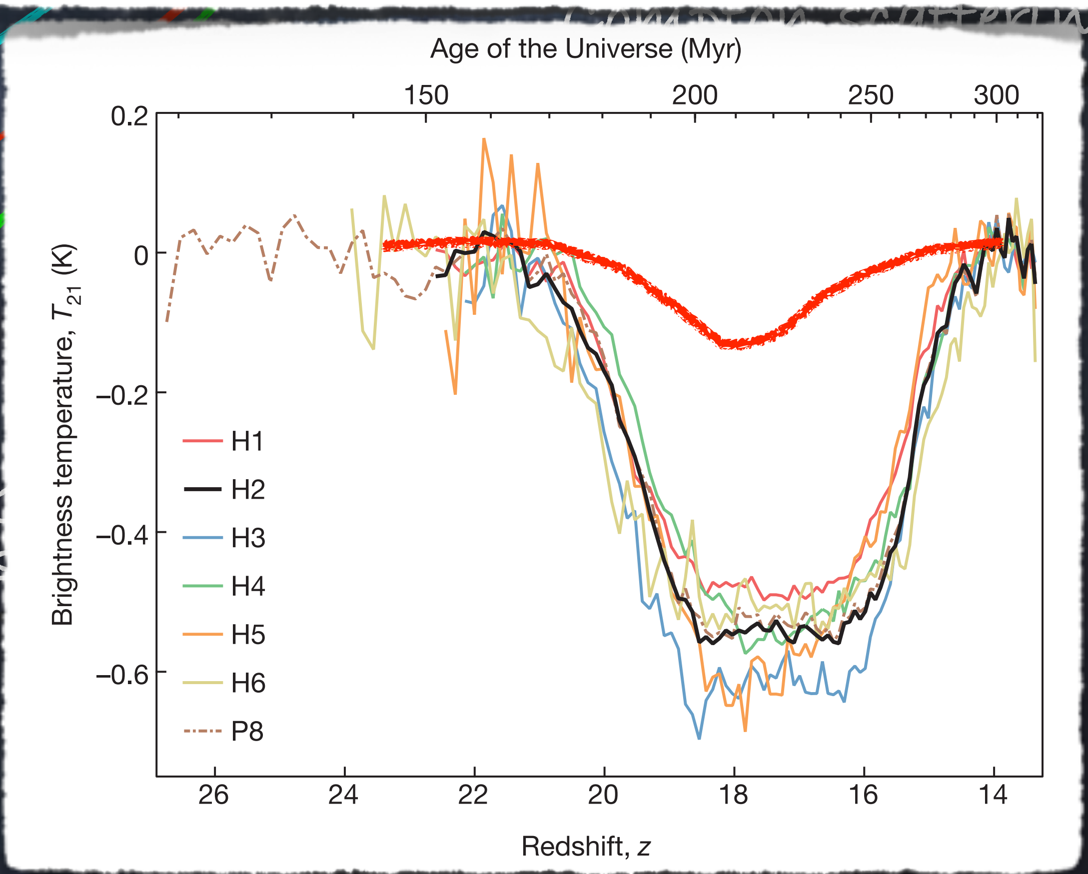
EDGES:

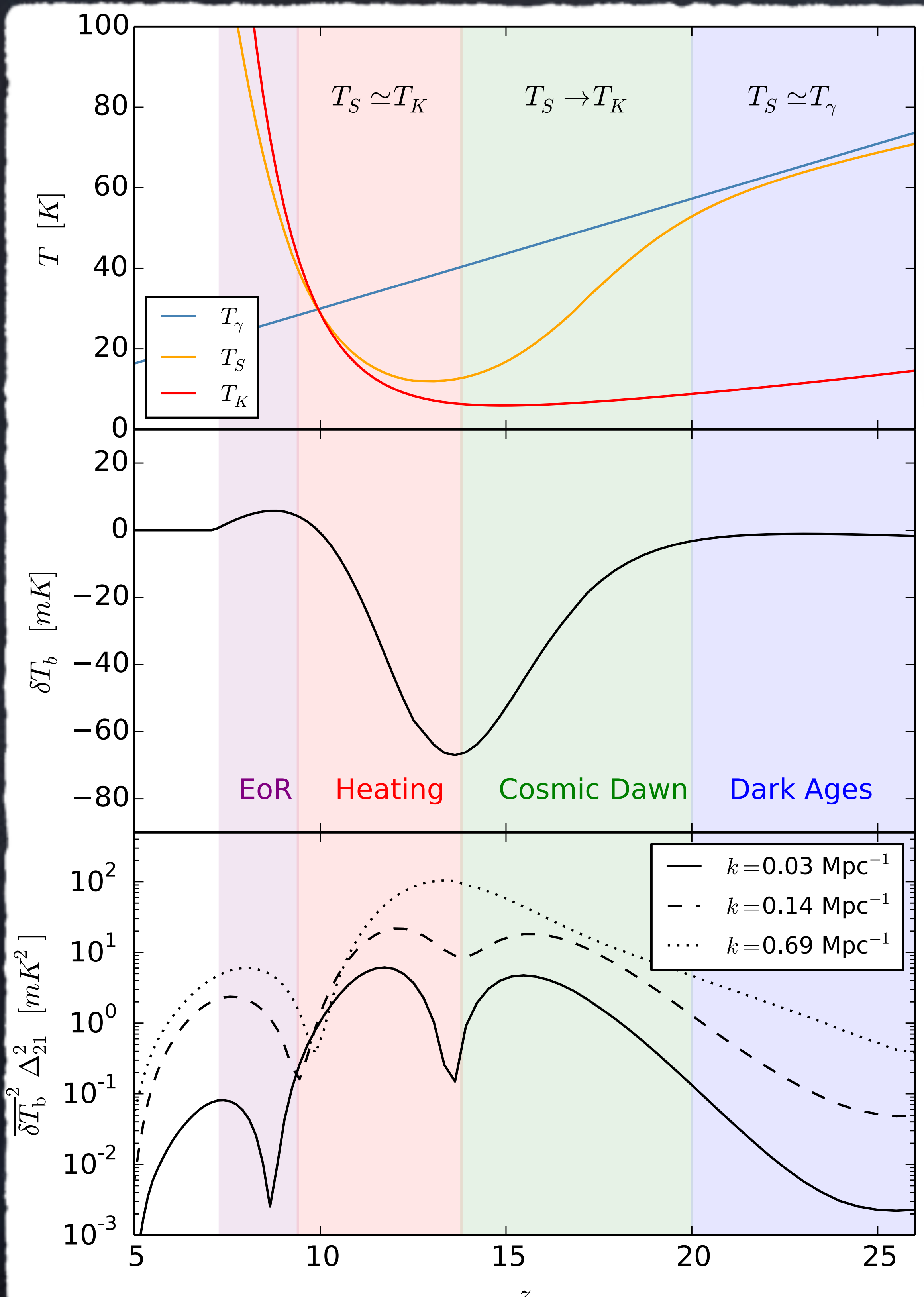
new physics? astrophysics?

systematics?



J. D. Bowman et al., Nature 555:67, 2018

The 21cm signal: Time evolution



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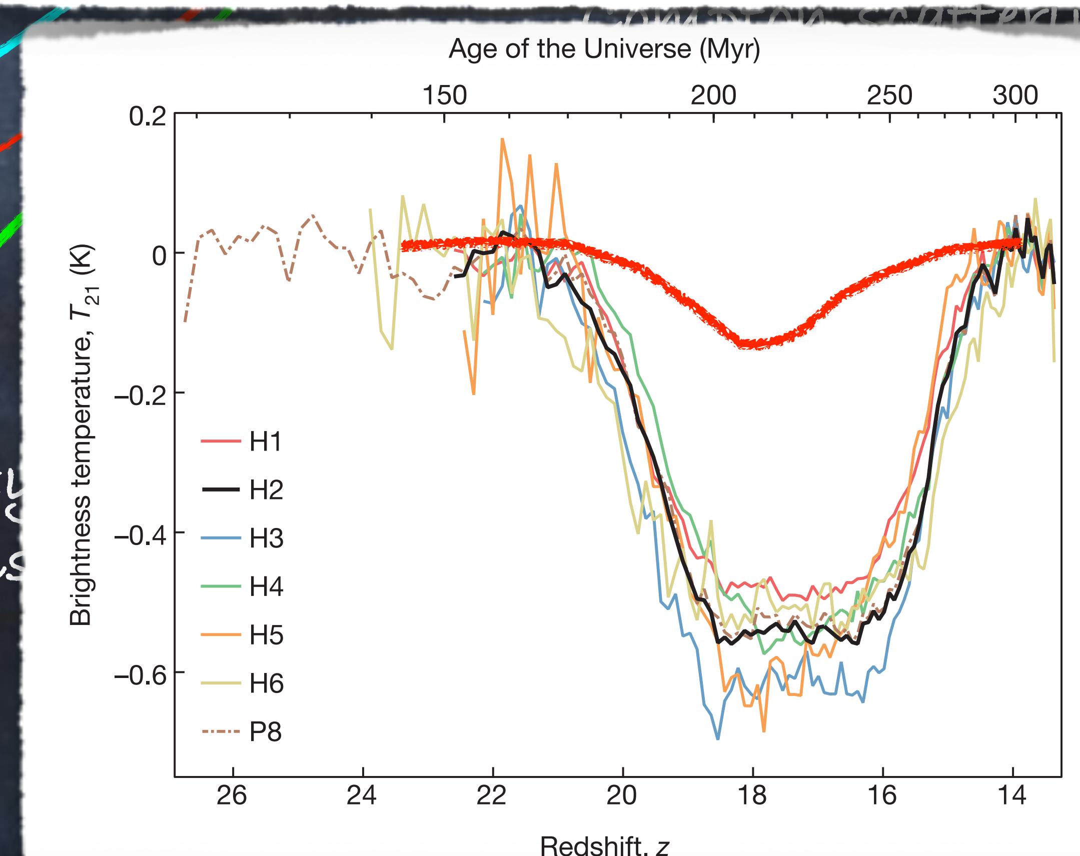
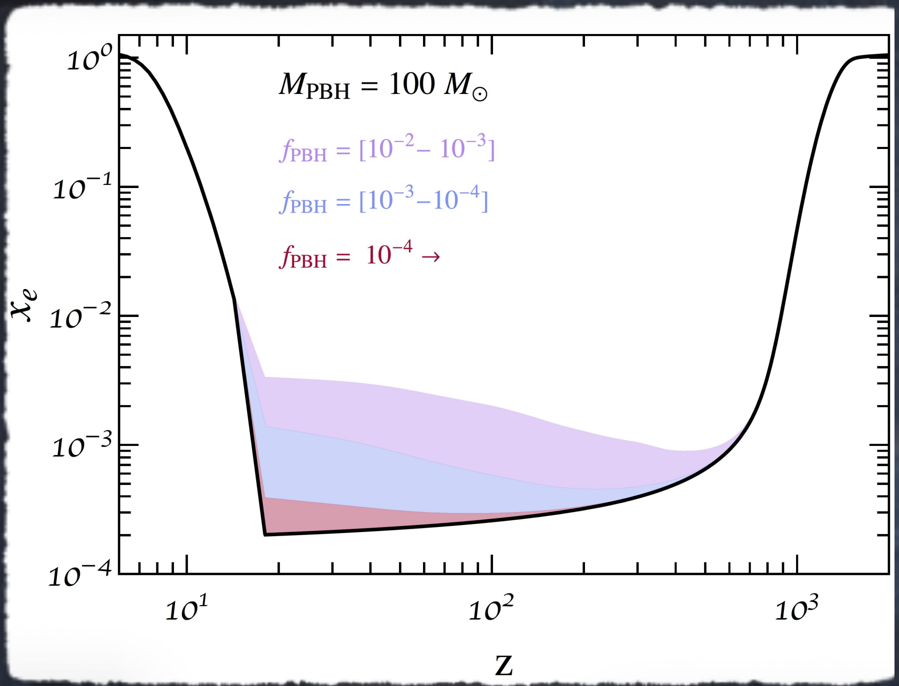


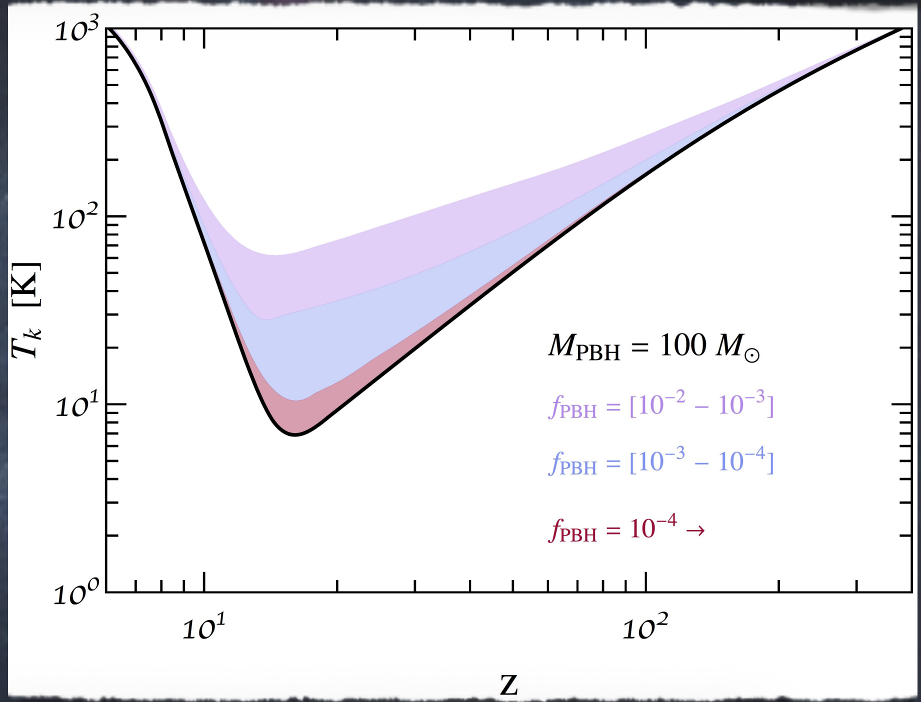
Fully incompatible (amplitude, location AND shape) with standard scenarios

S. Witte, P. Villanueva-Domingo, S. Gariazzo, O. Mena and SPR, Phys. Rev. D97:103533, 2018

PBHs: Brightness temperature

Accretion: Injected energy goes into ionizing and heating the IGM



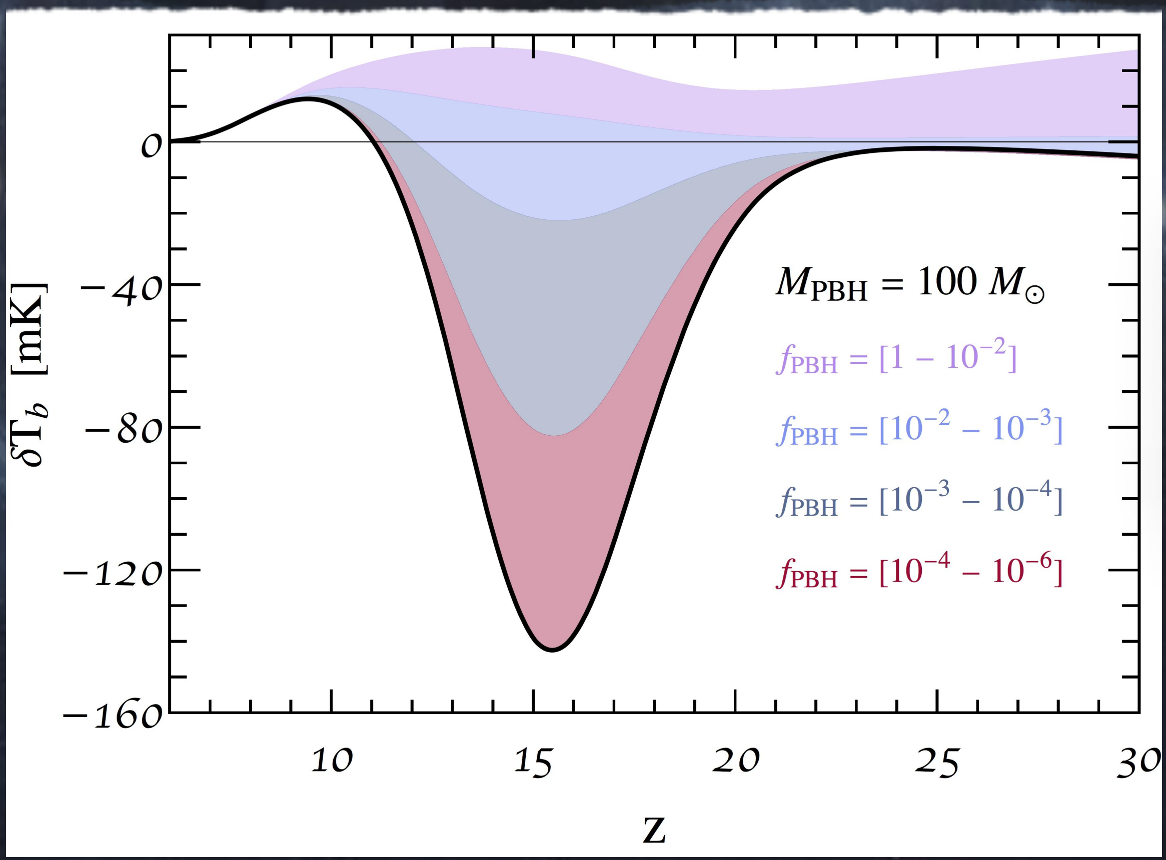


We use CosmoRec

J. Chluba and R. M. Thomas,

Mon. Not. R. Astron. Soc. 412:478, 2011

Impact on the brightness temperature: suppression of signal



From absorption to emission

We use 21cmFAST

A. Mesinger, S. Furlanetto and R. Cen,

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

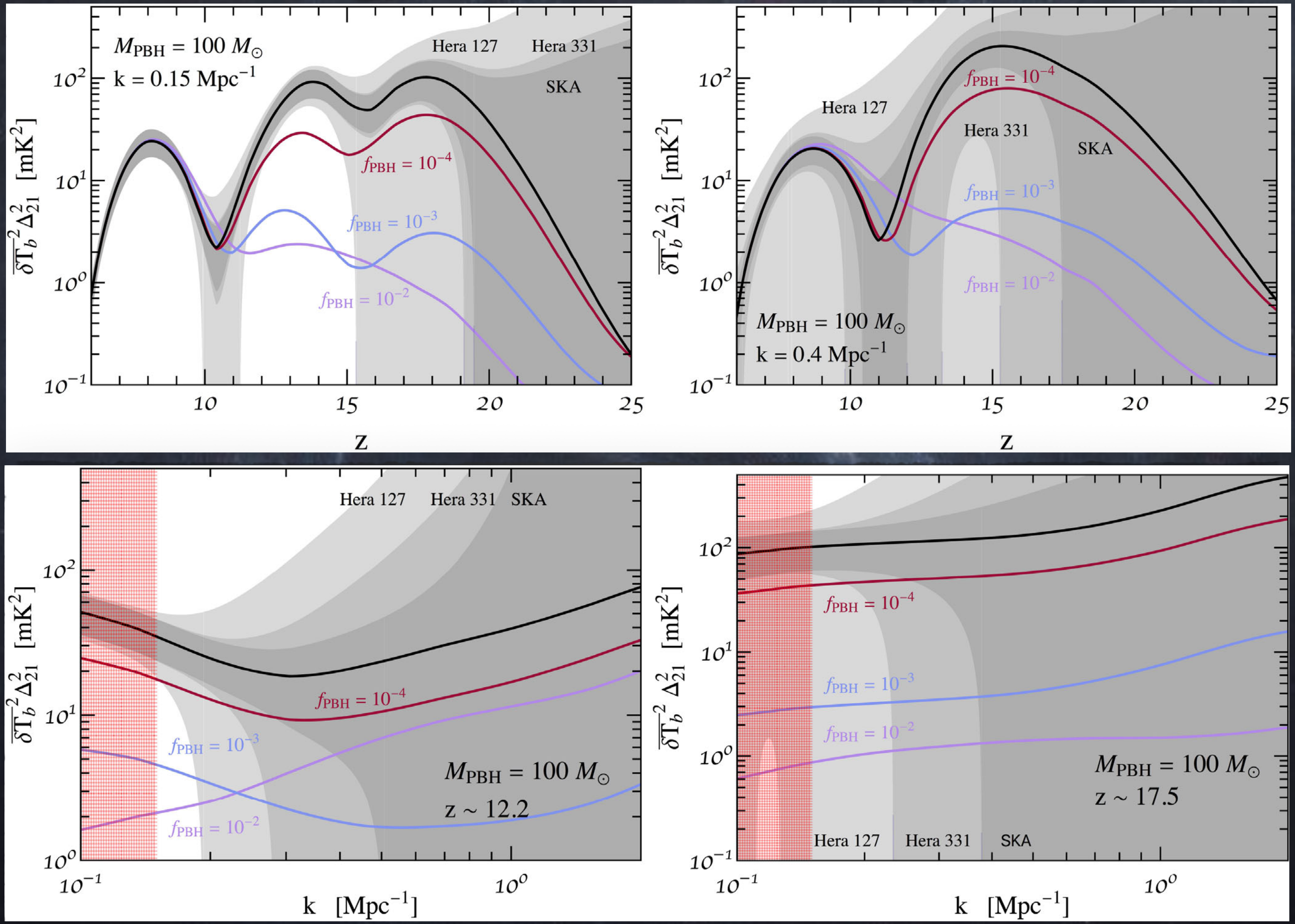
PBHs: 21cm power spectrum

We use 21cmSense

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

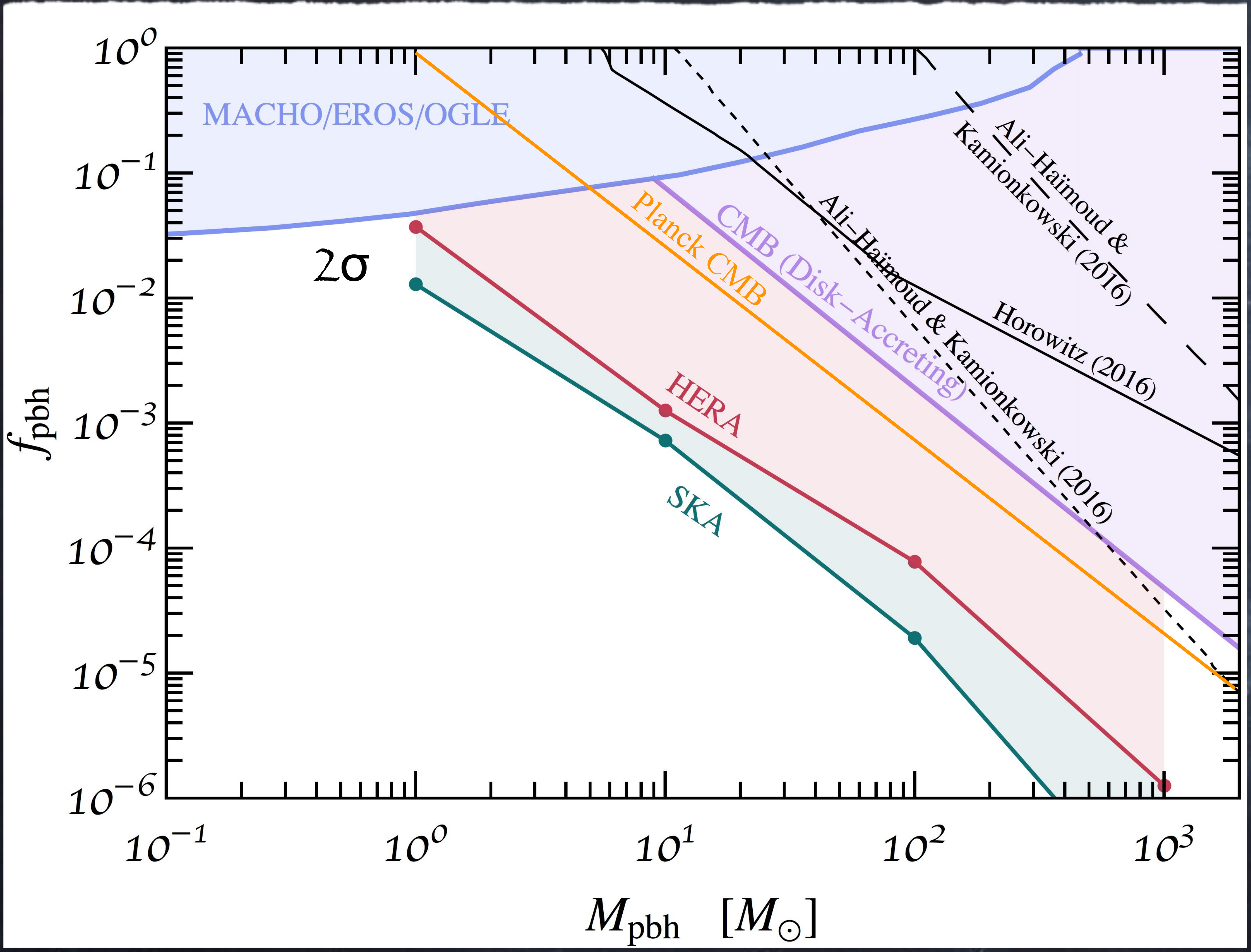
J. C. Pober et al., Astrophys. J. 782:66, 2014

Four-parameter astrophysical model



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

PBHs abundance: Sensitivity



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

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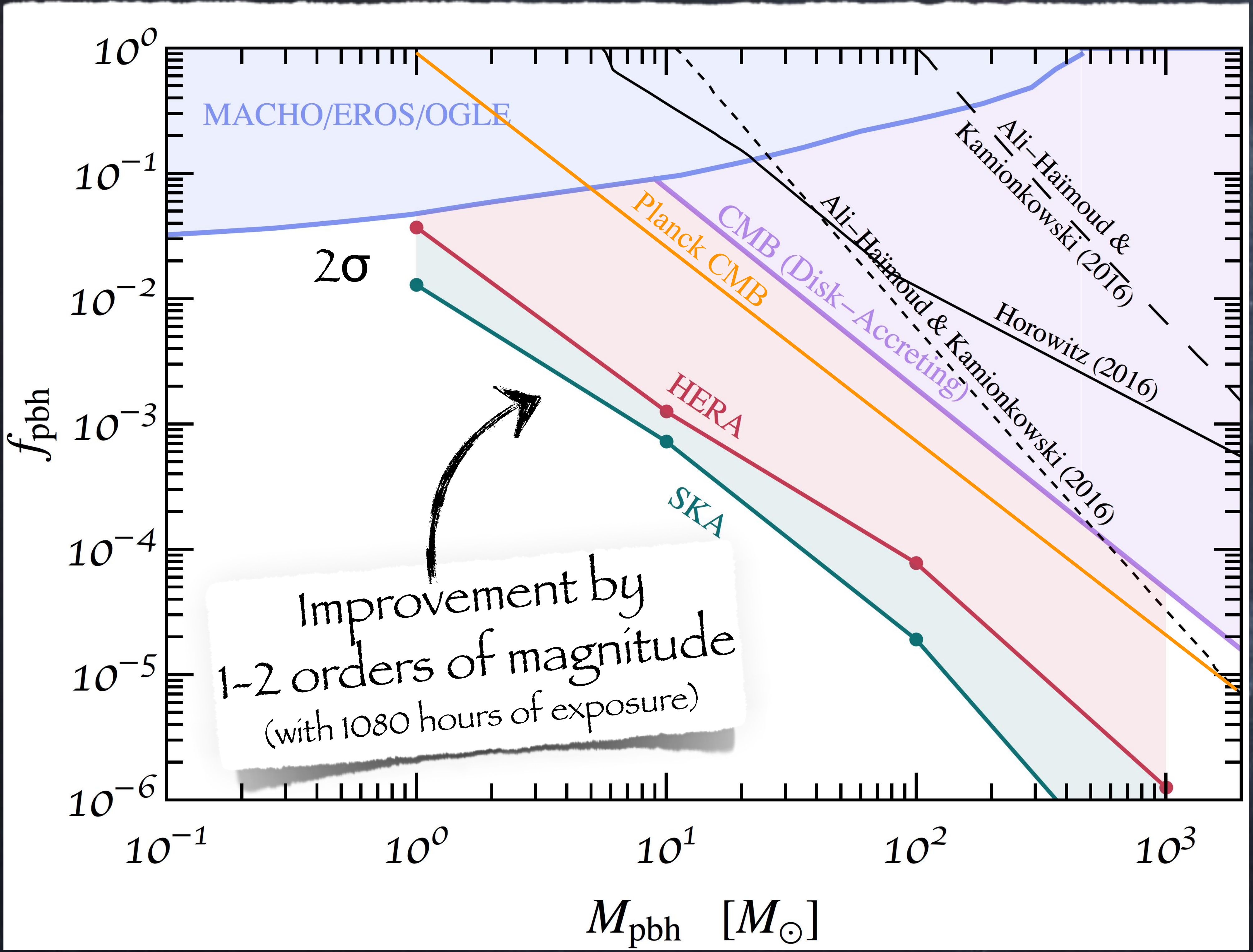

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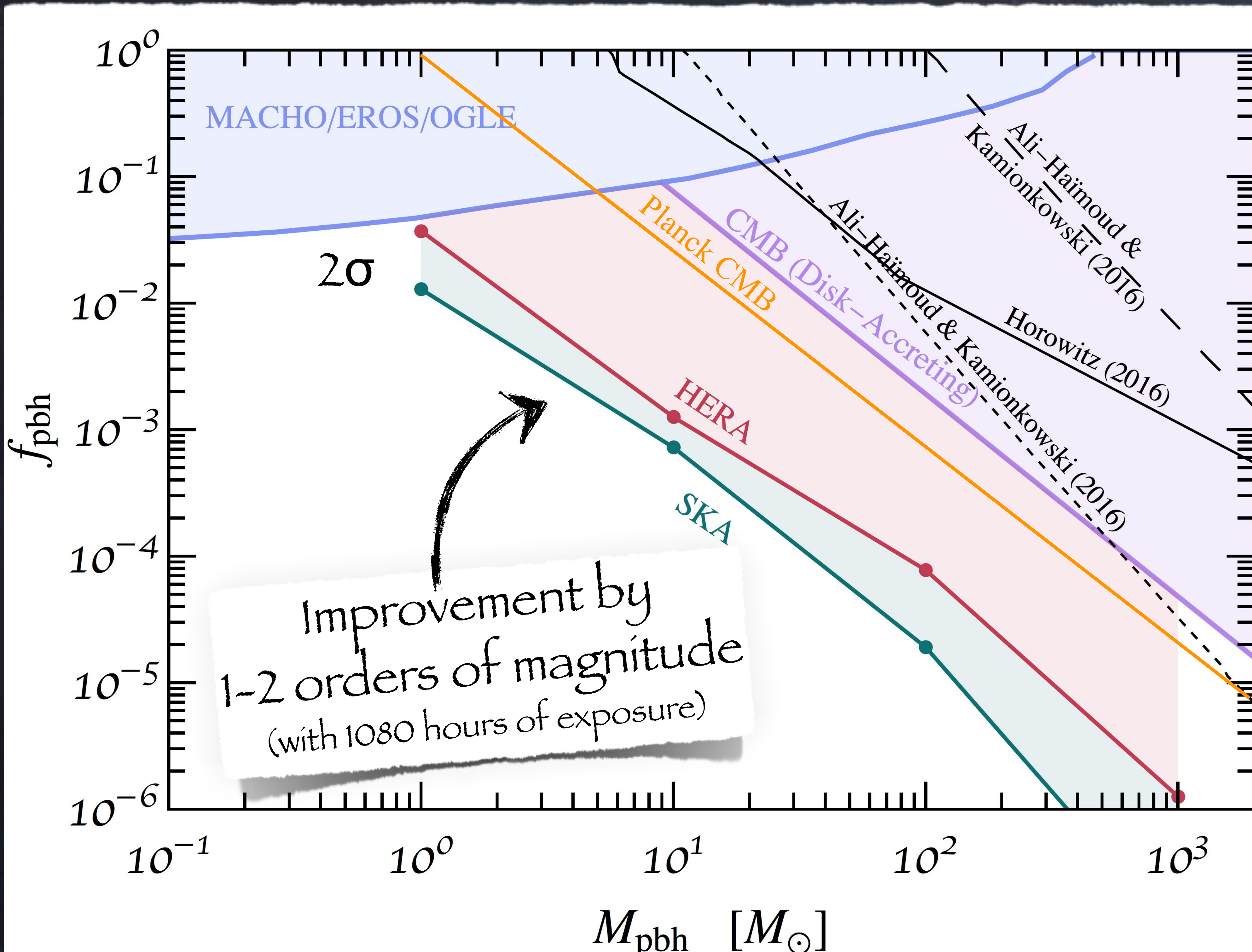

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Accretion model is critical

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

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Just to name a few...

Evaporation

Memory burden : slowing down of evaporation

Lensing

Size of sources, wave optics, halo properties...

Gravitational Waves

Clustering and PBH binaries survival

Accretion

Accretion modeling

Dynamical

Assumed initial stellar distribution
Are stellar binaries genuine or spurious?