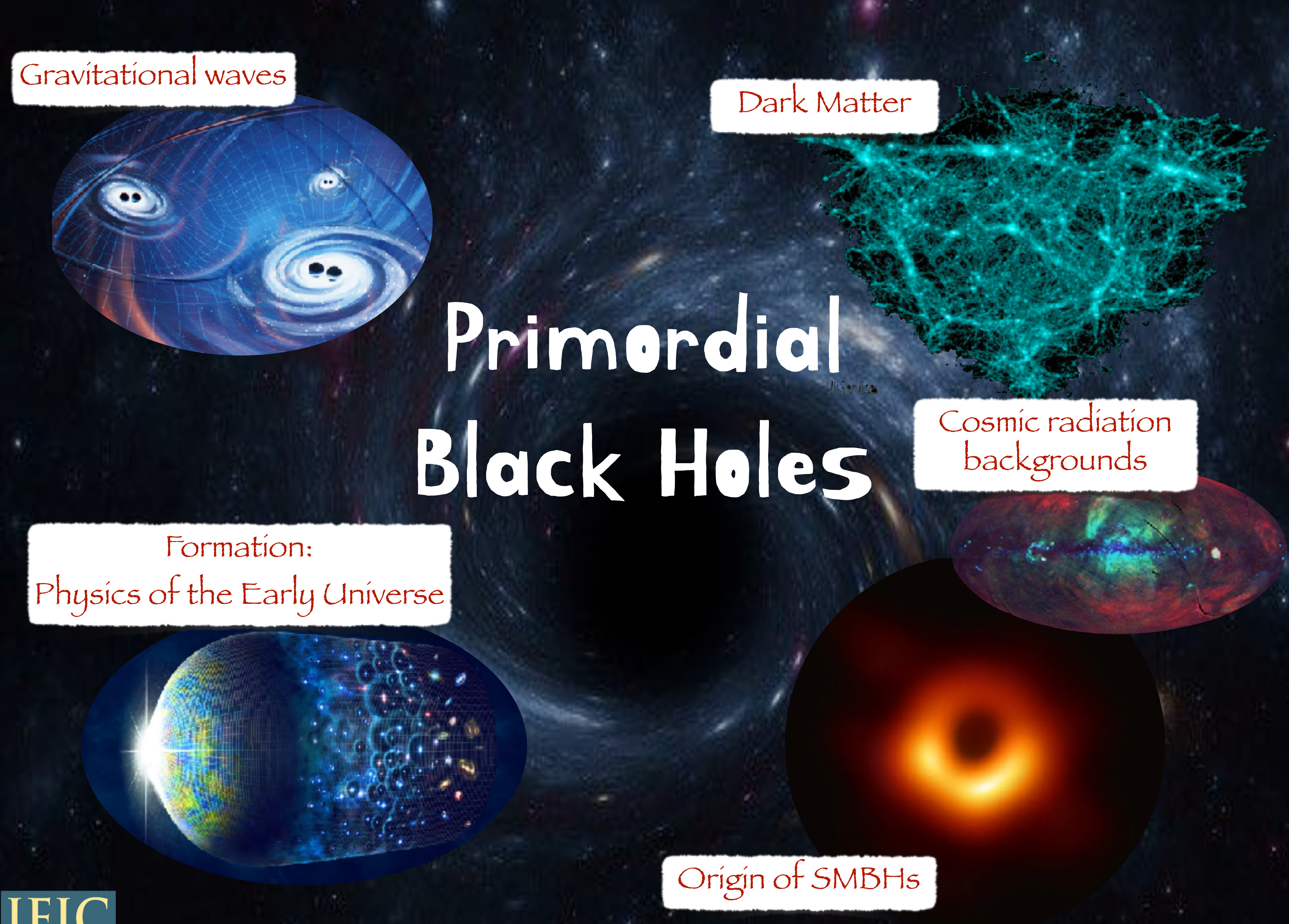
Primordial Black Holes and the 21 cm line

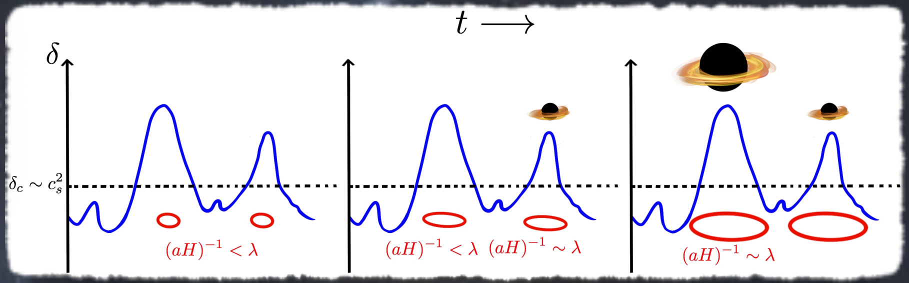
Sergio Palomares-Ruiz

IFIC, CSIC - U. Valencia


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

Formed during radiation era from the gravitational collapse of a large fluctuation (at horizon entry) with a mass of the order of the horizon mass… or via collapse of cosmic string loops or a scalar field, bubble collisions…

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

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

$$t = 1\,{\rm s} \rightarrow M_{\rm PBH} \sim 10^{5}\,M_\odot$$

see talks by P. Cole, Y. Tada, E. Tomberg, C. Animali, A. Escriva, A. Perez, A. Kusenko, M. Zantedeschi, P. Conzinu, J. I. Juan …

Primordial black holes

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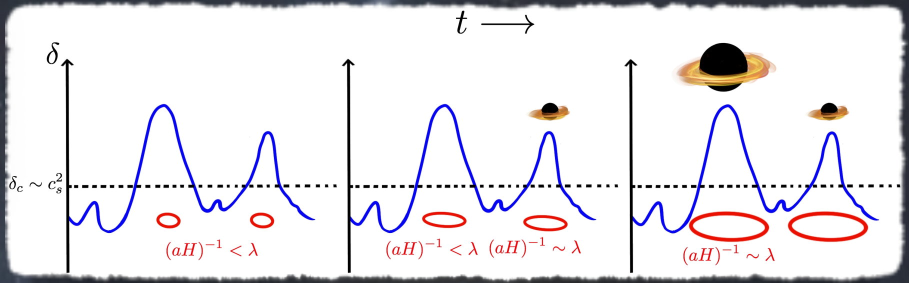

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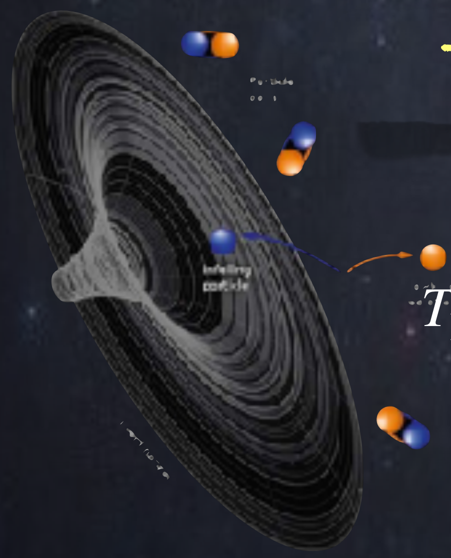

Black holes radiate thermally, so they eventually evaporate

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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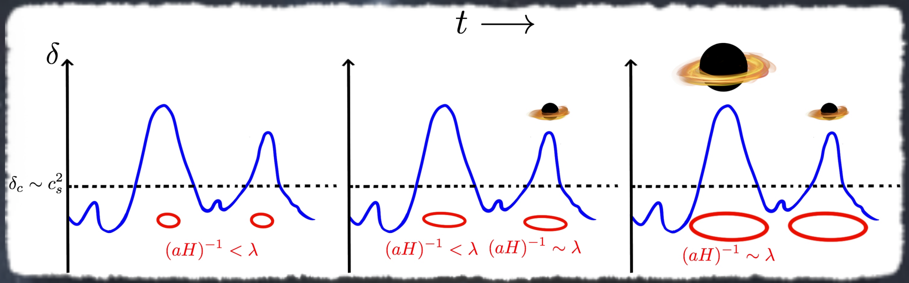

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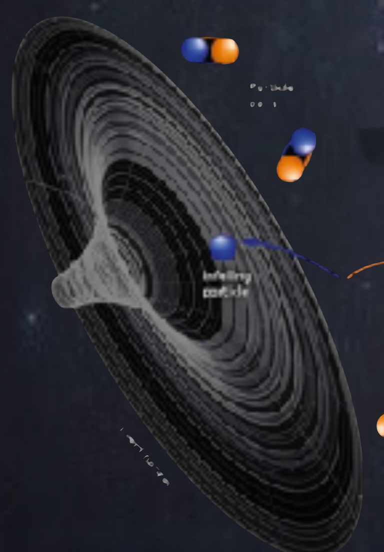

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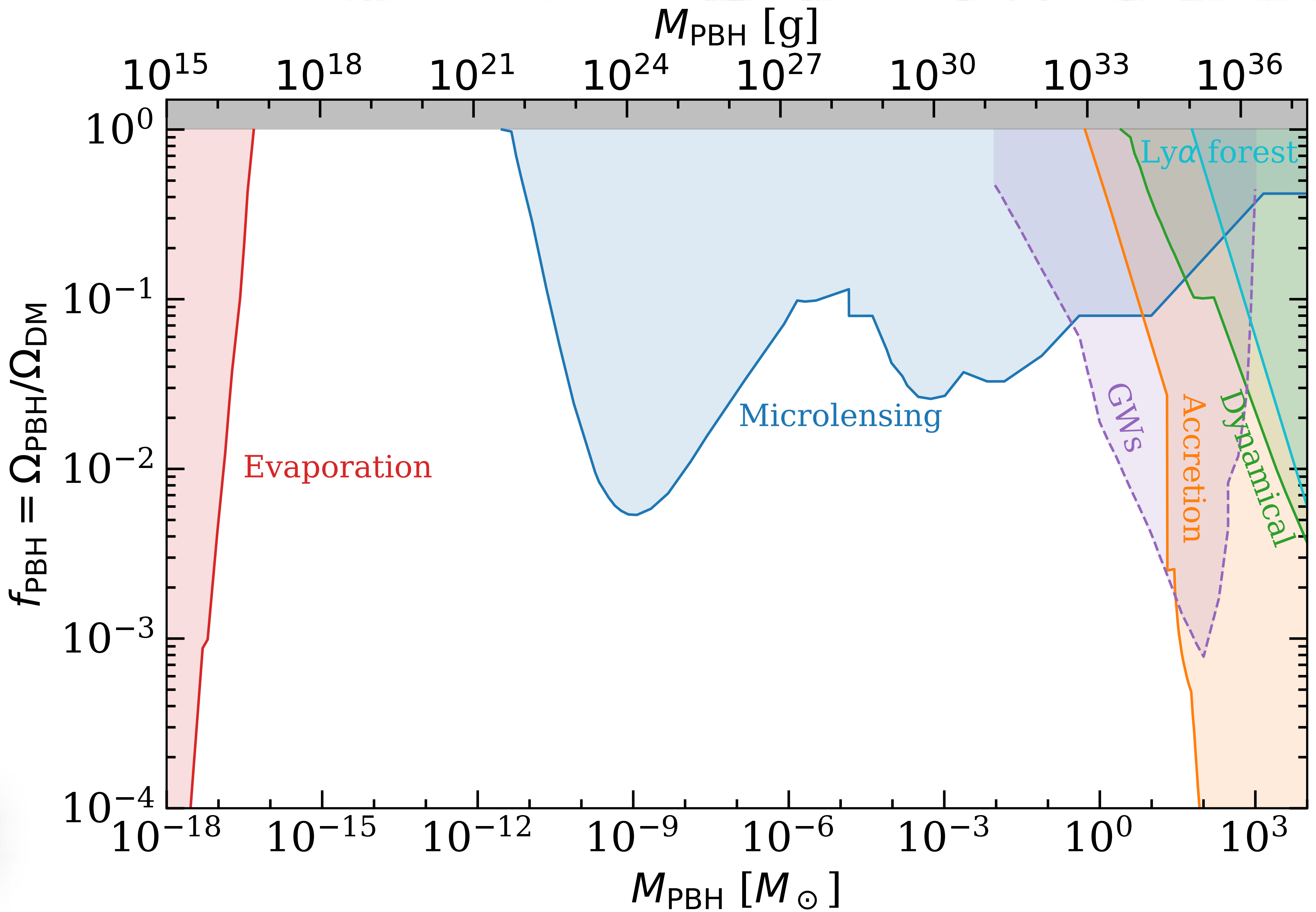
PBHs would form before BBN, so they would not count as baryonic matter

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

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



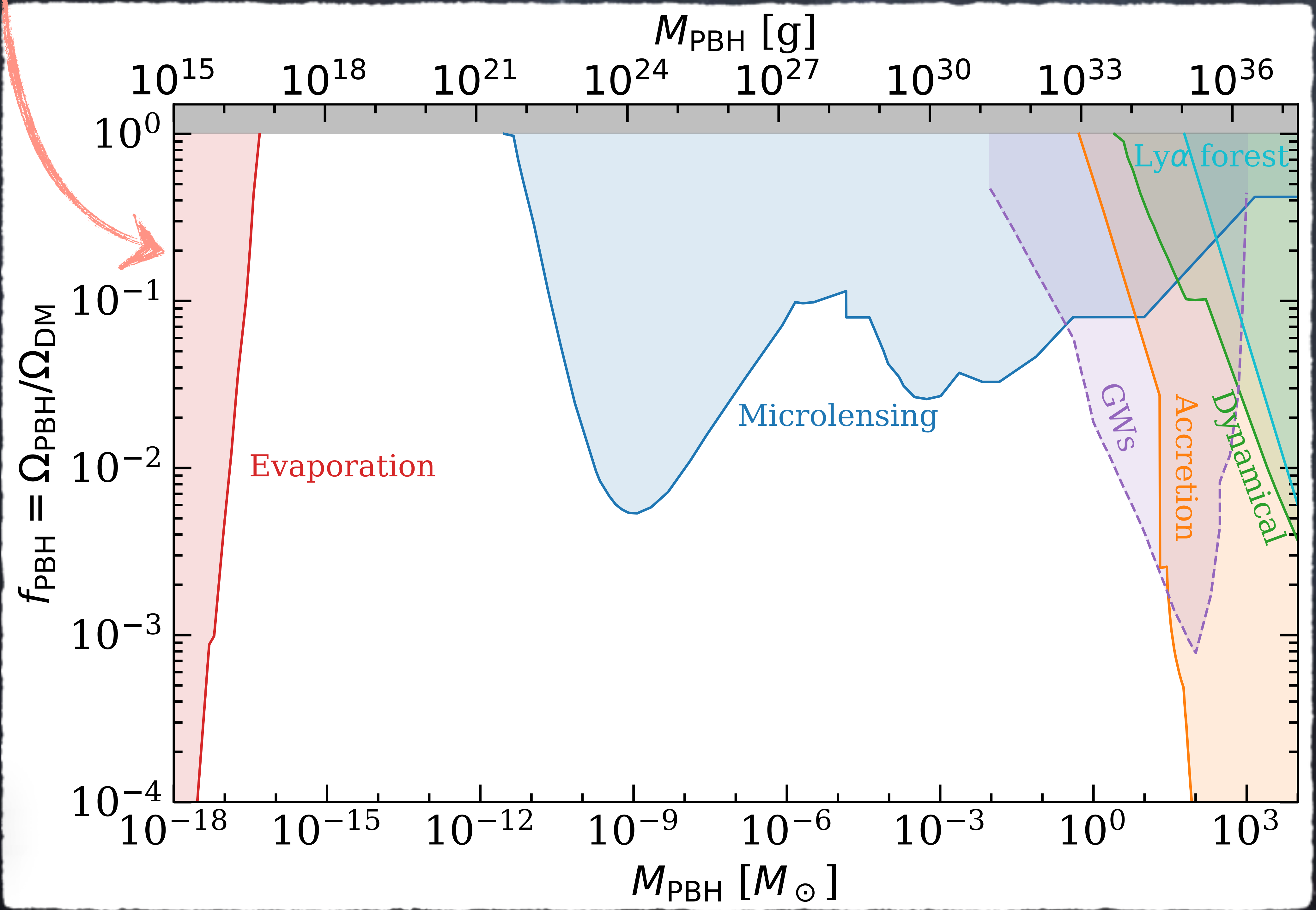
Using PBHbounds

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



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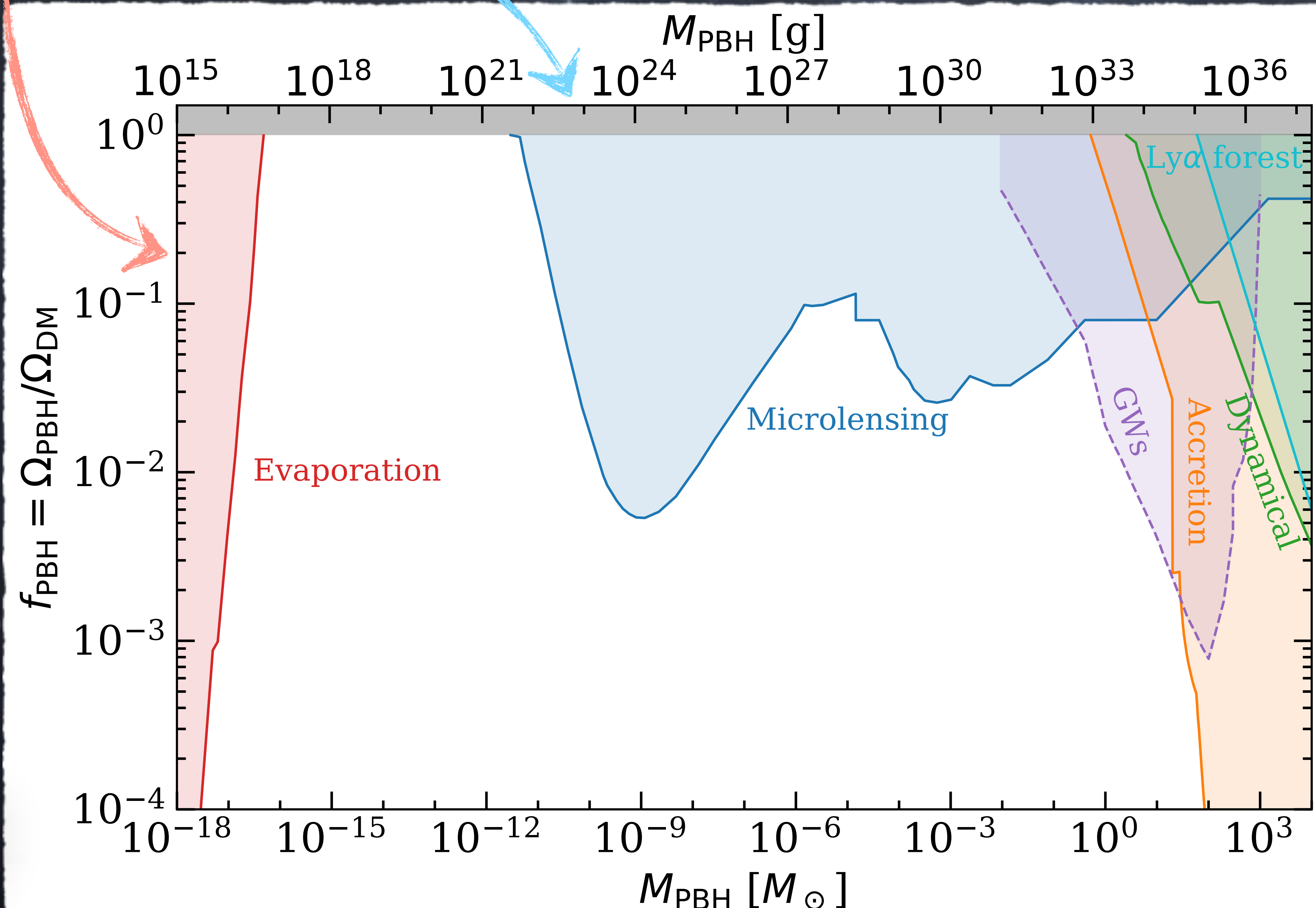
Partial evaporation

Gravitational lensing

(femto, micro, milli) Lensing of GRBs, stars, SN, QSO, pulsars, FRBs



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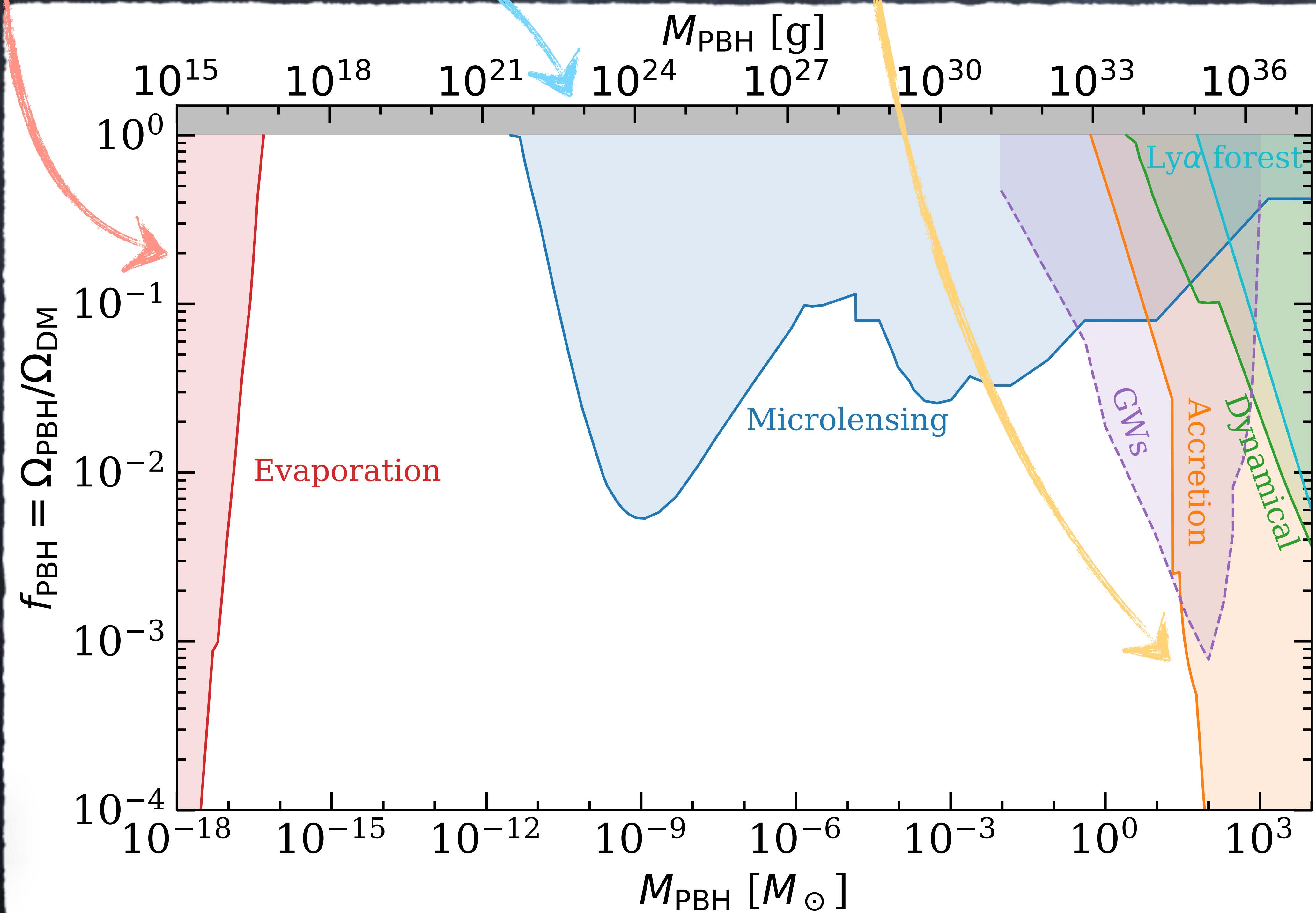
Partial evapo

Ionization and thermal history, radio and X-ray emission

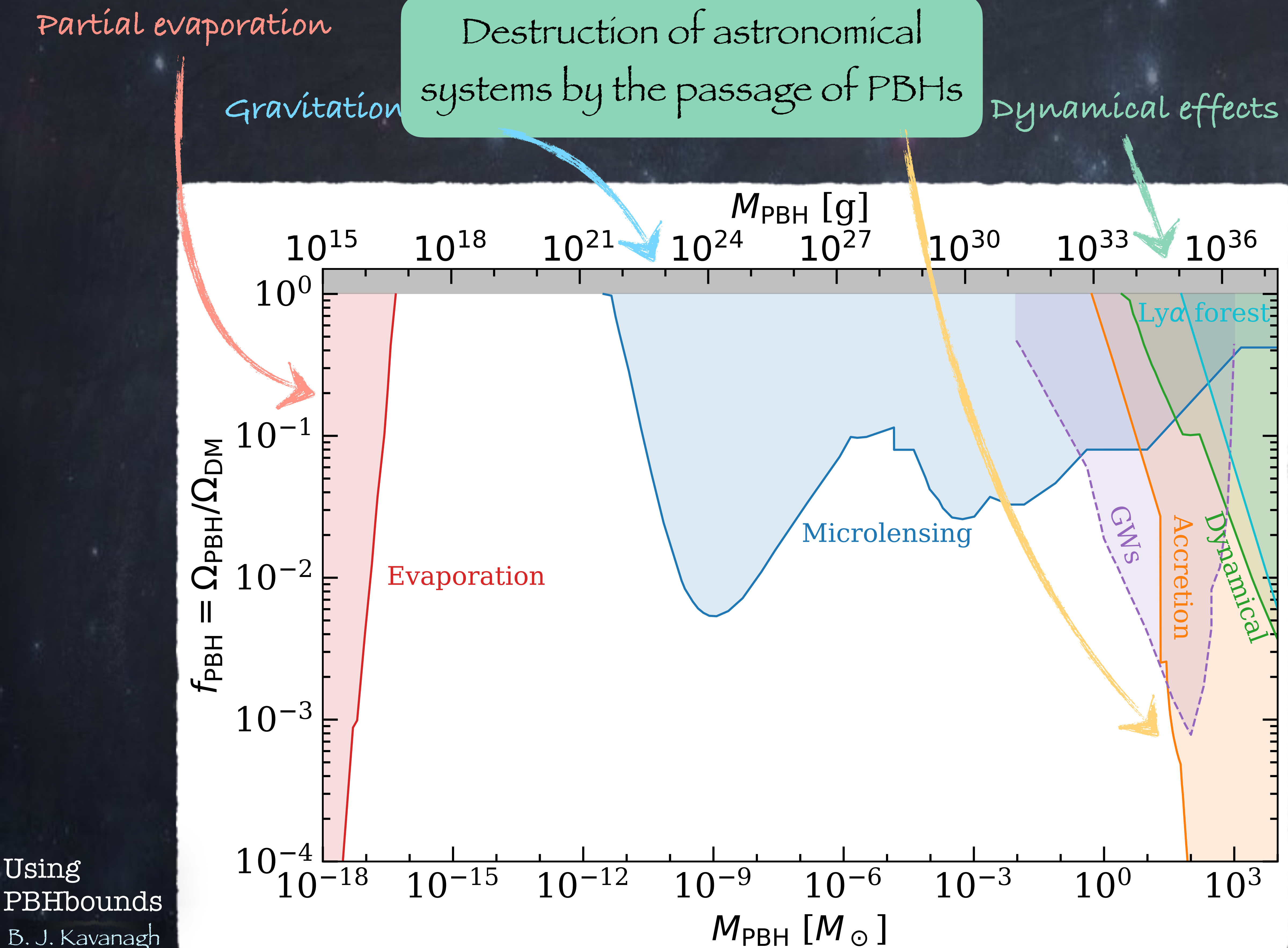
Accretion



Using PBHbounds
B. J. Kavanagh

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

Destruction of astronomical systems by the passage of PBHs



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

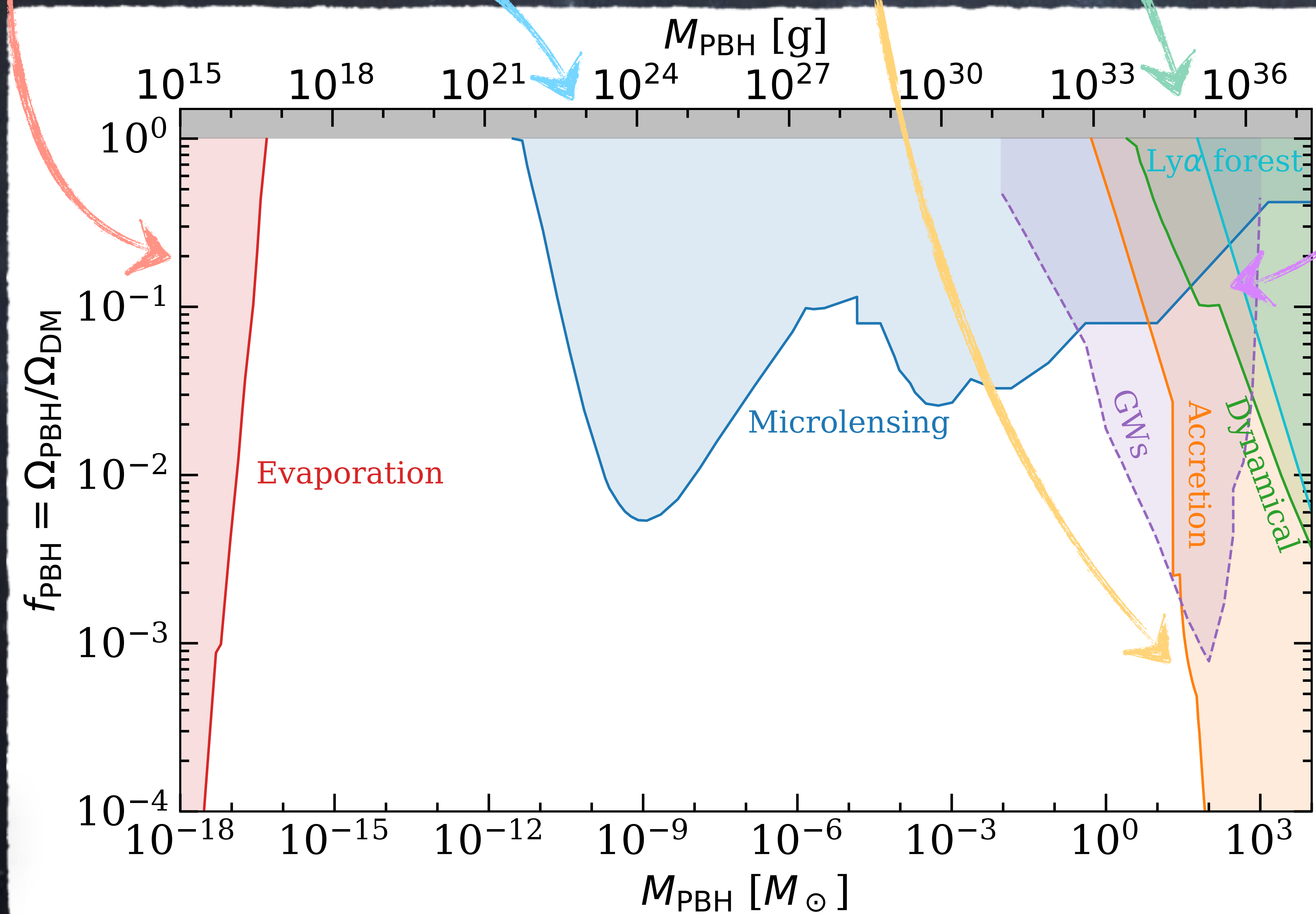
Partial evaporation

Gravitational lensing

LIGO/VIRGO events
stochastic background

Gravitational waves

cal effects



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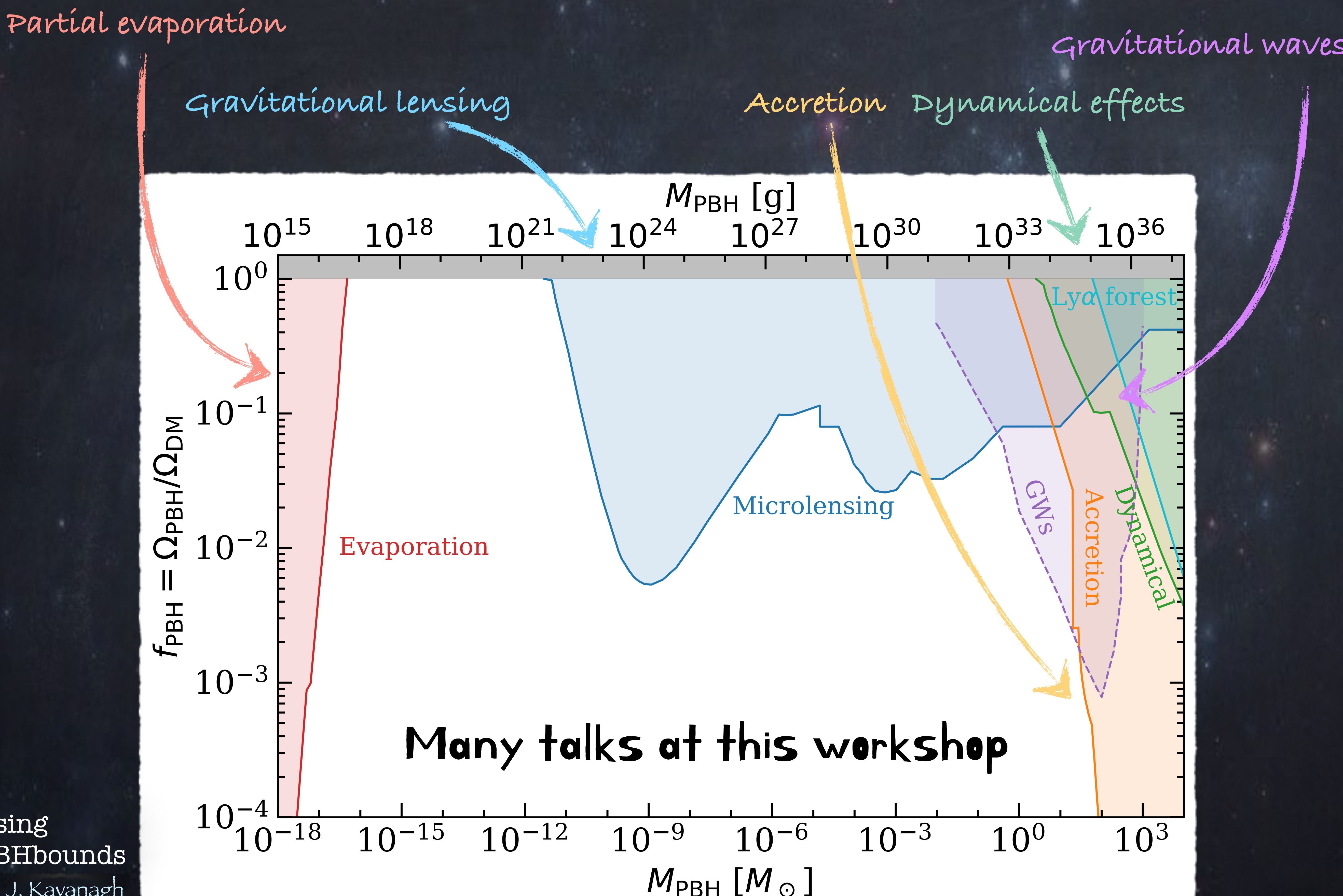

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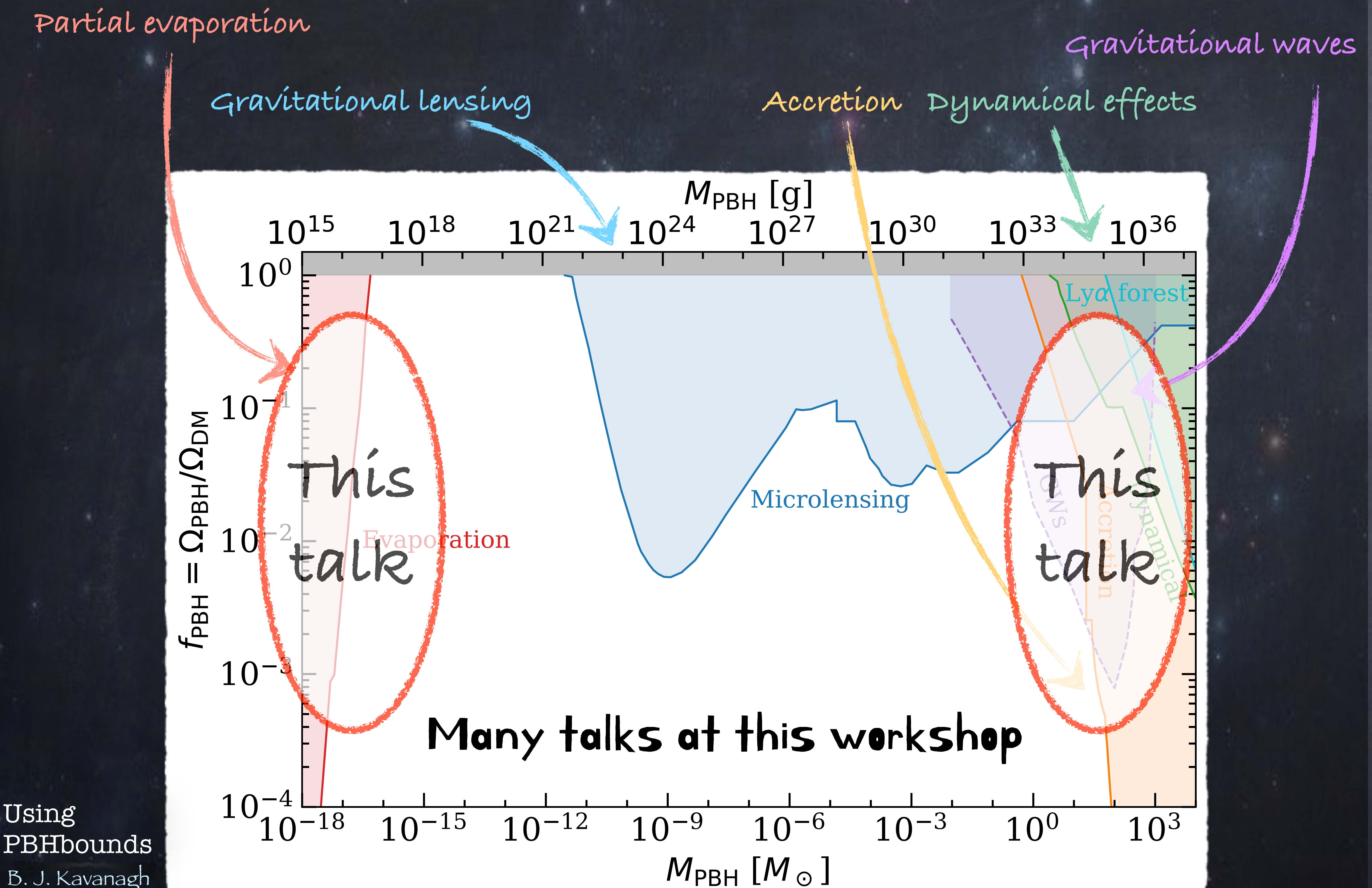

Using PBHbounds

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

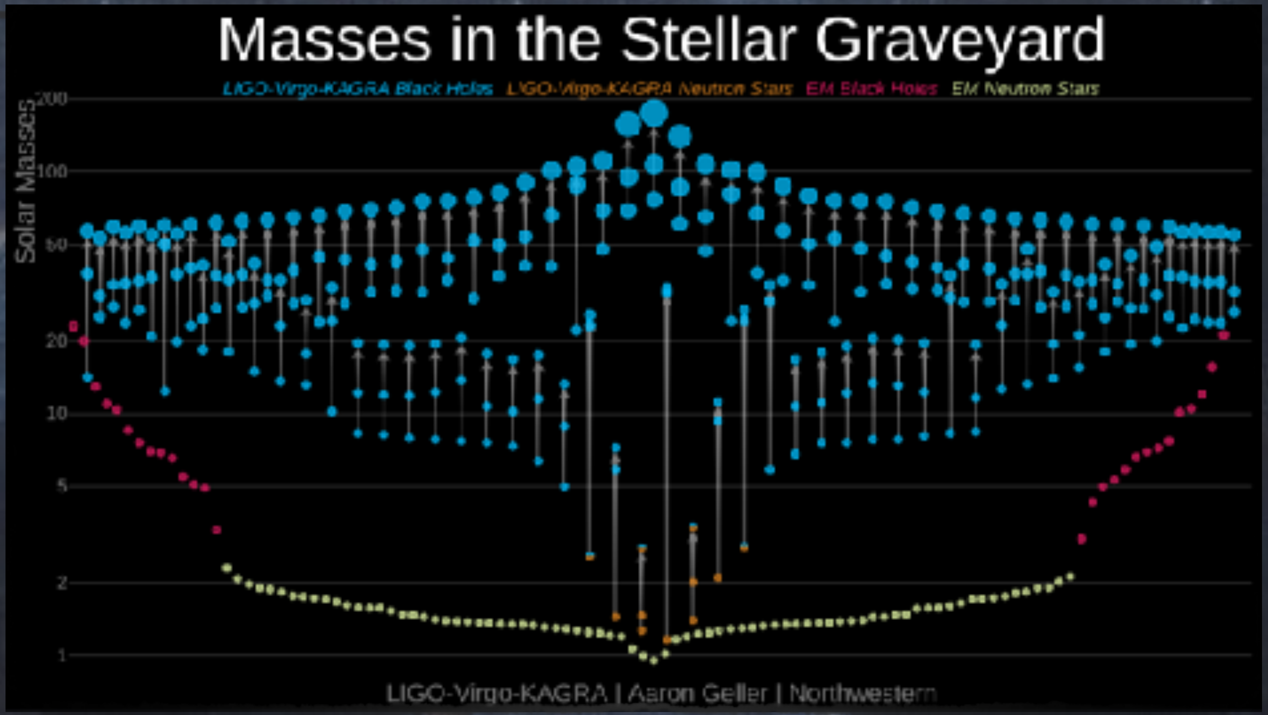
Primordial black holes

Even if they cannot form all the dark matter... still of great interest

see talks by B. Carr, L. Visinelli

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

see talks by A. Riotto, A. Miller

Insight into early Universe physics (inflation, phase transitions...)

many talks at this workshop

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

see talks by I. Masina, N. Bernal, A. Cheek, Y. Perez, D. Montanino

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

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

see A. Ireland's talk

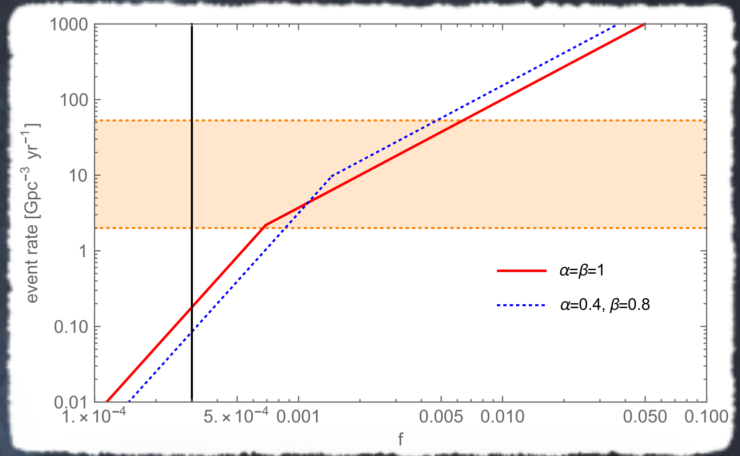
solar mass PBHs abundance

VIRGO/LIGO:

Merger rates and masses related to BHs abundance

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama,
Phys. Rev. Lett. 117:061101, 2016 (E: Phys. Rev. Lett. 121:059901, 2018)

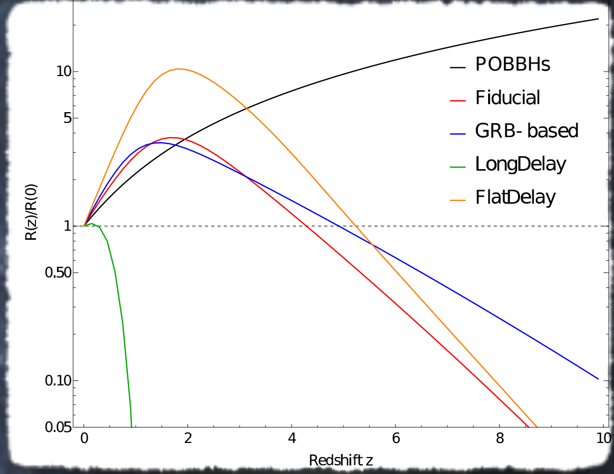
see A. Riotto's talk... but see also B. J. Kavanagh's talk



Gravitational waves at large redshifts (z>40) by O(10) solar mass PBH mergers: Einstein Telescope

S. M. Koushiappas and A. Loeb, Phys. Rev. Lett. 119:221104, 2017
Z.-C. Chen and Q.-G. Huang, JCAP 08:039, 2020

see A. Riotto's talk



Accretion of gas onto PBHs: Emission of broad band spectrum
observed excesses (X-rays, infrared, radio)

see F. Kuhnel's talk

heating and ionization of the IGM: cosmological implications

B. J. Carr, Mon. Not. R. Astron. Soc. 194:639, 1981

PBHs clustering modifies small scale structure:
shot noise → isocurvature perturbations → Cosmic Infrared and X-ray unresolved backgrounds?

N. Afshordi, P. McDonald and D. N. Spergel, Astrophys. J. 594, L71, 2003

A. Kashlinsky, Astrophys. J. 823:L25, 2016

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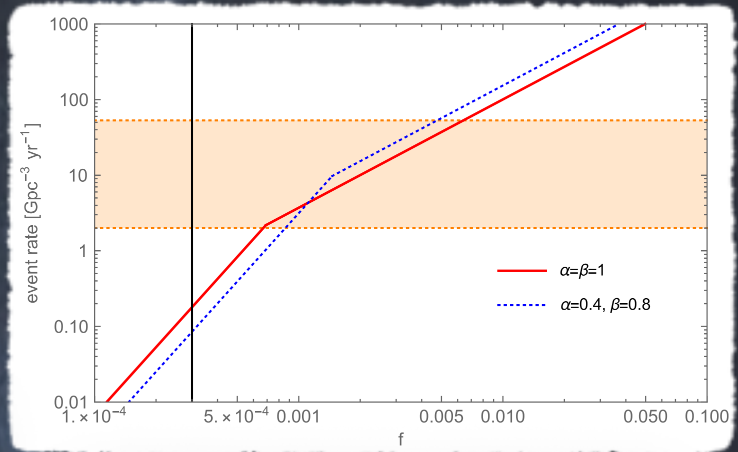

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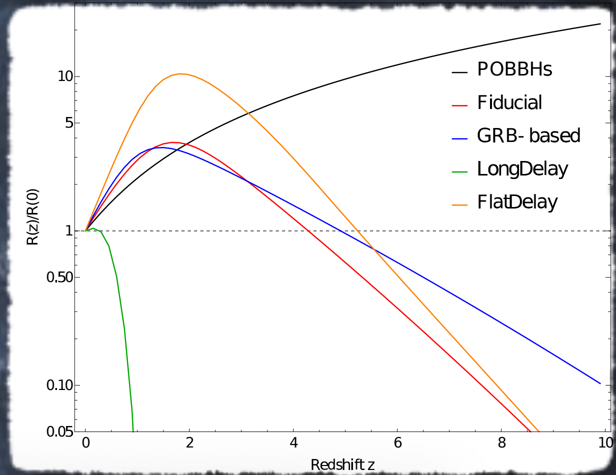

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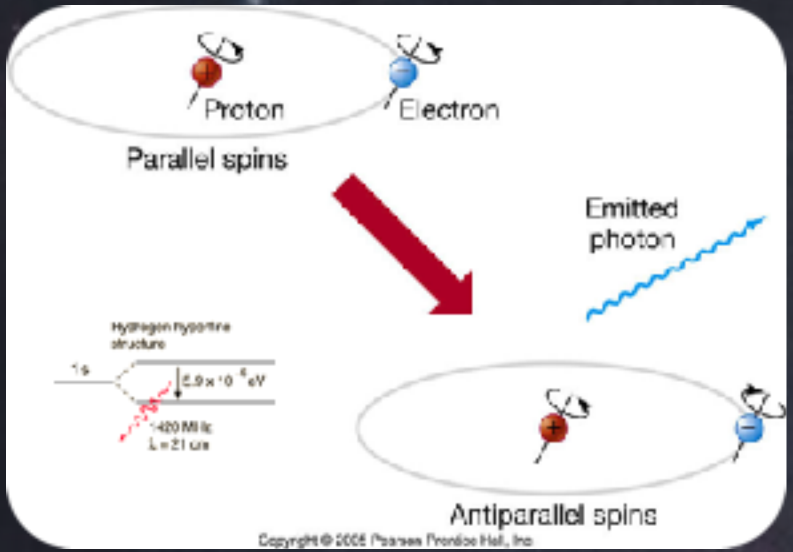
A. Kashlinsky, Astrophys. J. 823:L25, 2016

The 21cm line

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

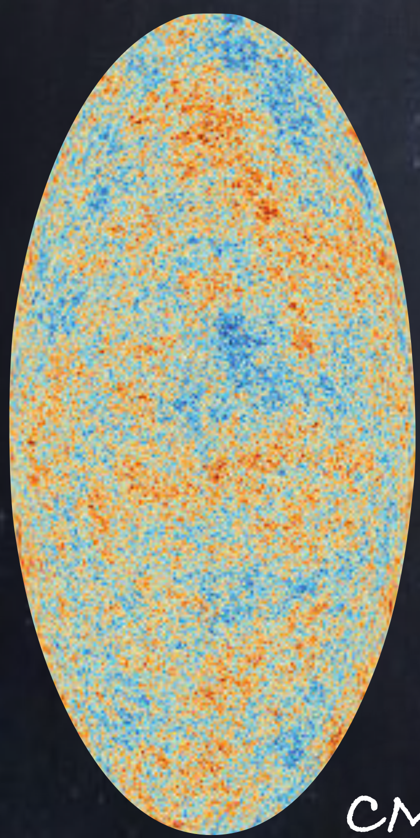


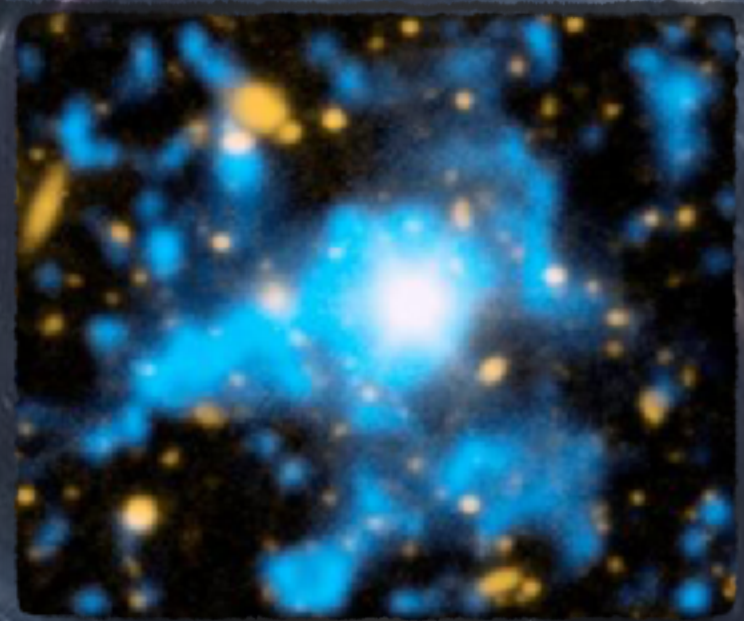
Hyperfine transition: ν = 1420 Mhz

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

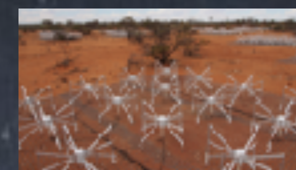
Population of ground and excited states controlled by:

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

The 21cm line

Probing Dark Ages and Cosmic Dawn

Cosmic tomography

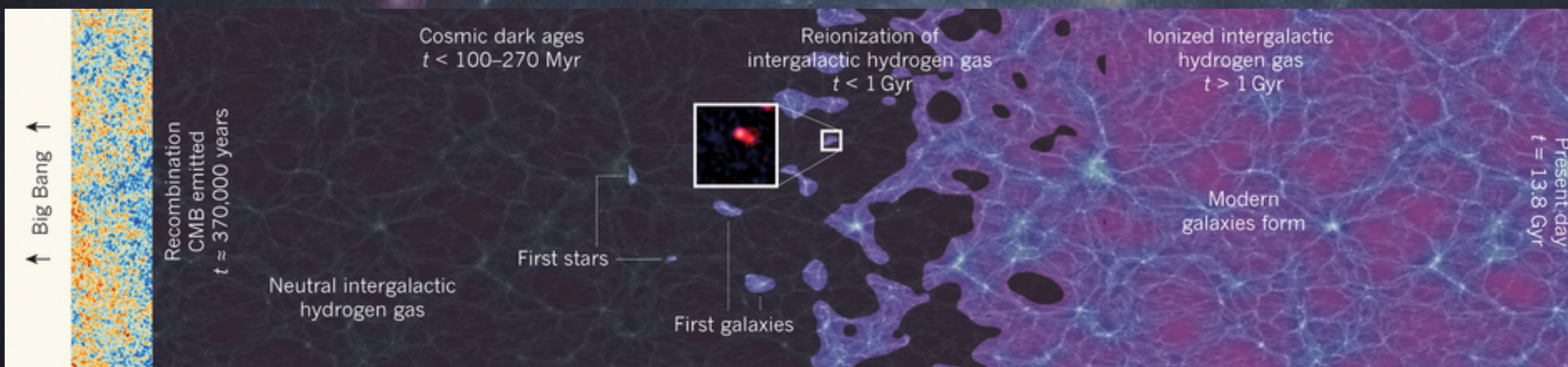


Interferometers
LOFAR, MWA, PAPER,
GMRT, LEDA, HERA, SKA

$z \sim 6-30$

Galaxy Surveys

$z < 6$



z~1000 | Dark ages | z~30 | Cosmic dawn | z~6 | Galaxy formation | z=0

First stars | Reionization

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

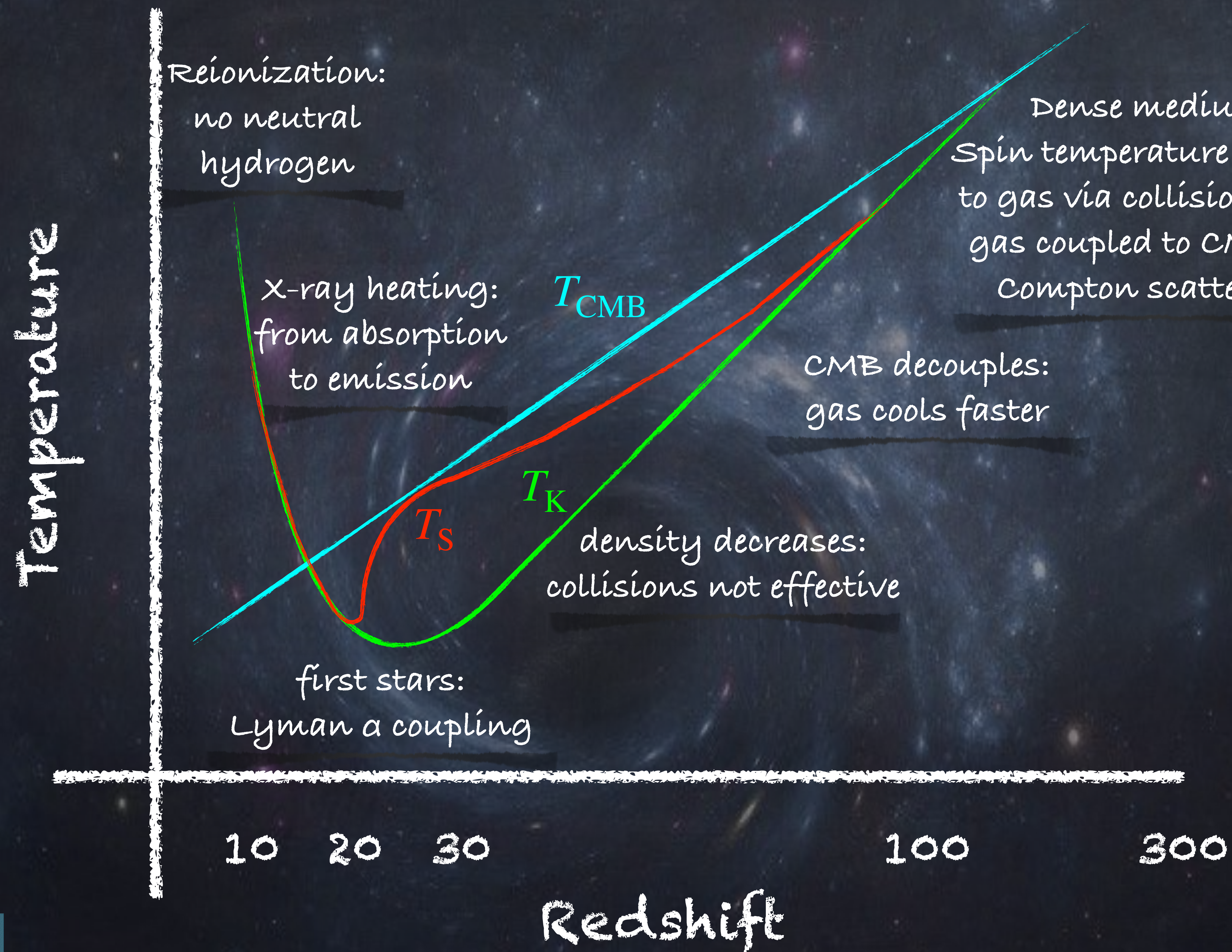
$\delta T_b \approx 0 \quad \text{if} \quad T_S \sim T_{CMB}$ no signal

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

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

Astrophysical processes decouple T_S from T_{CMB}

The 21cm signal: Time evolution



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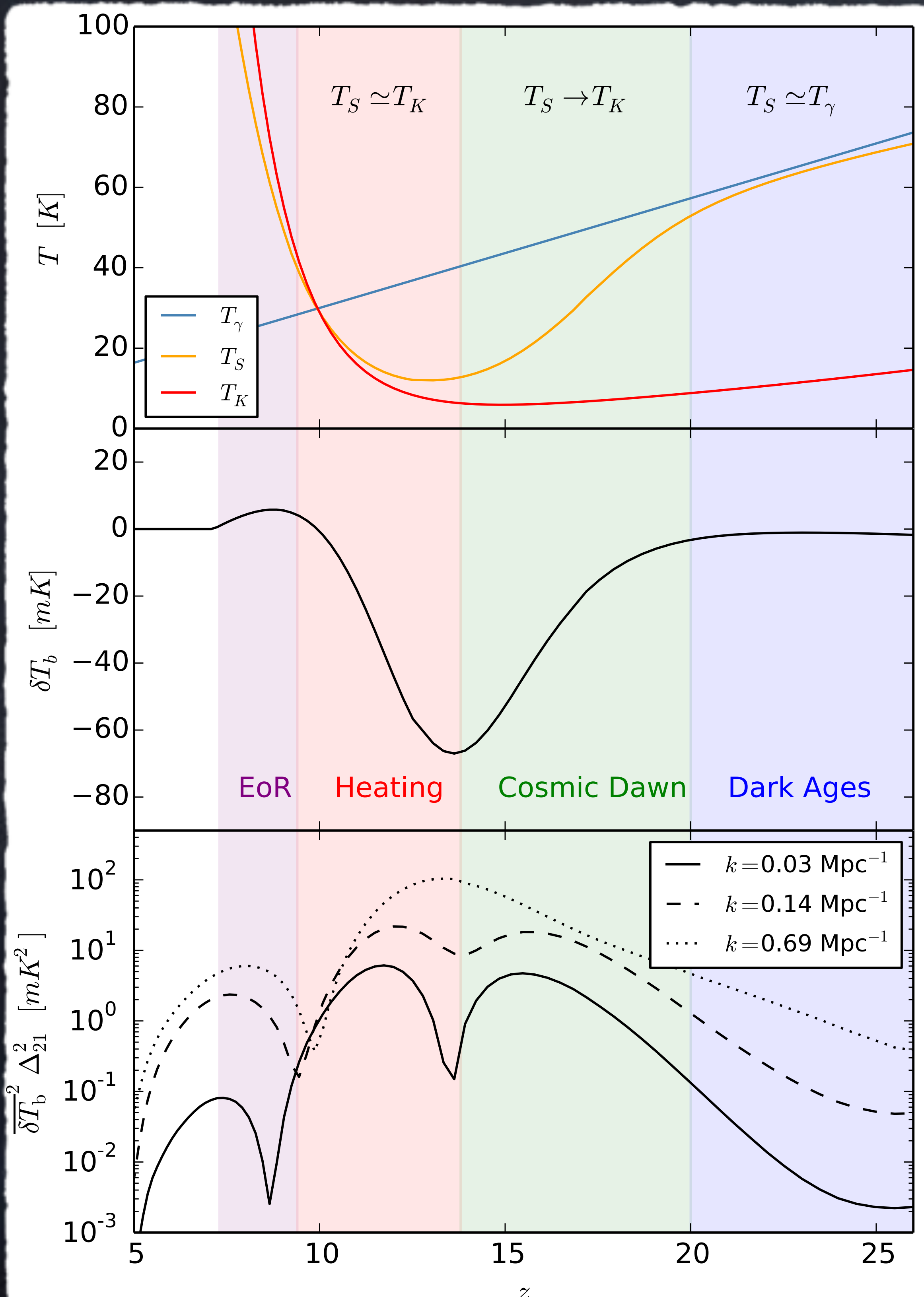


P. Villanueva-Domingo, PhD Thesis, 2021

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

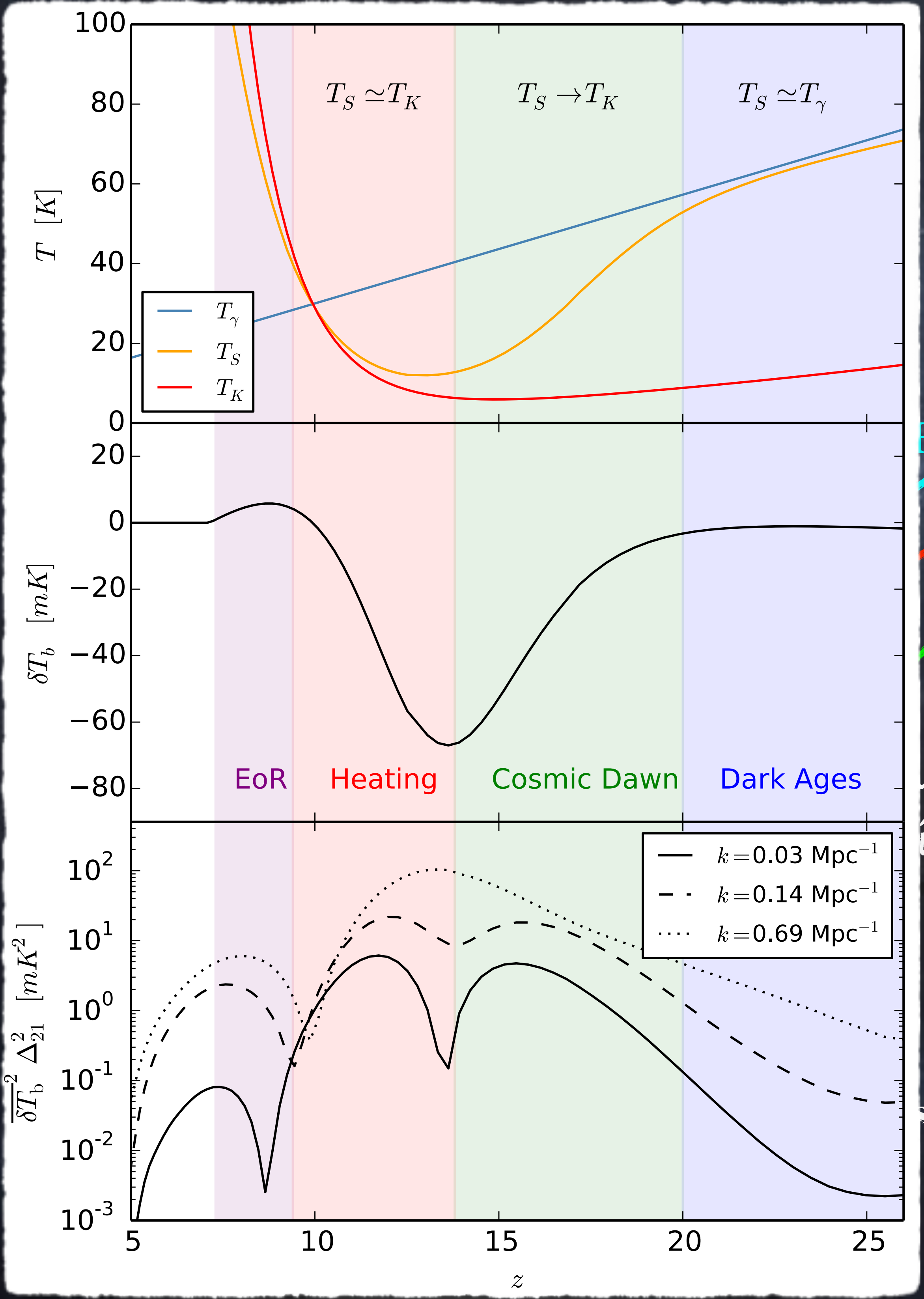
CMB decouples:
gas cools faster

...sity decreases:
...ions not effective

B

100 300

The 21cm signal: Time evolution



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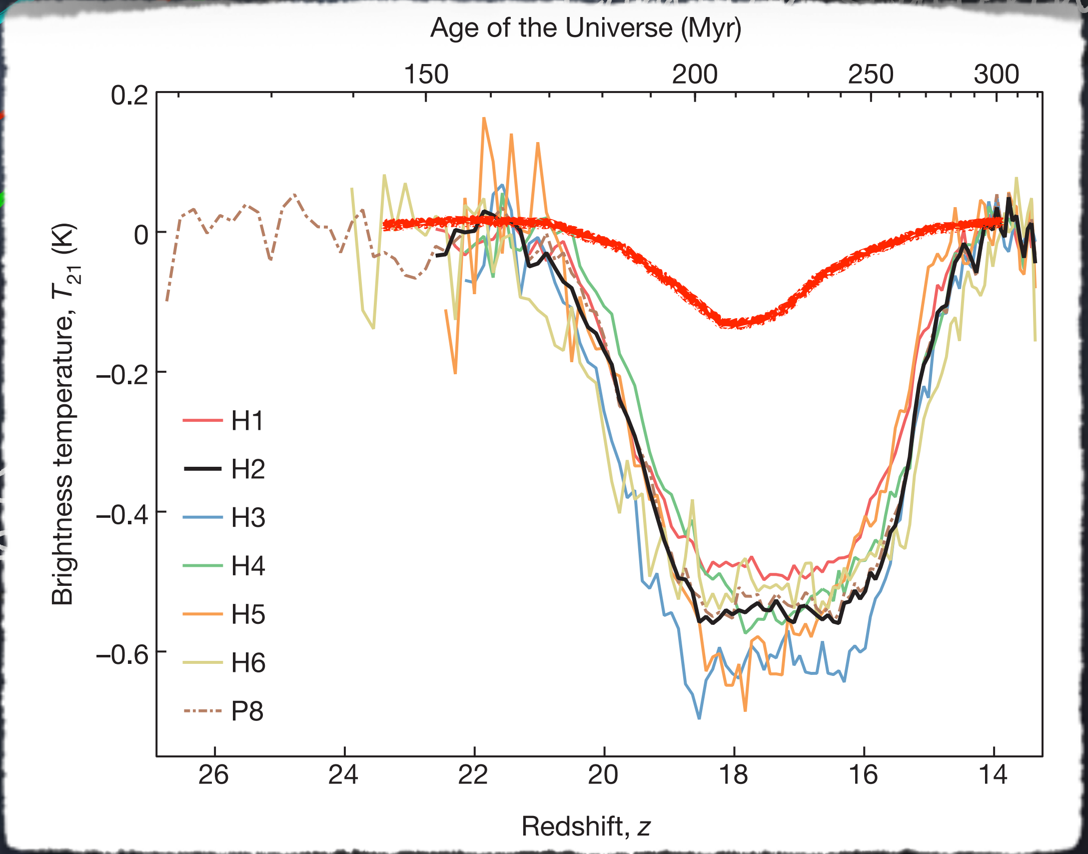
EDGES:

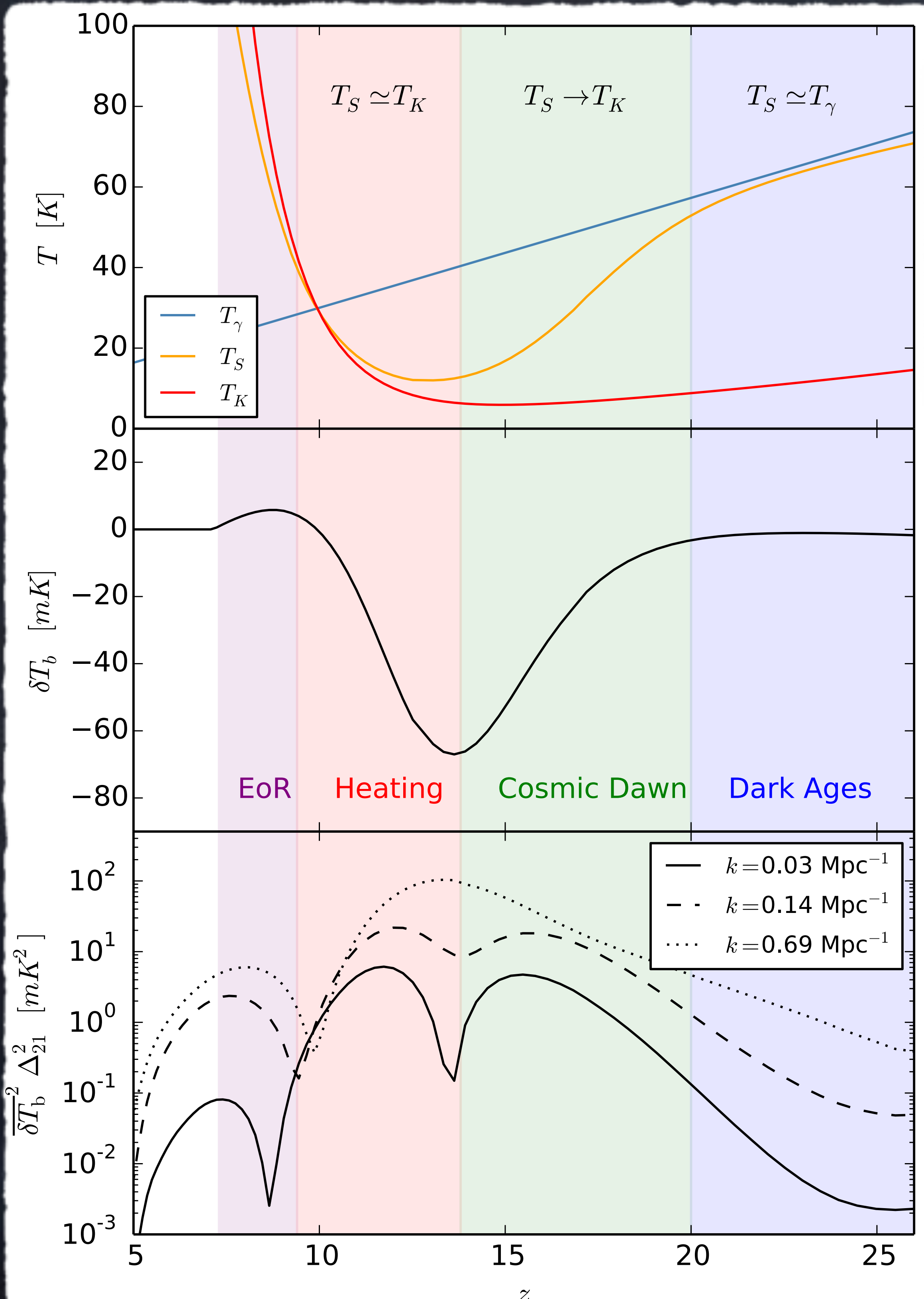
new physics? astrophysics?

systematics?



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

The 21cm signal: Time evolution



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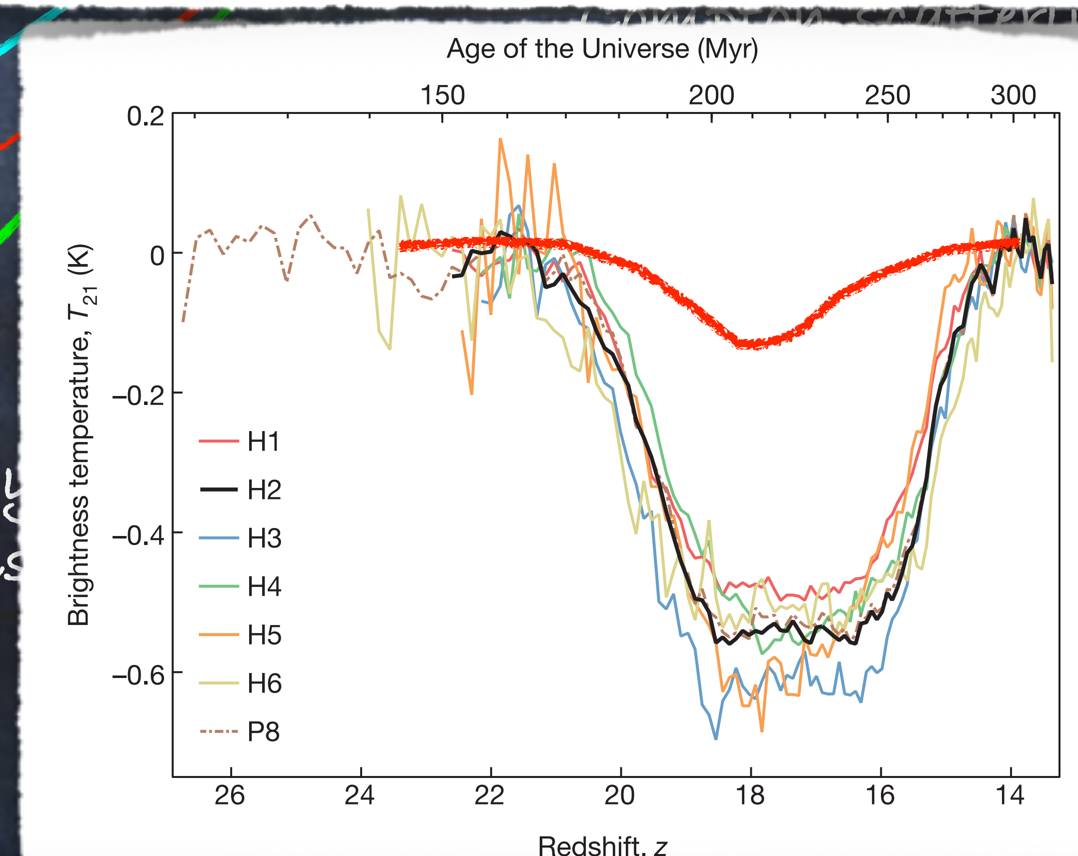


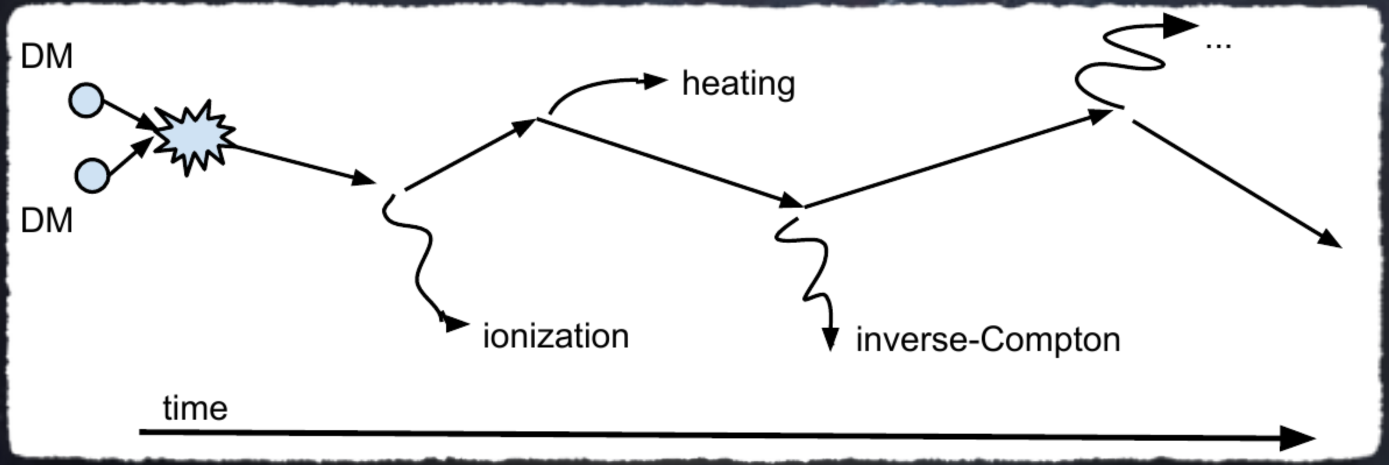
Fully incompatible (amplitude, location AND shape) with standard scenarios

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

Energy injection: Effect on the 21cm signal

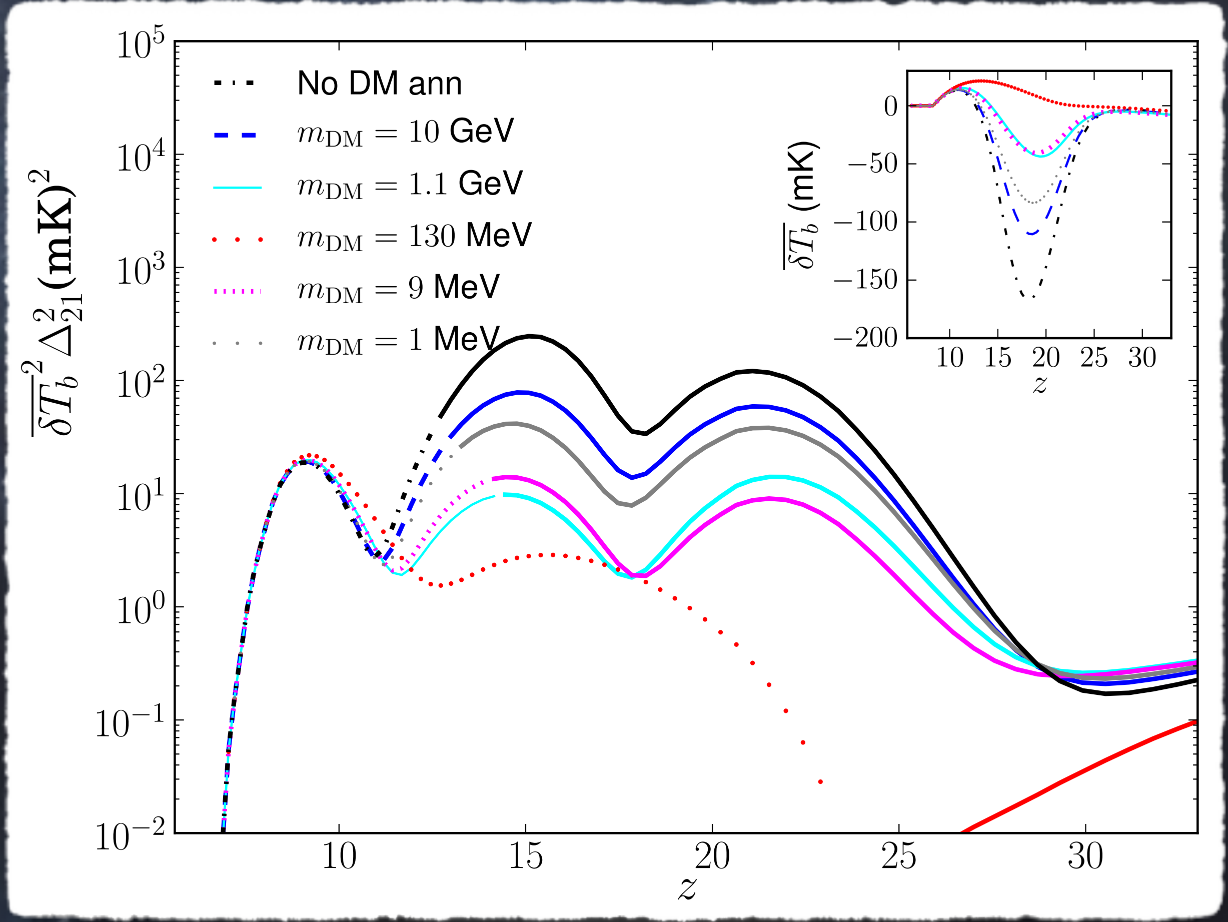
Dark matter annihilations:
inject energy into the IGM →
excite, ionize and heat

Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05, Shchenikov'06, Furlanetto'06, Valdes'07, Chuzhoy'07, Cumberbatch'08, Natarajan'09, Yuan'09, Valdes'12, Evoli'14, Poulin'16, Liu'18...



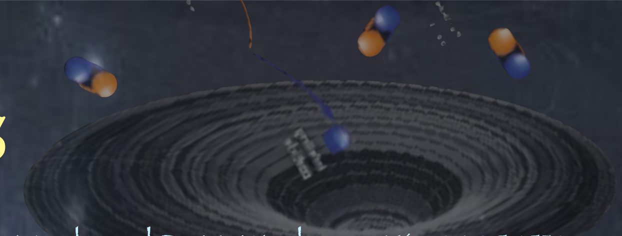
Credit: A. C. Vincent

DM annihilations: suppress power,
but effects are degenerate with astrophysics



L. Lopez-Honorez, O. Mena, A. Moliné, SPR and A. C. Vincent, JCAP 1608:004, 2016

21cm signal from PBHs



K. J. Mack and D. H. Wesley, arXiv:0805.1531

ACCRETION $M_{\rm PBH} \gtrsim 0.1 M_\odot$

$M_{\rm PBH} \lesssim 10^{-16} M_\odot$ **EVAPORATION**

Uniform heating and ionization of the IGM

In the context of EDGES (accretion):
A. Hektor et al., Phys. Rev. D98:023503, 2018
Y. Yang, Phys. Rev. D104:063528, 2021

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

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

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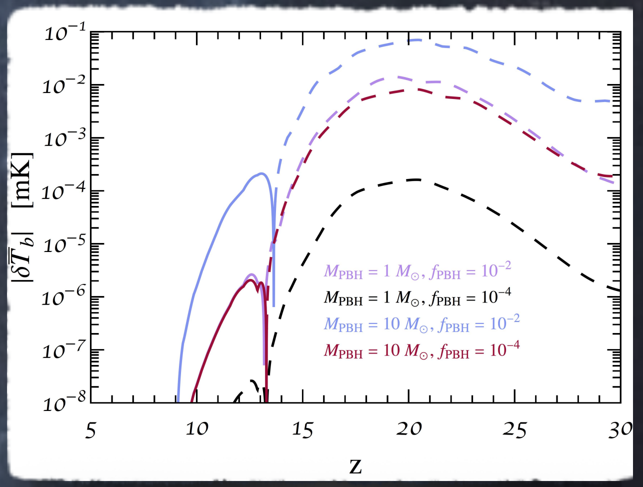
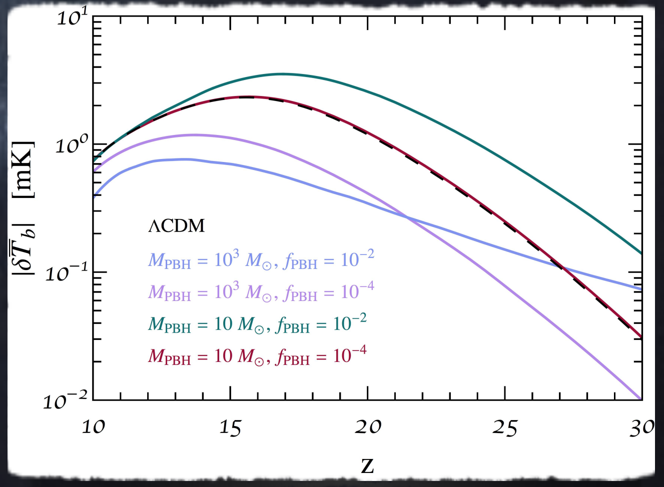
Forecasts (evaporation):
P. K. Natwariya, A. C. Nayak and T. Srivastava, MNRAS 510, 4236, 2021
J. Cang, Y. Gao and Y.-Z. Ma, JCAP 03:012, 2022
Y. Yang, Phys. Rev. D106:123508, 2022

ACCRETION

Heating and ionization of the local environment of isolated PBHs

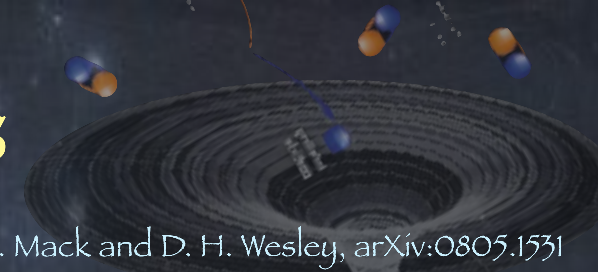


Enhanced signal from mini-halos by Poisson noise



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

21cm signal from PBHs

K. J. Mack and D. H. Wesley, arXiv:0805.1531

ACCRETION $M_{\rm PBH} \gtrsim 0.1 M_\odot$ $M_{\rm PBH} \lesssim 10^{-16} M_\odot$ **EVAPORATION**

Uniform heating and ionization of the IGM

In the context of EDGES (accretion):
A. Hektor et al., Phys. Rev. D98:023503, 2018
Y. Yang, Phys. Rev. D104:063528, 2021

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

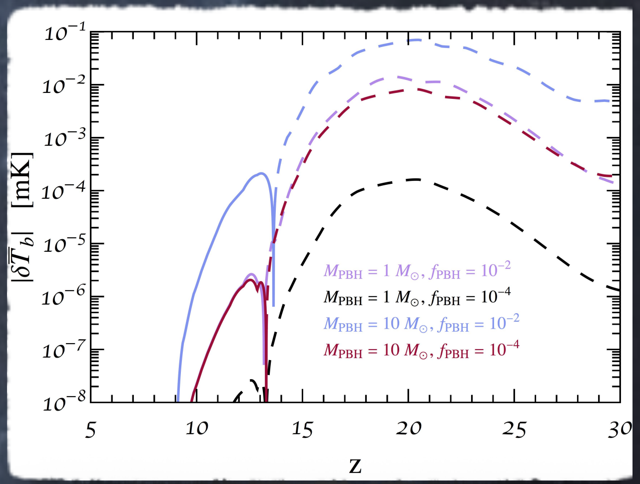
Forecasts (evaporation):
P. K. Natwariya, A. C. Nayak and T. Srivastava, MNRAS 510, 4236, 2021
J. Cang, Y. Gao and Y.-Z. Ma, JCAP 03:012, 2022
Y. Yang, Phys. Rev. D106:123508, 2022

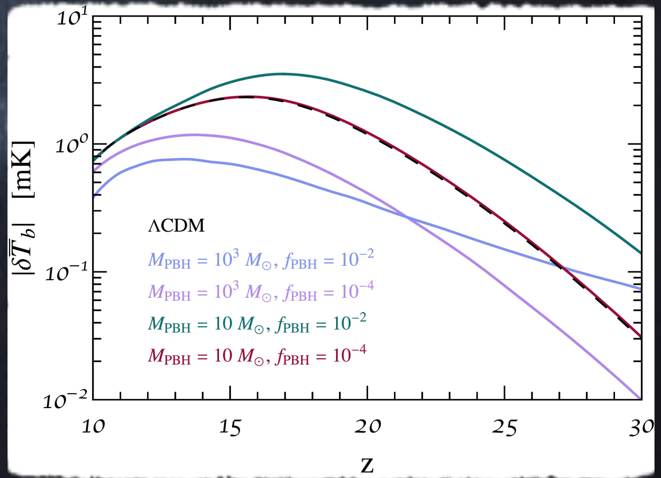
ACCRETION

Heating and ionization of the local environment of isolat

Small contributions

gnal from mini-halos by Poisson noise





See, however, effects on the 21cm forest:
P. Villanueva-Domingo and K. Ichiki, Publ. Astron. Soc. Jpn. 75, S33, 2023
K. Kadota et al., JCAP 03:017, 2023

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

Energy injection due to accretion by PBHs

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

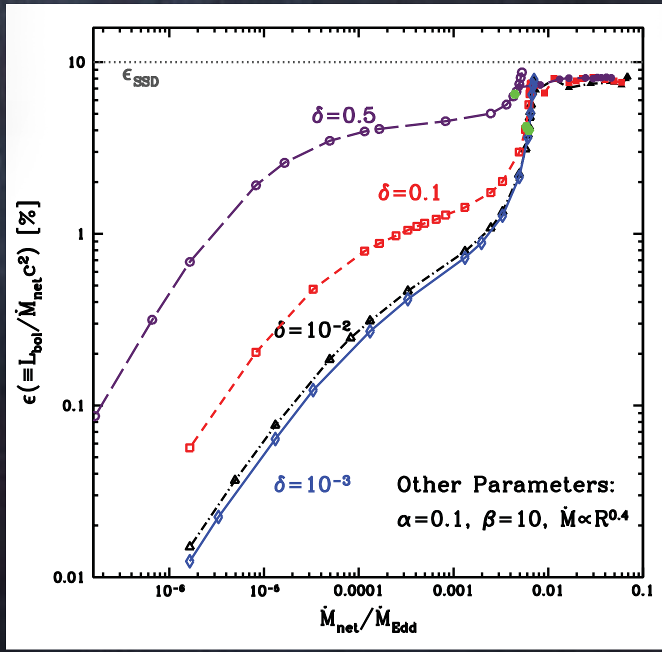
luminosity due to accretion: $$L_{acc} = \epsilon\, \dot{M}_{PBH}$$

if cooling is inefficient, accretion could form a thick disk

V. Poulin, P. D. Serpico, F. Calore, S. Clesse and K. Kohri, Phys. Rev. D96:083524, 2017

Radiative efficiency (ADAF)

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



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

Bondi-Hoyle-Lyttleton accretion

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

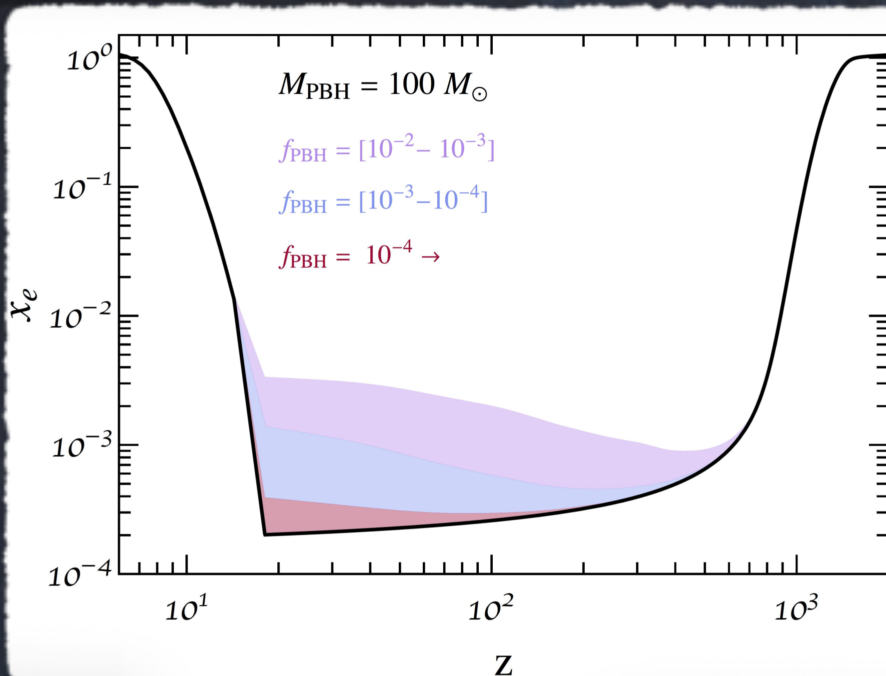
F. Hoyle and R. A. Lyttleton, Mon. Not. R. Astron. Soc. 101:227, 1941

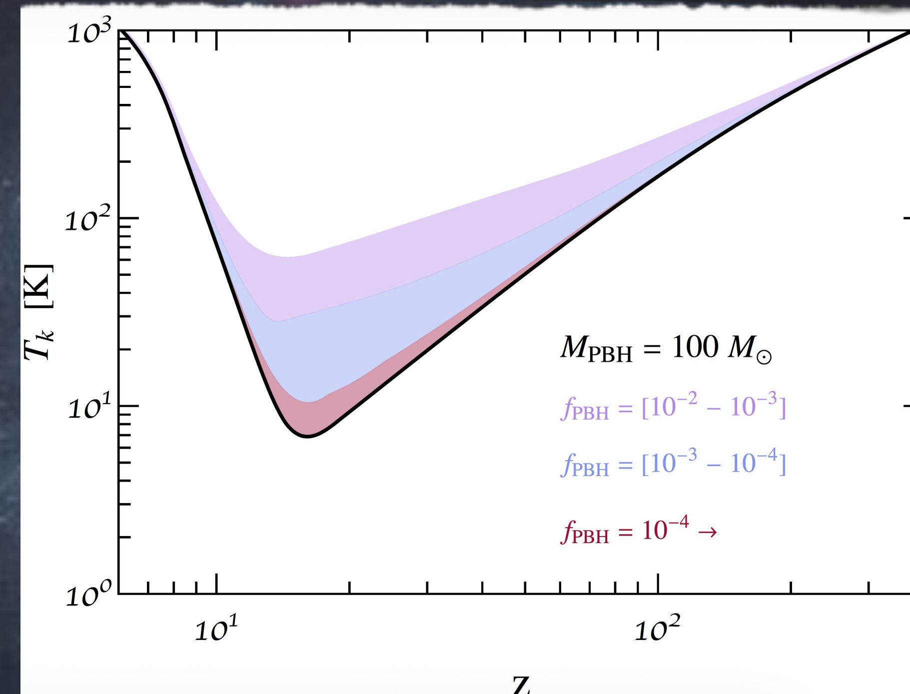
H. Bondi and F. Hoyle, Mon. Not. R. Astron. Soc. 104:273, 1944

H. Bondi, Mon. Not. R. Astron. Soc. 112:195, 1952

PBHs: Brightness temperature

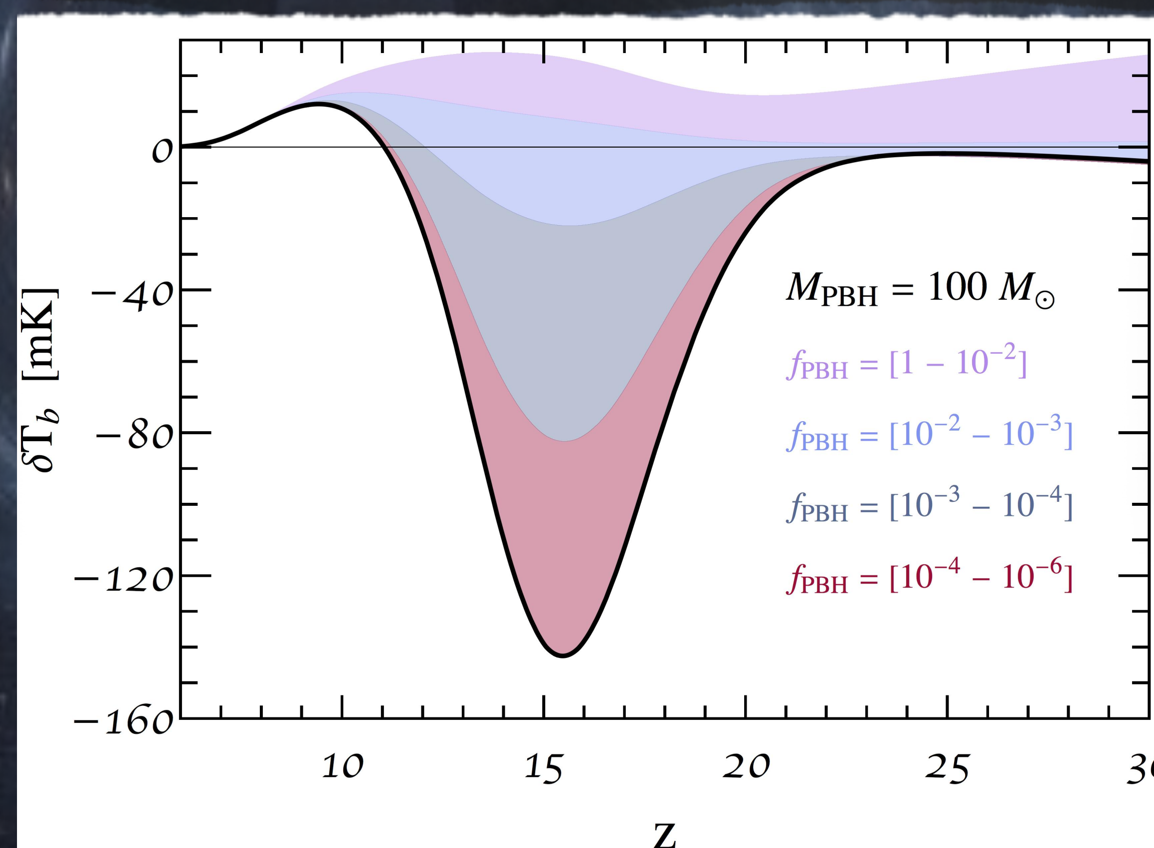
Accretion: Injected energy goes into ionizing and heating the IGM





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, Mon. Not. R. Astron. Soc. 411:955, 2011

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

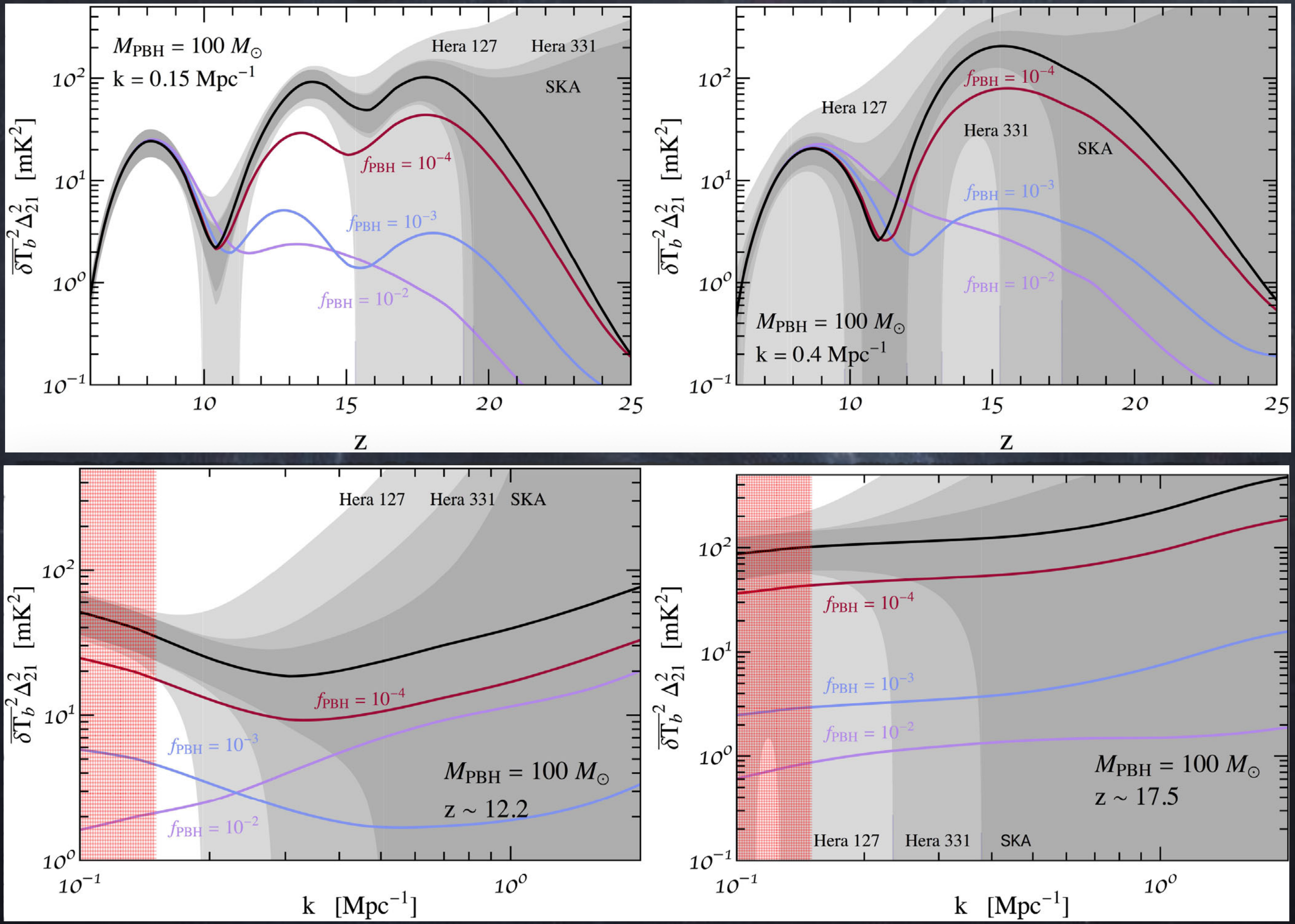
PBHs: 21cm power spectrum

We use 21cmSense

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

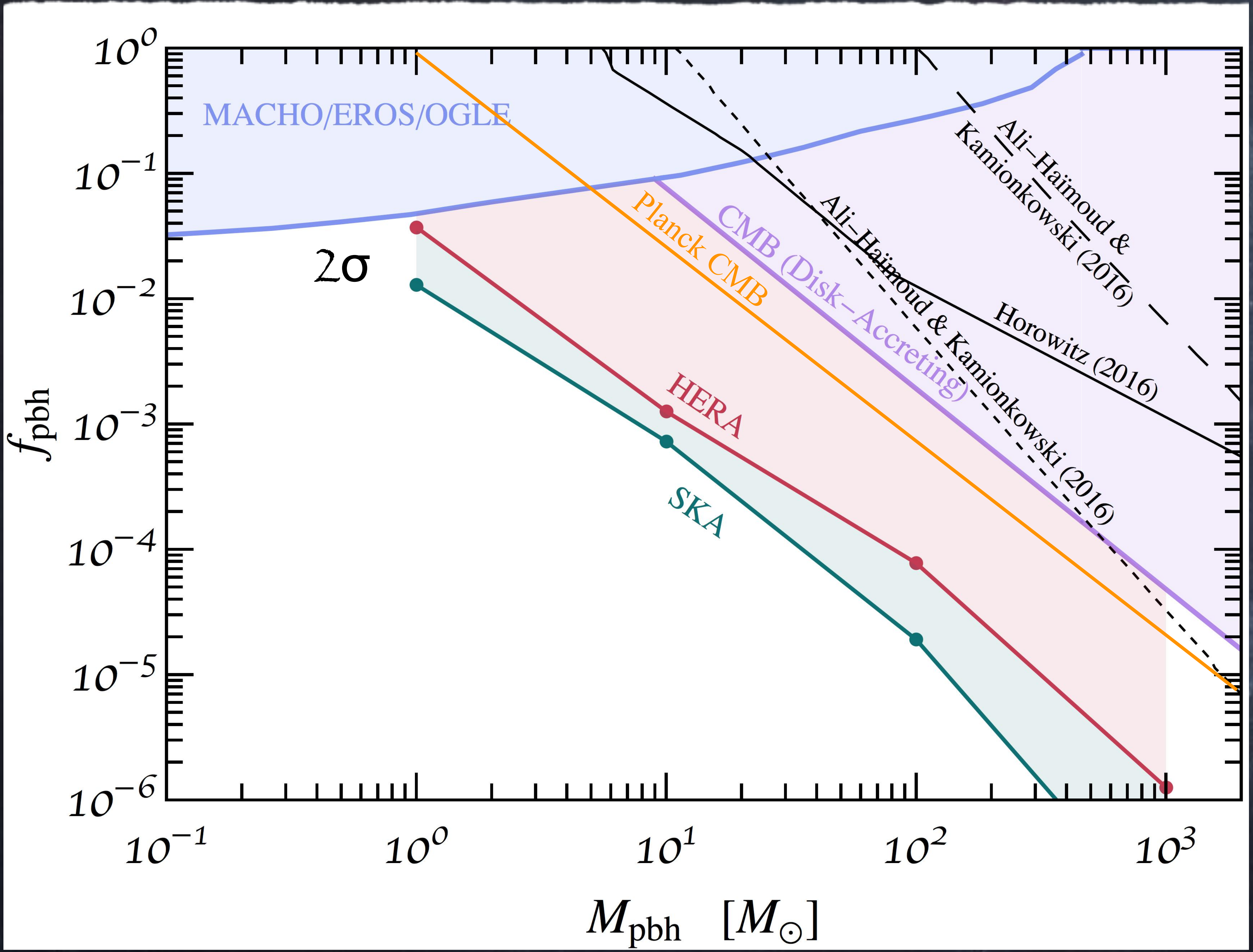
J. C. Pober et al., Astrophys. J. 782:66, 2014

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

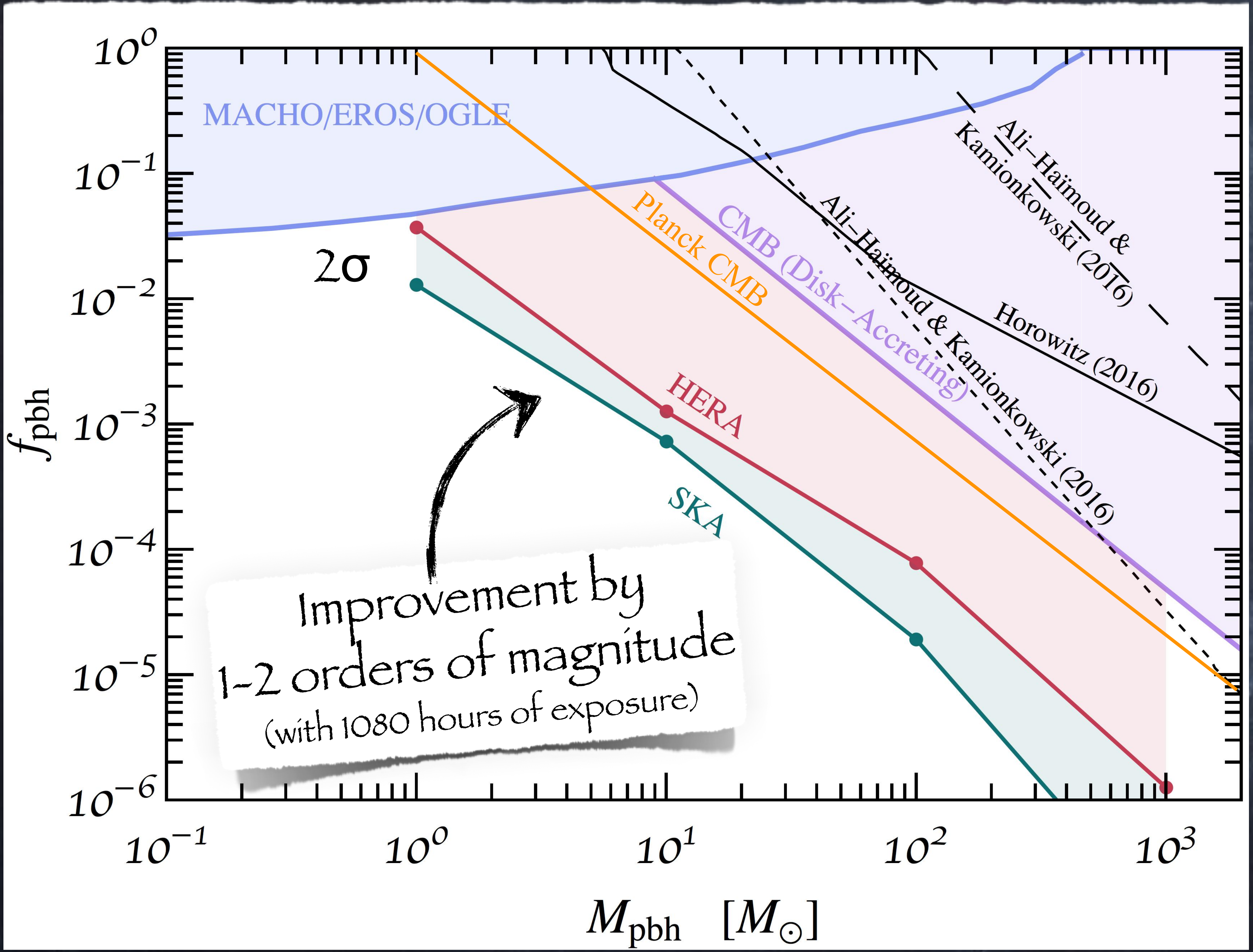
B. Horowitz, arXiv: 1612.07264

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

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

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

PBHs abundance: Sensitivity



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

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

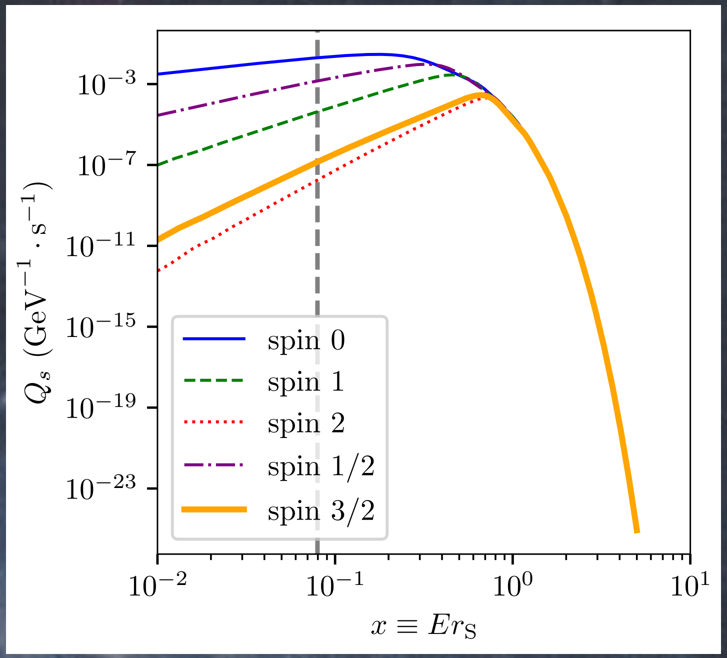
PBH evaporation effects on the 21cm signal

Emission of a quasi-thermal black-body spectrum

$$\left.\frac{d^2N_i(E,t)}{dt\,dE}\right|_{prim} = \frac{g_i}{2\pi}\frac{\Gamma_i(E,M_{BH})}{e^{E/T_{BH}} \pm 1}$$

S. W. Hawking, Mon. Nature 248:30, 1974
S. W. Hawking, Commun. Math, Phys. 43:199, 1975

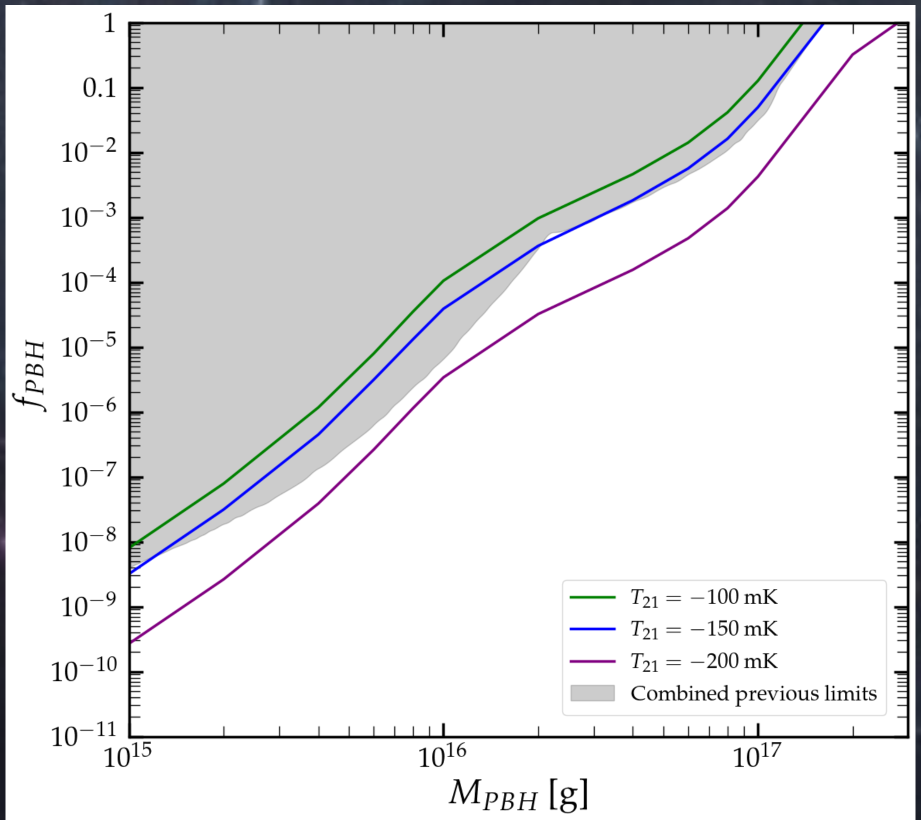
BlackHawk



A. Arbey and J. Auffinger, Eur. Phys. J. C79:693, 2019
A. Arbey and J. Auffinger, Eur. Phys. J. C81:10, 2021

PBH abundance: Sensitivity
(only using the global signal)

for other constraints, see talks by F. Calore, V. De Romeri



A. K. Saha and R. Laha, Phys. Rev. D105:103026, 2022

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

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

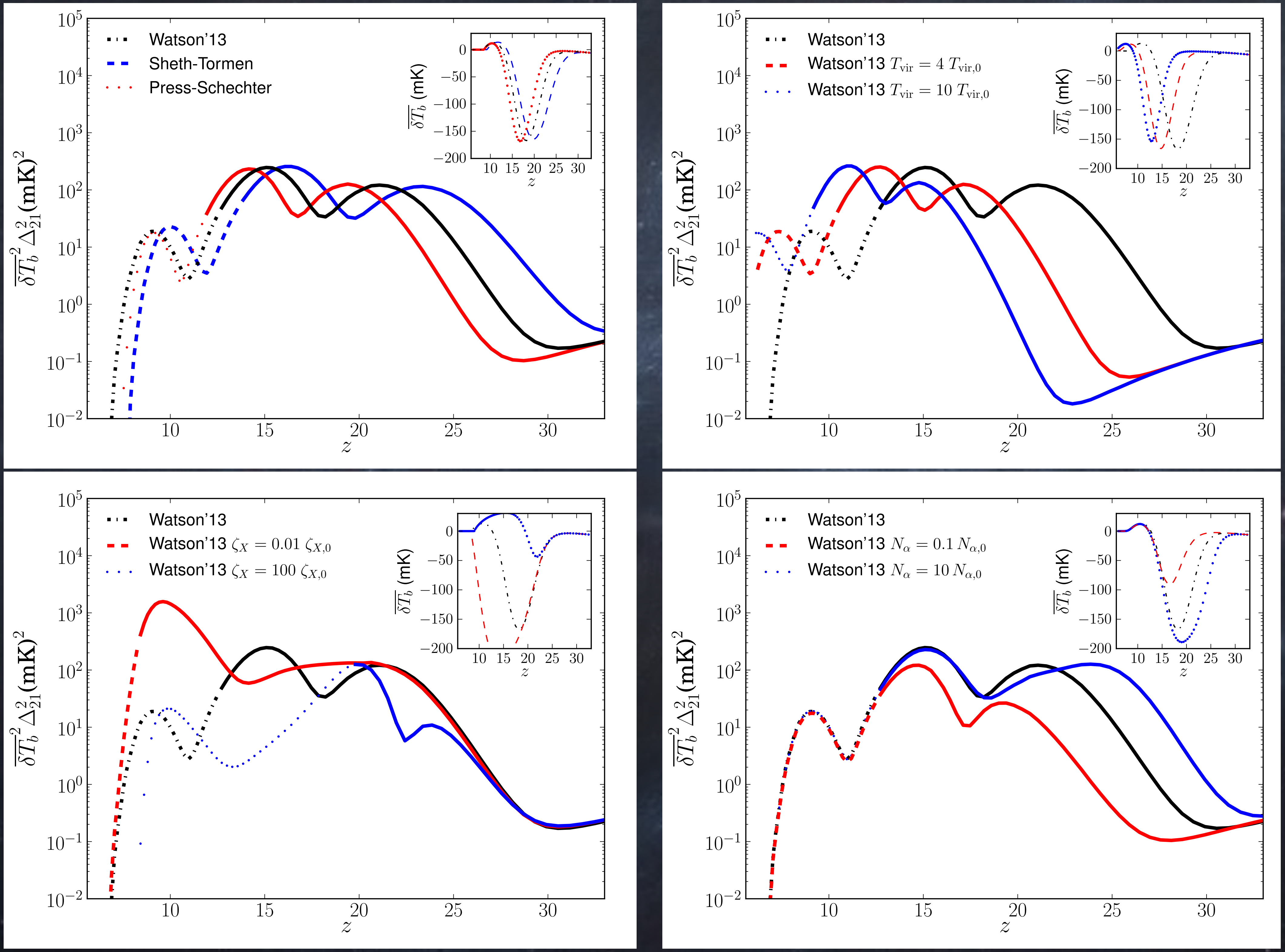
Conclusions

21cm radio observatories will be a powerful tool to learn about exotic energy injection mechanisms into the IGM (PBHs, particle DM...) during dark ages and cosmic dawn

Sensitivity to solar mass PBHs will be improved by up to 2 orders of magnitude with future interferometers (HERA, SKA)...
and also great sensitivity to comet-size PBHs

Extras

Dependence on astrophysical parameters



L. Lopez-Honorez, O. Mena, A. Moliné, SPR and A. C. Vincent, JCAP 1608:004, 2016