Primordial Black Holes and the 21 cm line

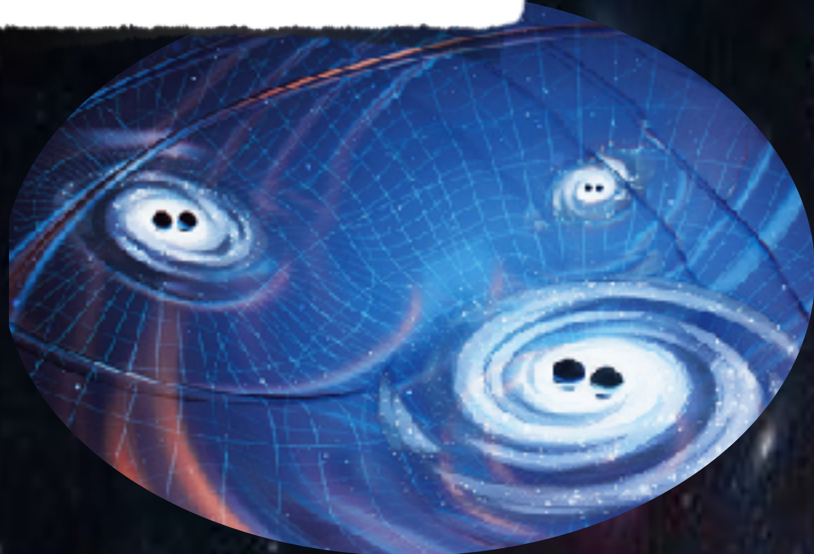
Sergio Palomares-Ruiz

IFIC, CSIC - U. Valencia

57th Rencontres de Moriond
Electroweak Interactions & Unified Theories

La Thuile,
March 21, 2023

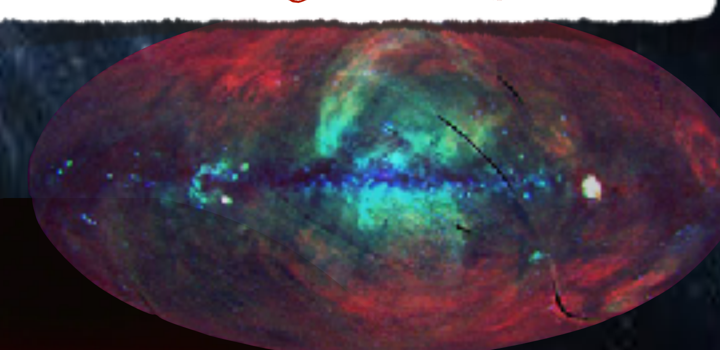
Gravitational waves



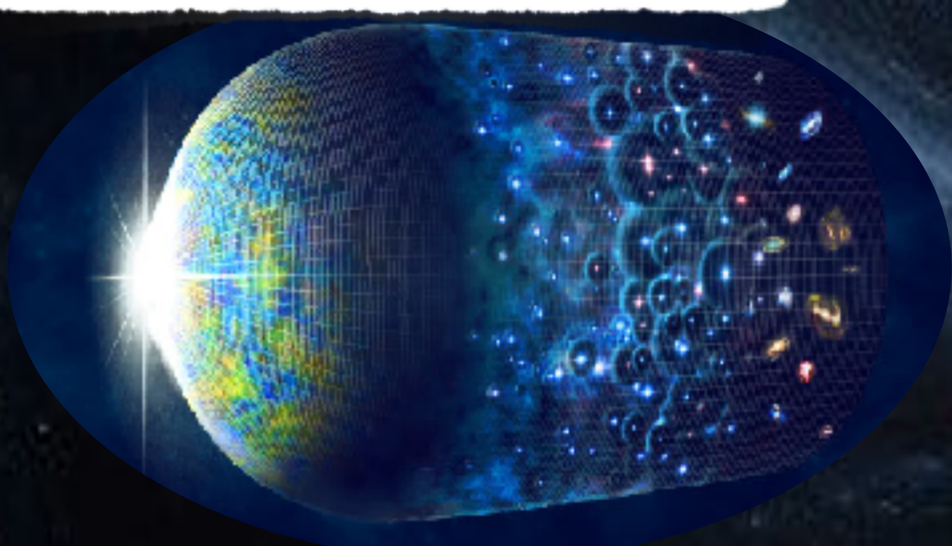
Dark Matter

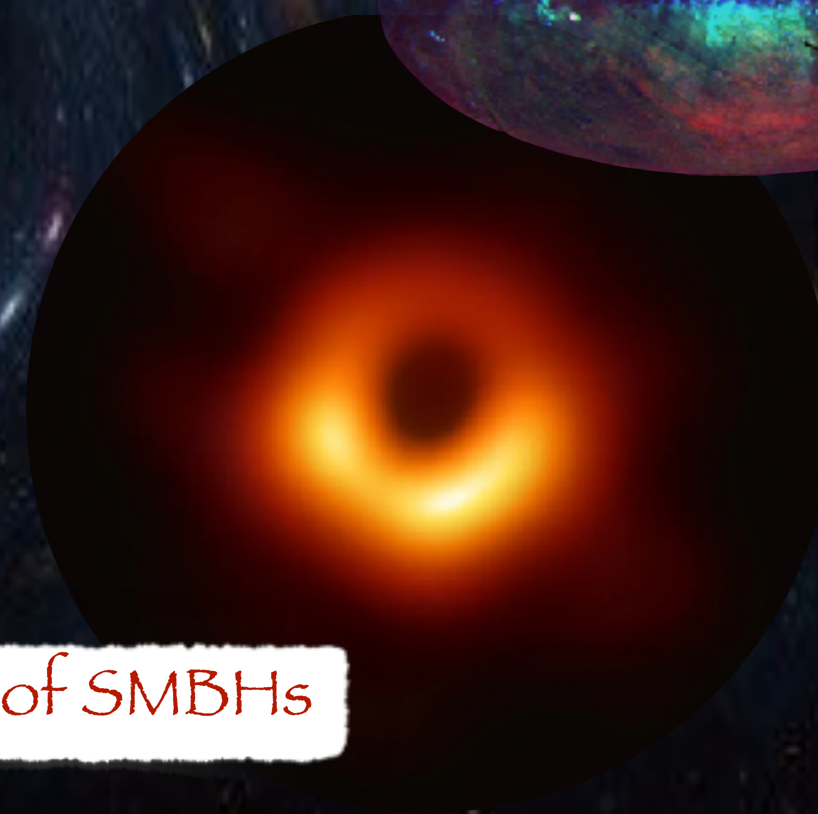
Primordial Black Holes

Cosmic X-ray background



Formation:
Physics of the Early Universe

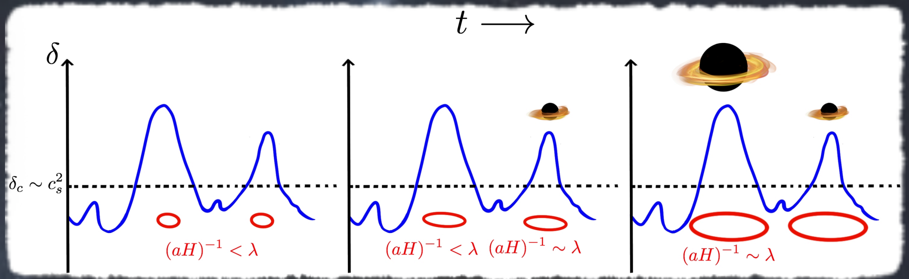




Origin of SMBHs

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. Roy. 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...

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

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

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

Primordial black holes

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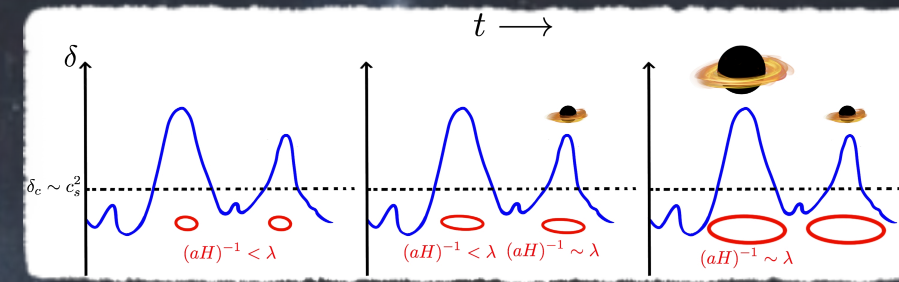

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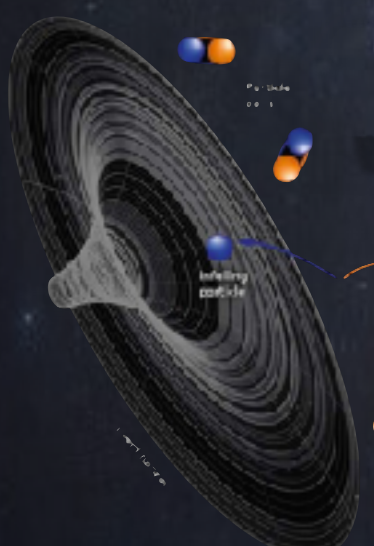

Black holes radiate thermally, so they eventually evaporate

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

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

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

$$\tau(M_{\rm BH}) \sim G^2\,M_{\rm BH}^3 \sim 10^9 \left(\frac{M_{\rm BH}}{10^{15}\,{\rm g}}\right)^3 {\rm yr}$$

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

Primordial black holes

The early universe is very hot and dense:
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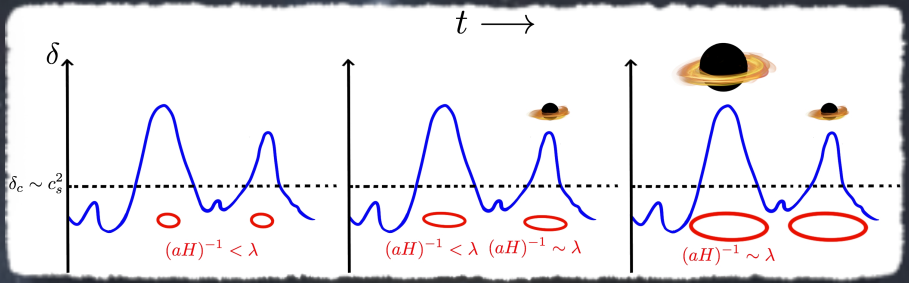

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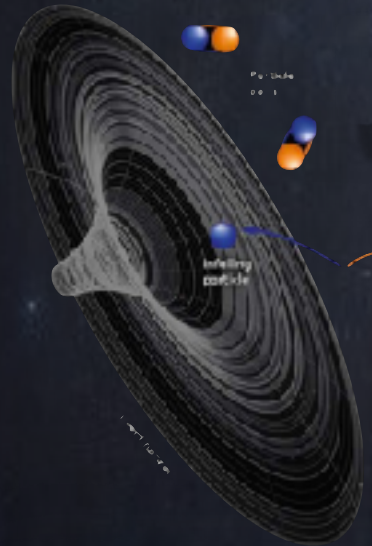

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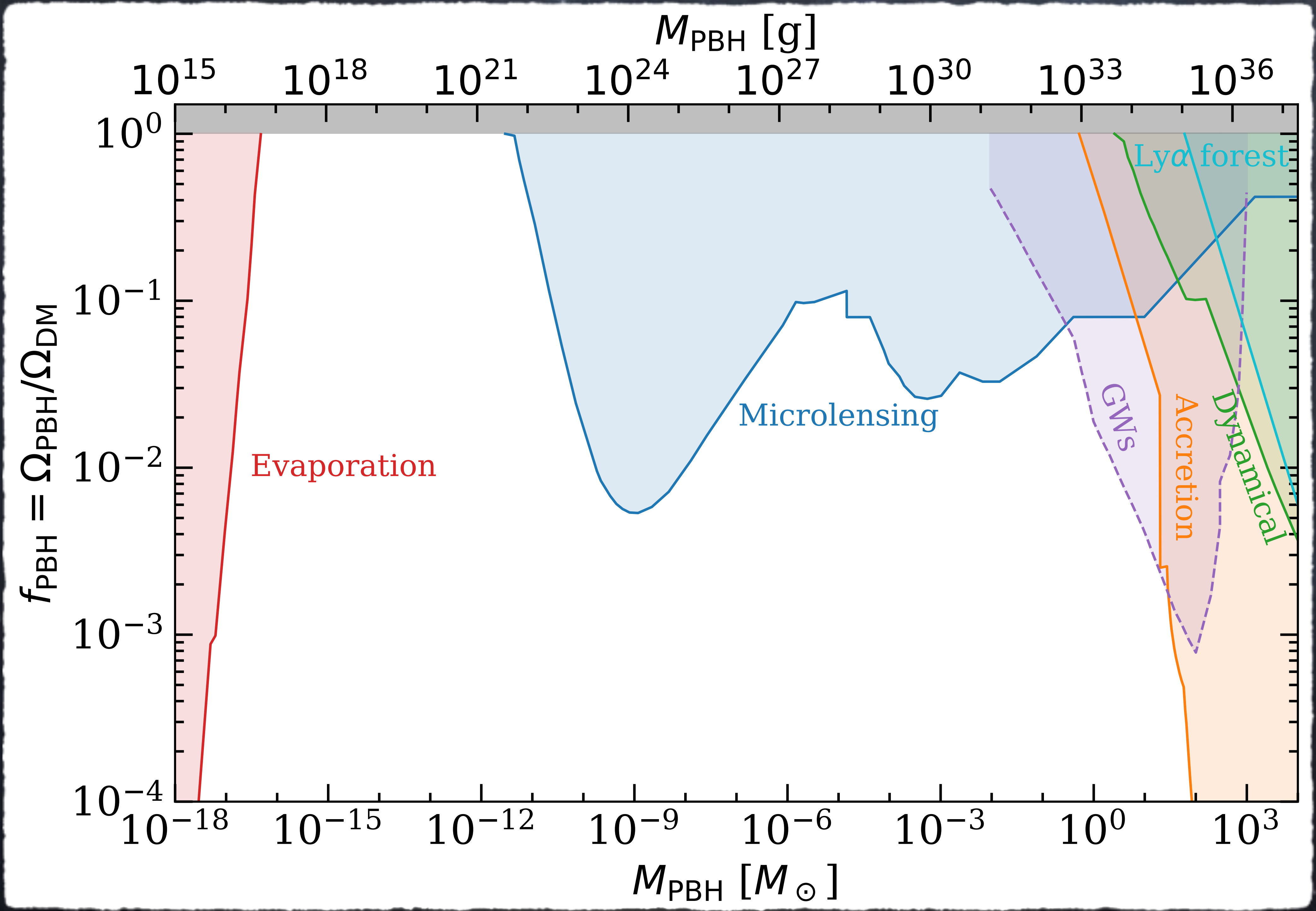
PBHs would form before BBN, so they would not count as baryonic matter

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

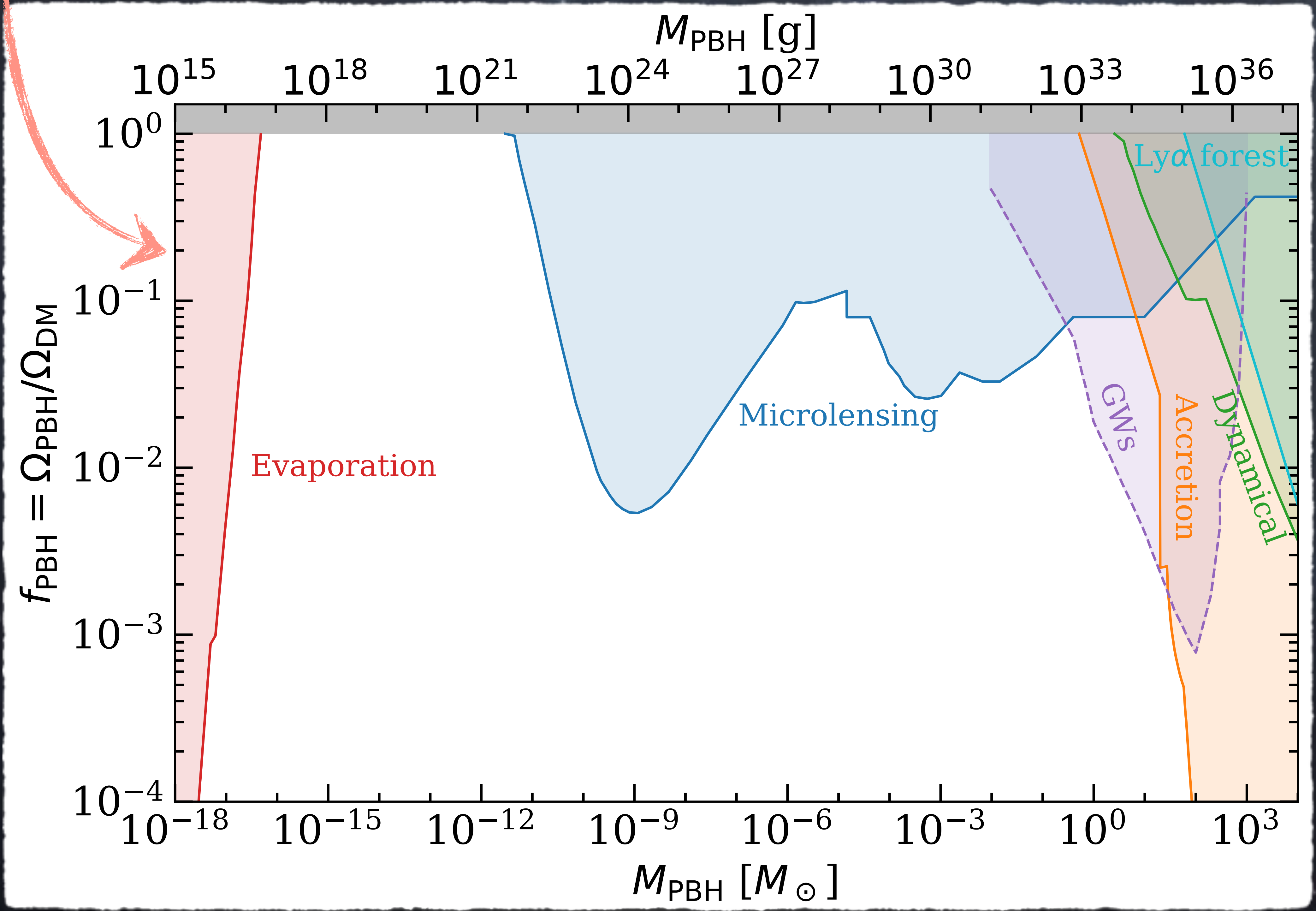
G. F. Chapline, Nature 253:251, 1975



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

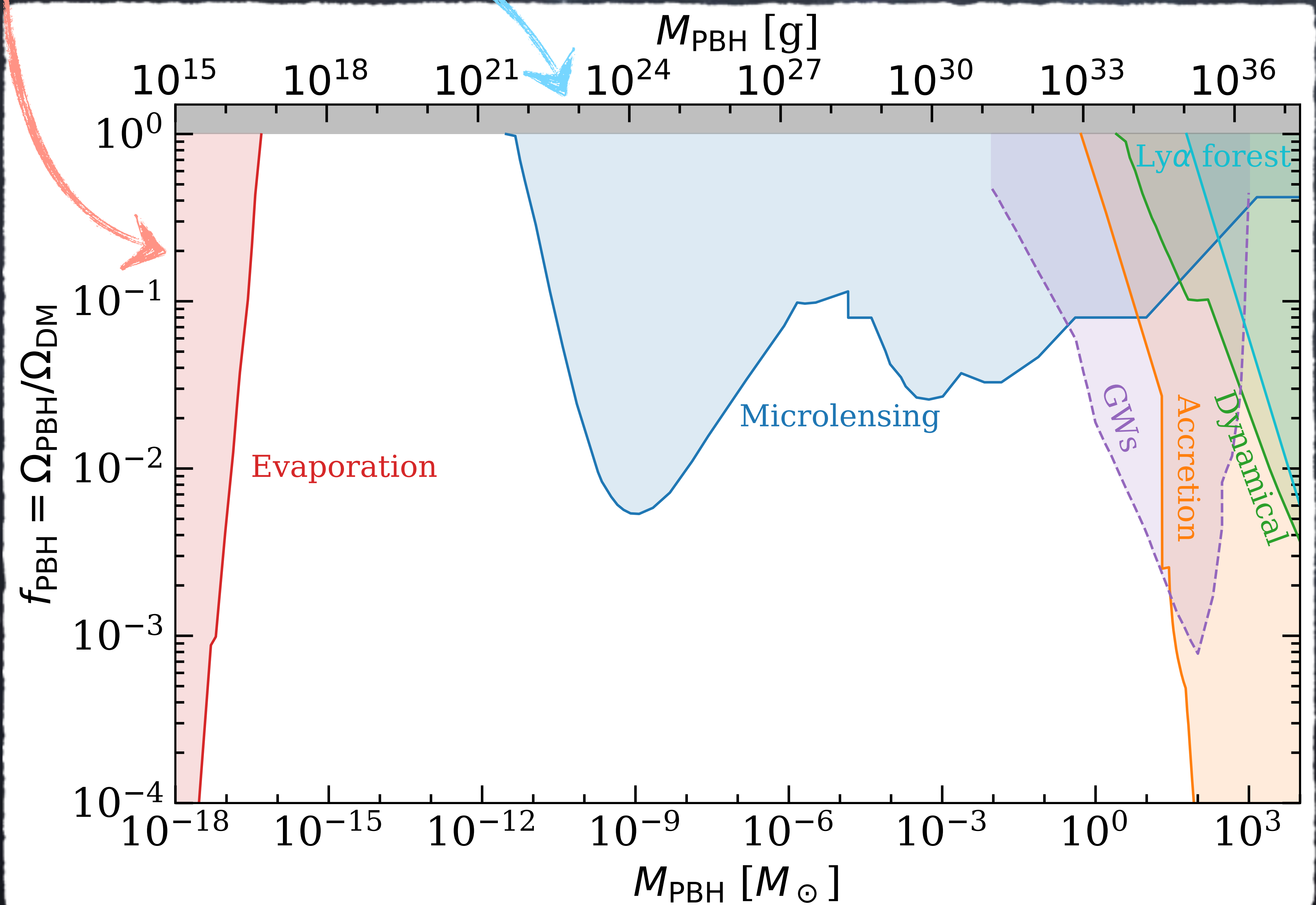


P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Partial evaporation

Gravitational lensing

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

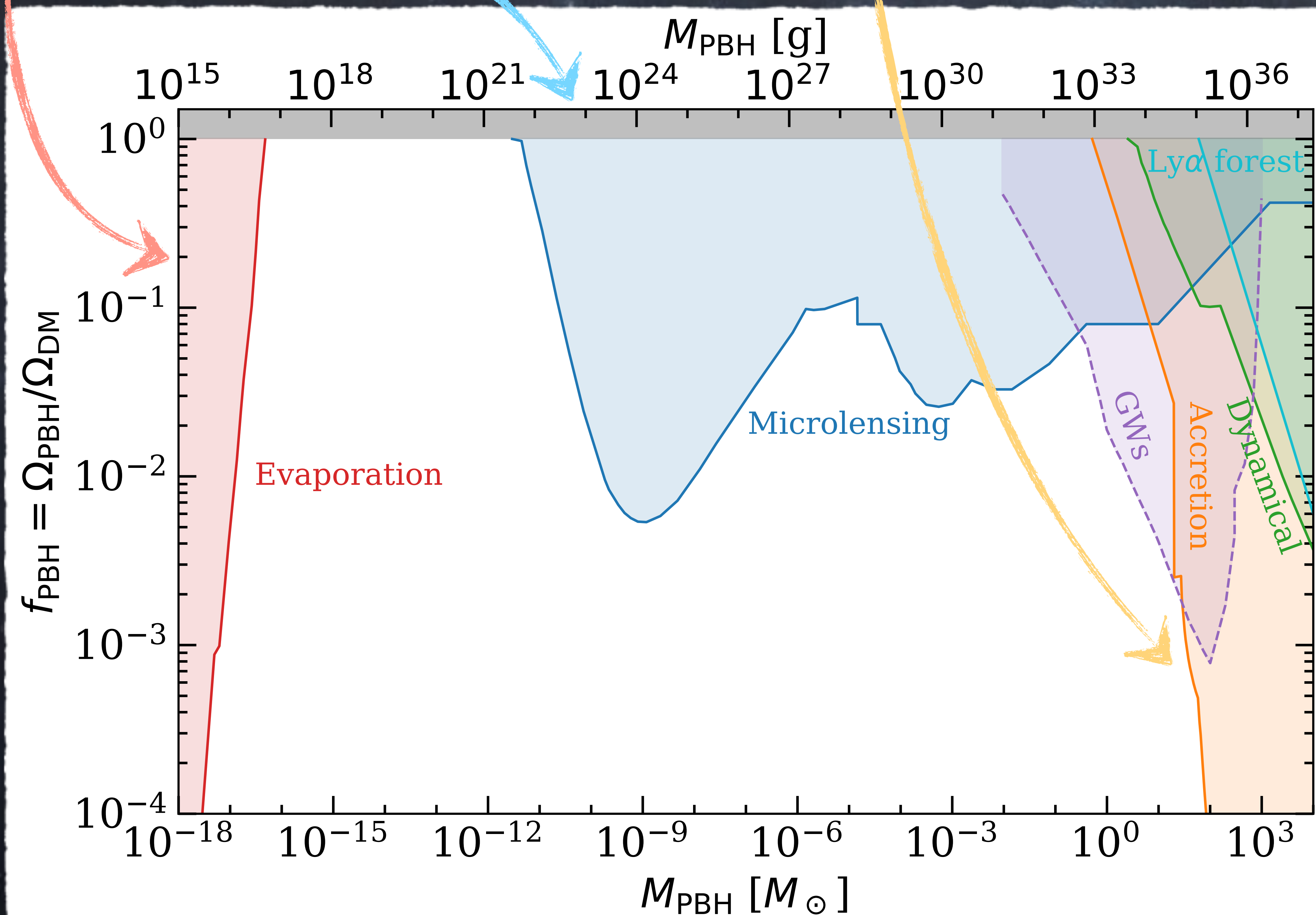


P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Partial evapo

Ionization and thermal history,
radio and X-ray emission

Accretion



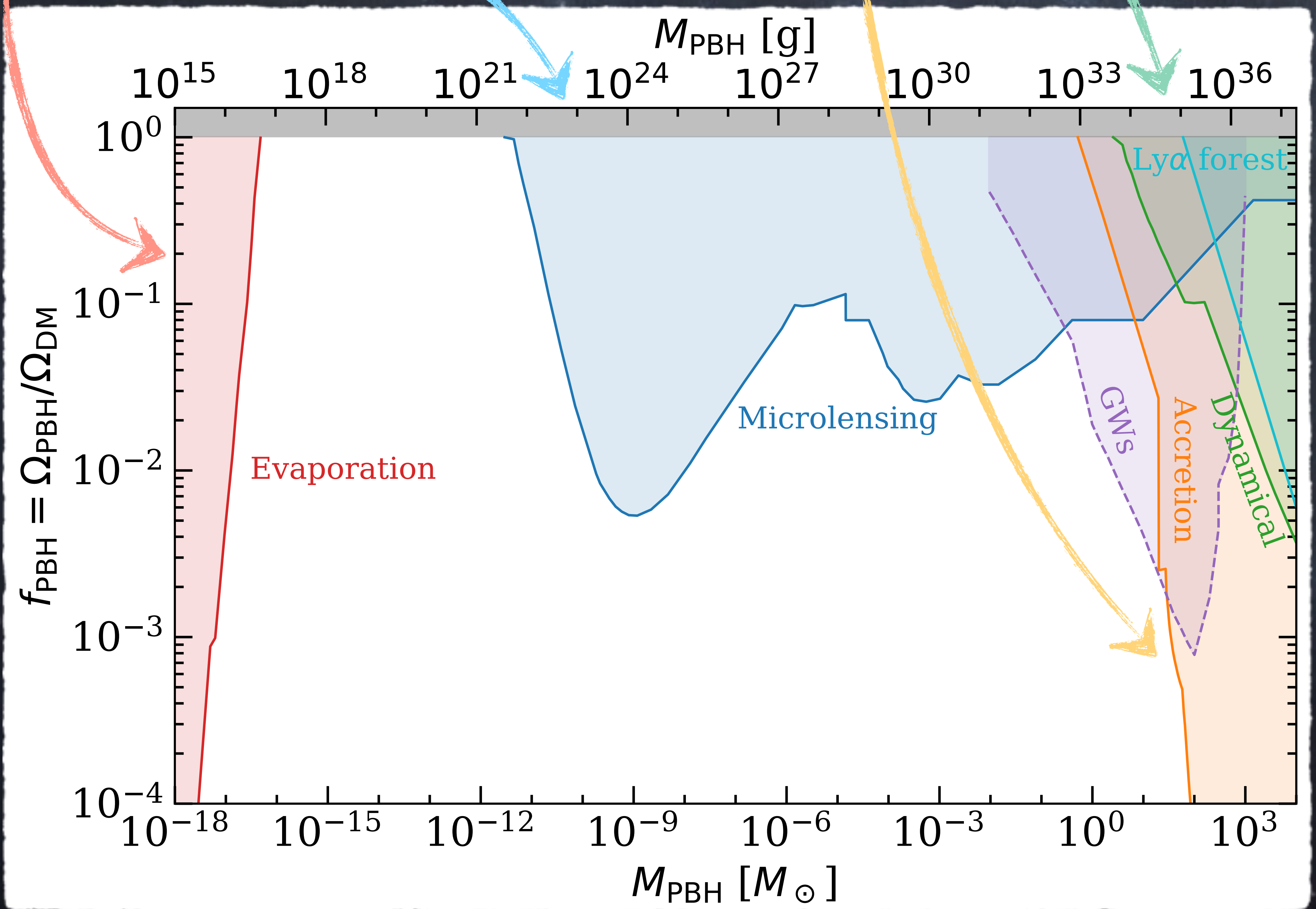
P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Partial evaporation

Gravitation

Destruction of astronomical systems by the passage of PBHs

Dynamical effects



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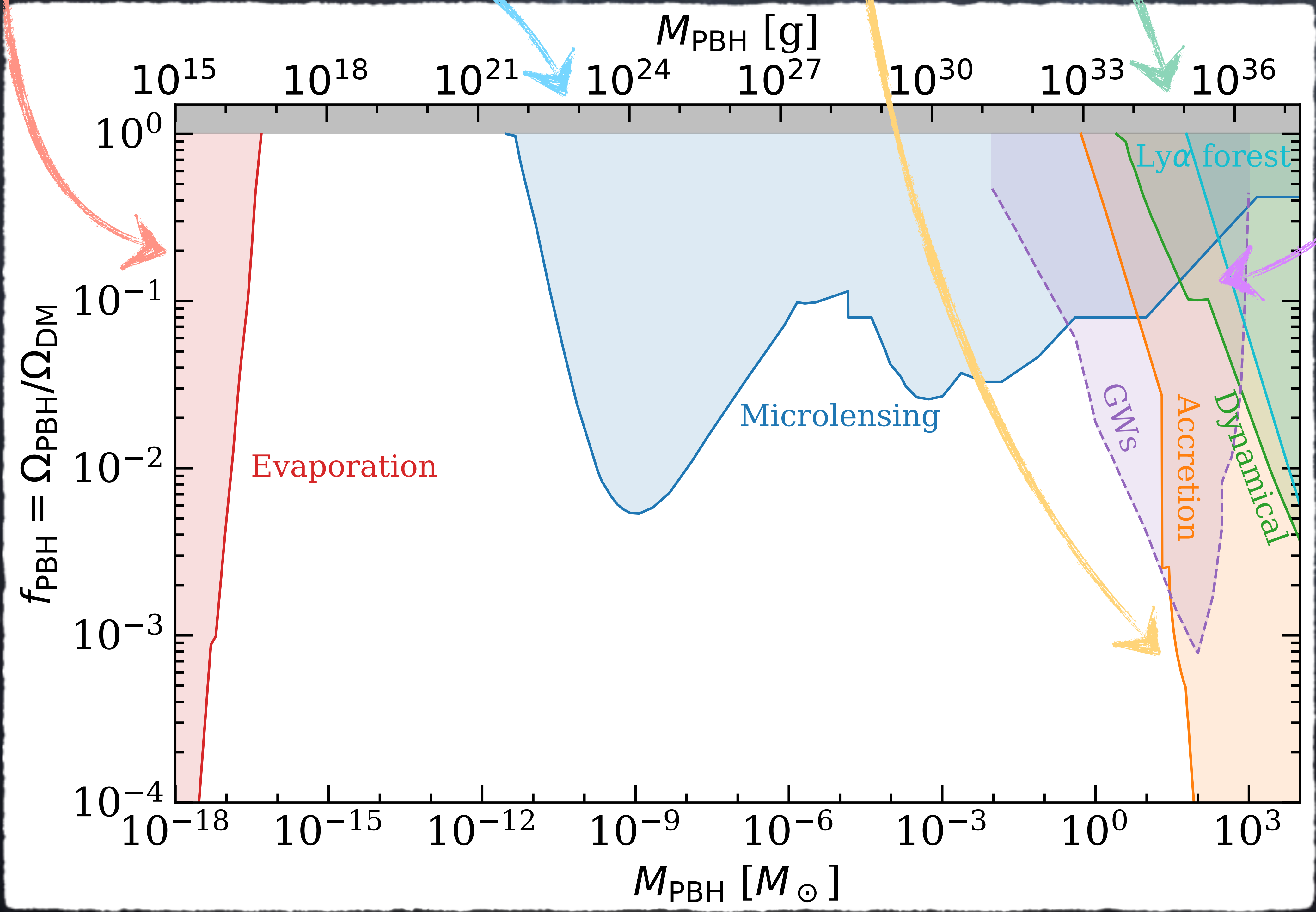
Partial evaporation

Gravitational lensing

LIGO/VIRGO events
stochastic background

Gravitational waves

...cal effects



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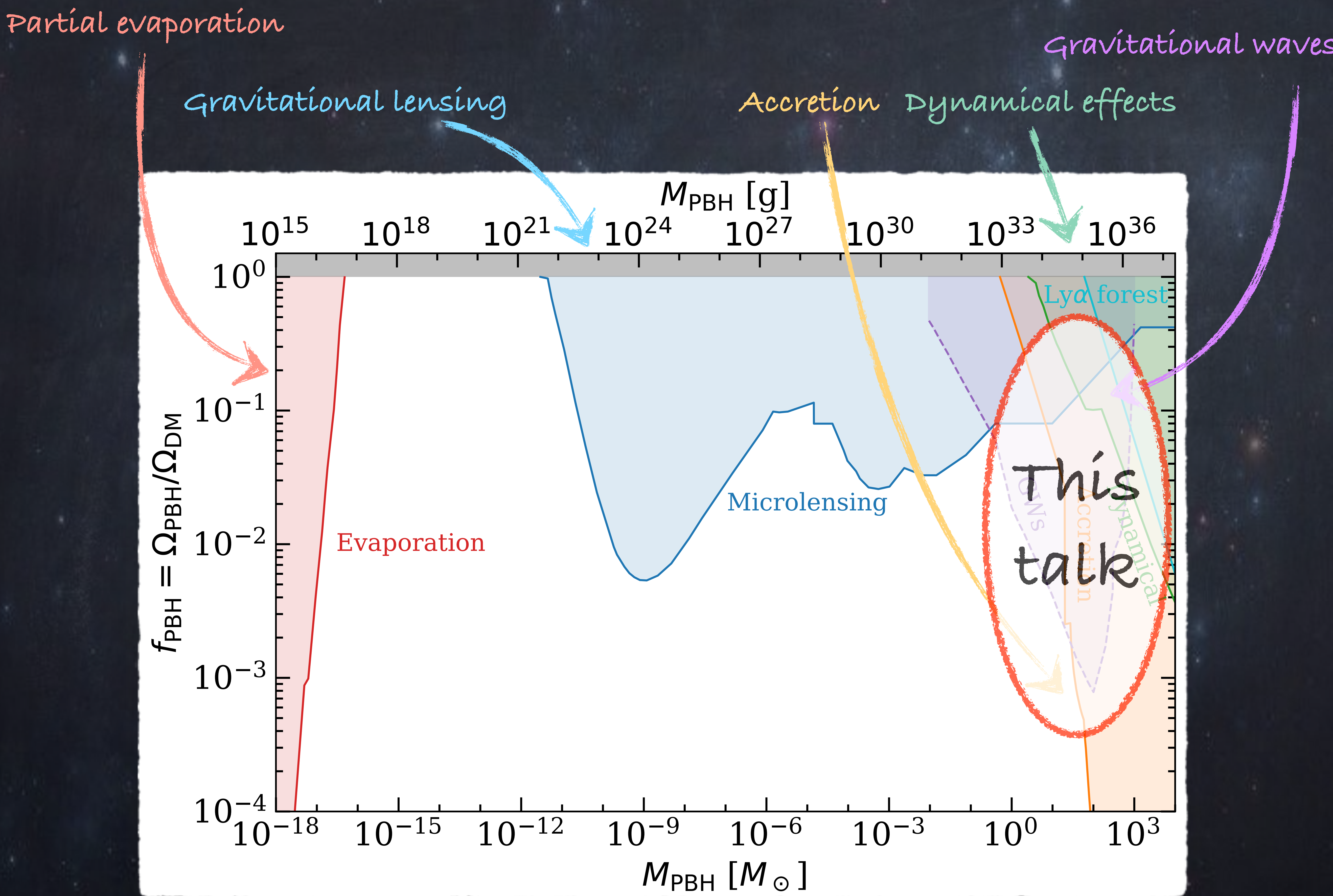


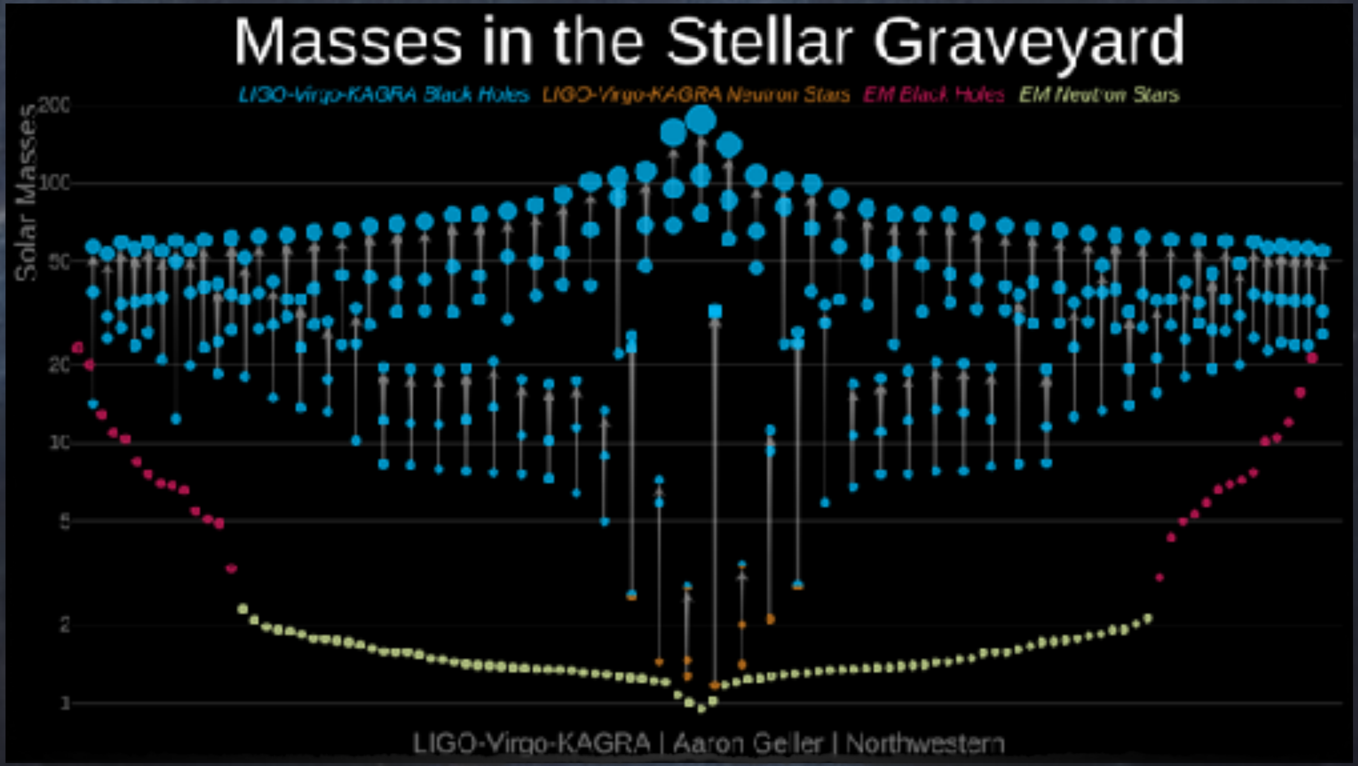
P. Villanueva-Domingo, O. Mena and SPR, Front. Astron. Space Sci. 8:87, 2021

Primordial black holes

Even if they cannot form all the dark matter… still interesting

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, topological defects, 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. Roy. Astron. Soc. 418:1850, 2011

Timing problem:

Could PBHs be connected to the origin of supermassive BHs?

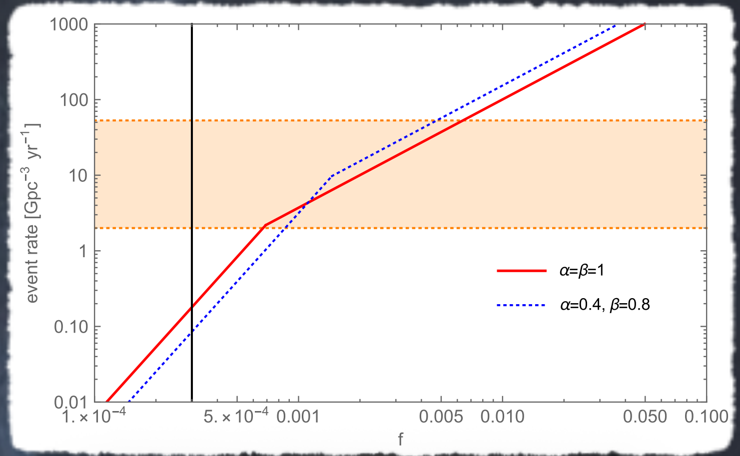
e.g., A. Smith and V. Bromm, Contemp. Phys. 60:111, 2019

SOLAR MASS PBHs ABUNDANCE

VIRGO/LIGO:

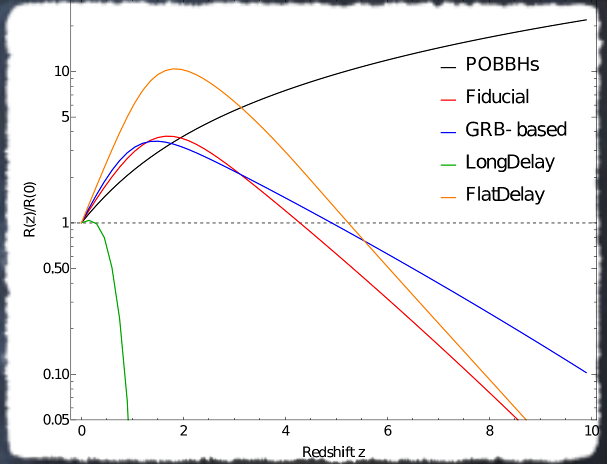
Merger rates and masses related to BHs abundance

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



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



Accretion of gas onto PBHs: Emission of broad band spectrum
local searches (X-rays, radio)
heating and ionization of the IGM: cosmological implications

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

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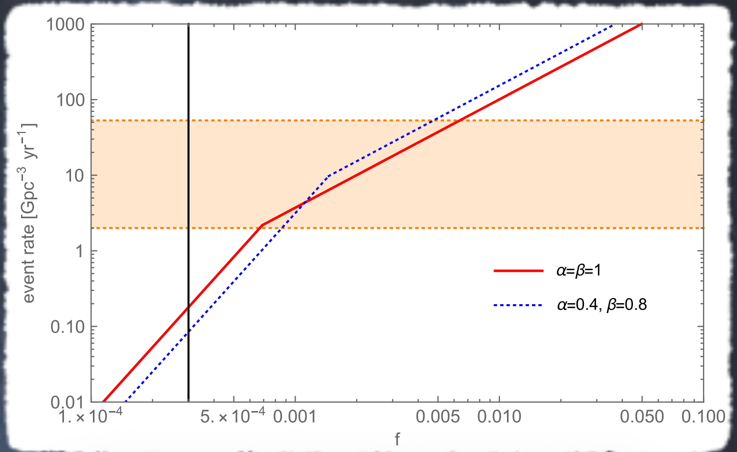

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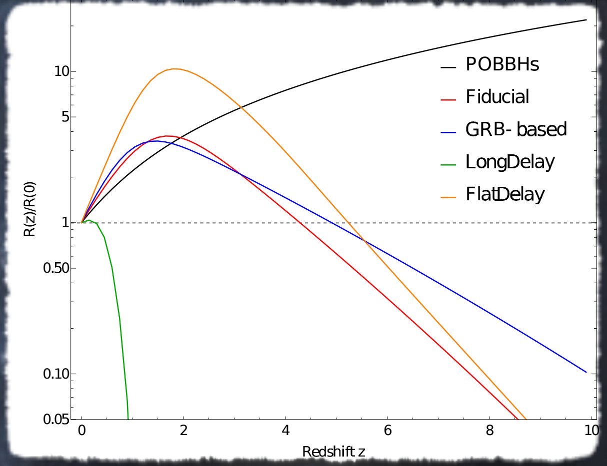

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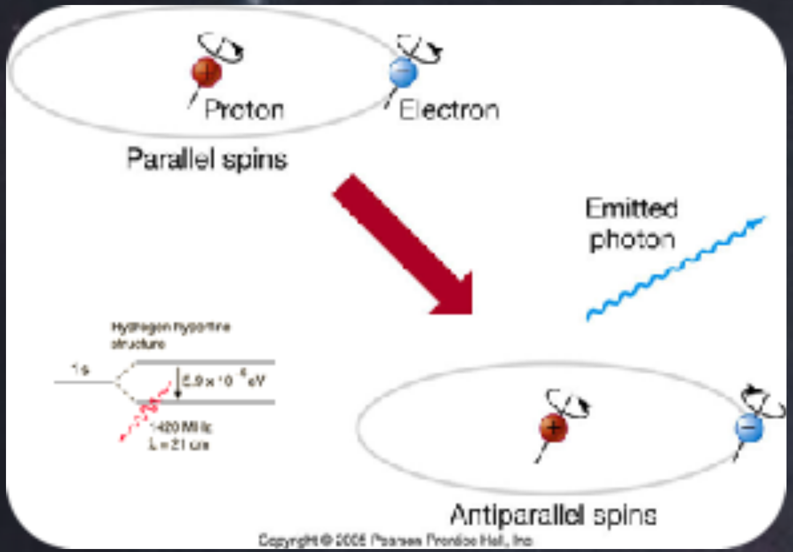
The 21cm line

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

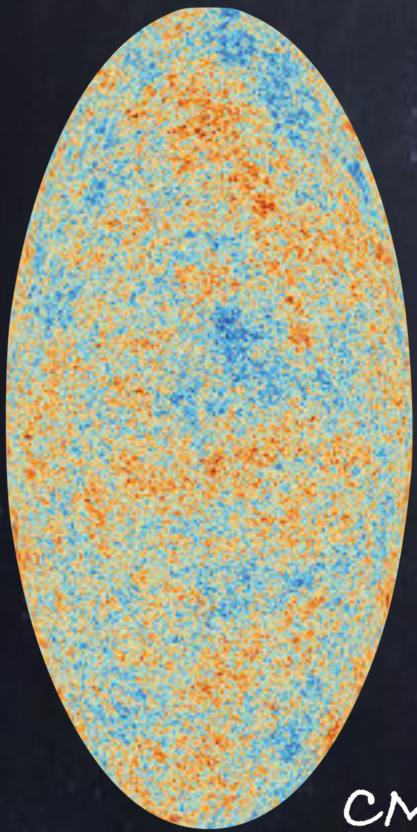


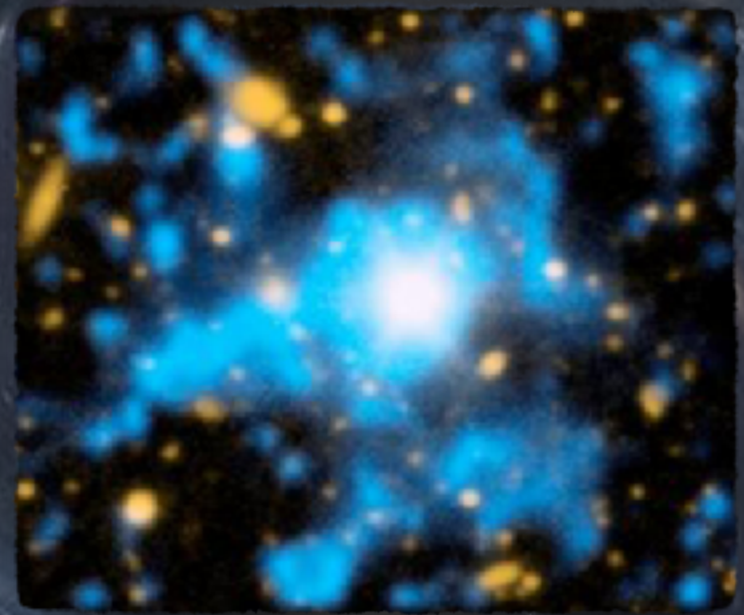
Hyperfine transition: ν = 1420 Mhz

21cm photon from HI clouds during the dark ages: 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

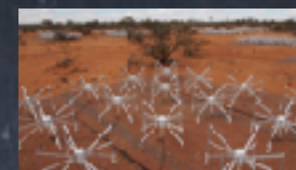
collisions of neutral hydrogen

excitation/de-excitation by Lyman-α photons

The 21cm line

Probing Dark Ages
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

Spin temperature:
occupation of the two states

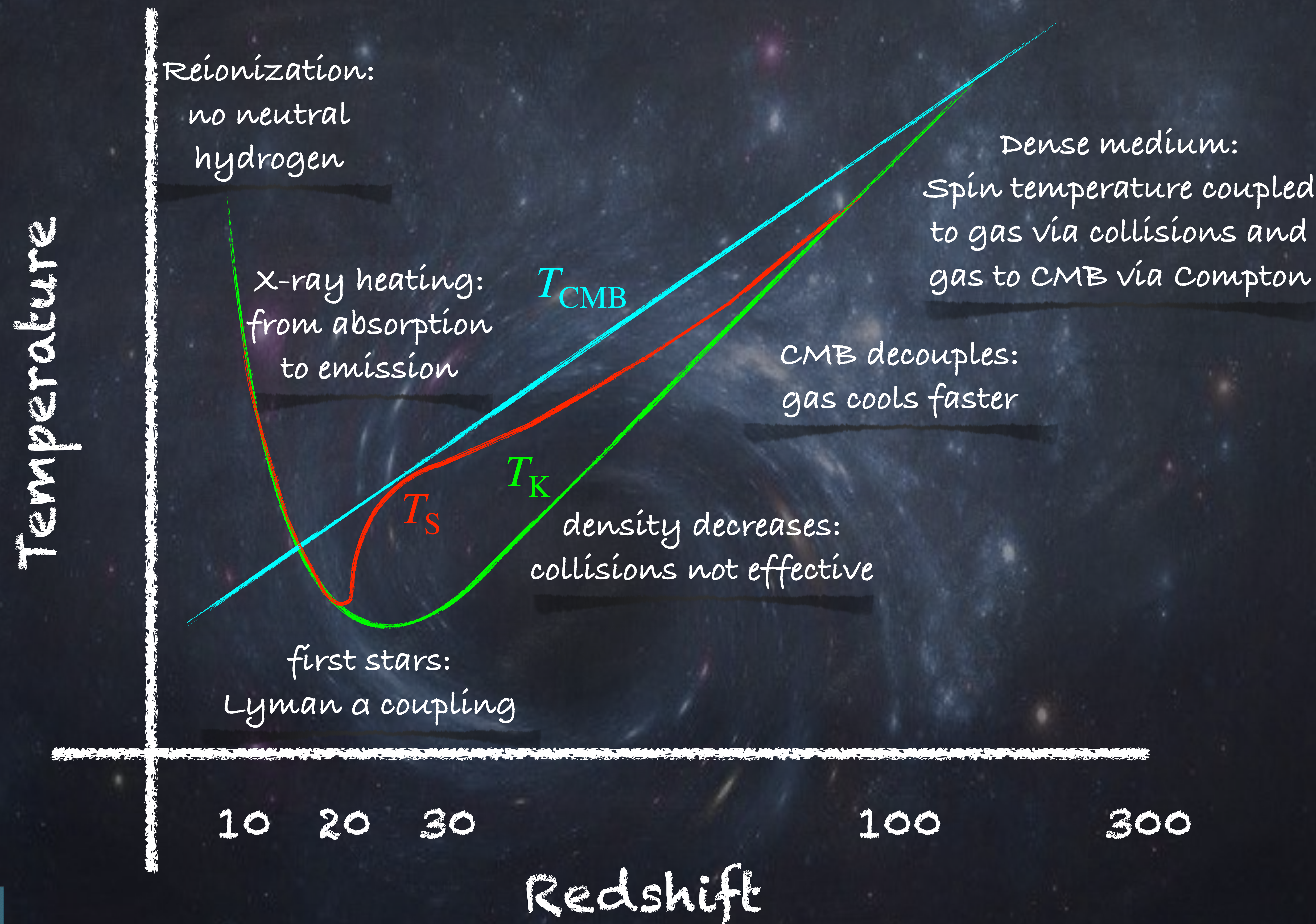
$\delta T_b \approx 0 \quad \text{if} \quad T_S \sim T_{CMB}$ — no signal

$\delta T_b > 0 \quad \text{if} \quad T_S > T_{CMB}$ — 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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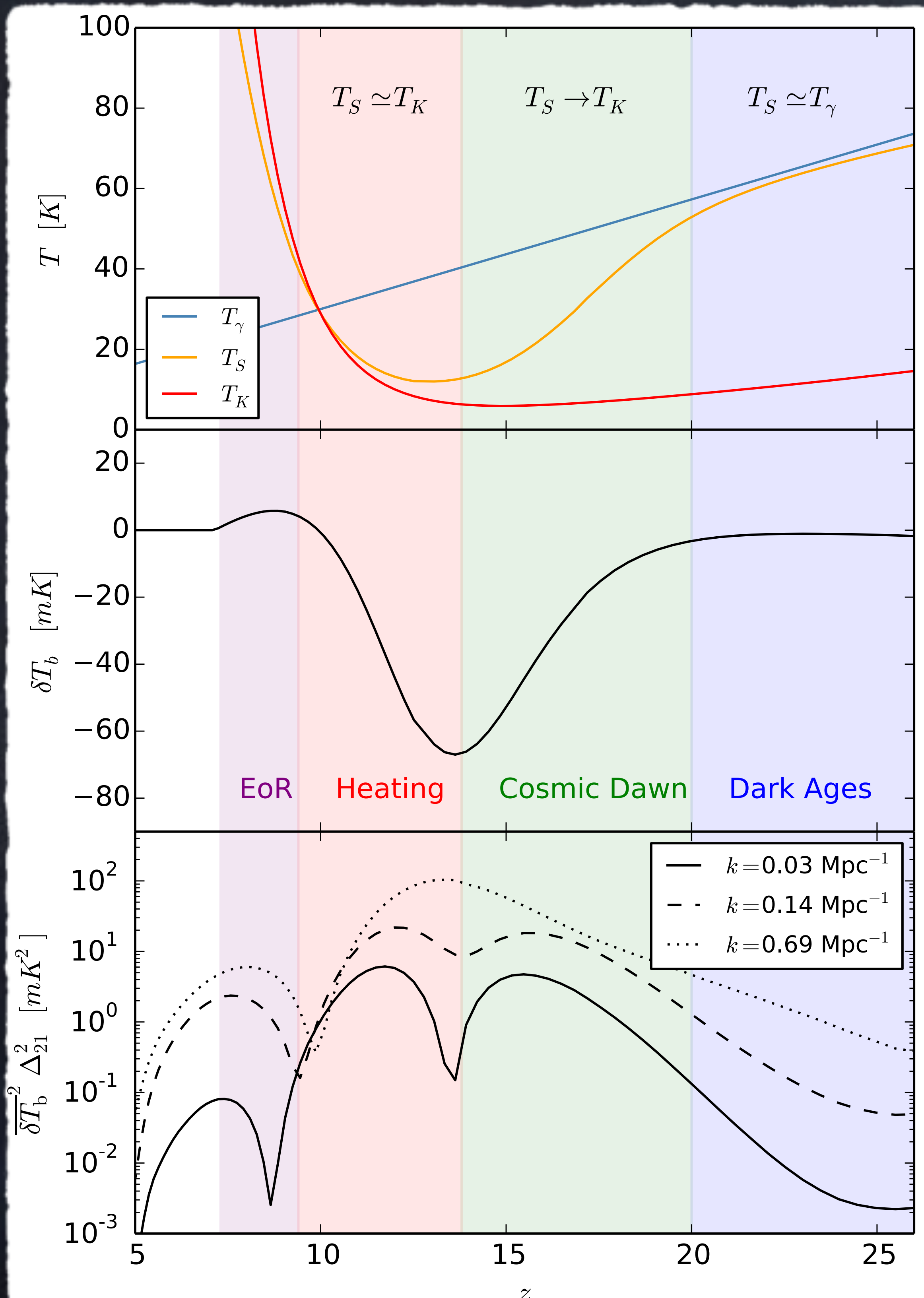
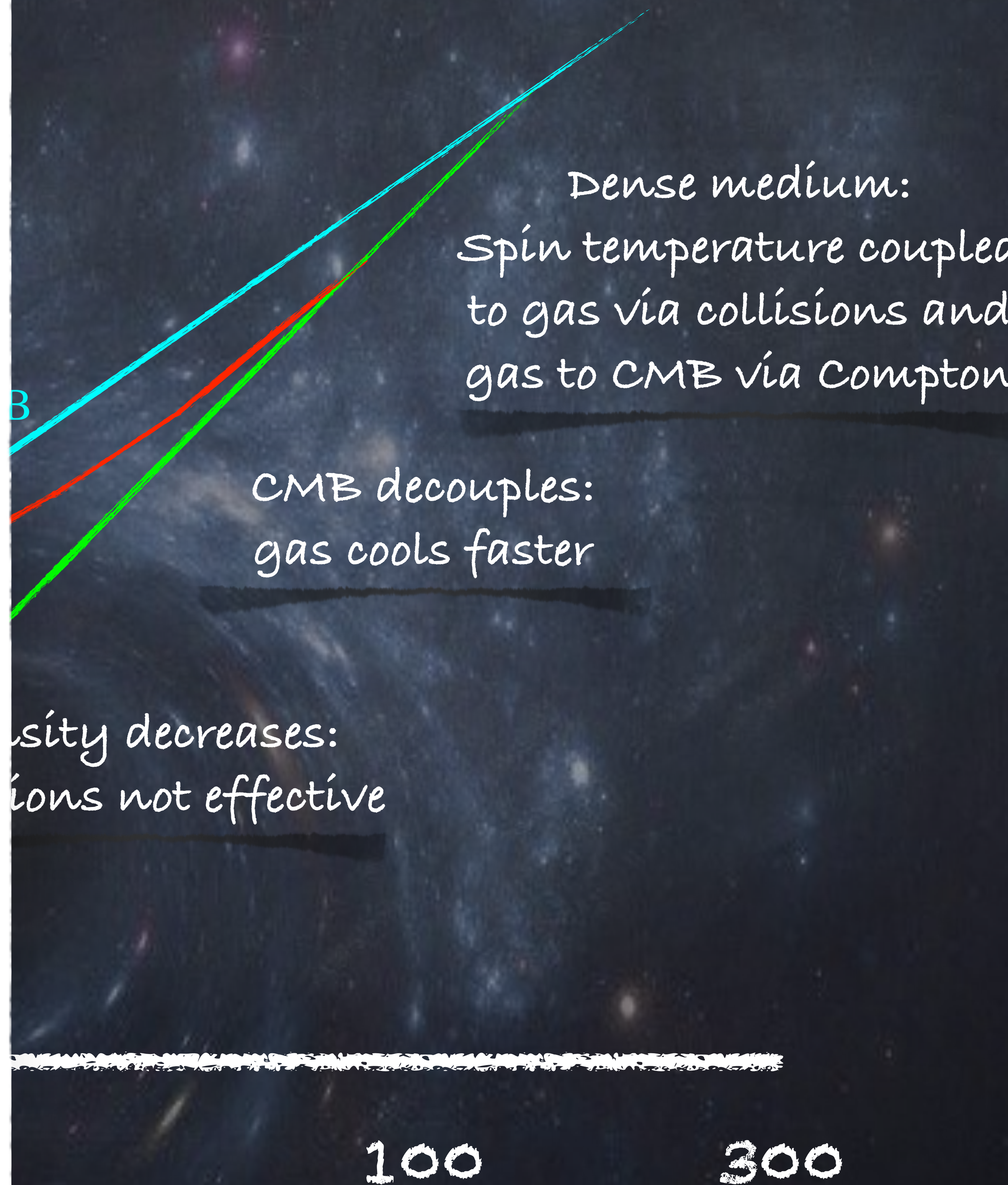


P. Villanueva-Domingo, PhD Thesis

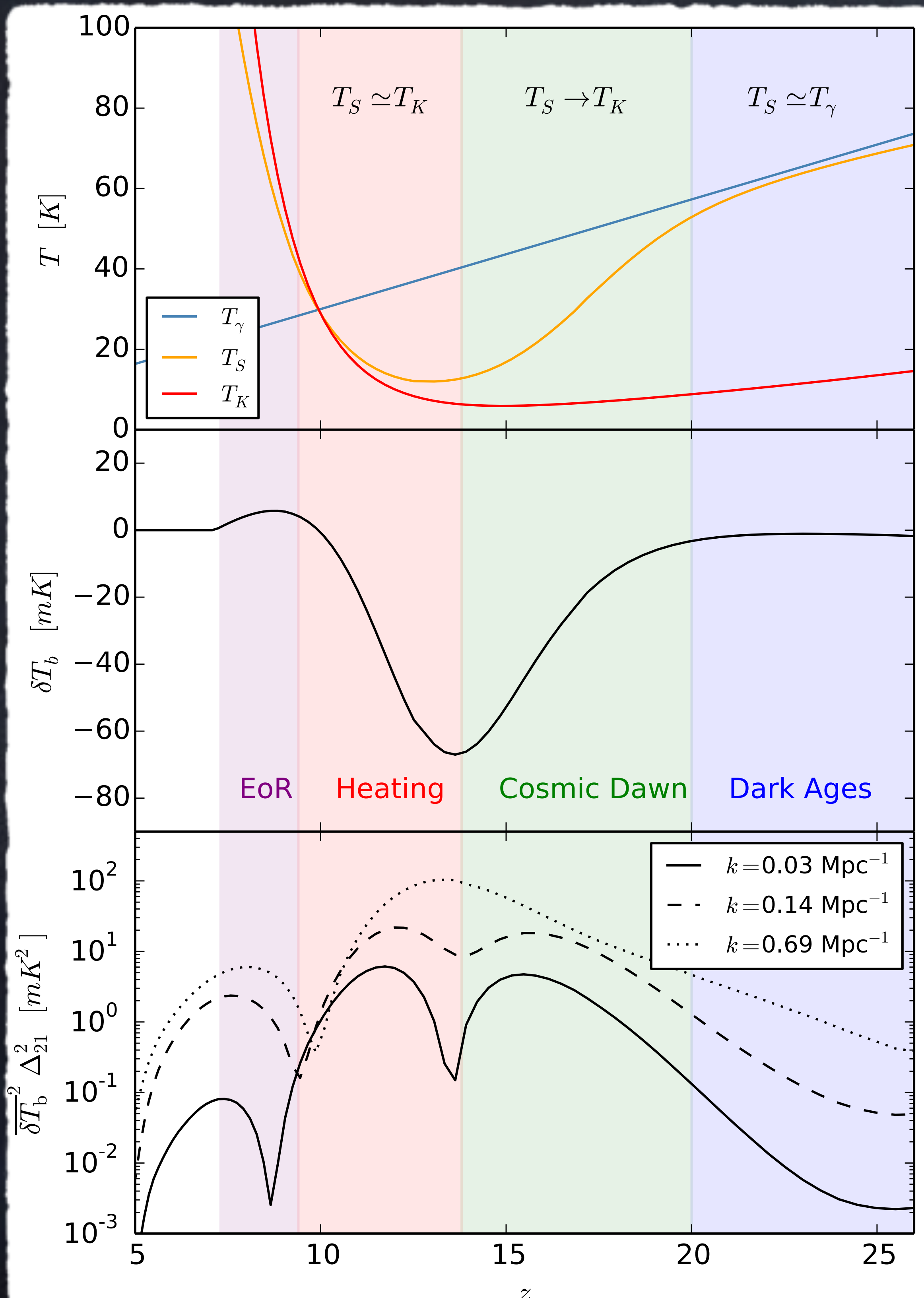


Dense medium:
Spin temperature coupled to gas via collisions and gas to CMB via Compton

CMB decouples:
gas cools faster

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

The 21cm signal: Time evolution



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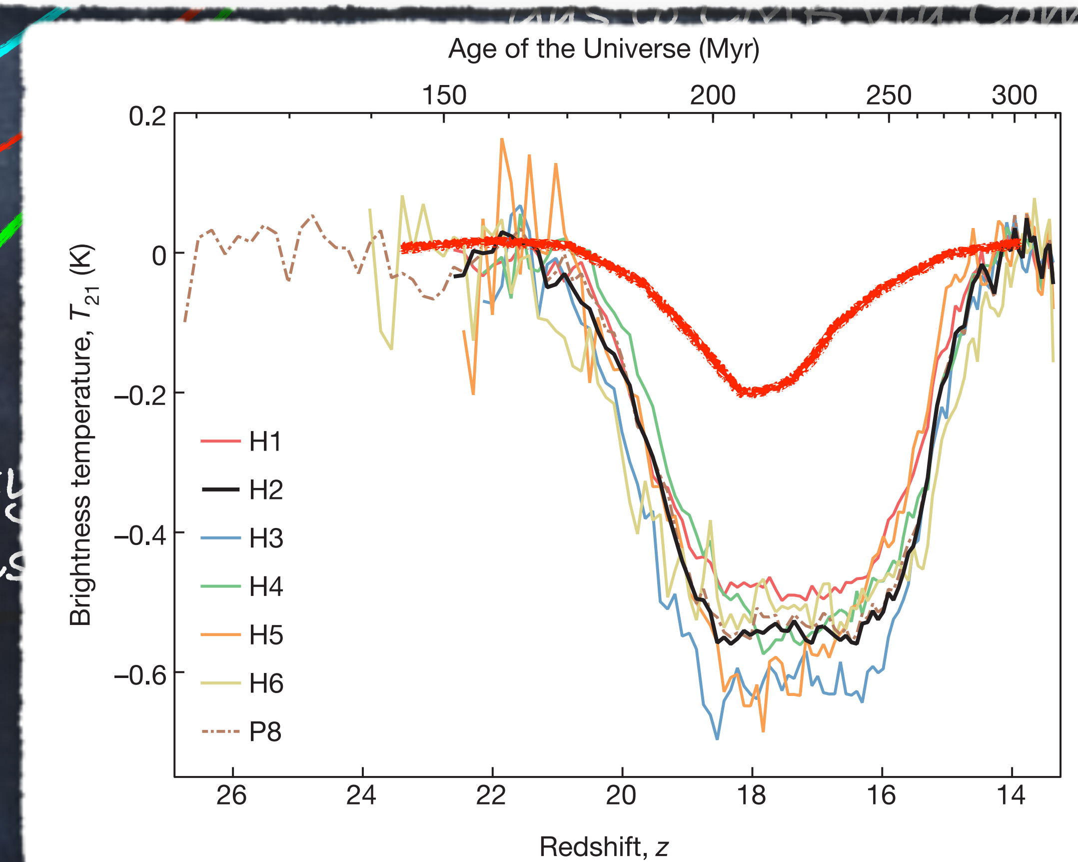
EDGES:

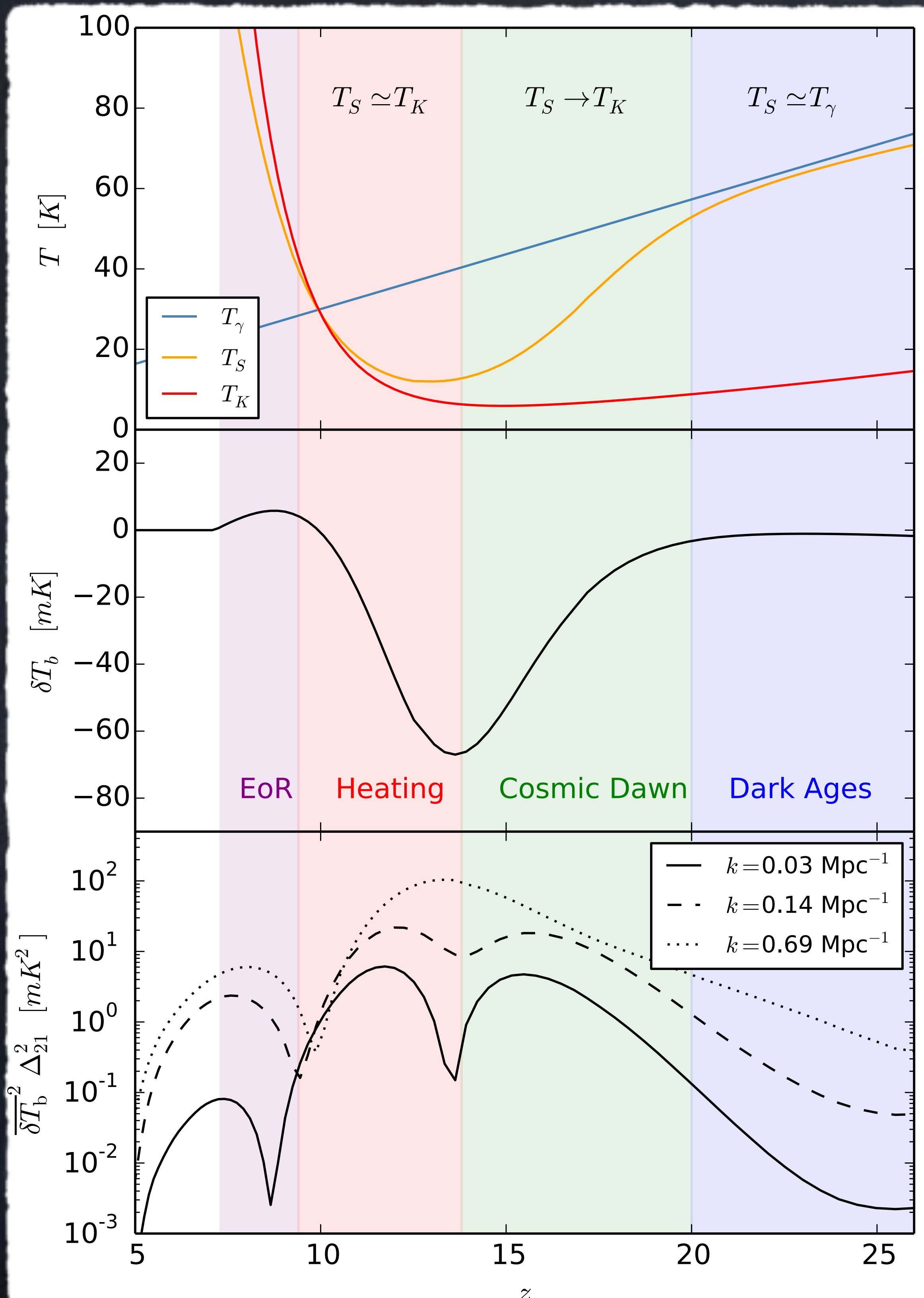
new physics? astrophysics?

systematics?



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

The 21cm signal: Time evolution



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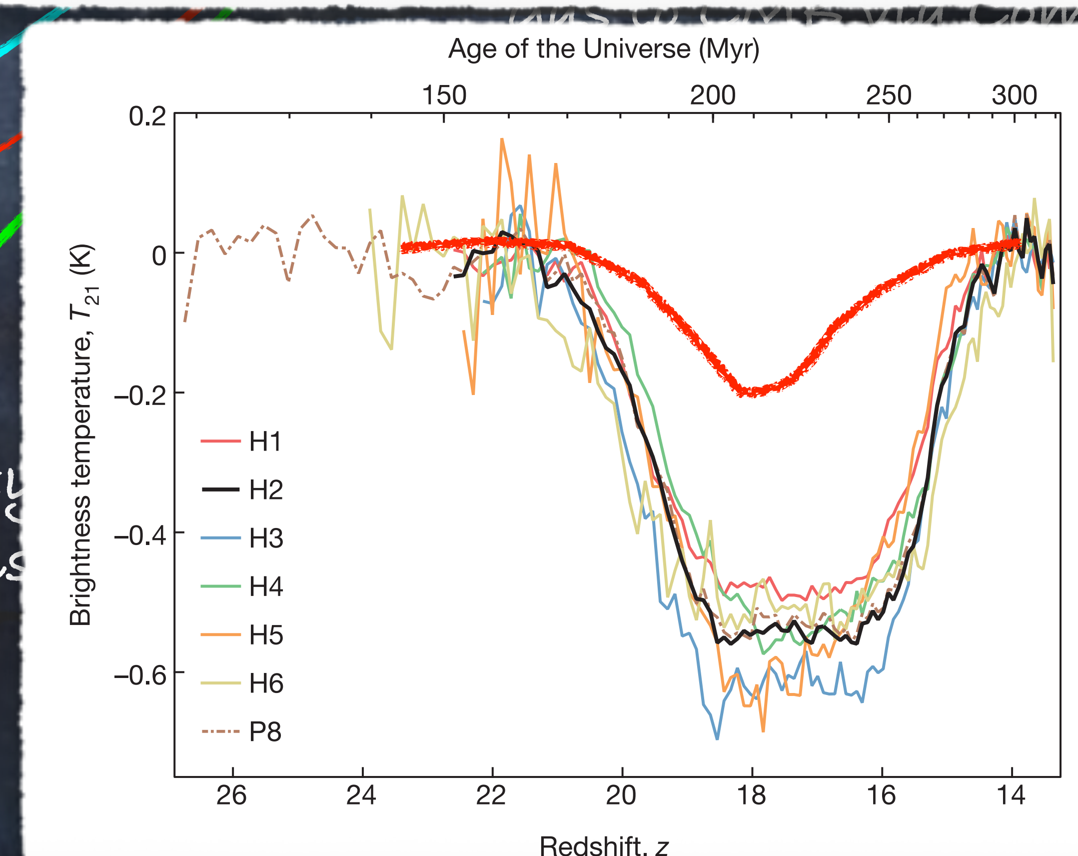
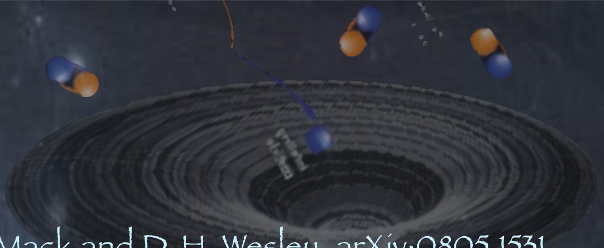


Fully incompatible (amplitude AND shape) with standard scenarios

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

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**

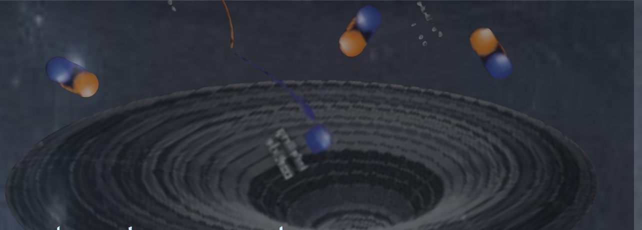
Uniform heating and ionization of the IGM

In the context of EDGES:
A. Ewall-Wice et al., Astrophys. J. 868:63, 2018
A. Hektor et al., Phys. Rev. D98:023503, 2018
Y. Yang, Phys. Rev. D104:063528, 2021

In the context of EDGES:
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:
O. Mena, SPR, P. Villanueva-Domingo and S. J. Witte, Phys. Rev. D100:043540, 2019
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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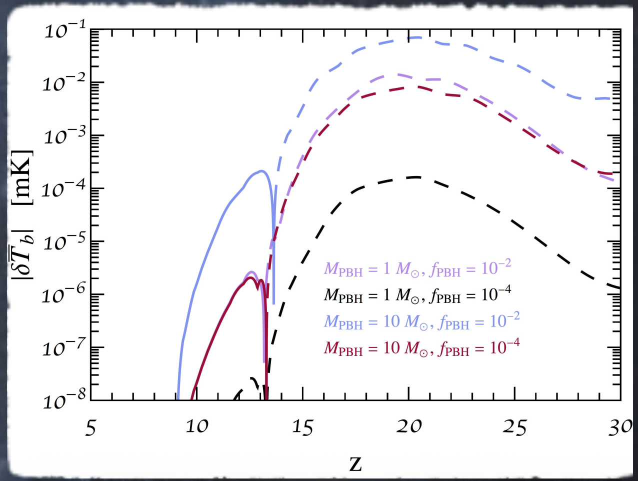
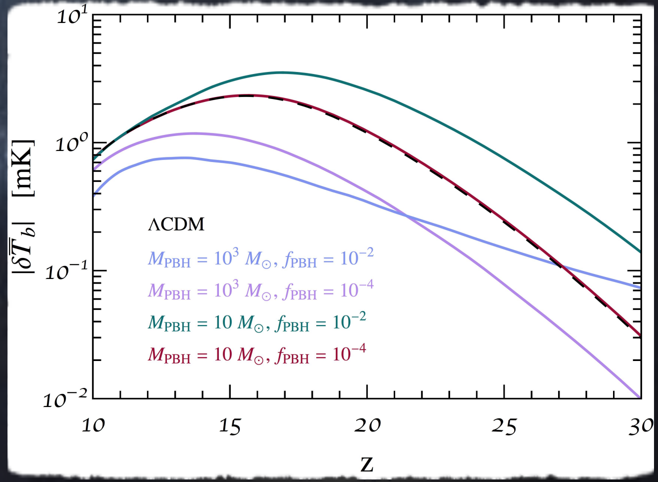
Y. Yang, Phys. Rev. D106:123508, 2022

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

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Y. Yang, Phys. Rev. D102:083538, 2020
A. Halder and M. Pandey, MNRAS 508:3446, 2021

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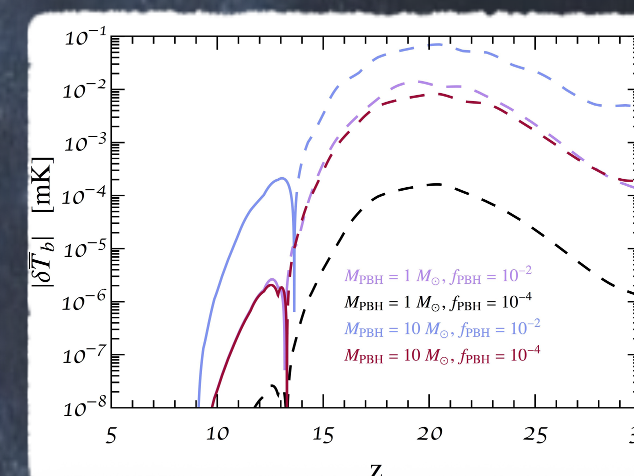
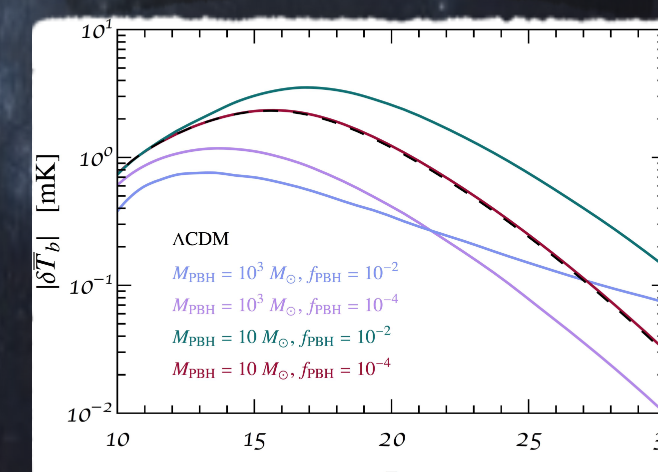
ACCRETION

Heating and ionization of the local environment of isolated

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
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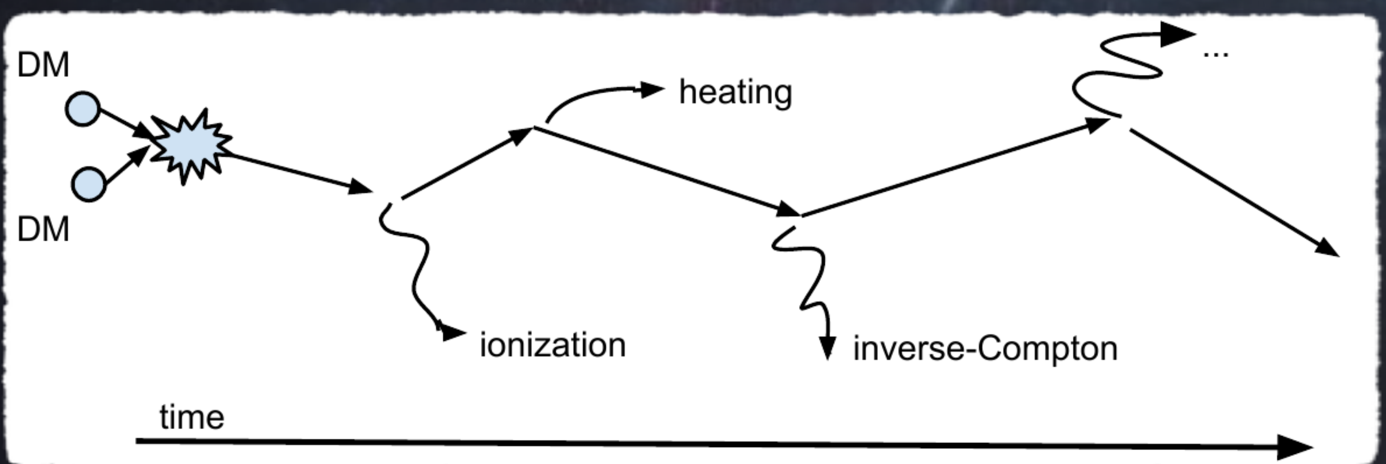
Energy injection: Effect on the 21cm signal

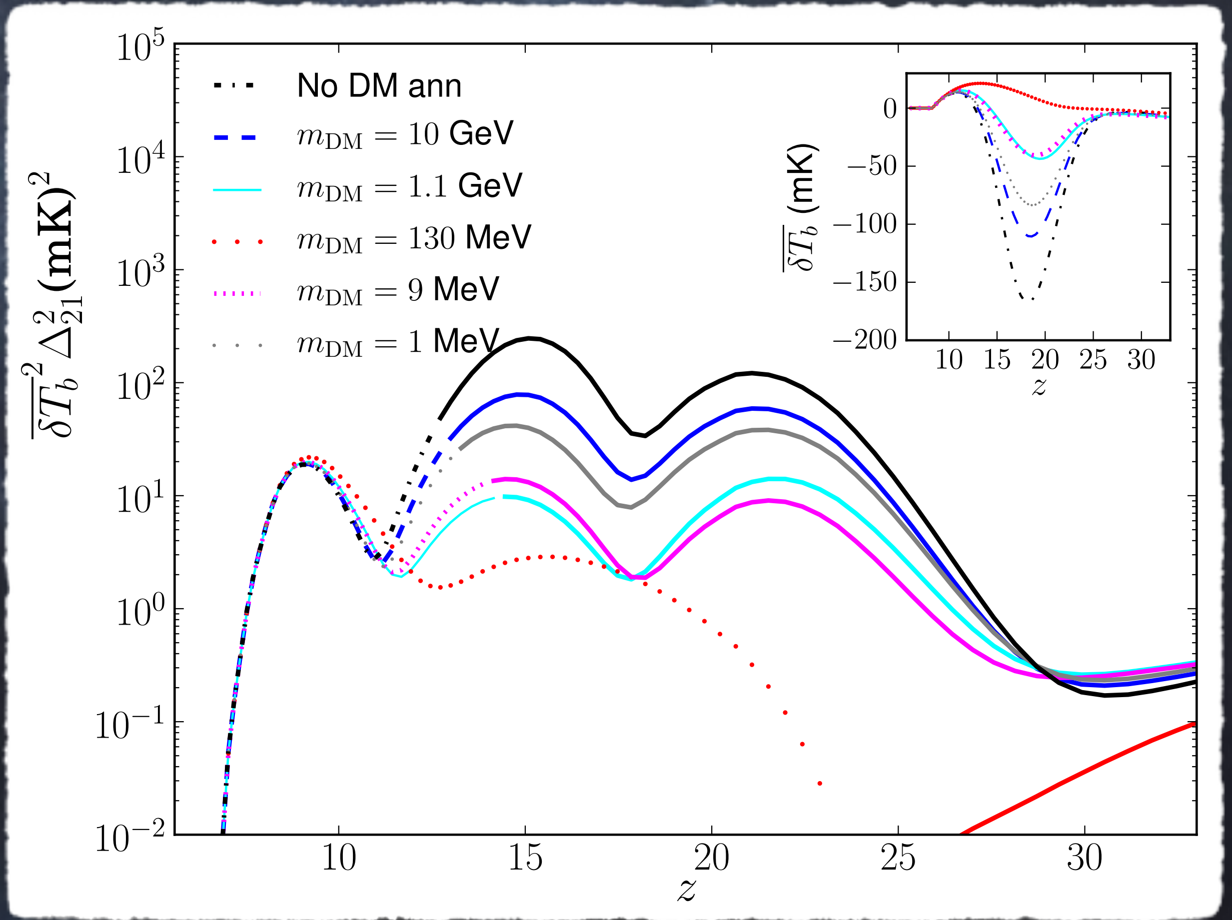
Dark matter annihilations:
inject energy into the IGM

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



Credit: A. C. Vincent

DM annihilations: suppress power
but effects are degenerated with astrophysics



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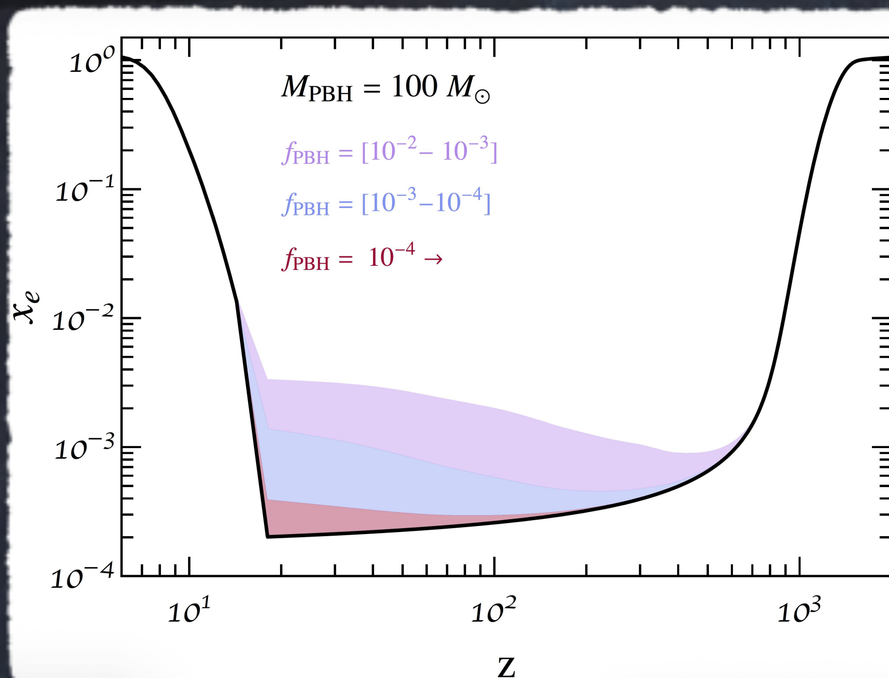
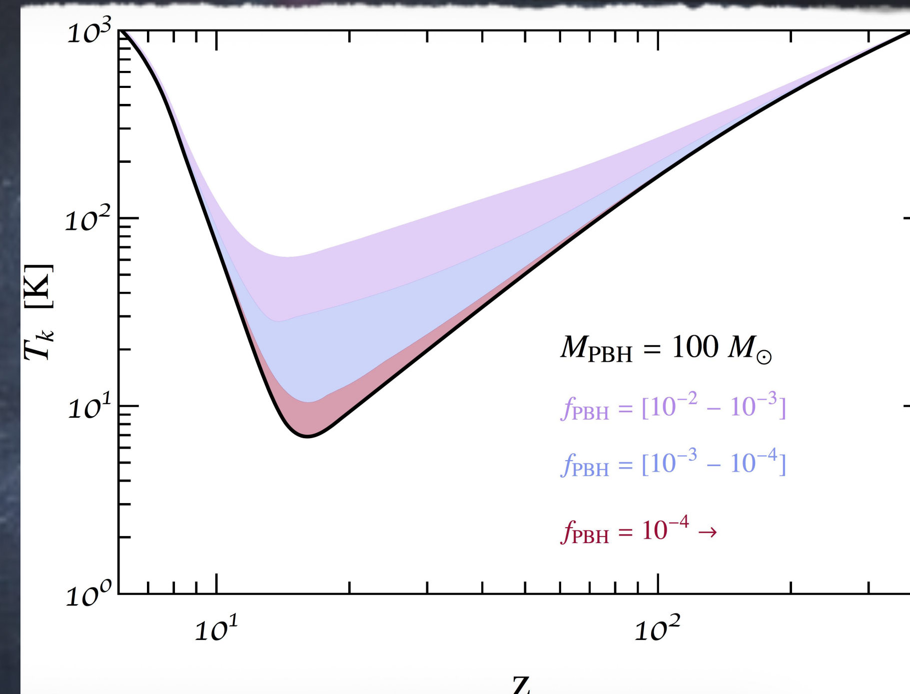
PBHs: Brightness temperature

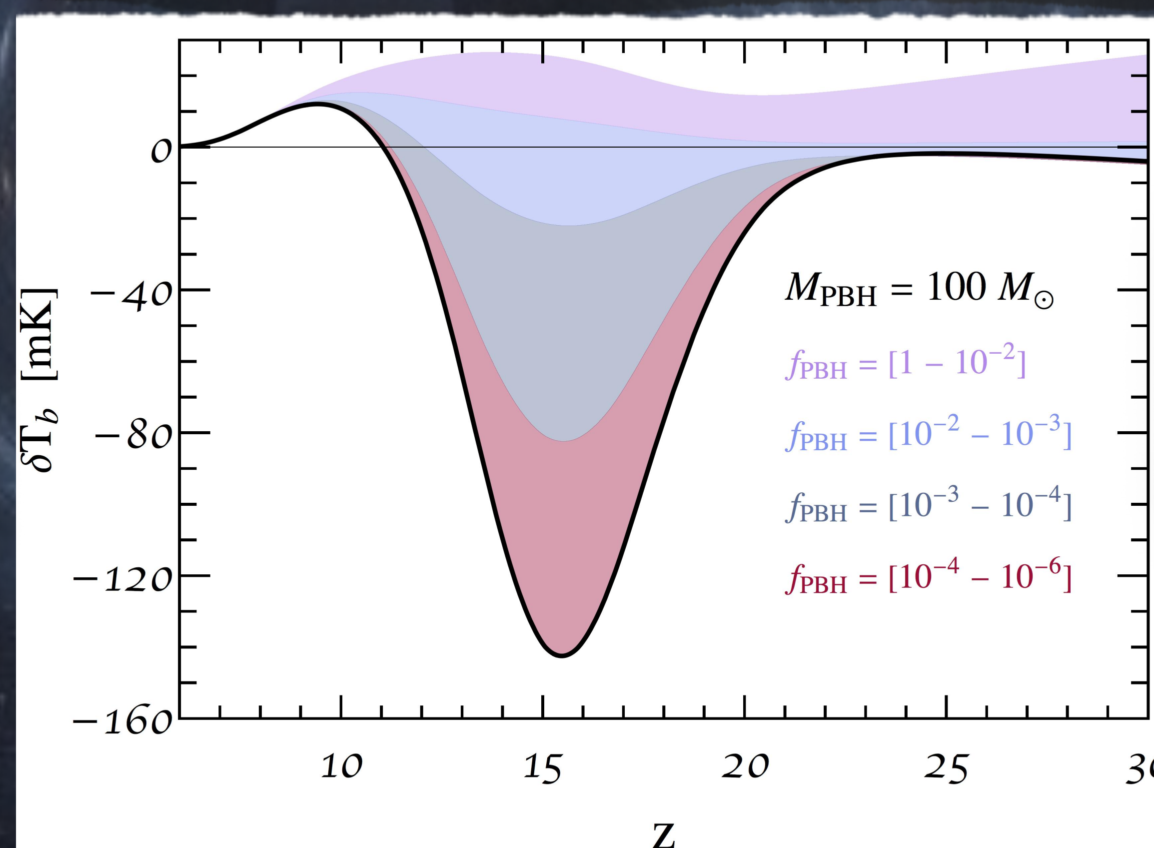
Accretion: Injected energy goes into ionizing and heating the IGM





We use CosmoRec

J. Chluba and R. M. Thomas, Mon. Not. Roy. Astron. Soc. 412:478, 2011



From absorption to emission

Impact on the brightness temperature: suppression of signal

We use 21cmFAST

A. Mesinger, S. Furlanetto and R. Cen, Mon. Not. Roy. Astron. Soc. 411:955, 2011

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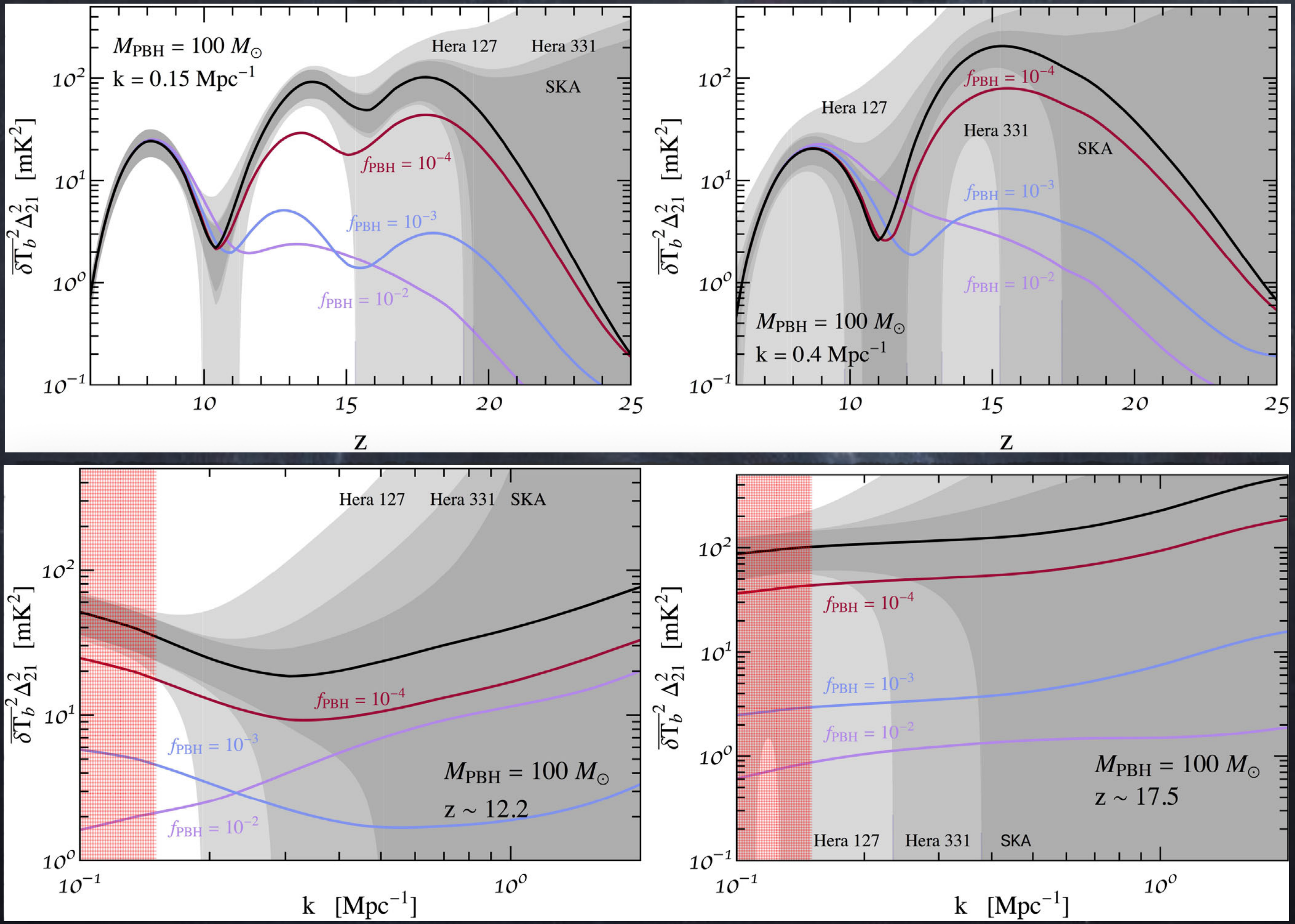
PBHs: 21cm power spectrum

We use 21cmSense

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

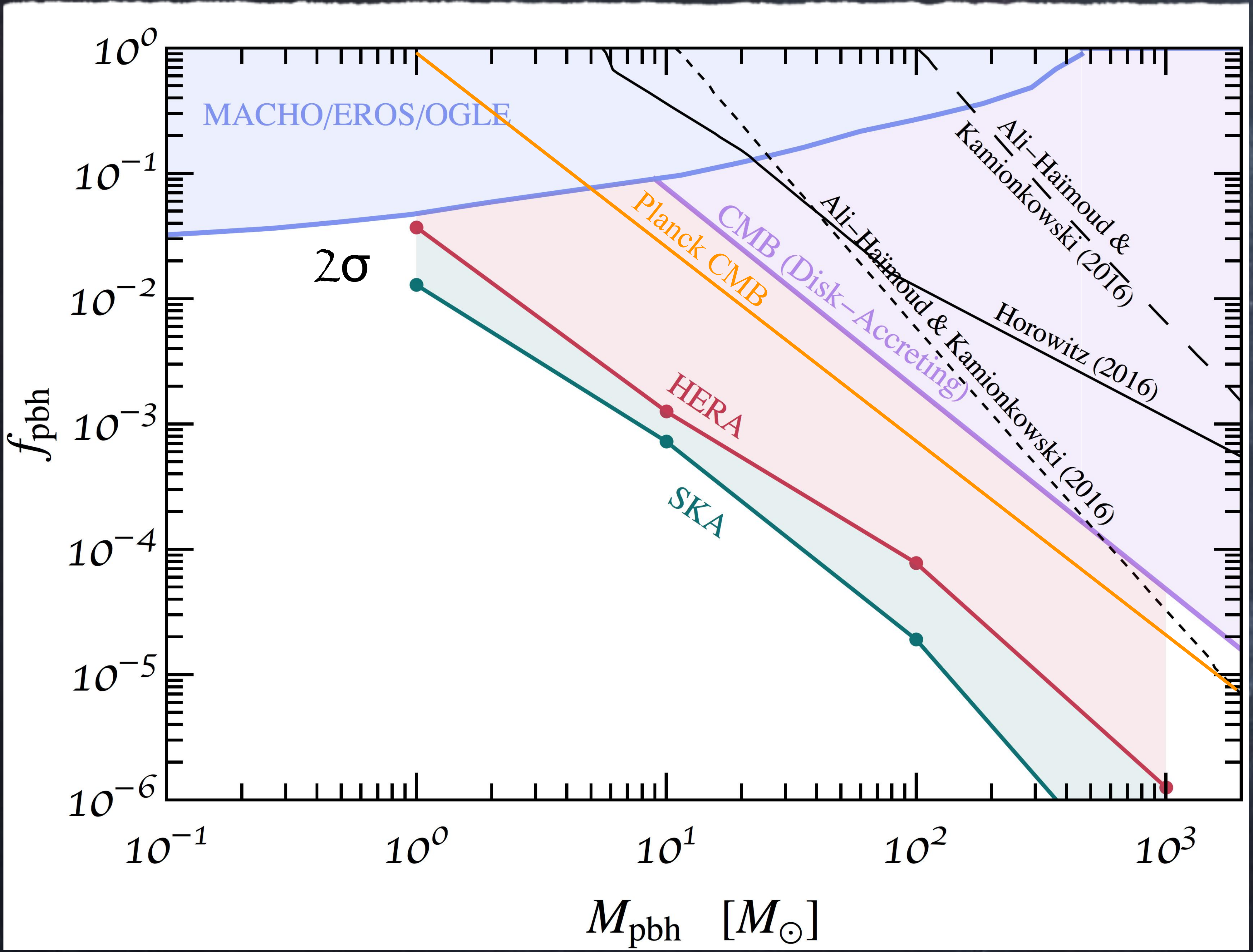
J. C. Pober et al., Astrophys. J. 782:66, 2014

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

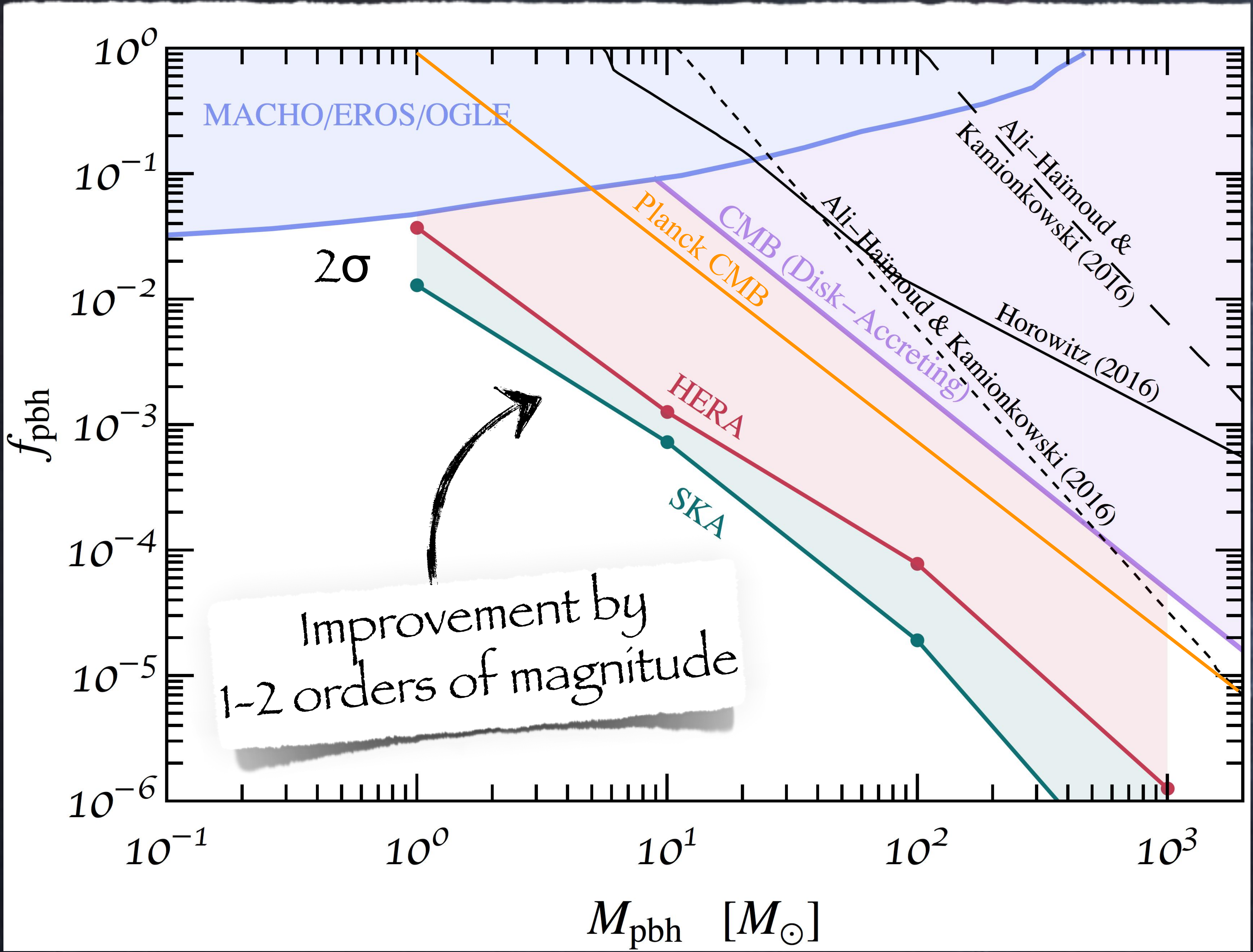
B. Horowitz, arXiv: 1612.07264

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



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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

Conclusions

Great interest in PBHs, triggered by GW measurements

21cm radio observatories will be a powerful tool to learn about exotic energy injection mechanisms into the IGM (PBHs, 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