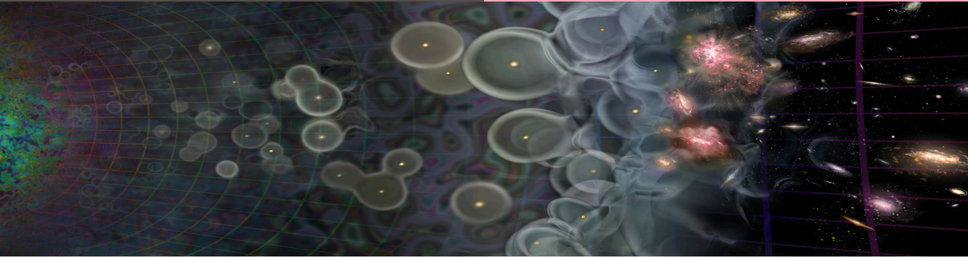


Signatures of Primordial Black Holes in 21cm Cosmology

Samuel J. Witte
Universidad de Valencia

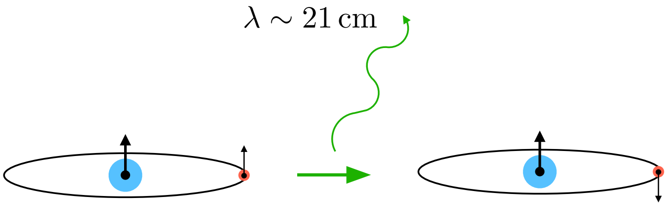
arXiv: 1905.xxxx

EXCELENCIA SEVERO OCHOA

In collaboration with:
Olga Mena, Sergio Palomares-Ruiz, and Pablo Villanueva-Domingo

The 21cm Line

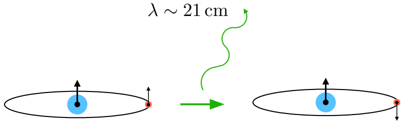
Produced via the hyperfine transition of neutral hydrogen

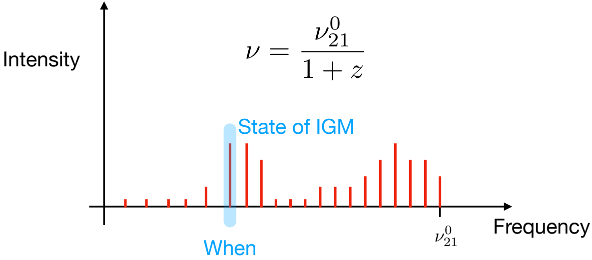


$$\mathcal{H}_{hf} \propto S_e \cdot S_p \tag{1}$$

The 21cm Line

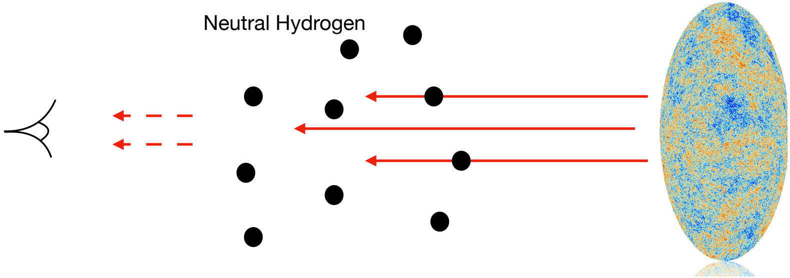
Produced via the hyperfine transition of neutral hydrogen





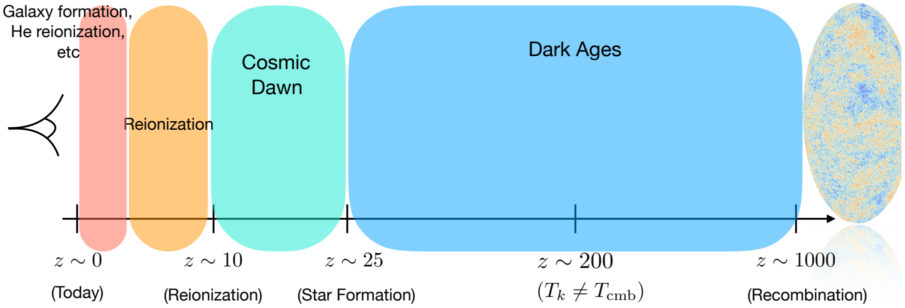
The 21cm Line

Neutral hydrogen at $z \gtrsim 7$ backlight by CMB

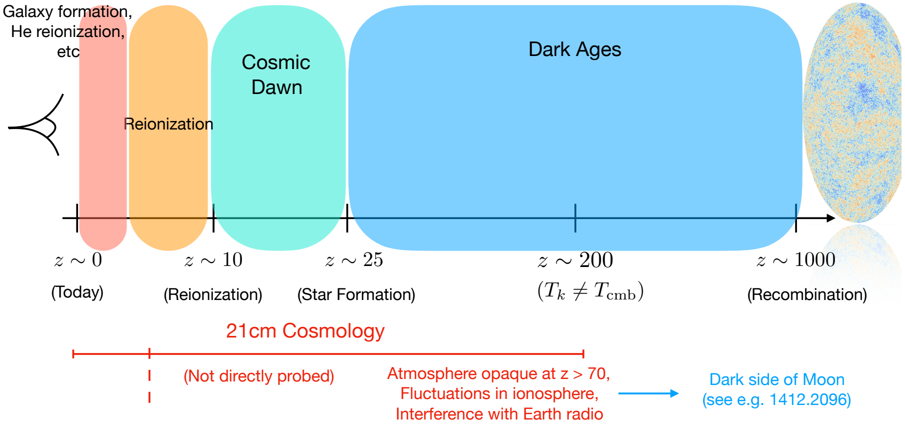


Absorption/Emission

Cosmological Timeline



Cosmological Timeline



Cosmological Timeline

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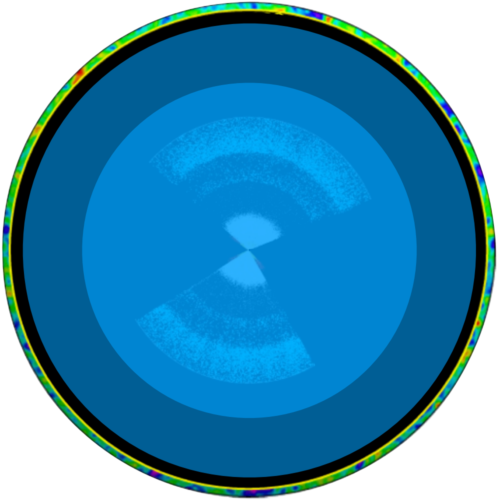


Timeline of 21cm Experiments

- → Now: LOFAR, MWA, PAPER, EDGES (single-dish) ⋯
- 2019 HERA(128) Results, HERA(240) Observations
- 2020 HERA(240) Results, HERA(350) Observations
- 2023 → SKA-Low initial results

arXiv: 1606.07473, SKA Whitepaper, Patil et al 2017, Ali et al 2015, Beardsley et al 2016

The 21cm Signal

IGM

$$\delta T_b \simeq 27\, x_{\rm HI}\,(1+\delta_b)\left(1-\frac{T_{\rm cmb}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\,{\rm mK} \tag{1}$$

The 21cm Signal

IGM

$$\delta T_b \simeq 27\, x_{\rm HI}\, (1 + \delta_b) \left(1 - \frac{T_{\rm cmb}}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \text{mK} \qquad (1)$$

Fraction of neutral hydrogen

At late time, reionization suppresses the signal

The 21cm Signal

IGM

$$\delta T_b \simeq 27\, x_{\mathrm{HI}} (1 + \delta_b) \left(1 - \frac{T_{\mathrm{cmb}}}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \mathrm{mK} \tag{1}$$

Fraction of neutral hydrogen
Baryon overdensity

The 21cm Signal

IGM

$$\delta T_b \simeq 27\, x_{\rm HI}\, (1+\delta_b) \left(1 - \frac{T_{\rm cmb}}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \,\mathrm{mK} \qquad (1)$$

Fraction of neutral hydrogen
Baryon overdensity
Spin temperature

Must understand spatial and redshift dependence of spin temperature!
(notice this controls sign of δT_b)

The 21cm Signal

IGM

$$\delta T_b \simeq 27\, x_{\rm HI}\, (1+\delta_b) \left(1 - \frac{T_{\rm cmb}}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \,\mathrm{mK} \tag{1}$$

Fraction of neutral hydrogen ($x_{\rm HI}$)
Baryon overdensity (δ_b)
Spin temperature (T_s)

$$\delta T_b \sim 0 \;\text{ if }\; T_s \sim T_{\rm cmb} \tag{2}$$

The 21cm Signal

IGM

$$\delta T_b \simeq 27\, x_{\rm HI}\, (1 + \delta_b) \left(1 - \frac{T_{\rm cmb}}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \text{mK} \tag{1}$$

Fraction of neutral hydrogen
Baryon overdensity
Spin temperature

$$\delta T_b > 0 \;\text{ if }\; T_s > T_{\rm cmb} \quad \text{Signal saturates} \tag{2}$$

The 21cm Signal

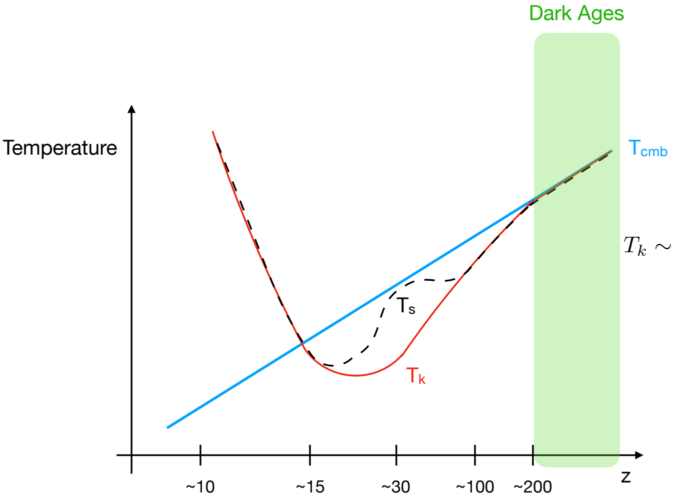
IGM

$$\delta T_b \simeq 27\, x_{\rm HI}\, (1+\delta_b) \left(1 - \frac{T_{\rm cmb}}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \rm mK \quad (1)$$

Fraction of neutral hydrogen ($x_{\rm HI}$)
Baryon overdensity (δ_b)
Spin temperature (T_s)

$$\delta T_b < 0 \ \text{ if } \ T_s < T_{\rm cmb} \quad (\text{here}, |\delta T_b| \ \text{ limited by } \ T_s \geq T_k) \quad (2)$$

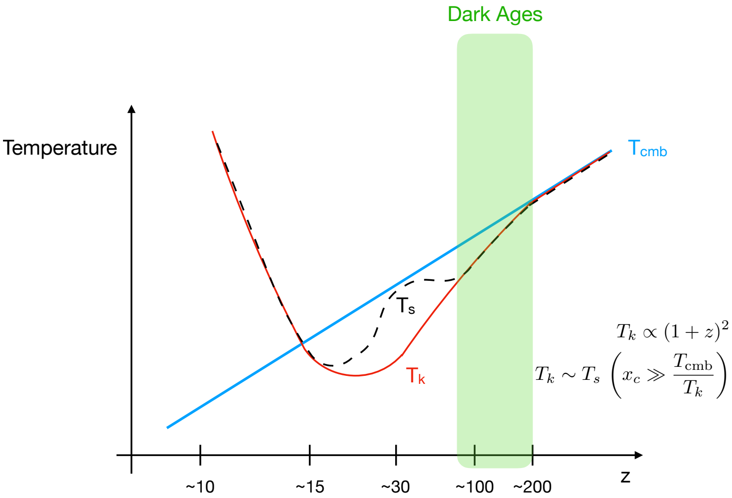
ΛCDM + Astro Expectations



$$T_{\rm cmb} \sim T_k$$

$$T_k \sim T_s \quad (x_c \gg 1)$$

ΛCDM + Astro Expectations



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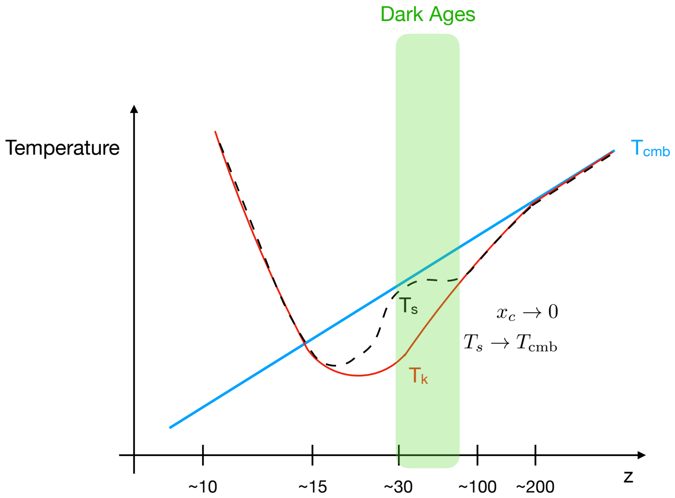

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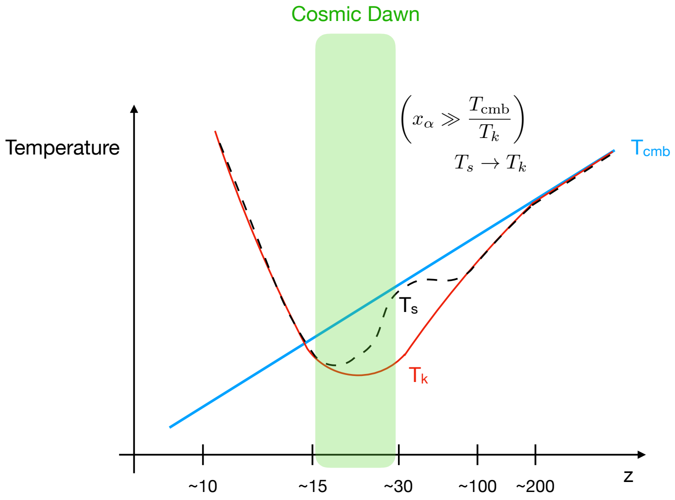

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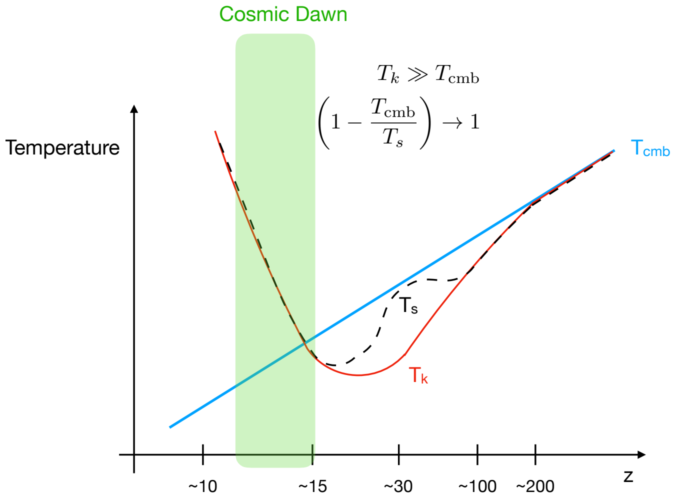

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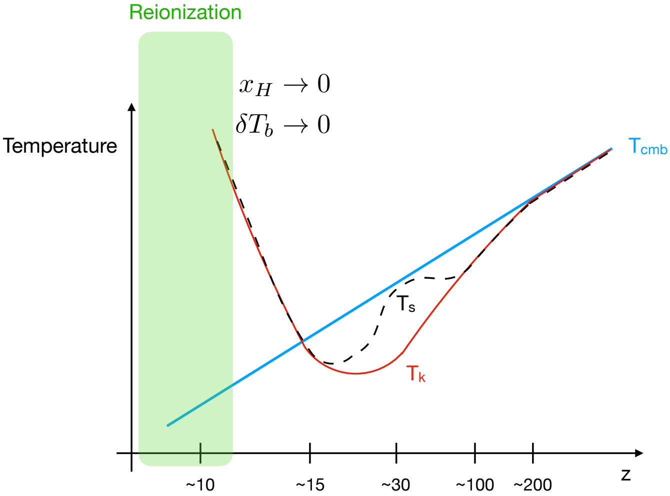
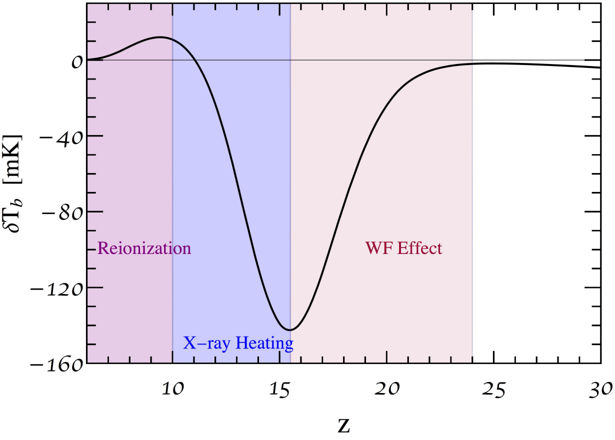


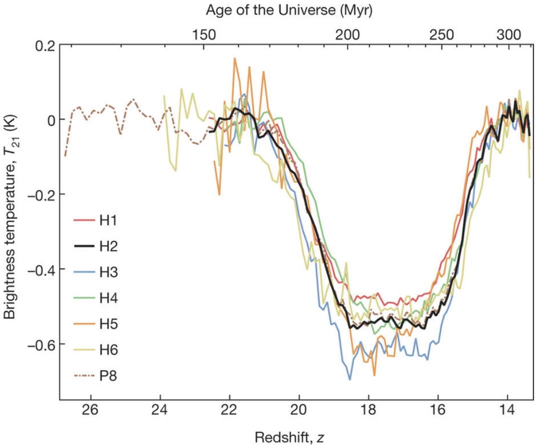
ΛCDM Expectations + Astro Modeling

Global average



EDGES

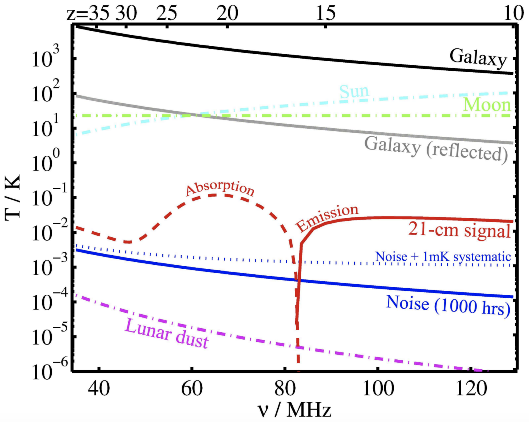
Experiment to Detect Global Epoch of reionization Signature



Bowman et al (2018)

EDGES

Experiment to Detect Global Epoch of reionization Signature



Pritchard, *Talk* (2011)

Legitimacy questioned by Hills et al (2018) and Bradley et al (2019)

Single Dish $\rightarrow$ Interferometer

- More powerful removal of foregrounds in k-space
- Access to power spectrum

Beyond Global Signal

Power Spectrum

Global temperature is only a 1^{st} order test statistic

$$\delta_{T_b} \sim \beta_b\delta_b + \beta_x\delta_x + \beta_\alpha\delta_\alpha + \beta_T\delta_T + \beta_v\delta_v \tag{3}$$

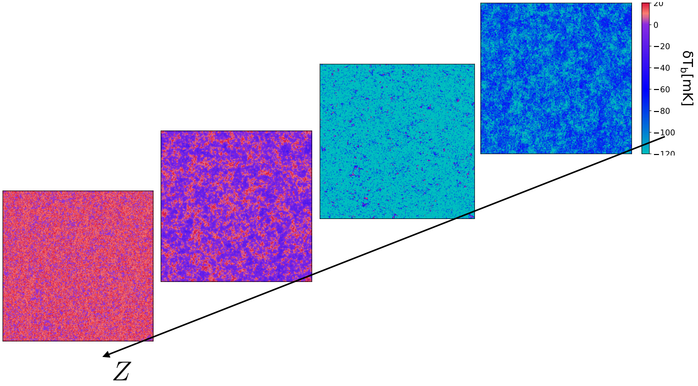
- Baryon overdensity
- Neutral hydrogen
- Ly-α
- Gas temperature
- Velocity gradient

$$\left\langle \delta_{T_b}(\vec{k}, z)\delta^*_{T_b}(\vec{k'}, z) \right\rangle = P_{21}(\vec{k}, z) \tag{4}$$

See e.g. Furlanetto, Oh, Briggs (2006), Pritchard and Loeb (2011)

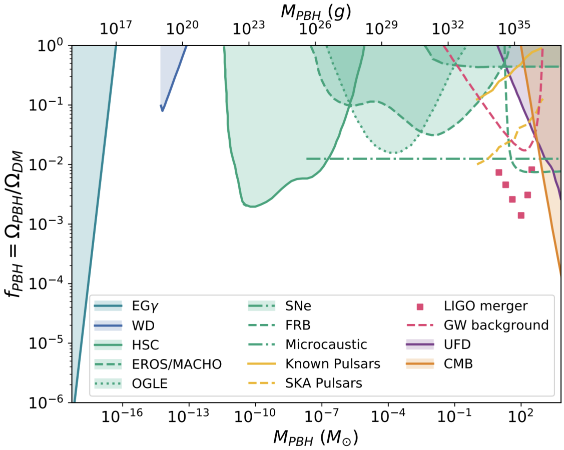
Beyond Global Signal

Tomography



Comments on this later

PBHs as Dark Matter



Sato-Polito, Kovetz, Kamionkowski (2019),

Solar Mass PBHs

$\mathcal{O}(M_\odot)$ PBHs cannot account for entirety of dark matter, but still of interest to community

- Detection $\rightarrow$ insight into early Universe
  Production from inflation, topological defects, phase transitions, etc
- Detection $\rightarrow$ WIMPs and PBHs, a no-go
  Bertone et al (2019), Adamek et al (2019), Boucennaa et al (2017), Lacki and Beacom (2010), Eroshenko (2016)
- SMBH timing problem $(10^9 - 10^{10} M_\odot$ at $z \sim 7)$
  Could be accomplished via $10^2 M_\odot - 10^6 M_\odot$ at $z \sim 15$
  Smith, Bromm, Loeb (2017), Haiman et al (2019)

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Cosmological Implications

Presence of $\sim M_\odot$ PBHs lead to 3 effects:

- Structure modified on small scales via PBH clustering
  Isocurvature perturbations induced via shot noise
- Accretion of gas onto PBH leads to:
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  - Local heating via advection, local absorption of X-rays

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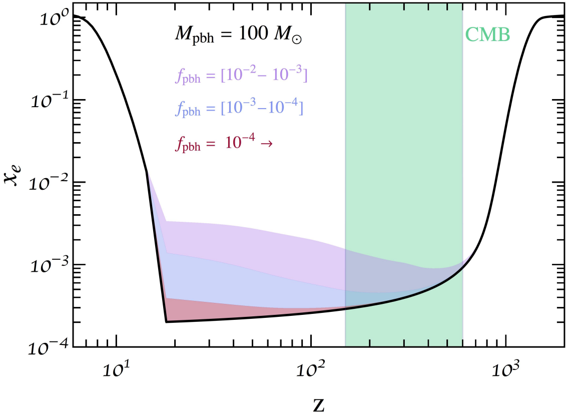
PBHs in the IGM

Injected energy goes into heating and ionizing IGM



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

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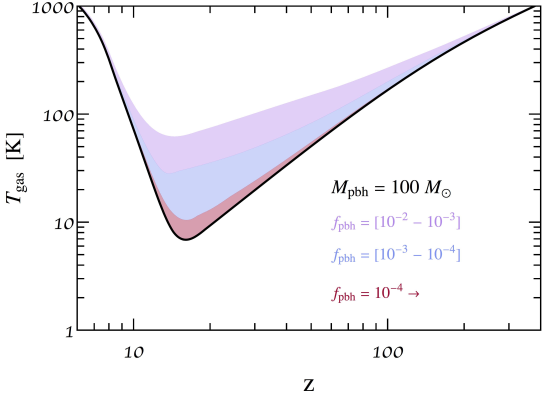
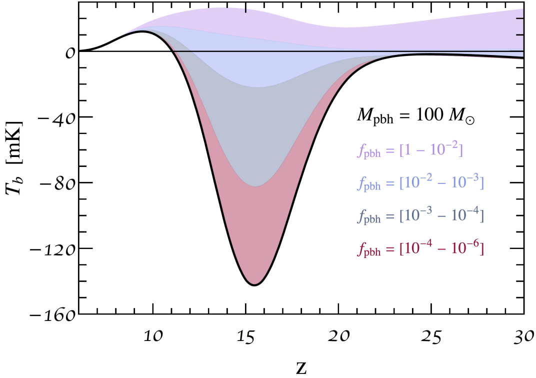


Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

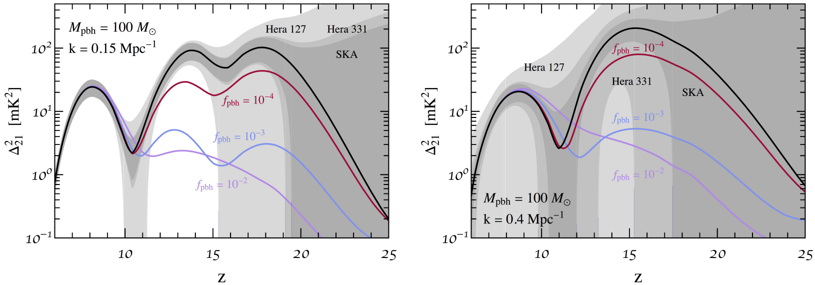
CMB and 21cm provide very complimentary probes!

PBH on δT_b



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

21cm Power Spectrum



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

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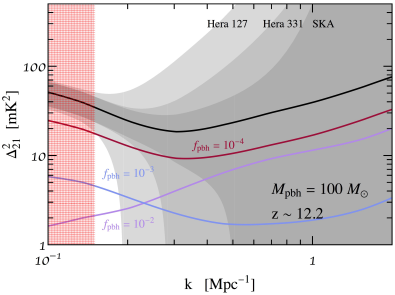
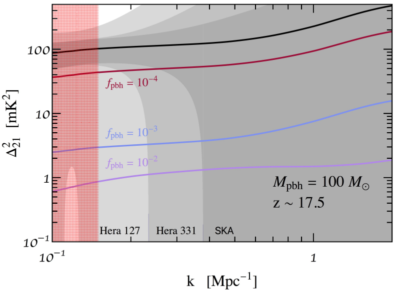
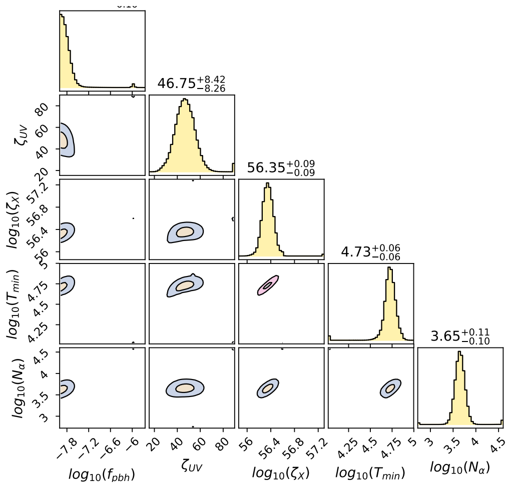




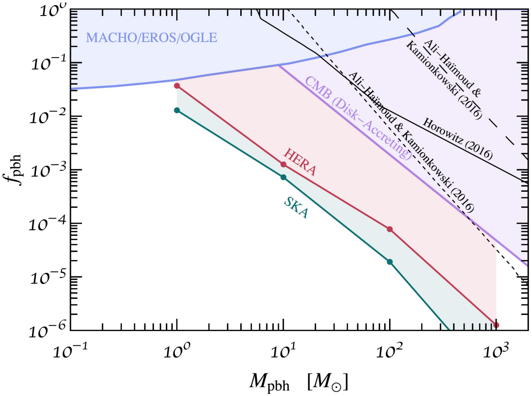
Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

Parameter Estimation



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

Sensitivity



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

HERA: Running Now (Upgrade soon), SKA-Low: $\sim$ 2020

A Comment on the Astrophysics

Why not use a more complicated astrophysical model?

$$\vec{X} \in (M_{\rm pbh},\, f_{\rm pbh},\, T_{\rm min},\, N_\alpha,\, \zeta_X,\, \zeta_{\rm UV}) \tag{5}$$

(6D parameter space) $\rightarrow$ Interpolation for MCMC ($\rightarrow$ linear?)
10 points / dim requires 10^6 evaluations

Each realization requires ~ 6 hours on ~ 8 cores...

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(6D parameter space) $\rightarrow$ Interpolation for MCMC ($\rightarrow$ linear?)
10 points / dim requires 10^6 evaluations

Each realization requires ~ 6 hours on ~ 8 cores...

$\rightarrow$ ML techniques allowed 10^6 to be reduced to $\sim 10^3$

Computational Complications

- Practical issue of computational time
  Producing one full realization of 21cm maps using semi-analytic techniques may require $\gtrsim 6$ hours on a cluster

- Issue of information extraction
  Power spectrum does not contain full wealth of information...

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- Issue of information extraction

  Power spectrum does not contain full wealth of information...

→ Wish list: quick map production, extract more information (move beyond PS), easily identify new physics

Ruiz De Austri, SJW, Mena + others (in progress)

Machine Learning 101

Consider simple χ^2 fit

$$\chi^2 = \sum_i \left(\frac{\mathrm{data}_i - f(\sigma, m, \cdots, x_i)}{\sigma_i} \right)^2 \tag{6}$$

Minimize χ^2 to determine $\hat{\sigma}, \hat{m}, \cdots$

Machine Learning 101

Consider simple χ^2 fit

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Minimize χ^2 to determine $\hat{\sigma}, \hat{m}, \cdots$

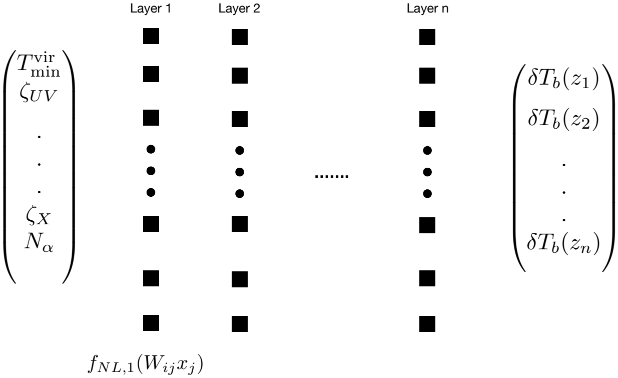
Neural net: $f \rightarrow$ generic function with unknown parameters $\vec{w}$, values attained from minimizing cost function

1) Supervised learning: data_i given

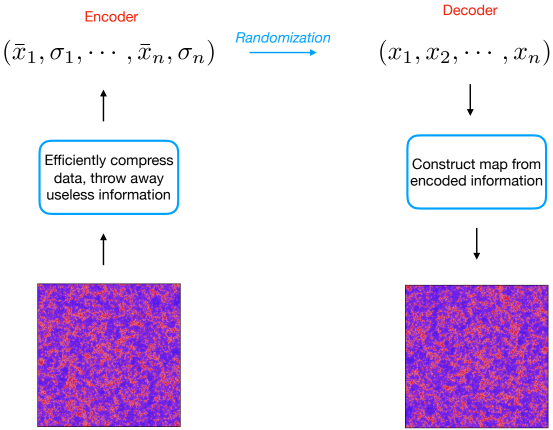
2) Unsupervised learning: no data_i, cost function replaced by alternative criteria independent of data

Neural Nets

Basic Architecture

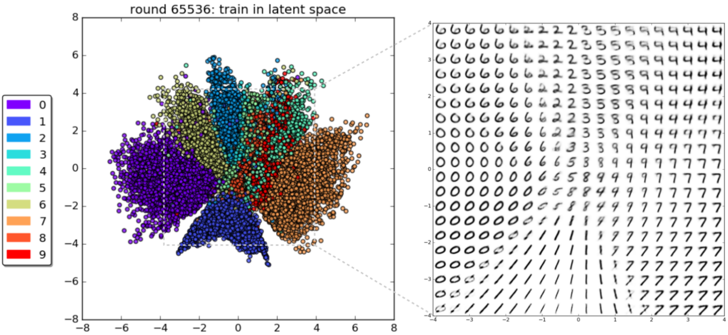


Variational Autoencoder

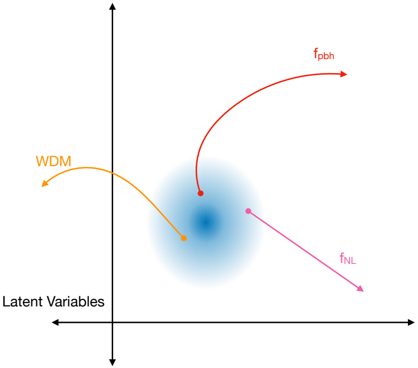


Variational Autoencoder

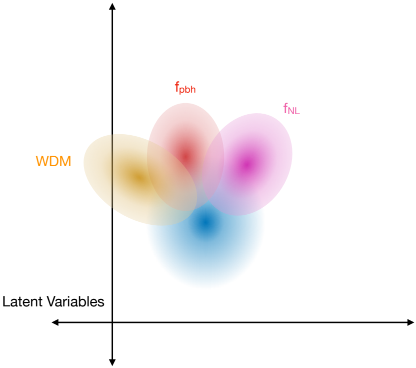
Example: Learning to recognize numbers



Variational Autoencoder for 21cm



Variational Autoencoder for 21cm



Conclusions

- 21cm Cosmology promises to be a power tool for both cosmology and particle physics alike
- $\sim M_\odot$ PBHs can give rise to various effects, leaving significant imprint on 21cm signal
  Near-future experiments could increase sensitivity by ~ 2 orders of magnitude
- New computational techniques necessary
  Practical computations and information extraction

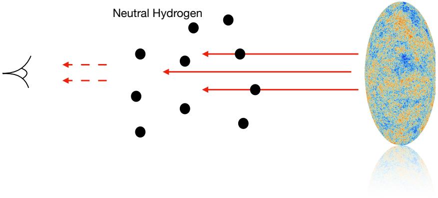
Thank you!

This project has received funding/support from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 674896

Back Up Slides

The 21cm Signal

Predictions are attained from absorption and emission properties of the IGM



Solve radiative transfer equation (neglect scattering) for IGM cloud...

$$\frac{dI_\nu}{d\ell} = -\alpha_\nu I_\nu + j_\nu \quad (7)$$

Opacity → α_ν

Emission Coefficient → j_ν

Absorption/Emission Coefficients

Solving for I_ν requires knowing j_ν, α_ν, which are dictated by:

$$\alpha_\nu \propto (n_0 B_{01} - n_1 B_{10}) \tag{9}$$

$$j_\nu \propto n_1 A_{10} \tag{10}$$

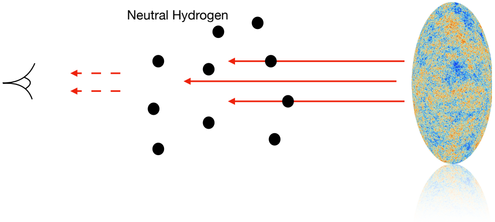
Rather than use n_0 and n_1 $\rightarrow$ use n_H and T_s

Boltzmann factor for excitation temperature ('spin temperature' T_s)

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\, e^{-\Delta E_{10}/k_B T_s}\,, \tag{11}$$

The 21cm Signal

$$I_\nu = I_{\rm cmb}\, e^{-\tau_\nu} + \int d\ell\, \frac{j_\nu}{\alpha_\nu}\, e^{-\tau_{\nu,r}(\ell)}\, \frac{d\tau_{\nu,r}}{d\ell} \tag{12}$$



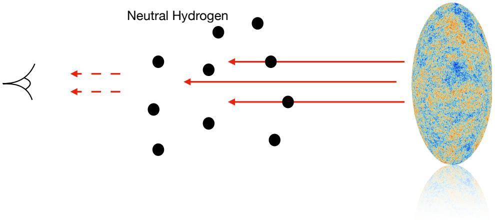
For IGM cloud $\frac{j_\nu}{\alpha_\nu}$ independent of ℓ and $\tau_\nu \ll 1$, leading to:

$$\delta I_\nu \equiv I_\nu - I_{\rm cmb}(\nu) = \left(\frac{j_\nu}{\alpha_\nu} - I_{\rm cmb}(\nu)\right)\tau_\nu \tag{13}$$

See e.g. Pritchard and Loeb (2011) for review

The 21cm Signal

$$I_\nu = I_{\rm cmb}\, e^{-\tau_\nu} + \int d\ell\, \frac{j_\nu}{\alpha_\nu}\, e^{-\tau_{\nu,r}(\ell)}\, \frac{d\tau_{\nu,r}}{d\ell} \tag{12}$$



Convert intensity to effective temperature $I_\nu \to 2\,\nu^2\, T_b$

$$\delta I_\nu \quad \to \quad \delta T_b \equiv \left(\frac{T_s - T_{\rm cmb}(z)}{1+z}\right)\tau_\nu \tag{13}$$

See e.g. Pritchard and Loeb (2011) for review

The Spin Temperature

T_s (equivalently n_1/n_0) determined by:

See e.g. Pritchard and Loeb (2011)

- Spontaneous absorption/emission and stimulated emission (A_{10}, $B_{10}I_{\rm cmb}$, $B_{01}I_{\rm cmb}$)
- Collision excitation/de-excitations with HH, He, Hp (C_{10}, C_{01})
- Indirect excitation/de-excitations via scattering with Ly$-\alpha$ photons (P_{10}, P_{01}), 'Wouthuysen-Field effect' (WF)

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- Indirect excitation/de-excitations via scattering with Ly$-\alpha$ photons (P_{10}, P_{01}), 'Wouthuysen-Field effect' (WF)

The Spin Temperature

T_s (equivalently n_1/n_0) determined by:

See e.g. Pritchard and Loeb (2011)

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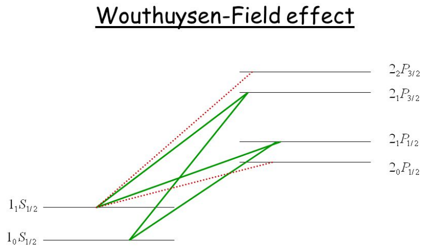

The Spin Temperature

The rates are fast enough that we can assume an equilibrium, allowing us to derive:

$$n_1(A_{10} + C_{10} + P_{10} + B_{10} I_{\rm cmb}) = n_0(C_{01} + P_{01} + B_{01} I_{\rm cmb}) \tag{14}$$

which can be expressed in terms of $T_{\rm cmb}$ and T_k

$$T_s \simeq \frac{T_{\rm cmb} + (x_c + x_\alpha) T_k}{1 + x_c + x_\alpha}\,, \tag{15}$$

where x_c and x_α are the collisional and WF coupling coefficients

See e.g. Pritchard and Loeb (2011)

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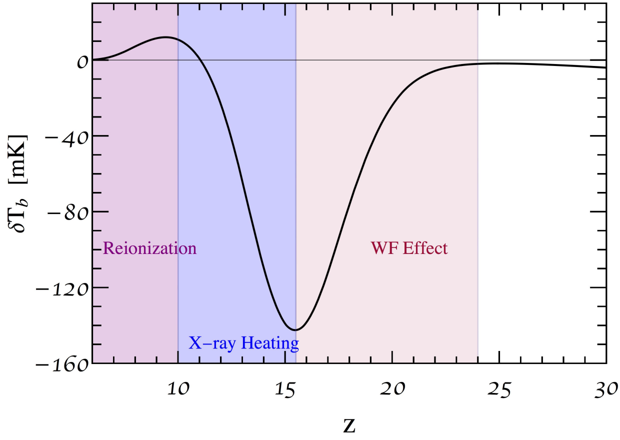
$$T_s \simeq T_{\rm cmb} \quad \text{if} \quad x_c, x_\alpha \ll T_{\rm cmb}/T_k \tag{16}$$

$$T_s \simeq T_k \quad \text{if} \quad x_c(x_\alpha) \gg T_{\rm cmb}/T_k \tag{17}$$

ΛCDM Expectations + Astro Modeling

Global average



ΛCDM Expectations + Astro Modeling

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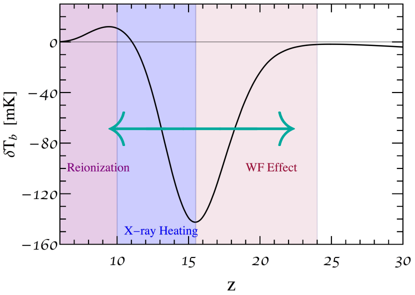
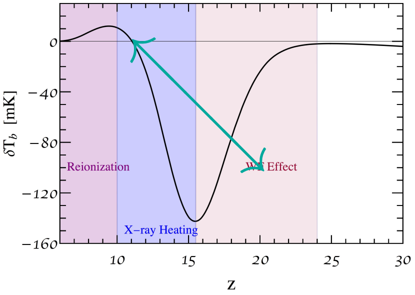


Appearance of WF effect depends on when stars form ($M_{\rm min}$ or $T^{\rm vir}_{\rm min}$)

Note: non SF halos ('minihalos') have $\sim$ negligible impact on 21cm signal in ΛCDM Furlanetto et al (2006)

ΛCDM Expectations + Astro Modeling

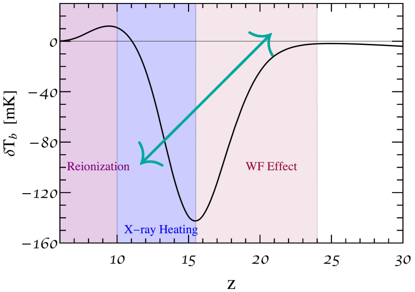
Global average



Strength of x_α depends on number of Ly-α produced by stars (N_α)

ΛCDM Expectations + Astro Modeling

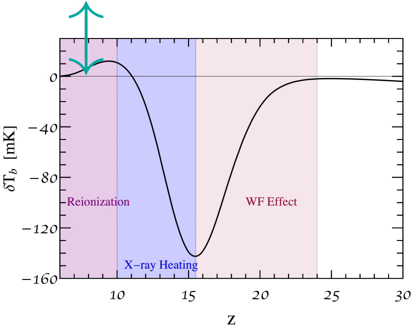
Global average



Depth of absorption depends on efficiency of X-ray heating (ζ_X)

ΛCDM Expectations + Astro Modeling

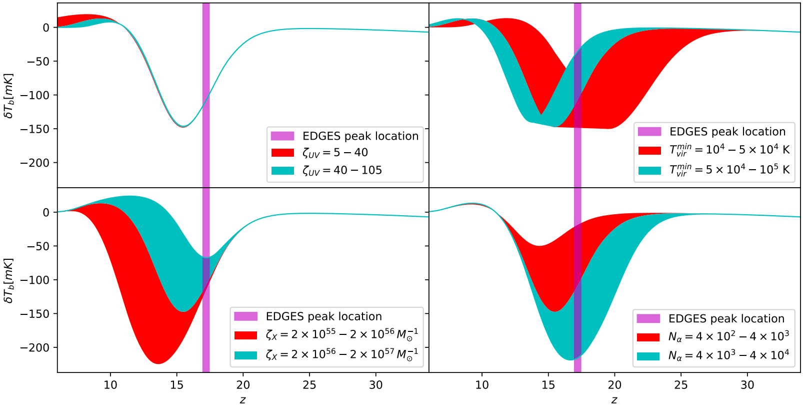
Global average



Heating bump depends on efficiency of ionizing photons (ζ_{UV})

ΛCDM Expectations

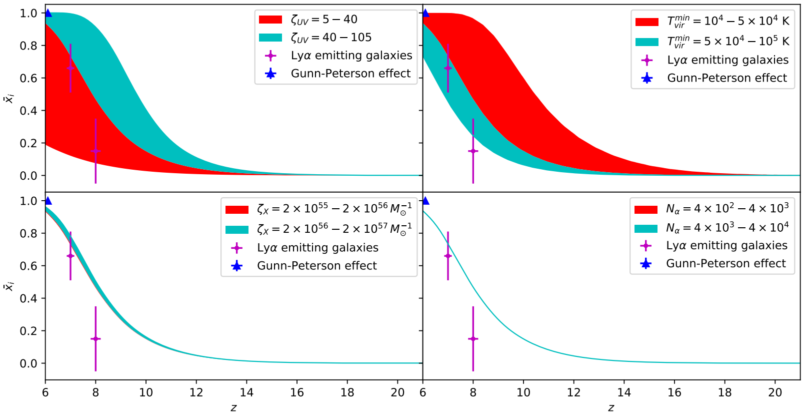
Simplified astrophysical model



SJW, Villanueva-Domingo, Gariazzo, Mena, Palomares-Ruiz (2018)

ΛCDM Expectations

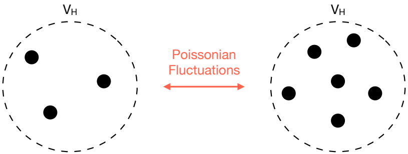
Simplified astrophysical model



SJW, Villanueva-Domingo, Gariazzo, Mena, Palomares-Ruiz (2018)

Shot Noise

For PBHs that form during radiation dominated epoch, one expects an average of N per Hubble volume

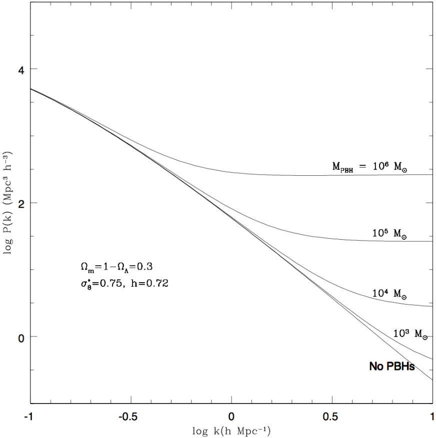


$\rightarrow$ Manifests as isocurvature modes that grow after M-R equality

Carr Hawking (1974), Mukhanov et al. (1992), Afshordi, McDonald, Spergel (2003)

Shot Noise

Matter Power Spectrum

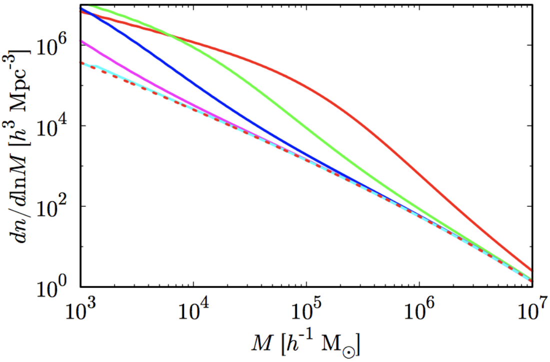


Afshordi, McDonald, Spergel (2003)

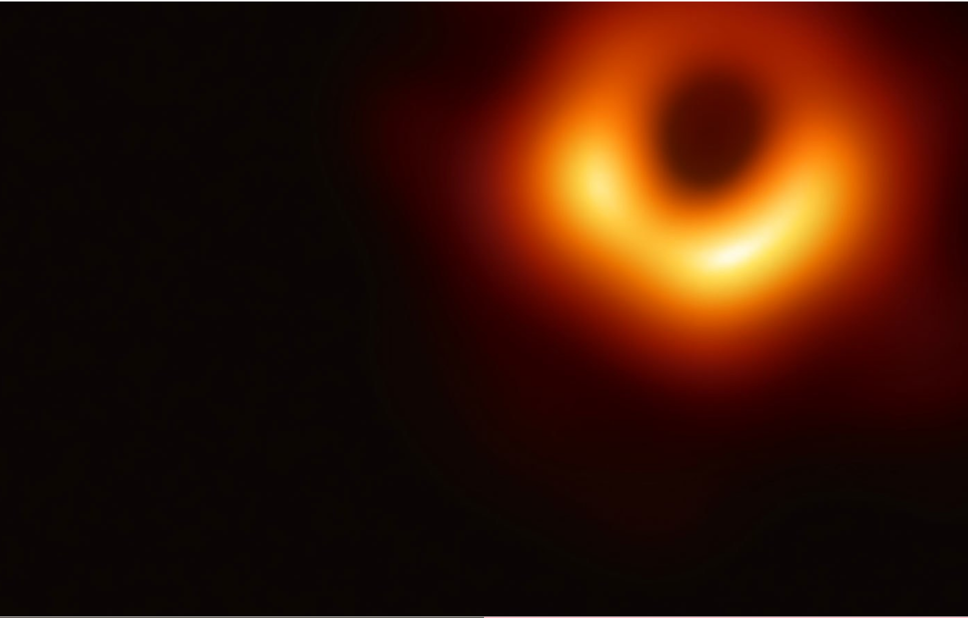
Shot Noise

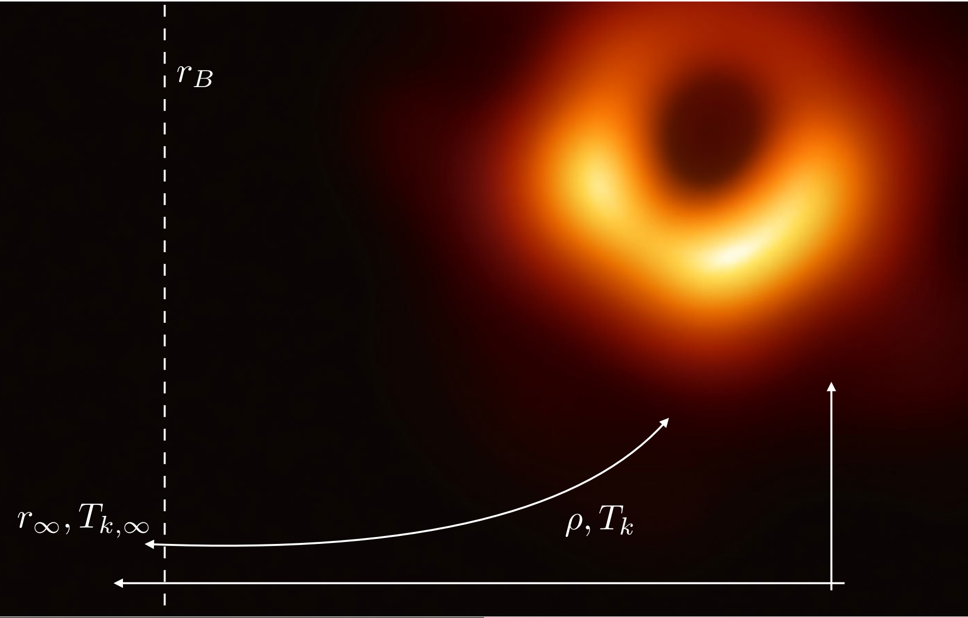
Halo Mass Function

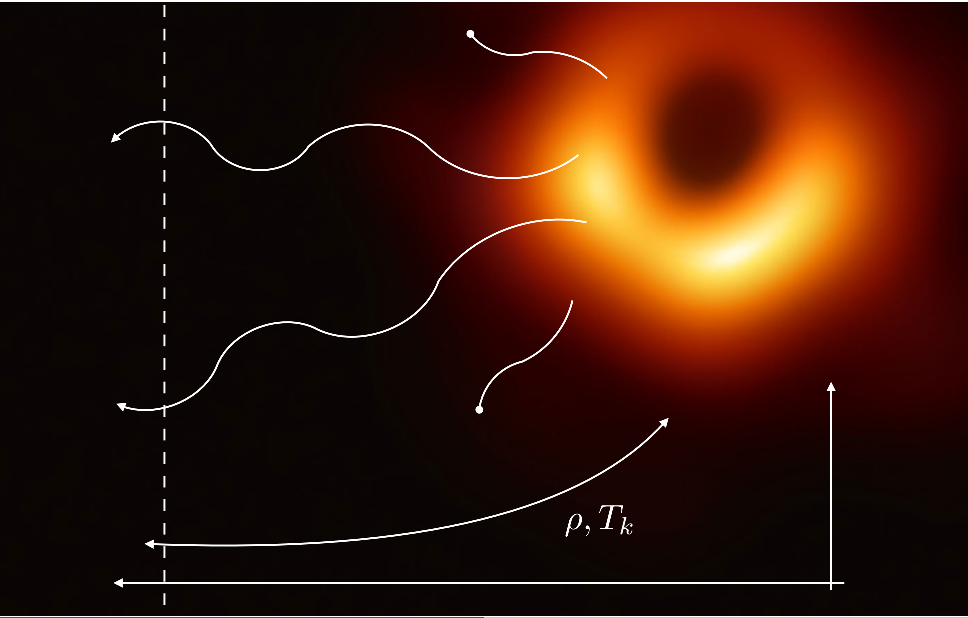
$M_{\rm pbh} = M_\odot$ and $f_{\rm pbh} = 10^{-1} \to 10^{-5}$



Gong, Kitajima (2017, 2018)




r_B
$r_\infty, T_{k,\infty}$
ρ, T_k


ρ, T_k

PBH Accretion

ADAF

Shapiro and Lightman (1976), Ipser and Price (1977), Ruffert (1999): Accretion disk should form when angular momentum at Bondi radius is sufficient to maintain Keplerian orbits at $r \gg r_S$

Poulin et al (2017): For PBHs this implies disk forms if

$$\sqrt{f_{\rm pbh}}\frac{M}{M_\odot} \gg \left(\frac{1+z}{730}\right)^3 \tag{18}$$

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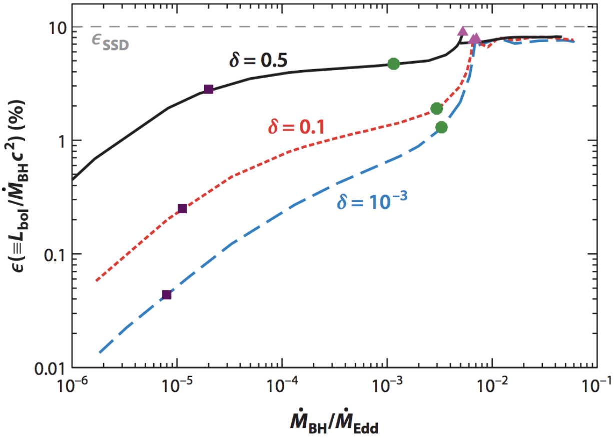
$\rightarrow$ Expect formation of optically thin puffy disk that radiates inefficiently (Advection Dominated Accretion Flow)

Expectations for ϵ and $\dot{M}$

PBH Accretion

ADAF



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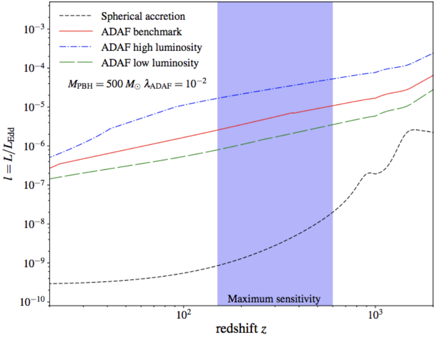
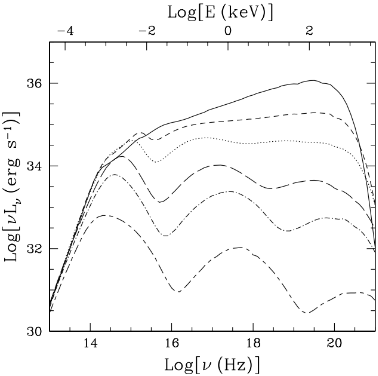


Poulin et al (2017)



Yuan and Narayan (2014)

Local Accretion

Must derive $[\rho(r), T(r), x_e(r)]$ from fluid equations
(specifically at $r \sim r_B$)

Using simplified set of accretion equations (e.g. adopting spherical symmetry, no X-ray absorption, etc), we can derive radial profiles
In $L/L_{\rm Edd} \to 0$ we get Bondi-like problem

Leading to $\rho \propto r^{-3/2}$ and $T \propto r^{-1}$ for $r/r_B \ll 1$

Local Accertion

Must resolve radiative transfer equation for local contribution
Iliev et al (2002)

$$T_{b,loc}(\nu) = T_{\rm cmb}\, e^{-\tau_{loc}(\nu)} + \int_{-\infty}^{\infty} dR\, T_s(R)\, e^{-(\tau_{\rm IGM}+\tau_{loc}(\nu,R))}\, \frac{d\tau_{loc}}{dR} \quad (18)$$

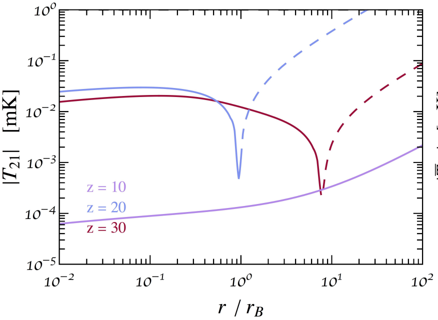
+ absorption of CMB locally
+ signal produced locally
+ absorption of signal produced locally

Total Signal:

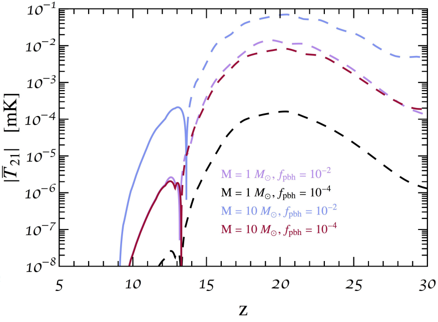
$$\bar{T}_b \propto n_{\rm pbh}\, \langle \Delta_{v_{\rm eff}} T_{b,\nu_0} \rangle \quad (19)$$

Local Accretion

Profile Single PBH



Total Signal All PBHs



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

Contrary to previous claims in literature, this contribution is negligible

Cosmological Implications

Summary

We said that PBHs can have ∼3 effects:

- Modify power spectrum → enhance number of halos
    - Current constraints do not allow enhanced number density of star forming halos
    - Signal from minihalos quite small
- Local heating from accretion
- Global heating from accretion

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- Local heating from accretion
- Global heating from accretion

Contrary to previous work, we show only global heating determines signal

Minihalos

Recall that dn/dM enhanced by shot noise
$\rightarrow$ question remains whether minihalos can contribute significantly

Gong and Kitajima (2017, 2018)

$$T_{b,mh}(\nu) = T_{\rm cmb}\, e^{-\tau_{mh}(\nu)} + \int_{-\infty}^{\infty} dR\; T_s(R)\; e^{-(\tau_{\rm IGM}+\tau_{mh}(\nu,R))}\, \frac{d\tau_{mh}}{dR} \tag{20}$$

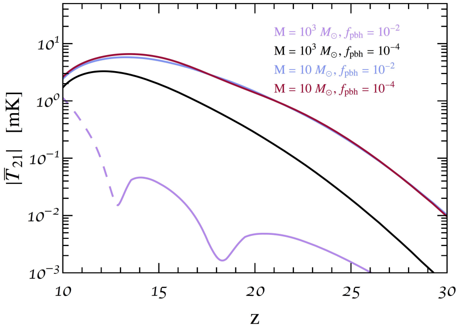
Model ρ_b and T_k → $T_s(R)$

$$\bar{T}_b \propto \int_{M_{\rm min}}^{M_{\rm max}} dM\, \frac{dn}{dM}\, \langle \Delta_{v_{\rm eff}} T_{b,\nu_0} \rangle \tag{21}$$

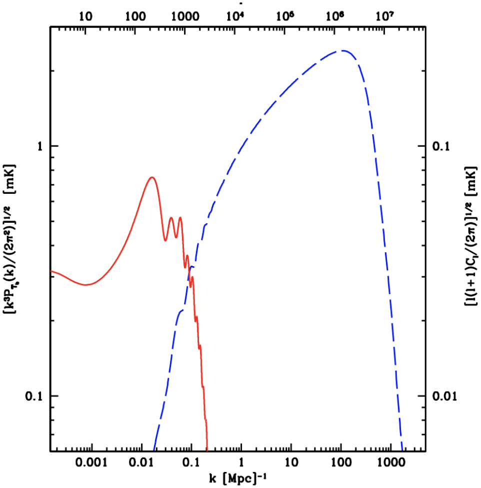
$M_{\rm max}$ set to star formation threshold, $M_{\rm min} = M_J$

Minihalos

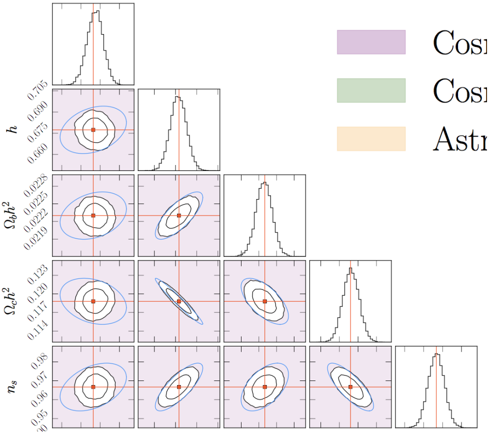
Observability



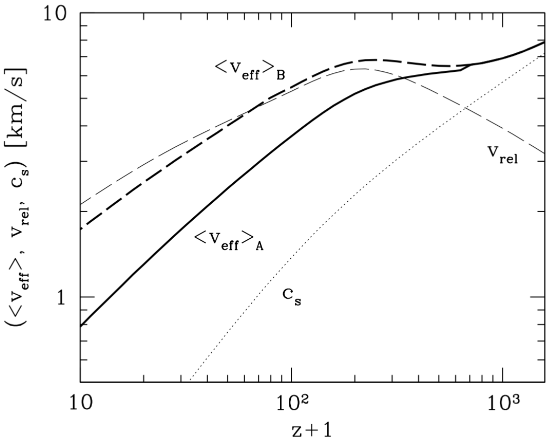
Mena, Palomares-Ruiz, Villanueva-Domingo, SJW Maximum minihalo contribution ~ 8mK (very small modifications)



Kleban et al (2007)



Kern et al (2017)



Ricotti et al (2007)

In limit that $L/L_{\rm Edd} \to 0$, local heating dictated by gravity

$$4\pi r^2 \rho |v| = \dot{M} = \text{constant} \tag{22}$$

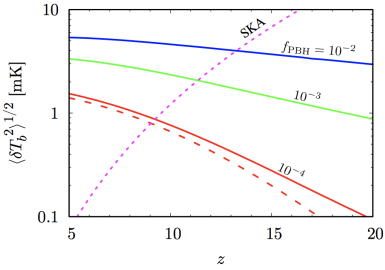
$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM}{r^2} \tag{23}$$

$$\Lambda_{\rm ion}(1 - x_e) = \alpha n_H x_e^2 \tag{24}$$

Leading to $\rho \propto r^{-3/2}$ and $T \propto r^{-1}$ for $r/r_B \ll 1$

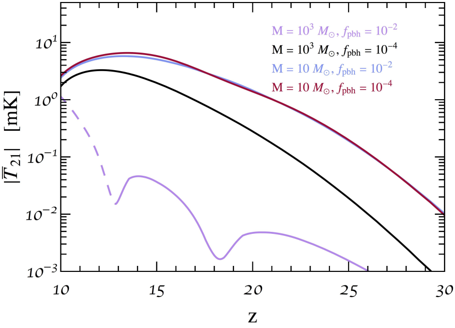
Minihalos

Observability



(d) $M_{\rm PBH} = 1000 M_\odot$

Gong and Kitajima (2017)



Mena, Palomares-Ruiz, Villanueva-Domingo, SJW

Discrepancy an issue of self-consistency $\rightarrow M_{\rm min} = M_{\rm Jeans} \propto T_k^{3/2}$