An indirect constraint on Primordial Black Holes from PLANCK

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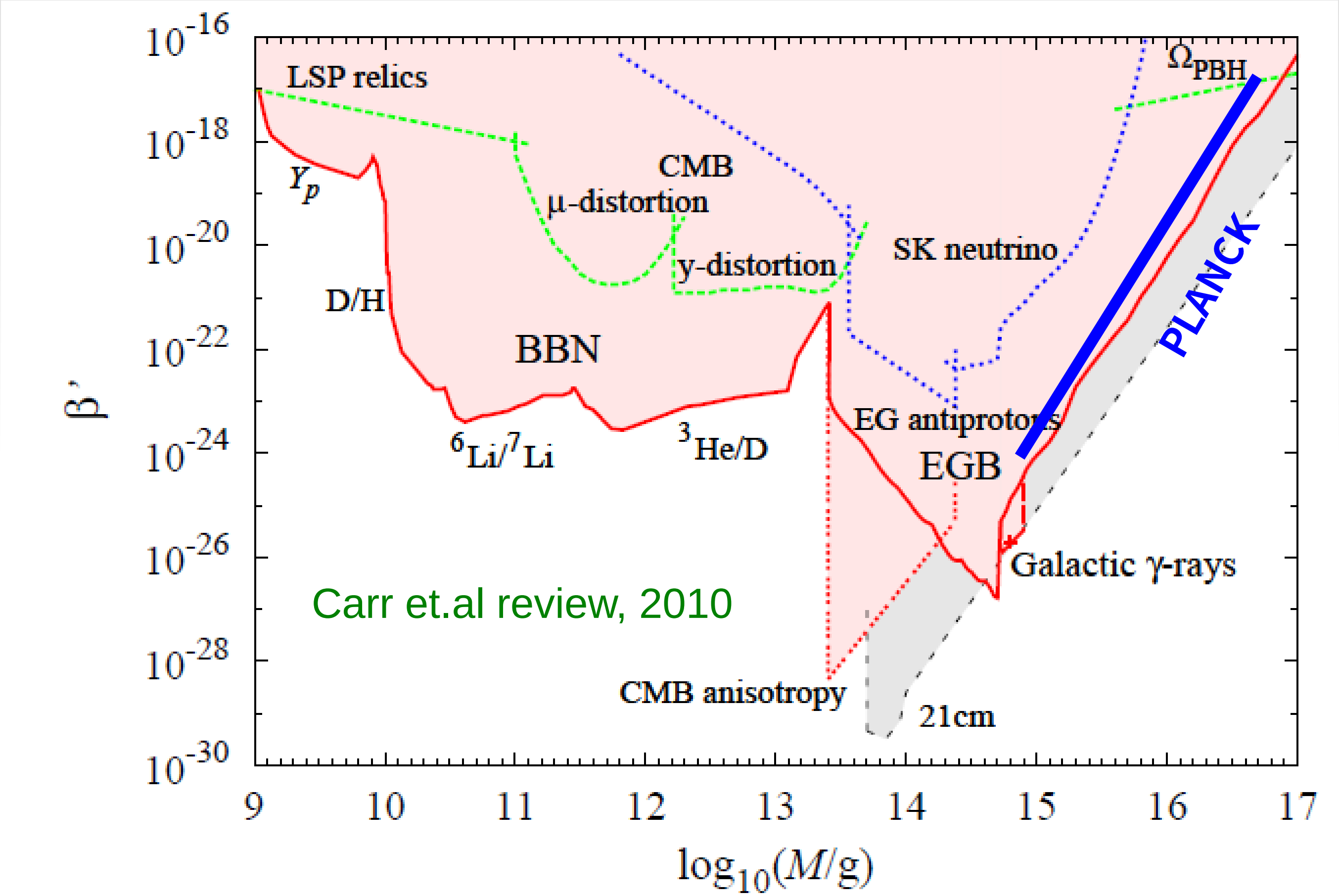
Take home pic



Motivations for PBHs

- Inhomogeneity in the high density at early universe may lead to BHs (not necessarily)
- Interesting for the power spectrum from inflation models
- Probing the equation of state: if reduction in pressure occurred (matter domination, e.g. `non-thermal' scenarios in a prolonged decay of moduli)
- Can be (a fraction of) the dark matter
- LIGO candidate?

The usual thermal PBH

- Radiation domination after end of inflation, PBHs mostly formed by fluctuations around `standard' horizon scale

$$M = \gamma M_{\rm PH} = \frac{4\pi}{3} \gamma \rho H^{-3} \approx 2.03 \times 10^5 \gamma \left(\frac{t}{1\,{\rm s}}\right) M_\odot$$

- A relatively narrow range of mass, determined by the time PBHs are formed

Original work by Carr and Hawking (many refinements since that time).

Mass Fraction in PBHs (Thermal History)

Equation of State ($w > 0$)

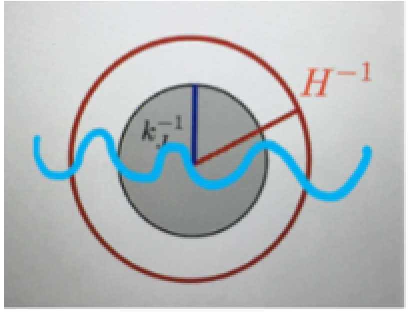
$$\beta_0(M) \simeq \delta_M(t_H)\exp\left(-\frac{w^2}{2\delta_M^2(t_H)}\right) \qquad \delta_M \equiv \frac{\delta M}{M}$$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(c_s^2 k_p^2 - \frac{3}{2}H^2\right)\delta_k = 0$$

Hubble "friction" slows the instability

Pressure prevents collapse

Gravity drives collapse



$$H \sim M_H \to M_{PBH}$$

Matter Domination

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~~Pressure prevents collapse~~

Gravity drives collapse

Sub-horizon Modes grow

$$\delta_k(t) = \delta_k(t_H)a(t)$$

Scott Watson's slides

Nonthermal scenarios

- Lowered pressure allows a wider range of BH mass
- A more complicated evolution of BHs
- An example from matter domination of moduli & late decay:

PBH formation starts from H~M_S

minimal BH mass ~ 10^9 g for M_S~ O(10 TeV)

& ends at the decay of moduli, modes can grow till reheat

maximal BH mass ~ O(10 M_{sun}) for Tr before BBN

$$m_\sigma = 50 \text{ TeV} \qquad T_r \simeq 5 \text{ MeV}$$

$$10^9 \text{ g} \lesssim M_{PBH} \lesssim 10\, M_\odot$$

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BH mass function dN/dM

M_{min} ⟷ M_{max}

dep. on power spectrum & growth

Hawking radiation, `lifetime' and BH mass

- BH evaporates at a temperature

Hawking 75'

$$T_{PBH} = \frac{1}{8\pi GM} = 1.06\text{TeV} \times \frac{10^{10}\text{g}}{M_{PBH}}$$

- with a peak energy of radiation

$$E_\gamma = 5.71 T_{PBH}, \; E_\nu = 4.22 T_{PBH}, \; E_{e^\pm} = 4.18 T_{PBH}$$

Mass loss rate:

$$\dot{M}_{10} = -5.34 \times 10^{-5} \left(\sum_i f_i \right) M_{10}^{-2} \text{ s}^{-1}$$

lifetime:

$$\tau(M) \sim \frac{G^2 M^3}{\hbar c^4} \sim 10^{64} \left(\frac{M}{M_\odot} \right)^3 \text{yr}$$

- BH evaporation can be a good source of cosmic rays, injection particle species determined by BH mass

Early-time constraints

- Density saturation
- Radiation/baryon ratio [$M<10^9$g] Zel'dovich, et.al. 77'
- BBN constraints [$10^9<M<10^{13}$g] Vainer, Nasel'skii 78', Zel'dovich, et.al. 77'
- CMB distortions:

  BH evaporation [$10^{11}<M<10^{13}$g] Zel'dovich, et.al. 77'

  X rays from accretion [$0.1M_{sun}<M$] Ricotti et.al. 07', Carr 81'

Late-time constraints

- Galactic lensing & dynamics

  Microlensing (MACHOs) Paczy´nski, 86'

  Binary disruption Bahcall et.al 85', Weinberg et.al. 87'

- Cosmic rays

  galactic gamma ray Wright, 96', anitiprotons Carr 76'

  extragalactic gamma ray Carr et.al. 09' neutrinos Bugaev, Konishchev 00'

  etc.

- Ionization (after recombination)

  reionization $z<6$ Fan, et.al. 06'

  proposed 21cm measurements Mack, Wesley 08'

  CMB damping (WMAP) Zhang, et.al. 07'

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with PLANCK data

A steady radiation injection below ~100 MeV

- Relevant for PBH mass above 10^{15} g, or peak radiation energy below muon mass
- Hawking evaporation after recombination yields (mostly) e+e- and gamma rays
- For M>>10^{15}g, mass loss negligble during the age of the Universe
- A steady injection of radiation that scales as $(1+z)^3$.

Extra-galactic source

Of Hawking evaporation rate

$$\dot{M}_{10} = -5.34 \times 10^{-5} \left(\sum_i f_i \right) M_{10}^{-2} \ \mathrm{s}^{-1}$$

into light (massless) species,

$$f_0 = 0.267, \quad f_1^{\gamma} = 0.06, \quad f_{3/2} = 0.02,$$
$$f_2^{g} = 0.007, \quad f_{1/2}^{\nu} = 0.147, \quad f_{1/2}^{e^{\pm}} = 0.142$$

J.MacGibbon, PRD, 1991

and photons & electrons affects the environment with unit volume injection rate, +redshift

$$\frac{dE}{dV\,dt} = \dot{M}_{PBH}\eta(E_i, z)n_{PBH}$$
$$= \frac{\dot{M}_{10}}{M_{10}}\rho_{cr}(z)\Omega_{PBH}(z)\eta_i(E, z)$$

$$\left.\frac{dE}{dV\,dt}\right|_{\mathrm{BH}} = \frac{\dot{M}_{10}}{M_{10}}\rho_{cr}(z)\Omega_{PBH}(z)\eta(E_{PBH}, z)$$

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$$= \frac{\dot{M}_{10}}{M_{10}} \rho_{cr}(z)\Omega_{PBH}(z)\eta_i(E, z)$$

$\Gamma^{-1} \sim \dot{M}/M$

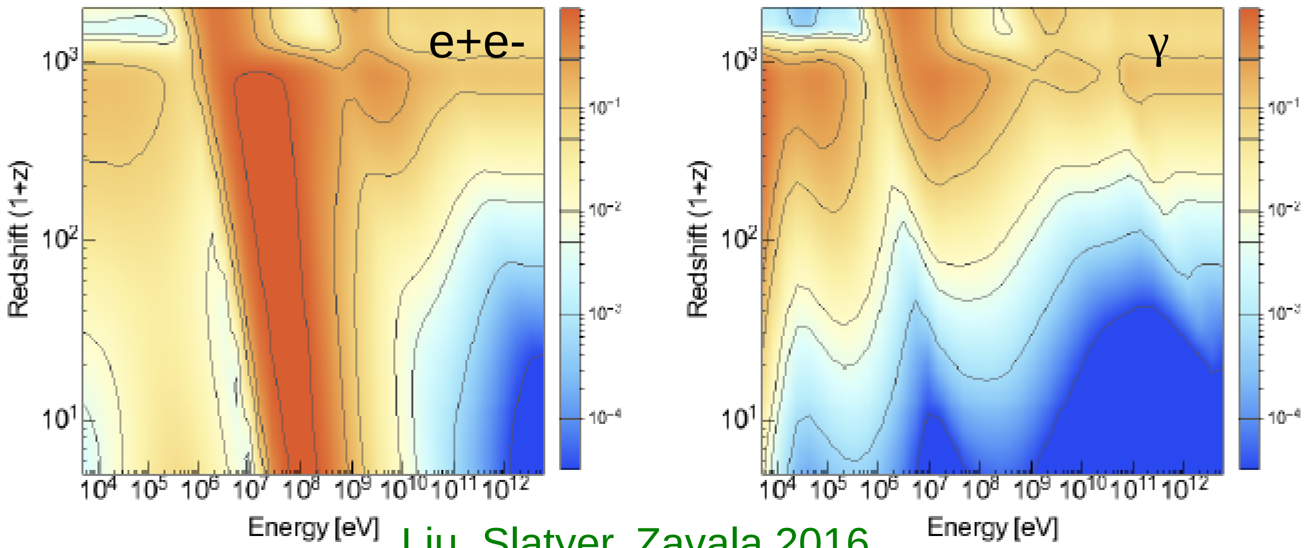
$$\left.\frac{dE}{dV\,dt}\right|_{\rm BH} = \frac{\dot{M}_{10}}{M_{10}} \rho_{cr}(z)\Omega_{PBH}(z)\eta(E_{PBH}, z)$$

Injection vs absorption

- photons interact via Compton scattering & absorptions
- electrons lose energy by inverse C. scattering & ionization

Not all energy is absorbed by the environment (gas)
esp. if particles are too energetic

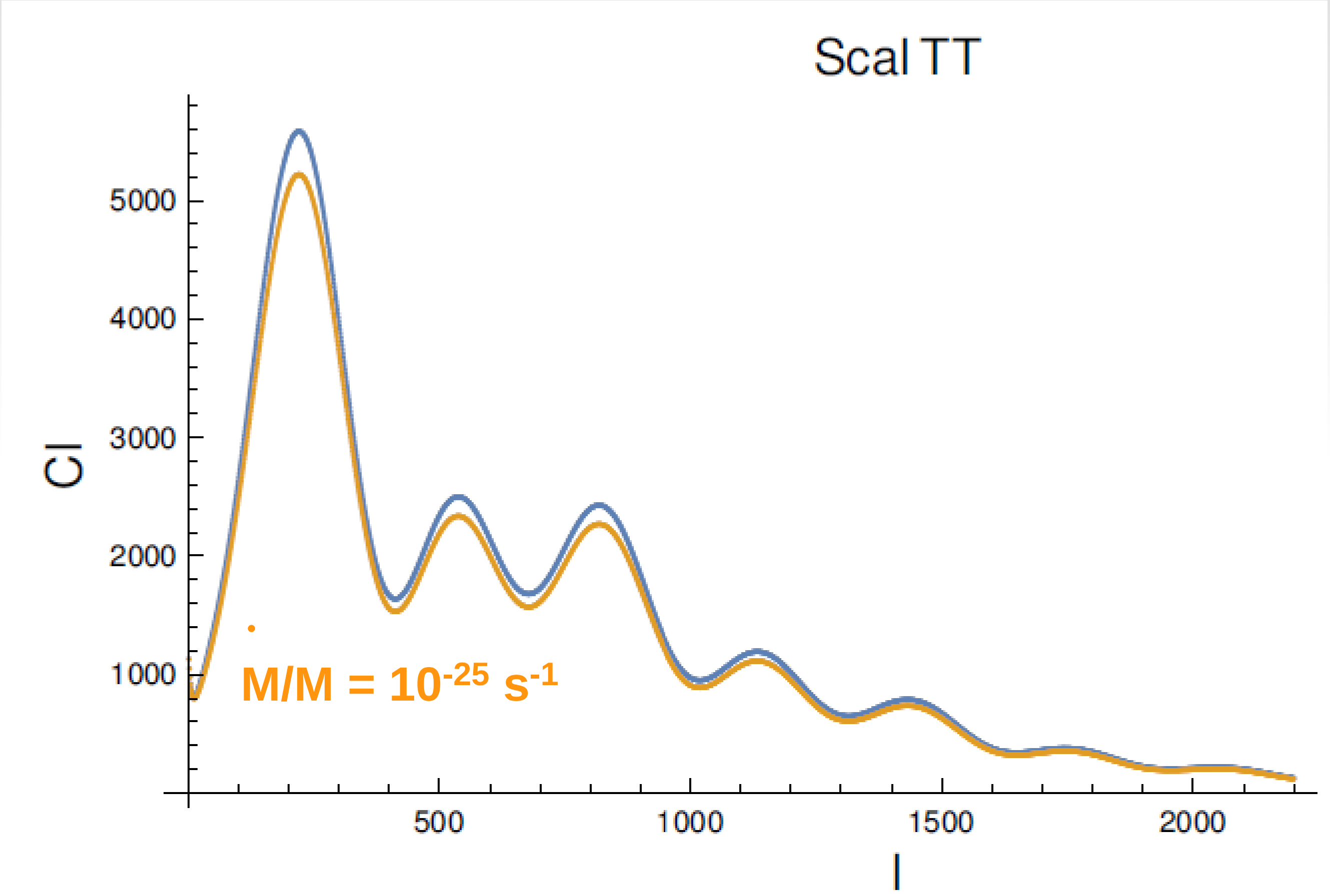
Energy “fraction” into ionization (of H)



Liu, Slatyer, Zavala 2016

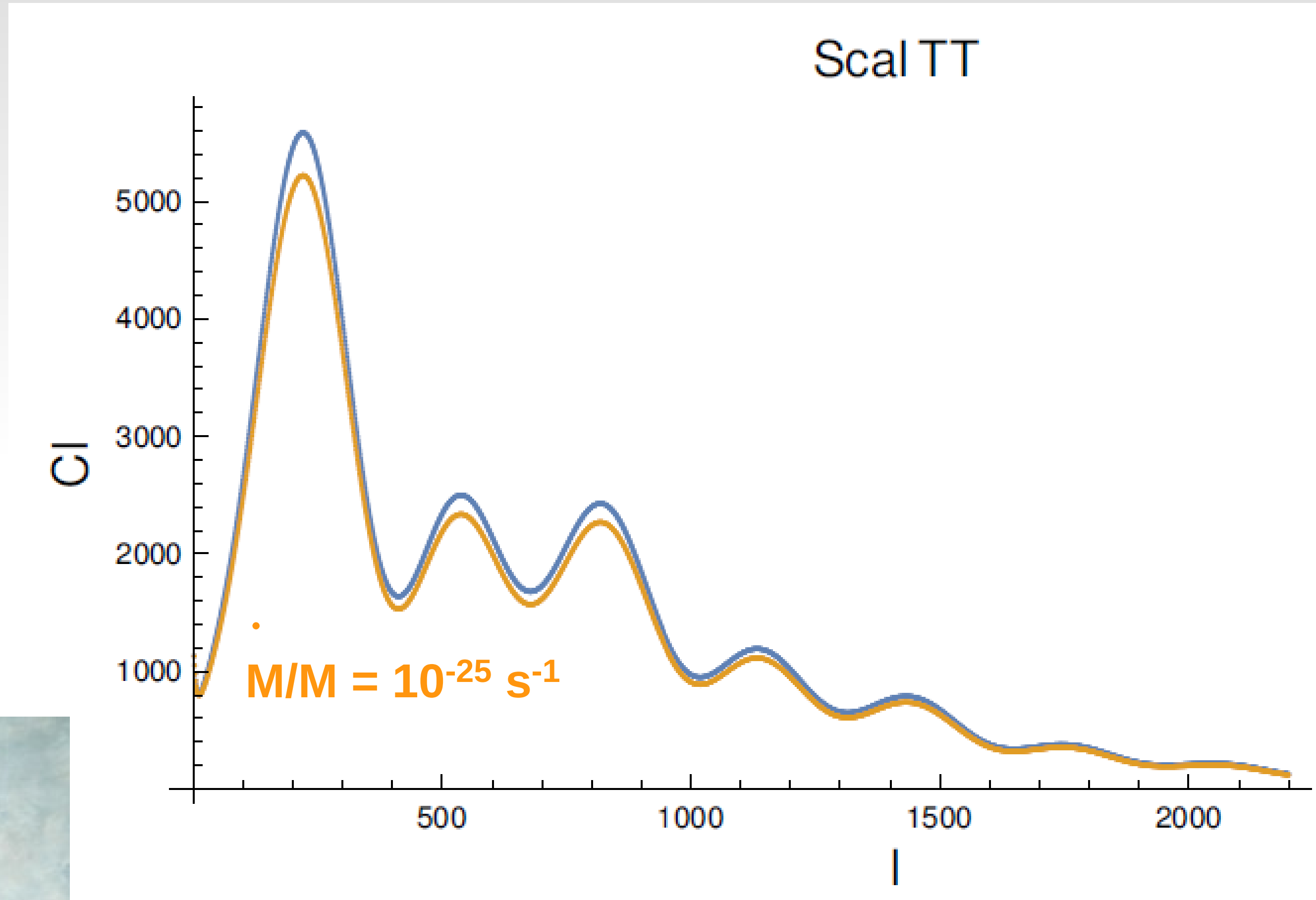
Also see:
Belotsky, Kirillov 2015

Impact on the CMB Cls



Reduced corelation over longer distances

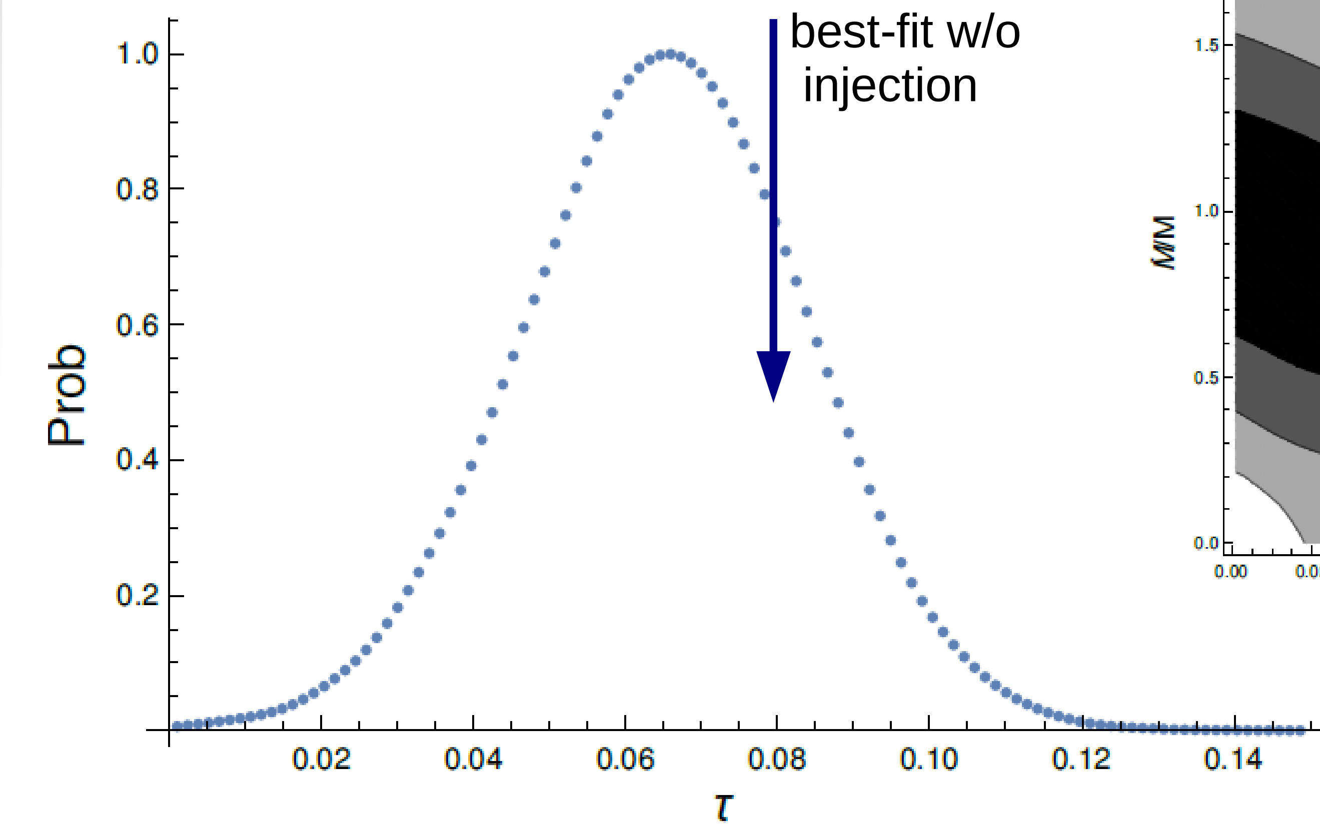
Impact on the CMB Cls

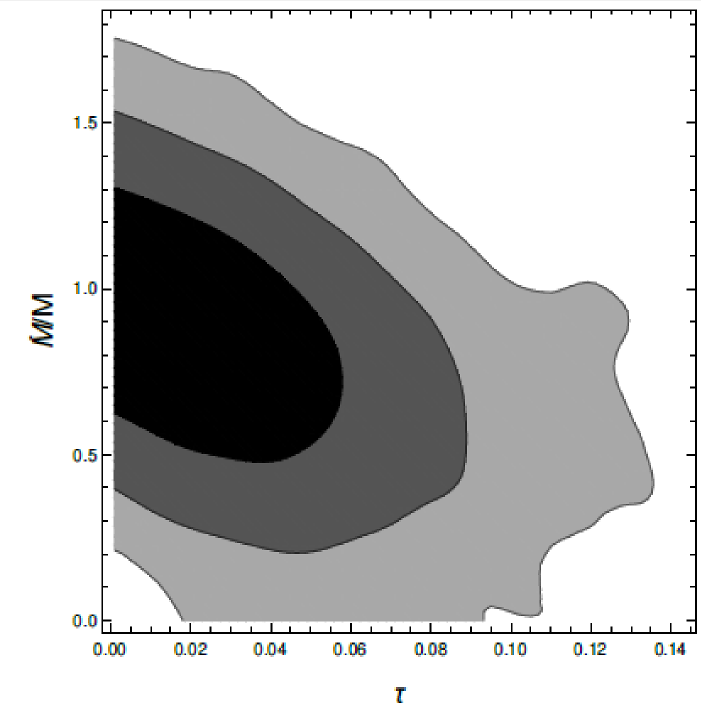


Reduced corelation over longer distances

Steven Clark, B.Dutta, Y.G., L. Strigari, in progress

Reduced optical depth





Consistent with PLANCK no injection fit within 2σ

PLANCK: temperation + polarization

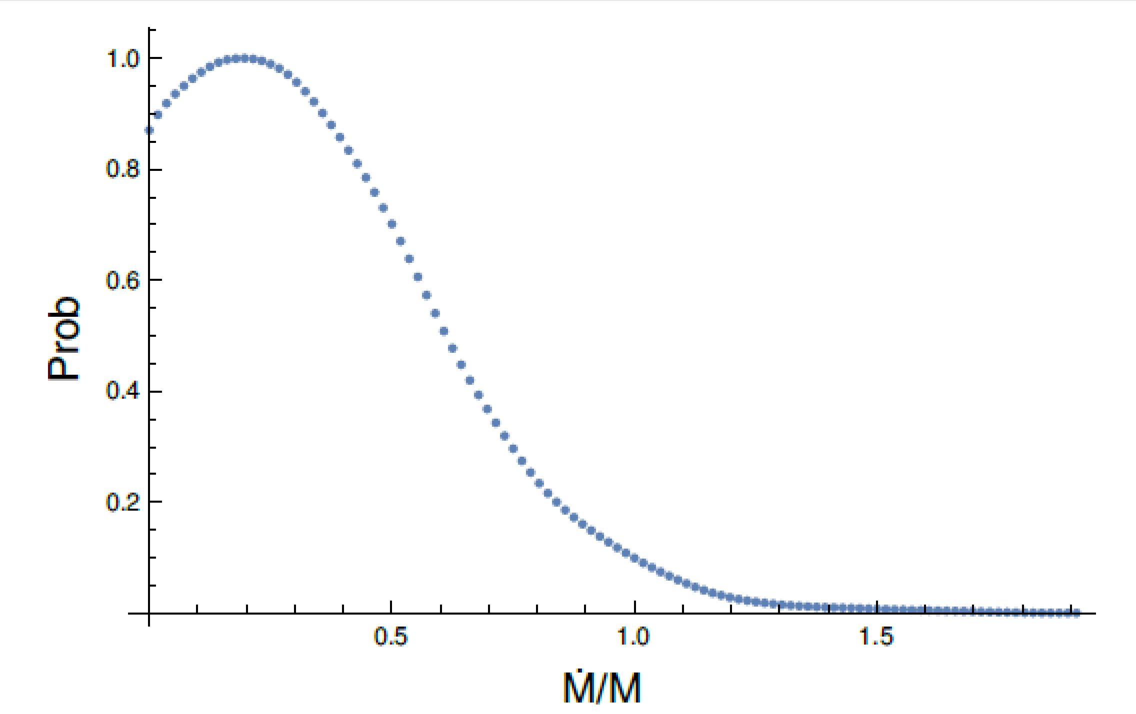
Consistent with reionization $z \leq 6$

DM Decay: $\tau > 10^{24}$ s

Liu, Slatyer, Zavala 2016

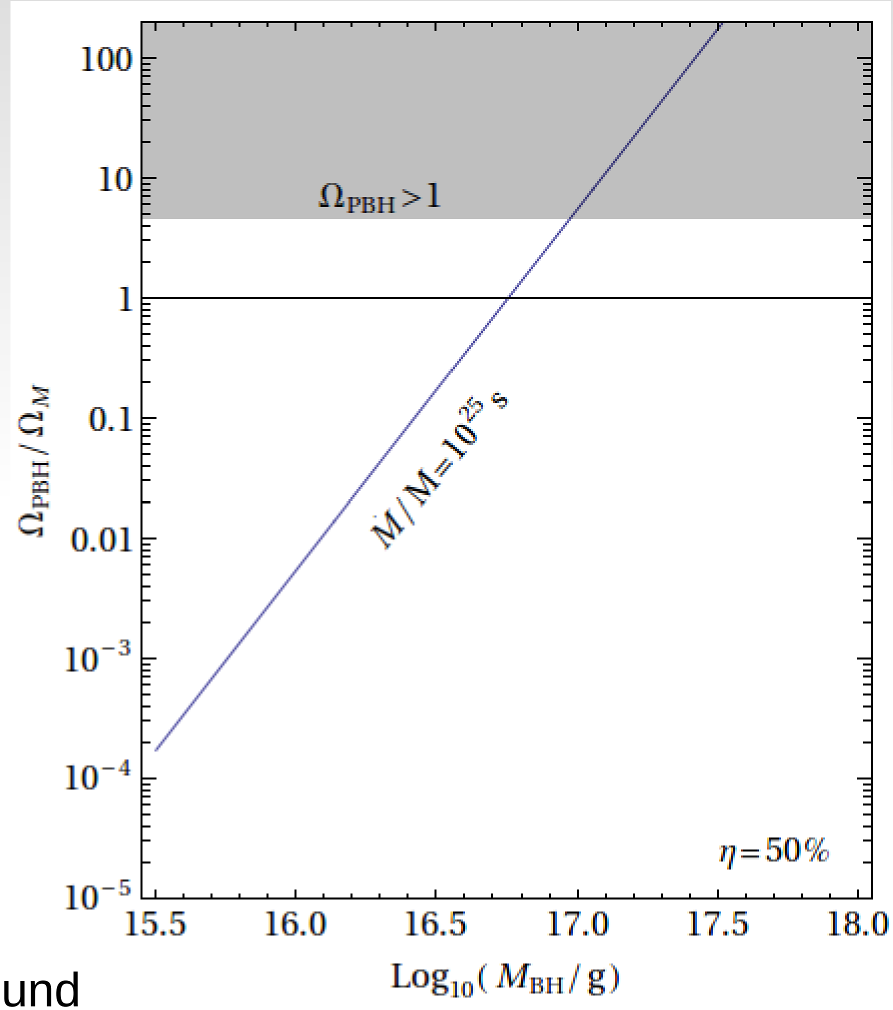
Need polarization data to break degeneracy

An upper bound on mass loss rate



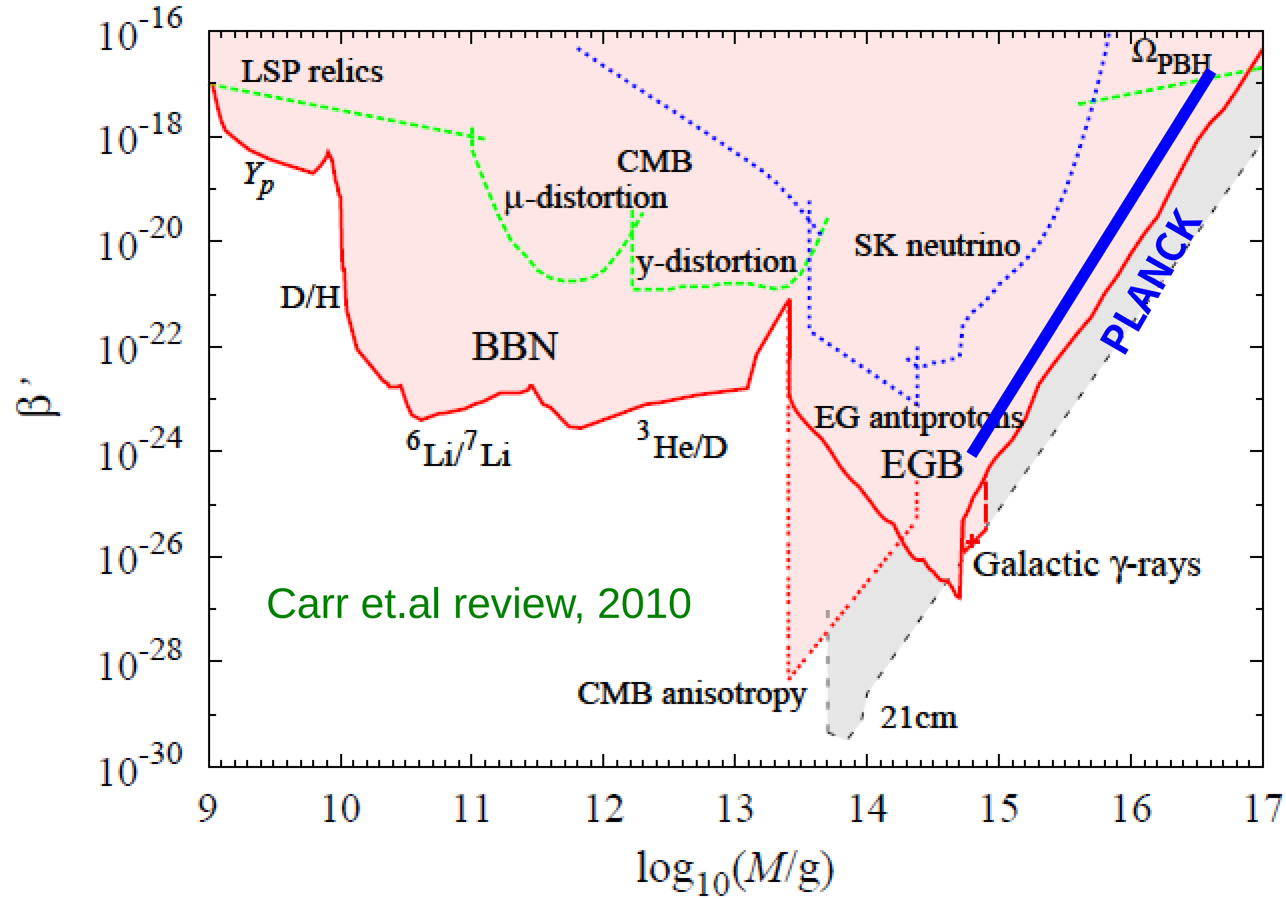
$\dot{M}/M < 10^{-25}\ s^{-1}$ (2σ)

Constraint on late-time PBH density



A simple upper bound
on (monochromatic) PBH density:

$\Omega_{PBH}(M) < \Omega_M * (M_{PBH} / 10^{16.8}\ \mathrm{g})^3$ [preliminary, may reduce]



Simple scaling, assume no entropy production after PBHs and $\Omega_r \sim 10^{-4}$ at CMB time, also β' ~ β:

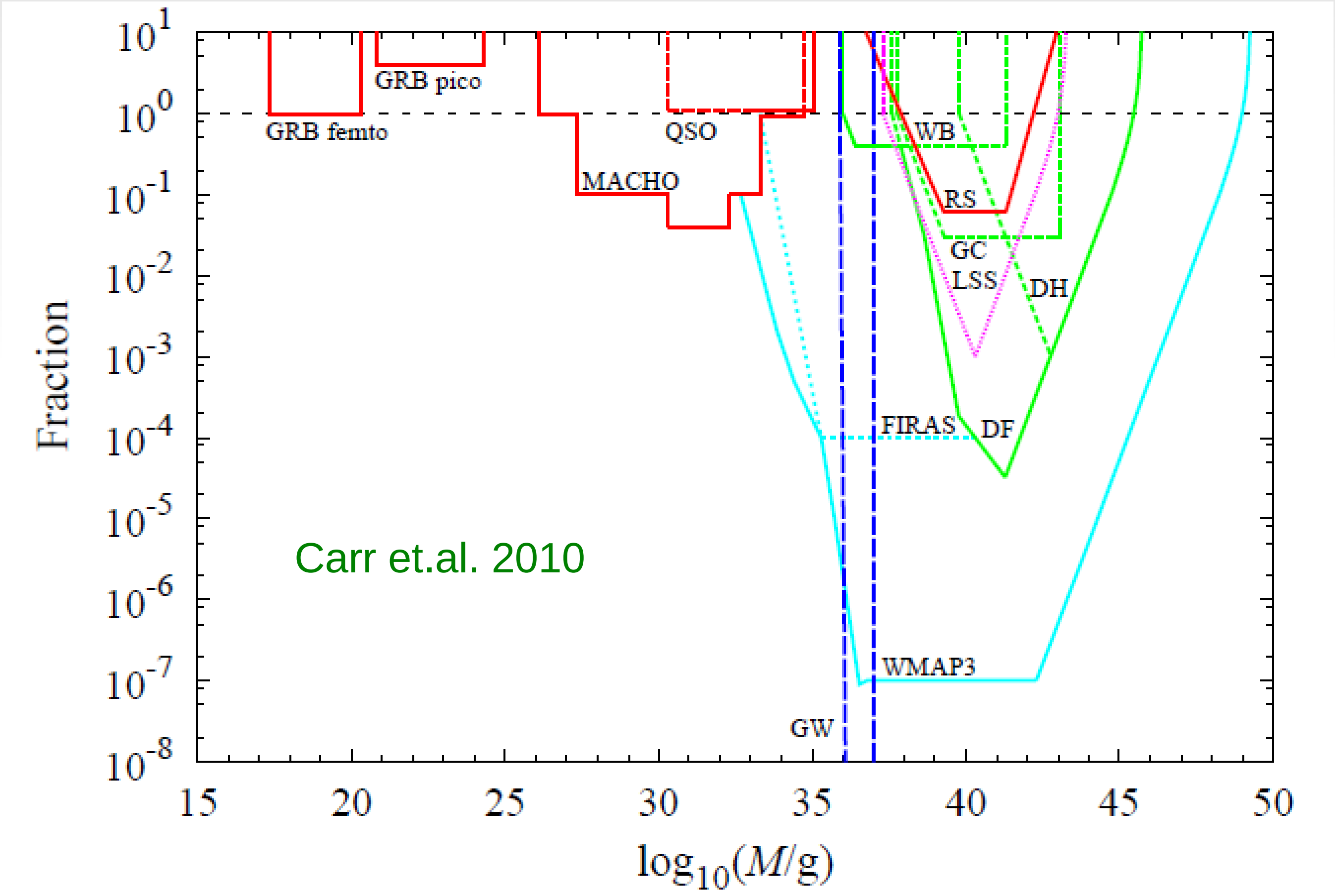
$$\Omega_{\rm PBH} \simeq \beta\,\Omega_{\rm r}\,(1+z) \sim 10^6\,\beta\left(\frac{t}{1\,{\rm s}}\right)^{-1/2} \sim 10^{18}\,\beta\left(\frac{M}{10^{15}\,{\rm g}}\right)^{-1/2} \quad (M > 10^{15}\,{\rm g})\,,$$

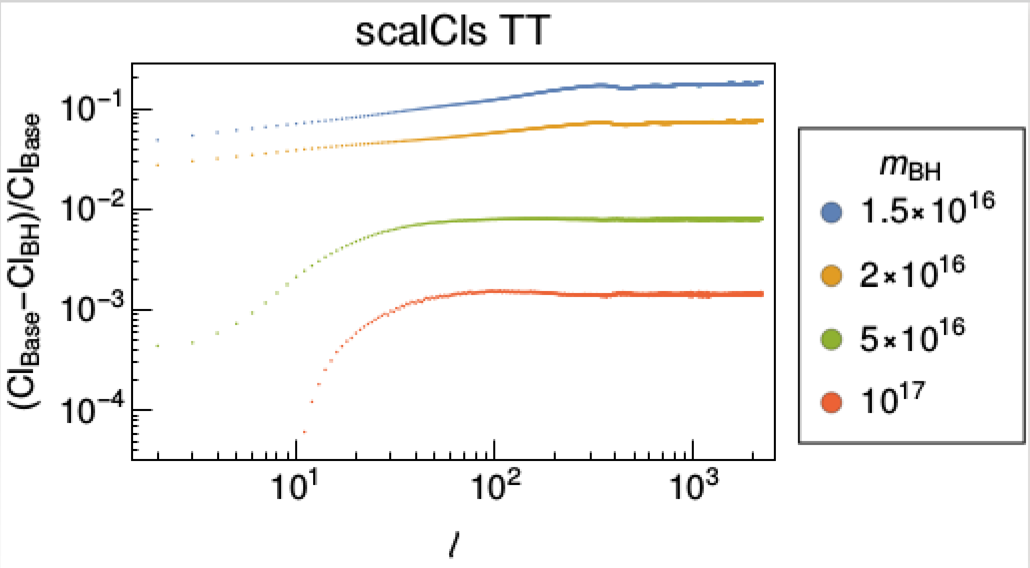
Summary

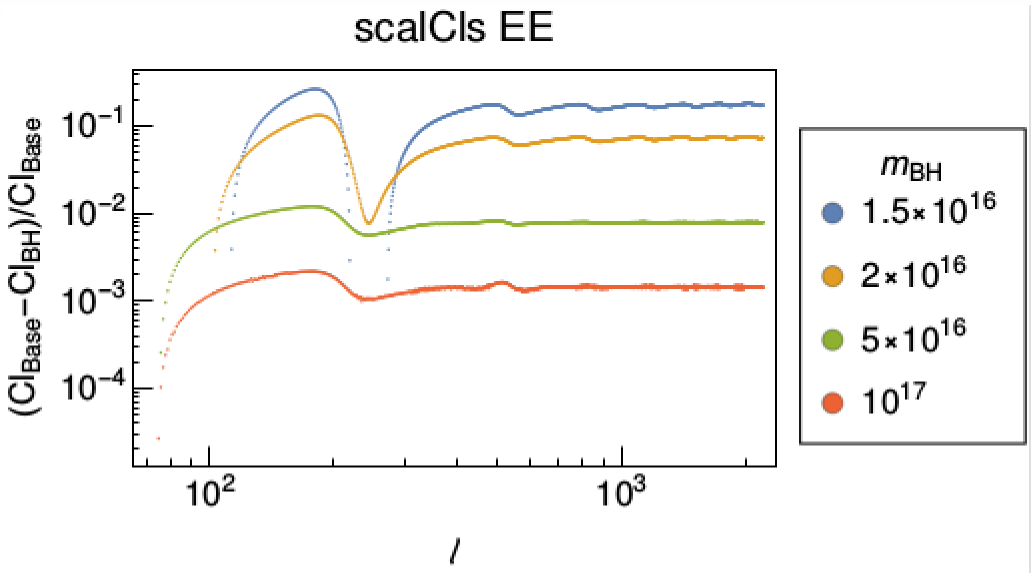
- A good late-time constraint on HR from PLANCK
- Comparable or better to extragalactic diffuse constraints
- For a limited mass range above $10^{\sim 17}$g (and below 10^{15}g)
- Relevant for PBH production mechanism(s) with a low mass distribution
- PBH production scenarios/histories to be explored!

backups

High BH mass constraints (Carr's review)




scalCls TT
$(Cl_{Base}-Cl_{BH})/Cl_{Base}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{1}
10^{2}
10^{3}
l
m_{BH}
1.5×10^{16}
2×10^{16}
5×10^{16}
10^{17}


scalCls EE
$(Cl_{Base}-Cl_{BH})/Cl_{Base}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{2}
10^{3}
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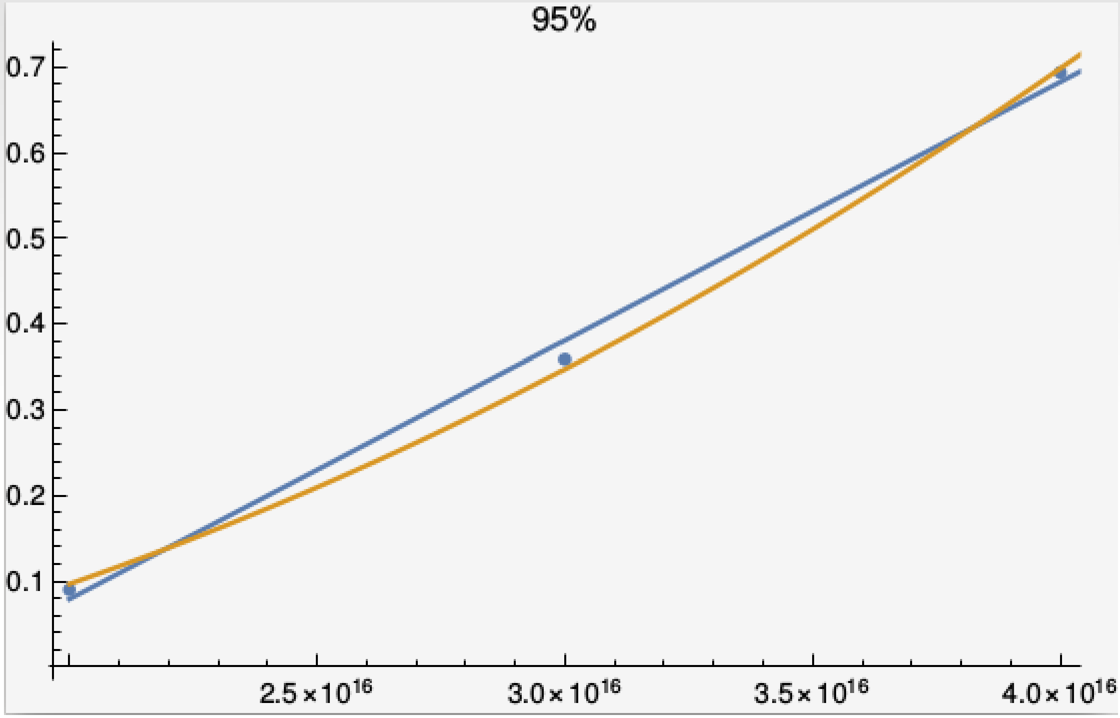
m_{BH}
1.5×10^{16}
2×10^{16}
5×10^{16}
10^{17}


95%
0.7
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