# *An indirect constraint on Primordial Black Holes from PLANCK*

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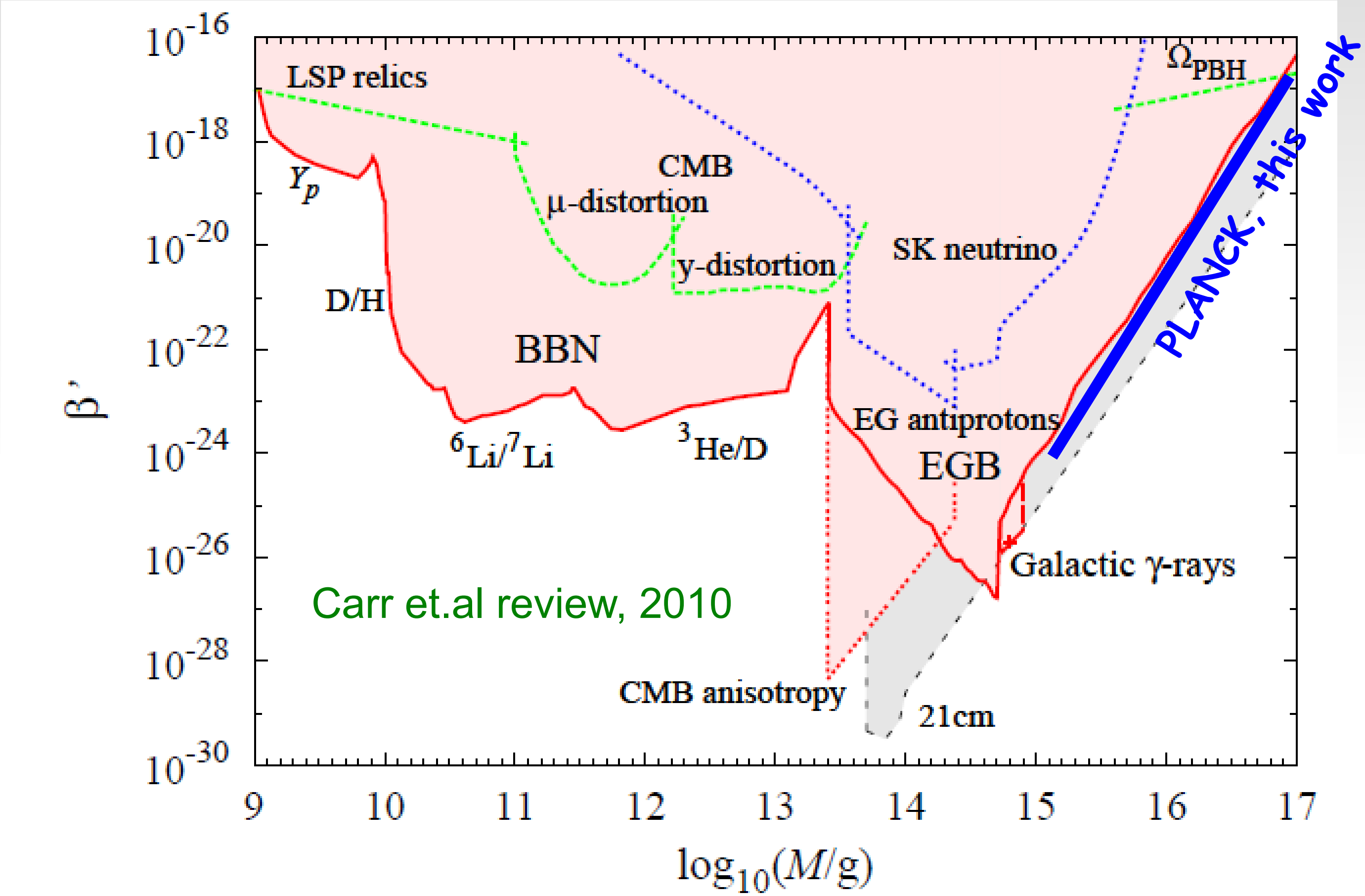
# Conclusions



# *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, see Scott's and Rouzbeh's talks)
- Can be (a fraction of ) the dark matter
- LIGO candidate?

# *The usual thermal PBH*

- Radition 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

# *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 $H \sim M_S$

minimal BH mass $\sim 10^9$ g for $M_S \sim O(10\ \text{TeV})$

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

see Scott's talk

maximal BH mass $\sim O(10\ M_{sun})$ for Tr before BBN

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$M_{min}$ ⟷ $M_{max}$

BH mass function dN/dM

dep. on power spectrum & growth

# *Hawking radiation, `lifetime' and BH mass*

- BH evaporates at a temperature

Hawking 75'

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

- 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:

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

lifetime:

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

- 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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  CMB damping

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

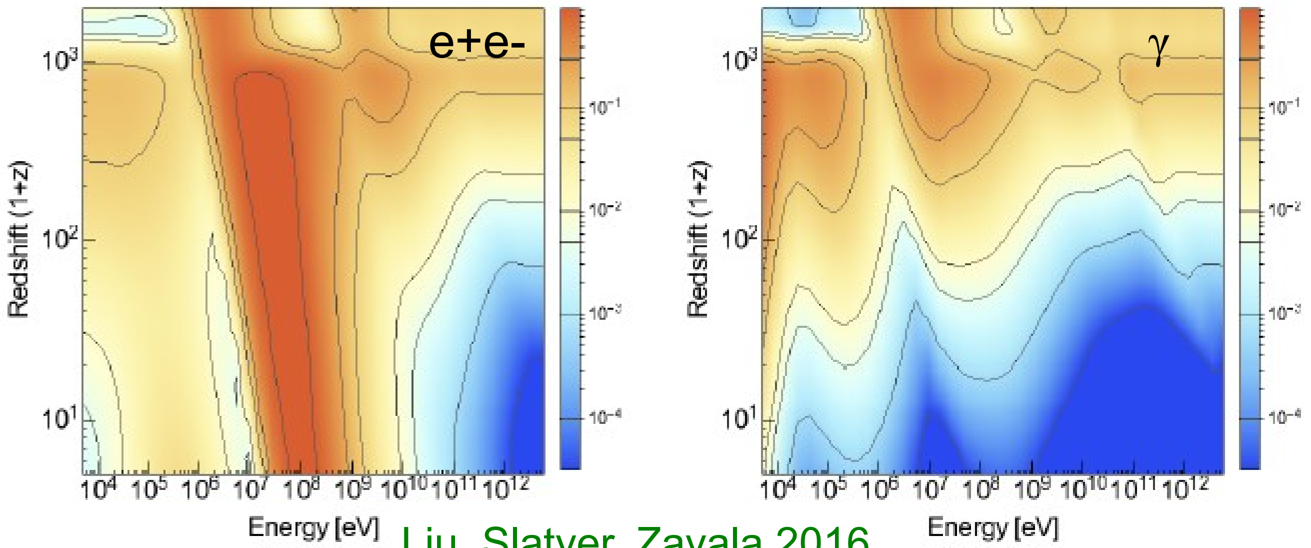
$$\left.\frac{dE}{dV\,dt}\right|_{\mathrm{BH}} = \frac{\dot{M}_{10}}{M_{10}}\rho_{cr}(z)\Omega_{PBH}(z)\eta(E_{PBH}, z)$$

# *Injection vs absorption*

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

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

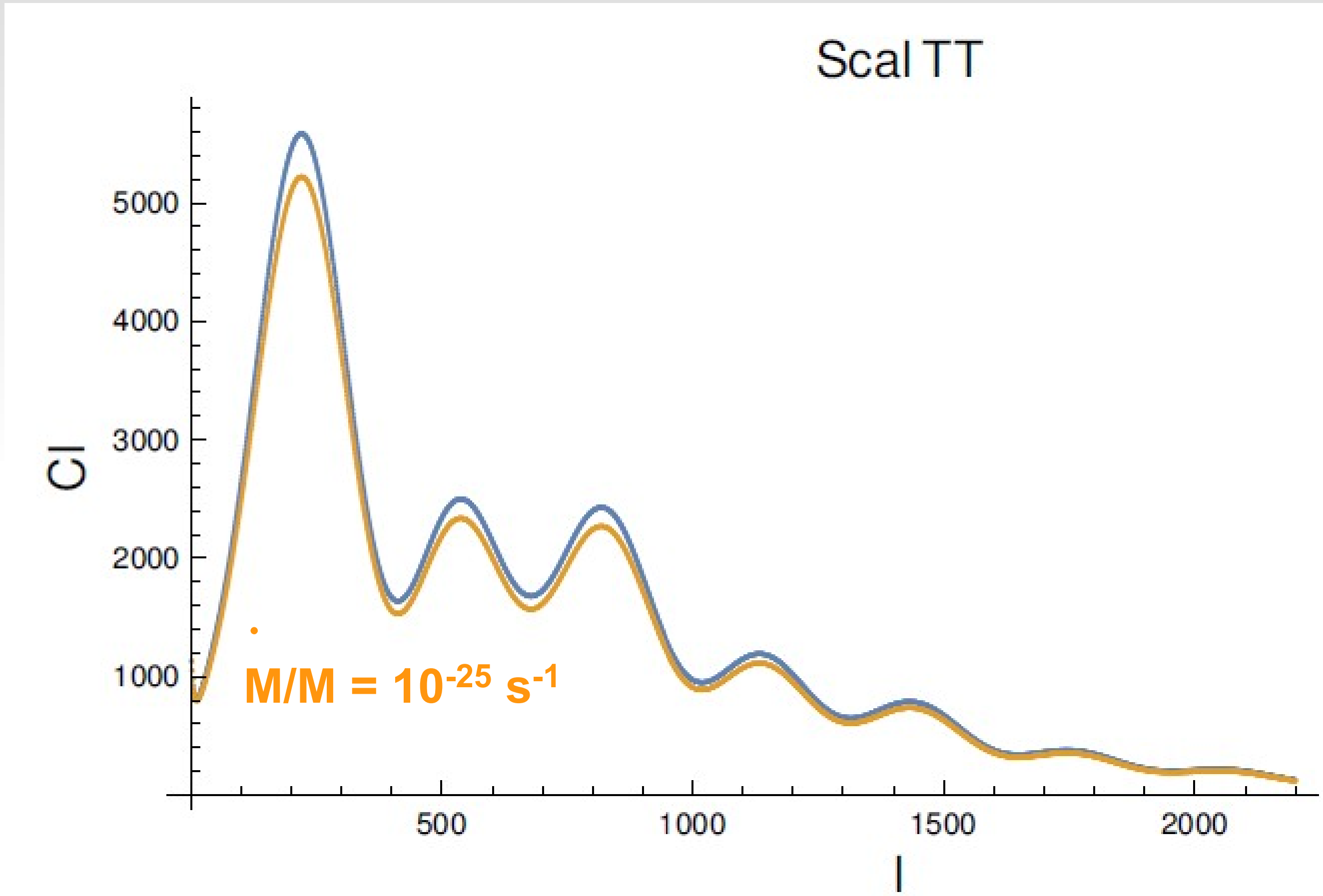
Energy "fraction" into ionization (of H)




Liu, Slatyer, Zavala 2016

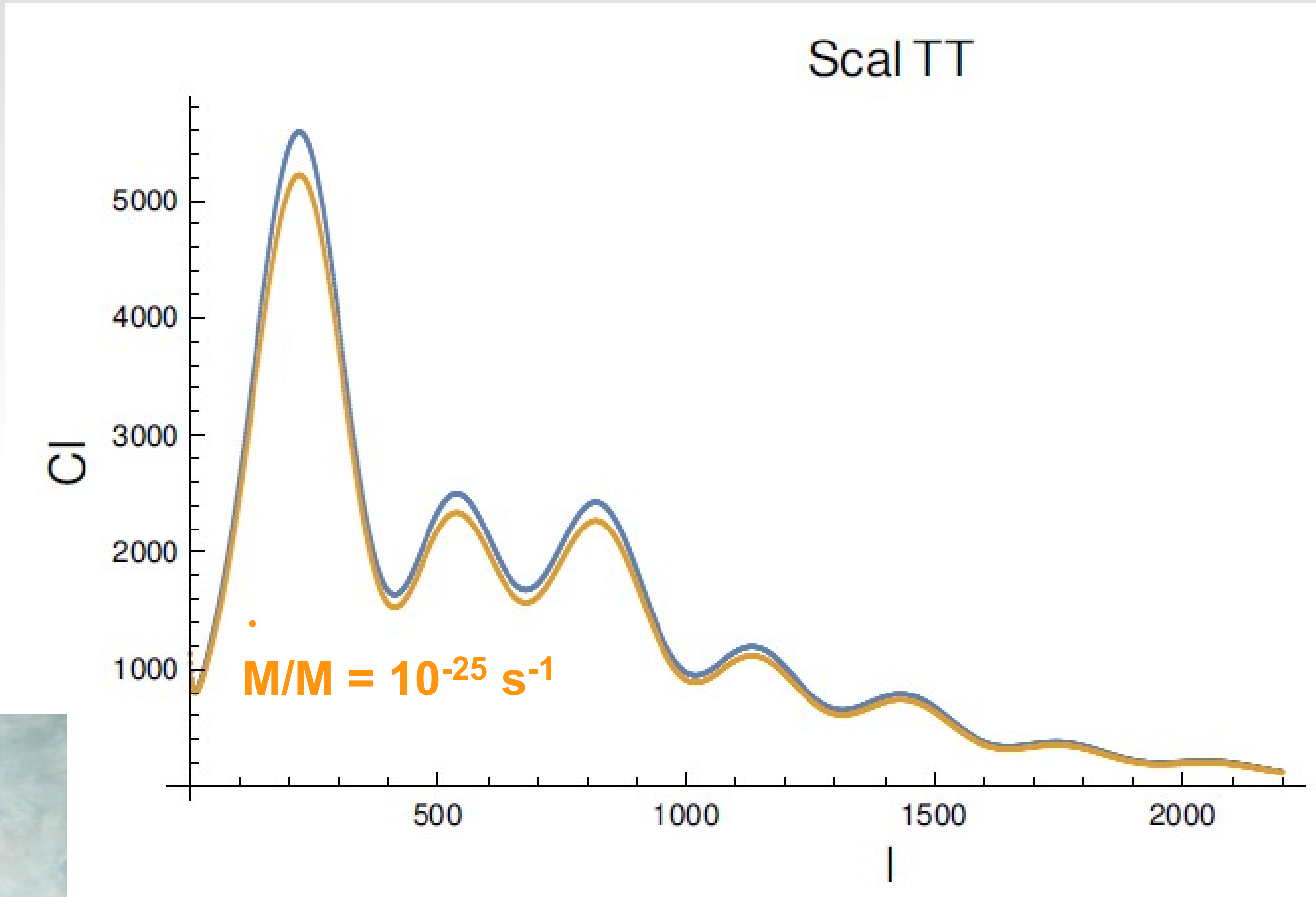
Also see:
Belotsky, Kirillov 2015

# *Impact on the CMB Cls*




Reduced corelation over longer distances

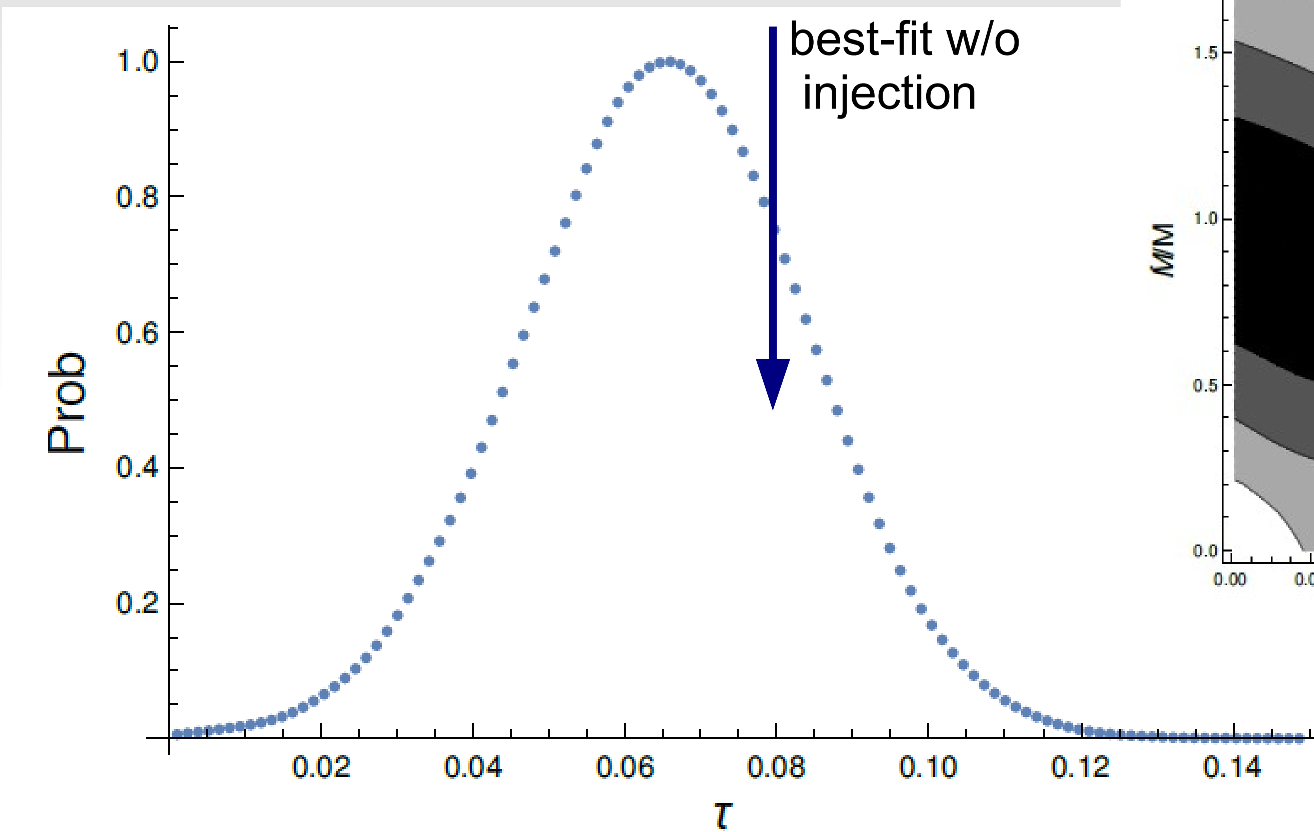
# *Impact on the CMB Cls*

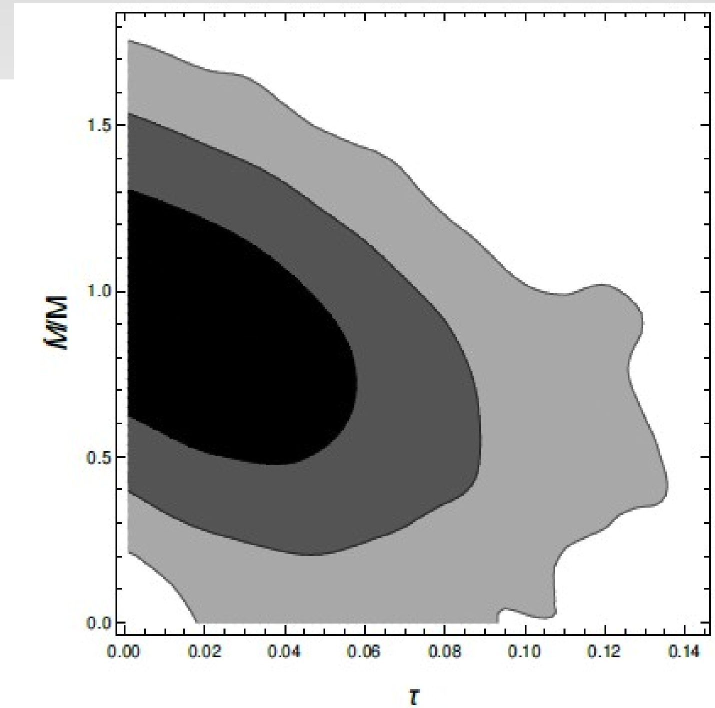



Reduced corelation over longer distances

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

# *Reduced optical depth*




Consistent with PLANCK no injection fit within 2σ

Consistent with reionization z ≤ 6

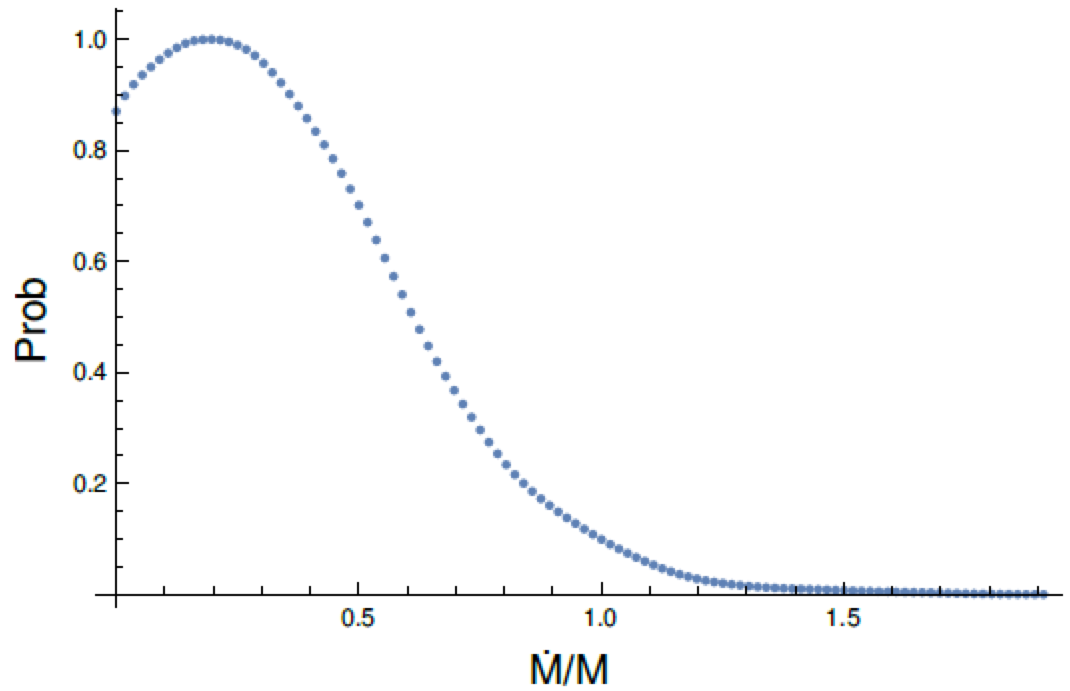
DM Decay: $\tau > 10^{24}$ s

Liu, Slatyer, Zavala 2016

PLANCK: temperation + polarization

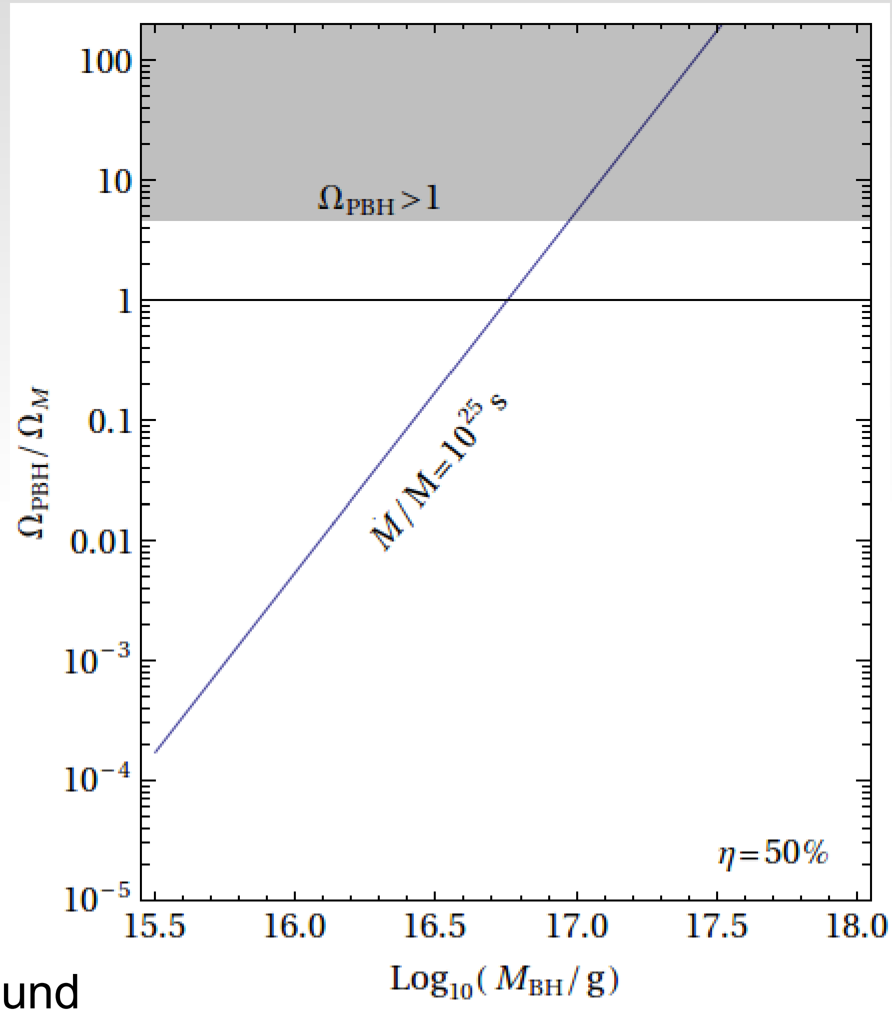
Need polarization data to break degeneracy

# *An upper bound on mass loss rate*



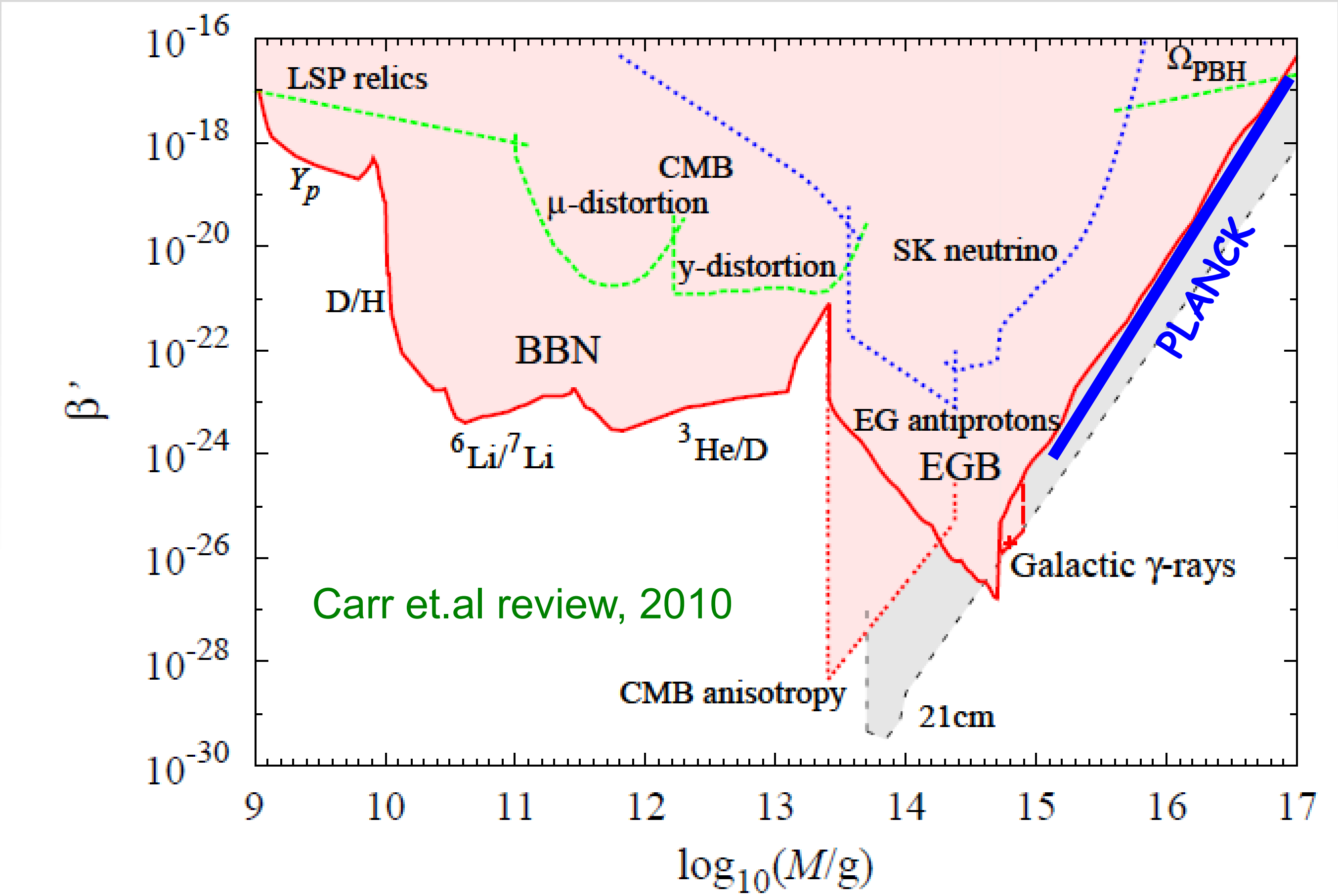

$\dot{M}/M < 10^{-25}\ s^{-1}$ (2σ)

# *Constraint on late-time PBH density*




A simple upper bound
on (monochromatic) PBH density:

$\Omega_{PBH}(M) < \Omega_M * (M_{PBH} / 10^{16.8}\ \mathrm{g})^{3}$




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)*