Black Holes as Dark Matter & Supernova Lensing

Miguel Zumalacárregui

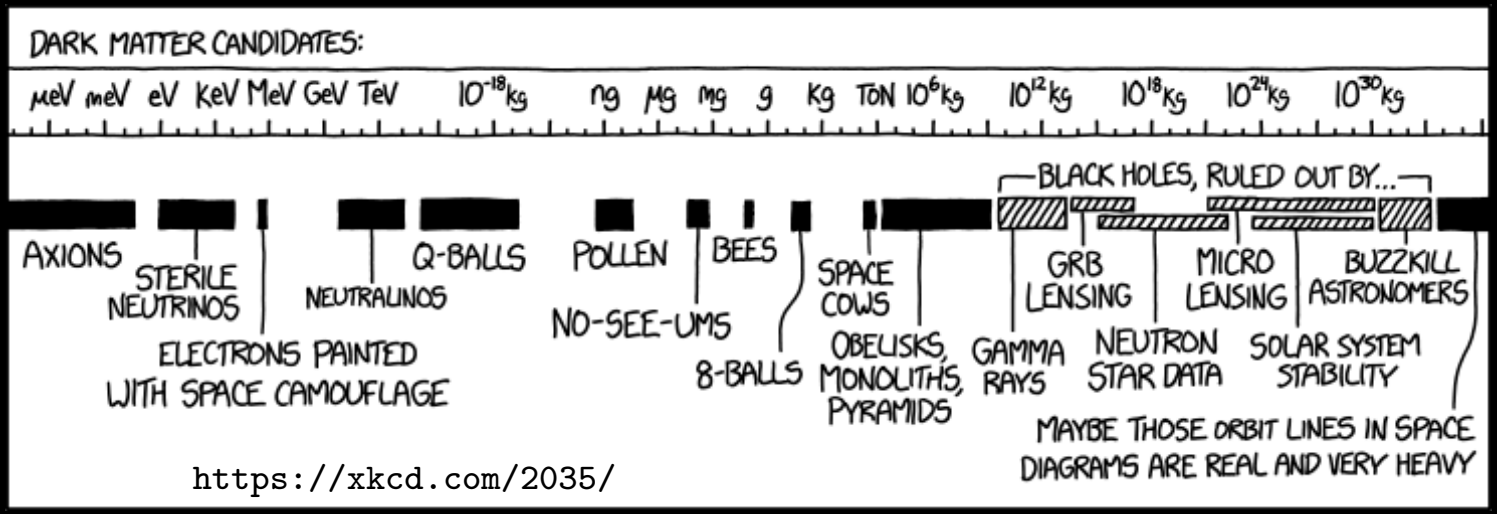
Accurate lensing in the era of precision cosmology

Jan 14^{th}, 2019

MZ & Seljak (1712.02240 PRL)

3G consortium (in prep)

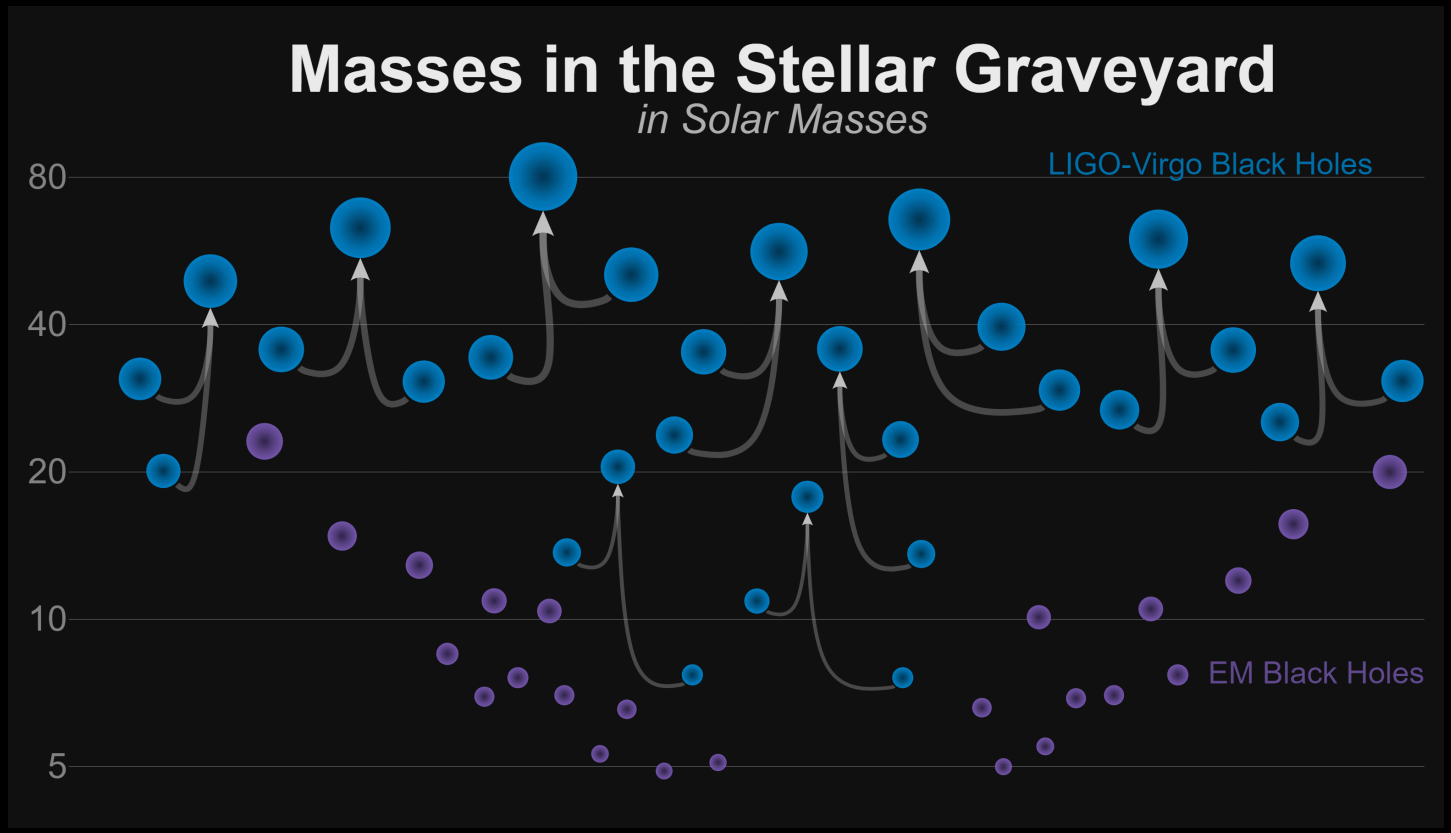
Dark Matter Candidates



~ 90 orders of magnitude in mass!!!

- "Fuzzy"DM: Ultra-light particles $m \gtrsim 10^{-22} eV$
- WIMPs: Weakly Interacting Massive Particles
- MACHOs: MAssive Compact Halo Objects $m \lesssim 100 M_\odot$
  - cold, dead stars $\rightarrow$ can't form early enough
  - Primordial Black Holes $\rightarrow$ form in the very early universe

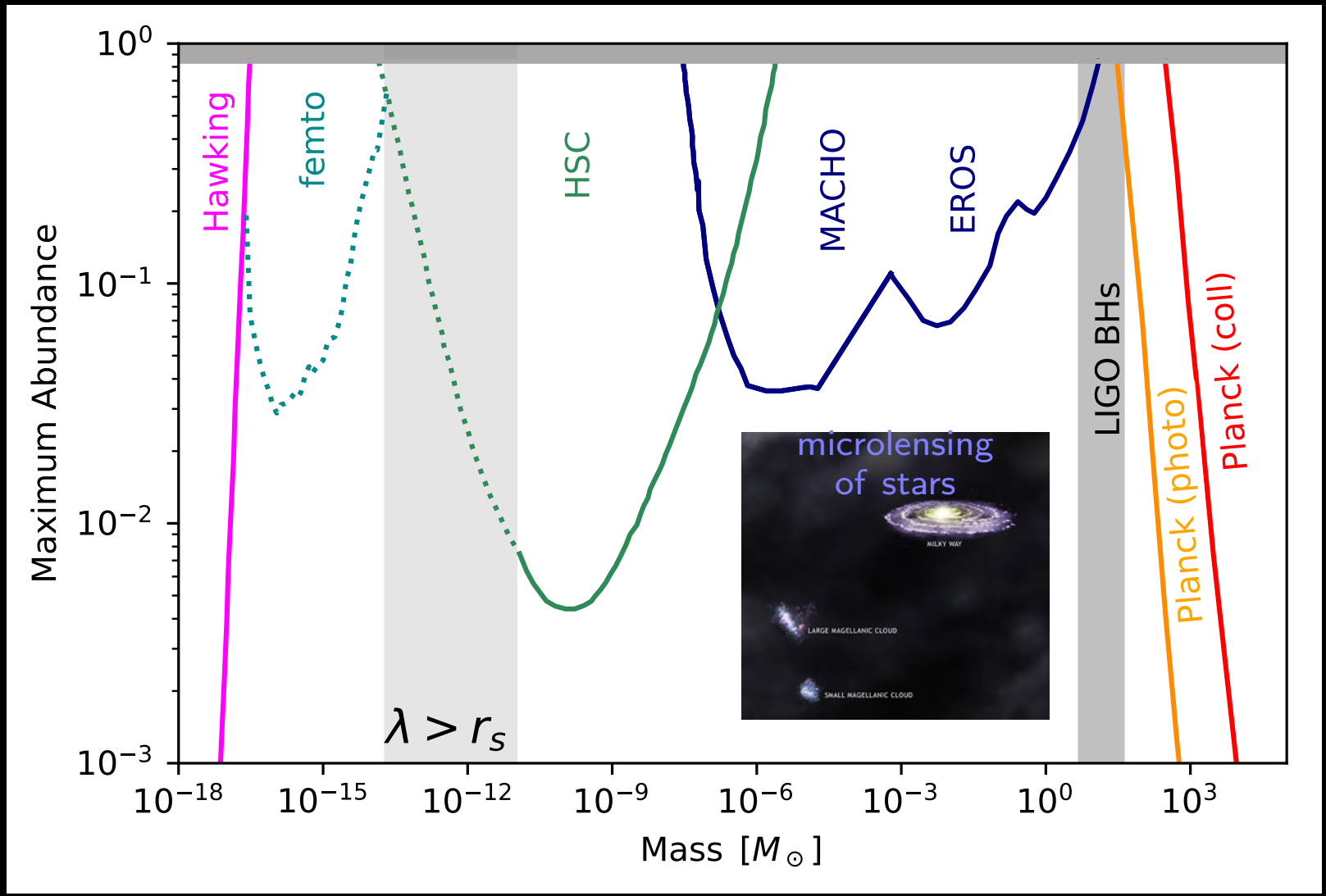
LIGO Black Holes



Heavy & Abundant (LIGO 1606.04856)

- *Primordial origin?* (Sasaki+ '16)
- *MACHO dark matter?* (Bird+, Clesse+ '16)

LIGO MACHO miracle?

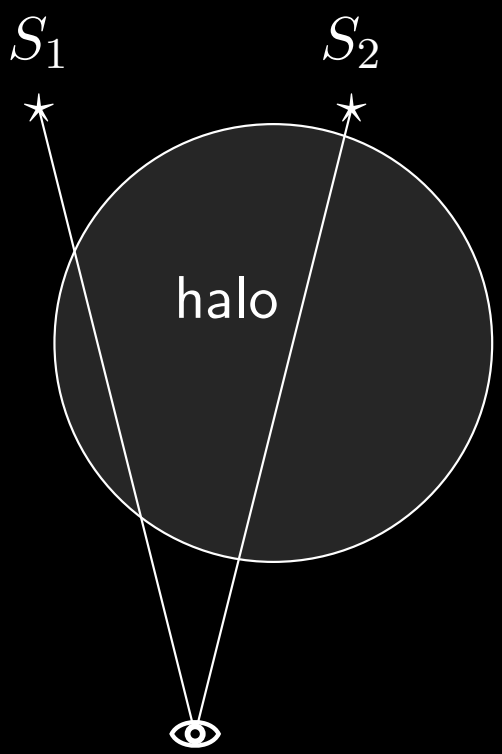


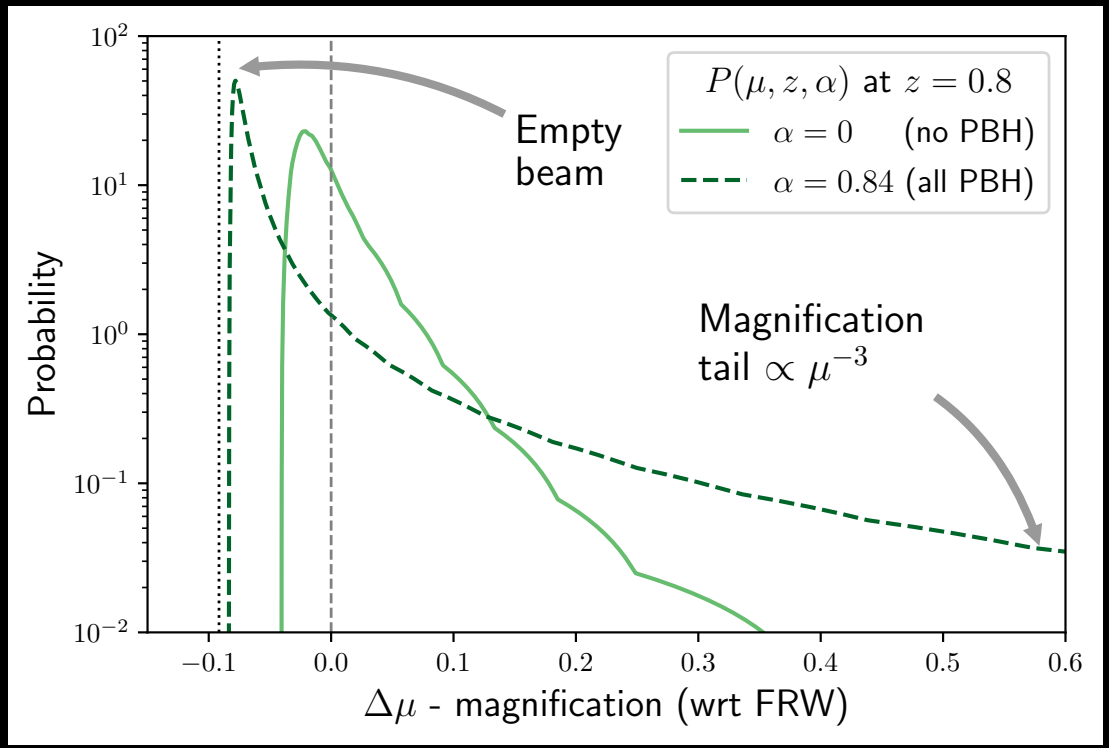
(Adapted from Ezquiaga+ 17, Reviews: Carr+ '16, Sasaki+ '18)

Lensing of Supernovae (Seljak & Holz '99)

$$D(z, \Delta\mu) = \frac{\bar{D}(z)}{\sqrt{1 + \Delta\mu}}$$

Distance (perceived vs average)
Magnification



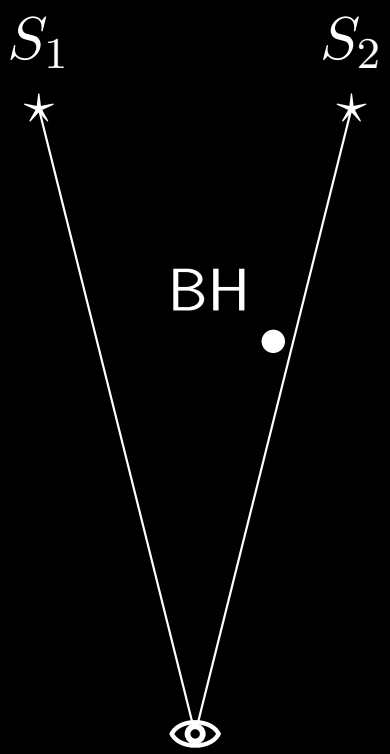


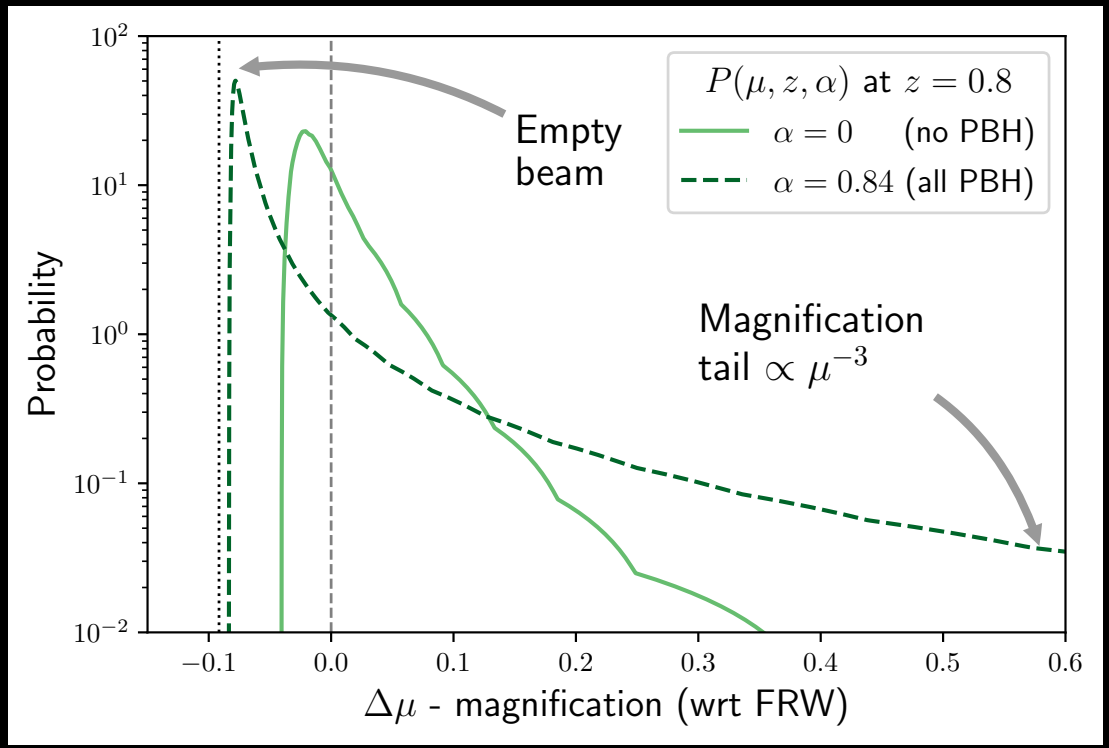
PBH signatures: { slight demagnification (most SNe)
highly magnified events (few SNe)

Lensing of Supernovae (Seljak & Holz '99)

$$D(z, \Delta\mu) = \frac{\bar{D}(z)}{\sqrt{1 + \Delta\mu}}$$

Distance (perceived vs average)
Magnification

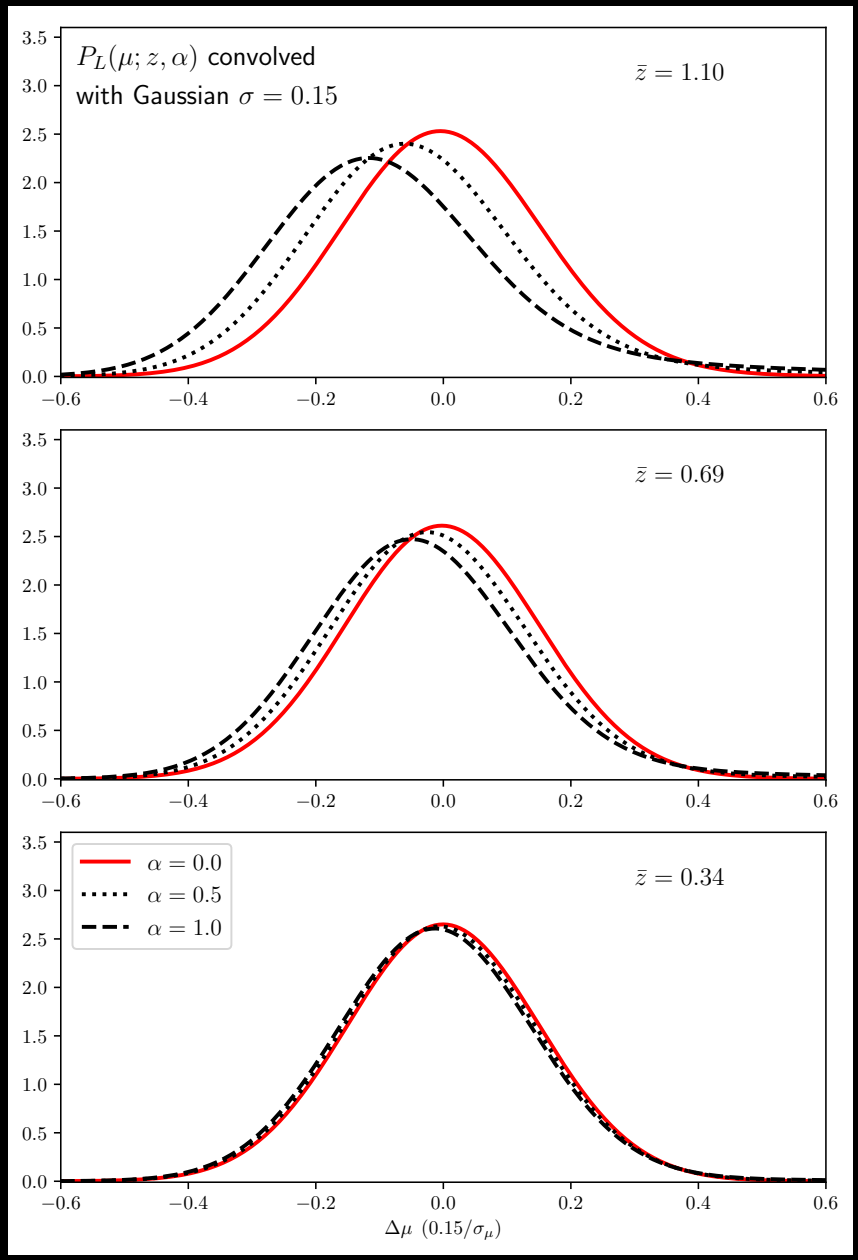




PBH signatures: { slight demagnification (most SNe)
highly magnified events (few SNe)

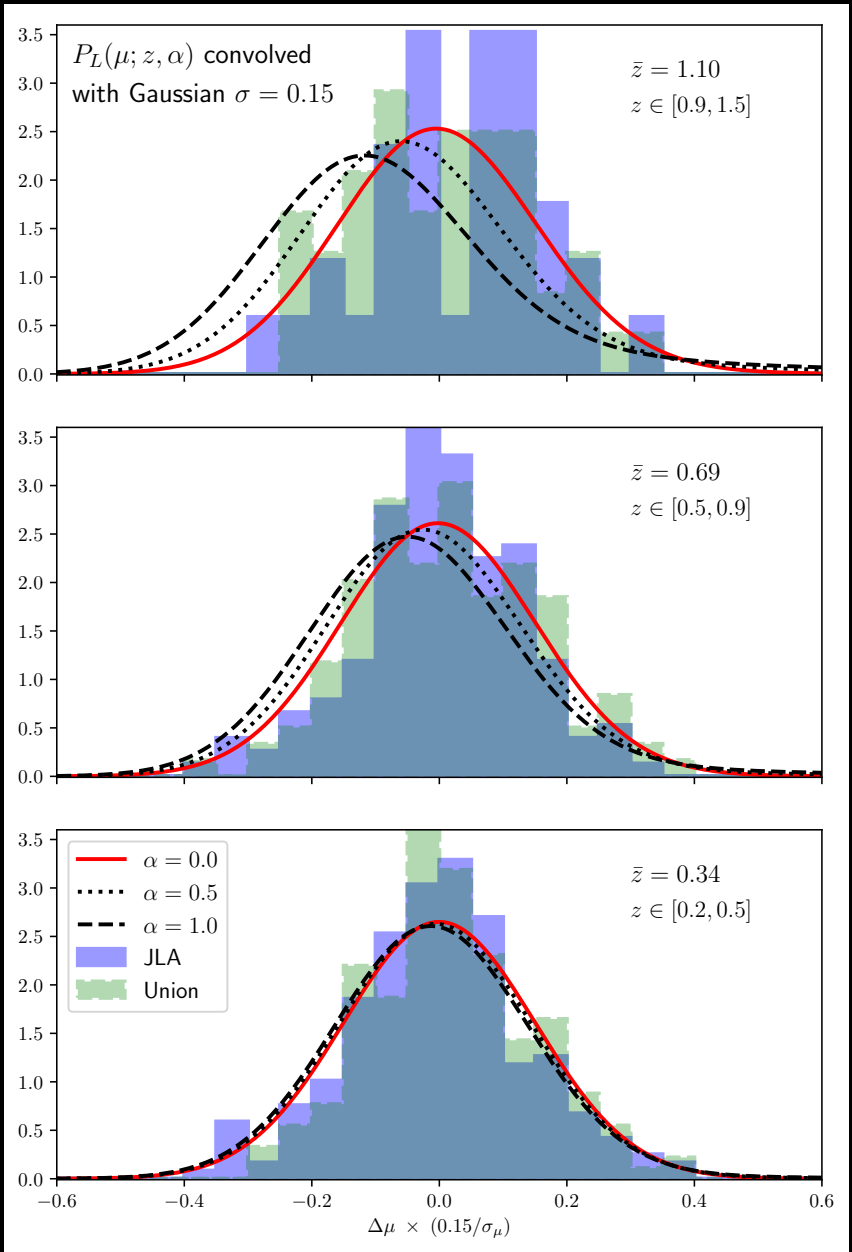
Theory vs Data

(MZ & Seljak '17)



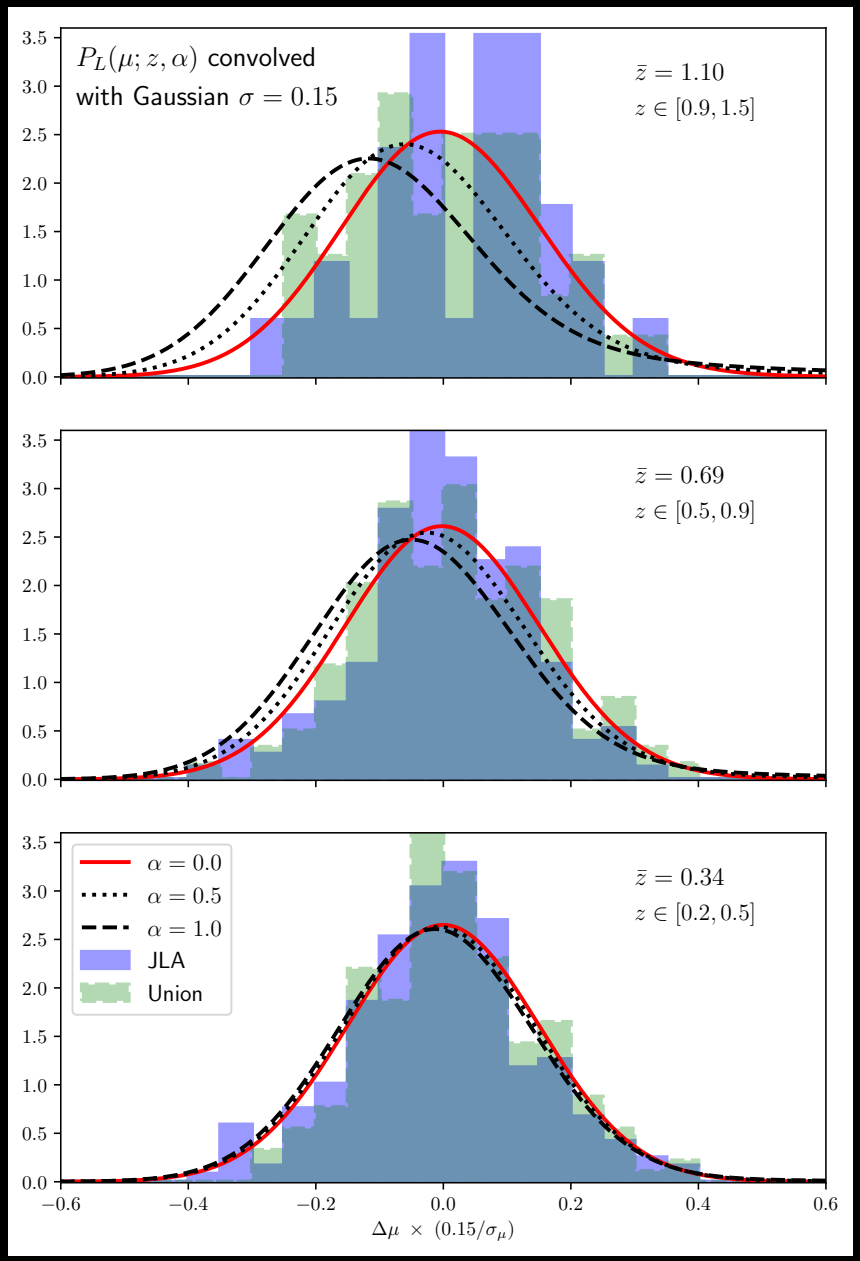
Theory vs Data

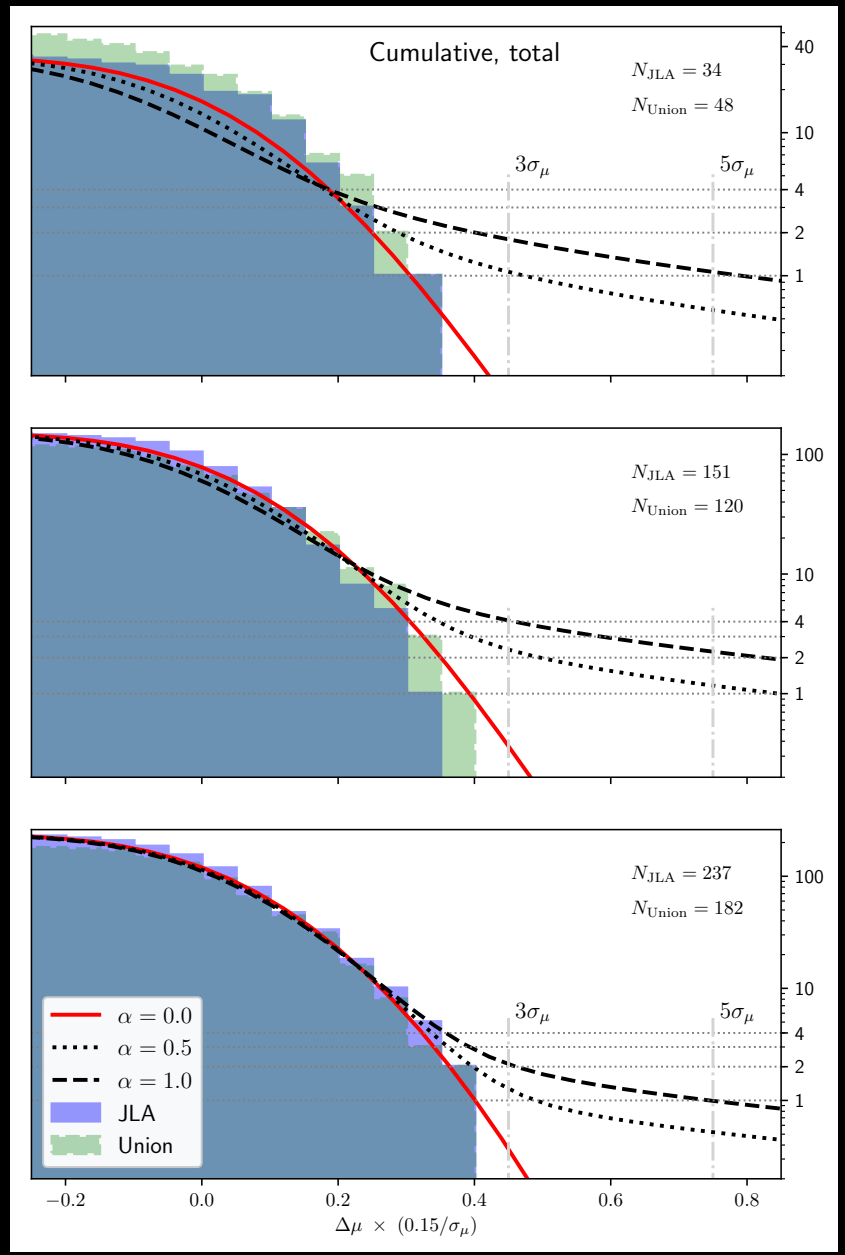
(MZ & Seljak '17)



Theory vs Data

(MZ & Seljak '17)





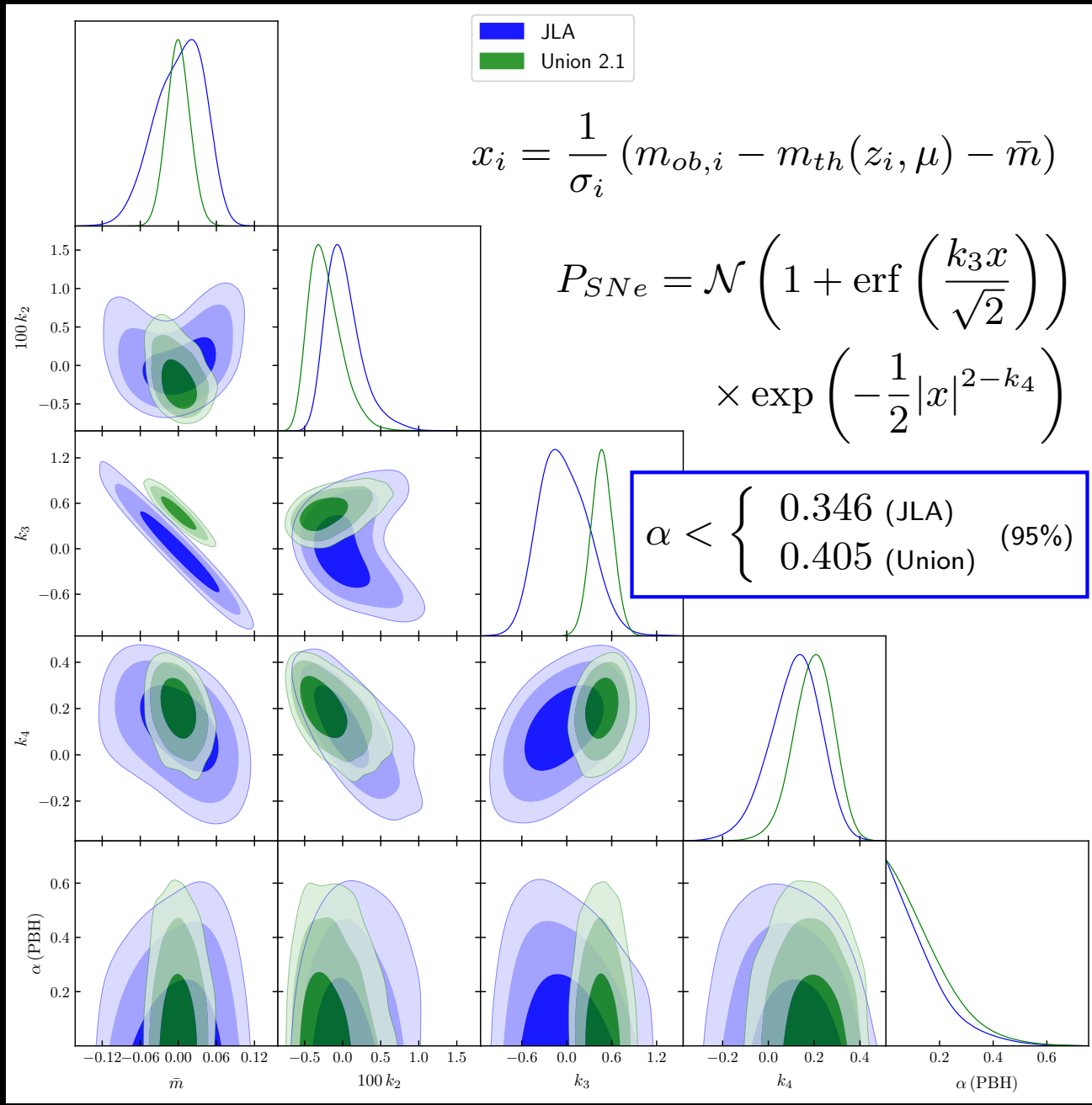
Results

Parameters:

- $\alpha = \dfrac{\Omega_{\rm PBH}}{\Omega_M}$
- mean $\bar{m}$
- dispersion correction $\sigma_i^2 = \sigma_{\rm obs,i}^2 + k_2 - \sigma_{\rm lens}^2$
- Skewness k_3
- Kurtosis k_4

Not shown:

- Ω_M (Planck+BAO)
- standardization (JLA)

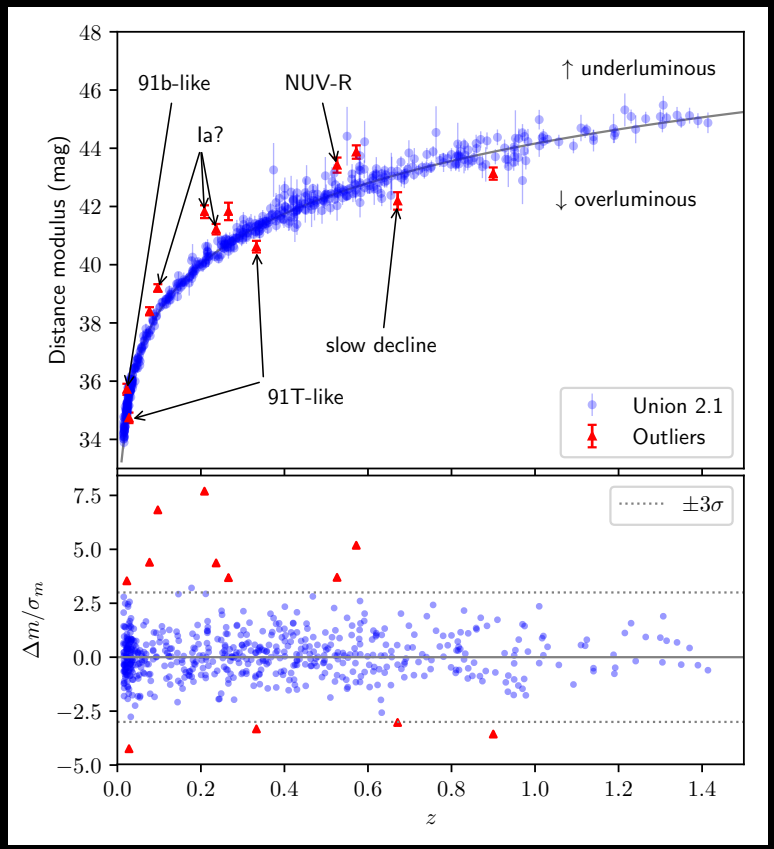


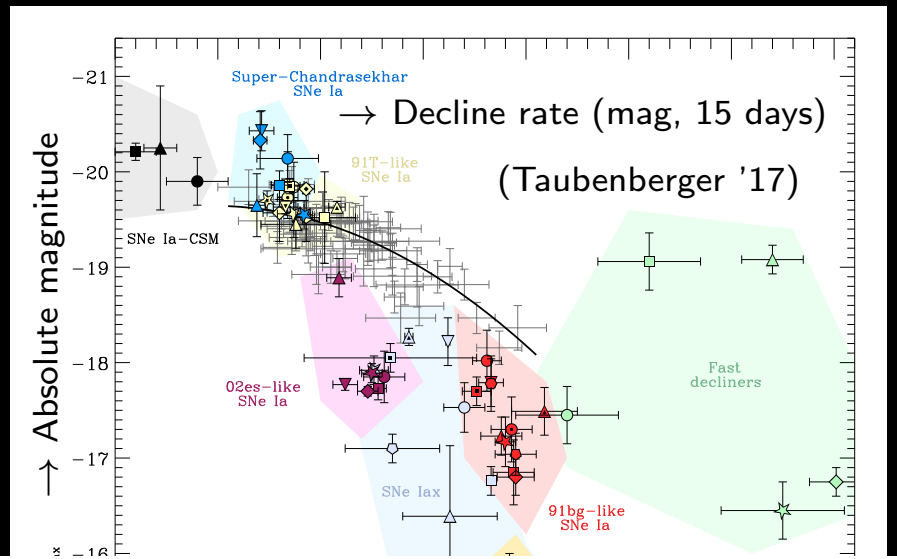
$$x_i = \frac{1}{\sigma_i}\left(m_{ob,i} - m_{th}(z_i,\mu) - \bar{m}\right)$$

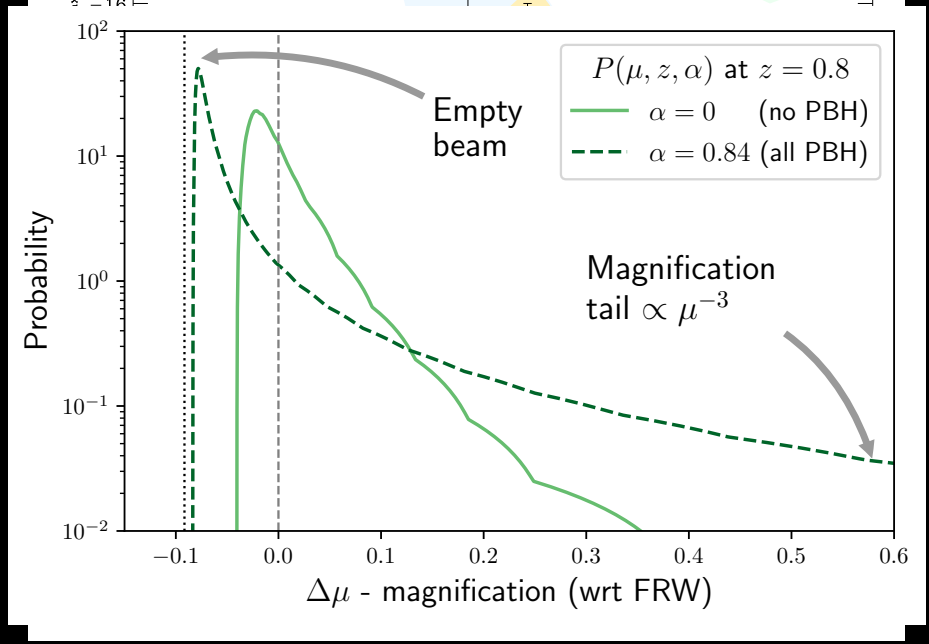
$$P_{SNe} = \mathcal{N}\left(1 + \mathrm{erf}\left(\frac{k_3 x}{\sqrt{2}}\right)\right) \times \exp\left(-\frac{1}{2}|x|^{2-k_4}\right)$$

$$\alpha < \begin{cases} 0.346 \text{ (JLA)} \\ 0.405 \text{ (Union)} \end{cases} \quad (95\%)$$

Magnified or peculiar SNe?





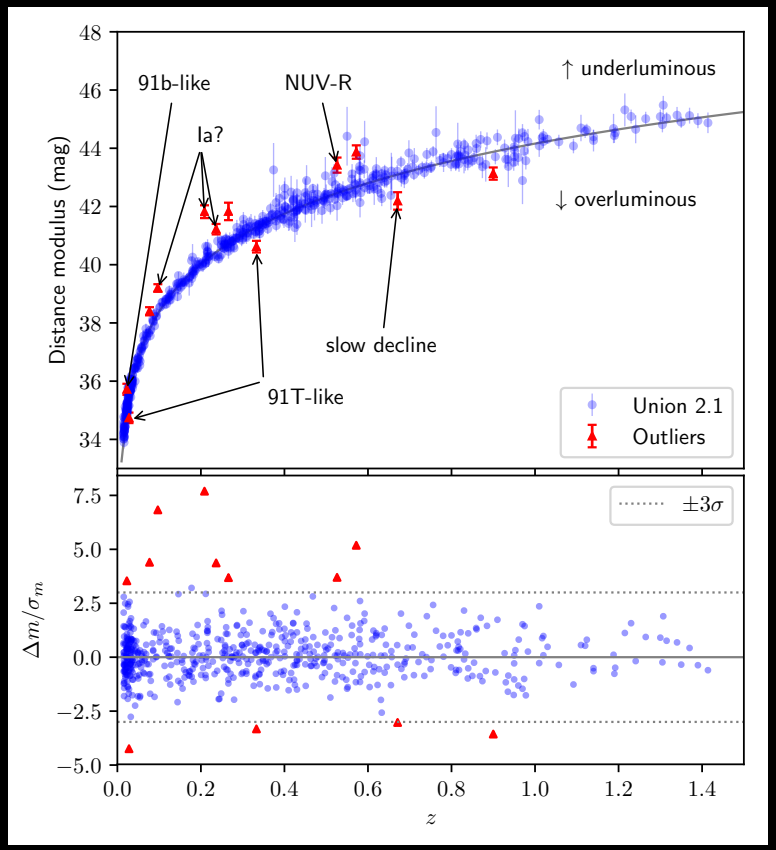


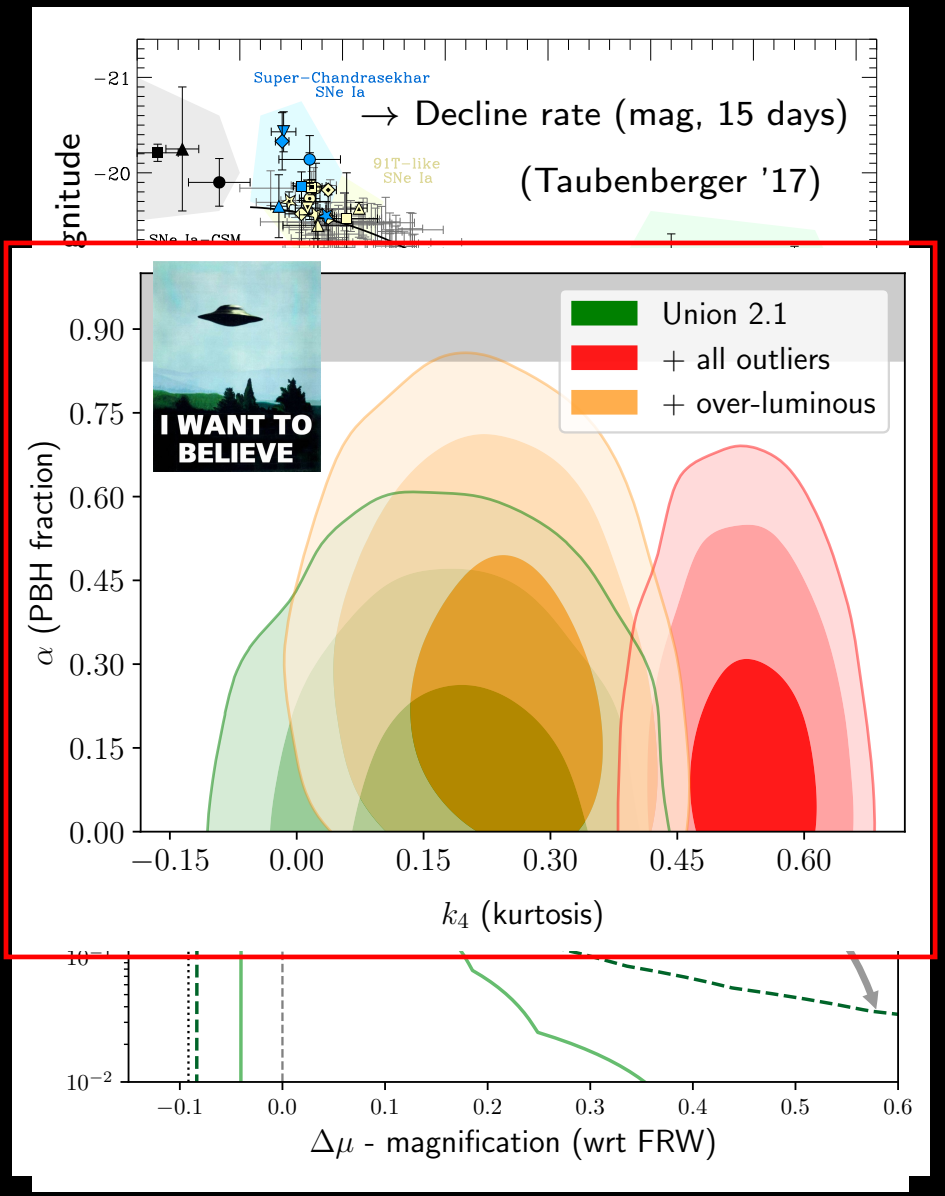
Outliers in Union 2.1

- 4 overluminous → 3 peculiar
- 8 subluminous → 5 peculiar

Thanks to D. Rubin (sample) & Ll. Galbany (assesment)

Magnified or peculiar SNe?



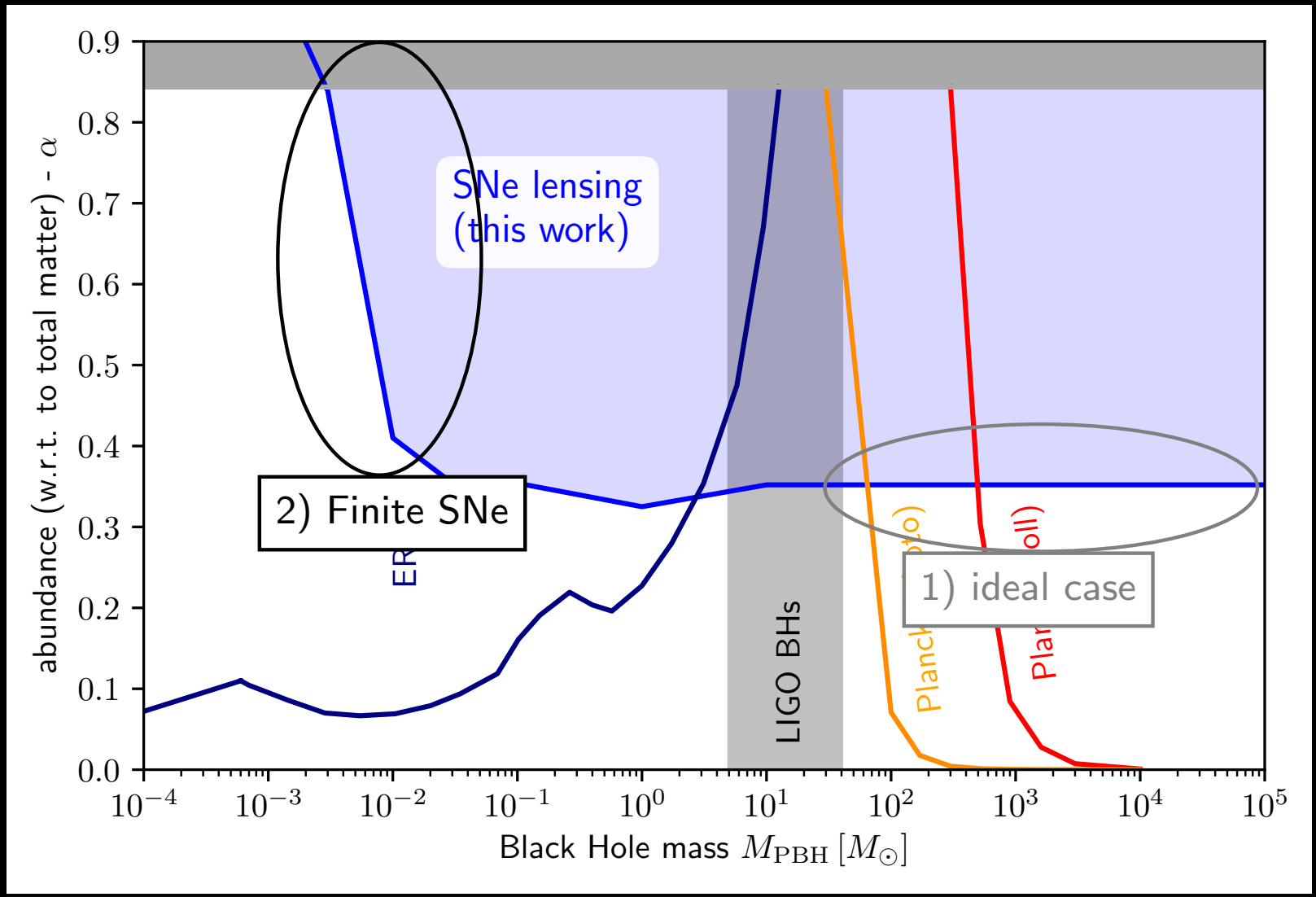


Outliers in Union 2.1

- 4 overluminous → 3 peculiar
- 8 subluminous → 5 peculiar

Thanks to D. Rubin (sample) & Ll. Galbany (assesment)

Limitation: Source Size vs Lens Mass



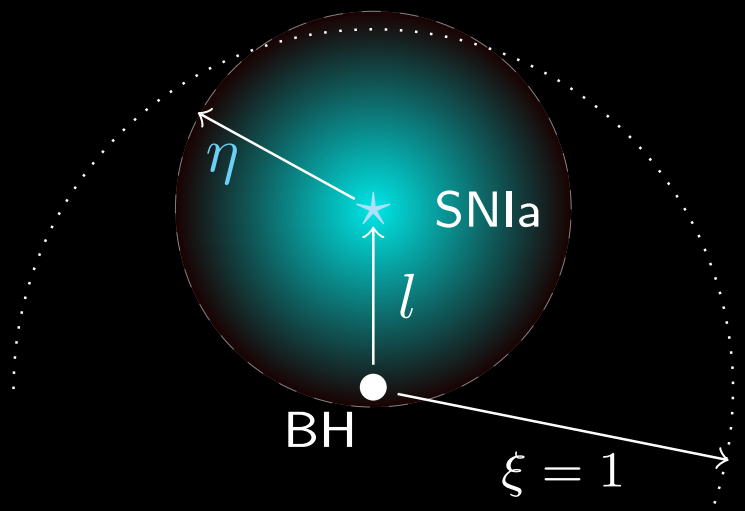
Finite sources magnification (Pei '93, MZ & Seljak '17)

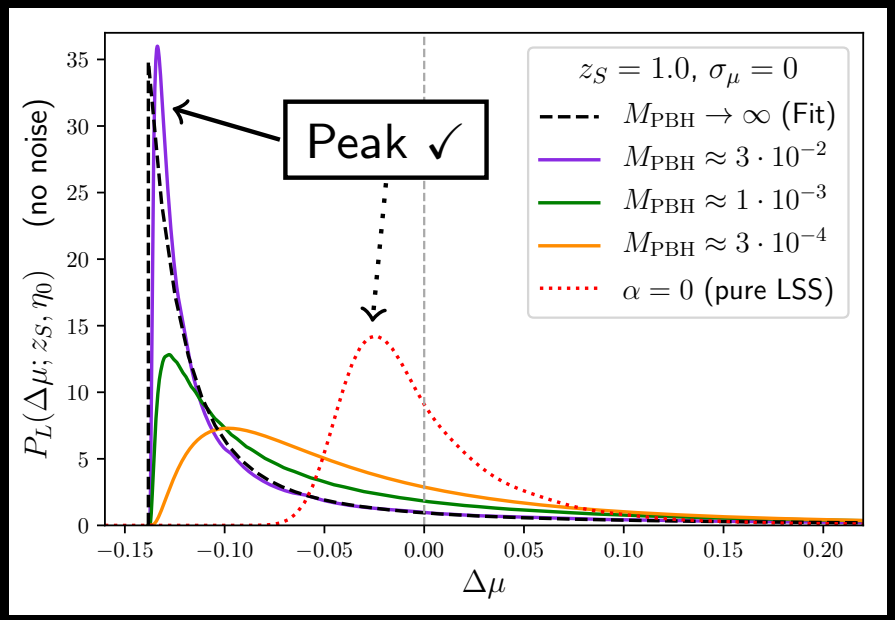
- Point lens + point source

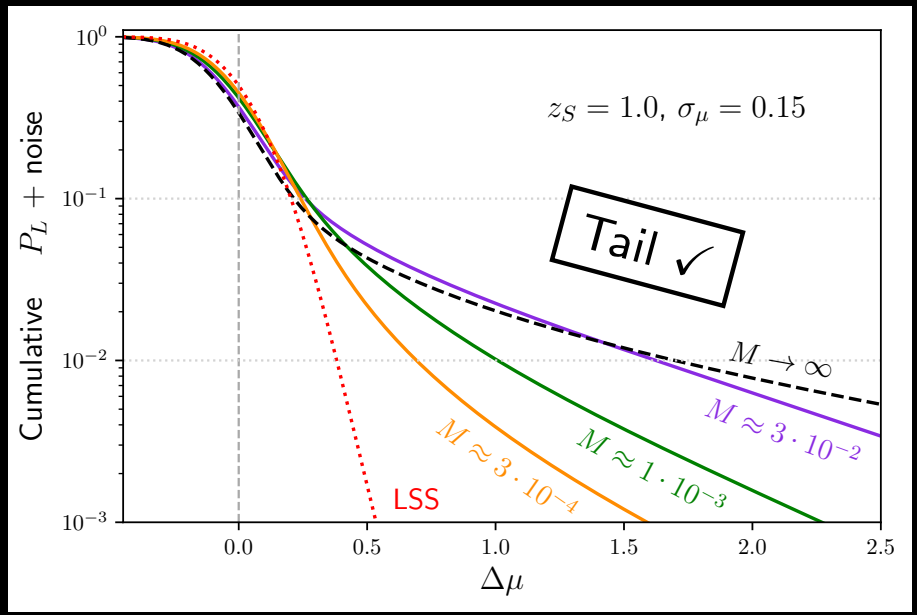
$$\mu = \frac{1}{l}\frac{l^2+2\xi^2}{\sqrt{l^2+4\xi^2}} - 1$$

- Finite source $\eta \equiv \dfrac{R_S}{\xi} = \dfrac{\text{source size}}{\text{Einstein radius}}$

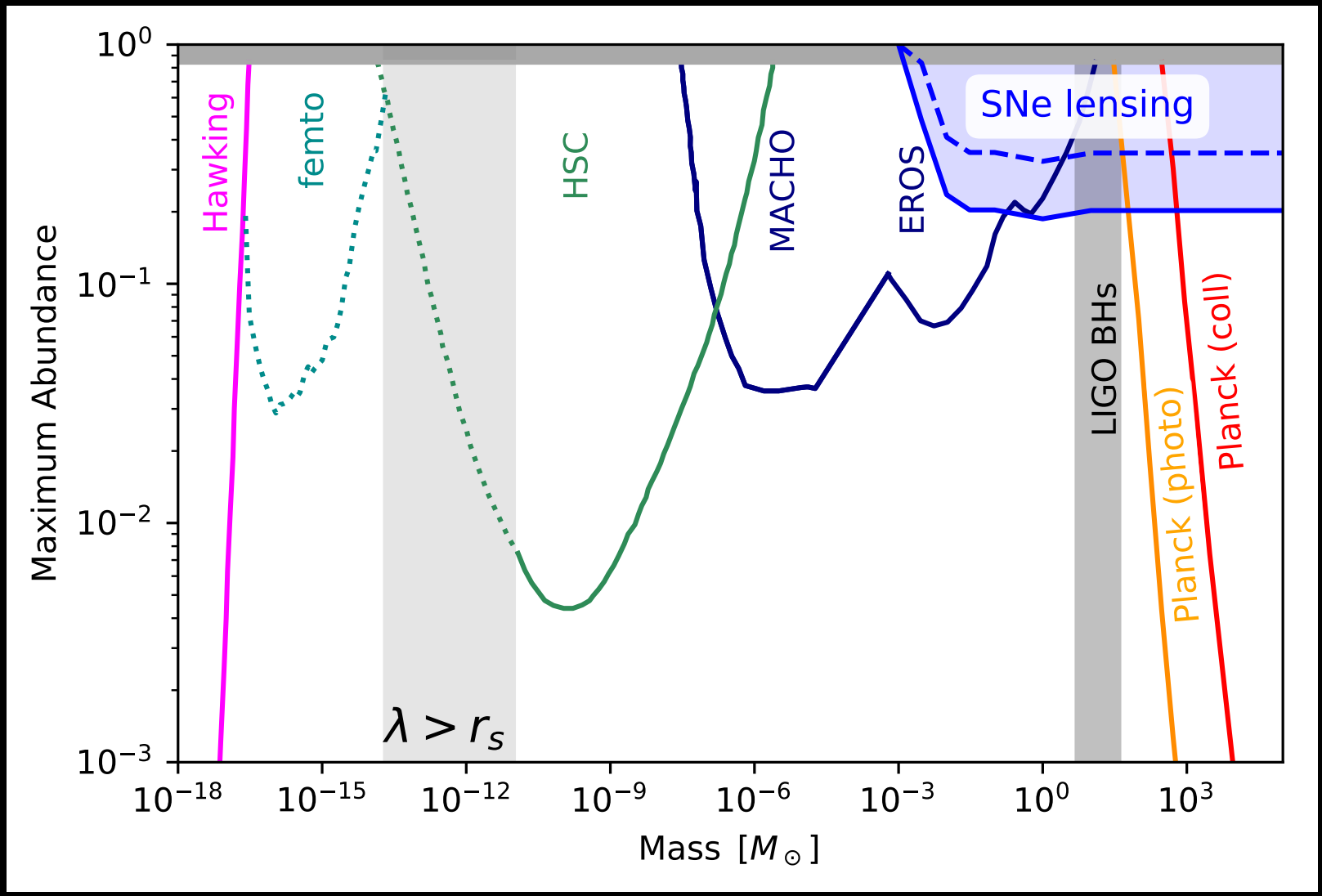
$$\mu_{\max} = \sqrt{1+4\eta^{-2}} - 1$$







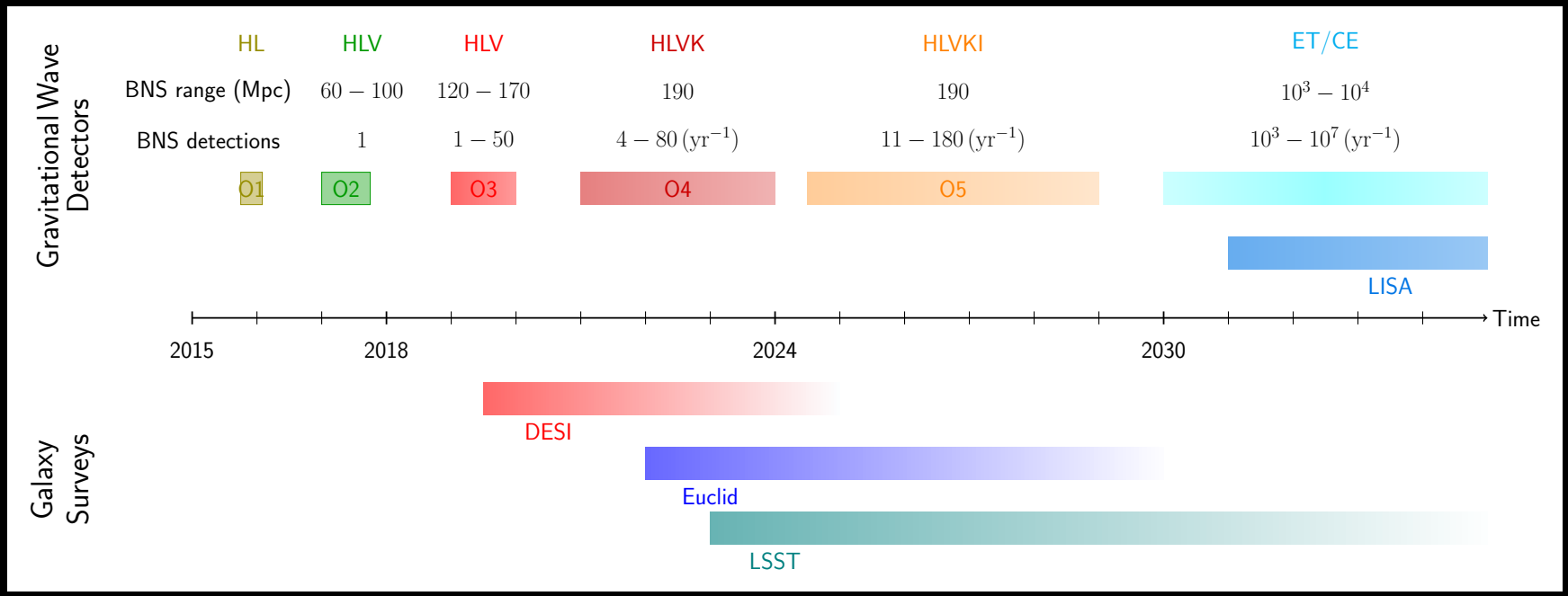
Stellar-mass black holes excluded as dark matter



complementary to other methods

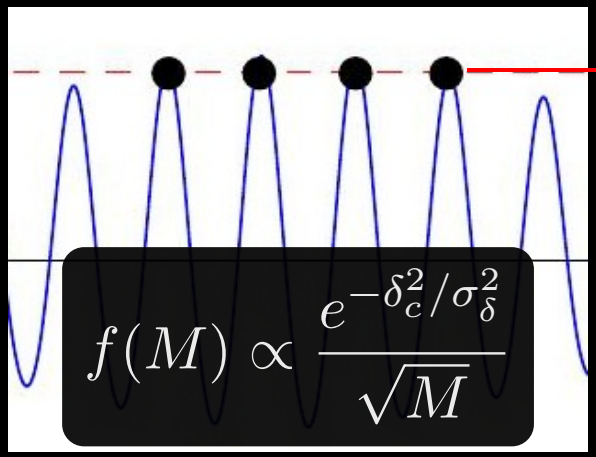
A bright Future

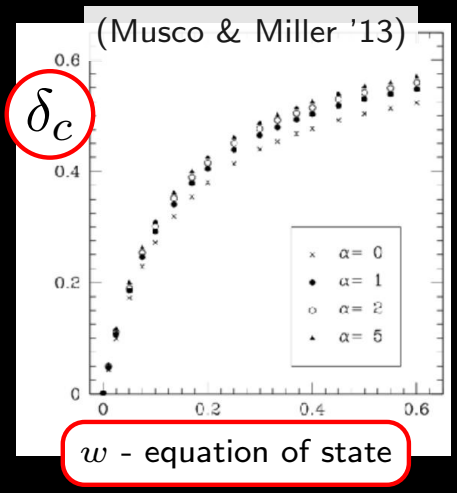
(from Ezquiaga & MZ '18)



LIGO MACHO miracle? (Byrnes, Hindmarsh, Young, Hawkings '18)

PBH formation $\rightarrow$ collapse of high-contrast density fluctuations

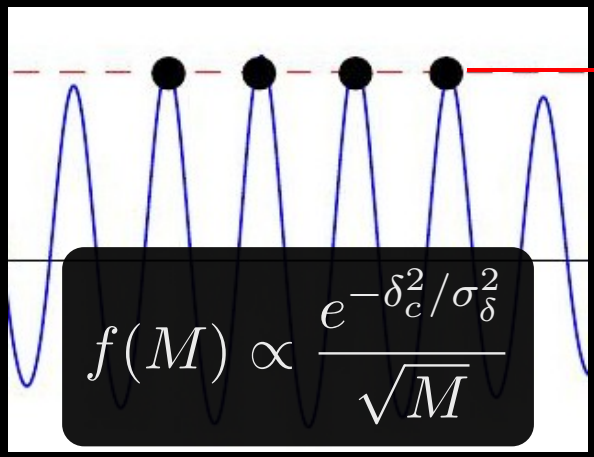


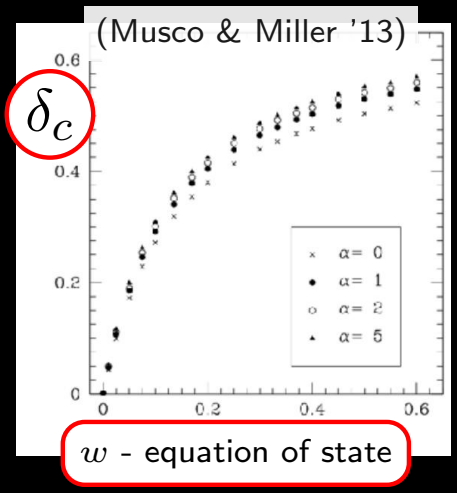


(Jedamizik '97, Widerin & Schmidt '98, Jedamzik & Niemeyer '99, Sobrinho '16...)

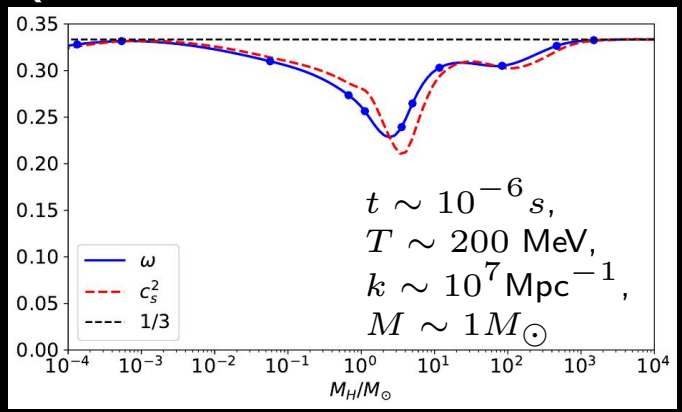
LIGO MACHO miracle? (Byrnes, Hindmarsh, Young, Hawkings '18)

PBH formation $\rightarrow$ collapse of high-contrast density fluctuations

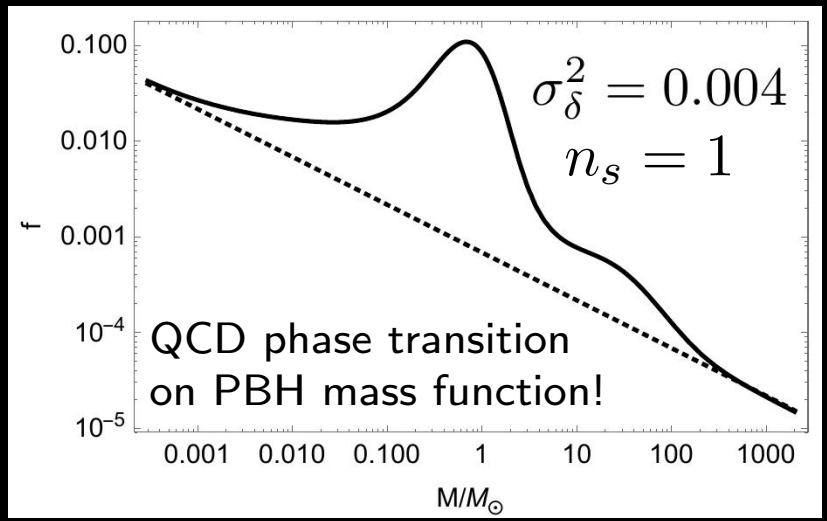




QCD Phase Transition



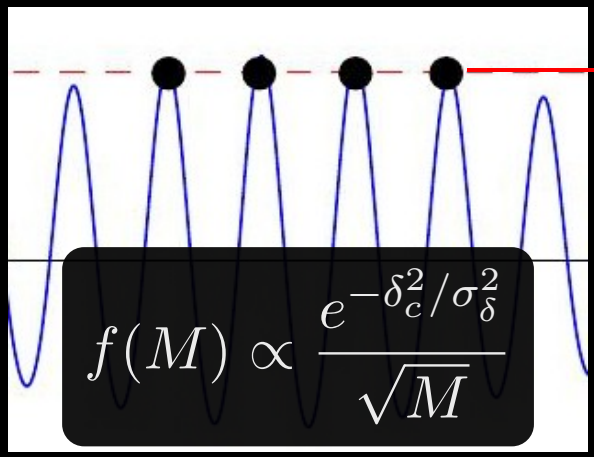
$\sim$ 1% accurate! (Borsanyi+ '16)

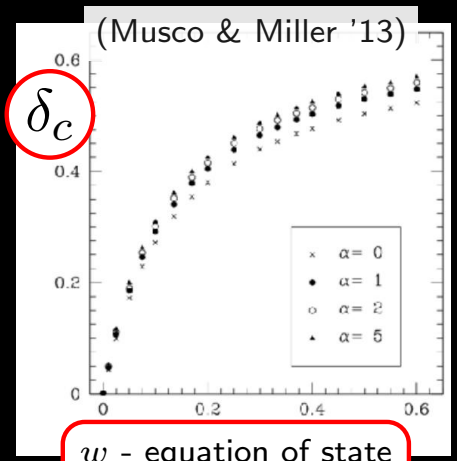


(Jedamizik '97, Widerin & Schmidt '98, Jedamzik & Niemeyer '99, Sobrinho '16...)

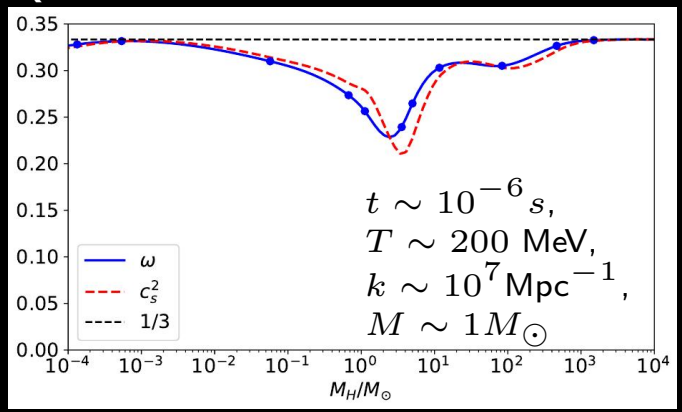
LIGO MACHO miracle? (Byrnes, Hindmarsh, Young, Hawkings '18)

PBH formation $\rightarrow$ collapse of high-contrast density fluctuations

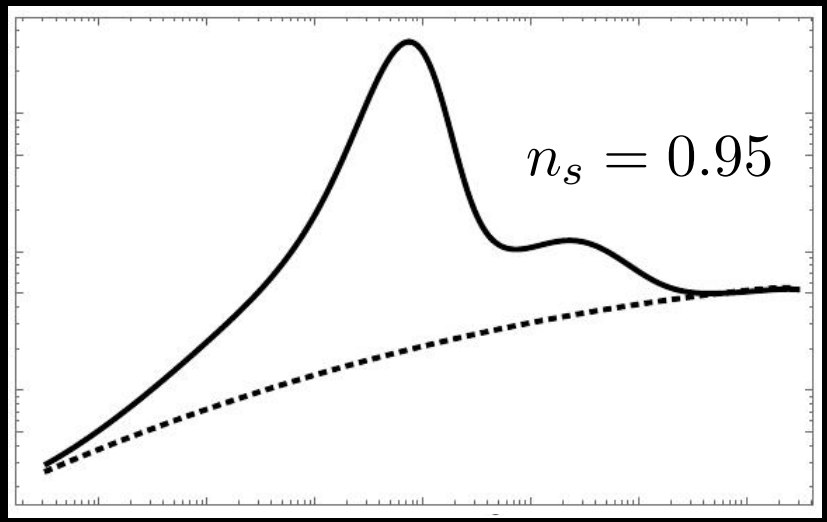




QCD Phase Transition

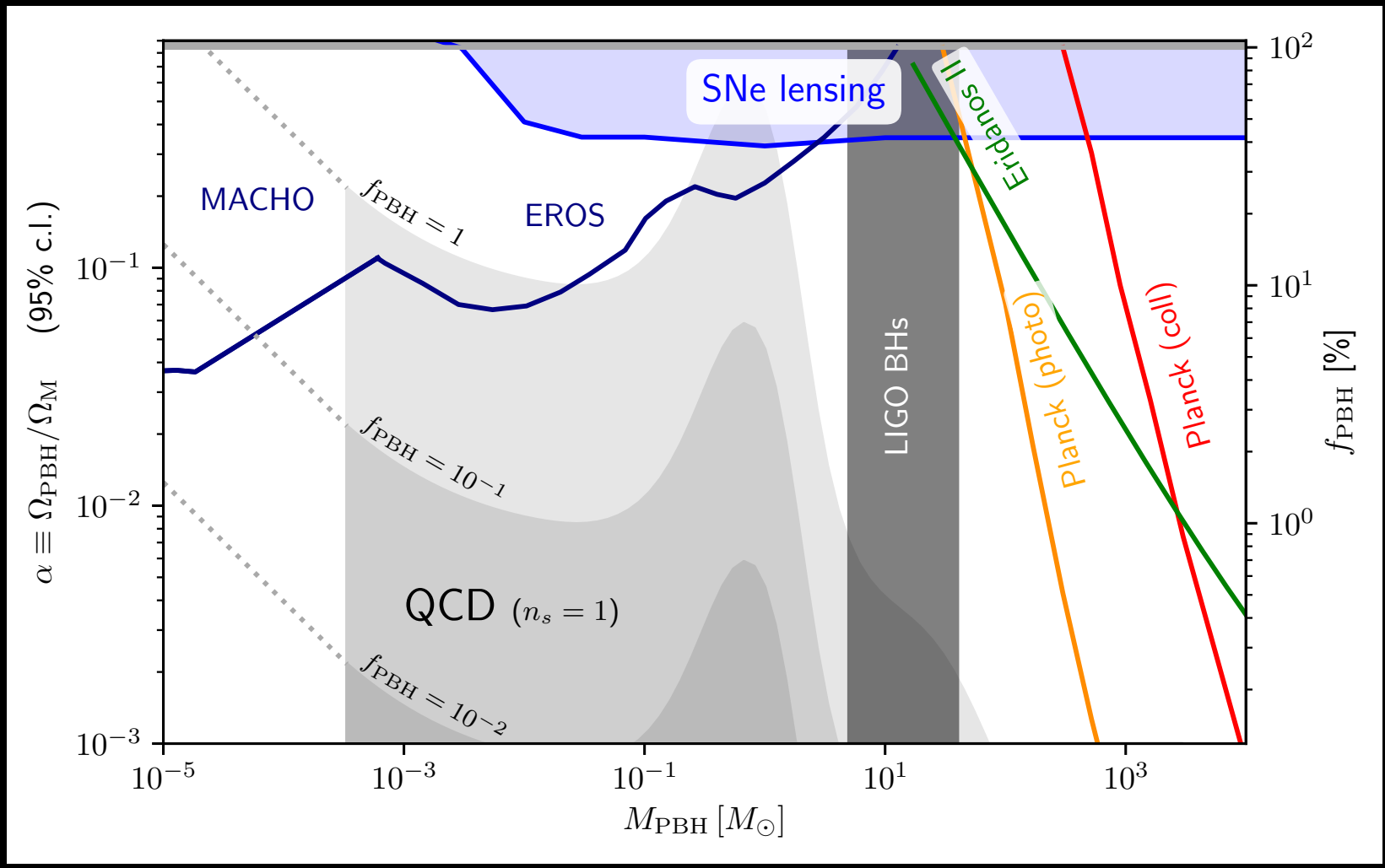


$\sim$ 1% accurate! (Borsanyi+ '16)



(Jedamizik '97, Widerin & Schmidt '98, Jedamzik & Niemeyer '99, Sobrinho '16...)

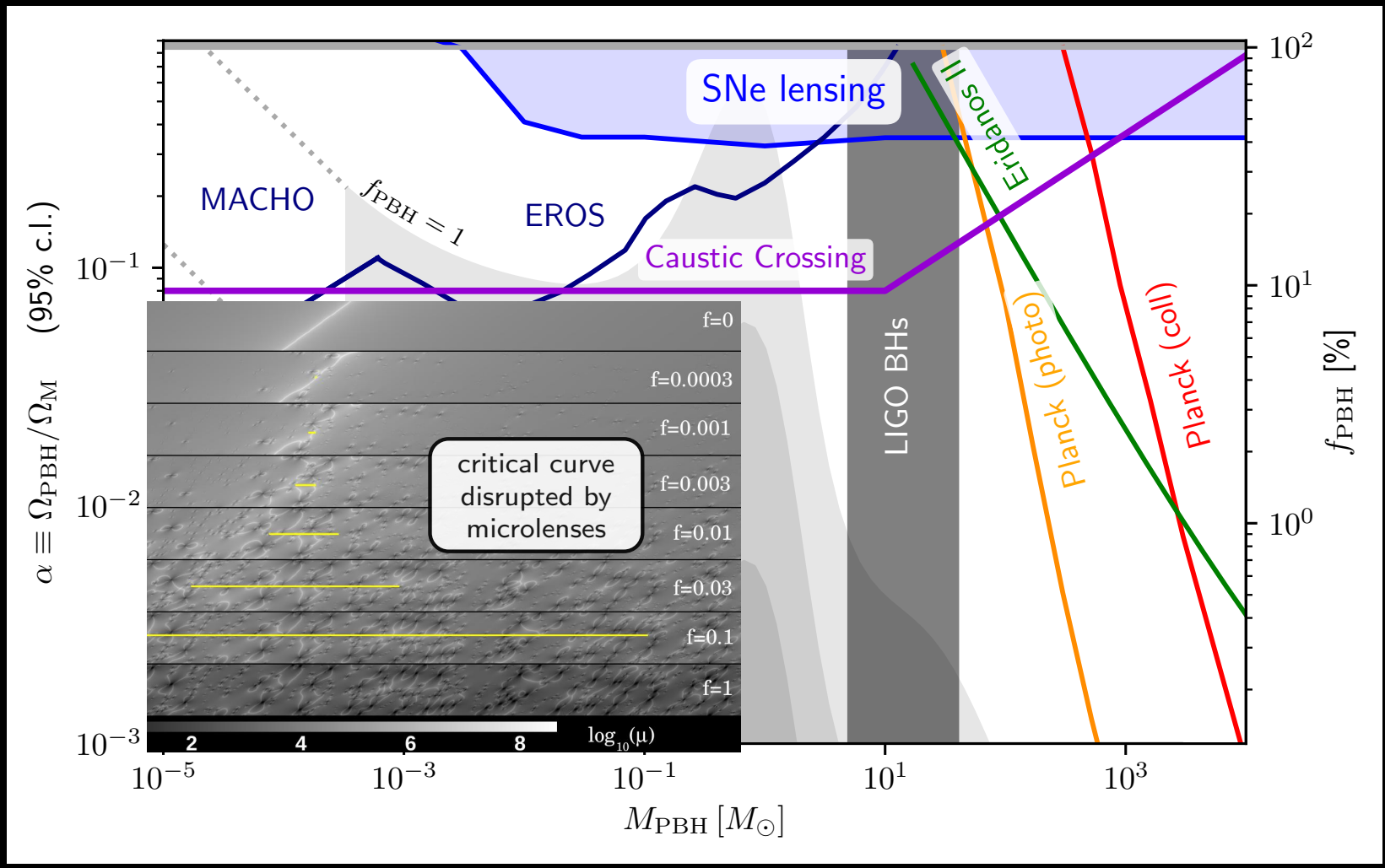
LIGO MACHO miracle?



Caustic Crossings → Diego+ '17, Venumadhav+ '17, Oguri+ '17
LIGO merger rates → Nakamura+ '97, Sasaki+ '16, Ali-Haimoud+ '17

+ GW stochast. (Wang+ 16), Quasar lens. (Mediavilla+ '16), x-ray/radio (Gaggero+ '17), 21cm (Hektor+ 18)...

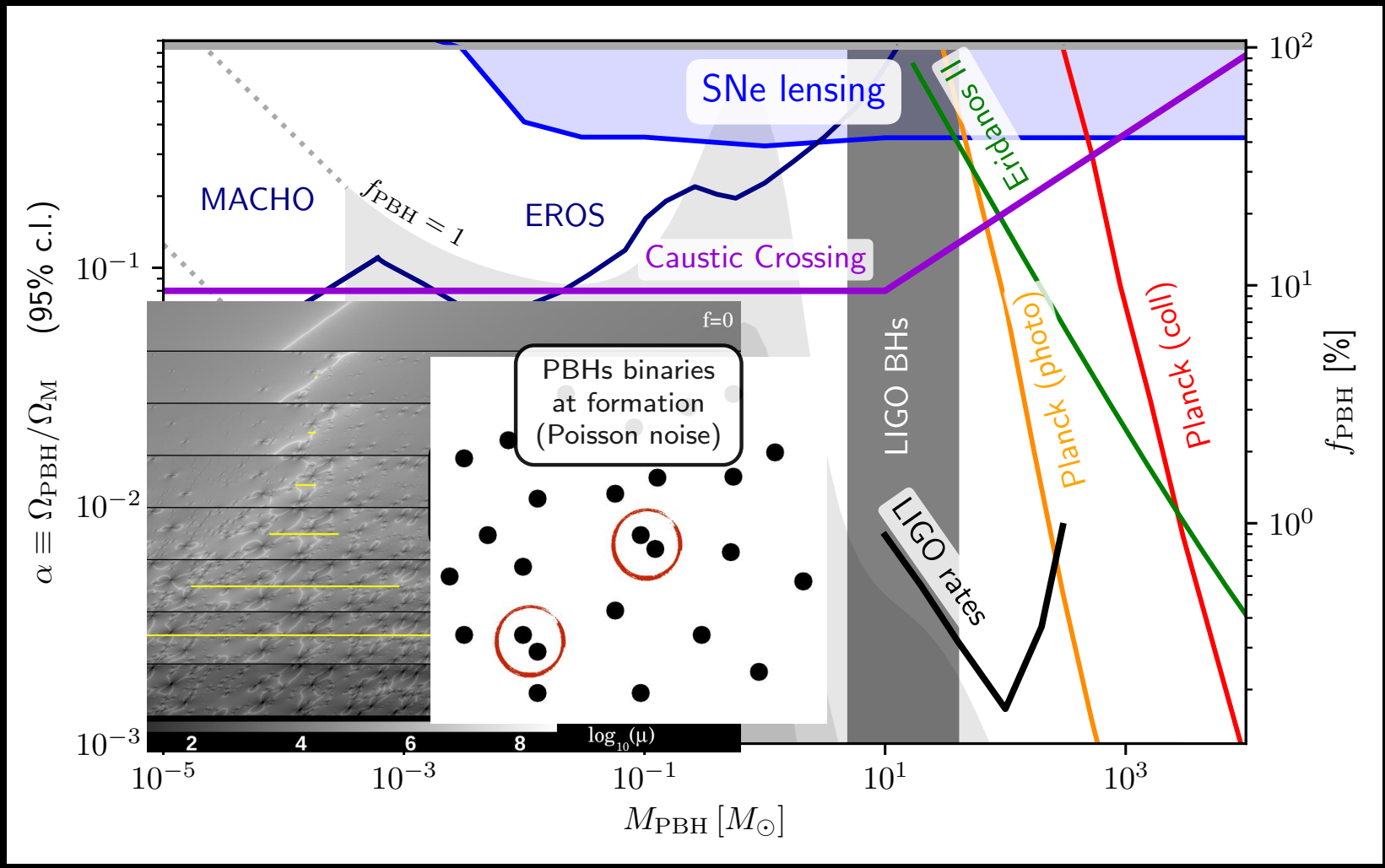
LIGO MACHO miracle?



Caustic Crossings → Diego+ '17, Venumadhav+ '17, Oguri+ '17
LIGO merger rates → Nakamura+ '97, Sasaki+ '16, Ali-Haimoud+ '17

+ GW stochast. (Wang+ 16), Quasar lens. (Mediavilla+ '16), x-ray/radio (Gaggero+ '17), 21cm (Hektor+ 18)...

LIGO MACHO miracle?



Caustic Crossings → Diego+ '17, Venumadhav+ '17, Oguri+ '17
LIGO merger rates → Nakamura+ '97, Sasaki+ '16, Ali-Haimoud+ '17

+ GW stochast. (Wang+ 16), Quasar lens. (Mediavilla+ '16), x-ray/radio (Gaggero+ '17), 21cm (Hektor+ 18)...

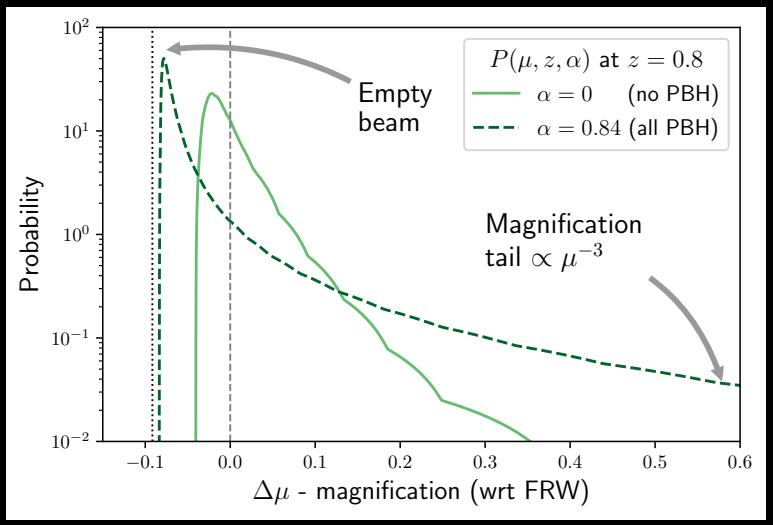
Cosmology Dependence

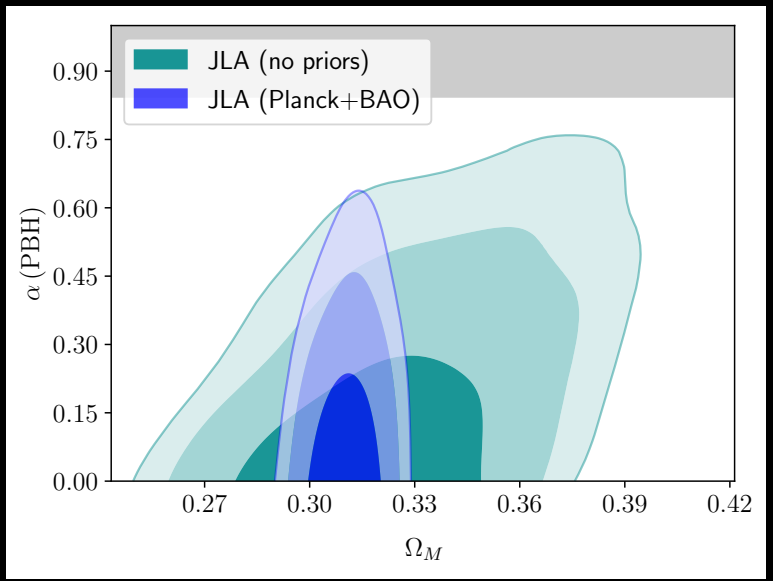
Assumed flat ΛCDM

- Planck+BOSS: $\Omega_M = 0.309 \pm 0.006$ (Alam+ '17)
- Weak effect of perturbations

  SNe: $\sigma_8 = 1.07^{+0.50}_{-0.76}$ (Macaulay+ '17)
- Degeneracy:

  empty-beam shift $\leftrightarrow$ expansion





No Ω_M prior

- slightly weaker results
- "best" case PBH

  Tension $\begin{cases} \alpha \approx 0.8 & \rightarrow 3\sigma \text{ w. SNe} \\ \Omega_M \approx 0.36 & \rightarrow 8\sigma \text{ w. P+B} \end{cases}$
- Lack of outliers!

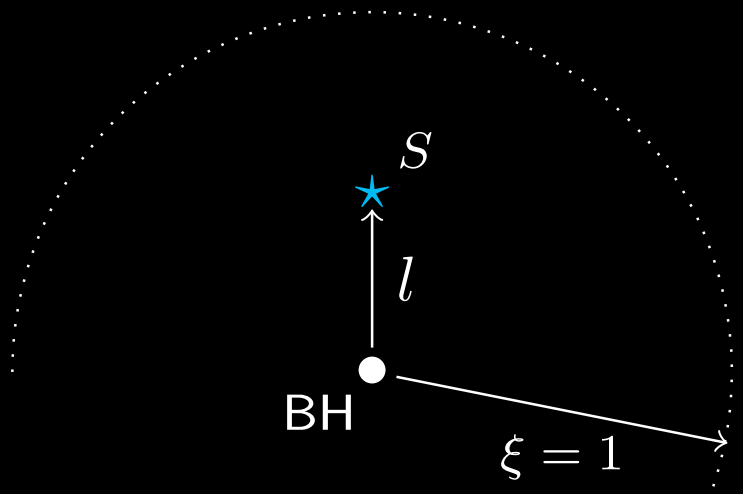
Finite sources (Pei '93)

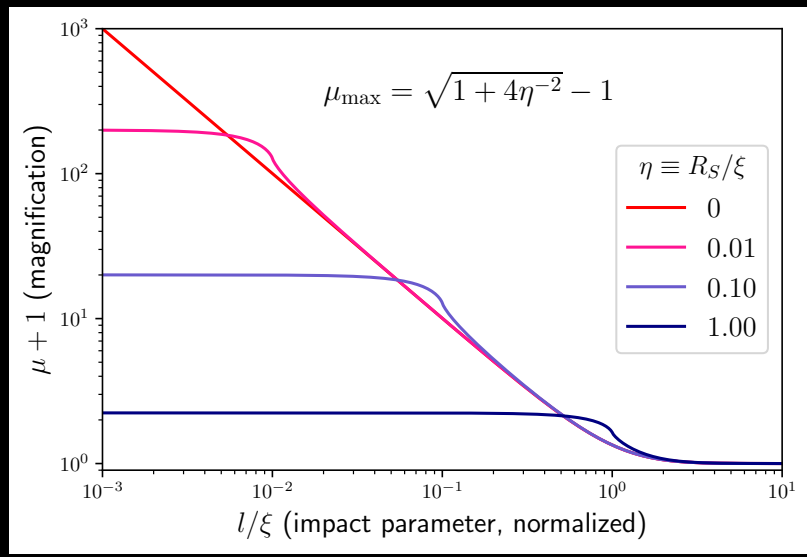
- Point lens + point source

$$\mu = \frac{1}{l}\frac{l^2 + 2\xi^2}{\sqrt{l^2 + 4\xi^2}} - 1$$

- Finite source $\eta \equiv \dfrac{R_S}{\xi} = \dfrac{\text{source size}}{\text{Einstein radius}}$

$$\mu_{\max} = \sqrt{1 + 4\eta^{-2}} - 1$$





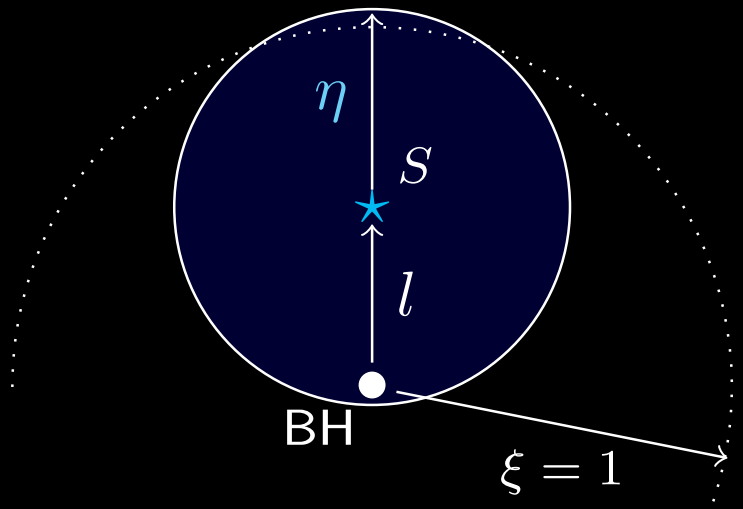
Finite sources (Pei '93)

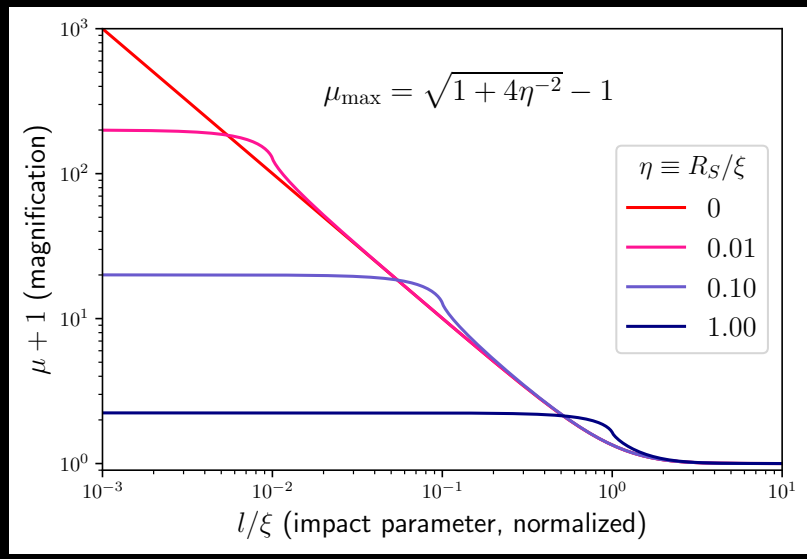
- Point lens + point source

$$\mu = \frac{1}{l}\frac{l^2+2\xi^2}{\sqrt{l^2+4\xi^2}} - 1$$

- Finite source $\eta \equiv \dfrac{R_S}{\xi} = \dfrac{\text{source size}}{\text{Einstein radius}}$

$$\mu_{\max} = \sqrt{1+4\eta^{-2}} - 1$$

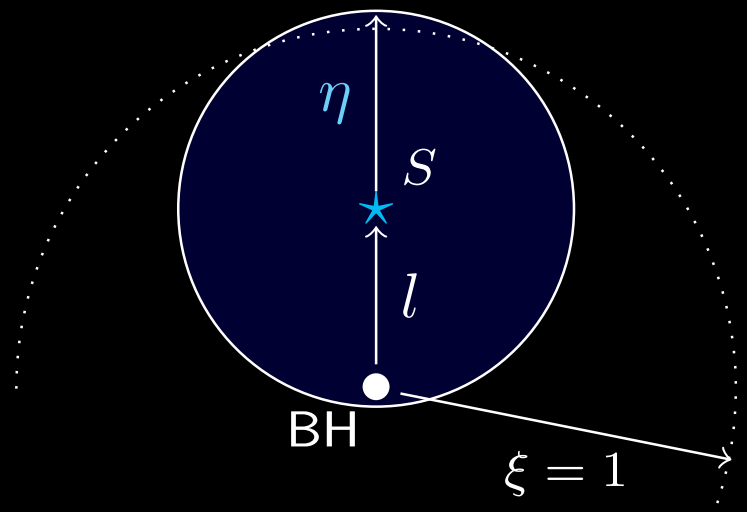




Finite sources (Pei '93)

- Point lens + point source

$$\mu = \frac{1}{l}\frac{l^2 + 2\xi^2}{\sqrt{l^2 + 4\xi^2}} - 1$$



- Finite source $\eta \equiv \dfrac{R_S}{\xi} = \dfrac{\text{source size}}{\text{Einstein radius}}$

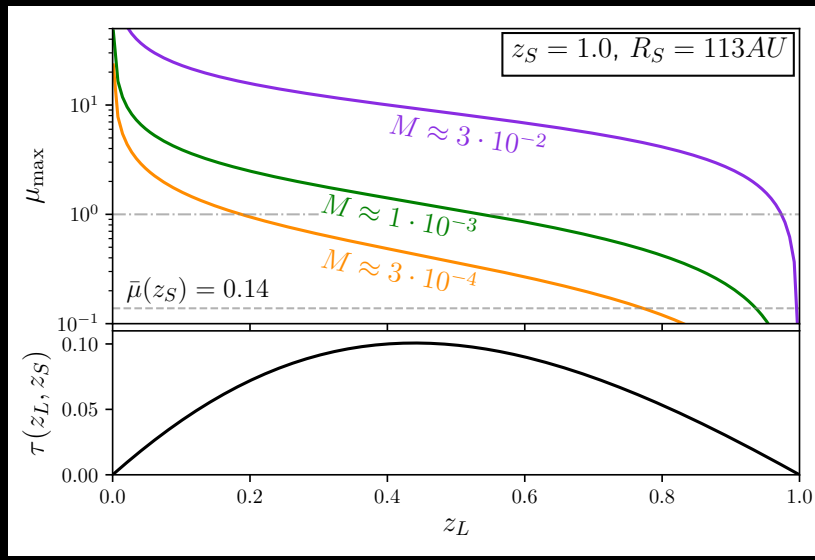
$$\mu_{\max} = \sqrt{1 + 4\eta^{-2}} - 1$$

- z-dependence

$$\eta(z_L, z_S) = \eta_0 \left[\frac{D_L}{H_0 D_S D_{LS}}\right]^{1/2}$$

$$\eta_0 = 0.02 h^{1/2} \left(\frac{R_S}{113AU}\right)\left(\frac{M_\odot}{M_L}\right)^{1/2}$$

- Optical depth $\langle\mu\rangle = e^{2\int_0^{z_S} dz' \tau(z', z_S)} - 1$

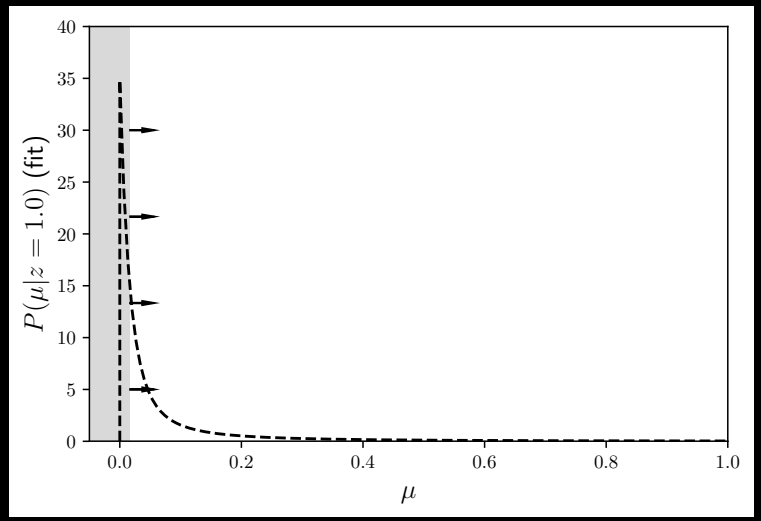


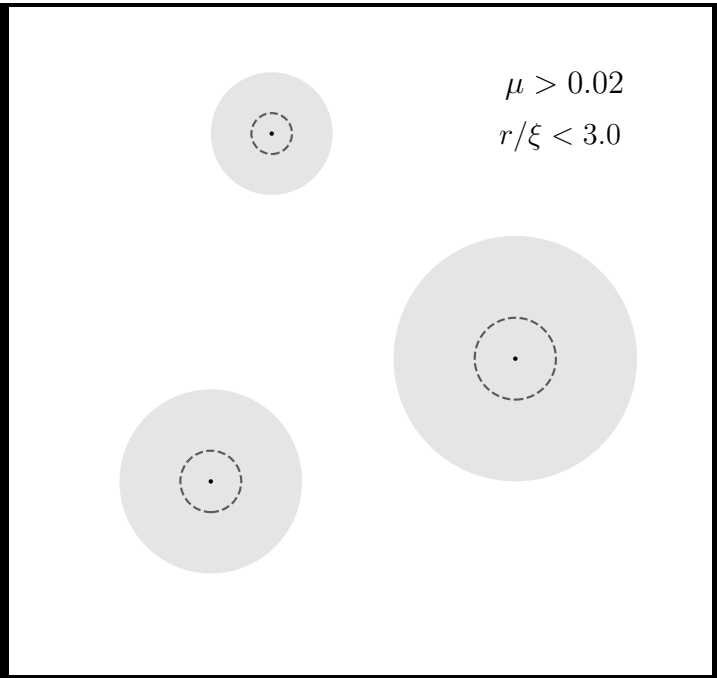
Probability $\propto$ Cross section

- Approximations (Pei '93)
  - Multiplicative magnification

$$(1+\mu) = \prod_i (1+\mu_i)$$

  - Independent lenses
- Probability $\propto \boxed{\sigma(>\mu) \propto \xi^2 \propto M}$
  - cut by finite size $\mu_{\rm max} = \sqrt{1+4/\eta^2}$
  - dependence through $\eta(z_L, z_S, M)$
  - low mass $\rightarrow$ affects tail





✓ when collective lensing can be neglected.

(?) when <u>strong clustering</u> ($r_{\rm bh} \lesssim \xi$)

(Chisholm '06, but see Ali-Haimoud '18)

Probability $\propto$ Cross section

- Approximations (Pei '93)
  - Multiplicative magnification

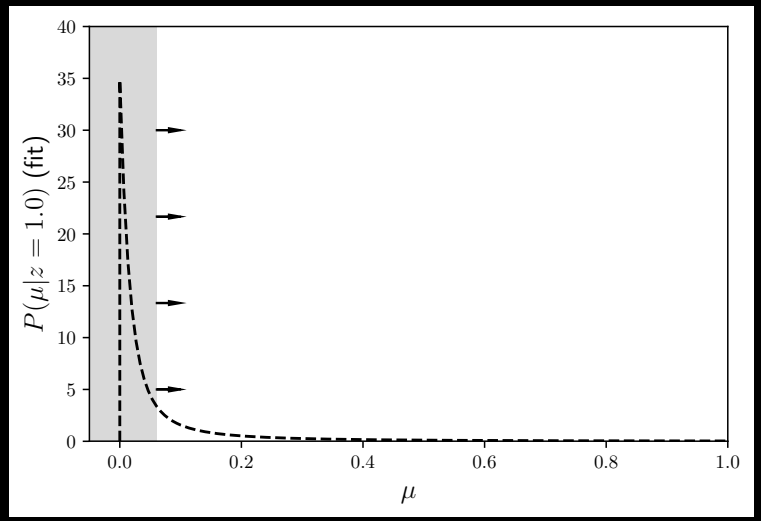
$$(1+\mu) = \prod_i (1+\mu_i)$$

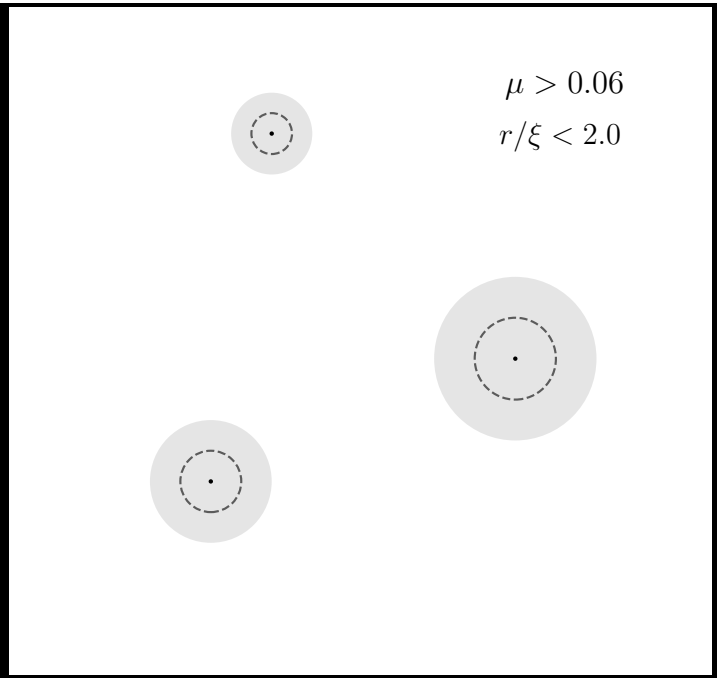
  - Independent lenses
- Probability $\propto \boxed{\sigma(>\mu) \propto \xi^2 \propto M}$
  - cut by finite size $\mu_{\rm max} = \sqrt{1+4/\eta^2}$
  - dependence through $\eta(z_L, z_S, M)$
  - low mass $\rightarrow$ affects tail

✓ when collective lensing can be neglected.

(?) when <u>strong clustering</u> ($r_{\rm bh} \lesssim \xi$)

(Chisholm '06, but see Ali-Haimoud '18)



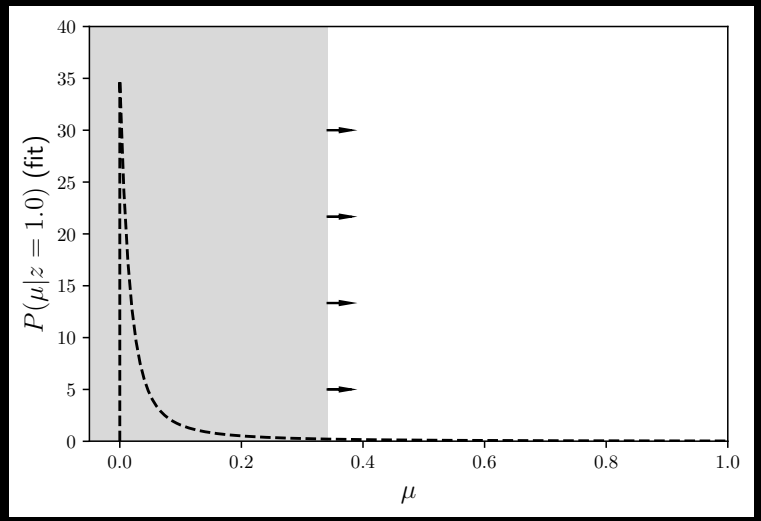


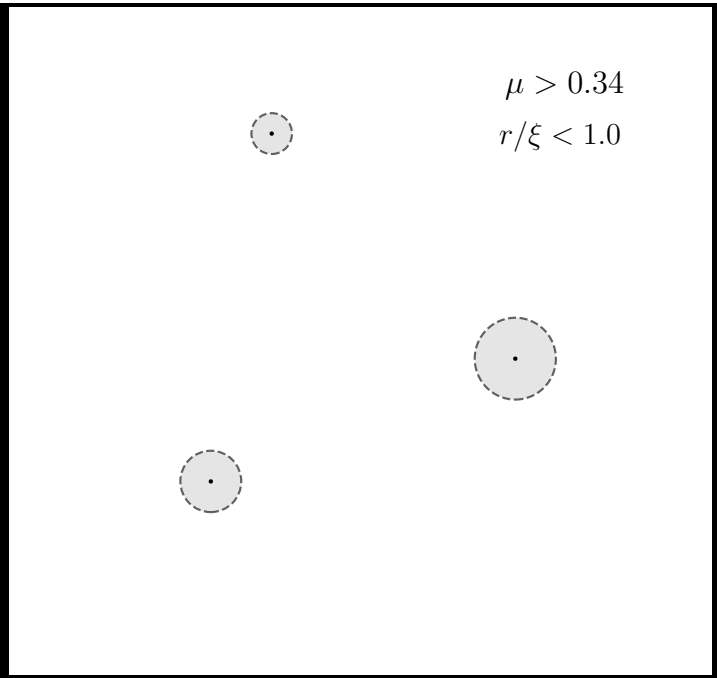
Probability $\propto$ Cross section

- Approximations (Pei '93)
  - Multiplicative magnification

$$(1+\mu) = \prod_i (1+\mu_i)$$

  - Independent lenses
- Probability $\propto \boxed{\sigma(>\mu) \propto \xi^2 \propto M}$
  - cut by finite size $\mu_{\rm max} = \sqrt{1+4/\eta^2}$
  - dependence through $\eta(z_L, z_S, M)$
  - low mass $\rightarrow$ affects tail





✓ when collective lensing can be neglected.

(?) when <u>strong clustering</u> ($r_{\rm bh} \lesssim \xi$)

(Chisholm '06, but see Ali-Haimoud '18)

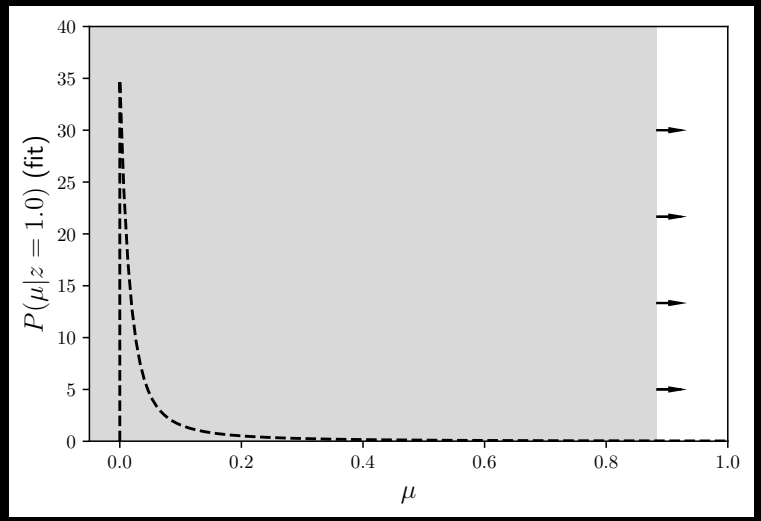
Probability $\propto$ Cross section

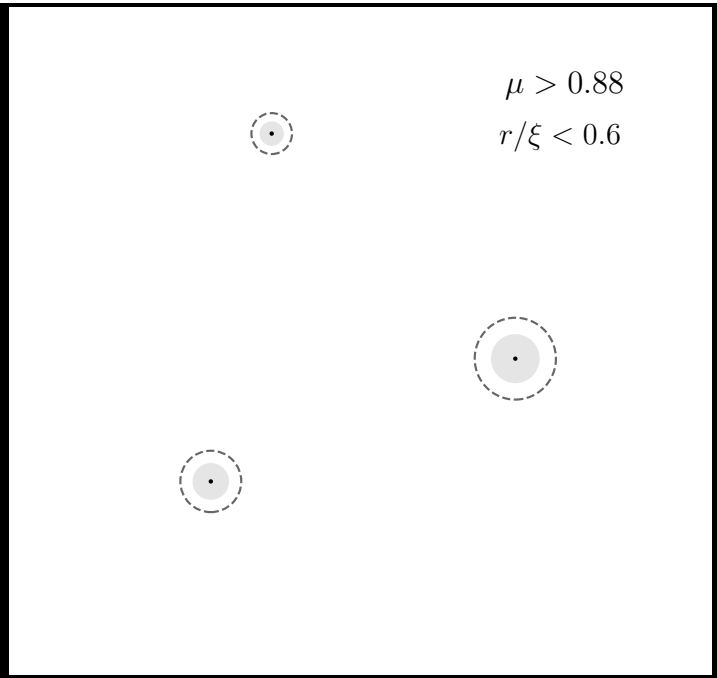
- Approximations (Pei '93)
  - Multiplicative magnification
    $$(1+\mu) = \prod_i (1+\mu_i)$$
  - Independent lenses
- Probability $\propto \boxed{\sigma(>\mu) \propto \xi^2 \propto M}$
  - cut by finite size $\mu_{\rm max} = \sqrt{1+4/\eta^2}$
  - dependence through $\eta(z_L, z_S, M)$
  - low mass $\rightarrow$ affects tail

✓ when collective lensing can be neglected.

(?) when <u>strong clustering</u> ($r_{\rm bh} \lesssim \xi$)

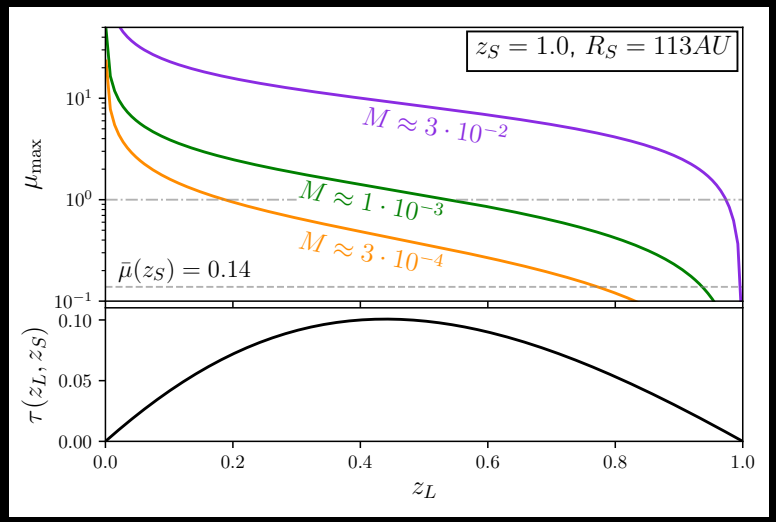
(Chisholm '06, but see Ali-Haimoud '18)

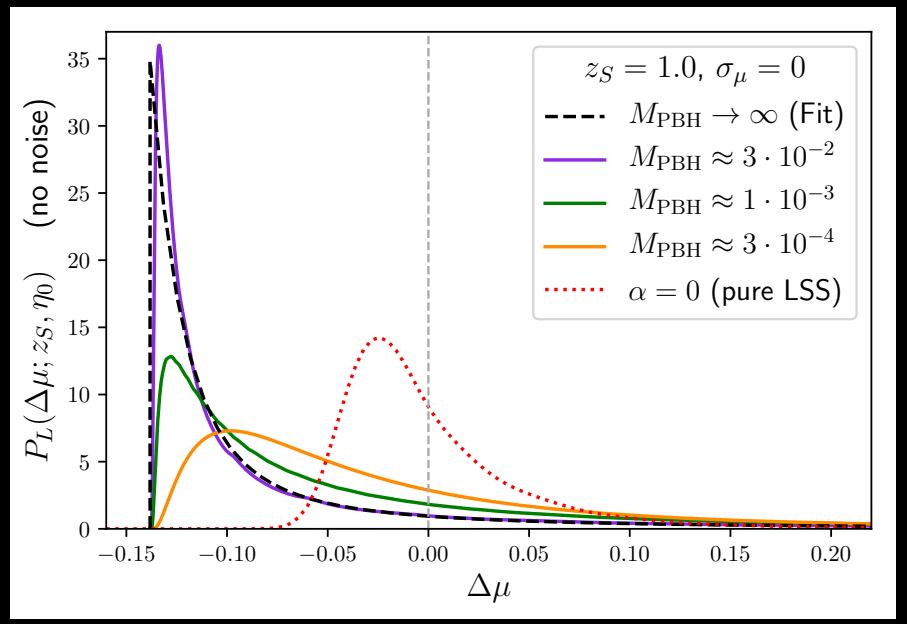




Finite source magnification PDF

(MZ & Seljak *in prep.*)





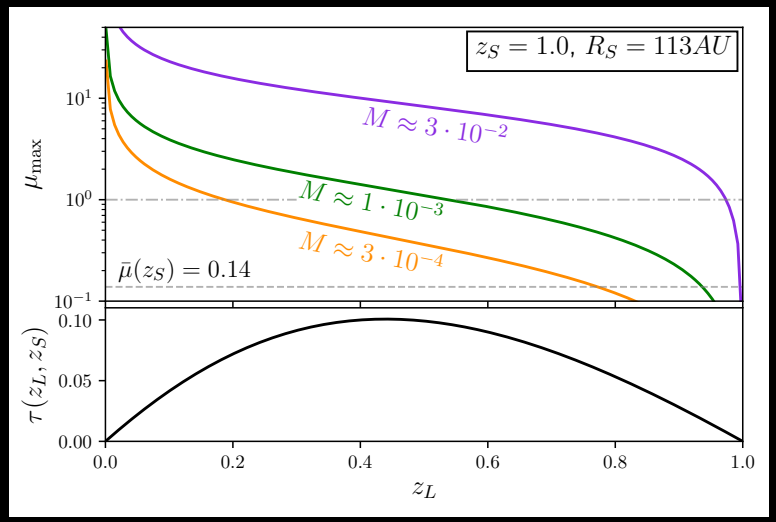
Results valid for $M \gtrsim 0.01 M_\odot$

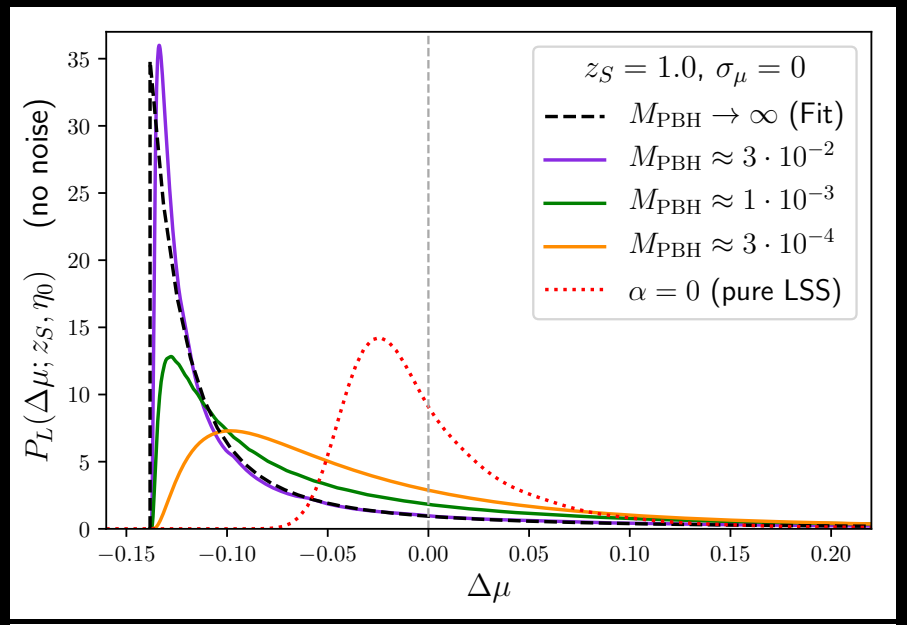
- Demagnification peak $\Delta\mu \sim -\bar{\mu}$

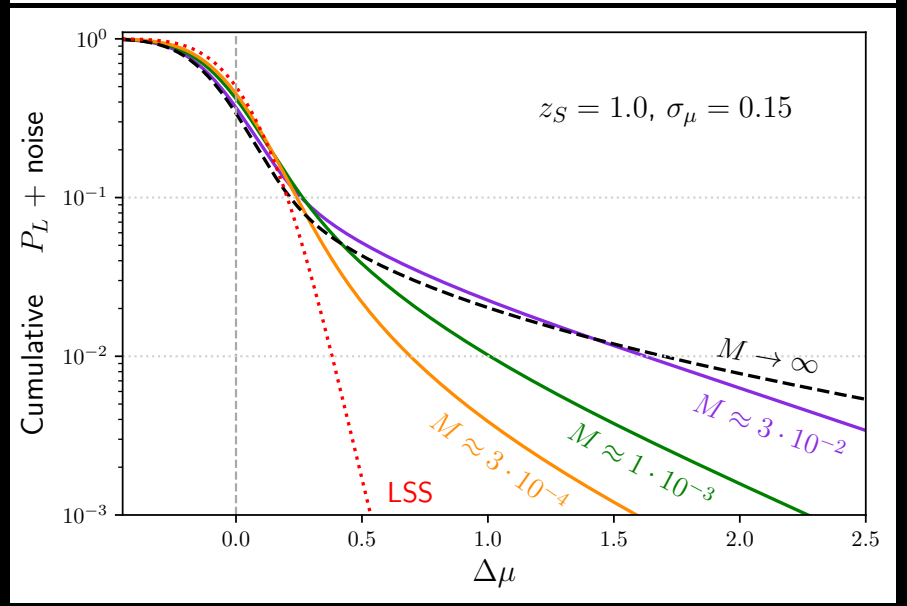
  indistinguishable w. noise ✓

Finite source magnification PDF

(MZ & Seljak *in prep.*)







Results valid for $M \gtrsim 0.01 M_\odot$

- Demagnification peak $\Delta\mu \sim -\bar{\mu}$

  indistinguishable w. noise ✓
- Magnification tail ($\Delta\mu \gtrsim 1$)

  outlier fraction to $\Delta\mu \sim 0.5$ ✓
- Base analysis was conservative:

  $M \sim 10^{-4}$ half way to LSS!