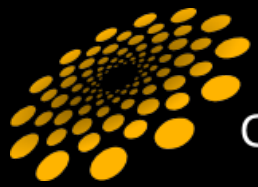
No LIGO MACHO

Primordial Black Holes in Light of Supernova Lensing

Miguel Zumalacárregui



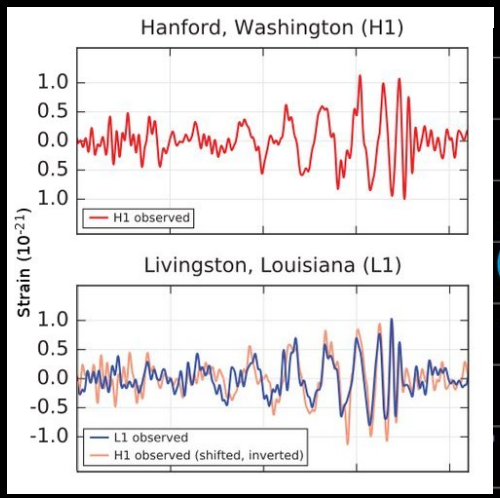
BERKELEY CENTER *for*
COSMOLOGICAL PHYSICS

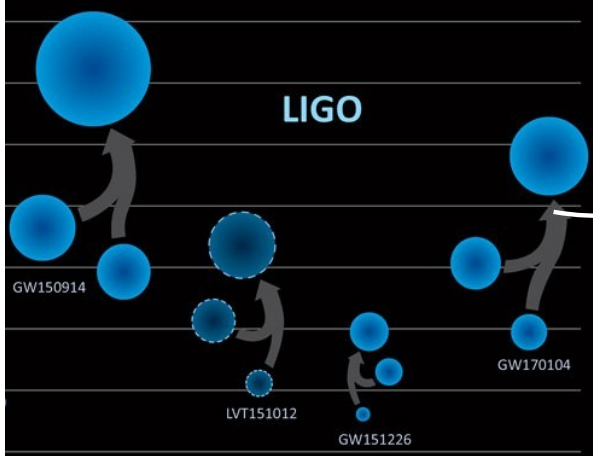
Primordial versus Astrophysical Origin of Black Holes

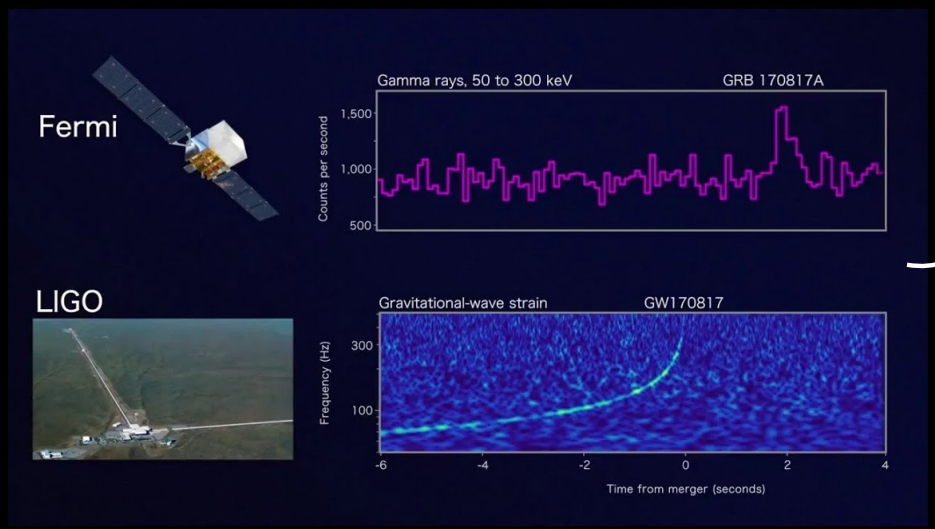
CERN - May 2018

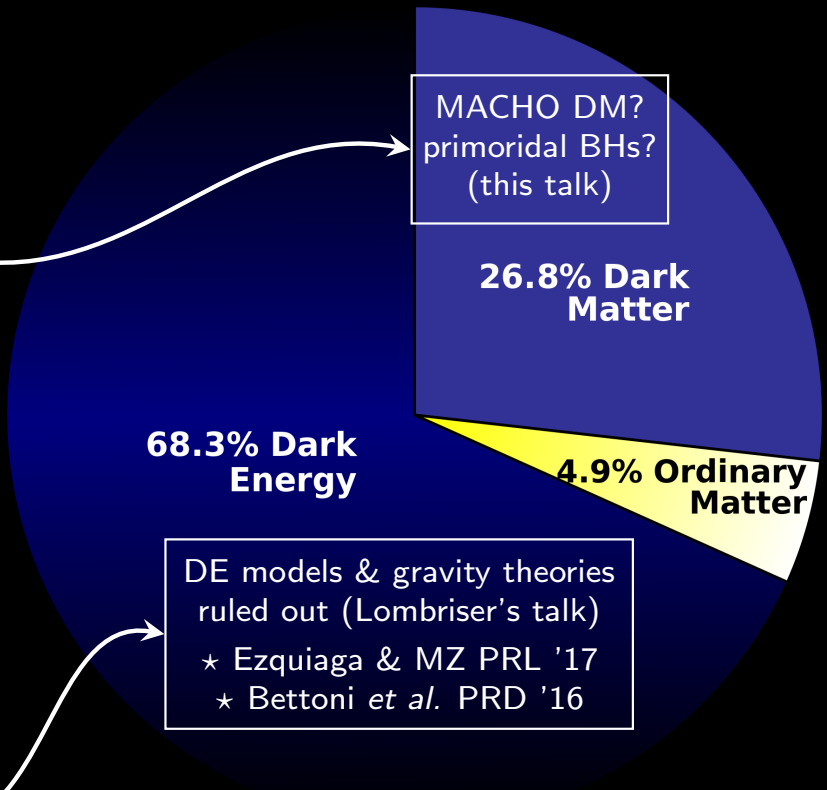
MZ & Seljak (1712.02240)

Gravitational Waves vs ΛCDM









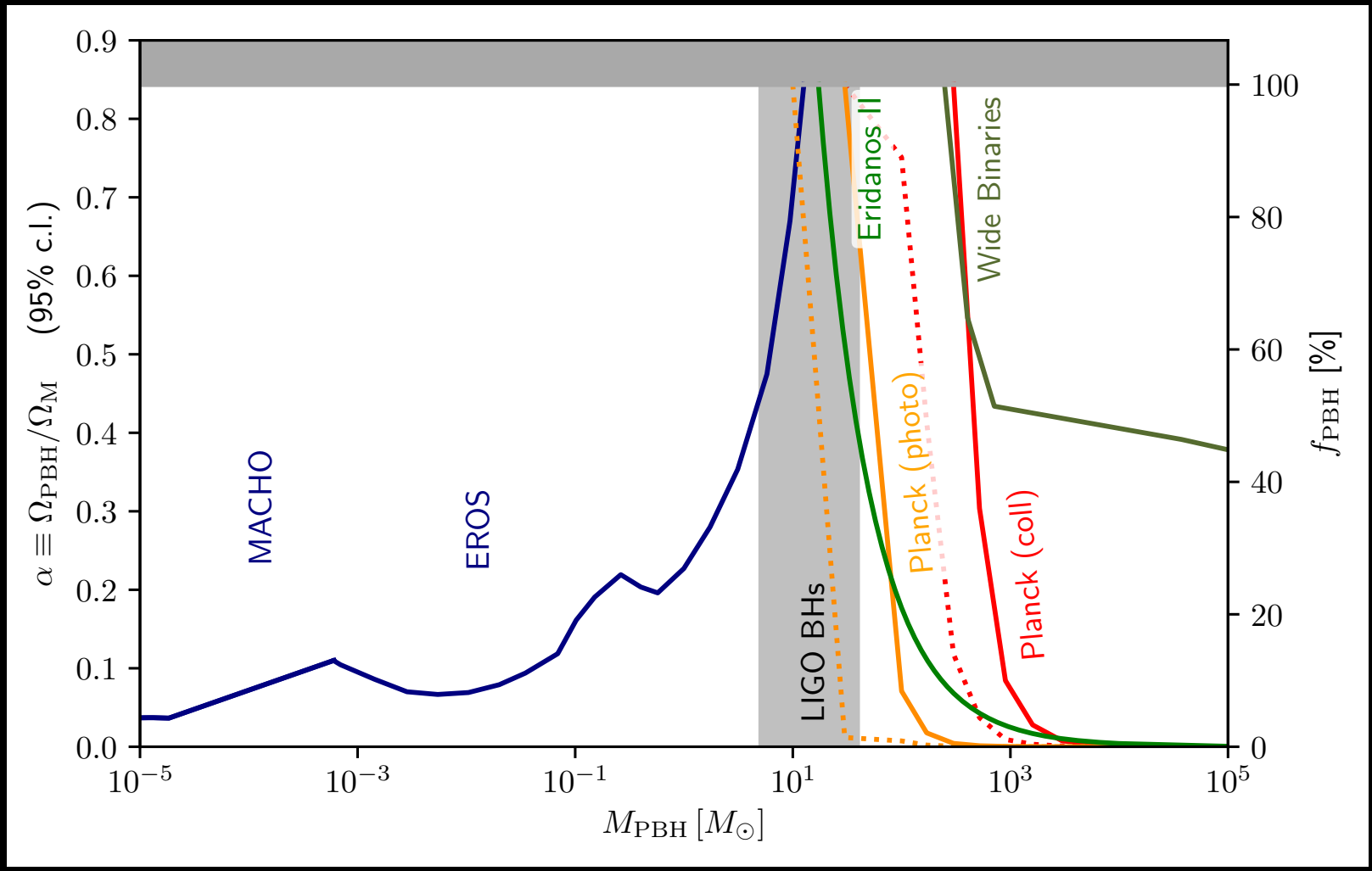
DE models & gravity theories ruled out (Lombriser's talk)

- ⋆ Ezquiaga & MZ PRL '17
- ⋆ Bettoni *et al.* PRD '16

$$
\begin{aligned}
100\Omega_b h^2 &= 2.222 \pm 0.023\ (1.0\%) \\
\Omega_c h^2 &= 0.1197 \pm 0.0022\ (1.8\%) \\
\Omega_\Lambda &= 0.685 \pm 0.013\ (1.9\%)
\end{aligned}
$$

Planck '15 (T+lowP only!)

LIGO MACHO miracle?



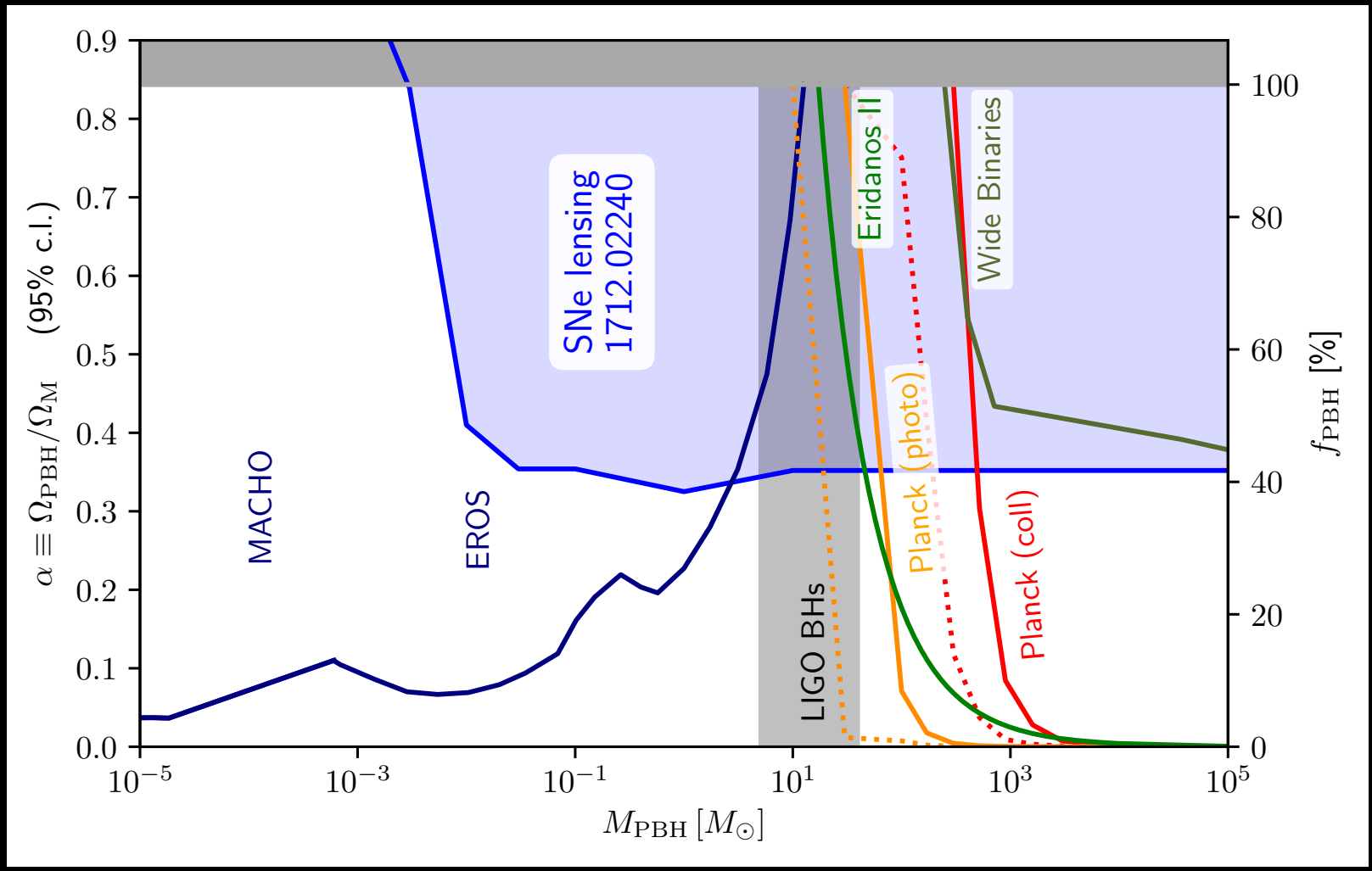
SNe lensing → MZ & Seljak '17

CMB → Bernal+ '17

(Tisserand+ EROS-2, '07)

Reviews: Carr+ '16, Sasaki+ '18)

LIGO MACHO miracle?



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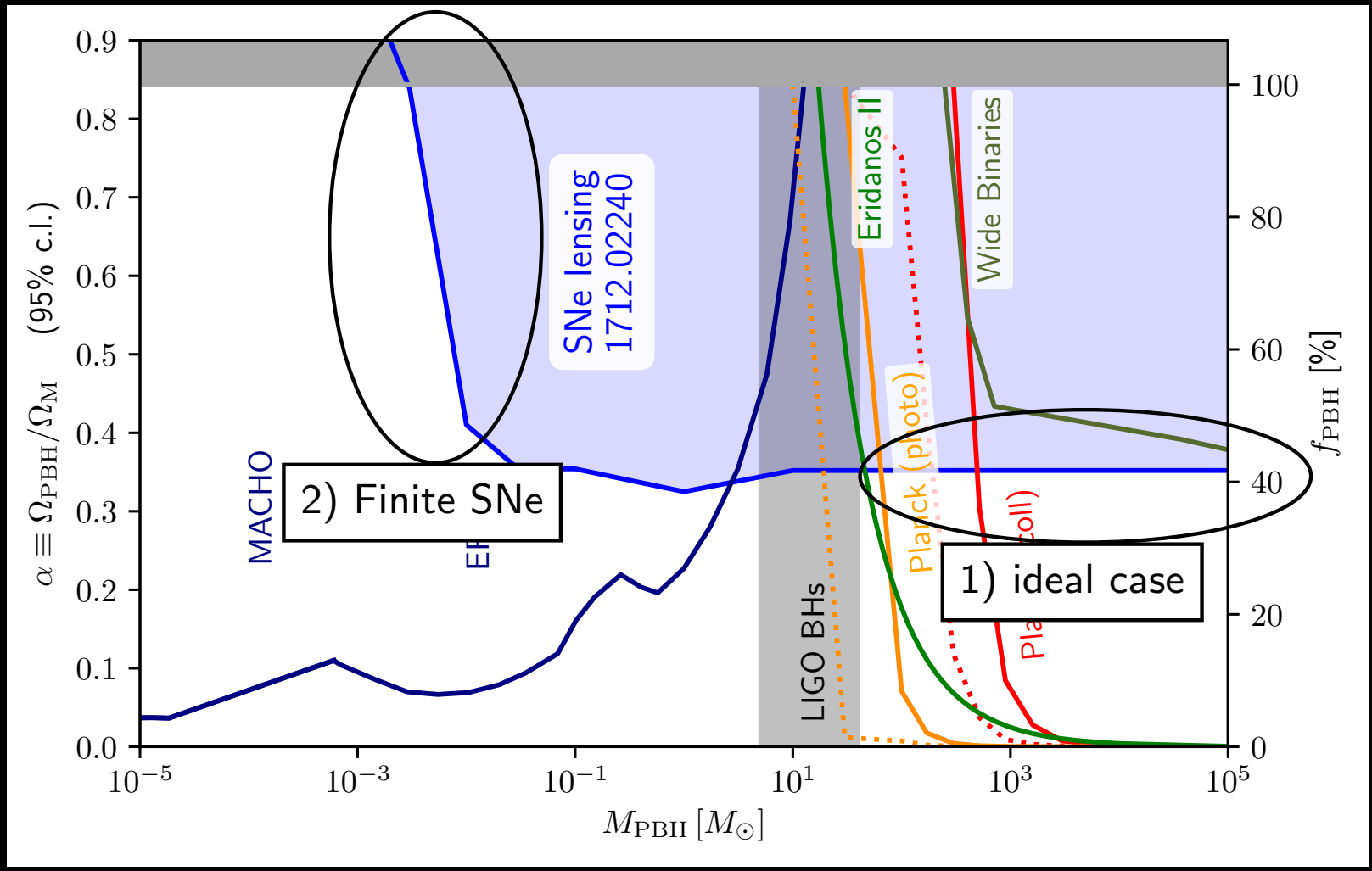

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No LIGO MACHO?

ligar *(verb)*

1. Bind, connnect.
2. [Colloquial] Flirt.

(yo) ligo $\rightarrow$ *I flirt*

macho *(noun)*

1. Male.
2. [Colloquial] Dude, bro.

No LIGO MACHO?

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(MZ & Seljak 1712.02240)

my love life sucks, bro

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(credit: Paramount Pictures 1972, Warner Bros. 1949)

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(MZ & Seljak 1712.02240)

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LIGO Lo(g)-normal MACHO

(Garcia-Bellido+ 1712.06574)

mine's normal, bro

PBH-DM models are still consistent with observations. Nevertheless, we believe that the idea of using SN lensing to *detect* such PBH population is very promising and worth pursuing with future surveys like DES, LSST and Euclid.

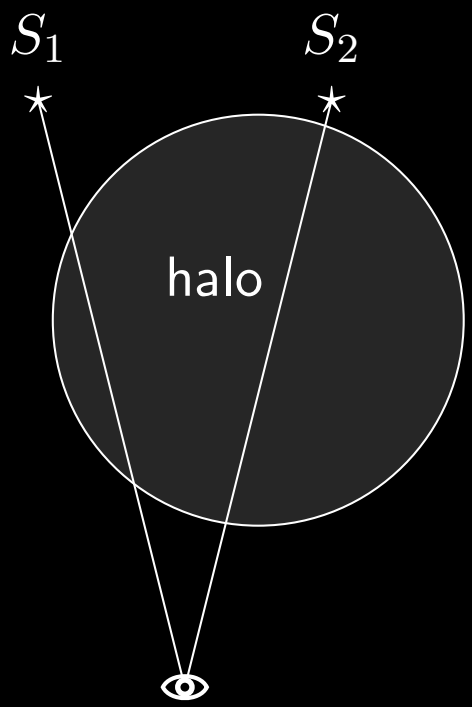
(↪ from Garcia-Bellido+ '17)

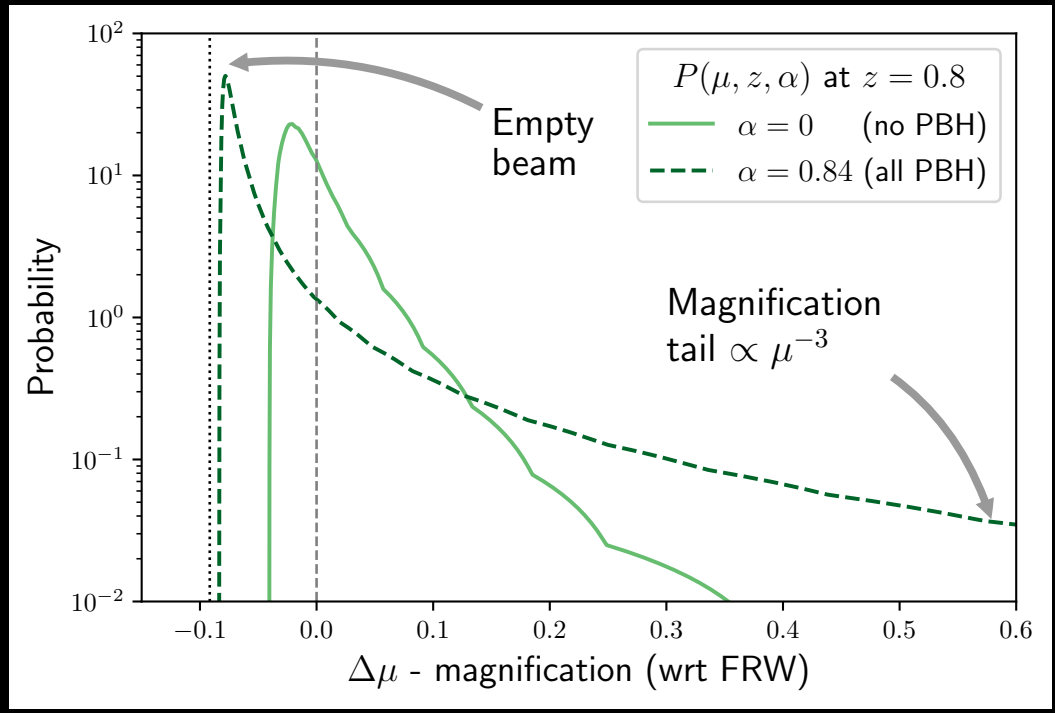
(credit: Paramount Pictures 1972, Warner Bros. 1949)

Lensing by compact objects (Rauch '91, Seljak & Holz '99, Metcalf & Silk '06)

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

Distance (perceived)
Magnification





PBH signatures: $\begin{cases} \text{slight demagnification (most sources)} \\ \text{highly magnified events (few sources)} \end{cases}$

$\rightarrow$ Different & complementary to stellar microlensing

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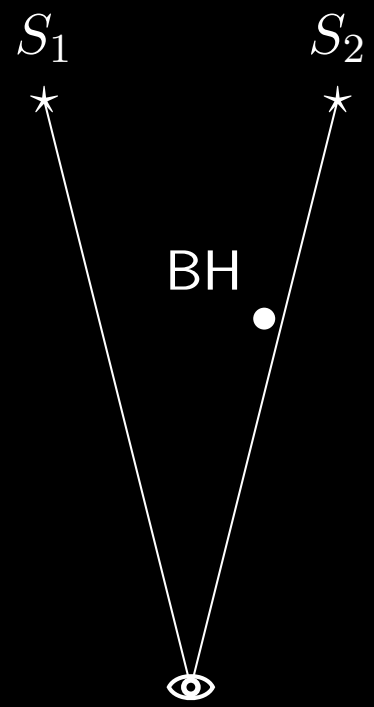

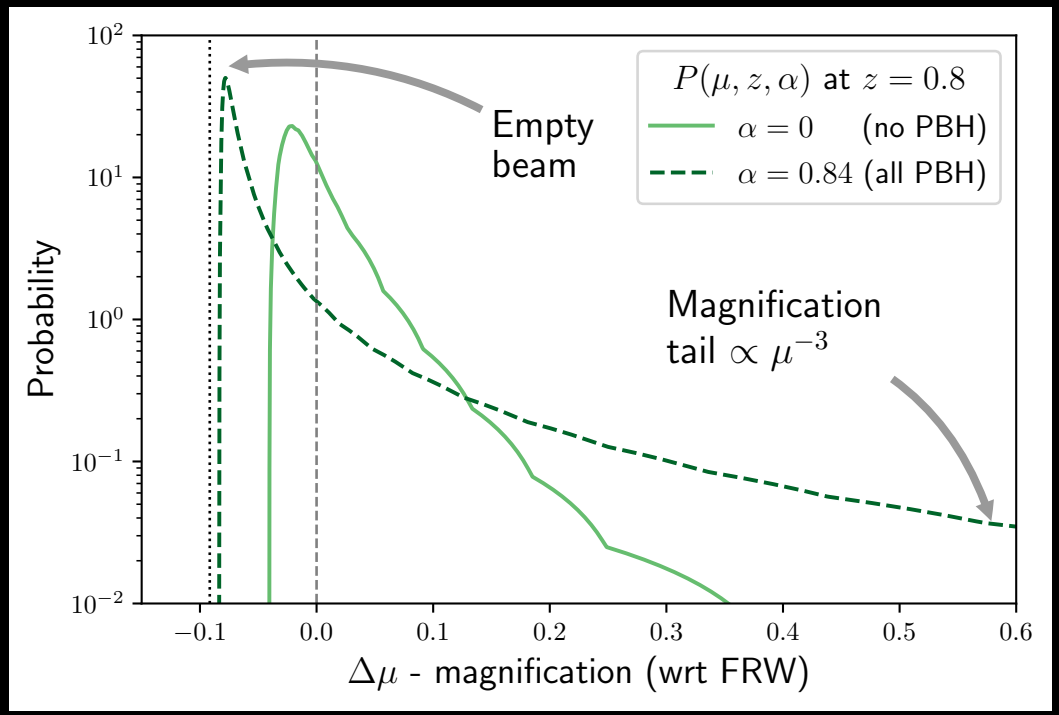

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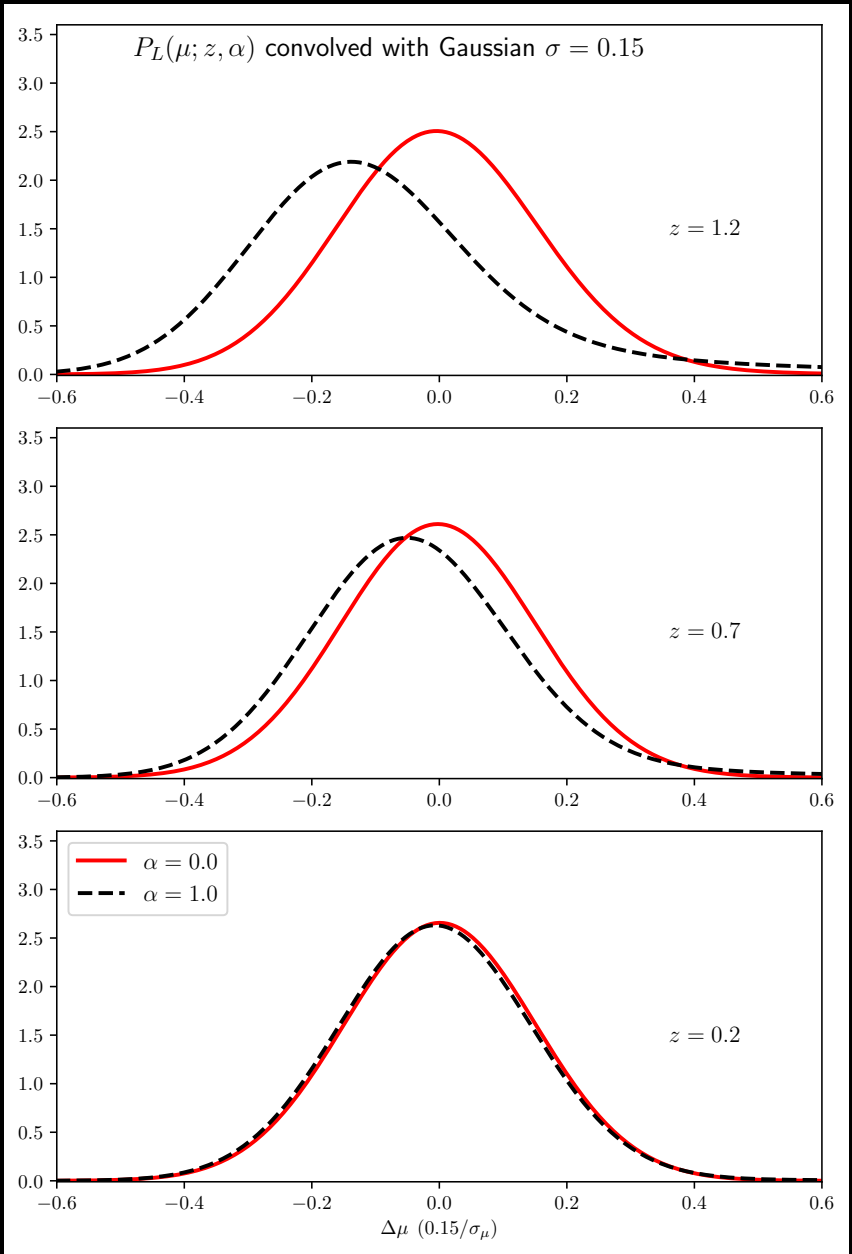
SNe Magnification

(MZ & Seljak '17)



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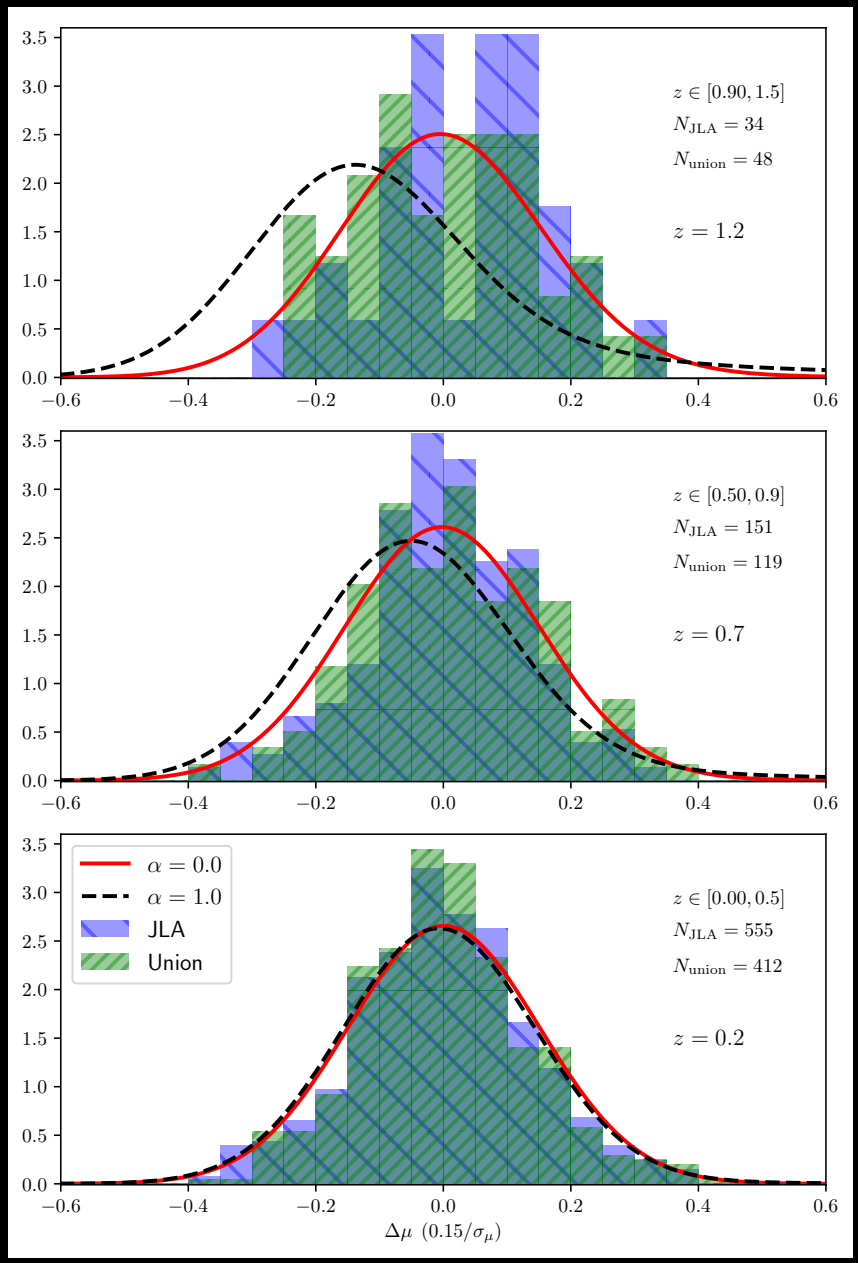

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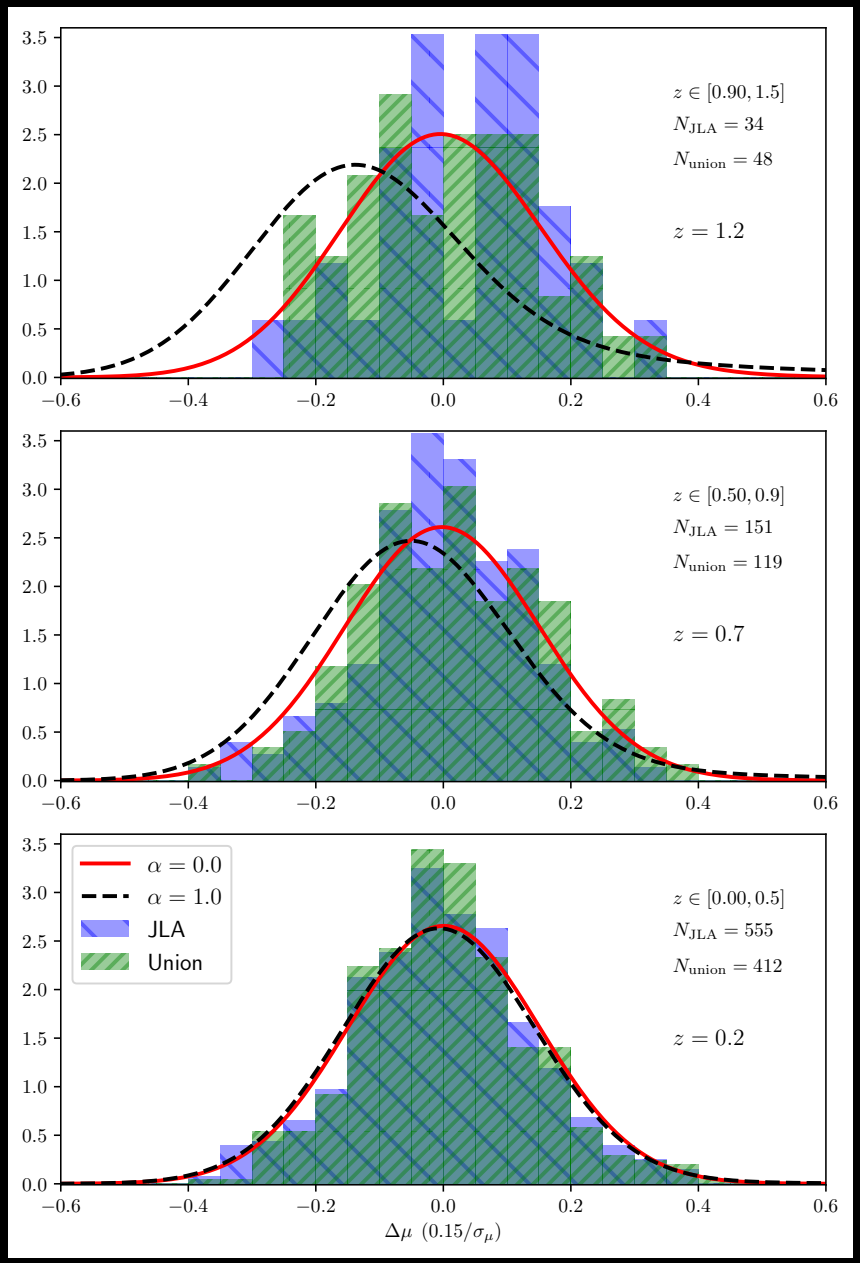
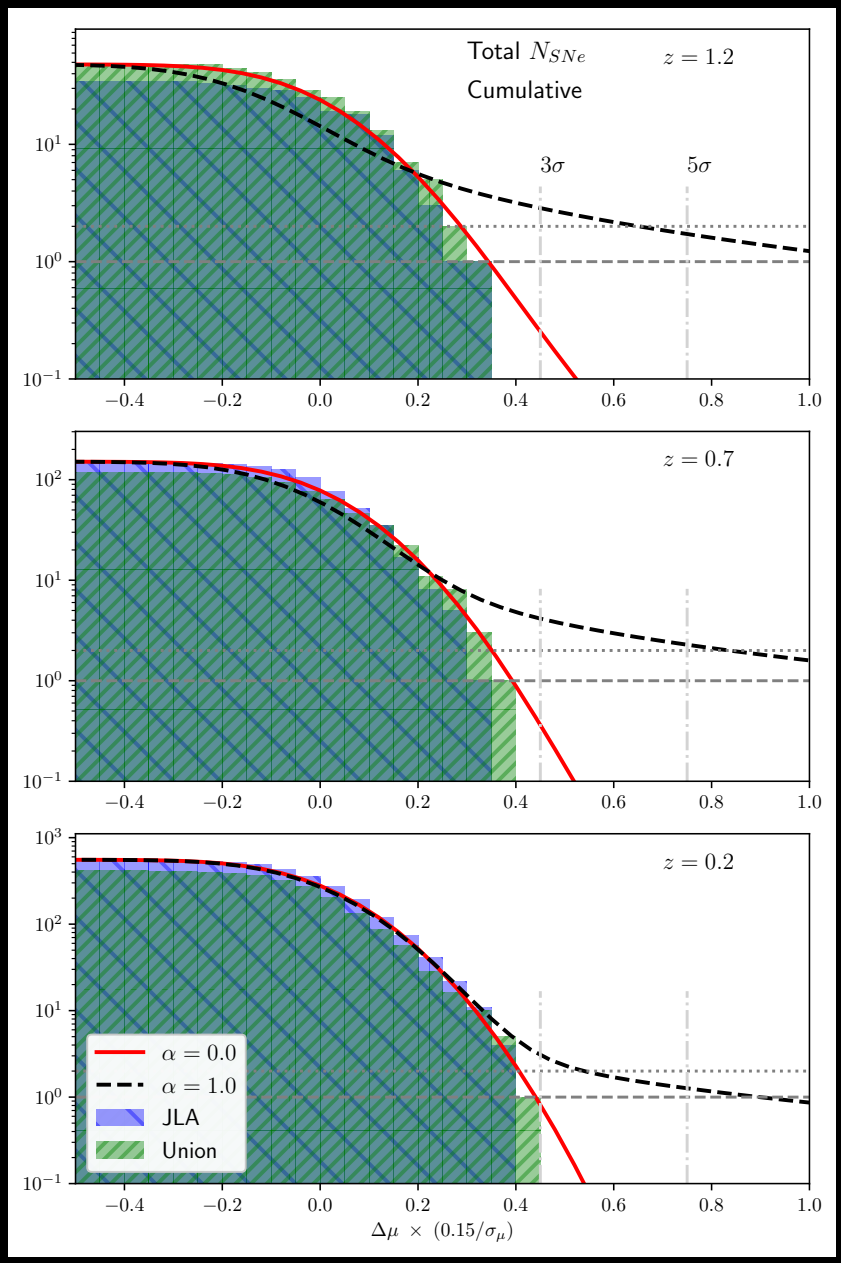




Likelihood

$$m_{th} = 5\log_{10}\left(\bar{D}_L(z)\right) - 2.5\log_{10}(1+\Delta\mu) + 25$$

$$L_i(\vec{\theta},\alpha) = \int d\mu P_L(\Delta\mu; z_i, \alpha) P_{SNe}(m_i, \sigma_i, z_i, m_{th}, \vec{\theta})$$

SNe distribution

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

$$\sigma_i^2 = \sigma_{ob,i}^2 + k_2 - \sigma_L^2(z)$$

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

$\theta \supset$ mean ($\bar{m}$), intrinsic scatter (k_2), skewness (k_3), kurtosis ($k4$),

standardization $m_{ob,i} = m^{\star}_{B,i} - (M_B - \alpha X_{1,i} + \beta C_i)$

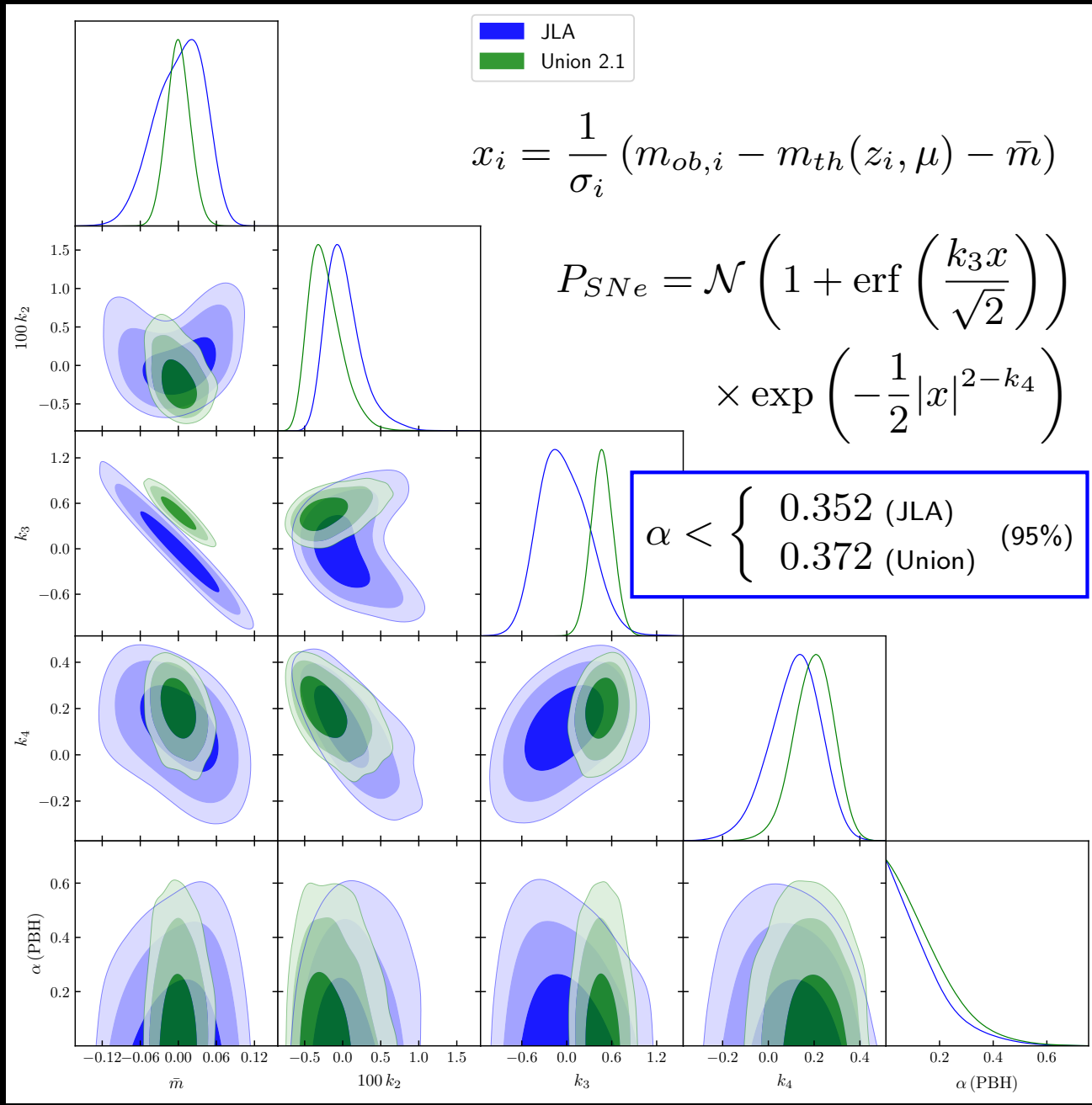
Results

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)

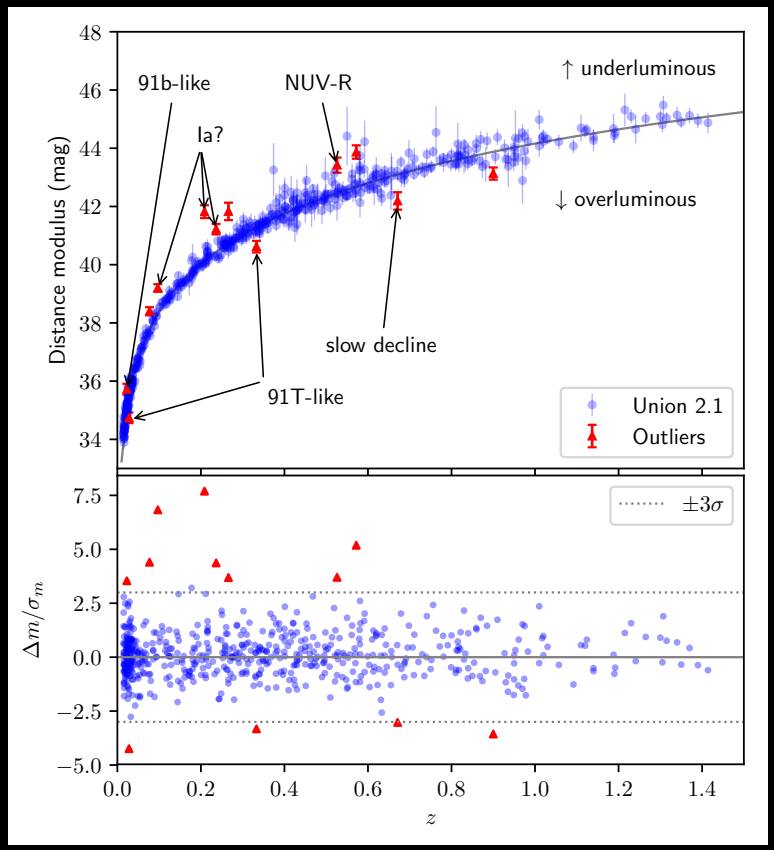


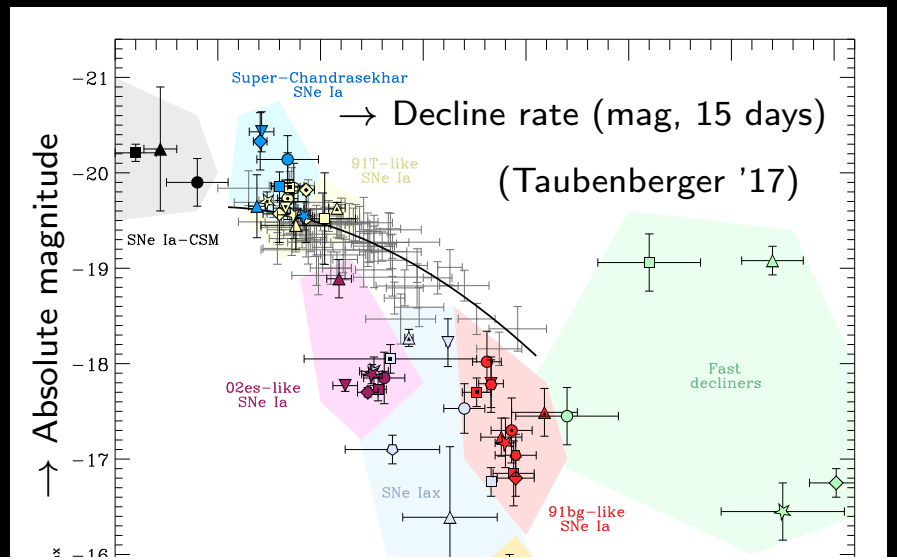
$$x_i = \frac{1}{\sigma_i}\left(m_{ob,i} - m_{th}(z_i,\mu) - \bar{m}\right)$$

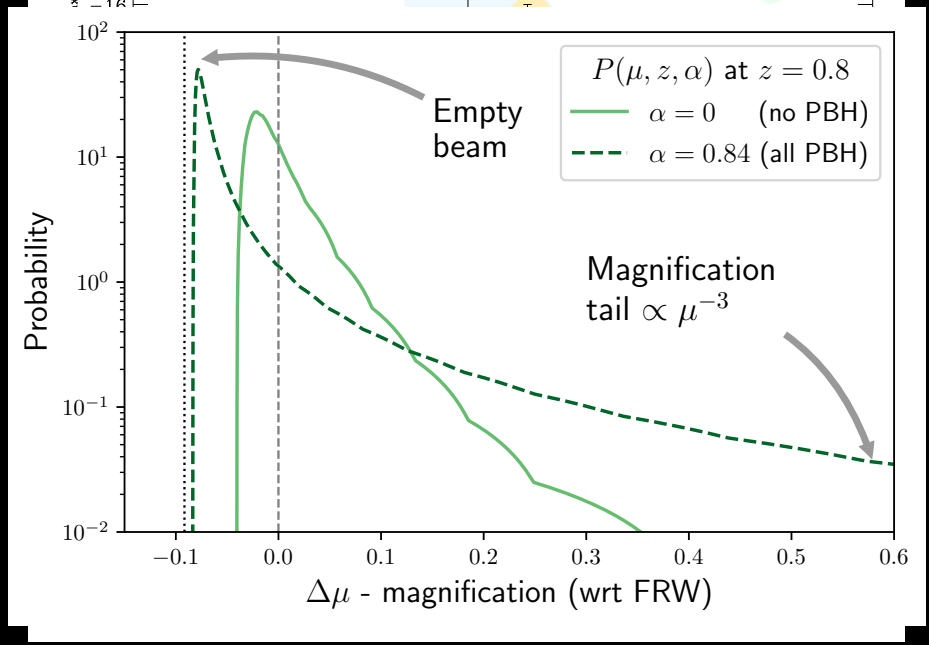
$$P_{SNe} = \mathcal{N}\left(1 + \mathrm{erf}\left(\frac{k_3 x}{\sqrt{2}}\right)\right) \times \exp\left(-\frac{1}{2}|x|^{2-k_4}\right)$$

$$\alpha < \begin{cases} 0.352\ \text{(JLA)} \\ 0.372\ \text{(Union)} \end{cases} \quad (95\%)$$

Highly-magnified events or peculiar SNe?







Outliers in Union 2.1

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

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

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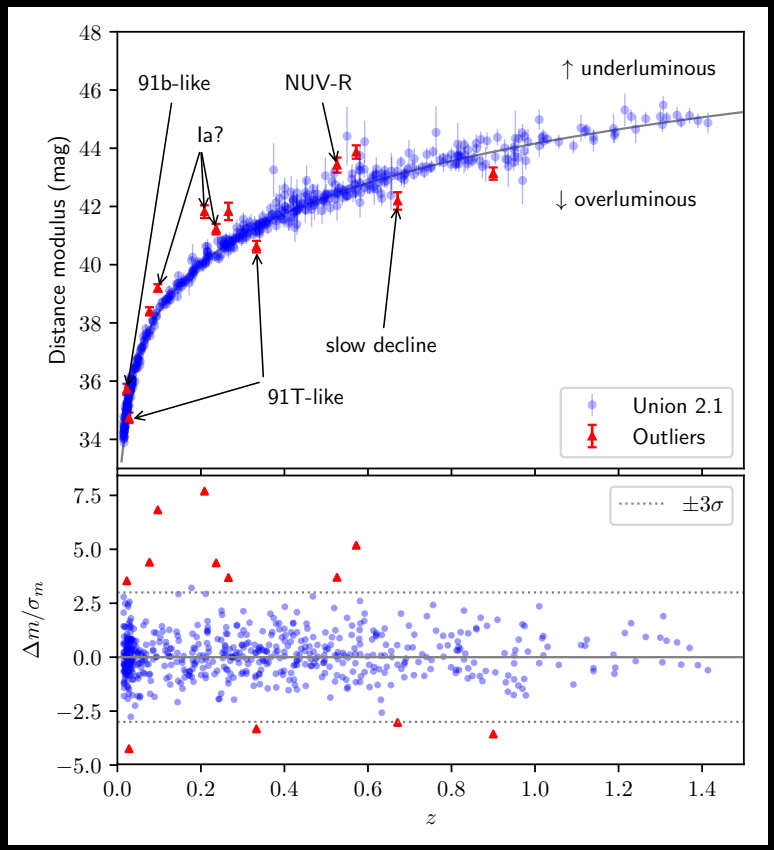

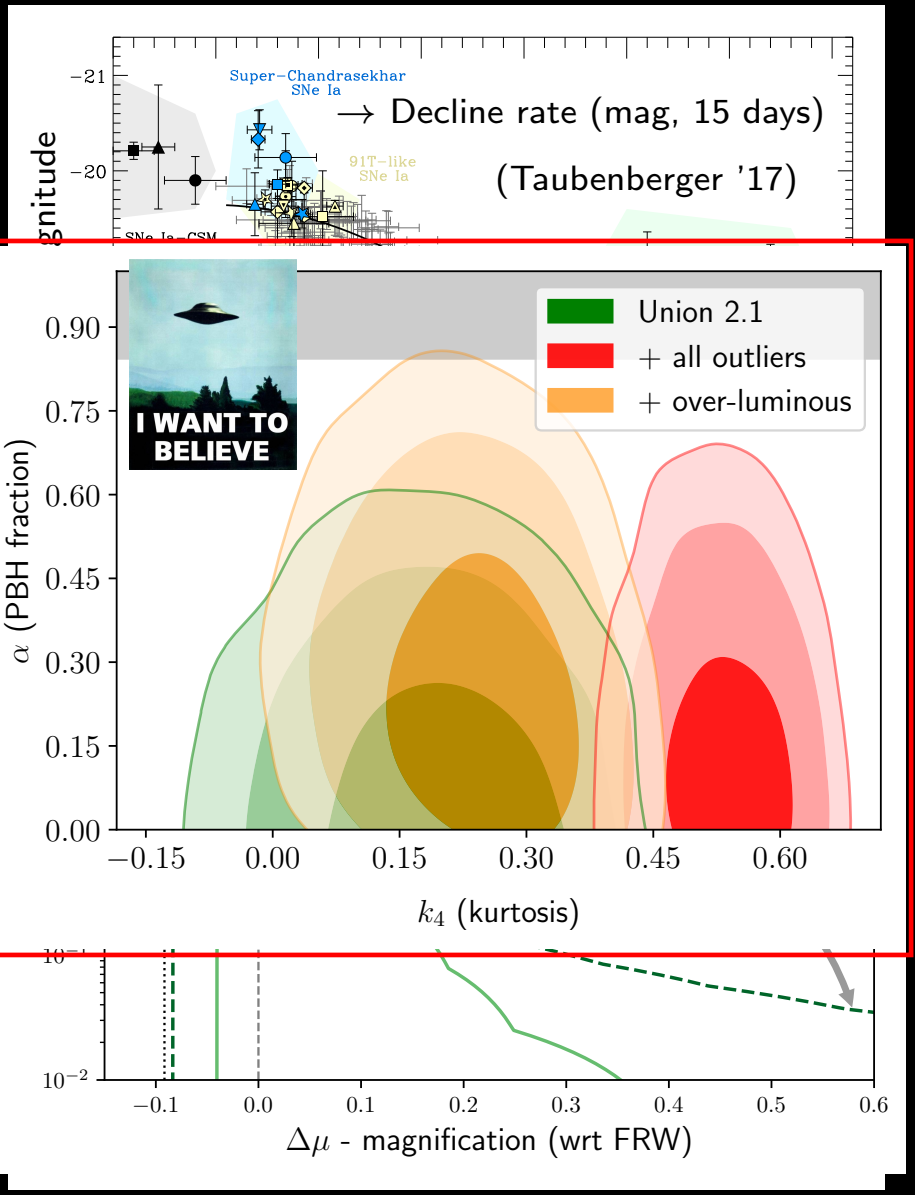

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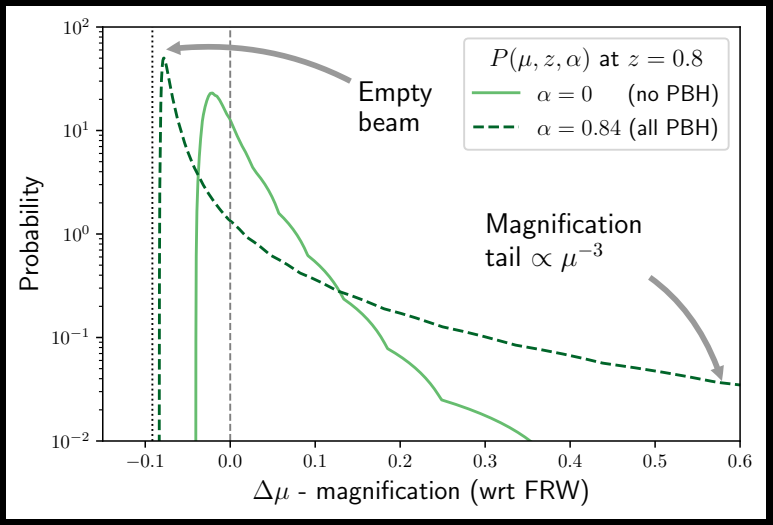
Cosmology Dependence

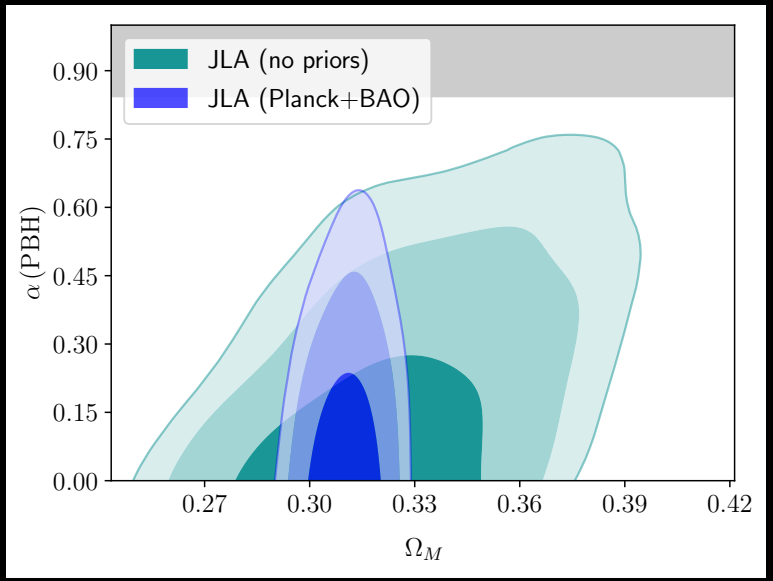
Assumed flat ΛCDM

- 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



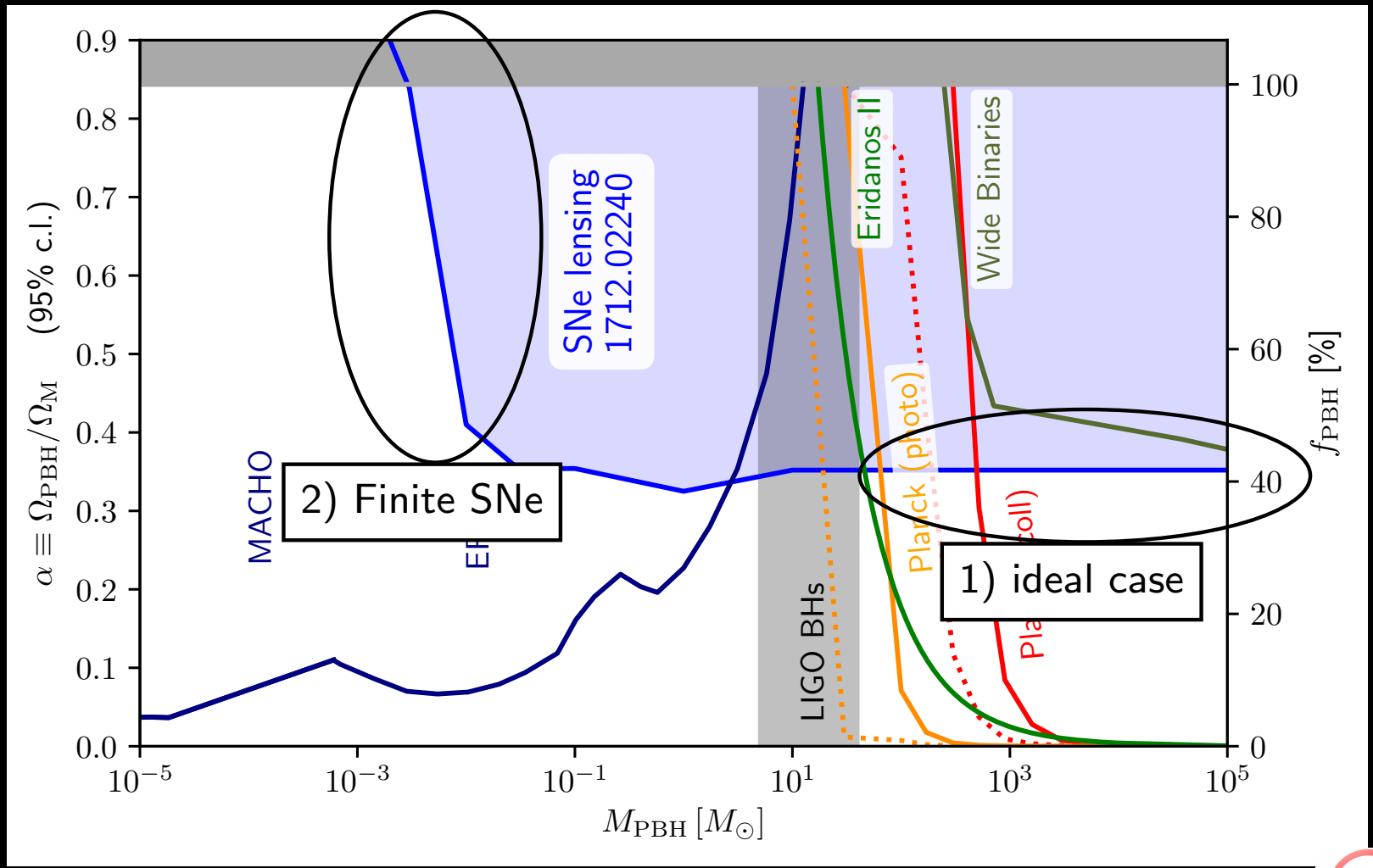


No Ω_M prior

- 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!

Source size vs Lens Mass



Errors/typos in Sec. IIC. New version coming ⇒ Basic results hold

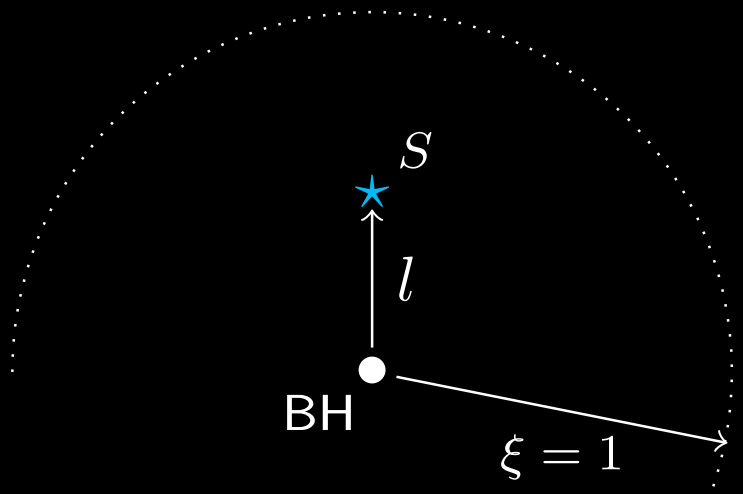
Finite sources (Pei '93)

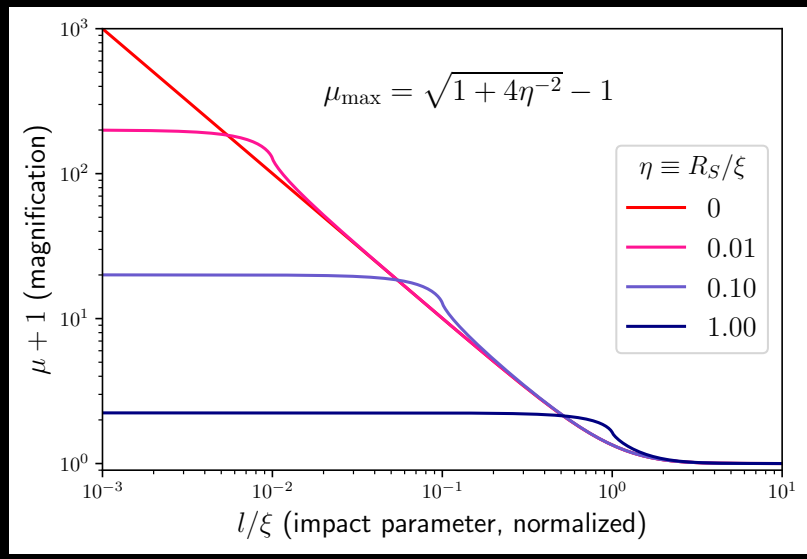
- Point lens + point source

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

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

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





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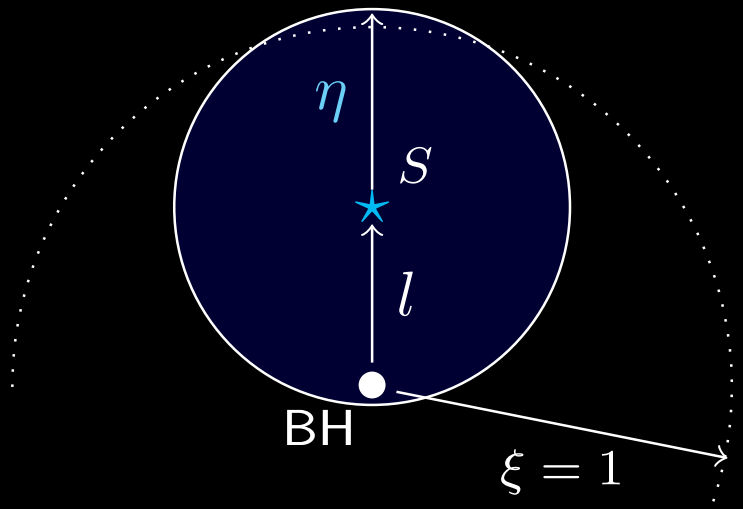

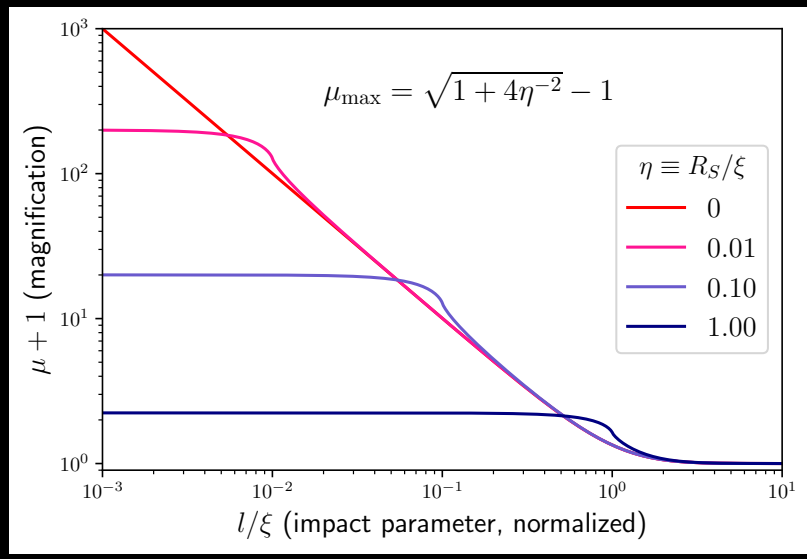

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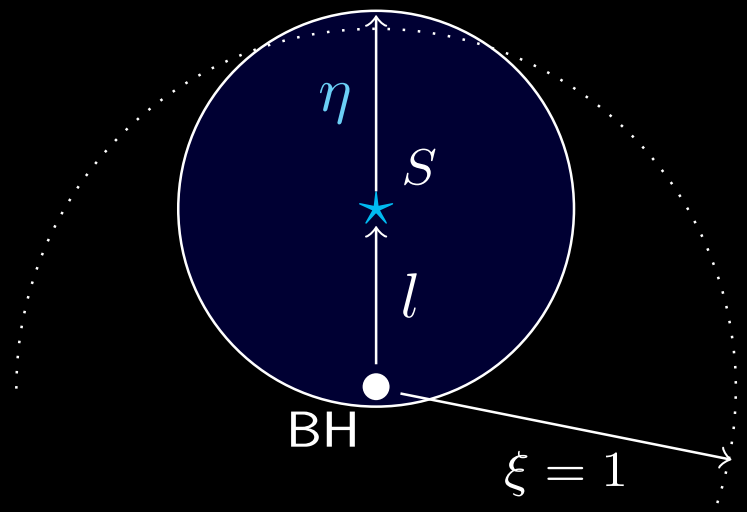
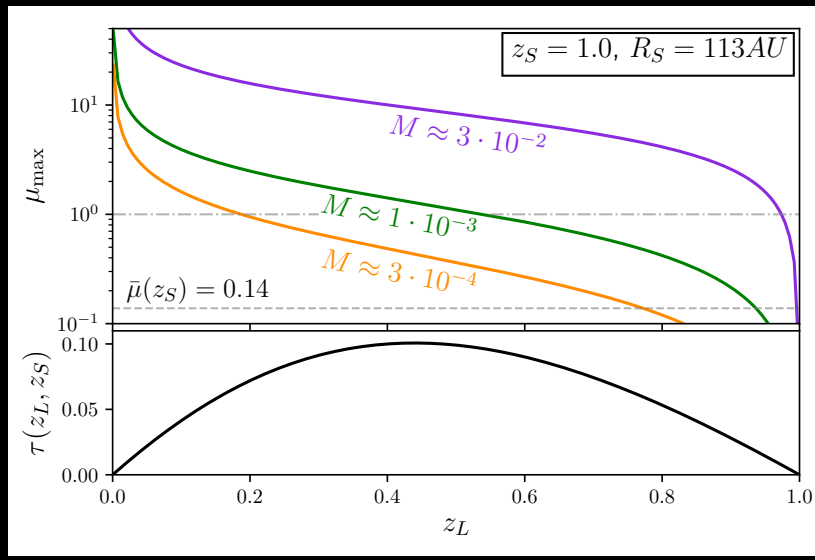
- z-dependence

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

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

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





Probability $\propto$ Cross section

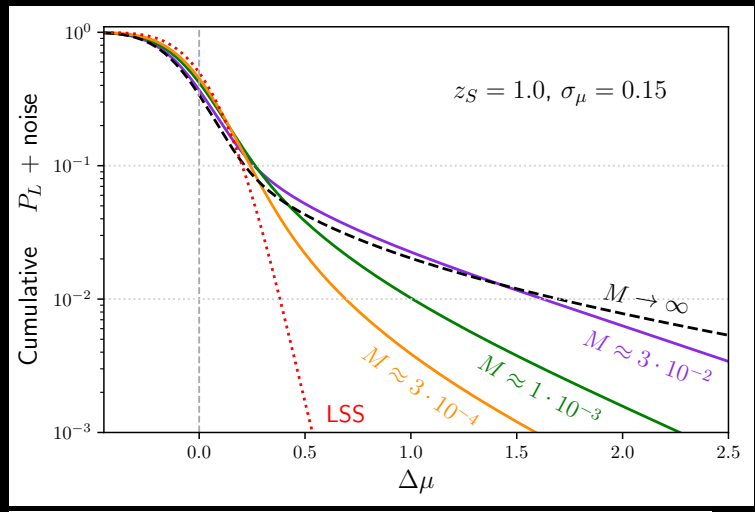
- Approximations (Pei '93)
  - Multiplicative magnification

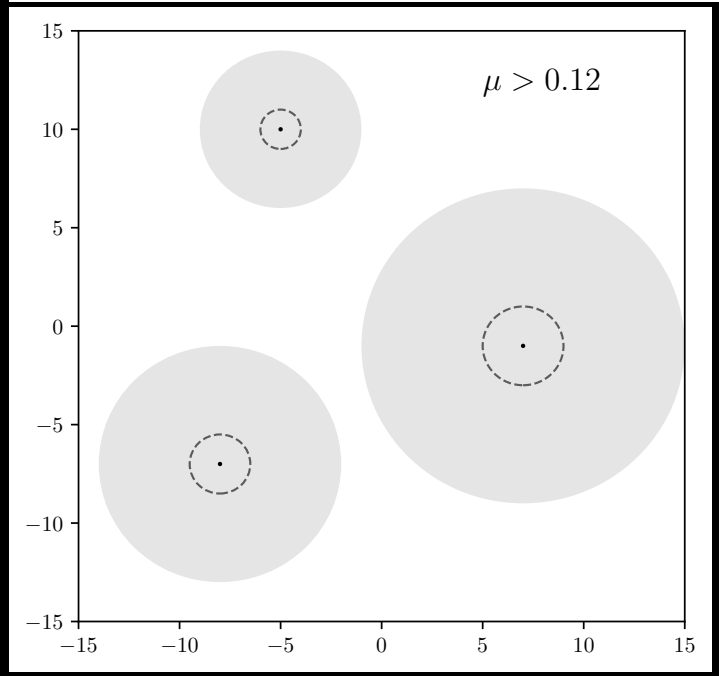
$$(1+\mu) = \prod_i (1+\mu_i)$$

  - 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 strong clustering ($r_{\rm bh} \lesssim \xi$)





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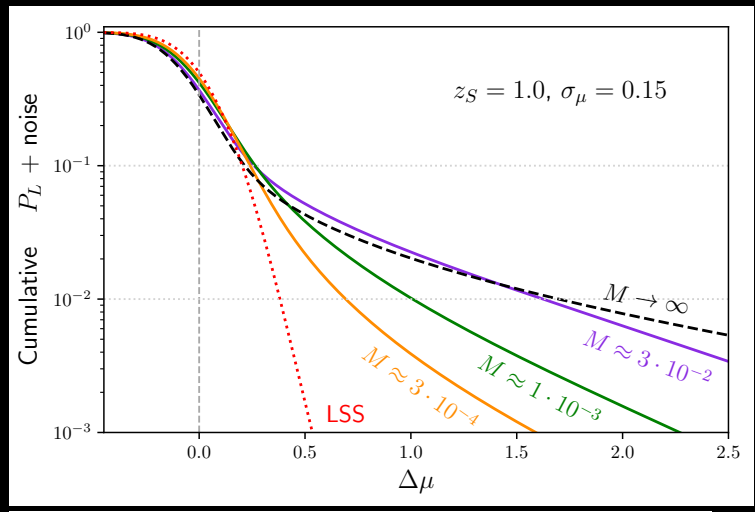

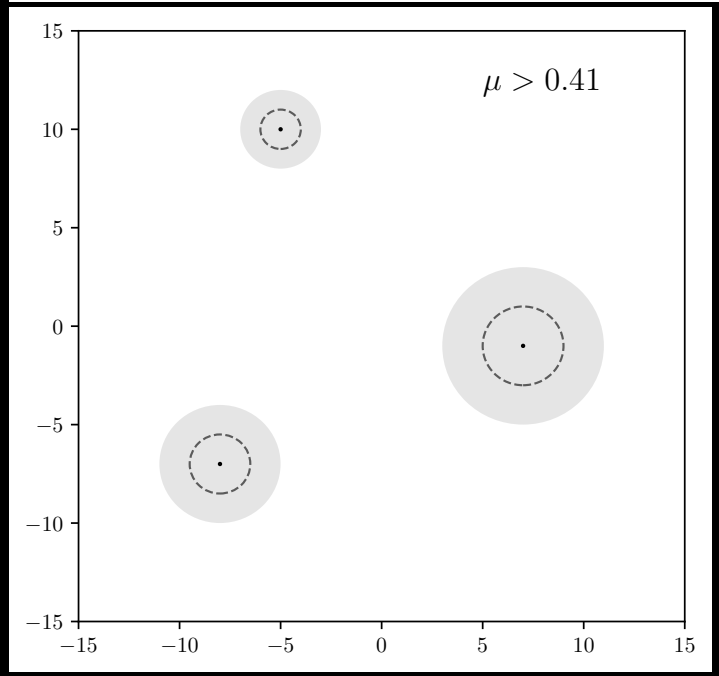

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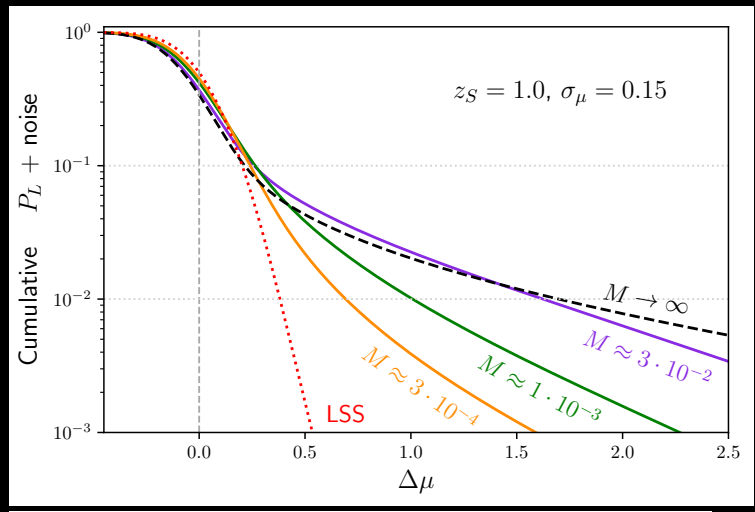
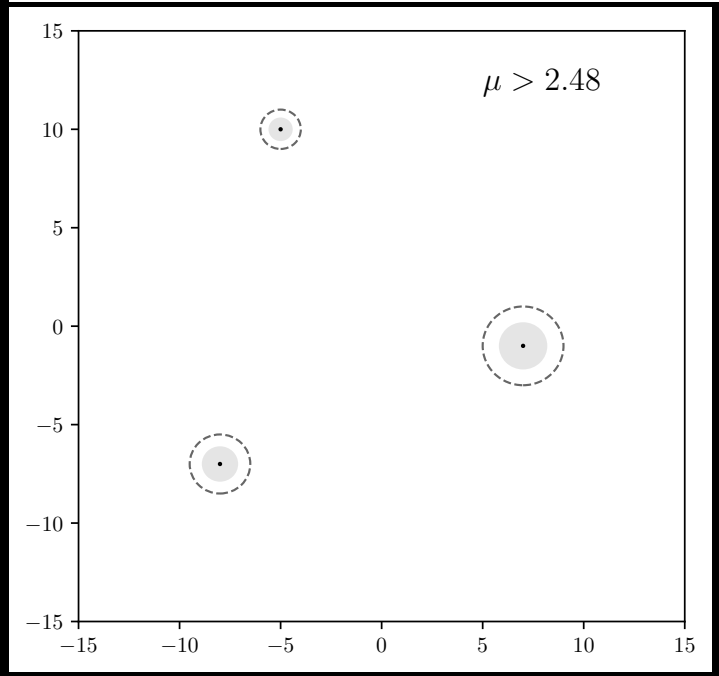
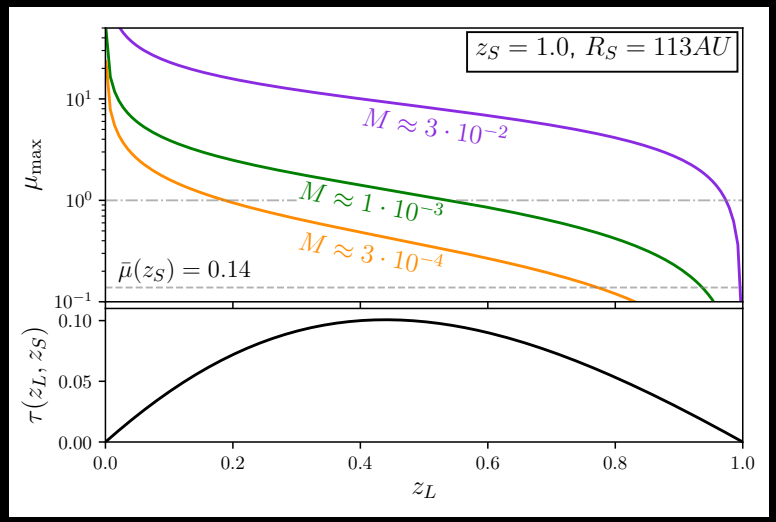
(?) when strong clustering ($r_{\rm bh} \lesssim \xi$)

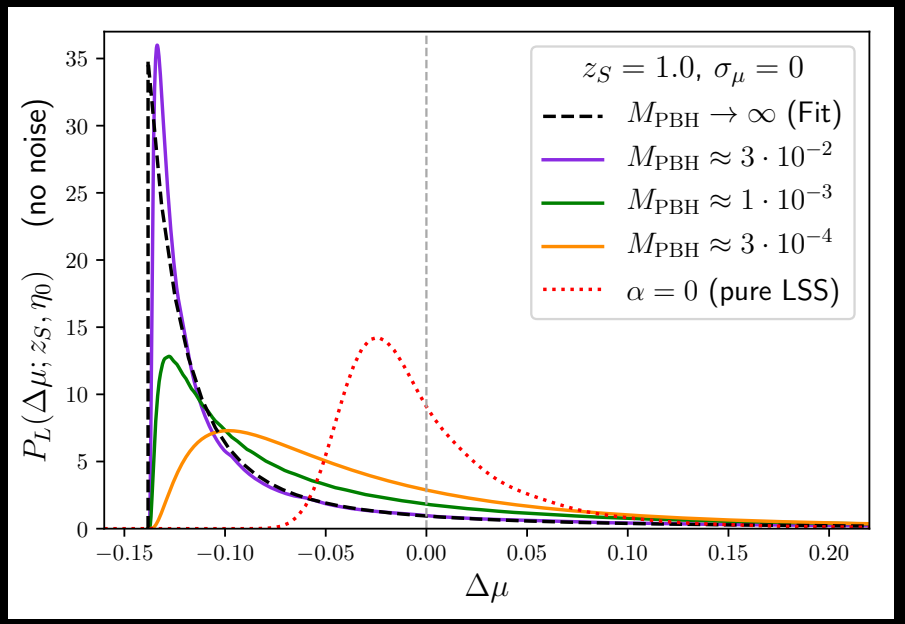




Finite source magnification PDF

(MZ & Seljak *in prep.*)





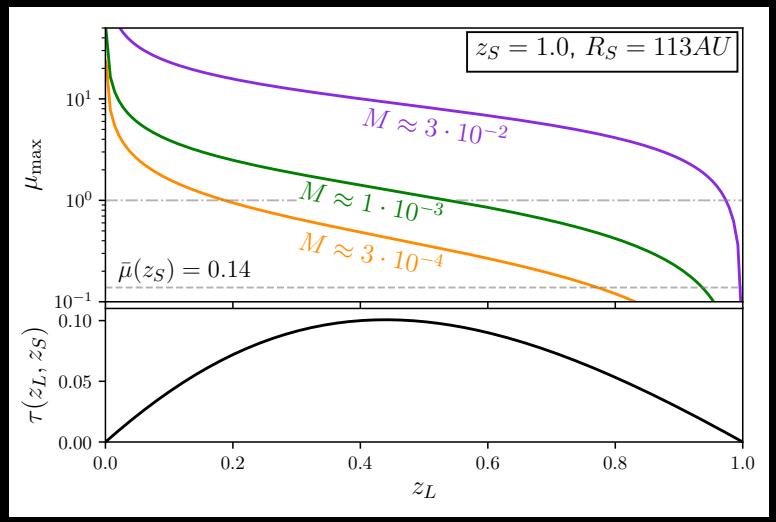
Results valid for $M \gtrsim 0.01 M_\odot$

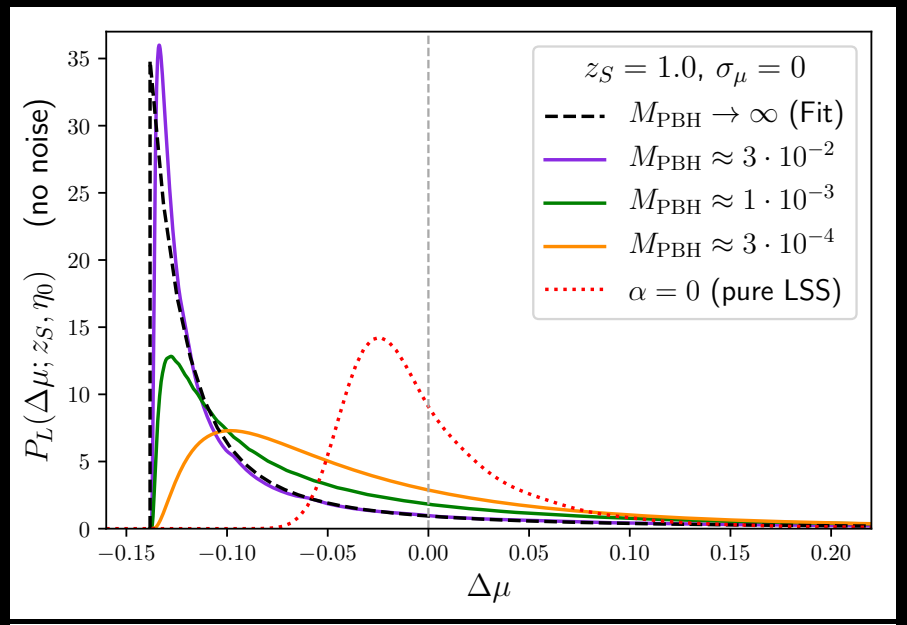
- Demagnification peak $\Delta\mu \sim -\bar{\mu}$

  indistinguishable w. noise ✓

Finite source magnification PDF

(MZ & Seljak *in prep.*)





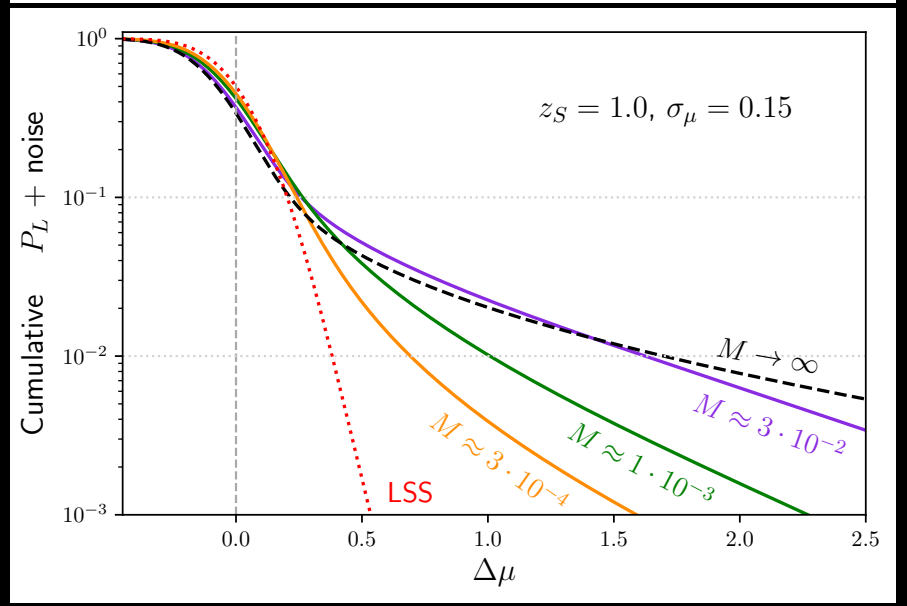
Results valid for $M \gtrsim 0.01 M_\odot$

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

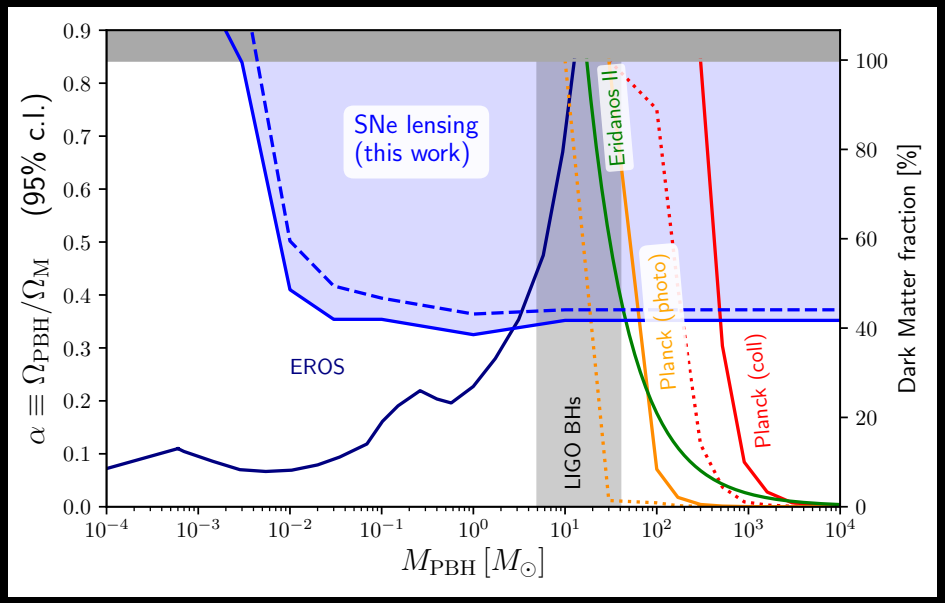
  indistinguishable w. noise ✓
- Magnification tail ($\Delta\mu \gtrsim 1$)

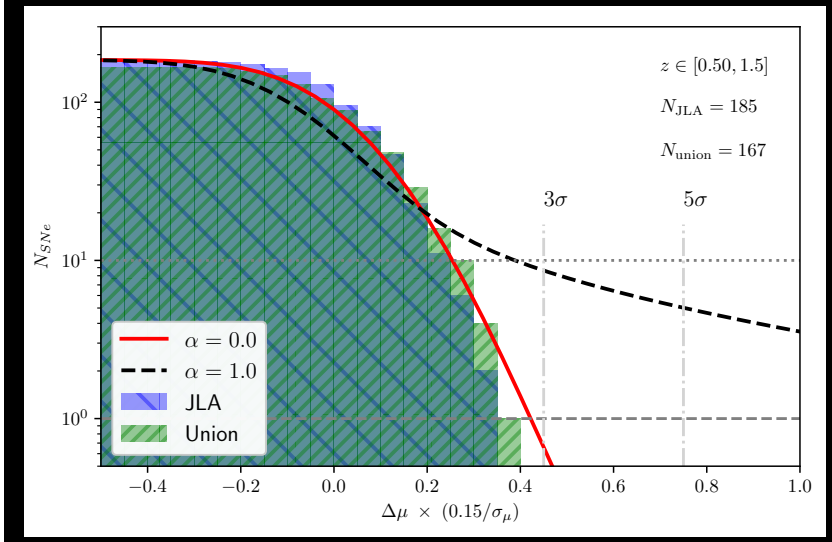
  outlier fraction to $\Delta\mu \sim 0.5$ ✓
- Base analysis was conservative:

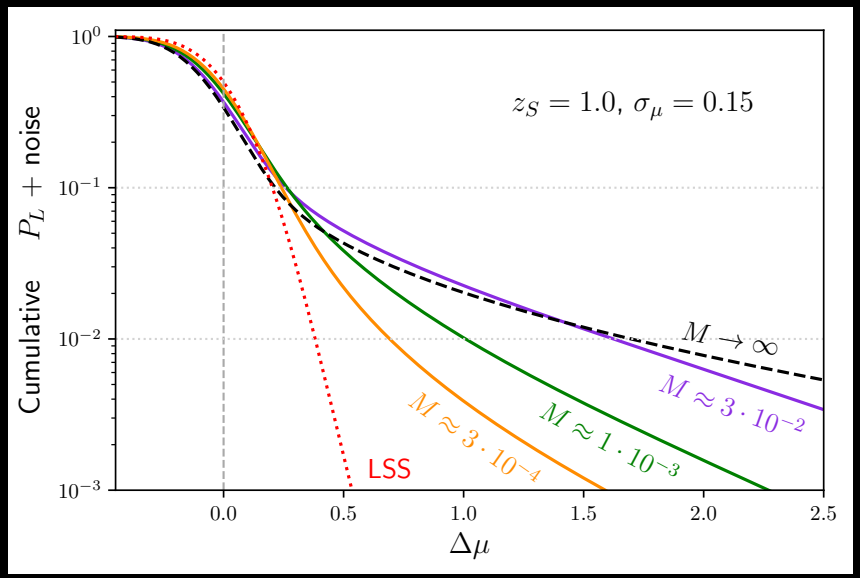
  $M \sim 10^{-4}$ half way to LSS!



No LIGO MACHO (size matters, conclusion stands)







- $\dfrac{\Omega_{\rm PBH}}{\Omega_M} < 0.35$ (95% c.l. JLA)

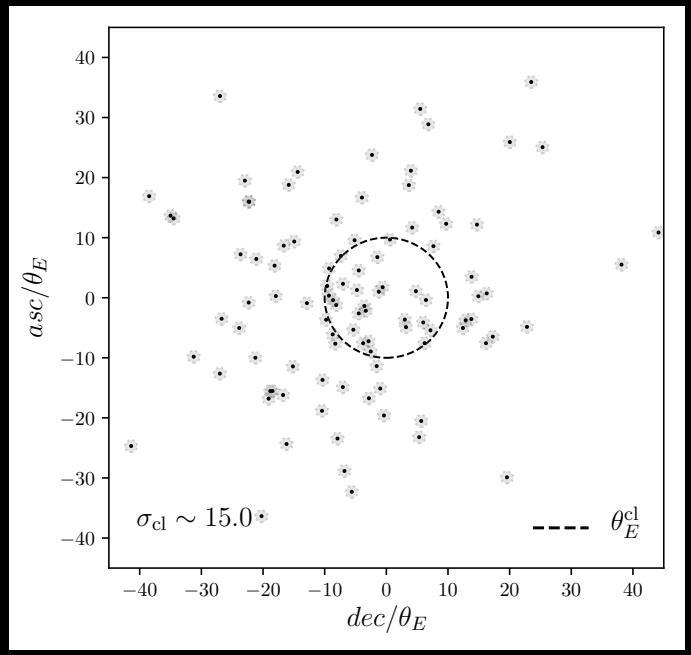
  100% DM excluded at 4.8σ!
- Finite SNe $\rightarrow M \gtrsim 0.01 M_\odot$
- Robust against outliers, cosmology, correlated noise
- Hope for clustered PBHs?

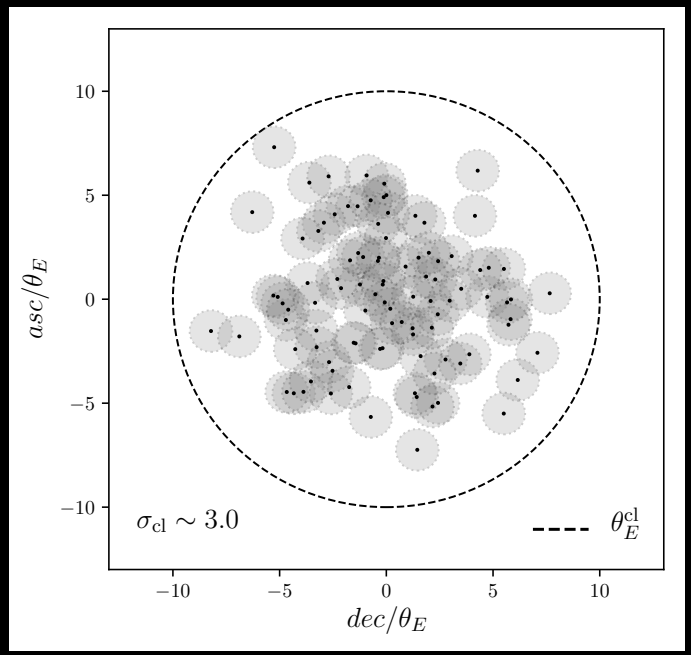
Clustering *might be* important*

- Weak clustering included by convolution with $P_{\rm LSS}(\mu)$
- Collective lensing effects not included: caustics, demagnification $\mu < 0$...
- Two limits with similar results
  - Sparse PBHs ($r_{\rm bh} \gg \xi$)
  - Compact cluster ($R_{\rm cl} \lesssim \xi_{\rm cl}$) $\sim$ single lens with $M_{\rm cl} \gg M_{\rm BH}$!

  z-dependent statements
- Cross section/area is what matters!

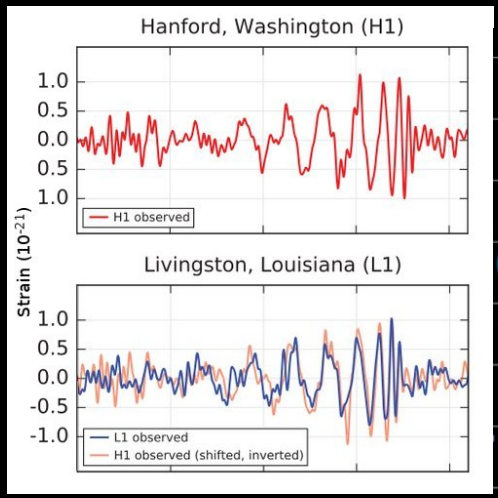
* For the scope of this constraints. Clustering crucial for other studies, GW merger tests, etc...

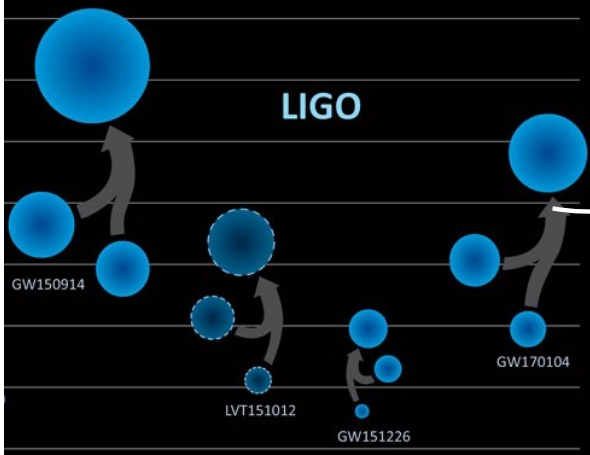


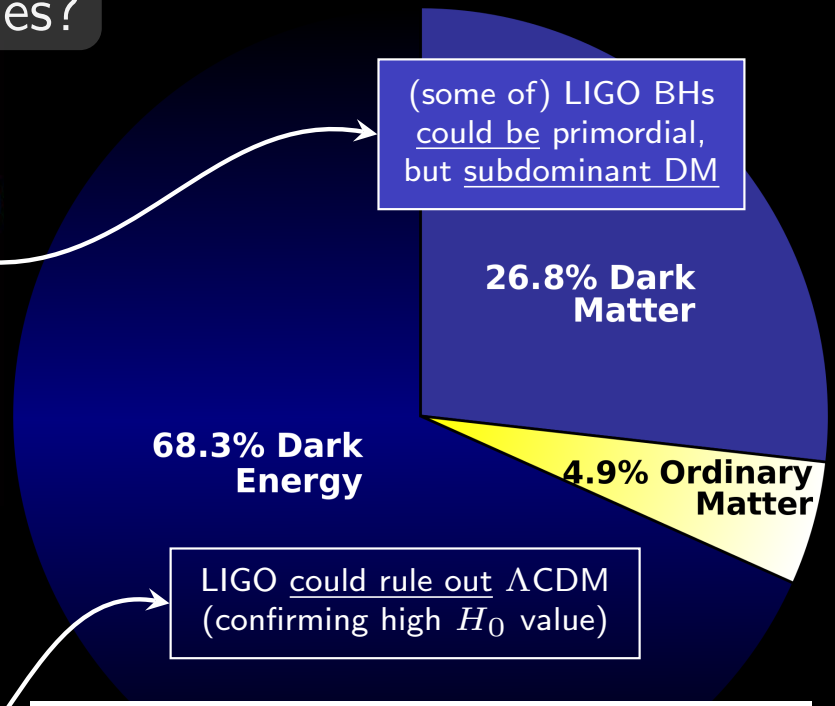


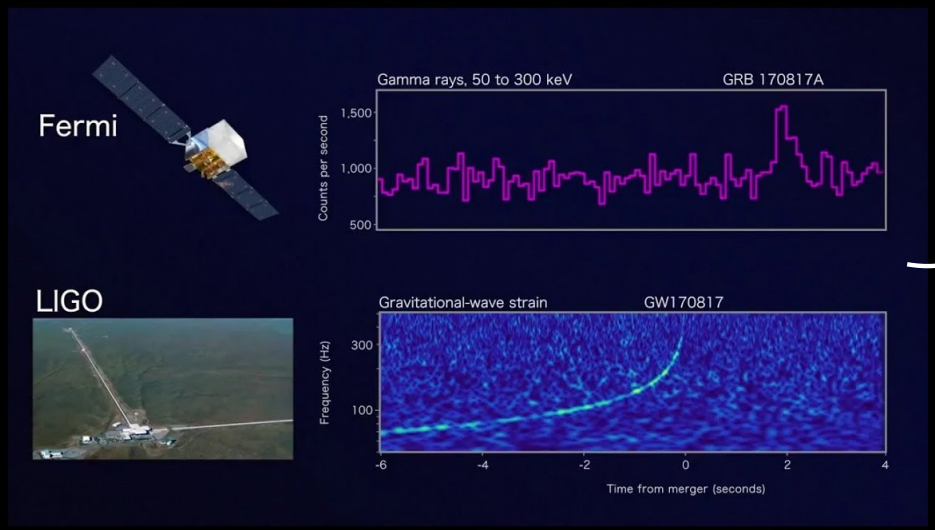
Gravitational Waves vs ΛCDM

Primordial Black Holes?

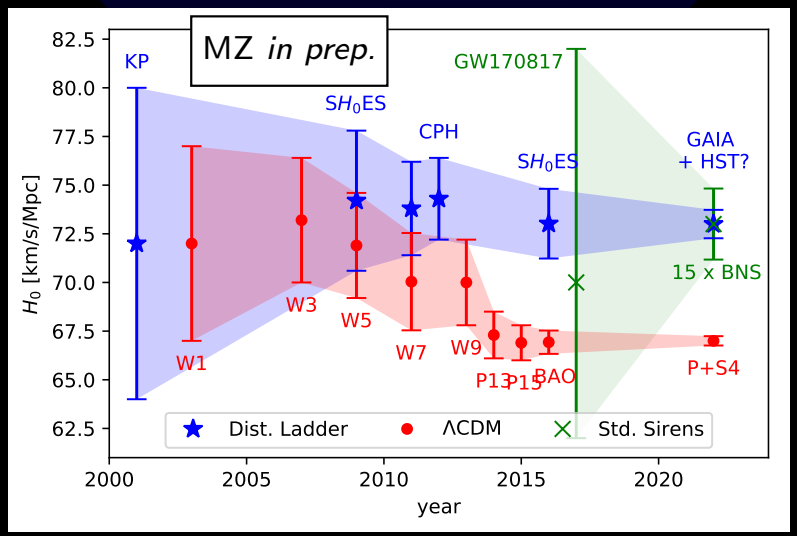




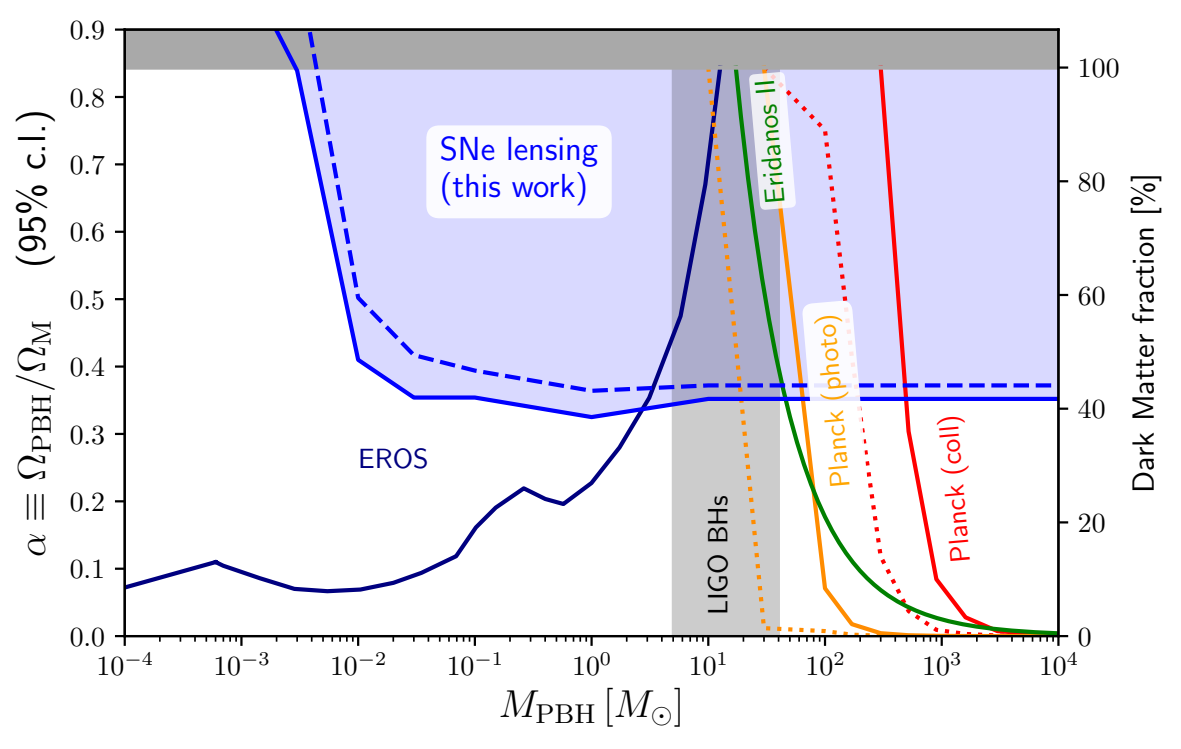




LIGO could rule out ΛCDM (confirming high H_0 value)



Backup Slides



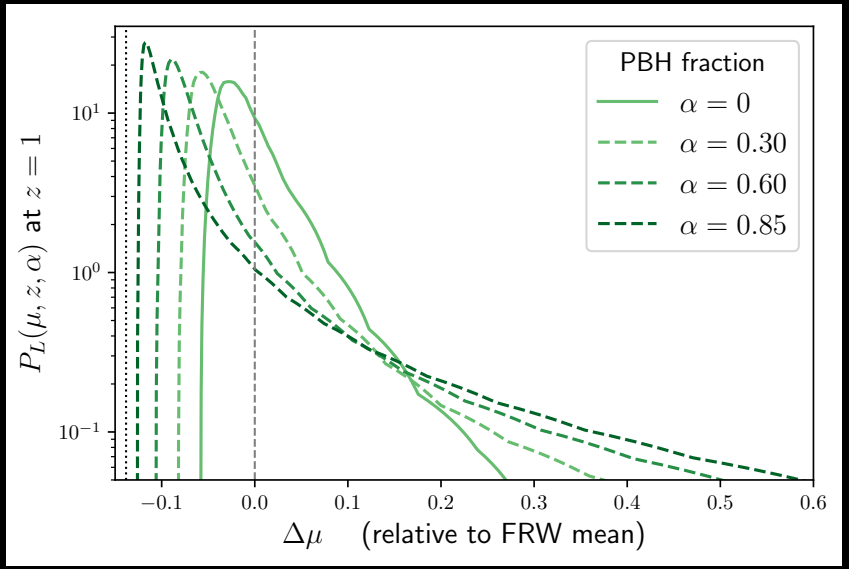
Base magnification PDF + LSS

Fit to simulations (Rauch '91)

$$P = A\left[\frac{1-e^{-\mu/\delta}}{(\mu+1)^2-1}\right]^{3/2} \quad \text{(if } \mu > 0\text{)}$$

$A, \delta \rightarrow$ normalize & $\boxed{\langle\mu\rangle = \mu_{\rm FRW}(z)}$

- Dependence $P(\mu, \bar{\mu})$ only
- Universal (point lens/source)

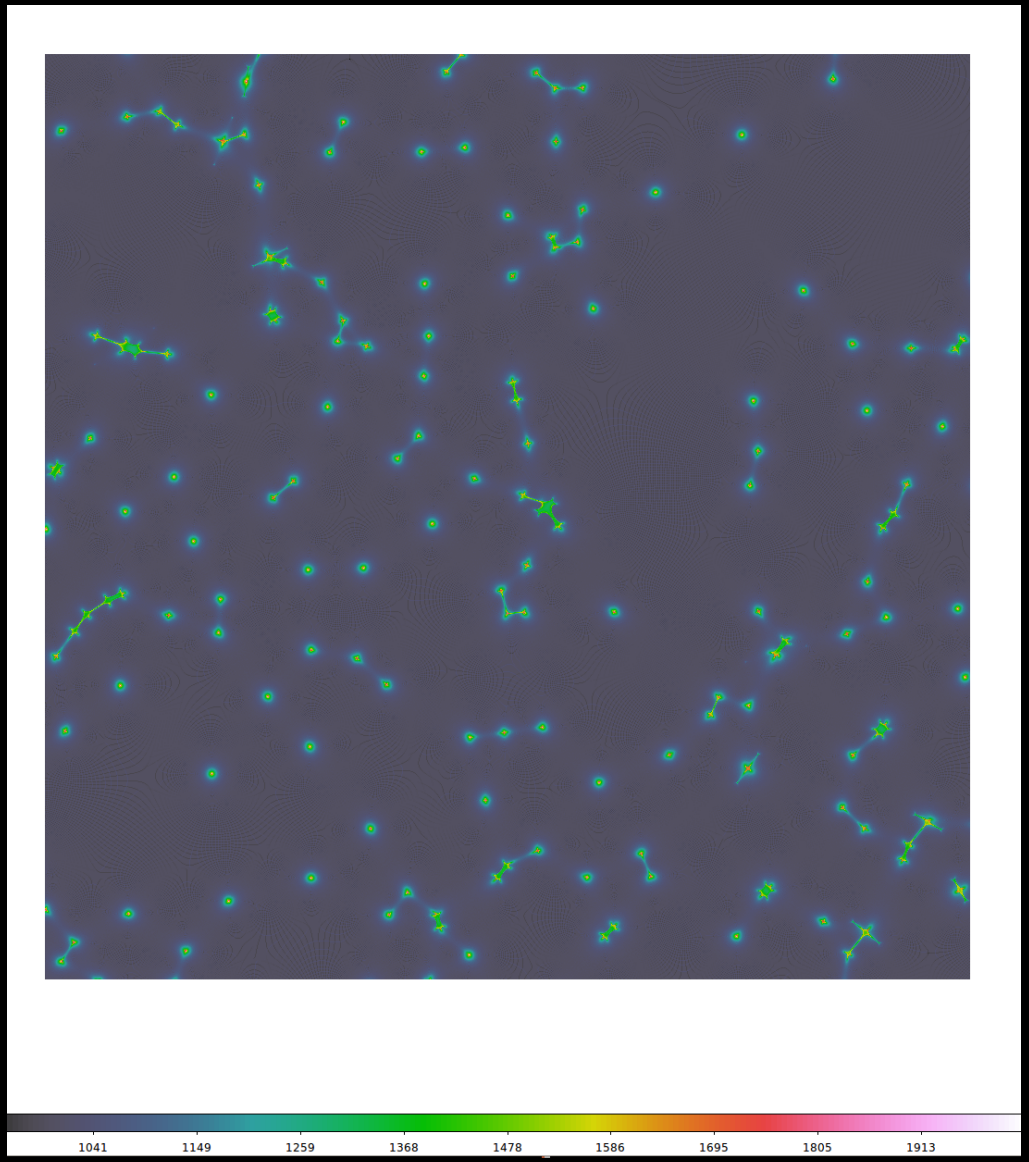


Adding LSS: (Seljak & Holz '99)

$$P_L(\mu; z, \alpha) = \int_0^{\frac{\mu}{1-\alpha}} d\mu' P_{LSS}(\mu', z) P_C[\mu - \underbrace{\mu'(1-\alpha)}_{\text{smooth contrib}}, \underbrace{\alpha\mu'}_{\text{mean}}]$$

$P_{LSS} \rightarrow$ Turbo GL (Marra & Pääkkönen '12)

Neglecting collective clustering



(convergence = 0.05, no shear Simulation by Danny Goldstein)

Finite source PDF computation (MZ & Seljak *in prep.*)

- Fourier space PDF (wrt $\log(1+\mu)$)

$$\log\left(\tilde{P}(s|z)\right) = \int_0^z dz' \left(\tilde{\rho}(s) - \tilde{\rho}(0)\right)$$

- Density of lenses magnifying by $\sim \mu$

$$\rho(\mu, z'|z) = n_L \frac{(1+z')^2}{H(z')} \left|\frac{\partial \sigma}{\partial \mu}\right|$$

Slow PDF computation $\rightarrow$ conservative prescription for effective PBH fraction

Finite source PDF computation (MZ & Seljak *in prep.*)

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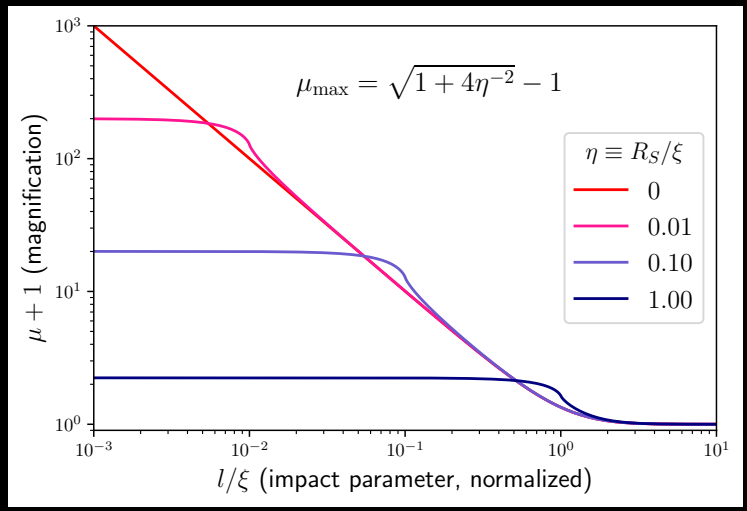
- Cross section $\sigma = \pi l(\mu, \eta)^2$



Slow PDF computation → conservative prescription for effective PBH fraction

Finite source PDF computation (MZ & Seljak *in prep.*)

- Fourier space PDF (wrt $\log(1+\mu)$)

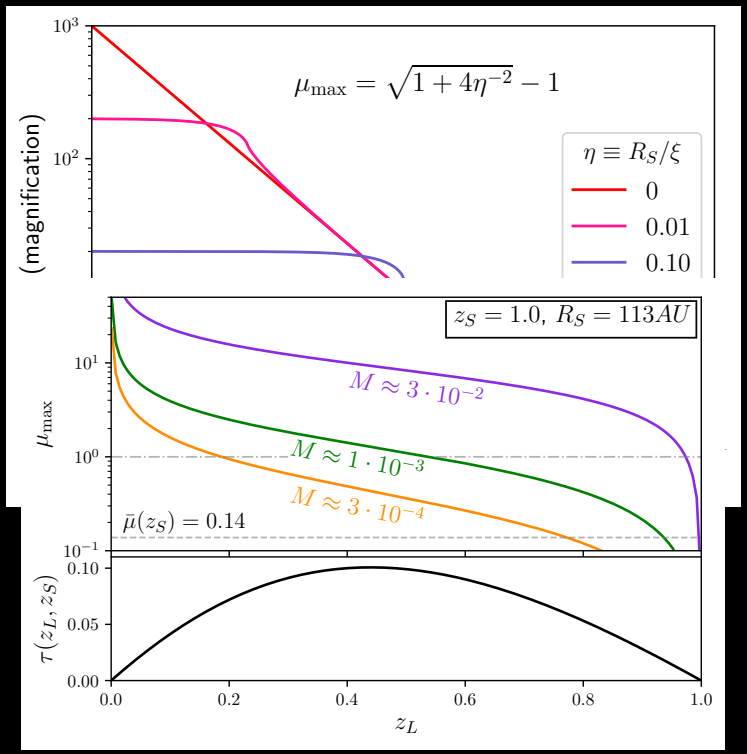
$$\log\left(\tilde{P}(s|z)\right) = \int_0^z dz' \left(\tilde{\rho}(s) - \tilde{\rho}(0)\right) = \int_0^z dz' \, \tau(z'|z) \, \tilde{F}(s,\eta)$$

- Density of lenses magnifying by $\sim \mu$

$$\rho(\mu, z'|z) = n_L \frac{(1+z')^2}{H(z')} \left|\frac{\partial \sigma}{\partial \mu}\right|$$

- Cross section $\sigma = \pi l(\mu,\eta)^2$

- Optical depth: $\tau(z'|z) \propto \xi^2 \propto M_L$



Slow PDF computation → conservative prescription for effective PBH fraction

Finite source prescription

- Effective PBH fraction

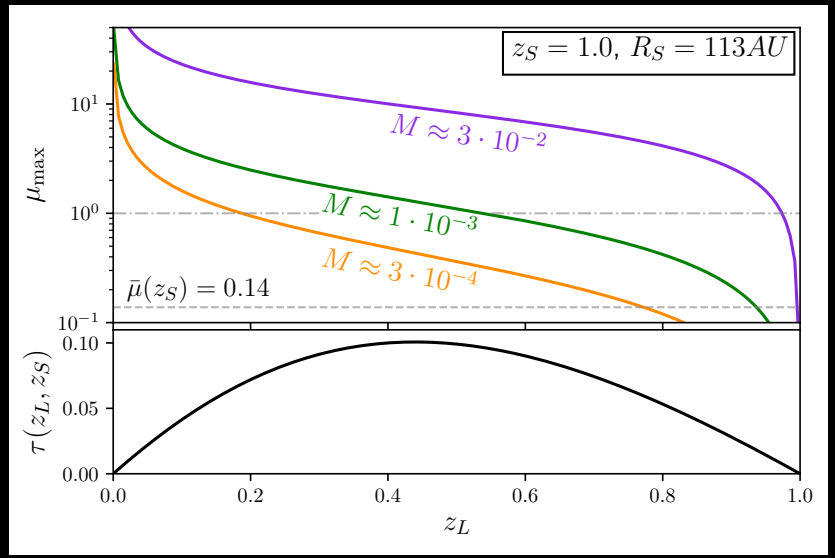
$$\tilde{\alpha}(z_S, M) = \alpha \cdot f_L(z_S, M)$$

- Count only the fraction for which

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

- Normalize by the optical depth

$$f_L(z_S, M) = \mathcal{N} \int_0^{z_S} \tau(z_L, z_S) \Theta\left(\mu_{\rm max}(z_L, z_S, M) - \mu_{\rm cut}\right) dz_L$$



Very conservative:

- Full PDF $\Rightarrow$ PBH signatures strong for $M \sim 3 \cdot 10^{-4}$
- $\mu_{\rm thr} = 1 \gg \bar{\mu}$ is strong cutoff! ($\forall$ SNe: $\mu/\sigma_\mu \lesssim 0.45$)

Correlated noise

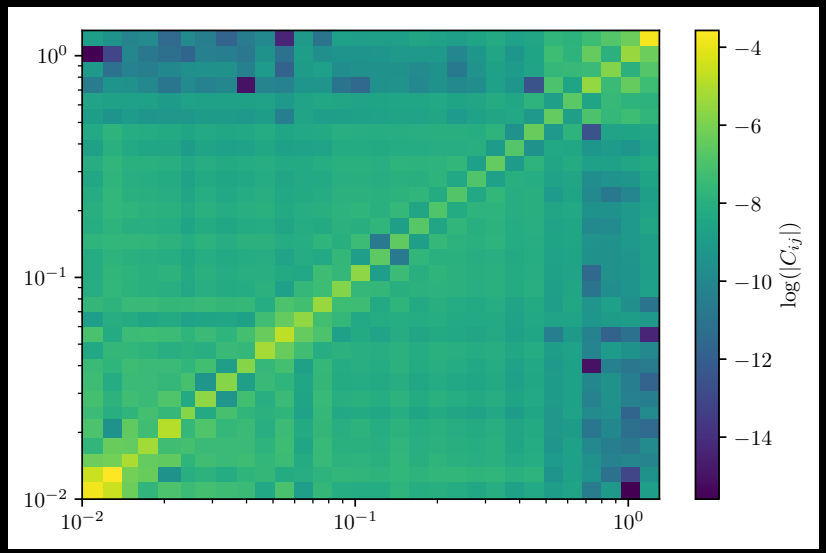
- Assumed independent

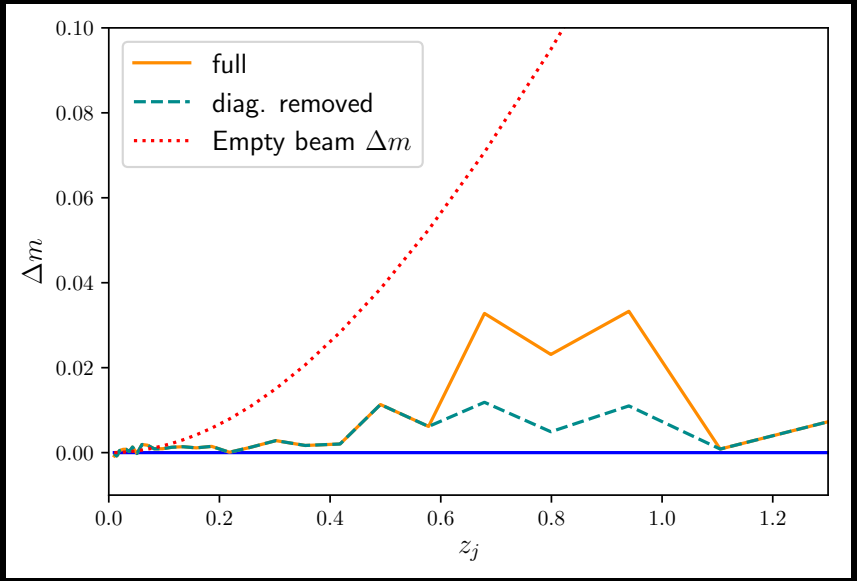
$$L_{tot} = \prod_i L_i$$

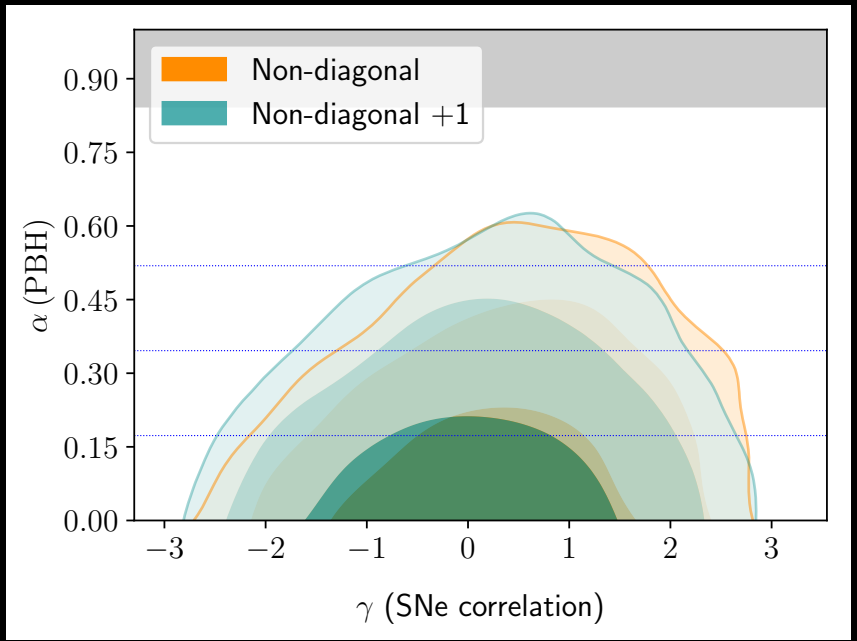
- Use JLA simple covariance

$$\Delta m(z_j) = \gamma \frac{1}{3} \sum_i \frac{C_{ij}}{\sqrt{C_{jj}}}$$

$i \in (26, 27, 28)$ connects low-high z







Mass function not important (unless support on small masses)

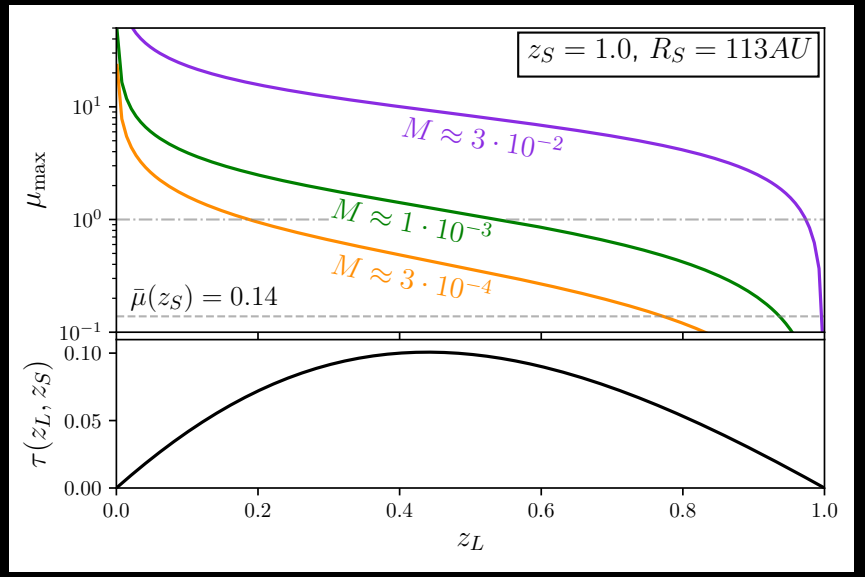
- PDF Computation factorizes

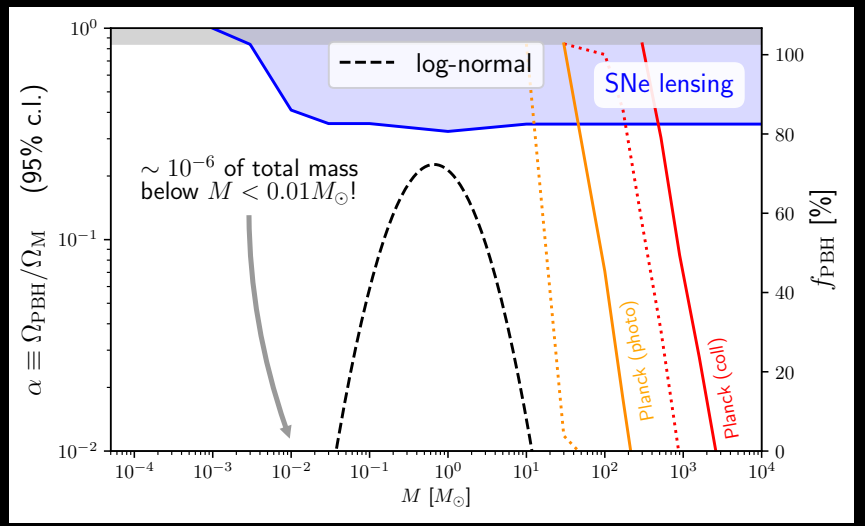
$$\int_0^z dz' \tau(z', z) \cdot \tilde{F}\left[s, \eta(M, z', z)\right]$$

Mass distribution $P(M) \Rightarrow$ average

$$\tilde{F} \to \int P(M) \tilde{F}(s, \eta) dM$$

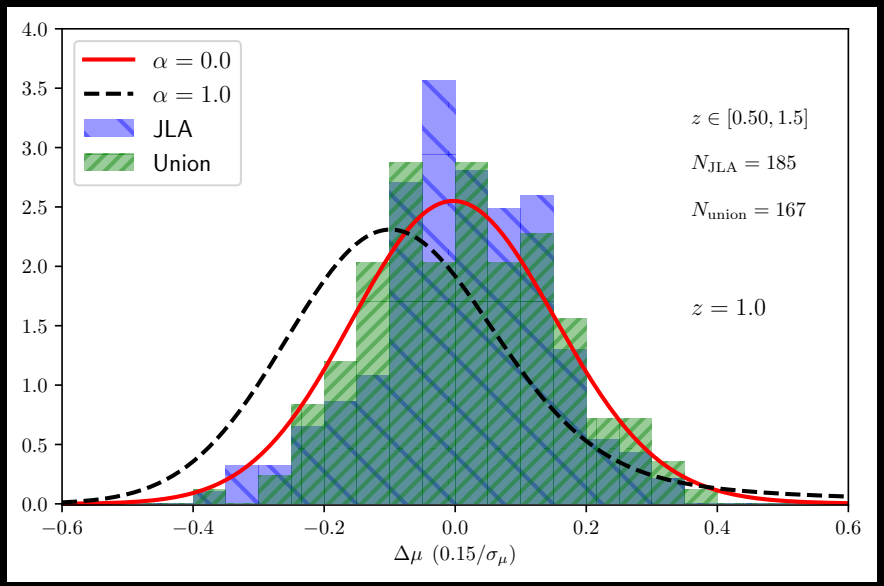
- Negligible effect for $\mu \ll \mu_{\max}$
- SNe data: predictions equivalent to monochromatic (for small μ)
- Might play a role if clustered PBHs





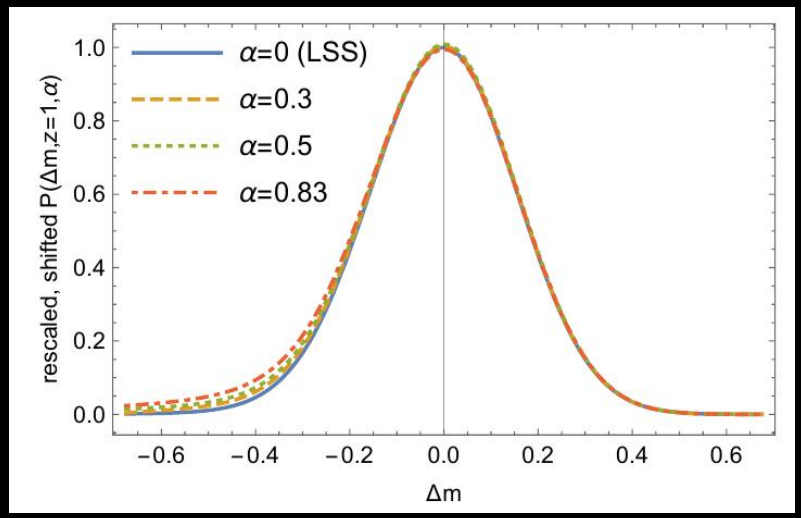
Every non-lensed SNe counts against α

No LIGO MACHO
(MZ & Seljak '17)



LIGO Lo(g)-normal MACHO
(Garcia-Bellido+ '17)

Shiftted + rescaled PDF

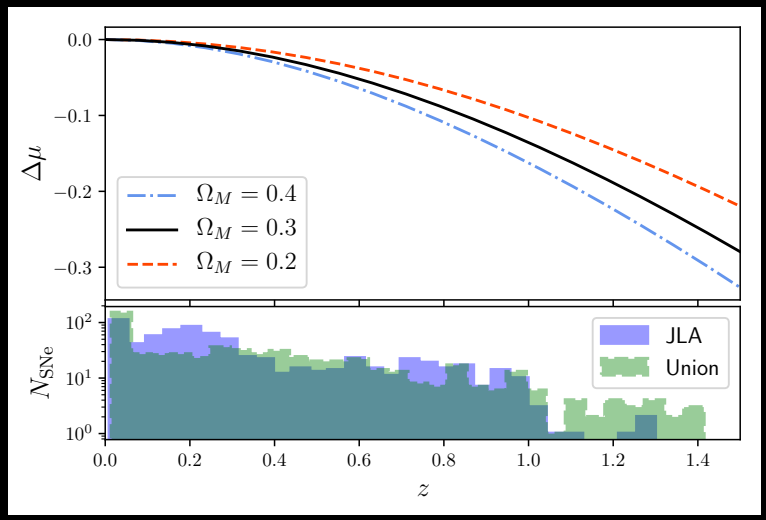


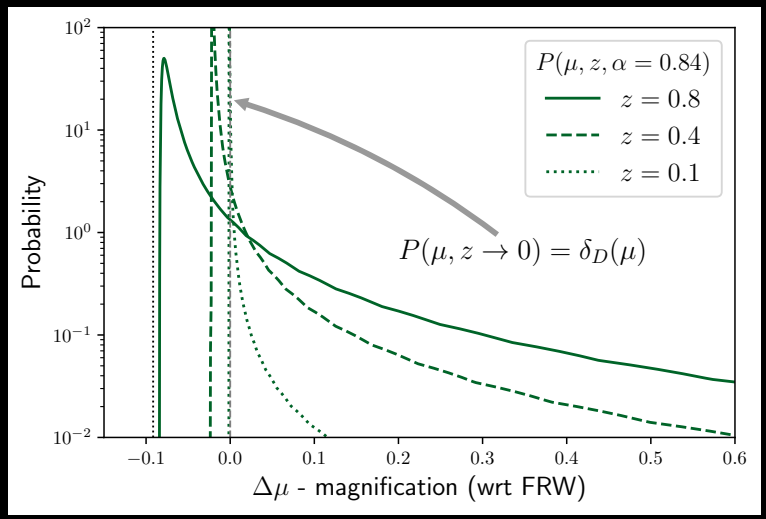
- Shift violates flux conservation $\Rightarrow \Delta\mu \neq 0$ (OK, if funny $w(z)$)
- Rescaling violates normalization: $\int d\mu P(\mu) > 1$

$\Rightarrow$ Equivalent to a non-flat prior on α (i.e. belief in PBH)

Redshift dependence is critical!

No LIGO MACHO
(MZ & Seljak '17)





LIGO Lo(g)-normal MACHO
(Garcia-Bellido+ '17)

that the lensing effect of PBH on SN-Ia magnitudes is independent of redshift (see the previous footnote for a caveat), and that each redshift bin contributes equally to the final effective value of the PBH fraction,

$$\tilde{\alpha}_{\rm eff} = \alpha \int f_{\rm P}(z) \frac{{\rm d}N}{{\rm d}z}(z)\, {\rm d}z\,. \qquad (14)$$

gives $\alpha_{\rm eff} \approx 0.4\alpha$!

$\Rightarrow$ double counting that low-z not sensitive to PBH fraction α!

(likelihood takes $\tilde{\alpha}(z_s)$ $\forall$ SNe).

critical for their "result" of 100% DM in PBH compatible w. SNe.