# Effect of magnification on Ia supernova cosmology

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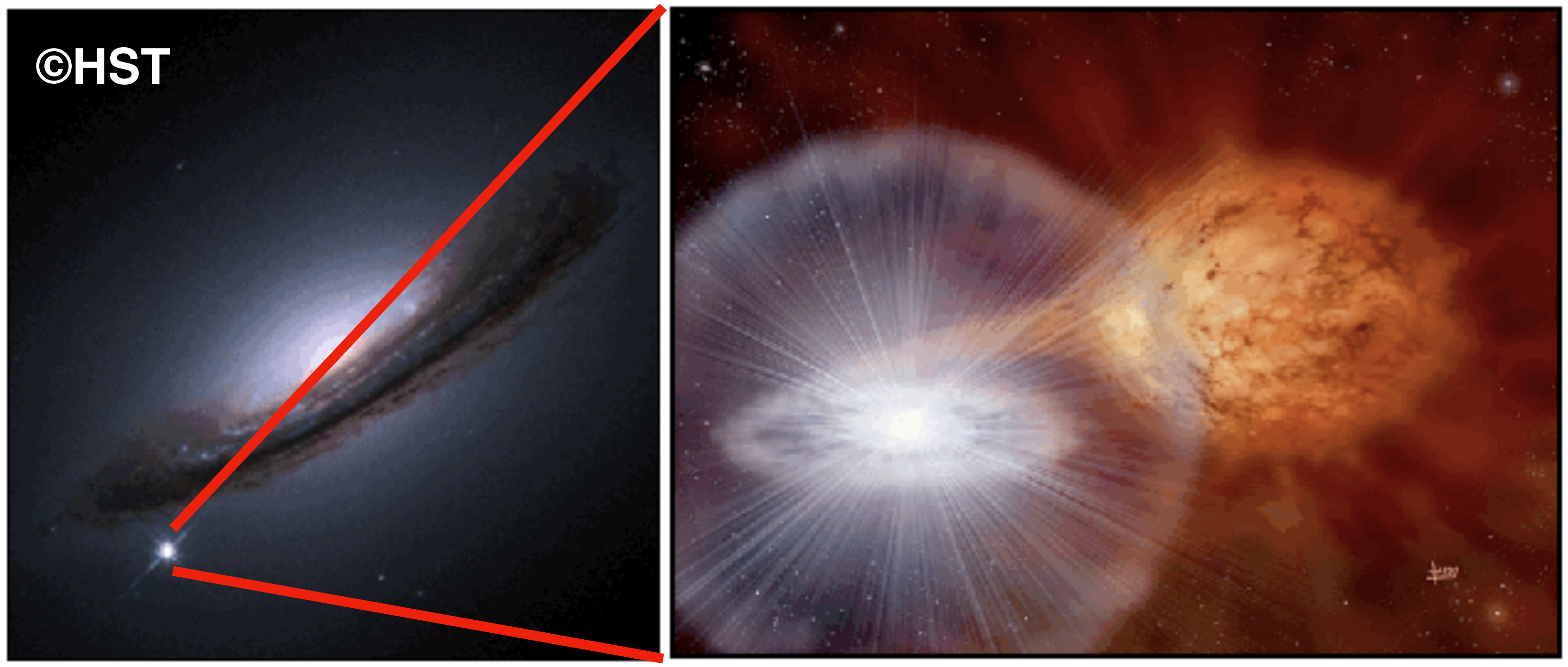
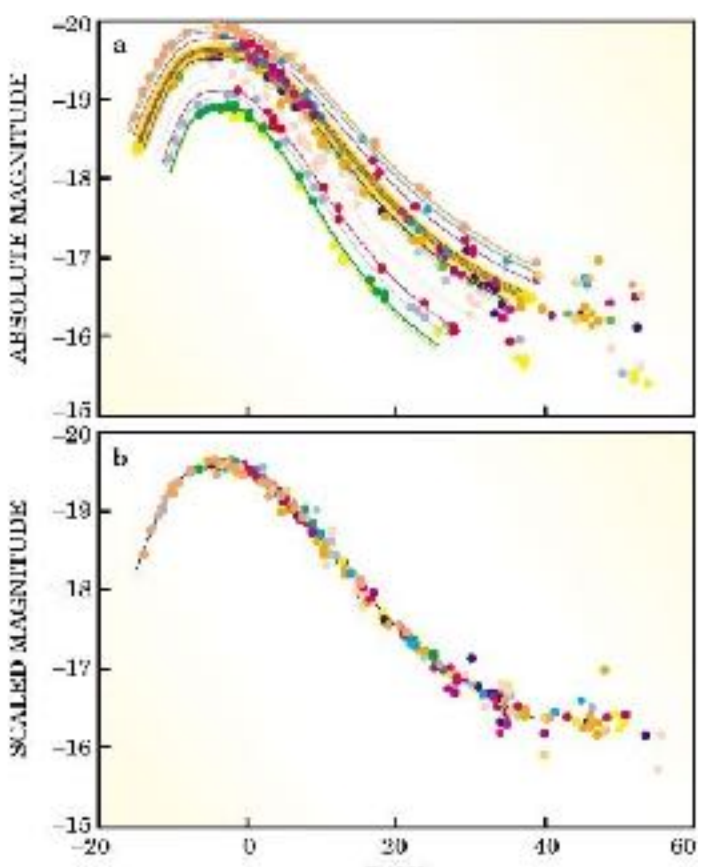
Sakakibara, AJN+ 2019 https://arxiv.org/abs/1901.10129

# type Ia Supernova as a standard candle



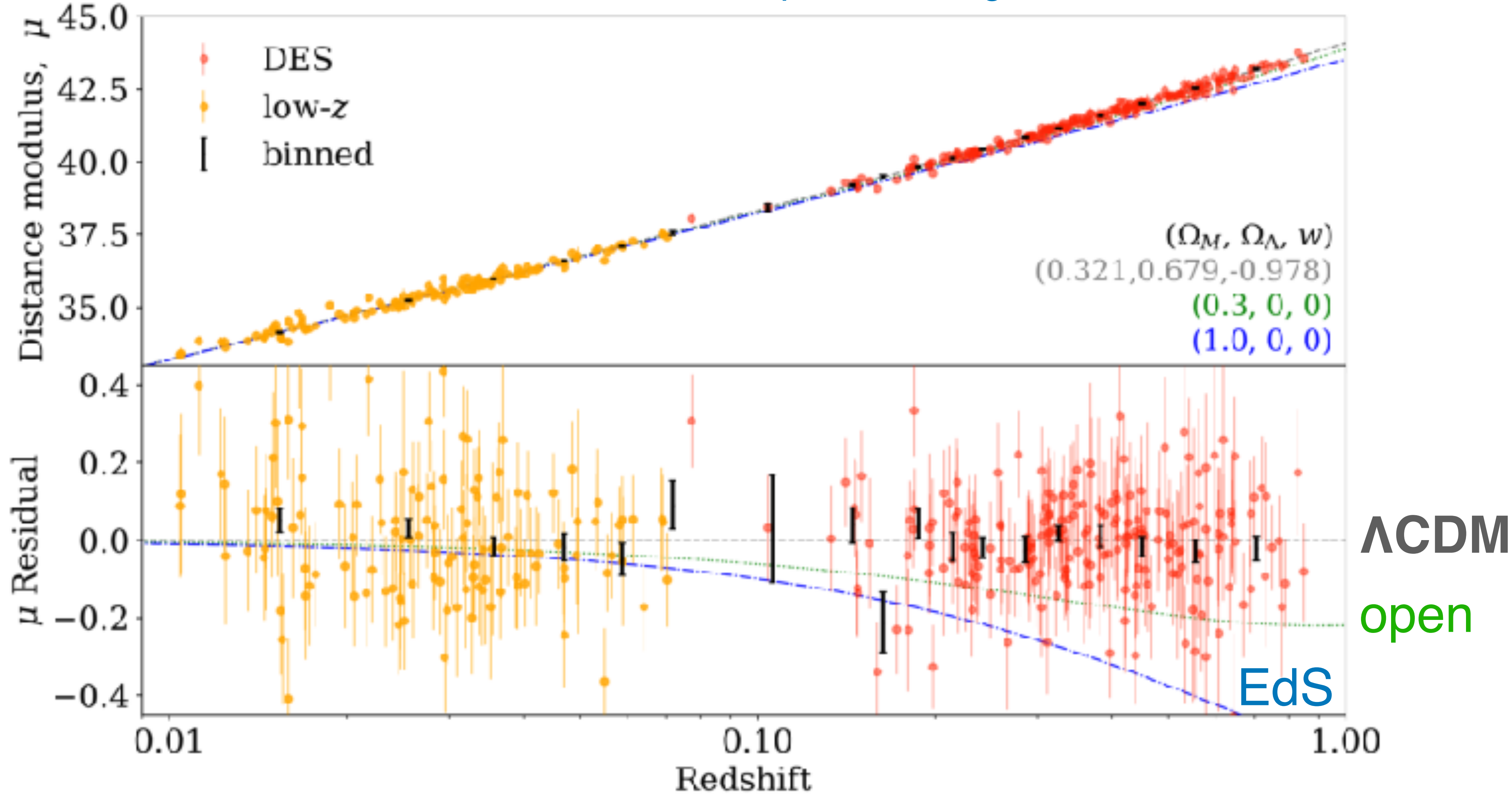

SN 1994d in NGC 4526 White dwarf with companion




- type Ia supernova can be a powerful tool for cosmology
- Almost uniform progenitor mass limit ~1.44 Msun white dwarf
- Almost uniform absolute flux
- Empirical laws to correct abs. flux

# Supernova Cosmology

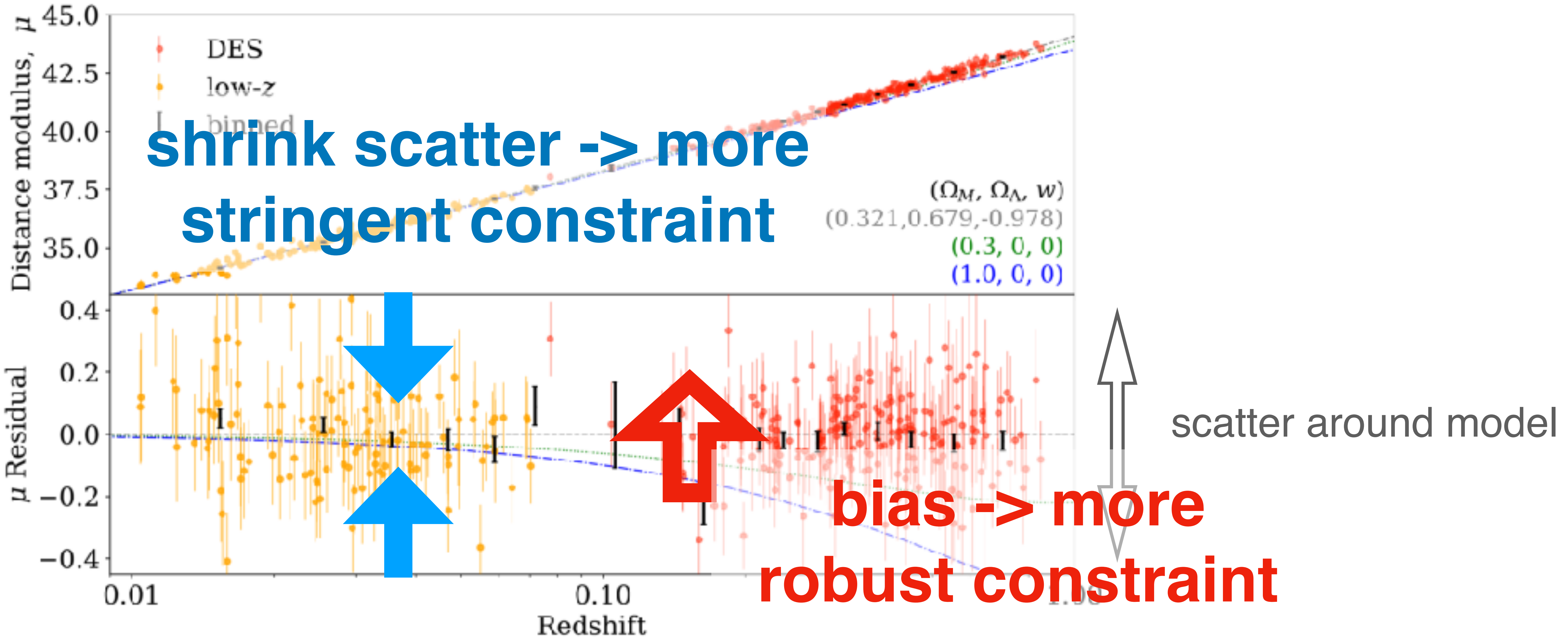
https://arxiv.org/abs/1811.02374




$$\mu = m - M = 5\log_{10}(d_L/[\mathrm{pc}]) - 5$$

$$d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H0\sqrt{\Omega_m(1+z')^3 + \Omega_{\mathrm{DE}}(1+z)^{3(1+w_{\mathrm{DE}})}}}$$

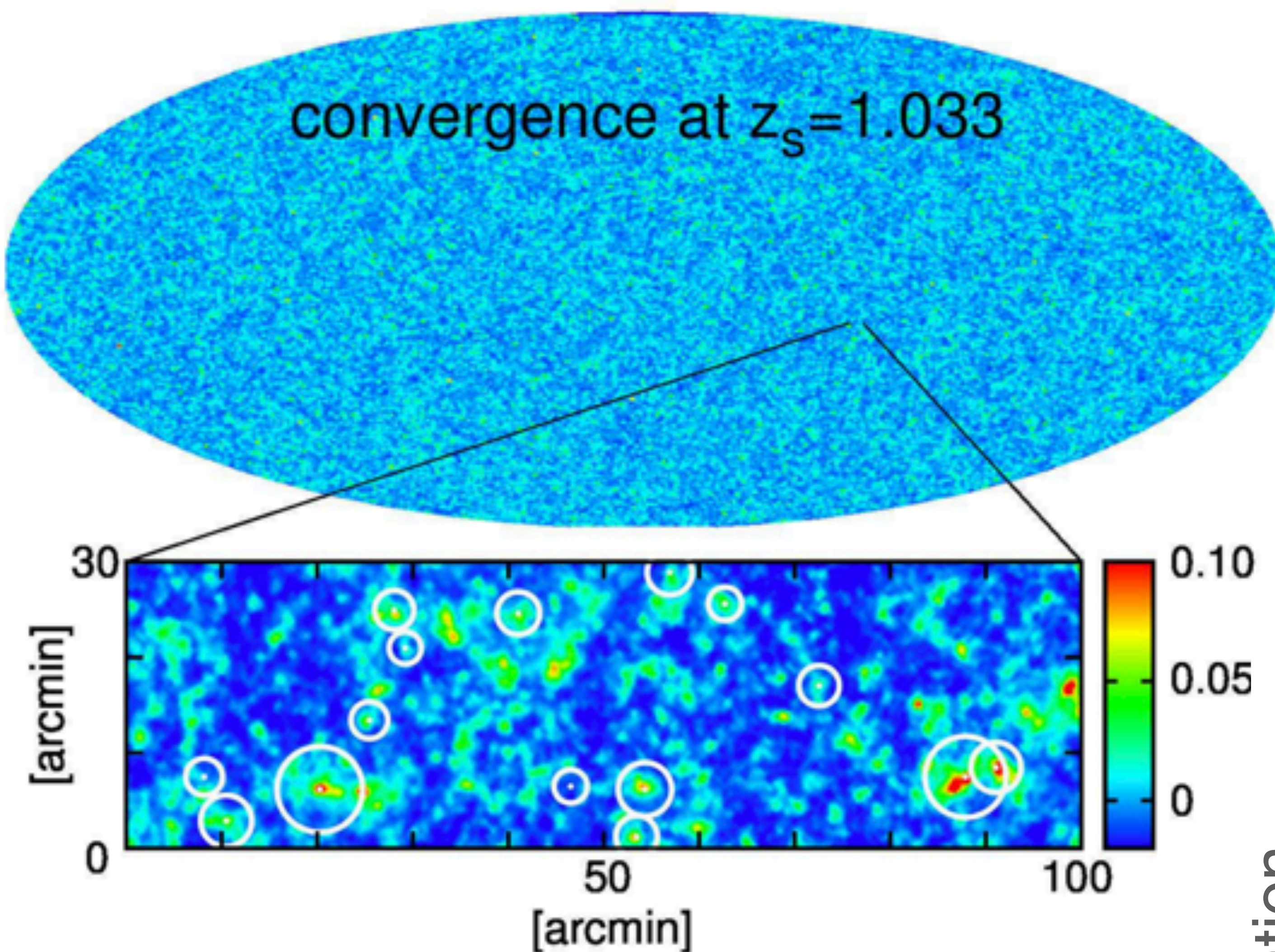
# What's wrong with SNe cosmology?



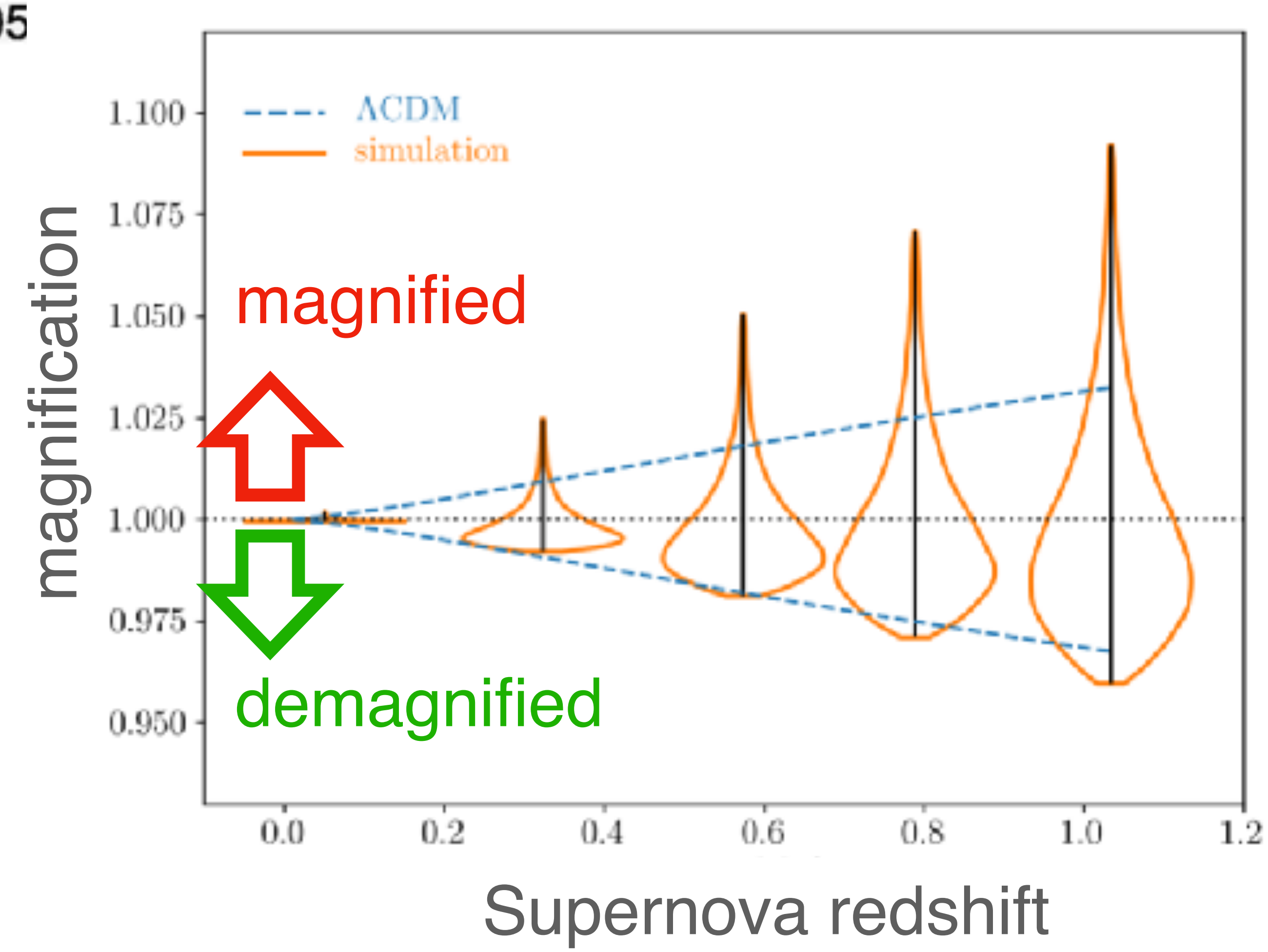

scatter around LCDM best-fitting model can be explained by…

- Intrinsic scatter of SNe
  - SNe diversity(e.g. WD rotation, dust extinction,…)
- magnification due to the foreground LSS
- correcting for magnification may bring both accurate and precise measurement of cosmological parameters.

# Expected impact from simulation

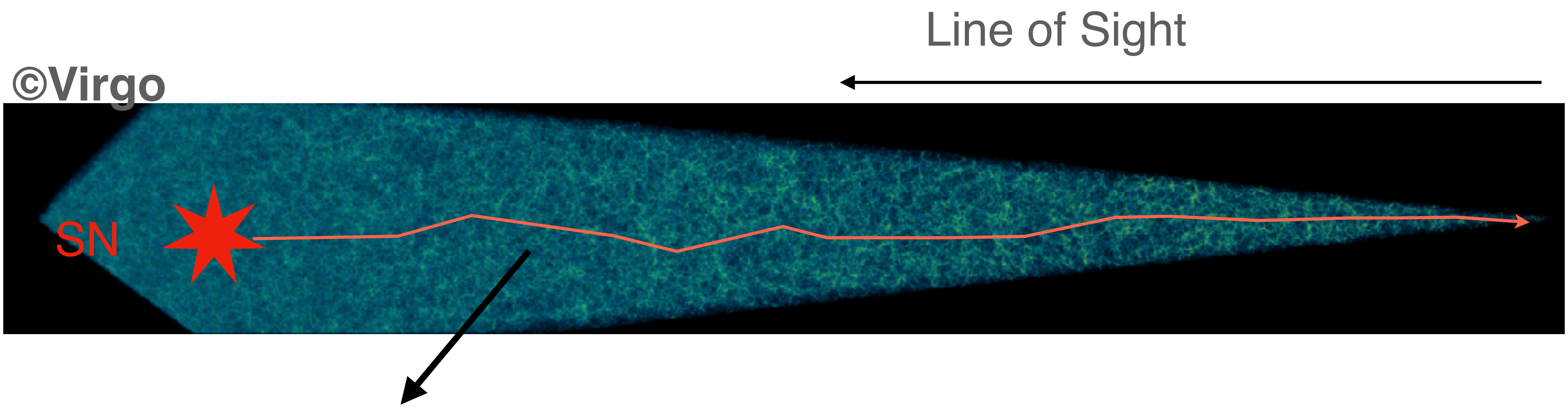



Takahashi+ 2017




- Use N-body + ray-trace simulations (Takahashi et al. 2017)
- The expected impact of magnification is ~3% at $z_{SN}$~1
- Will be important for future SNe cosmology where sigma(w) < a few %

# Method overview




measure intervening matter distribution for magnification correction by

1. convergence mass reconstruction

2. galaxy distribution

# data set

## SNLS3 from CFHT

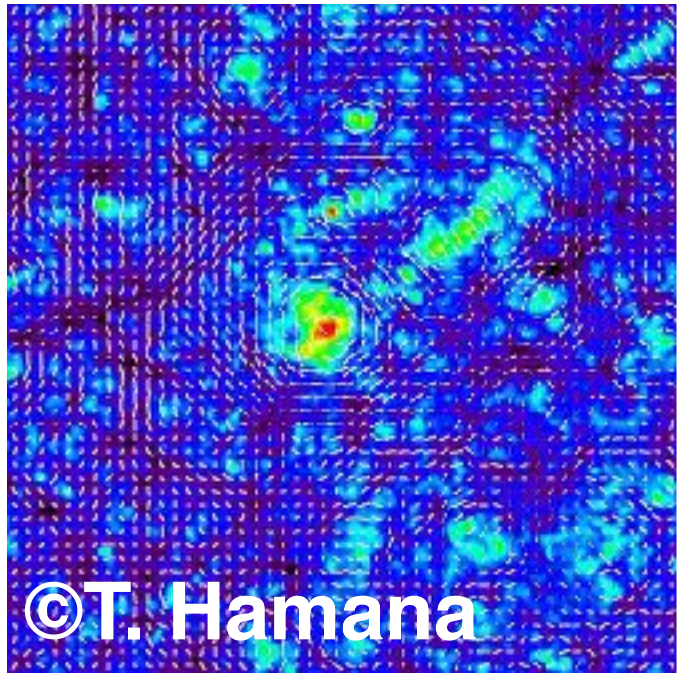
- D1, D2, D3, D4 fields ~ 4 sq. deg. (**Guy+2010**)
- time domain photometry to track the light curve
- multi-color observation for color-dependent Phillips relation correction
- spec-z followups for accurate redshift determination of host galaxy

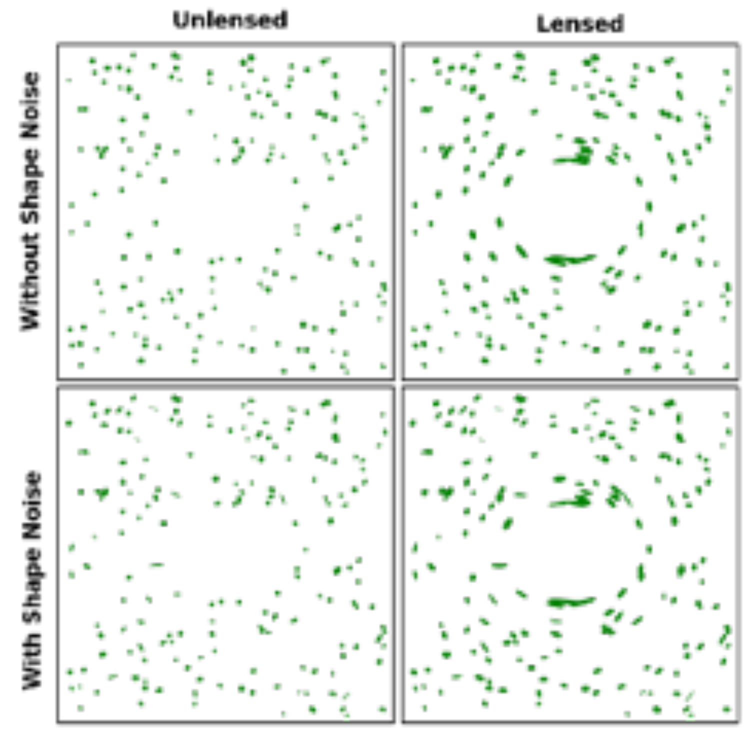
## LSS from Subaru-HSC

- HSC Wide S16A (in D1, D2, D3) for photometric redshift and weak lensing shape catalogs (**Tanaka+2018, Mandelbaum+2018**).
- HSC Deep S17A (COSMOS, XMM, AEGIS) photometric redshift catalog -> redshift PDF, stellar mass (**Hsieh+2014, Tanaka+2015, Tanaka, AJN+2018**).

| | convergence | direct measure |
|---|---|---|
| ref. | Sec. 5.1 | Sec.5.2 |
| HSC | HSC-Wide | HSC-Wide/Deep/U-Deep |
| SNLS | D1 | D1, D2, D3 |
| $N_{\rm SNe}$ | 49 | 151 |

# measurement of foreground matter : WL convergence



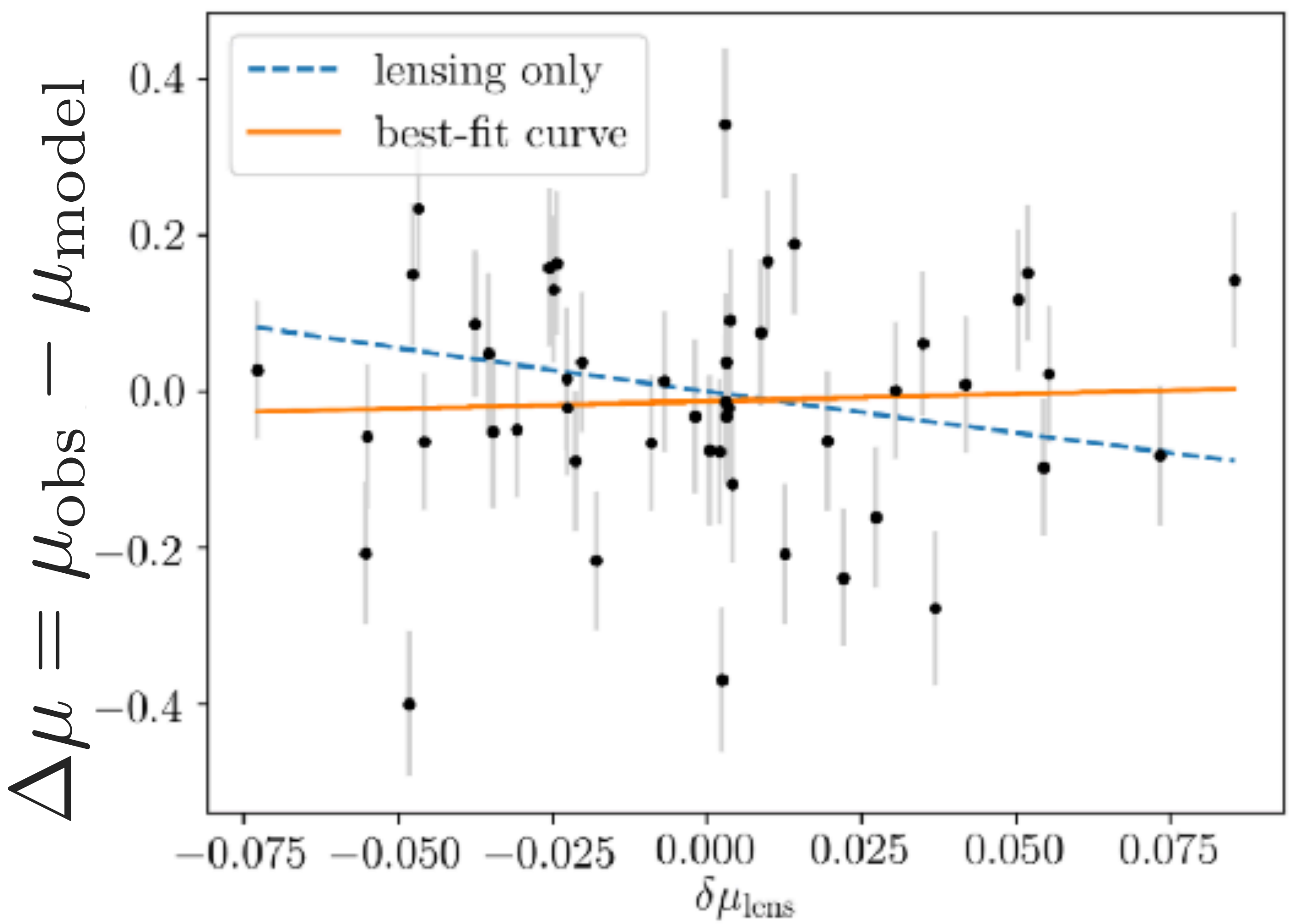

https://en.wikipedia.org/wiki/Weak_gravitational_lensing

$$\gamma_\alpha(\boldsymbol{\theta}) \simeq \frac{1}{2}\langle e_\alpha(\boldsymbol{\theta}_i)\rangle \qquad \kappa(\boldsymbol{\theta}) = \int d\boldsymbol{\theta}' \gamma(\boldsymbol{\theta}')\mathcal{D}^*(\boldsymbol{\theta}-\boldsymbol{\theta}')$$

$$\mu_{\rm lens} = 1 + 2\kappa = 1 + \delta\mu_{\rm lens}$$

- Assume Weak Lens approximation
- gamma-kappa are related with each other
- apply smoothing to avoid divergence at small scales (~3 arcmin)

# WL convergence - distance modulus correlation?




best-fitting curve

$$\Delta\mu = (0.19 \pm 0.36)\delta\mu_{\rm lens} + (-0.01 \pm 0.01)$$

If Hubble residual is totally explained by magnification

$$\Delta\mu = -2.5\log_{10}(1+\delta\mu_{\rm lens})$$
$$\simeq -1.086\delta\mu_{\rm lens}$$

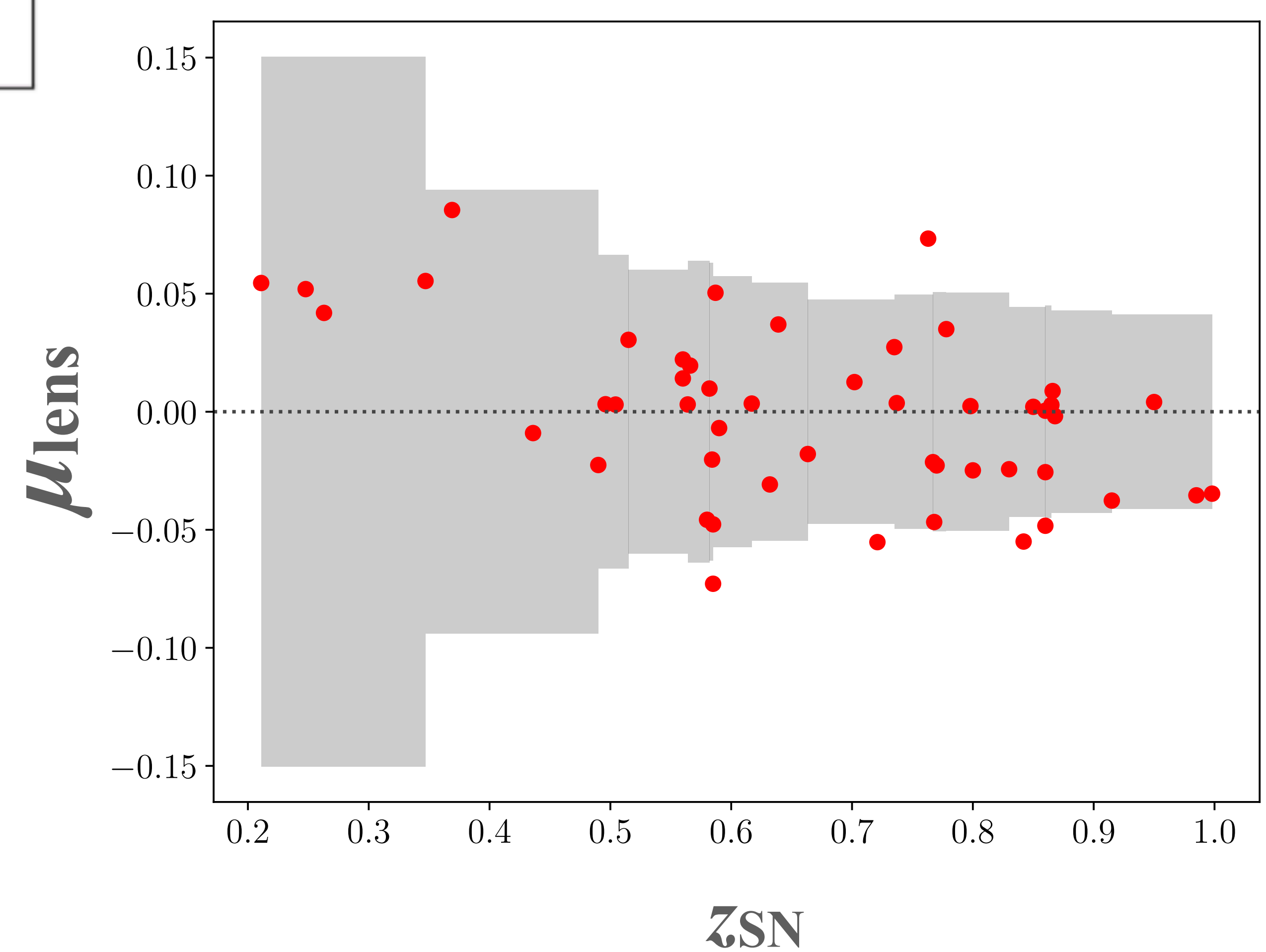
correlation coefficient

$$r = 0.03 \pm 0.14$$

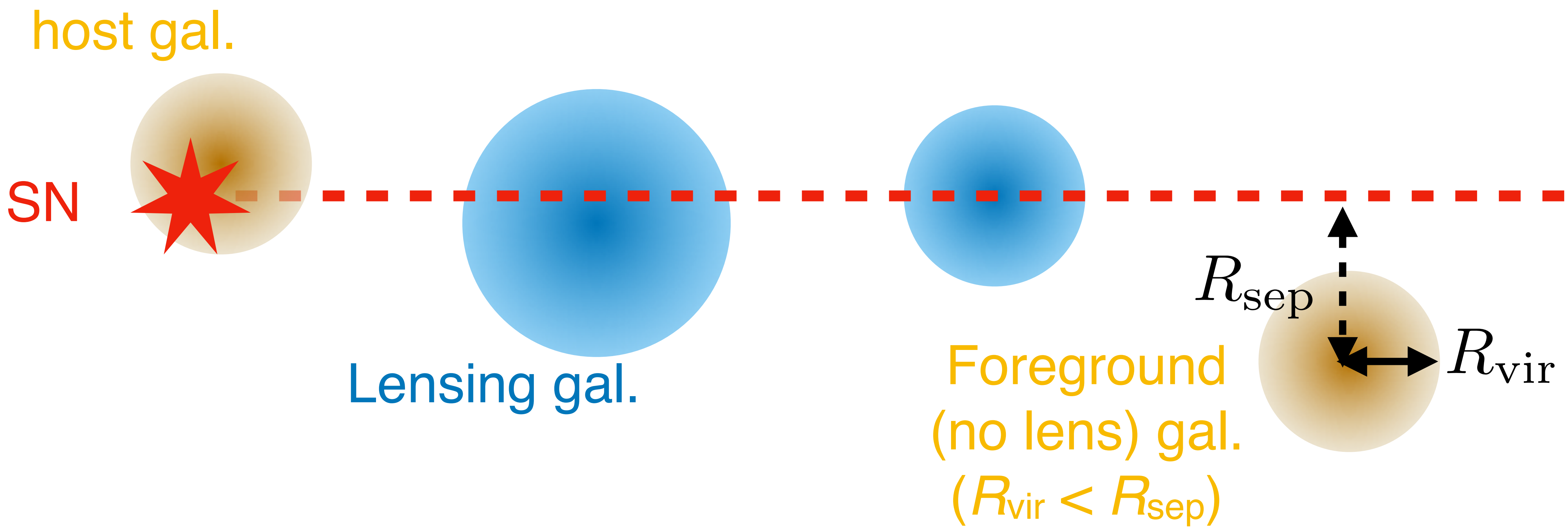
**no correlation**

Error estimation

- rotate galaxy orientation randomly
- signal is well consistent with random (within errors)
- smoothing scale ↔ $n_{\rm gal}$

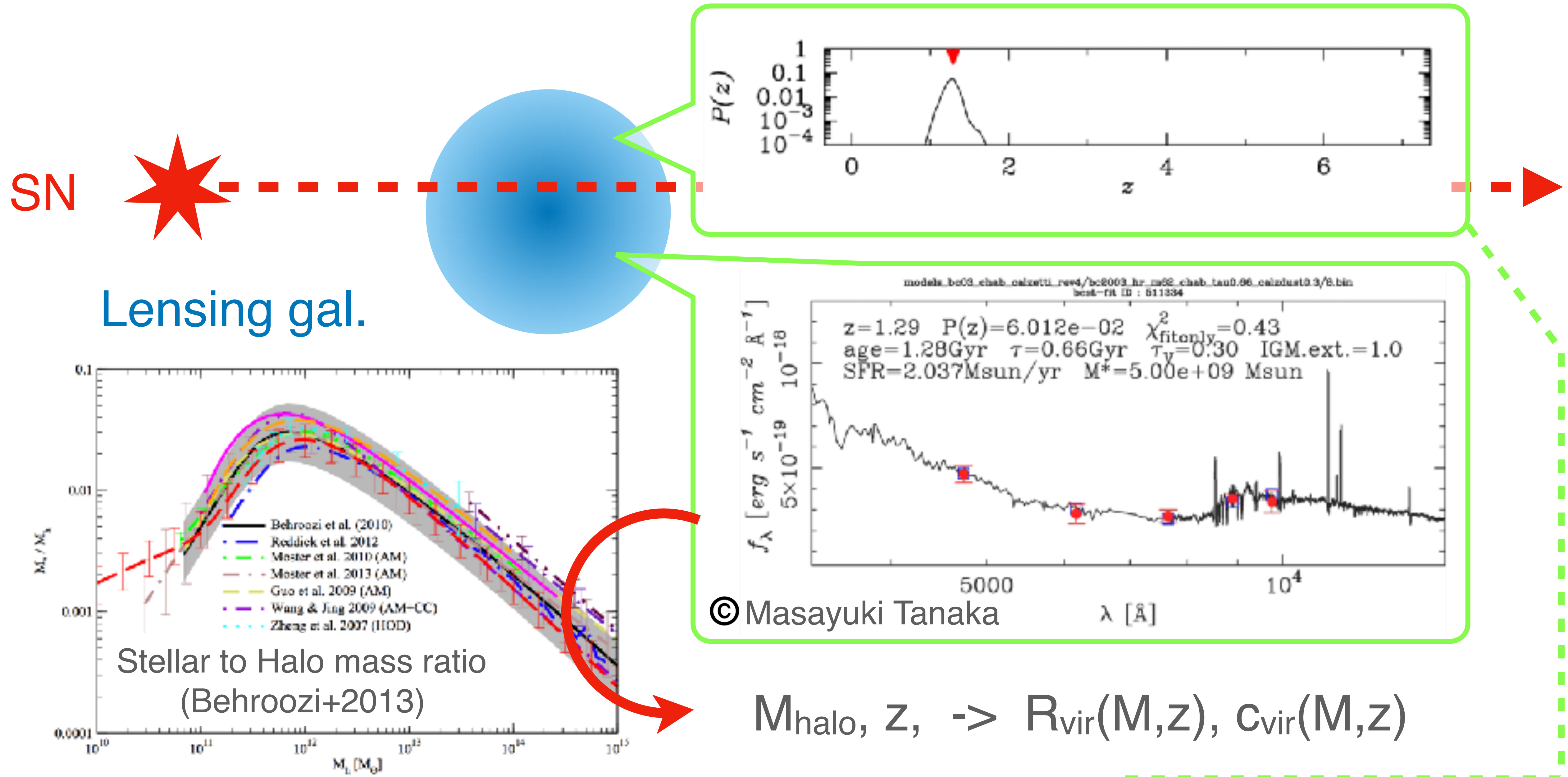


# measurement of foreground matter : galaxy distribution




- All galaxy has NFW profile with radius (Rvir) and concentration are derived from stellar mass
- use HSC galaxy and photo-z catalogs to obtain Mstellar + redshift of galaxies.
- Only galaxies interrupt SN light ray with their Rvir can contribute

# measurement of foreground matter : galaxy distribution




$M_{\rm halo}$, z, -> $R_{\rm vir}(M,z)$, $c_{\rm vir}(M,z)$

projected mass : $\Sigma(R) = \int dr_z \rho(r_z, R; M_{\rm h}, c_v)$

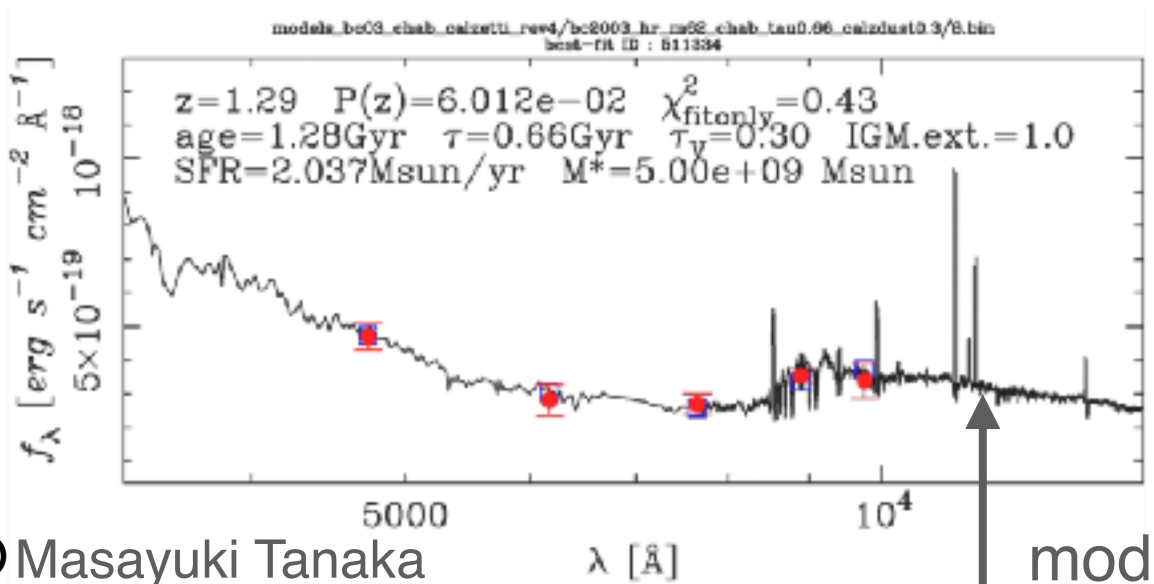
Mandelbaum+2008
Takada, Jain 2003

convergence : $\kappa(R) = \Sigma(R)\langle\Sigma_{\rm cr}^{-1}\rangle \propto \Sigma(R)\int_0^{z_s} P(z_l)\Sigma_{\rm cr}^{-1}(z_l, z_s)dz_l$

total magnification : $\log f^{\rm obs} = \log f^{\rm SN} + \sum_i \log \mu_i^{\rm lens} + \mathcal{M}$ mean magnification from random LoS

# Tow different photo-z catalogs

## Mizuki (Template fitting)

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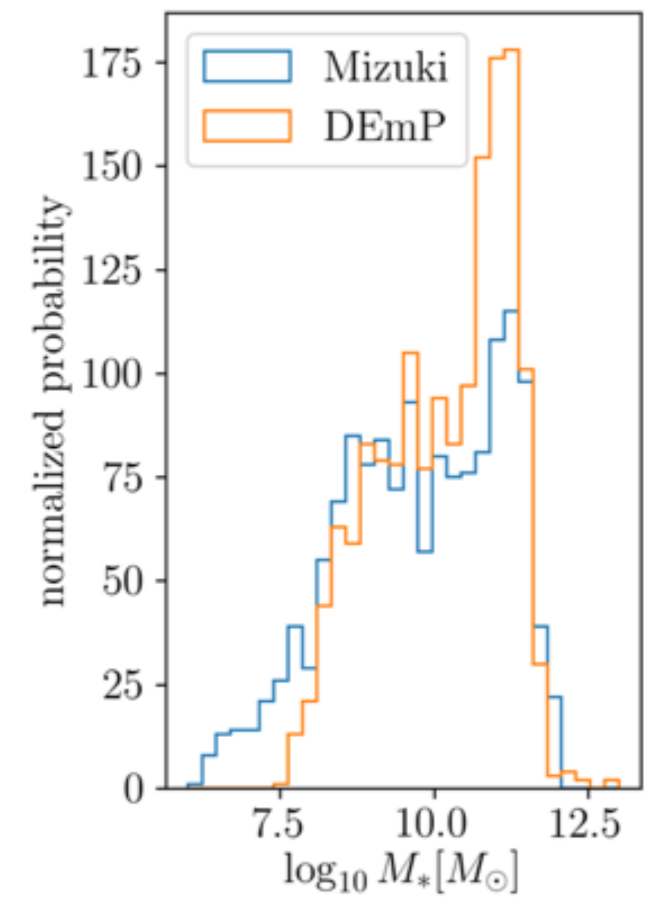
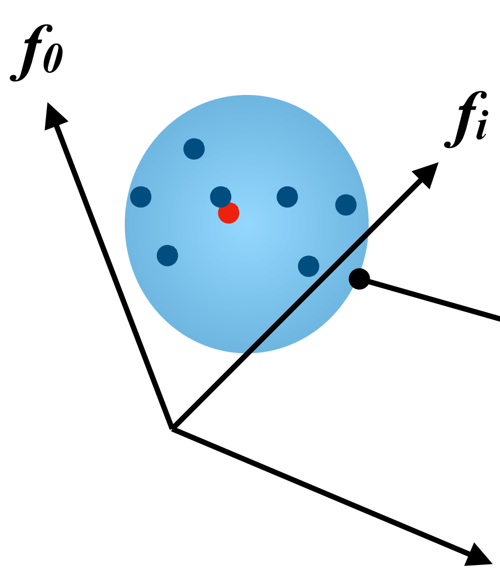
model fitting

$$f(\lambda_{\rm obs}) = f(\lambda_{\rm em}(1+z)|t, M_*, \tau, A_V, Z, ...)$$

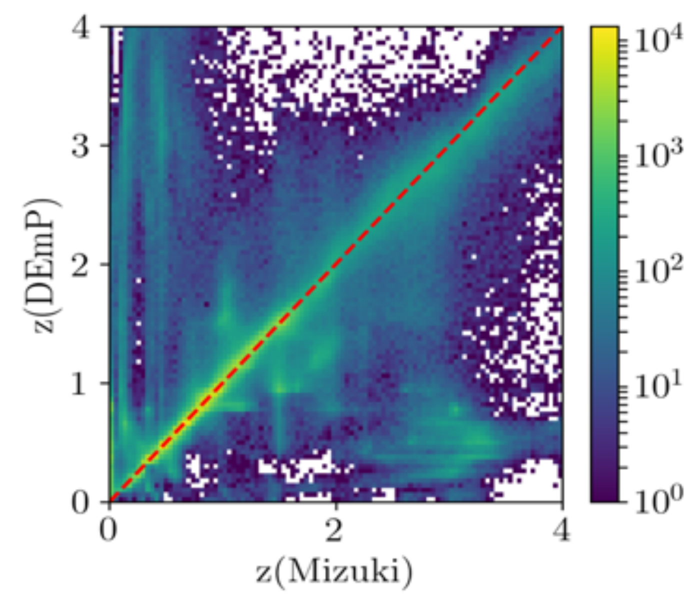


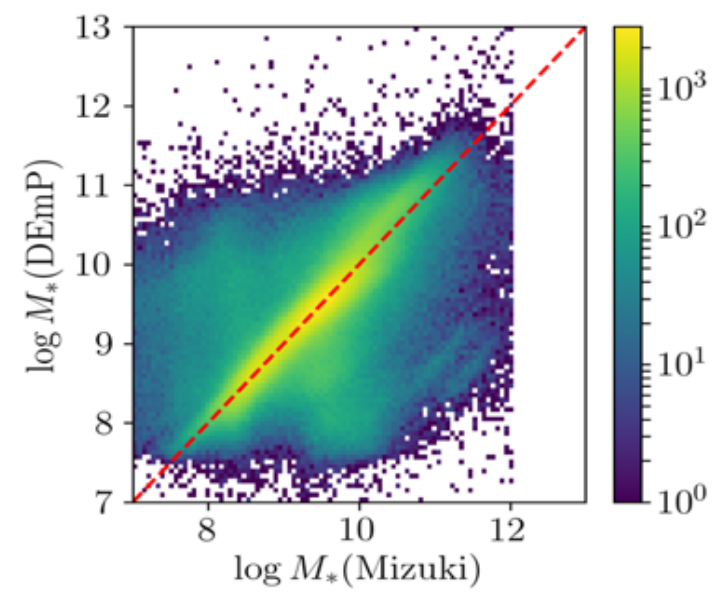

## DEmP (empirical)



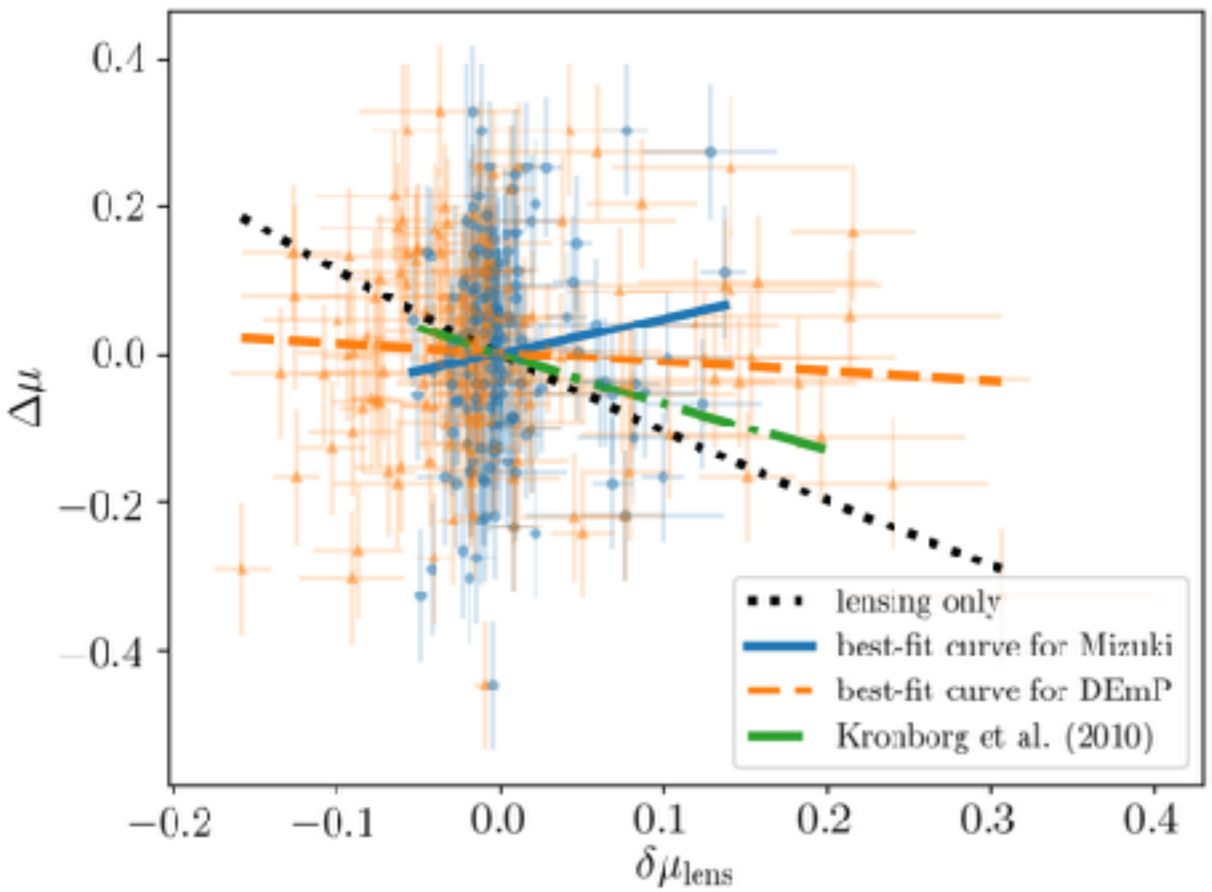

$$z_{\rm ph} = \frac{1}{k}\sum_i^k z_{{\rm spec},\, i}$$

sphere includes k-nearest neighbors for given photometric sample



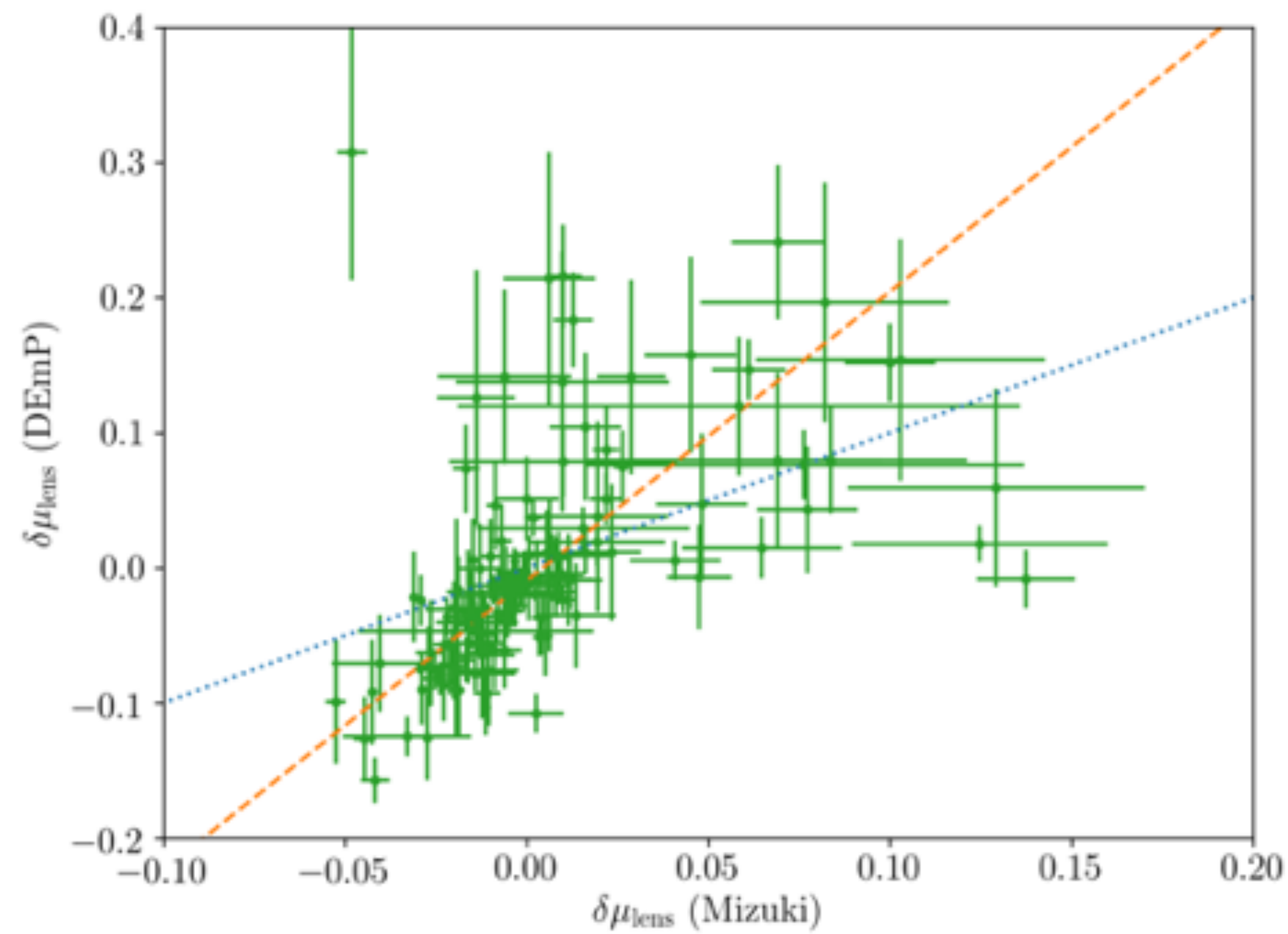
# galaxy distribution - distance modulus correlation?




| | $\Delta\mu$ slope | corr. coeff. |
|---|---|---|
| Mizuki | 0.47±0.22 | 0.07±0.08 |
| DEmP | -0.13±0.10 | -0.04±0.08 |

still not strong correlation

- Grobal trend is consistent
- Mizuki underestimates (DEmP overestimates) the magnification



# cosmological parameter estimation

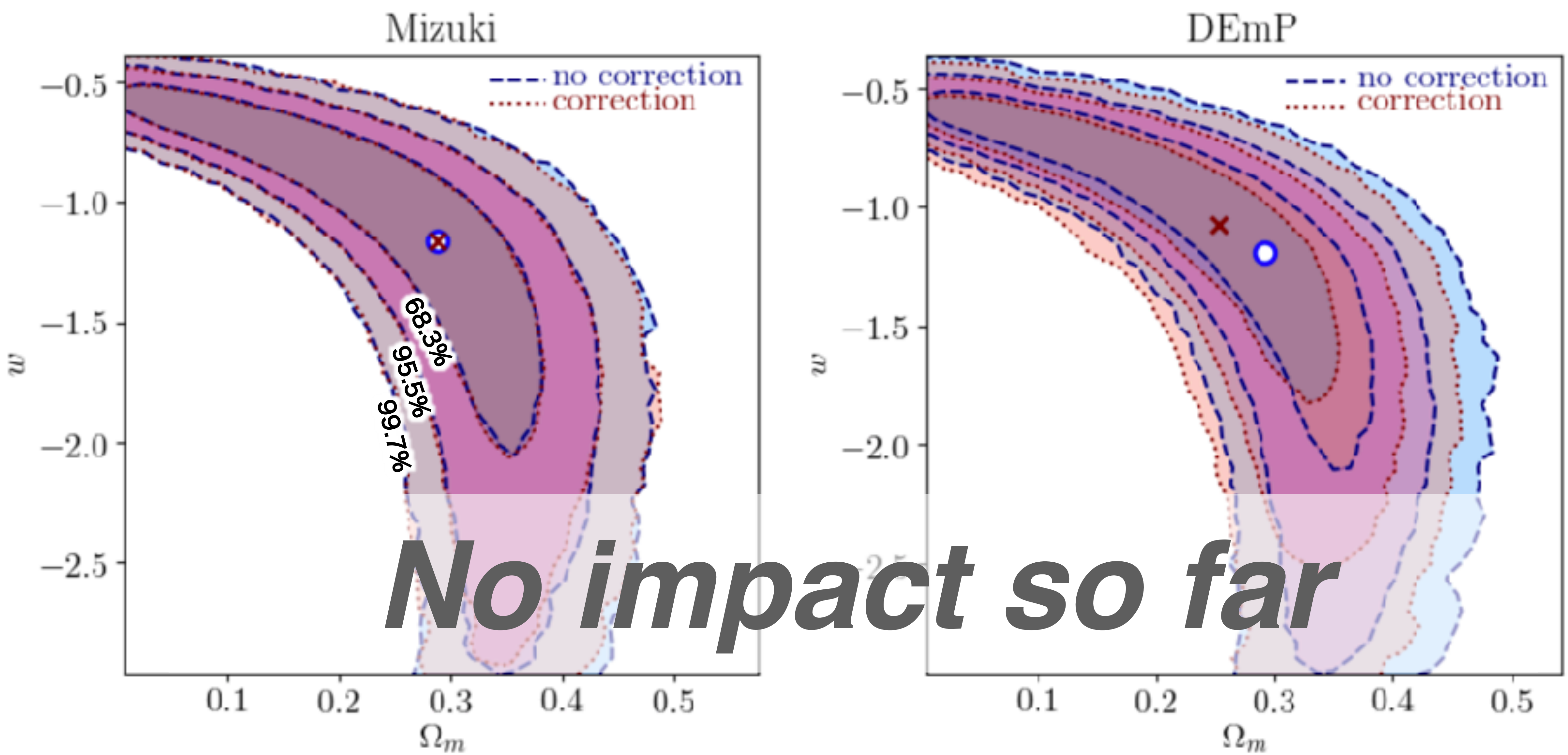
$$-2\ln\mathcal{L} = \sum_s \frac{\left[\mathbf{V}^{\mathrm{T}}\mathbf{X}_s - M - 5\log_{10}[D_L(\Omega_m, w, z_s)] + 5\right]^2}{\mathbf{V}^{\mathrm{T}}\mathbf{Cov}(\mathbf{X}_s)\mathbf{V} + \sigma_{\mathrm{int}}^2}$$

$$m \to m' = \mu_{\mathrm{lens}} m$$

$$\boldsymbol{X}_s = \begin{pmatrix} m^*_{B,s} \\ \Gamma_s \\ C_s \end{pmatrix}, \boldsymbol{V} = \begin{pmatrix} 1 \\ \alpha \\ -\beta \end{pmatrix}$$

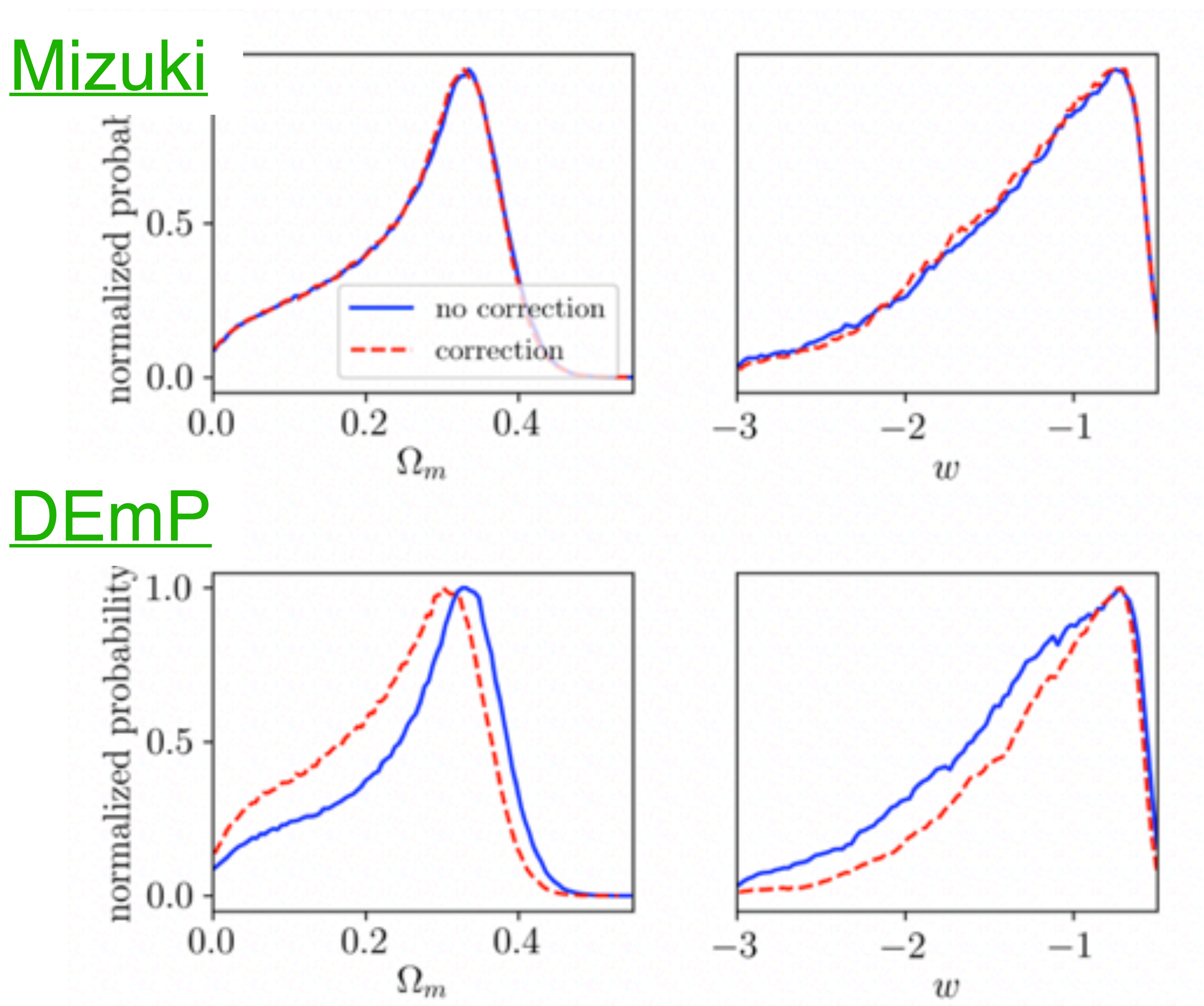
$m^*_{B,s}$ : apparent mag.
$\Gamma_s$ : shape of light curve
$C_s$ : color of light curve

cosmological information




**No impact so far**

# cosmological parameter estimation contd.




- bias in $w$ is <1%(Mizuki) and ~10% (DEmP)
- for WFIRST/LSST SNe, sigma($w_0$)~3-5% (**Hounsell+2018**) which may be affected by the magnification effect
- PS1 already got ~4% constraint on w which approaches to the systematic limit
- no error shrink (Mizuki), ~10% error shrink (DEmP)

| | Mizuki | | DEmP | |
|---|---|---|---|---|
| | w/o corr. | w/ corr. | w/o corr. | w/ corr. |
| $\Omega_{m,0}$ | $0.288^{+0.105}_{-0.086}$ | $0.287^{+0.104}_{-0.085}$ | $0.292^{+0.102}_{-0.082}$ | $0.253^{+0.113}_{-0.087}$ |
| $w$ | $-1.160^{+0.597}_{-0.363}$ | $-1.161^{+0.595}_{-0.358}$ | $-1.189^{+0.625}_{-0.354}$ | $-1.078^{+0.498}_{-0.297}$ |

# summary

- Deep and good quality imaging of HSC enables us to measure the foreground mass of the SNe.
- We measure foreground mass by different two methods: convergence mass reconstruction, and galaxy mass distribution.
- Although both methods are still noisy, we estimate the impact of the magnification on the cosmological parameter estimation.
- Need careful measurement of stellar mass in this regime.
- bias on w is <1%(Mizuki), and ~10%(DEmP) which is not a issue with the current data set where statistical error dominates.
- In future SNe dataset (LSST, WFIRST,…), where sigma(w)~a few%, the magnification will be important for unbiased estimate of the cosmological parameters.