Cosmo – Chicago – Aug 2014

Measuring cosmic structure with weak lensing of SNe

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In collaboration with:
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Supernova Lensing

- Standard SNe analysis → geodesics in FLRW
- Real universe → structure (filaments & voids) → weak-lensing (WL) → very skewed PDF (Probab. Distr. Function)!
  - Most SNe → demagnified a little (light-path in voids)
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  - Most SNe → demagnified a little (light-path in voids)
  - A few → magnified "a lot" (path near large structures)
- The lensing PDF is the key quantity
  - Hard to measure → need many more SNe
  - Can be computed: ray-tracing in N-body simulations
    - See: *Takahashi et al. 1106.3823*
      Hilbert et al. astro-ph/0703803
    - N-body→ too expensive to do likelihoods → many parameter values (many Ω_{m0}, σ_8, w_{DE}, etc.)

Supernova Lensing (2)

- Supernova light travels huge distances
  - Lensing → *on average* → no magnification (photon # conser.)
- Important quantity → magnification PDF
  - Zero mean; very skewed (most objects de-magnified)
    - Adds non-Gaussian dispersion to the Hubble diagram

$$\bar{\mu} \equiv \mathrm{magn} = \frac{1}{(1-\kappa)^2 - \gamma^2} \simeq 1 + 2\kappa$$

$$\kappa(z_s) = \int_0^{r_s} dr\, \rho_{M0}\, G(r, r_s)\, \delta_M(r, t(r))$$

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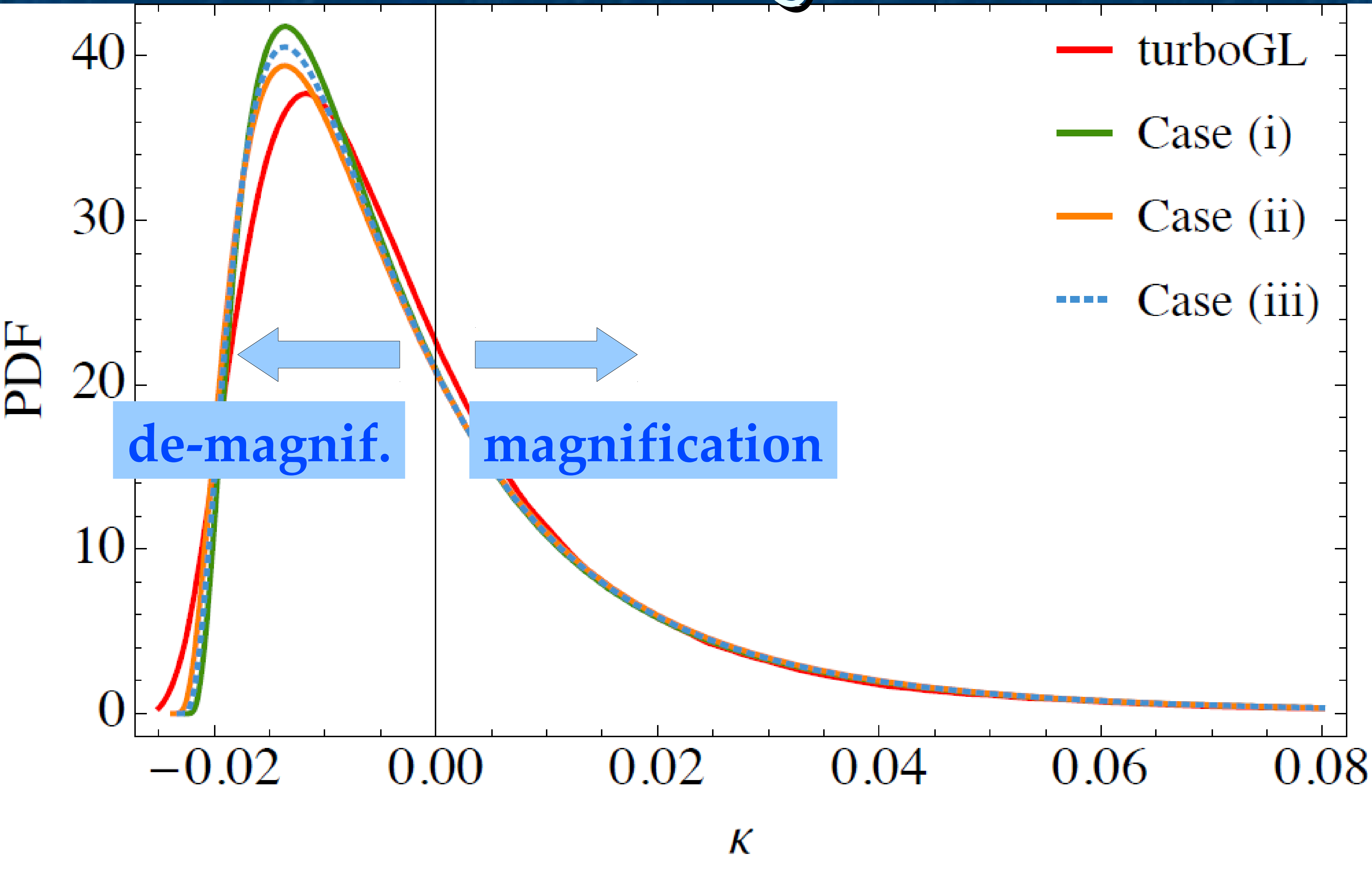
Function of three $d_A(z)$

The Lensing PDF

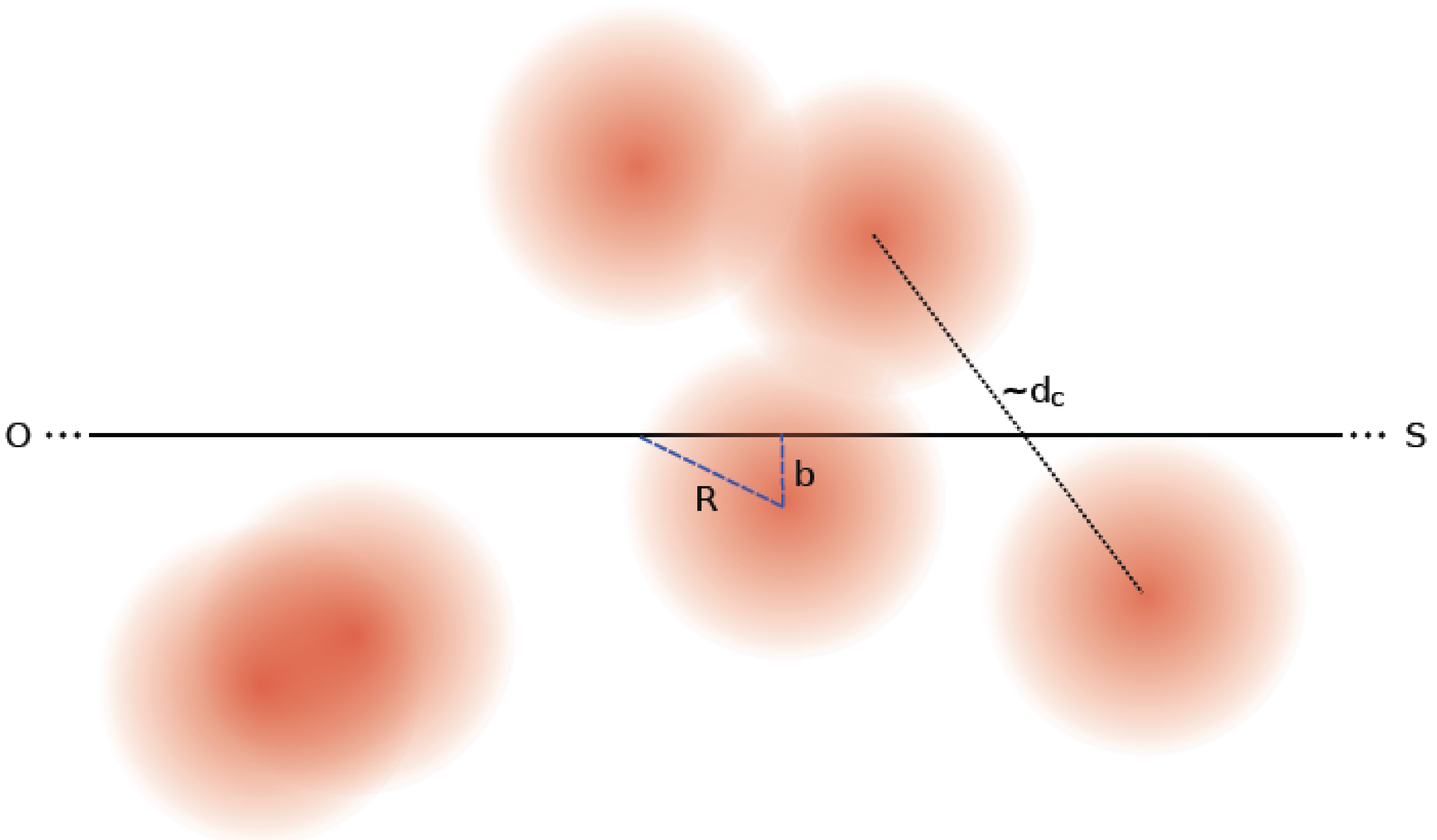


A New Method

- We need something faster than full N-body → stochastic GL analysis (sGL)
- Populate the universe with NFW halos → Halo Model
  - need prescriptions for
    - mass function (Jenkins or corrected Sheth & Tormen)
    - concentration parameter
- In a given direction, draw nearby distribution of halos
  - compute the convergence (fast)

K. Kainulainen & V. Marra
(0906.3871, PRD)
(0909.0822 , PRD)

A New Method (2)



NFW Profile

- Simple fit to N-body simulations
  - But diverges at the center
- Another possibility: Einasto profile

NFW Profile

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

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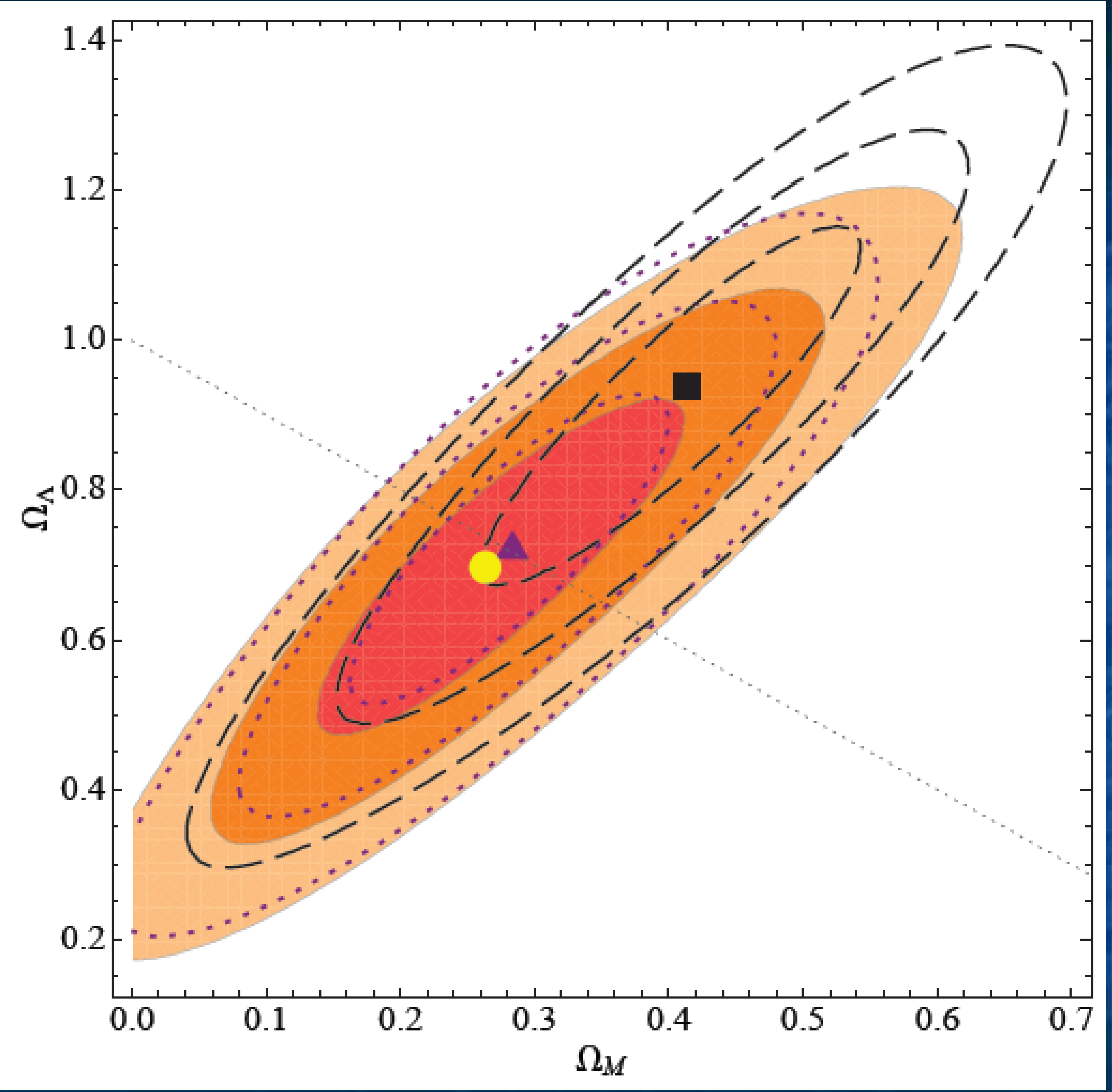
  - But diverges at the center
- Another possibility: Einasto profile

Lensing bias

Toy Model: exagerated, effect



Amendola, Kainulainen, Marra & Quartin (1002.1232, PRL)

Supernova Lensing (3)

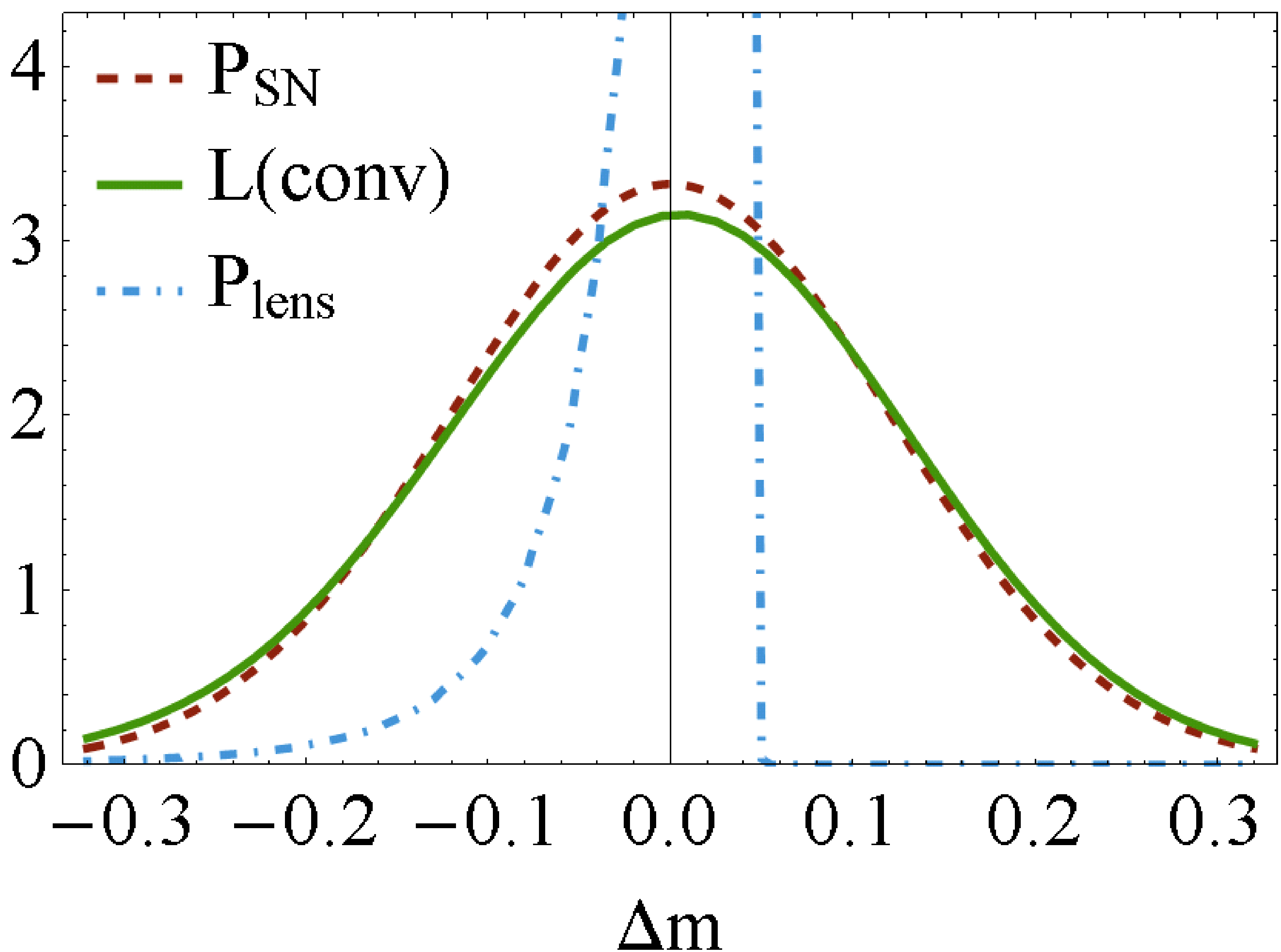
- sGL → fast way to compute the κPDF
  - FAST & accurate when compared to N-body simulations
- PDF is well parametrized by the *first 3 central moments*

$$\mu_2,\ \mu_3,\ \mu_4$$

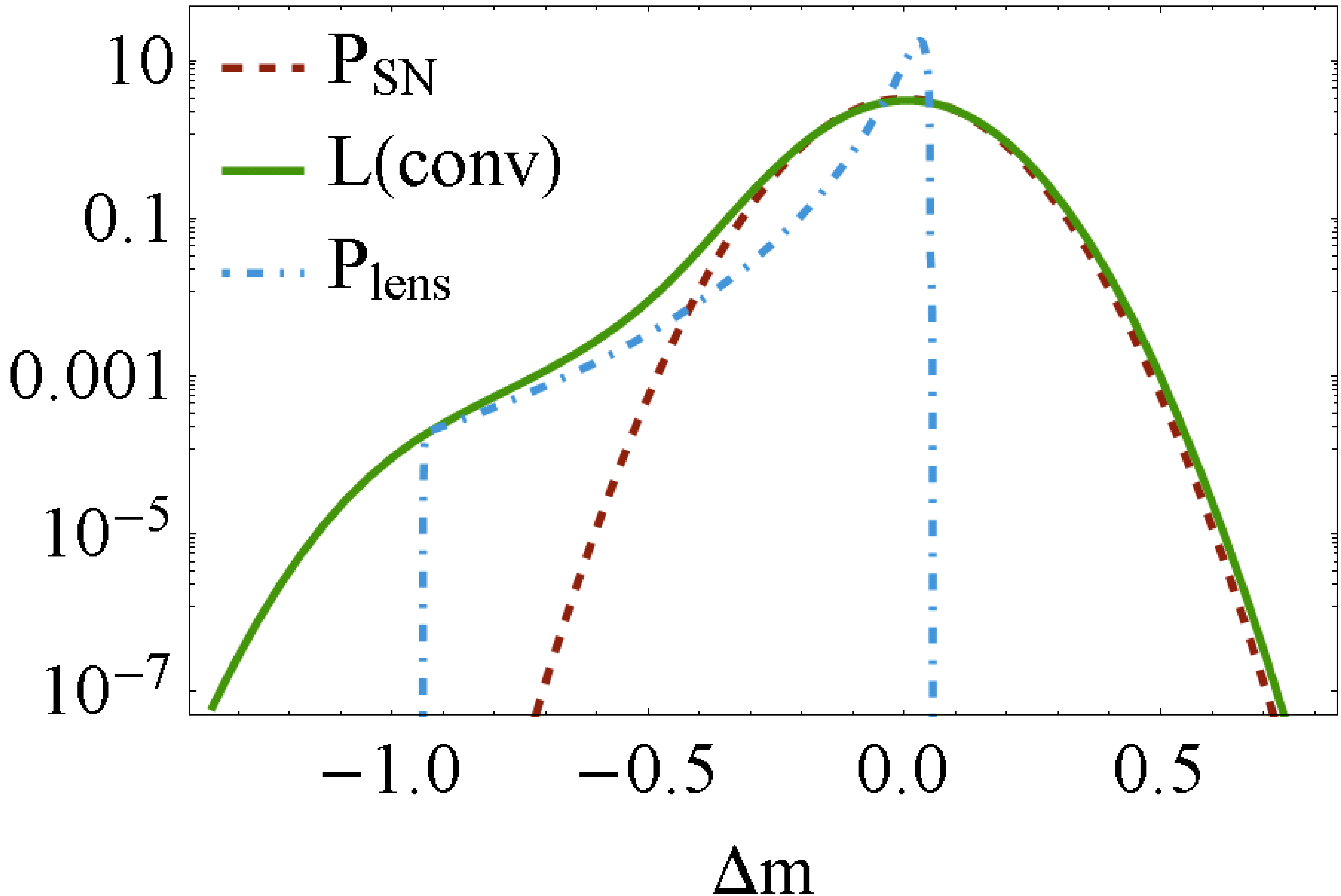
  - Lensing depends mostly on Ω_{m0} & σ_8
- Likelihood for SNe analysis → convolution of lensing PDF and intrinsic (standard) SNe PDF

$$L(\mu) = \int \mathrm{d}y\, P_{\mathrm{wl}}(y, \Omega_{m0}, \sigma_8, \cdots) P_{SN}(\Delta m - \mu - y, \sigma)$$

Marra, Quartin & Amendola 1304.7689 (PRD)

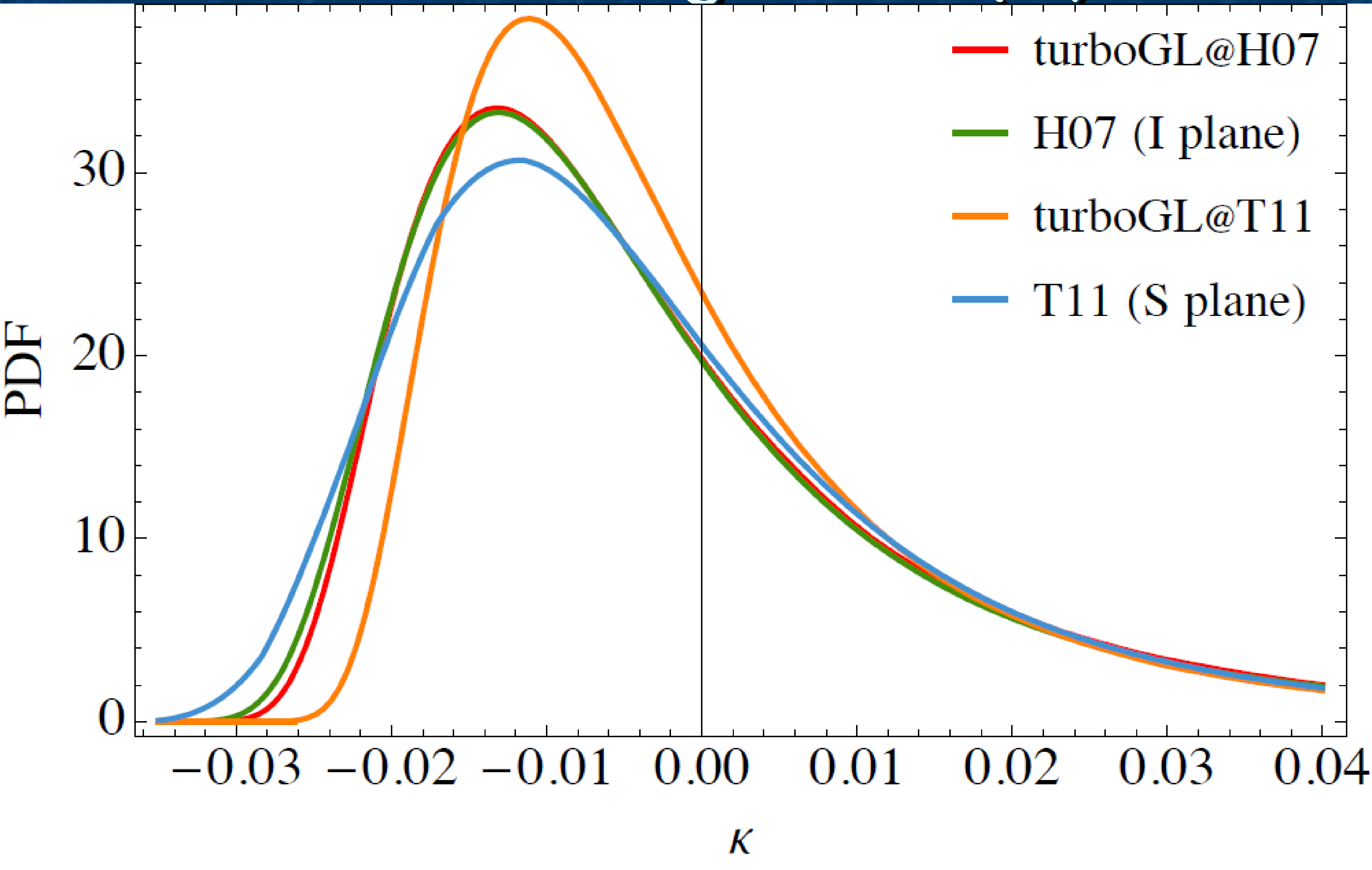


P_{SN}
L(conv)
P_{lens}
0
1
2
3
4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
Δm

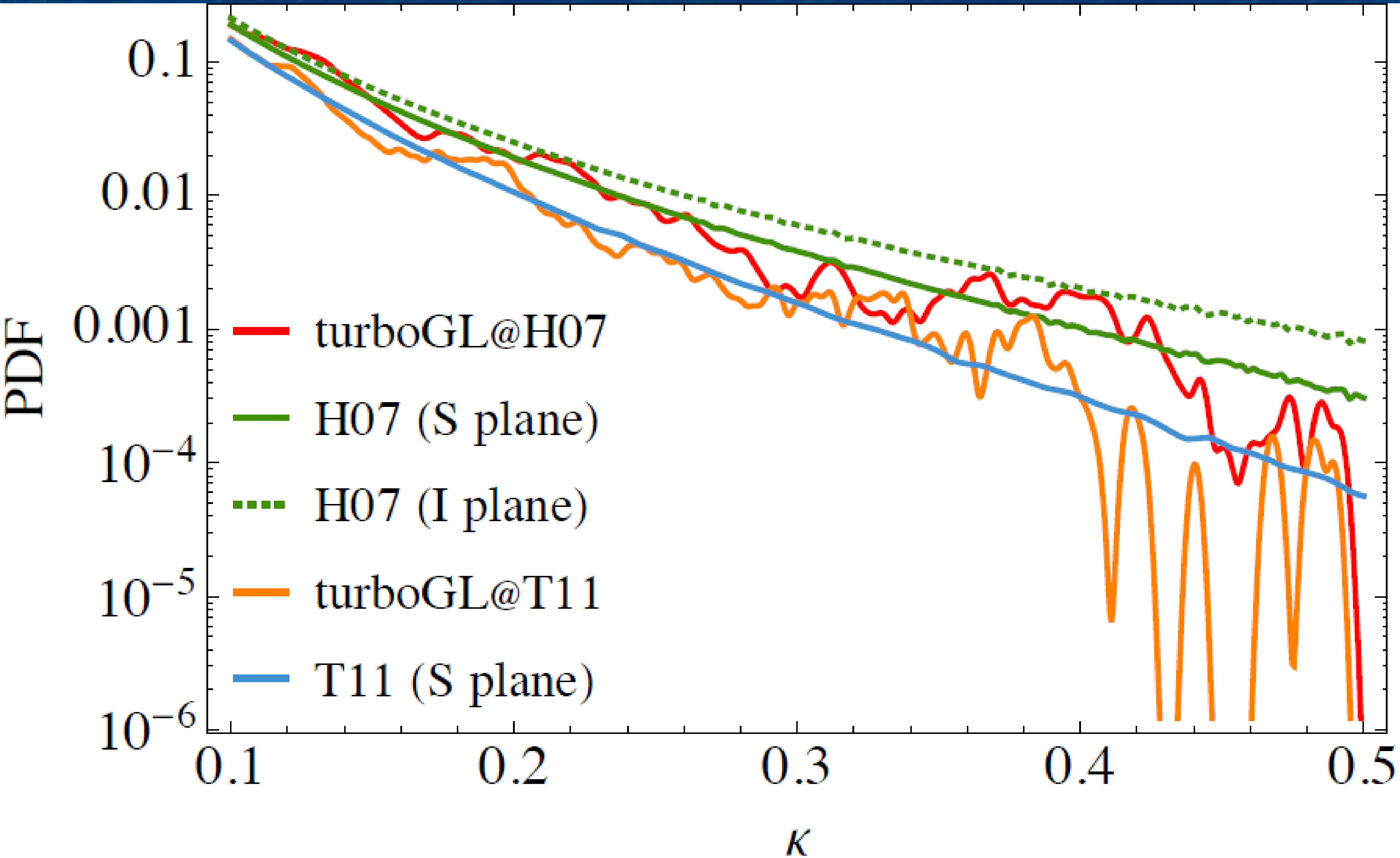


P_{SN}
L(conv)
P_{lens}
10
0.1
0.001
10^{-5}
10^{-7}
−1.0
−0.5
0.0
0.5
Δm

The Lensing PDF (2)



The Lensing PDF (3)



Fitting Functions

- We provide accurate and flexible analytical fits for the variance, skewness & kurtosis
  - Significant improvement upon usual (HL) fit: $\sigma_{\mathrm{lens}}^{\mathrm{HL}} = 0.093z$

$$
\begin{aligned}
0 &\leq z \leq 3 \\
0.35 &\leq \sigma_8 \leq 1.25 \\
0.1 &\leq \Omega_{m0} \leq 0.52
\end{aligned}
$$

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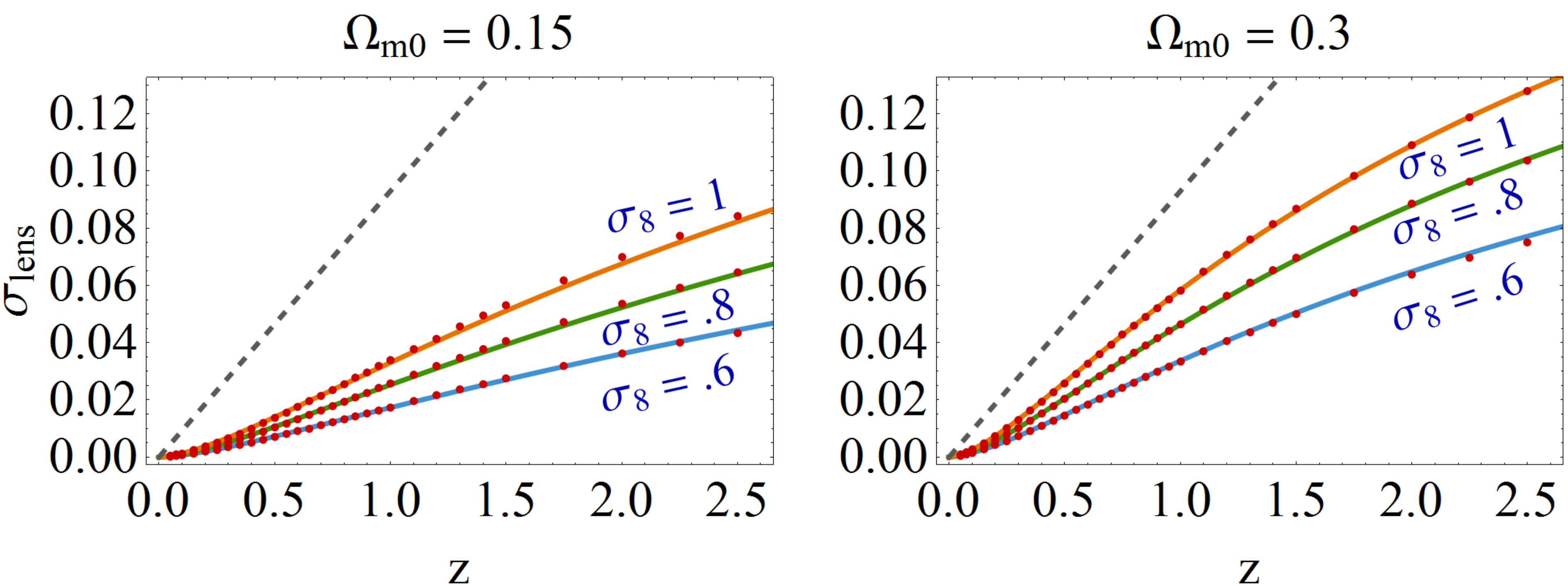
$0 < z < 3$



The Inverse Lensing Problem

- Can we turn Noise into Signal?
  - Can we learn about cosmology from the scatter of supernovae in the Hubble diagram?

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- Can we turn Noise into Signal?
  - Can we learn about cosmology from the scatter of supernovae in the Hubble diagram?
  - Answer: YES! We can constrain σ_8!
    - Caveat 1: no revolutionary precision
      - need ~10^4 SNe to get to ~10%, ~10^6 to get to ~1%
        - LSST will give us ~10^6
    - Caveat 2: need to assume halo profiles: e.g. NFW
  - It is a new observable & good cross-check

Dodelson & Vallinotto (astro-ph/0511086, PRD)

Quartin, Marra & Amendola (1307.1155, PRD)

The MeMo Likelihood

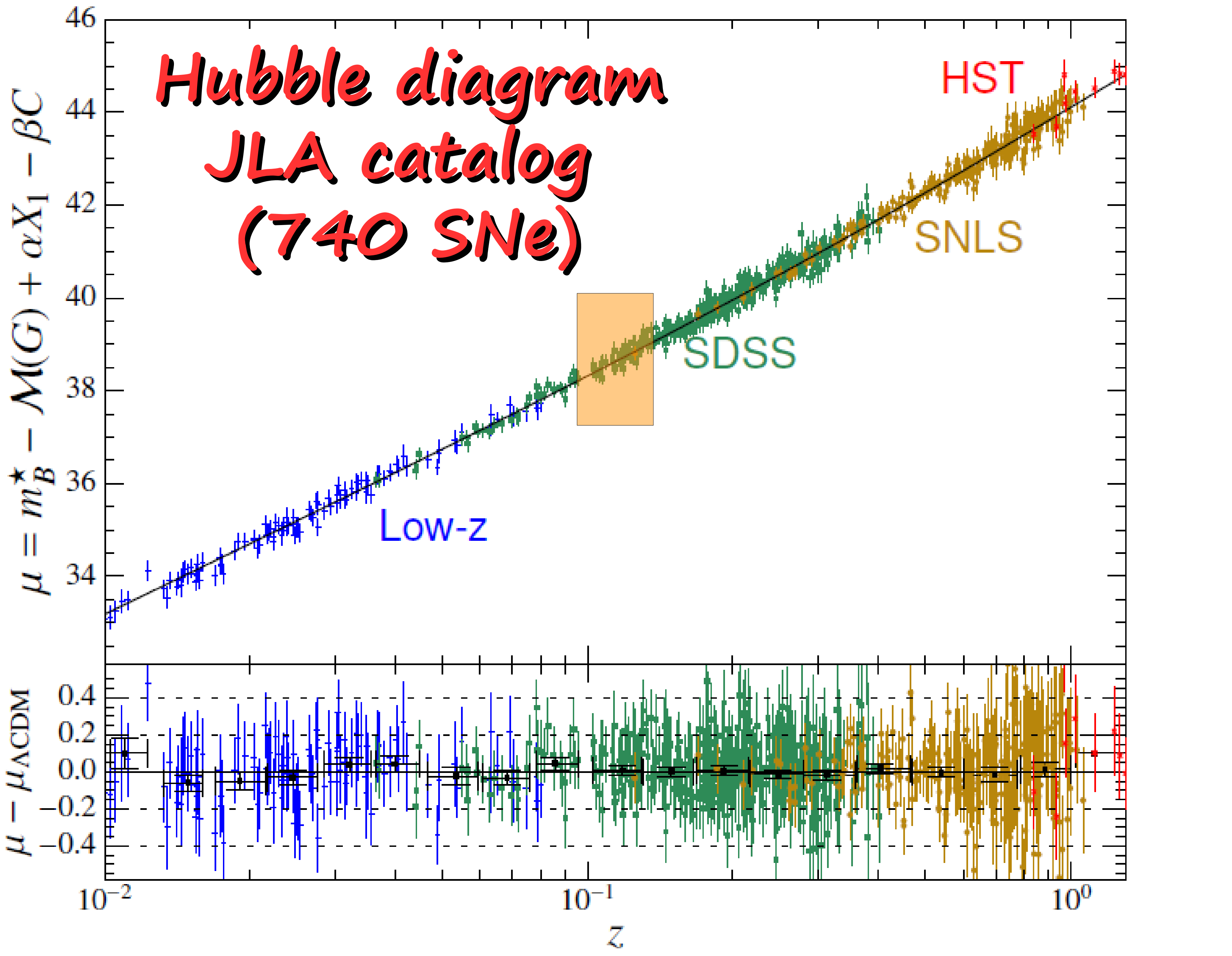
- Using the first 4 moments, we write:

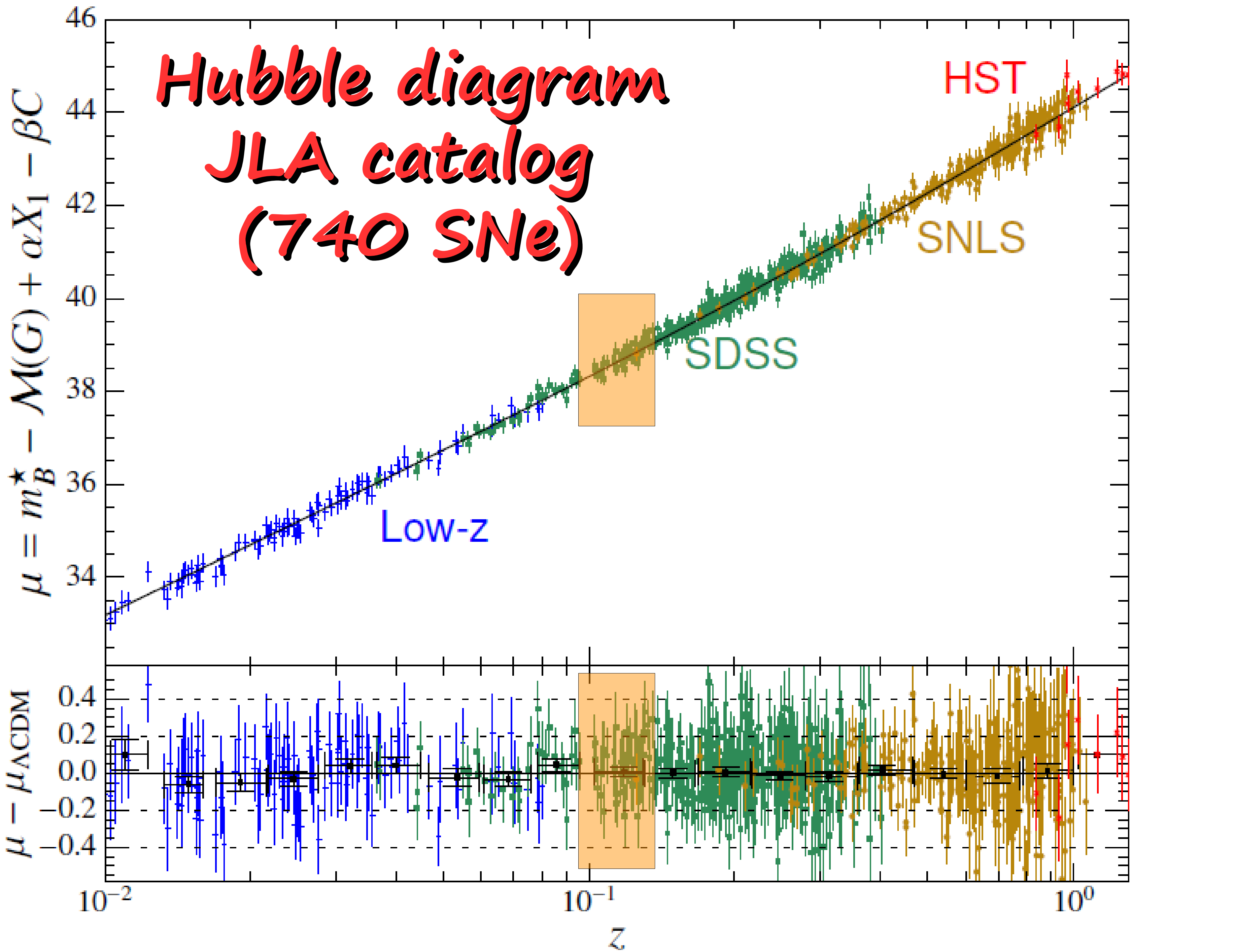
$$L_{\mathrm{MeMo}}(\Omega_{m0}, \sigma_8, \{\sigma_{\mathrm{int},j}\}) = \exp\left(-\frac{1}{2}\sum_j^{\mathrm{bins}} \chi_j^2\right),$$

$$\chi_j^2 = (\boldsymbol{\mu} - \boldsymbol{\mu}_{\mathrm{fid}})^t \, \Sigma_j^{-1} \, (\boldsymbol{\mu} - \boldsymbol{\mu}_{\mathrm{fid}}),$$

$$\boldsymbol{\mu} = \{\mu_1', \mu_2, \mu_3, \mu_4\},$$

- Very complicated covariance matrix
  - Involves up to 8th moment
    - There is reason to believe it is under control


Hubble diagram
JLA catalog
(740 SNe)
HST
SNLS
SDSS
Low-z
$\mu = m_B^\star - M(G) + \alpha X_1 - \beta C$
$\mu - \mu_{\Lambda CDM}$
z



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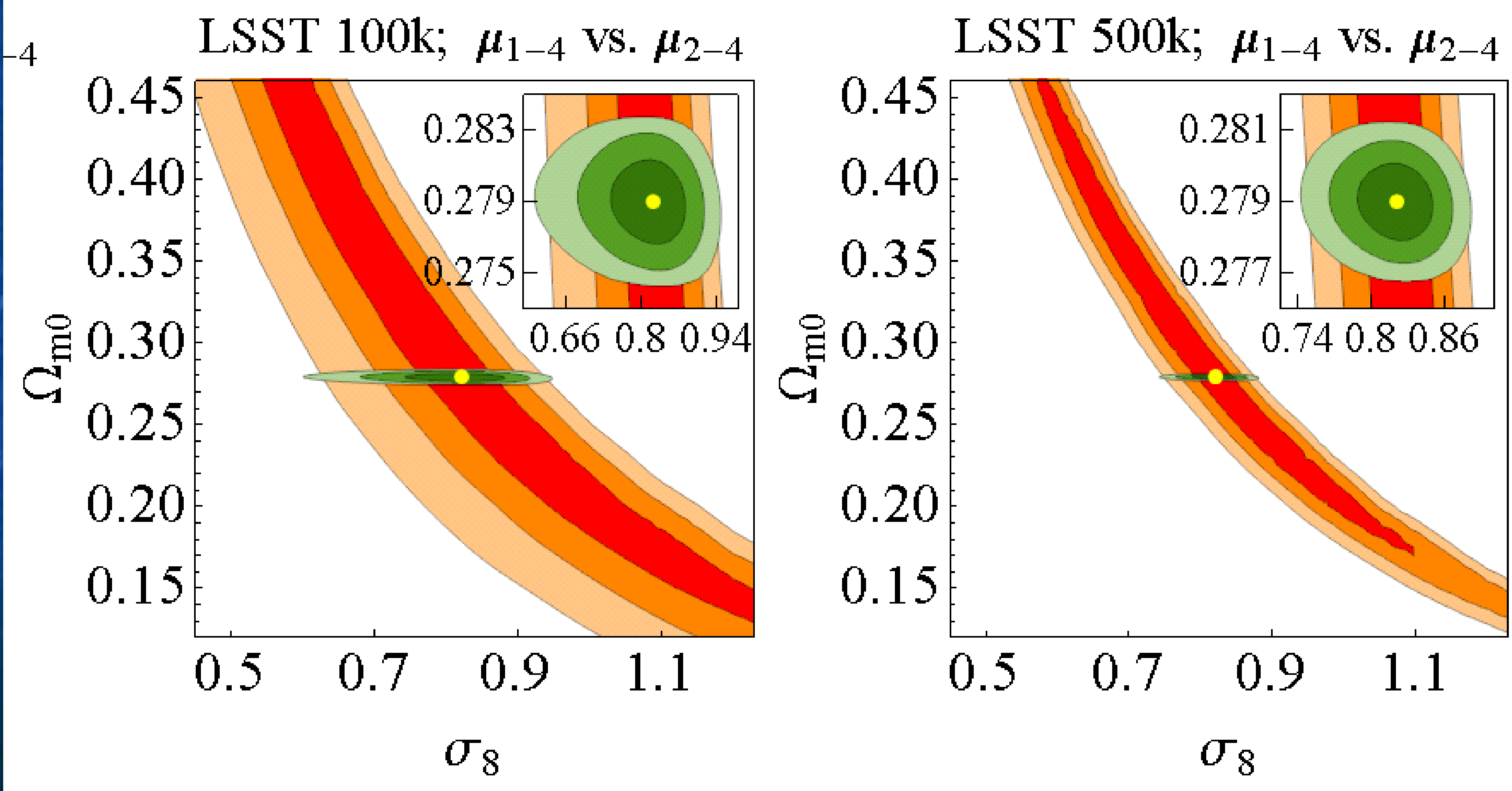
The Inverse Lensing Problem (2)

- LSST will tell us about σ_8 up to **~ 3 – 7%** precision!



What IS a standard candle?

- Supernovae are assumed to be a standard candle
  - Intrinsic magnitude M → const. in z + gaussian scatter
  - A fine-tuned M(z) → no acceleration → no Nobel prize
- So why a Nobel prize?

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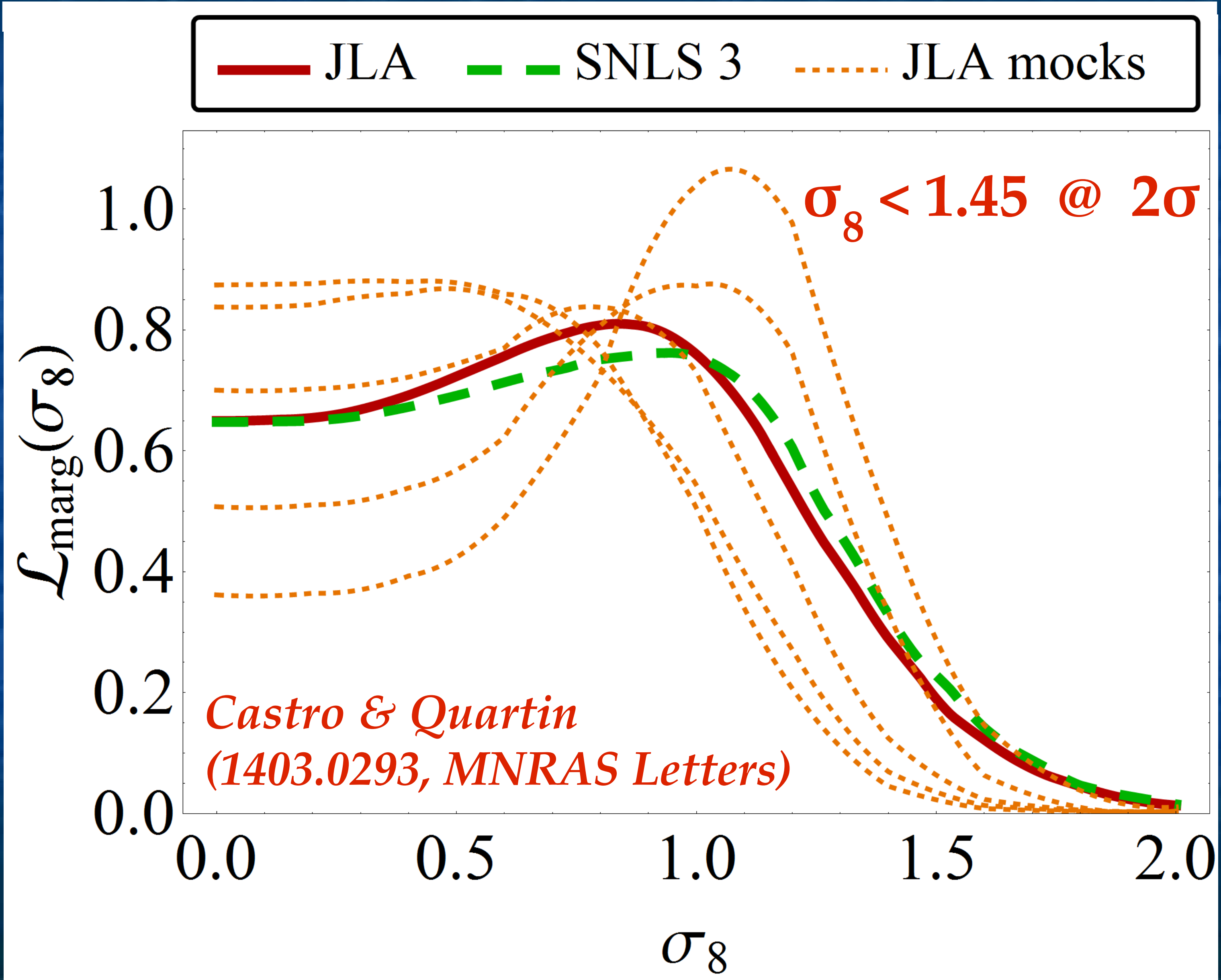
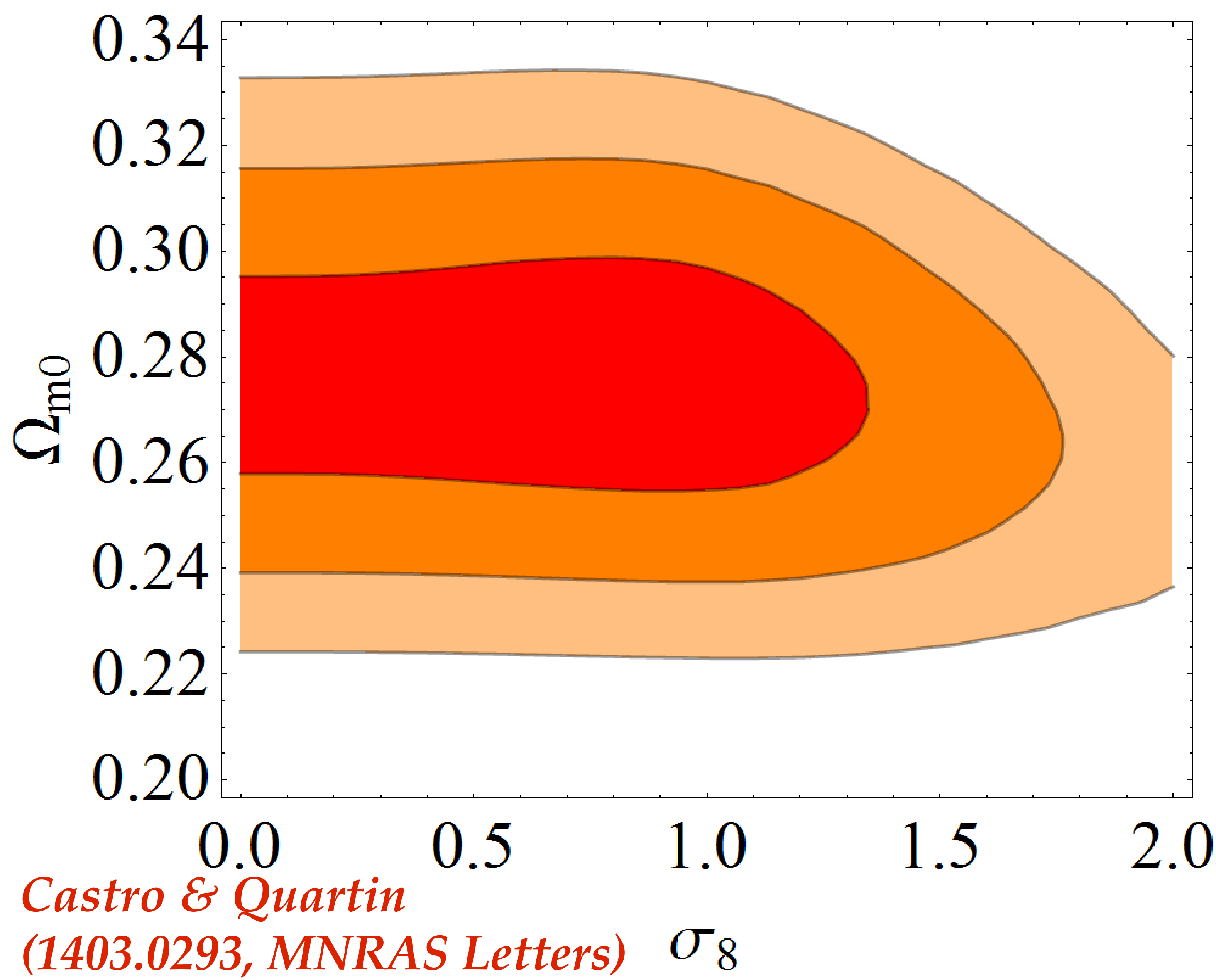
- So why a Nobel prize?
  - It agrees with CMB & BAO (baryon acoustic oscillations)
  - Occam's Razor → acceleration is the simplest model!
- Apply same reasoning for intrinsic non-Gaussianity
  - Add nuisance parameters for intrinsic central moments
  - We tested this idea with the SNLS-3 and JLA catalogs

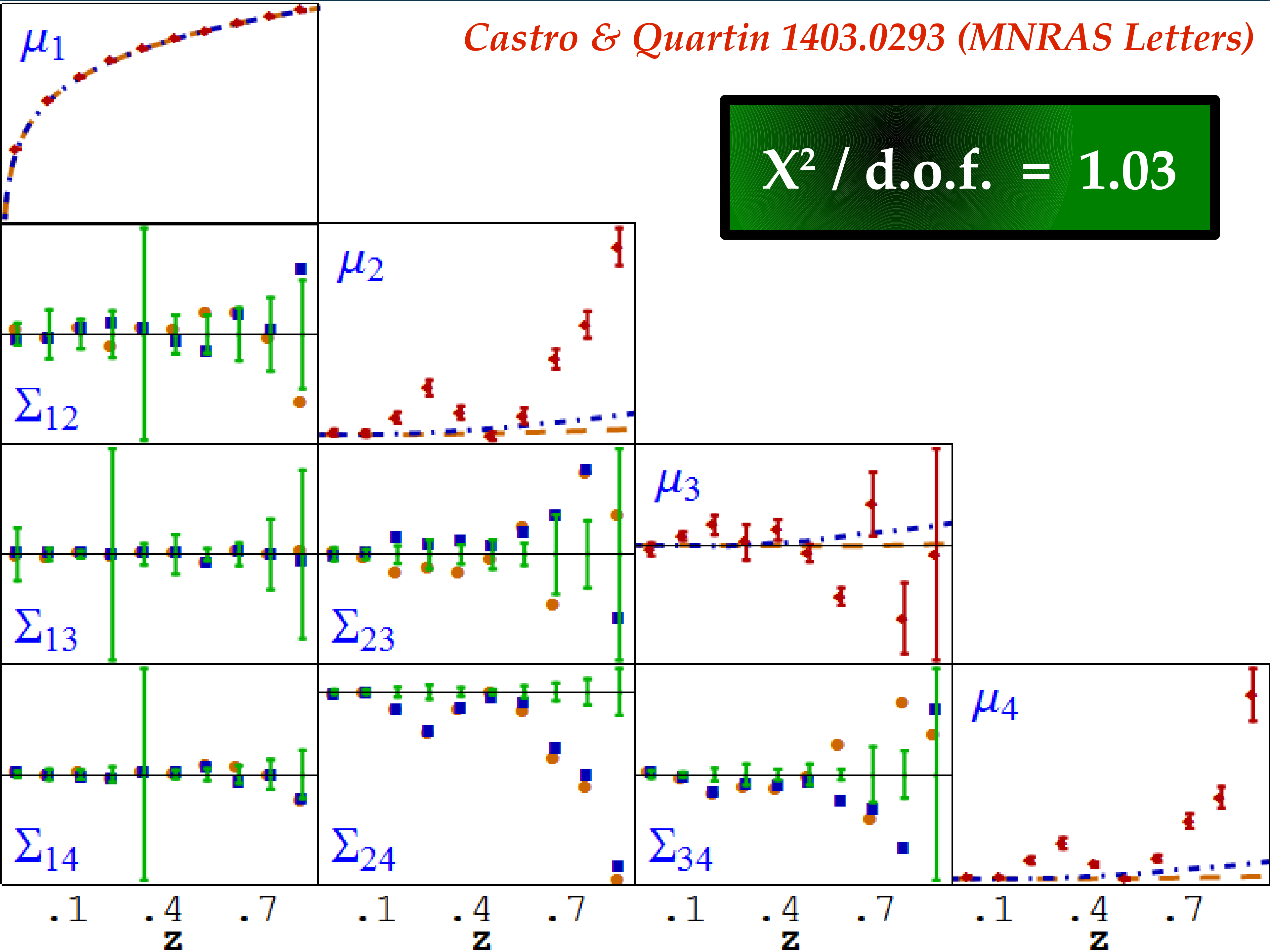
Real data: JLA



Real data: JLA (2)



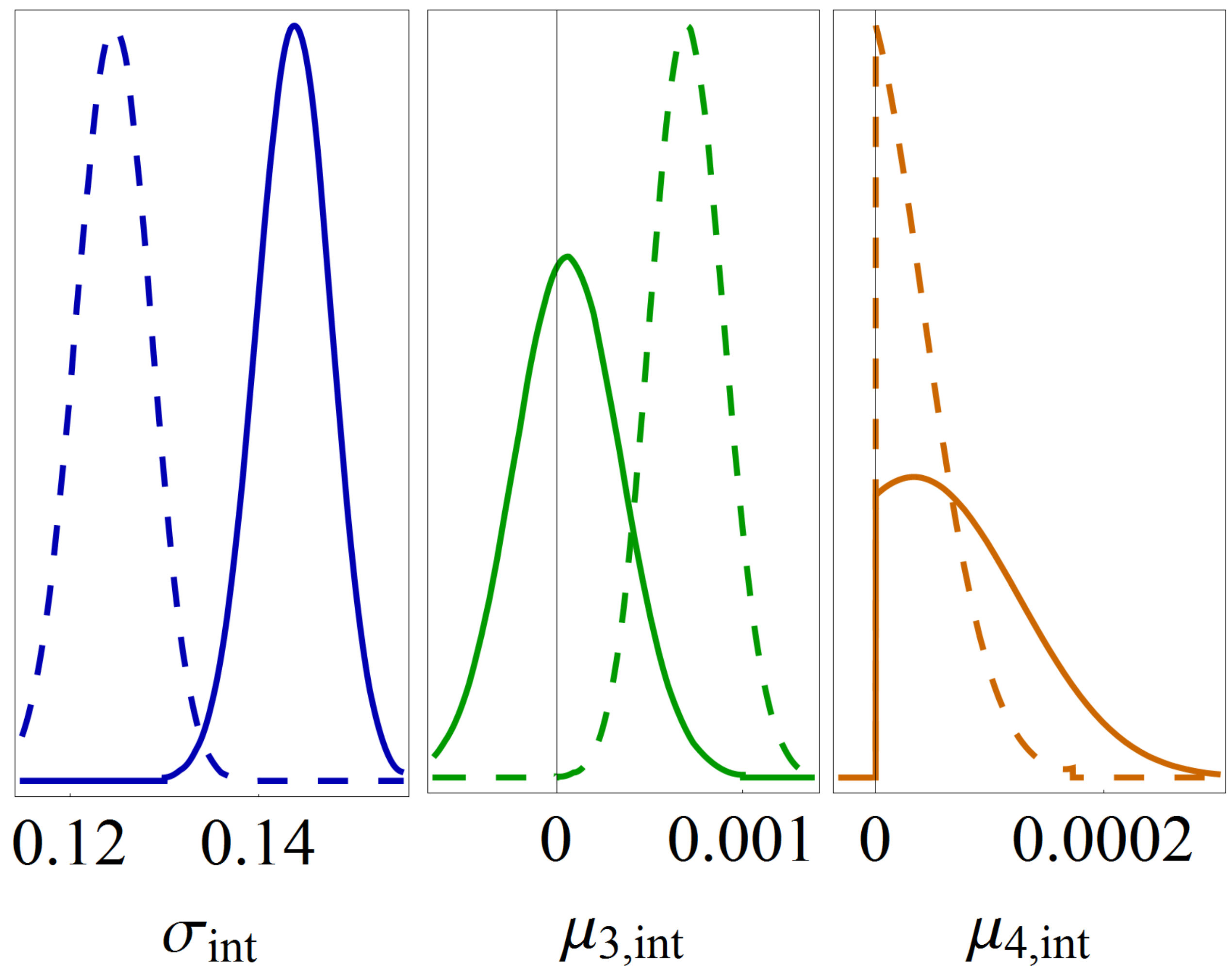
Castro & Quartin (1403.0293, MNRAS Letters)


Castro & Quartin 1403.0293 (MNRAS Letters)
X² / d.o.f. = 1.03
μ1
μ2
μ3
μ4
Σ12
Σ13
Σ14
Σ23
Σ24
Σ34
.1 .4 .7
z

Real data: JLA (4)

We can also measure the intrinsic SNe moments.

i.e., we don't need to assume SNe are intrinsically Gaussian



Conclusions

- SNe Lensing has already been detected at ~3σ (1307.2566)
  - But until 2014 not detected from SNe data alone!
- Detailed lensing modeling important to avoid biases
- Supernova can constrain also perturbation parameters!
  - $\sigma 8$ to %–level with LSST
- We may need to refine our modeling for future data
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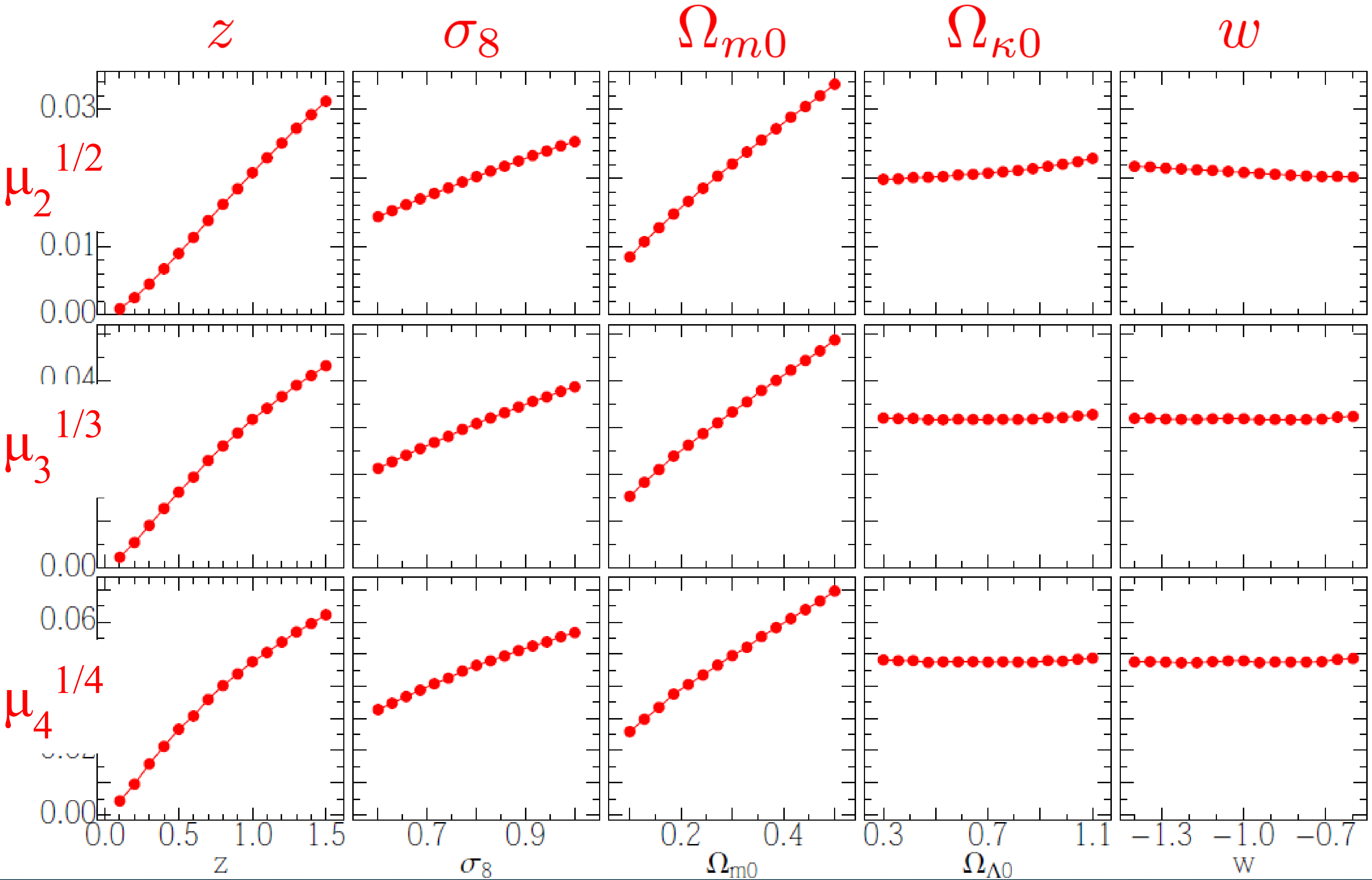
Thanks!

Extra slides

Variance, Skewness & Kurtosis



Type Ia Supernovae

Type Ia Supernovae

- SNe Ia are so far the only proven standard(izible) candles for cosmology
- With good measurements → scatter < 0.15 mag in the Hubble diagram
- But arguably they are subject to more systematic effects than BAO (baryon acoustic oscillations) & CMB
  - Systematic errors already the dominant part (N_{SNe} ~ 1000)
  - In the next ~10 years → statistics will increase by 100x
    - Huge effort to improve understanding of systematics

Howell, 1011.0441 (review of SNe)

Type Ia Supernovae (2)

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- Supernovae (SNe) are very bright explosions of stars
- There are 2 major kinds of SNe
  - Core-collapse (massive stars which run out of H and He)
  - Collapse by mass accretion in binary systems (type Ia)
    - White dwarf + red giant companion (single degenerate)
    - White dwarf + White dwarf (double degenerate)
    - Type Ia SNe explosion → ~ standard energy release
      - Chandrasekar limit on white dwarf mass: $M_{max} = 1.44\ M_{sun}$
      - Beyond this → instability → explosion
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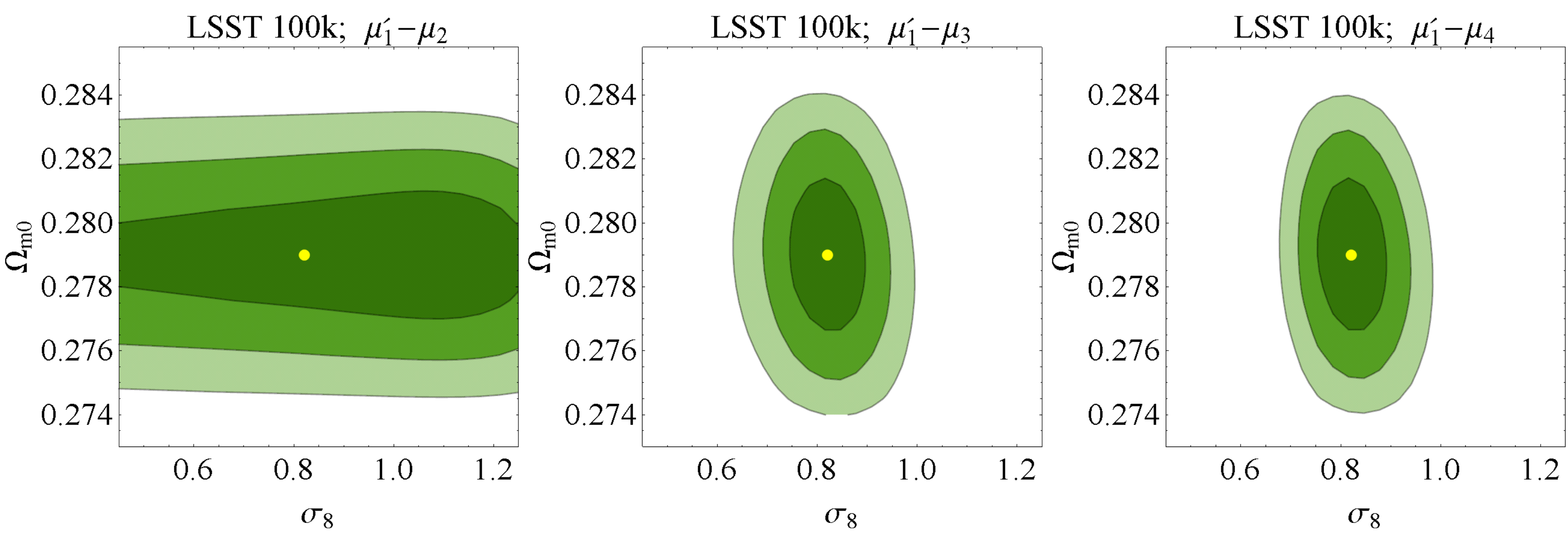
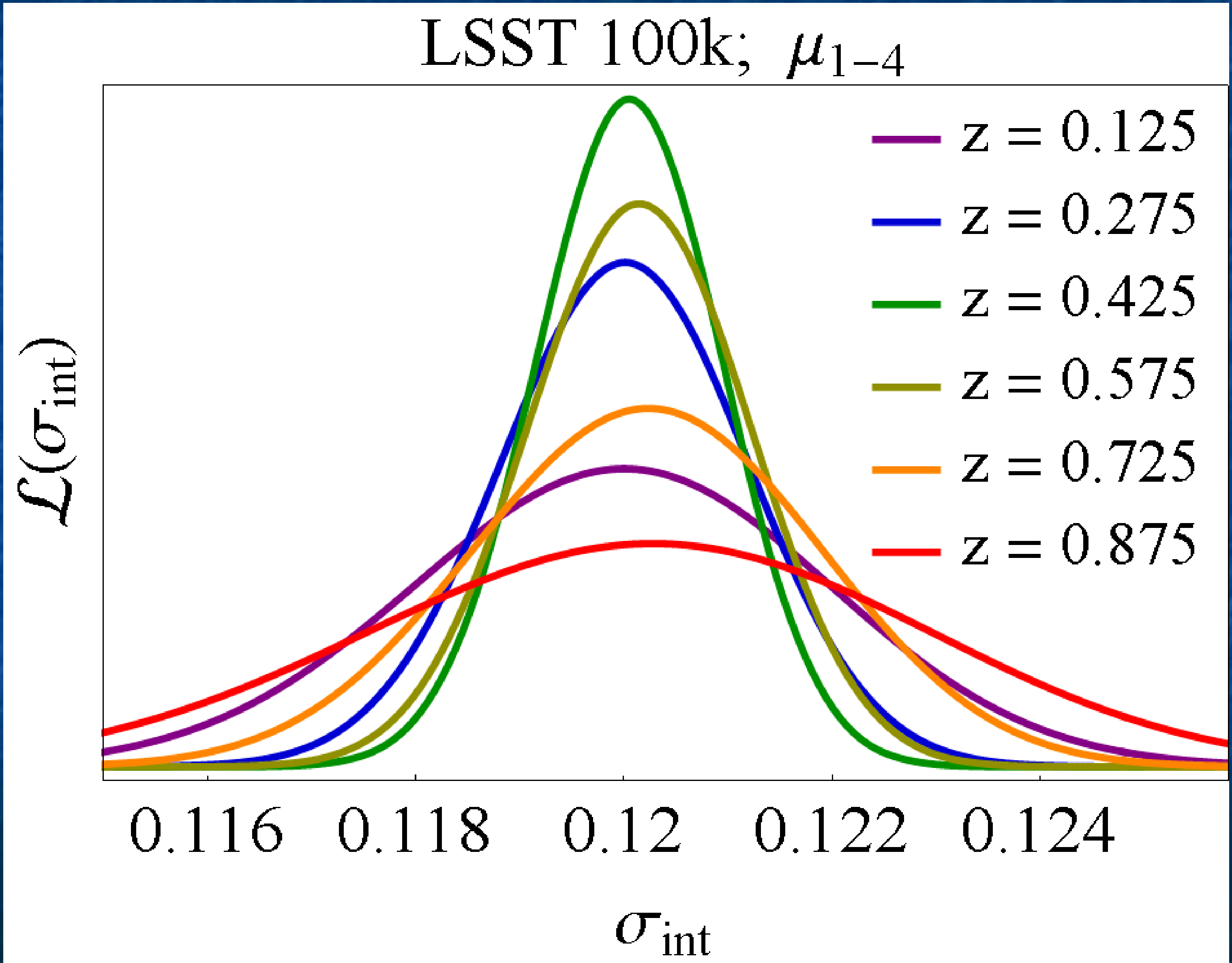
$$\Sigma_{\mathrm{gau},j} = \frac{1}{N_j}\begin{pmatrix} \sigma_j^2 & 0 & 0 & 0 \\ 0 & 2\sigma_j^4 & 0 & 12\sigma_j^6 \\ 0 & 0 & 6\sigma_j^6 & 0 \\ 0 & 12\sigma_j^6 & 0 & 96\sigma_j^8 \end{pmatrix}$$

The MeMo Likelihood (2)

- How many moments are needed?
  - More moments → more information
  - With first 3 we already have ~90% of the information
    - With first 4, we have close to 100%.



σint posteriors



Scary Movie

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- The full covariance matrix is very complicated.
  - Variance of the variance
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  - Covariance terms...
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$$\Sigma_j = \frac{1}{N_j} \times$$

$$\begin{pmatrix} K_2 & K_3 & K_4 & 6K_2K_3 + K_5 \\ - & 2K_2^2 + K_4 & 6K_2K_3 + K_5 & 12K_2^3 + 14K_4K_2 + 6K_3^2 + K_6 \\ - & - & 6K_2^3 + 9K_4K_2 + 9K_3^2 + K_6 & 72K_3K_2^2 + 18K_5K_2 + 30K_3K_4 + K_7 \\ - & - & - & 96K_2^4 + 204K_4K_2^2 + 216K_3^2K_2 + 28K_6K_2 + 34K_4^2 + 48K_3K_5 + K_8 \end{pmatrix}$$

What is σ_8?

- σ_8 is the amplitude of the matter fluctuations at the scale of 8 Mpc/h

$$\Delta^2(r,z) \equiv \left(\frac{\delta M}{M}\right)^2 = \int_0^\infty \frac{dk}{k}\Delta^2(k,z)W^2(kr)$$

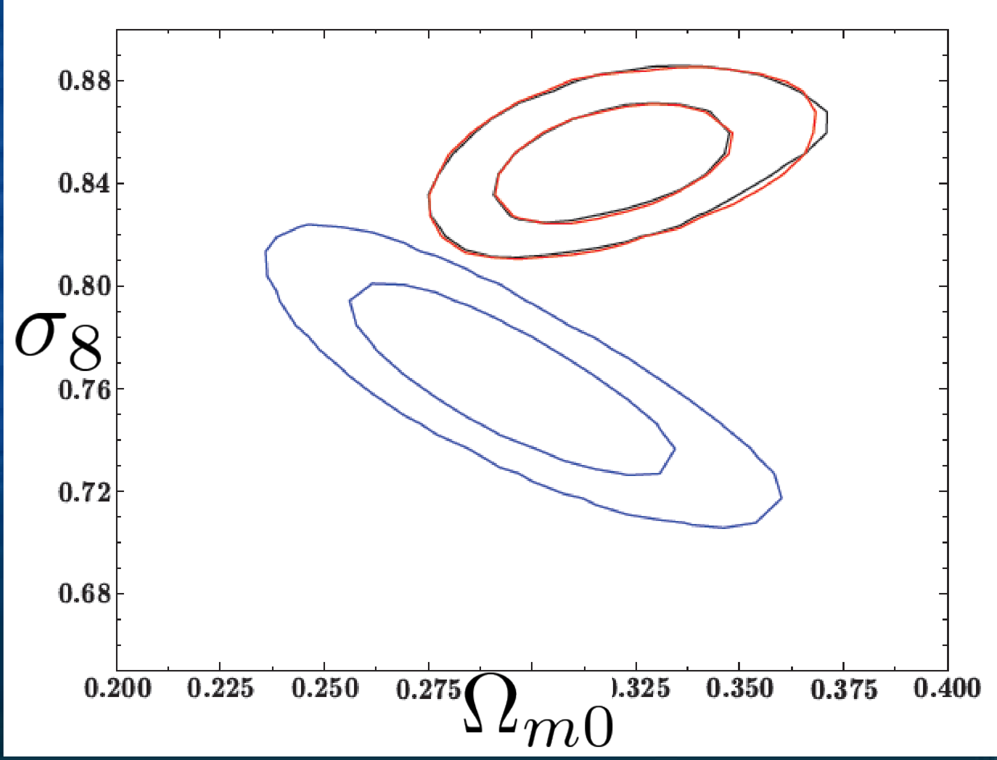
$$\Delta^2(k,z) \equiv \frac{k^3}{2\pi^2}P(k,z) = \delta_{H0}^2\left[\frac{ck}{a_0 H_0}\right]^{3+n_s} T^2(k/a_0)D^2(z)$$

$$\Delta(r = 8\ \mathrm{Mpc}/h,\ z = 0) = \sigma_8$$

What is σ_8?

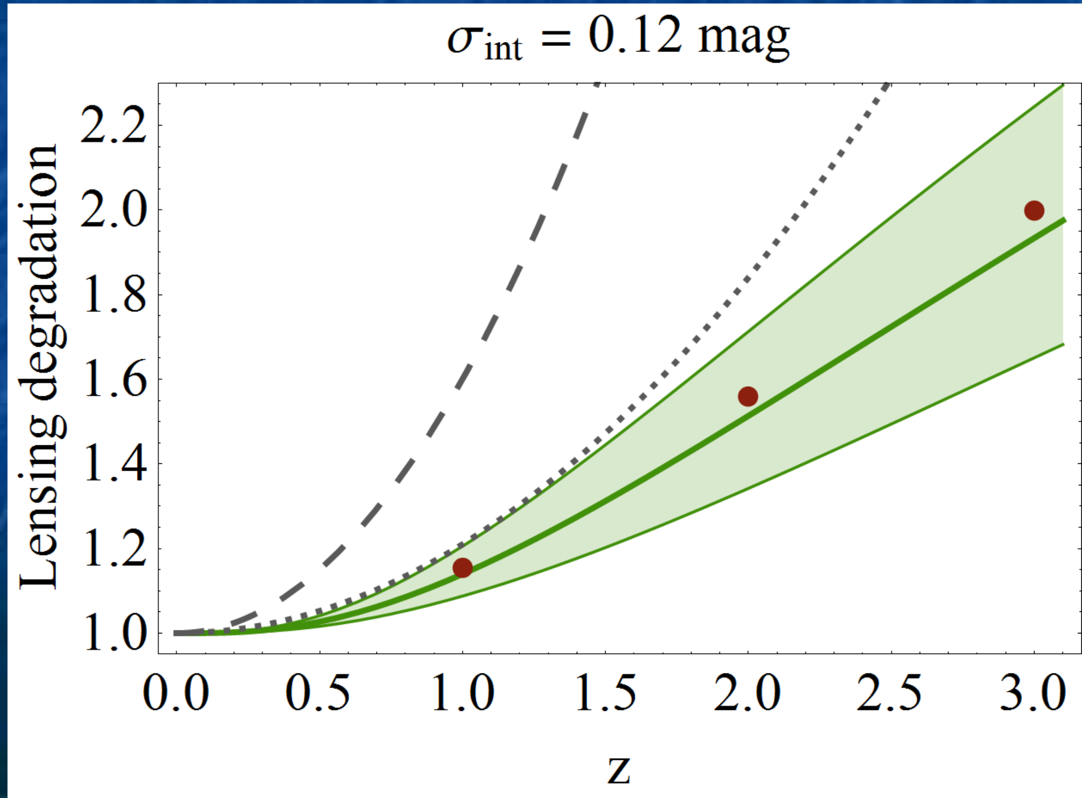
- $\sigma_8 \rightarrow$ amplitude of matter fluctuations @ 8 Mpc/h scale
- Standard ways to measure σ_8:
  - CMB $\rightarrow$ propagate fluctuations from $z = 1090$ to $z = 0$
  - Cosmic Shear $\rightarrow$ requires galaxy shapes
  - Cluster abundance
- Some tension between these measurements
  - Cross-check important!

Planck XX (1303.5080)



Fitting Functions (2)

- We find that the variance is ~2x smaller than some previous estimates *D. Holz & E. Linder 0412173 (ApJ)*
  - But are in better agreement w/ SNLS *Jonsson et al. 1002.1374 (MNRAS)*
- Conclusion → high-z supernovae are more useful than sometimes thought
- Lensing bias less of a problem



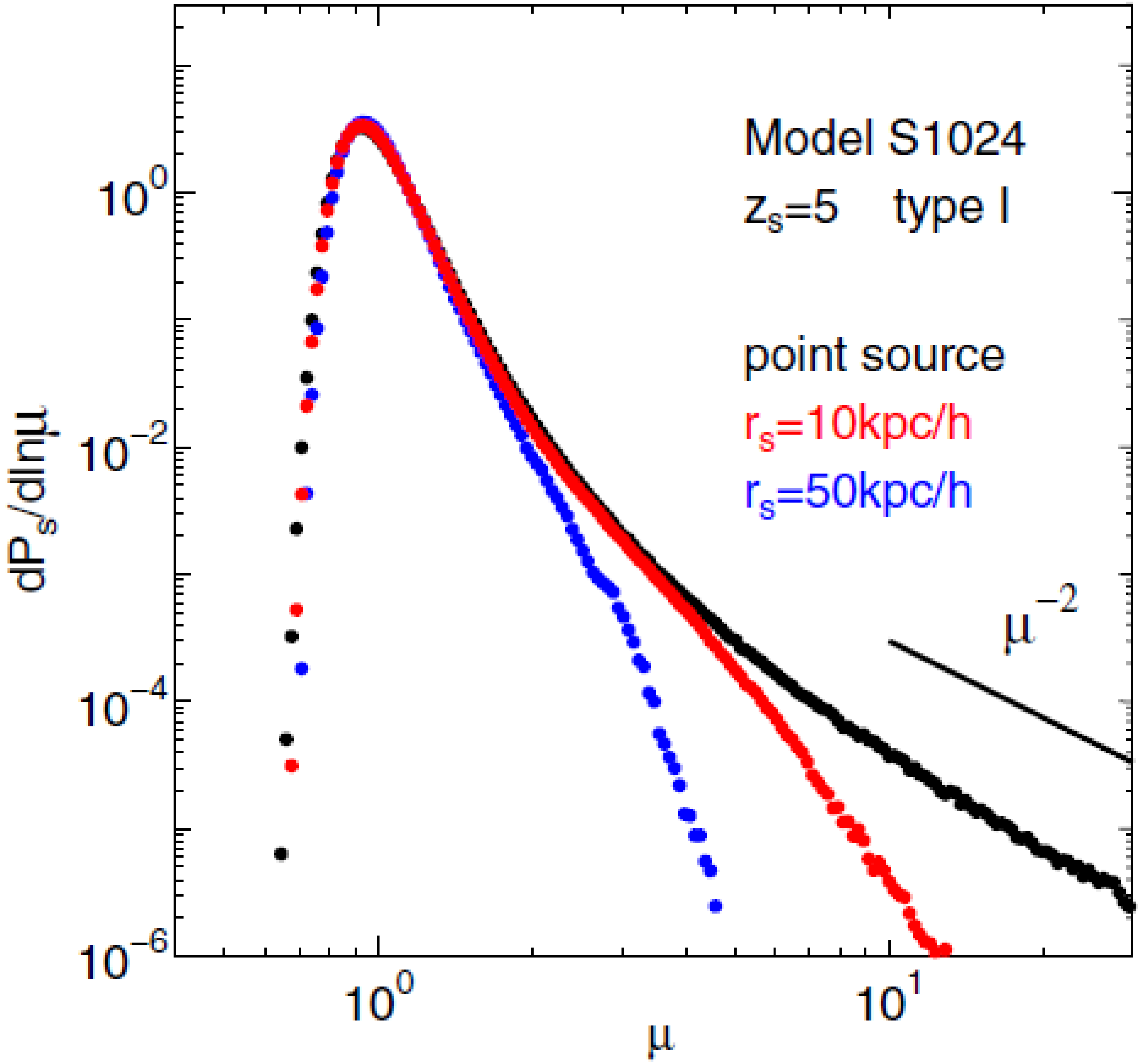
The Inverse Lensing Problem (2)

- Information from lensing ↔ full, lensing-dependent likelihood:

$$L(\mu) = \int \mathrm{d}y \, P_{\mathrm{wl}}(y, \Omega_{m0}, \sigma_8, \cdots) P_{SN}(\Delta m - \mu - y, \sigma)$$

- It works BUT there is a faster & more interesting method: the Method of the Moments (MeMo)
  - Instead of the full lensing PDF we just use the first 3 central moments
  - *Advantages*: faster; directly related to observations → simpler to control systematics step-by-step
  - *Disadvantage*: more involved equations

Finite sources



Takahashi et al. 1106.3823

SNe Systematics

Systematic	SNLS3[143]	CfA[27]/ESSENCE[44]	SDSS-II[26]	SCP[28
Best fit w (assuming flatness)	...	-0.987	-0.96	-0.997
Statistical error	...	0.067	0.06	0.052
Total stat+systematic error	...	0.13	0.13	0.08
Systematic error breakdown				
Flux reference	0.053	0.02	0.02	0.042
Experiment zero points	0.01	0.04	0.030	0.037
Low-z photometry	0.02	0.005	...	...
Landolt bandpasses	0.01	...	0.008	...
Local flows	0.014	...	0.03	...
Experiment bandpasses	0.01	...	0.016	...
Malmquist bias model	0.01	0.02	...	0.026
Dust/Color-luminosity (β)	0.02	0.08	0.013	0.026
SN Ia Evolution	...	0.02	...	...
Restframe U band	...	...	0.104	0.010
Contamination	...	...	...	0.021
Galactic Extinction	...	...	0.022	0.012