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Measuring Perturbations with Weak Lensing of SNe

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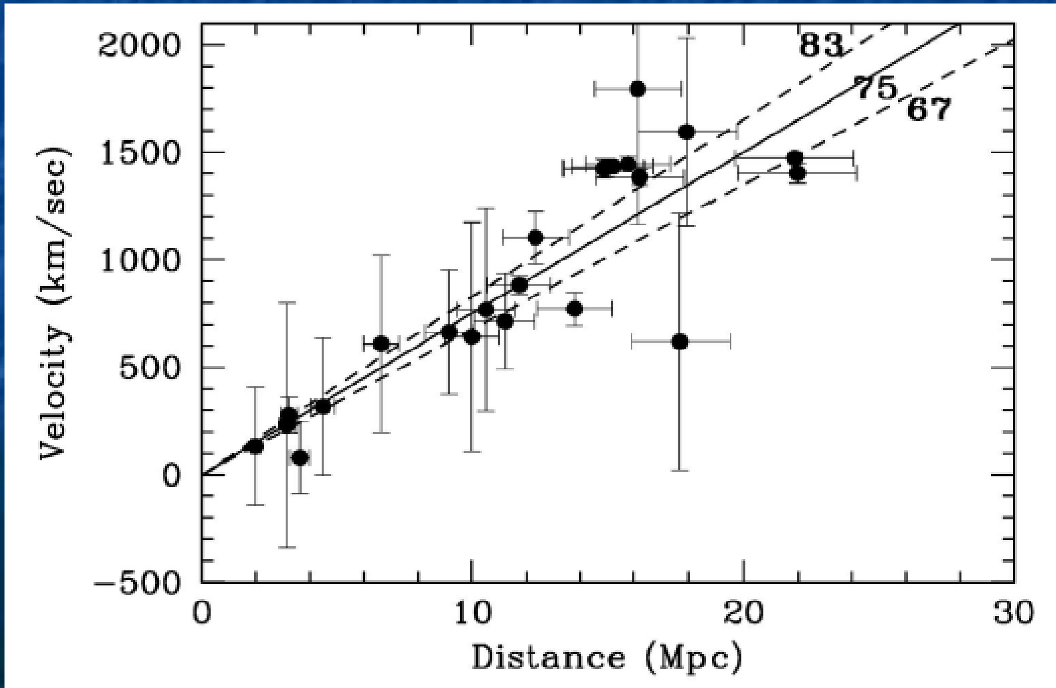
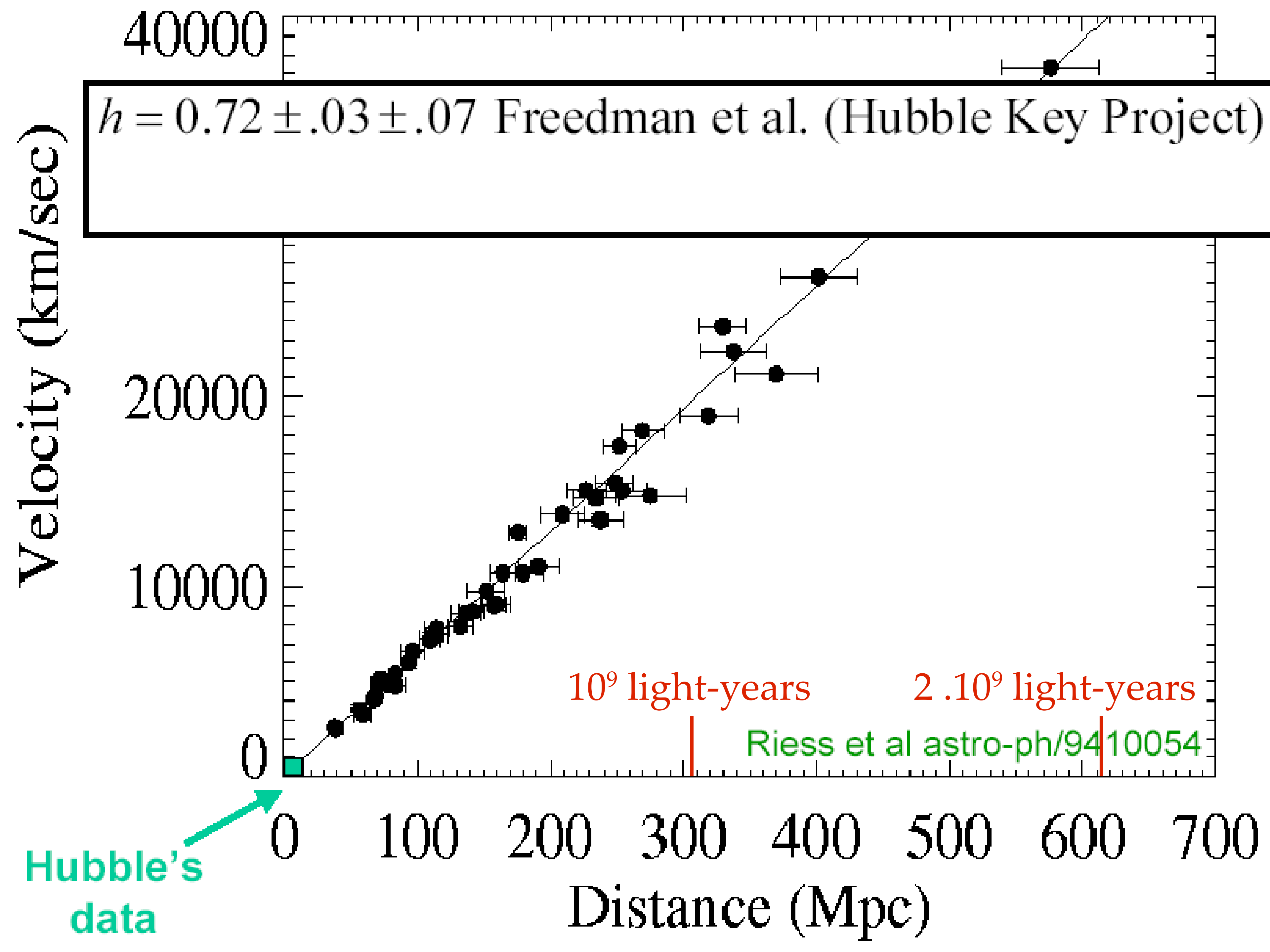
The Hubble's Law

- Lemaître (and later Hubble)* found out that galaxies are, in average, receding from us;
  - The redshift z is linear with distance
  - The velocity is approx. also linear with distance
    - * Stigler's law of eponymy: "No scientific discovery is named after its original discoverer."

$$z = \frac{H_0}{c} D$$

$$v = H_0 D + \mathcal{O}\left(\frac{v}{c}\right)^2$$





Velocity (km/sec)
40000
20000
10000
0
$h = 0.72 \pm .03 \pm .07$ Freedman et al. (Hubble Key Project)
10⁹ light-years
2 .10⁹ light-years
Riess et al astro-ph/9410054
0
100
200
300
400
500
600
700
Distance (Mpc)
Hubble's data

Distances in Cosmology

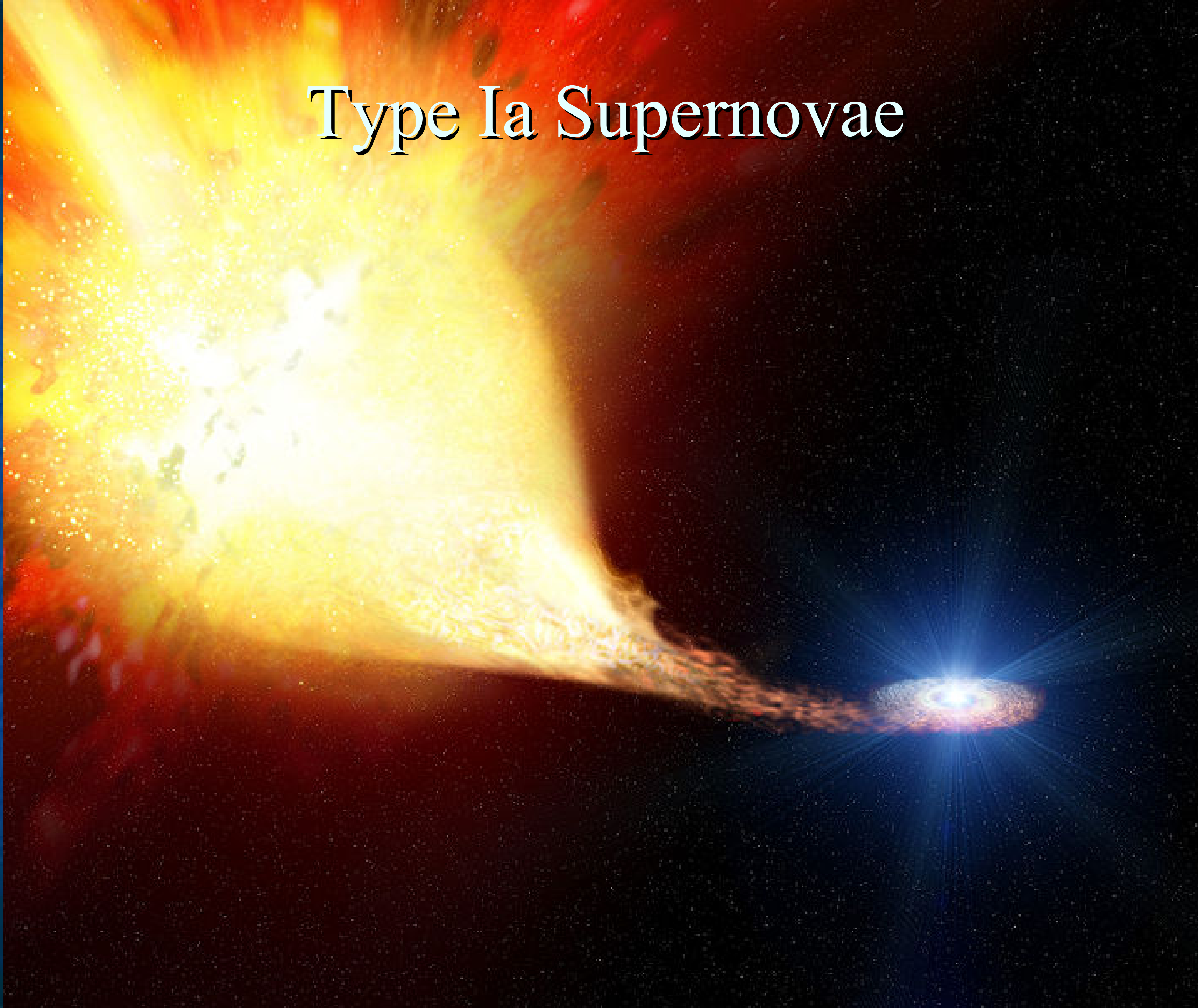
- Inside the solar system → Laser Ranging
  - Shoot a strong laser at a planet and measure the time it takes to be reflected back to us
- Inside the galaxy → stellar parallax
  - Requires precise astrometry
  - Maximum distance measured: 500 pc (1600 ly), by the Hipparcos satellite (1989–1993)
    - Dec. 2013 → Gaia satellite launched (2013 – 2019) → parallax up to ~50 kpc
- Compare with:
  - Milky Way → ~15 kpc radius
  - Andromeda → ~1 Mpc

Standard Candles

- A plot of distance vs. z is called a Hubble Diagram
- To measure distances at z >~ 0.0001 (~0.4 Mpc) we need good standard candles (known intrinsic luminosity)
- There are 2 classic standard (rigorously, *standardizible*) candles in cosmology:
  - Cepheid variable stars ($0 < z < 0.05$)
  - Type Ia Supernovae ($0 < z < 1.91$*)
- Both classes have intrinsic variability, but there are empirical relations that allow us to calibrate and *standardize* them

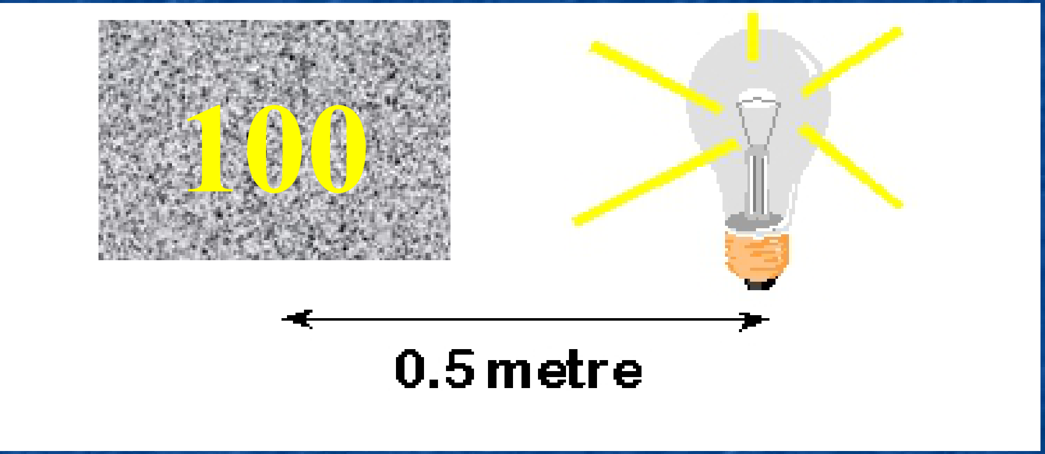
***** Jones et al., 1304.0768**

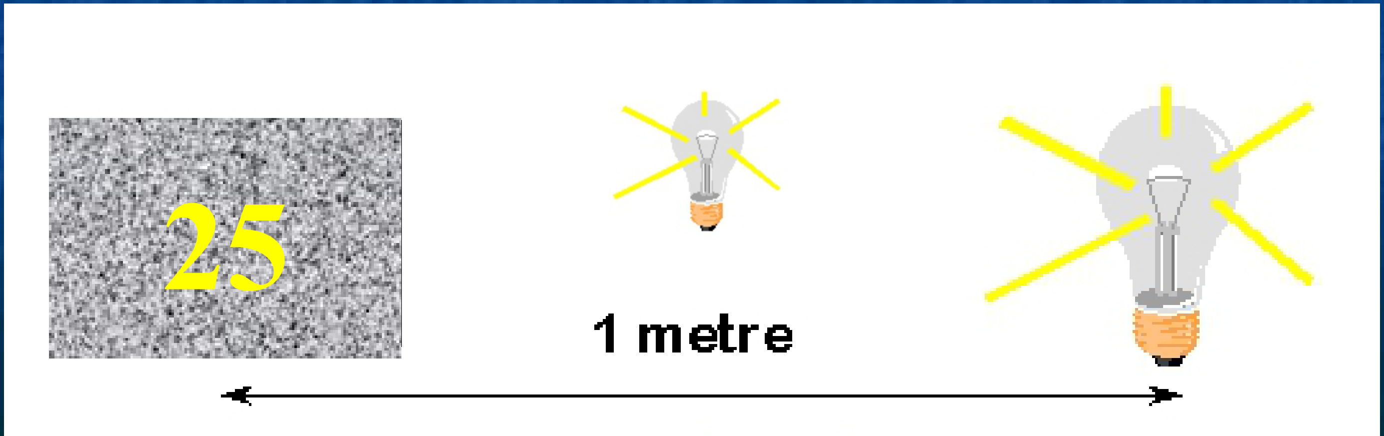
Type Ia Supernovae



Type Ia Supernovae (2)

- Standardizable candles





Type Ia Supernovae (3)

- 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
    - SNe Ia → less intrinsic scatter + strong correlation between brightness & duration

Type Ia Supernovae (4)

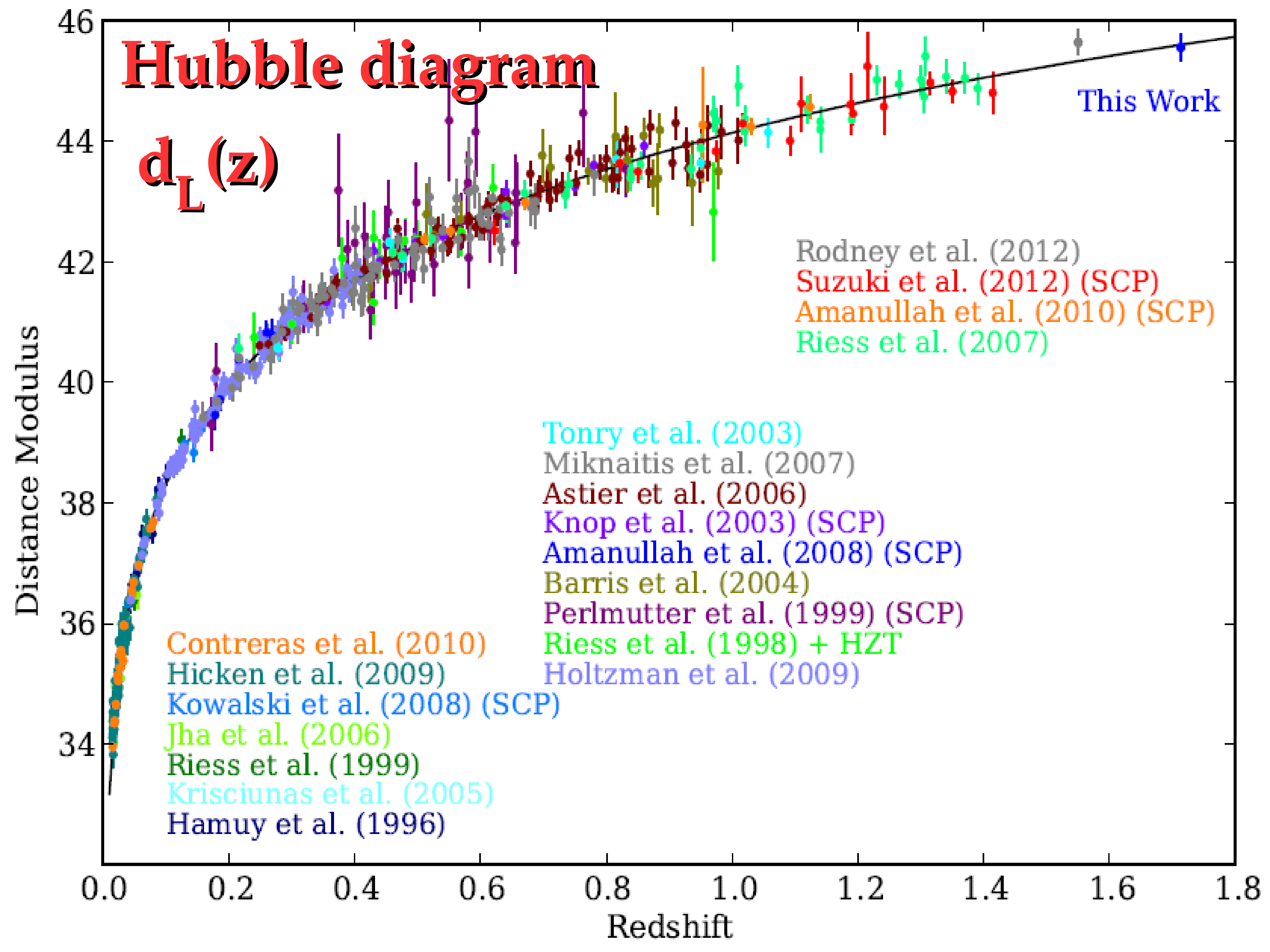
- SNe Ia are so far the only proven standard(izible) candles for cosmology
- With good measurements → scatter < 0.15 mag in the Hubble diagram
- But arguably they are subject to more systematic effects than BAO (baryon acoustic oscillations) & CMB
  - Systematic errors already the dominant part (N_{SNe}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

Howell, 1011.0441 (review of SNe)

SNe Systematics

Systematic	SNLS3[143]	CfA[27]/ESSENCE[44]	SDSS-II[26]	SCP[28]
Best fit w (assuming flatness)	$\cdots$	-0.987	-0.96	-0.997
Statistical error	$\cdots$	0.067	0.06	0.052
Total stat+systematic error	$\cdots$	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	$\cdots$	$\cdots$
Landolt bandpasses	0.01	$\cdots$	0.008	$\cdots$
Local flows	0.014	$\cdots$	0.03	$\cdots$
Experiment bandpasses	0.01	$\cdots$	0.016	$\cdots$
Malmquist bias model	0.01	0.02	$\cdots$	0.026
Dust/Color-luminosity (β)	0.02	0.08	0.013	0.026
SN Ia Evolution	$\cdots$	0.02	$\cdots$	$\cdots$
Restframe U band	$\cdots$	$\cdots$	0.104	0.010
Contamination	$\cdots$	$\cdots$	$\cdots$	0.021
Galactic Extinction	$\cdots$	$\cdots$	0.022	0.012

Table 1: **Best-fit values of $\langle w \rangle$ and error estimates.** For the CfA3/ESSENCE colum



Hubble diagram
$d_L(z)$
This Work
Rodney et al. (2012)
Suzuki et al. (2012) (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
Distance Modulus
Redshift
46
44
42
40
38
36
34
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

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)
  - 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

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

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

Function of three $d_A(z)$

Supernova Lensing (3)

- Note that the N-body approach might not be appropriate
  - Supernovae light bundles form a very thin (< 1 AU) pencil
  - N-body simulations coarse grained in scales >>> 1 AU
  - Relativistic effects (e.g. Ricci + Weyl focusing) might be important

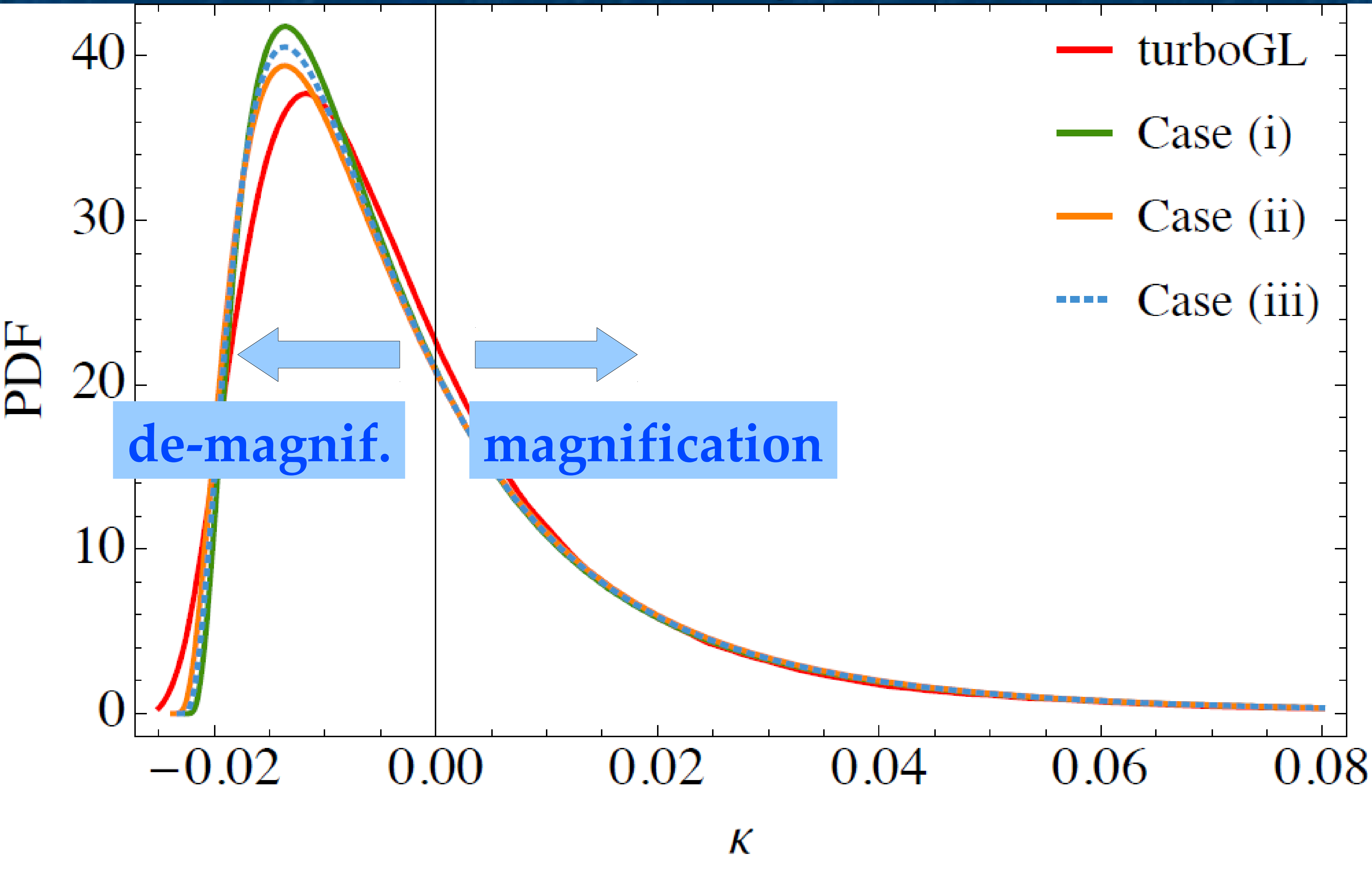
Clarkson, Ellis, Faltenbacher, Maartens, Umeh, Uzan (1109.2484, MNRAS)

- There are also corrections due to a neglected Doppler term

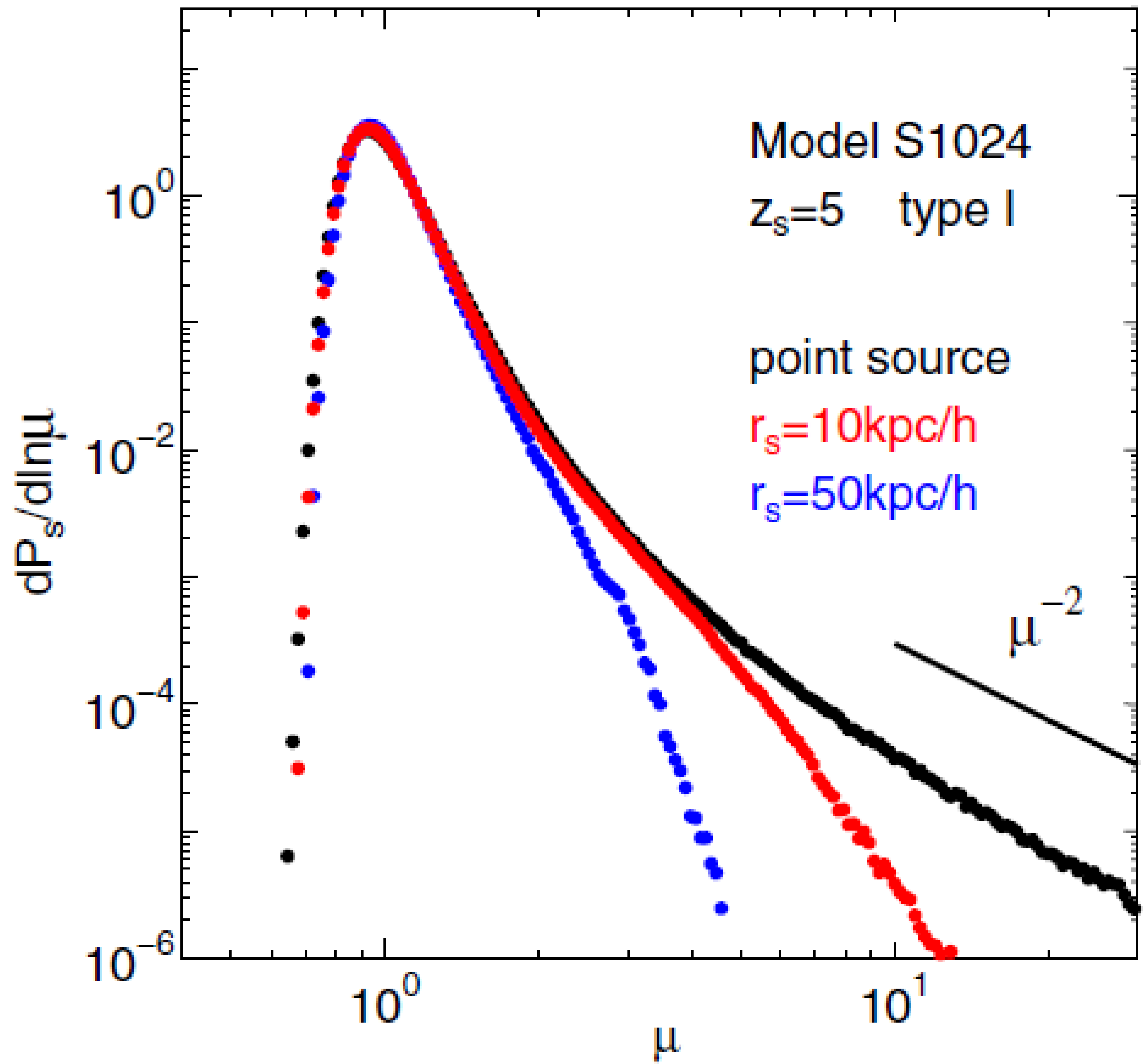
Bolejko, Clarkson, Maartens, Bacon, Meures, Beynon (1209.3142, PRL)

- We neglect these corrections here

The Lensing PDF



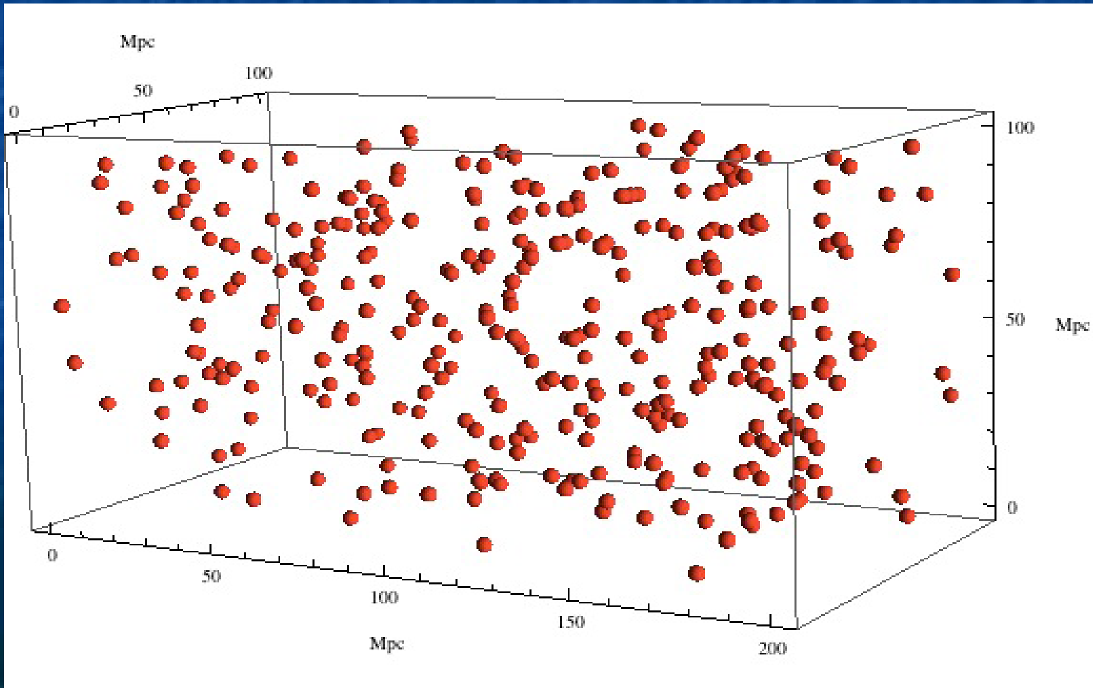
Finite sources



Takahashi et al. 1106.3823

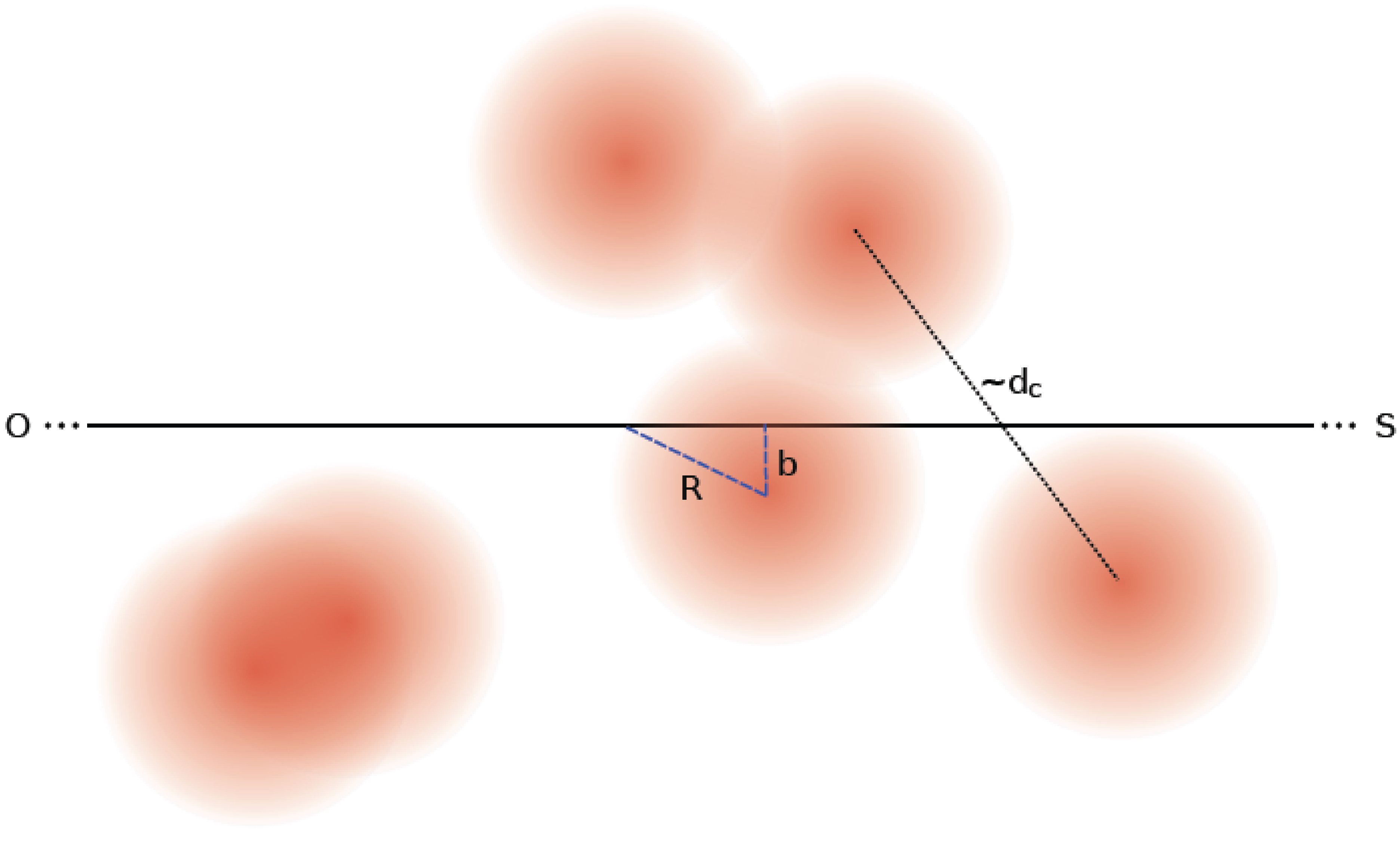
A New Method

- We need something faster → stochastic GL analysis (sGL)
  - Populate the universe with NFW halos → Halo Model
    - need prescriptions for mass fun. & concentration param.
  - In a given direction, draw nearby distribution of halos
  - Bin in distance & impact parameter
  - compute the convergence (fast)



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

A New Method (2)



NFW Profile

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

Supernova Lensing (4)

- sGL → fast way to compute the κPDF
  - accurate when compared to N-body simulations
  - many redshift bins; different cosmological parameters
  - fast enough to be used on likelihood analysis
  - Mathematica code available at www.turbogl.org
- We computed the κPDF for a broad parameter range
  - PDF is well parametrized by the *first 3 central moments*

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

  - Lensing depends mostly on Ω_{m0} & σ_8
    - Very weak dependence on: w, h, Ω_{k0}, n_s, w, ...

Marra, Quartin & Amendola 1304.7689 (PRD)

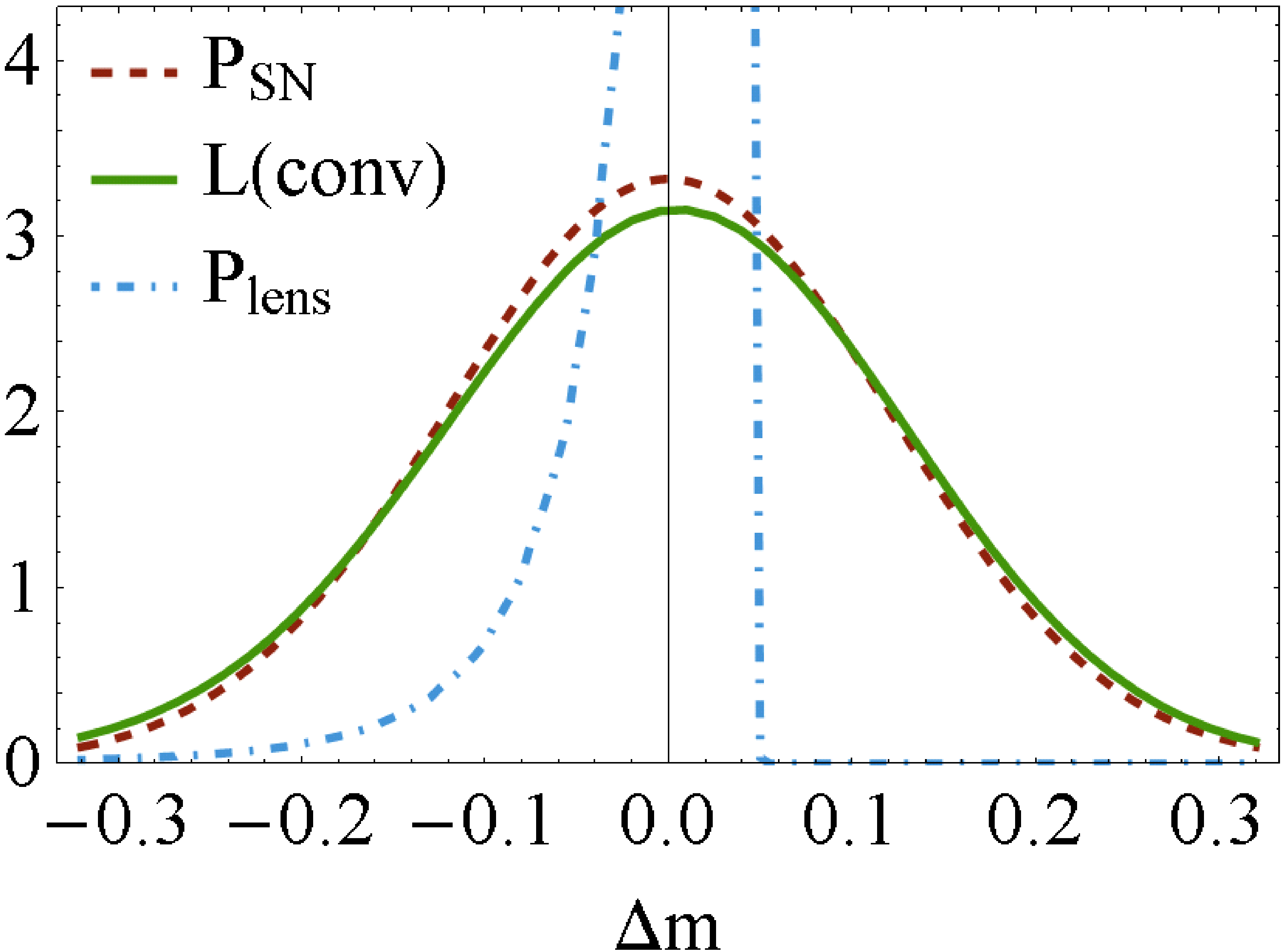
Supernova Lensing (5)

- Likelihood for SNe analysis → convolution of lensing PDF and intrinsic (standard) SNe PDF

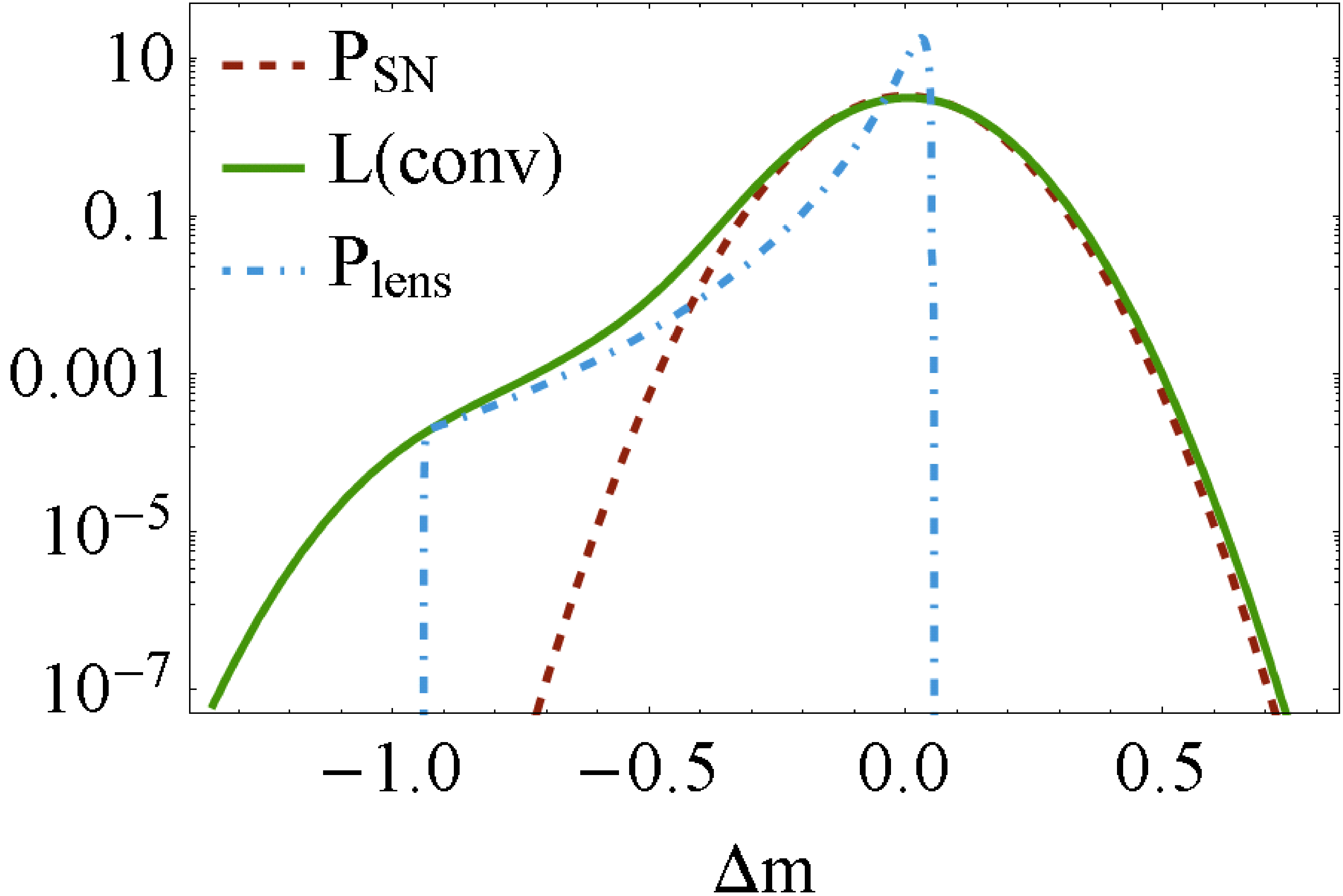
Gaussian!

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

- It is useful to compute the *first central moments* of the PDF
  - Mean (zero); variance; skewness & kurtosis
  - "Cumulants cumulate":
    - Convolution variance = lensing var + intrinsic var
    - Convolution skewness = lensing skew + "0"
- We computed the κPDF for many cosmological params.

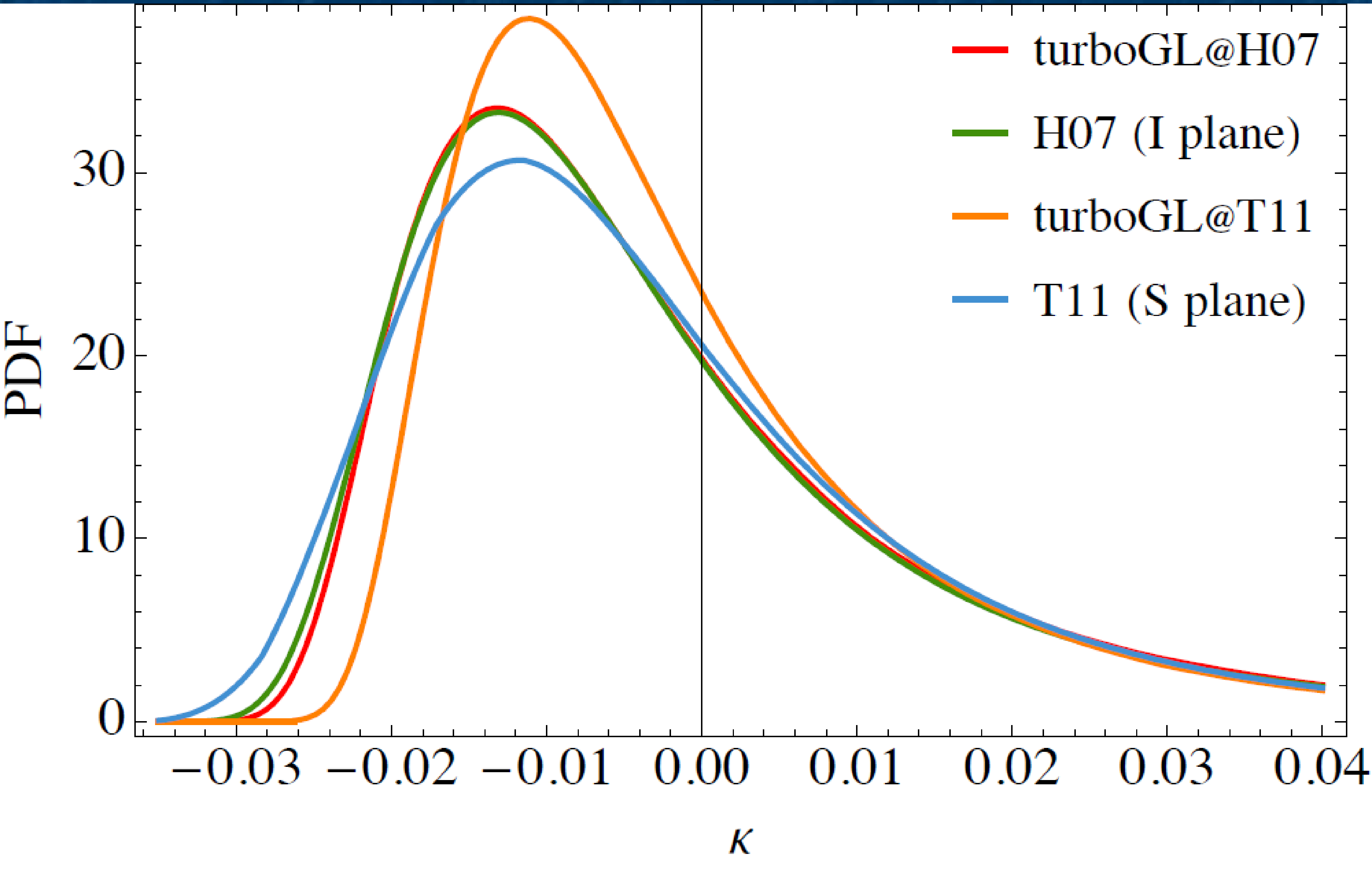


P_SN
L(conv)
P_lens
4
3
2
1
0
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
Δm

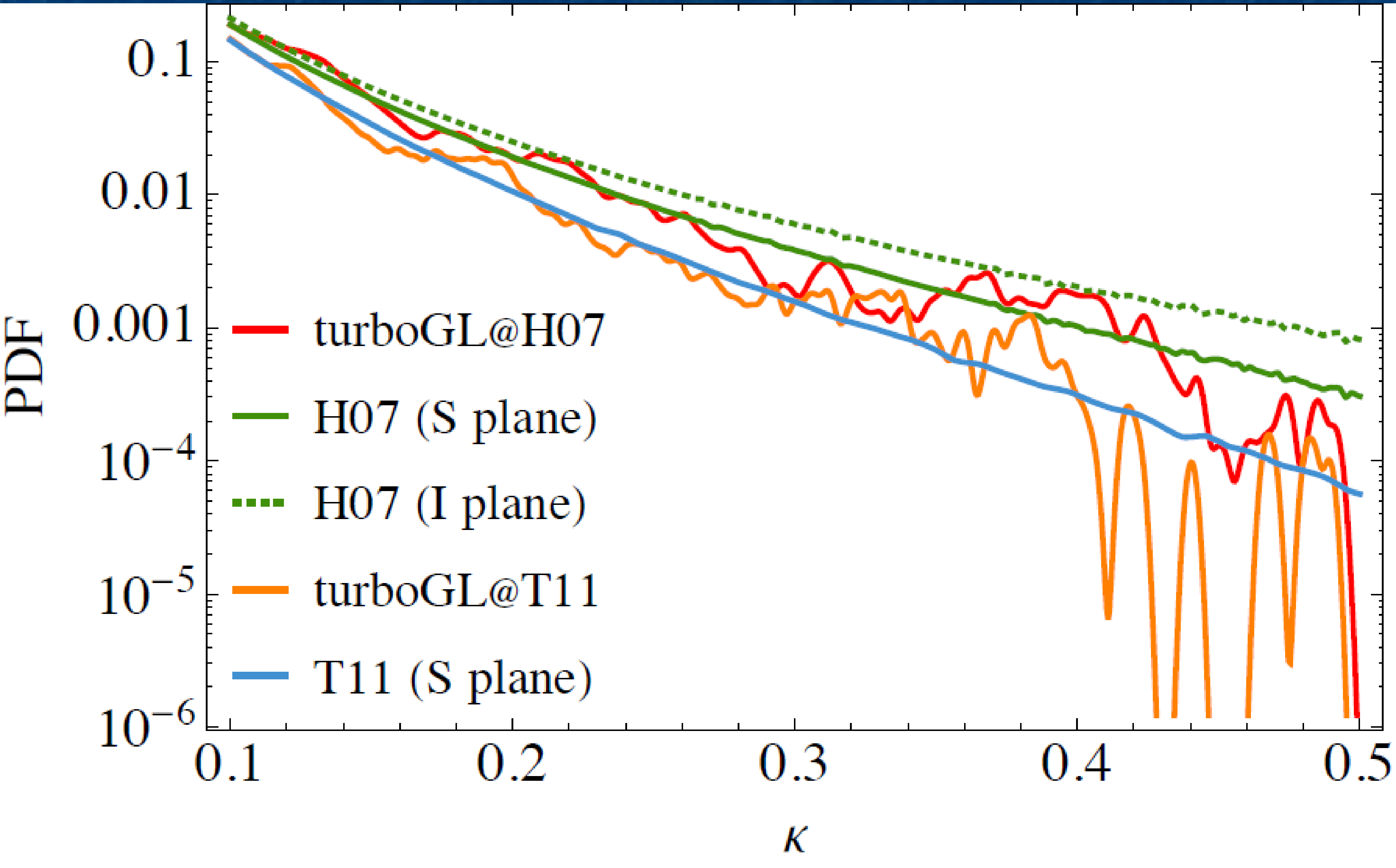


10
0.1
0.001
10^{-5}
10^{-7}
P_{SN}
L(conv)
P_{lens}
−1.0
−0.5
0.0
0.5
Δm

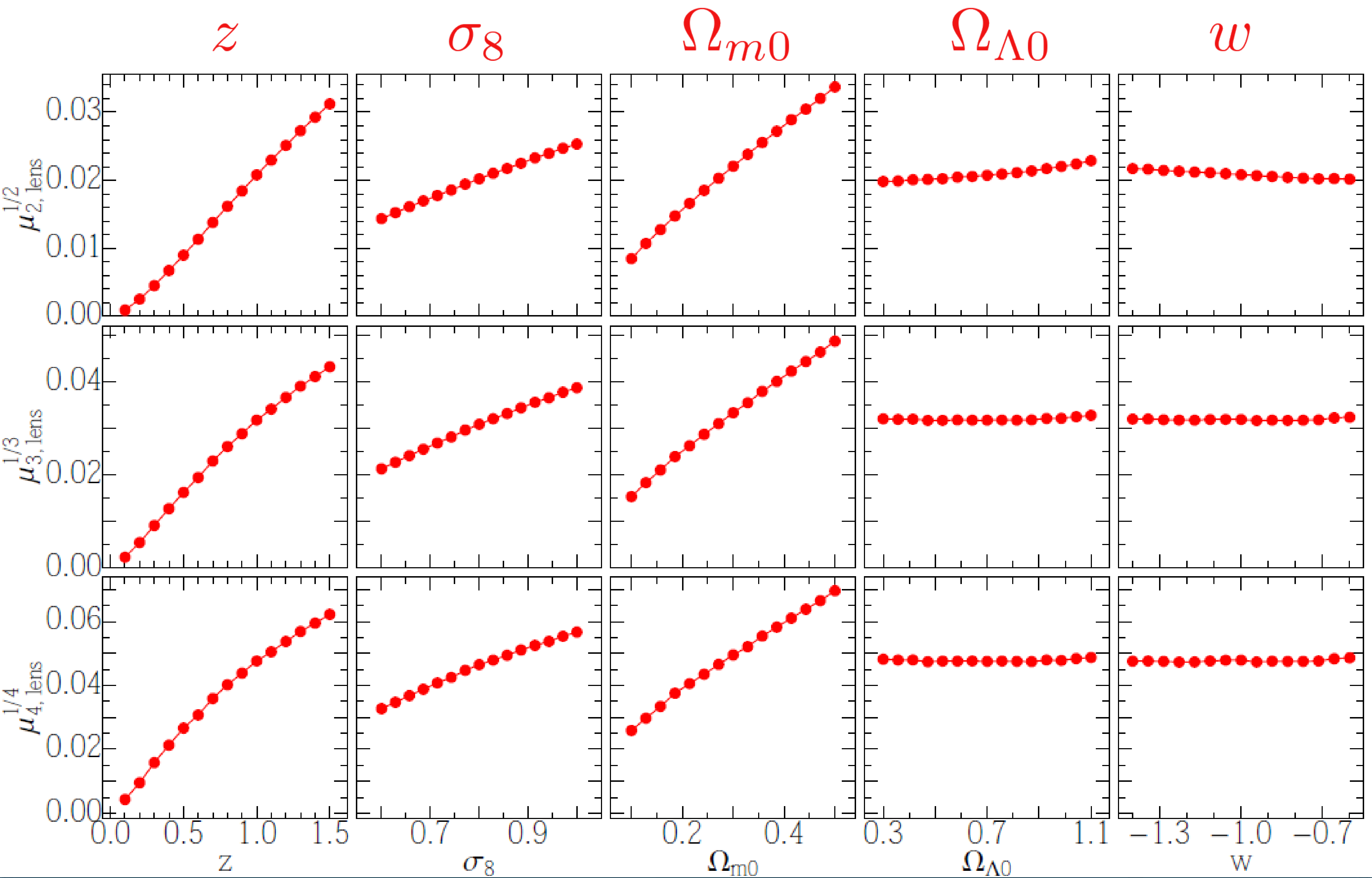
The Lensing PDF (2)



The Lensing PDF (3)



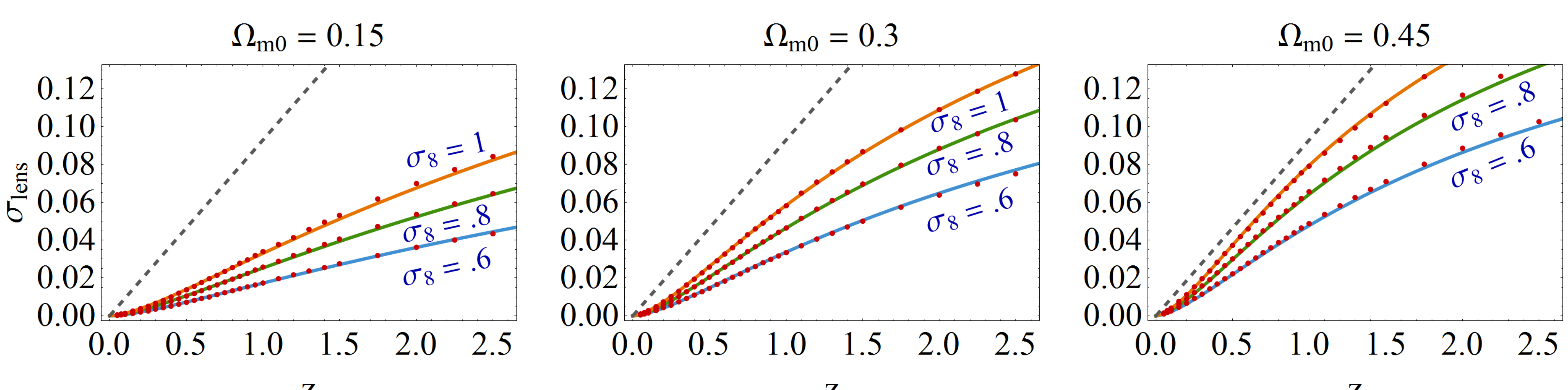
Variance, Skewness & Kurtosis



Fitting Functions

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

$$0 \le z \le 3$$
$$0.35 \le \sigma_8 \le 1.25$$
$$0.1 \le \Omega_{m0} \le 0.52$$

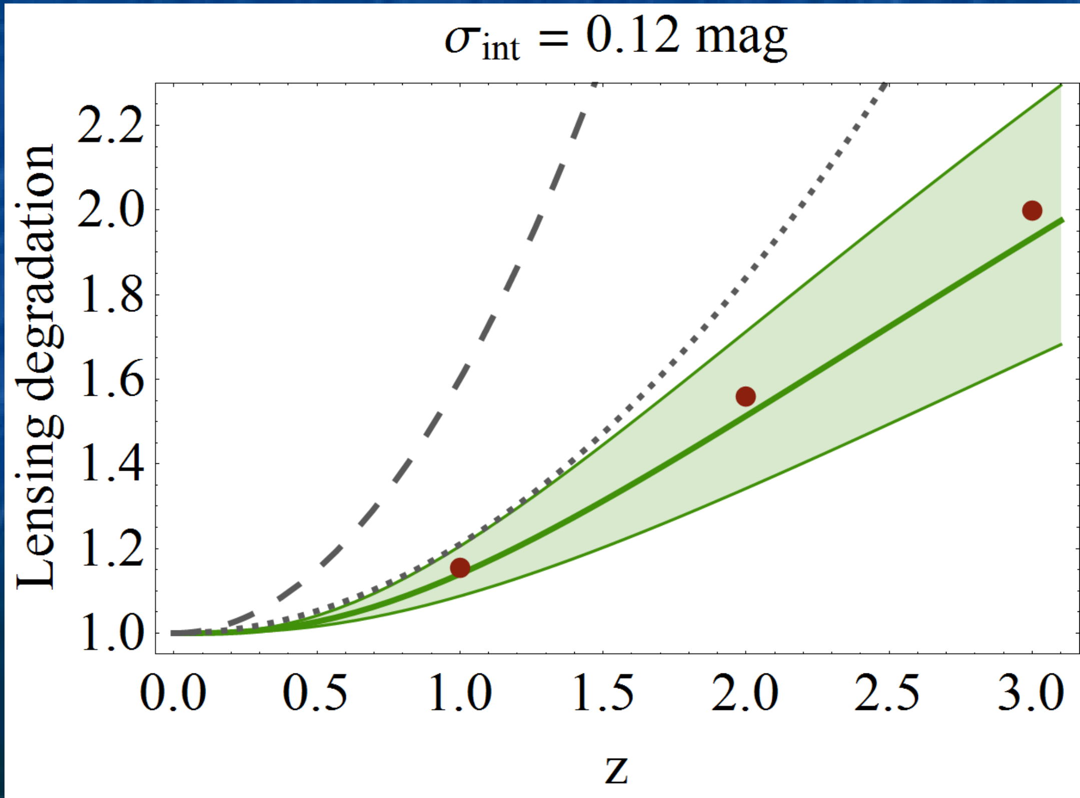


Fitting Functions (2)

- 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)*

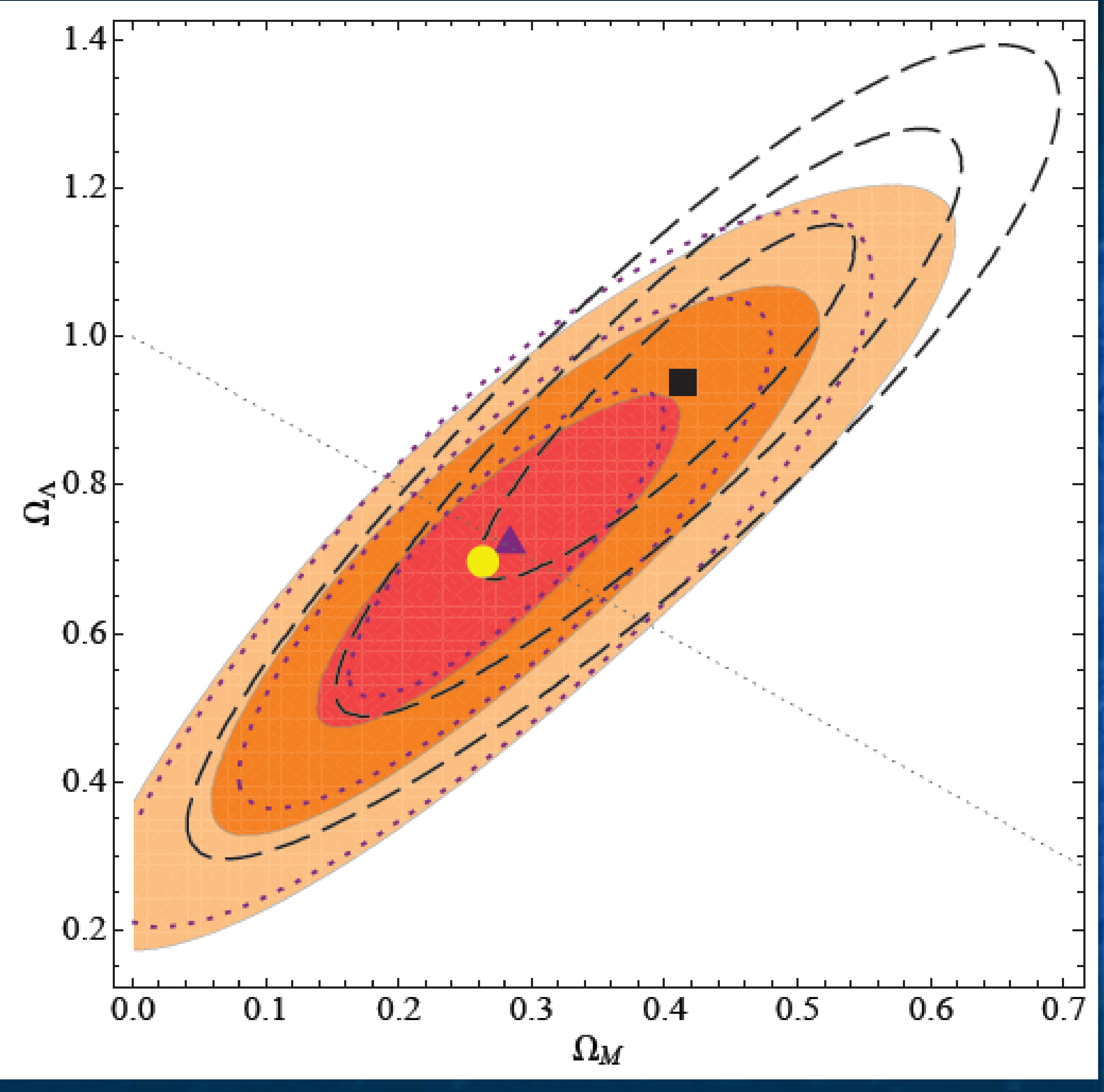
- Conclusion → high-z supernovae are more useful than sometimes thought

- Lensing bias less of a problem



Lensing bias

Exagerated effect



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

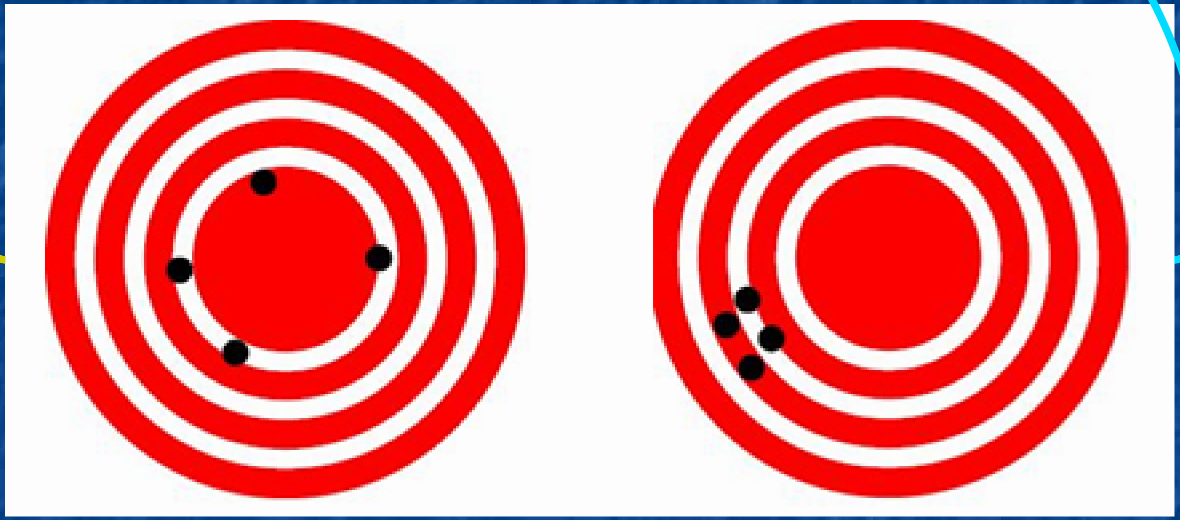
The Inverse Lensing Problem

- 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 very good cross-check
  - It is a new observable

Dodelson & Vallinotto (astro-ph/0511086)

Quartin, Marra & Amendola 1307.1155 (PRD)

Precision Cosmology vs. Accuracy Cosmology



- Precise parameter estimation in ΛCDM not enough
  - Very important to cross-check observations
    - Rule-out systematics
  - Very important to cross-check theoretical assumptions
    - e.g.: homogeneity, isotropy

What is σ_8?

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

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

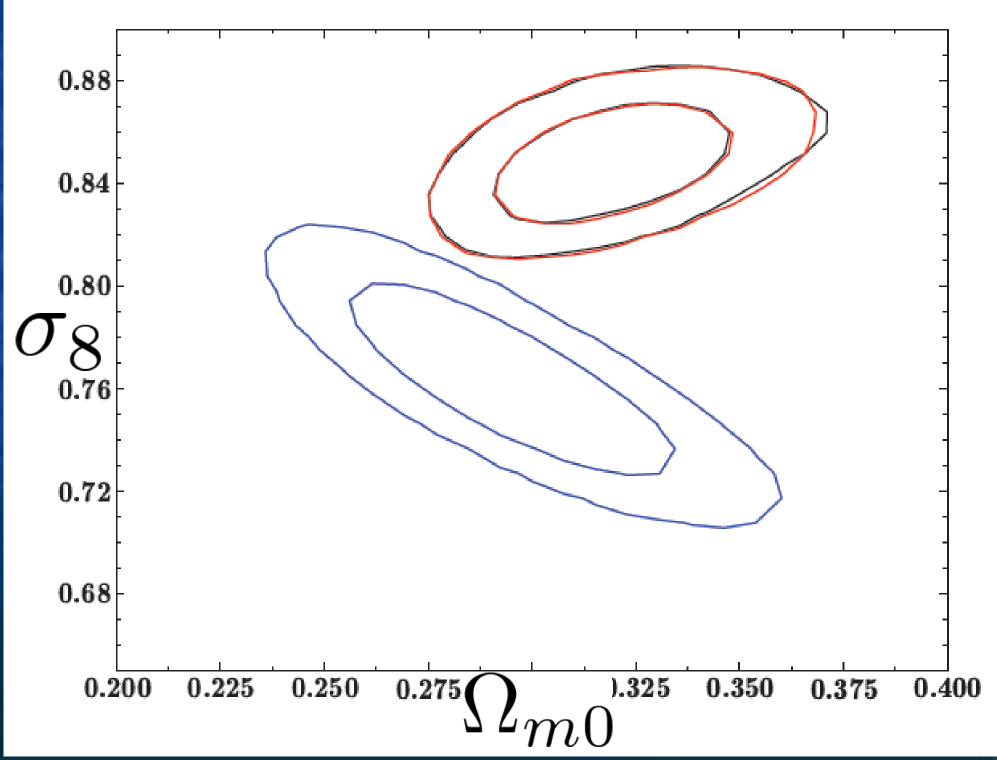
$$\Delta^2(k,z) \equiv \frac{k^3}{2\pi^2}P(k,z) = \delta_{H0}^2\left(\frac{ck}{a_0 H_0}\right)^{3+n_s} T^2(k/a_0)D^2(z)$$

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

What is σ_8? (2)

- σ_8 measurements are usually done in either of 3 ways:
  - CMB → measure fluctuations at z = 1090 and propagate them to z = 0
  - Cosmic Shear → requires galaxy shapes
  - Cluster abundance
- Some tension between these measurements
  - Cross-check important!

Planck XX (1303.5080)

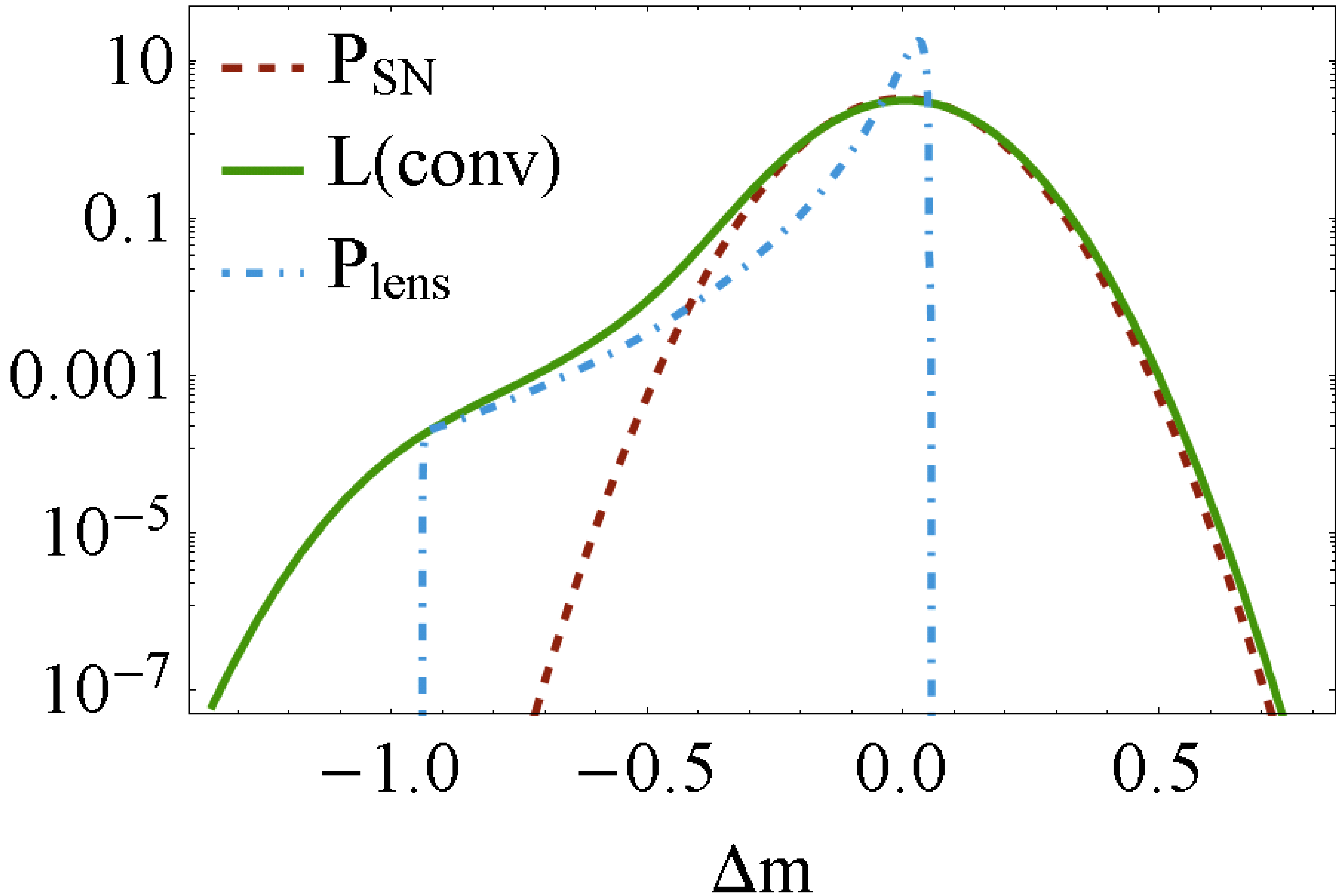


The Inverse Lensing Problem (2)

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

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

- 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



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

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: if the PDFs were gaussian, it would be:

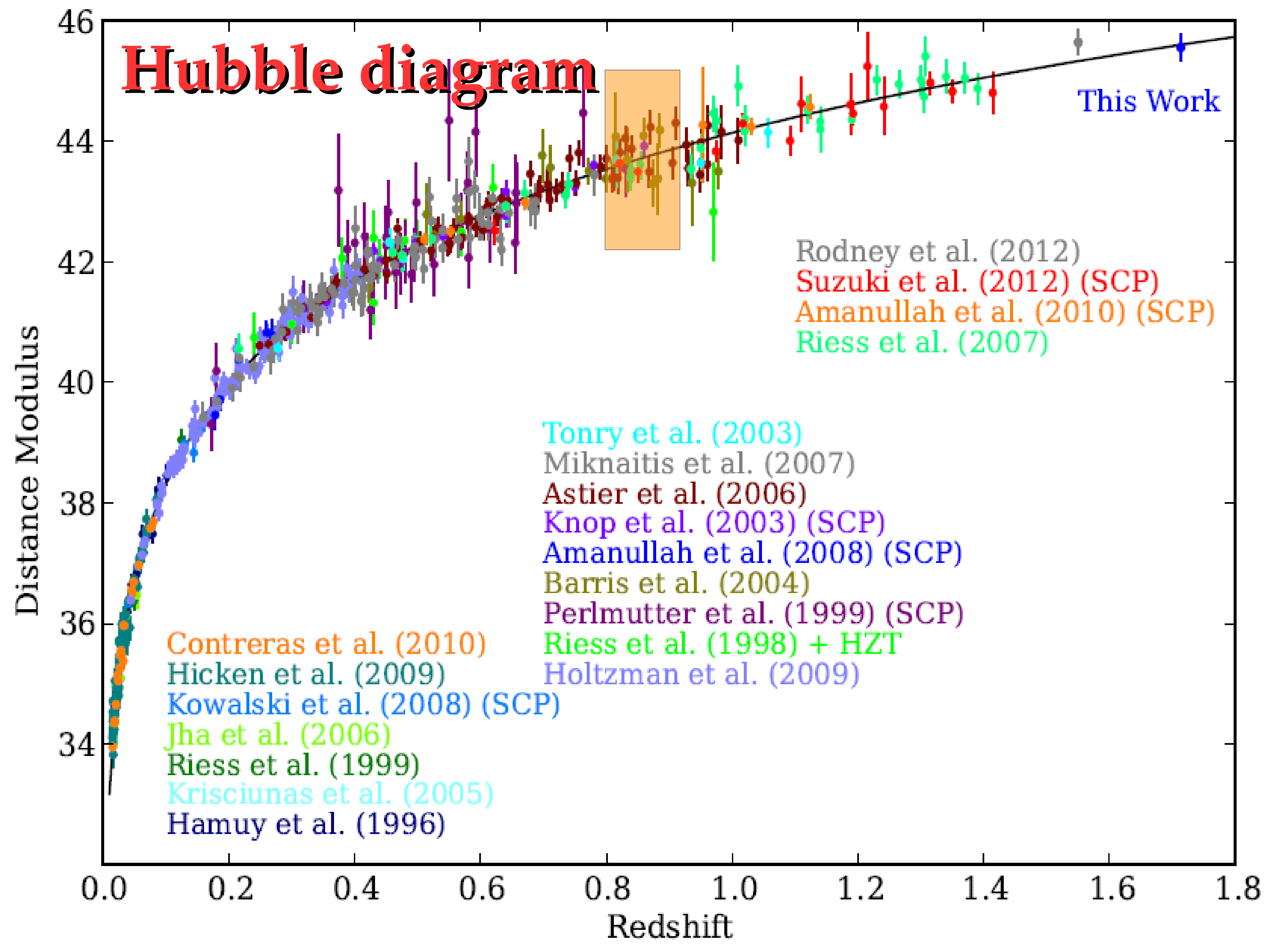
$$\Sigma_{\mathrm{gau},j} = \frac{1}{N_j}\begin{pmatrix} \sigma_j^2 & 0 & 0 & 0 \\ 0 & 2\sigma_j^4 & 0 & 12\sigma_j^6 \\ 0 & 0 & 6\sigma_j^6 & 0 \\ 0 & 12\sigma_j^6 & 0 & 96\sigma_j^8 \end{pmatrix}$$

Scary Movie

- The full covariance matrix is very complicated.
  - Variance of the variance
  - Variance of the skewness
  - Variance of the kurtosis
  - Covariance terms...
- Must actually use the sample central moments (not the true central moments)
  - But could be done with a little help from Mathematica...

$$\Sigma_j = \frac{1}{N_j} \times$$

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



Hubble diagram
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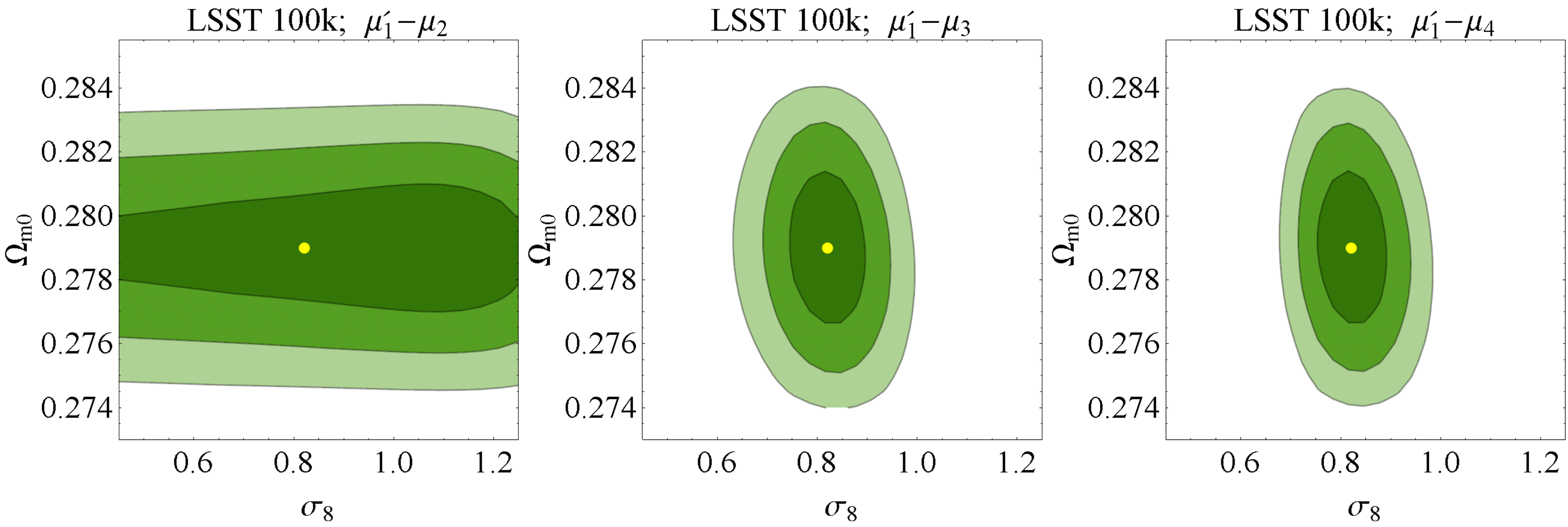
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

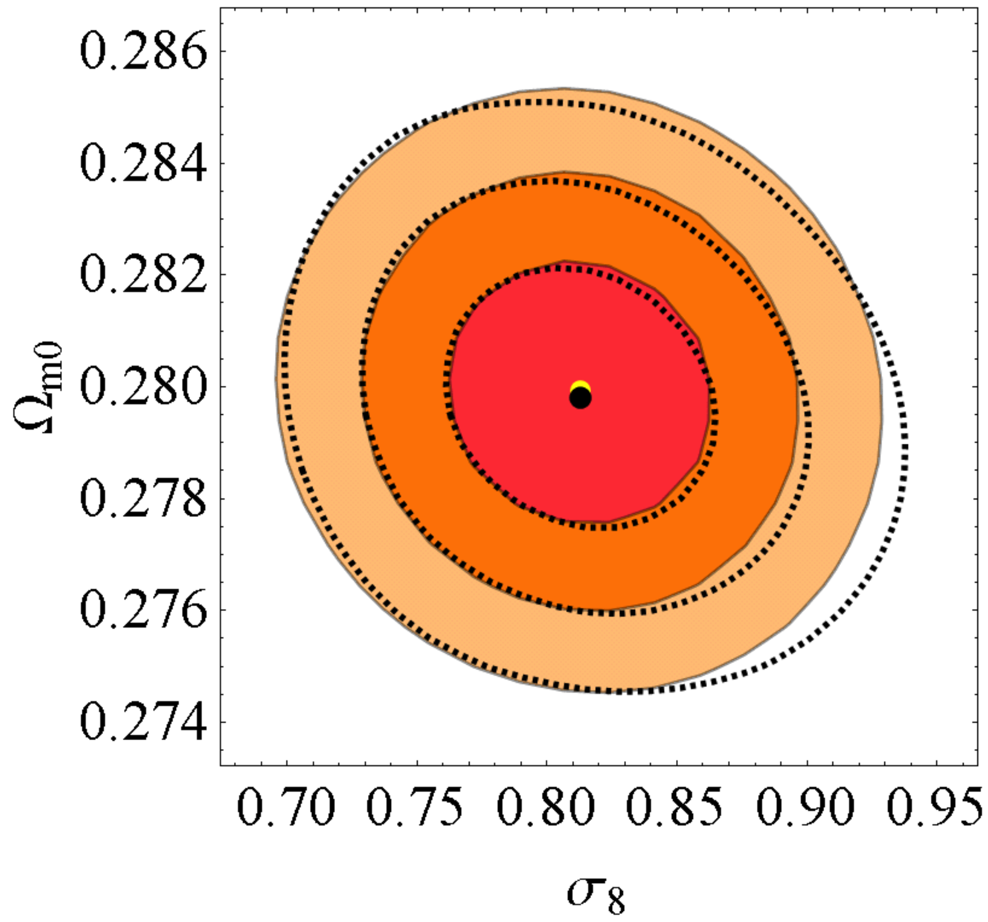
The MeMo Likelihood (2)

- 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%.



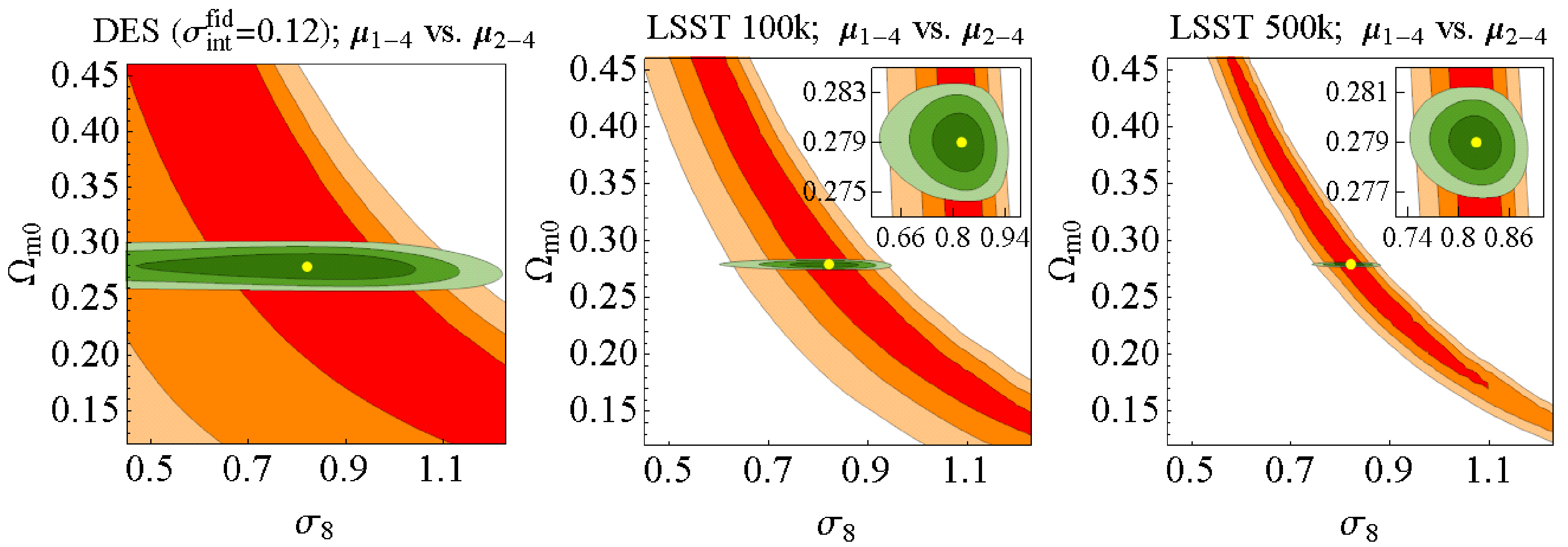
The MeMo Likelihood (3)

- Comparison between MeMo and full likelihood with first 4 moments:



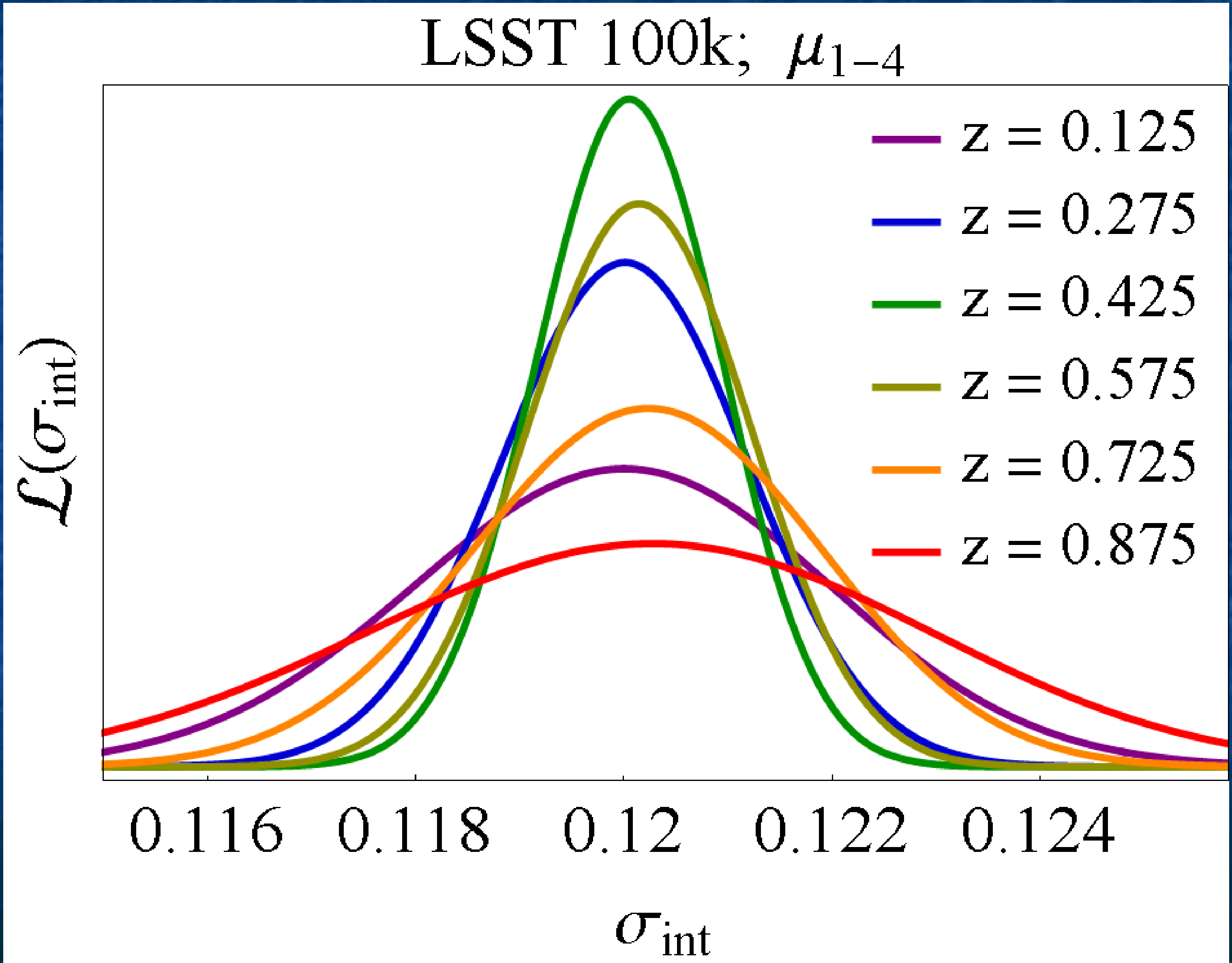
The Inverse Lensing Problem (2)

- The *non-gaussian* scatter of 10^5 supernovae in the Hubble diagram will tell us about σ_8 up to **~7%** precision!



Quartin, Marra & Amendola 1307.1155 (PRD)

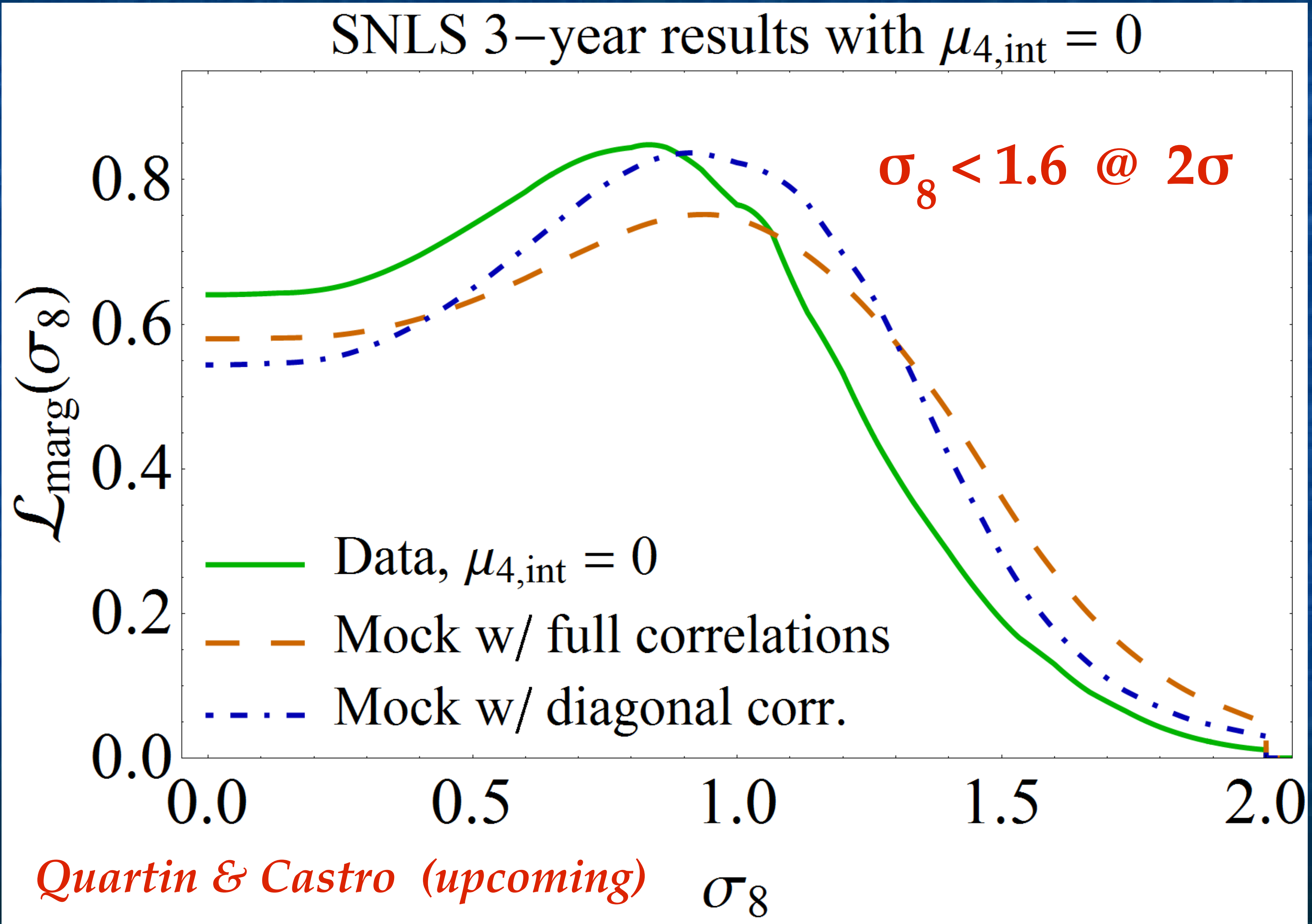
σint posteriors

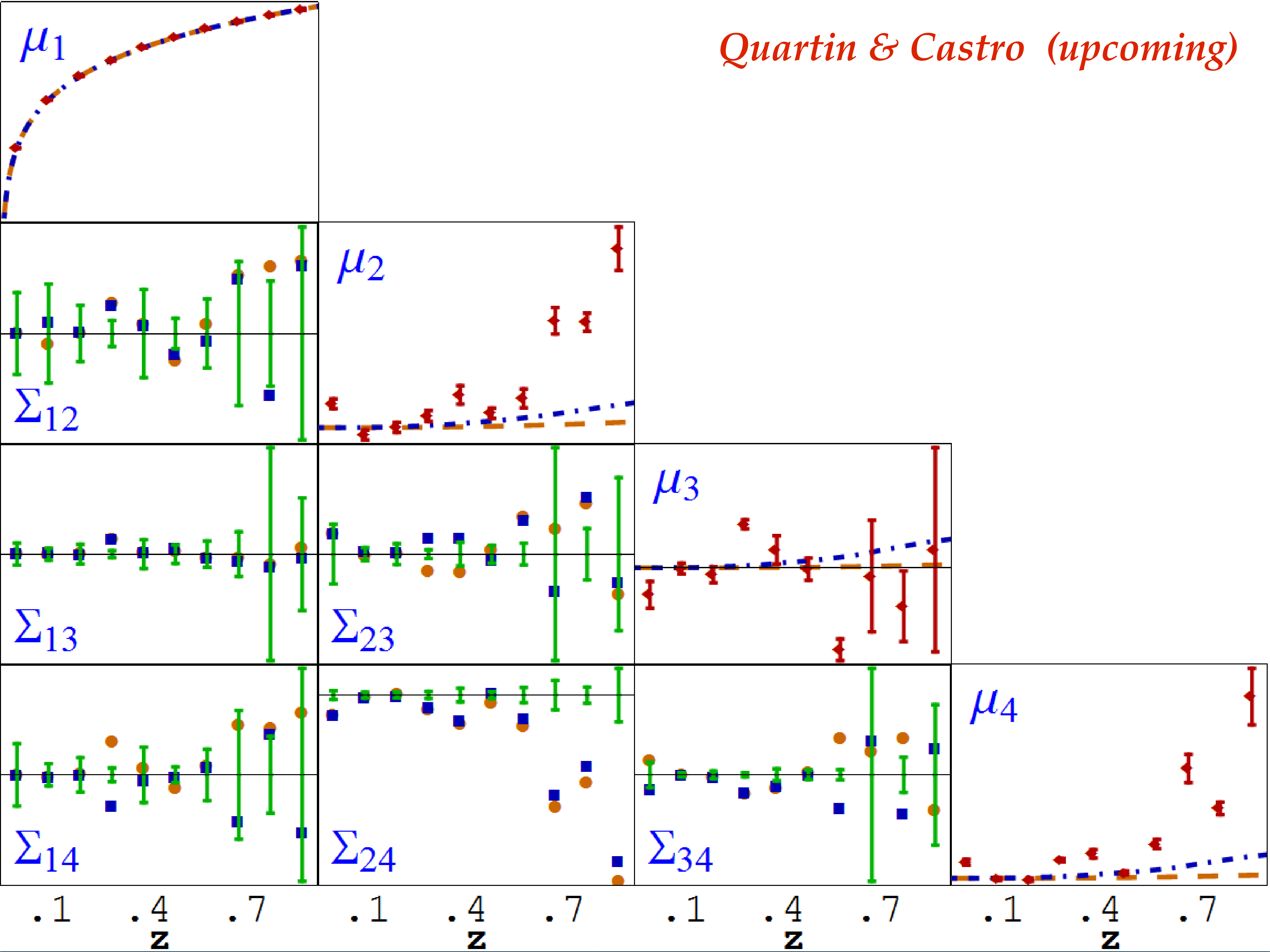


What IS a standard candle?

- 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?
  - 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-year catalog

Proof-of-concept: SNLS 3-year data




Quartin & Castro (upcoming)
μ1
μ2
μ3
μ4
Σ12
Σ13
Σ14
Σ23
Σ24
Σ34
.1 .4 .7
z
.1 .4 .7
z
.1 .4 .7
z
.1 .4 .7
z

Conclusions

- SNe Lensing has already been detected at ~3σ (1307.2566)
  - But not detected from SNe data alone!
- Detailed lensing modeling important to avoid biases
- Lensing degradation smaller than previous estimate
- Supernova can constrain also perturbation parameters!
  - σ8 to percent level with LSST.
  - SNLS3 (at face value) → σ8 < 1.6 @ 2σ
- Can also constrain halo profiles and dark matter clustering *Fedeli & Moscardini (1401.0011)*

Danke!

Extra slides