V Challenges – CBPF – Apr 2013

Accurate Weak Lensing of Standard Candles

Amendola, Marra & Quartin (1304.7689)

Amendola, Marra & Quartin (1305.xxxx)

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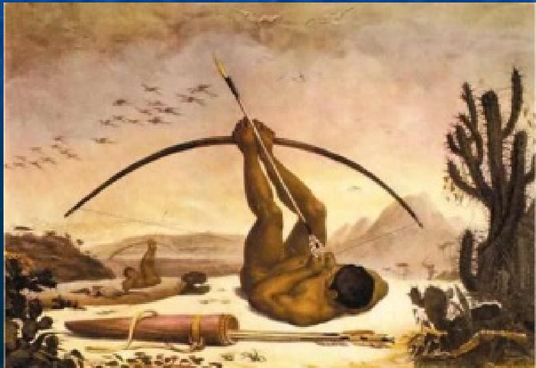
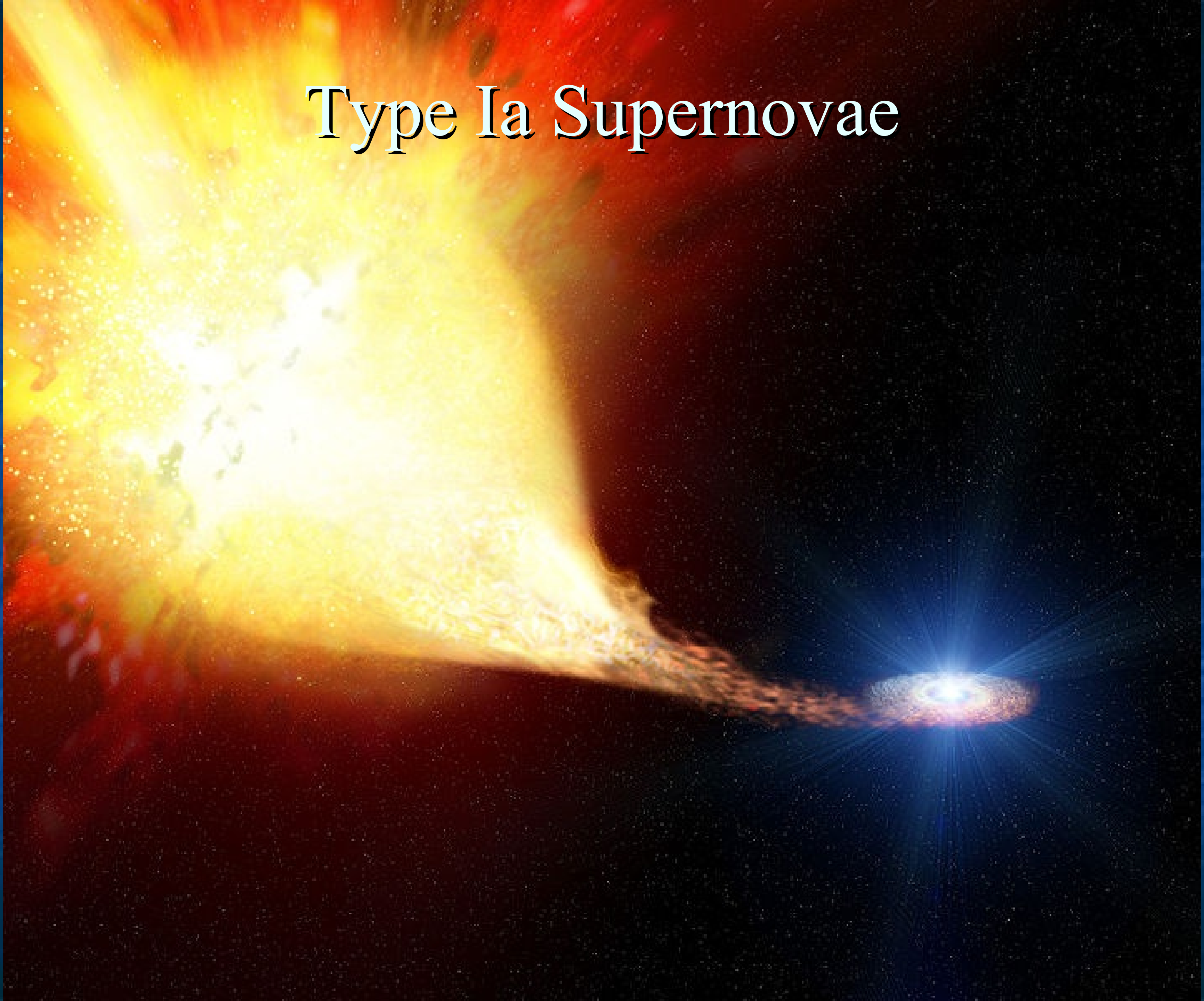


Type Ia Supernovae



Type Ia Supernovae (2)

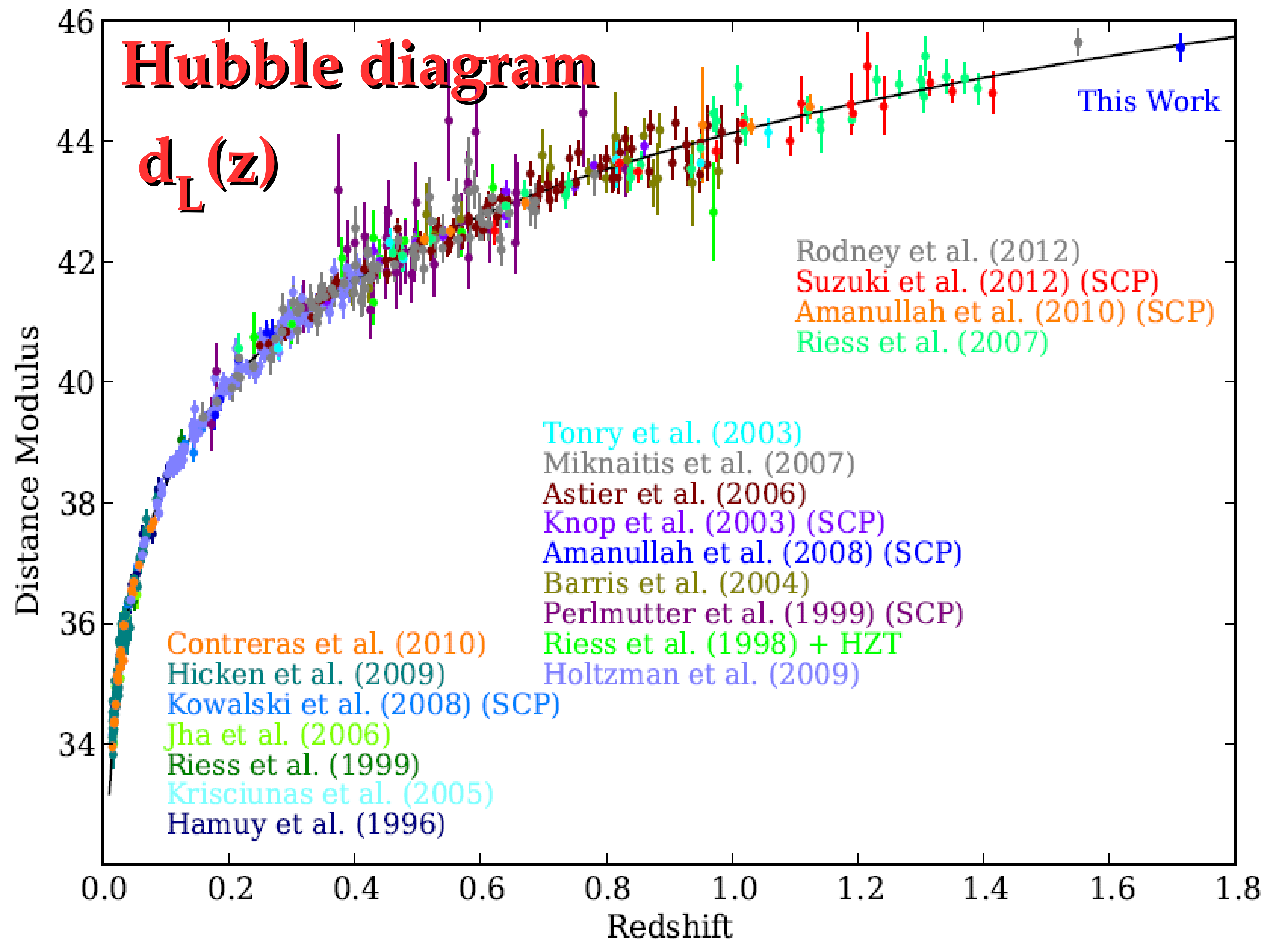
- Supernovae Ia are so far the only proven standard(izible) candles for cosmology
- With good measurements → scatter < 0.15 mag in the Hubble diagram
- Have been detected in a broad redshift range: $0 < z < 1.91$
- But arguably they are subject to more systematic effects than BAO & CMB
  - Systematic errors already the dominant part ($N_{SNe} \sim 1000$)
  - In the next ~10 years → statistics will increase by 100x
    - Huge effort to improve understanding of systematics

D. Andrew 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)	...	-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

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
34
36
38
40
42
44
46
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. Distrib. Fcn.)!
  - 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 but not impossible to measure → need many more Sne
  - Can be computed using 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

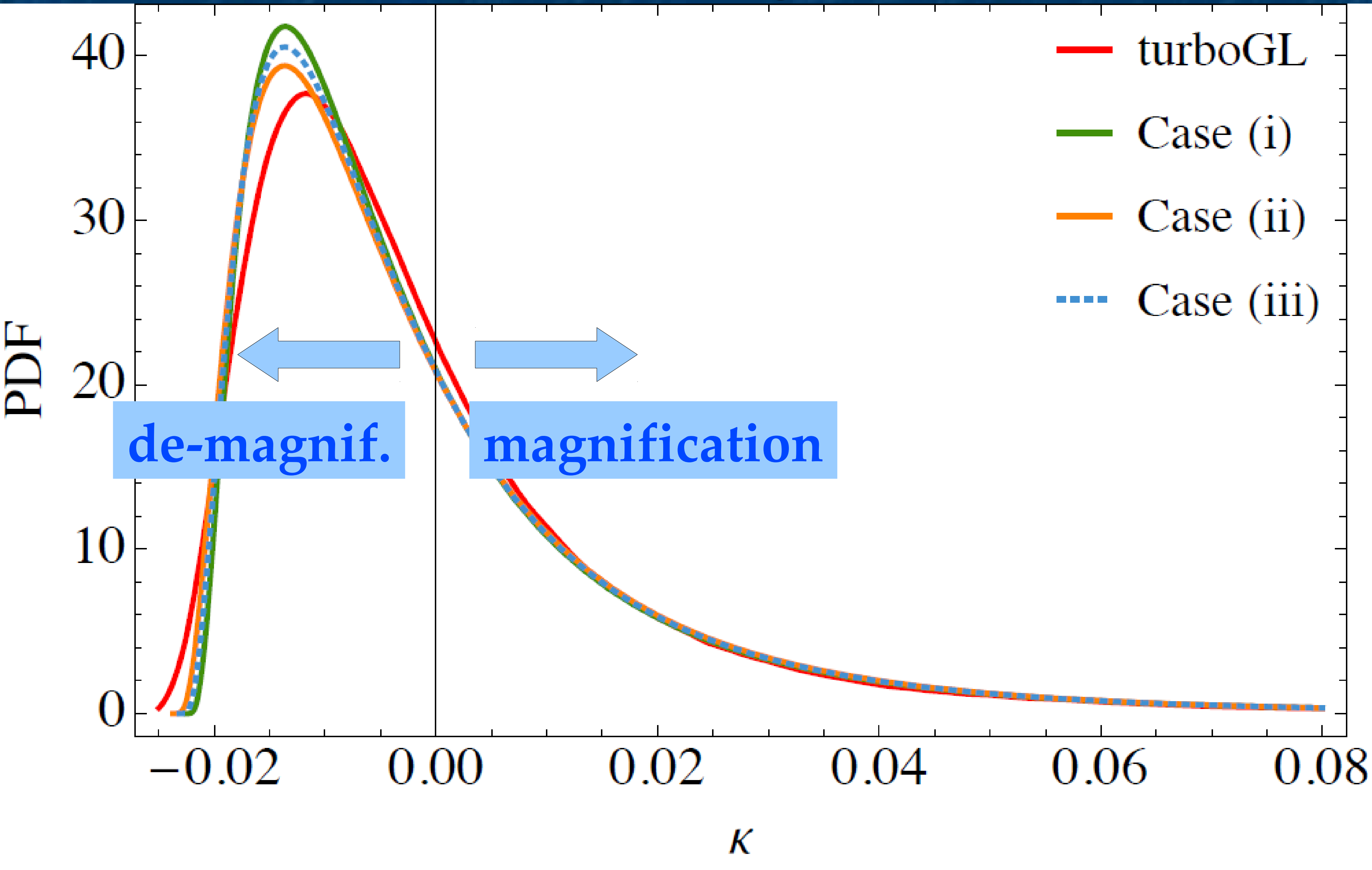
Clarkson, …, Uzan (1109.2484)

- There are also corrections due to a neglected Doppler term

Bolejko, Clarkson, et al. (1209.3142)

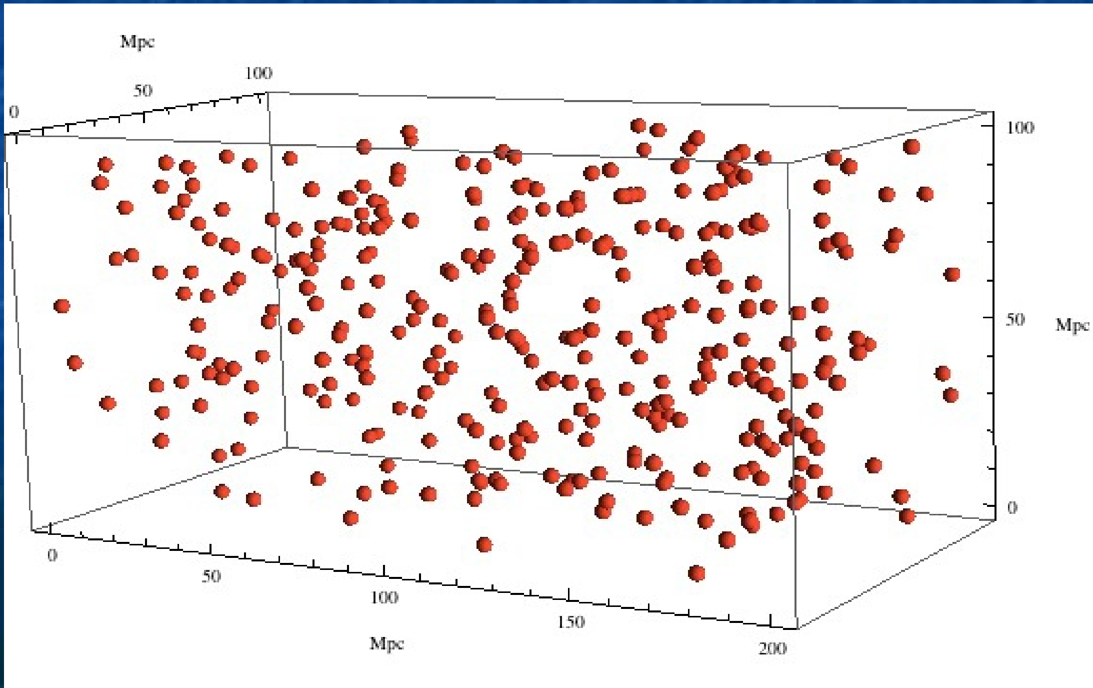
- We neglect these corrections here

The Lensing PDF



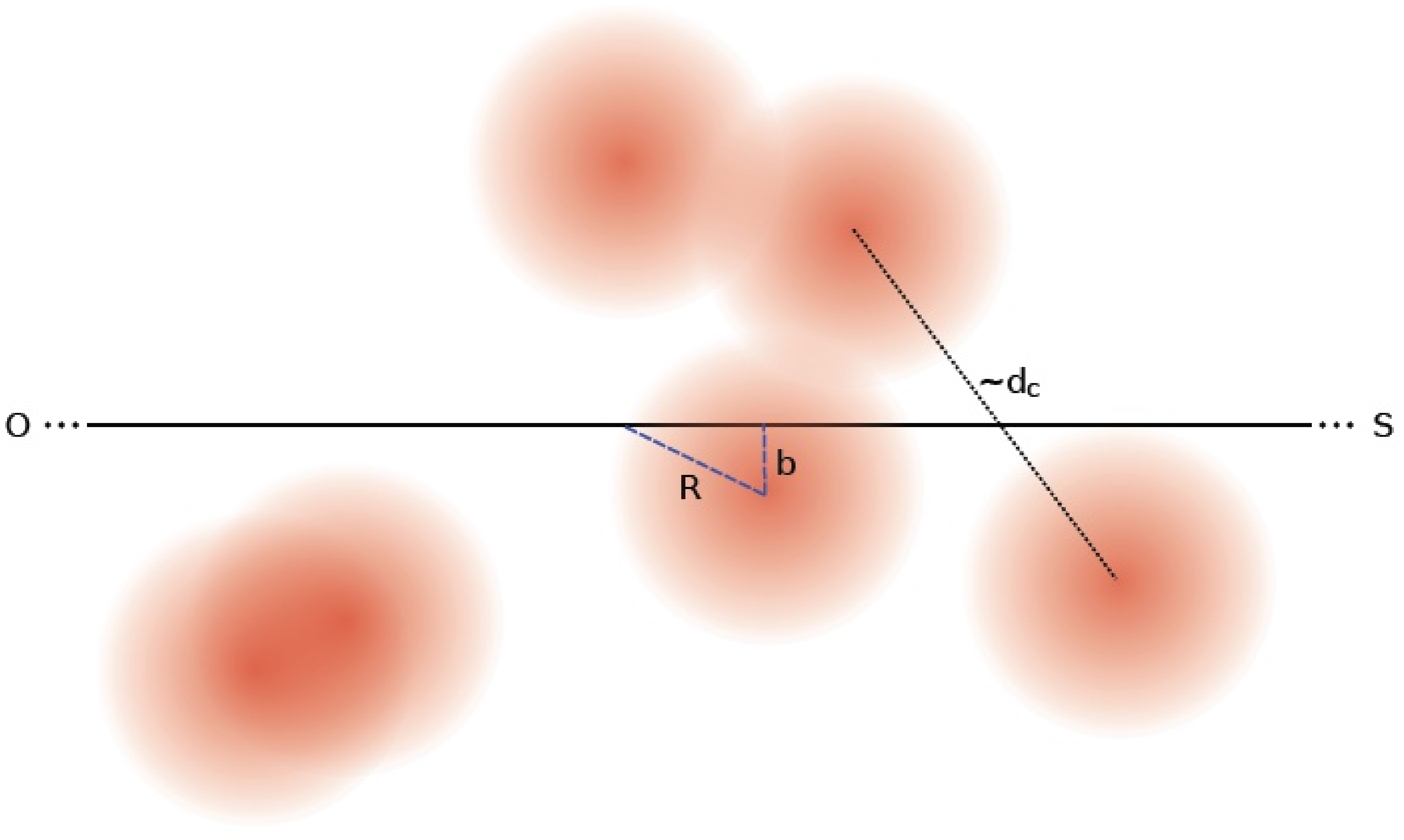
A New Method

- 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

NFW

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, ...

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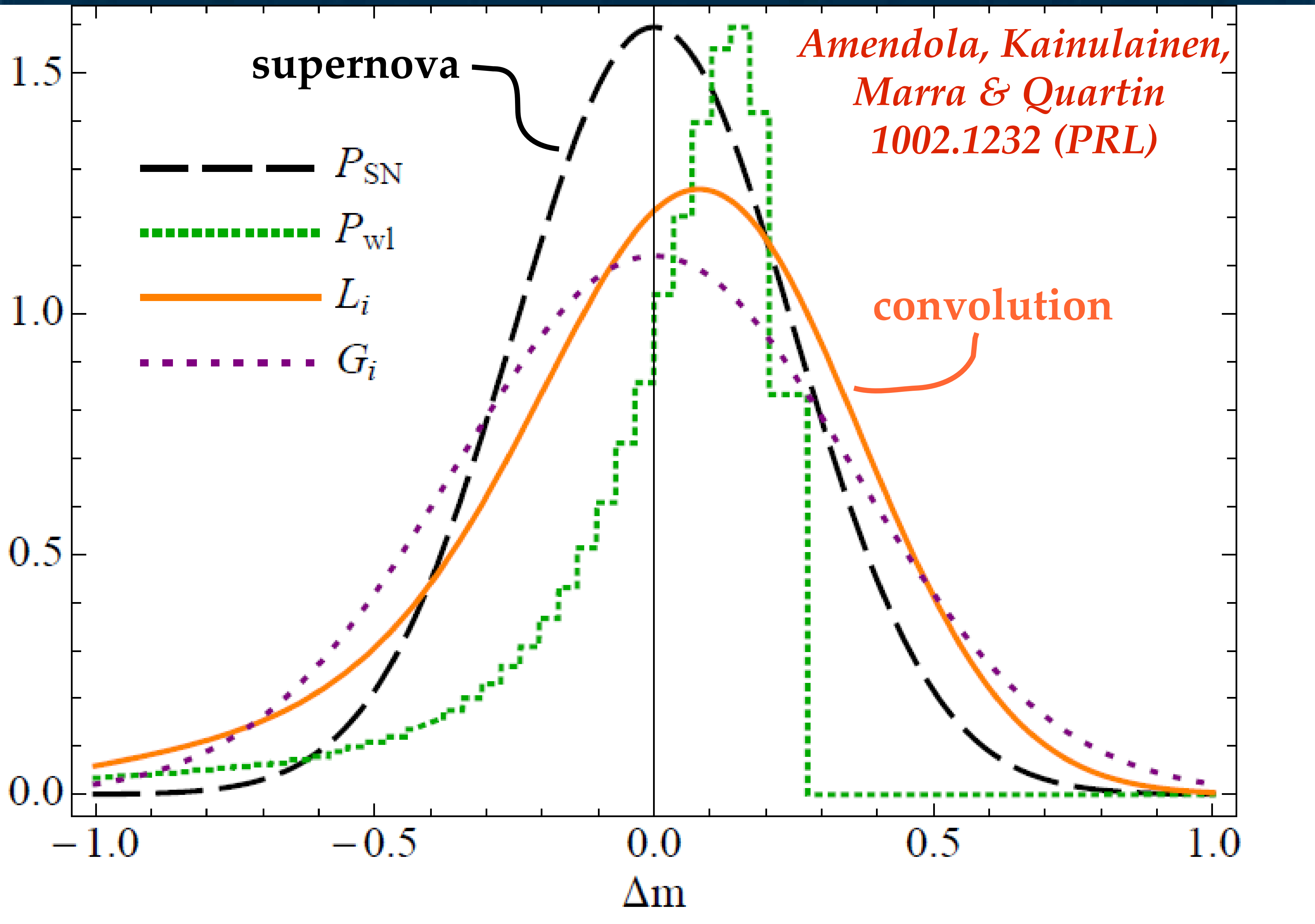
Supernova Lensing (5)

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

Gaussian!

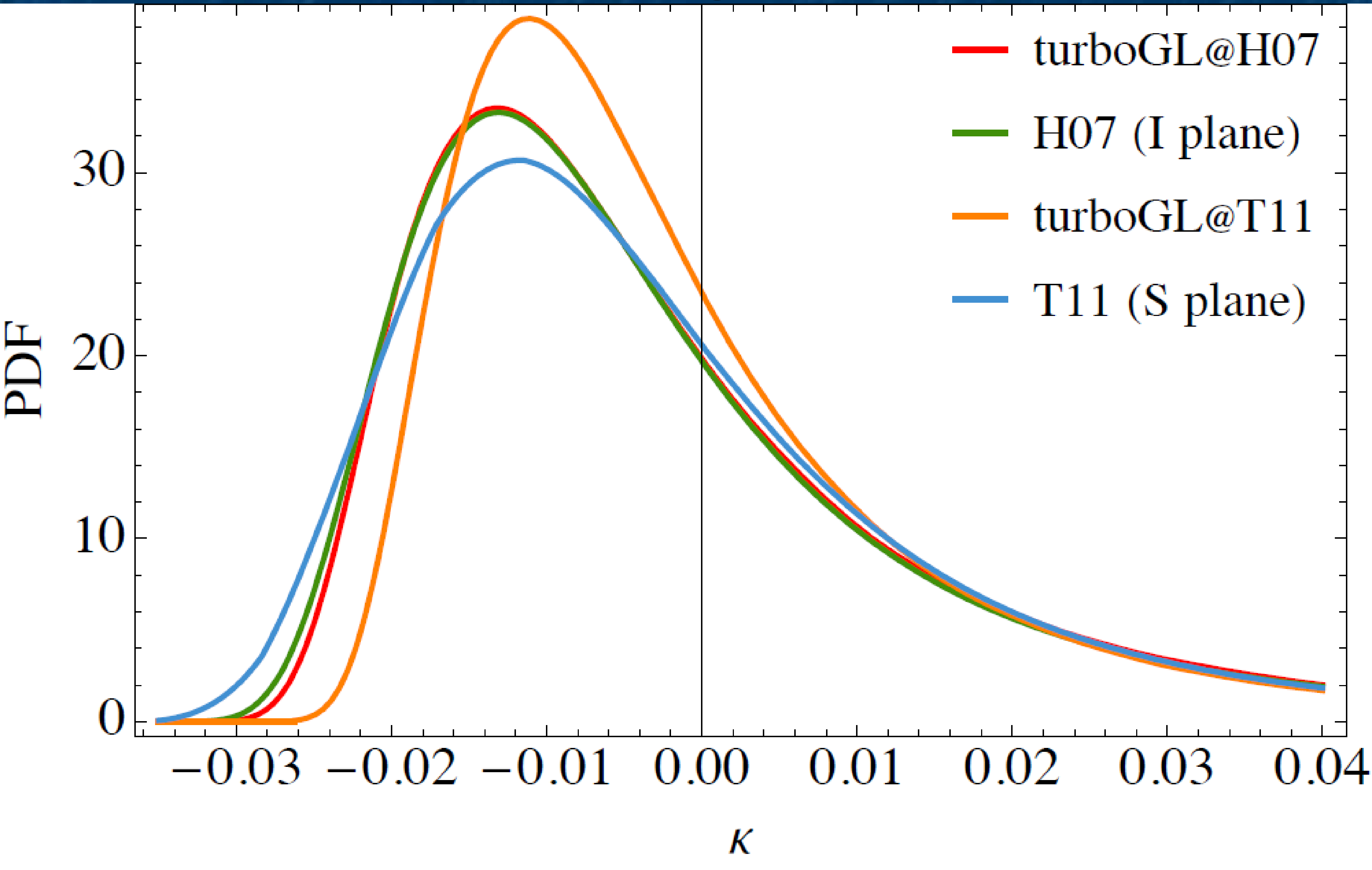
$$L(\mu) = \int \mathrm{d}y \, P_{\mathrm{wl}}(y, \Omega_{m0}, \sigma_8, \cdots) P_{SN}(\Delta m - \mu - y, \sigma)$$

- 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.

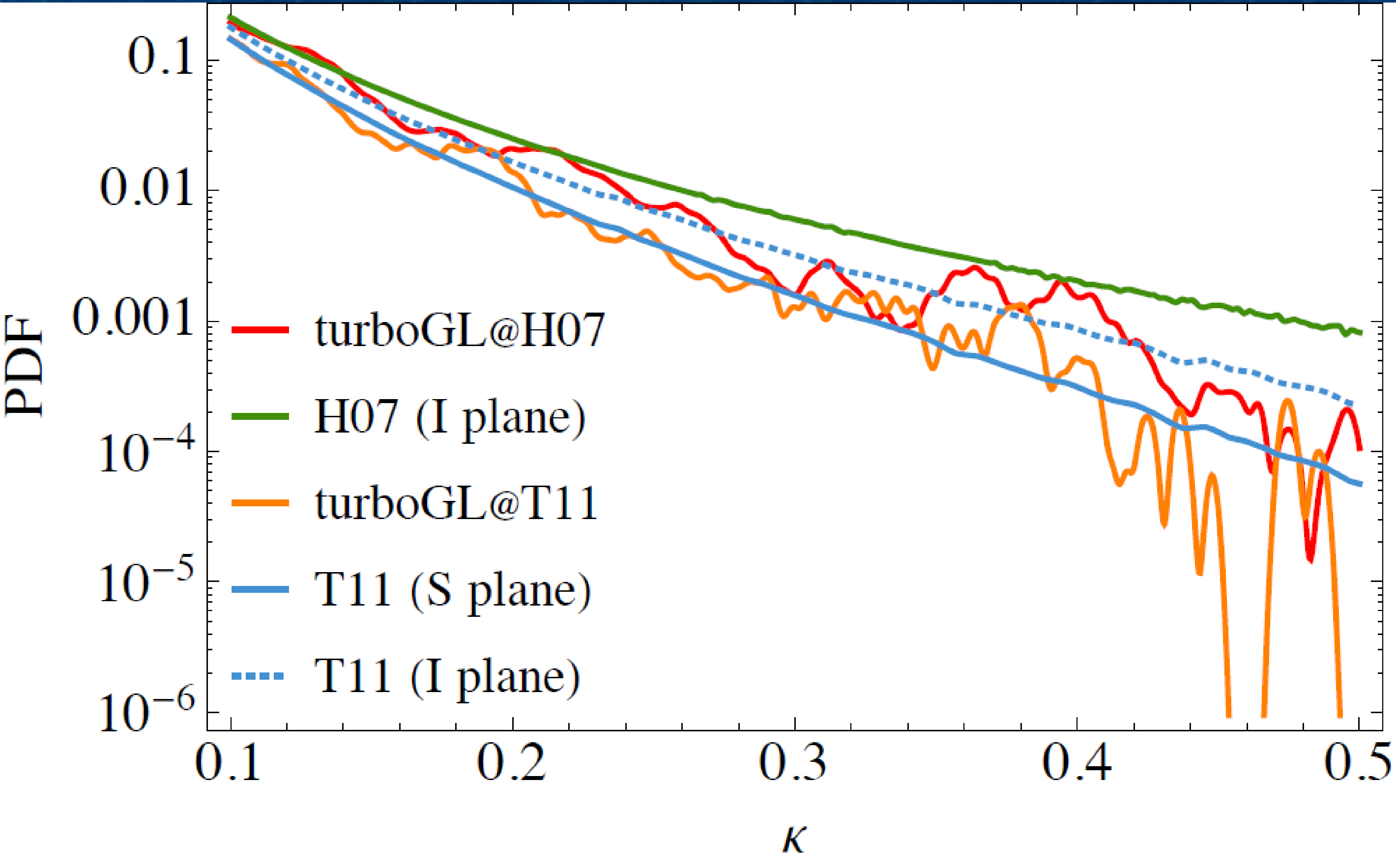


supernova
P_{SN}
P_{wl}
L_i
G_i
Amendola, Kainulainen, Marra & Quartin 1002.1232 (PRL)
convolution
1.5
1.0
0.5
0.0
−1.0
−0.5
0.0
0.5
1.0
Δm

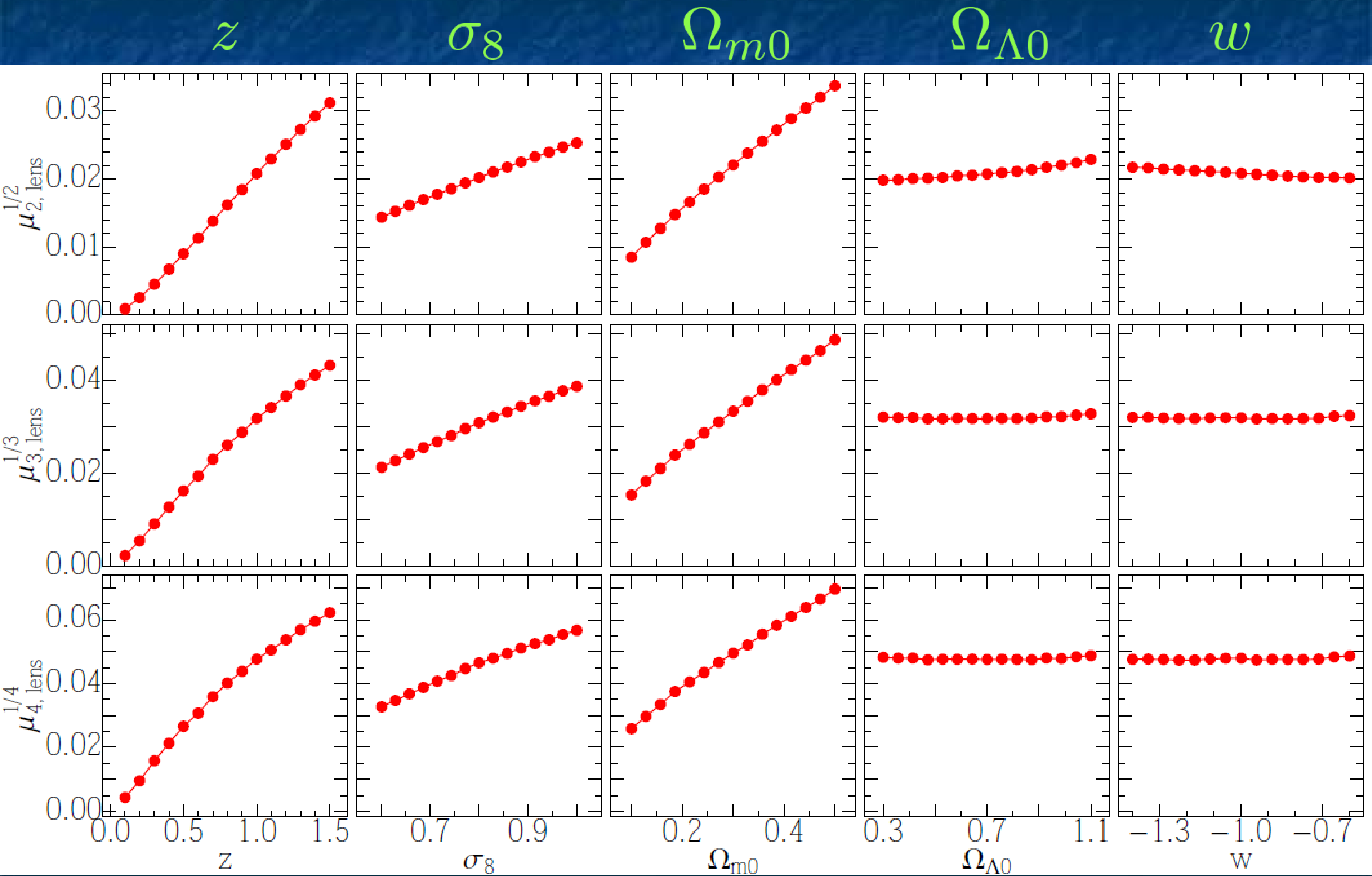
The Lensing PDF (2)



The Lensing PDF (3)



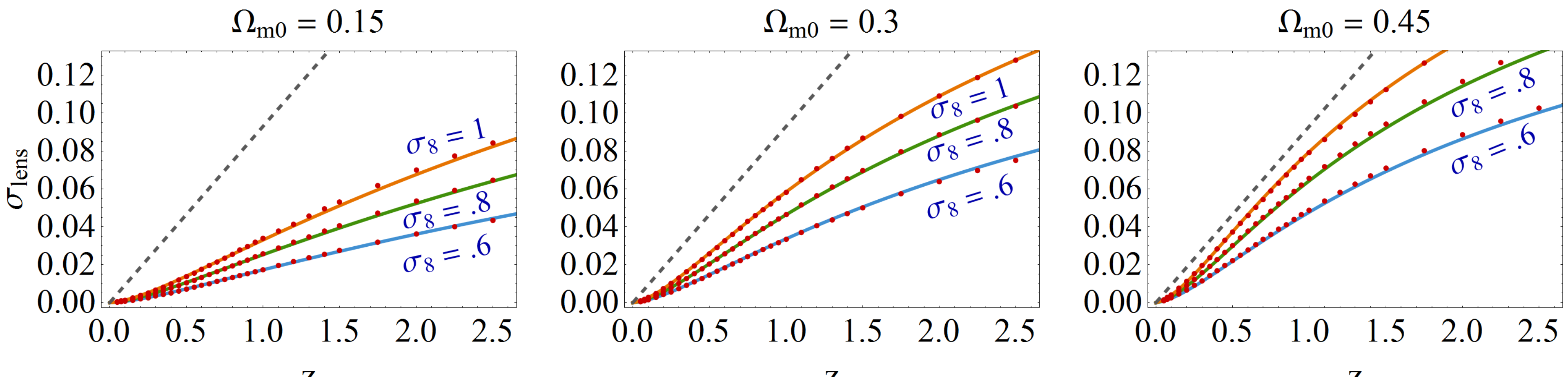
Variance, Skewness & Kurtosis



Fitting Functions

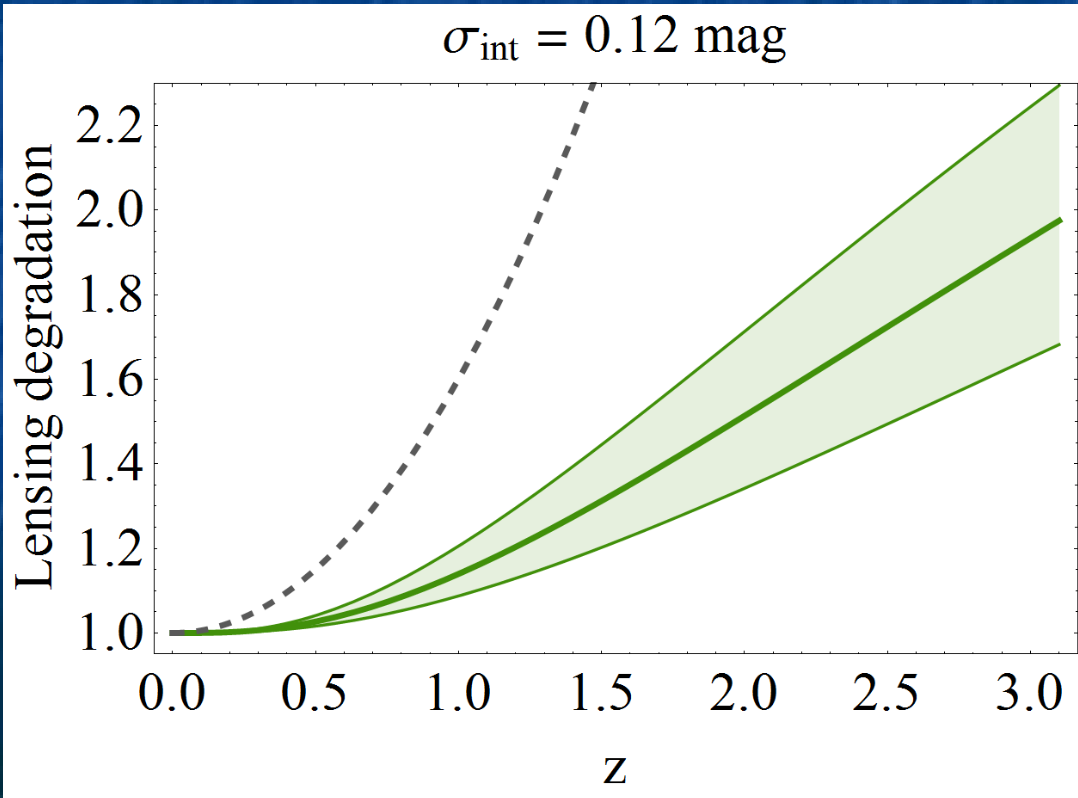
- We provide accurate and flexible analytical fits for the variance, skewness & kurtosis
  - Significant improvement upon current HL fit: $\sigma_{\rm lens}^{\rm HL} = 0.093z$

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



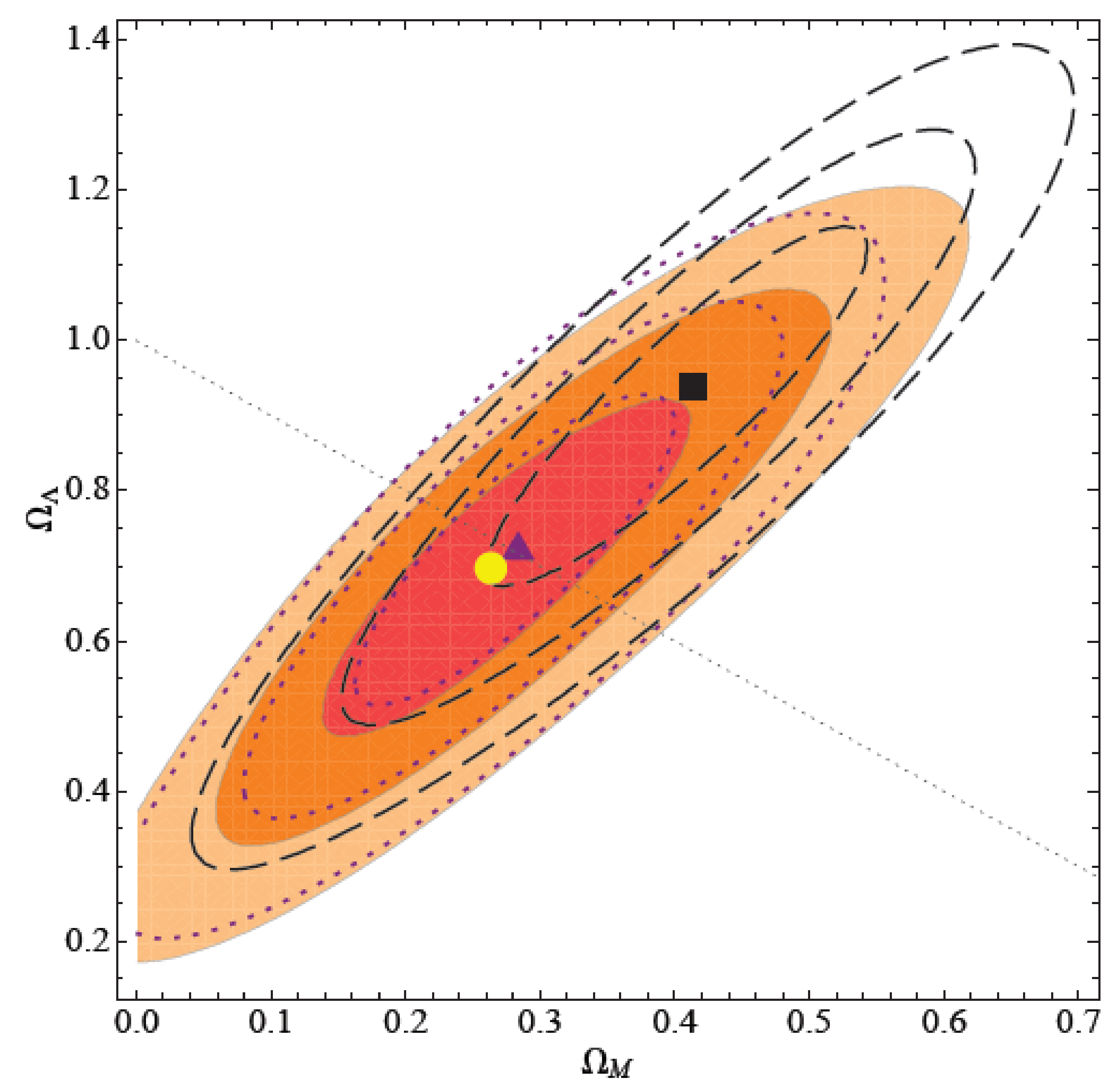
Fitting Functions (2)

- 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)

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 constraining power
      - need ~10^4 Sne to get to <10%, ~10^6 to get to <1%
        - LSST will give us ~10^6
    - Caveat 2: maybe the SNe are not gaussian (intrinsically or due to systematics)
  - It is a very good cross-check
  - It is a new observable

Dodelson & Vallinotto (astro-ph/0511086)

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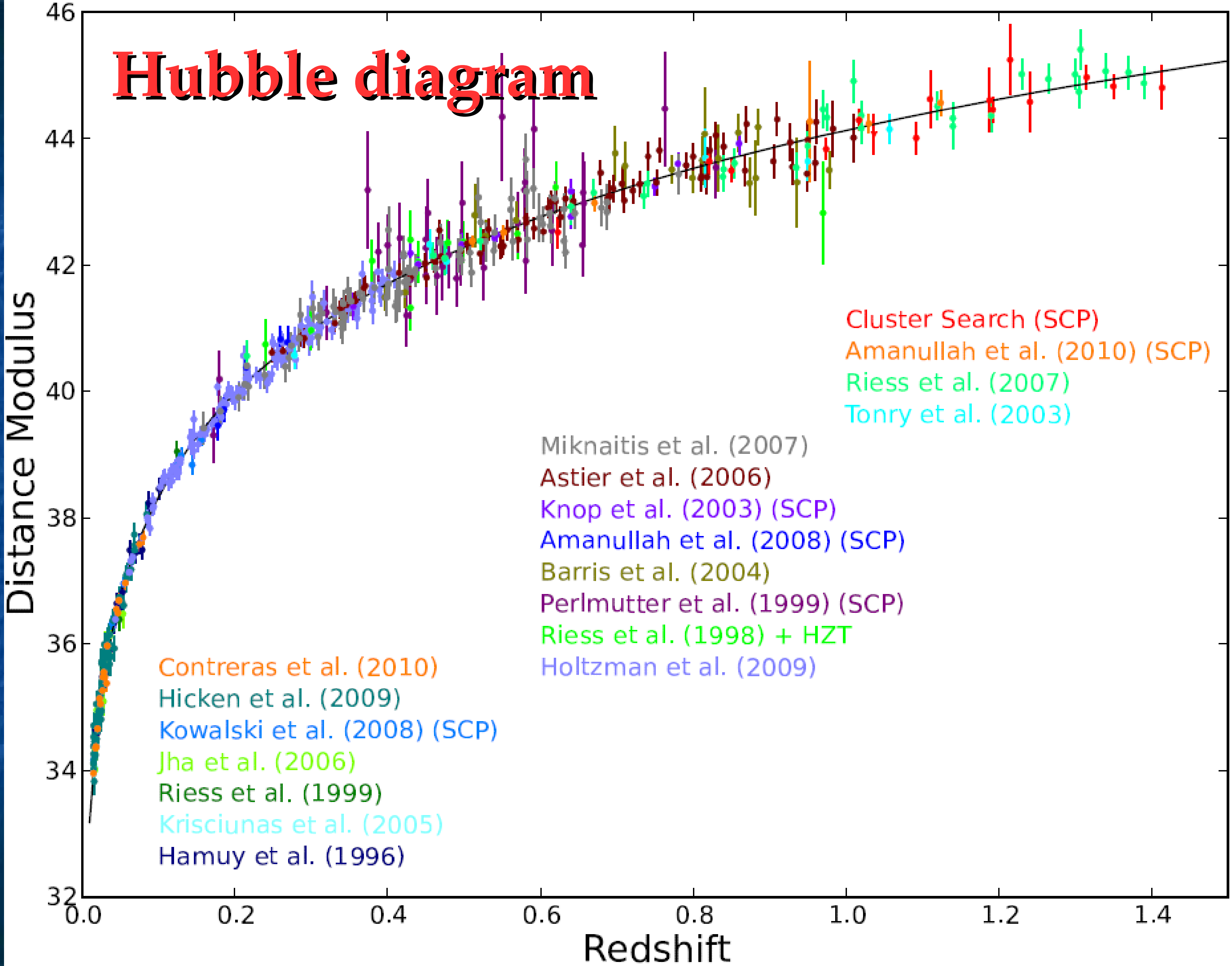
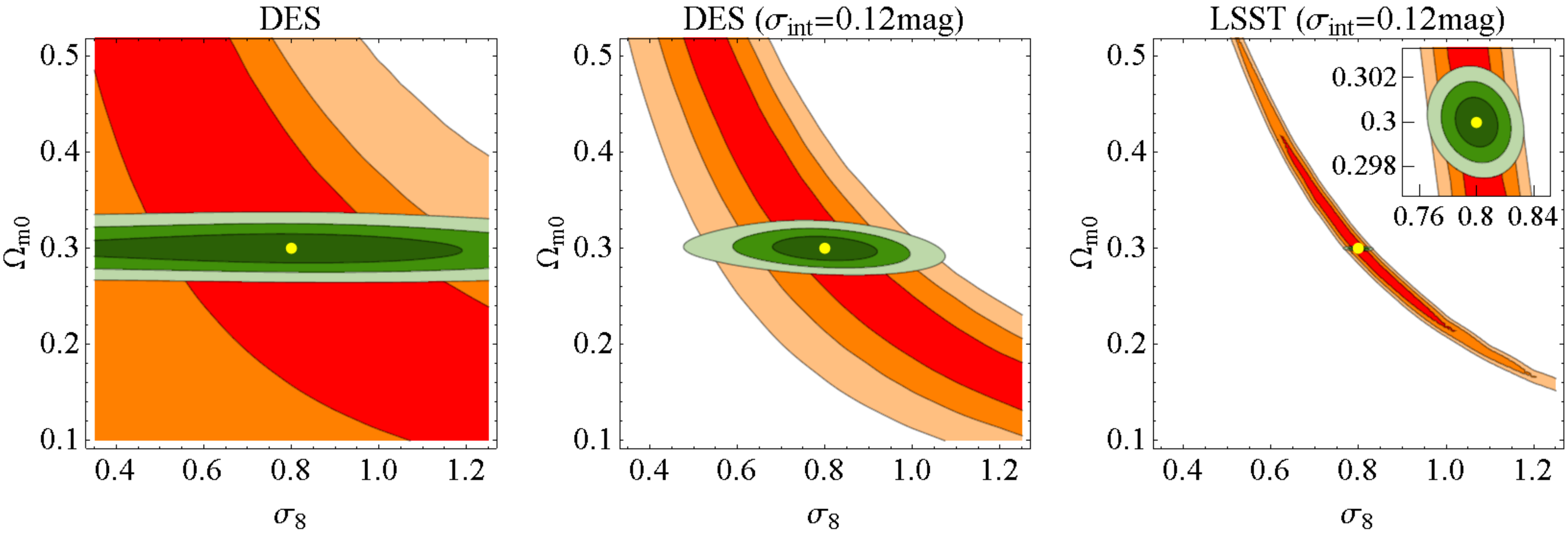
Hubble diagram



The Inverse Lensing Problem (2)

- The *non-gaussian* scatter of supernovae in the Hubble diagram will tell us about σ_8 up to **~1%** precision!



Amendola, Marra & Quartin (1305.xxxx)

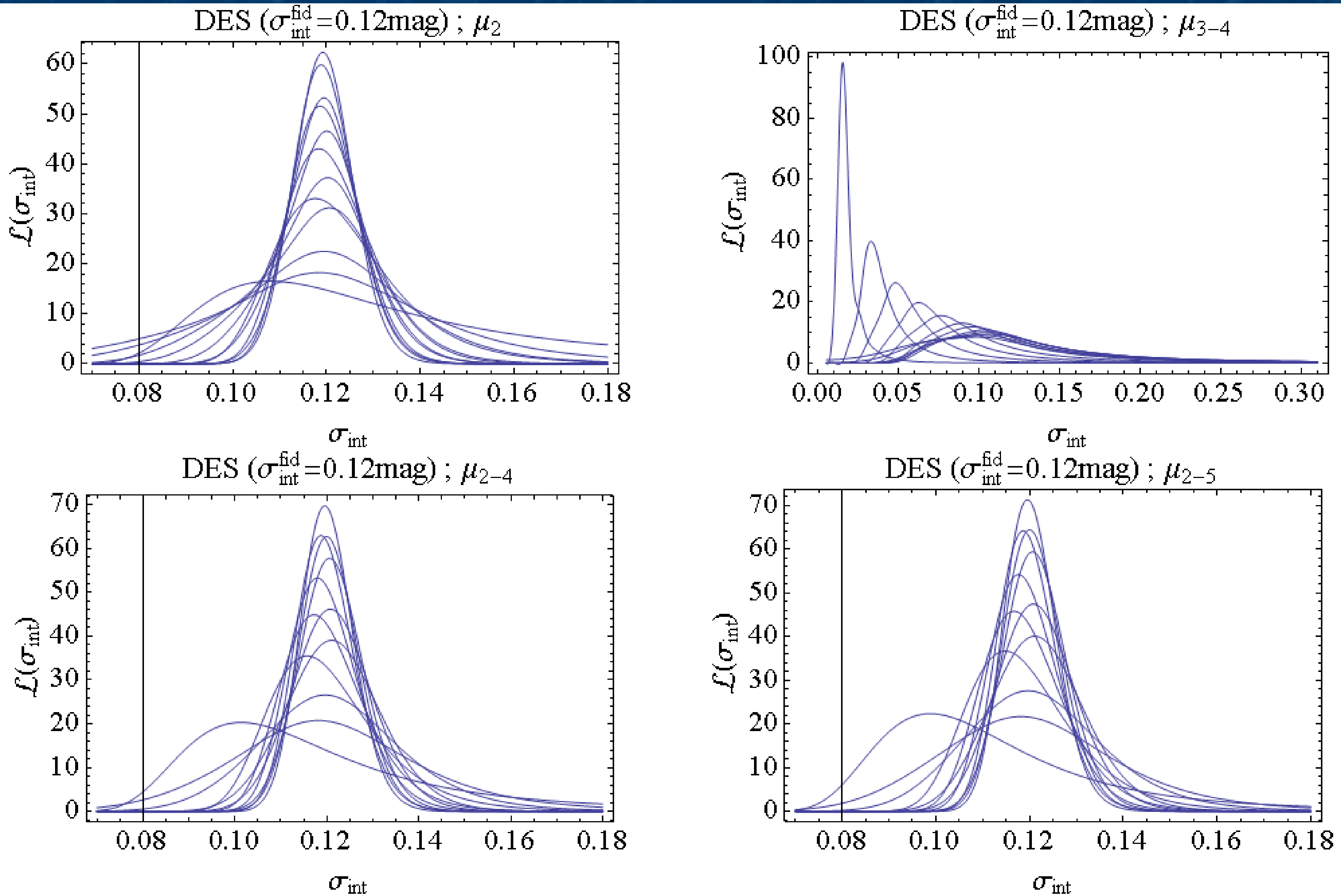
Conclusions

- Detailed lensing modeling important to avoid biases
- Fitting functions of the moments is the easier way to implement lensing
- Lensing degradation smaller than previous estimate
  - Good news for high-z standard candle candidates
- Supernova can constrain also perturbation parameters!
  - Measure $\sigma8$ to ~1% level with LSST.
  - Interesting cross-check of Sne & coarse-grained lensing analysis

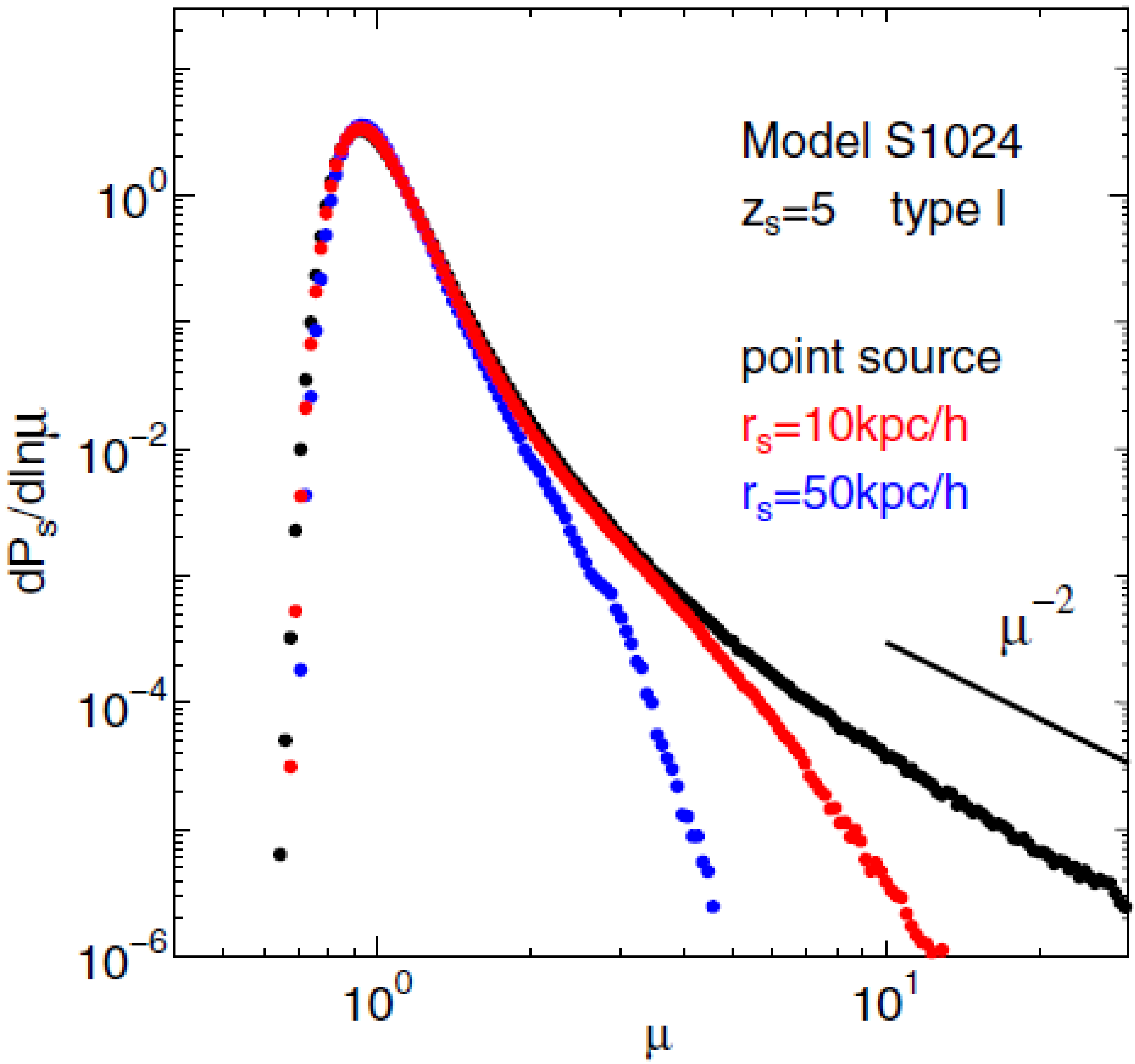
Obrigado!

Extra slides

σint posteriors



Finite sources



Takahashi et al. 1106.3823