Rencontres de Moriond – 50 years – Mar 2016

The Cosmic Supernova Recycling Program

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SNe Ia & Structure

- SNe Ia → traditionally a background cosmological probe
- There are (at least) 2 ways SNe Ia can measure also cosmic structure
  - Through SNe lensing ("hard")
    - Even without cross-correlation with LSS surveys
  - Peculiar-velocity correlations of Sne ("easy")

Supernova Lensing

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- Real universe → structure (filaments & voids) → weak-lensing (WL) → very skewed PDF (Prob. Distr. Function)!

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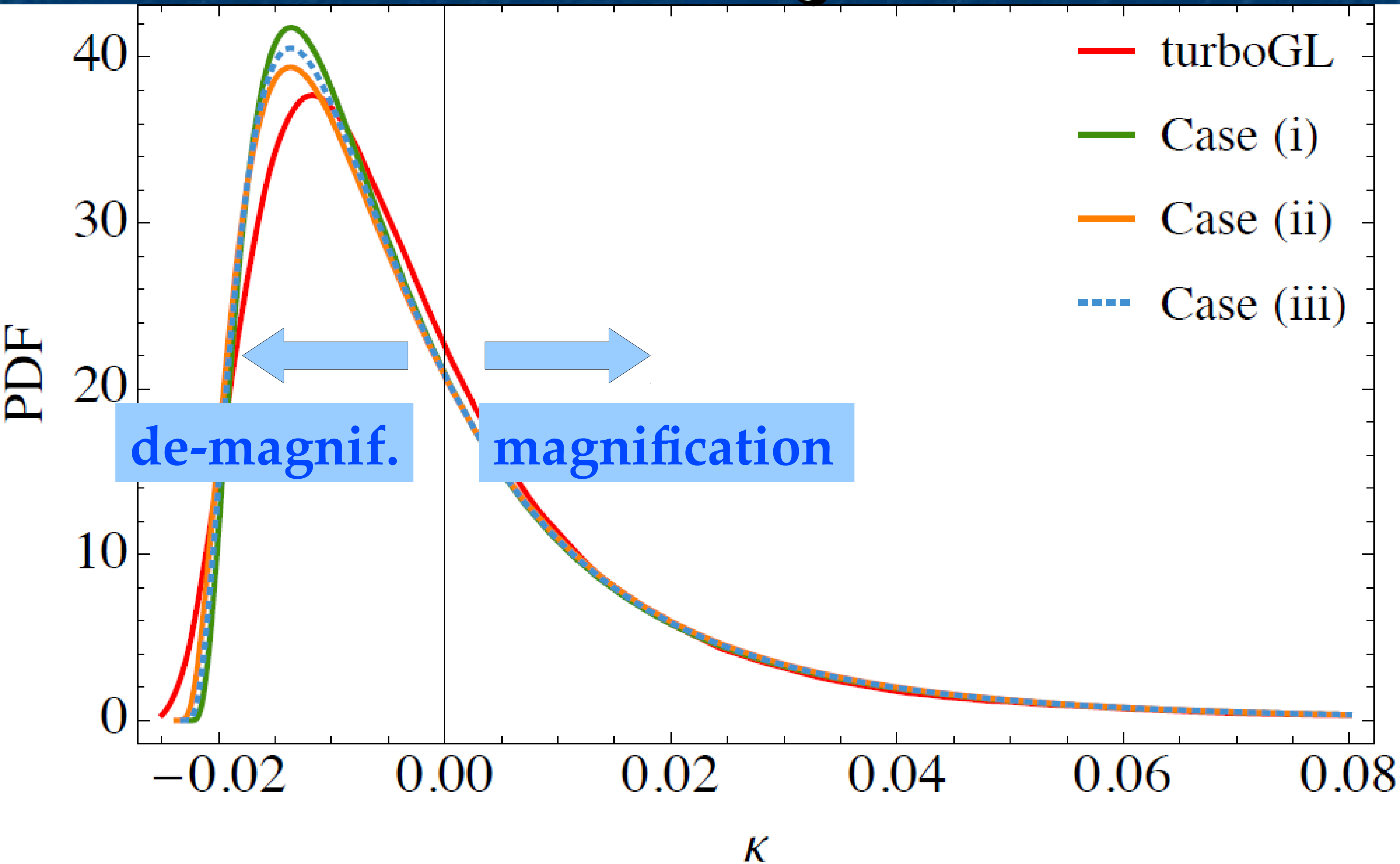
  - Most SNe → demagnified a little (light-path in voids)
  - A few → magnified "a lot" (path near large structures)
  - Adds non-Gaussian dispersion to the Hubble diagram
  - Lensing → *on average* no magnification (photon # conser.)

The Lensing PDF



Supernova Lensing (3)

- The lensing PDF is the key quantity
  - Can be computed: ray-tracing in N-body / Hydro simulations
    - See: *Takahashi et al. 1106.3823*

      Hilbert et al. astro-ph/0703803
    - Full simulations → too expensive to do likelihoods → many parameter values (many Ω_{m0}, σ_8, w_{DE}, etc.)
    - We thus relied on a semi-analytical approach → stochastic GL analysis (sGL)
      - Gives comparable results to simulations (ask me later)

Supernova Lensing (3)

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- PDF is well parametrized by the *first 3 central moments*

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

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- Observed SNe PDF → convolution of lensing & intrinsic SNe PDFs

$$L(\mu) = P_{\rm lens}(\Omega_{m0}, \sigma_8, \cdots) * P_{SN}(\Delta m - \mu, \sigma)$$

Marra, Quartin & Amendola 1304.7689 (PRD)

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  - It is a new observable & good cross-check

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

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The Method of the Moments (MeMo)

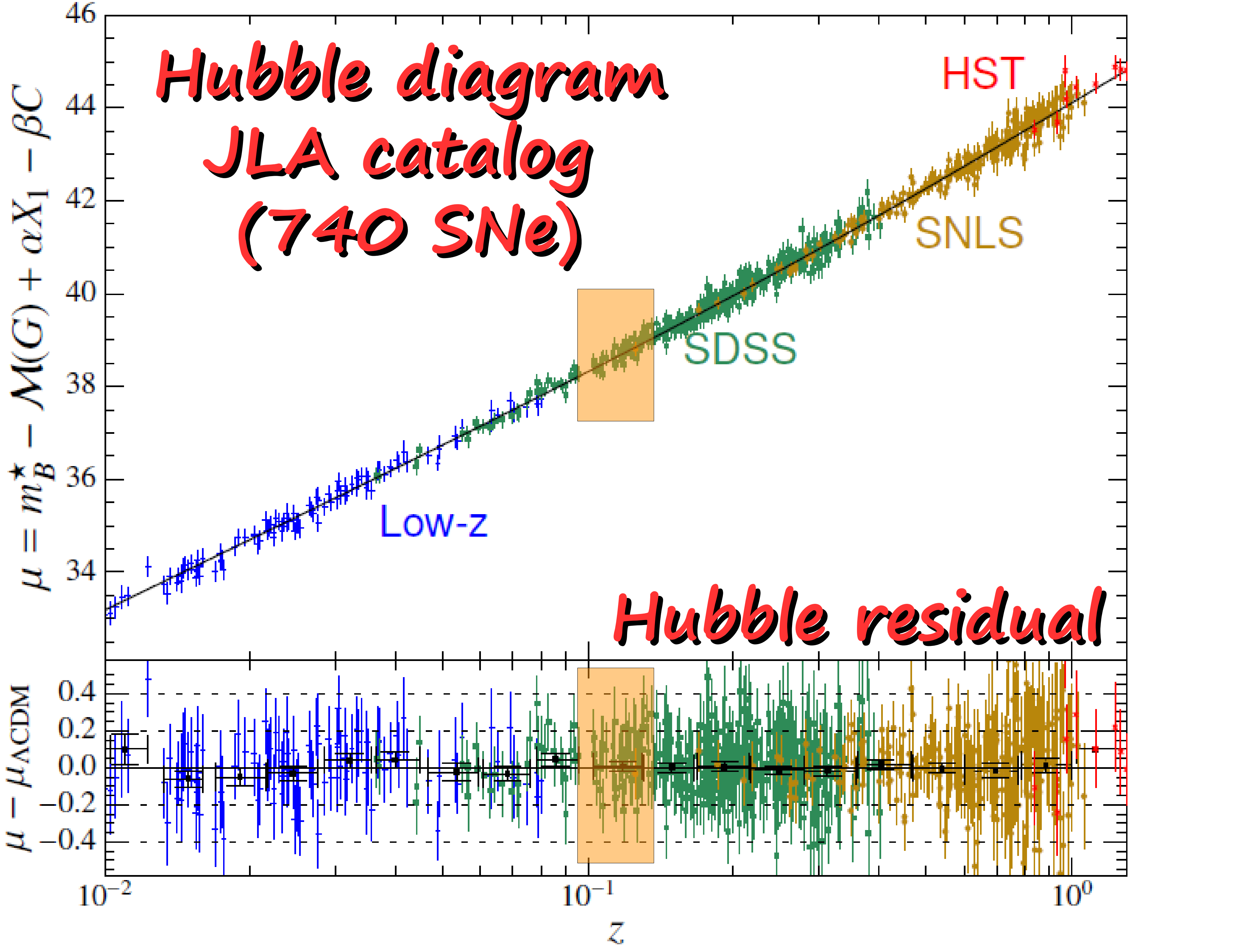
- Using the first 4 moments, we write:

$$L_{\mathrm{MeMo}}(\mathrm{cosmo}, \mathrm{nuisance}) \;\propto\; \exp\left(-\frac{1}{2}\sum_{j}^{\mathrm{z\ bins}} \chi_j^2\right),$$

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

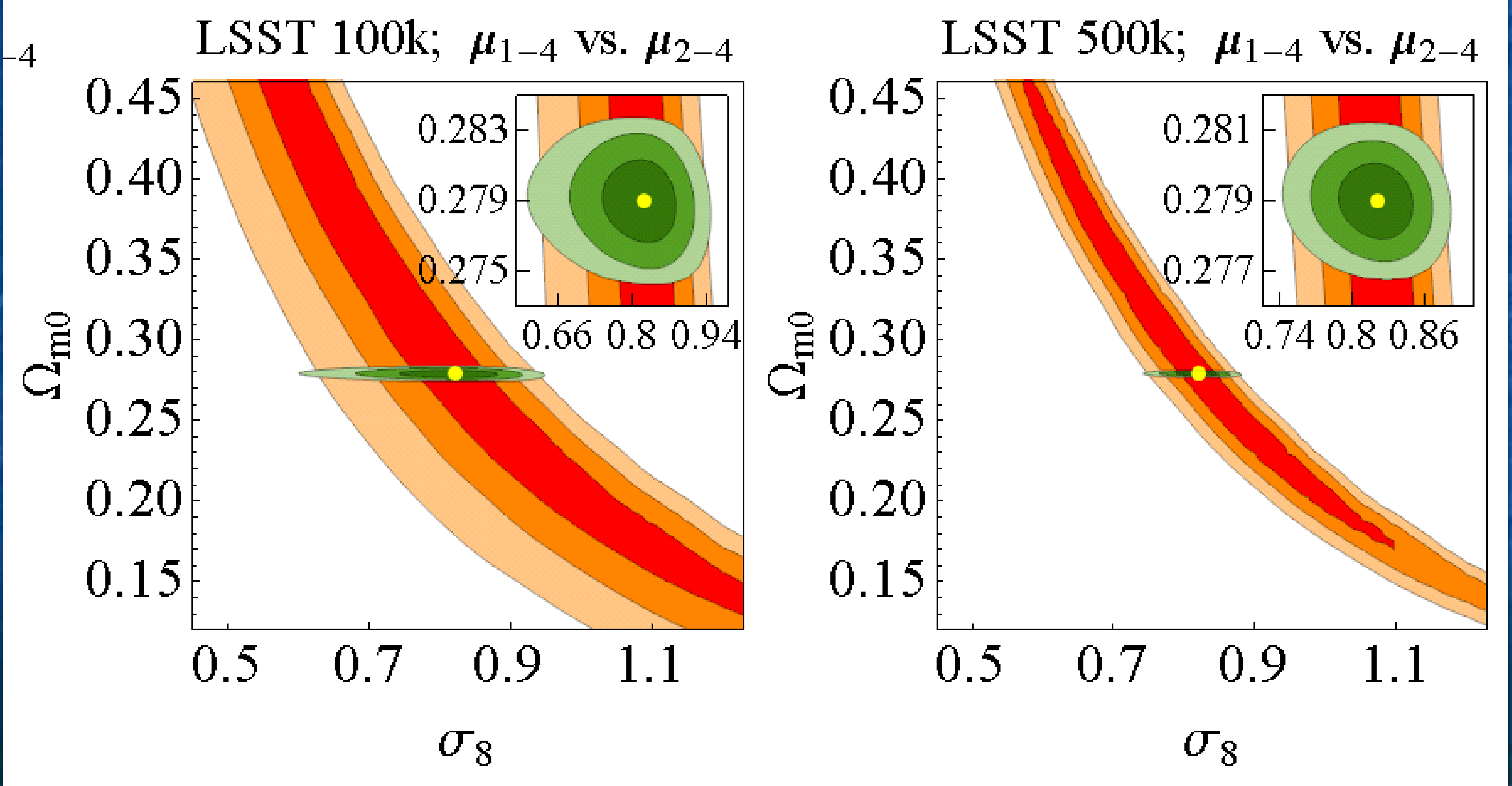
$$\boldsymbol{\mu} = \{\mu_1', \mu_2, \mu_3, \mu_4\}$$

- 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
Hubble residual
$\mu = m_B^\star - M(G) + \alpha X_1 - \beta C$
$\mu - \mu_{\Lambda CDM}$
z

The Inverse Lensing Problem (2)

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



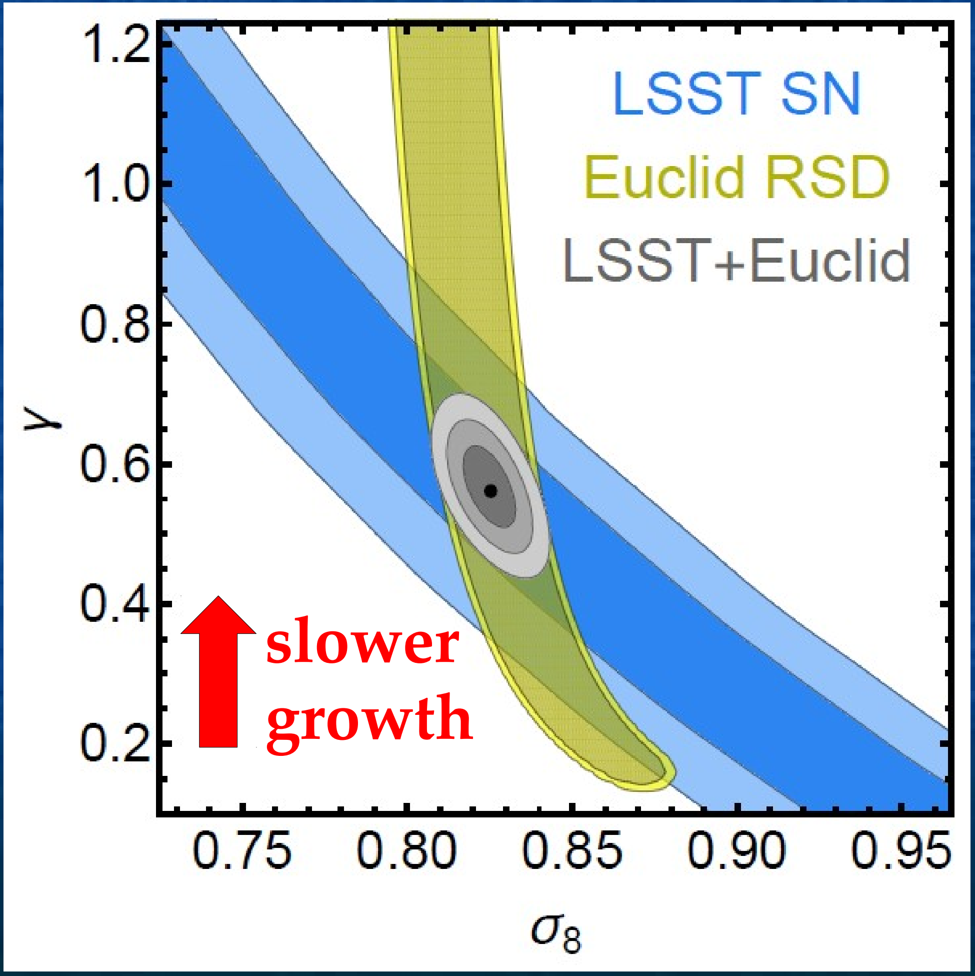
Modified Gravity

- SNe lensing can also measure if gravity is GR or not
- Mod. gravity models often exhibit a distinct growth of structures

$$f_g \equiv \frac{-\mathrm{d}\ln G}{\mathrm{d}\ln 1+z} \approx [\Omega_m(z)]^\gamma$$

$$\mathrm{GR} \rightarrow \gamma = \frac{6}{11} \simeq 0.55$$

Amendola, Castro, Marra & Quartin (1412.3703, MNRAS)

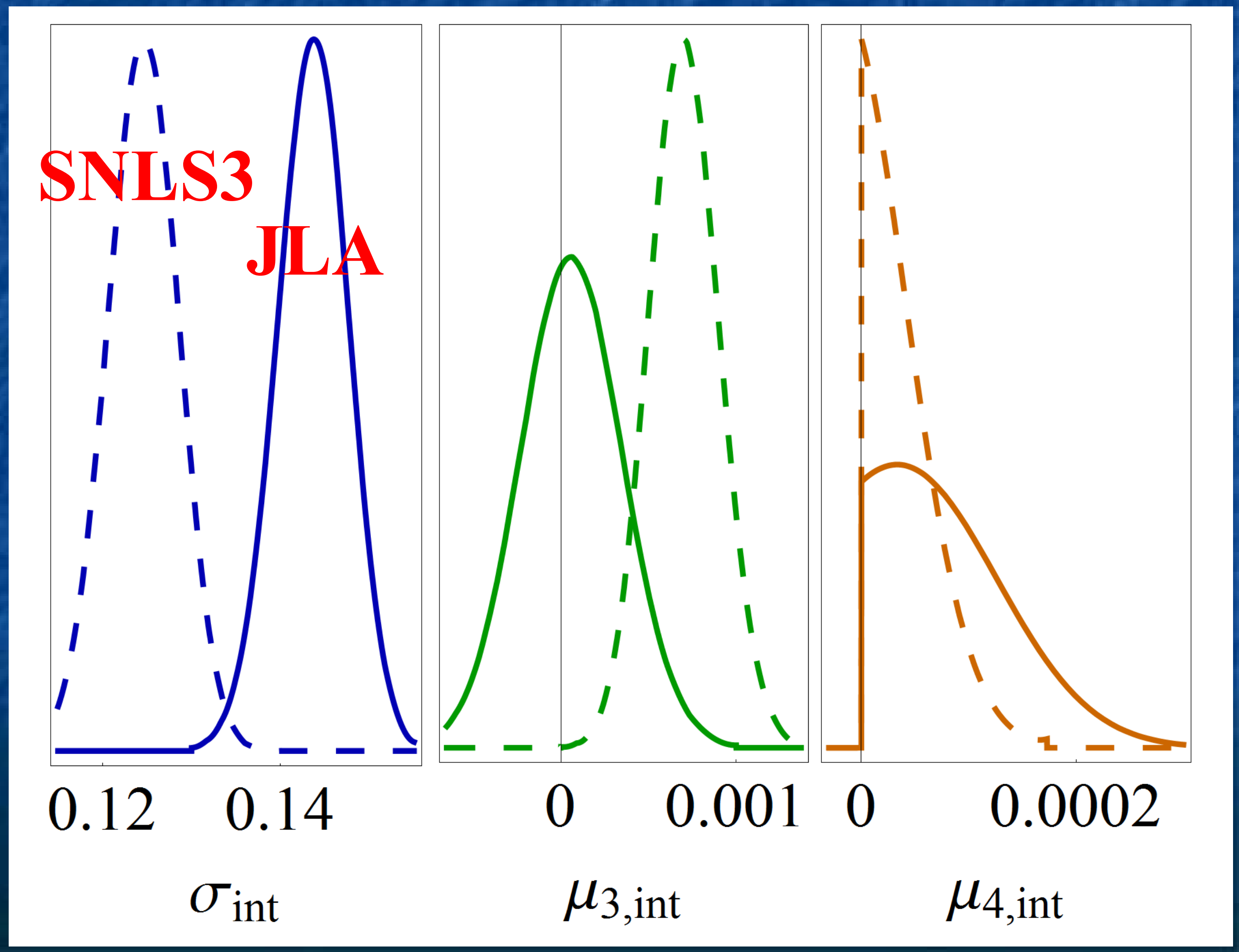


Real data: JLA

Castro & Quartin (1403.0293, MNRAS Letters)

We can also measure the intrinsic SNe moments.

i.e., no need to assume SNe are intrinsically Gaussian



SN Peculiar Velocity

- Lensing only affects far SNe ($z >\sim 0.4$)
- At low redshift ($z <\sim 0.1$) another effect becomes relevant
  - "Peculiar velocities" (PV) in cosmology refers to velocities outside of the "Hubble flow" (i.e., expansion)
  - Typical PV @ $z=0 \rightarrow \sim 600$ km/s   ($v / c \sim 0.002$)
    - "extra blue/redshift"
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  - Typical PV @ z=0 → ~600 km/s (v / c ~ 0.002)
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  - These *perturbations* are high for low z (large relative error)
- Crucial point: these velocities are correlated
  - Correlations → linear matter power spectrum
  - We can measure them & infer the power spectrum!

SN Peculiar Velocity (2)

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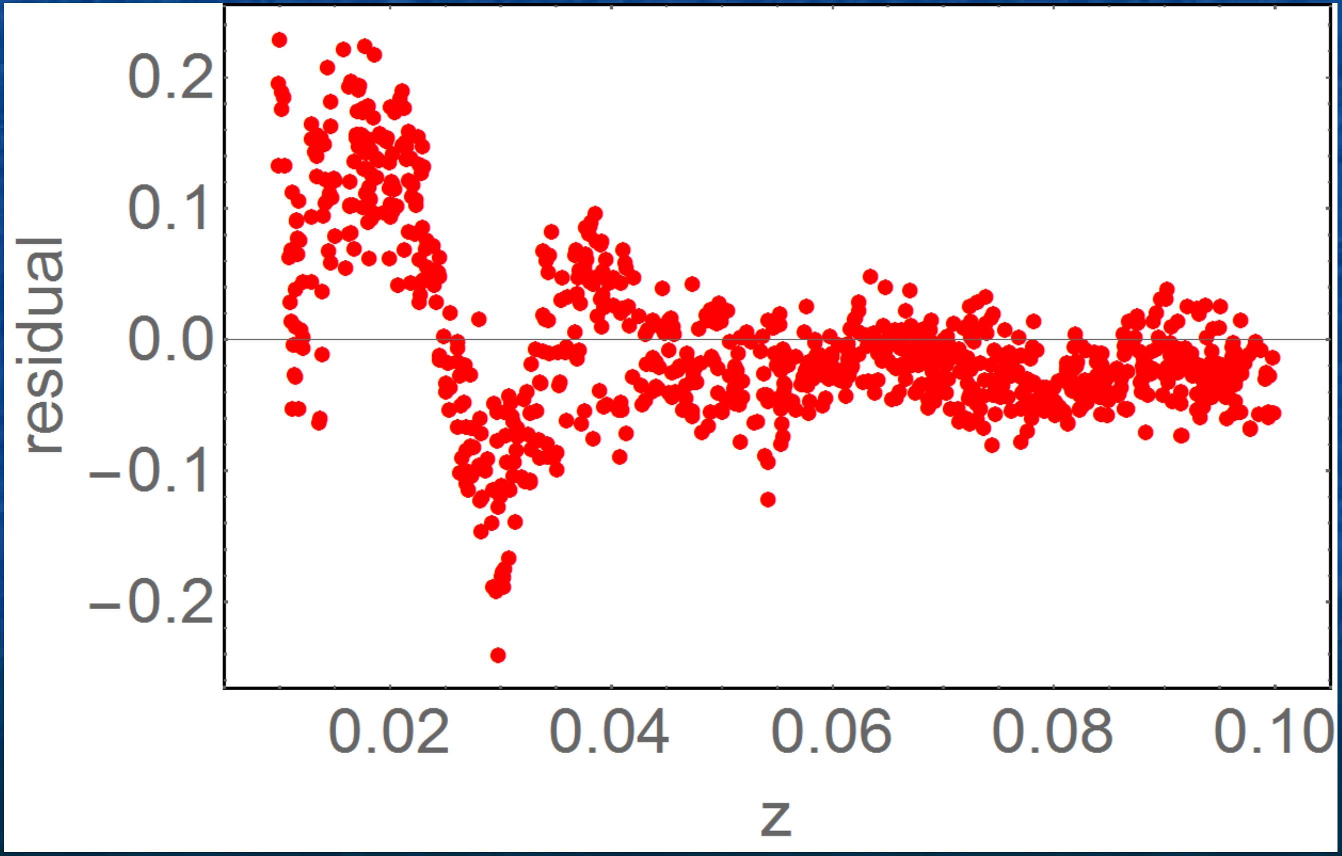
- Part of the SNe Hubble residual due to their PV
  - At low z, it is the dominant source of uncertainty
- The 2-point correlation function relate velocities of SNe which are close to each other
  - If one is receding, the other is probably receding too → angular correlations in magnitude (proportionally to σ_8)

Gordon, Land & Slosar (0705.1718, PRL)

Castro, Quartin & Benitez (1511.08695)

Hubble Diagram w/ PV's

- To get some intuition → ideal case of perfect Sne Ia (i.e. no intrinsic dispersion, $\sigma_{int} = 0$) in a 400 deg^2 patch



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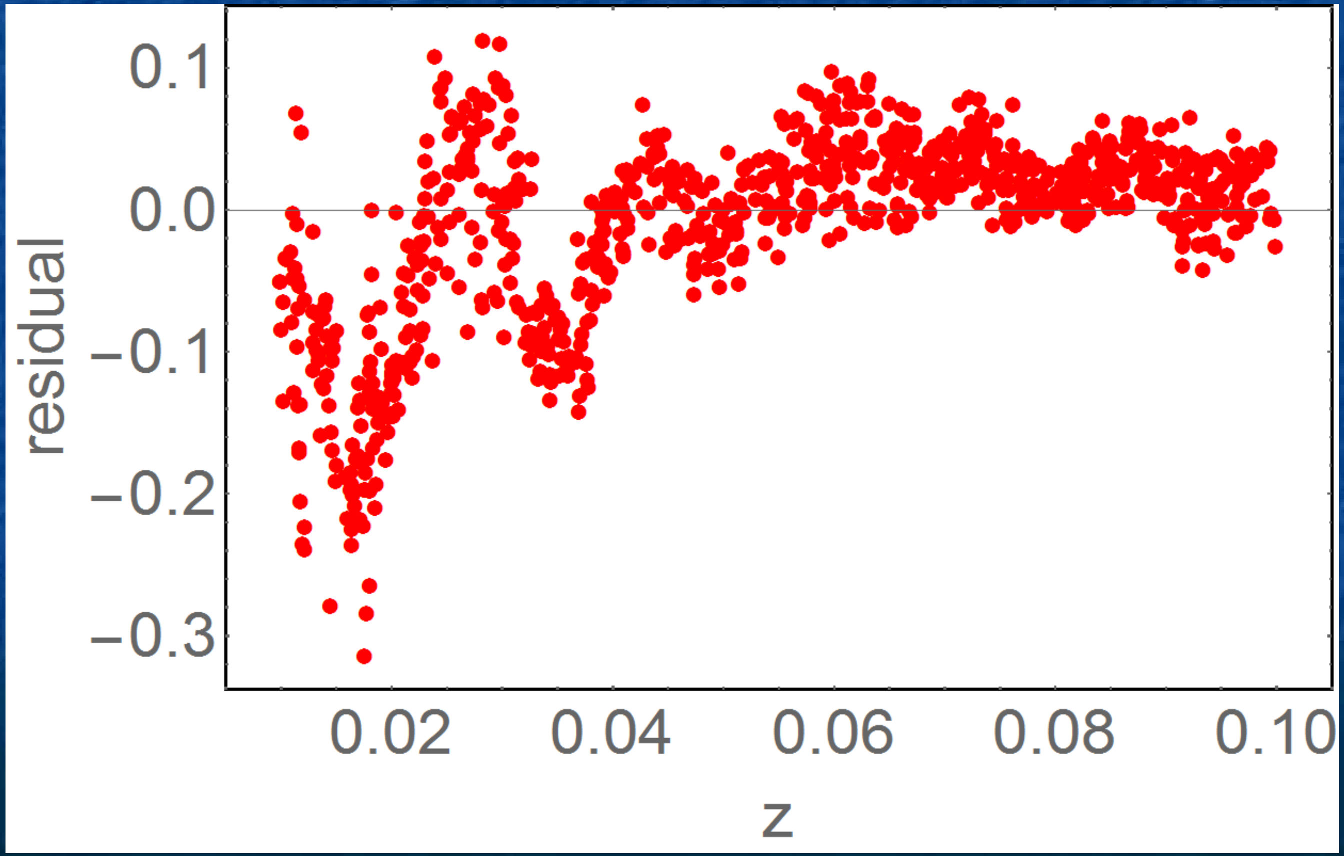

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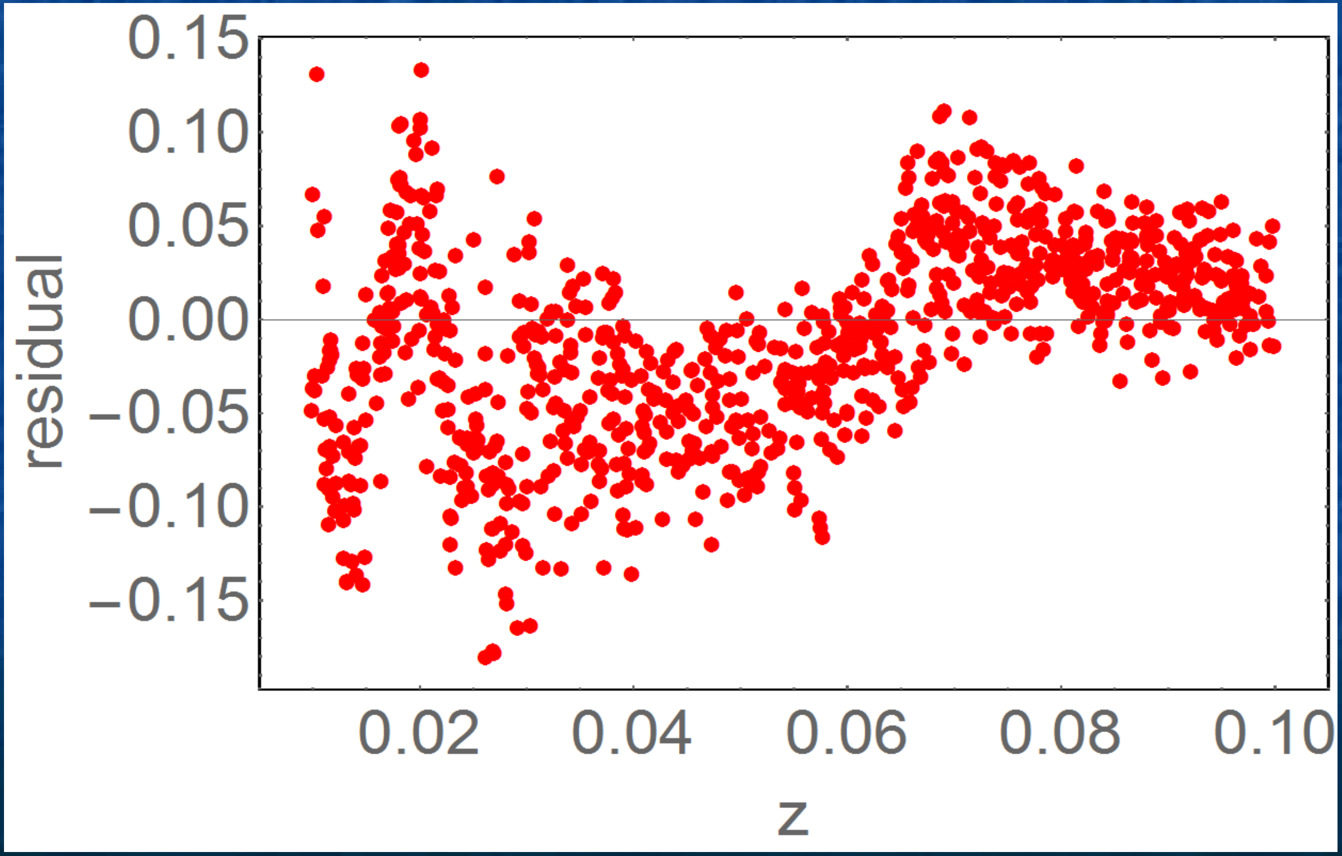
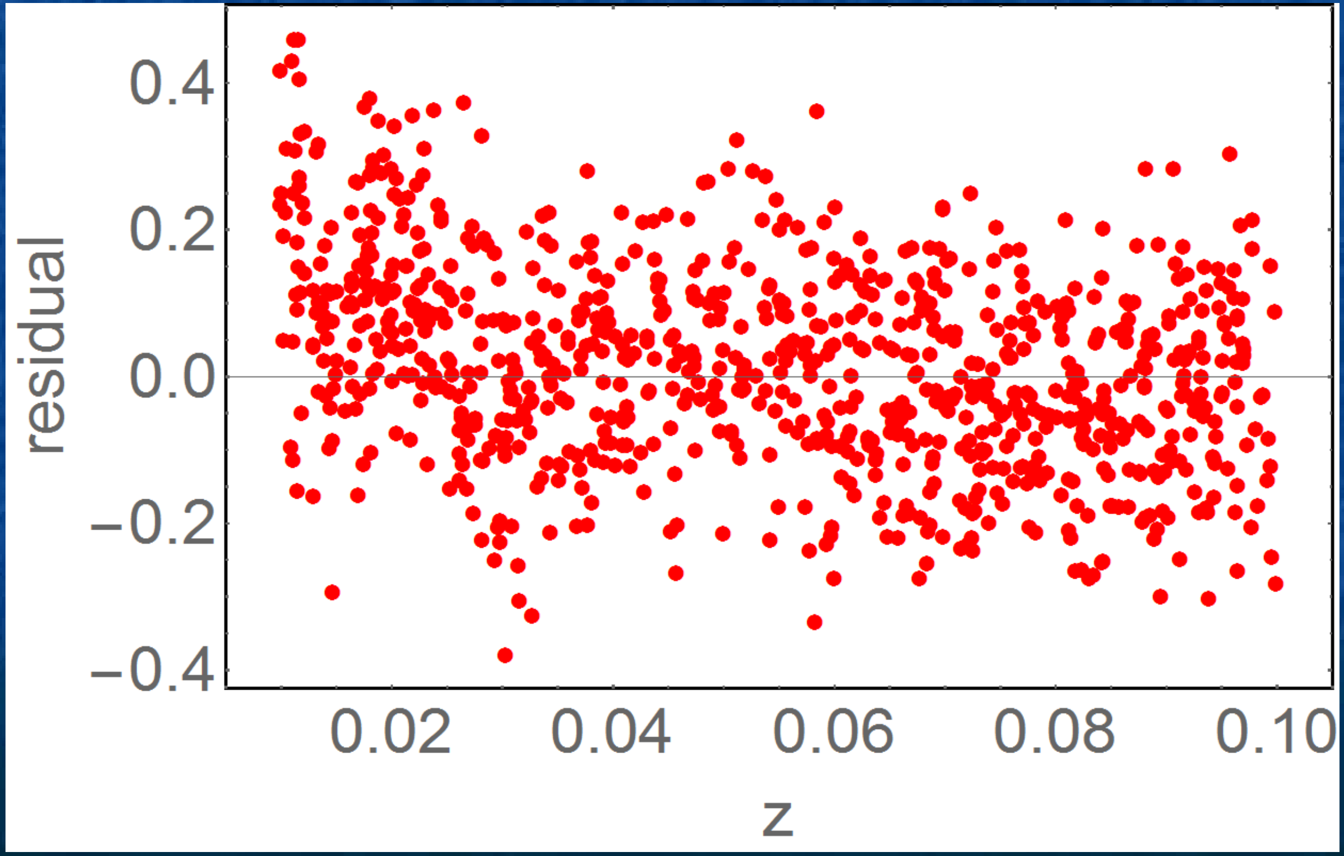


Hubble Diagram w/ PV's

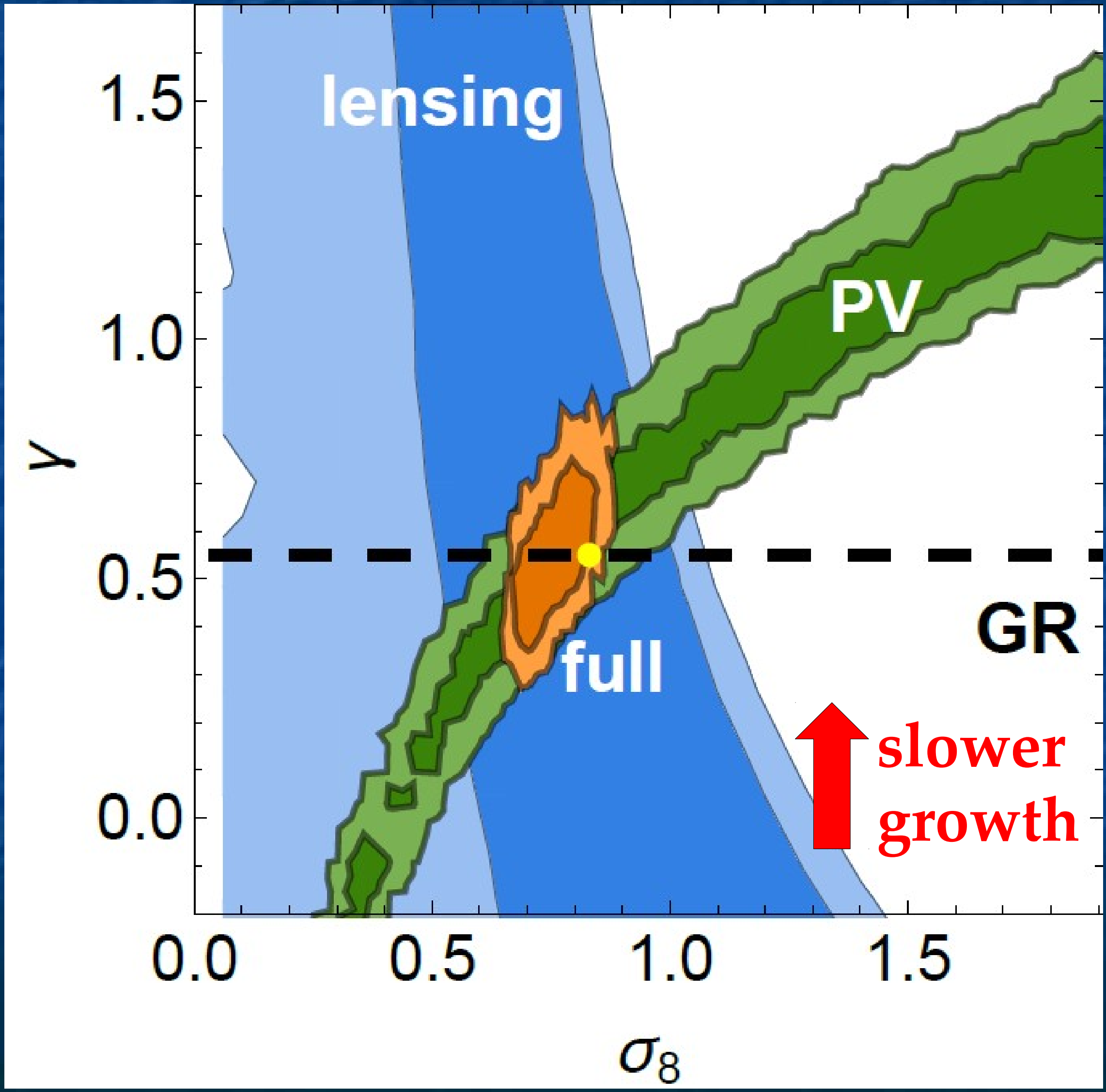
- The signal becomes much weaker for realistic supernovae (σ_{int} = 0.12mag) → but it is still measurable



Forecast: DES + 1000 low-z

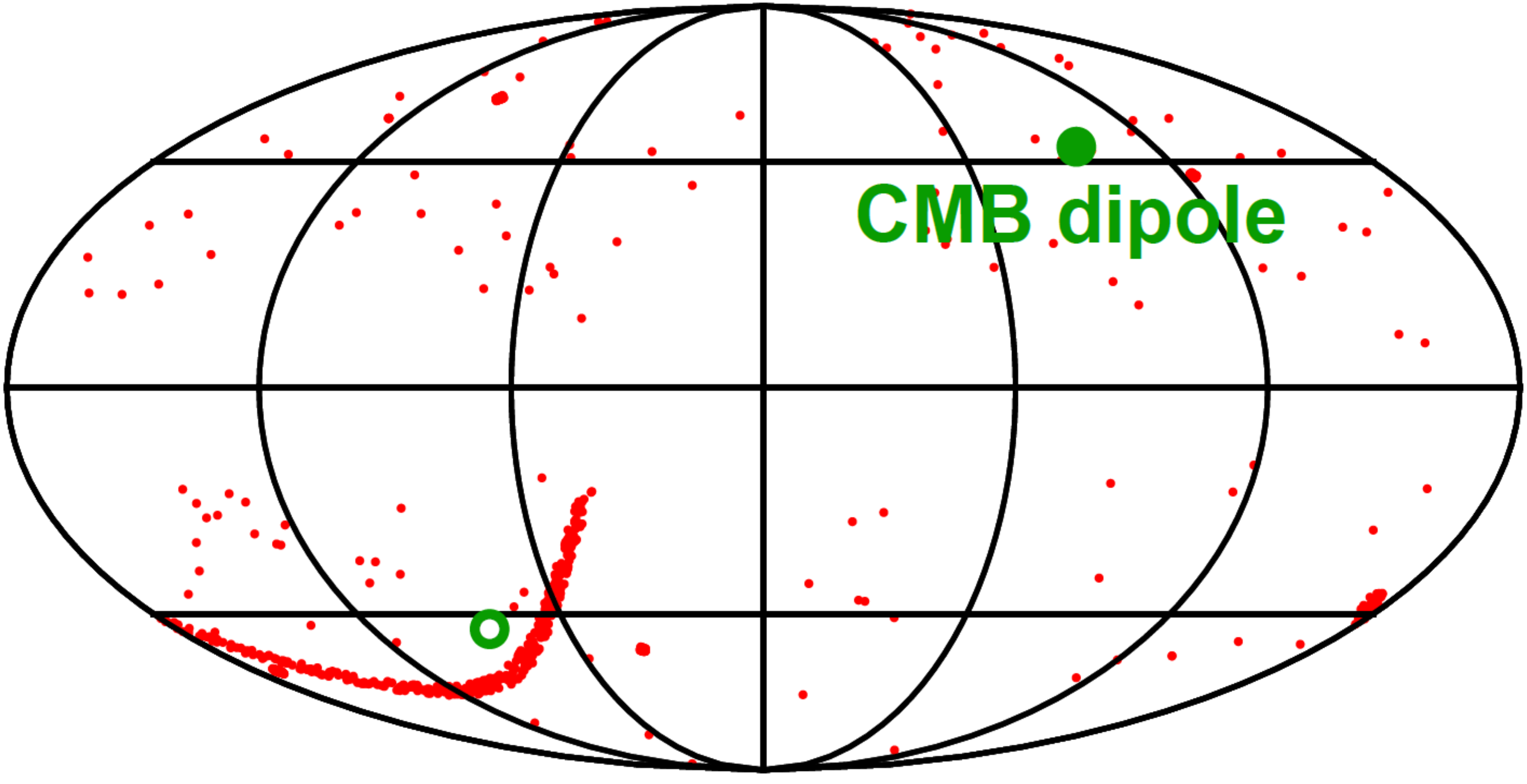
- Forecast for the DES SNe + 1000 SNe in $0.01 < z < 0.1$
- Uncertainties:
  - In σ_8: ~0.1 (~12%)
  - In γ: ~0.2 (~35%)

Castro, Quartin & Benitez (1511.08695)

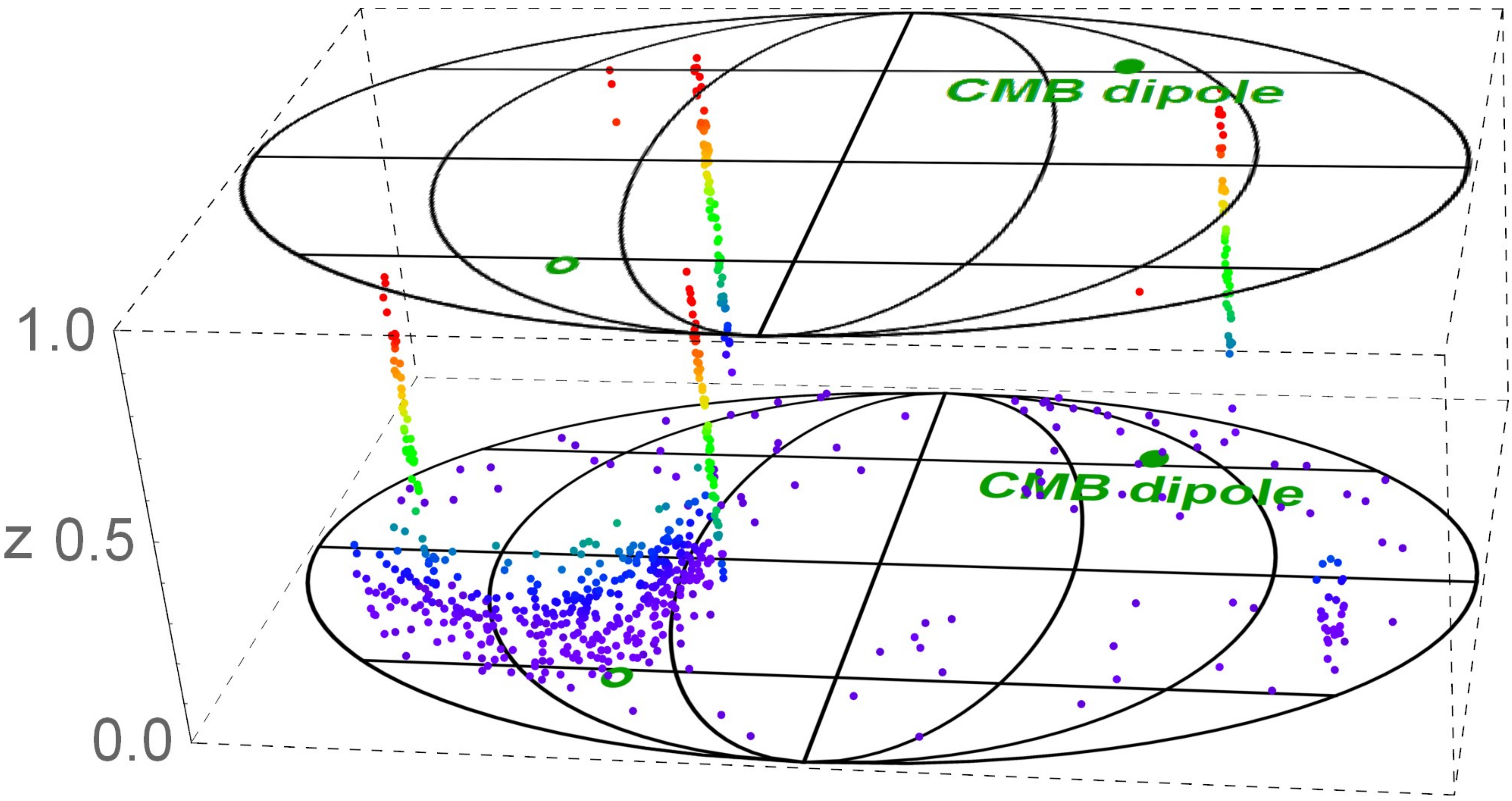


JLA supernova distribution

- In galactic coordinates (as cosmologists like)



JLA SNe distribution (2)



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- We analyzed JLA with a 14-dimensional MCMC
  - 6 cosmo params: Ω_{b0}, Ω_{c0}, h, A, n_s, γ
  - 8 nuisance params: M, α, β, δM, $\sigma_{v\text{-nonlin}}$, σ_{int1}, σ_{int2}, μ_{3int}
  - Priors only needed in h and Ω_{b0}

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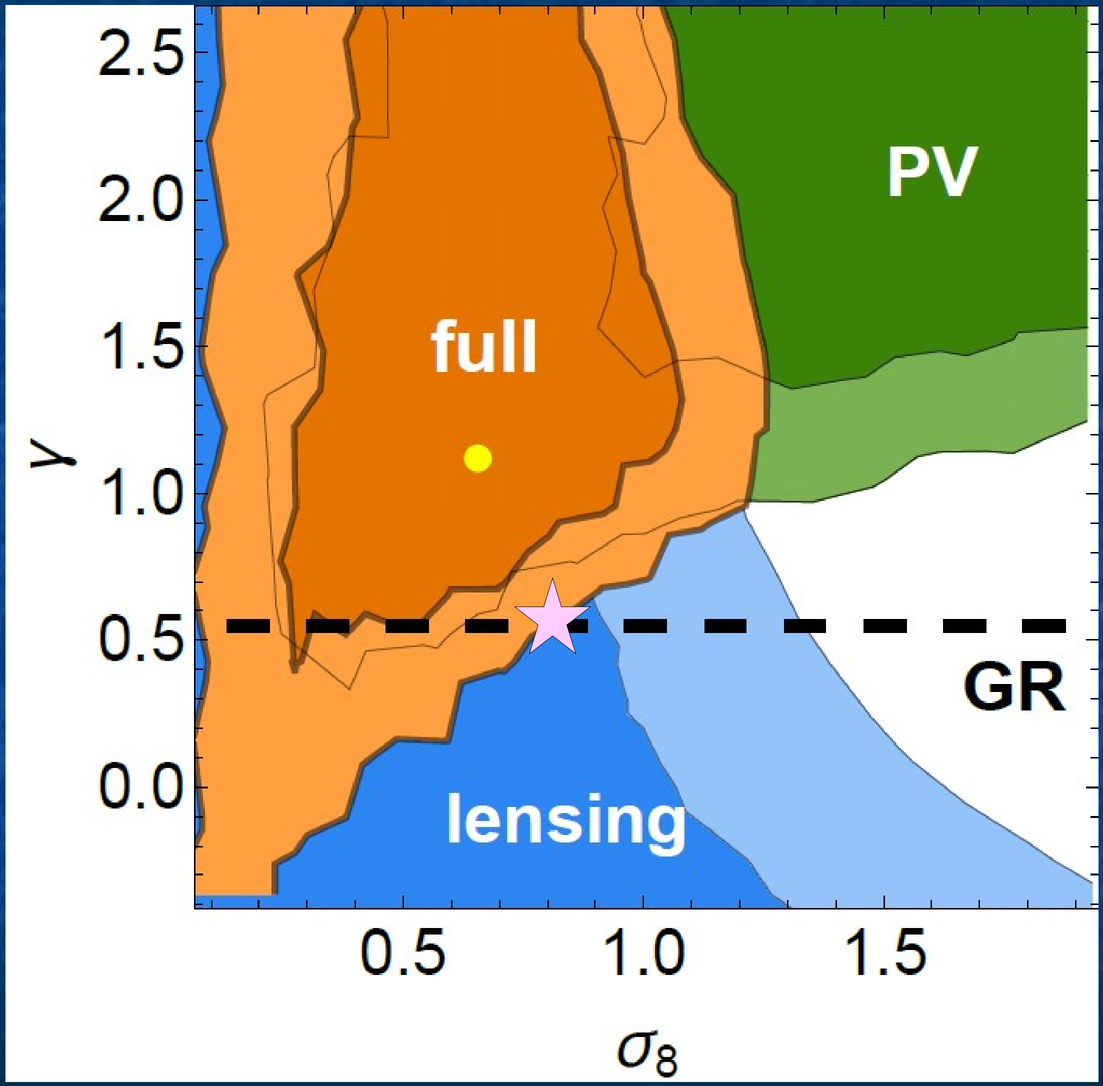

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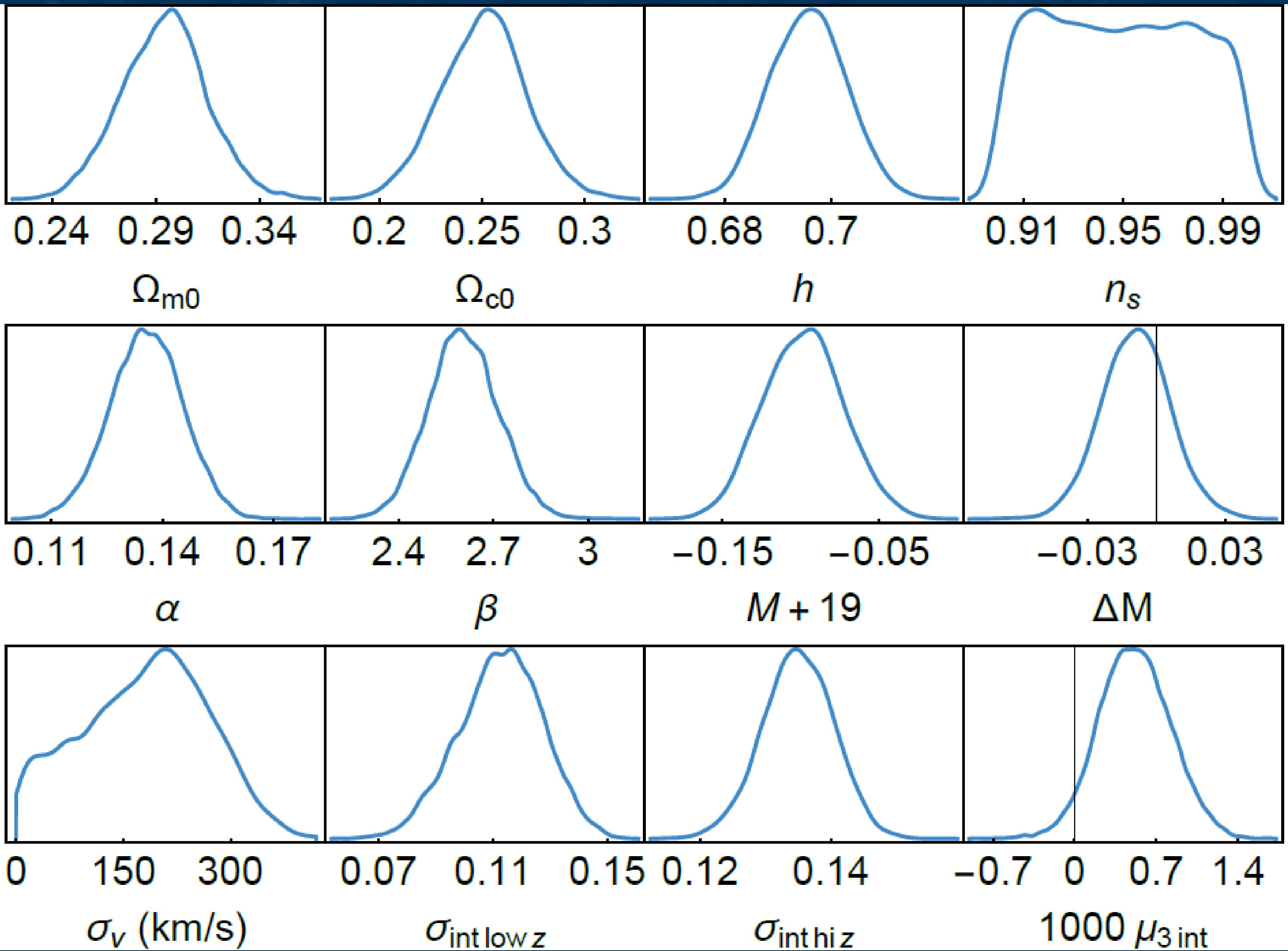
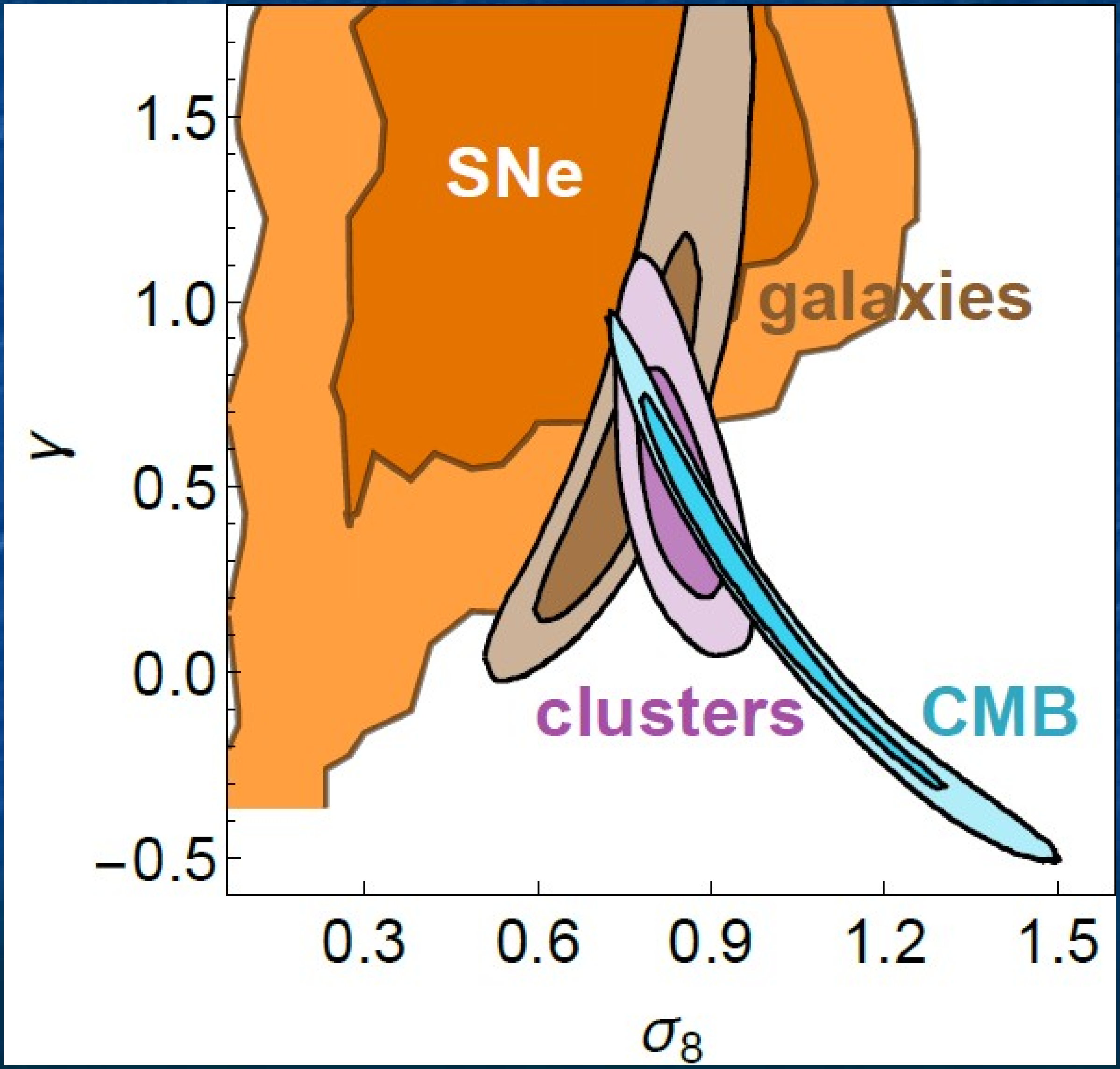


Comparing with other data



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Mantz, von der Linden et al., MNRAS (1407.4516)

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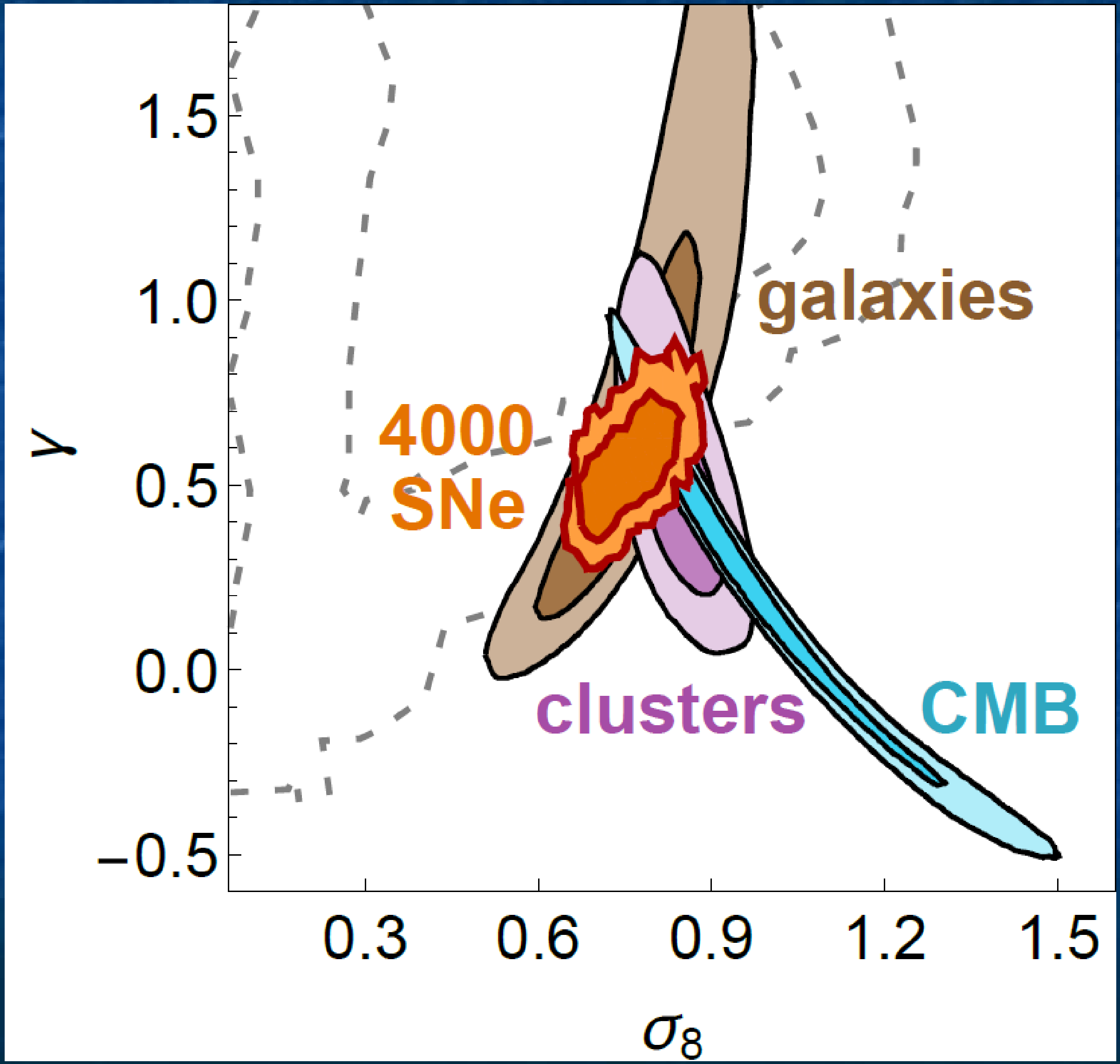

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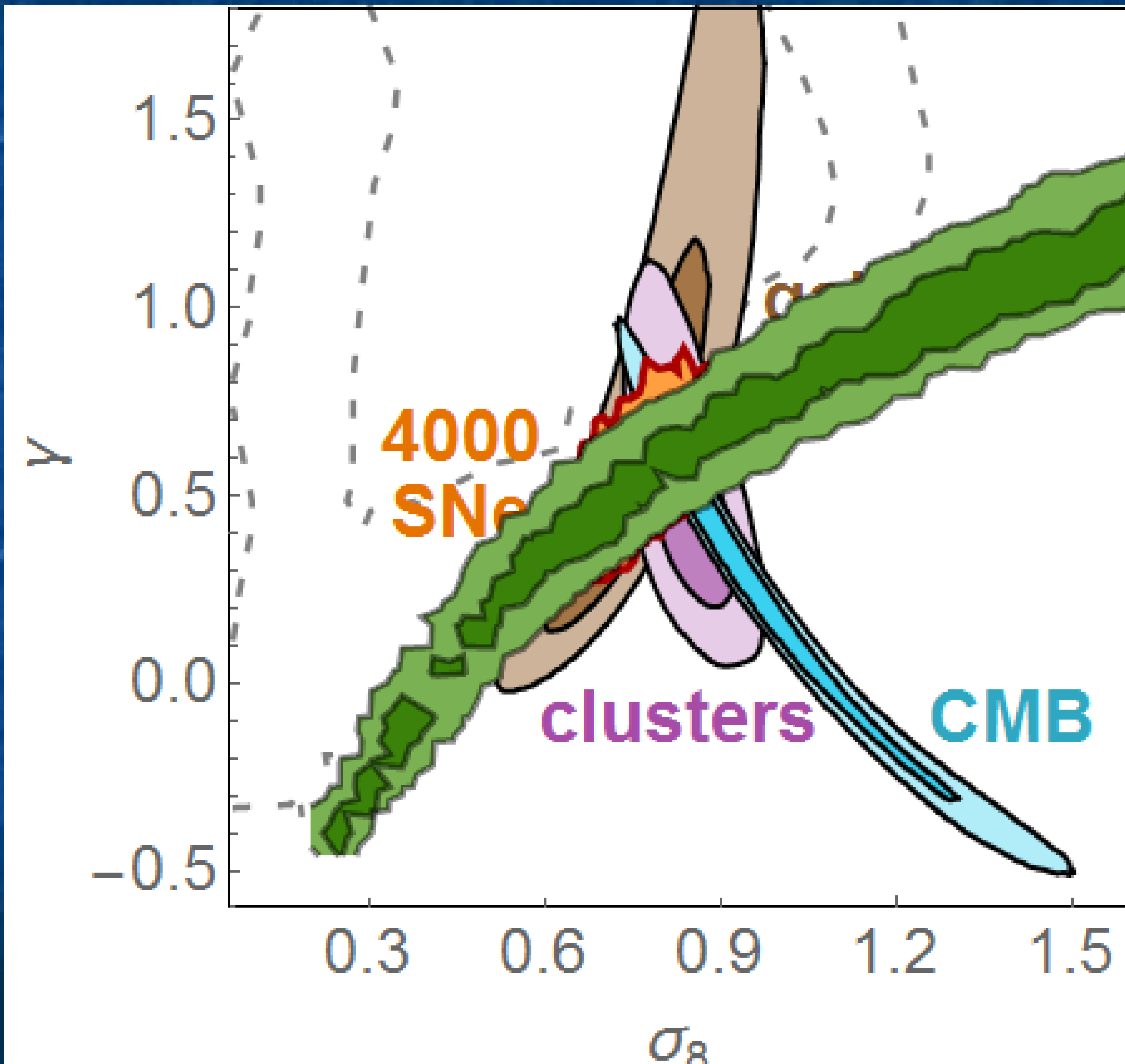

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Conclusions

- Supernova can constrain also perturbation parameters!

- Lensing and pec. vel. very complementary
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  - Pec Vel: $z < 0.15$ → correlations in the Hub. Diag.
  - Good (if not great) precision in the future for σ_8 & γ
    - **If** SNe systematics can be kept under control

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Recycle!