Corfu Tensions in Cosmology – Sep 2022

Reaching precision cosmology faster with velocities

In collaboration with
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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")

    Amendola, Kainulainen, Marra & Quartin (1002.1232, PRL)
    Marra, Quartin & Amendola (1304.7689, PRD)
    Quartin, Marra & Amendola (1307.1155, PRD)
    Macaulay, Davis et al., (1607.03966, MNRAS)
    Castro & Quartin (1403.0293, MNRASL)

  - Peculiar-velocity correlations of SNe ("easy")
  - Both methods work even without cross-correlation with large-scale structure (LSS) surveys

SN Peculiar Velocity

- Lensing mostly affects distant SNe (z > ~0.4
- For z < ~0.4 "Peculiar velocities" (PV) effect becomes relevant
- Crucial point: these velocities are correlated
- Correlations → linear matter power spectrum *Howlett+*
  - We can measure them & infer the power spectrum!
  - Basically parametrized by either $f(z)\,\sigma_8(z)$ or $\gamma\ \sigma_8$

$$f \equiv \frac{d\log\delta_m}{d\log a} \equiv \Omega_m(z)^\gamma$$

T. Castro

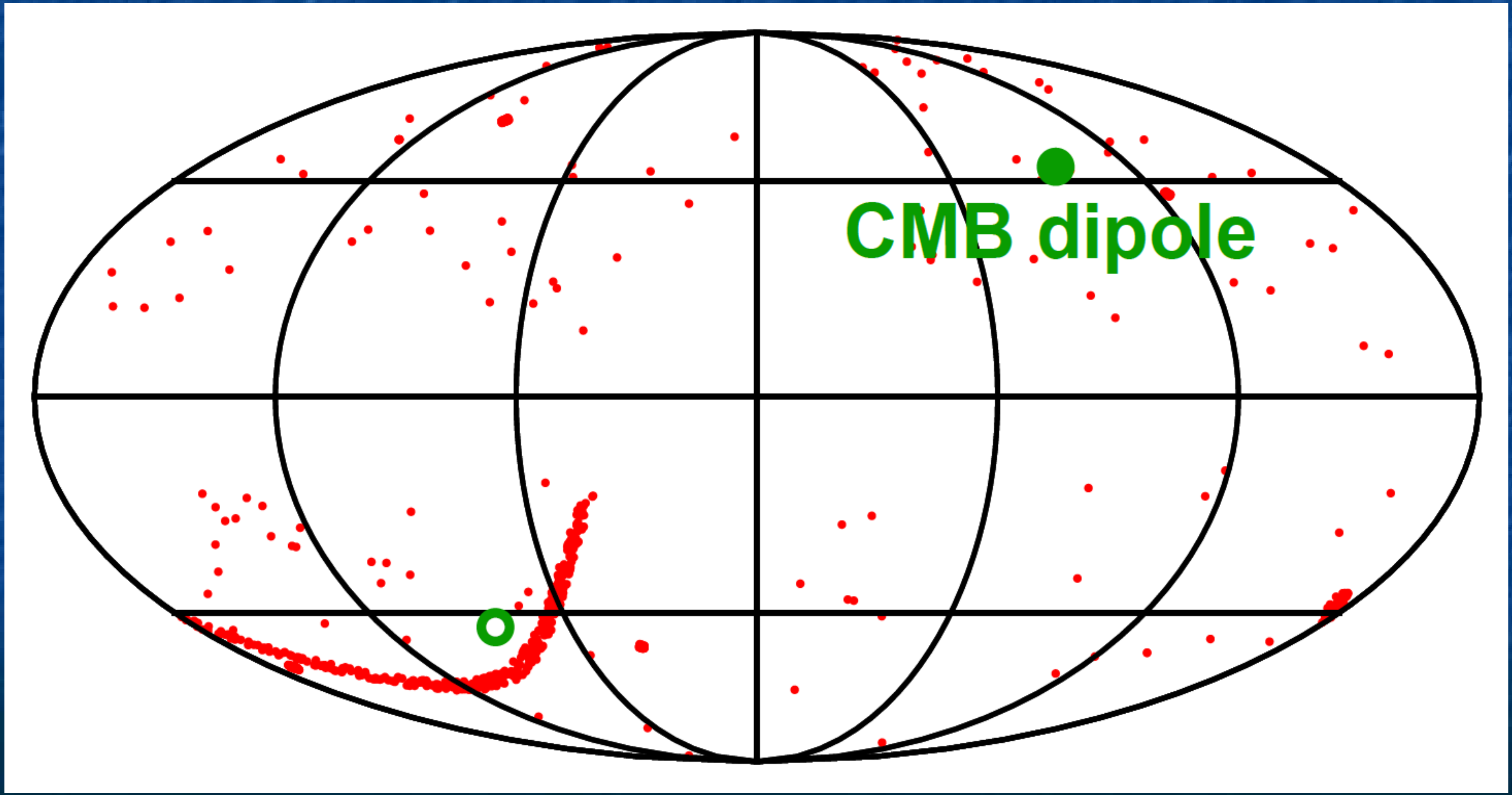
Gordon, Land & Slosar (0705.1718, PRL)

Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)

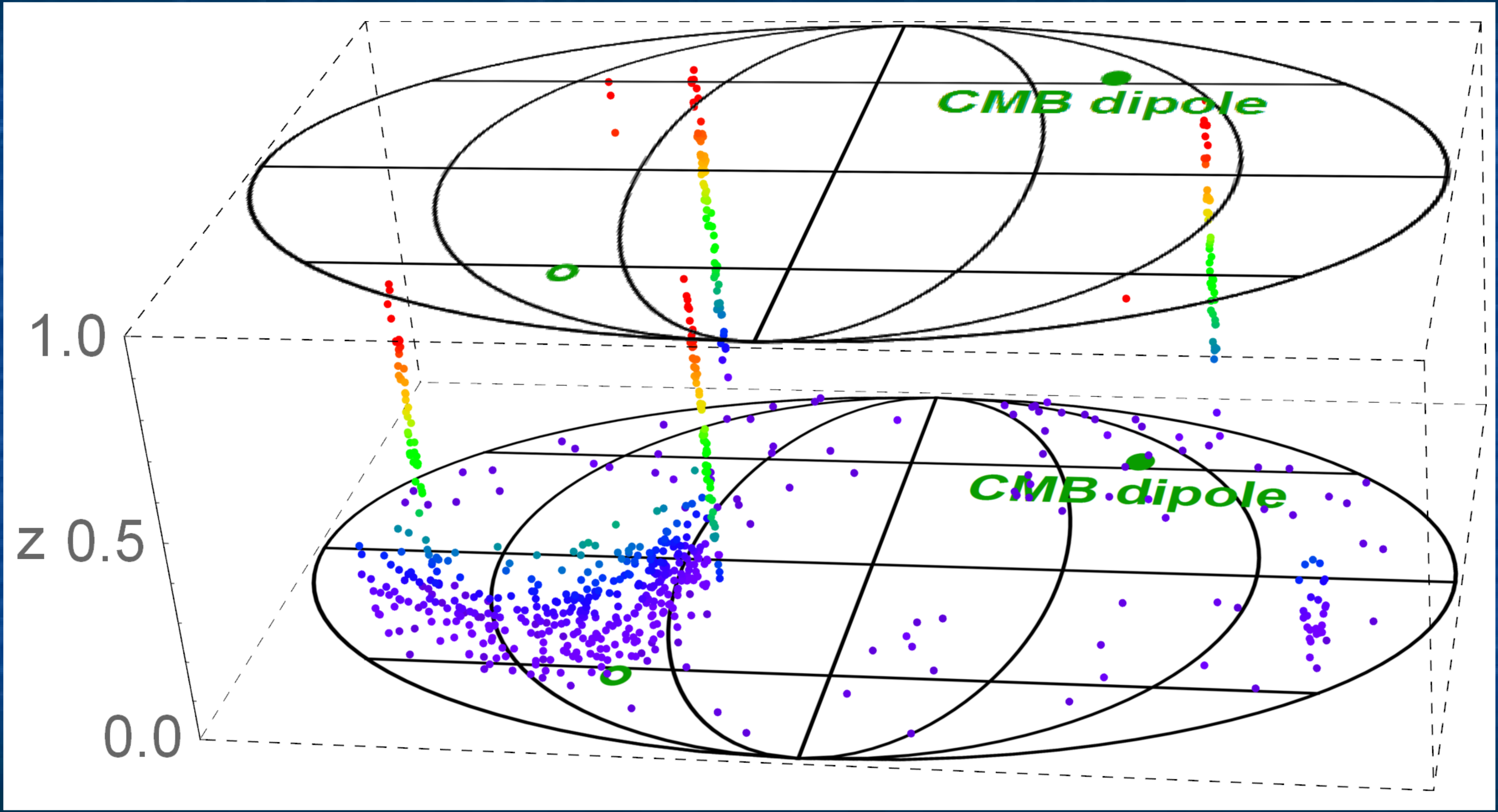
Howlett, Robotham, Lagos, Kim (1708.08236)

JLA supernova distribution

- In galactic coordinates (as cosmologists like)

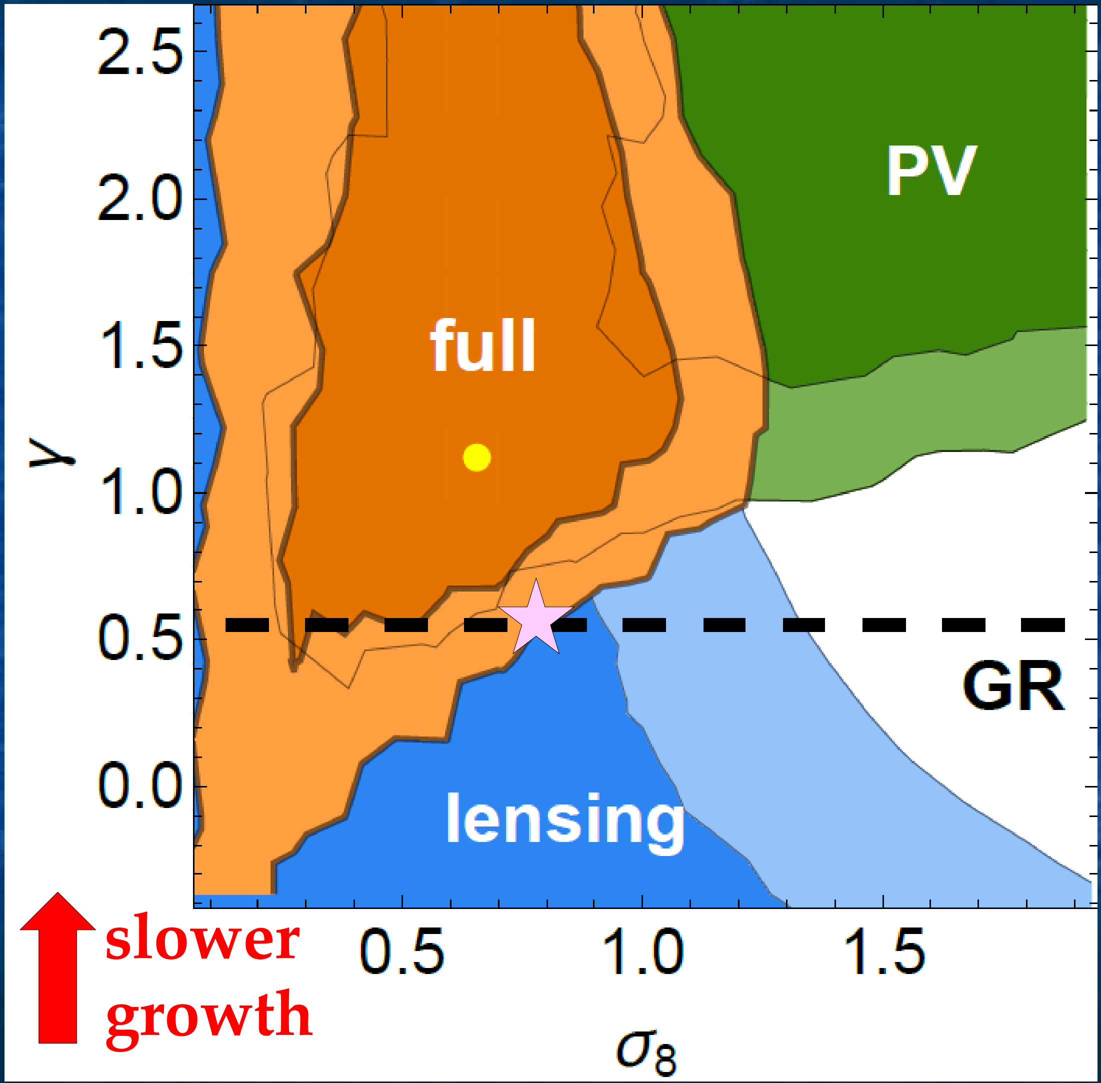


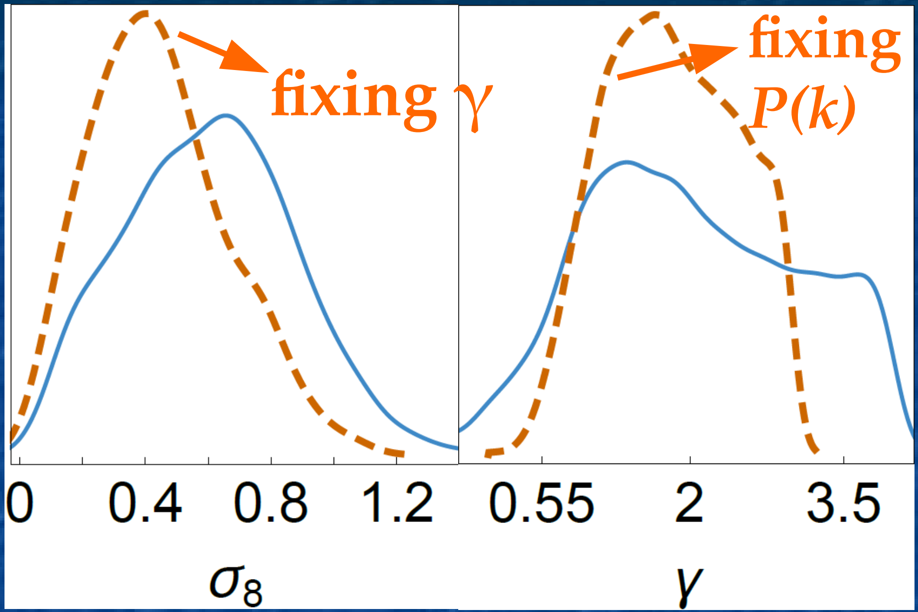
JLA supernova distribution



Castro, Quartin & Benitez (1511.08695)

JLA SN constraints (lens+PV)



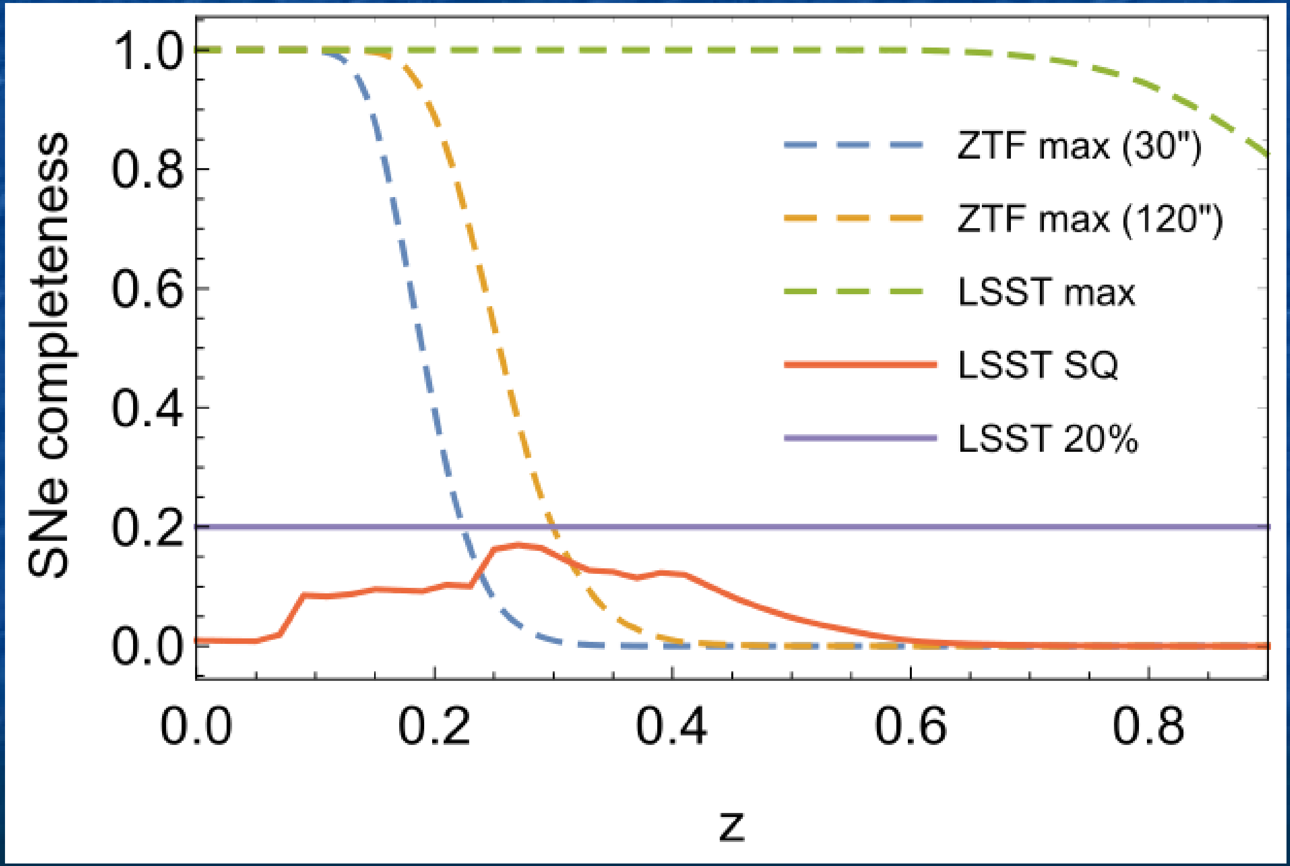


$$f \equiv \frac{d\log\delta_m}{d\log a} \equiv \Omega_m(z)^\gamma$$

Castro, Quartin & Benitez (1511.08695)

SN completeness

- Status Quo of LSST strategy (as of 2019): quality cuts remove most SNe (specially at low-z and hi-z)



K. Garcia

Garcia, Quartin & Siffert (1905.00746, PDU)

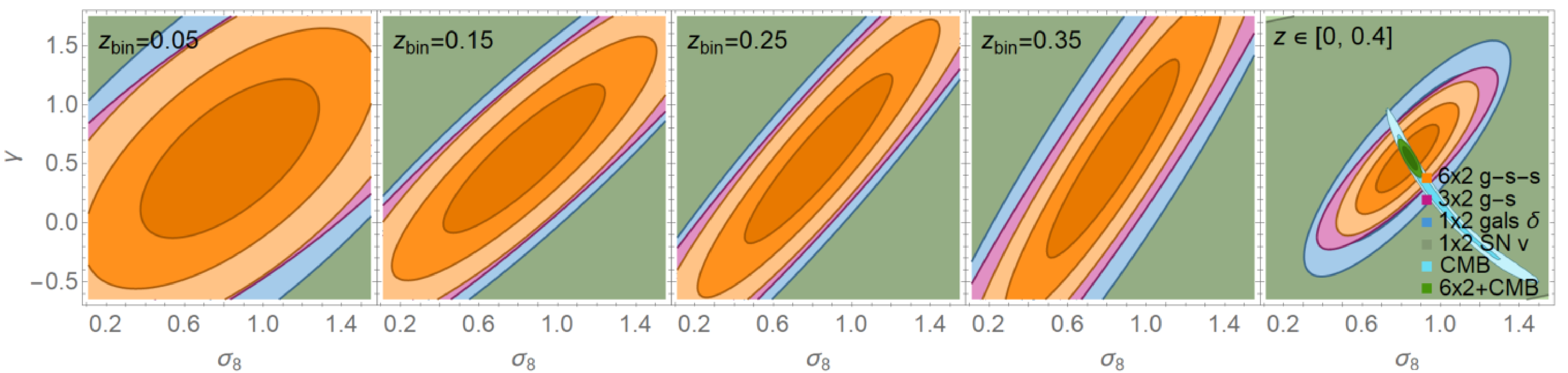
The 6 power spectra

- P_{vv} does not depend on the bias of your tracer
  - Adding $P_{\delta\delta}$ and $P_{\delta v}$ increases the signal and combined they constrain better both the cosmological and bias parameters
    - We refer to the method that uses of all three as: 3×2pt g-s
  - SNe also can trace the density field
    - With LSST we can use both galaxies and SNe to measure δ and use SNe to measure v simultaneously
      - This is the bases of the 6×2pt g-s-s method
    - Let's compare results of 1×2, 3×2 and 6×2pt approaches

Quartin, Amendola & Moraes (2111.05185, MNRAS)

6×2pt vs 3×2pt vs 1×2pt

- Assuming
  - a 4MOST-like spectroscopic survey (7500 deg^2) + LSST SNe detections with 15% completeness ($0 < z < 0.4$)
  - one pair of bias (nuisance) parameters $\{b_g, b_s\}$ per redshift bin
  - 3 global non-linear RSD parameters
- Constraints are orthogonal to those from the CMB!

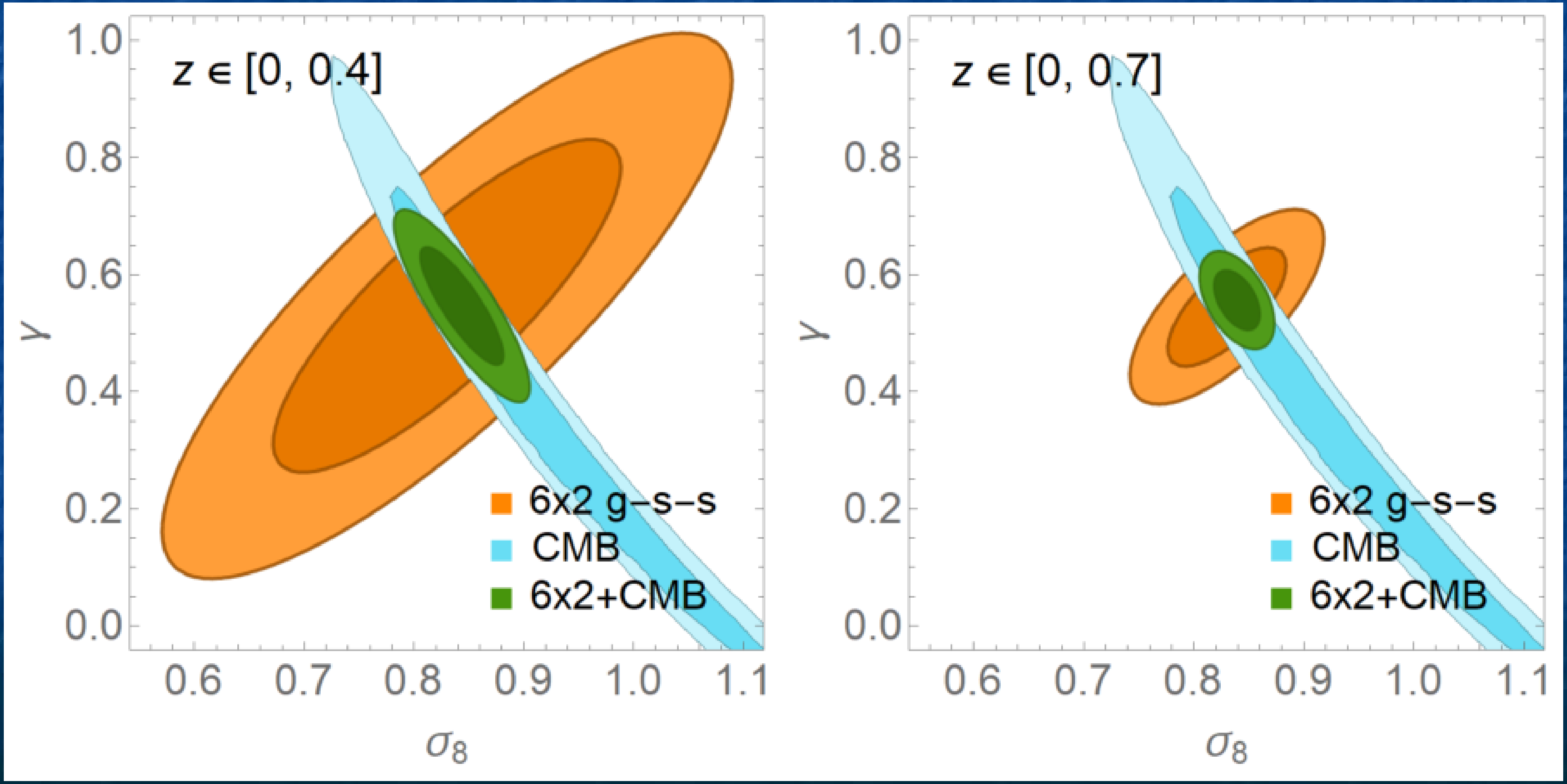


$$f \equiv d\log\delta_m / d\log a \equiv \Omega_m(z)^\gamma$$

Future 6×2pt vs Planck CMB data

- Constraints are orthogonal to those from the CMB!

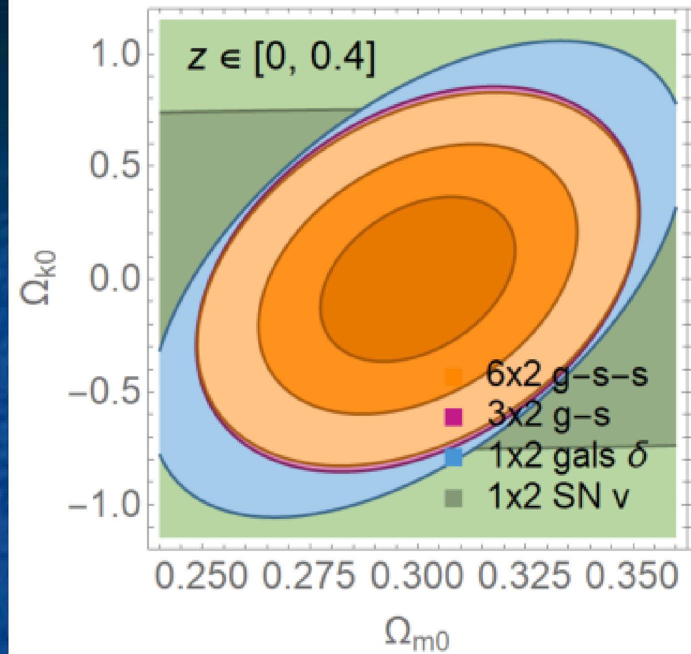
7500 deg^2, 15% SN completeness   15000 deg^2, 30% SN completeness

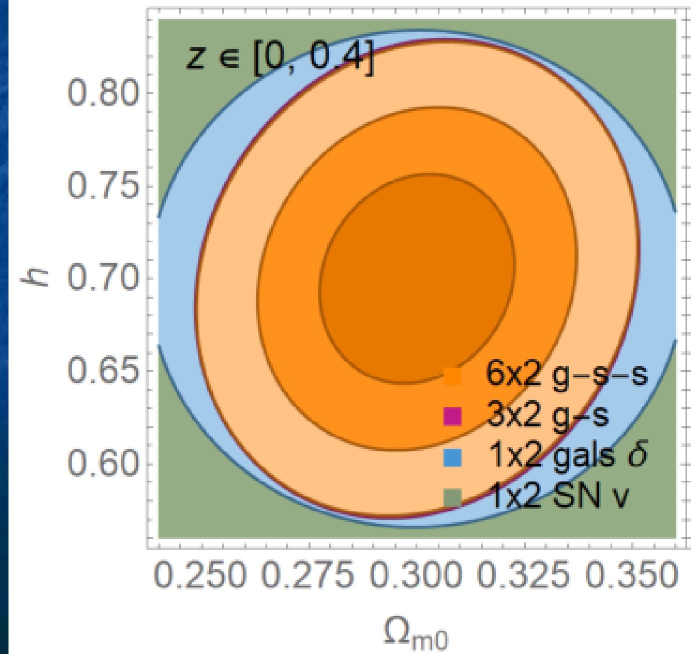


6×2pt constraints

- Results marginalized over all other parameters
  - Similar precision to CMB TTTEEE (no lensing), but very complementary
  - 6×2 + CMB: factor of 5 improvements

1σ uncertainties in:	σ_8	γ	h	Ω_{m0}	Ω_{k0}
Conservative	0.10	0.19	0.037	0.015	0.24
Conservative (no AP)	0.11	0.20	0.070	0.019	0.36
Conservative (flat)	0.10	0.19	0.028	0.014	-
Conser. ($k_{\max} = 0.05$)	0.15	0.28	0.12	0.031	0.39
Conser. ($k_{\max} = 0.15$)	0.091	0.16	0.019	0.010	0.19
CMB ($\star$)	0.11	0.29	0.037	0.064	0.017
Conservative + CMB	0.022	0.058	0.0073	0.010	0.0037





Binary Neutron Star GWs

- Standard sirens measure absolute distance
  - Can also constrain H_0, contrary to SNe alone
- Ligo-Virgo only detected 1 siren so far O1 – O3
  - Many more w/ Einstein Telescope or Cosmic Explorer
- Advanges:
  - No known fundamental intrinsic scatter of sirens
  - Better S/N → better distances → @ low-*z* outperforms SN
  - Less systematics than SNe
- Disadvanges
  - Smaller event rate than SNe
  - Electromagnetic follow-up is resource intensive

V. Alfradique

A. Toubiana

BNS sirens & 6x2pt

- Sirens can measure both H_0 and perturbation parameters to good precision
  - PV improves H_0 precision by ~30%
  - Third gen GW detectors not in the near future

Telescope	t_{exp}^{max}(s)	z_{max}	$f_{20\,deg^2}$	f_{obs}	N_{SS}/yr	F_{time}
Rubin	90	0.49	0.89	0.4	819	0.1
WFST	200	0.27	0.94	0.4	244	0.1
ZTF	3200	0.17	0.98	0.4	78	0.1
Mephisto	140	0.23	0.96	0.4	157	0.1

1σ uncertainties in:	σ_8	γ	H_0	Ω_{m0}	Ω_{k0}
Low z ($0 \leq z \leq 0.5$)					
DESI BGS gg	0.081	0.165	2.1	0.0095	0.171
Rubin 3×2pt g–k	0.079	0.137	2.1	0.0094	0.168
Rubin 6×2pt g–k–k	0.070	0.129	2.1	0.0093	0.167
Rubin BNS distances	-	-	0.12	0.24	0.41
Rubin BNS dist + 6×2pt	0.069	0.128	0.085	0.0063	0.018

Alfradique, Quartin, Amendola, Castro & Toubiana (2111.05185)

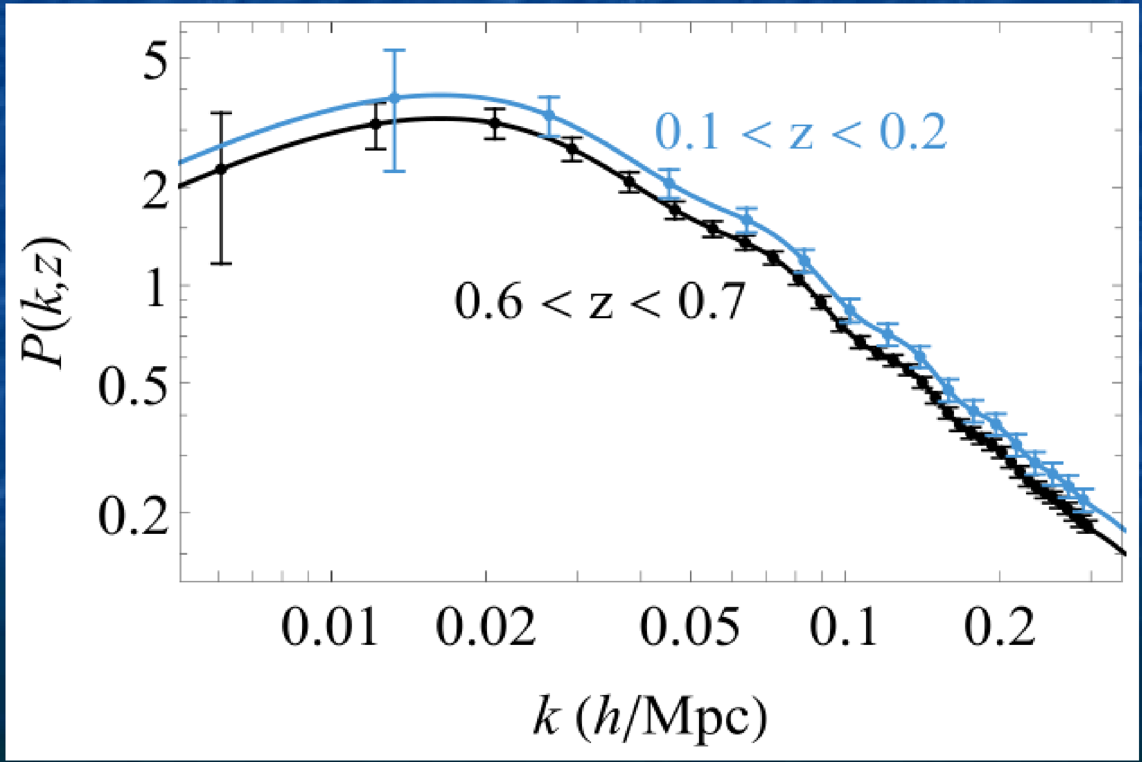
Model-independent clustering

- The most common way of using "full shape" $P(k)$ measurements is to assume a given parametrization
  - Both background and perturbation parameters
- Alcock-Paczynski (AP) + Kaiser effects (RSD), allow model-independent constraints
- In particular, it is possible to constrain $E(z) = H(z)/H_0$
  - Only a few model-independent observables of $H(z)$
    - Radial BAO measures $H\, r_S$ → subject to understanding of r_S: the sound horizon at the drag epoch
    - Redshift-drift → needs lots of time in Extremely Large Telescopes *(Liske+ 0802.1532, Quartin & Amendola 0909.4954)*
    - Cosmic Chronometers → rely on astrophysical modeling of passive galaxies & pop synthesis simulations *(Liu+ 1509.08046)*

Model-independent clustering

- The Clustering of Standard Candles method: combines SN velocities and SN clustering
  - Good precision in both model-indep and model-dep cases
  - Also model-indep measurements of *P(k,z)* and *β(k,z)*

$z_{\rm bin}$	LSST 20% $10^3 \cdot n_{\rm SN}$ $({\rm h/Mpc})^3$	$\Delta H/H$ (%)
0.05	0.064	13.2
0.15	0.07	8.9
0.25	0.076	7.6
0.35	0.081	6.9
0.45	0.087	6.3
0.55	0.093	5.8
0.65	0.099	5.4



Amendola & Quartin (1912.10255)

Limits of the method?

- SYSTEMATICS?
- Like in standard full-shape $P(k)$ measurements, precision increases fast with higher k_{MAX}
  - To which scales can we get while maintaining accuracy?
- Big effort in the cosmology community to develop solid mildly non-linear theory (0.05 – 0.4 h/Mpc)
  - EFT of LSS → counter-terms, higher-order bias, etc.
  - Velocities help measuring bias parameters → may increase robustness
- Model-independent method remains precise when including 1-loop EFT nuisance parameters

Challenges for PV

- Peculiar velocity tracers exist mostly in high density regions
  - Velocity and density tracers become correlated
  - What we observed is momentum (product of density and velocity)
    - *Howlett 1906.02875*

$$\boldsymbol{p}(\boldsymbol{r}) = \big(1 + \delta(\boldsymbol{r})\big)\boldsymbol{v}(\boldsymbol{r})$$

$$\begin{aligned}(2\pi)^3\delta^D(\boldsymbol{k}-\boldsymbol{k}')P^p(\boldsymbol{k}) &= \langle (1+\delta_g(\boldsymbol{k}))u(\boldsymbol{k})(1+\delta_g(\boldsymbol{k}'))u(\boldsymbol{k}')\rangle \\ &= \langle u(\boldsymbol{k})u(\boldsymbol{k}')\rangle + \langle u(\boldsymbol{k})\delta_g(\boldsymbol{k}')u(\boldsymbol{k}')\rangle + \langle \delta_g(\boldsymbol{k})u(\boldsymbol{k})u(\boldsymbol{k}')\rangle + \langle \delta_g(\boldsymbol{k})u(\boldsymbol{k})\delta_g(\boldsymbol{k}')u(\boldsymbol{k}')\rangle\end{aligned}$$

  - This introduces non-linearities at scales of $k > \sim 0.1$ h/Mpc

- Like for density surveys, in practice the observing window function needs to be well modelled
  - FKP-like or Yamamoto-like estimators required
    - *Feldman, Kaiser & Peacock 1994; Yamamoto 2006*

Conclusions

- SNe & sirens can constrain also perturbation parameters!
- Lensing and peculiar velocities very complementary
  - Lensing: $z > 0.4$ → non-Gaussianity in the Hubble Diag.
  - Pec. Vel.: $z < 0.5$ → correlations in the Hubble Diag.
  - Measure density & velocity possible with only SN: $P_{\delta\delta}$, $P_{\delta v}$, P_{vv}
  - It gets even better when combining with galaxies → 6×2pt
- Very good precision with LSST for σ_8 & γ
  - It is a new observable & a nice cross-check of ΛCDM
- SNe PV & weak-lensing traditionally considered noise
  - Don't throw away the noise… Recycle!

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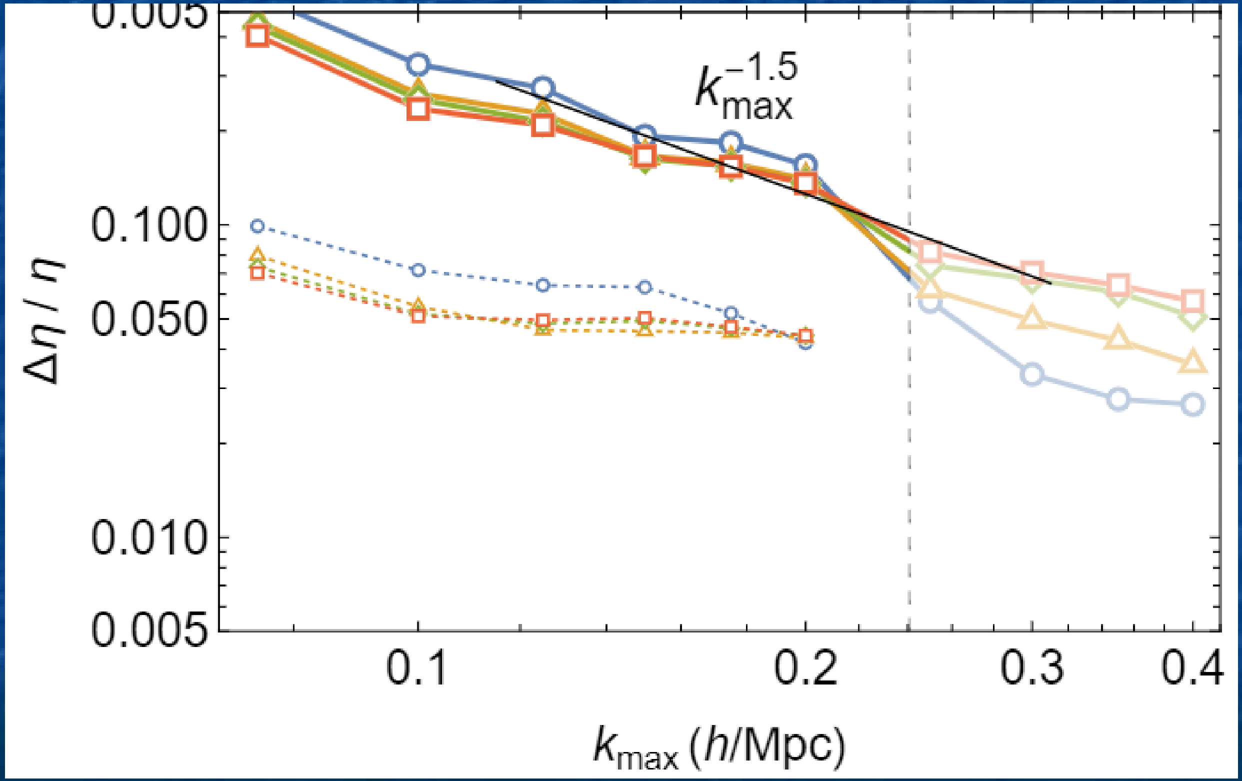
Ευχαριστώ!

Extra Slides

1-loop Model-Independent Forecasts

- Full lines → 1-loop with uninformative priors
- Dashed lines → linear $P(k)$



Amendola, Pietroni & Quartin (2205.00569)

Power spectra

$$v \equiv \boldsymbol{v}\cdot\hat{\boldsymbol{r}}$$

$$\beta \equiv f/b$$

$$\mu \equiv \hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{r}}$$

- There are 6 spectra of interest and 2 bias functions $b(z)$

$$P_{\rm gg}(k,\mu,z) = \left[1+\beta_{\rm g}\mu^2\right]^2 b_{\rm g}^2\, S_{\rm g}^2\, D_+^2 P_{\rm mm}(k) + \frac{1}{n_{\rm g}}$$

$$P_{\rm ss}(k,\mu,z) = \left[1+\beta_{\rm s}\mu^2\right]^2 b_{\rm s}^2\, S_{\rm s}^2\, D_+^2 P_{\rm mm}(k) + \frac{1}{n_{\rm s}}$$

$$P_{\rm gs}(k,\mu,z) = \left[1+\beta_{\rm g}\mu^2\right]\left[1+\beta_{\rm s}\mu^2\right] b_{\rm g}\, b_{\rm s}\, S_{\rm g}\, S_{\rm s}\, D_+^2 P_{\rm mm}(k) + \frac{n_{\rm gs}}{n_{\rm g} n_{\rm s}}$$

$$P_{\rm gv}(k,\mu,z) = \frac{H\mu}{k(1+z)}\left[1+\beta_{\rm g}\mu^2\right] b_{\rm g}\, S_{\rm g}\, S_{\rm v}\, f D_+^2 P_{\rm mm}(k)$$

$$P_{\rm sv}(k,\mu,z) = \frac{H\mu}{k(1+z)}\left[1+\beta_{\rm s}\mu^2\right] b_{\rm s}\, S_{\rm s}\, S_{\rm v}\, f D_+^2 P_{\rm mm}(k)$$

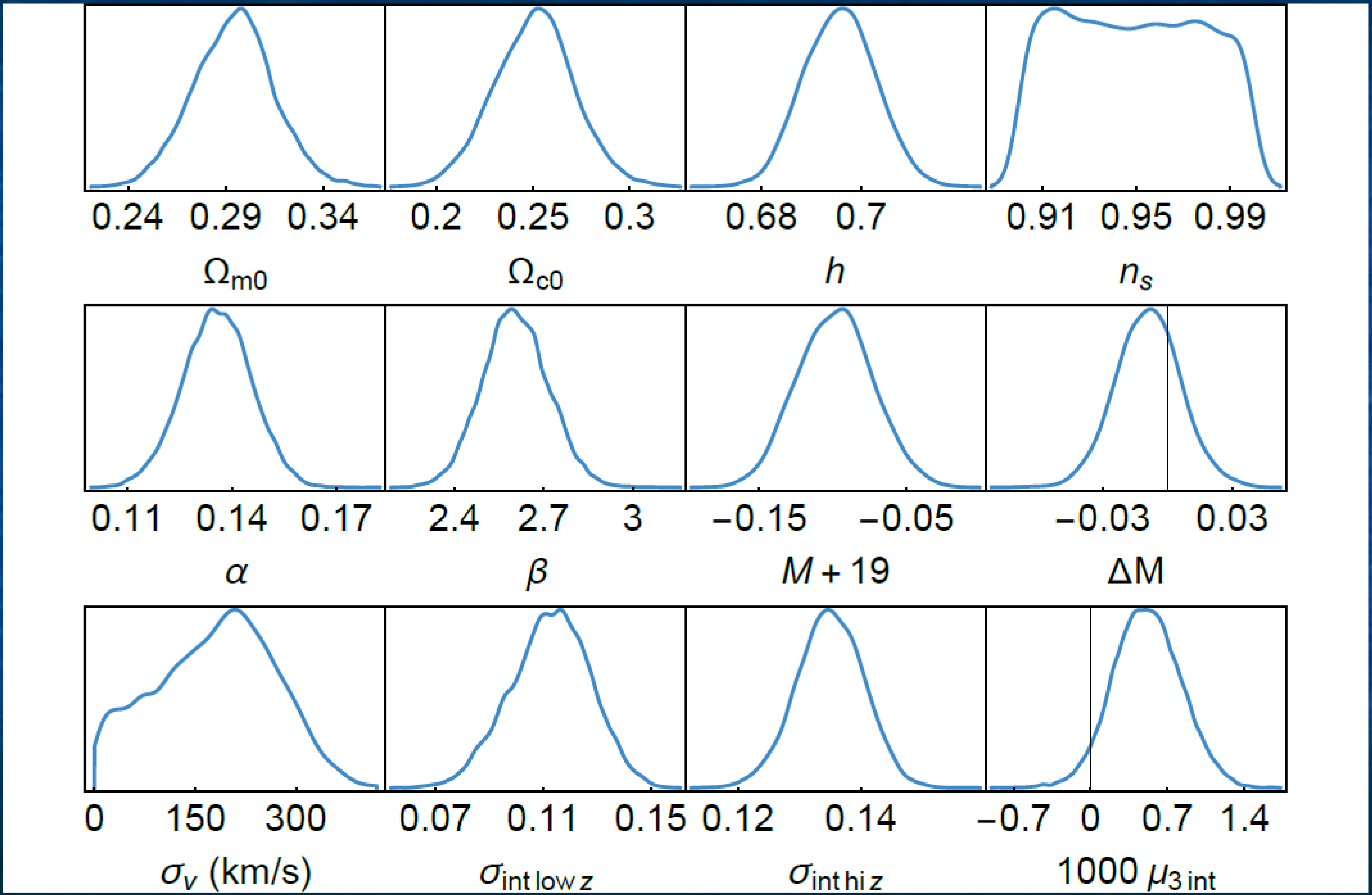
$$P_{\rm vv}(k,\mu,z) = \left[\frac{H\mu}{k(1+z)}\right]^2 S_{\rm v}^2\, f^2\, D_+^2 P_{\rm mm}(k) + \frac{\sigma_{v,\rm eff}^2}{n_{\rm s}}$$

JLA SN constraints (lens+PV)

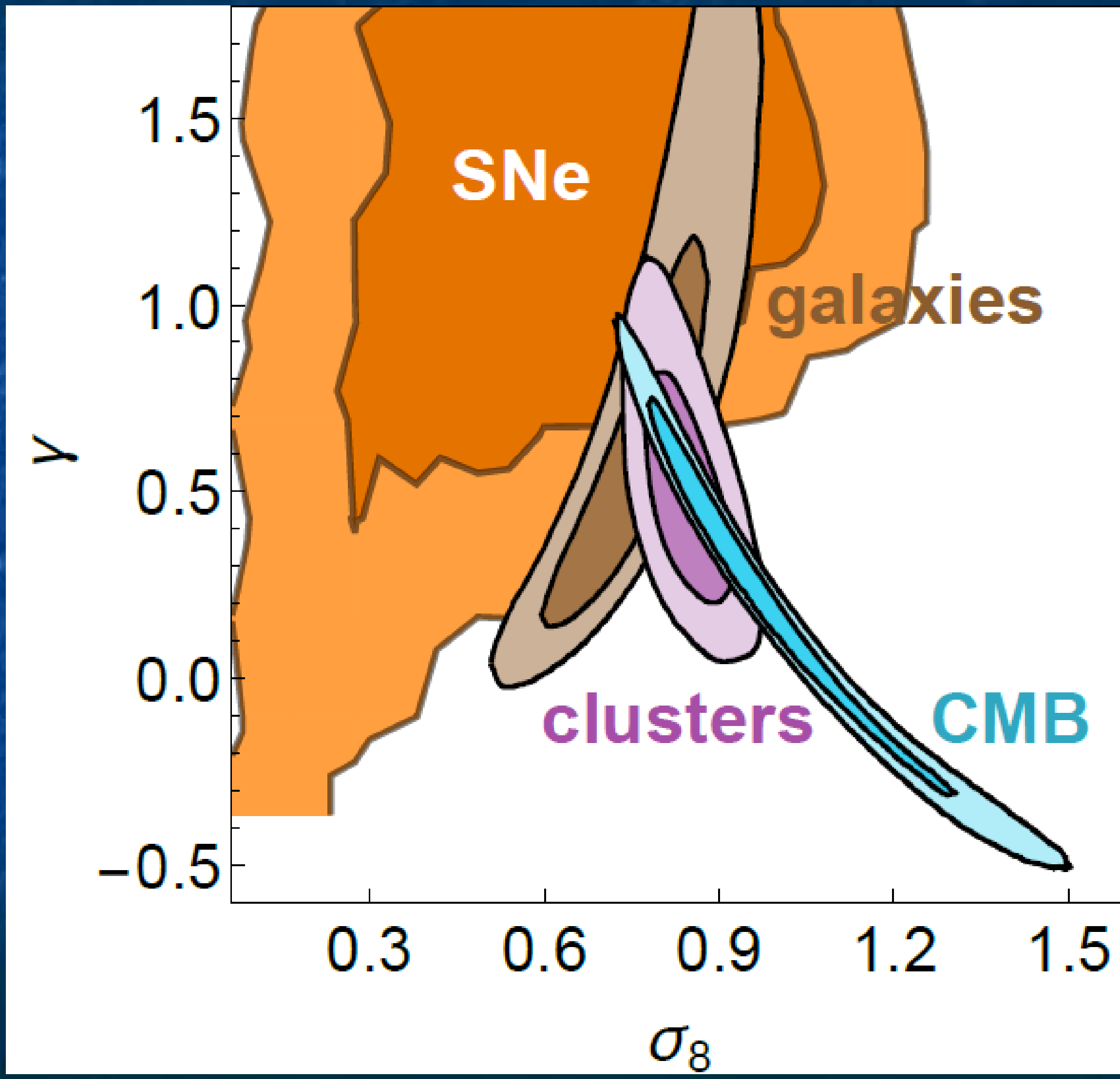
- These correlations are all linear – we can model them and infer properties of the matter power spectrum
  - Problem: JLA removed (by modelling) the PV correlations – it was noise to them
- We analyzed JLA with a 14-dimensional MCMC
  - 6 cosmo params: Ω_{b0}, Ω_{c0}, h, A, n_s, γ
  - 8 nuisance params: M, α, β, ΔM, $\sigma_{\text{v-nonlin}}$, σ_{int1}, σ_{int2}, μ_{3int}
  - Priors only needed in h, n_s and Ω_{b0}

$$L_{PV} \propto \frac{1}{\sqrt{|C^{PV}|}} \exp\left[-\frac{1}{2}\delta_{DM}^T (C^{PV})^{-1} \delta_{DM}\right] \qquad \delta_{DM} \equiv DM - DM_{\text{fid}}$$

JLA SN constraints (lens+PV)



Comparing with other data

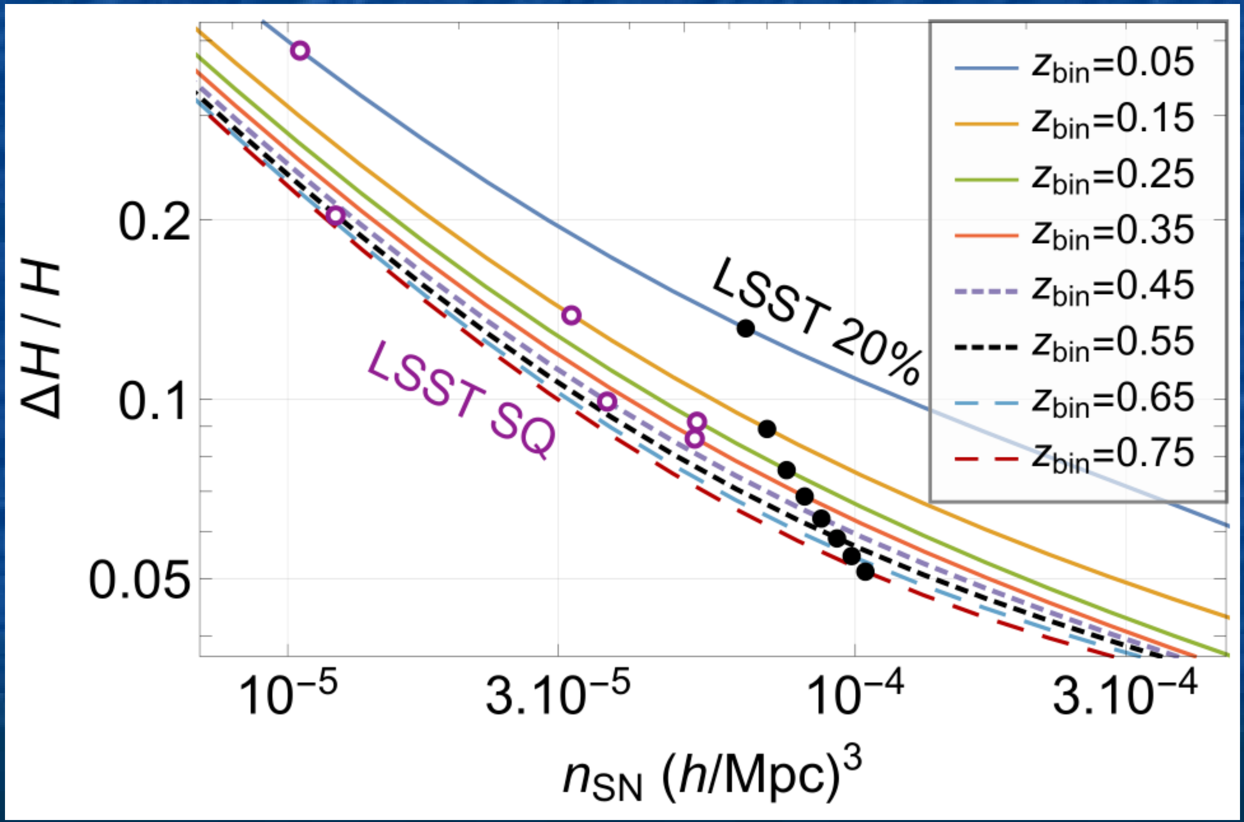


Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)

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

Information scaling with n_{SN}

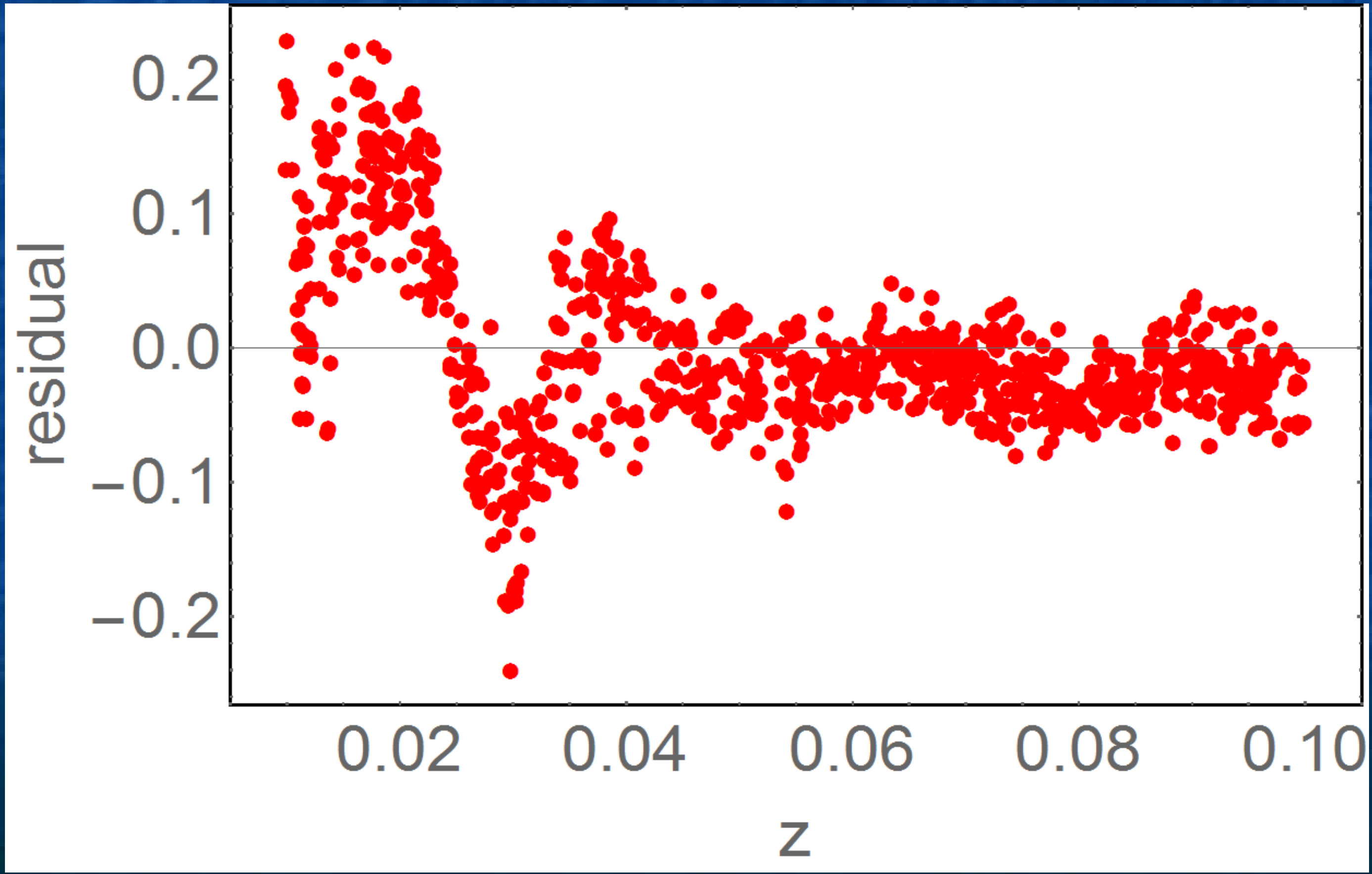
- FM shows how the $P_{\delta\delta}$ and P_{vv} information scales with the number density of SN → still far from the CV limit!



Amendola & Quartin (1912.10255)

Hubble Diagram residual with 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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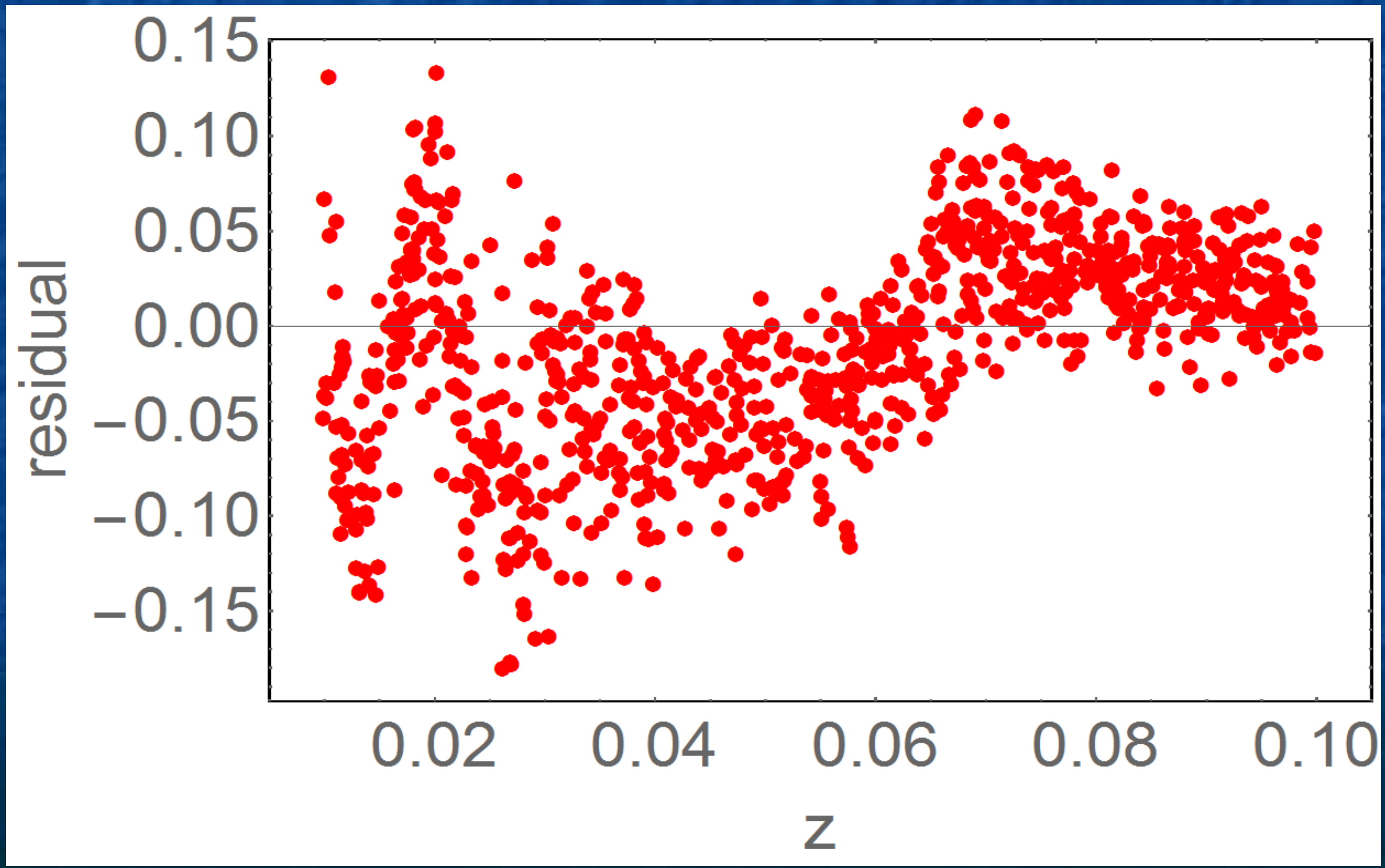

Hubble Diagram residual with PV's

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