Reuven Opher Workshop on
Challenges of New Physics in Space – ICTP-SAIFR – 2021

Reaching precision cosmology faster with velocities

In collaboration with
L. Amendola, T. Castro, K. Garcia, B. Moraes, B. Siffert

Miguel Quartin
Univ. Fed. Rio de Janeiro
Univ. Heidelberg
http://arcos.if.ufrj.br/

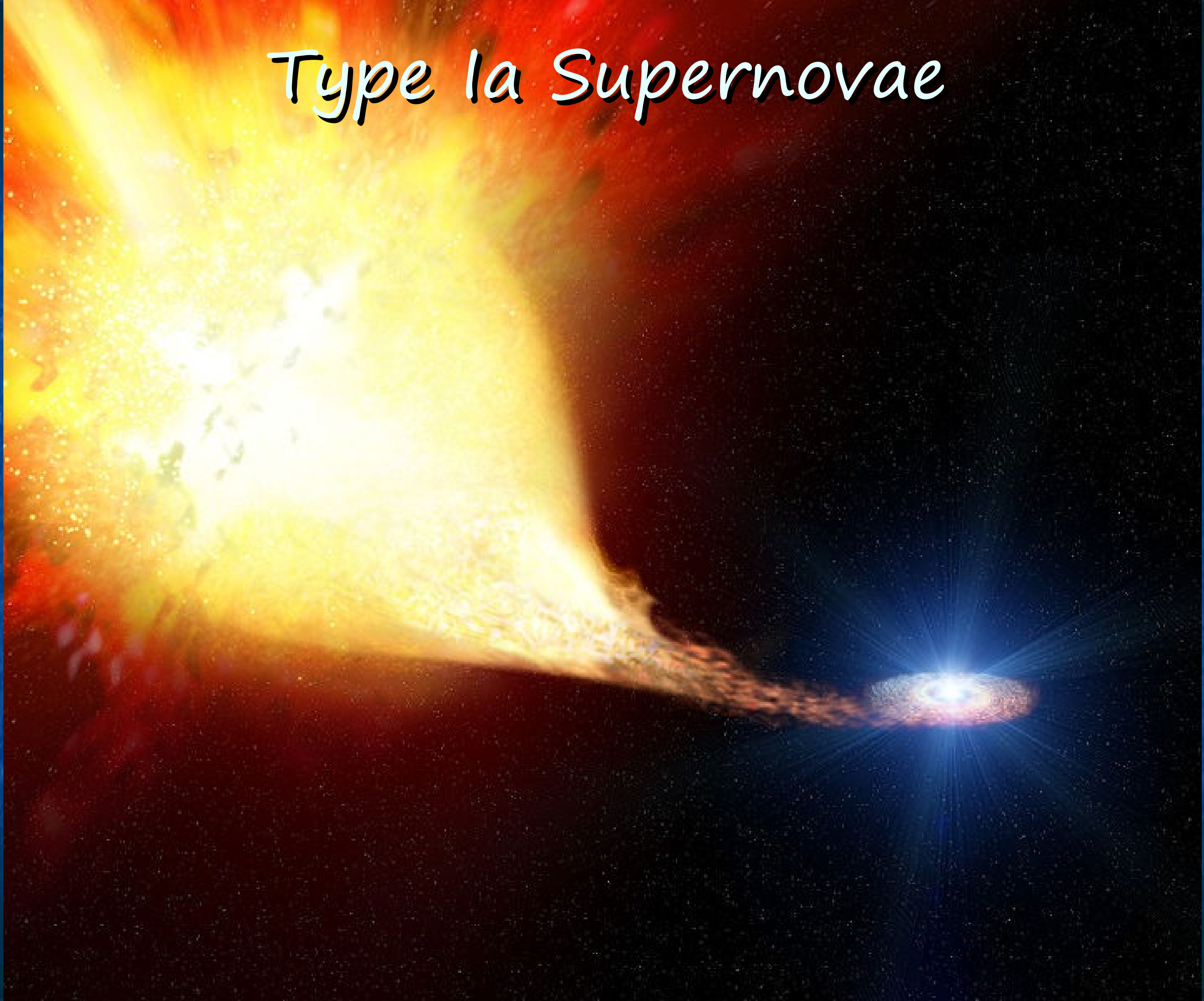
Distances in Cosmology

- 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 Milky Way → stellar parallax
  - Requires precise astrometry.
  - Maximum distance measurable: ~10 kpc by the Gaia satellite (2014 – 2021+)
  - Compare with: Milky Way (~15 kpc radius)
- Nearby galaxies
  - Detached Eclipsing Binaries → %-level distance to LMC
    - Can we extend it to Andromeda (~800 kpc)?
  - Cepheid variables

Standard Candles

- A plot of distance vs. z is called a Hubble Diagram
- To measure distances at $z_{\mathrm{cosmo}} >\sim 10^{-5}$ (~0.04 Mpc) we need good standard candles (known intrinsic luminosity) or good standard rulers (known intrinsic size)
- There are 2 classic standard (rigorously, *standardizible*) candles in cosmology:
  - Cepheid variable stars ($0 < z < 0.01$)
  - Binary Neutron Stars ($0 < z < 0.04$) *[with LIGO-Virgo O4]*
  - Type Ia Supernovae ($0 < z < 2$)
- Cepheids & SNe Ia have intrinsic variability, but empirical relations allow us to calibrate and *standardize* them

Type Ia Supernovae



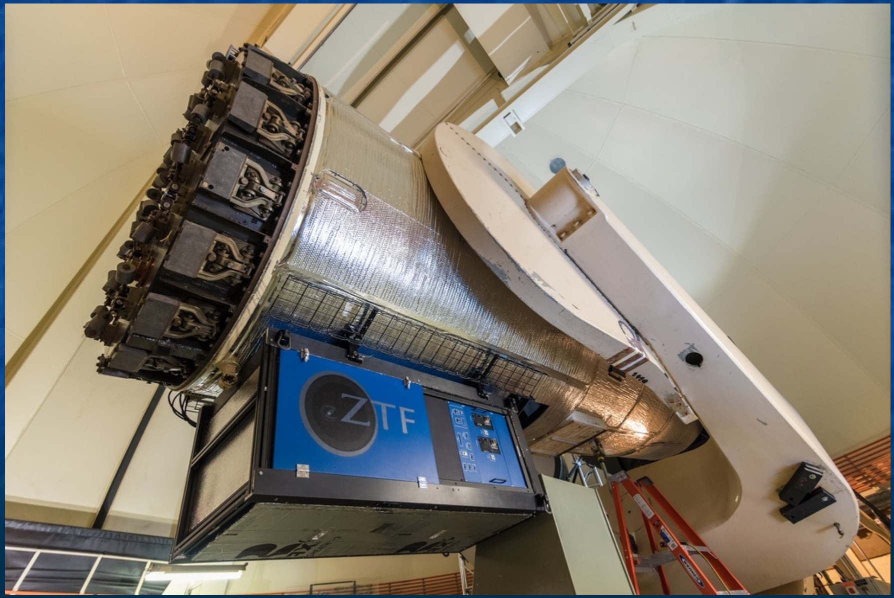
Type Ia Supernovae

- SNe Ia are so far the only proven hi-z 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 ($N_{SNe} \sim 2000$)
  - In the next ~10 years → statistics will increase by 100× (mostly due to the LSST survey – but also from ZTF)
    - Huge effort to improve understanding of systematics

Howell, 1011.0441 (review of SNe)

Upcoming SNe surveys

- LSST: ~100x more SNe than current catalogs
- But for low-z SNe (useful for PVs) the Palomar Zwicky Transient Facility (ZTF) is also very promising!
    - 1.2m Schmidt telescope
    - 47 square deg FOV!



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

SN Peculiar Velocity

- Lensing only affects distant SNe ($z > \sim 0.4$)

- At lower redshift ($z < \sim 0.4$) another effect becomes relevant
  - "Peculiar velocities" (PV) in cosmology refers to velocities outside of the "Hubble flow" (i.e., expansion)
  - Typical PV @ $z = 0$ → ~600 km/s ($v / c \sim 0.002$)
    - "extra blue/redshift"
  - 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

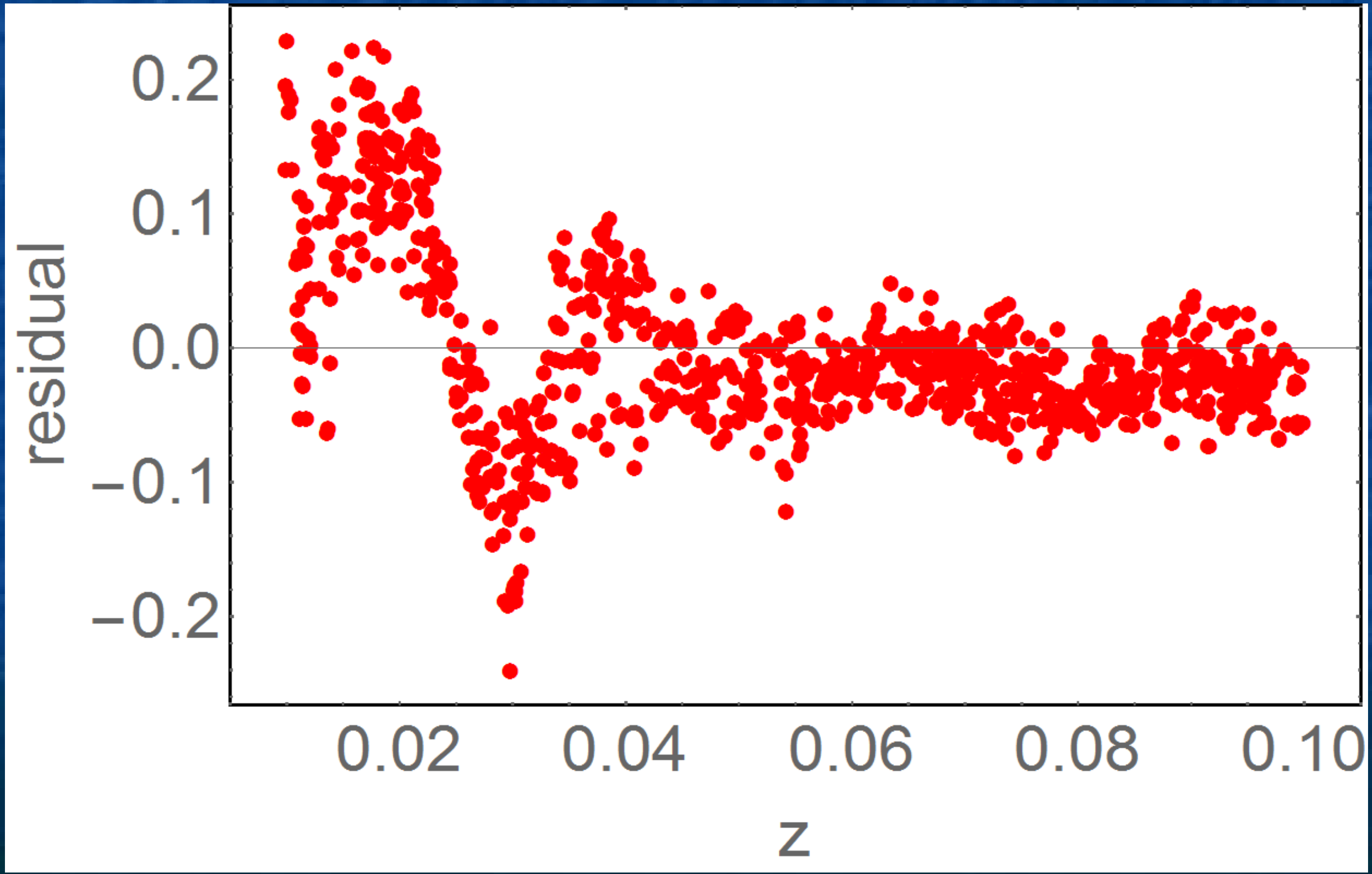
- SNe that are “close” to each other → peculiar velocity correlations!
- Part of the SNe Hubble residual due to their PV
- The 2-point correlation function relate velocities of SNe which are close to each other
  - If one is receding, the other is probably receding too → angular correlations in magnitude (proportionally to σ_8)

Gordon, Land & Slosar (0705.1718, PRL)

Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)

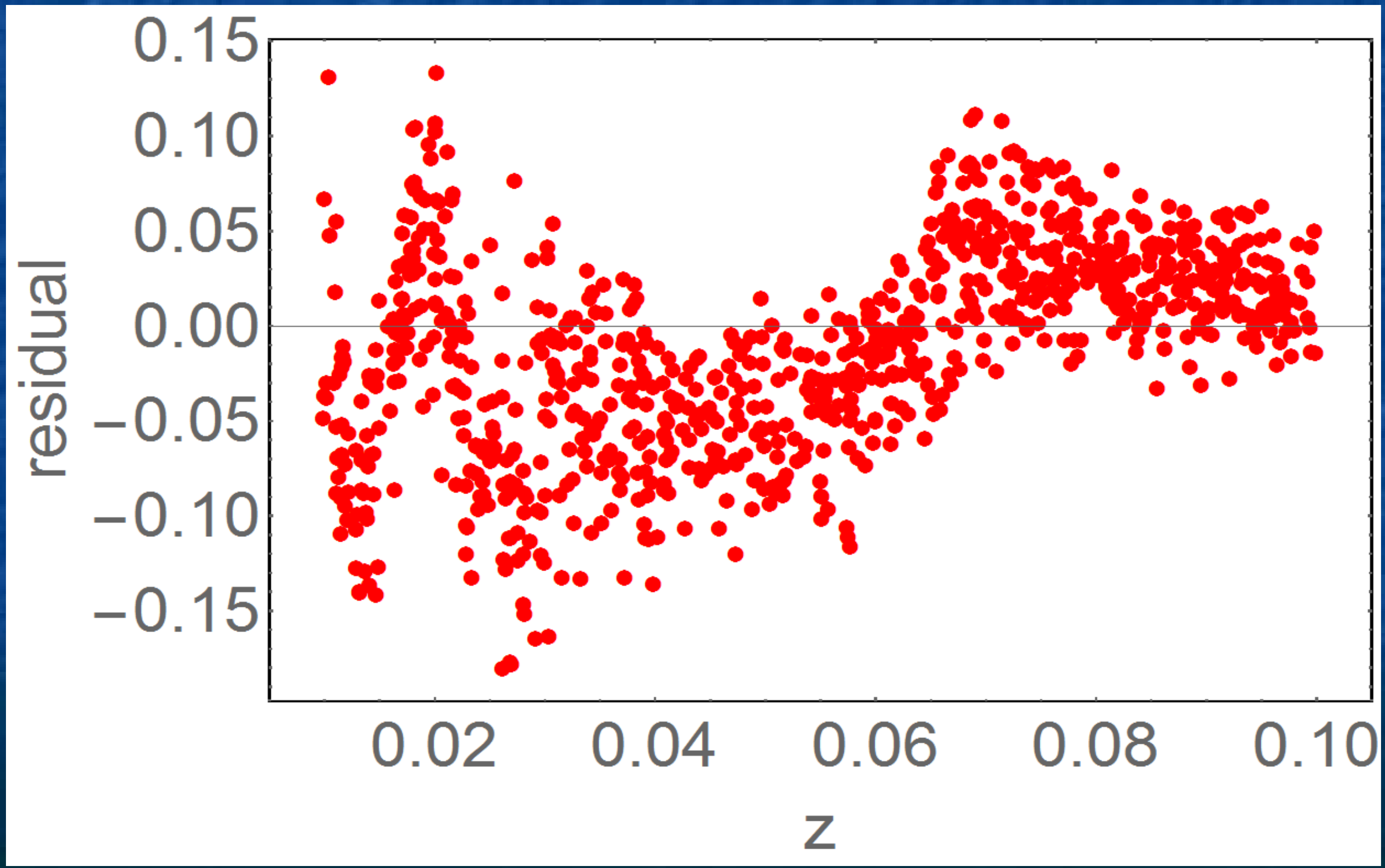
Hubble Diagram with PV's

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



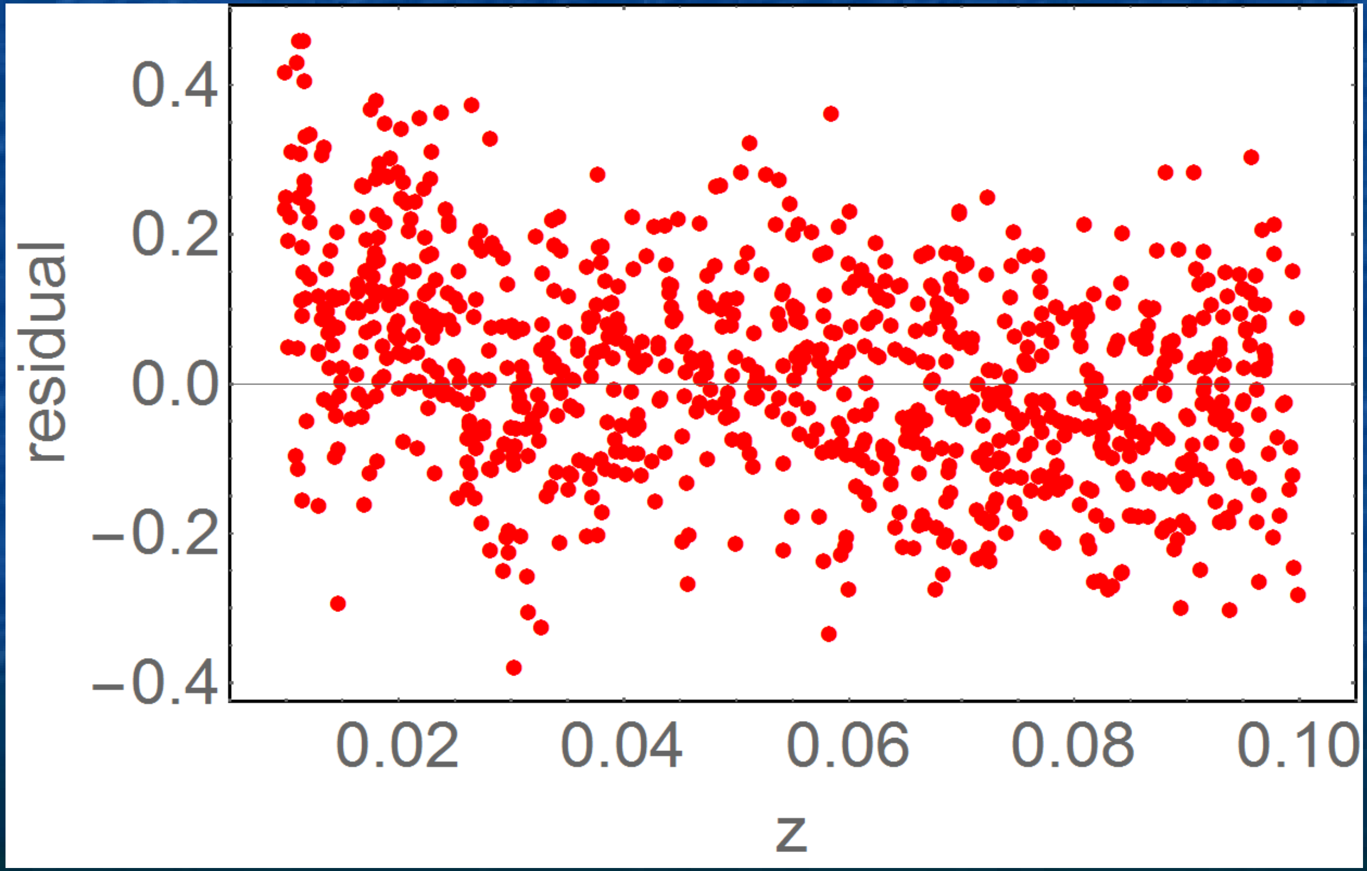
Hubble Diagram with PV's

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



Hubble Diagram with PV's

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



Power spectra

- P_{vv} spectrum does not depend on the bias $\quad v \equiv \boldsymbol{v} \cdot \hat{\boldsymbol{r}}$

$$P_{\delta\delta}(k,\mu,z) = \left(1+\beta\mu^2\right)^2 b^2\, S_\delta^2\, D_+^2 P_{mm}(k),$$

$$P_{vv}(k,\mu,z) = \left[\frac{H\mu}{k(1+z)}\right]^2 S_v^2\, f^2\, D_+^2 P_{mm}(k)\,,$$

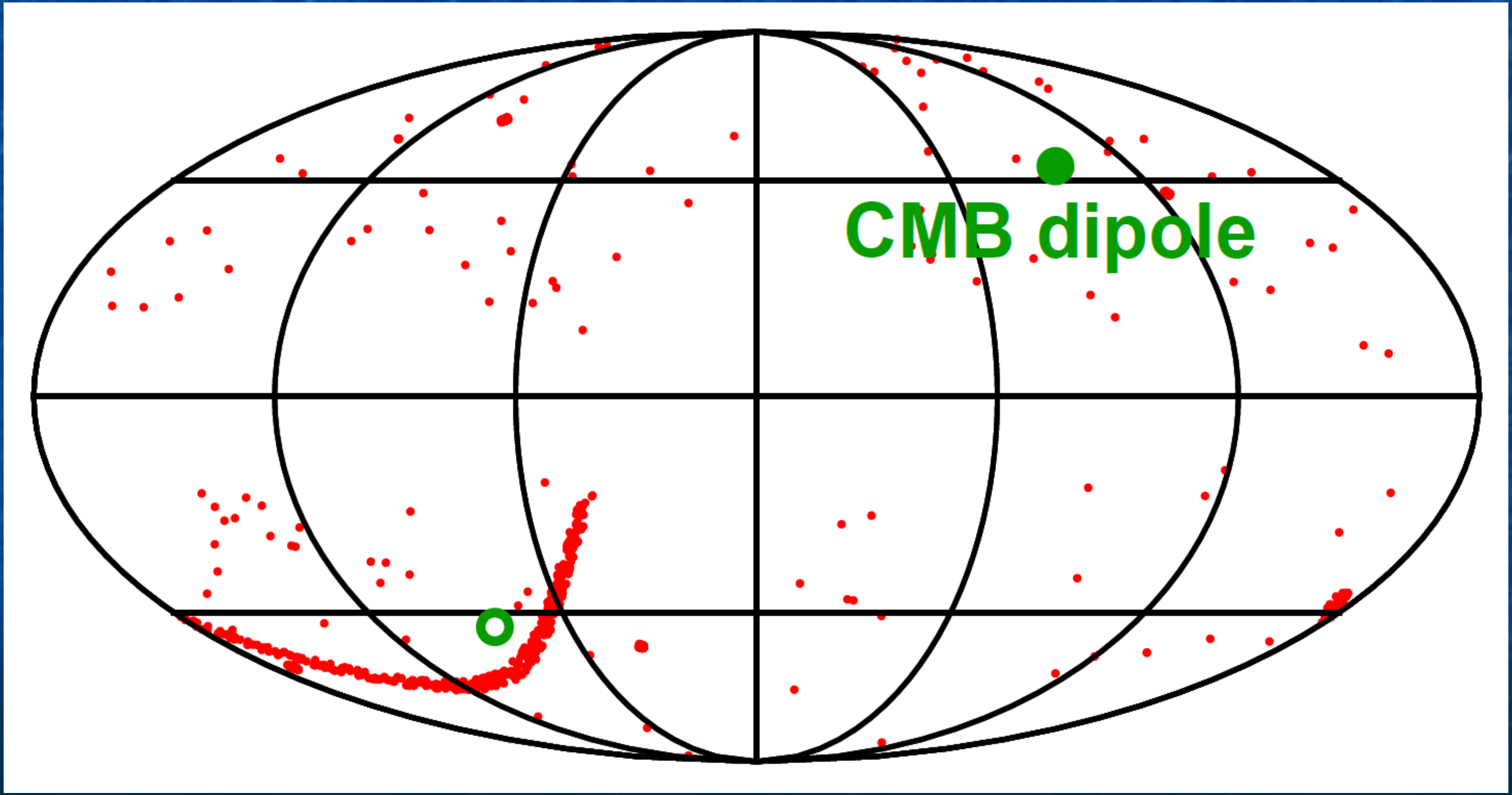
- The density-density power spectrum has a monopole (μ^0), quadrupole (μ^2) and hexadecuple (μ^4) part

$$P_{vv}^{\rm quad} \propto \frac{1}{1+z}\left[f(z)\sigma_8(z)\right]^2$$

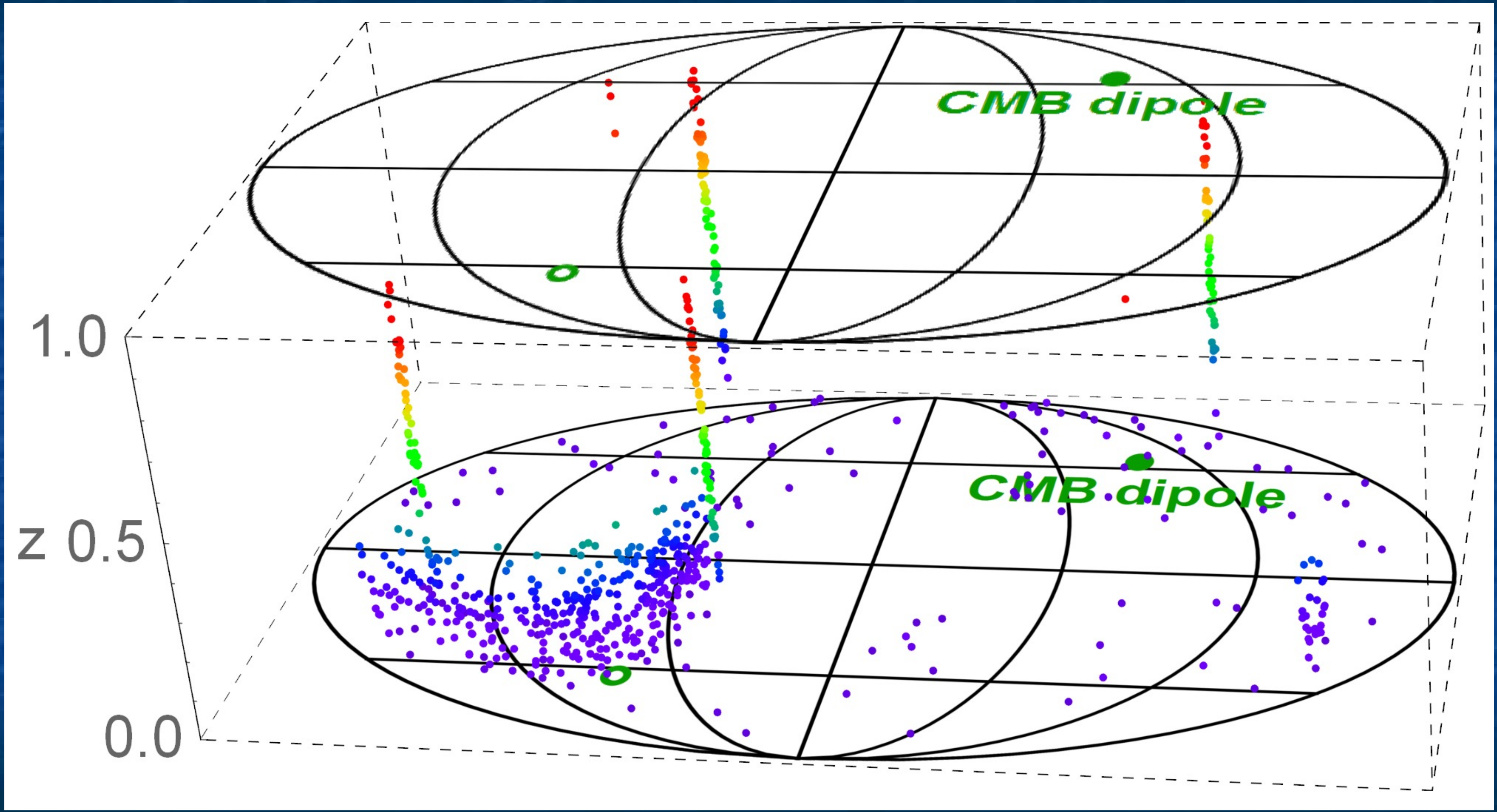
$$P_{\delta\delta}^{\rm hexad} \propto \left(f D_+ \sigma_8\right)^2 = \left[f(z)\sigma_8(z)\right]^2$$

JLA supernova distribution

- In galactic coordinates (as cosmologists like)



JLA supernova distribution



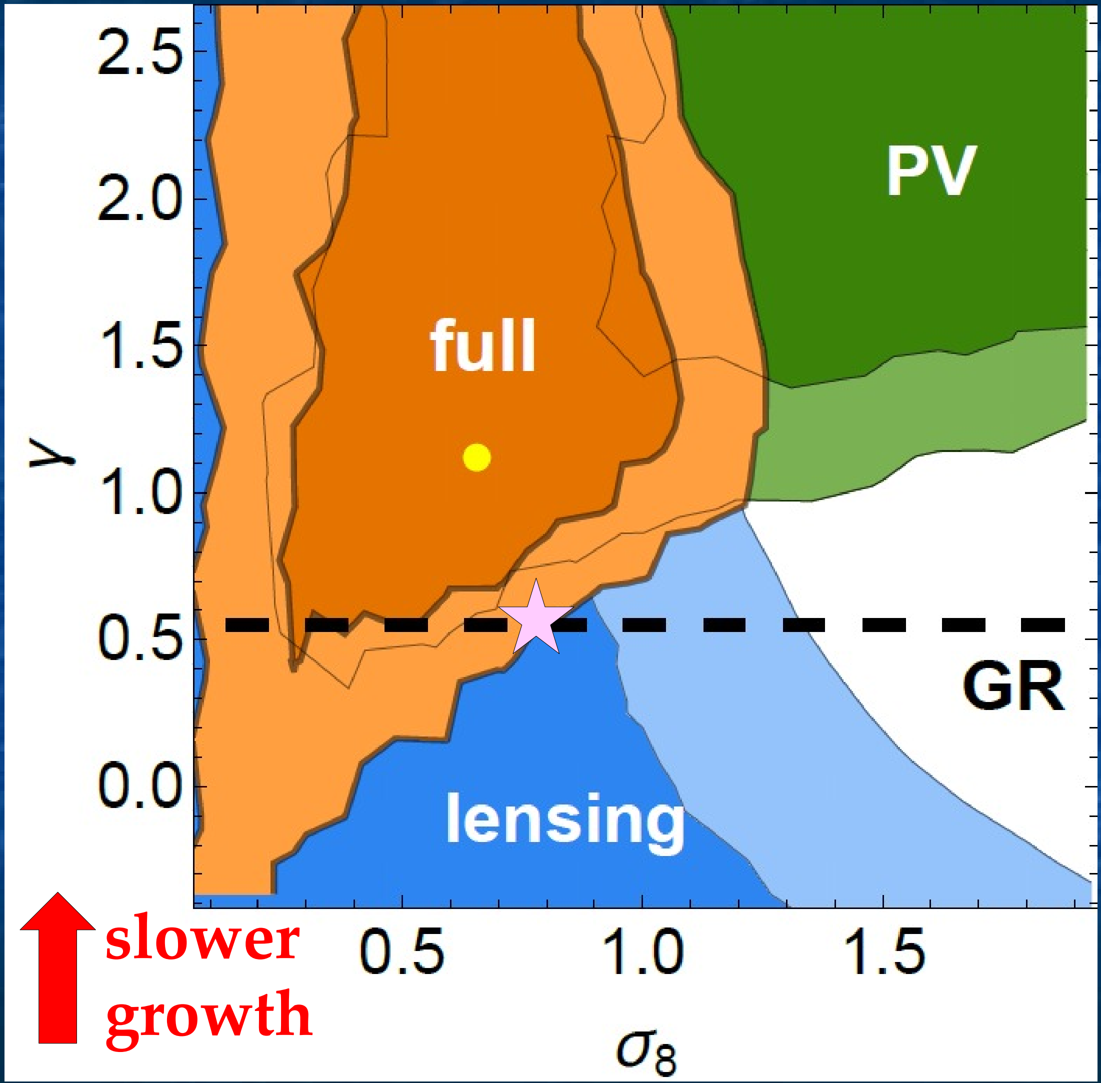
Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)

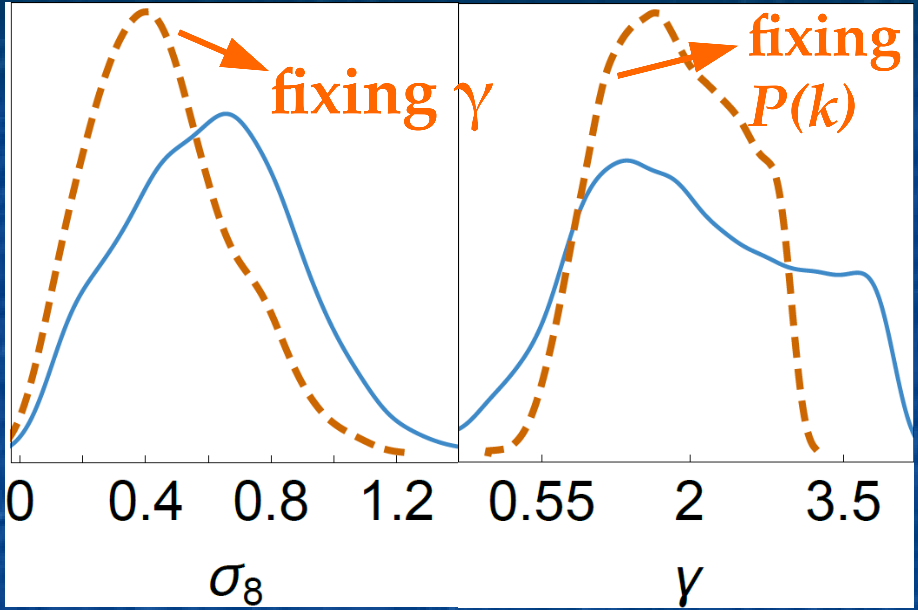
JLA SN constraints (lens+PV)

- 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, $\sigma_{v\text{-nonlin}}$, 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)

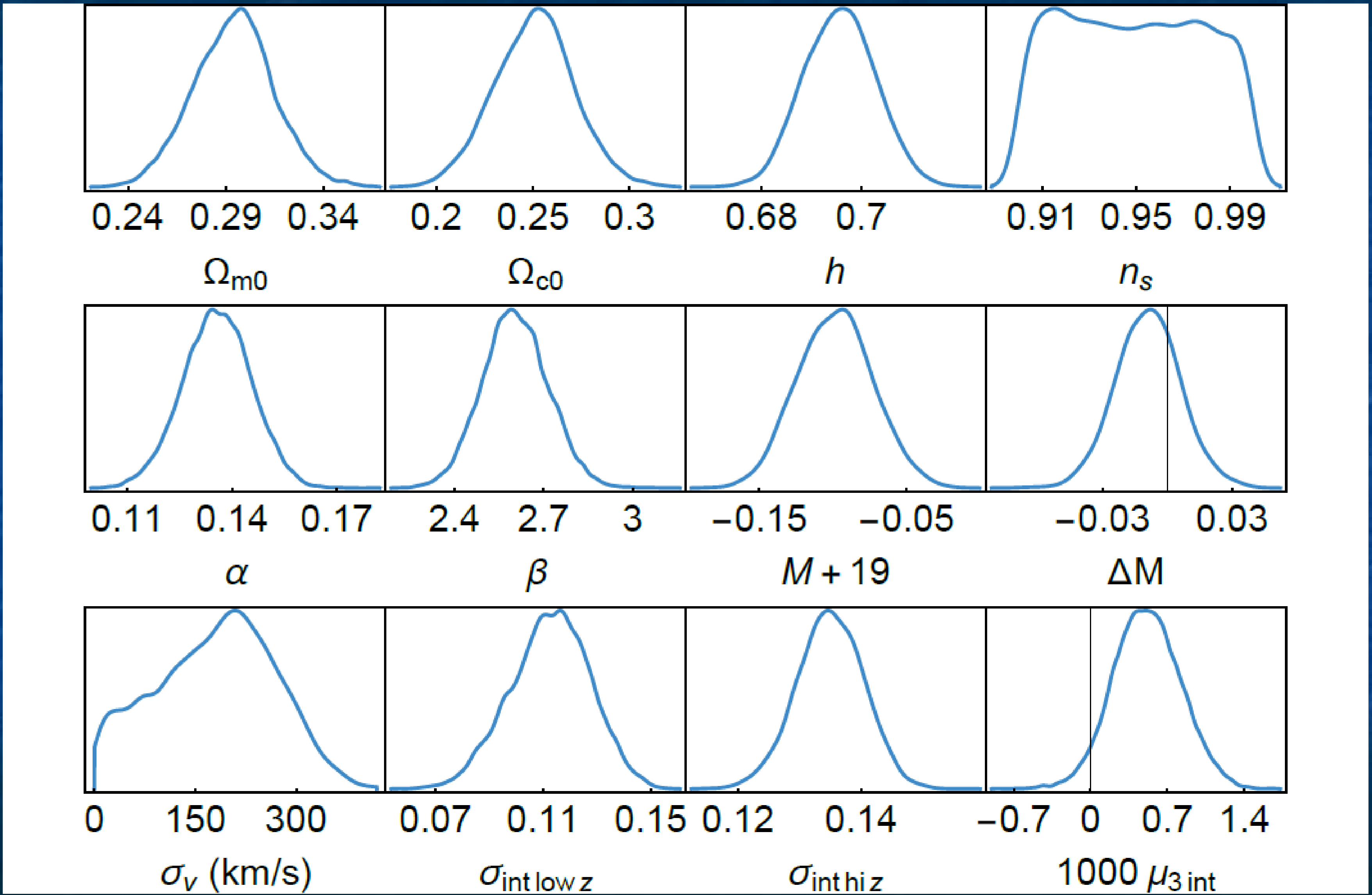




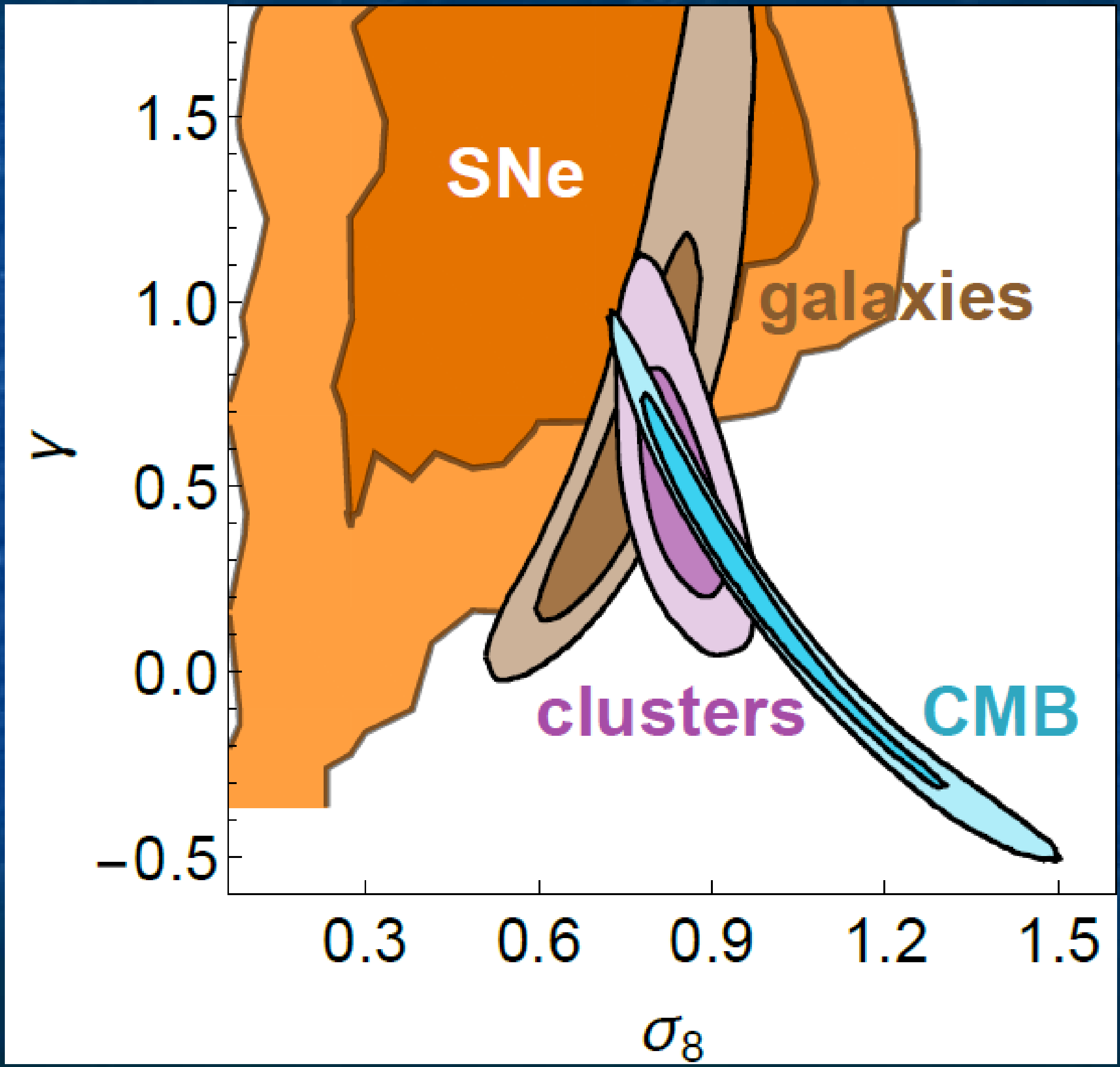
$$f \equiv \frac{d\log\delta_m}{d\log a} \equiv \Omega_m(z)^\gamma$$

Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)

JLA SN constraints (lens+PV)



Comparing with other data



Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)

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

More realistic PV forecasts

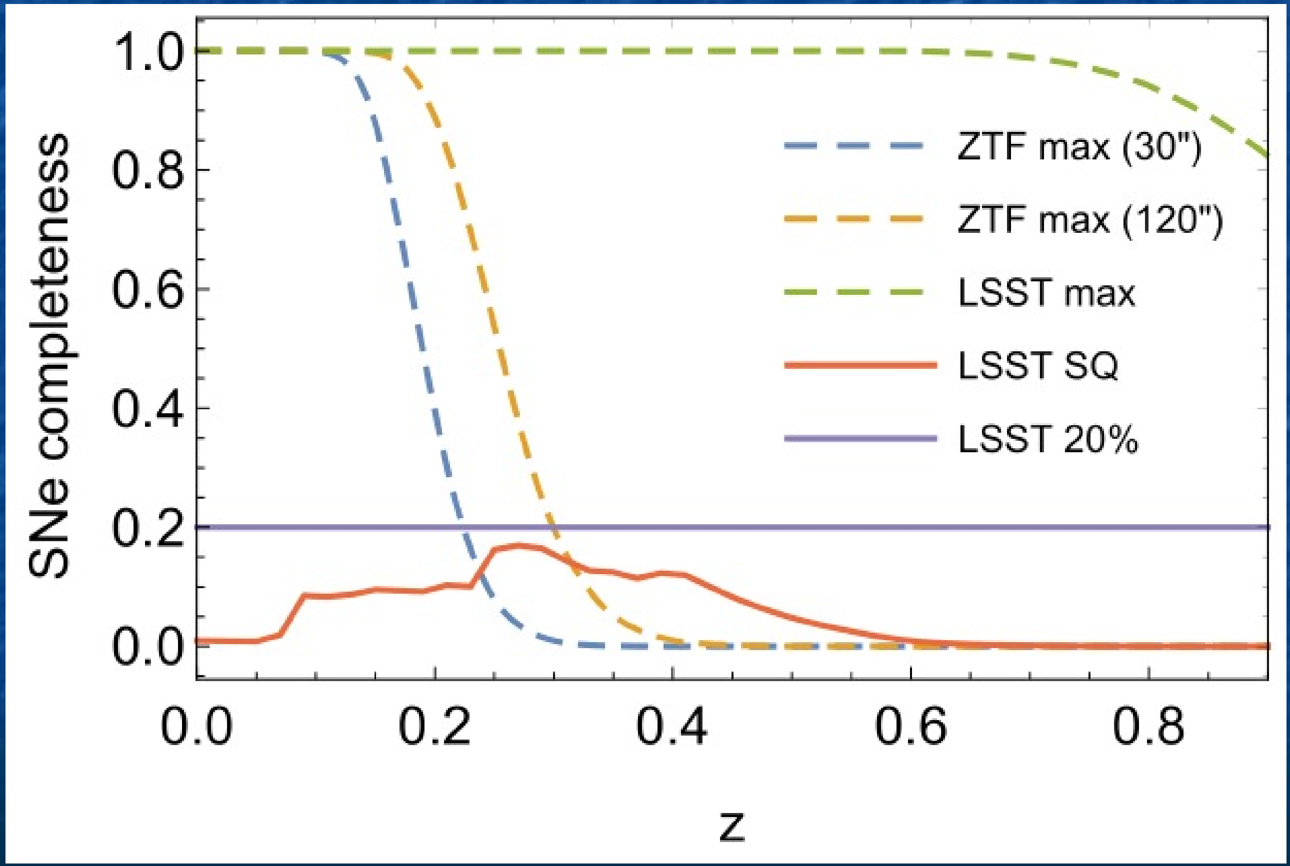
- How the final precision changes in different z_s and with different survey parameters
  - Area covered, depth, number density of SNe (n_{SN})
- Simple to test with the $P_{vv}(k)$ Fisher Matrix

$$F_{lm} = \frac{1}{8\pi^2} \int_{-1}^{+1} d\mu \int_{k_{\min}}^{k_{\max}} k^2 \mathrm{d}k \frac{\partial \ln P}{\partial p_l} \frac{\partial \ln P}{\partial p_m} \left[\frac{P(k,\mu)}{P(k,\mu) + \sigma_{v,\mathrm{eff}}^2 / n} \right]^2 V$$

$$\sigma_{v,\mathrm{eff}}^2 \equiv \left[\frac{\log 10}{5} H_0 d_C \sigma_{\mathrm{int}} \right]^2 + \sigma_{v,\mathrm{nonlin}}^2$$

SN completeness

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



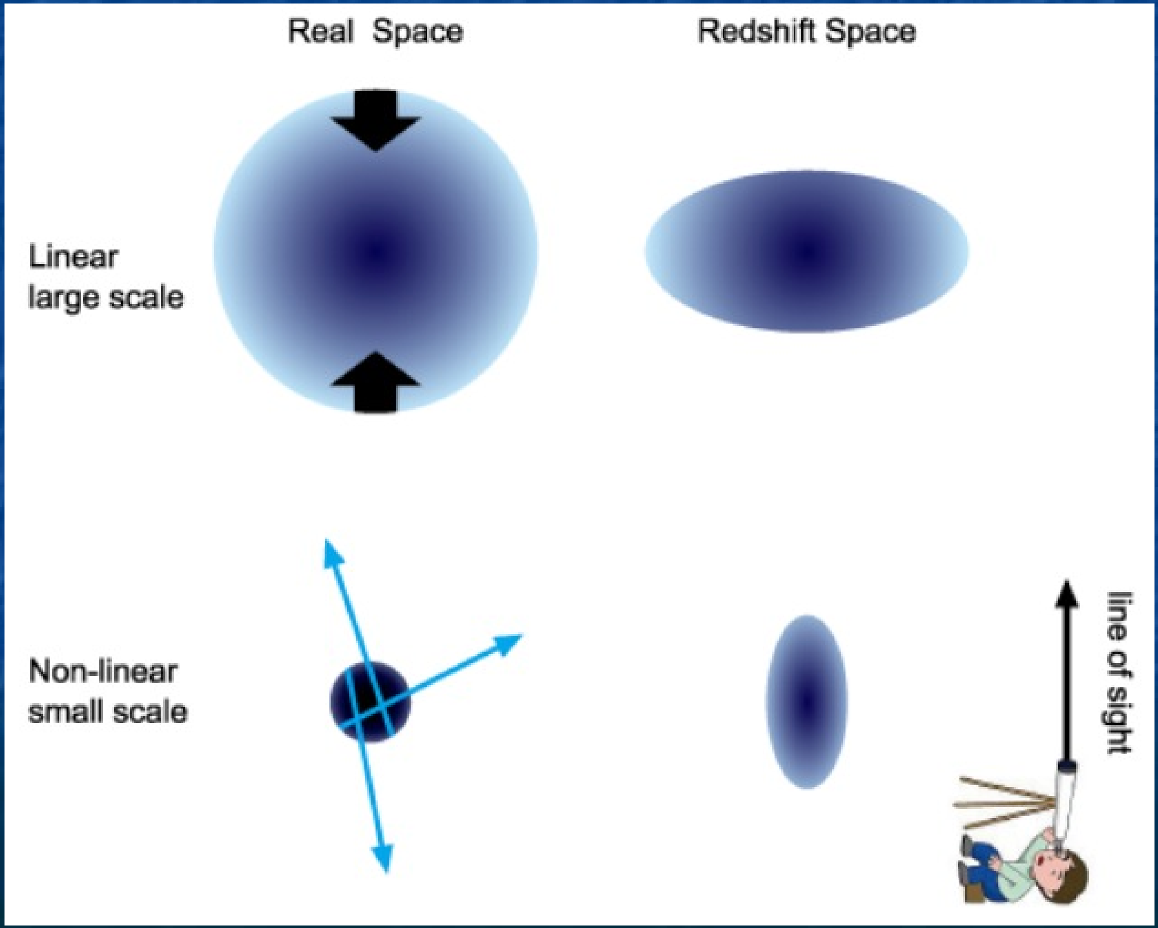
Garcia, Quartin & Siffert (1905.00746)

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
- Using both the Alcock-Paczynski and Kaiser effects (RSD), it is also possible to get model-independent constraints
- In particular, it is possible to constrain $E(z) = H(z)/H_0$
  - There are 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+ 0909.4954)
    - Cosmic Chronometers → rely on astrophysical modeling of passive galaxies & pop synthesis simulations (Liu+ 1509.08046)

Kaiser and Alcock-Paczynski

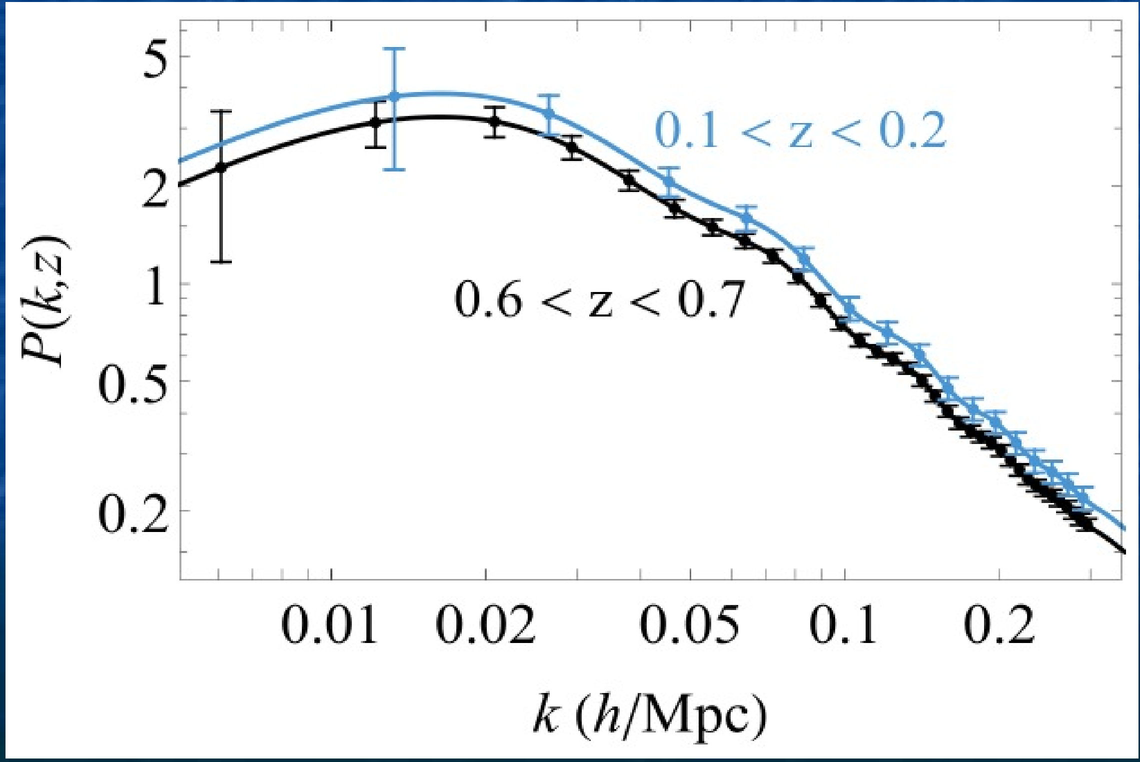
- The Kaiser effect (RSD): linear grav collapse turns (real-space) spheres into (redshift-space) ellipsoids along the line-of-sight
  - Non-linear collapse creates "Fingers of God"
- Alcock-Paczynski (AP): spheres are mapped into larger/smaller spheres if the assumed background cosmology is wrong



Model-independent clustering

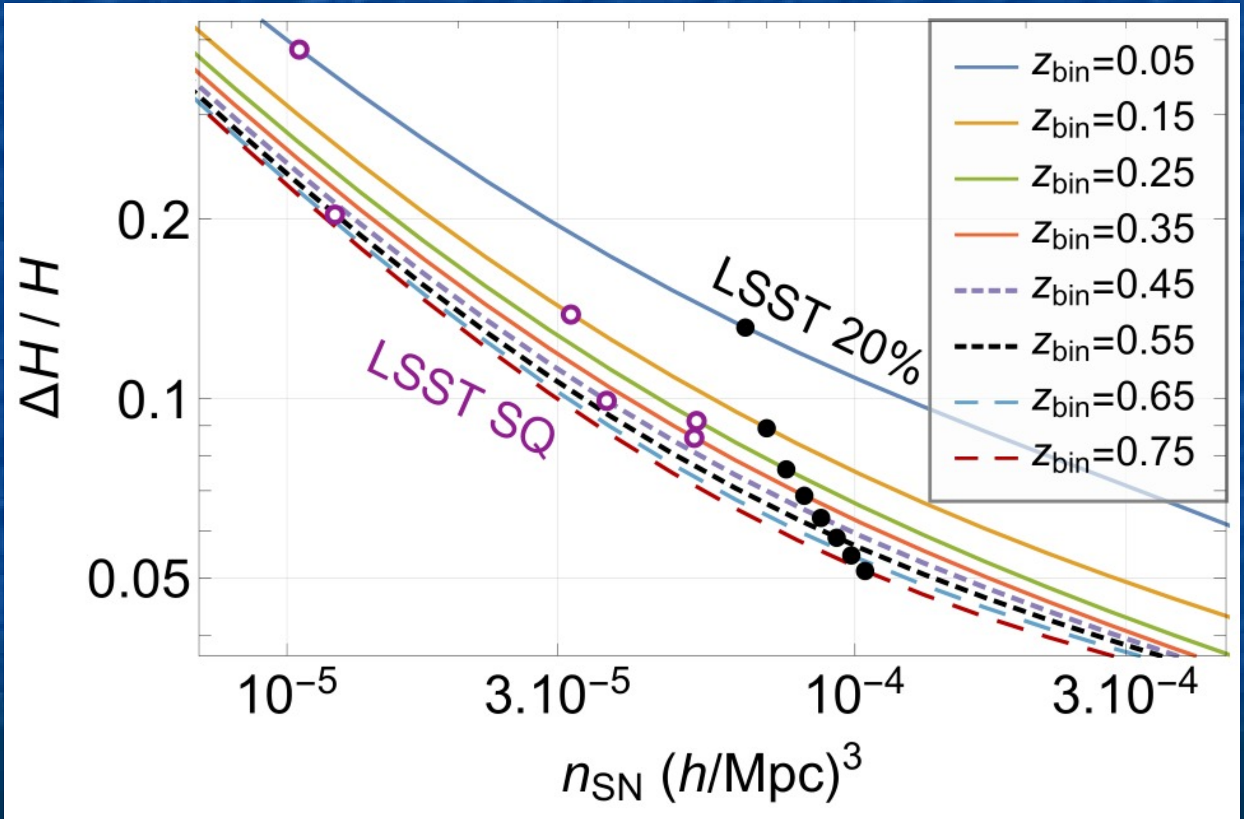
- The Clustering of Standard Candles method: combines SN velocities and SN clustering
  - Good precision in both model-indep and model-dep cases
  - Also model-indep measurements of *P(k,z)* and *β(k,z)*

			LSST 20%	
$z_{\rm bin}$	V $({\rm Gpc}/h)^3$	$k_{\rm min}$ (h/Mpc)	$10^3 \cdot n_{\rm SN}$ $({\rm h/Mpc})^3$	$\Delta H/H$ (%)
0.05	0.046	0.0175	0.064	13.2
0.15	0.296	0.0094	0.07	8.9
0.25	0.727	0.0070	0.076	7.6
0.35	1.27	0.0058	0.081	6.9
0.45	1.88	0.0051	0.087	6.3
0.55	2.51	0.0046	0.093	5.8
0.65	3.13	0.0043	0.099	5.4
0.75	3.72	0.0041	0.10	5.1



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)

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)

Power spectra

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

$$\beta \equiv f/b$$

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

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

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

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

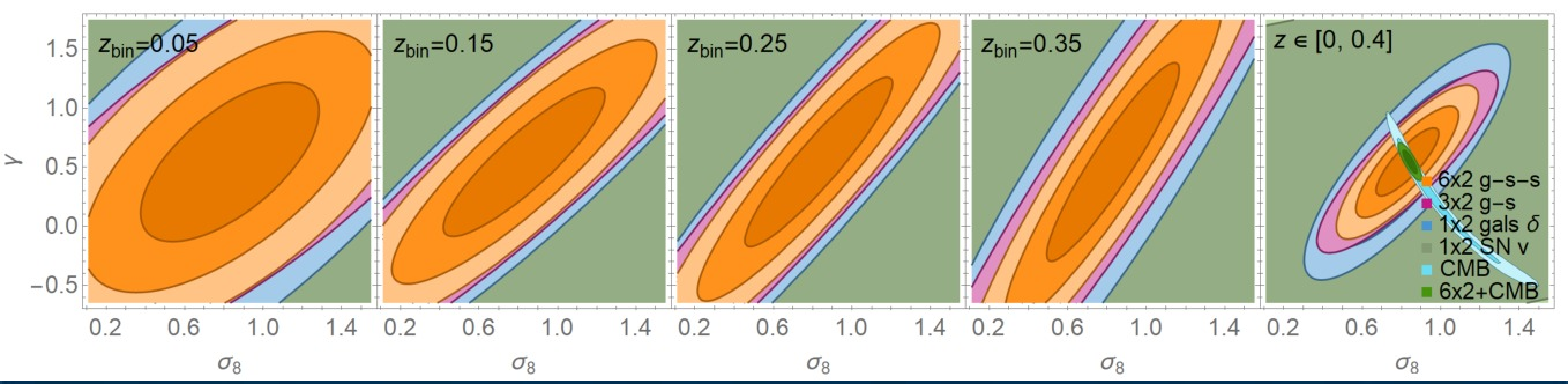
$$P_{\rm gv}(k,\mu,z) = \frac{H\mu}{k(1+z)}\left[1+\beta_{\rm g}\mu^2\right] b_{\rm g}\, S_{\rm g}\, S_{\rm v}\, f D_+^2 P_{\rm mm}(k)$$

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

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

6×2pt vs. 3×2pt vs 1×2pt

- We assume:
  - 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!

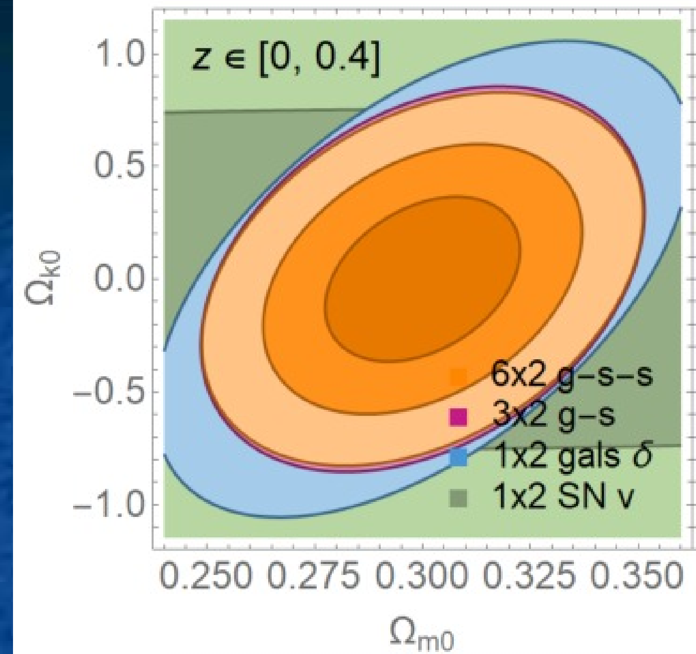


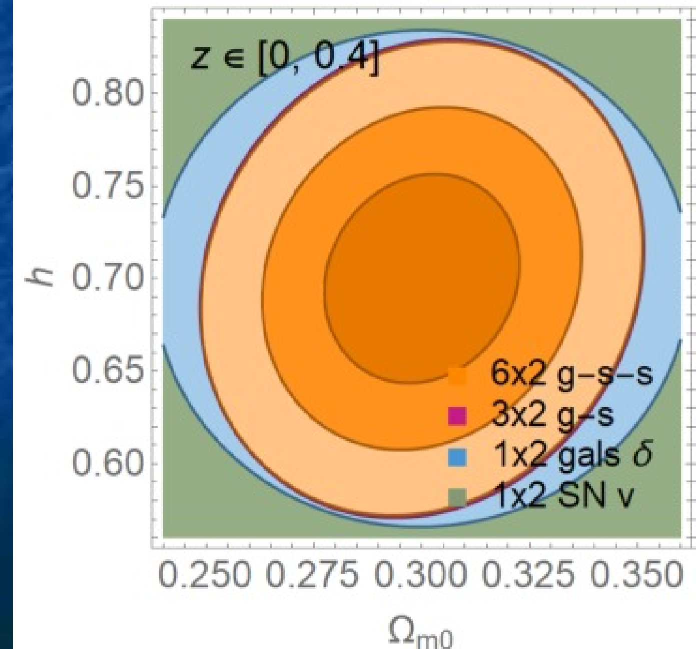
$$f \equiv d\log\delta_m / d\log a \equiv \Omega_m(z)^\gamma$$

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

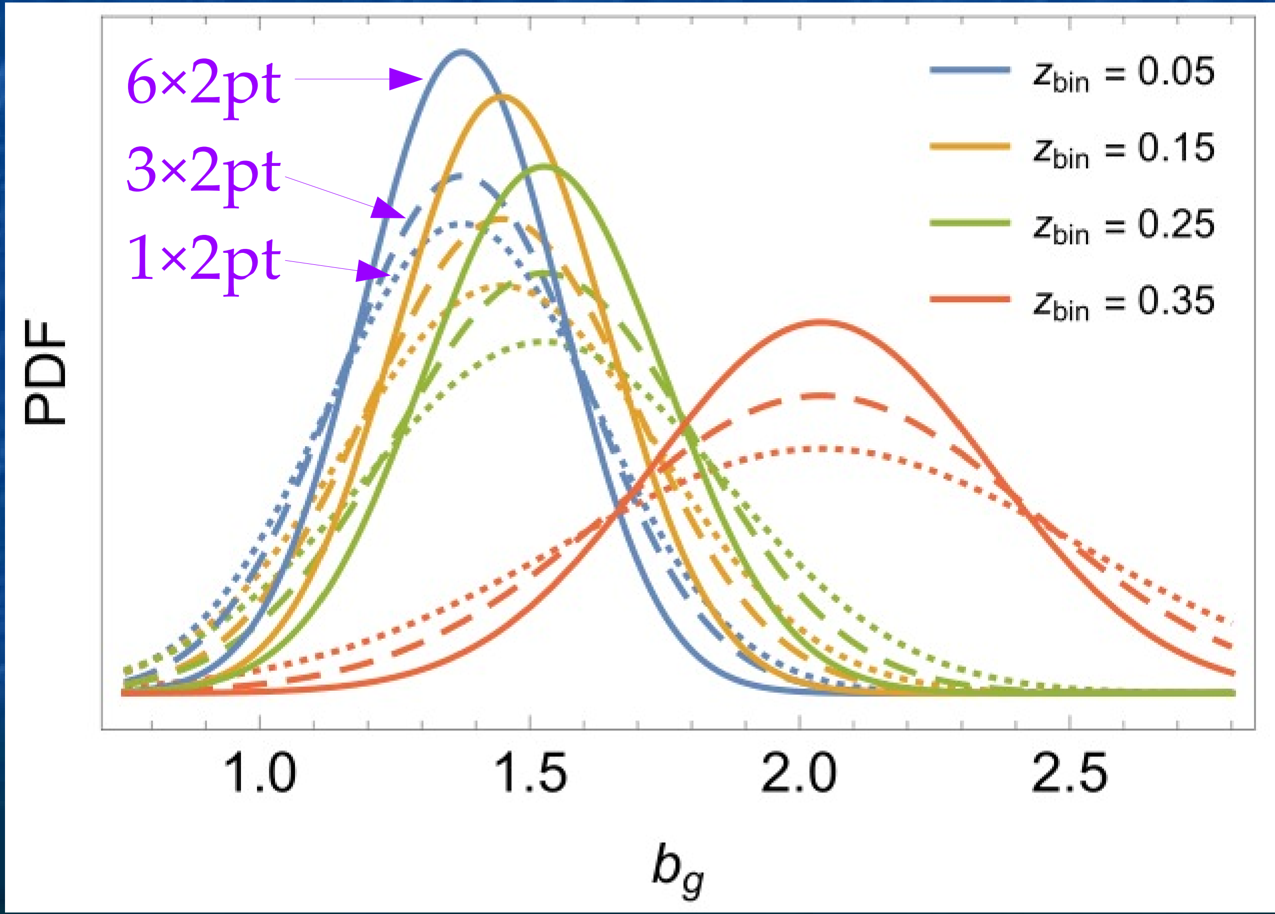
1σ uncertainties in:	σ_8	γ	h	Ω_{m0}	Ω_{k0}
Conservative	0.10	0.19	0.037	0.015	0.24
Conservative (no AP)	0.11	0.20	0.070	0.019	0.36
Conservative (flat)	0.10	0.19	0.028	0.014	-
Conser. ($k_{\max} = 0.05$)	0.15	0.28	0.12	0.031	0.39
Conser. ($k_{\max} = 0.15$)	0.091	0.16	0.019	0.010	0.19
CMB ($\star$)	0.11	0.29	0.037	0.064	0.017
Conservative + CMB	0.022	0.058	0.0073	0.010	0.0037
Aggressive	0.036	0.067	0.013	0.0048	0.079





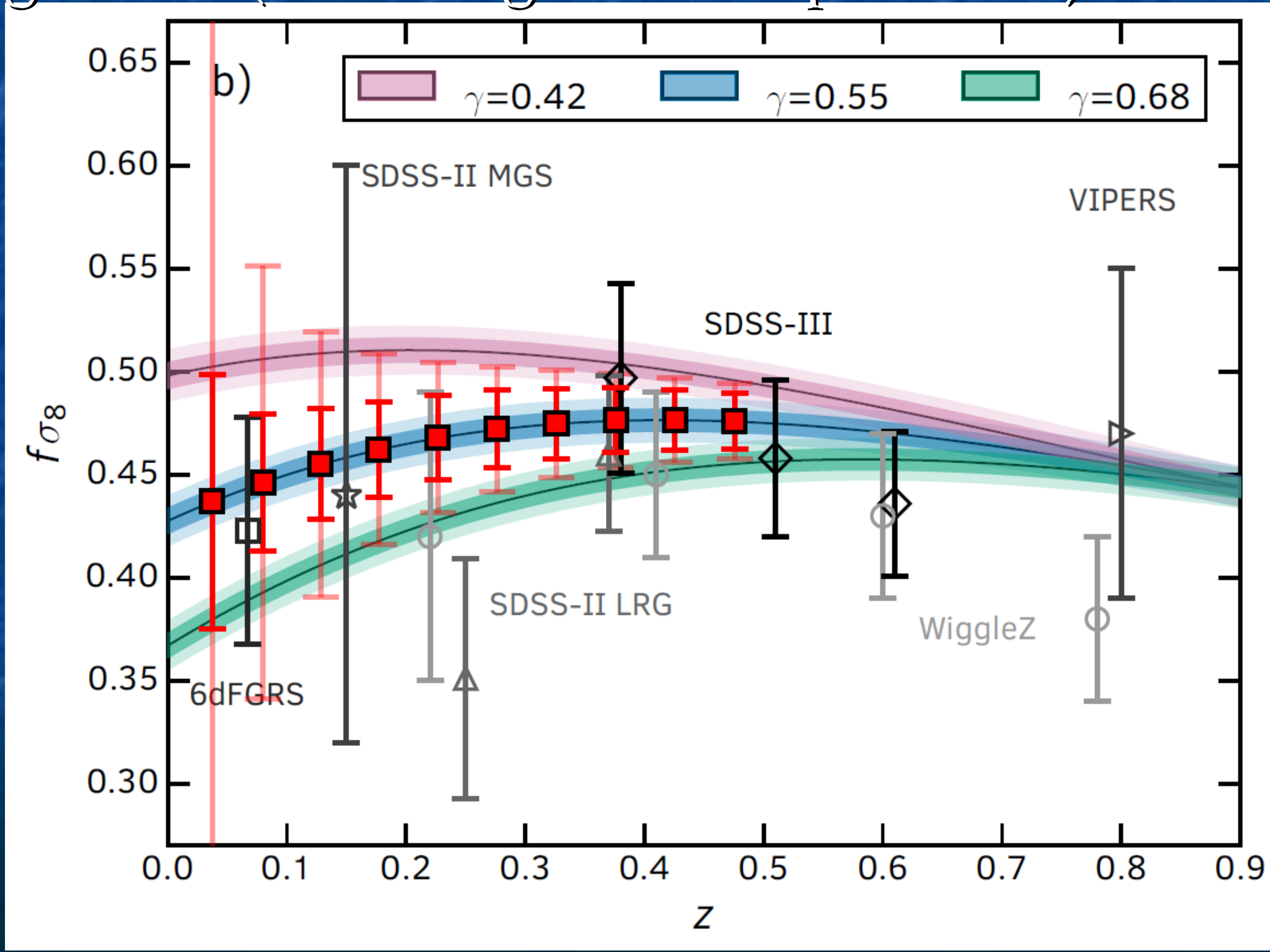
6×2pt is also more accurate

- Adding SNe velocities and densities, the galaxy bias is better constrained from data → more robust results



LSST 3x2 forecasts (H17)

- Howlett et al. (1708.08236) also made LSST forecasts combining SN and galaxies (assuming 40% completeness)



Conclusions

- SNe 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 all 3 Ps is possible with only SNe: $P_{\delta\delta}$, $P_{\delta v}$, P_{vv}
  - But 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 and weak-lensing often considered noise
  - Don’t throw away the noise…

Recycle!

Extra Slides