Reaching precision cosmology faster with velocities

In collaboration with
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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 $z_{\text{cosmo}} \sim 10^{-5}$ (~0.04 Mpc) we need good standard candles (known intrinsic luminosity) or good standard rulers (known intrinsic size).

- There are 2 classic standard (rigorously, standardizable) 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 standardizable candles for cosmology

- With good measurements $\rightarrow$ 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 ($N_{\text{SNe}} \sim 2000$)

  - In the next $\sim10$ years $\rightarrow$ statistics will increase by $100\times$ (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 @ \(z = 0\) \(\to\) \(\sim 600 \text{ km/s}\) \((v / c \sim 0.002)\)
    - “extra blue/redshift”
  - These *perturbations* are high for low \(z\) (large relative error)

- **Crucial point**: these velocities are correlated
  - Correlations \(\to\) 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 $\sigma_8$)

*Gordon, Land & Slosar* (0705.1718, PRL)

*Castro, Quartin & Benitez* (1511.08695, PhysDarkUniv)
To get some intuition → ideal case of perfect SNe Ia (i.e. no intrinsic dispersion, $\sigma_{\text{int}} = 0$) 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, $\sigma_{\text{int}} = 0$) in a 400 deg² patch
The signal becomes weaker for realistic supernovae ($\sigma_{\text{int}} = 0.12$ mag) → but it is still measurable.

Hubble Diagram with PV's
Power spectra

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

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

- The density-density power spectrum has a monopole ($\mu^0$), quadrupole ($\mu^2$) and hexadecupole ($\mu^4$) part

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

- $P_{\delta\delta}^{\text{hexad}} \propto (f D_+ + \sigma_8)^2 = \left[ f(z) \sigma_8(z) \right]^2$
JLA supernova distribution

- In galactic coordinates (as cosmologists like)
JLA supernova distribution

Castro, Quartin & Benitez (1511.08695, PhysDarkUniv)
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: $\Omega_{b0}$, $\Omega_{c0}$, $h$, $A$, $n_s$, $\gamma$
- 8 nuisance params: $M$, $\alpha$, $\beta$, $\Delta M$, $\sigma_{v\text{-nonlin}}$, $\sigma_{\text{int1}}$, $\sigma_{\text{int2}}$, $\mu_{3\text{int}}$
- Priors only needed in $h$, $n_s$ and $\Omega_{b0}$

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

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

\[
\sigma_{v,\text{eff}}^2 \equiv \left[ \frac{\log 10}{5} H_0 d_C \sigma_{\text{int}} \right]^2 + \sigma_{v,\text{nonlin}}^2
\]
**SN completeness**

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

![Graph showing SN completeness across different redshifts for various surveys.](image)

_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 $H r_s \rightarrow$ subject to understanding of $r_s$: the sound horizon at the drag epoch
    - Redshift-drift \(\rightarrow\) needs lots of time in Extremely Large Telescopes (Liske+ 0802.1532, Quartin+ 0909.4954)
    - Cosmic Chronometers \(\rightarrow\) 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 $\beta(k,z)$

<table>
<thead>
<tr>
<th>$z_{\text{bin}}$</th>
<th>$V$ (Gpc/h$^3$)</th>
<th>$k_{\text{min}}$ (h/Mpc)</th>
<th>$10^3 \cdot n_{\text{SN}}$</th>
<th>$\Delta H/H$ (%)</th>
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<tbody>
<tr>
<td>0.05</td>
<td>0.046</td>
<td>0.0175</td>
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<td>0.081</td>
<td>6.9</td>
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<tr>
<td>0.45</td>
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<td>0.087</td>
<td>6.3</td>
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<tr>
<td>0.55</td>
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<td>5.8</td>
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<tr>
<td>0.65</td>
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<td>0.099</td>
<td>5.4</td>
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<tr>
<td>0.75</td>
<td>3.72</td>
<td>0.0041</td>
<td>0.10</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Graph showing $P(k,z)$ for $0.1 < z < 0.2$ and $0.6 < z < 0.7$.
Information scaling with $n_{SN}$

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

\[ \Delta H / H \]

\[ n_{SN} (h/\text{Mpc})^3 \]

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: $3\times2pt\ g-s$

- SNe also can trace the density field
  - With LSST we can use both galaxies and SNe to measure $\delta$ and use SNe to measure $v$ simultaneously
    - This is the bases of the $6\times2pt\ g-s-s$ method
  - Let’s compare results of $1\times2$, $3\times2$ and $6\times2pt$ approaches

*Quartin, Amendola & Moraes (2111.05185)*
Power spectra

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

\[
\begin{align*}
P_{gg}(k, \mu, z) &= \left[1 + \beta_g \mu^2 \right]^2 b_g^2 S_g^2 D^2 + P_{mm}(k) + \frac{1}{n_g} \\P_{ss}(k, \mu, z) &= \left[1 + \beta_s \mu^2 \right]^2 b_s^2 S_s^2 D^2 + P_{mm}(k) + \frac{1}{n_s} \\P_{gs}(k, \mu, z) &= \left[1 + \beta_g \mu^2 \right] \left[1 + \beta_s \mu^2 \right] b_g b_s S_g S_s D^2 + P_{mm}(k) + \frac{n_{gs}}{n_g n_s} \\P_{gv}(k, \mu, z) &= \frac{H \mu}{k(1 + z)} \left[1 + \beta_g \mu^2 \right] b_g S_g S_v f D^2 + P_{mm}(k) \\P_{sv}(k, \mu, z) &= \frac{H \mu}{k(1 + z)} \left[1 + \beta_s \mu^2 \right] b_s S_s S_v f D^2 + P_{mm}(k) \\P_{vv}(k, \mu, z) &= \left[ \frac{H \mu}{k(1 + z)} \right]^2 S_v^2 f^2 D^2 + P_{mm}(k) + \frac{\sigma_{v,eff}^2}{n_s}
\end{align*}
\]
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!

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

<table>
<thead>
<tr>
<th>1σ uncertainties in:</th>
<th>σ₈</th>
<th>γ</th>
<th>h</th>
<th>Ωₘ₀</th>
<th>Ωₖ₀</th>
</tr>
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<tbody>
<tr>
<td>Conservative</td>
<td>0.10</td>
<td>0.19</td>
<td>0.037</td>
<td>0.015</td>
<td>0.24</td>
</tr>
<tr>
<td>Conservative (no AP)</td>
<td>0.11</td>
<td>0.20</td>
<td>0.070</td>
<td>0.019</td>
<td>0.36</td>
</tr>
<tr>
<td>Conservative (flat)</td>
<td>0.10</td>
<td>0.19</td>
<td>0.028</td>
<td>0.014</td>
<td>-</td>
</tr>
<tr>
<td>Conser. (kₘₐₓ = 0.05)</td>
<td>0.15</td>
<td>0.28</td>
<td>0.12</td>
<td>0.031</td>
<td>0.39</td>
</tr>
<tr>
<td>Conser. (kₘₐₓ = 0.15)</td>
<td>0.091</td>
<td>0.16</td>
<td>0.019</td>
<td>0.010</td>
<td>0.19</td>
</tr>
<tr>
<td>CMB (*)</td>
<td>0.11</td>
<td>0.29</td>
<td>0.037</td>
<td>0.064</td>
<td>0.017</td>
</tr>
<tr>
<td>Conservative + CMB</td>
<td>0.022</td>
<td>0.058</td>
<td>0.0073</td>
<td>0.010</td>
<td>0.0037</td>
</tr>
<tr>
<td>Aggressive</td>
<td>0.036</td>
<td>0.067</td>
<td>0.013</td>
<td>0.0048</td>
<td>0.079</td>
</tr>
</tbody>
</table>
Adding SNe velocities and densities, the galaxy bias is better constrained from data → more robust results.
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: $z > 0.4 \rightarrow$ **non-Gaussianity** in the Hubble Diag.
  - Pec. Vel.: $z < 0.5 \rightarrow$ **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 $\rightarrow 6 \times 2pt$
- Very good precision with LSST for $\sigma_8$ & $\gamma$
- It is a new observable & a nice **cross-check** of $\Lambda$CDM
- SNe PV and weak-lensing often considered noise
  - Don’t throw away the noise...

Recycle!
Extra Slides