Open questions in cosmology with type Ia supernovae

Ana M. Mourão

Work with: S. Gonzalez-Gaitan (CENTRA), L. Galbany (Pittsburgh), V. Stanishev (CENTRA), M. Rodrigues (ObPM, Oxford), H. Flores (ObsPM), F. Patat (ESO)
COSMOLOGY WITH TYPE Ia SUPERNOVAE

Hubble Plots

SCP, Perlmutter et al, AAS meeting 1998
Many observatories: Hawaii and ESO, La Palma, etc
DARK ENERGY?

THE UNIVERSE
WILL NOT LOOK THE SAME AGAIN
COSMOLOGY WITH TYPE Ia SUPERNOVAE

Pantheon Sample: 1048 SNe  0.03<z<2.3
Scolnic et al, 2018

\[ m^* - M = 5 \log_{10}(d_L/10\,pc) \]
COSMOLOGY WITH TYPE Ia SUPERNOVAE

SN Ia PROGENITORS
COSMOLOGY WITH TYPE Ia SUPERNOVAE

\[ m^* - M = 5 \log_{10} \left( \frac{d_L}{10 \text{ pc}} \right) \]

\[ \mu = m_B - (M_B - \Delta) \]

\[ \mu = m_B - (M_B - \alpha(s - 1) + \beta C) \]

Pantheon Sample: 1048 SNe 0.03<z<2.3
Scolnic et al, 2018
### Table 8.

<table>
<thead>
<tr>
<th>Analysis</th>
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<th>$w$</th>
<th>$\Omega_m$</th>
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<tr>
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LambdaCDM model: flat, $\omega = -1$, $\Omega_K = 0$

$\omega$CDM model: flat, $\omega = -1$, $\Omega_k$ varies

$w$CDM model: flat, $\omega_0$ varies, $\omega_a = 0$

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COSMOLOGY WITH TYPE Ia SUPERNOVAE

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Pantheon Sample: 1048 SNe 0.03<z<2.3
Scolnic et al, 2018
SYSTEMATICS IN SN COSMOLOGY

- Progenitor properties: mass, metallicity
- Explosion model: double/single degenerate asymmetries in the explosion
- Dust
SYSTEMATICS IN SN COSMOLOGY

INTEGRAL FIELD SPECTROSCOPY

- Local versus global host properties
- Progenitor properties from metallicity of gas and stellar populations
- ...

POLARIMETRY

- Dust
- Explosion models
INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY
INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY

One image: data cube
INDIRECT STUDIES OF SN PROGENITORS

Photometry

Slit spectroscopy

Fiber

IFS: SNIFS
FoV 5”x5”
INDIRECT STUDIES OF SN PROGENITORS

IFS @ CAHA (PPAK)

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Stanishev, Mourao Rodrigues Flores, 2012
INDIRECT STUDIES OF SN PROGENITORS

IFS @ CAHA

Stanishev, Mourao Rodrigues Flores, 2012
INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY

331 fibers D=2.7"
FoV~1’x1’
1\textsuperscript{st} observations 2009

Test run: Stanishev et al '12
CALIFA: Galbany et al '14
PISCO: Galbany et al '18
INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY

PISCO- PMAS IF Supernova Compilation:
232 SN hosts
272 SNe

Galbany+ '18
INDIRECT STUDIES OF SN PROGENITORS

GAS METALLICITY

Oxygen abundances in 1kpc SN environment

Galbany et al '18
INDIRECT STUDIES OF SN PROGENITORS

GAS METALLICITY

Galbany et al '18
Moreno-Raya et al '16: including metallicity reduces the scatter in ~5%
DUST PROPERTIES: COMPOSITION AND SIZE

M. Bocchio 2014
DUST PROPERTIES: COMPOSITION AND SIZE

Jones+ 2014
DUST PROPERTIES AND INTERSTELLAR POLARIZATION

Lazarian '08
DUST PROPERTIES AND INTERSTELLAR POLARIZATION

Lazarian '08

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Host of the SN1976G

Scarrott+ 1996
Fig. 3.—The normalized wavelength dependence of interstellar linear polarization derived from the observations with the Siding Spring multichannel polarimeter-photometer. The solid line is calculated from eq. (4) for $K = 1.15$. Every open circle is based on 20 stars, while each dot represents the observations of an individual star with a particular filter.

$$p(\lambda) = p(\lambda_{\text{max}}) \exp\left[-K \ln^2 \left(\frac{\lambda}{\lambda_{\text{max}}}\right)\right]$$

$$K = 1.86 \lambda_{\text{max}} - 0.1$$

$$R_V = \frac{A_V}{A_B - A_V}$$

$$\lambda_{\text{max}}(\mu m) = (0.17 \pm 0.05) R_V$$

Serkovski+ '75,
Clayton and Mathis '98
Draine '03
Wilking+ '82
Tielens, Interstellar Medium, '05
DUST PROPERTIES AND INTERSTELLAR POLARIZATION

\[ p(\lambda) = p(\lambda_{\text{max}}) \exp\left[ -K \ln^2 \left( \frac{\lambda}{\lambda_{\text{max}}} \right) \right] \]

\[ K = 1.86 \lambda_{\text{max}} - 0.1 \]

\[ R_V = \frac{A_V}{A_B - A_V} \]

\[ \lambda_{\text{max}} (\mu m) = (0.17 \pm 0.05) R_V \]

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DUST PROPERTIES FROM LINEAR SN POLARIMETRY

Patat+ '15
DUST PROPERTIES FROM LINEAR SN POLARIMETRY

Patat+ '15
SN2014J
Serkowski and Rayleigh scattering

Nagao+ '18, '19: polarimetry of SNe to infer the presence of CSM

Zelaya+ '13; 18: Sodium lines and spectropolarimetry of SNIIa
POLARIMETRY of SN HOST GALAXIES

ESO-VLT FORS2 – Focal Reducer and low dispersion Spectrograph

Polarimetric modes
Imaging Polarimetry mode (IPOL)
Spectro Polarimetry mode
FoV: 6.8x6.8
0.25"/pixel
In progress:
First statistical study of multi-band optical polarimetry of supernova host galaxies

@ESO FORS2

with
PI: S. Gonzalez-Gaitan (CENTRA)
   F. Patat, J. Andersen (ESO)
   A. Cikota (LBNL)

Goal
Map the wavelength of the polarization
Infer dust properties
POLARIMETRY of SN HOST GALAXIES
Schematic representation of a dual-beam polarimeter

initial light ray with two polarization states (shown in blue and red)
FORS2: POLARIZATION OPTICS

WOLLASTON PRISM

Stokes parameters

\[
\begin{pmatrix}
I \\
Q \\
U \\
V
\end{pmatrix}
\]

Gonzalez-Gaitan '19 in preparation
Patat & Romaniello '06

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FORS2: POLARIZATION OPTICS

WOLLASTON PRISM

Stokes parameters

\[
\begin{pmatrix}
I \\
Q \\
U \\
V
\end{pmatrix}
\]

\[
P = \frac{\sqrt{Q^2 + U^2}}{I}
\]

\[
\chi = \frac{1}{2} \arctan \frac{U}{Q}
\]

Gonzalez-Gaitan '19 in preparation
Patat & Romaniello '06
FORS2: POLARIZATION OPTICS

WOLLASTON PRISM: check for systematics

B HIGH: $y_o - y_e$

Gonzalez-Gaitan '19 in preparation
FORS2: POLARIZATION OPTICS

Retarder plate

Gonzalez-Gaitan '19 in preparation
Plots by J. Lopes
\[ F_i \equiv \frac{f_{O,i} - f_{E,i}}{f_{O,i} + f_{E,i}} \]

\[ F_i = \frac{Q}{I} \cos 4\theta_i + \frac{U}{I} \sin 4\theta_i = P \cos(4\theta_i - 2\chi) \]

\[ P = \frac{\sqrt{Q^2 + U^2}}{I} \]

\[ \chi = \frac{1}{2} \arctan \frac{U}{Q} \]

\[ \sigma_P = \frac{1}{\sqrt{N/2(S/N)}} \quad \text{and} \quad \sigma_\chi = \frac{\sigma_P}{2P} \]

Gonzalez-Gaitan '19 in preparation

Patat & Romaniello '06
FORS2: POLARIZATION OPTICS

\[ F_i = \frac{Q}{I} \cos 4\theta_i + \frac{U}{I} \sin 4\theta_i = P \cos(4\theta_i - 2\chi) \]

\[ F_i = Q_0 + \sum_{k=1}^{N/2} Q_k \cos \left( k \frac{2\pi i}{N} \right) + U_k \sin \left( k \frac{2\pi i}{N} \right) \]

\[ Q_0 = \frac{1}{N} \sum_{i=0}^{N-1} F_i , \]

\[ Q_k = \frac{2}{N} \sum_{i=0}^{N-1} F_i \cos \left( k \frac{2\pi i}{N} \right) \]

\[ U_k = \frac{2}{N} \sum_{i=0}^{N-1} F_i \sin \left( k \frac{2\pi i}{N} \right) \]

Polarization spectrum

\[ P_k = \sqrt{Q_k^2 + U_k^2} \]

Signal @N/4 harmonic

Gonzalez-Gaitan '19 in preparation

Patat & Romaniello '06
FORS2: IPOL MODE CALIBRATION

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estimation of the instrumental polarization in FORS2, including

- A radial dependence of the instrumental polarization was confirmed
- Extra properties of the detector that must be considered in polarimetry

fundamental step towards precision polarimetry with FORS2
FORS2: IPOL MODE CALIBRATION

Filter B

bin: 30x30
FORS2: IPOL MODE CALIBRATION

Polarization spectrum

Filter B
\[ \Delta P = (P_0 + P_1 + P_3)/3 \]
The Future of SN Ia Cosmology at a Glance

**Low-z [z<0.1]**
- Discovery: ~2000/yr from ASASSN, PS, ATLAS, ZTF, LSST
- Imaging Follow-up: 1500 SN - Foundation, full LSST/ZTF
- Spectroscopic Follow-up: (on 2m telescopes)
- Confirmation: single-object spectroscopy
- Twinning: integral field spectroscopy

**Boxes:** Total anticipated discoveries across each redshift range

**Points:** Expected classifications with spec. follow-up (shown approximately at median z)

**Mid-z [0.1<z<1]**
- Discovery + Imaging: ~300,000 photometric, 6,000 spectroscopic from SDSS, SNLS, PS1, DES, LSST, WFIRST
- Spectroscopic Follow-up: multi-object spec. on 4-8m telescopes

**High-z [z>1]**
- Discovery + Imaging: ~6,000 photometric, 1,000 spectroscopic from HST, JWST, WFIRST
- Spectroscopic Follow-up: JWST, WFIRST, 8m+, ELTs

**Constraints on \( w(z) \) from the SNIa Hubble diagram**
- Top Systematics for measuring \( w \):
  - Calibration across wavelength range
  - Intrinsic scatter, Population Drifts
  - Classification

**\( \sigma_8 \) via Weak Lensing**
- Limited by max redshift of survey
- Signal goes with ~0.05z
- Top systematics: population drift, selection effects

**\( f_0 \) via Peculiar Velocities**
- Limited by SNIa Rate and intrinsic dispersion of SN luminosity (0.08 twin/NIR, -0.15 optical mag)
- Top systematics: MW extinction

**Strong Lensing Time Delay Cosmography**
- Limited by lensed SN discovery rates and follow-up
- Dedicated follow-up necessary
- Top systematics: microlensing, lens model systematics

**Other Avenues:**
- **Local \( H_0 \)**
  - Limited by low-z SNIa Rate
  - ~1 SN / yr in distance-calibrated galaxy at z<0.01
  - Top systematics: cross-matching cepheid and Hubble flow host galaxy properties

**Scolnic+ 18**
CONCLUSIONS

INTEGRAL FIELD SPECTROSCOPY

IMAGING AND SPECTROPOLARIMETRY

UNDERSTAND SUPERNOVAE IMPACT ON COSMOLOGY