From Einstein and Eddington to LIGO: 100 years of gravitational light deflection

Open questions in cosmology with type Ia supernovae

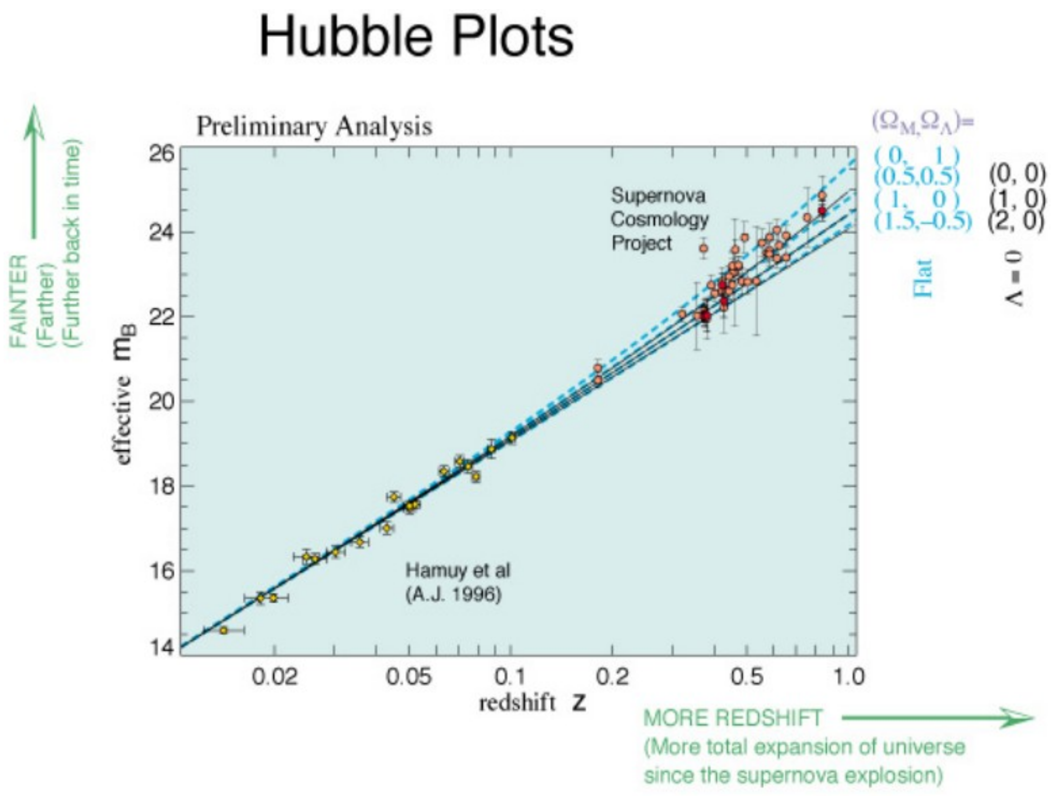
Ana M. Mourão

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

TÉCNICO LISBOA

centra

COSMOLOGY WITH TYPE Ia SUPERNOVAE



SCP, Perlmutter et al, AAS meeting 1998

Many observatories: Hawaii and ESO, La Palma, etc

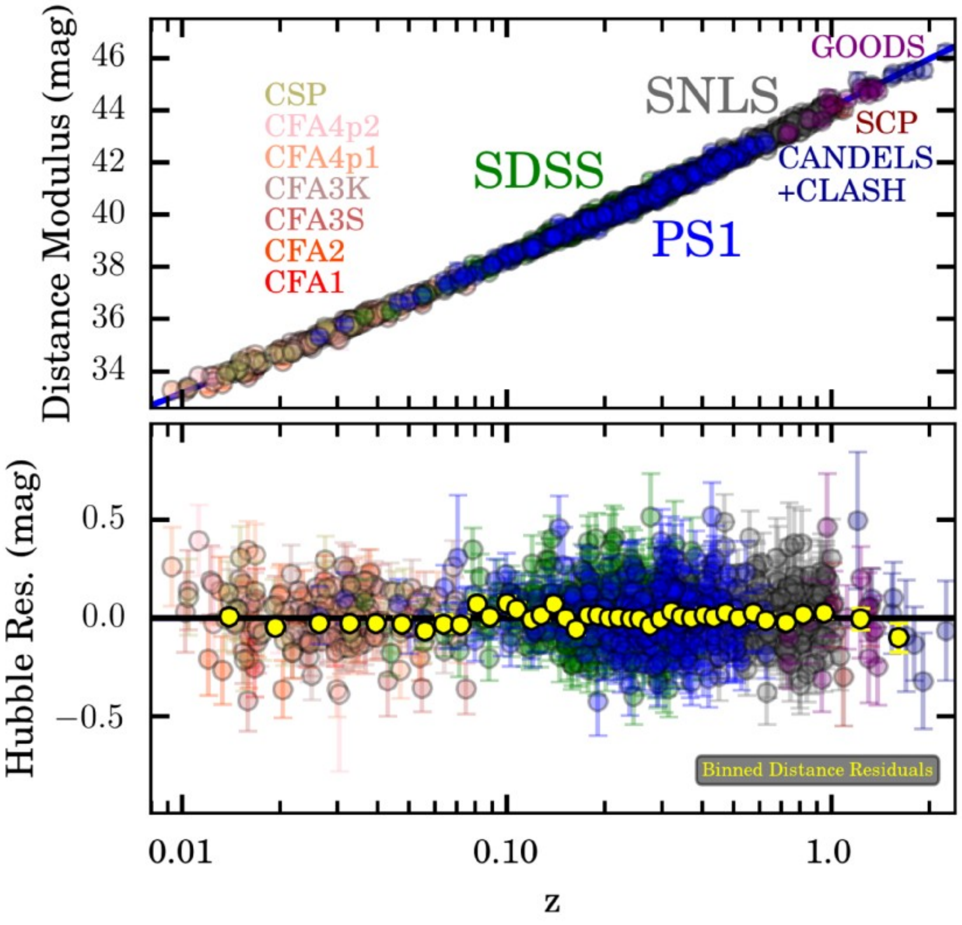
COSMOLOGY WITH TYPE Ia SUPERNOVAE

DARK ENERGY?

THE UNIVERSE

WILL NOT LOOK THE SAME AGAIN

COSMOLOGY WITH TYPE Ia SUPERNOVAE

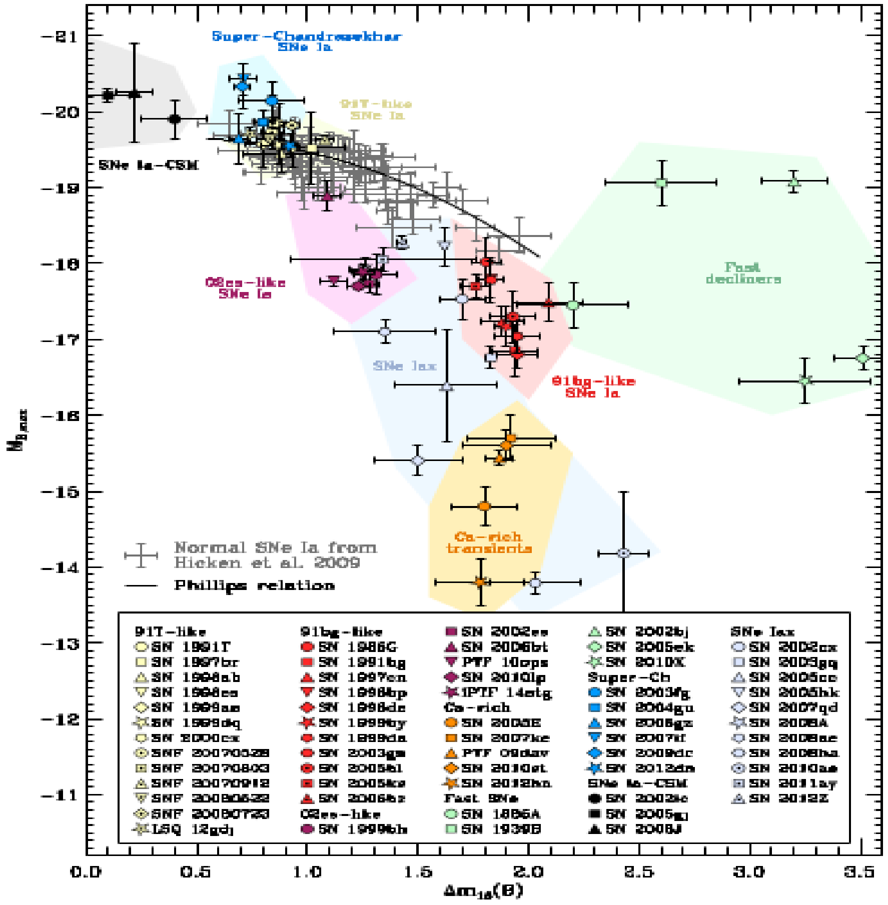


$$m^* - M = 5\log_{10}(d_L/10\,pc)$$

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

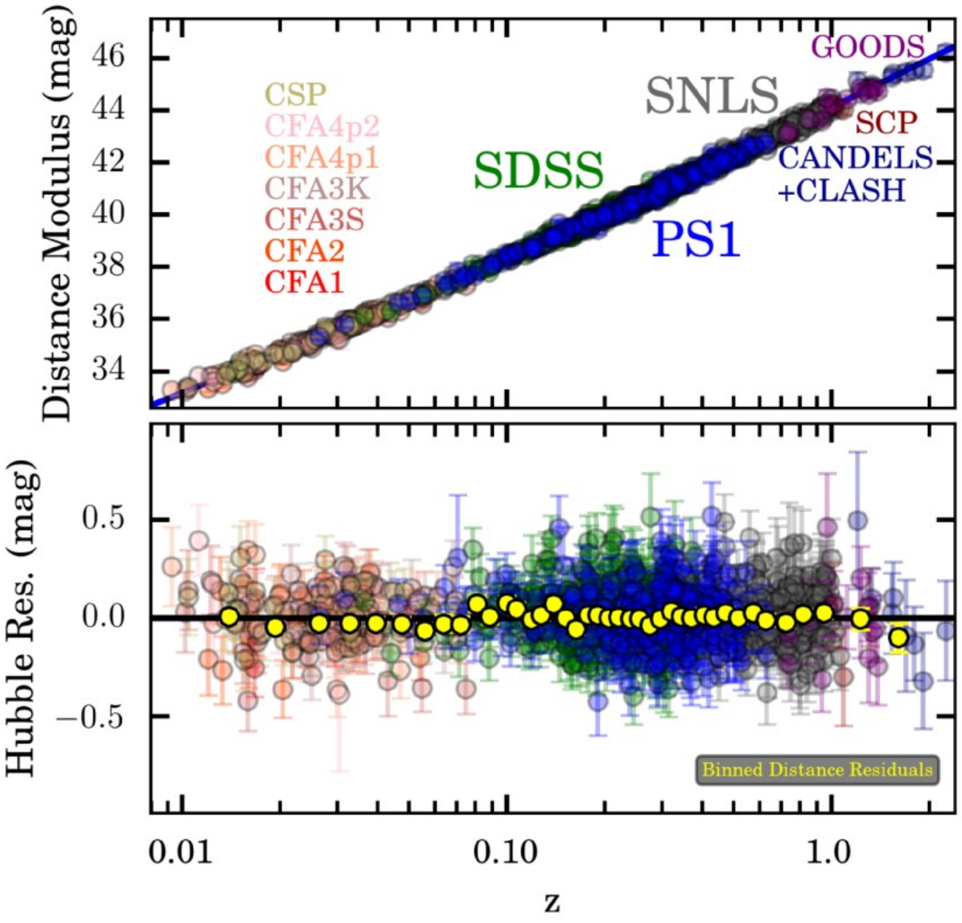
COSMOLOGY WITH TYPE Ia SUPERNOVAE

SN Ia PROGENITORS



Taubenberger '17

COSMOLOGY WITH TYPE Ia SUPERNOVAE



$$m^* - M = 5\log_{10}(d_L/10\,pc)$$

$$\mu = m_B - (M_B - \Delta)$$

$$\mu = m_B - (M_\mathrm{B} - \alpha(s-1) + \beta C)$$

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

COSMOLOGY WITH TYPE Ia SUPERNOVAE

Table 8.

Analysis	Model	w	Ω_m	Ω_Λ
SN-stat	ΛCDM		0.284 ± 0.012	0.716 ± 0.01[illegible]
SN-stat	oCDM		0.348 ± 0.040	0.827 ± 0.06[illegible]
SN-stat	wCDM	-1.251 ± 0.144	0.350 ± 0.035	
SN	ΛCDM		0.298 ± 0.022	0.702 ± 0.02[illegible]
SN	oCDM		0.319 ± 0.070	0.733 ± 0.11[illegible]
SN	wCDM	-1.090 ± 0.220	0.316 ± 0.072	

ΛCDM model: flat, $\omega = -1\,, \Omega_K = 0$

oCDM model: flat, $\omega = -1$, Ω_k varies

ωCDM model: flat, ω_o varies, $\omega_a = 0$

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

COSMOLOGY WITH TYPE Ia SUPERNOVAE

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

COSMOLOGY WITH TYPE Ia SUPERNOVAE

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

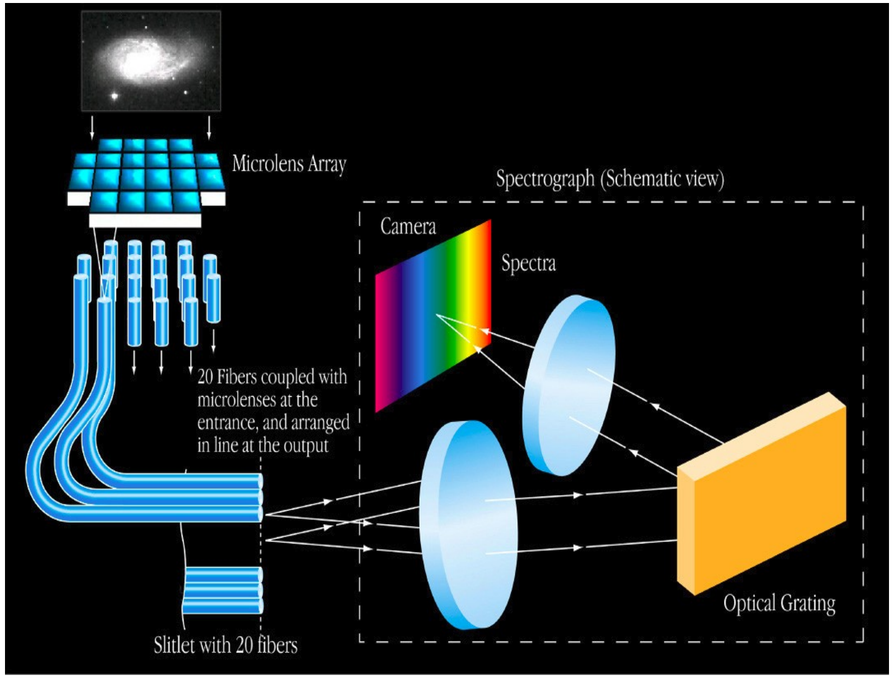
- Local versus global host properties
- Progenitor properties from metallicity of gas and stellar populations
- ...

POLARIMETRY

- Dust
- Explosion models

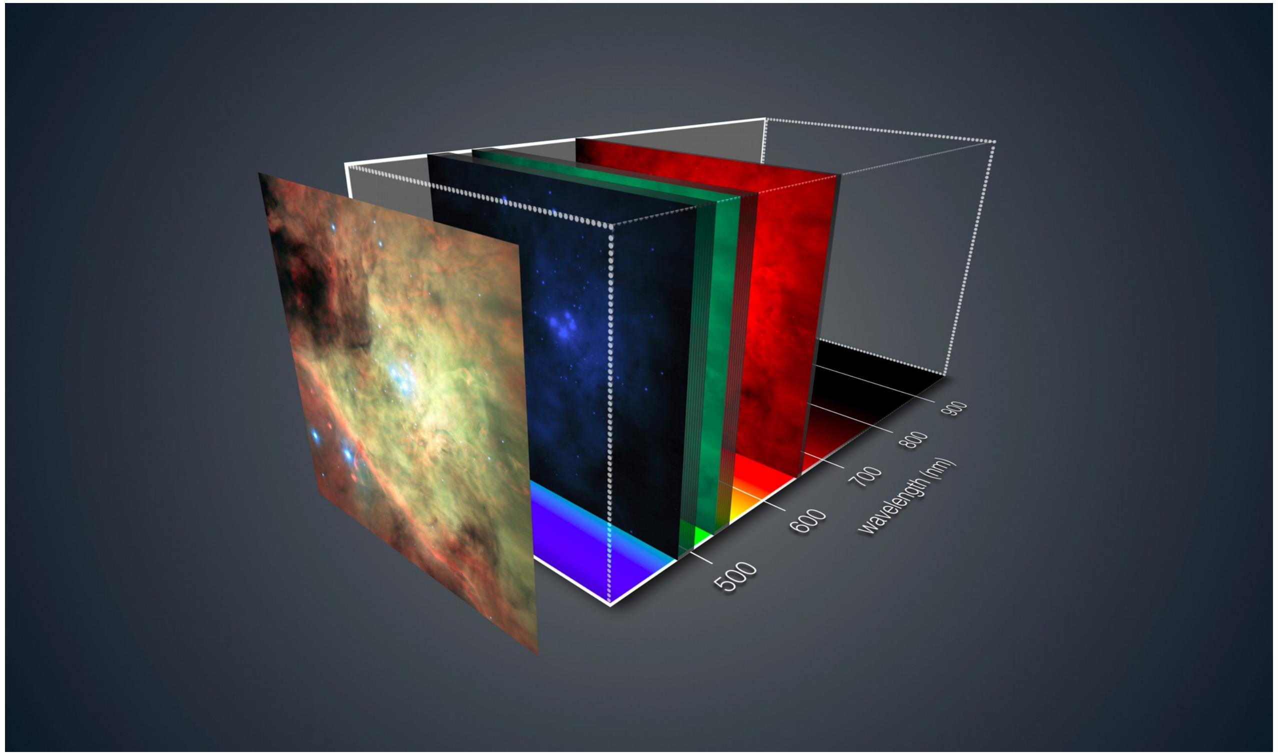
INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY



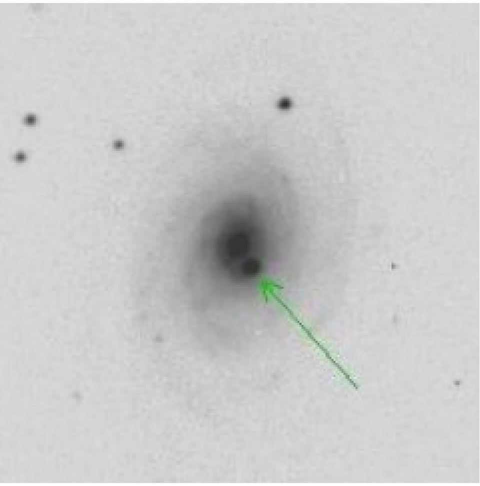
INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY

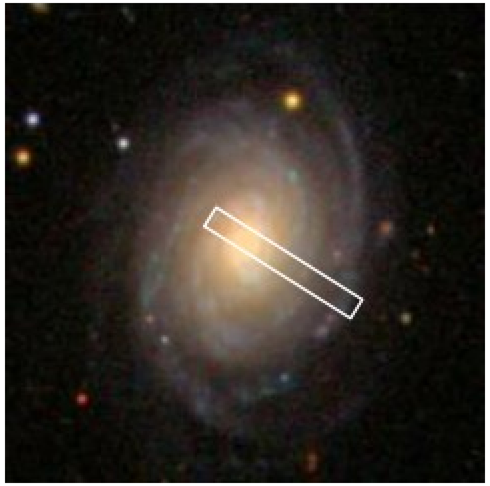


One image: data cube

INDIRECT STUDIES OF SN PROGENITORS



Photometry

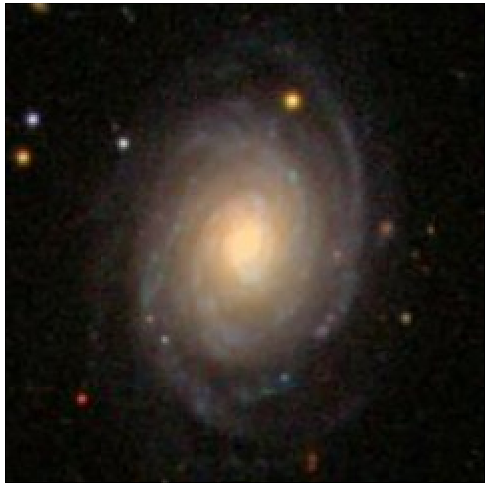


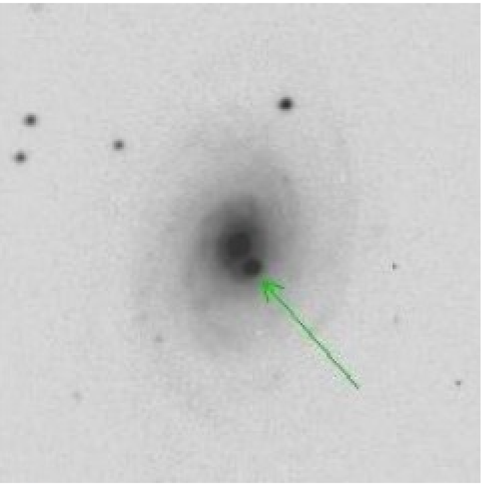
Slit spectroscopy

Fiber

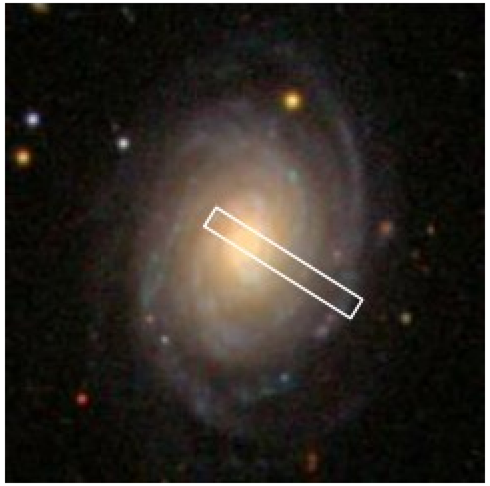
IFS: SNIFS
FoV 5”x5”

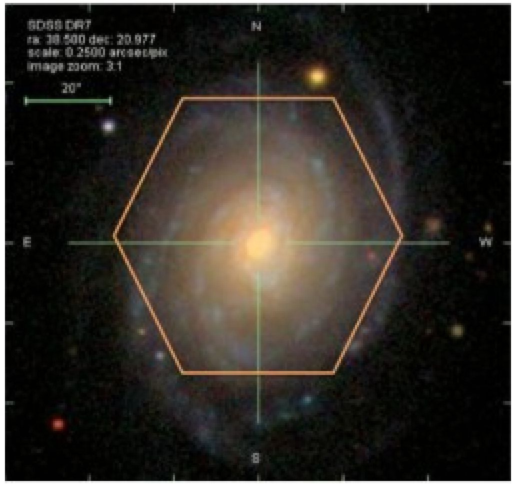
INDIRECT STUDIES OF SN PROGENITORS





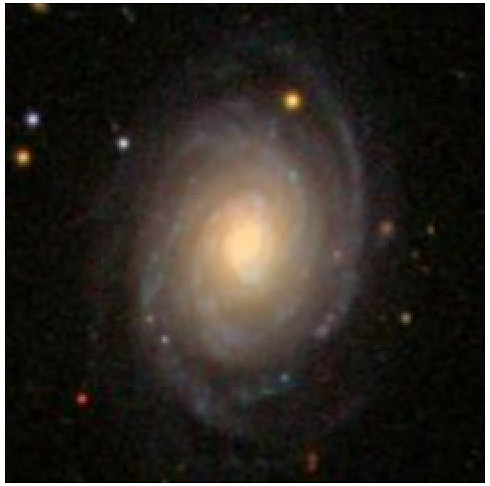
IFS @ CAHA (PPAK)

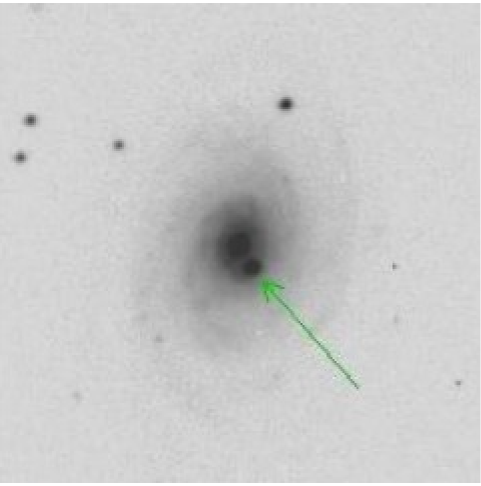


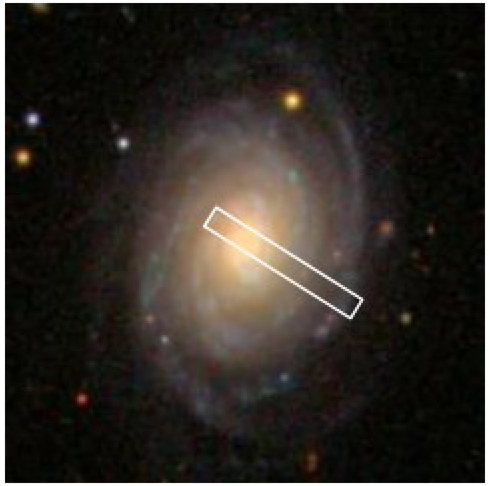


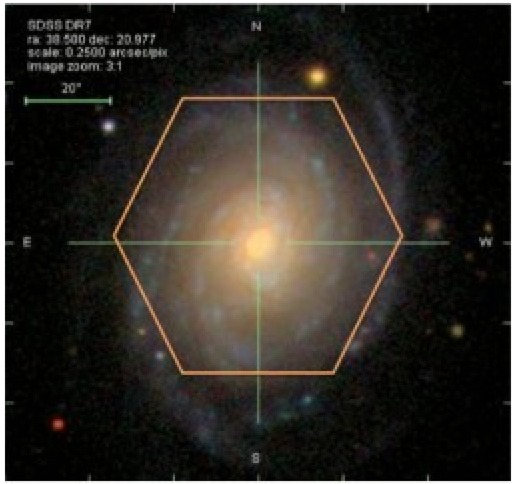
Stanishev, Mourao Rodrigues Flores, 2012

INDIRECT STUDIES OF SN PROGENITORS







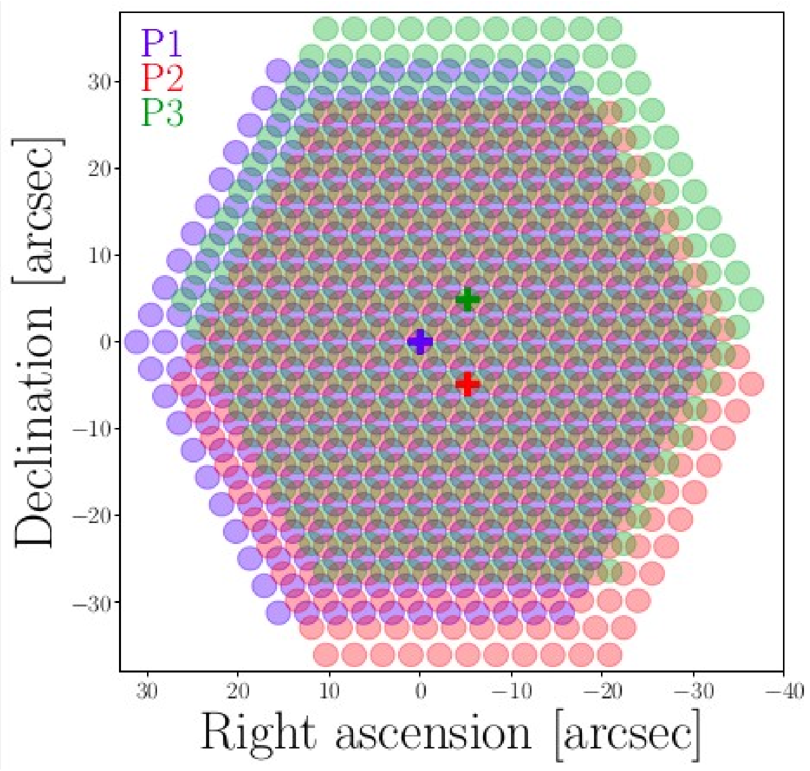


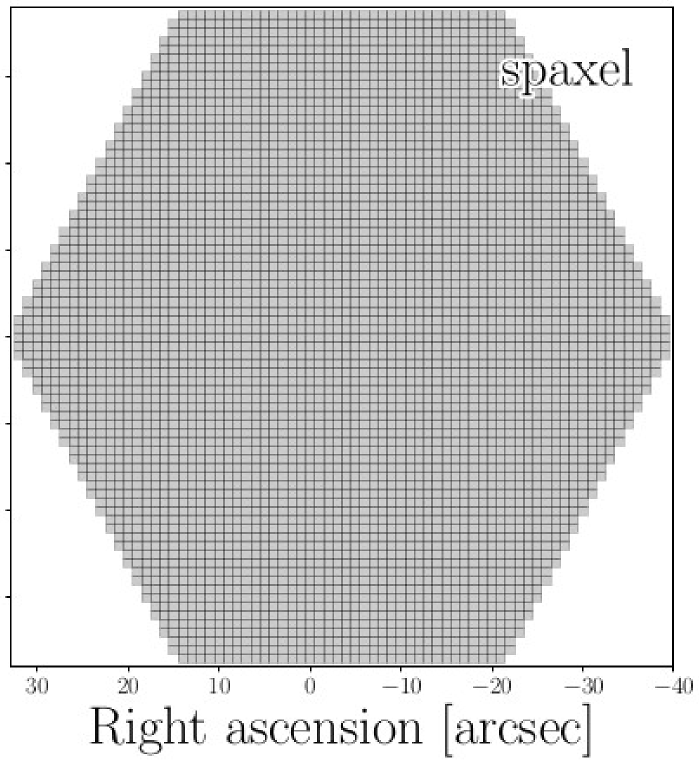
IFS @ CAHA

Stanishev, Mourao Rodrigues Flores, 2012

INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY





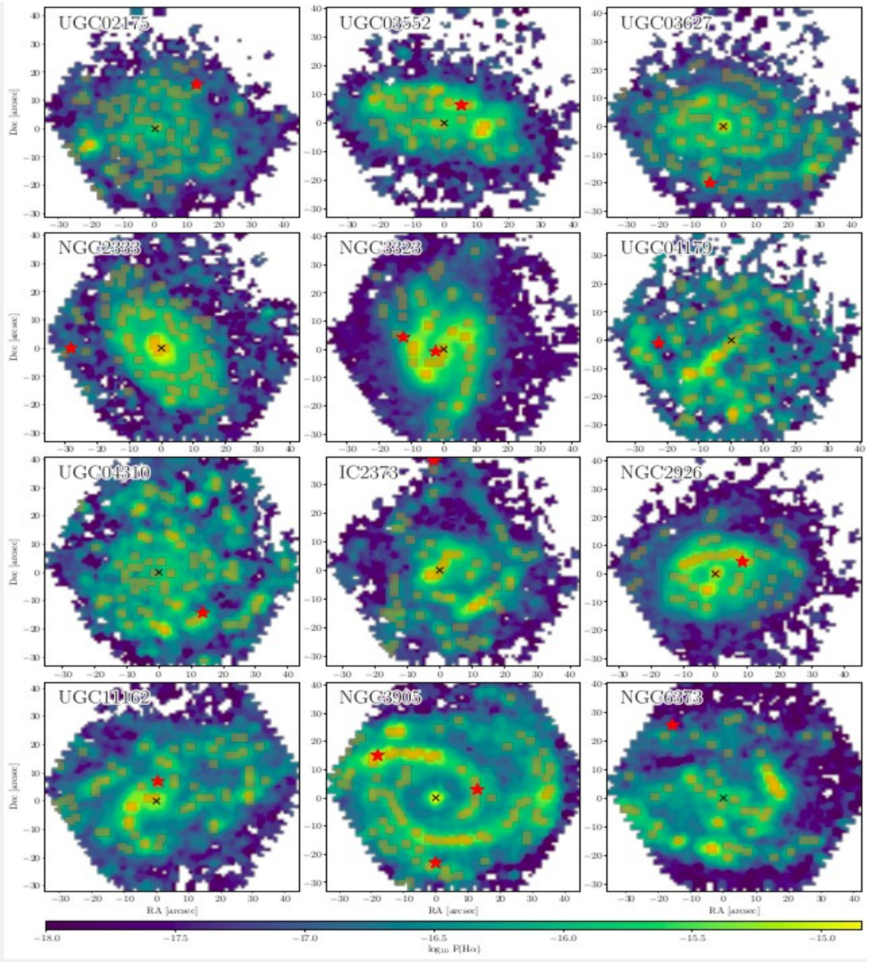
331 fibers D=2.7”
FoV~1'x1'
1st observations 2009

Test run: Stanishev et al '12
CALIFA: Galbany et al '14

PISCO: Galbany et al '18

INDIRECT STUDIES OF SN PROGENITORS

INTEGRAL FIELD SPECTROSCOPY

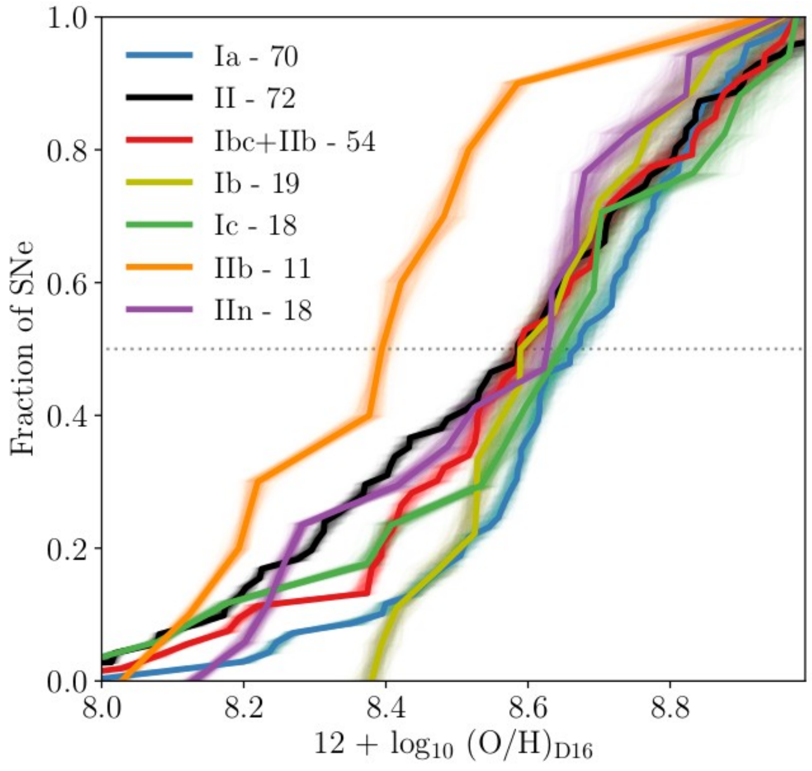


PISCO- PMAS IF Supernova Compilation:
232 SN hosts
272 SNe

Galbany+ '18

INDIRECT STUDIES OF SN PROGENITORS

GAS METALLICITY

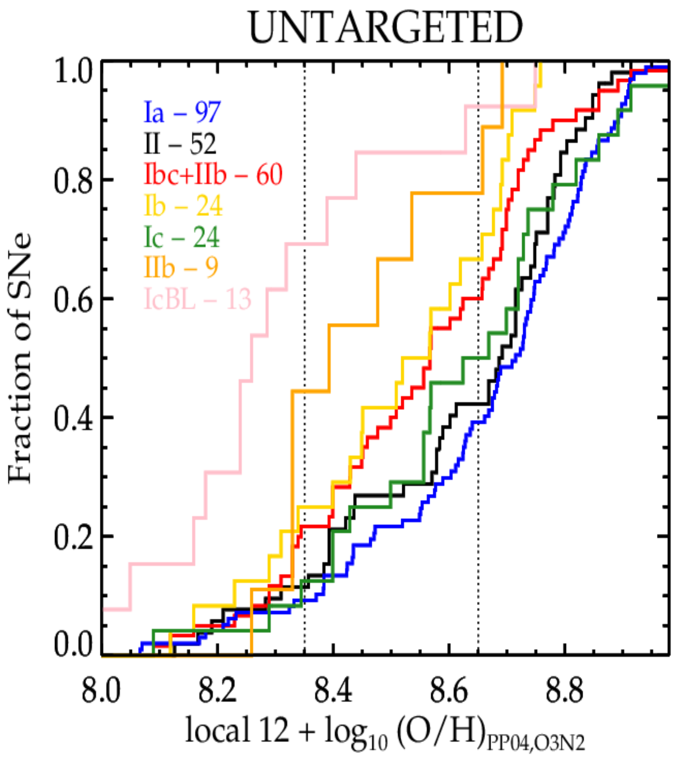


Galbany et al '18

Oxygen abundances in 1kpc SN environment

INDIRECT STUDIES OF SN PROGENITORS

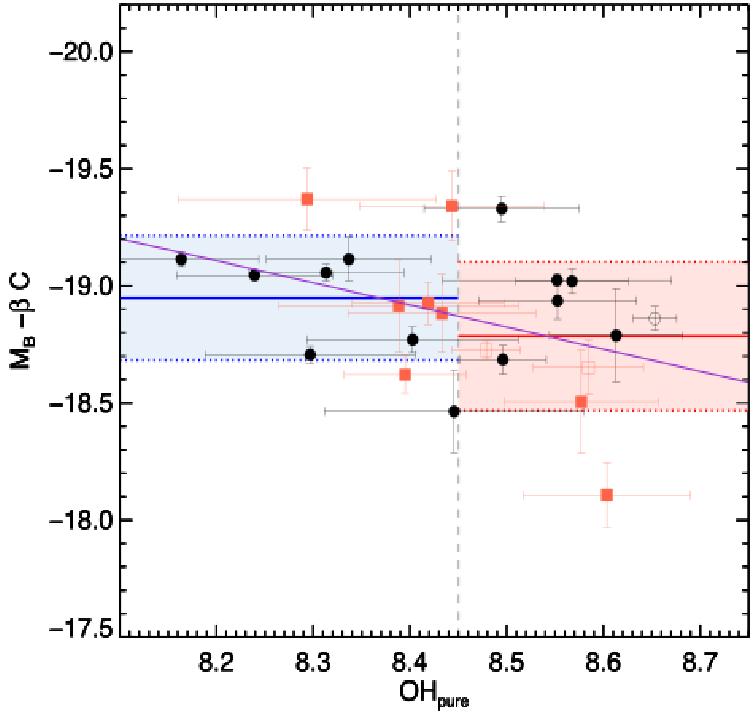
GAS METALLICITY



Galbany et al '18

INDIRECT STUDIES OF SN PROGENITORS

GAS METALLICITY



$$M_B = -18.95 \pm 0.27 \text{ mag}$$

$$M_B = -18.78 \pm 0.32 \text{ mag}$$

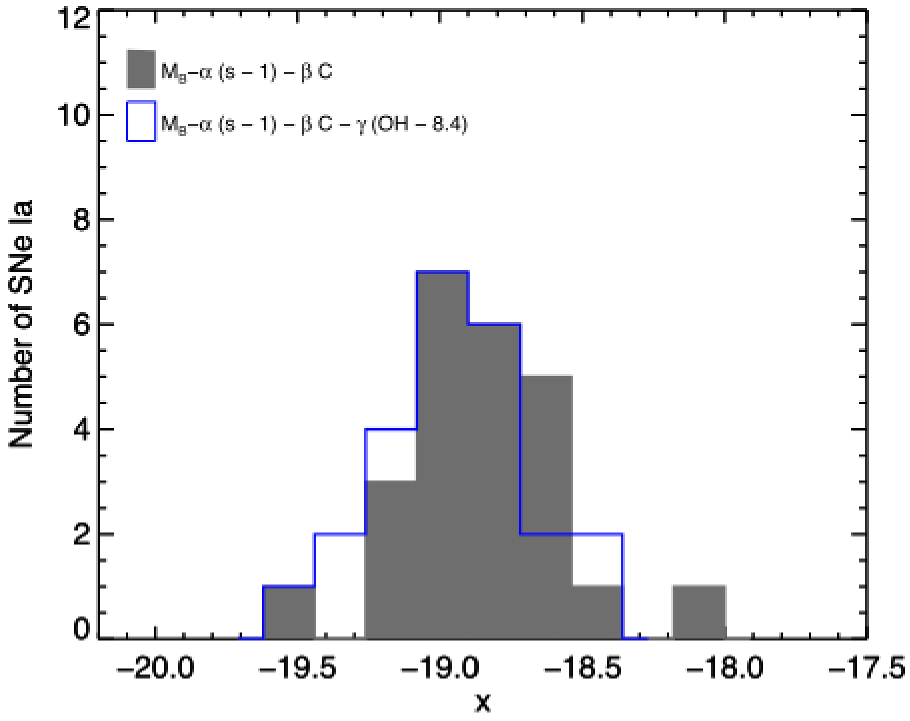
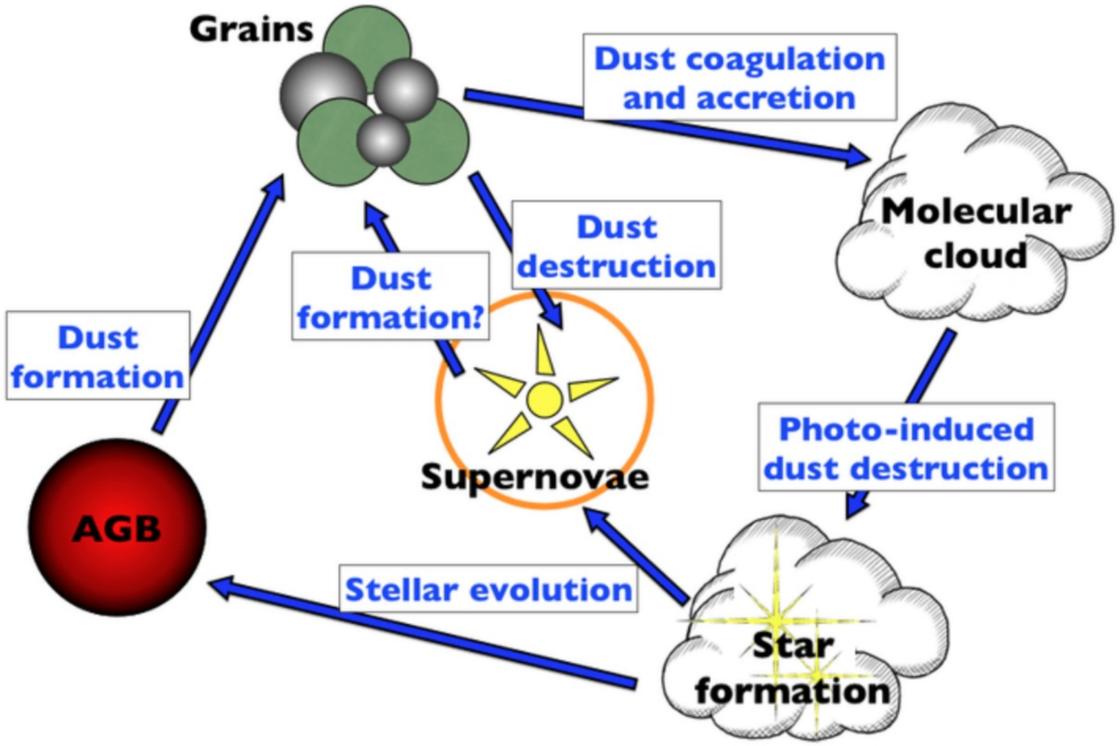


Figure 13. Histogram showing the distribution for M_B, labelled as x in the horizontal axis, with C and s dependence subtraction (grey) and removing as well metallicity dependence (blue).

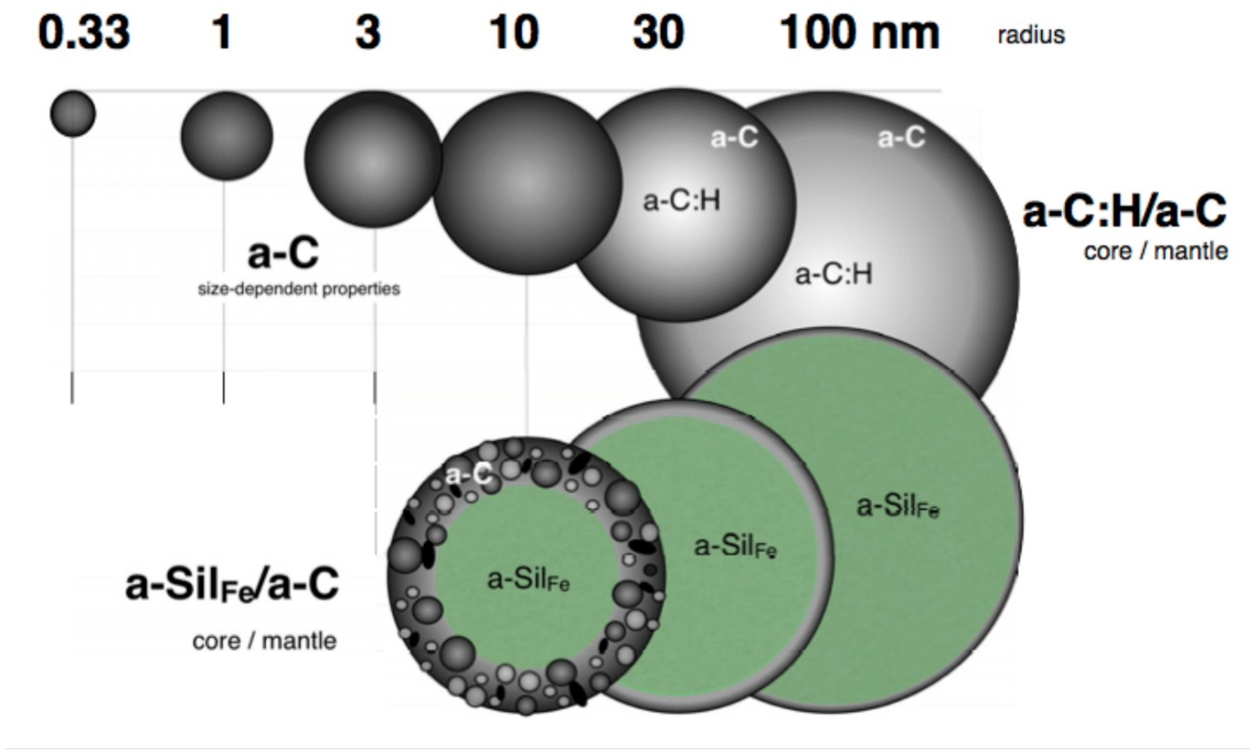
Moreno-Raya et al '16 : including metallicity reduces the scatter in ~5%

DUST PROPERTIES: COMPOSITION AND SIZE



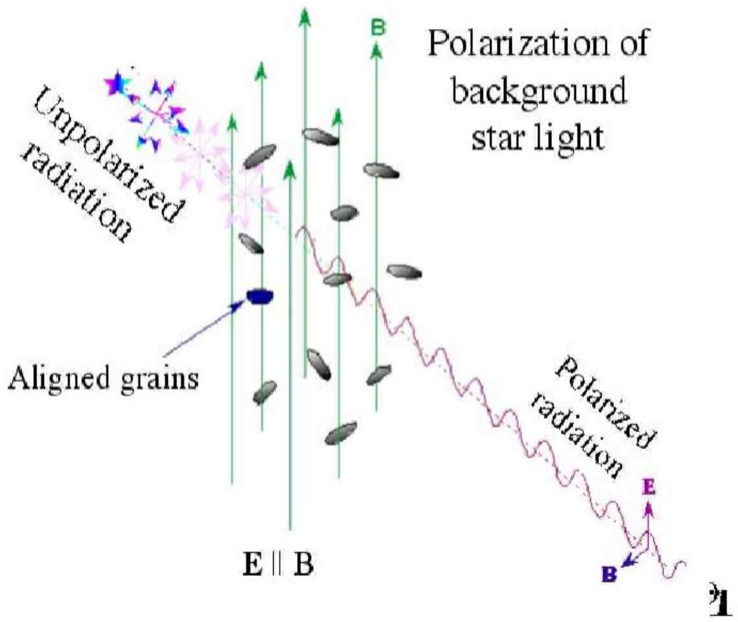
M. Bocchio 2014

DUST PROPERTIES: COMPOSITION AND SIZE



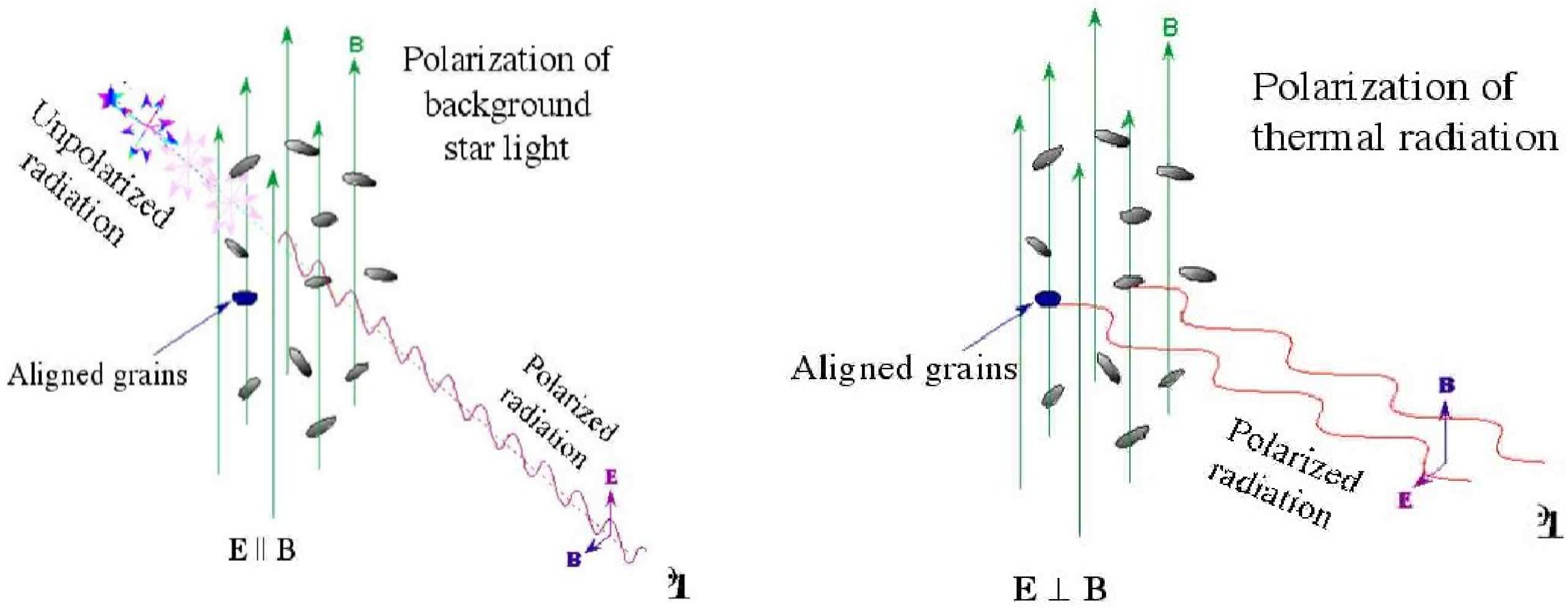
Jones+ 2014

DUST PROPERTIES AND INTERSTELLAR POLARIZATION



Lazarian '08

DUST PROPERTIES AND INTERSTELLAR POLARIZATION



Lazarian '08

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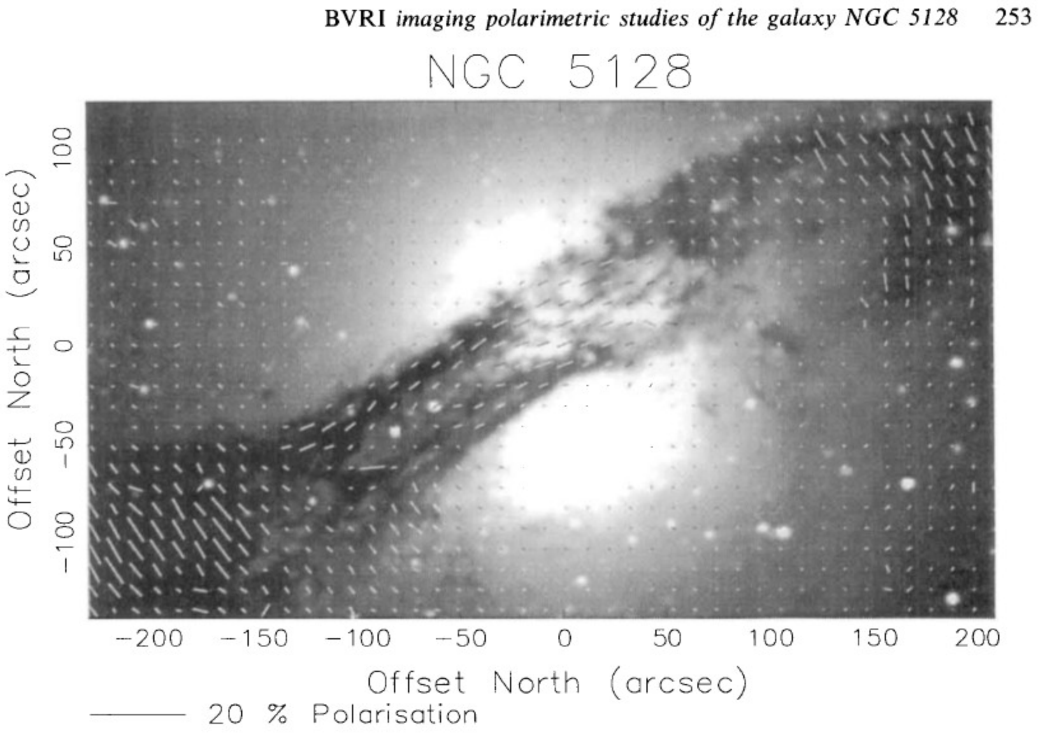


Host of the SN1976G

Scarrott+ 1996

DUST PROPERTIES AND INTERSTELLAR POLARIZATION

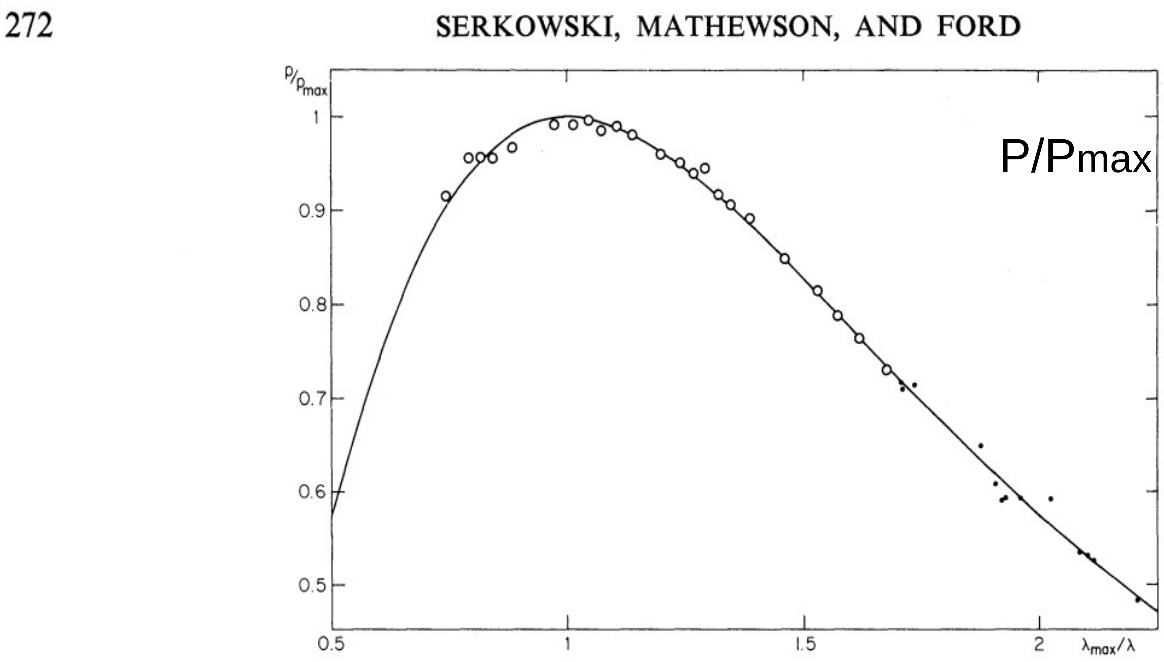


FIG. 3.—The normalized wavelength dependence of interstellar linear polarization derived from the observations with the Siding Spring multichannel polarimeter-photometer. The solid line is calculated from eq. (4) for $K = 1.15$. Every open circle is based on 20 stars, while each dot represents the observations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

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

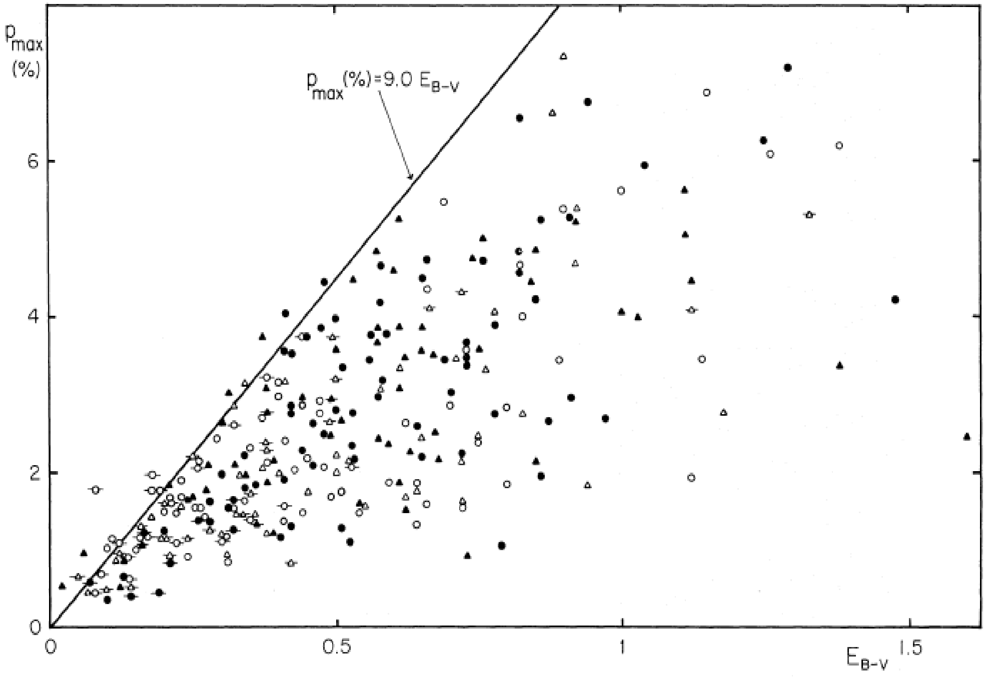
$$K = 1.86\,\lambda_{max} - 0.1$$

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

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

Serkovski+ '75,
Clayton and Mathis '98
Draine '03
Wilking+ '82
Tielens, Interstellar Medium, ' 05

DUST PROPERTIES AND INTERSTELLAR POLARIZATION



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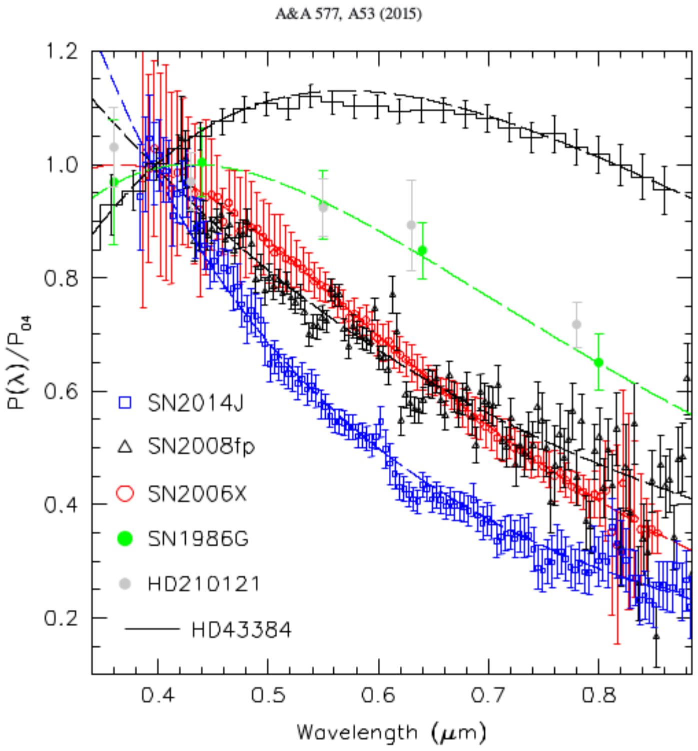
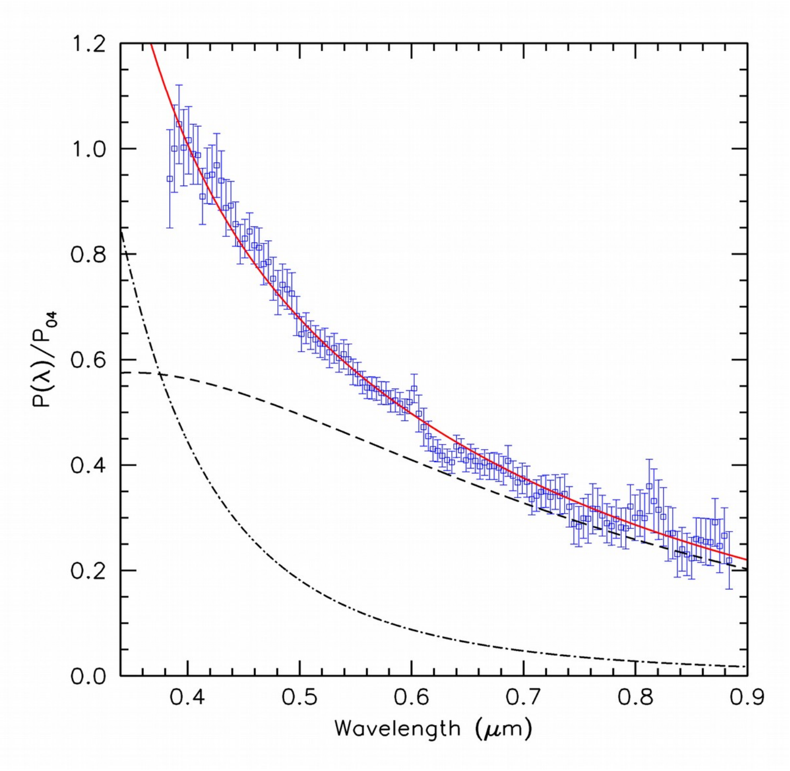
DUST PROPERTIES FROM LINEAR SN POLARIMETRY



Patat+ '15

DUST PROPERTIES FROM LINEAR SN POLARIMETRY



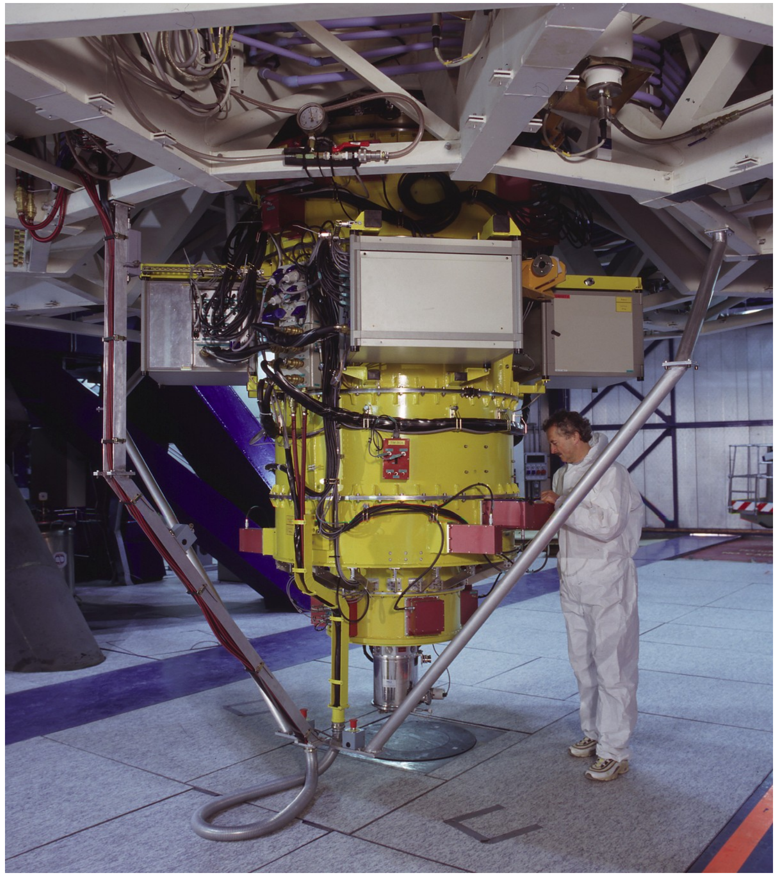
Patat+ '15

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 SNIa

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

POLARIMETRY of SN HOST GALAXIES

In progress:
First statistical study of
multi-band optical polarimetry
of supernova host galaxies

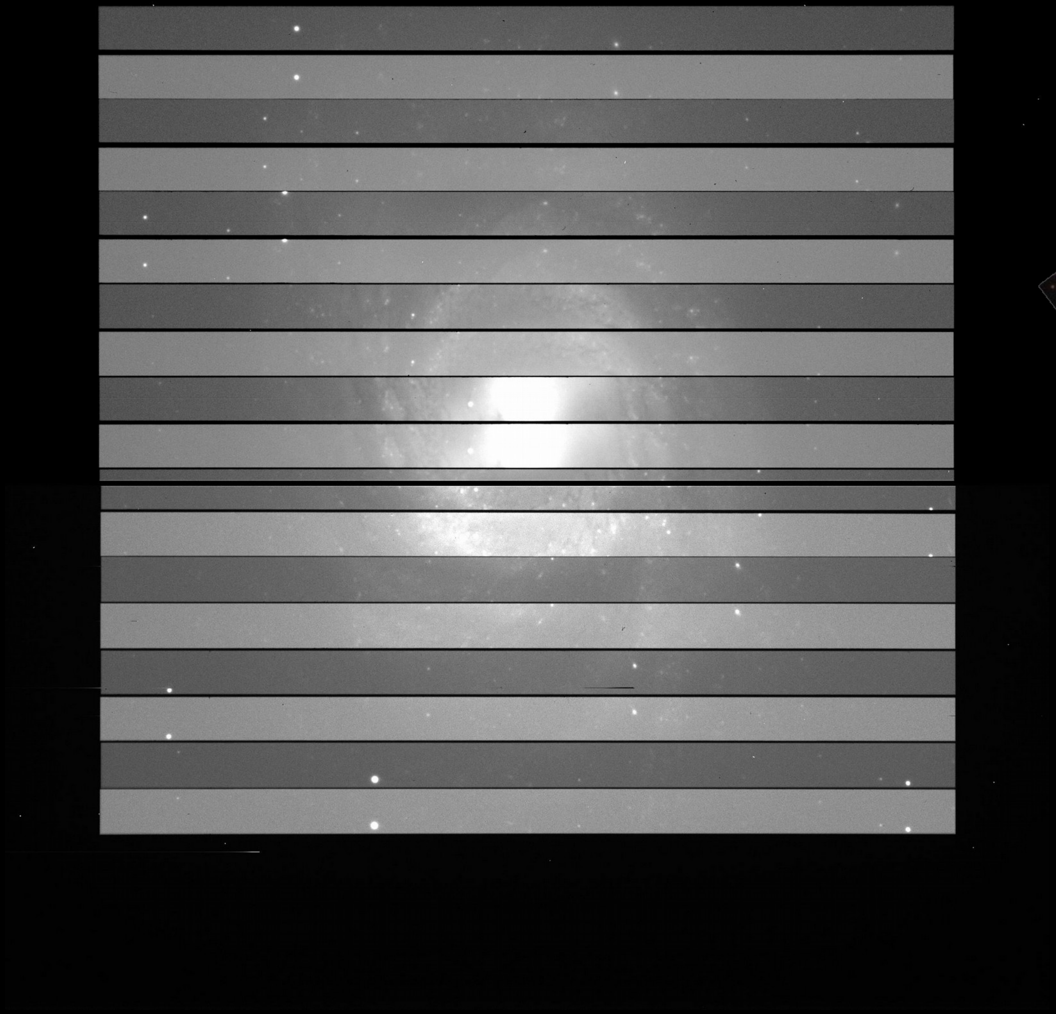
@ESO FORS2

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

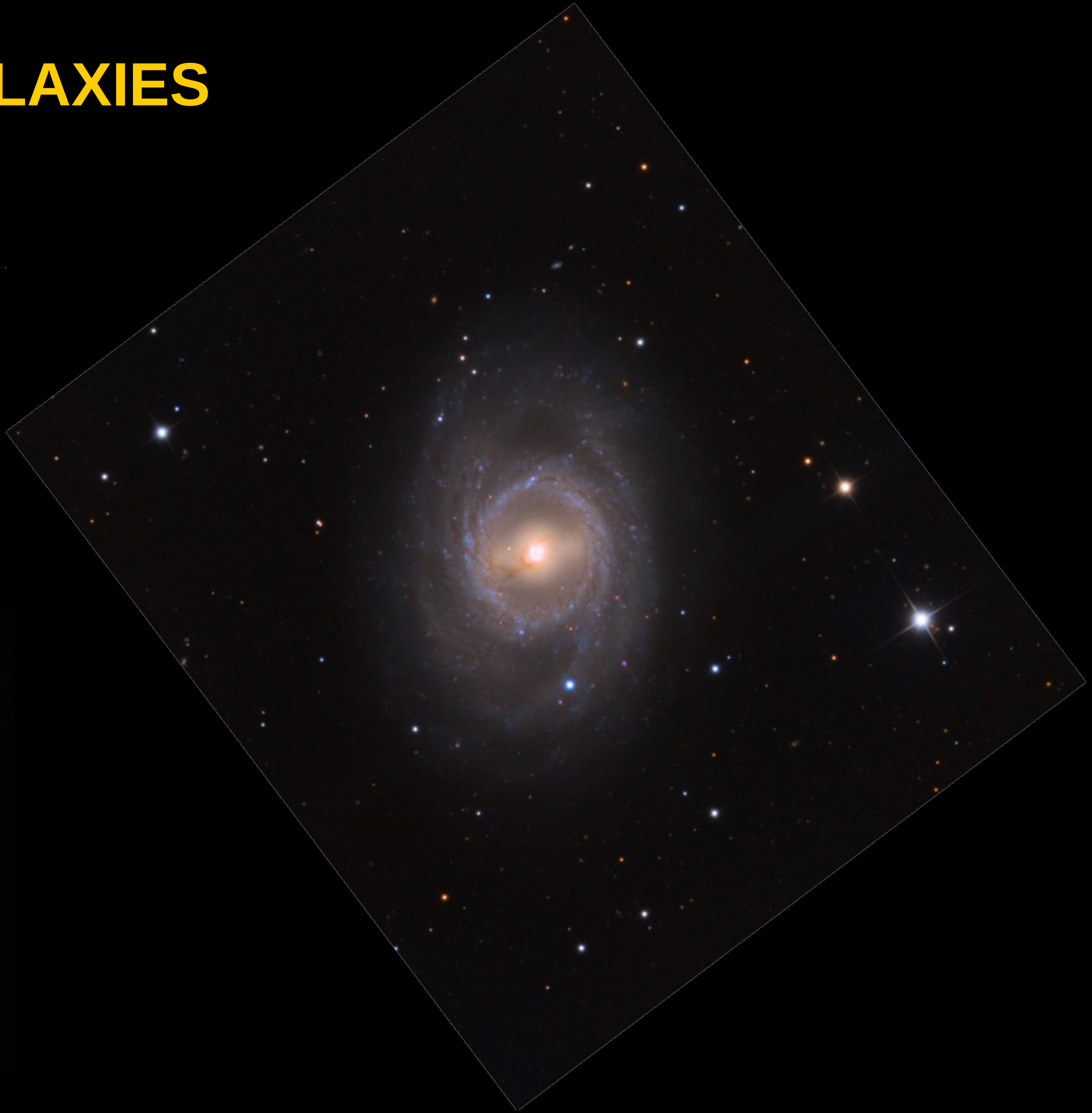
Goal
Map the wavelength of the polarization

Infer dust properties

POLARIMETRY of SN HOST GALAXIES



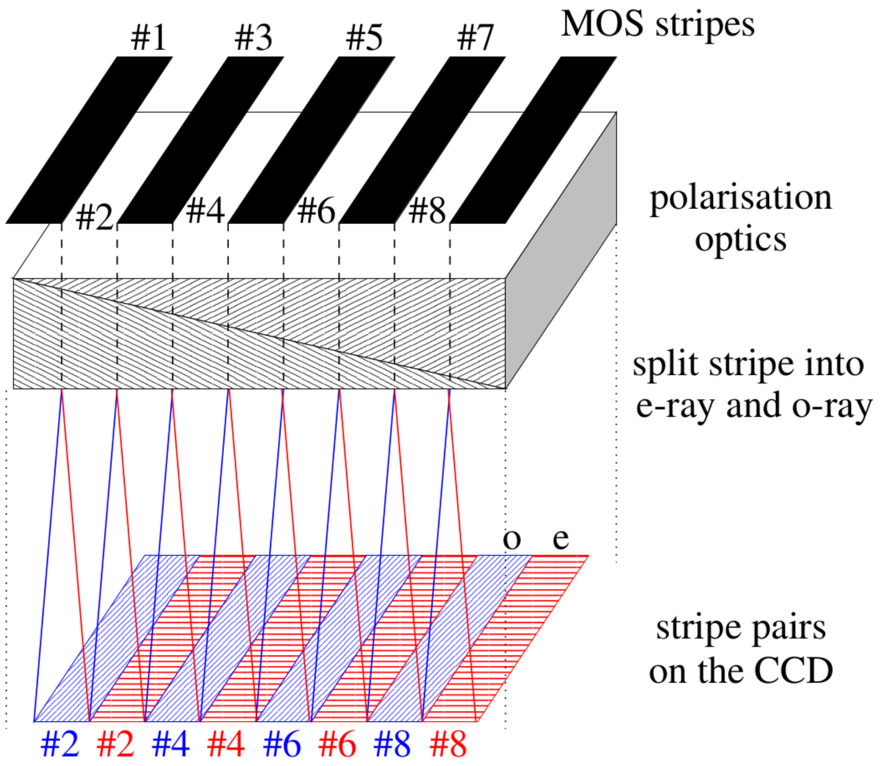
NGC 3351



dam Block, Mt. Lemmon SkyCenter, University of Arizona

FORS2: POLARIZATION OPTICS

WOLLASTON PRISM



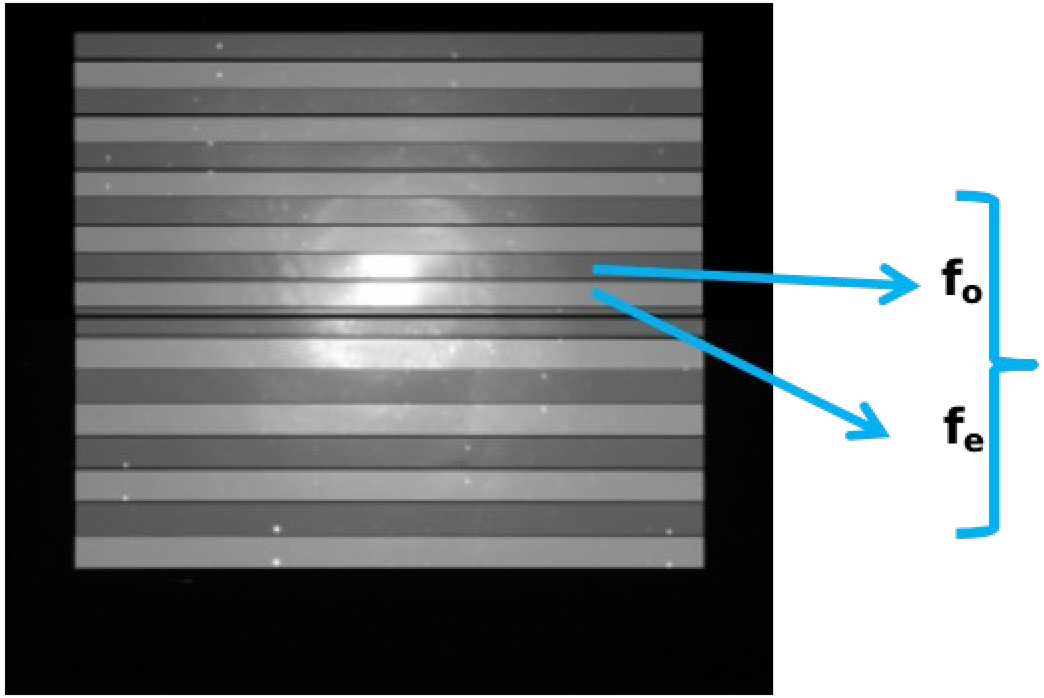
Schematic representation of a dual-beam polarimeter

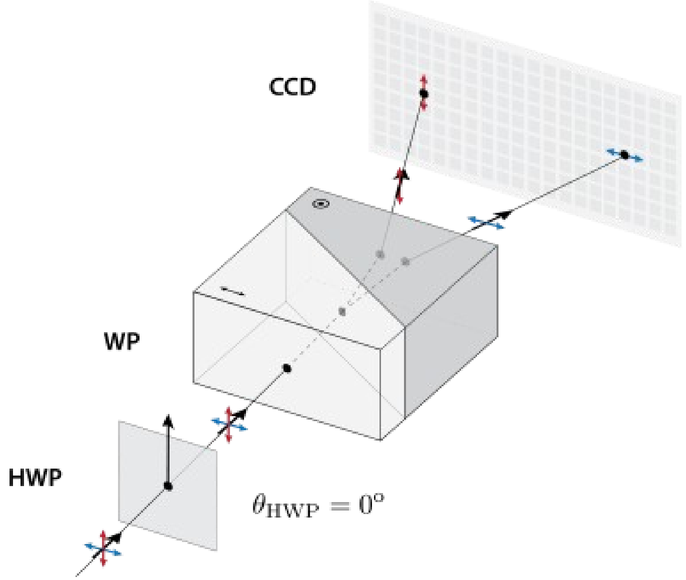
initial light ray with two polarization states (shown in blue and red)

ESO FORS2 Manual

FORS2: POLARIZATION OPTICS

WOLLASTON PRISM





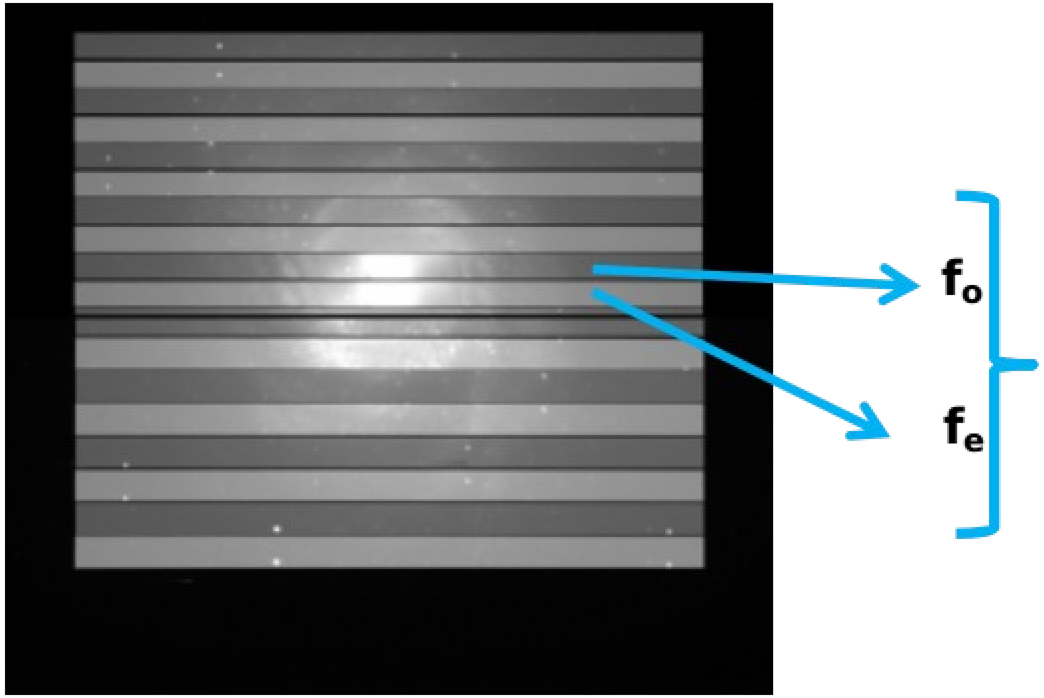
Stokes parameters $\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$

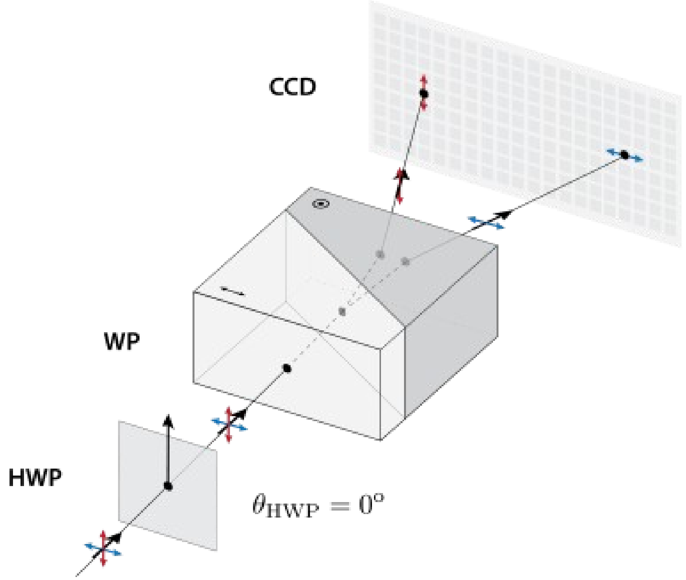
Gonzalez-Gaitan '19 in preparation

Patat & Romaniello '06

FORS2: POLARIZATION OPTICS

WOLLASTON PRISM





Stokes parameters
$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \qquad P = \frac{\sqrt{Q^2 + U^2}}{I}$$
$$\chi = \frac{1}{2} \arctan \frac{U}{Q}$$

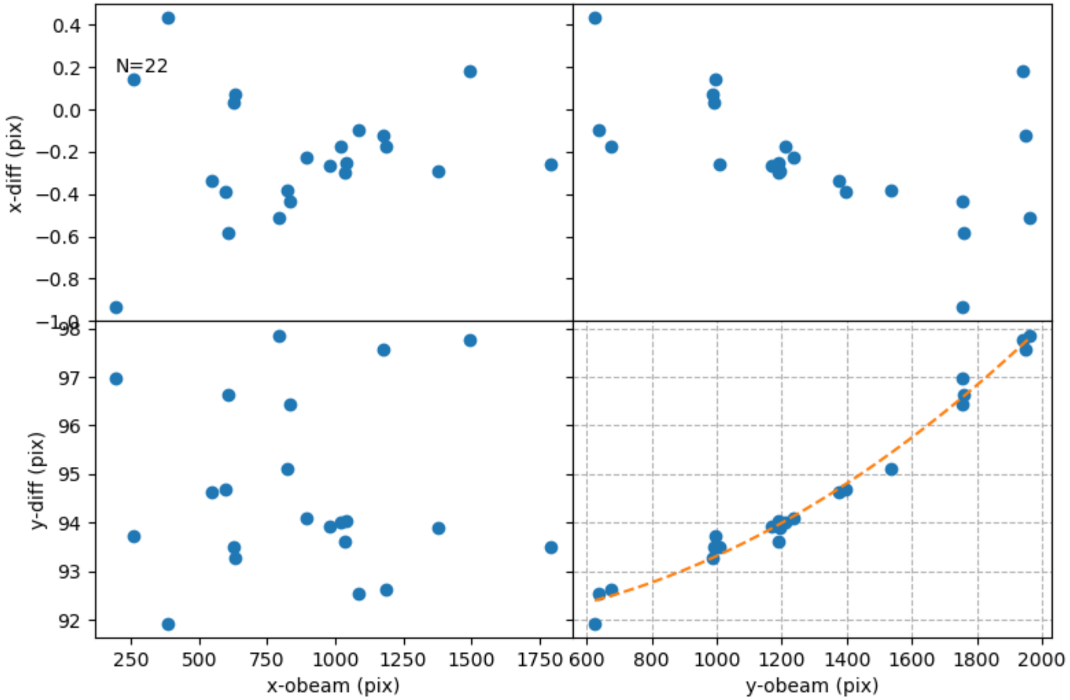
Gonzalez-Gaitan '19 in preparation

Patat & Romaniello '06

FORS2: POLARIZATION OPTICS

WOLLASTON PRISM: check for systematics

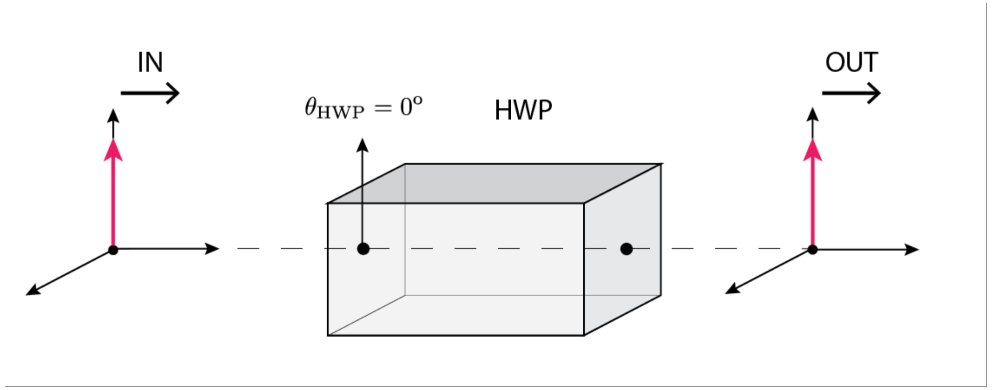
B HIGH: y_o-y_e

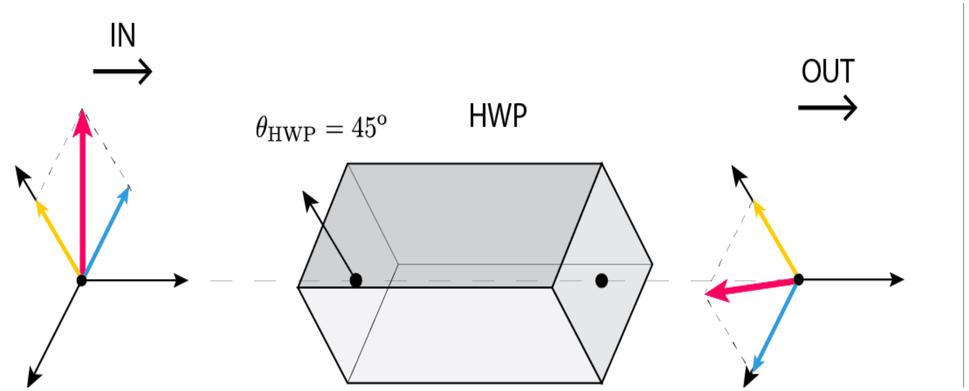


Gonzalez-Gaitan '19 in preparation

FORS2: POLARIZATION OPTICS

Retarder plate





Gonzalez-Gaitan '19 in preparation

Plots by J. Lopes

FORS2: POLARIZATION OPTICS

$$F_i \equiv \frac{f_{O,i} - f_{E,i}}{f_{O,i} + f_{E,i}}$$

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

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

$$\chi = \frac{1}{2}\arctan\frac{U}{Q}$$

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

Gonzalez-Gaitan '19 in preparation

Patat & Romaniello '06

FORS2: POLARIZATION OPTICS

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

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

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

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

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

Polarization spectrum

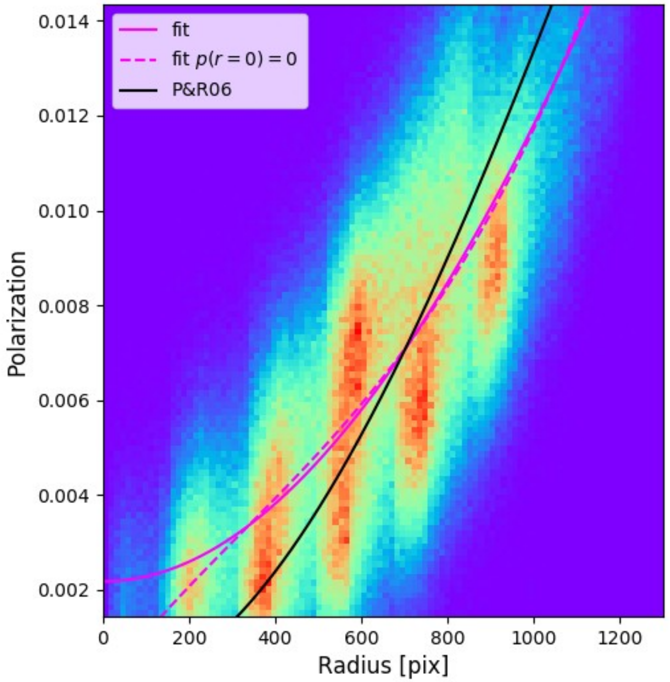
$$P_k = \sqrt{Q_k^2 + U_k^2}$$

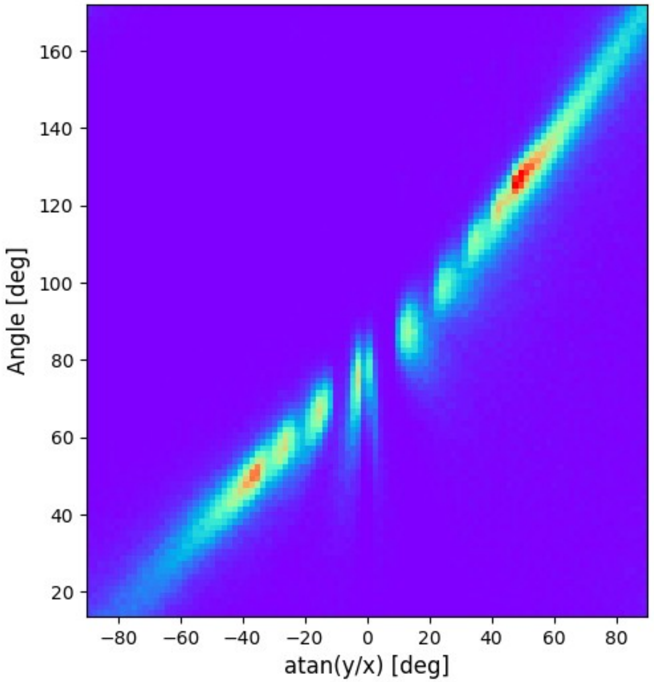
Signal @*N*/4 harmonic

Gonzalez-Gaitan '19 in preparation

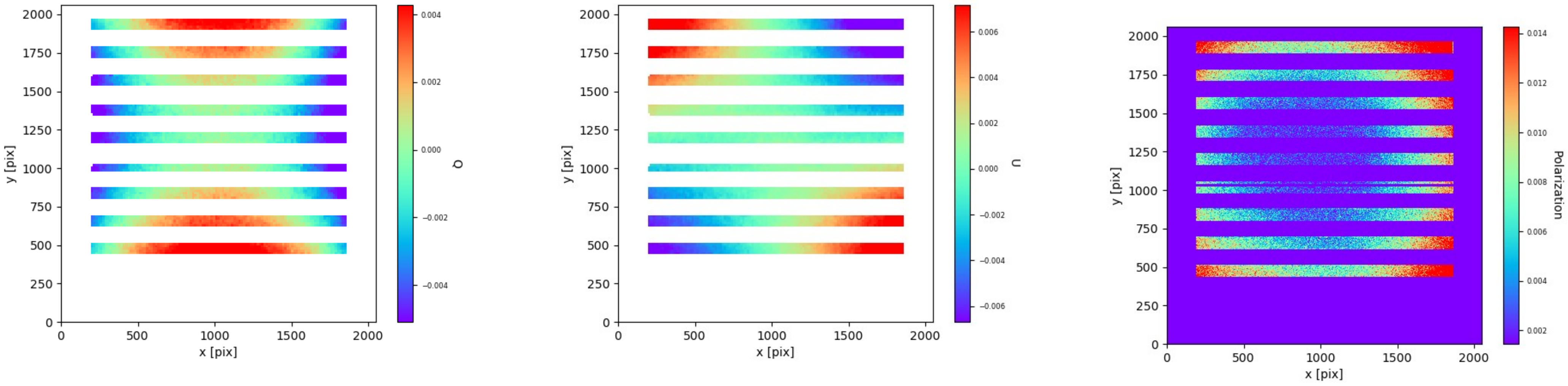
Patat & Romaniello '06

FORS2: IPOL MODE CALIBRATION





FORS2: IPOL MODE CALIBRATION WITH FULL MOON



in B

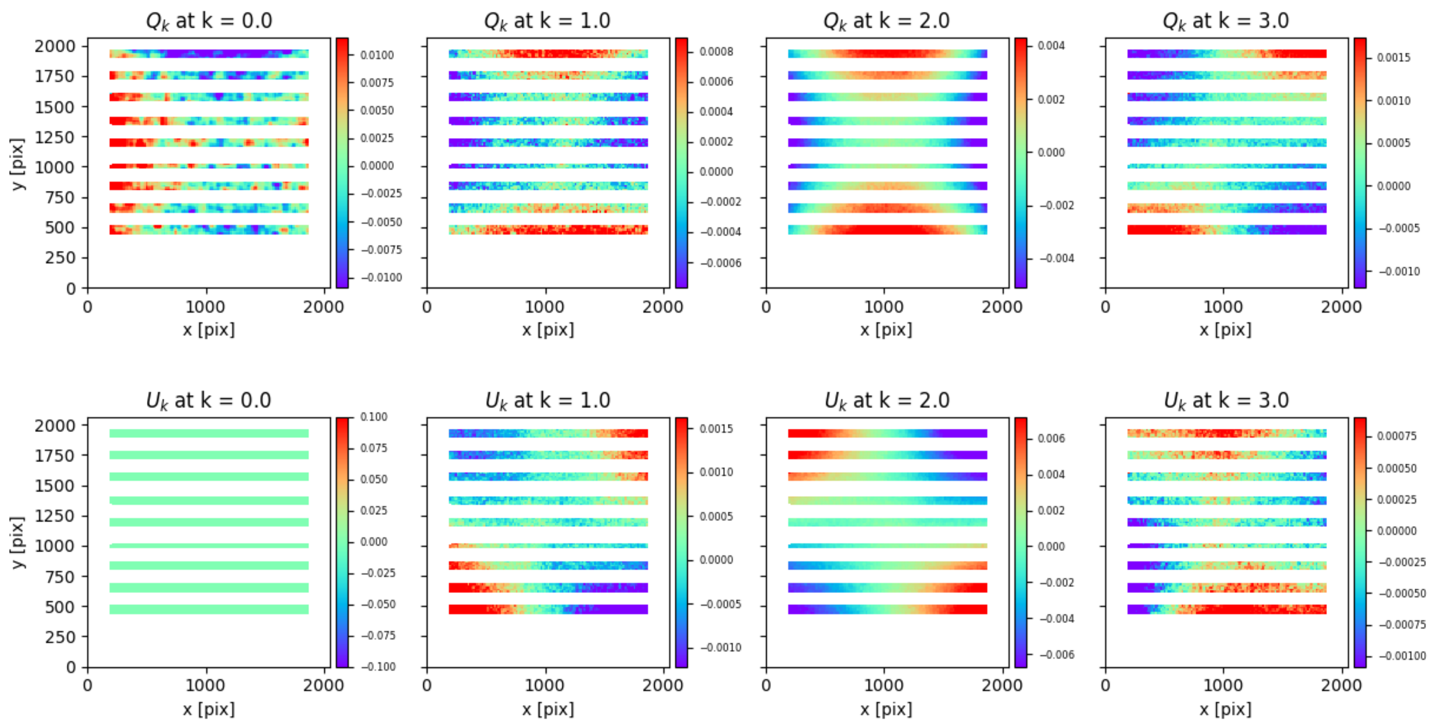
estimation of the instrumental polarization in FORS2, including

- 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

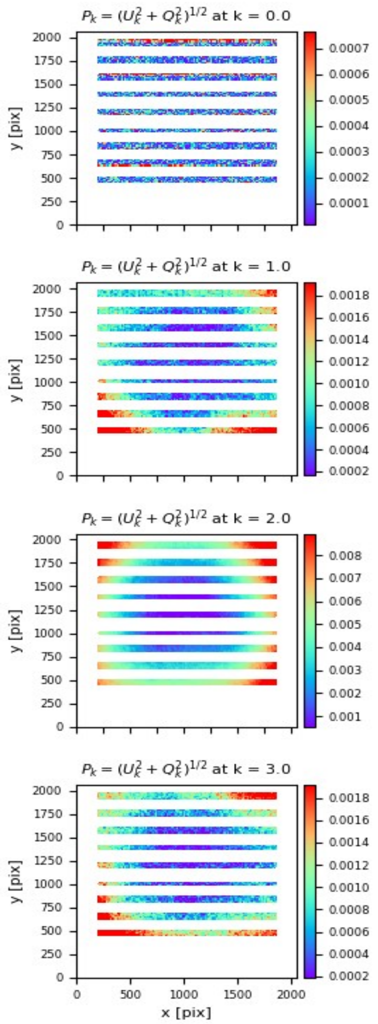
Filter B



bin: 30x30

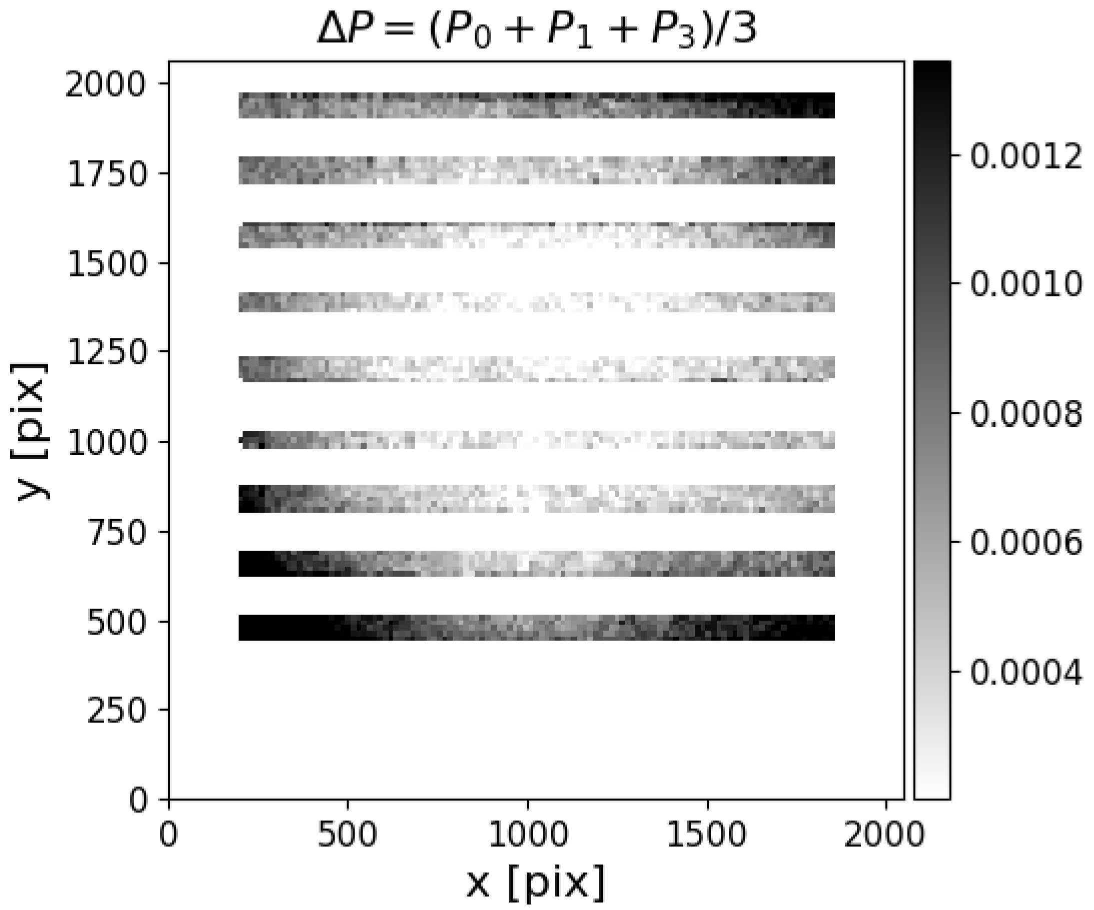
FORS2: IPOL MODE CALIBRATION

Polarization spectrum



Filter B

FORS2: IPOL MODE CALIBRATION



Residual in B

The Future of SN Ia Cosmology at a Glance

Low-z [z<0.1]

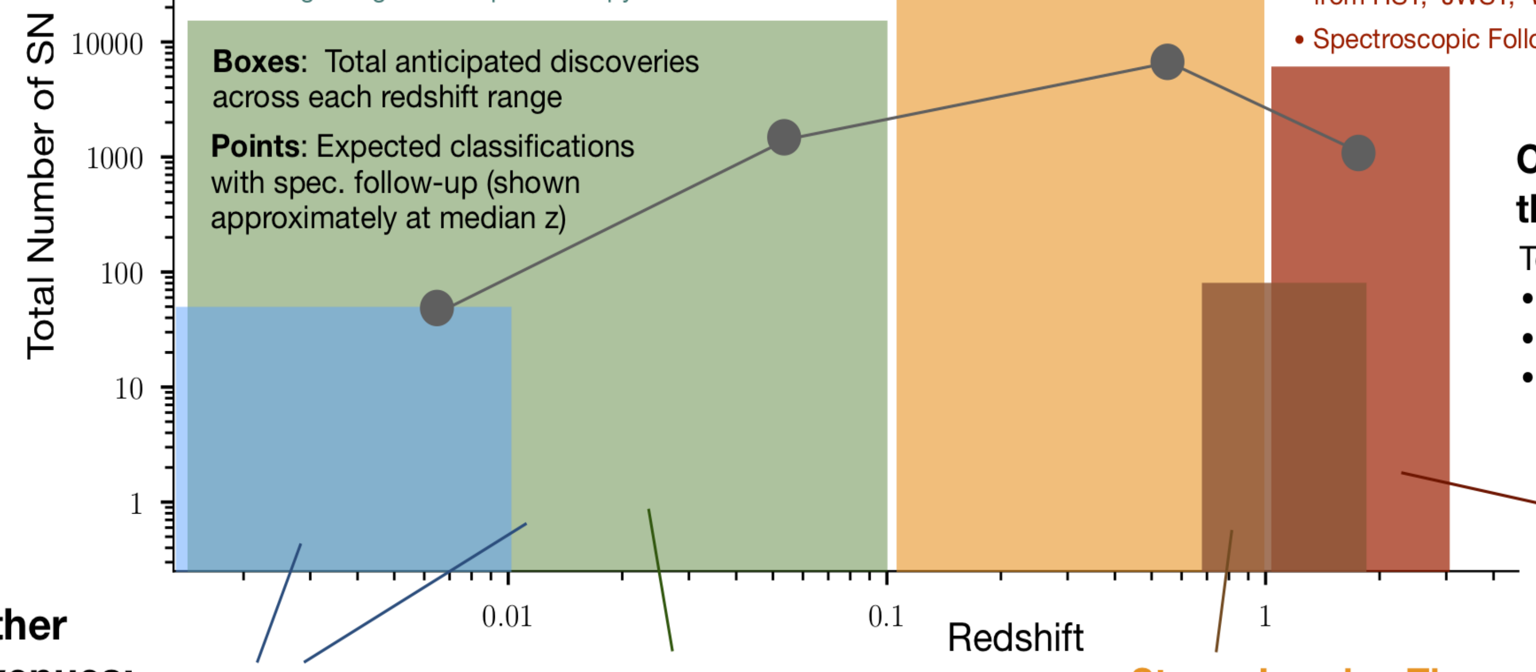
- Discovery: ~2000/yr from ASASSN, PS, ATLAS, ZTF, LSST
- Imaging Follow-up: 1500 SN - Foundation, full LSST/ZTF
- Spectroscopic Follow-up: (on 2m telescopes)
  Confirmation: single-object spectroscopy
  Twinning: integral field spectroscopy

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

σ_8 via Weak Lensing

- Limited by max redshift of survey
- Signal goes with ~0.05z
- Top systematics: population drift, selection effects

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

$f\sigma_8$ 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

Additional avenues include isotropy tests and galaxy survey correlations

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CONCLUSIONS

INTEGRAL FIELD SPECTROSCOPY

IMAGING AND SPECTROPOLARIMETRY

UNDERSTAND SUPERNOVAE

IMPACT ON COSMOLOGY