SPICA FIR Polarimetry for ISM and Transient Objects

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- Summary

Context of SAFARI_Pol ($\boldsymbol{\sigma_P = 0.3\%}$, $\boldsymbol{T_d = 20}$K,)

SPICA/SAFARI fact sheet; Dowel+ 2010

- Planck mapped 850μm pol. of entire MW gal. where $A_V > 4$ with $\sim$5' resolution.
- ALMA performs high-reso. ($\sim$0.3") 450μm pol. mapping over 20" FoV where $A_V > 100$.
- JCMT and SOFIA perform Sub-mm and FIR pol. mapping for arcmin-sized clouds where $A_V > 4$ with $\sim$10" reso.

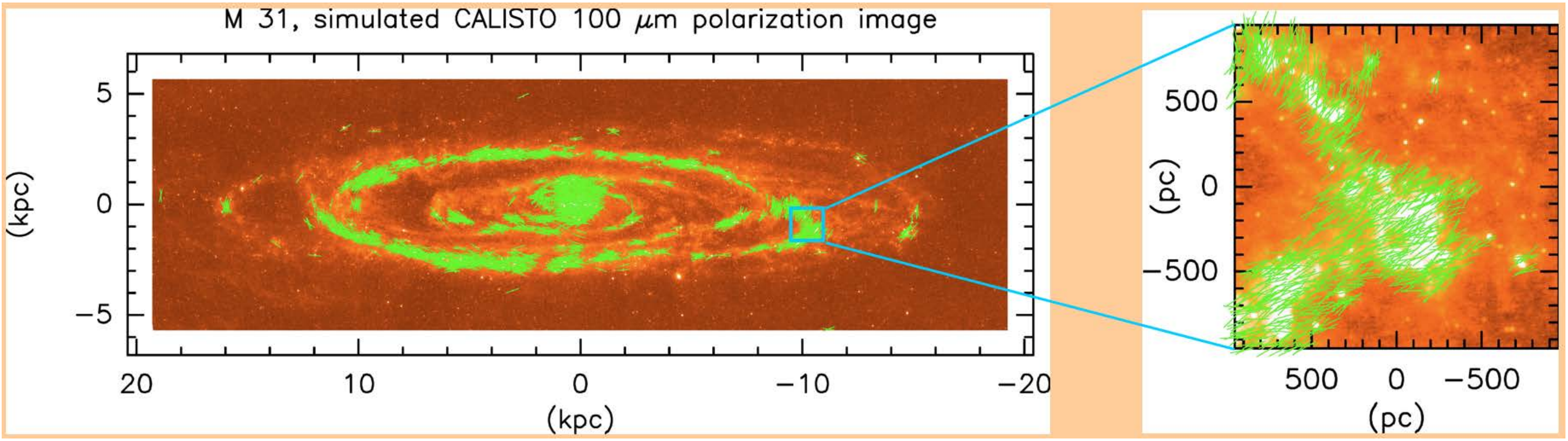
- **SPICA/SAFARI_Pol reaches**
  - **pol. mapping $1° \times 1°$ field with $\sim$20" reso. where $A_V > 0.01$(?) within 1 hr.** ← **Magnetic field of HI region**
  - **pol. of point-source of $F_\nu > 0.1$ Jy within 1 hr**

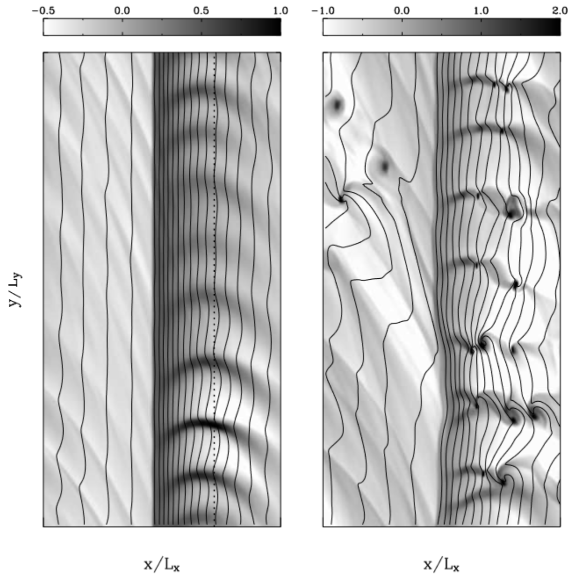
    ($F_\nu > 0.01$ Jy within 1 hr for $\sigma_P = 1\%$)

Observation of transient objects has a merit because measuring time variability is confusion-limit free!

Extragalactic IS $B_\perp$ mapping

Dowell et al. (2010)





MHD simulation of structures with spiral arms.
(Magneto-Jeans instability > swing-amplification or Parker instability; Kim 2004)

→ Probing magnetic fields associated with GMCs and their formation

See also other talks in this meeting

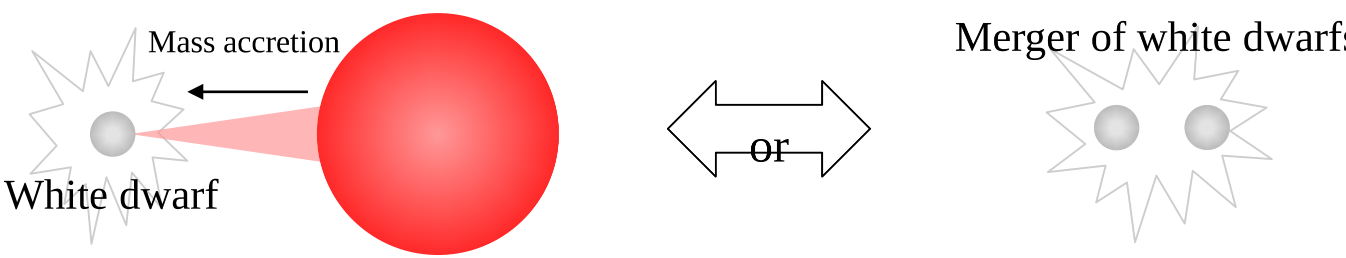
SPICA/SAFARI_Pol for

Extragalactic Interstellar dust probed by SNe Ia observation

Normal SNe Ia and Polarization

SNe Ia = Cosmic Standard Candles

Explosion of white dwarfs reaching Chandrasekhar's limiting mass ($\sim 1.4\ M_{\odot}$)



Polarimetry: Probe for asphericity of photosphere

Past polarimetry suggests a normal SNe Ia gives little or no polarization in continuum ($< 0.3\%$).

→ Photosphere is round; explosion is spherically symmetric.

→ **SNe Ia are also `bright unpolarized' light source.**

→ **Observed polarization should be interstellar origin.**

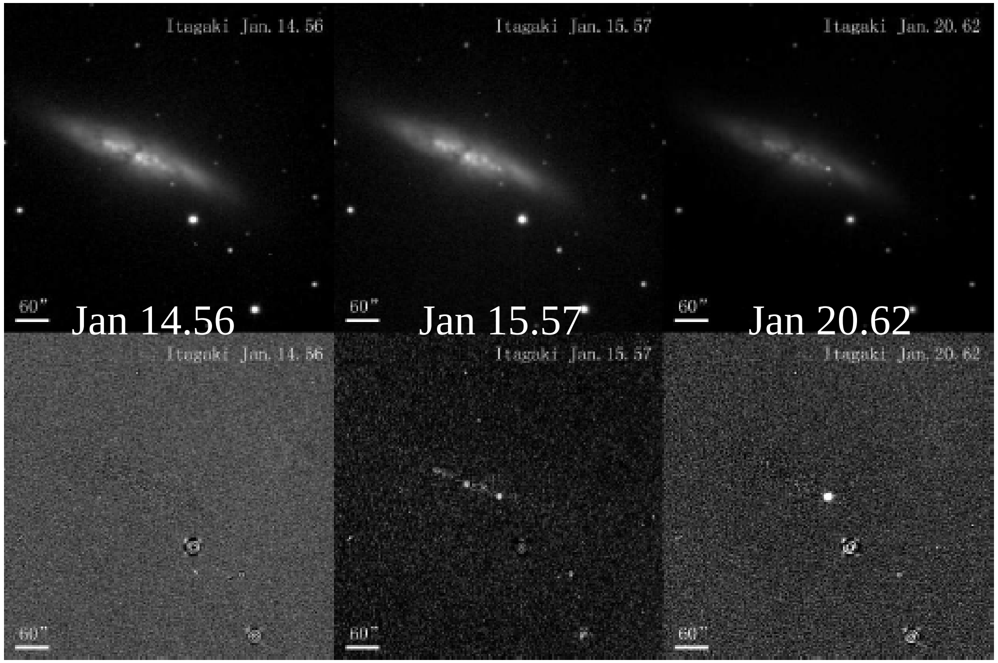
SN 2014J

- Appeared in M82 (d~4 Mpc)

Nearest SN Ia in recent quarter decade.

- Large extinction (E_V~1.3)

Opportunity to probe IS dust along the line of sight within the host galaxy.



M82銀河とSN 2014J（板垣氏撮影; Zheng+ 2014）

About 4th highly-reddened ($E_V > 1$) SNe Ia:
1986G (4Mpc), 2006X (16Mpc). 2008fp (26Mpc)

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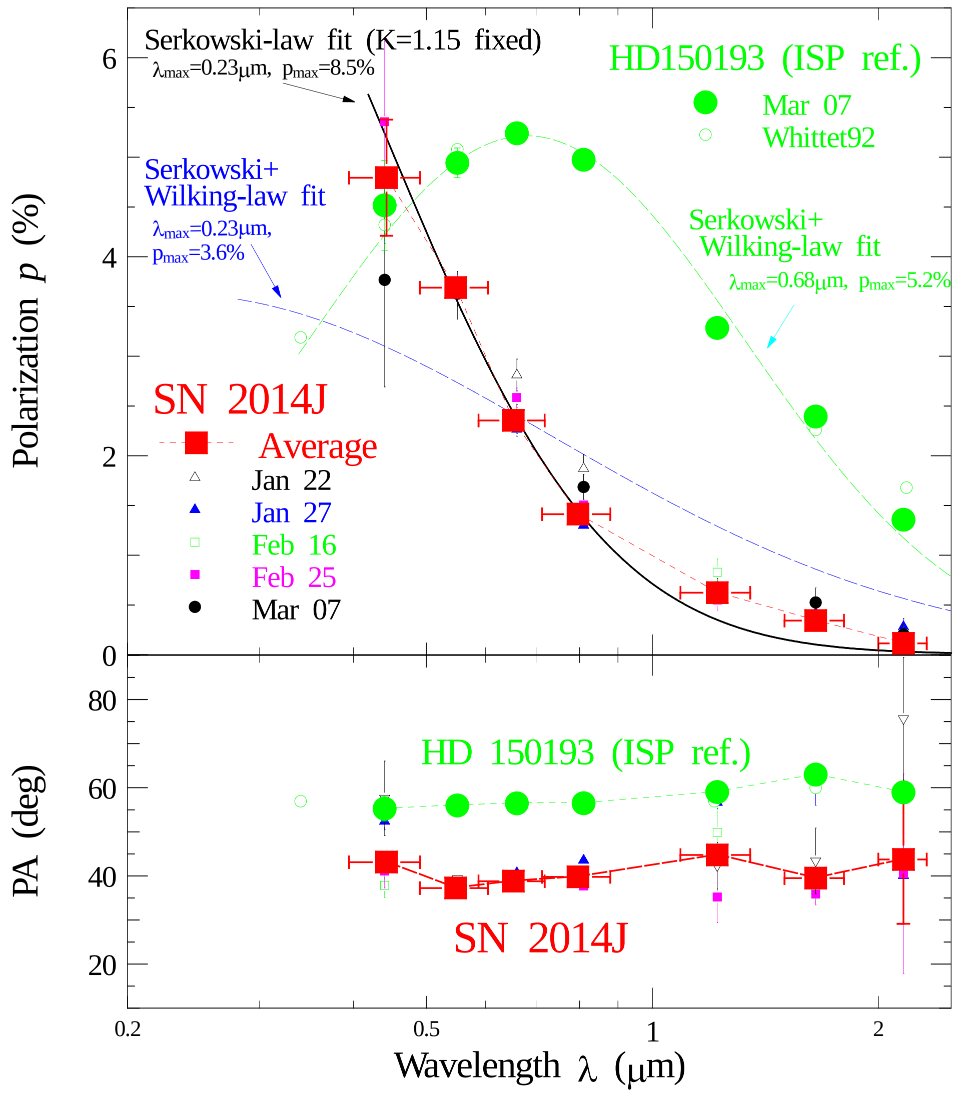
Opt-NIR Polarization of SN 2014J



KK+ 2014

Larger polarization at bluer
(p = 4.8% in B−band;
$\lambda_{max} < 0.4\mu m$)

Constant PA of polarization
in optical through NIR
(paralell to dust lane)

No time variation
→ Non circumstellar origin

Empirical laws of MW ISP and extinction

- Serkowski law

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

  - Maximum polarization efficiency

$$p_{\max} \leq 3 \times E_{\mathrm{B-V}}$$

E_{B-V}: color excess

  - Serkowski−Whittet law

$$R_V = (5.6 \pm 0.3)\lambda_{\max}(\mu\mathrm{m})$$

$R_V = A_V \,/\, E_{B-V}$

  - Mie theory (for cylindrical grain)

$$\lambda_{\max} \sim 2\pi a_{\mathrm{eff}}(n-1)$$

a_{eff}: dust radius

Small λ_{max} indicates small λ_{max} and a_{eff}

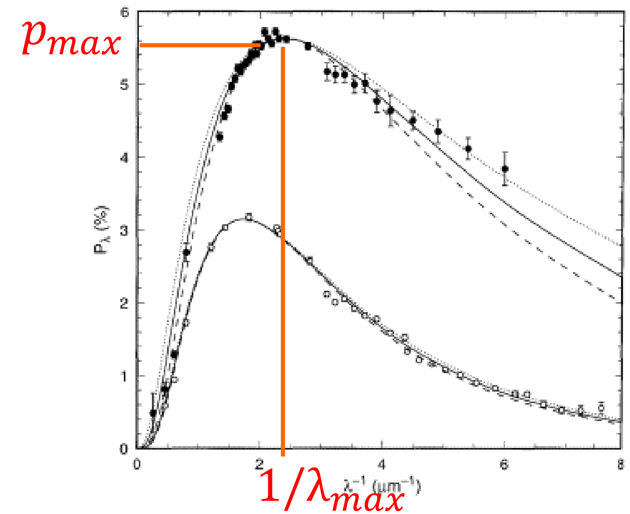
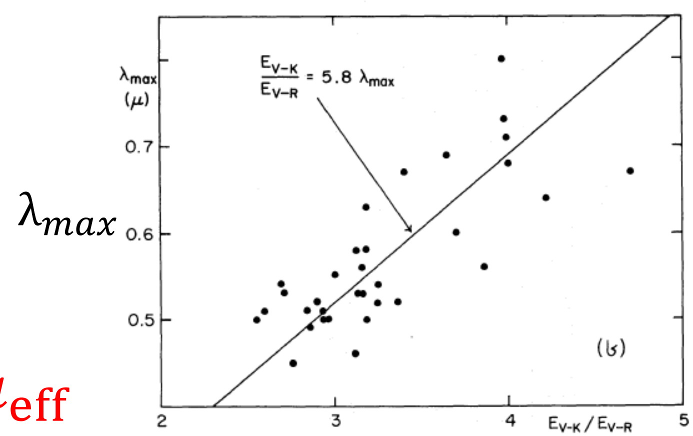
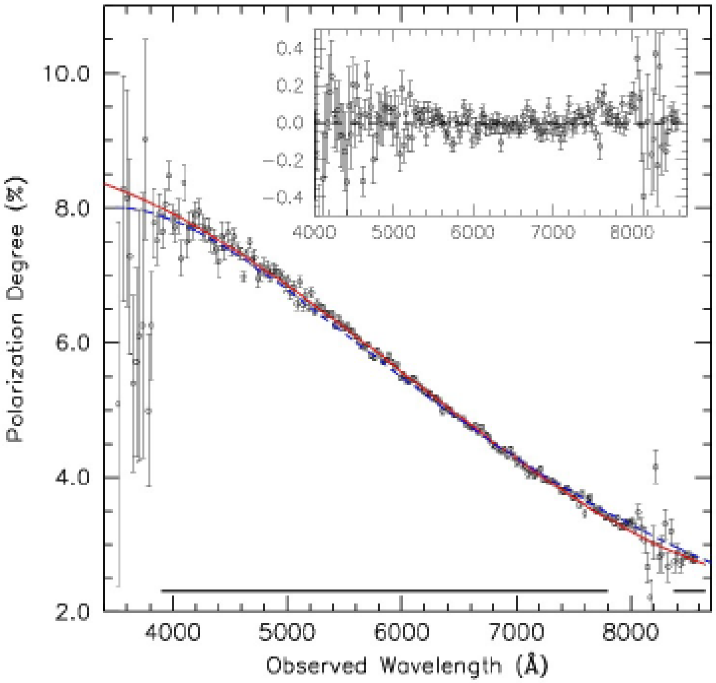


Figure 4.7. Interstellar linear polarization curves for two stars with different values of the wavelength of maximum polarization. Top: HD 204827 (full circles, λ_{max} = 0.42 μm); bottom: HD 99872 (open circles, λ_{max} = 0.58 μm). Observational data are from Martin et al (1999) and references therein. Also shown are empirical fits based on the Serkowski law: VIR-optimized fit (broken curve); VUV-optimized fit (dotted curve); compromise fit (full curve).



Serkowski+ (1975)

Other Highly-Reddened SNe Ia



SN 2006X (Patat+ 2009)

λ_{max}~0.43μm for SN 1986G (Hough+ 1987)

λ_{max}~0.35μm for SN 2006X (Patat+ 2009)

$\lambda_{max} < 0.4\mu m$ for SN 2014J (KK+ 2014)

Typical MW ISP: $\lambda_{max} = 0.54 \pm 0.06\mu m$

(Serkowski+ 1975; Whittet+ 1992)

Small R_V is confirmed independently by analyses of SED.

Commonly small λ_{max} (and therefore small R_V) for extragalactic ISP… Is this really common?

Including mildly-reddened SNe

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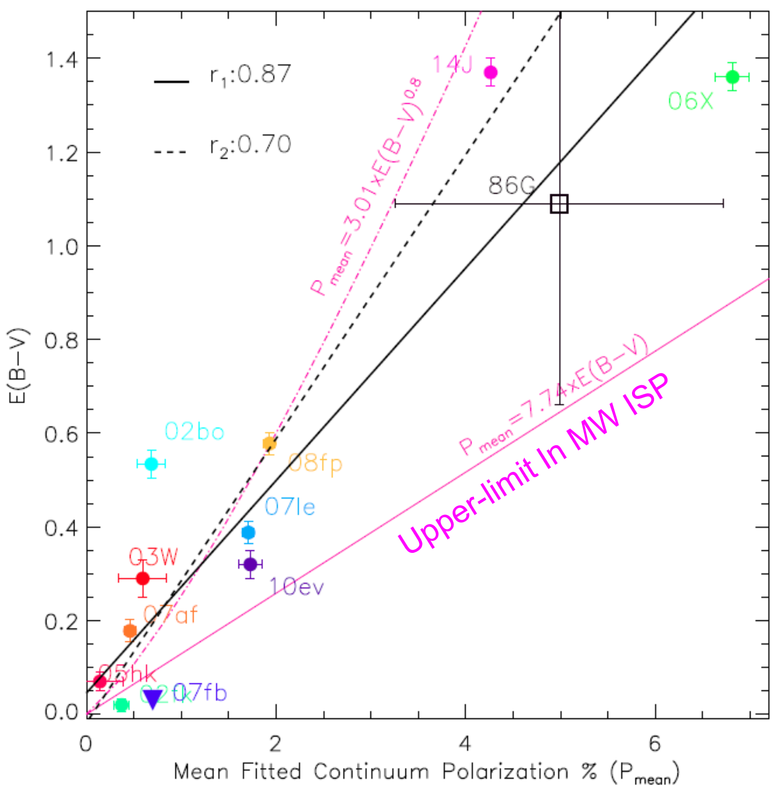
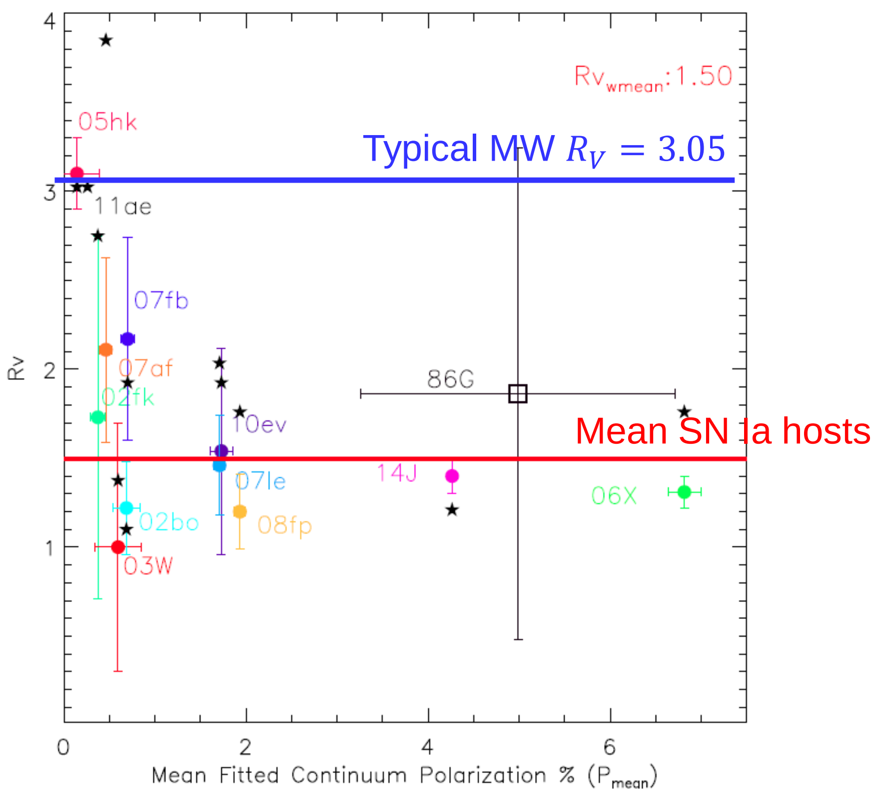
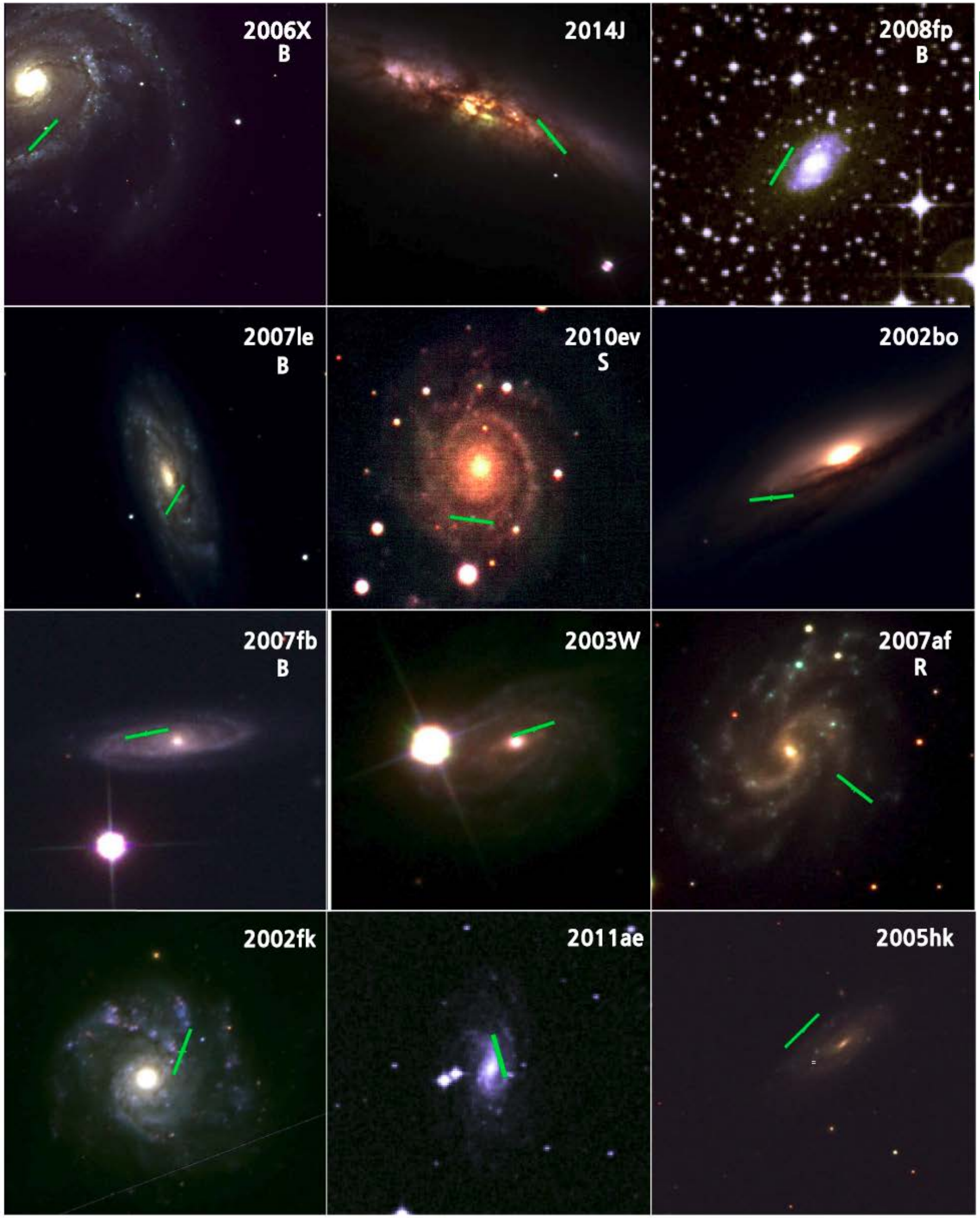
19 SNe Ia polarization spectra (VLT/FORS; Zelaya+ 2017)





Commonly high pol. efficiency and small R_V (and λ_{max})

→ Adopting mean MW values to extragalaxies is problematic.


2006X
B
2014J
2008fp
B
2007le
B
2010ev
S
2002bo
2007fb
B
2003W
2007af
R
2002fk
2011ae
2005hk

(Zelaya+ 2017)

SPICA/SAFALI_Pol obs

- SPICA/SAFALI can see ISM along multi lines of sight within an extragalaxy (in contrast to single los for SN observation).
- Measuring FIR polarization of extragalactic ISM may directly see thermal emission of aligned dust grains.
- Comparing polarization efficiencies near the reddened SN site in the host galaxies, diagnosing origin or universality of small R_V dust in extragalaxies

SPICA/SAFARI_Pol for

Dust production in core-collapse SNe ($M_{\mathbf{initial}} \geq \sim\mathbf{10M_{\odot}}$)

MW Interstellar Dust

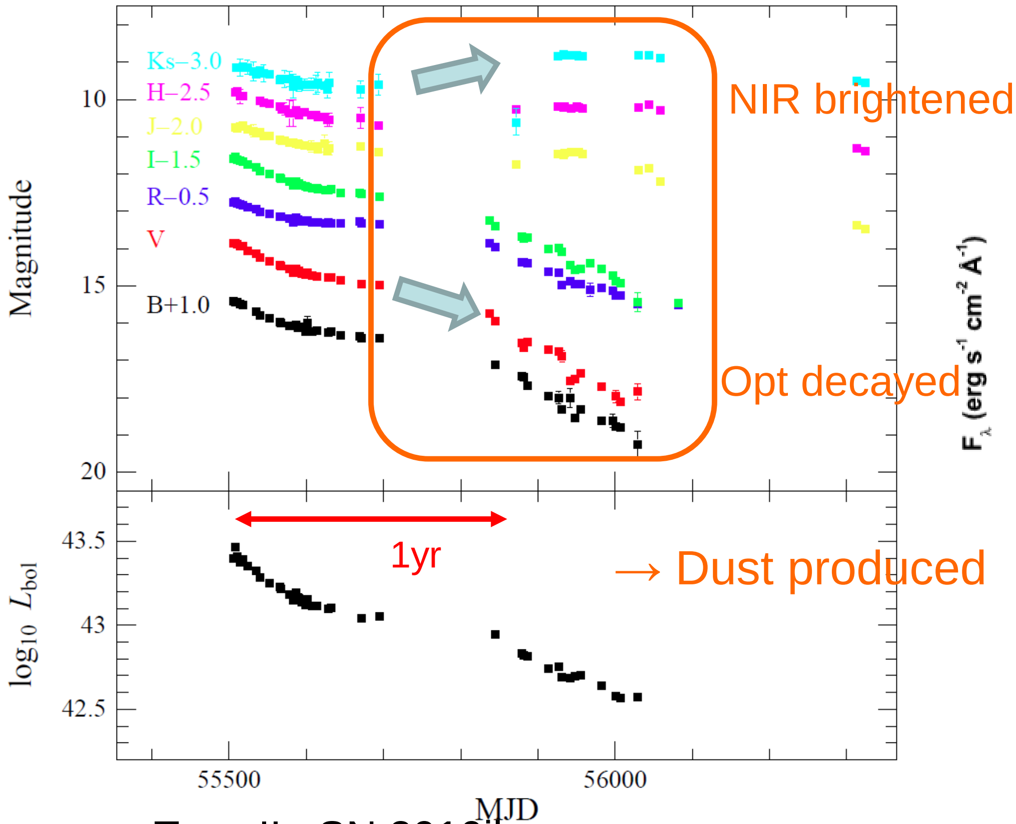
Estimates of dust production rates in MW disk

Stellar type	C or O	Dust production ($10^3\ M_\odot$/year)
O-rich AGB	O	3
C-rich AGB	C	3
Supernovae	both?	1 (?)
M giants	O	0.2
M supergiants	O	0.1
WC stars	C	0.06
Novae	both	0.02

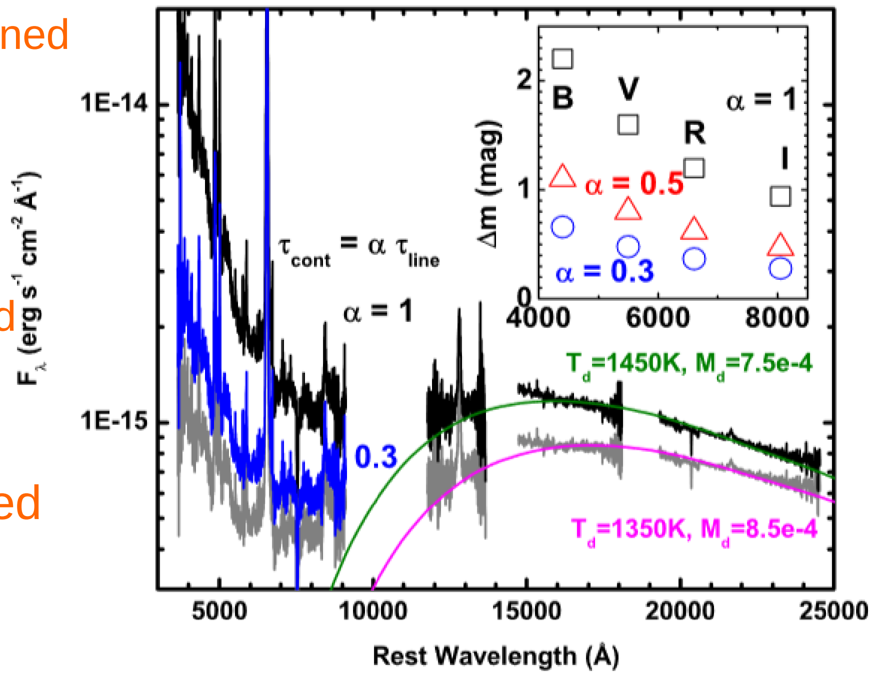
Whittet (2003)

These are simply from rates of mass loss and their occurrence (e.g., constant dust to gas ratio), but it is gradually being confirmed for young supernova remnant.
It is still unclear how SNe produces dust grains in their ejecta.

Dust Producing SNe (only a few samples so far)



Type IIn SN 2010jl (~50Mpc, Ueno, KSK+ 2014)



Maeda, Nozawa+ 2014

Observed hot dust in dusty SN amounts only $\sim 10^{-3} M_\odot$ at most.
(⇔ $0.1 - 1 M_\odot$ in evolved galactic SNRs) (e.g., Nozawa+ 2015)
Most of produced dust should be cooler or condensed later.
(Time scale is months~year for SNe IIn. ⇦SPICA monitoring)

SPICA/SAFARI_Pol obs

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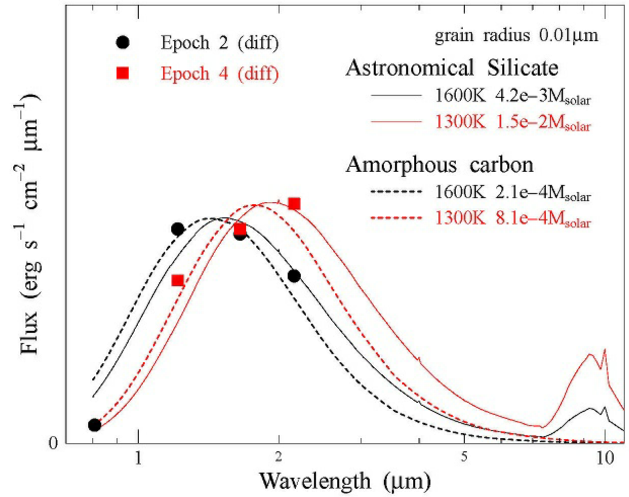
Accessible for possible dust condensation in normal core-collapse SNe



Assuming BB-like SED, $\sim 10^{-5} M_{\odot}$ hot dust ($\sim$1500K) gives $\sim$0.01 mJy at 50 Mpc. (~a dozen SNe nearer than 50 Mpc per year.)

Additional cooler dust may brightening the SN.

→ More reliable estimation of dust mass from SED to FIR by SPICA photometry

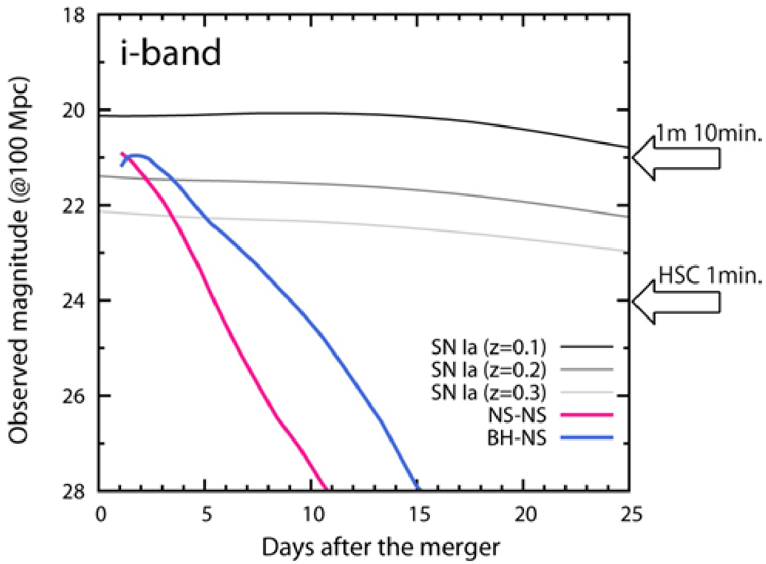
→ SAFALI_Pol polarimetry may probe whether the cooler dust grains are pre-existing or newly formed. (If polarized, they would be pre-existing or quickly aligned after condensation).

SPICA/SAFARI for

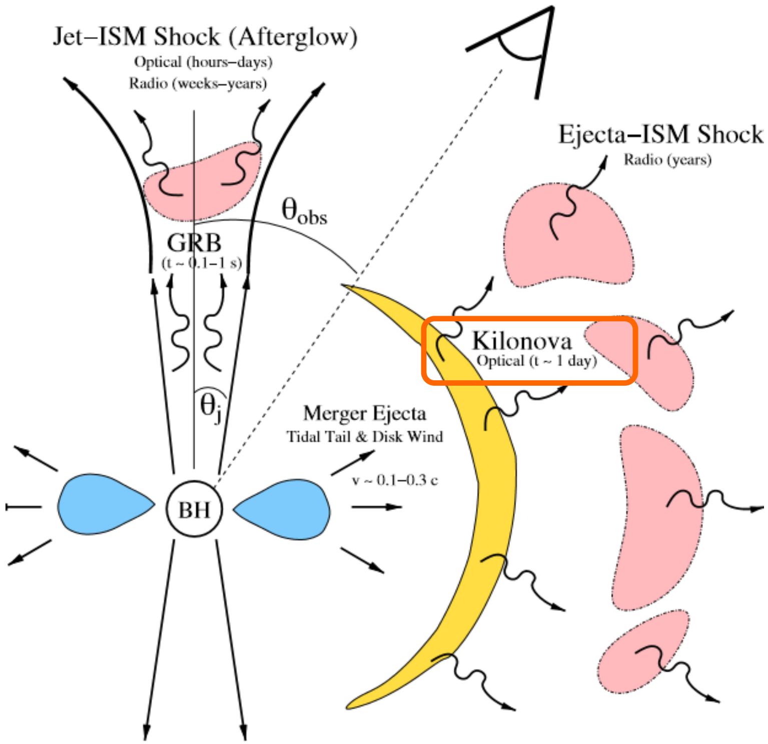
Ejecta mass in kilo novae

Kilo Novae

Merger of neutron stars



Tanaka+ (2014)



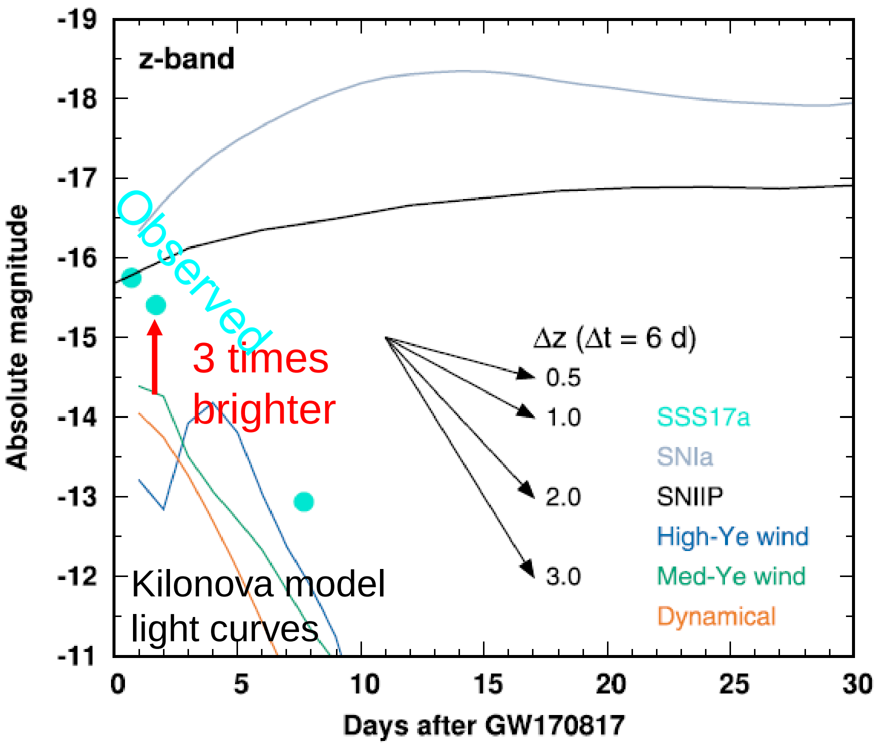
Metzger & Berger 2012, ApJ 746, 48

Decay energy of radioactive heavy elements → Brightening the ejecta

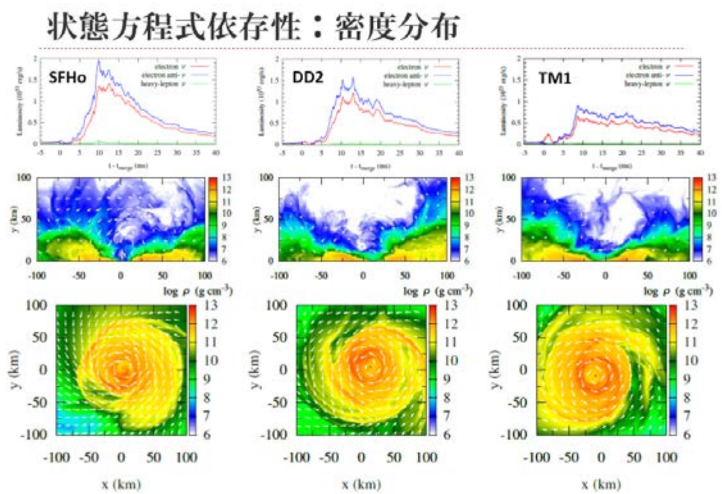
GW170817: First `Bright' GW event

Utsumi+ 2017; Tanaka+ 2014

$0.01M_\odot$ ejecta at 40Mpc



Sekiguchi 2017



Tidal disruption may give only ~$0.01M_\odot$ ejecta in NS merger (possibly depending on mass ratio of the BNS).

Additional post-merger ejecta or wind ejecta is necessary.

Dust in Kilo nova?

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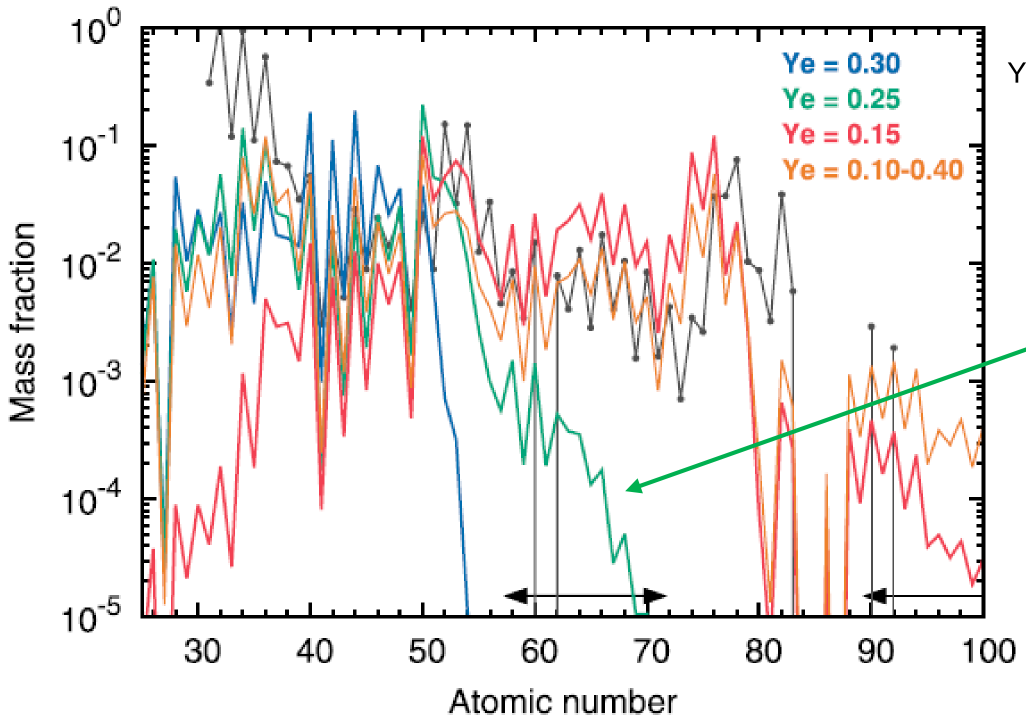
Elements produced with r-process (Tanaka et al. 2017; Wanajo et al. 2014)



Ye: Electron fraction of ejecta

Optical/NIR SED of GW170817 prefers to medium Ye.

Ejecta primarily consists of heavy elements (r-process neutron capture). → may condense into dust grains.

May be visible by SPICA/SAFALI-Pol (similar context with dusty SNe)
→Independent estimation of ejecta mass

→Diagnosing FIR spectrum itself may be essentially interesting.

Summary

- Opt/NIR polarimetry for reddened SNe Ia suggest polarization/absorption properties in extragalaxies are commonly different. SPICA may contribute to understand details
- SPICA may outline the dust condensation process in the ejecta core-collapse SNe
- SPICA may also outline the production of dust consisting of pure r-process elements in kilo novae.