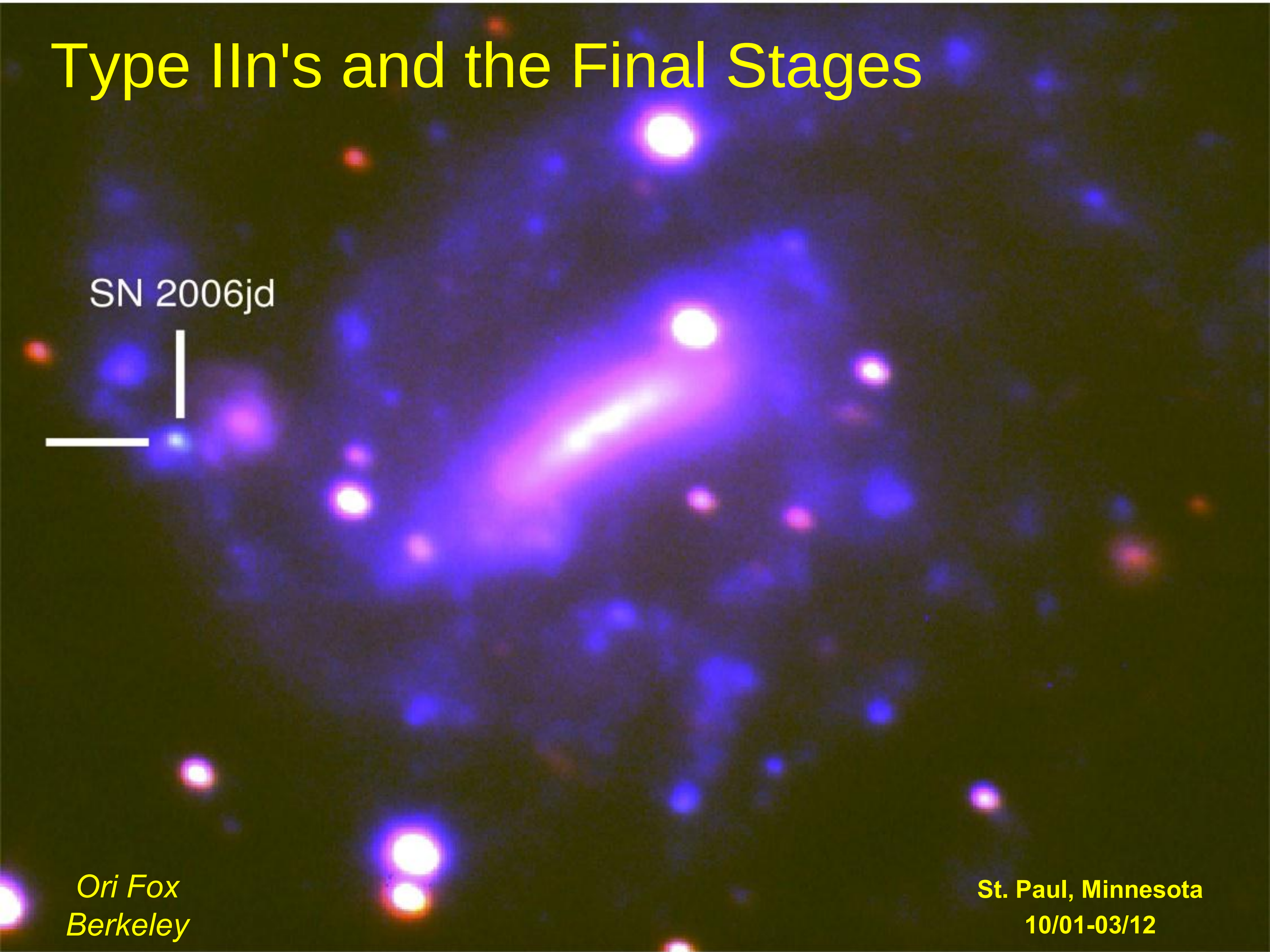
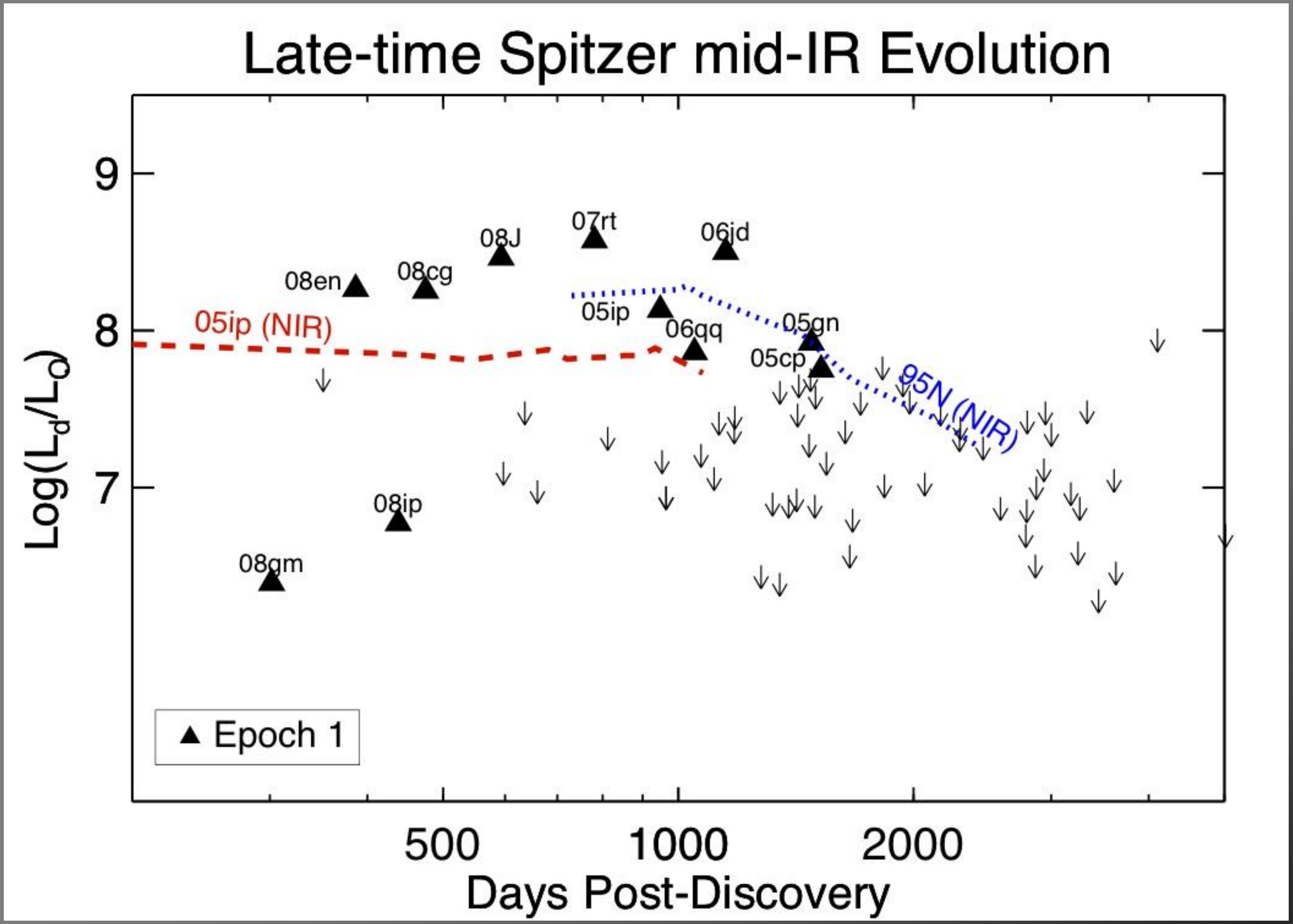
Type IIn's and the Final Stages



Ori Fox
Berkeley

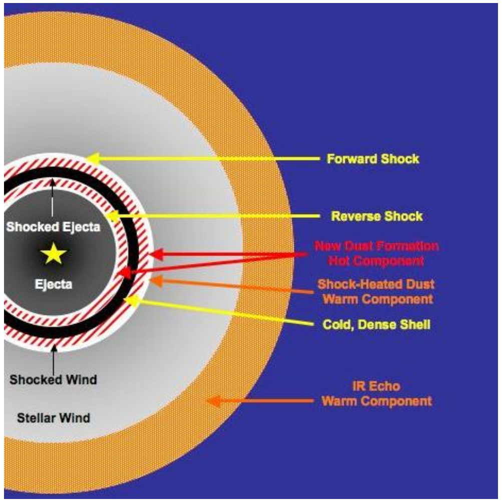
St. Paul, Minnesota
10/01-03/12

Type IIn's in the Mid-IR



LBV Progenitor Eruptions?

$$\dot{M} = \frac{M_{\rm d}}{Z_{\rm d}\Delta r} v_{\rm w}$$
$$= \frac{3}{4}\left(\frac{M_{\rm d}}{{\rm M}_\odot}\right)\left(\frac{v_{\rm w}}{120\ {\rm km\ s^{-1}}}\right)\left(\frac{0.05\ {\rm ly}}{r}\right)\left(\frac{r}{\Delta r}\right)\frac{{\rm M}_\odot}{\rm yr}$$



Mass Loss Associated with Radiatively Heated Graphite Dust Shell

SN	$\dot{M} \times (10\Delta r)/r$ (${\rm M}_\odot$ yr^{-1})	$t_{\rm eruption}$ (yr)
2005cp	2.2e-3	30
2005gn	7.5e-4	25
2005ip	1.8e-3	235
2006jd	2.8e-3	106
2006qq	9.2e-3	17
2007rt	1.2e-3	181
2008J	1.6e-3	55
2008cg	2.3e-3	57
2008en	1.4e-3	49
2008gm	1.6e-4	4
2008ip	3.3e-4	13

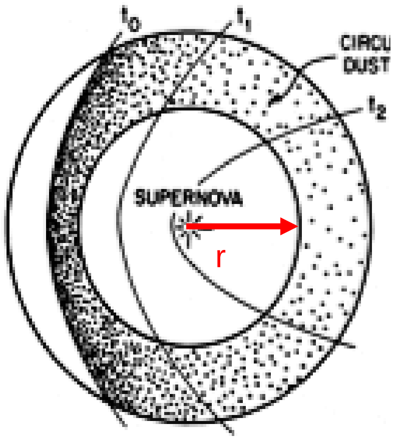
Blackbody, Shock, Echo Plateau, and Vaporization Radii

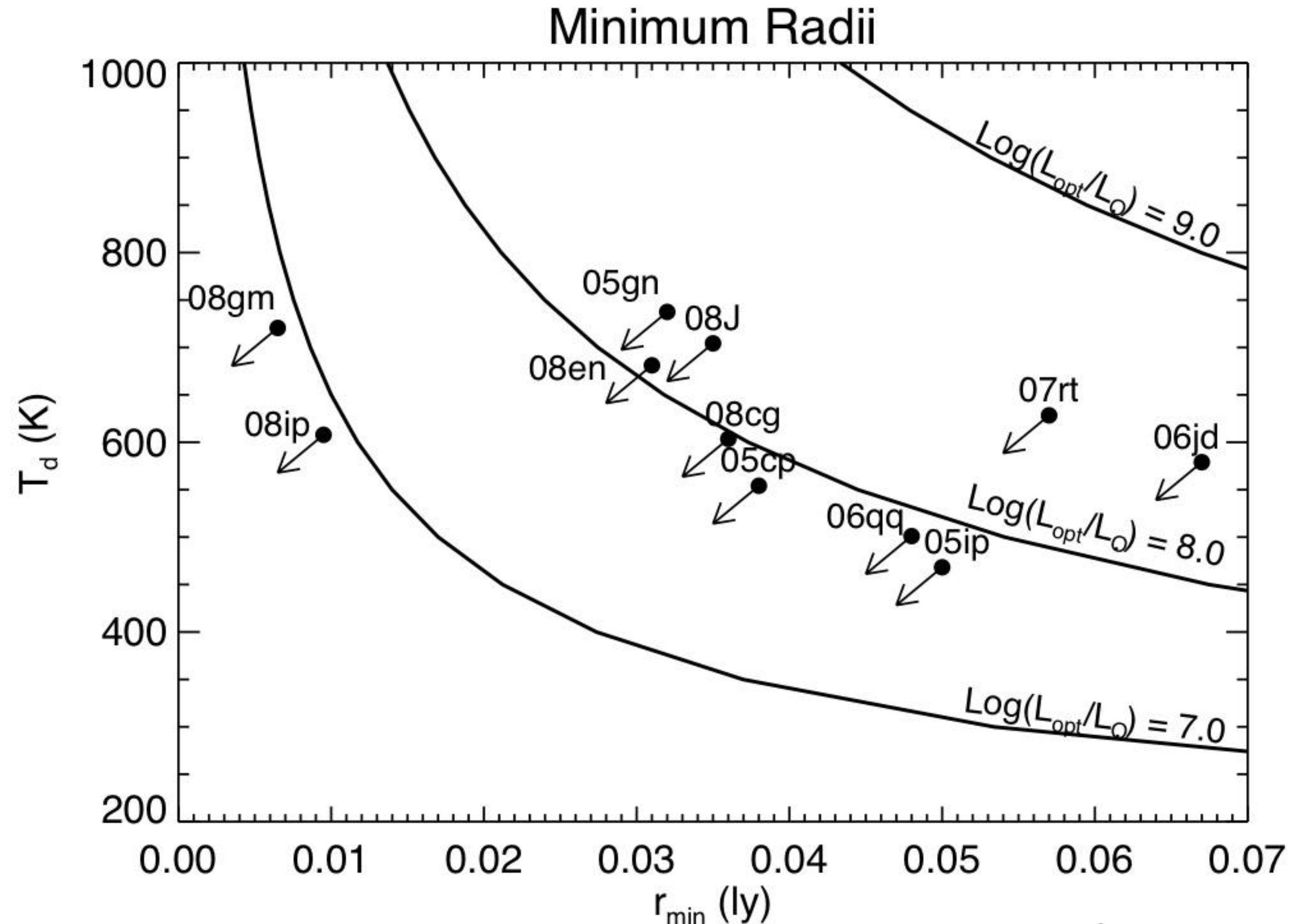
SN	Epoch (days)	$r_{\rm bb}$ [a] (ly)	$r_{\rm s2}$ [b] (ly)	$r_{\rm s1}$ [c] (ly)	$r_{\rm ech}$ [d] (ly)	$r_{\rm evap}$ [e] (ly)
2005cp	1523	0.038	0.033	0.20	2.1	0.012
2005gn	1479	0.016	0.032	0.19	2.0	0.013
2005ip	948	0.031	0.020	0.12	1.3	0.01
2006jd	1149	0.067	0.025	0.15	1.6	0.01
2006qq	1048	0.048	0.022	0.14	1.4	0.016
2007rt	780	0.057	0.017	0.10	1.1	0.02
2008J	593	0.035	0.013	0.077	0.81	0.02
2008cg	474	0.036	0.010	0.061	0.65	0.02
2008en	386	0.031	0.008	0.050	0.53	0.011
2008gm	301	0.004	0.007	0.039	0.41	0.0065
2008ip	438	0.008	0.010	0.057	0.60	0.015

ODF+11

Expected High Energy Emission

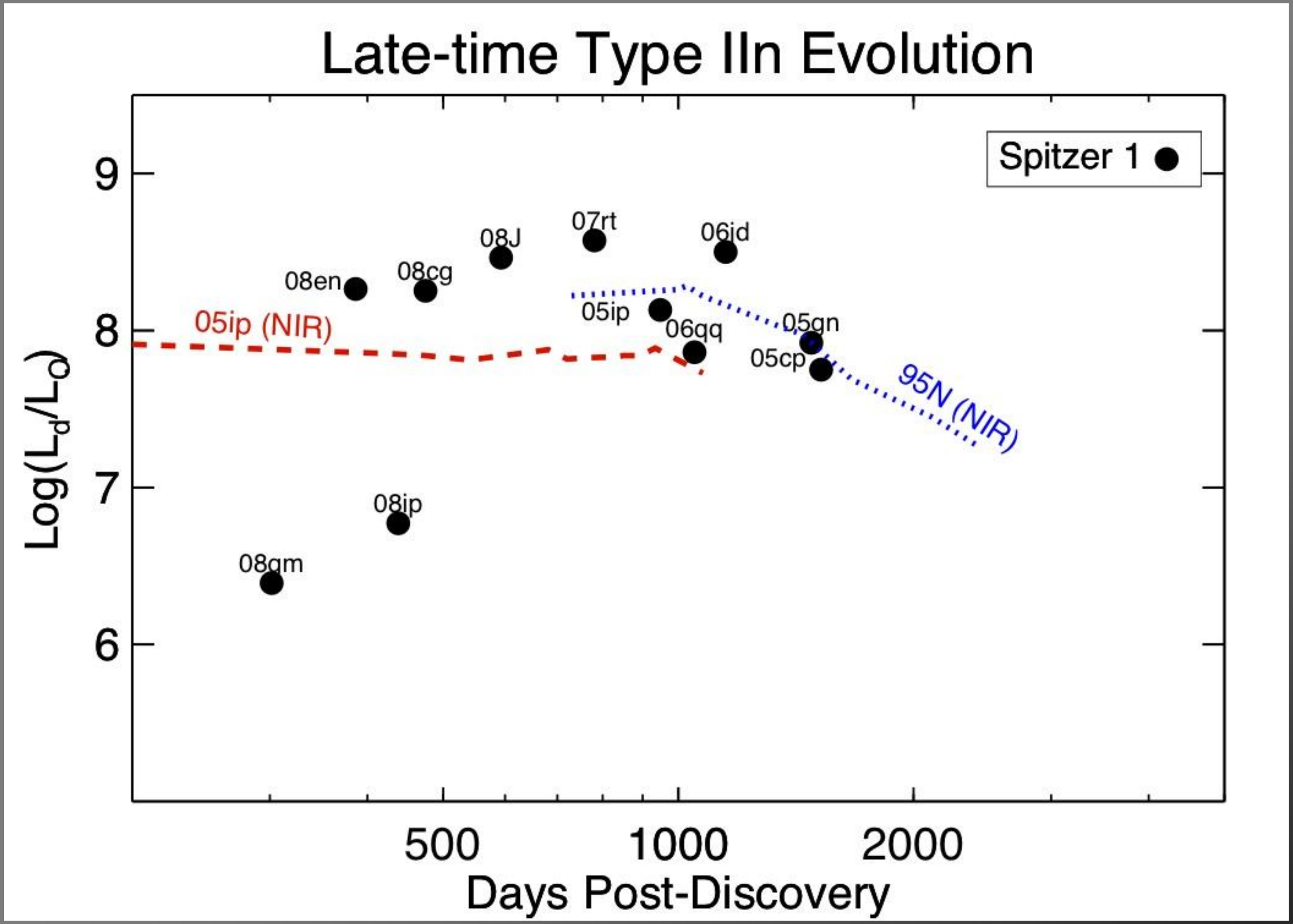
$$L_{\rm bol} = \frac{64}{3}\rho a r_v^2 \sigma T_{\rm SN}^4 \frac{\int B_\nu(T_d)\kappa(\nu)d\nu}{\int B_\nu(T_{\rm SN})Q_{\rm abs}(\nu)d\nu}.$$



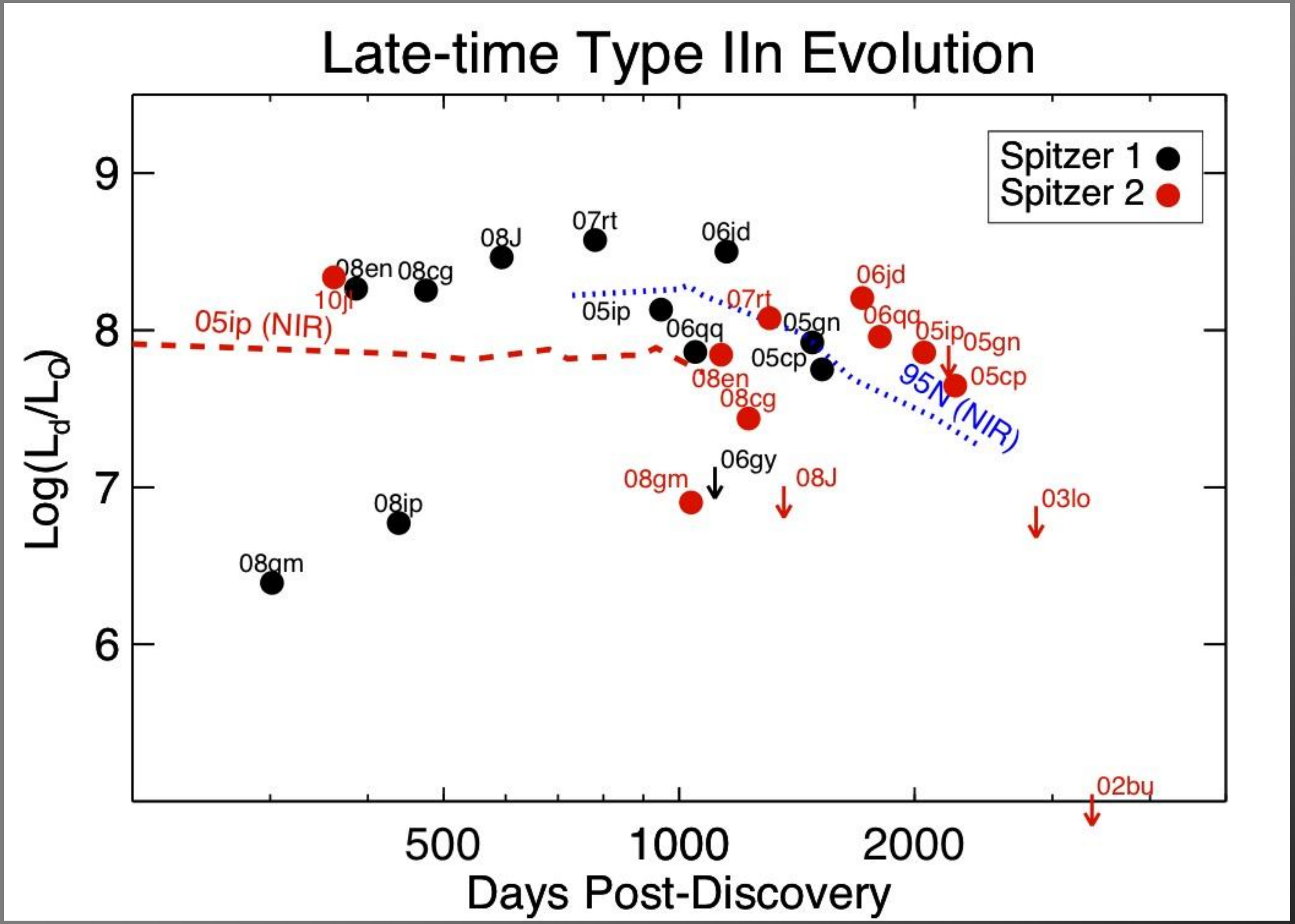


ODF+11

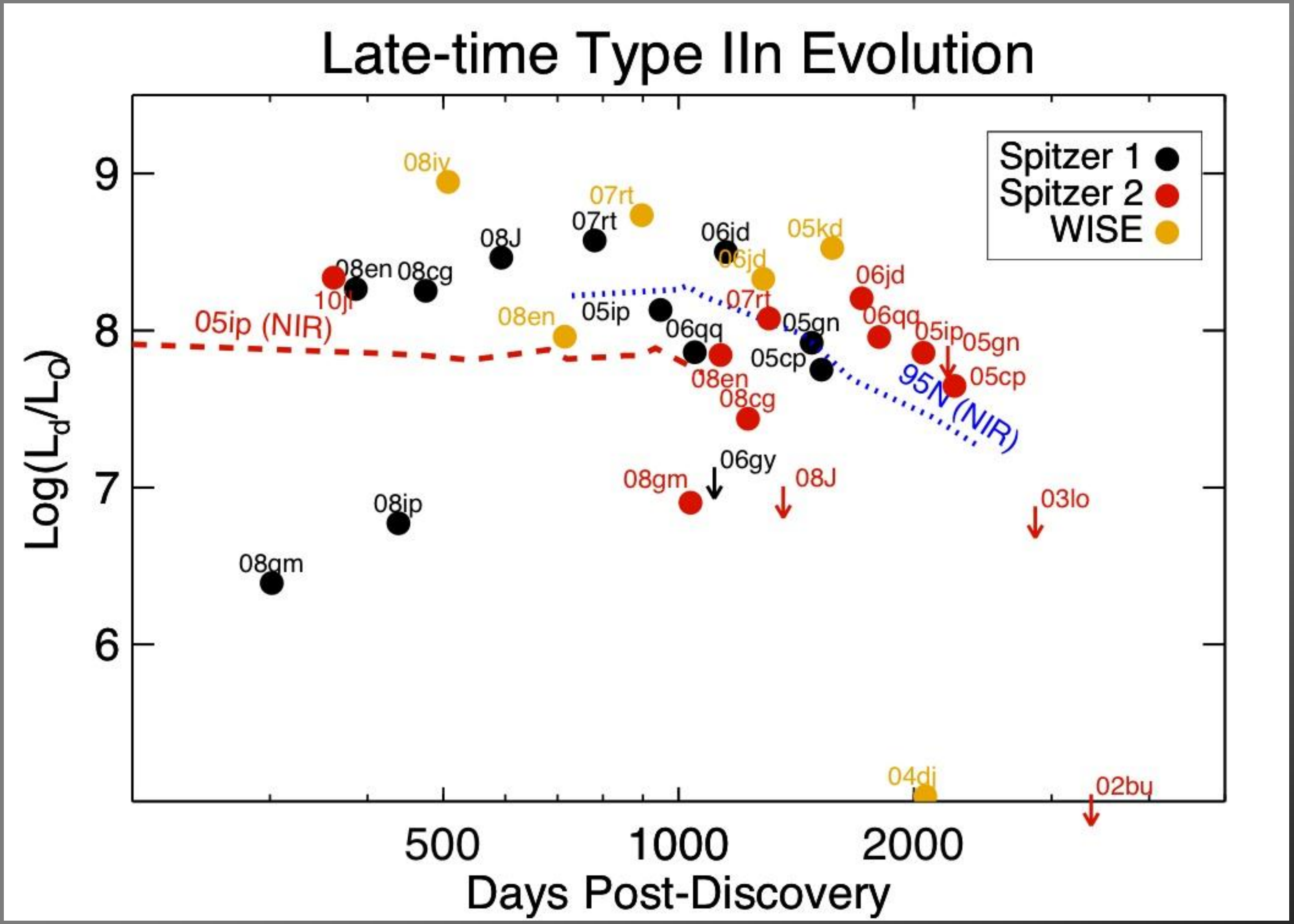
Type IIn's at late-times



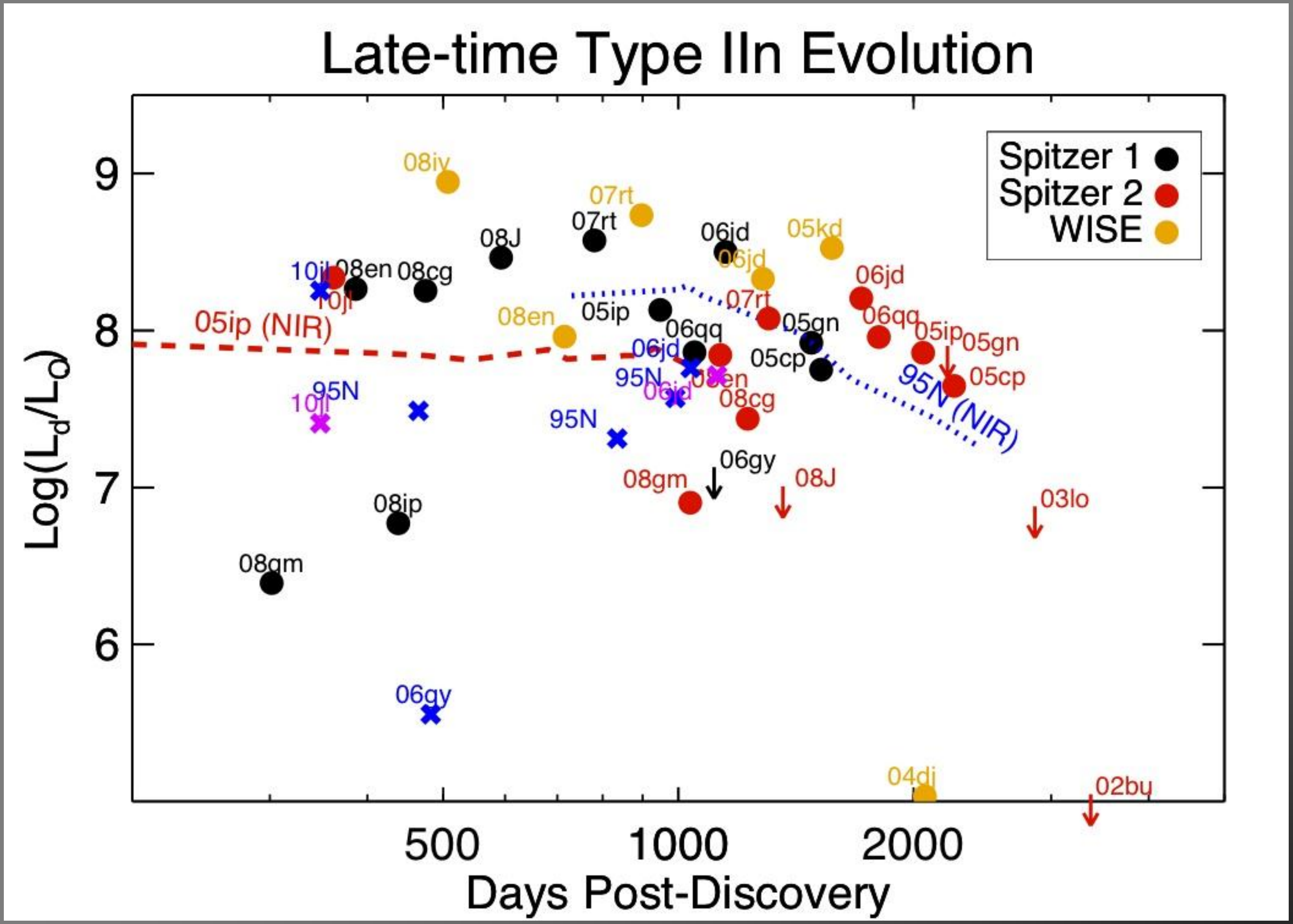
Type IIn's at late-times



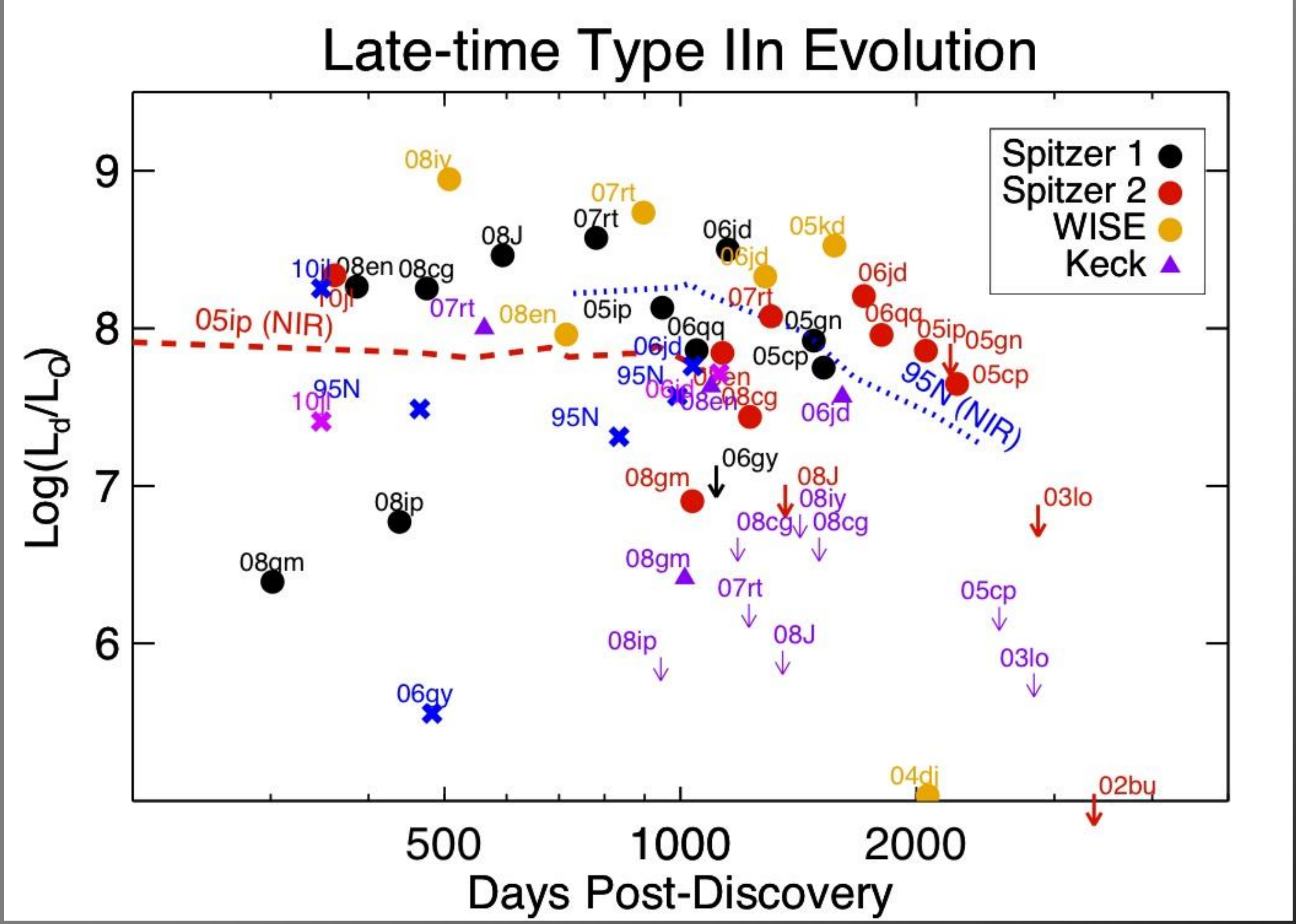
Type IIn's at late-times



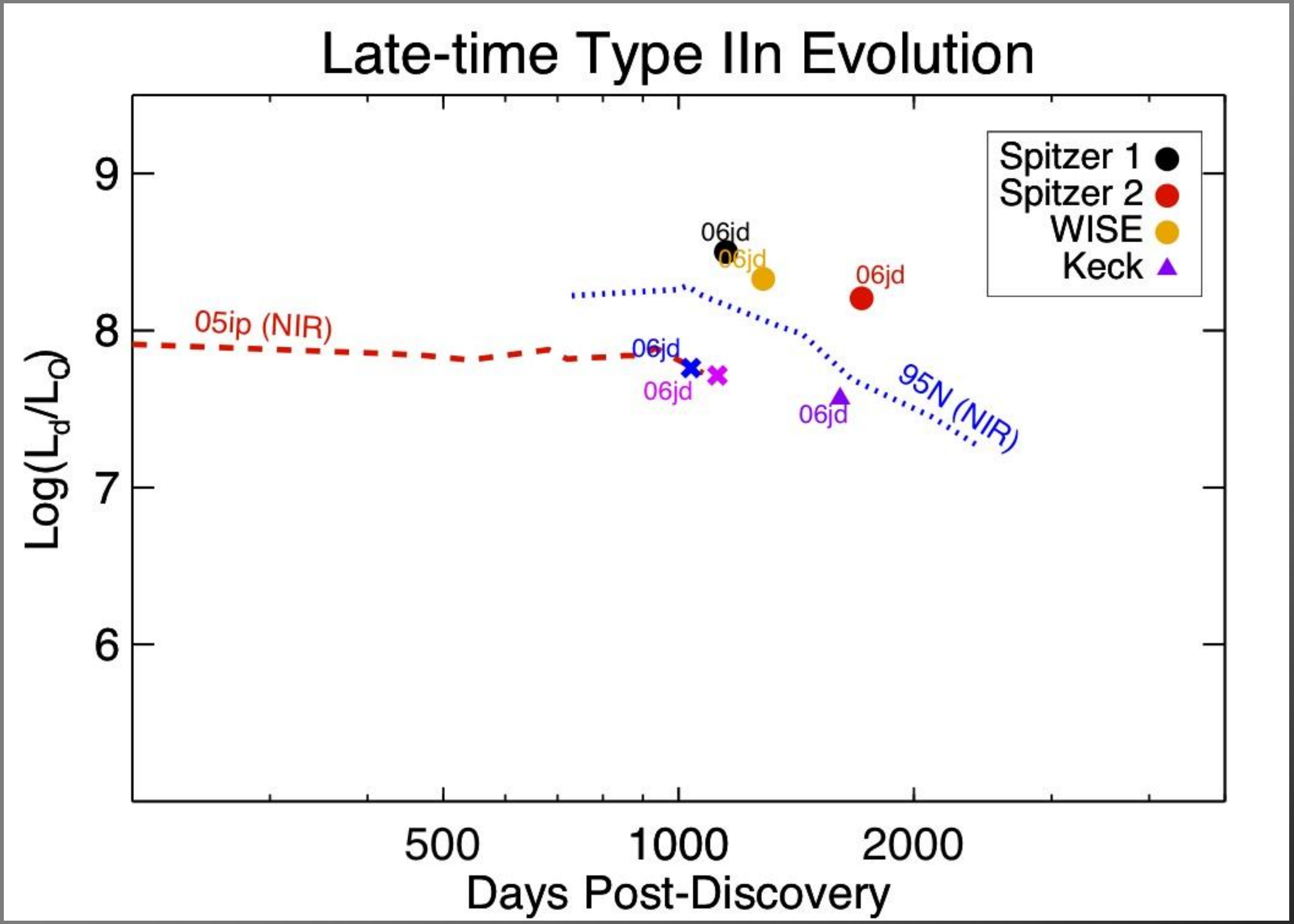
Type IIn's at late-times



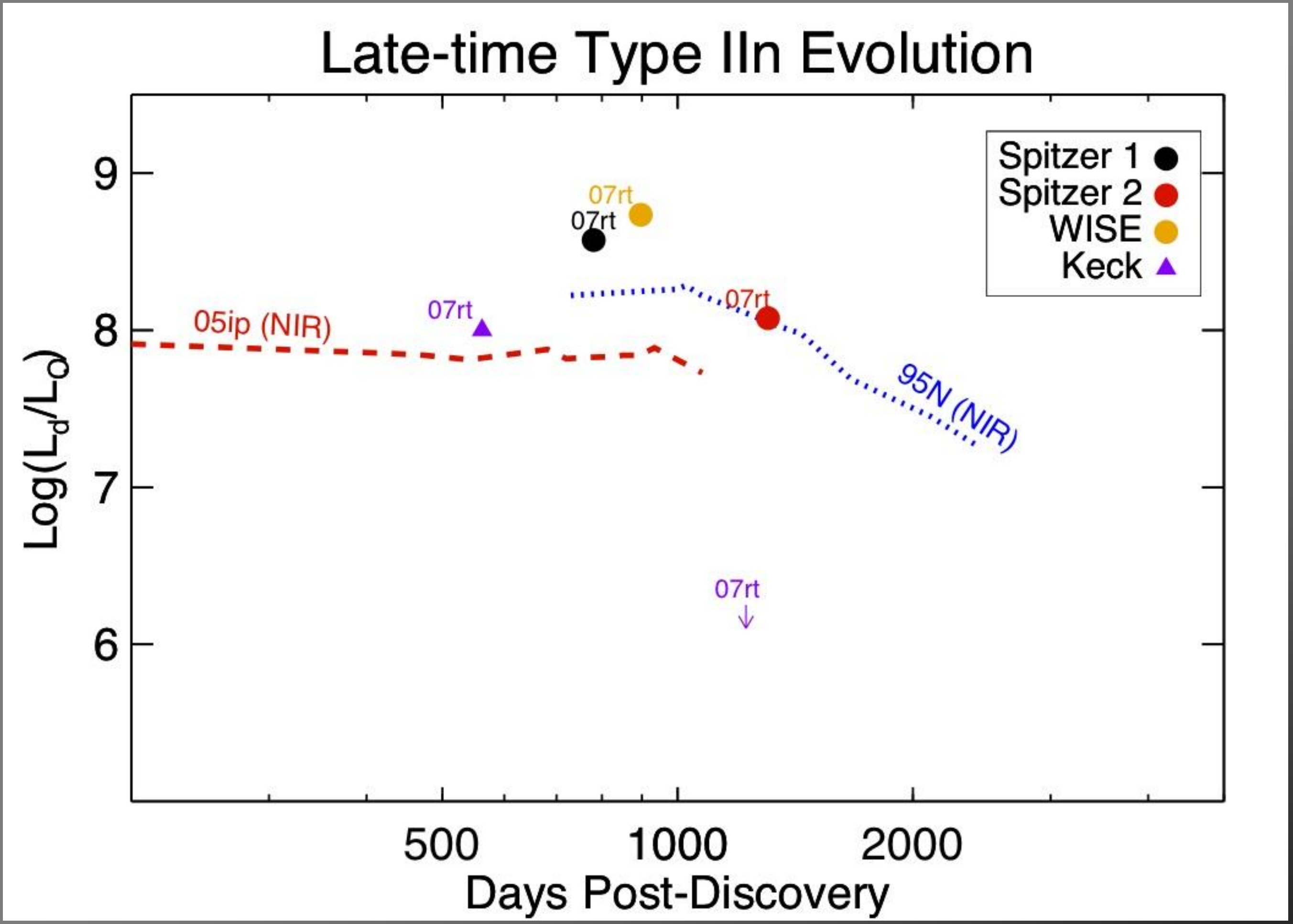
Type IIn's at late-times



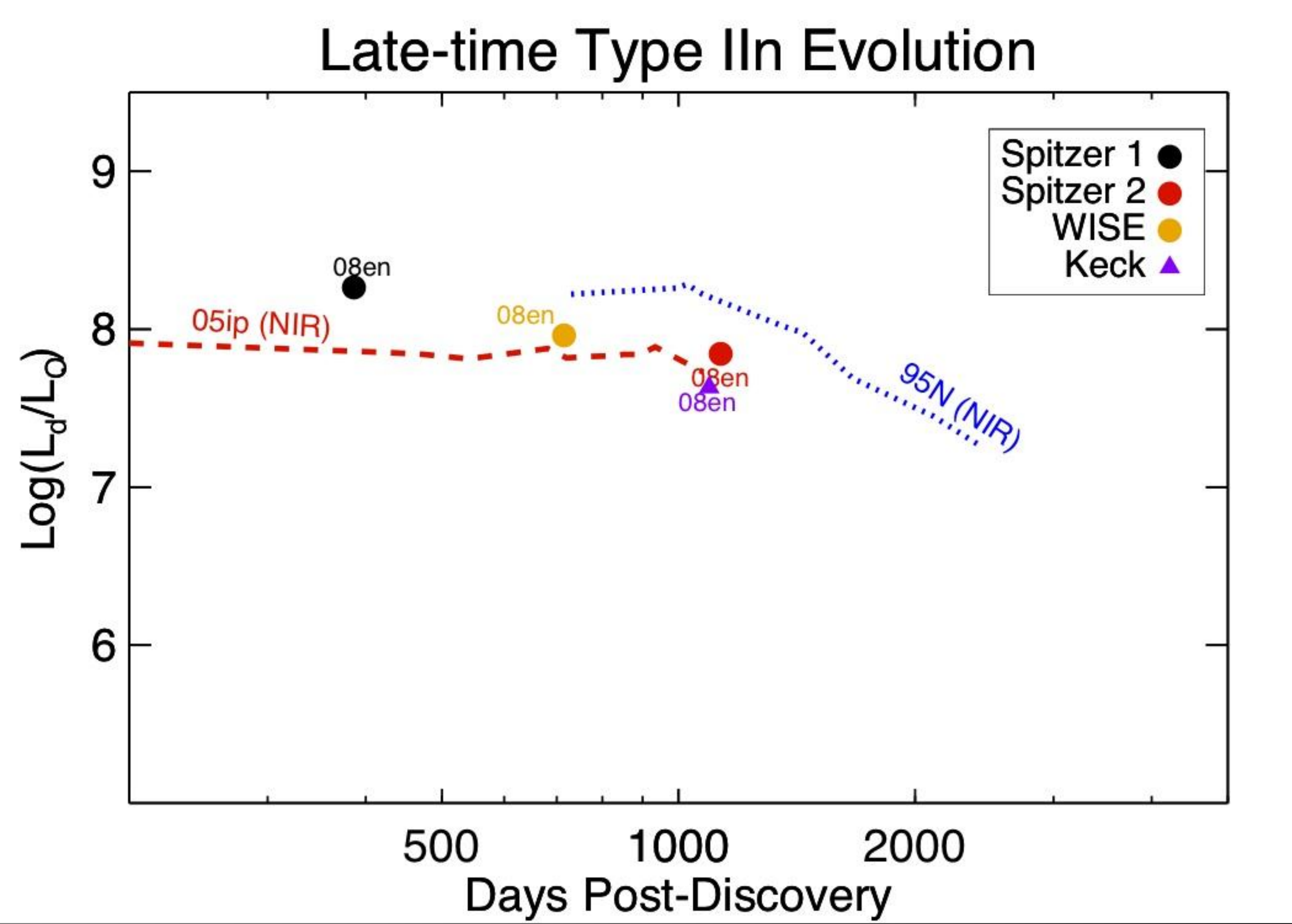
Type IIn's at late-times



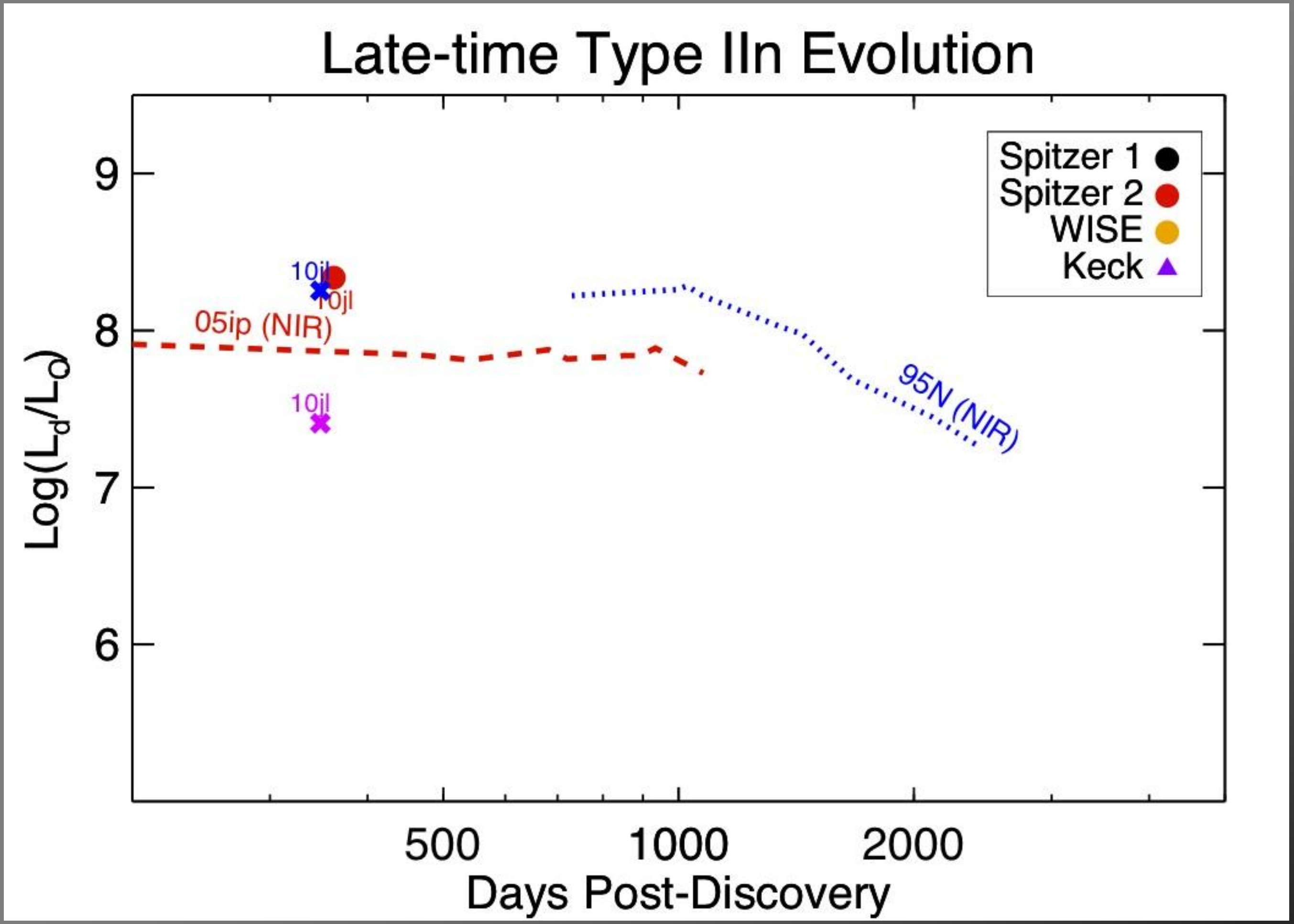
Type IIn's at late-times



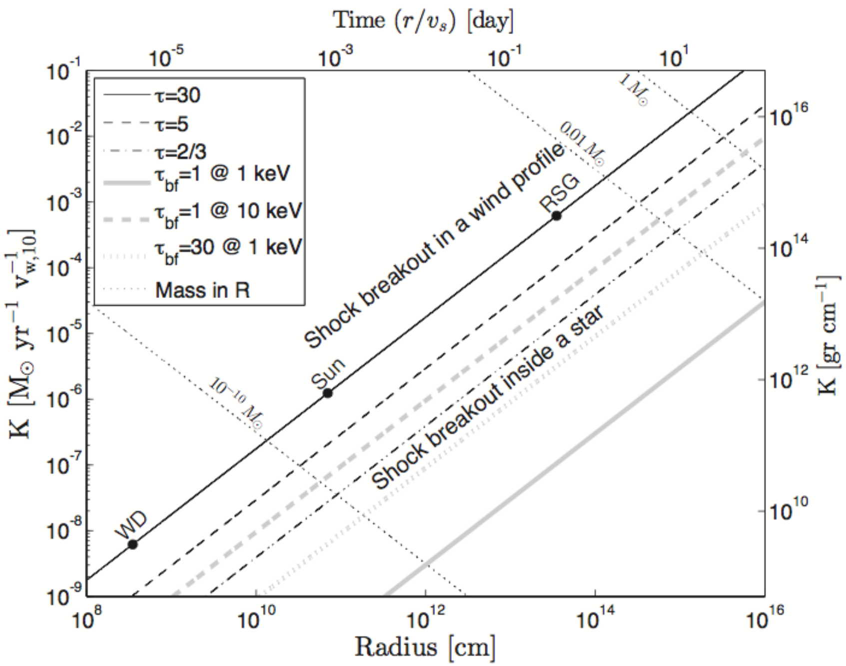
Type IIn's at late-times

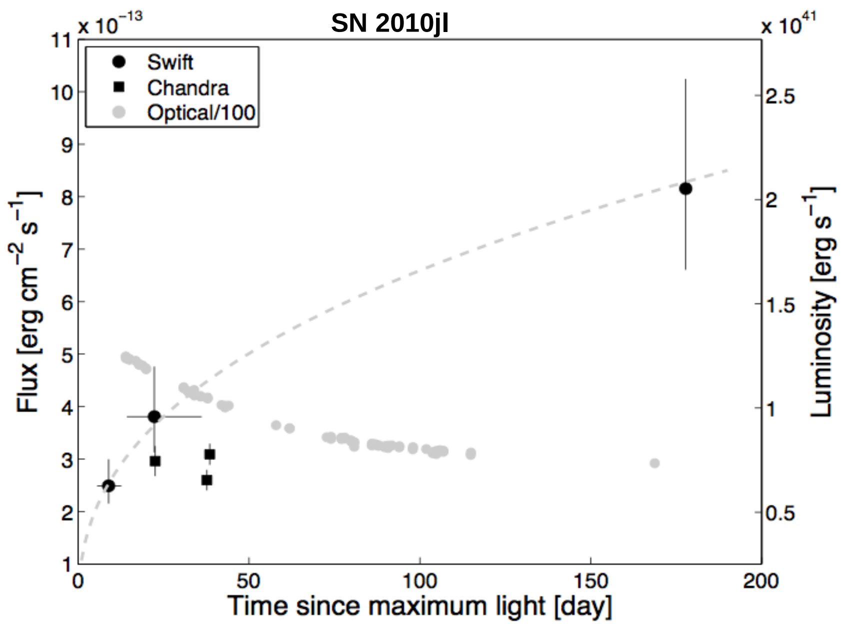


Type IIn's at late-times



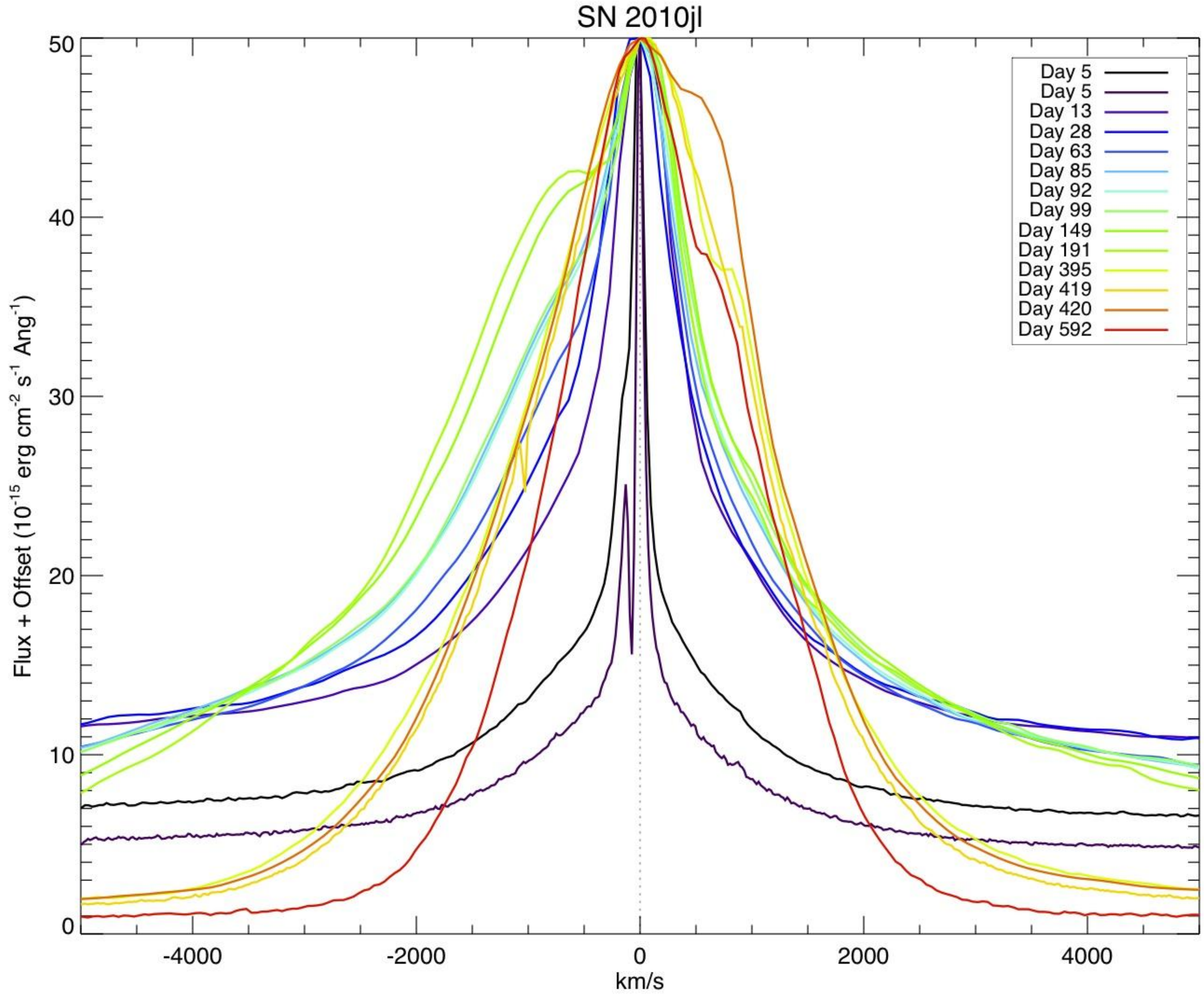
X-Rays as a Discriminator





Ofek+12

SN 2010jl - H/alpha



Techniques Apply to All Varieties

- Type II: 05ip
- Type Ib/c: 06jc, 01em
- Impostors: 02bu, 08S, NGC 300-OT1
- SLSNe: 06gy, 06tf, 10jl
- Type Ia: 00cx, 02ic, 05gl, 08J (?), 08cg (?)

- Are All Type IIn Supernovae?
- What are the progenitors to SLSNe?
- Why Do All the SNe in my sample look the same? Or do they?

What traits distinguish subclasses?

- Peak Luminosity
- Expansion Speed
- Rise/Fall Time
- Infrared?
- X-rays?
- Radio?
- Rates?
- Environments?

Implications and Future Work

- In general, the Type IIn subclass seems to have a warm dust component that likely is due to an `IR echo' that forms from the heating of a large, pre-existing dust shell. The heating mechanism is likely the optical luminosity generated from the forward forward shock interaction with the circumstellar medium.

- Mass-loss rates and progenitor wind speeds suggest LBV progenitors that have undergone eruptive events tens to hundreds of years before going SN.

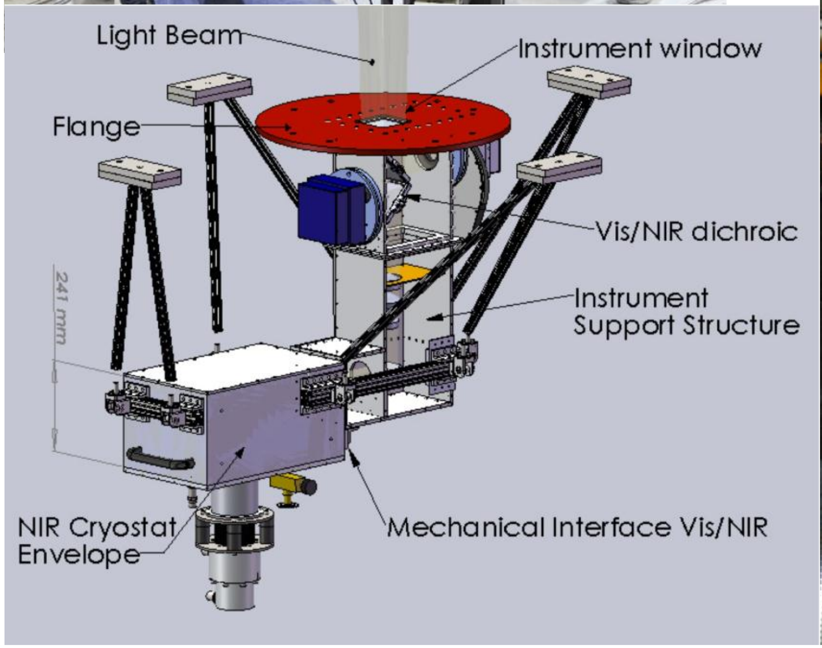
- Will be be able to observe the echo turn off? What is the mechanism?

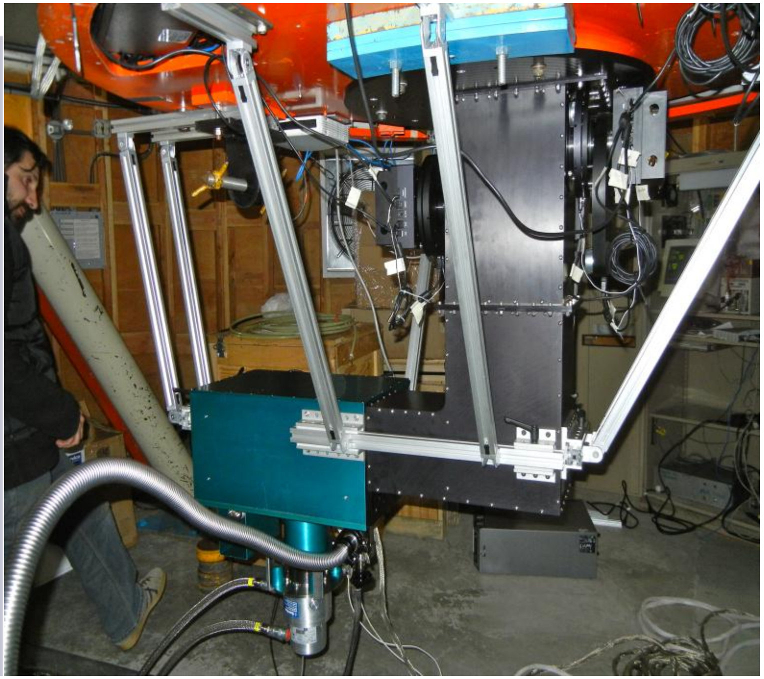
- And more…
  - Can these techniques be used for other supernova/transient types?
  - If LBVs can go supernova, than their cores are significantly more evolved than stellar evolution models predict?
  - If LBVs yield large amounts of dust in their progenitor winds, then perhaps there is a connection to the large mass stars associated with Pop. III stars in the early universe?

RATIR

THE REIONIZATION AND TRANSIENTS INFRARED/OPTICAL PROJECT

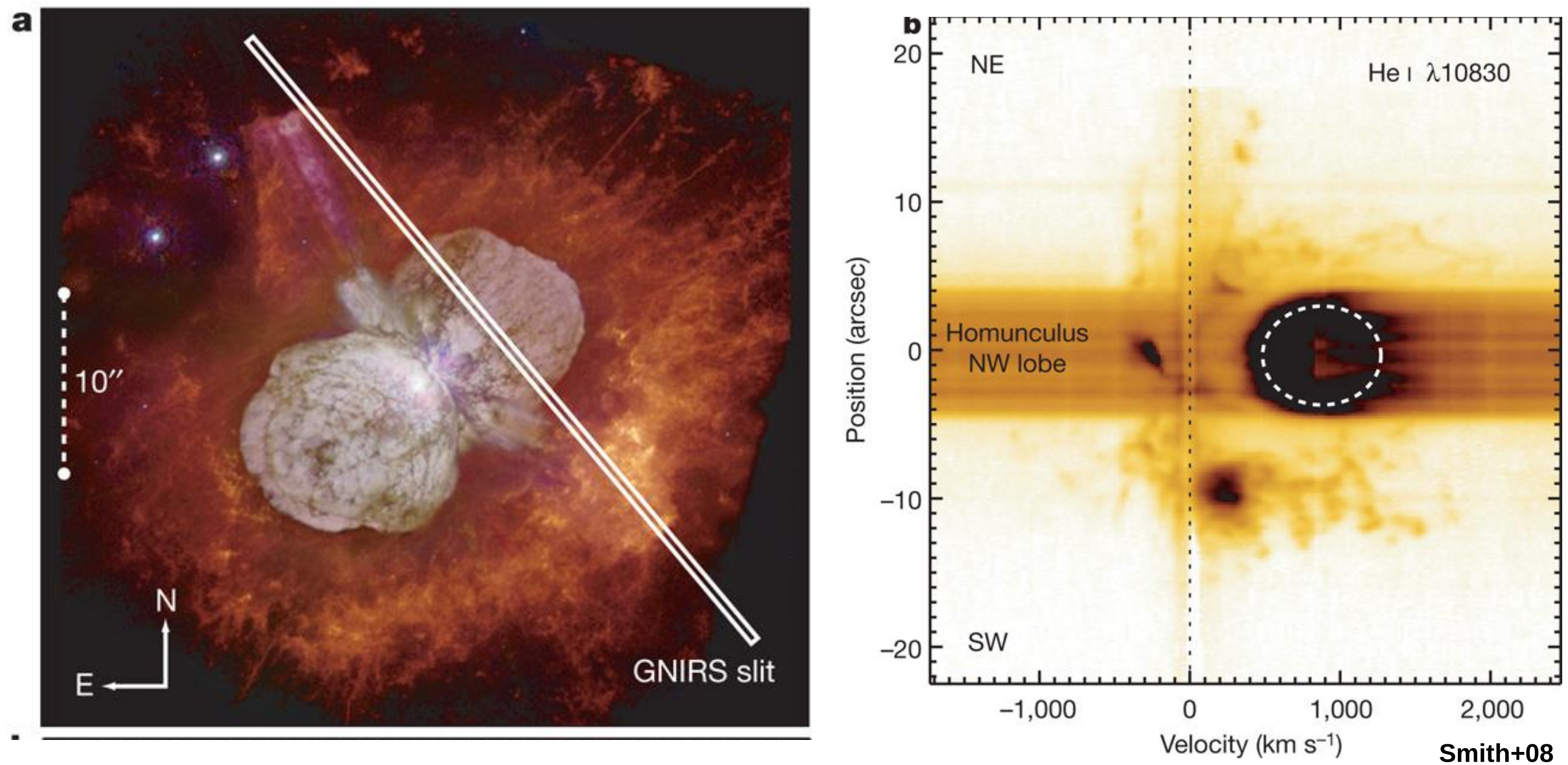
RATIR





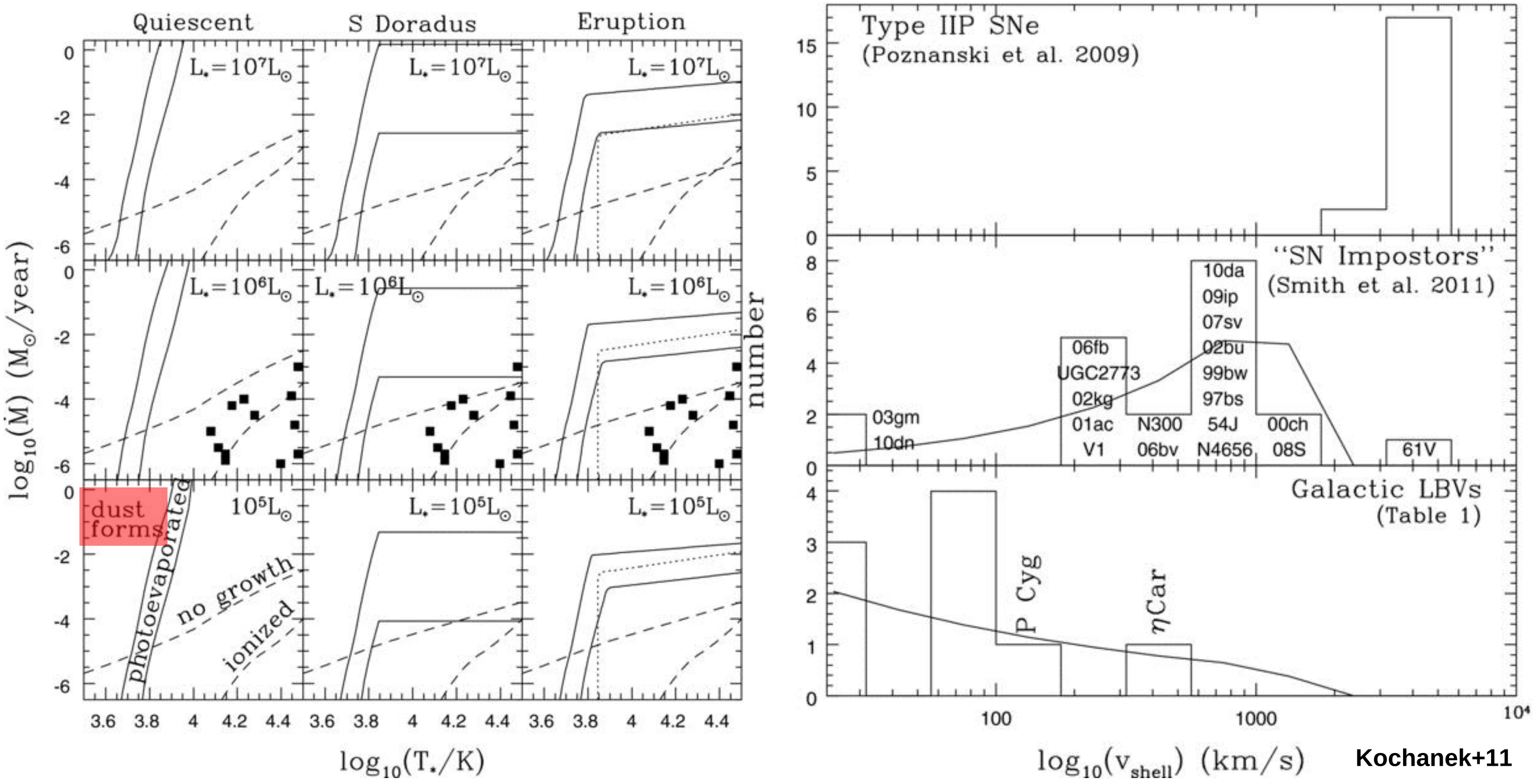
ODF+12, Butler+12

X-Rays From LBV Eruptions?



Smith+08

2) Dust In Other Transients



Kochanek+11

What About the Non-Detections?

Likely Heating Mechanisms

Evidence for Dust Origin and Heating Mechanism

SN	Newly Formed?	Shock Heating?	IR Echo?	Shock Echo?
2005cp	no	maybe	no	yes
2005gn	no	maybe	no	maybe
2005ip	yes	no	no	yes
2006jd	no	no	no	maybe
2006qq	no	no	no	yes
2007rt	yes [a]	no	no	maybe
2008J	maybe	maybe	no	maybe
2008cg	yes	no	no	yes
2008en	no	maybe	no	yes
2008gm	no	yes	no	yes
2008ip	no	yes	no	yes

[a] Trundle et al. (2009)

Origin and Heating of Warm Dust

Origin

- Newly Formed
  - SN Ejecta
    - Radioactivity
  - Post-Shock Gas
    - Radioactivity
    - Collisional Radiation
- Pre-existing CSM
  - Shock Heating
  - Radiative Echo

Must Consider:
1) Energetic Constraints
2) Dust Temperature Constraints

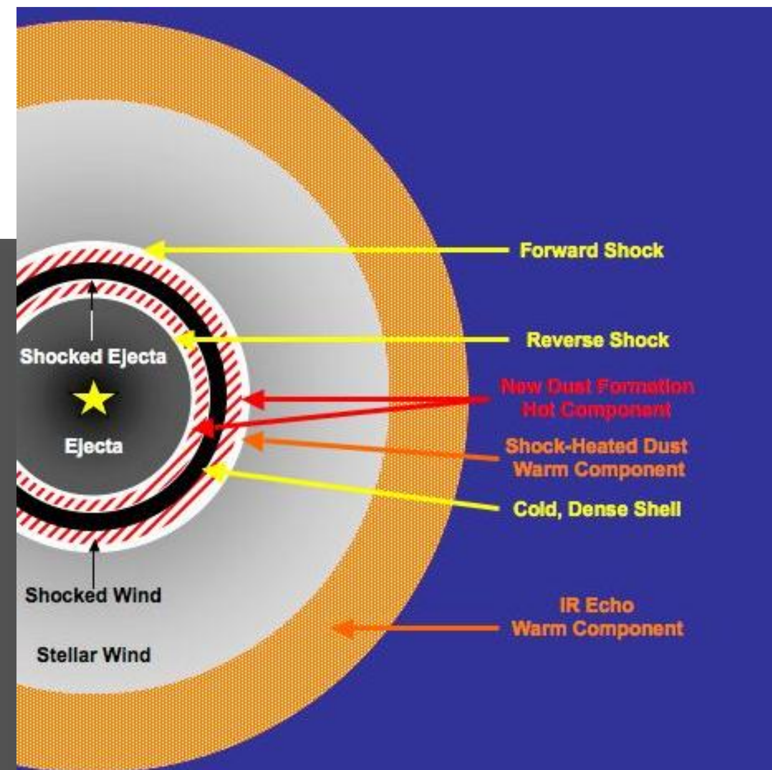
Quick Definition:
1) Blackbody Radius
2) Shock Radius
3) Evaporation Radius
4) Echo Radius

$$r_{bb} = \left(\frac{L_{bb}}{4\pi\sigma T_{bb}^4}\right)^{\frac{1}{2}}$$

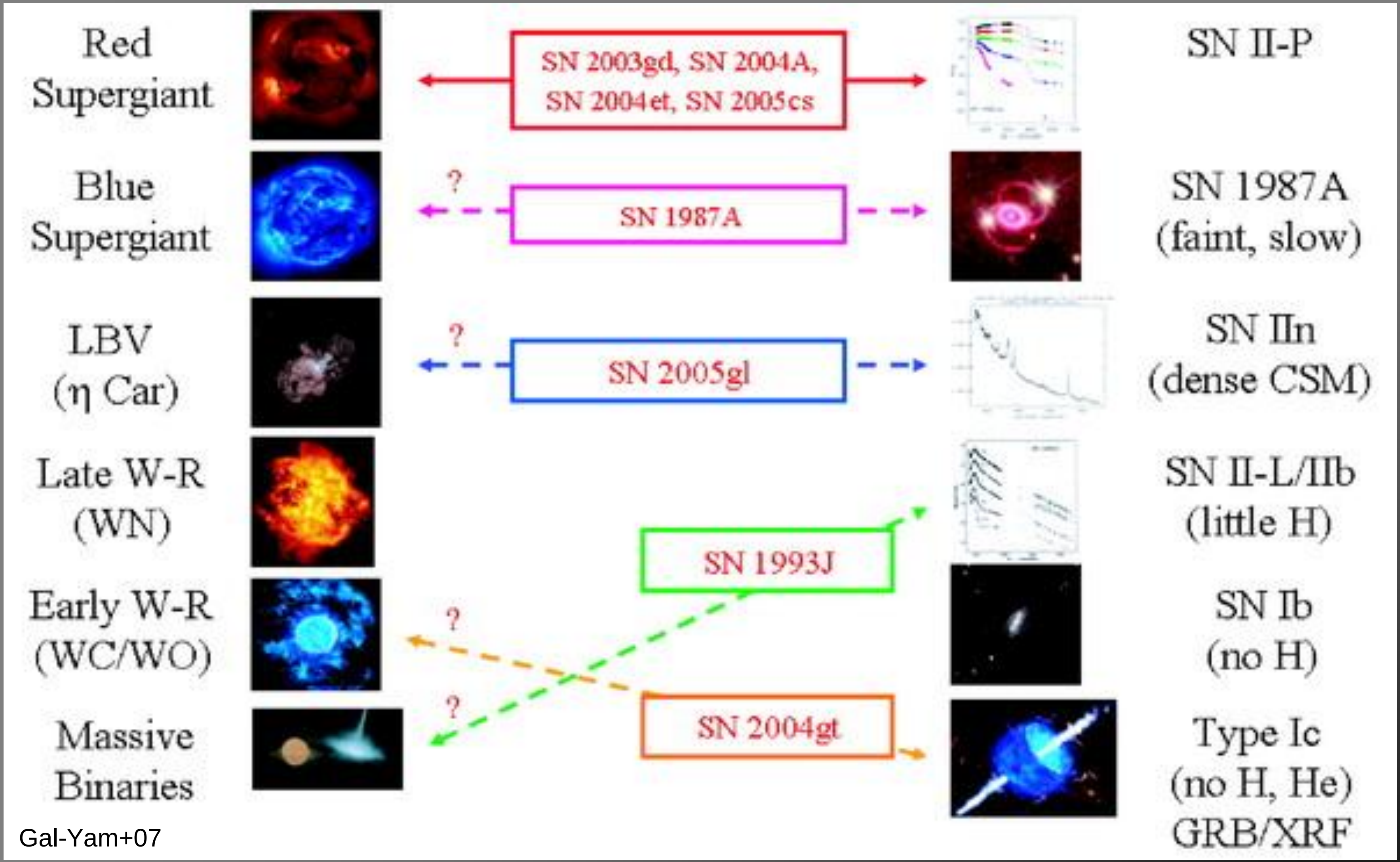
$$r_s = v_s t$$

$$r_{evap}$$

$$r_{ech} = \frac{ct_{ech}}{2}$$

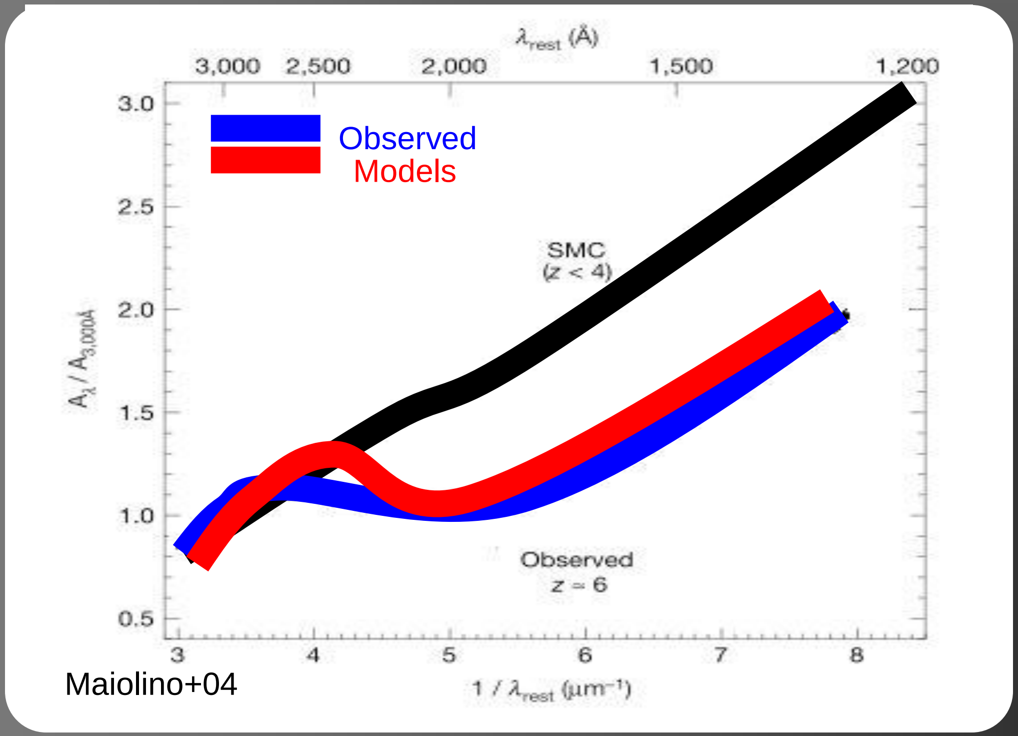


Physical Mechanism



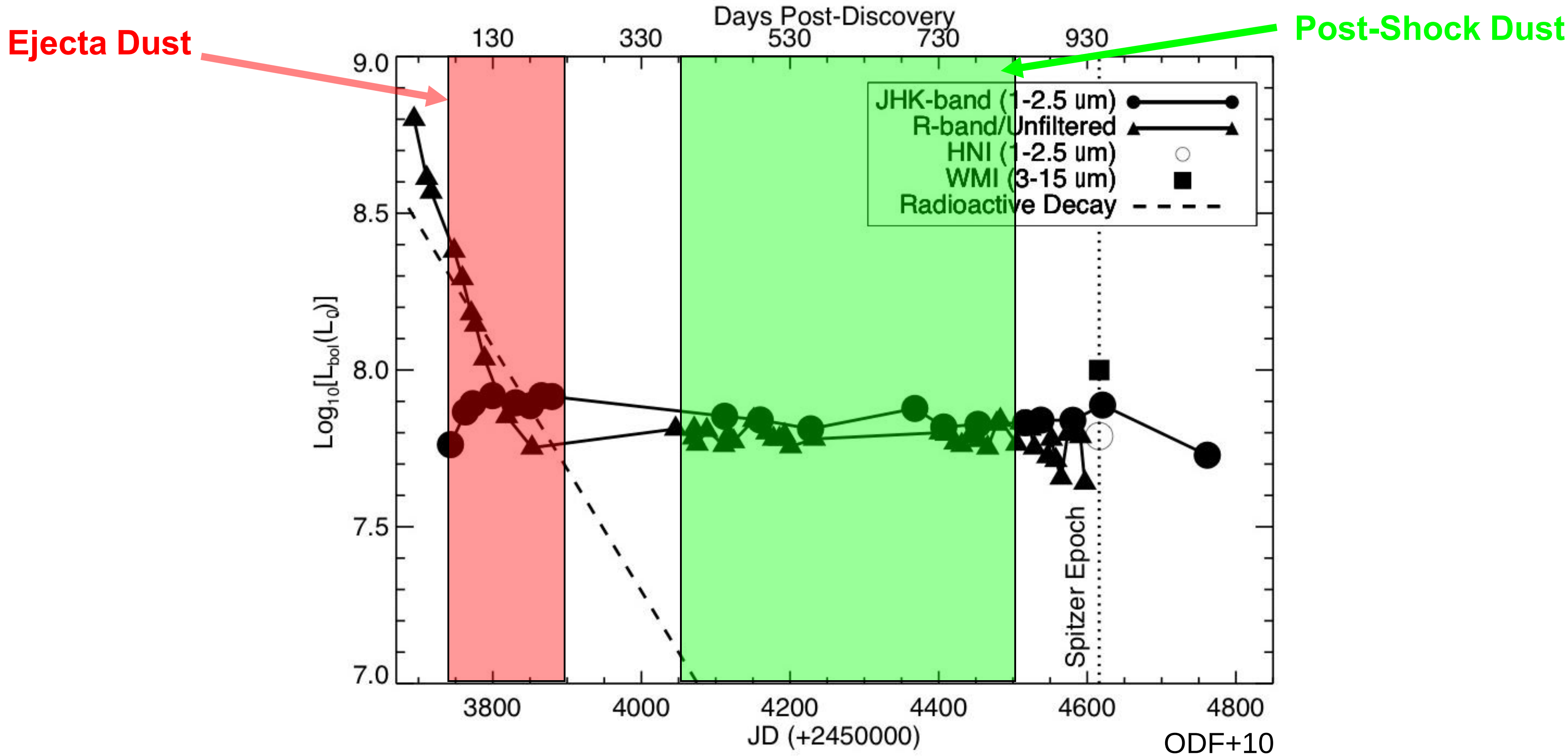
Why do we care about dust?

- The presence of dust yields various clues about the supernova explosion and the progenitor system, including:
  - ***Geometry of circumstellar medium and progenitor evolution***
  - Peak supernova luminosity & explosion mechanics
  - Shock velocity & circumstellar interaction
- The presence of dust also allows us to probe the possibility that supernovae are significant sources of dust in the early universe
  - –Observations reveal large amounts of reddening (i.e. dust) in the early universe (Maiolino+04)
  - –But at less than 1 Gyr (Z>6), the universe was not populated by low-mass AGB stars, which are the dominant sources of dust in our local universe

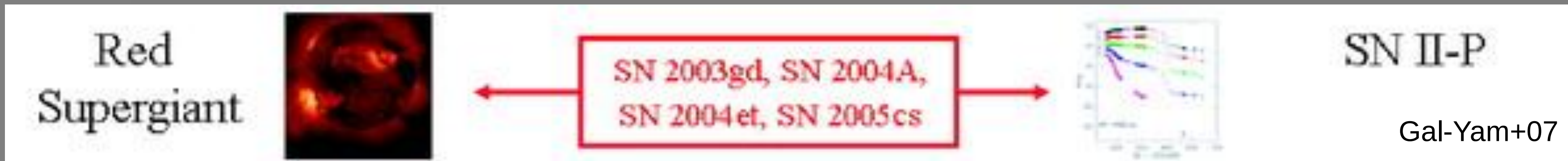


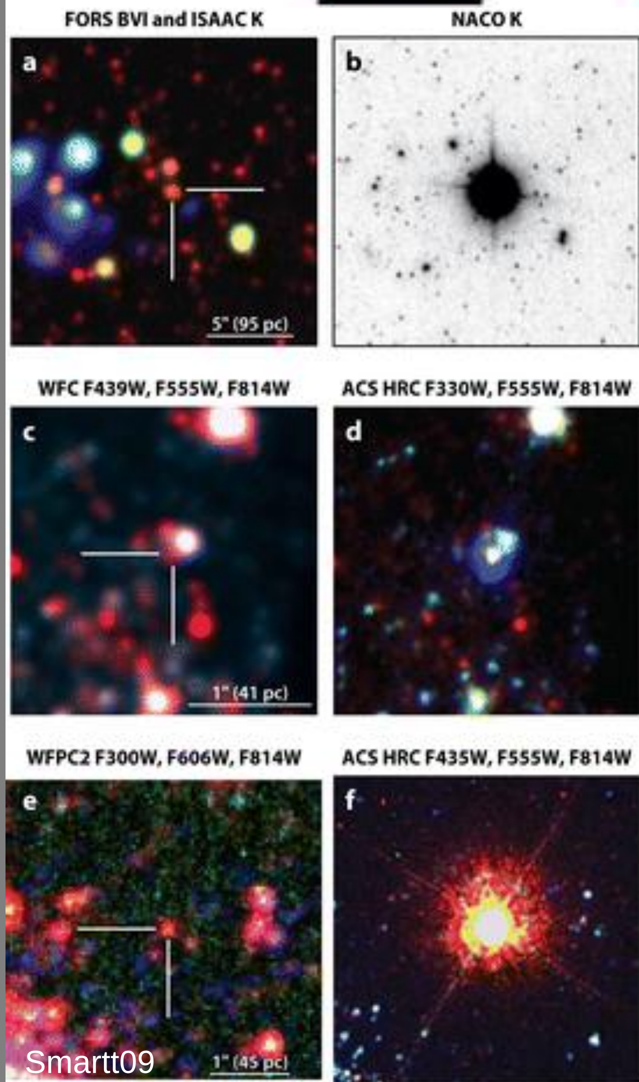
New Dust Contribution

Fit	T_{warm} (K)	T_{hot} (K)	M_{warm} ($M_\odot$)	M_{hot} ($M_\odot$)	L_{warm} ($L_\odot$)	L_{hot} ($L_\odot$)	χ^2
1.0 μm(warm) + 0.1 μm(hot)	540	847	5.9×10^{-3}	5.9×10^{-4}	1.0×10^{8}	5.8×10^{7}	1.17
0.3 μm(warm) + 0.1 μm(hot)	408	838	2.8×10^{-2}	6.7×10^{-4}	1.0×10^{8}	6.2×10^{7}	1.12
0.1 μm(warm) + 0.1 μm(hot)	453	859	4.3×10^{-2}	5.2×10^{-4}	1.1×10^{8}	5.5×10^{7}	1.10
0.01 μm(warm) + 0.1 μm(hot)	472	862	4.5×10^{-2}	5.0×10^{-4}	1.1×10^{8}	5.5×10^{7}	1.10
0.001 μm(warm) + 0.1 μm(hot)	472	862	4.5×10^{-2}	5.0×10^{-4}	1.1×10^{8}	5.5×10^{7}	1.10



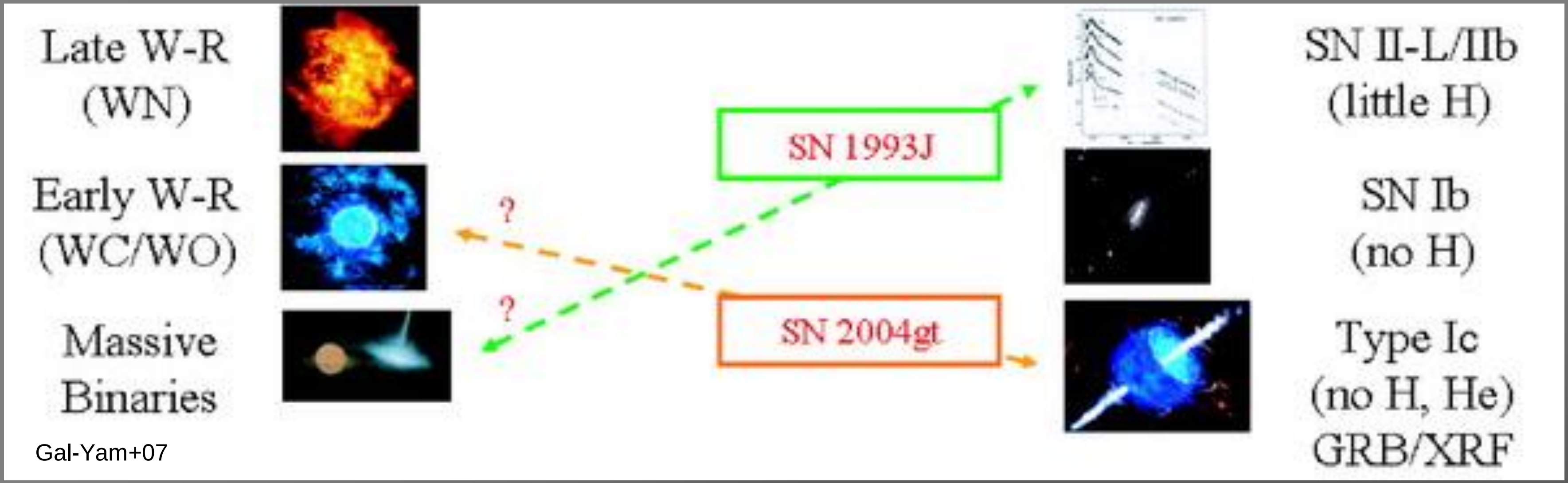
Physical Mechanism





- Type II-P SNe dominate the observed explosions.
- Direct observations of progenitors (SNe 2003gd, 2005cs, 2008bk, 2004dj, and 2004am) identify red-supergiant (RSG) progenitors. But all have masses from 8.5-17 $M_{\odot}$.
- If true, where are the higher mass RSG progenitors?
  - New IMF?
  - New theory of stellar evolution and explosions?
  - Need to account for dust extinction?

Physical Mechanism



- Type Ib/c progenitors never observed directly.
- Lack of H -> progenitor wind -> Wolf-Rayet (WR) stars. But with known galactic WR characteristics, little chance we haven't directly detected a progenitor yet. Also, Type Ib/c rate would require WR stars to form as low as 16 $M_{\odot}$.
- These results suggest 2 progenitor systems:
  - Interacting binaries
  - WR stars (But what happens to the WR stars that don't form SNe?)

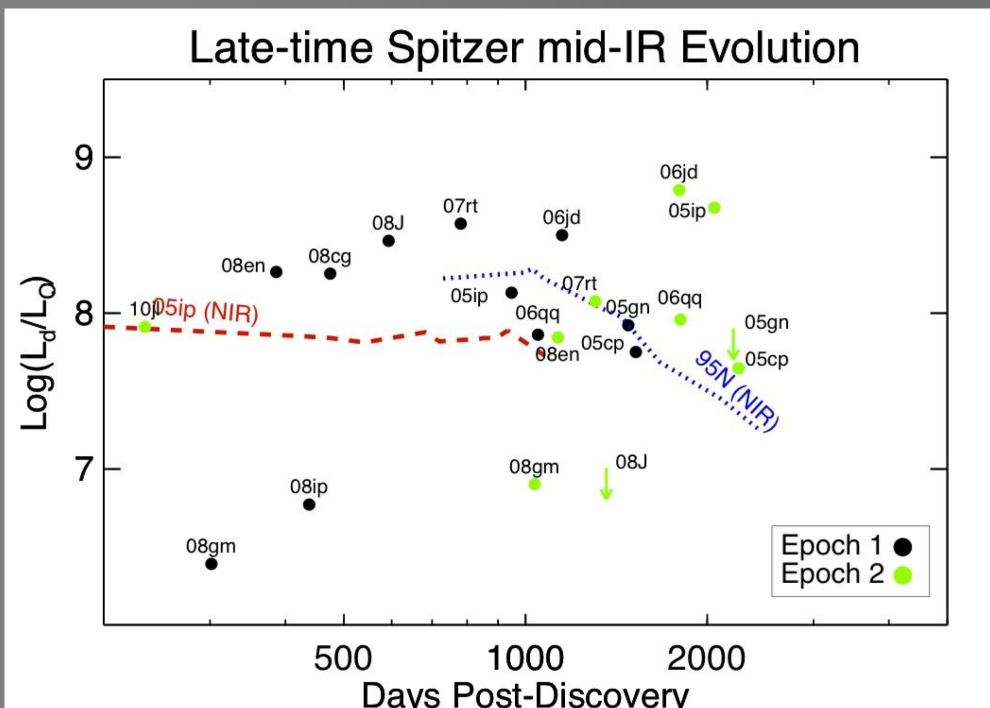
Physical Mechanism

- **What is the fate of the most massive stars (i.e., LBVs) w/ masses 80-120 $M_{\odot}$? Evolution theory suggests they lose their H/He envelopes and end up WR stars. And any eventual core-collapse should result in a black hole.**

- **Direct detection of a single LBV progenitor (SN2005gl). An additional event (SN2006jc) was observed coincident w/ a prior LBV-like outburst. Furthermore, ultra-bright (10^{51} erg), H-rich events (e.g., SNe 2006gy, 2005ap, 2008es, 2006tf) require massive progenitors, consistent with LBVs.**

- **But physical mechanism that produces the ultra-bright Type IIn (and II-L) SNe remains controversial and unresolved. If LBVs, this would imply the cores are significantly more evolved than predicted by stellar evolution models.**
  - **Perhaps the core-collapse model doesn't even work in this case (e.g., pair-instability)?**

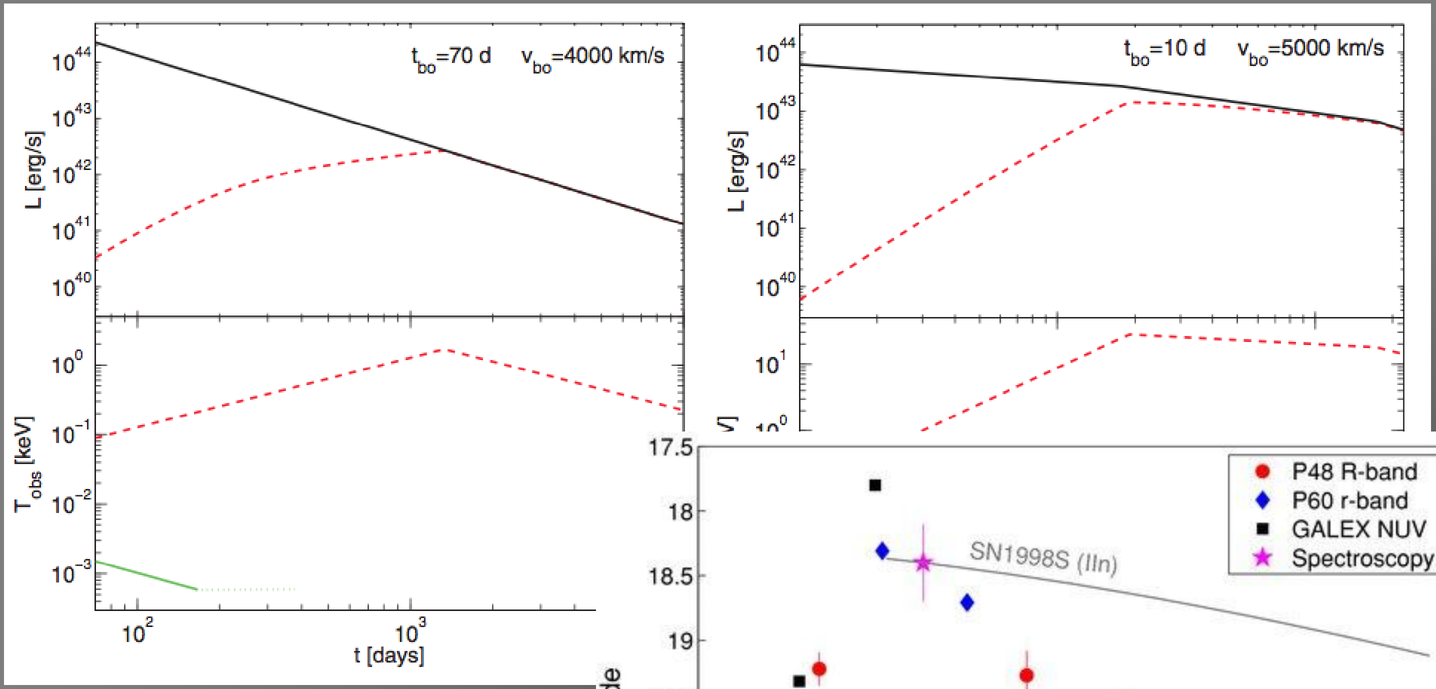
Late-time IR Emission From SNe IIn



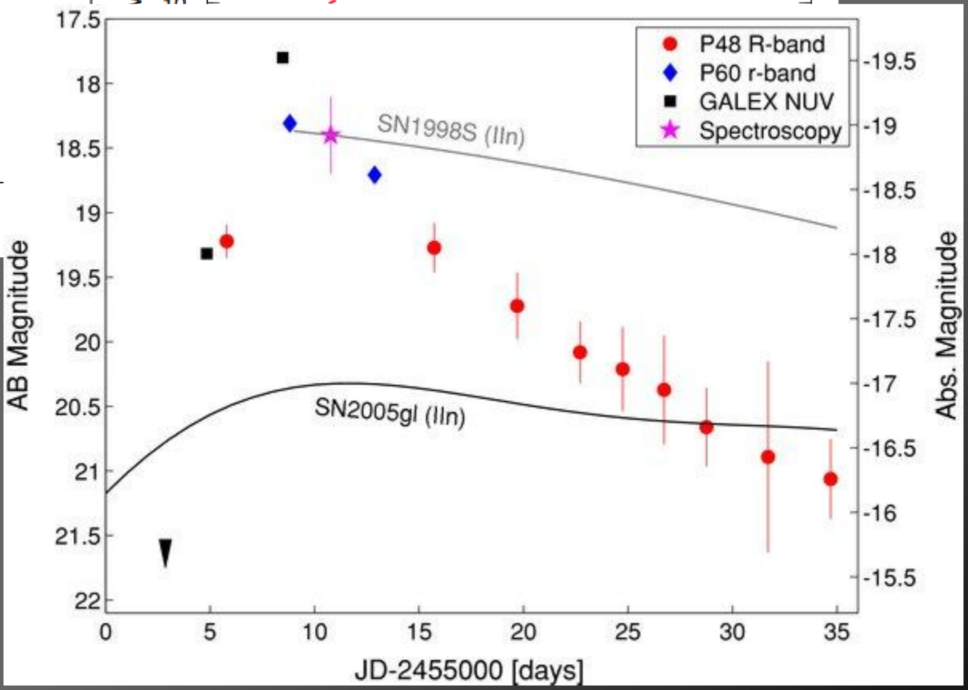
Type IIn
Undefined
before 1990

SN	Subclass	*Spitzer* Observations?/ Detections?
1979c	II	No/No
1980k	II	No/No
1982e	?	No/No
1982l	II	No/No
1982r	I	No/No
1985l	II	No/No
1986J	IIn	No/No
1987A	II	Yes/Yes
1993J	IIb	No/No
1994Y	?	No/No
1995G	IIn	No/No
1995N	IIn	No/No
1997ab	IIn	No/No
1998S	IIn	No/No
1999Z	IIn	No/No
1999bw	IIn	Yes/Yes
1999el	IIn	No/No
1999em	IIP	No/No
2002bu	IIn	Yes/Yes
2002hh	IIP	Yes/Yes
2002ic	Ia/IIn	No/No
2003gd	IIP	Yes/Yes
2004dj	IIP	Yes/Yes
2004et	IIP	Yes/Yes
2005af	IIP	No/No
2005kd	IIn	No/No
2005ip	IIn	No/No
2006gy	IIn	No/No
2006jc	Ib	No/No
2006tf	IIn	No/No
2007it	IIP	Yes/Yes
2007od	IIP	No/No
2007rt	IIn	No/No
2008iy	IIn	No/No

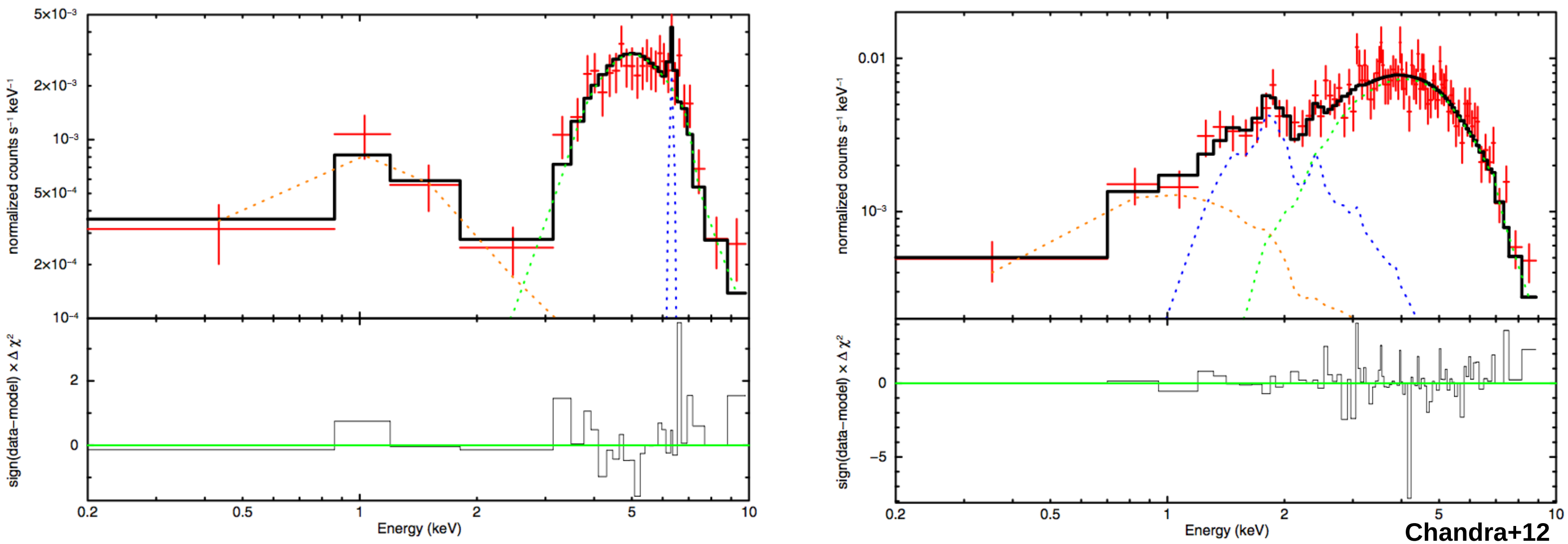
X-Rays



t_{bo}=70 d v_{bo}=4000 km/s
t_{bo}=10 d v_{bo}=5000 km/s
L [erg/s]
T_{obs} [keV]
t [days]

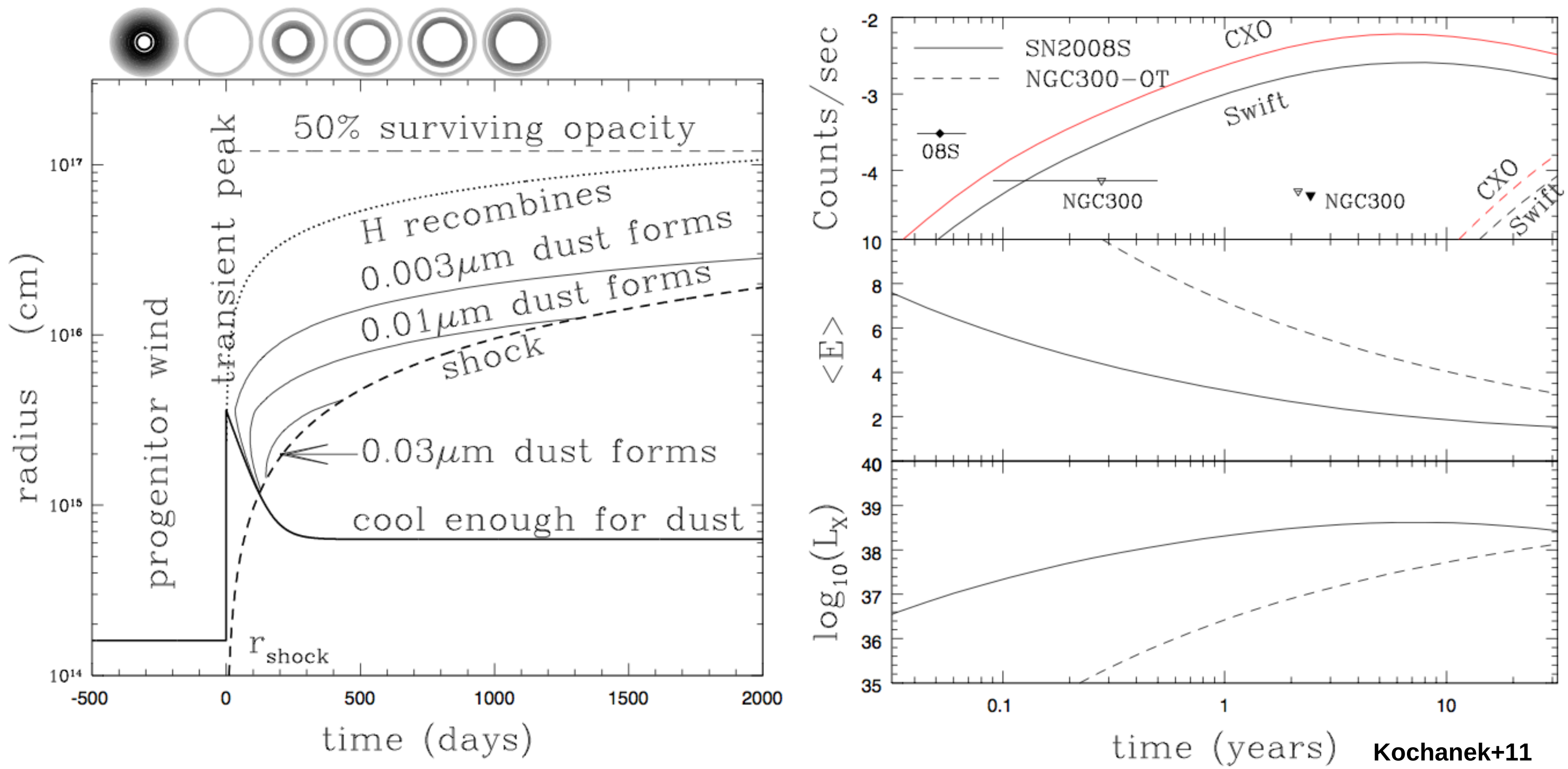


P48 R-band
P60 r-band
GALEX NUV
Spectroscopy
SN1998S (IIn)
SN2005gl (IIn)
AB Magnitude
Abs. Magnitude
JD-2455000 [days]


normalized counts s⁻¹ keV⁻¹
sign(data−model) × Δ χ²
Energy (keV)
0.2
0.5
1
2
5
10
5×10⁻³
2×10⁻³
10⁻³
5×10⁻⁴
2×10⁻⁴
10⁻⁴
0.01
−5

Chandra+12

2) Dust From Impostors?



Kochanek+11