The Type Ia SN 2007if: Super-Chandrasekhar?

Talk presented at the Astronomy Workshop
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PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

With a large team of colleagues from Europe, US, and England!

MILLENNIUM INSTITUTE OF ASTROPHYSICS

Outline:

1. Type Ia SNe
   1. Concepts
   2. Diversity
   3. Models of diversity
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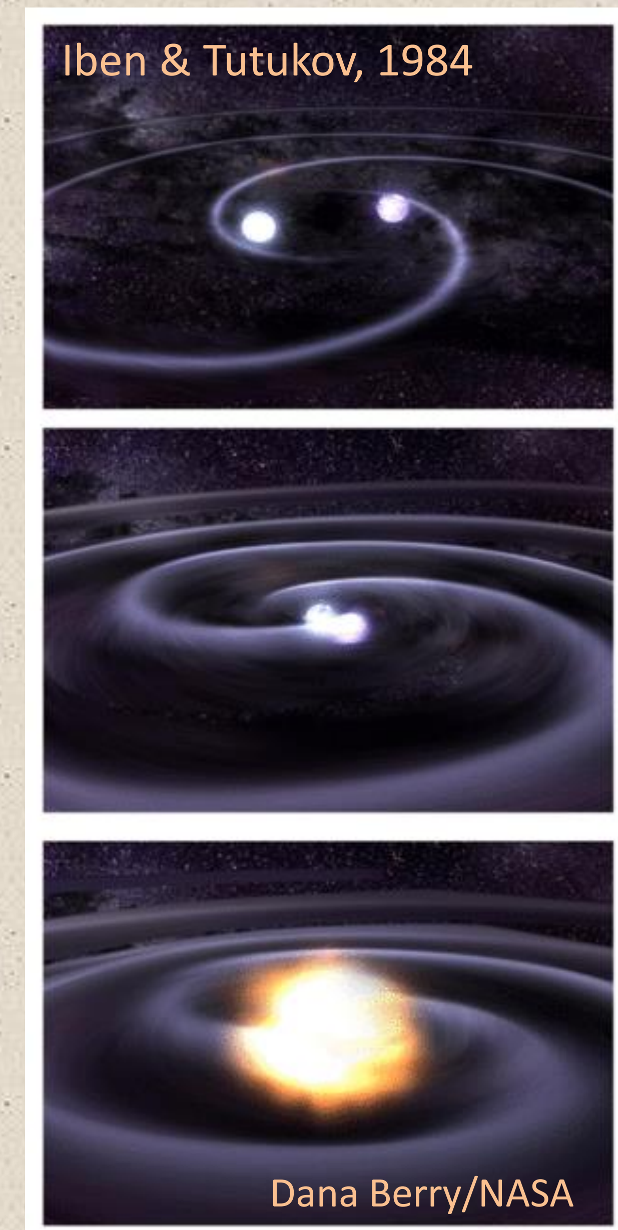
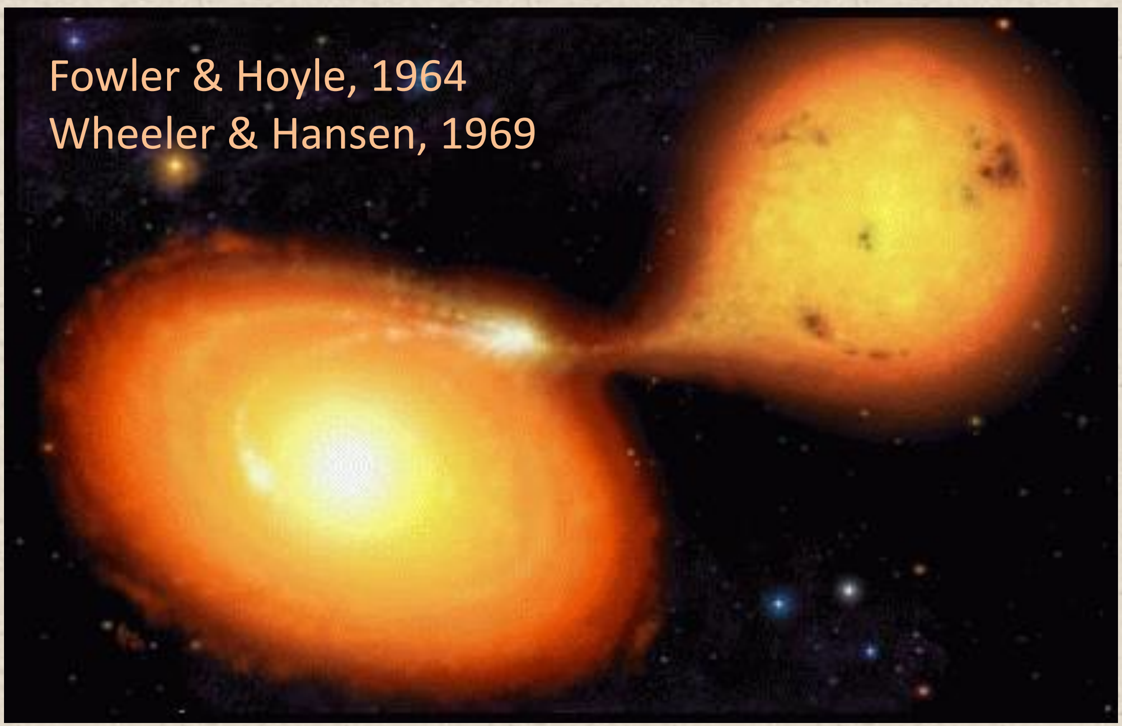
4. Putting the pieces together: A model under construction

Cartoon concepts of Type Ia SNe progenitors

Double Degenerate (DD)
Merger version

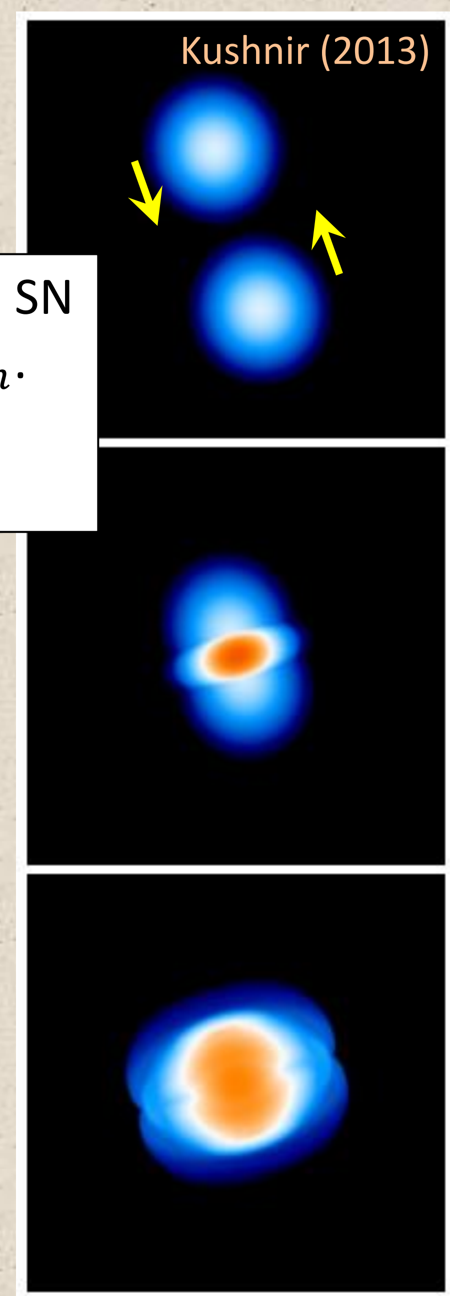


Single Degenerate (SD)



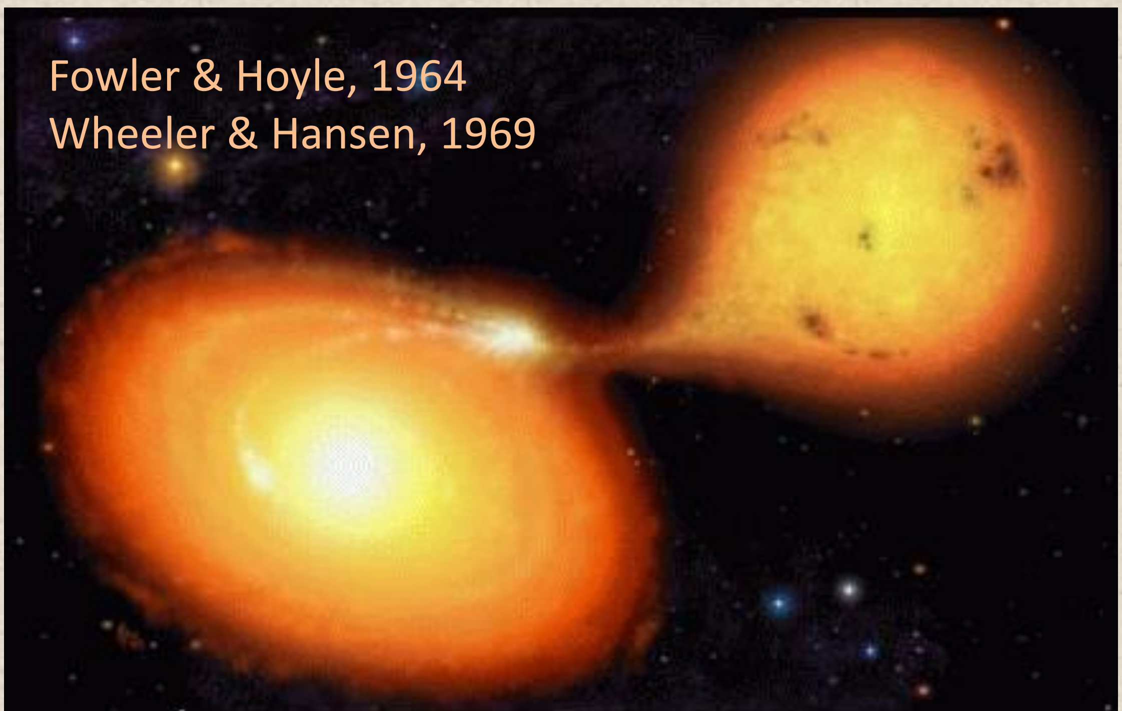
Cartoon concepts of Type Ia SNe progenitors

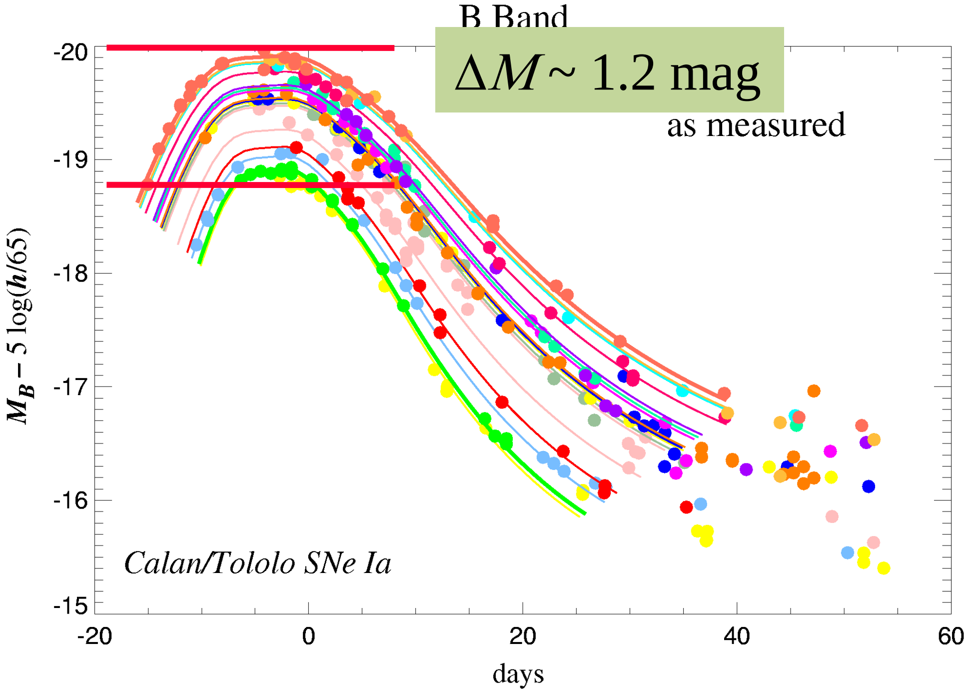
Double Degenerate (DD)
Collision version

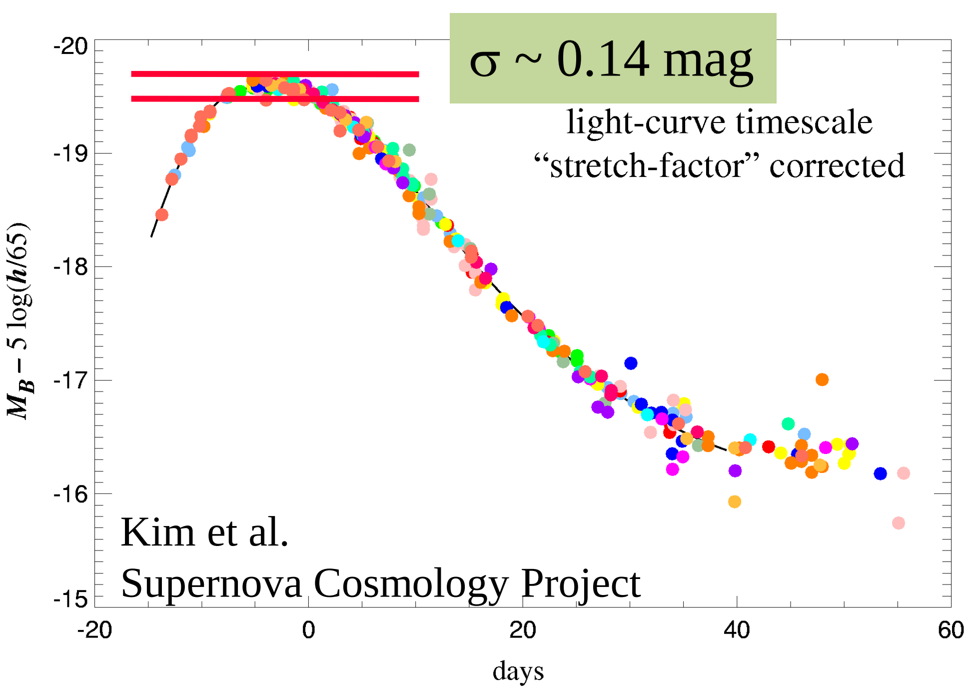


- The SD channel leads naturally to a SN distribution strongly peaked at M_{Ch}.
- The DD channels could provide explosions with a range of masses.

Single Degenerate







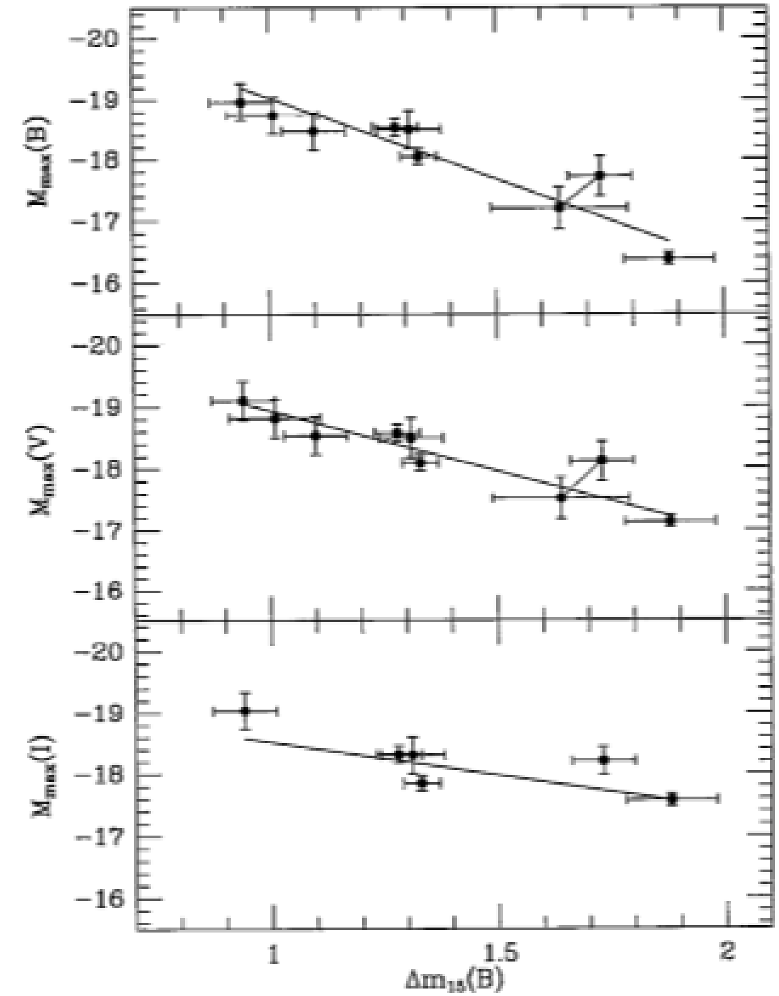


FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.

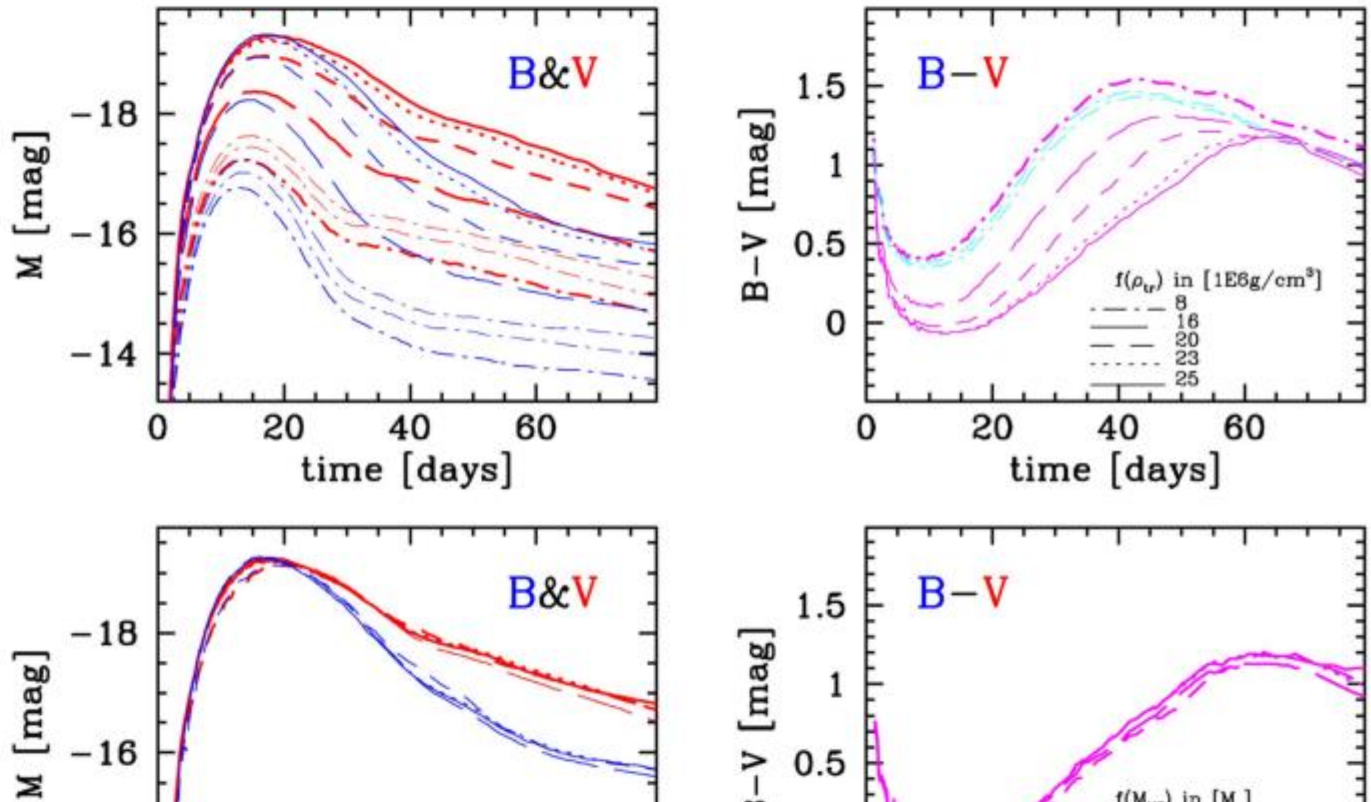
Type Ia SNe are NOT all the same.

THE ASTROPHYSICAL JOURNAL, 846:58 (28pp), 2017 September 1

(Hoeflich et al. 2017)

…s a M_{Ch} WD explodes?

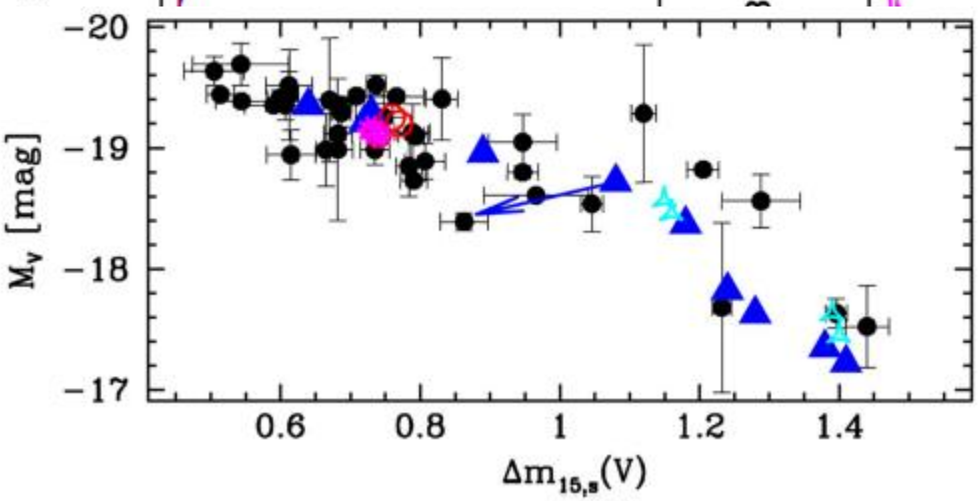
…nuclear burning types:
…to's W7)
…etonation (Woosley)
…khlov)
…eflich & Khokhlov)
…r ignition (Maeda)



…E 1

…PE Ia SUPERNOVA MODELS[a]

ρ_{tr} (5)	E_{kin} (6)	M_{Ni} (7)	$\langle v \rangle$ (8)
…	1.30	0.53	8.9
2.6	1.52	0.56	9.0
3.0	1.56	0.67	9.2
2.4	1.52	0.60	9.1
2.0	1.49	0.51	9.0



…ss of the white dwarf is $\simeq 1.4\ M_\odot$ for all models.

Nuclear combustion physics

The diversity of Type Ia SNe can be reasonably well reproduced by the diversity of combustion modes expected for C-O degenerate matter.

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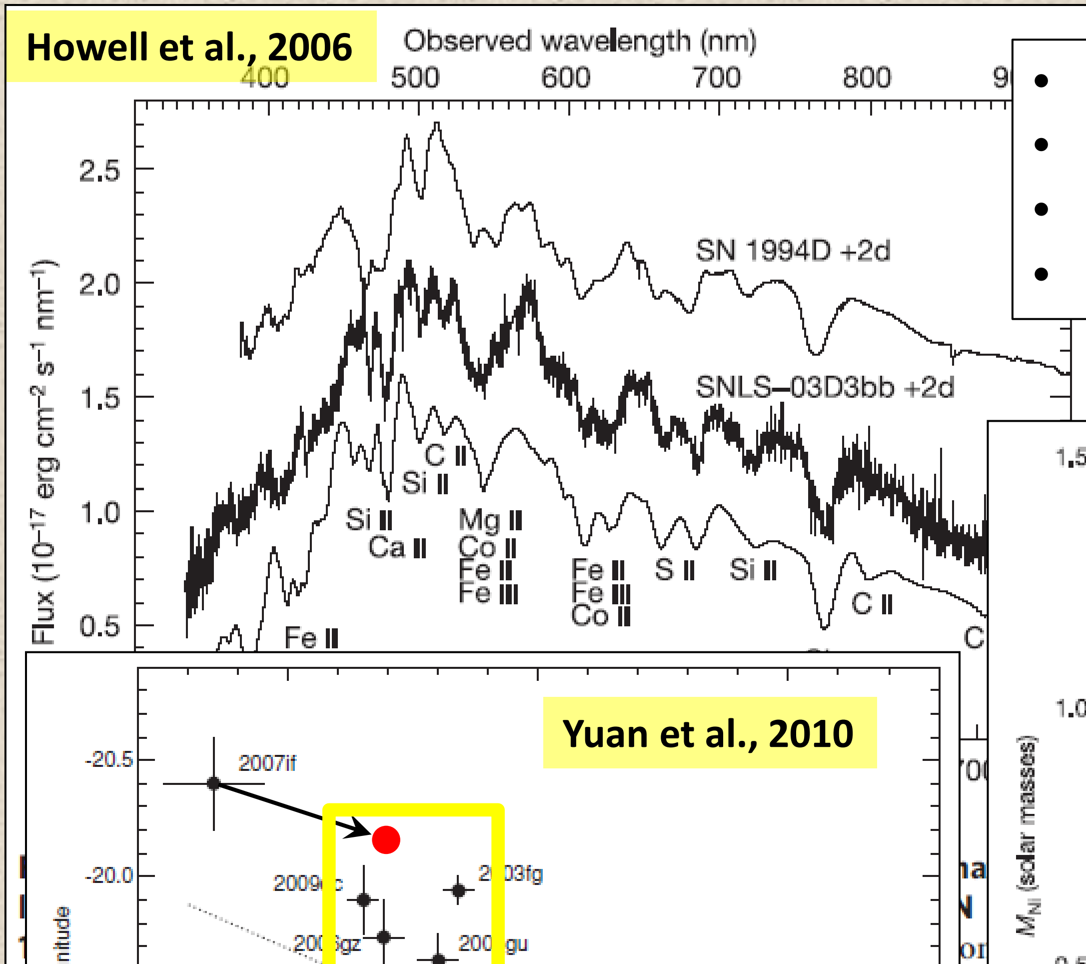
- Slow light curve ($\Delta m_{15} < 0.9$)
- Low velocities
- High brightness → $M_{\mathrm{Ni}} \cong 1.3 M_{\odot}$
- High mass? → Super-Chandrasekhar



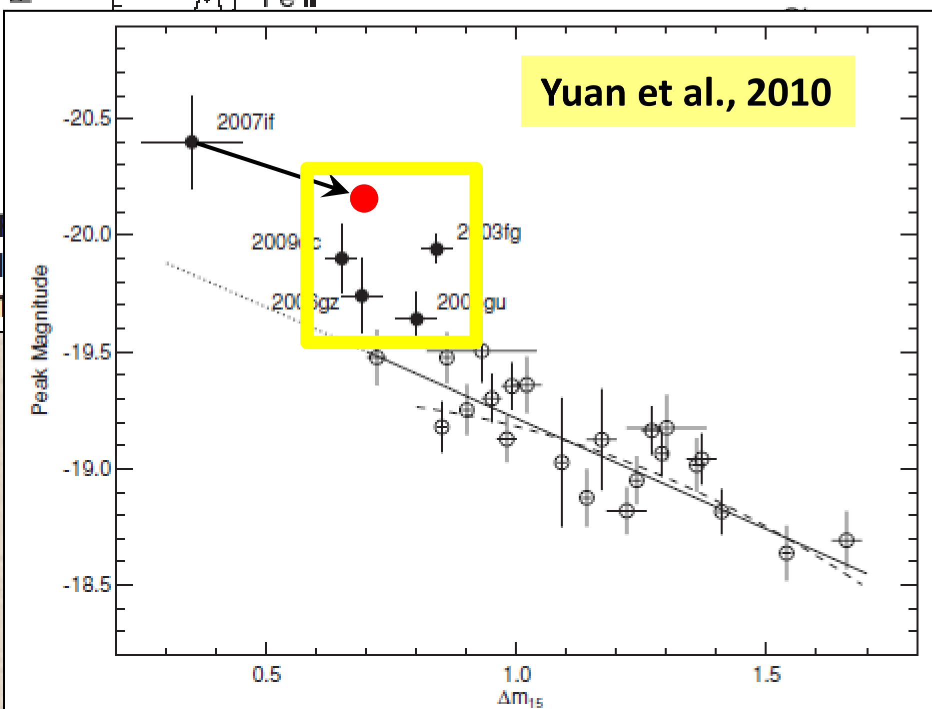


Figure 2. Peak luminosity vs. decay rate for SN 2007if and other SNe Ia. Except

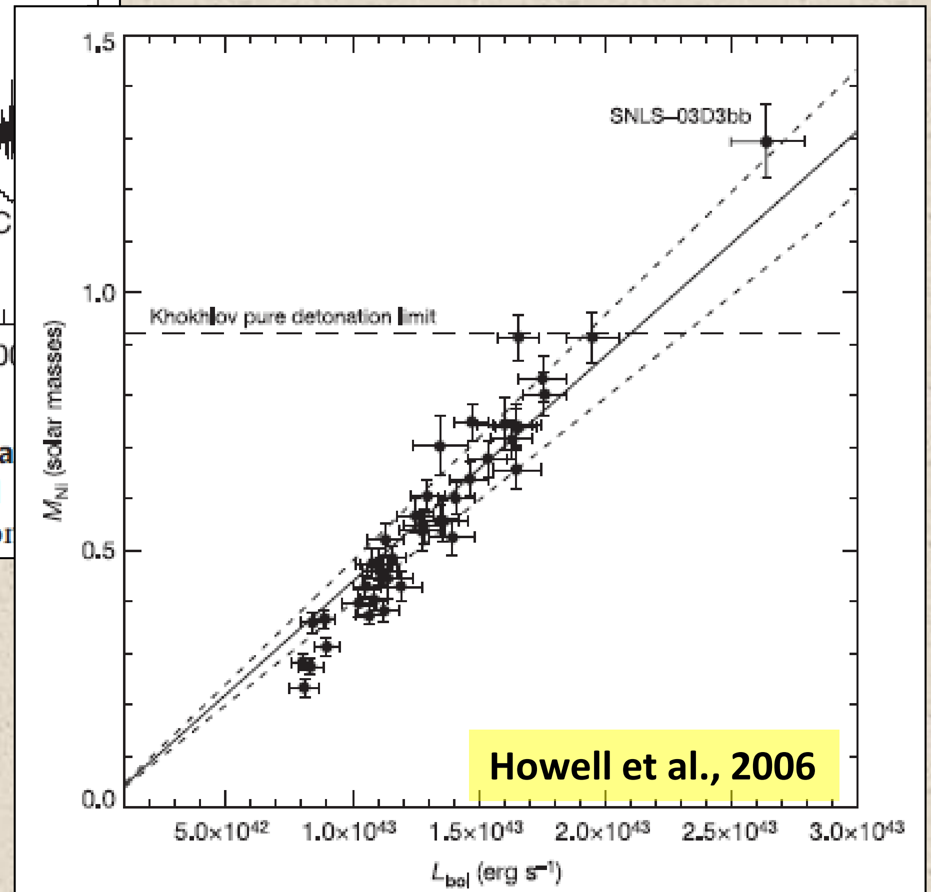


Figure 2 | Bolometric luminosity versus implied ^{56}Ni mass for SNLS-03D3bb and low-redshift type Ia supernovae[7]. The low-redshift

Taubenberger et al., 2013

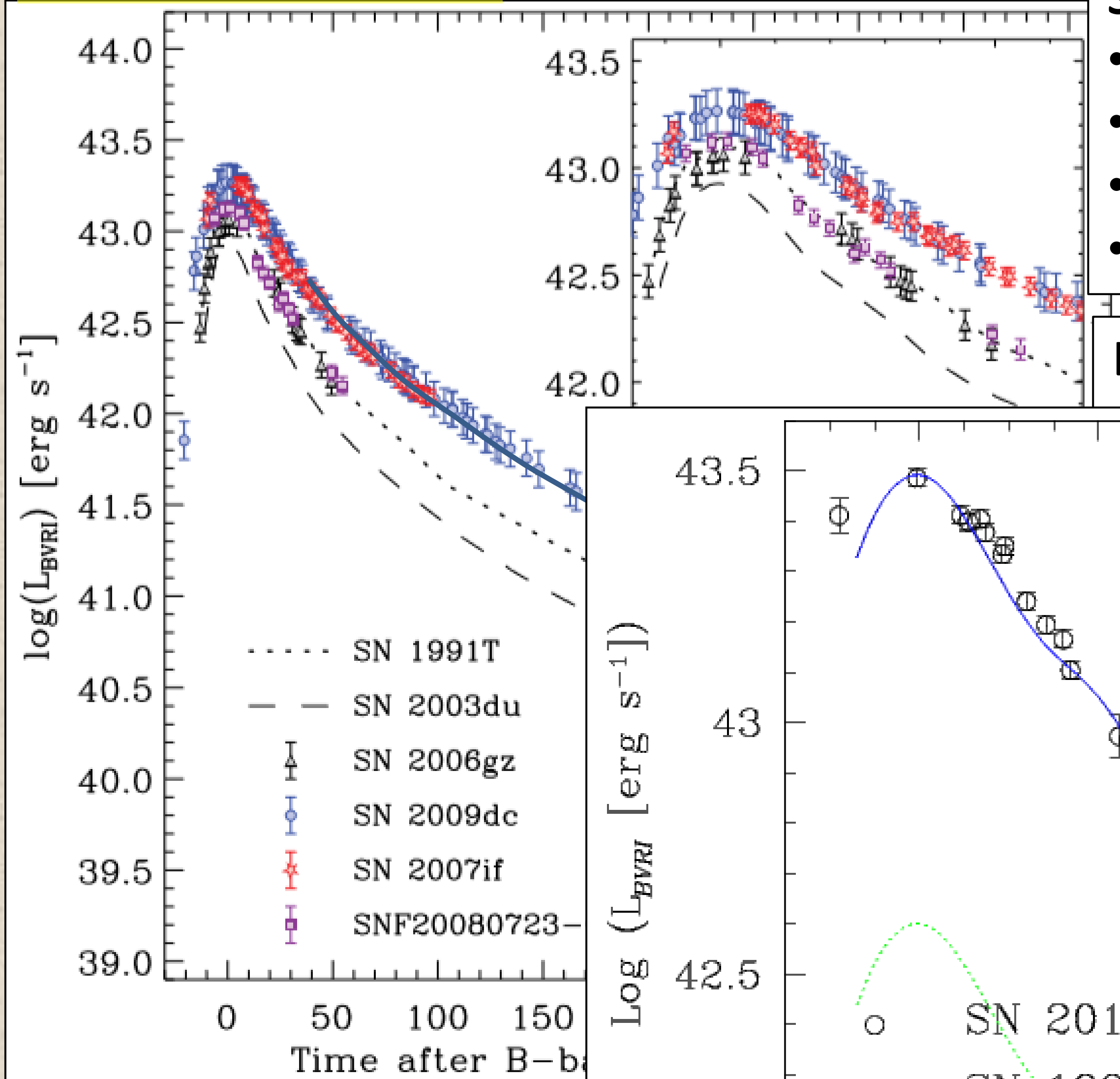
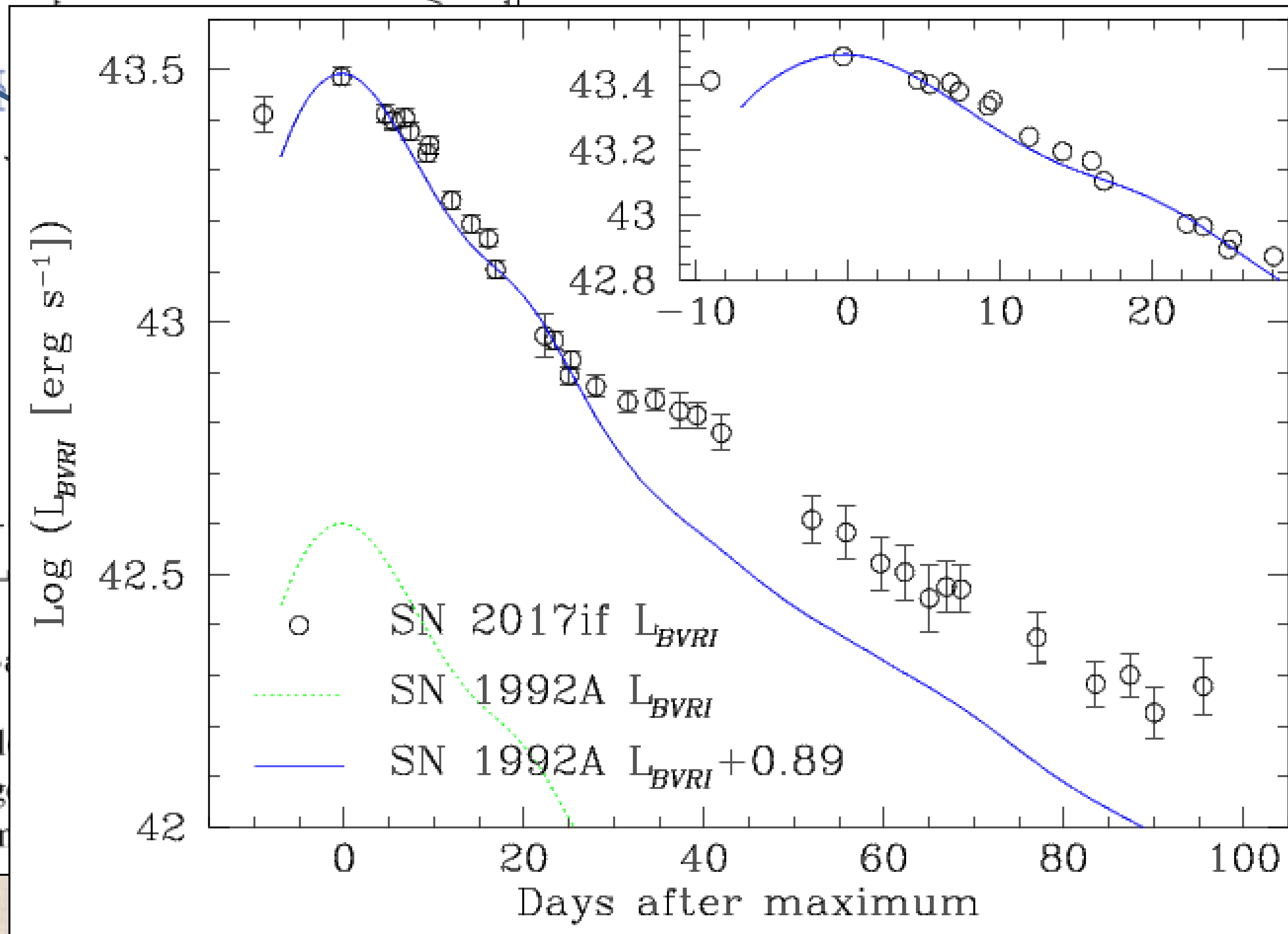


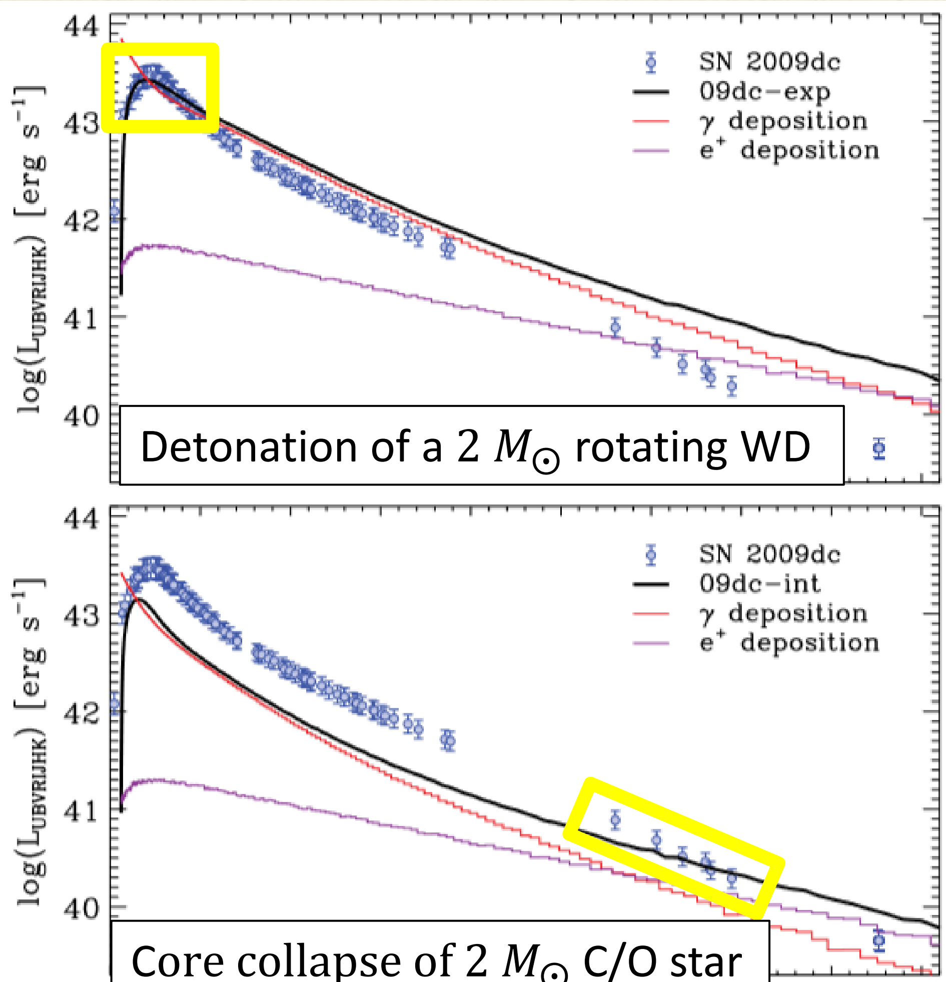
Figure 3. *BVRI*-integrated pseudo-bol
as in Fig. 2. The peak phase is enlarg
rest-frame days after *B*-band maximum

SN 2007if (Scalzo el al. 2010)

- Slow light curve ($\Delta m_{15} \cong 0.7$)
- Low velocities – Si plateau
- High maximum brightness
- If Super-Chandra $M_{\mathrm{Ni}} \cong 1.7 M_{\odot}$

LCs @ late times open questions:





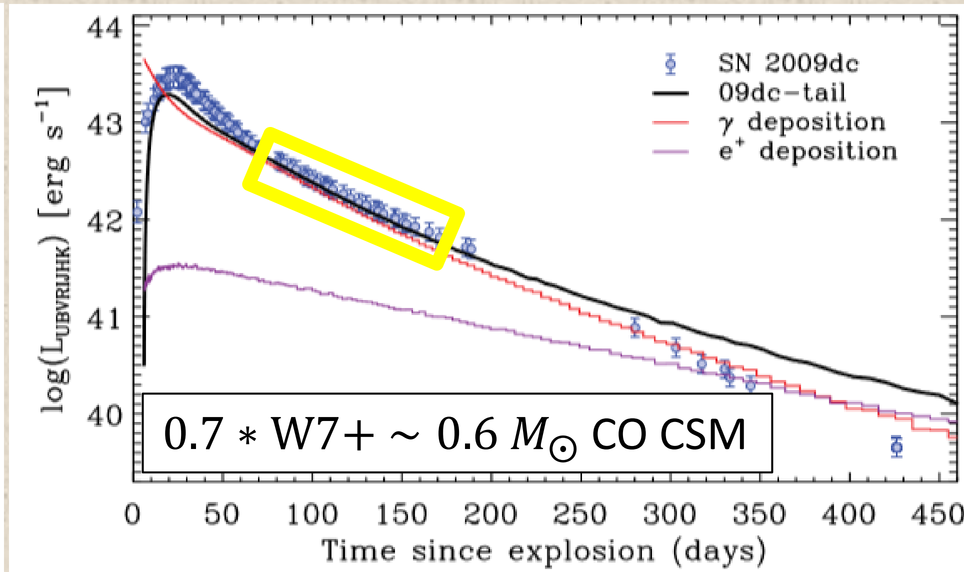
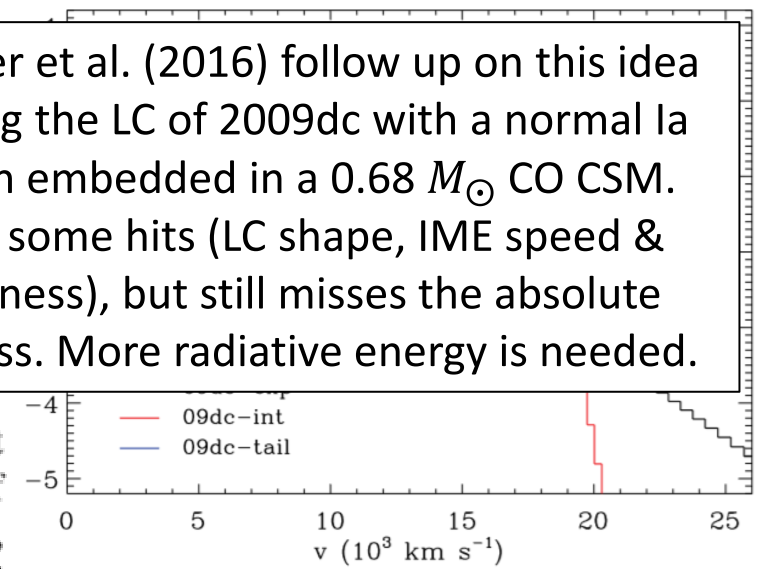


Figure 9. Synthetic bolometric light curves (black solid lines) for different models compared to the observed *UBVRIJHK*-bolometric light curve of SN 2009dc (Taubenberger et al. 2011, blue (in online version) data points, assuming a *B*-band rise time of 23 d). The contributions of γ-rays (red solid lines in online version) and positrons (purple solid lines in online version) to the synthetic bolometric light curves are shown individually.
Top panel: the 09dc-exp model of Hachinger et al. (2012).
Middle panel: the 09dc-int model of Hachinger et al. (2012).
Bottom panel: 09dc-tail (∼2 $M_\odot$ of ejecta, ∼1 $M_\odot$ of ^{56}Ni).

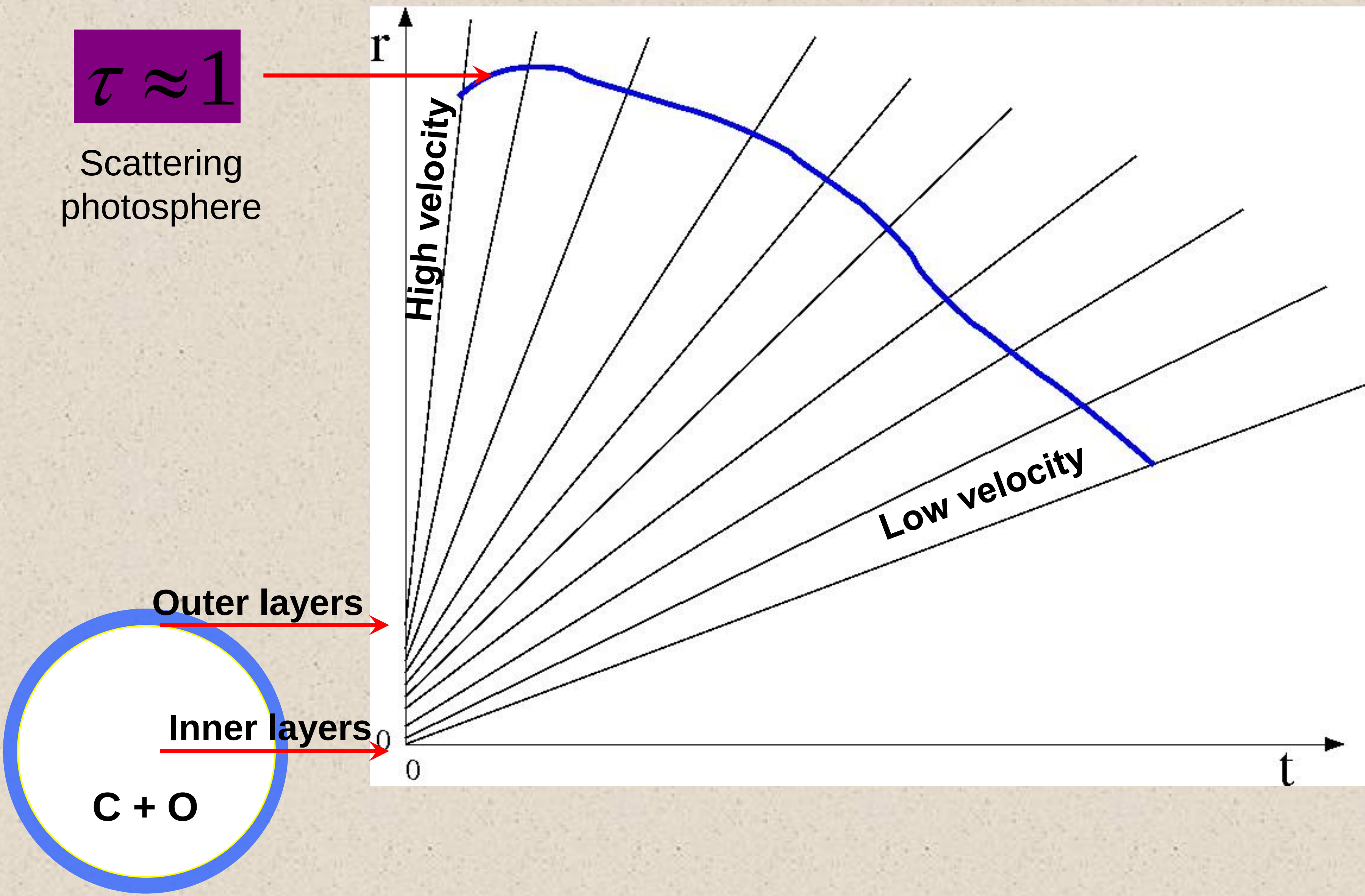
Noebauer et al. (2016) follow up on this idea modelling the LC of 2009dc with a normal Ia explosion embedded in a 0.68 $M_\odot$ CO CSM. They get some hits (LC shape, IME speed & compactness), but still misses the absolute brightness. More radiative energy is needed.



ure 10. Density profiles of the models shown in Fig. 9, evaluated at a rence time of 100 s after the explosion.

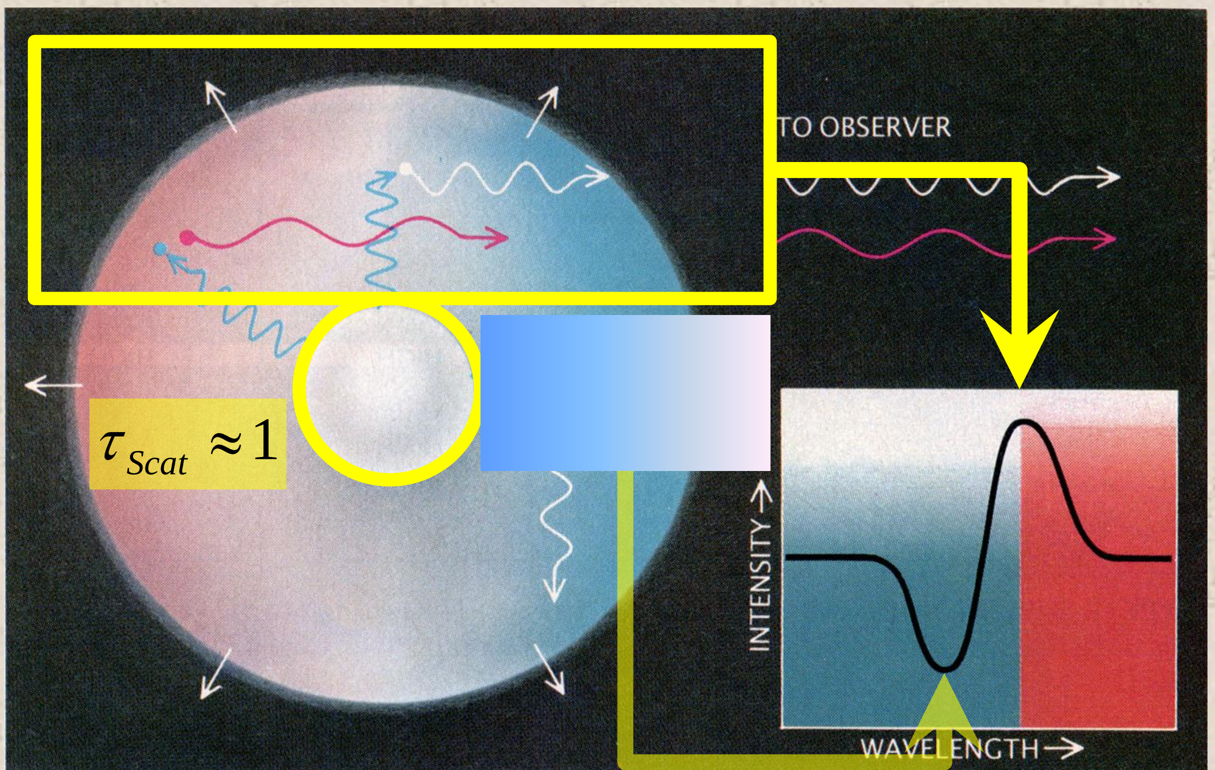
Taubenberger et al. (2013) study of SN 2009dc light curves.

Crash course on SN spectroscopy (2 slides) ☺



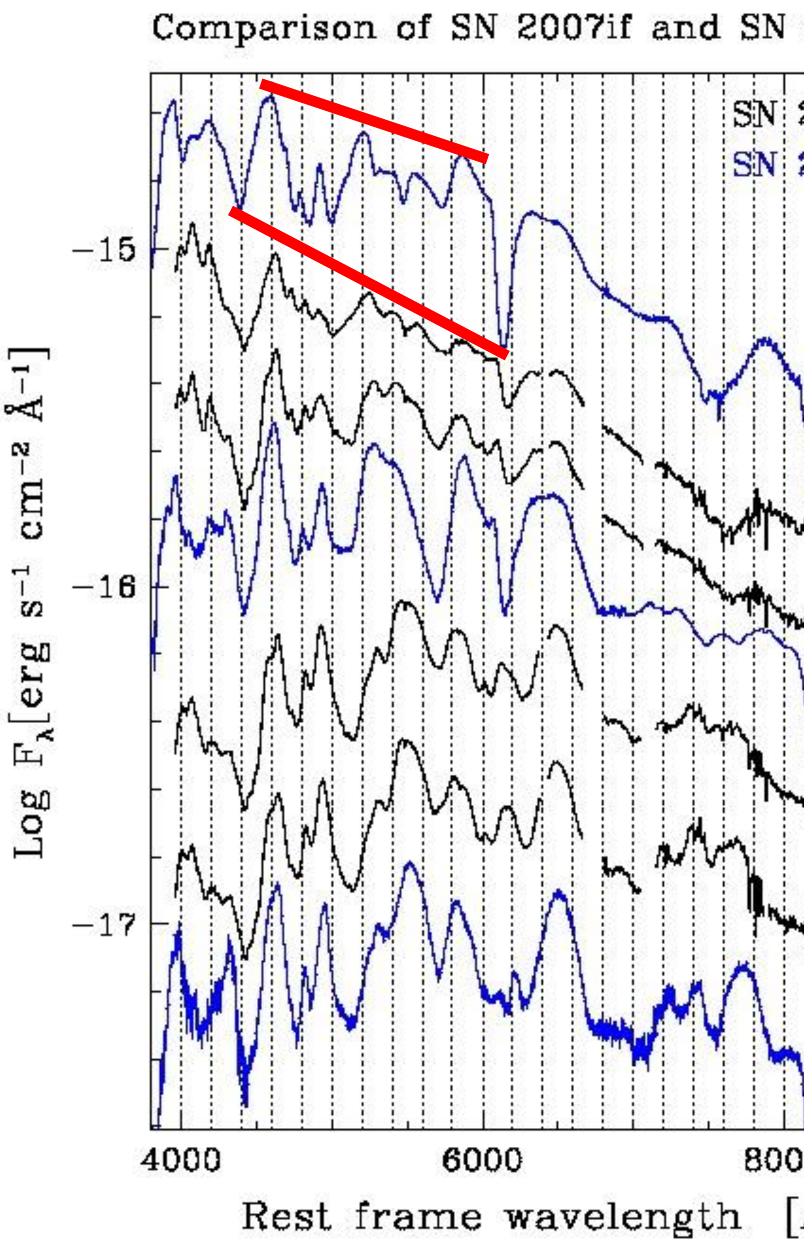
Spectrum formation: lines & continuum

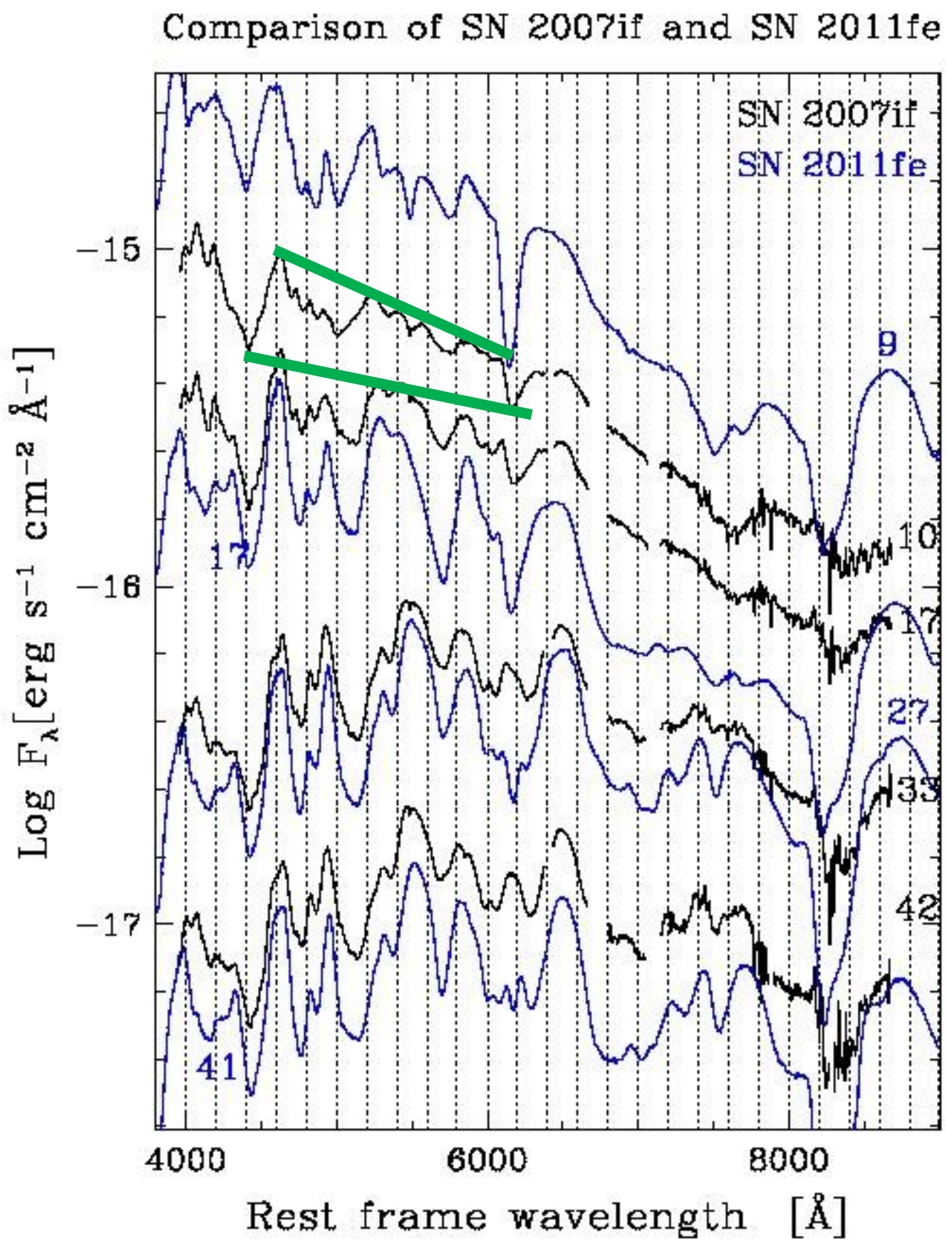
Resonant scattering zone: Generates the emission maximum (both blueshifted & redshifted)



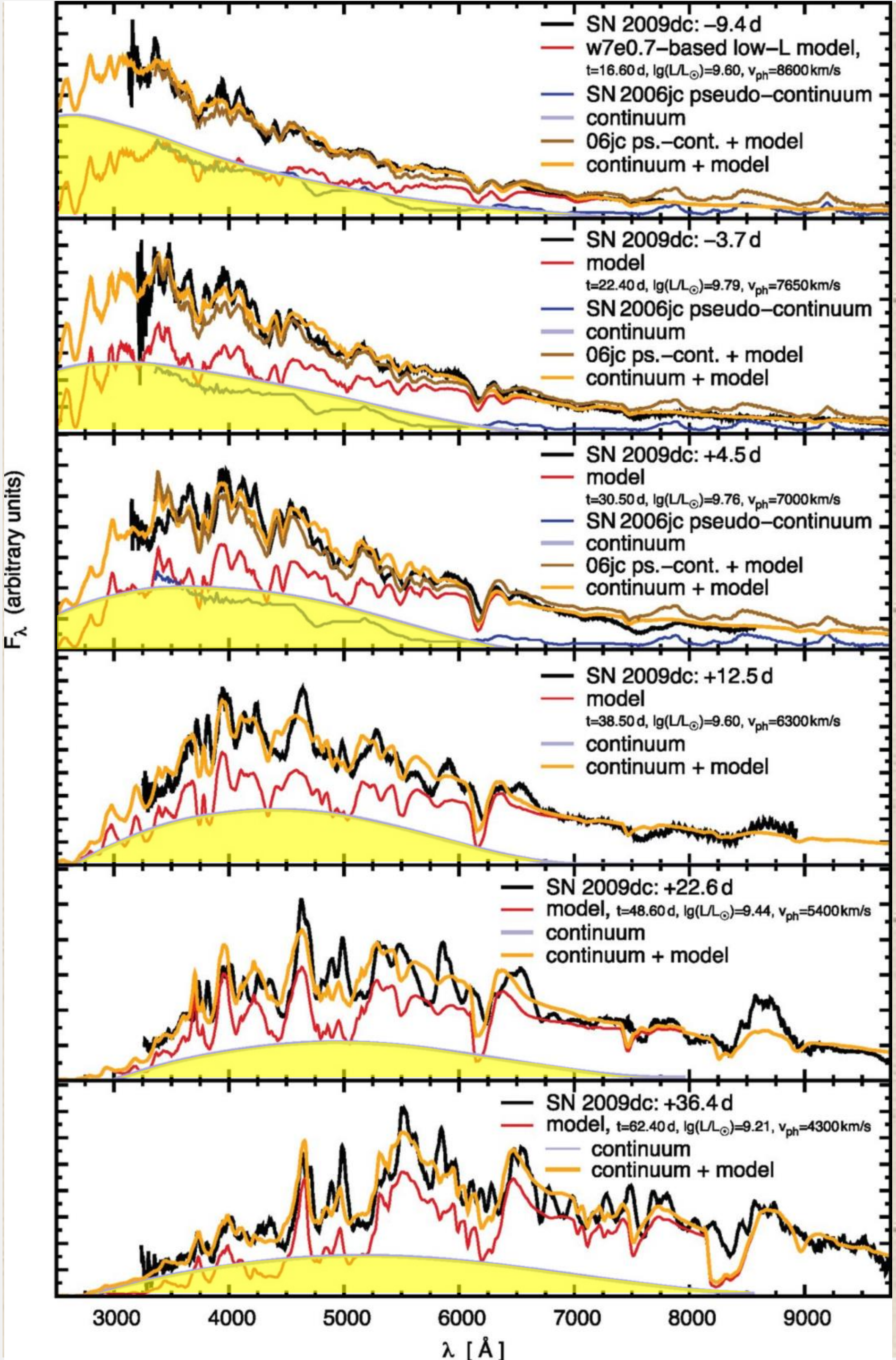
Obscuration zone: Generates the absorption minimum (blueshifted)

Continuum source provided by electron scattering


Comparison of SN 2007if and SN
SN
SN
−15
−16
−17
Log F_λ[erg s^{-1} cm^{-2} Å^{-1}]
4000
6000
800
Rest frame wavelength [


Comparison of SN 2007if and SN 2011fe
SN 2007if
SN 2011fe
−15
−16
−17
Log F_λ[erg s^{-1} cm^{-2} Å^{-1}]
9
10
17
17
27
33
42
41
4000
6000
8000
Rest frame wavelength [Å]

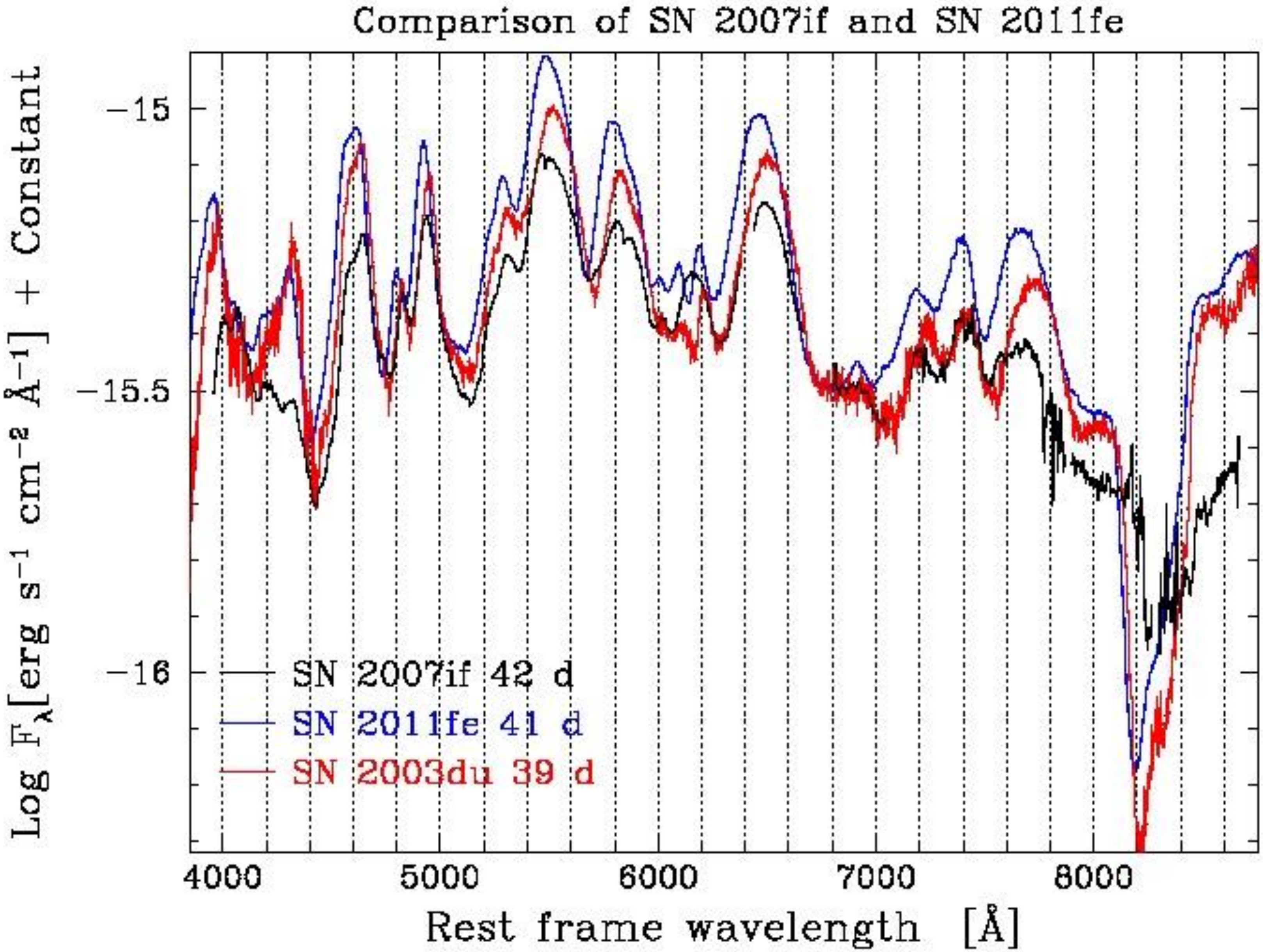
SN 2009dc



Spectrum model based on Nomoto's W7 like explosion with 0.7 the original E_K and an additional continuum *fitted to the difference*.

1. Continuum is not BB
2. Diminish & reddens in time
3. Pseudo-continuum shape as resulting from multiple emission lines (alla Ibn SN 2006jc)

(Hachinger et al. 2012)



Comparison of SN 2007if and SN 2011fe
Log F_λ[erg s^{-1} cm^{-2} Å^{-1}] + Constant
−15
−15.5
−16
4000
5000
6000
7000
8000
Rest frame wavelength [Å]
SN 2007if 42 d
SN 2011fe 41 d
SN 2003du 39 d

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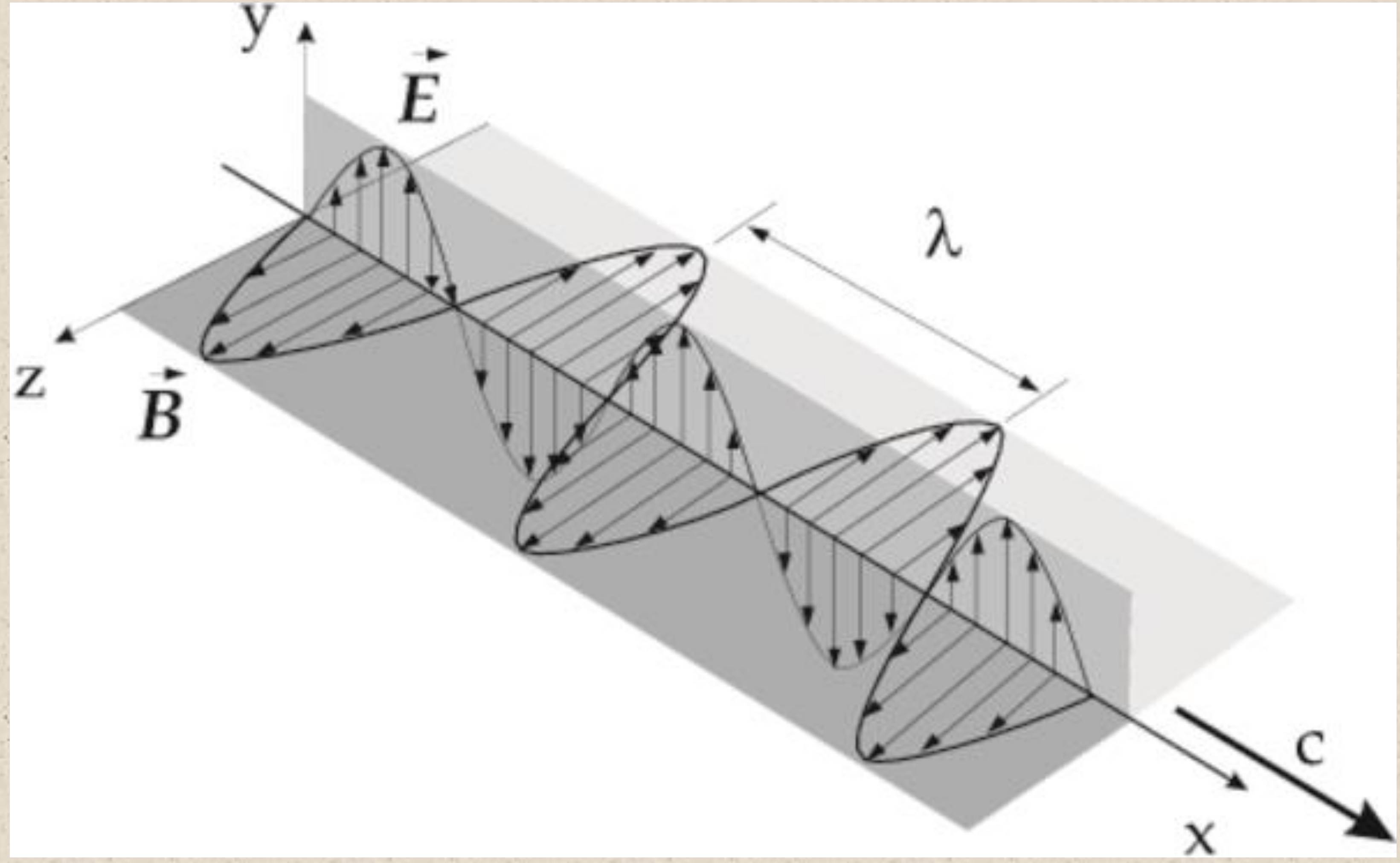
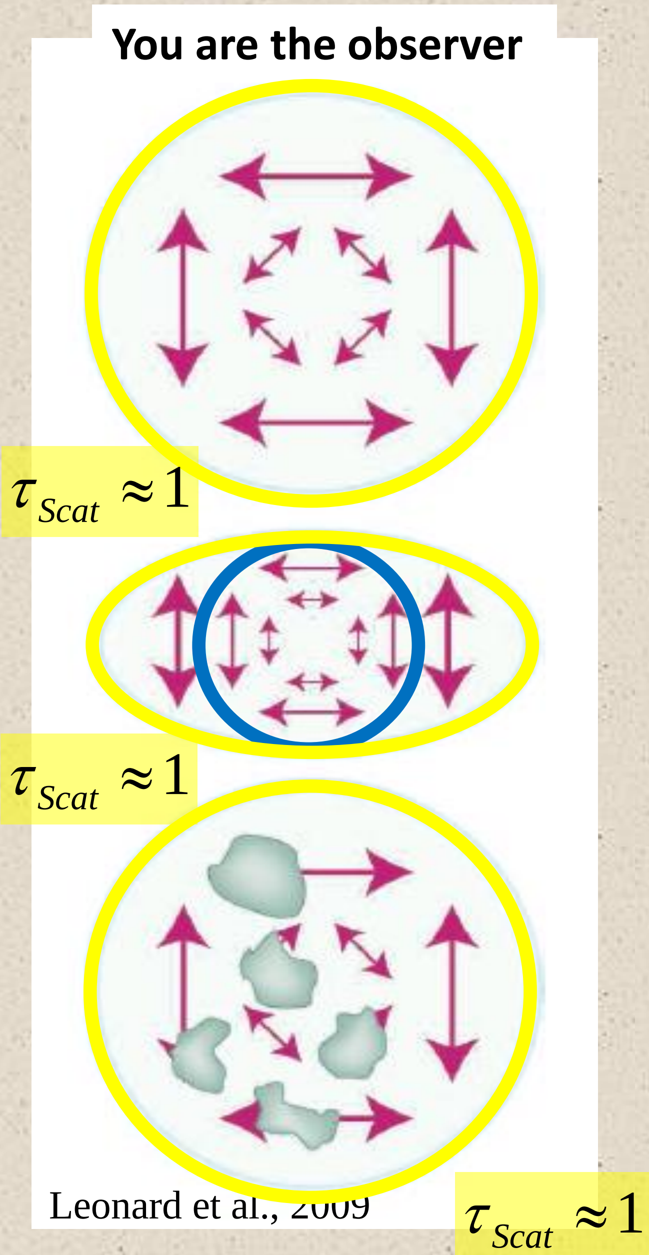
Crash course on SN polarization: 2 slides



Continuum & Line Polarization in SNe



Leonard et al., 2009

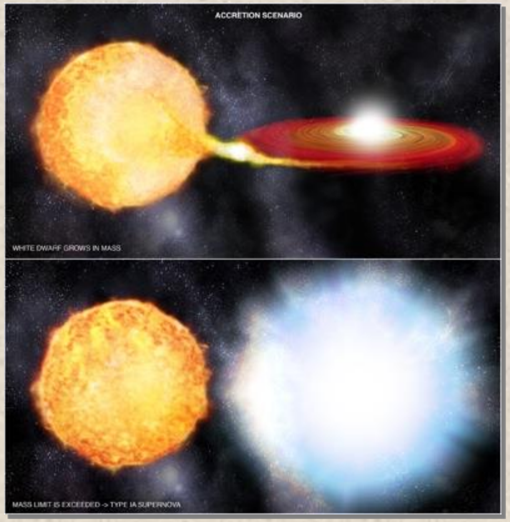
Continuum polarization

Reveals a global asymmetry of the photosphere

Line polarization

Reveal local inhomogeneities in density, chemical composition and/or excitation

Conceptual basis for polarization in Type Ia SNe



Global departures from spherical symmetry

Progenitor Scenarios: It is difficult to contrive a progenitor that does not involve some degree of asymmetry. <u>More so for “Super-Chandra Ia SNe”.</u>

Accretion disks, fast & slow DD mergers, rotating WDs...

THE ASTROPHYSICAL JOURNAL, 785:105 (13pp), 2014 April 20 MOLL ET AL.

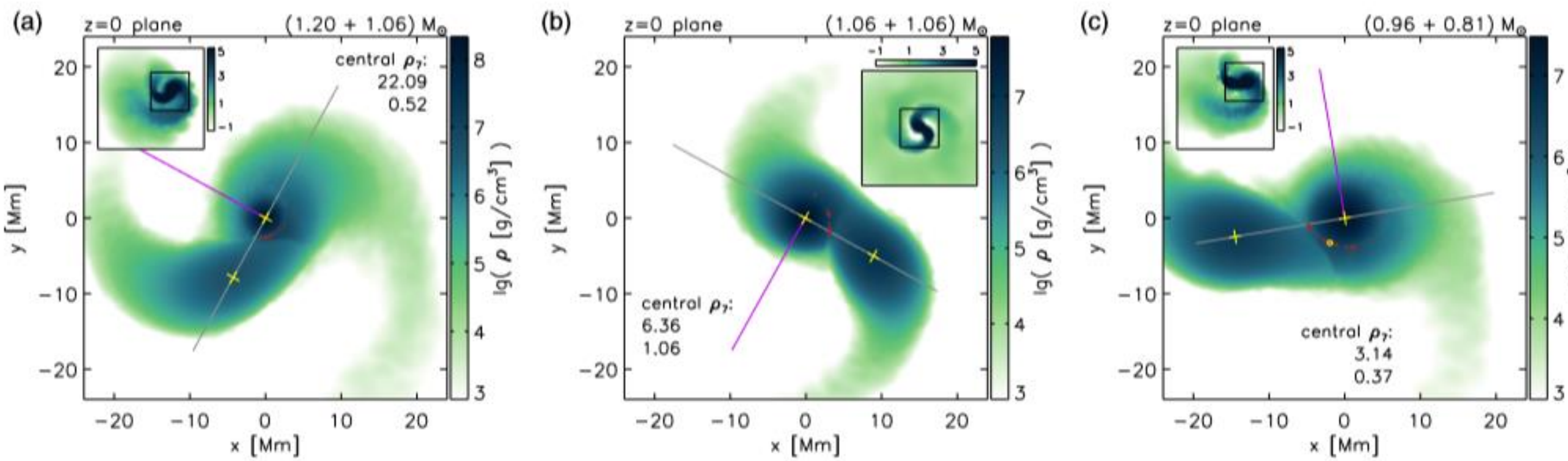


Figure 2. Density in the orbital plane at the beginning of the detonation simulations. Yellow crosses mark the density maxima of the two stars, which for clarity are also written inside each plot (in units of 10^7 g cm^{-3}). The denser primary is centered at the coordinate origin. Red contours indicate the hottest regions in the plane (the respective levels are $T_9 = 2.0$, 1.2, and 0.8 for panels (a), (b), and (c)). The small yellow circle in panel (c) represents the perimeter of the detonator (contours at $T_9 = 2.0$) that is needed to get a detonation going in this model. The insets in each panel show a larger region, with the small black squares indicating the boundaries of the respective main plot. The gray and magenta lines indicate axes in the orbital plane that are used in the description of the results.

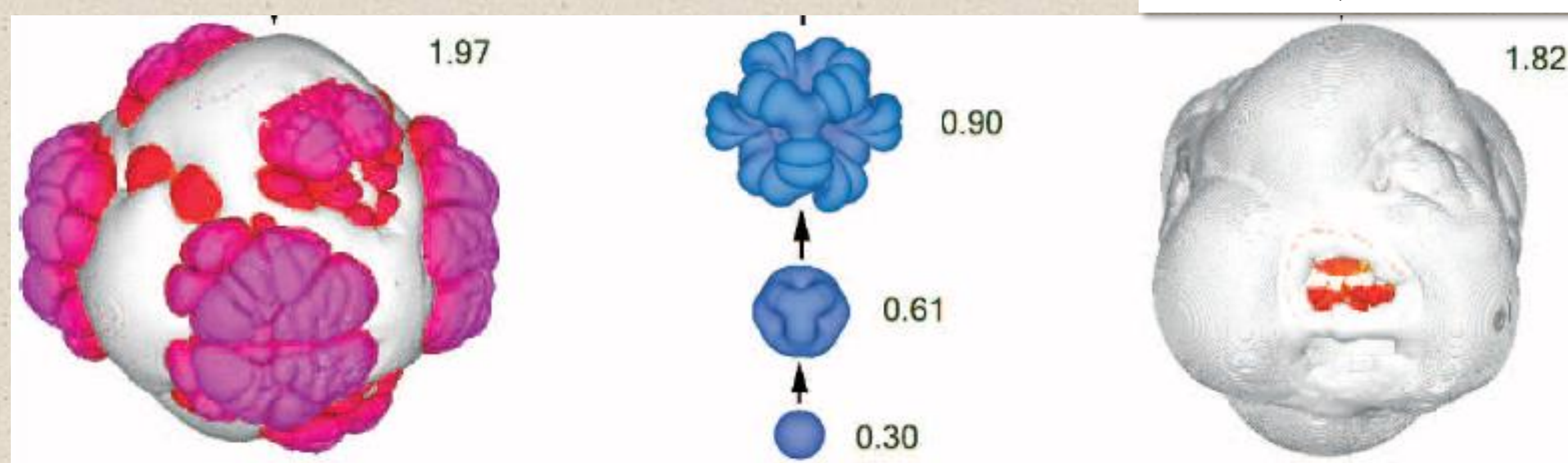
Conceptual basis for polarization in Type Ia SNe

Local departures from spherical symmetry

Combustion Physics:

Nuclear combustion flame in deflagration regime is R-T unstable leaving mushroom shaped “scarfs” in distribution of synthesis products.

Gamezo, et al. 2005

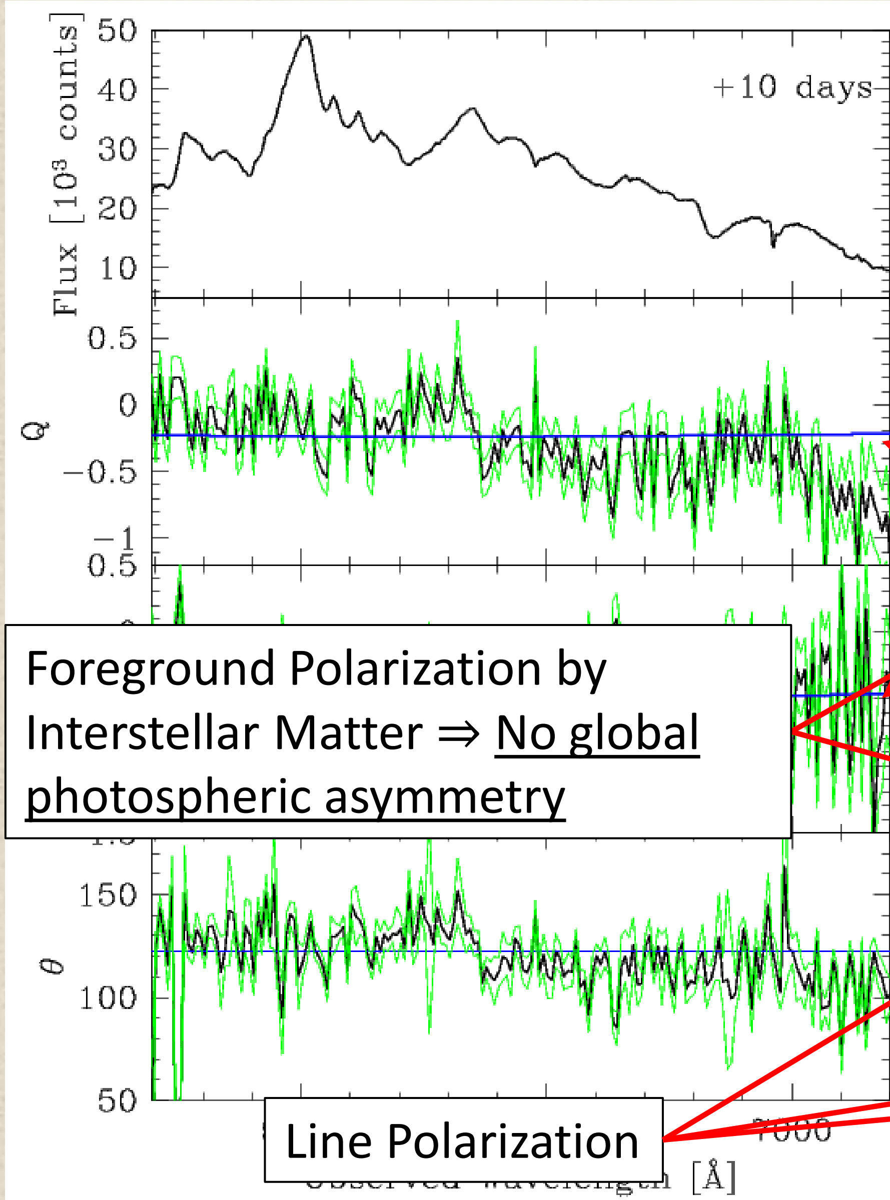


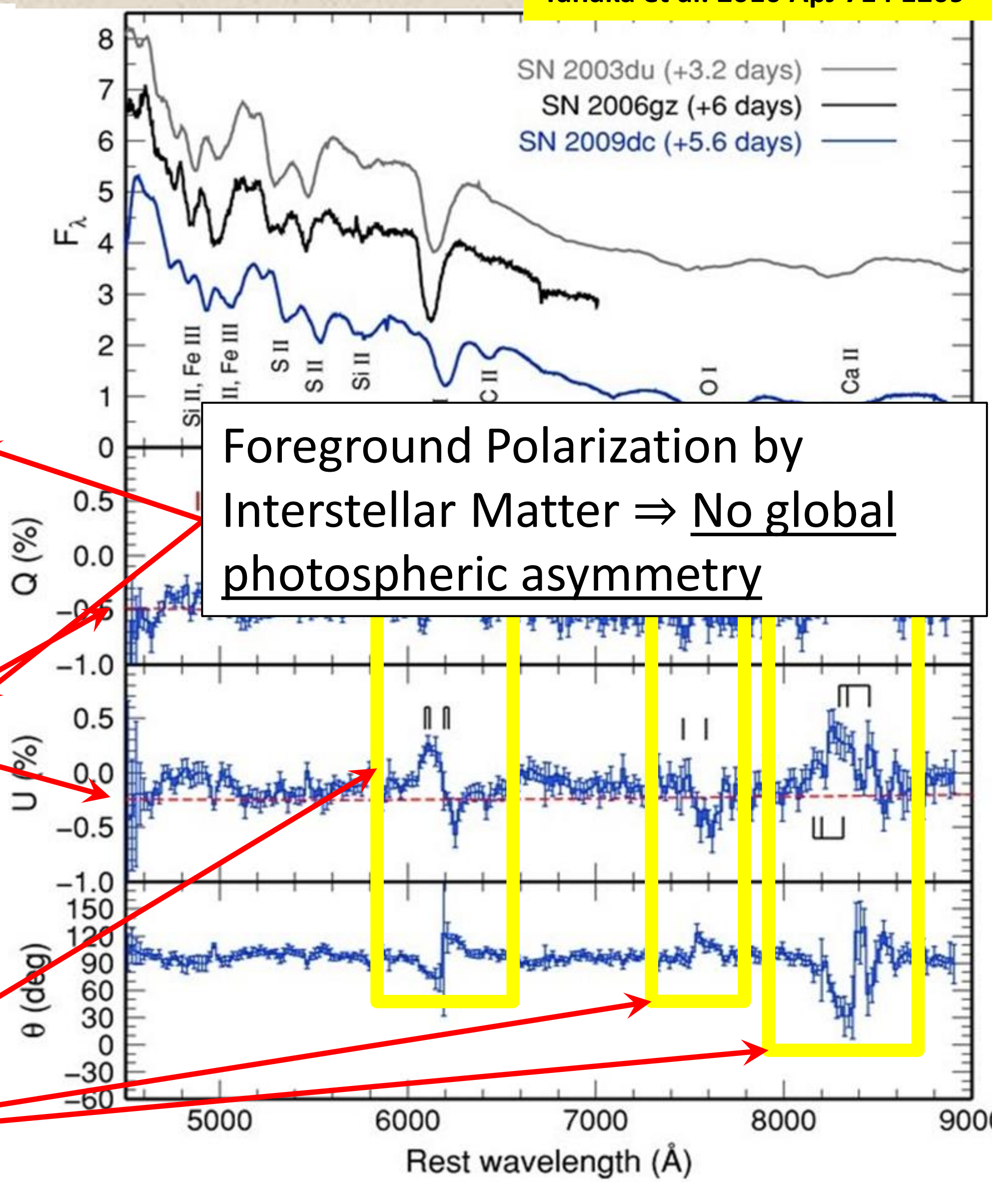
Spectropolarimetry of SN 2007if & SN 2009dc

V ≅ 17.5
Exposure ≅ 6000s

V ≅ 15
Exposure ≅ 10800s

Tanaka et al. 2010 ApJ 714 1209





Foreground Polarization by Interstellar Matter ⇒ <u>No global photospheric asymmetry</u>

Foreground Polarization by Interstellar Matter ⇒ <u>No global photospheric asymmetry</u>

Line Polarization

Balance:

- “Superchandrasekar” mass SNe are bright at maximum and rare.
- Expansion velocities are slow and tend to show “plateaus” in Si 5355
- They are not bright at late times (Maeda et al. 2009, Taubemberger et al. 2016)
- SN 2007if becomes more of a standard SN Ia as you look deeper inside
- Overproduction of ^{56}Ni helps at maximum but is inconsistent at late times
- Envelope models based on concepts of fast mergers & collisions appear to be inconsistent with spectropolarimetry (2 out of 2 SNe)

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Remnant evolution after a carbon–oxygen white dwarf merger

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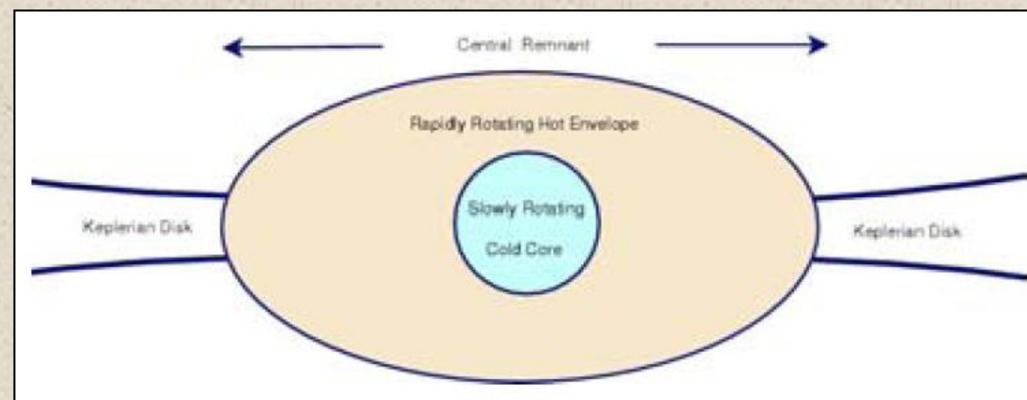
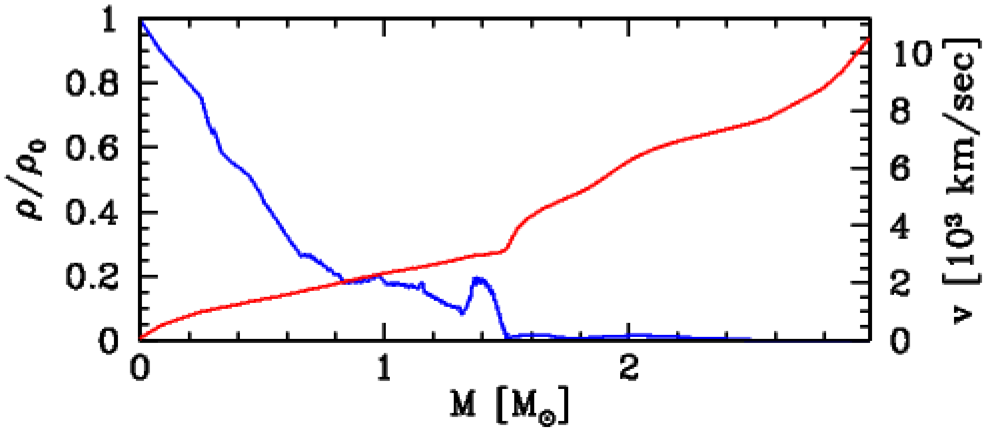
Accepted 2007 June 27. Received 2007 June 19; in original form 2007 April 2

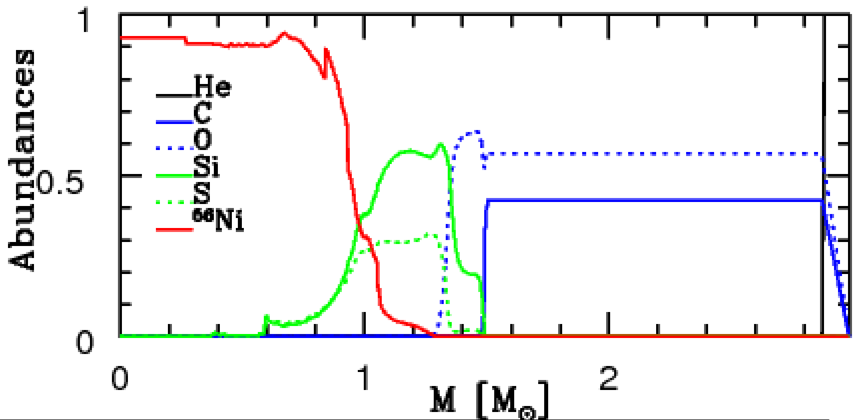
…the merger remnant may be better described as a *differentially rotating single CO star* consisting of a slowly rotating cold core and a rapidly rotating hot extended envelope surrounded by a Keplerian disc…

olution of the merger of two carbon–oxygen (CO) white
f a 0.9 $M_\odot$ + 0.6 $M_\odot$ CO white dwarf merger is followed
ynamics (SPH) simulation. The calculation uses a state-of-
pled to an efficient nuclear reaction network that accurately



A model for SN 2007if (under construction)





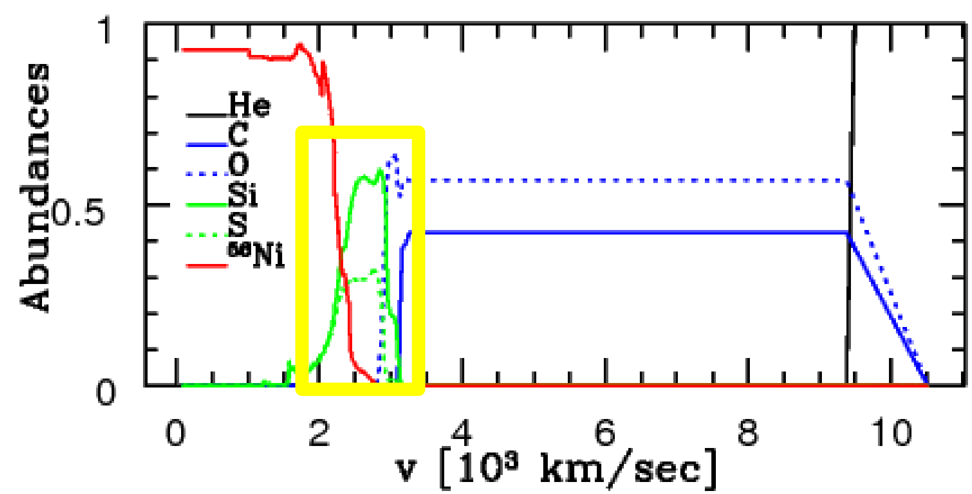
We took at hearth Yoon's proposal:

Isothermal CD (resulting from shell burning during RG stage)

Mix of classical detonation models (Höflich & Khokhlov 1996) and Yoon's envelope models $\sim 3M_{\odot}$ total mass.

Detonation starts at $\rho_c = 10^8 \mathrm{g\ cm}^{-3}$
Produces 1.05 $M_{\odot}$ of ^{56}Ni.

- High ^{56}Ni mass but no extreme
- IME at lower than needed velocity
- IME in a much too compact layer
- Too much unprocessed CO



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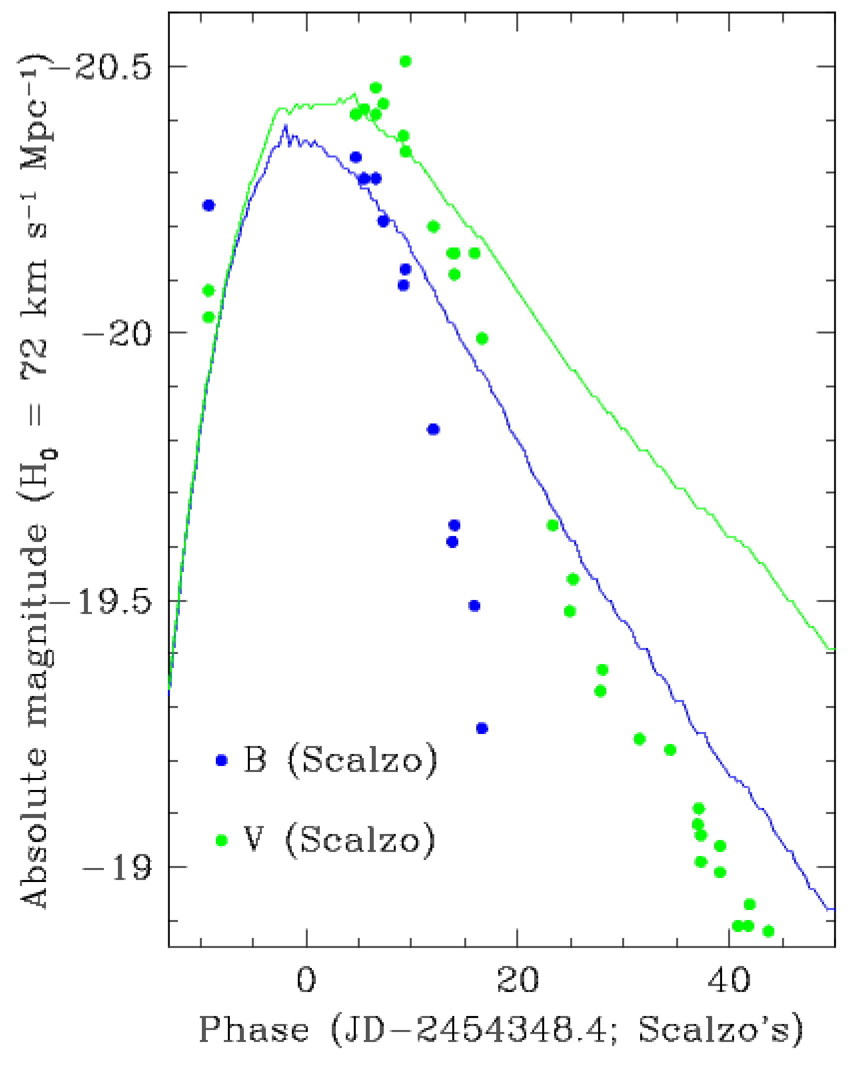

Our first try at the Ia explosion inside a C/O envelope suffers some of the same problems that affected the original Super-Chandrasekhar idea.

But there are some parameters to explore and we are doing so.

I am reasonably hopeful ☺

ありがとうございました

Thank you!

Team (& History):

- Paula Zelaya (PUC)
- Dietrich Baade (ESO)
- Alejandro Clocchiatti (PUC)
- Peter Höflich (Florida State University)
- Justyn Maund (Queen's University, Belfast)
- Nando Patat (ESO)
- Jason Quinn (left astronomy?)
- Jason Spyromilio (ESO)
- Lifan Wang (Texas A&M University)
- J. Craig Wheeler (University of Texas @ Austin)