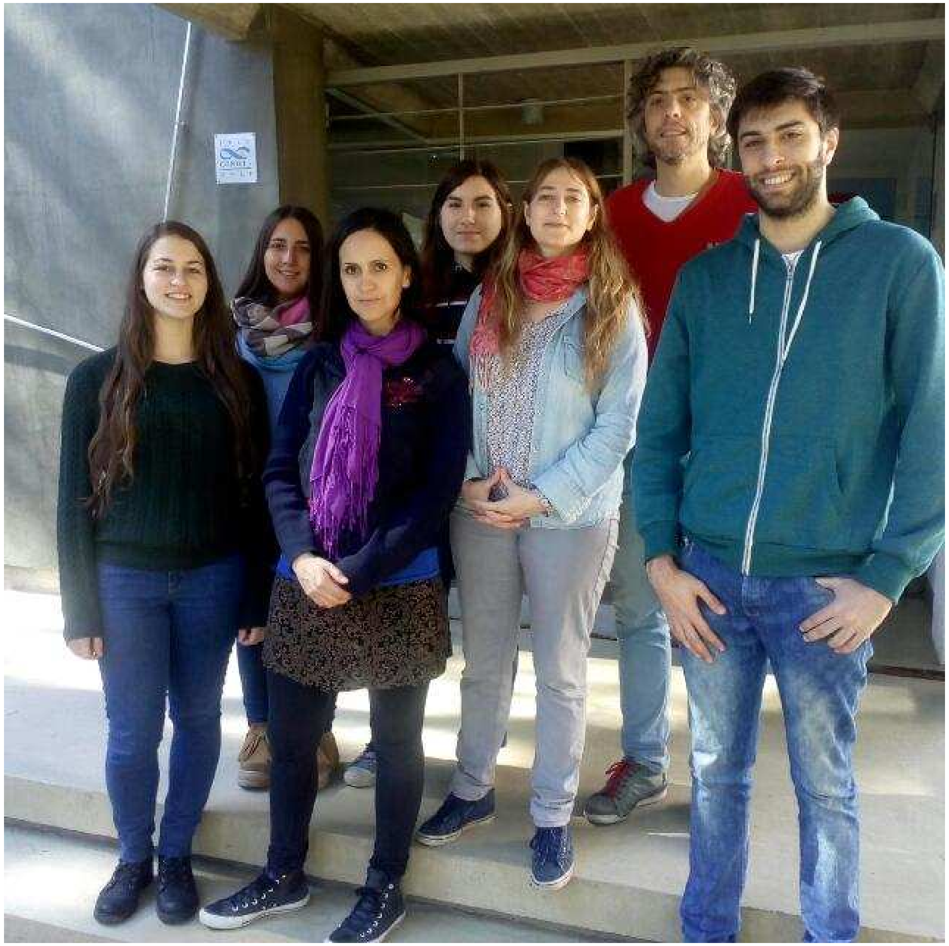
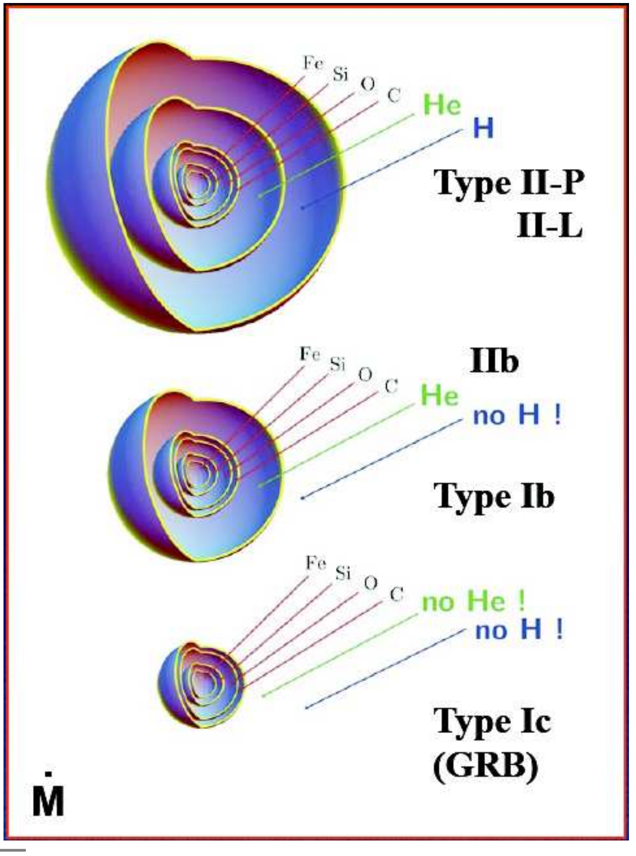
Hydrodynamical models of CCSNe and Shock Breakout

Melina Cecilia Bersten

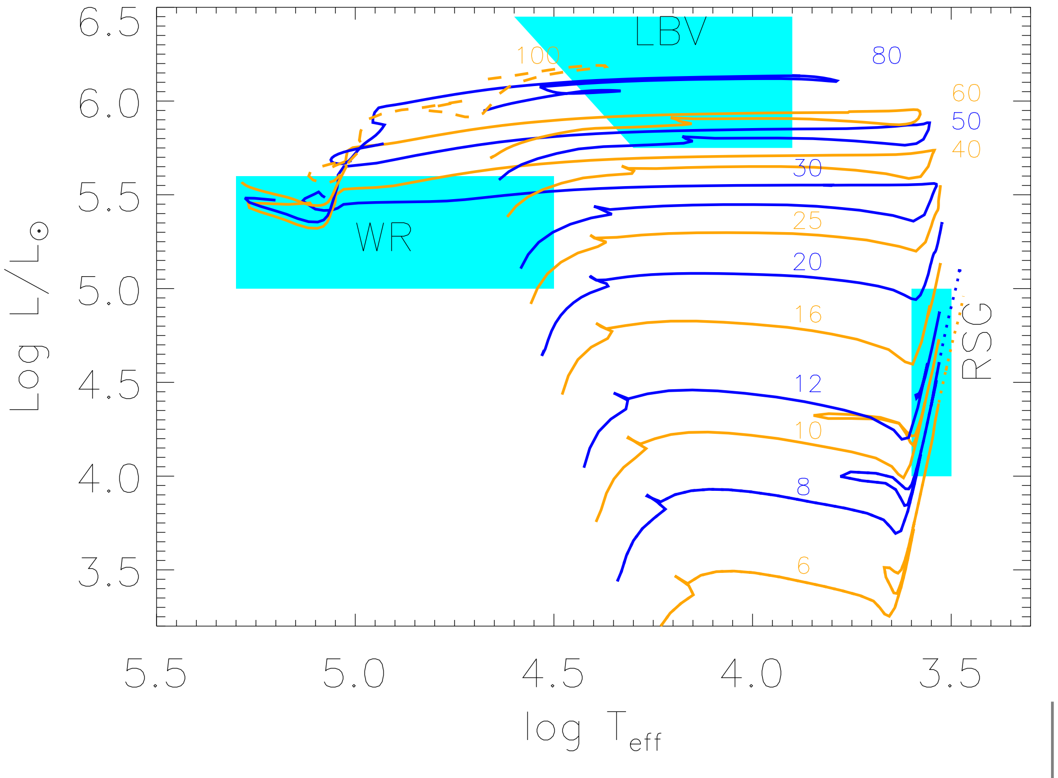


Core-Collapse Supernovae

- End of massive stars ($M_0 \gtrsim 8 M_\odot$) – Stellar evolution test
- Which type of progenitor corresponds to each type of SN?
- How do massive stars lose their envelopes?
- Isolated stars or interacting binary systems?



Credit: M. Modjaz



Smartt+09

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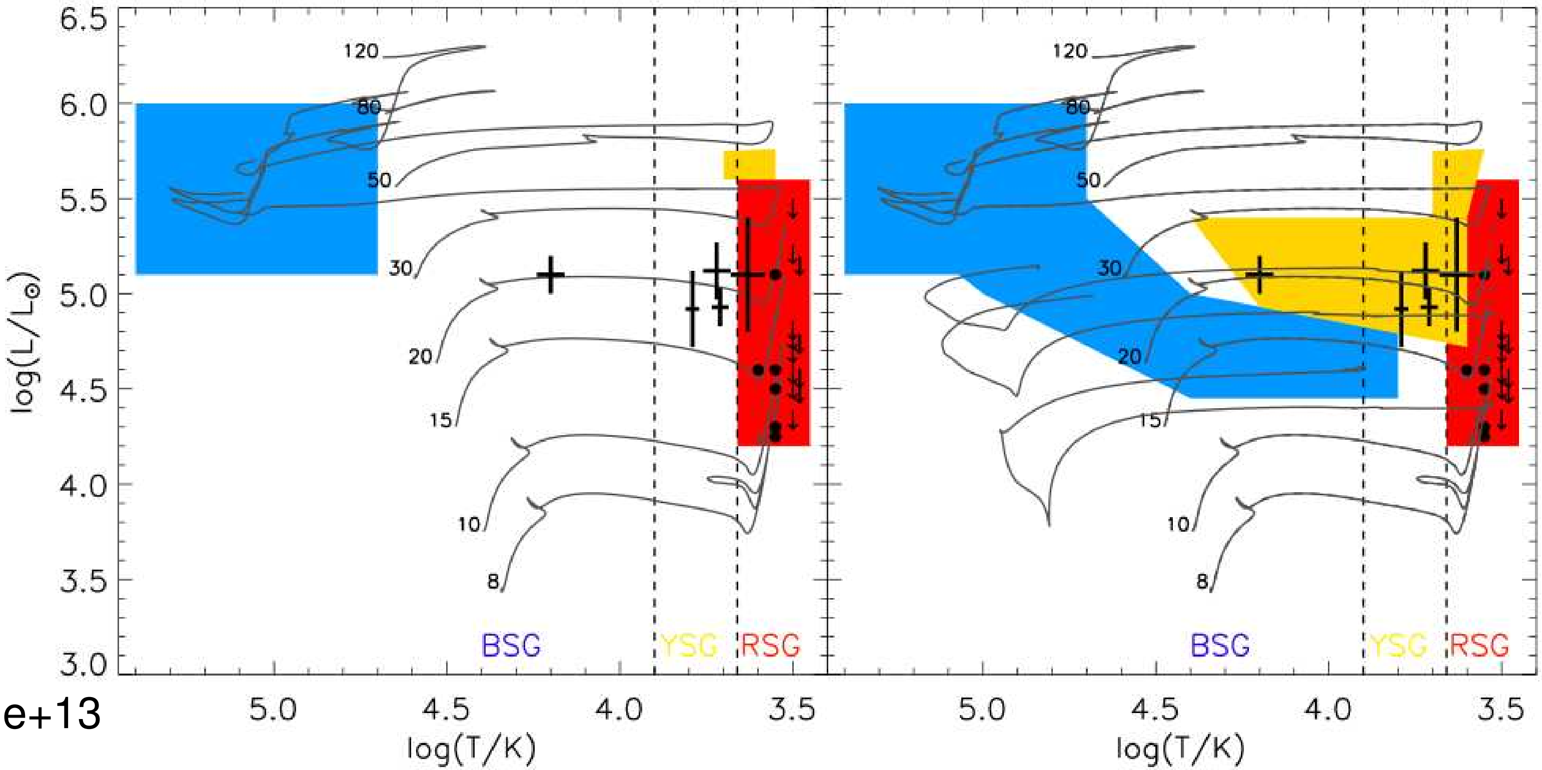
Single stars Binaries



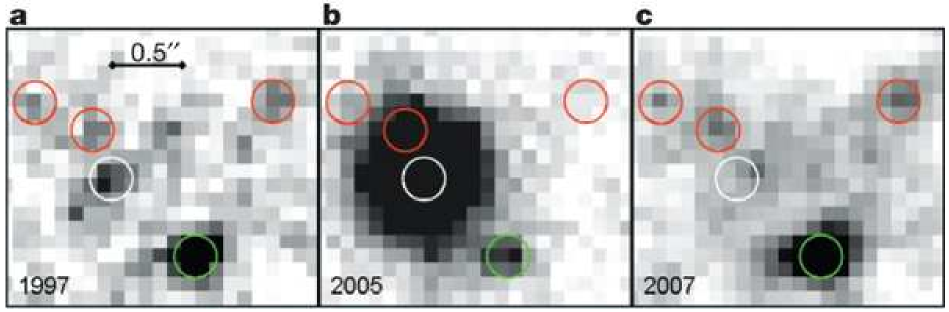
Eldridge+13

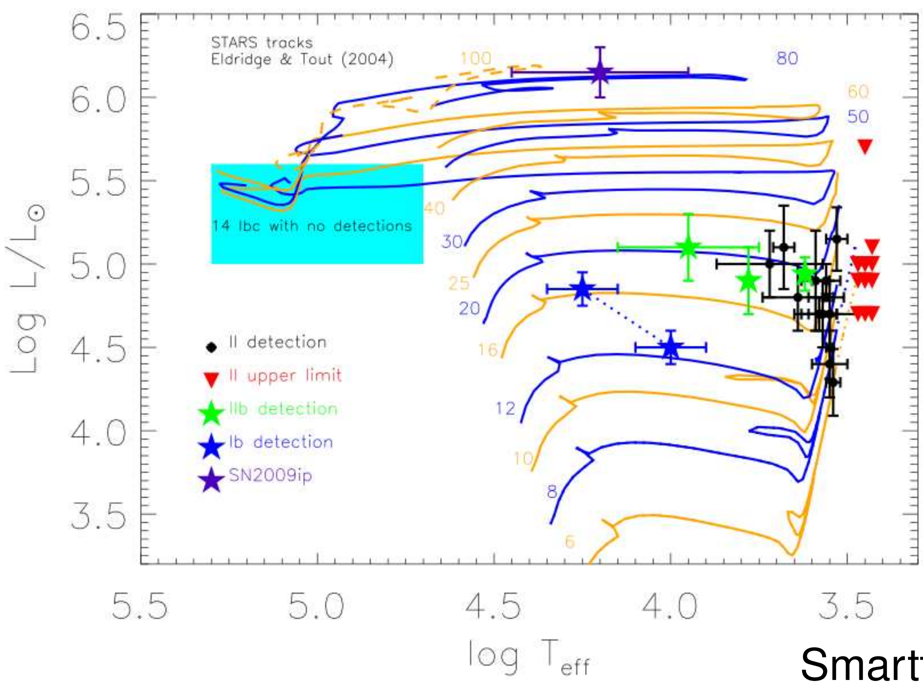
Progenitor Stars

- Archival pre-explosion imaging
- Environmental and metallicity studies
- SN rates
- Mass-loss rates from radio & X-rays
- Spectropolarimetry
- Flash spectroscopy
- Light-curve and spectrum modeling

Progenitor Stars

- High-resolution, deep archival imaging (HST) ($\lesssim$ 30 Mpc)
  $\approx$ 30 detections + 38 upper limits (Van Dyk, Smartt, etc.)
  - Most are RSG – SNe II
  - A few YSG – SNe IIb
  - One detections for SN Ib
  - One candidate for SN Ic
  - LBV – SNe IIn
  - BSG – SN 1987A
  - Deficiency of progenitors with $\log L/L_\odot \gtrsim 5.1 \Longrightarrow$ $M_{\rm ZAMS} \lesssim$ 16-18 $M_\odot$?

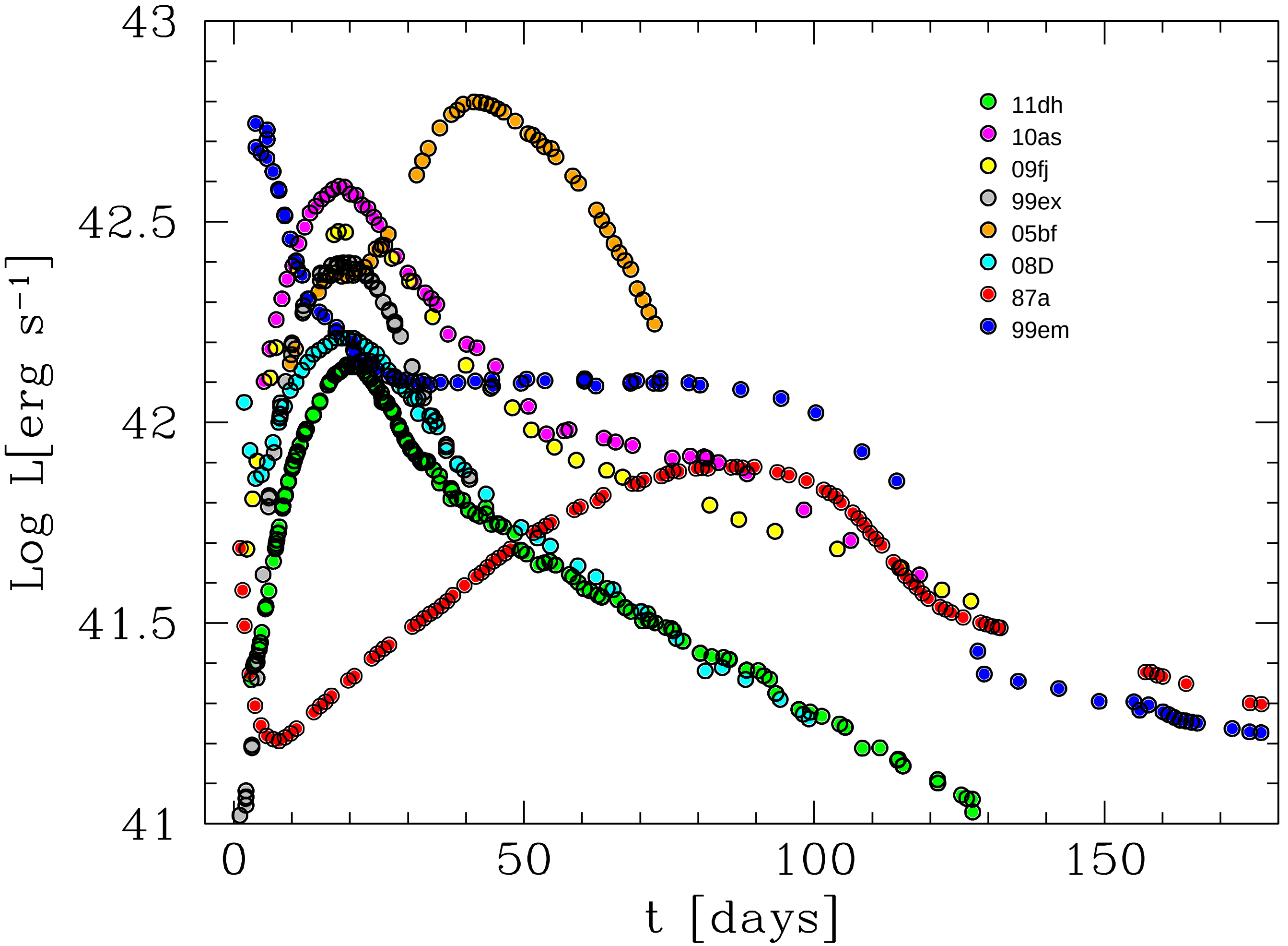




Smartt+15

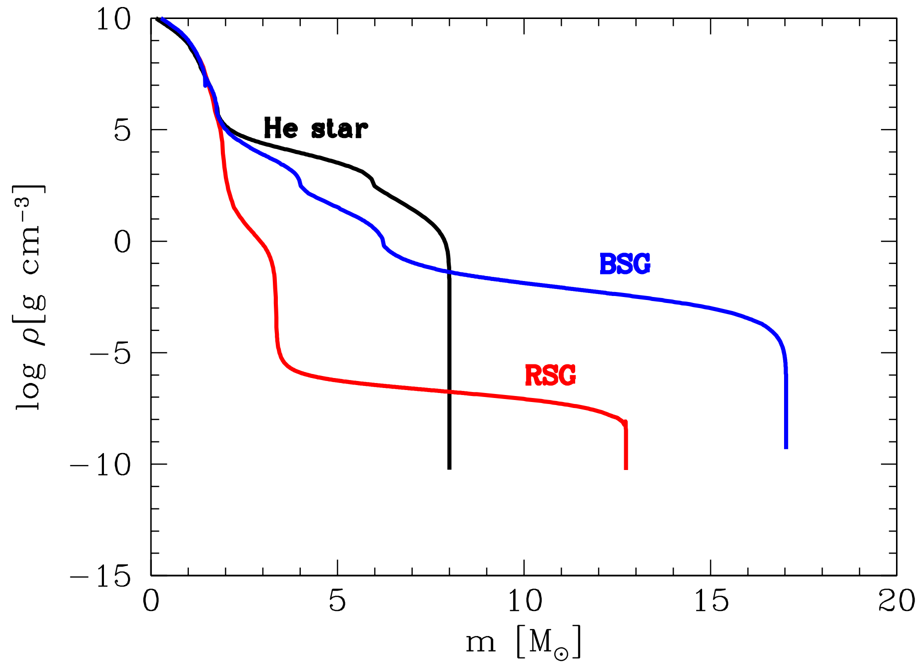
Progenitor Stars

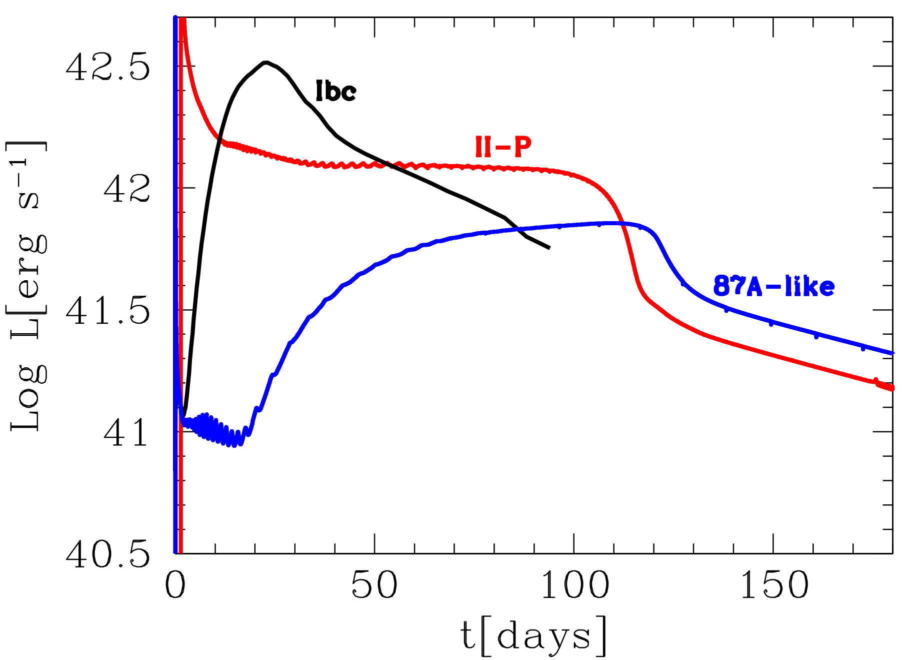
- Hydrodynamic modeling: LC + expansion velocities
- Progenitor mass, radius, explosion energy, ^{56}Ni mass (Kepler, Stella, Utrobin, Bersten+, SNEC,...)



Hydrodynamical Models

- Different time scales for core and envelope $\Longrightarrow$ ejection of the envelope treated independently of core collapse
- Numerical integration of the hydro equations + radiative transfer
  1-D code with flux-limited radiation + gray transfer for γ-rays (Bersten+11)
- Pre-SN structures: stellar evolution and parametric models

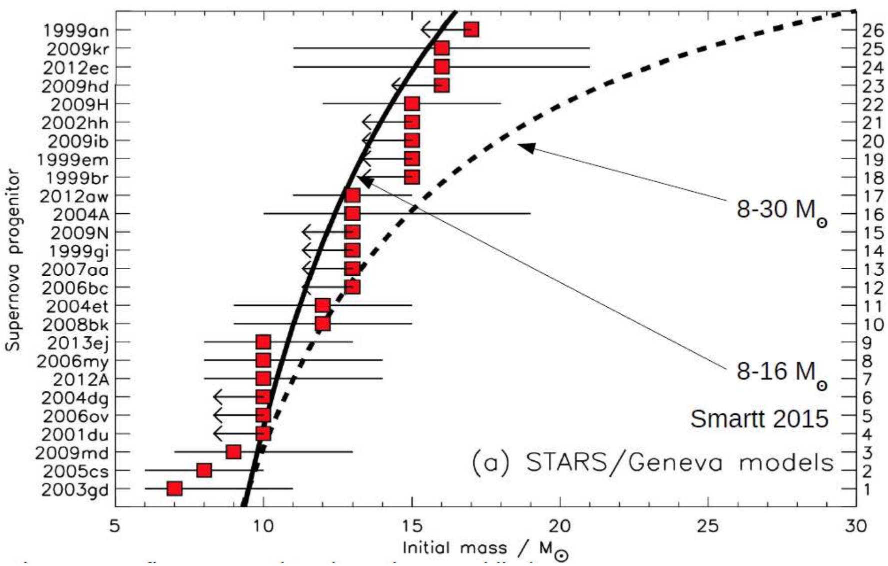


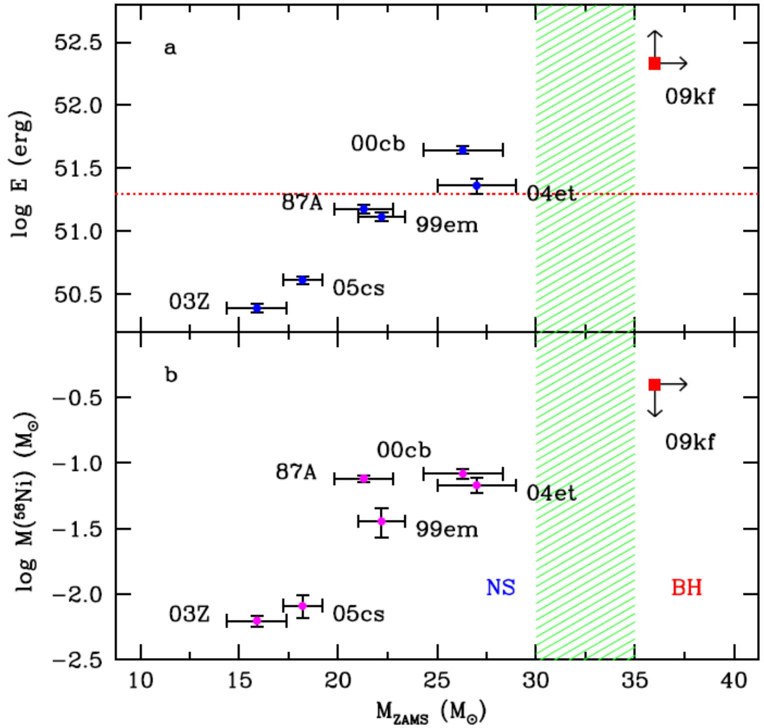


H-rich progenitors

Type II Supernovae

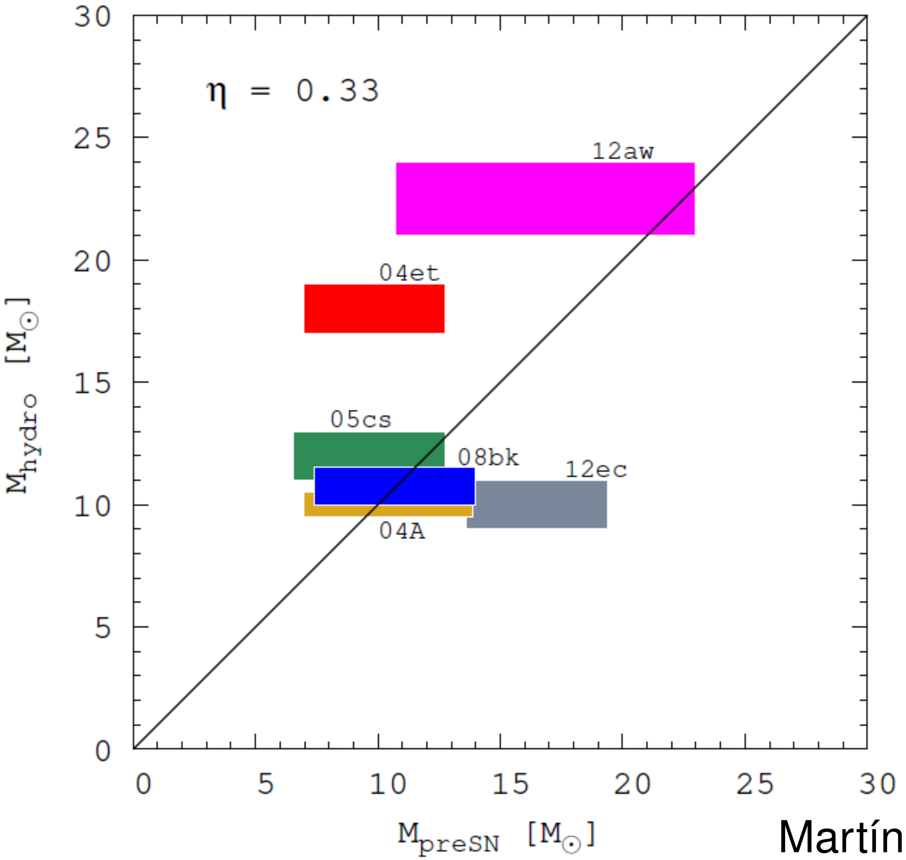
- Most common type of stellar explosion
- Good distance indicators: EPM, SEAM, and SCM
- RSG structure with H-rich envelope
- Pre-SN imaging + stellar evolution models: $M_{\rm ZAMS}$: 8 –16 $M_\odot$ (Smartt+15)
- Hydro modeling favors high mass range (Utrobin & Chugai)





Type II Supernovae

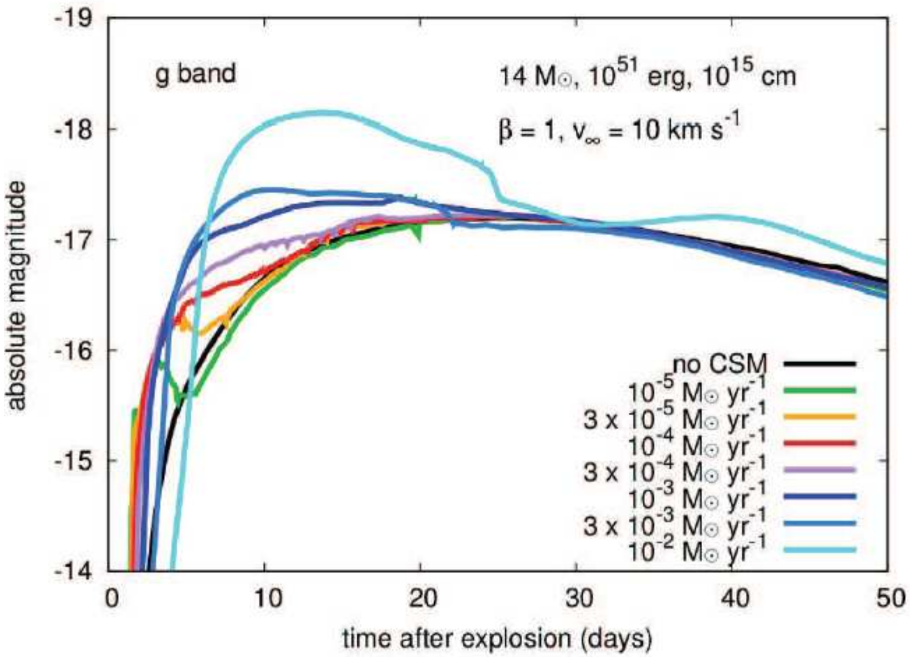
- Most common type of stellar explosion
- Good distance indicators: EPM, SEAM, and SCM
- RSG structure with H-rich envelope
- No systematic differences between mass estimations



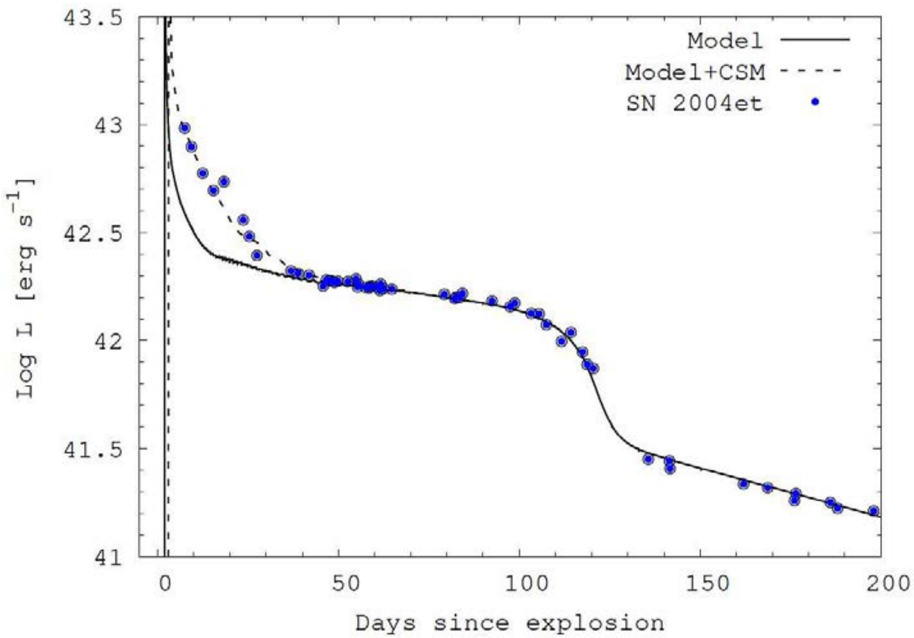
Martínez & Bersten, submitted

Type II Supernovae

- Possible good metallicity indicators (Dessart+13, Anderson+16)
- Evidence of some CSM arround in most SNe II (Moriya+11,González-Gaitán+15, Nagy & Vinko+16, Morozova+16, Yaron+17,...)
- SBO delay due to CSM



Förster+18

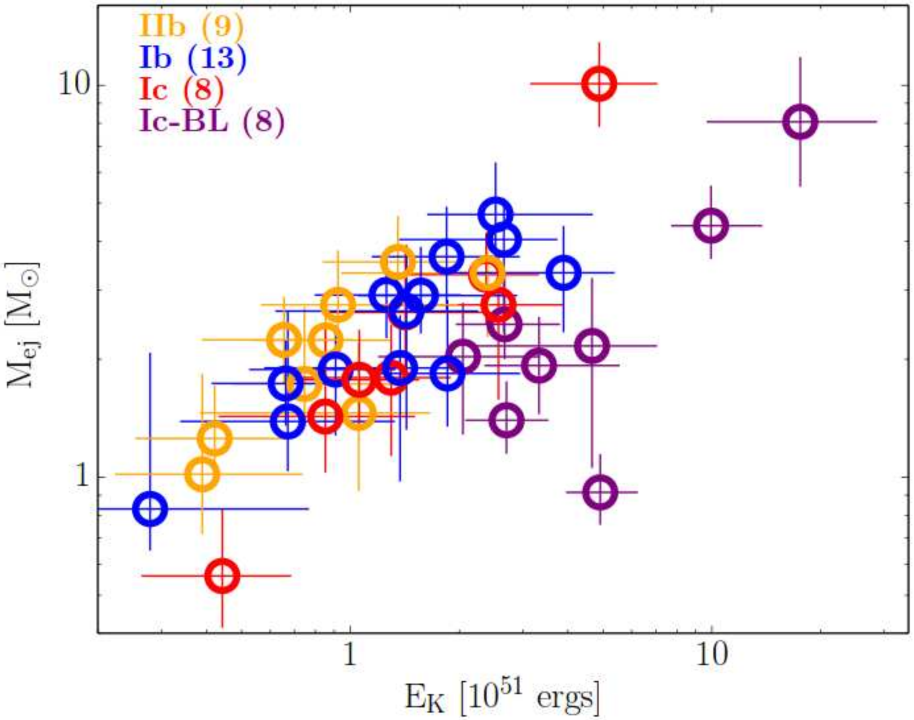


Englert & Bersten, in prep.

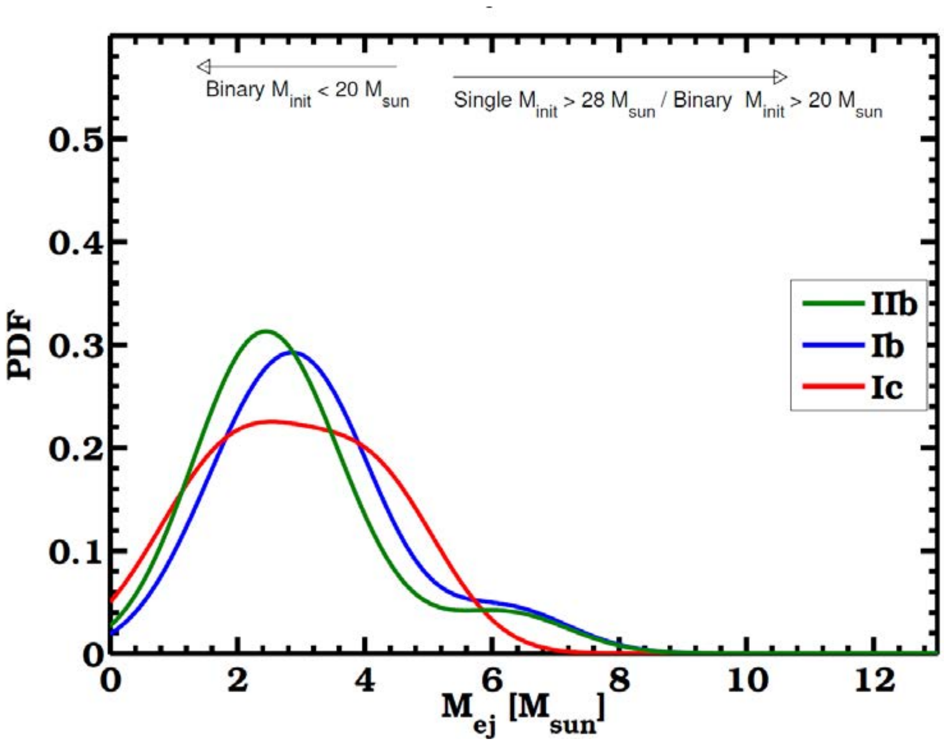
H-poor progenitors

Stripped-envelope SNe

- Low ejecta masses ≈1-4 $M_\odot$ from LC of SE-SN sample (Drout+11, Cano+13, ...) $\Longrightarrow$ binarity



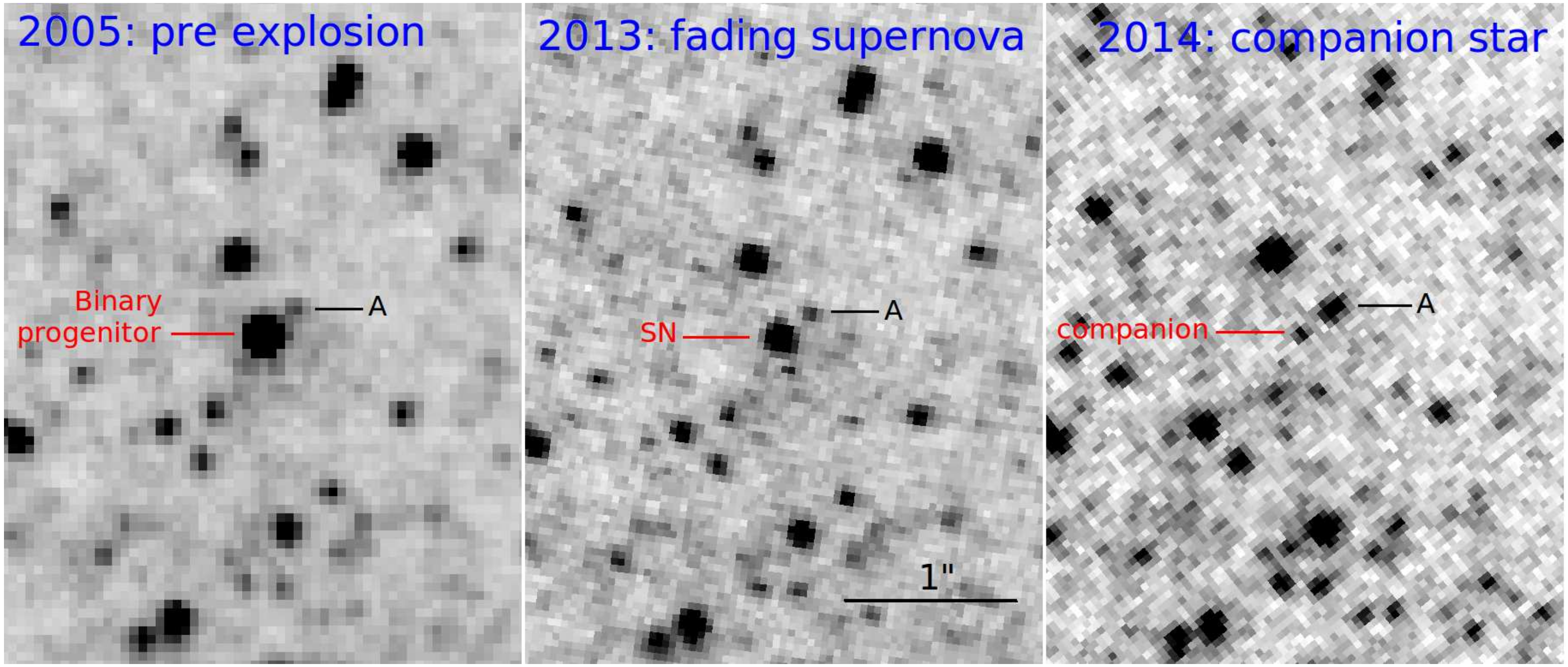
Lyman+16



Taddia+18

Stripped-envelope SNe

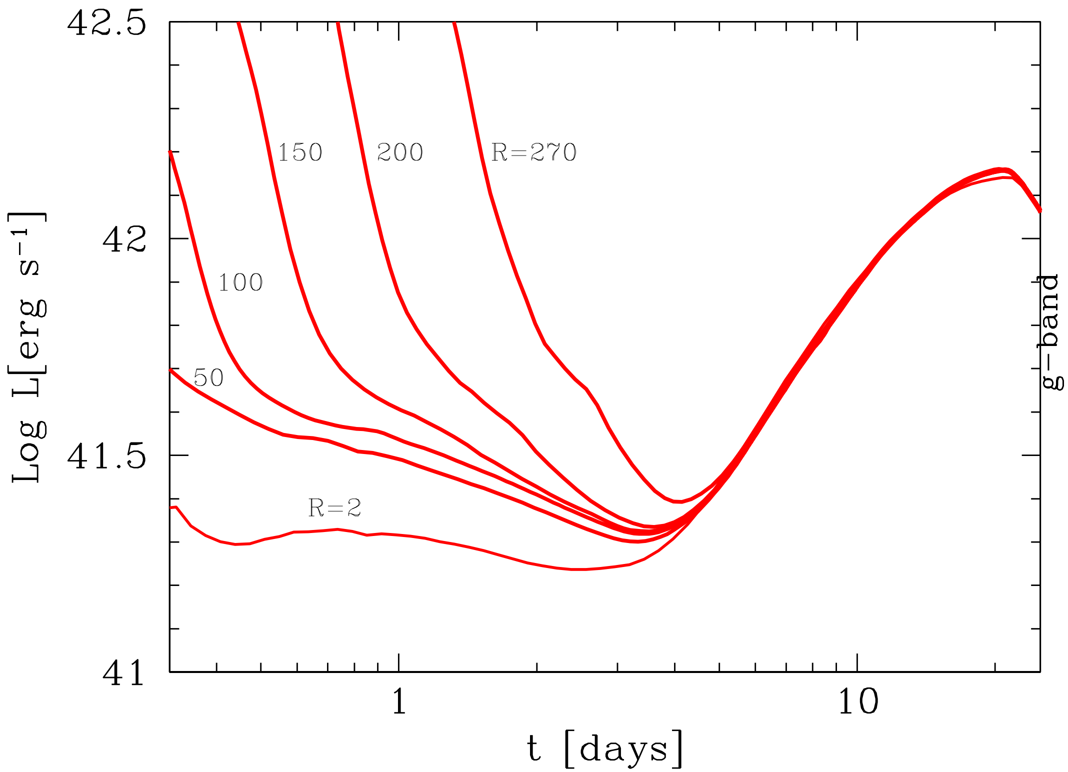
- Low ejecta masses $\approx$1-4 $M_\odot$ from LC of SE-SN sample (Drout+11, Taddia+18, ...) $\Longrightarrow$ binarity
- SNe IIb: four YSG confirmed. Three possible companion detections
- SN Ib: one confirmed progenitor (iPTF13bvn; Eldrige+Maund 16, Folatelli+16)
- SN Ic: one progenitor candidate (SN 2017ein; Van Dyk+18)

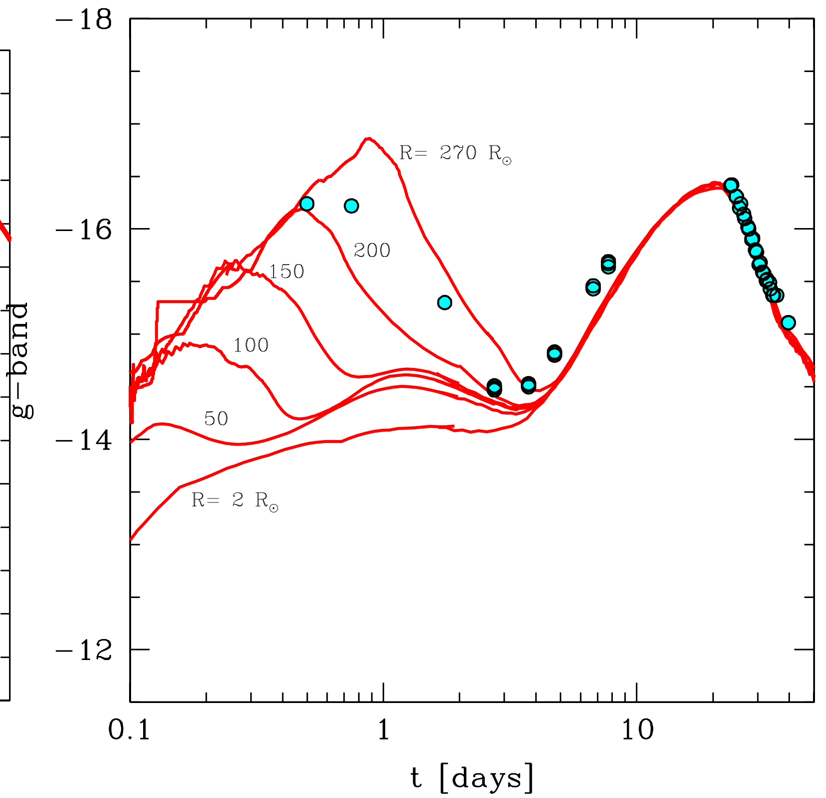


Folatelli, MB+14

Early Emission

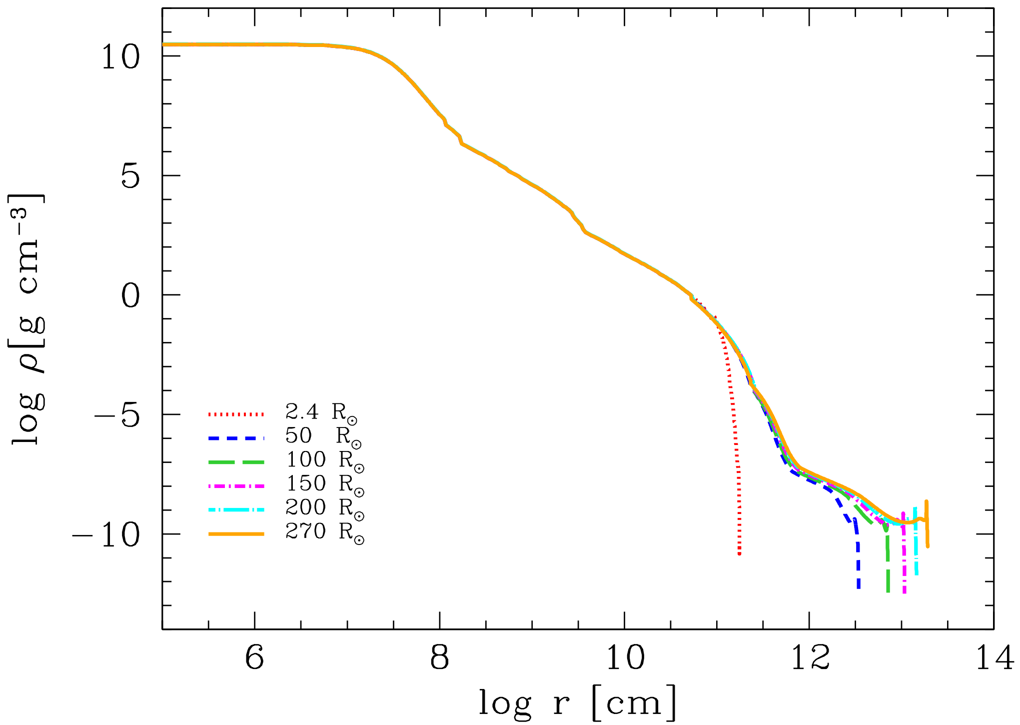
- Important clues on the progenitor structure, mixing process, presence of possible CSM, interaction with a possible companion
- Strong dependence on progenitor radius
- Models for compact progenitors show initial plateau (see also Dessart+11)

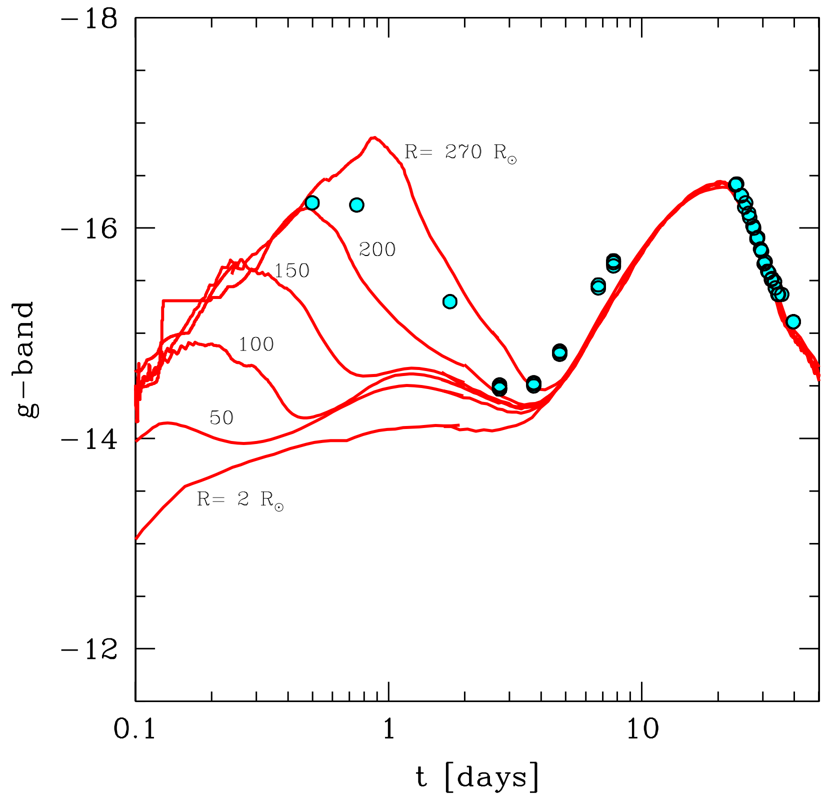




Early Emission

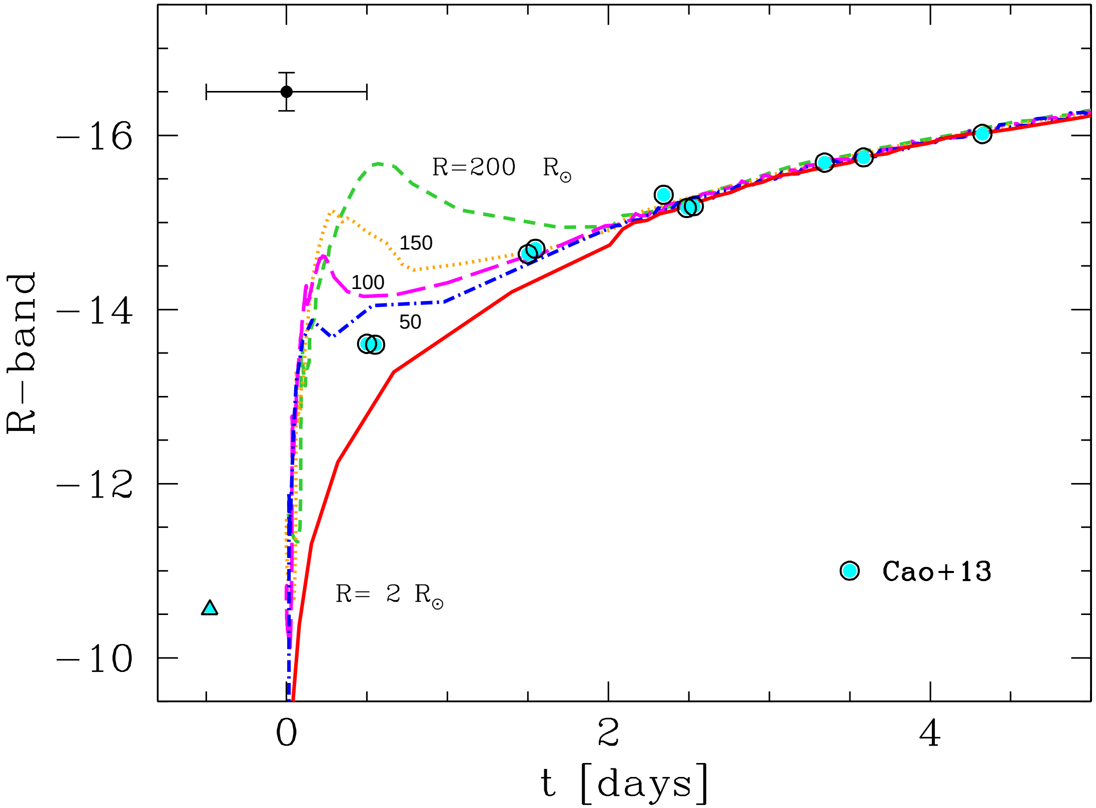
- Important clues on the progenitor structure, mixing process, presence of possible CSM, interaction with a possible companion
- A handful of Type IIb observed during cooling phase: e.g. 93J, 11dh, ...
- A low-density extended H-rich envelope is required for the LC morphology (Bersten+12, Nakar&Piro'14)



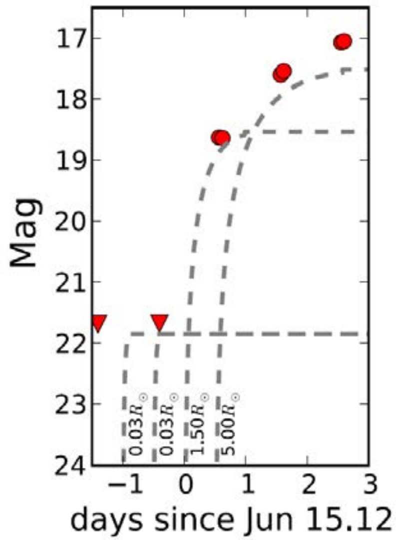


Early Emission

- Important clues on the progenitor structure, mixing process, presence of possible CSM, interaction with a possible companion
- For Ib/Ic several observations per night are necessary to well constrained the radius



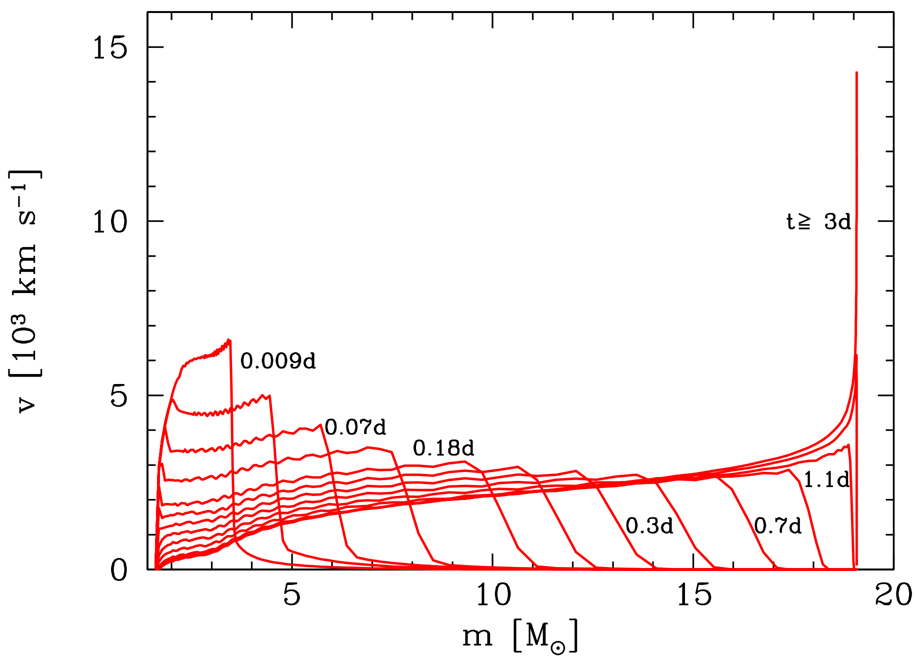
Bersten+14

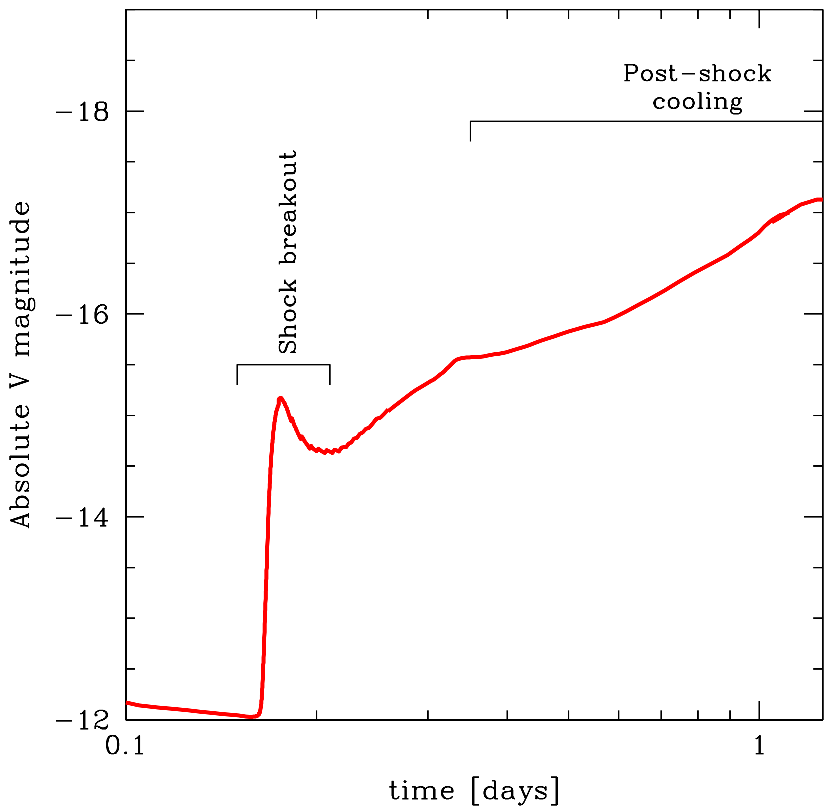


Cao+13

Shock Breakout (SBO)

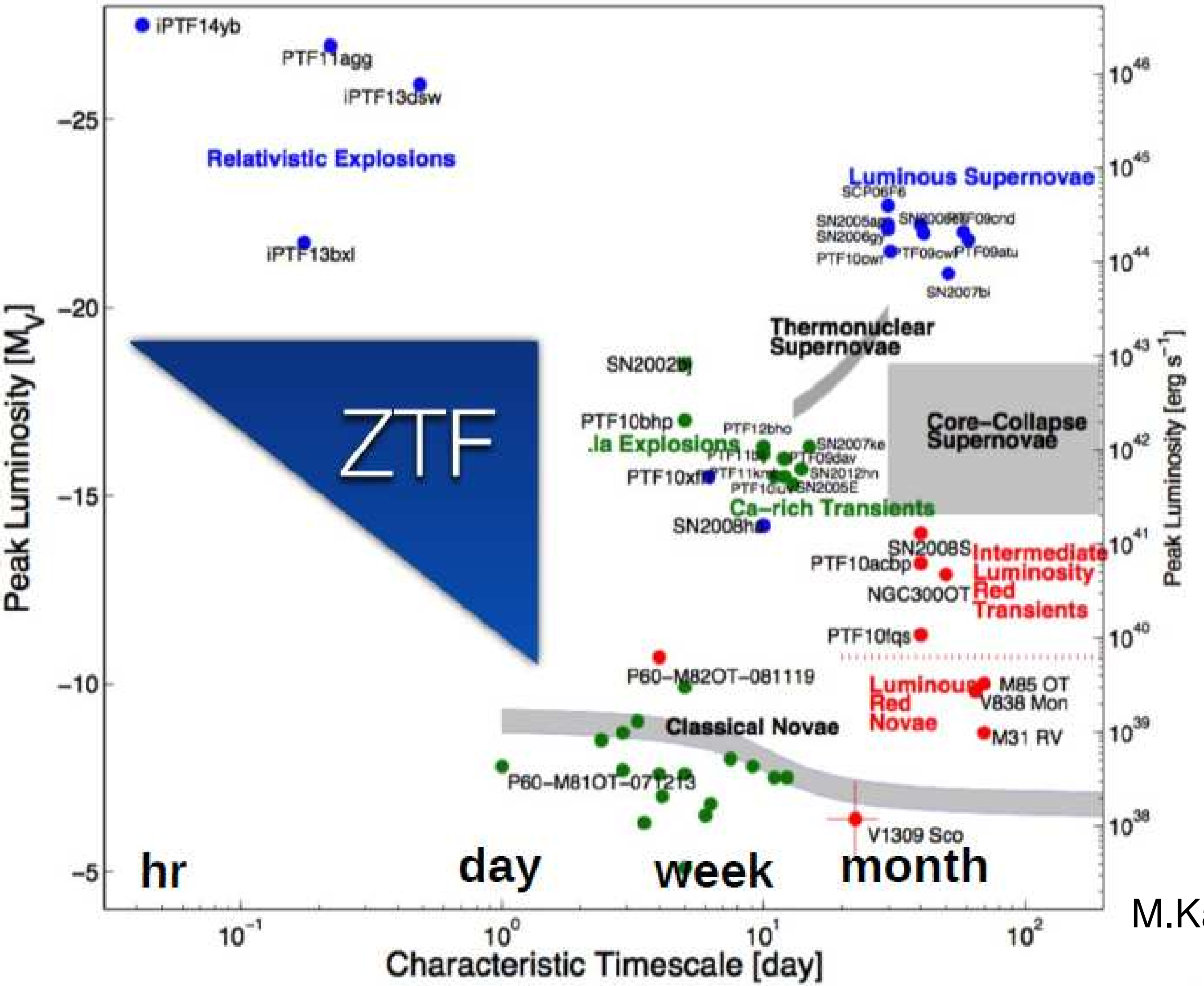
- A luminous burst in UV/X-ray: shock-wave emerges on the stellar surface ($\tau < v_{\rm sock}/c$)
- Produces an emission peak in the optical
- SBO emission $\neq$ shock cooling emission





Early Discovery

- Increasing number of surveys focused on earlier-time observations (iPTF, KISS, HiTS, HSC-SHOOT, ZTF, LSST, ULTRASAT)



M.Kasliwal/ZTF

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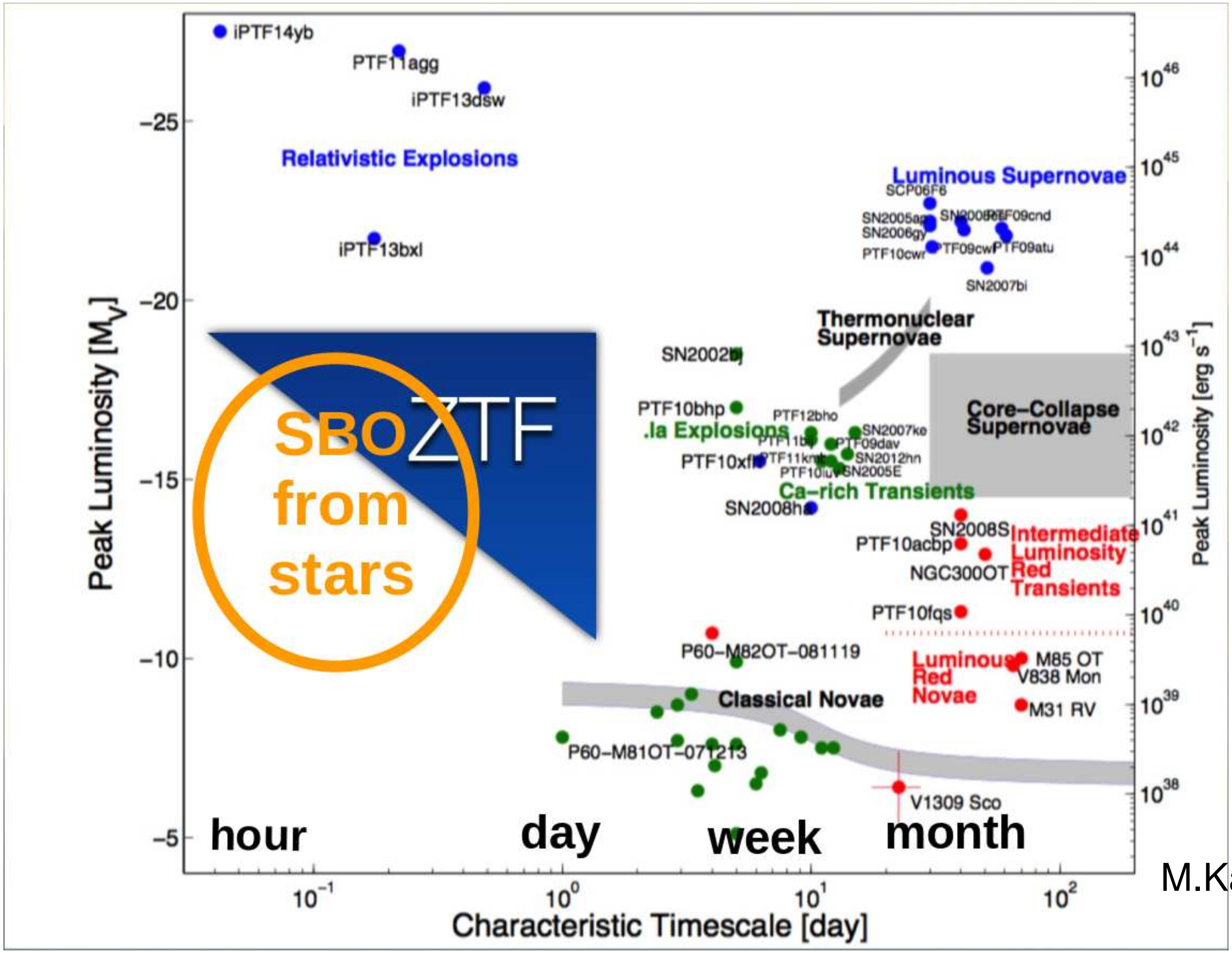

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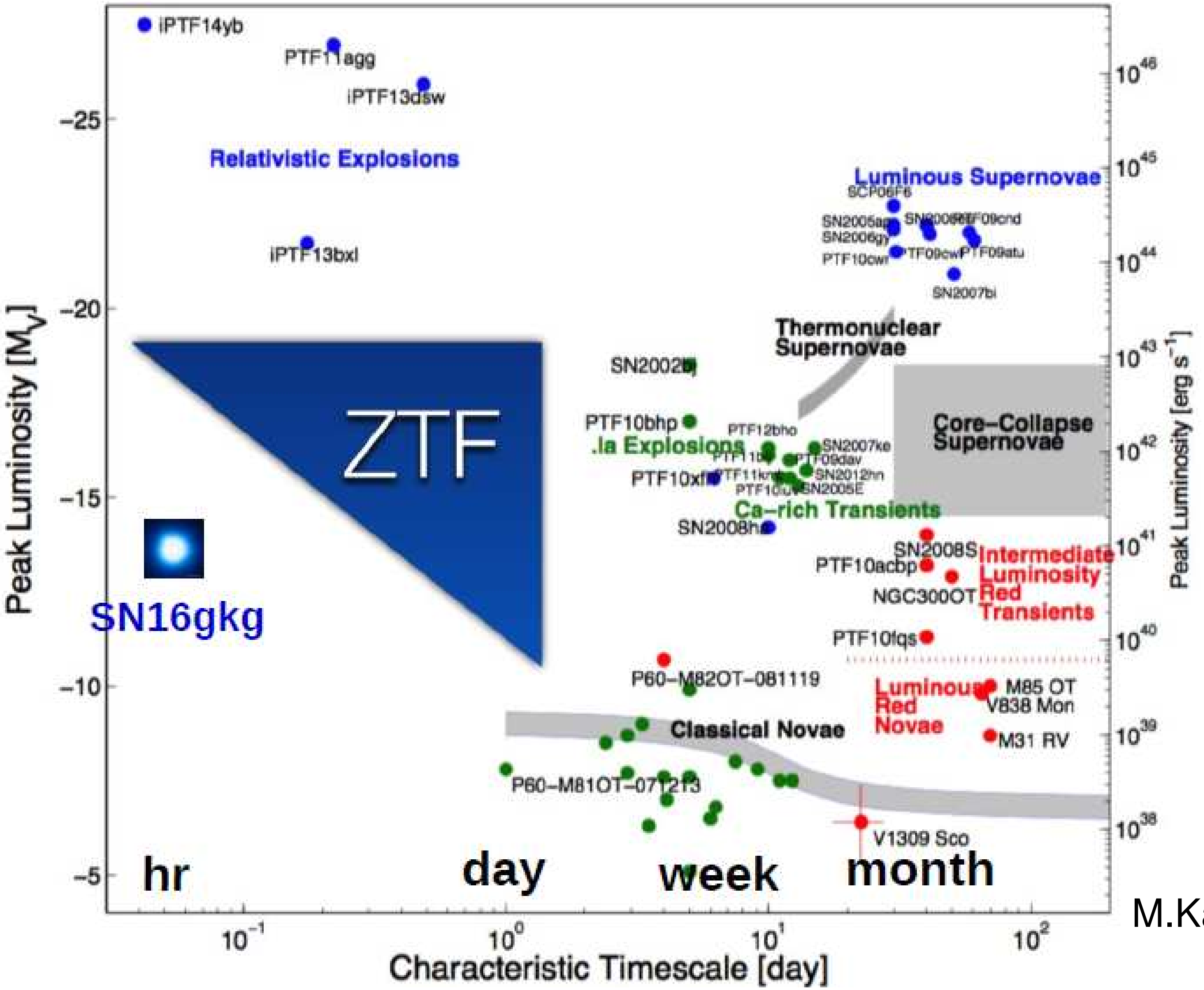


M.Kasliwal/ZTF

Supernova 2016gkg

Discovered on Sept. 20th 2016 by amateur Víctor Buso

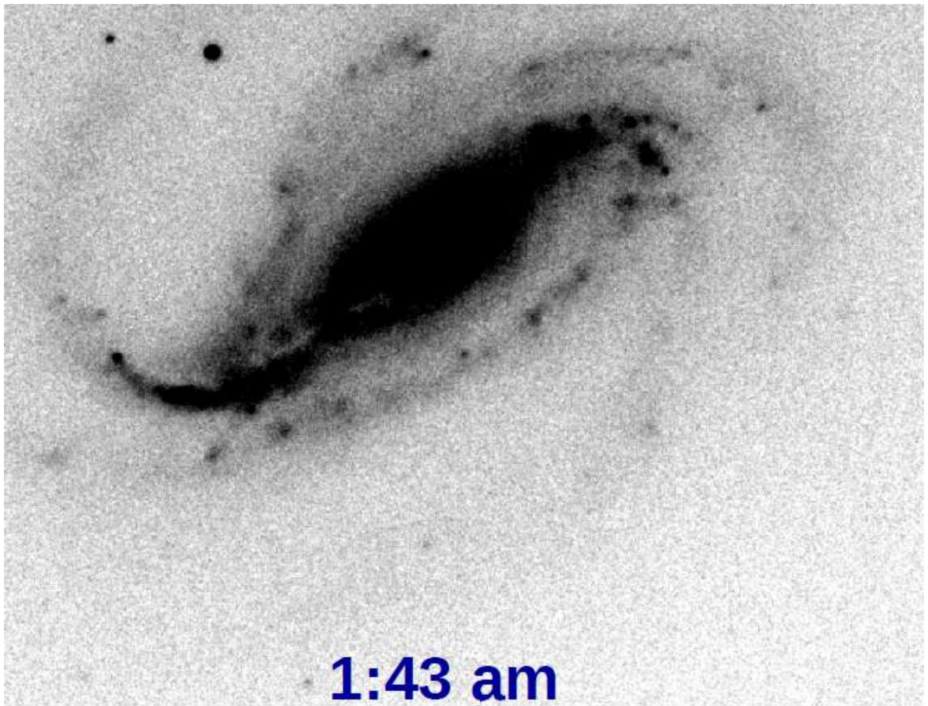
The “Observatorio Busoniano” in Rosario

Buso with his 40cm Newtonian

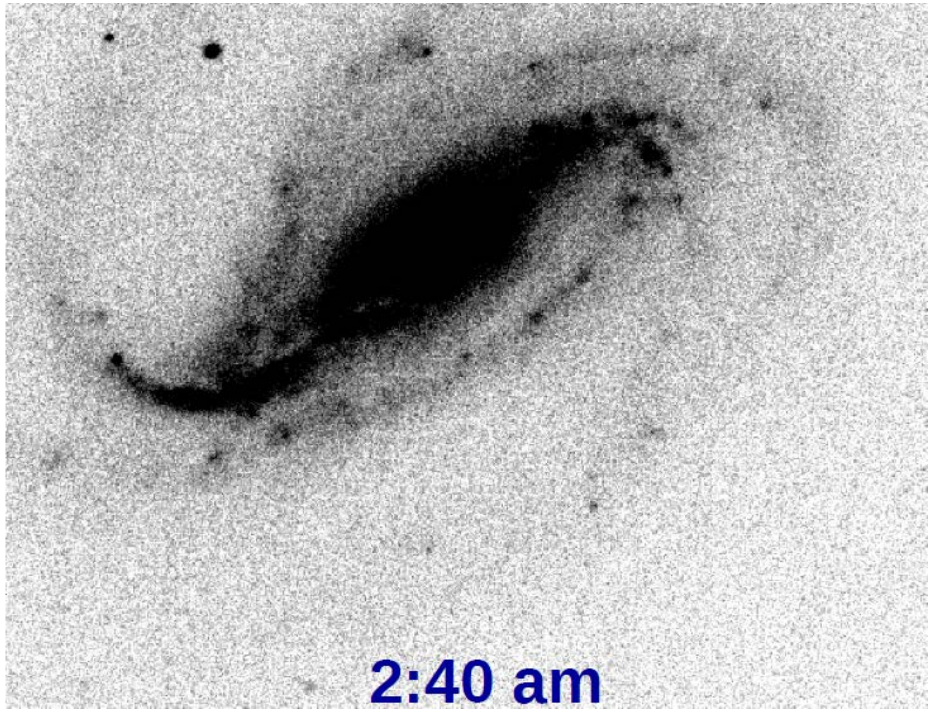
Supernova 2016gkg

The SN appears during Víctor's observations

NGC 613



40 images



20 images

Supernova 2016gkg

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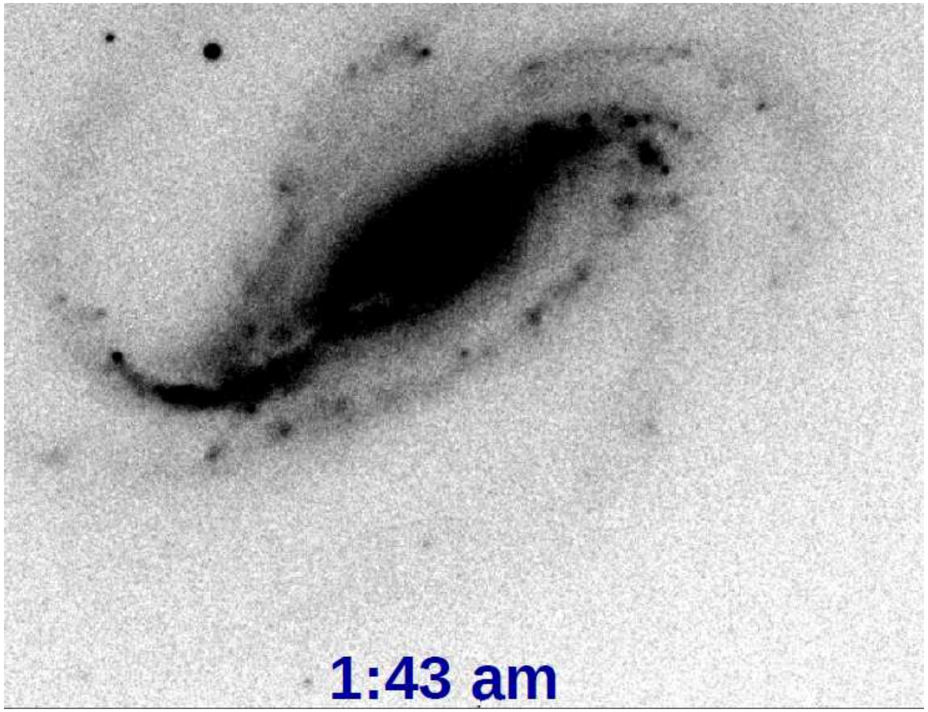
NGC 613



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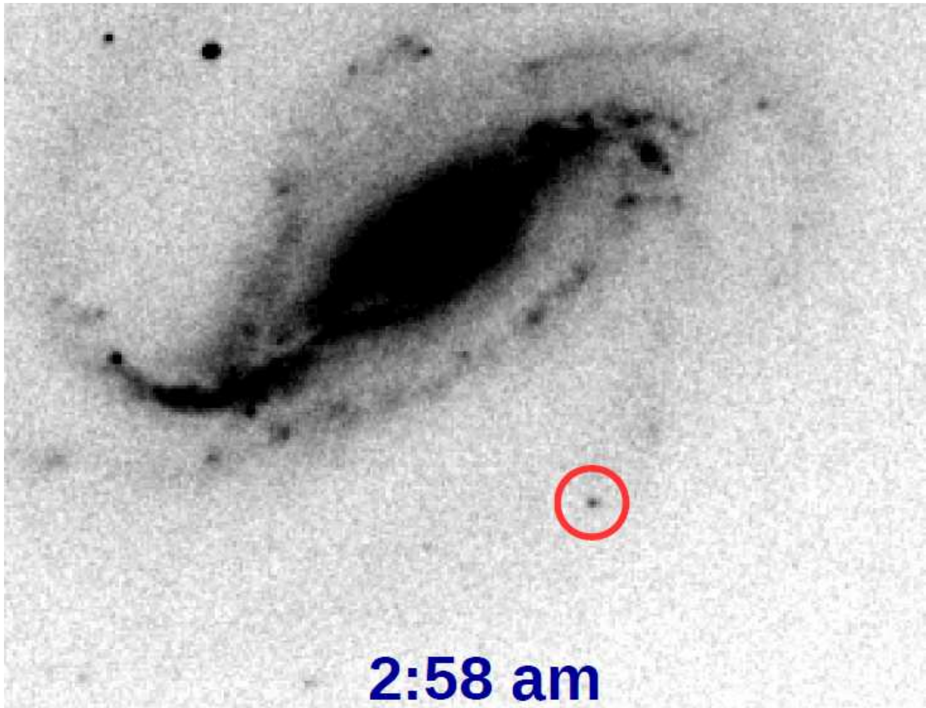
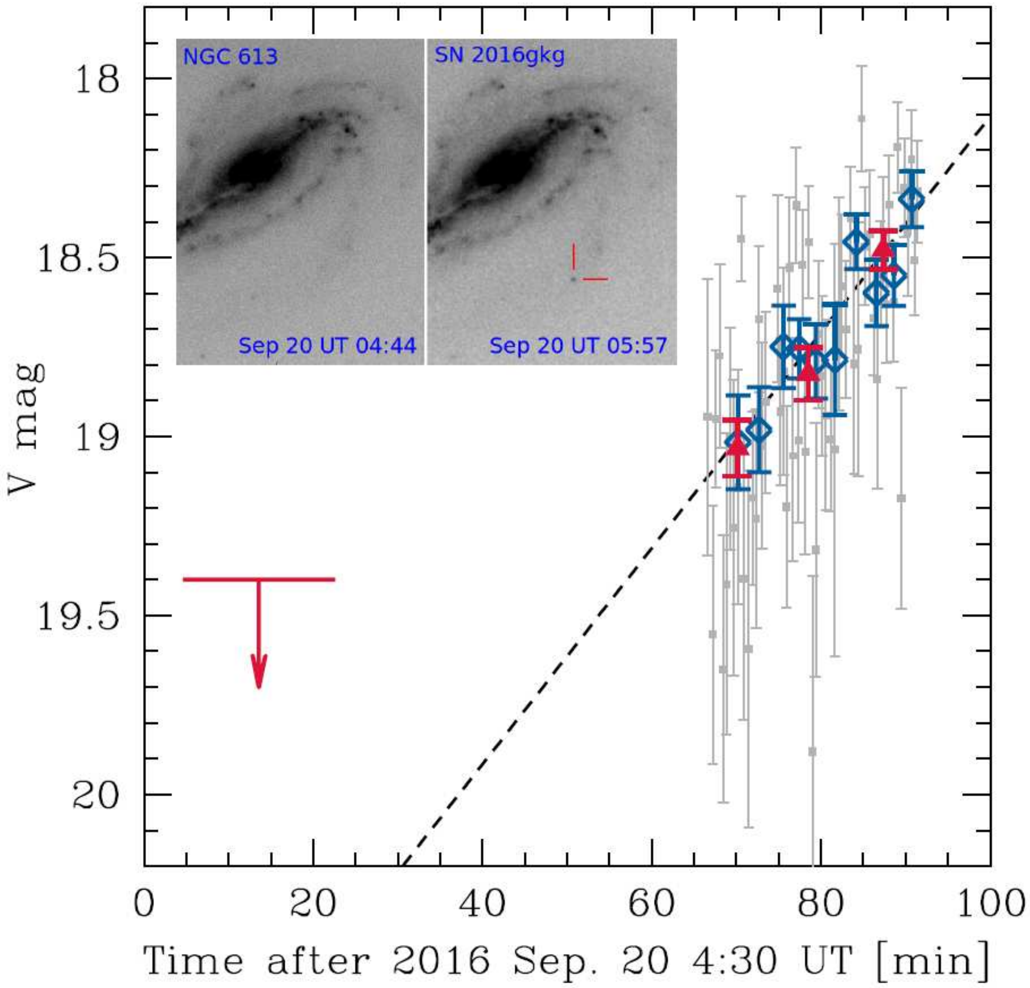


20 images

SN IIb 2016gkg

- No sign in 40 images (in $\approx$ 20 min). SN became visible 45 min later
- Unprecedented time sampling of the initial rise at a rate of 43 mag/day



Bersten et al., Nature 2018

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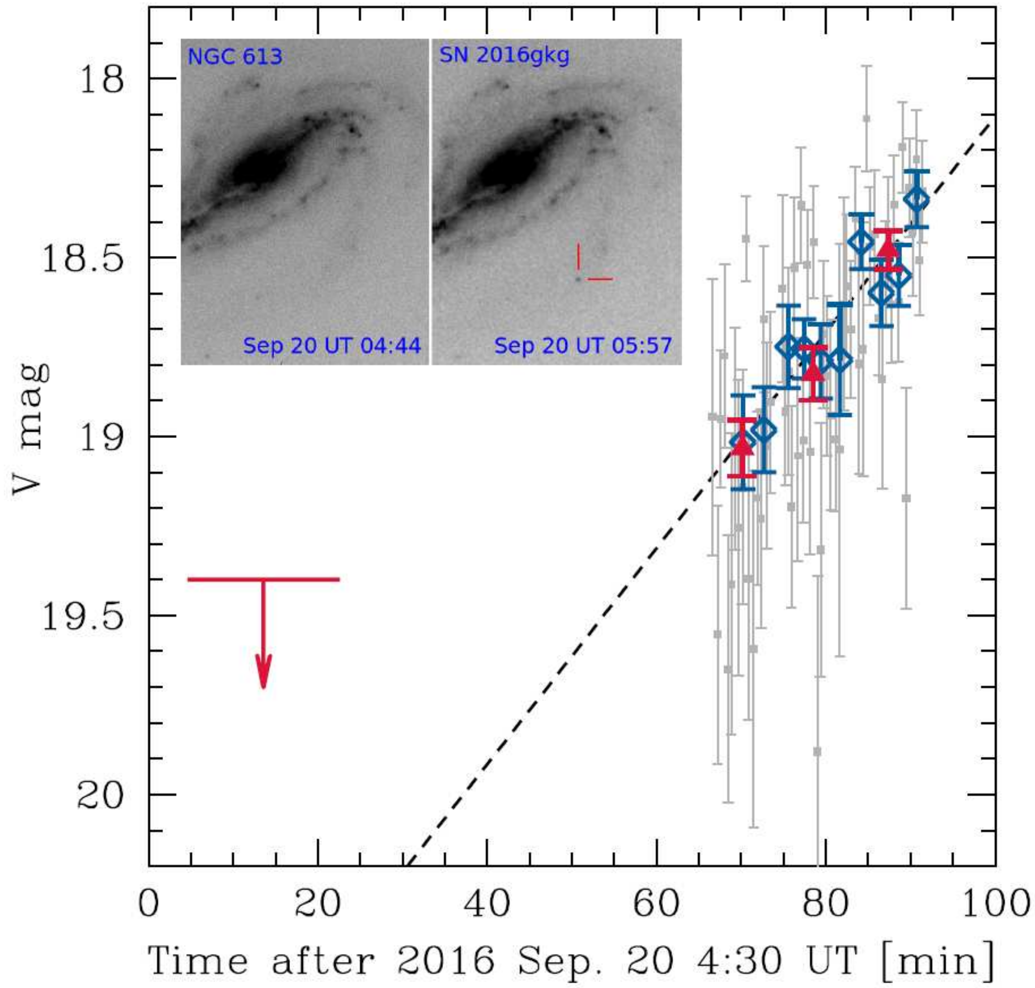
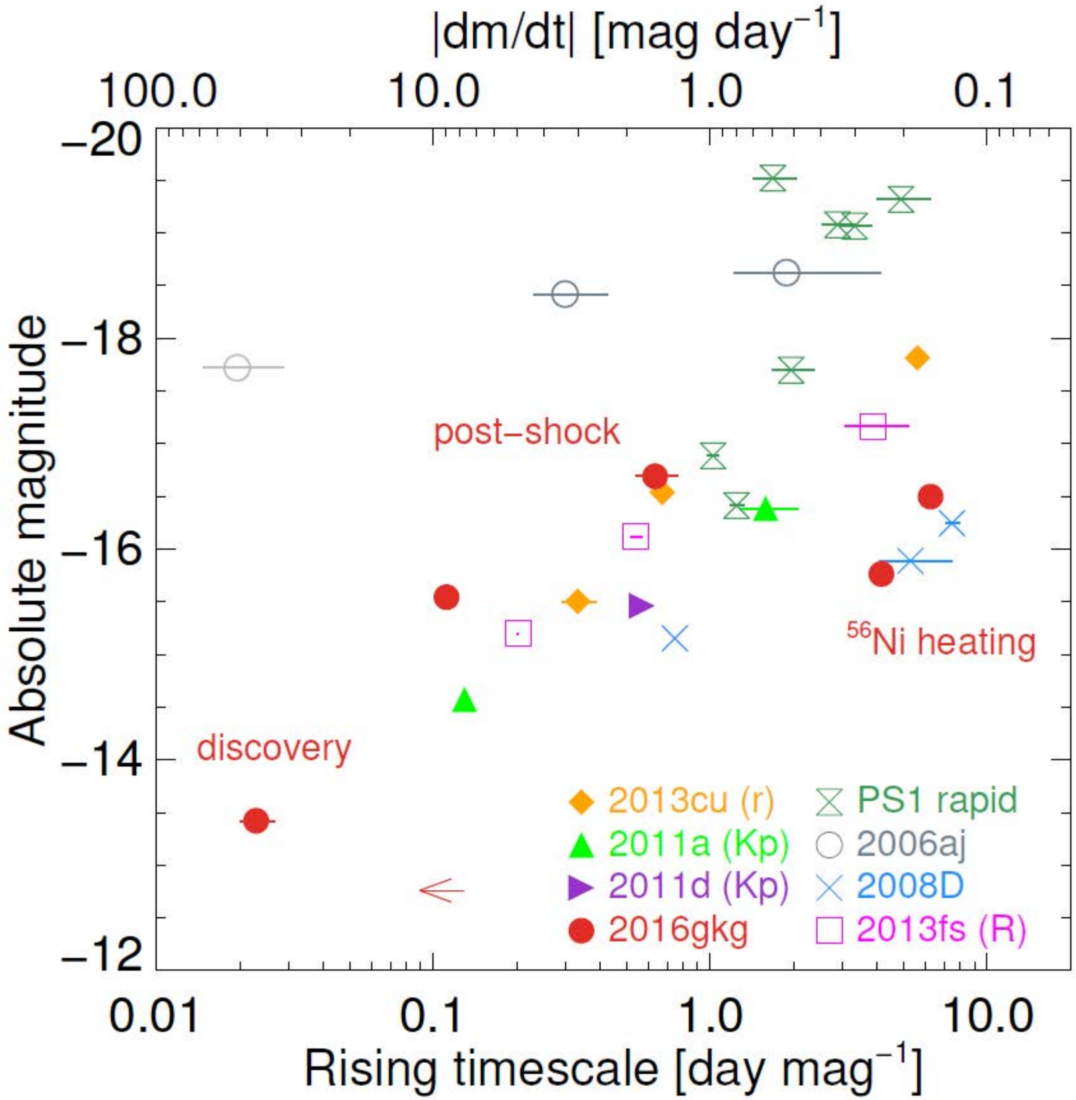


Was SN 2016gkg detected during the shock breakout (SBO) ?

Bersten et al., Nature 2018

SBO rise time

- The lowest luminosity and the fastest rise ever observed (in optical) $\Longrightarrow$ a different physical origin for the initial rise



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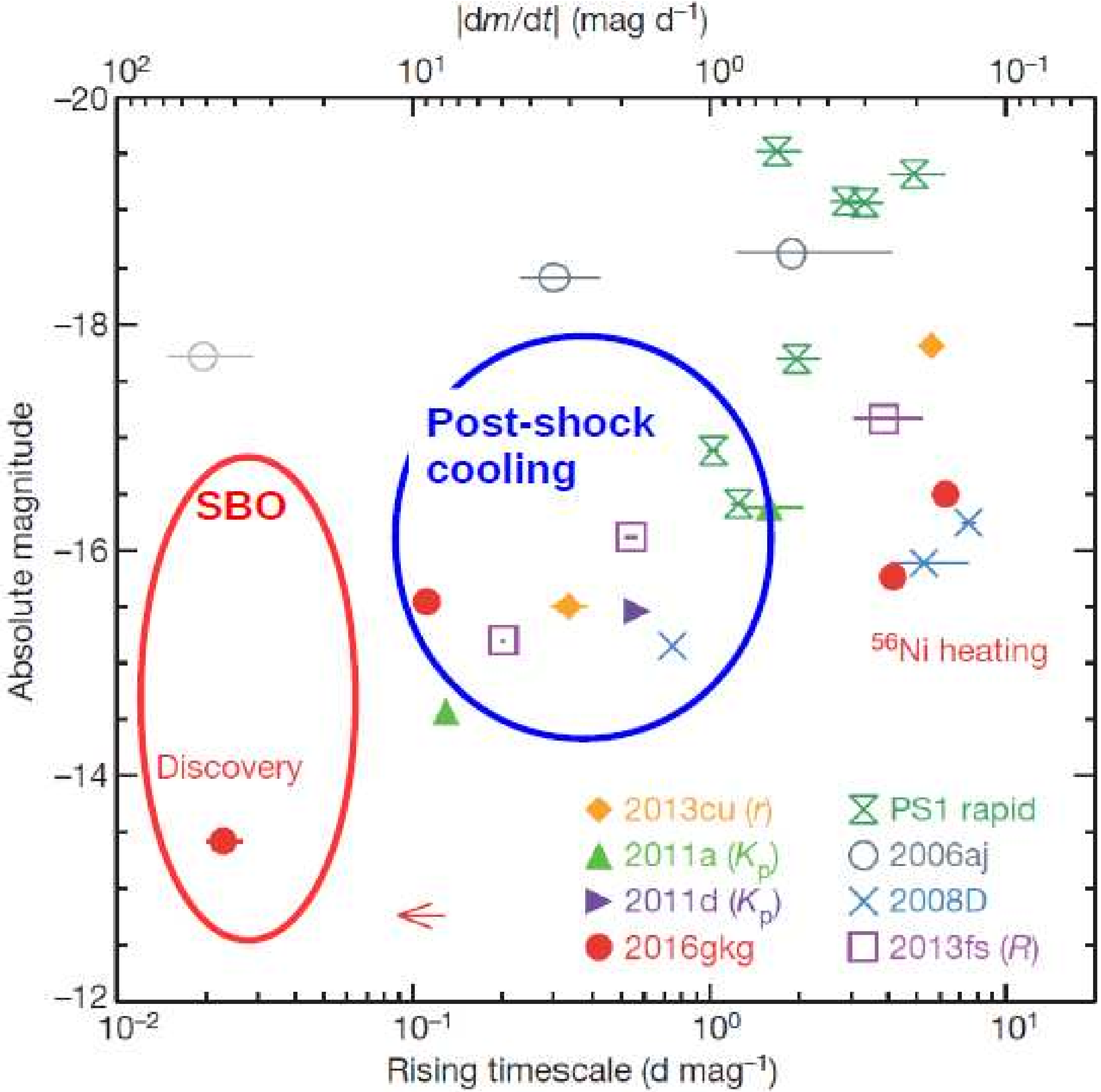
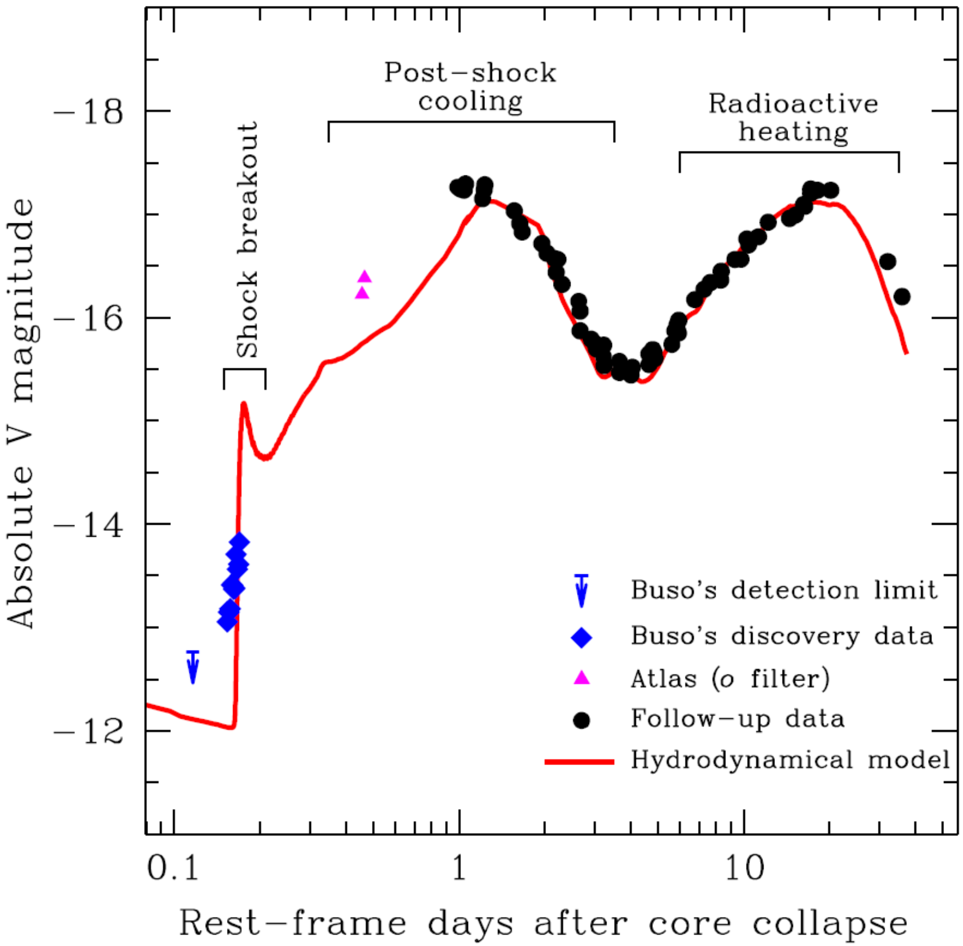


Hydrodynamical model of SN 2016gkg

- First-time, self-consistent model for the whole SN evolution
- Fast initial rise and brightness naturally reproduced

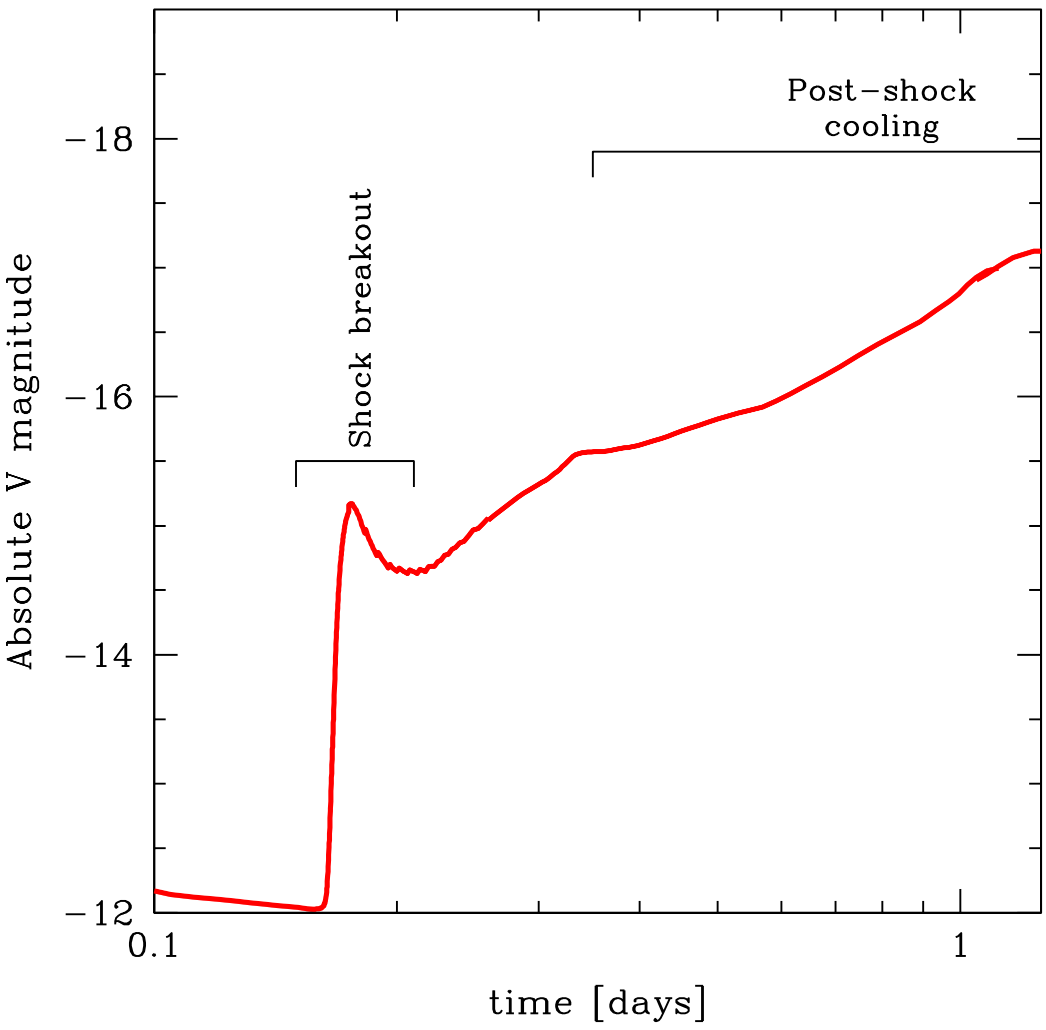


- Triple-peak light curve
- Low ejecta mass ≈ 3.5 $M_\odot$
- $E_{\rm exp}$= 1.2 $\times 10^{51}$ erg and ^{56}Ni mass 0.09 $M_\odot$
- A low-density H-envelope with R= 320 $R_\odot$

Bersten et al., Nature 2018

Hydrodynamical model of SN 2016gkg

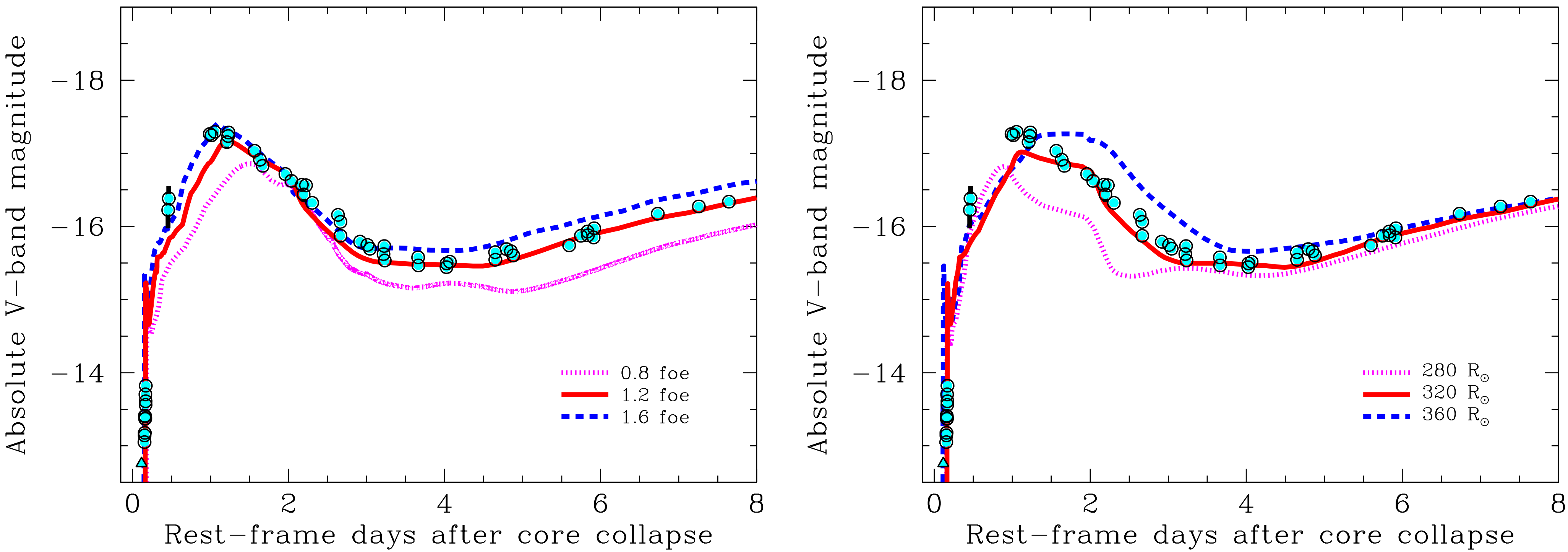
- Physical origin of Víctor's data: SBO or post shock-cooling (PSC)?



- The rise to the SBO peak is significantly faster than that of the (PSC)
- No physical parameter can reconcile the slopes

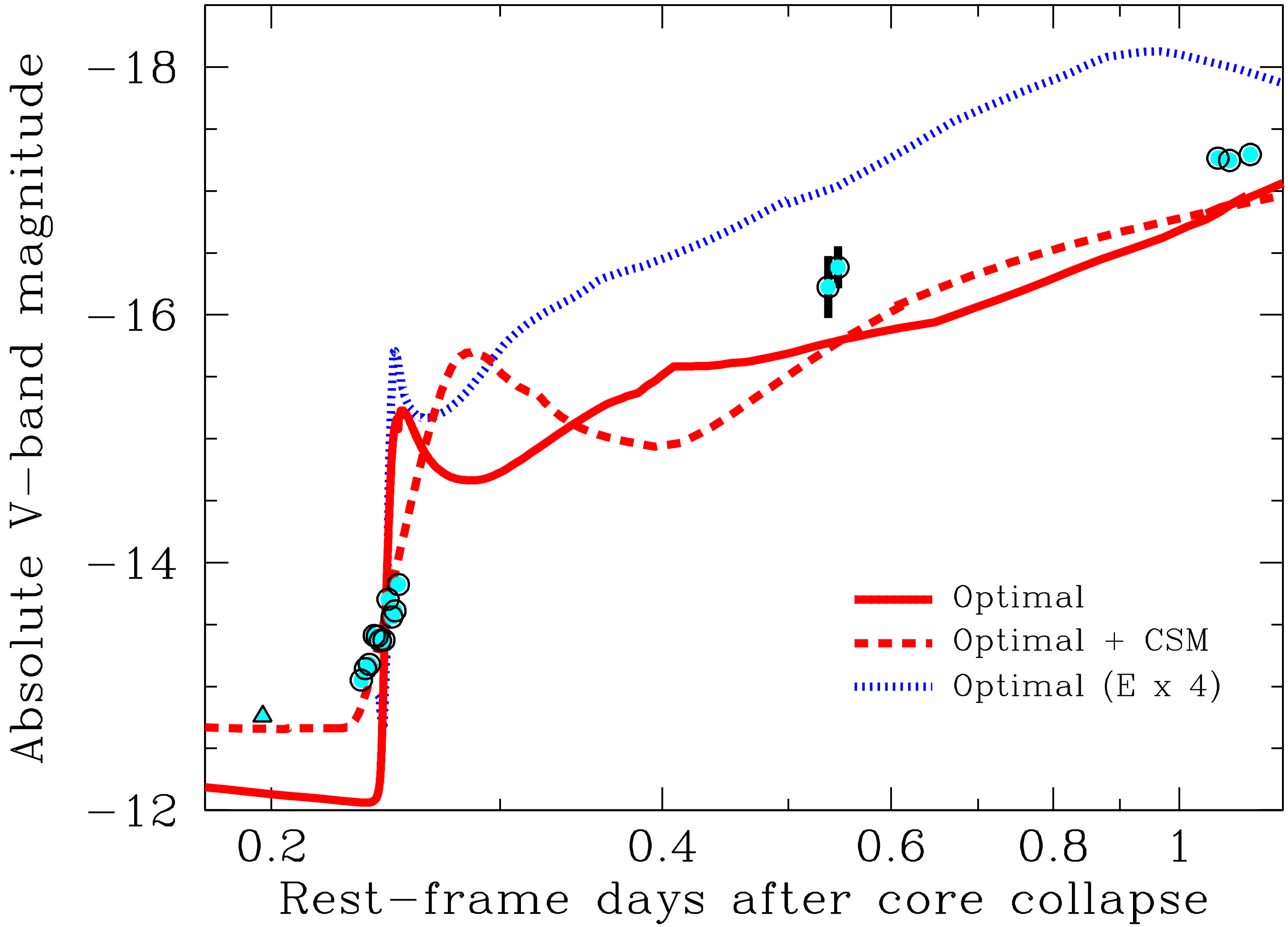
Hydrodynamical model of SN 2016gkg

- Fast initial rise and brightness only compatible with the SBO
- No physical parameter can reconcile the SBO and cooling slopes



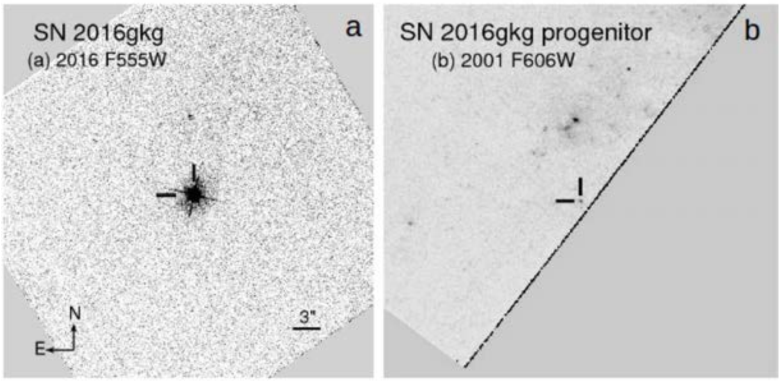
Hydrodynamical model of SN 2016gkg

- Our model shows slightly higher SBO slope
- Possible solution presence of some circumstellar material (CSM)

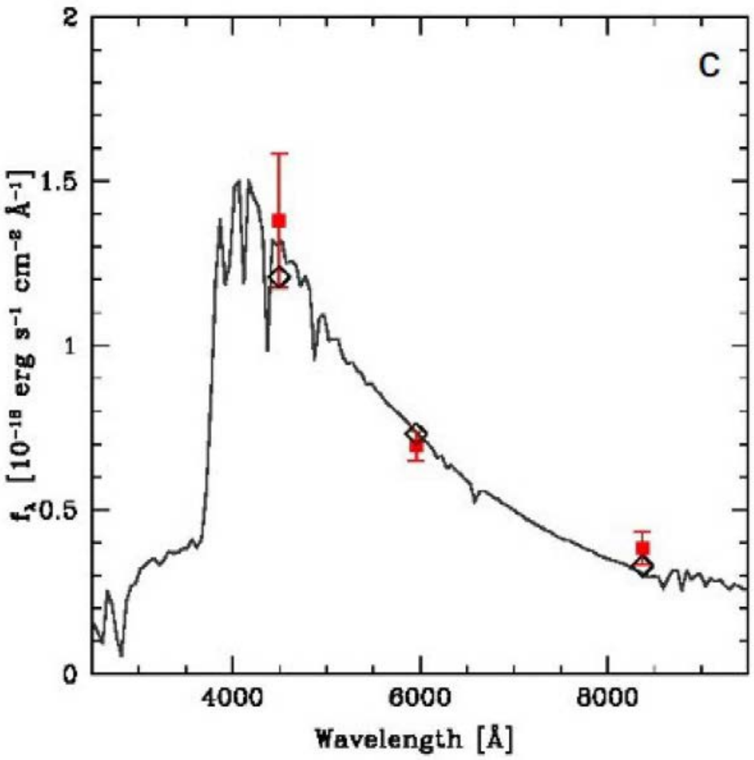


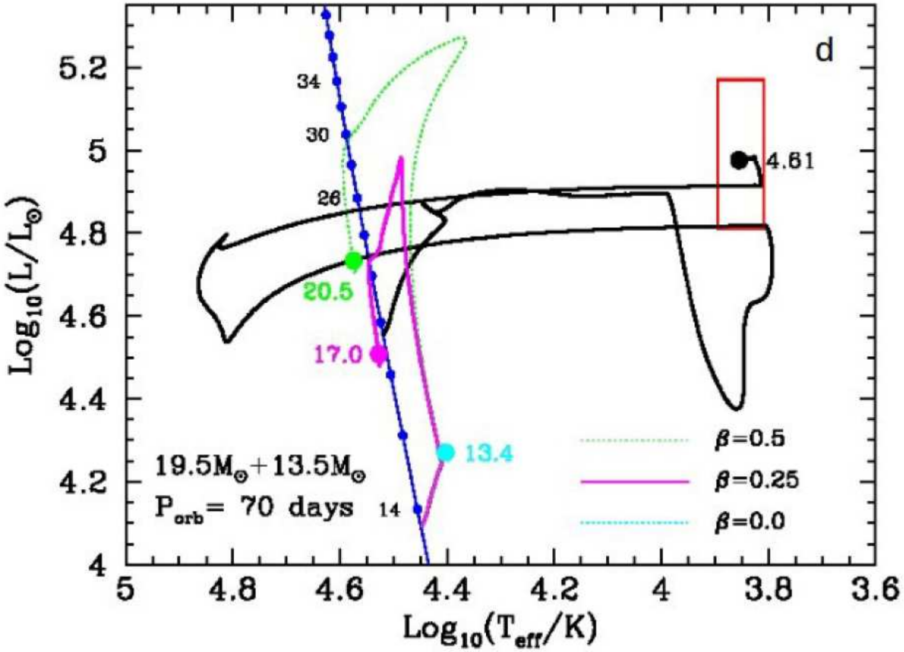
Progenitor of SN 2016gkg

- HST pre-SN images $\Longrightarrow$ YSG star with $R \approx 250 R_\odot$ at SN position
- Binary calculations: progenitor is a H-deficient star with $\approx$ 4.5 $M_\odot$ and $R \approx 200 R_\odot$



see also Tartaglia+17, Arcavi+17 & Kilpatrick+17





Summary

- Light-curve modeling a useful tool to derive physical properties of SN progenitors and thus to test stellar evolution models
- SNe II: masses derived from hydro models are not systematically larger than those from pre-explosion imaging
- SESNe seem to come predominantly from binaries. Where are the binary companions? How to find them?
- Early emission highly dependent on the external stellar structure.Hydrodynamical models required to reproduce the early emission
- SN16gkg model explains for the first time three distinct phases of IIb
- SBO in SN16gkg may suggest low-density CSM (not affecting the cooling phase!)
- SBO detections require minute/hour cadence