Models of Core-Collapse SNe and Shock Breakout

Melina Cecilia Bersten

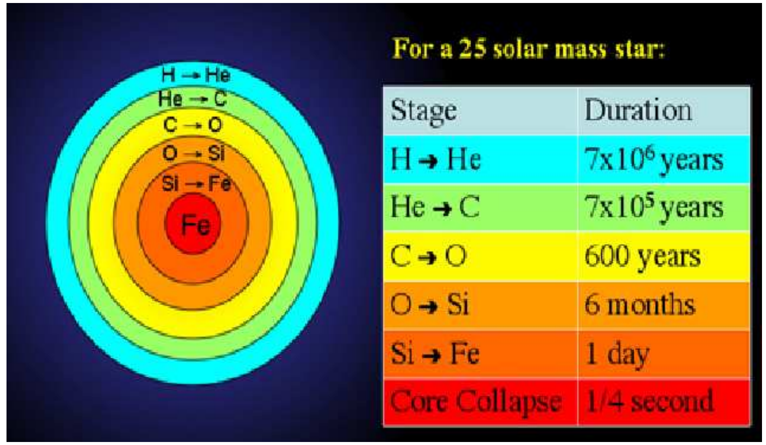
Facultad de Ciencias Astronómicas y Geofísicas
UNIVERSIDAD NACIONAL DE LA PLATA

IALP
CONICET
UNLP

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Importance of Supernovae

- Astrophysics
  - Death of a star $\longrightarrow$ Stellar evolution
  - Chemical enrichment of interstelar medium
  - Energetics events $\longrightarrow$ trigger new star formation, remanants

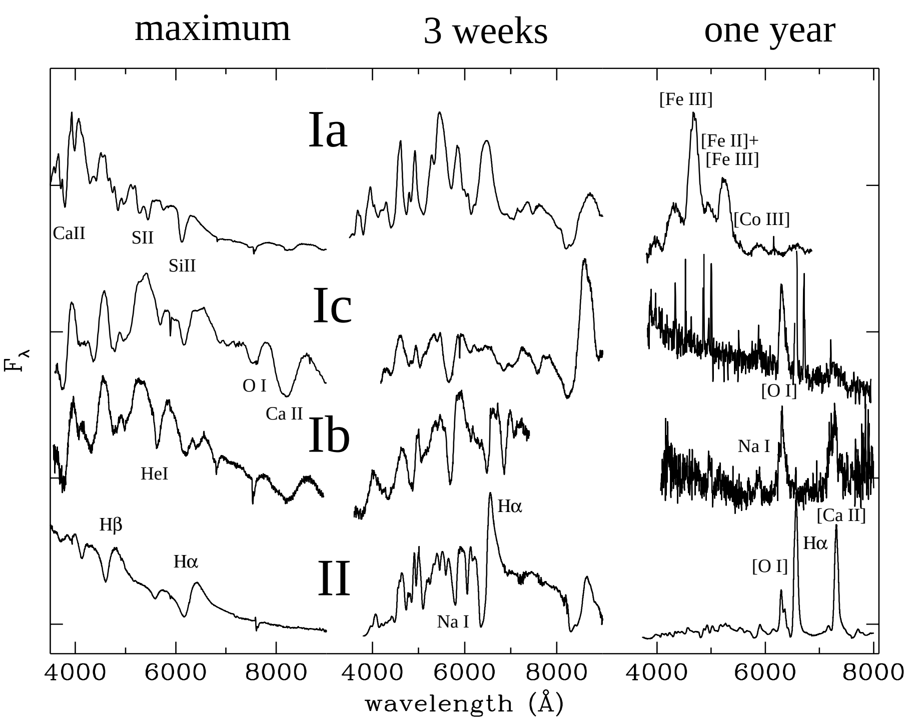


- Cosmology
  - Powerful distance indicators
  - Accelerated expansion of the Universe - Dark energy

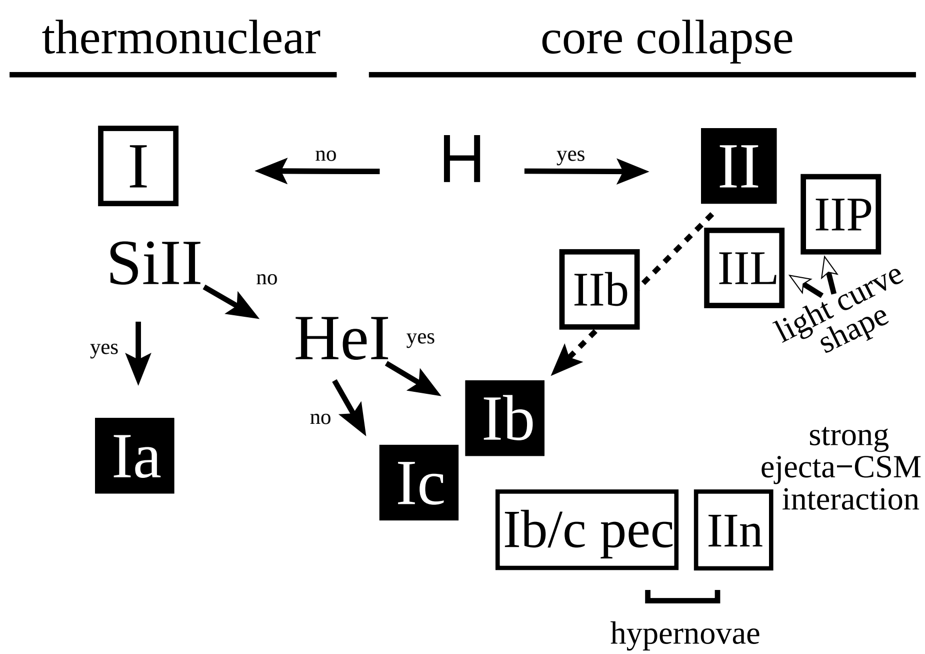
Nobel Prize 2011

Supernova diversity

- Normal SN: $E_k \sim 10^{51}$ erg, $\sim$1–10% E_k during weeks/months ($\sim 10^{10} L_\odot$)
- Broad line Ic ($v \sim 30000$ km s^{-1}) connected to LGRBs ($E \sim 10^{52}$ erg)
- Superluminous SN: $\approx$ 10 – 100 $\times$ more luminous than “ordinary” SNe

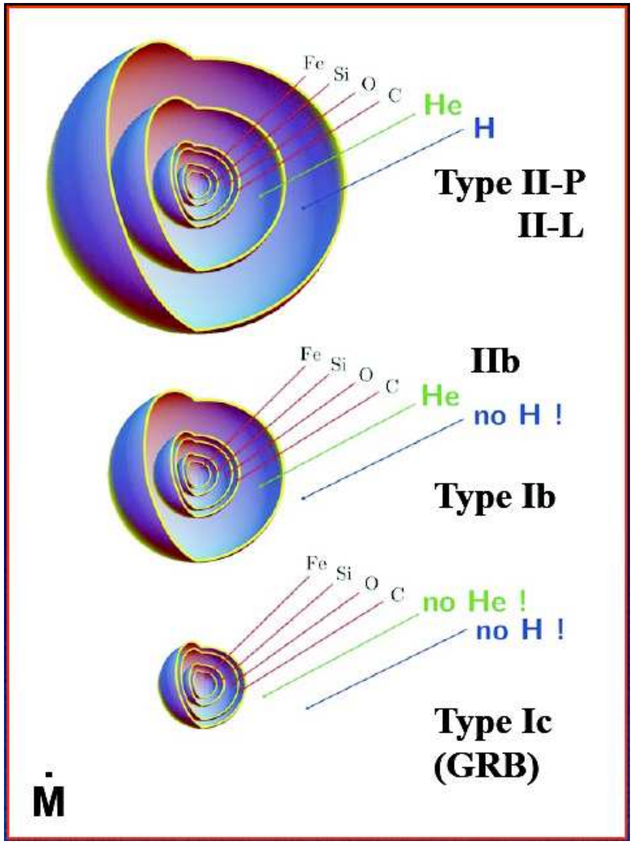


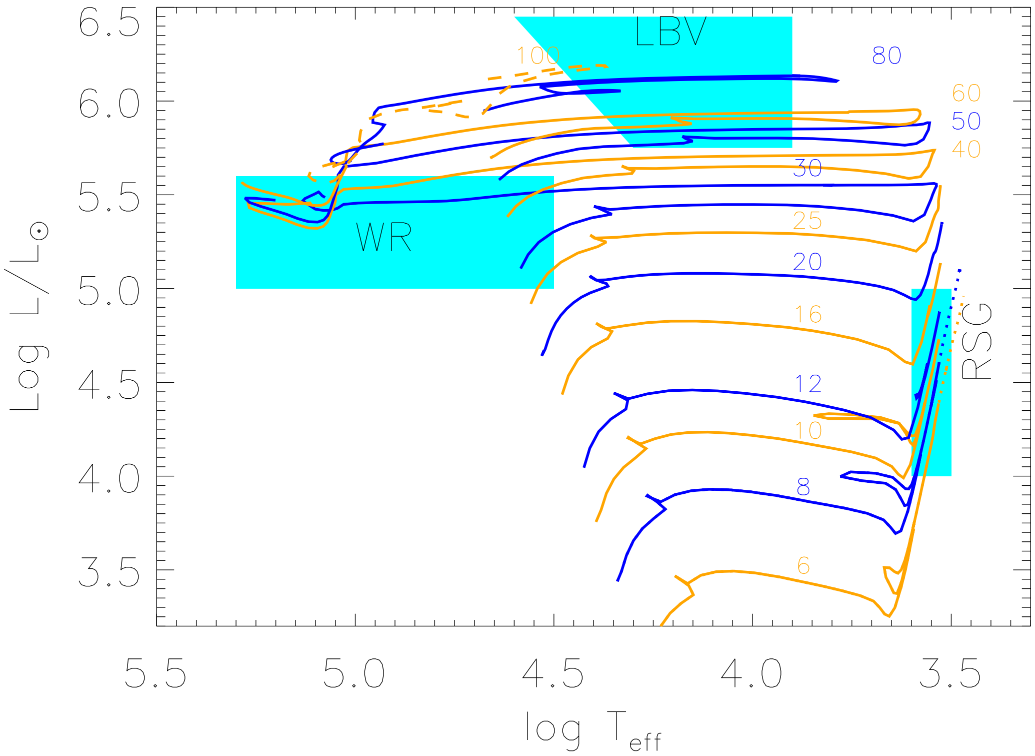
Turatto (2003)



Core-Collapse Supernovae

- End of massive stars ($M_0 \gtrsim 8M_\odot$) – 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?





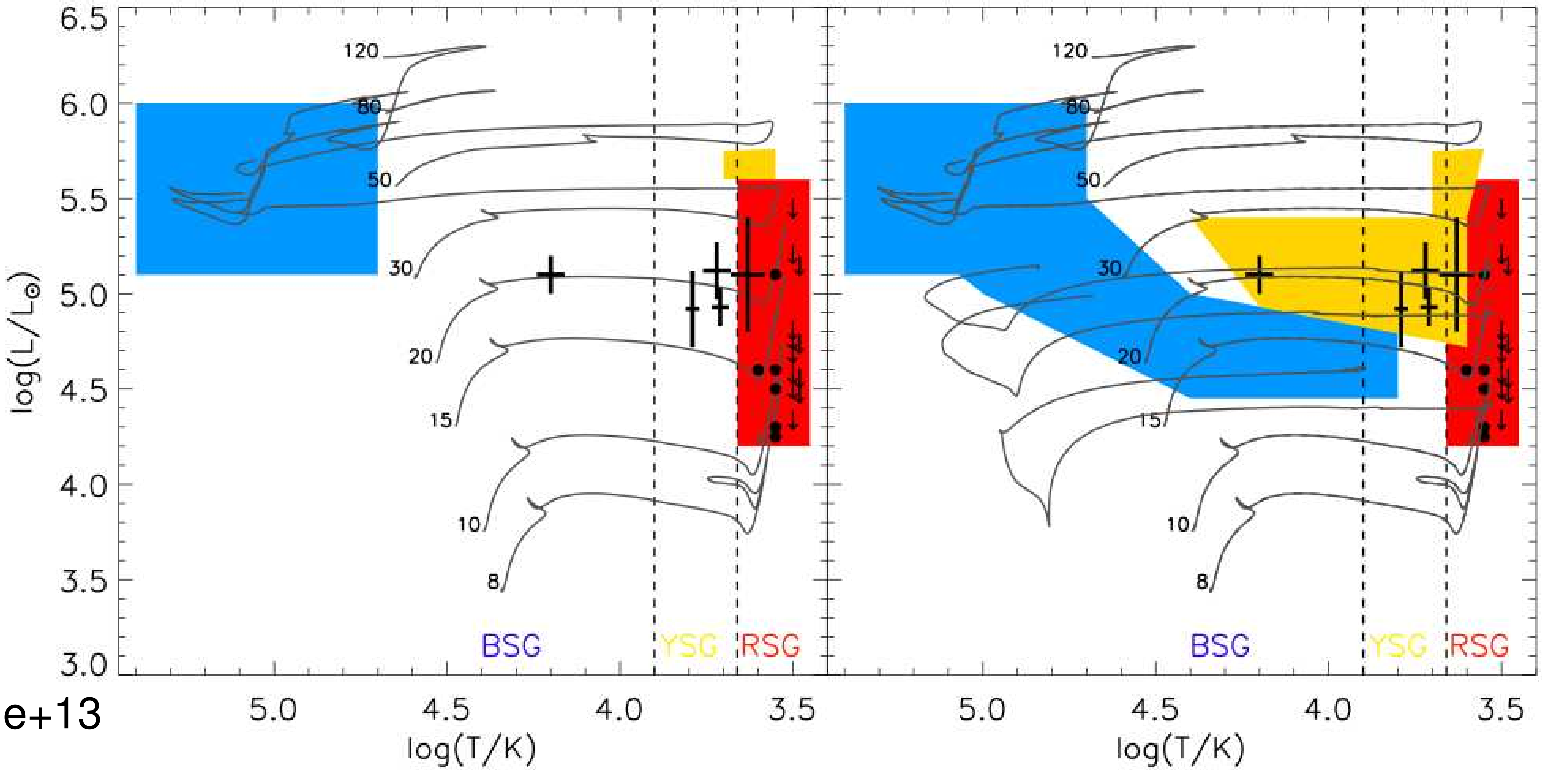
Credit: M. Modjaz

Smartt+09

Core-Collapse Supernovae

- End of massive stars ($M_0 \gtrsim 8M_\odot$) – 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?

Single stars Binaries



Eldridge+13

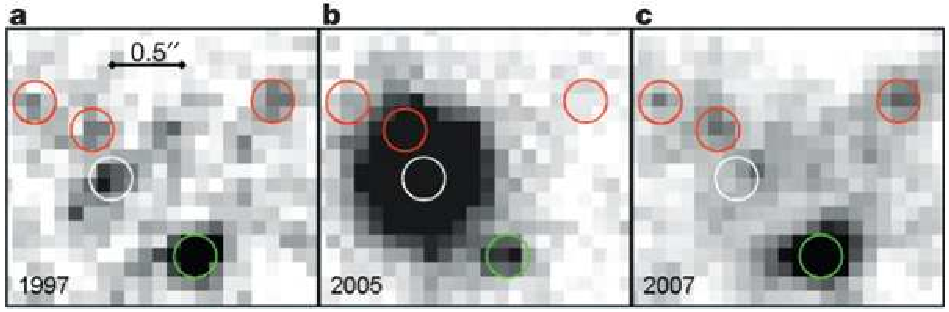
Progenitor Stars

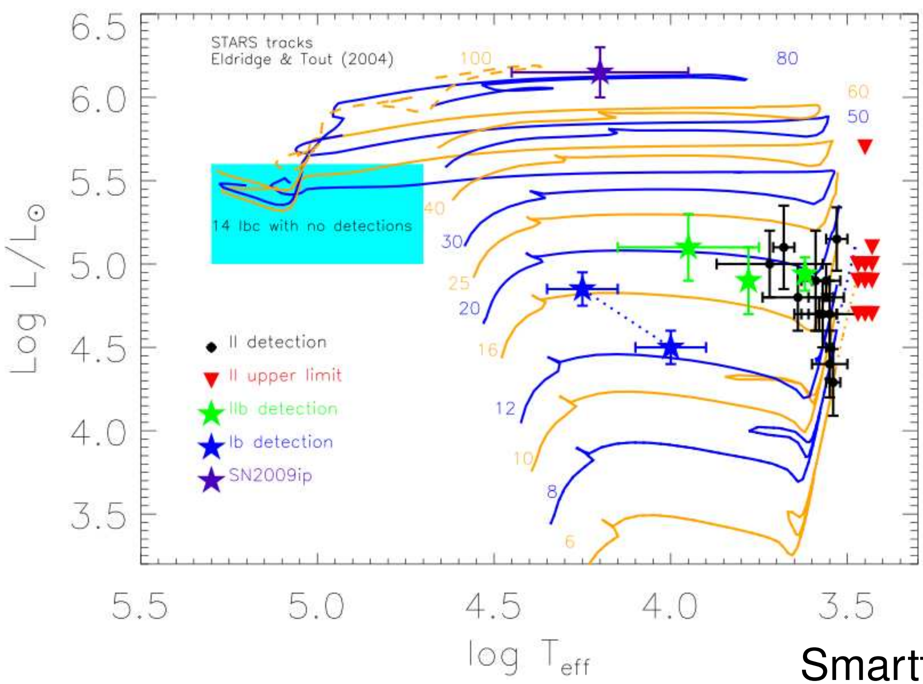
- Archival pre-explosion imaging
- Environmental and metallicity studies
- SN rates
- Mass-loss rates from radio & X-rays
- Spectropolarimetry
- Flash spectroscopy
- Light-curve and spectrum modeling

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 $M_\odot$?

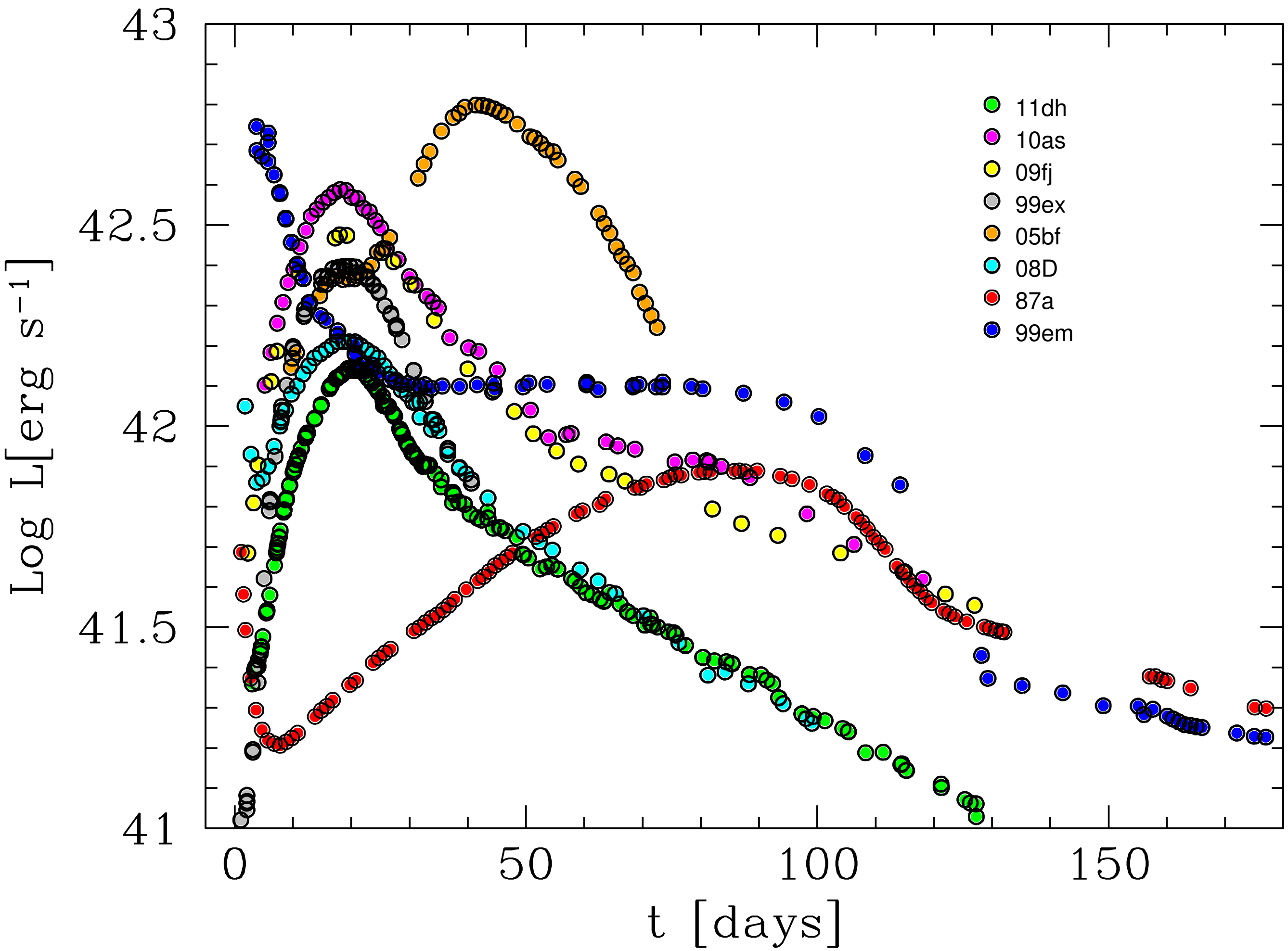




Smartt+15

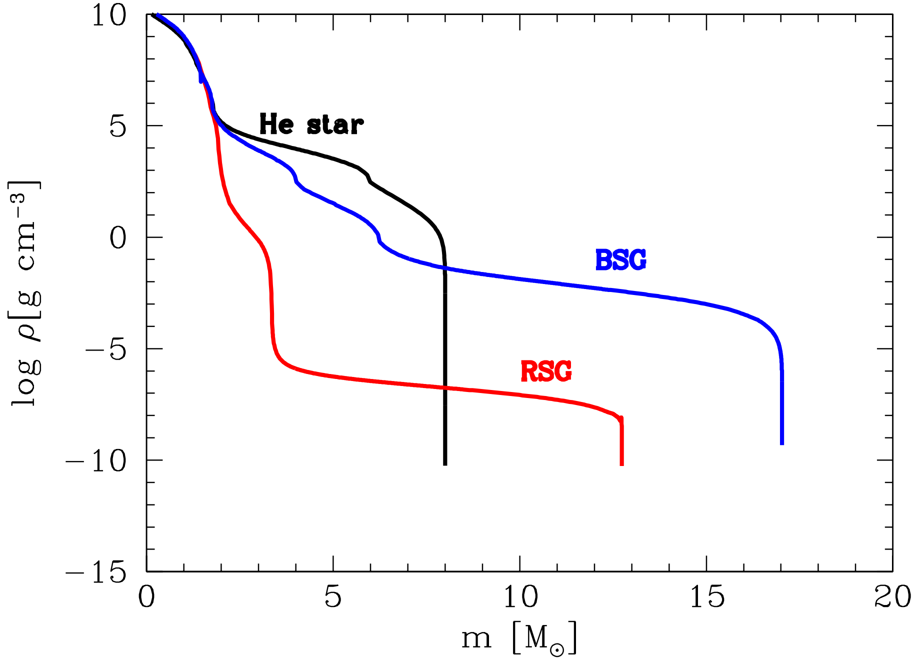
Progenitor Stars

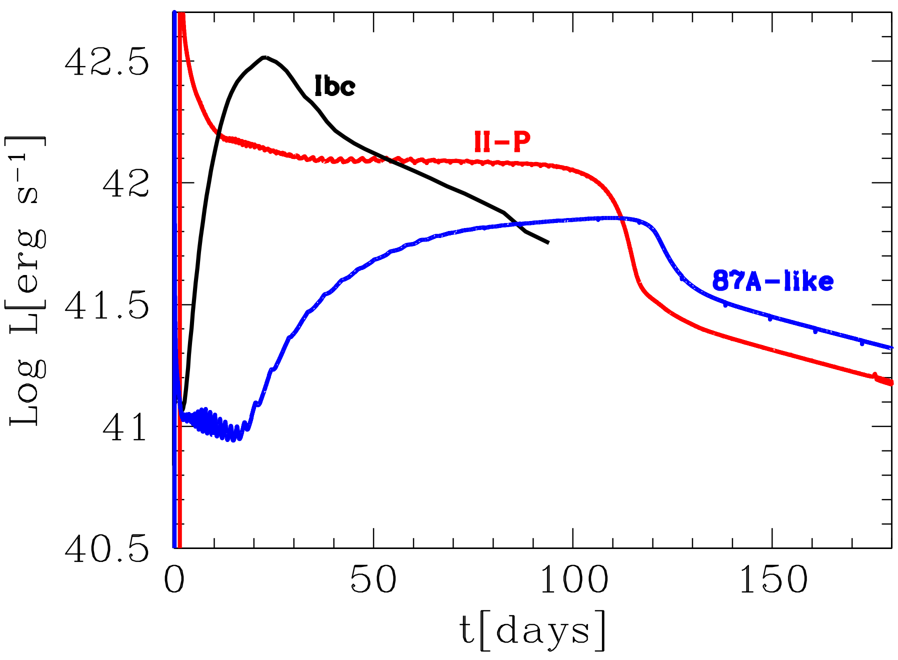
- Hydrodynamic modeling: LC + expansion velocities
- Progenitor mass, radius, explosion energy, ^{56}Ni mass



Hydrodynamical Models

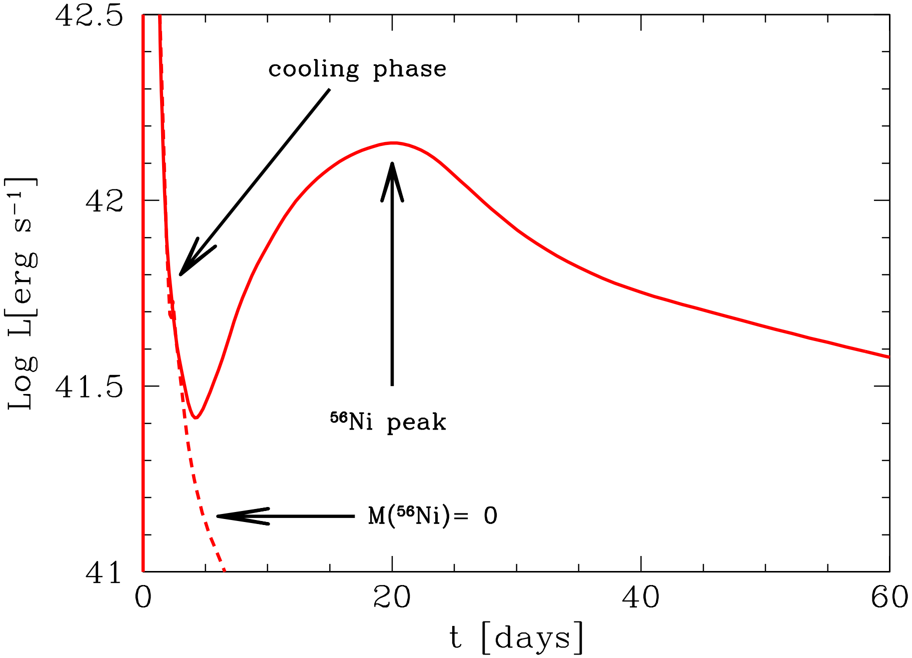
- Different time scales for core and envelope $\Longrightarrow$ ejection of the envelope treated independently of core collapse
- Numerical integration of the hydro equations $+$ radiative transfer
  1-D code with flux-limited radiation $+$ gray transfer for γ-rays (Bersten+11)
- Pre-SN structures: stellar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

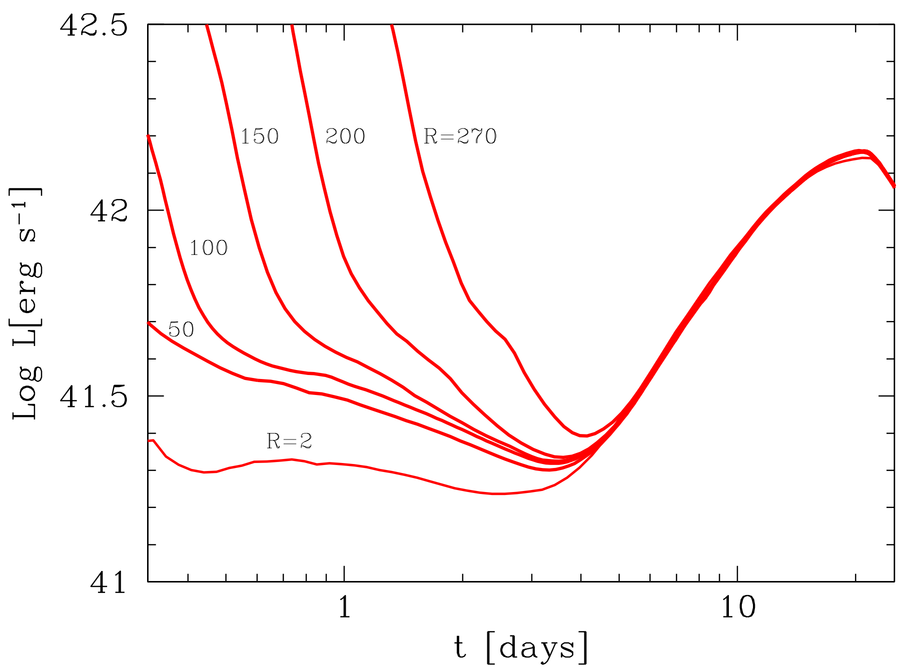




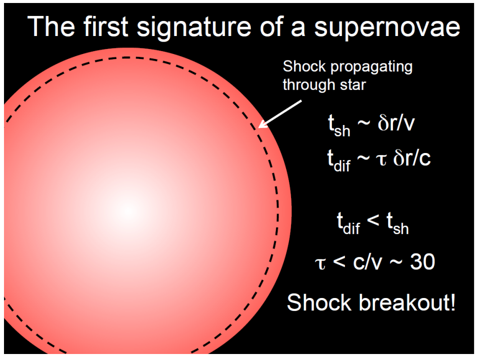
H-poor Supernovae

- Type IIb-Ib-Ic: Stripped envelope SNe
- Cooling phase with strong dependence on progenitor radius
- Second peak powered by radioactive decay
  Depends on $E_{\rm exp}$, $M_{\rm ej}$, $M_{\rm Ni}$ and $^{56}\rm Ni$ distribution

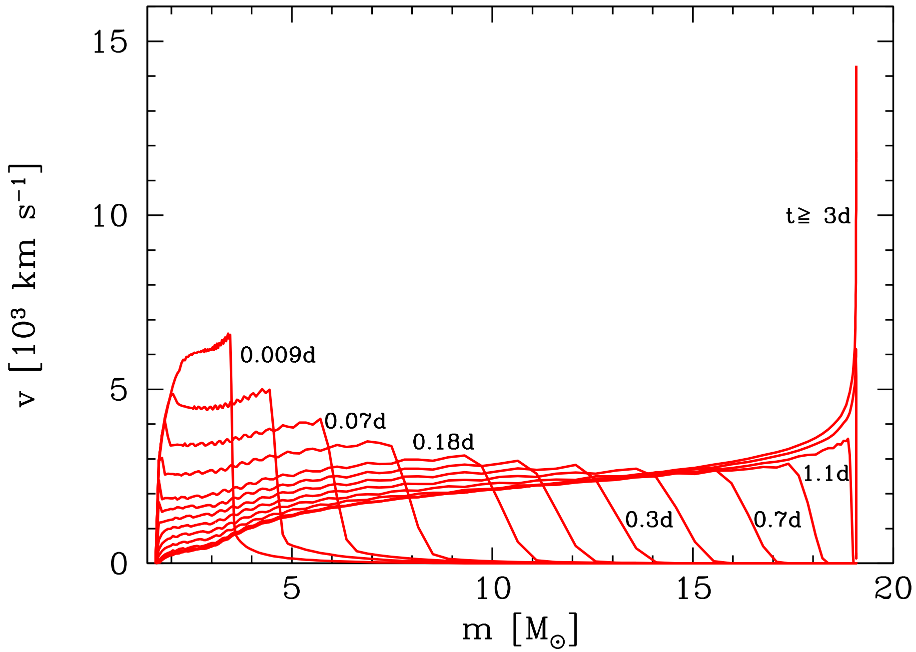


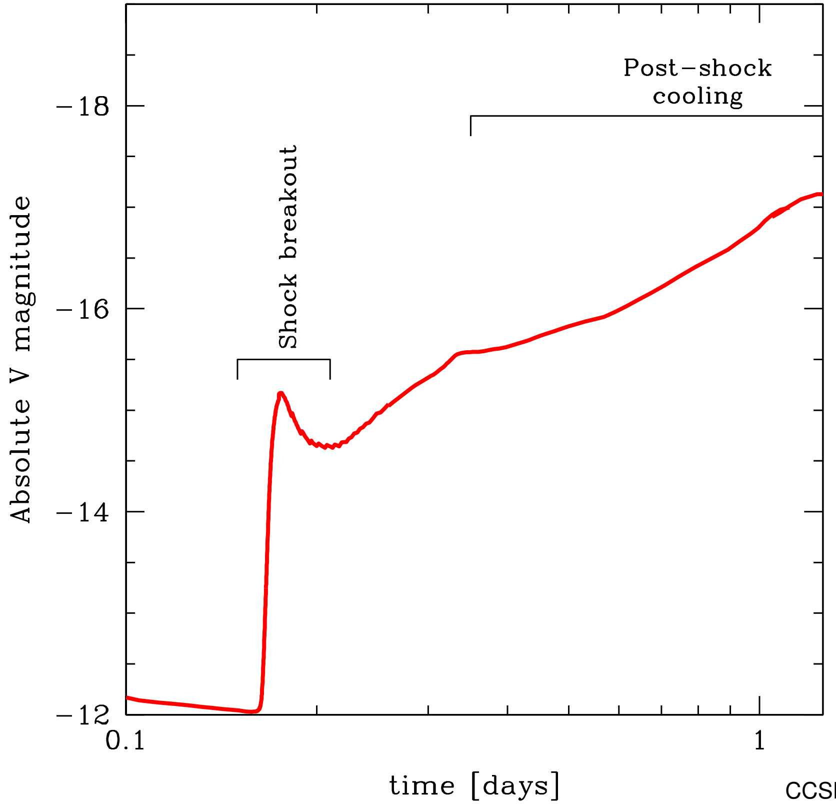


Shock Breakout (SBO)



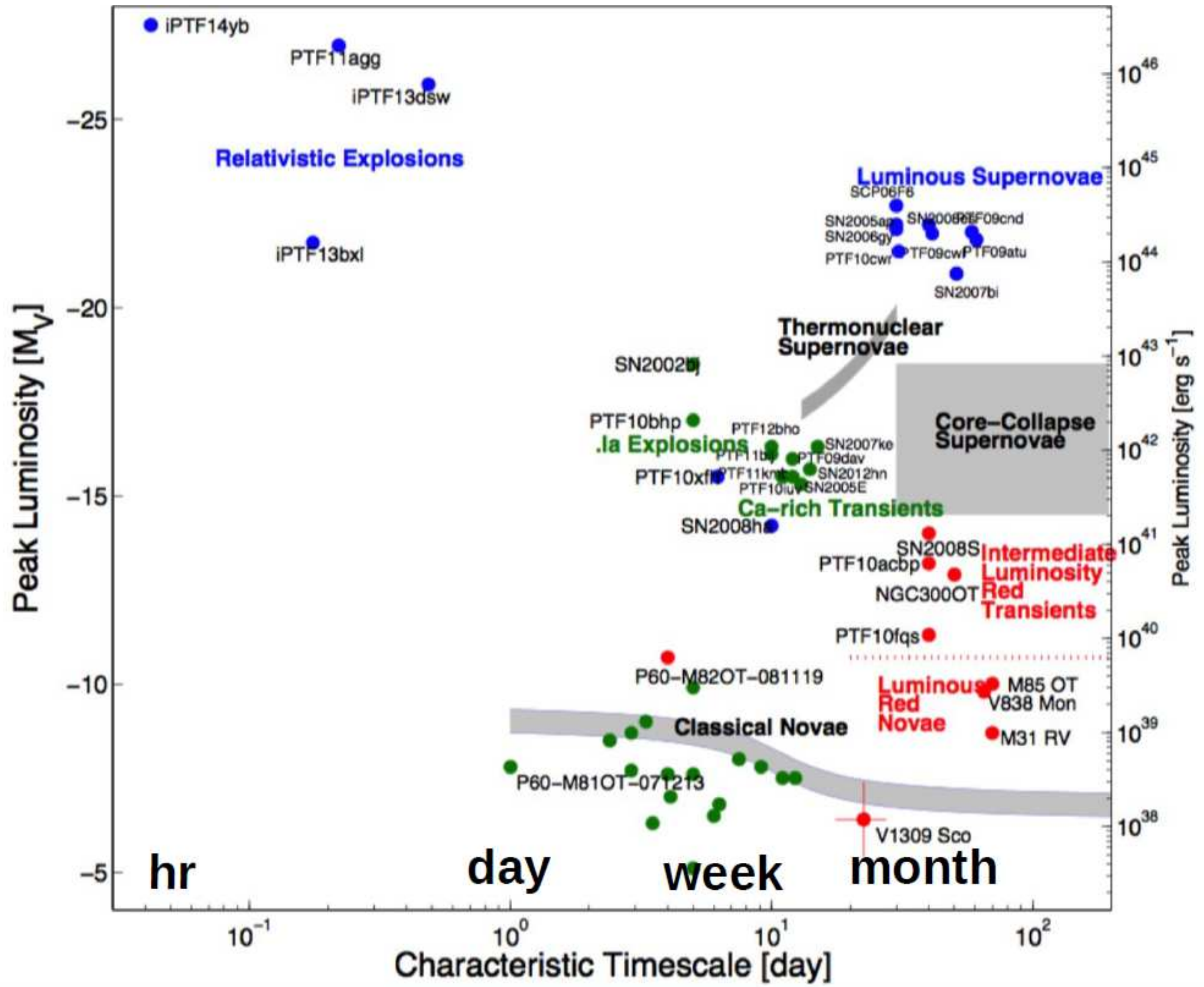
- A luminous burst in UV/X-ray: shock-wave emerges on the stellar surface ($\tau < v_{\rm sock}/c$)
- Produces an emission peak in the optical
- SBO emission $\neq$ shock cooling emission





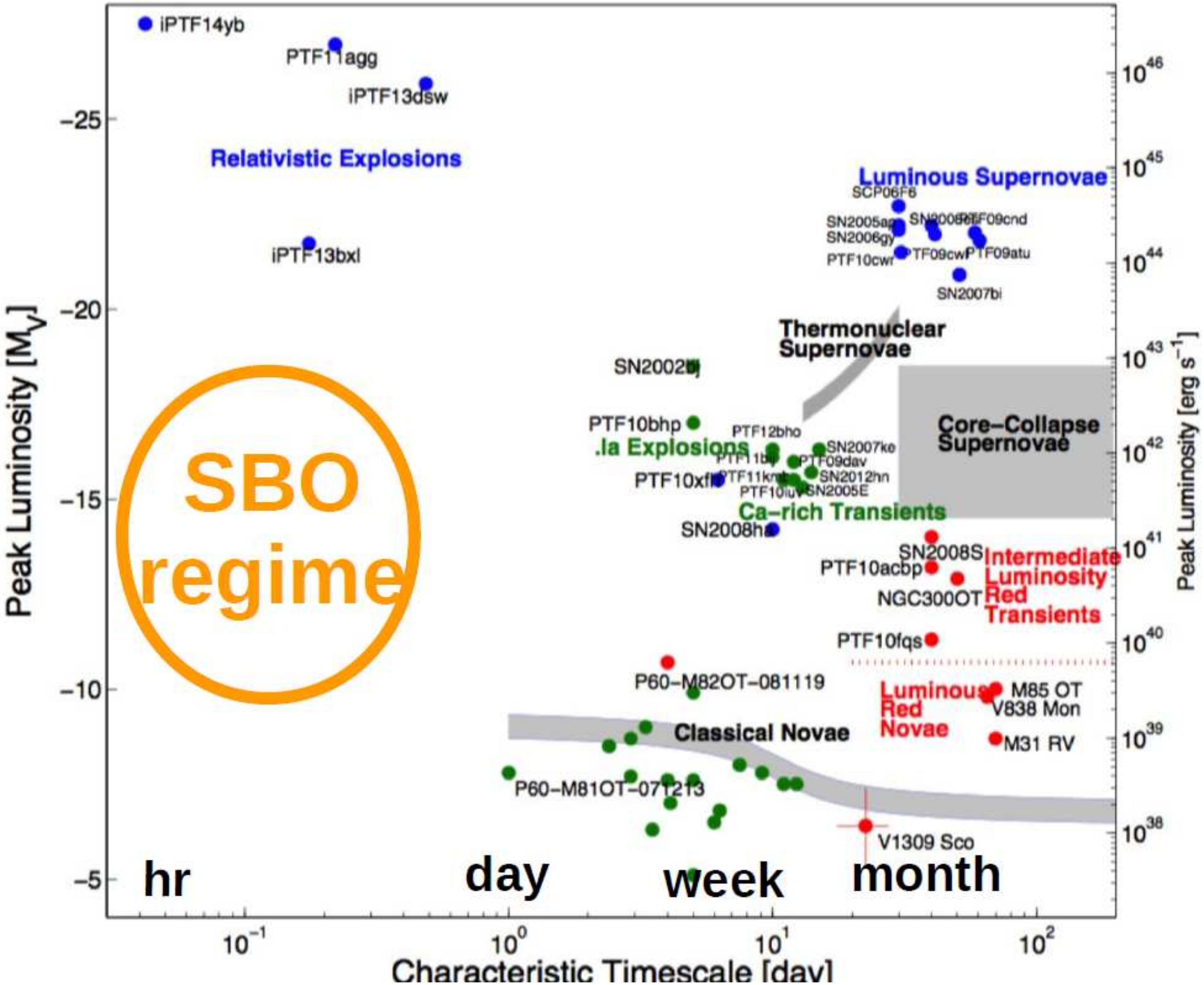
Early Discovery

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



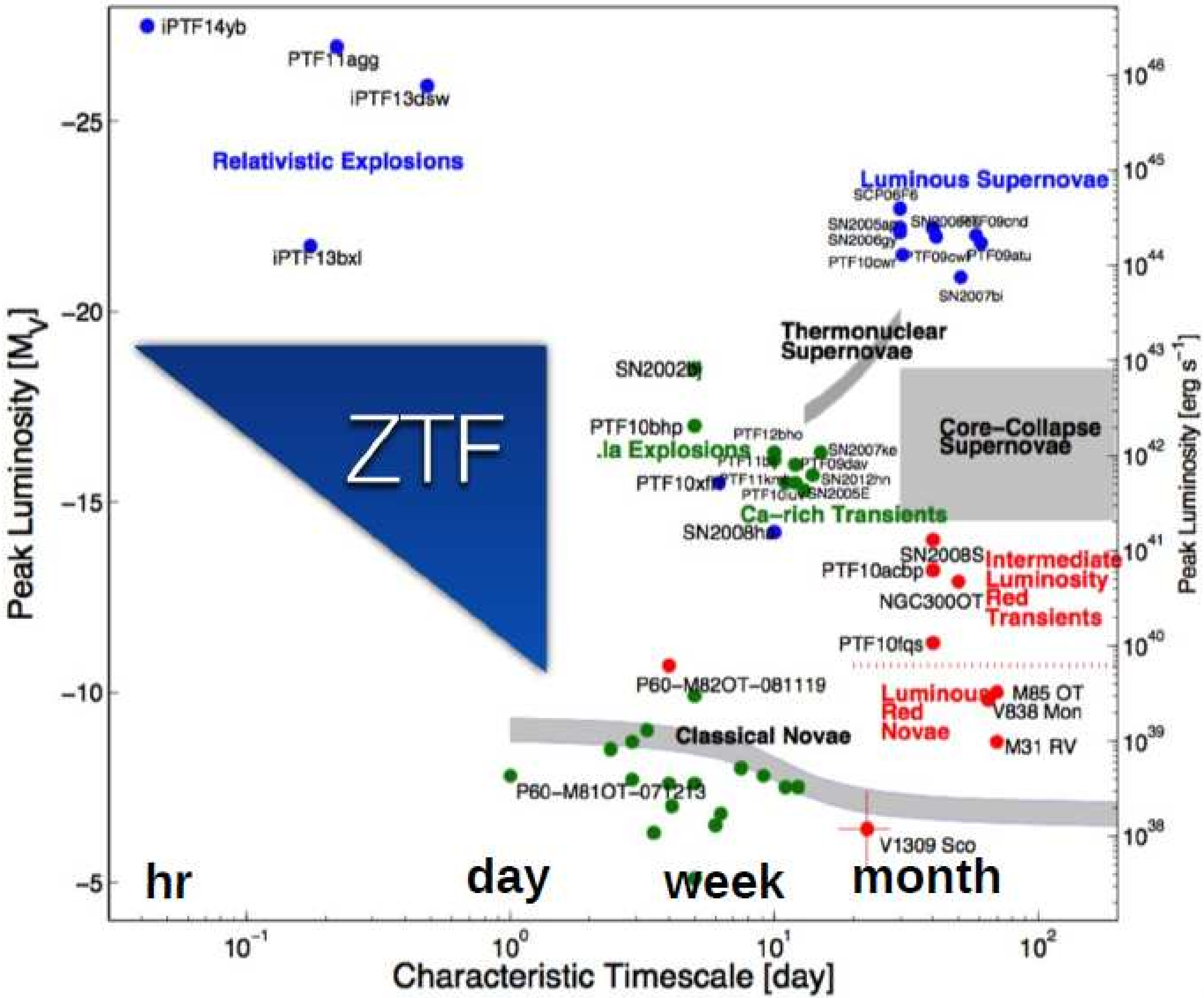
Early Discovery

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



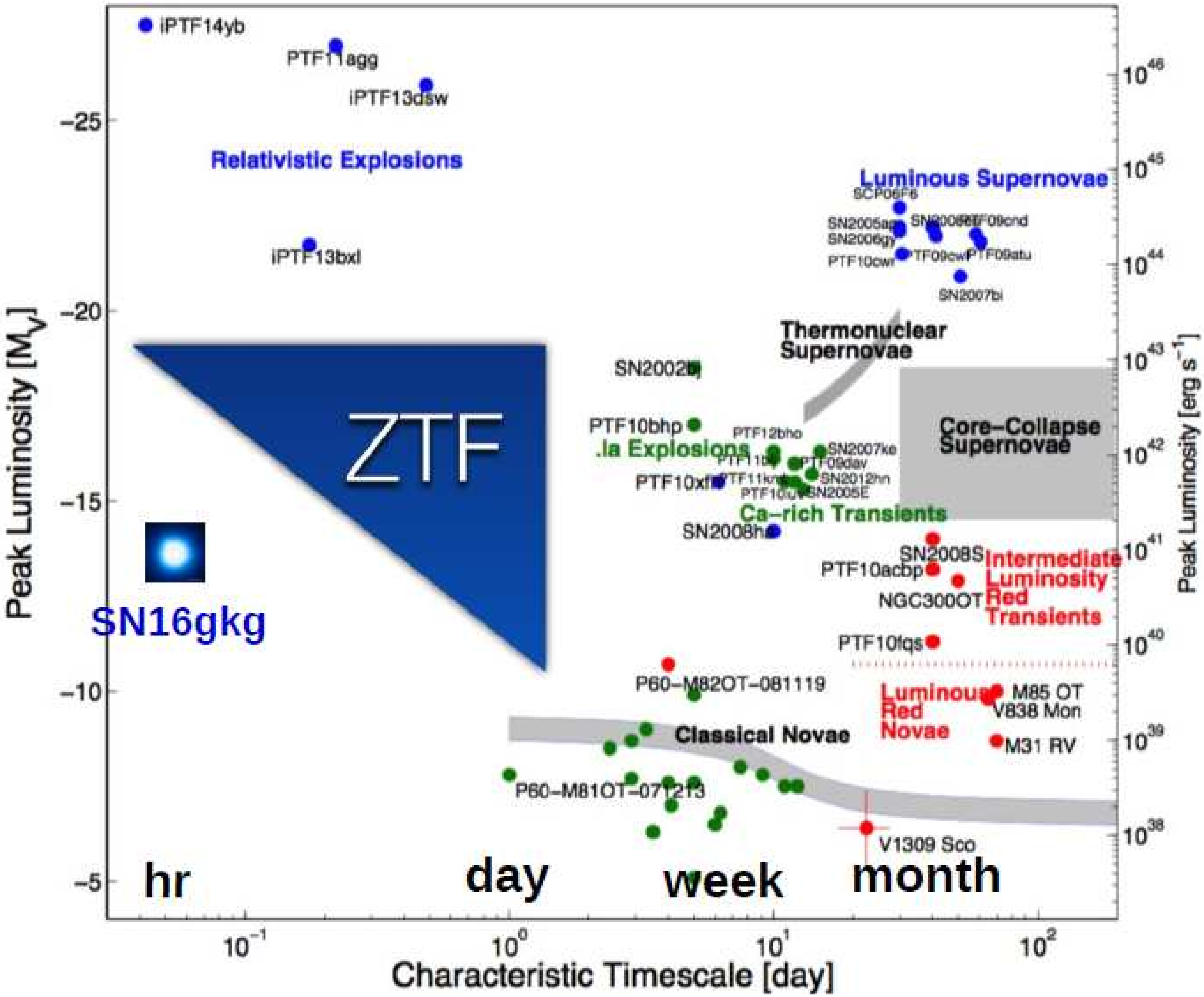
Early Discovery

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



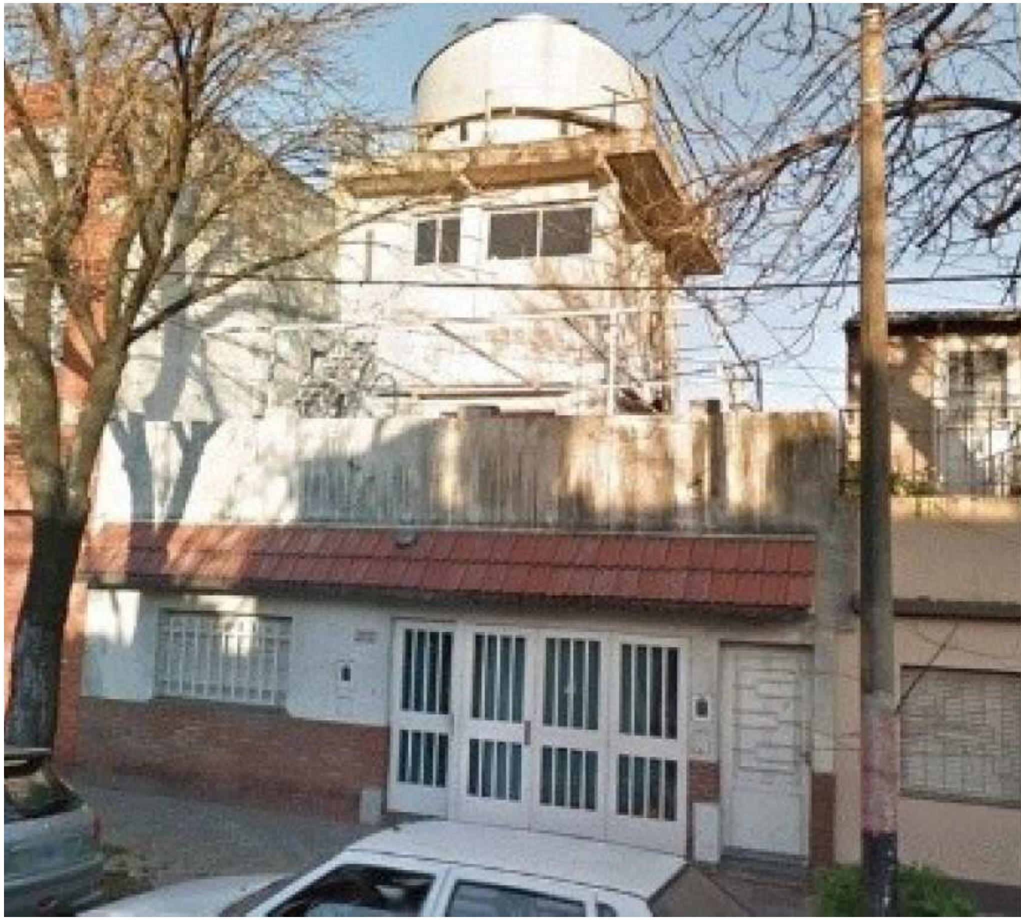
Early Discovery

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



Supernova 2016gkg

Discovered on Sept. 20th 2016 by amateur Víctor Buso



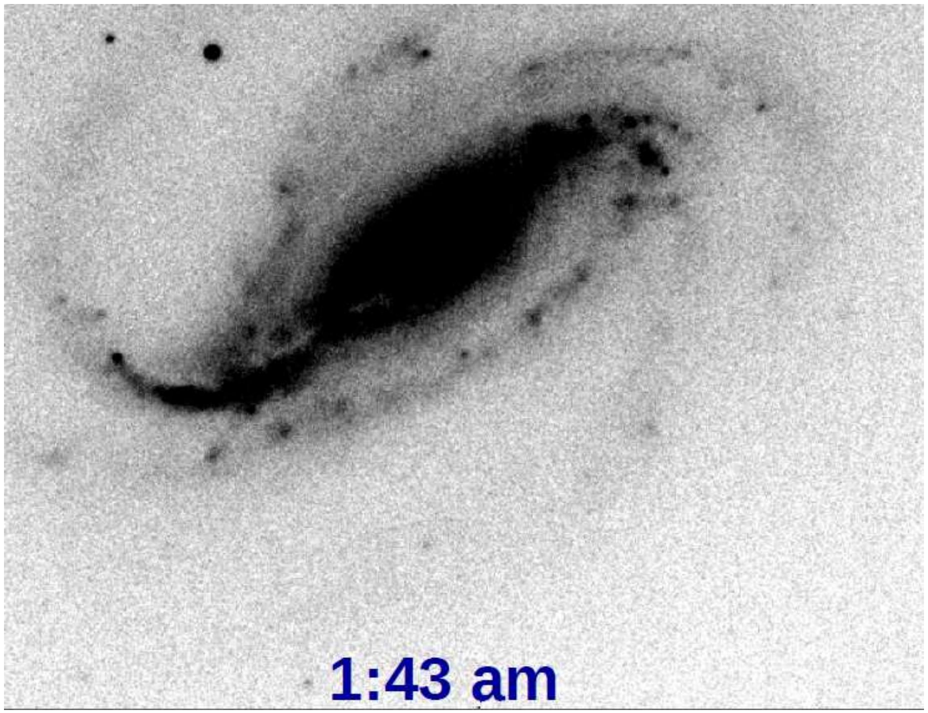
The “Observatorio Busoniano” in Rosario

Buso with his 40cm Newtonian

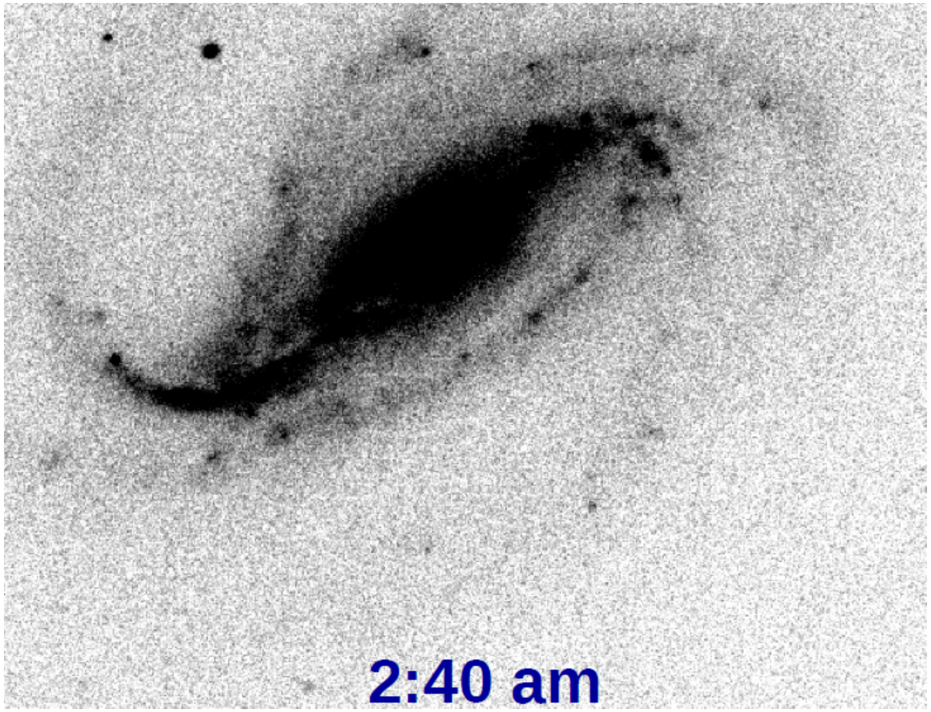
Supernova 2016gkg

The SN appears during Víctor's observations

NGC 613



40 images

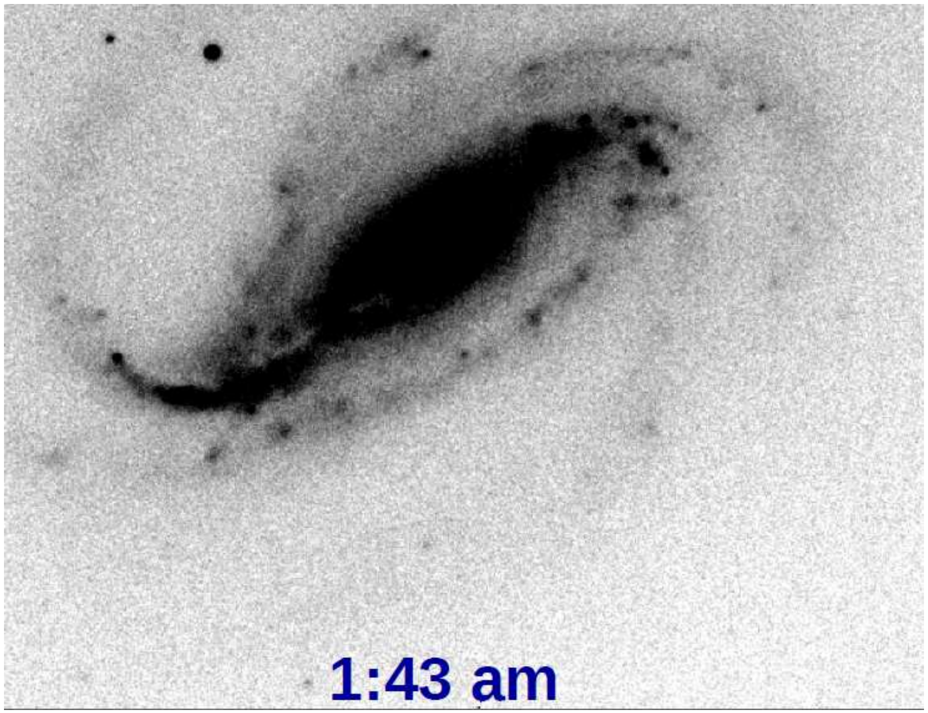


20 images

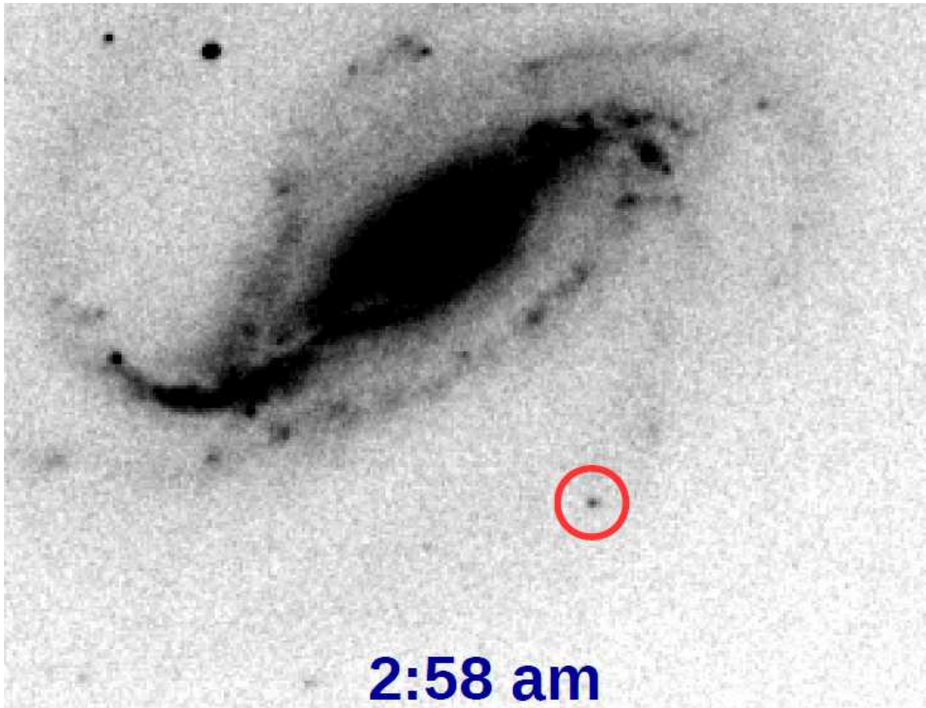
Supernova 2016gkg

The SN appears during Víctor's observations

NGC 613



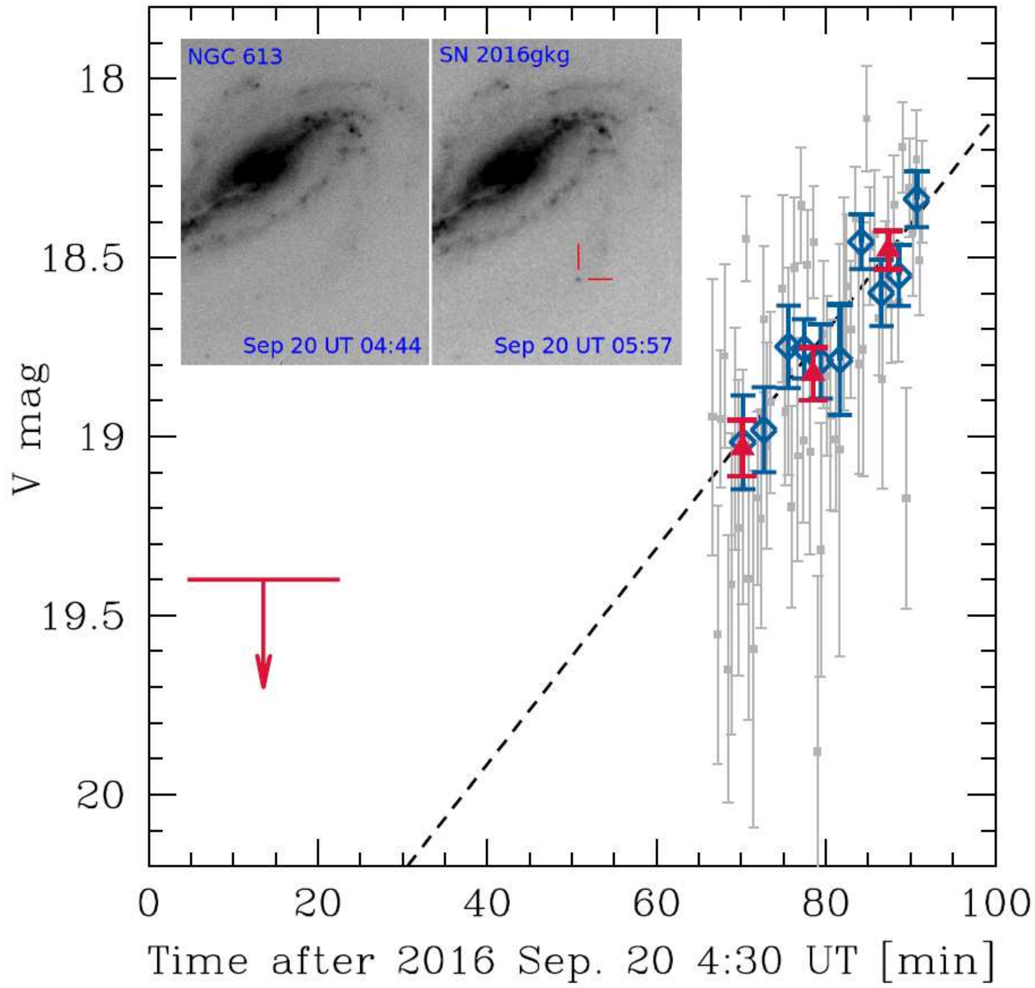
40 images



20 images

SN IIb 2016gkg

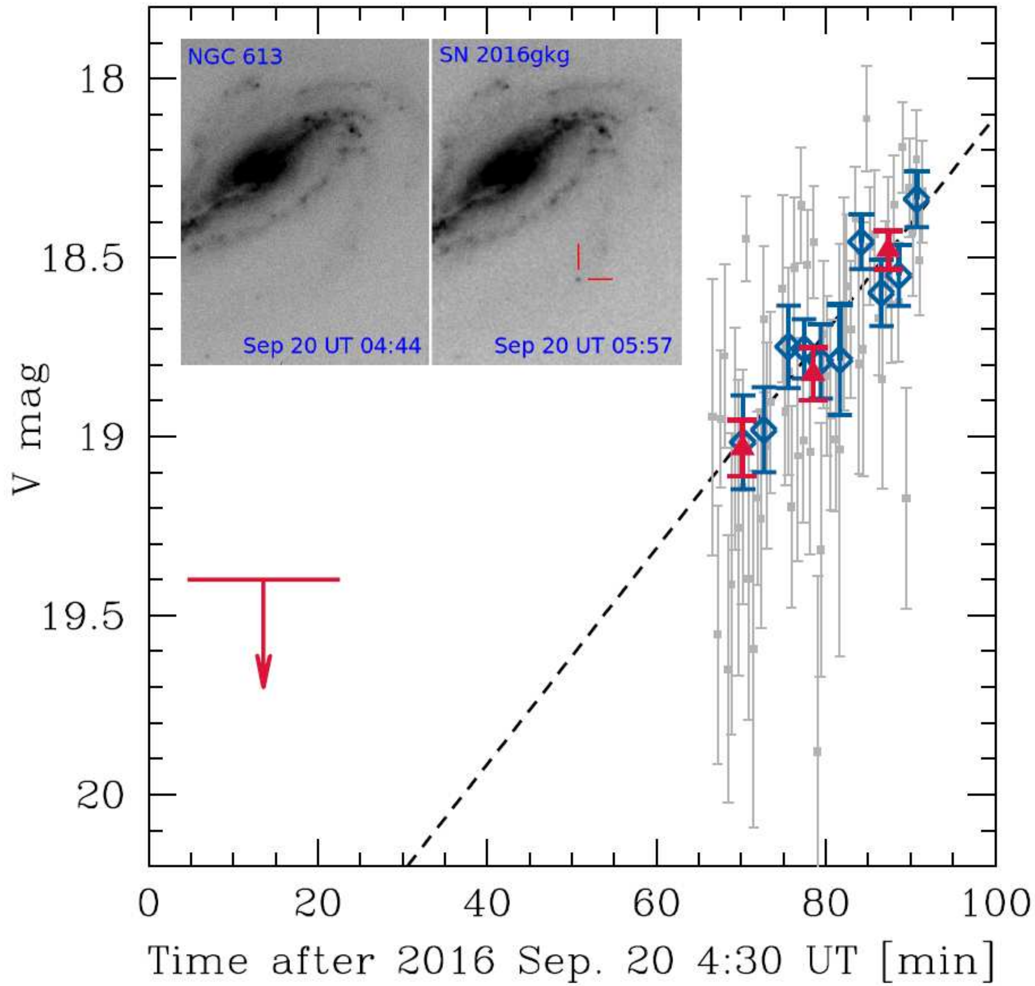
- No sign in 40 images (in $\approx$ 20 min). SN became visible 45 min later
- Unprecedented time sampling of the initial rise at a rate of 43 mag/day



MB, Folatelli et al., Nature 2018

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

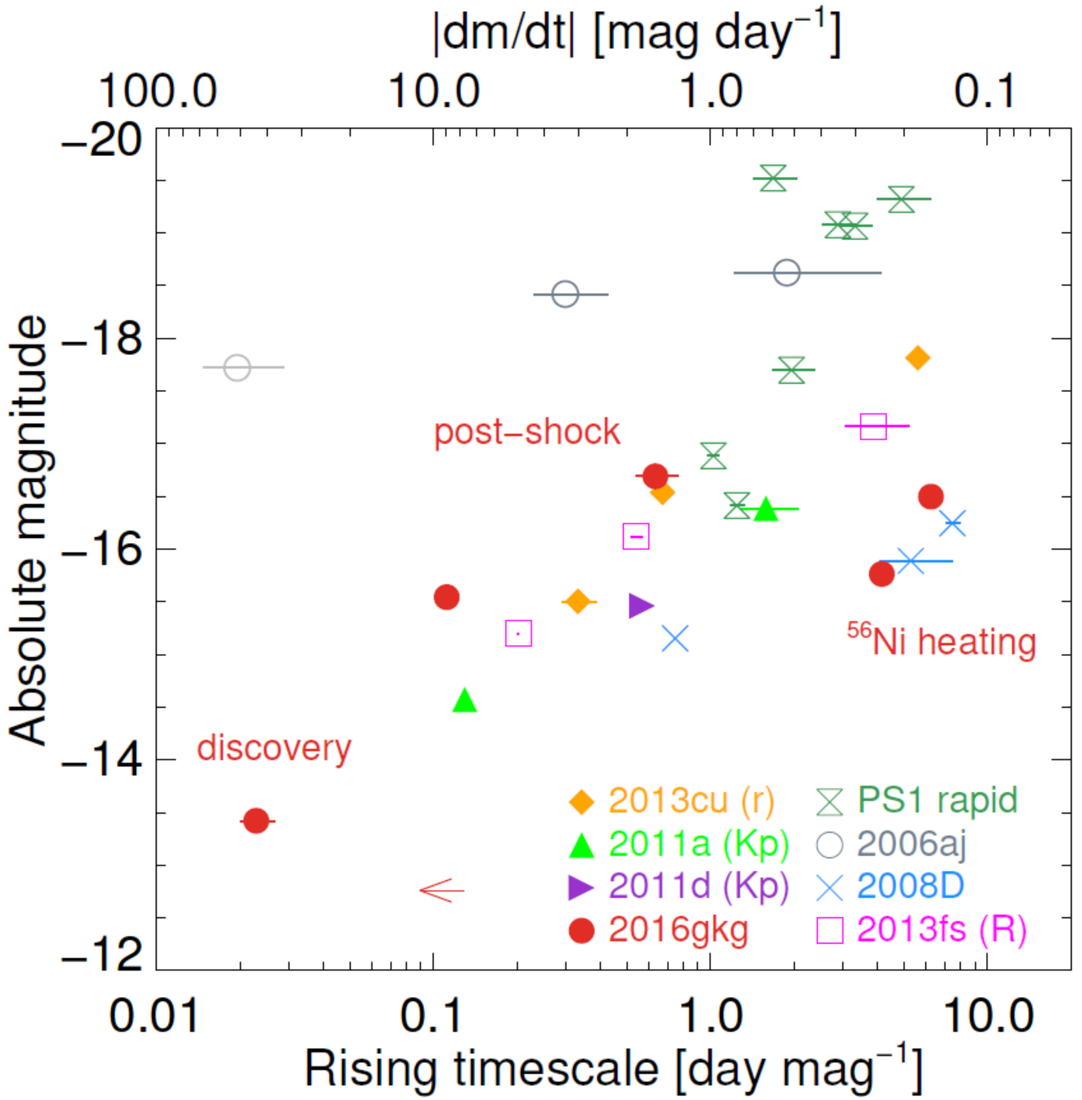


Was SN 2016gkg detected during the shock breakout (SBO) ?

MB, Folatelli et al., Nature 2018

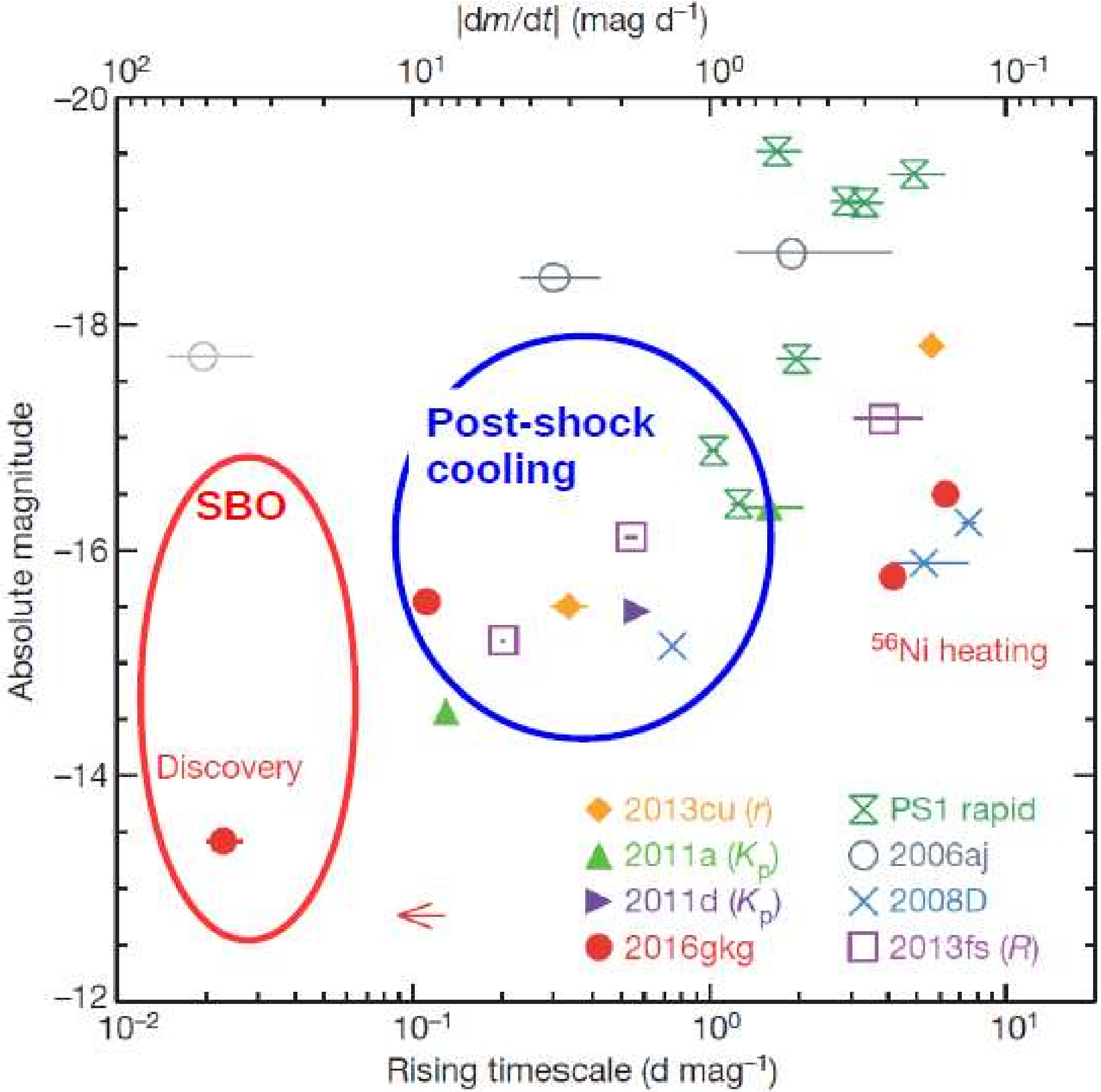
SBO rise time

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



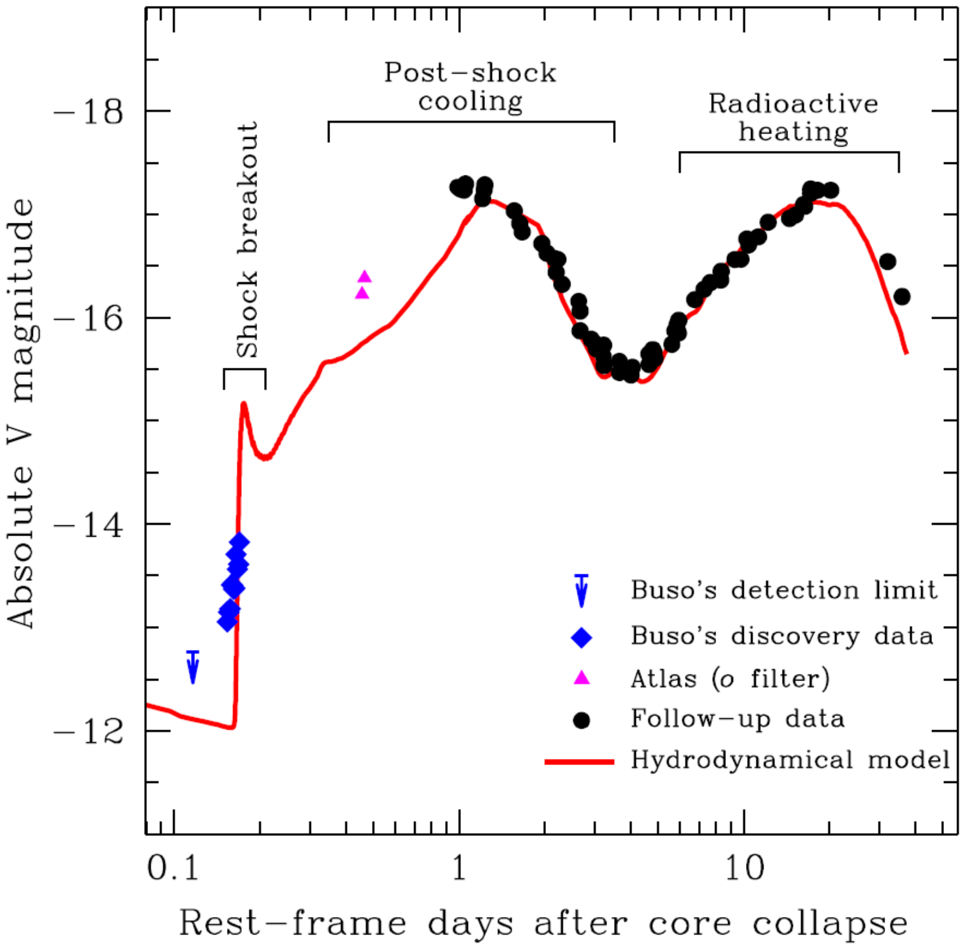
SBO rise time

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



Hydrodynamical model of SN 2016gkg

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

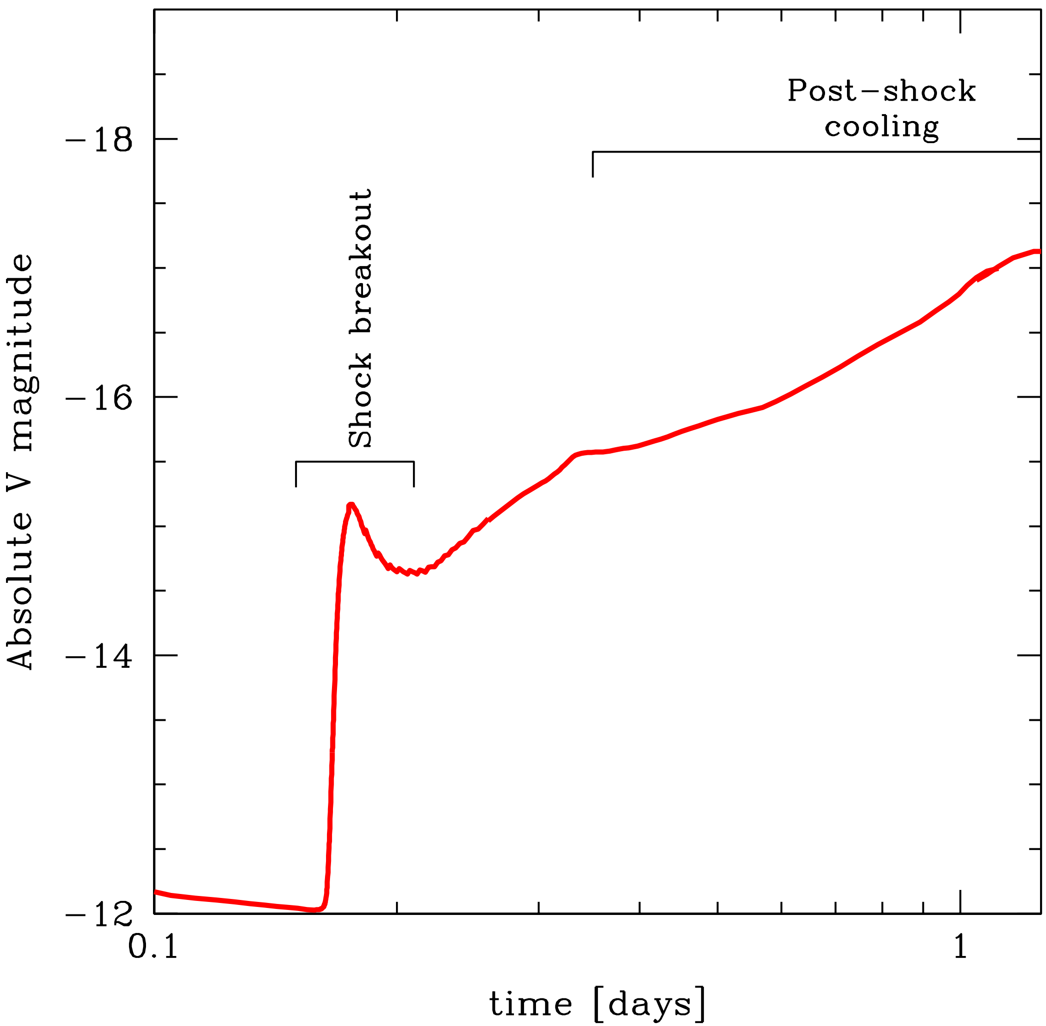


- Triple-peak light curve
- Low ejecta mass $\approx$ 3.5 $M_\odot$
- $E_{\rm exp}$= 1.2 $\times 10^{51}$ erg and ^{56}Ni mass 0.09 $M_\odot$
- A low-density H-envelope with R= 320 $R_\odot$

MB, Folatelli et al., Nature 2018

Hydrodynamical model of SN 2016gkg

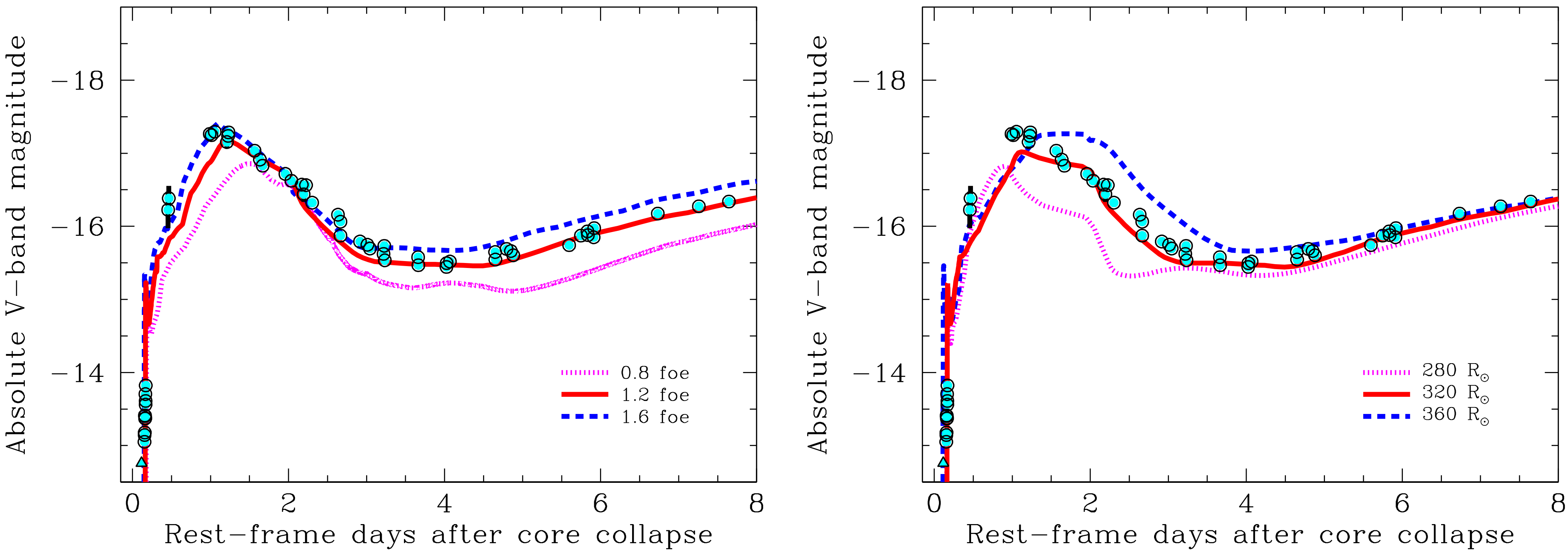
- Physical origin of Víctor's data: SBO or post shock-cooling (PSC)?



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

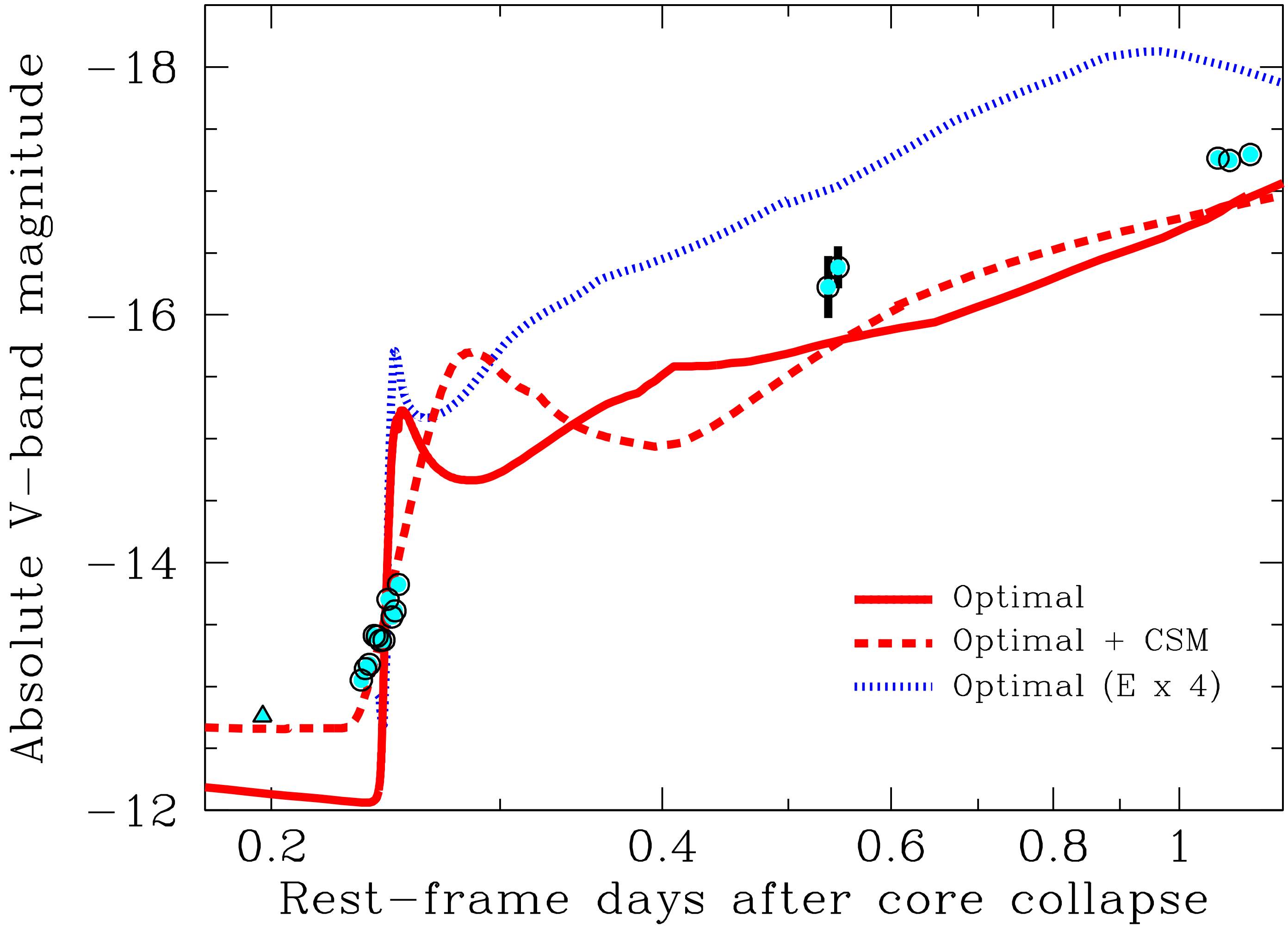
Hydrodynamical model of SN 2016gkg

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



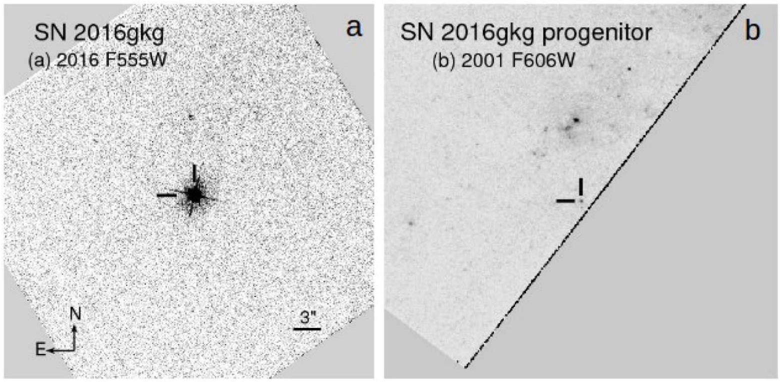
Hydrodynamical model of SN 2016gkg

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

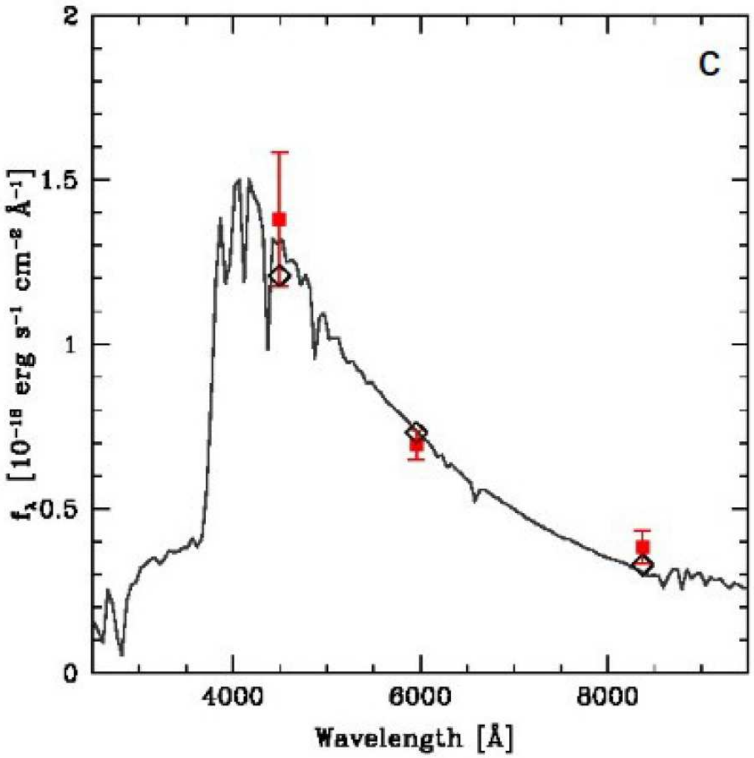


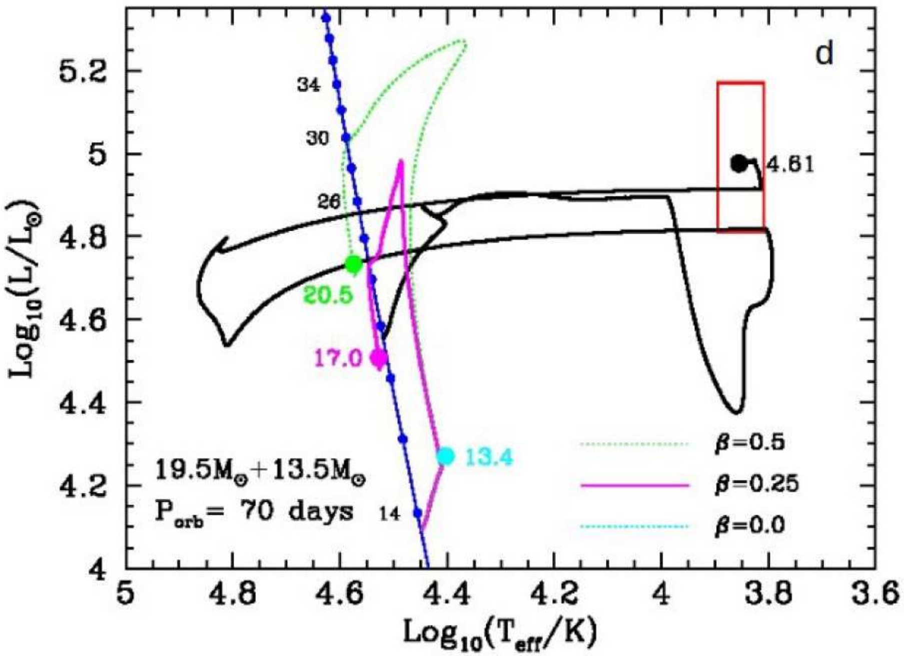
Progenitor of SN 2016gkg

- HST pre-SN images $\Longrightarrow$ YSG star
- Binary calculations: progenitor is a H-deficient YSG star
- New HST images obtained to confirm progenitor



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





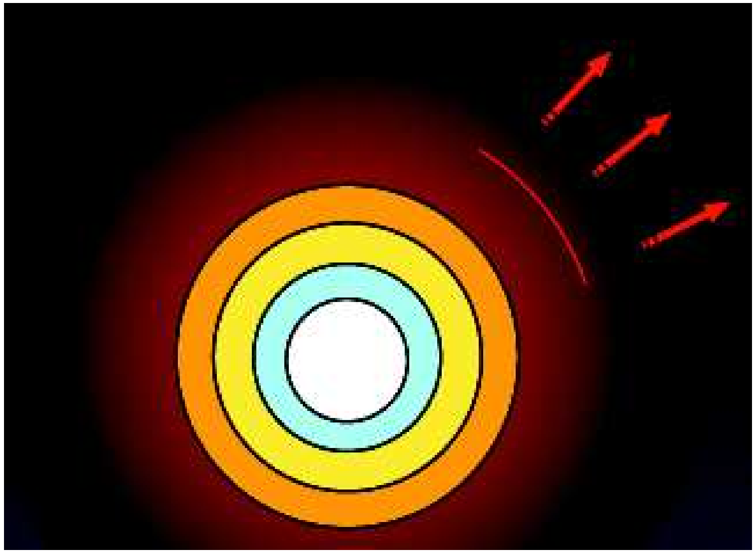
Summary

- Light-curve modeling a useful tool to derive physical properties of SN progenitors and thus to test stellar evolution models
- This methodology is particularly powerful when combined with stellar evolution calculations and direct imaging of nearby SN
- Detailed analysis of the SBO signal gives unique diagnostics of the outermost progenitor structure and of the physical processes that occur during the shock emergence.
- A chance probability of $\approx 10^{-7}$–10^{-8} is estimated for this discovery $\Longrightarrow$ systematic studies are extremely difficult
- SN16gkg model explains for the first time three distinct phases of IIb
- SBO in SN16gkg may suggest low-density CSM
- SBO detections require minute/hour cadence observations

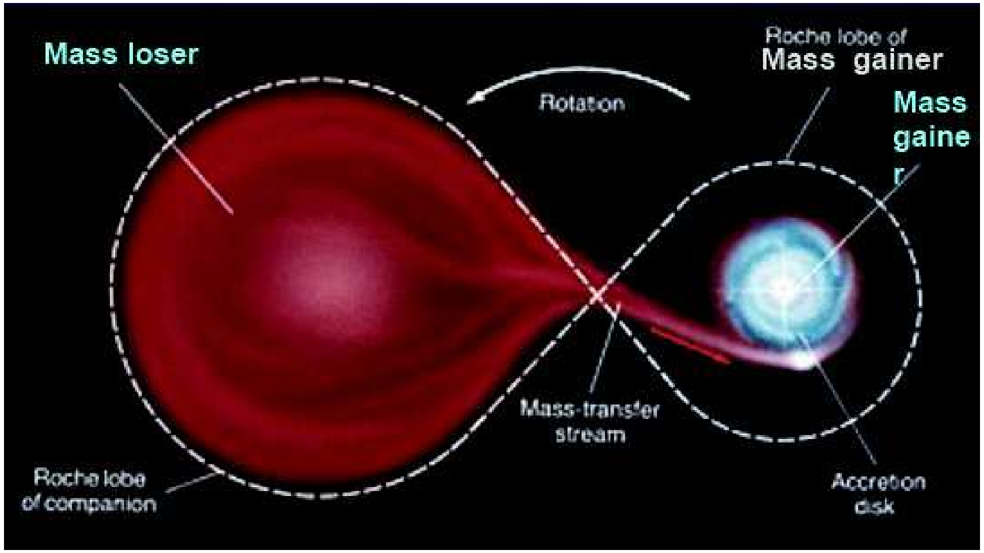
Mass-loss Mechanisms

- Single, massive ($\gtrsim 25\ M_\odot$) Wolf-Rayet stars with strong winds
  $\Longrightarrow$ He core mass $\gtrsim 8\ M_\odot$
- Interacting binaries can make lower-mass stars lose their envelopes

Single-star mass-loss

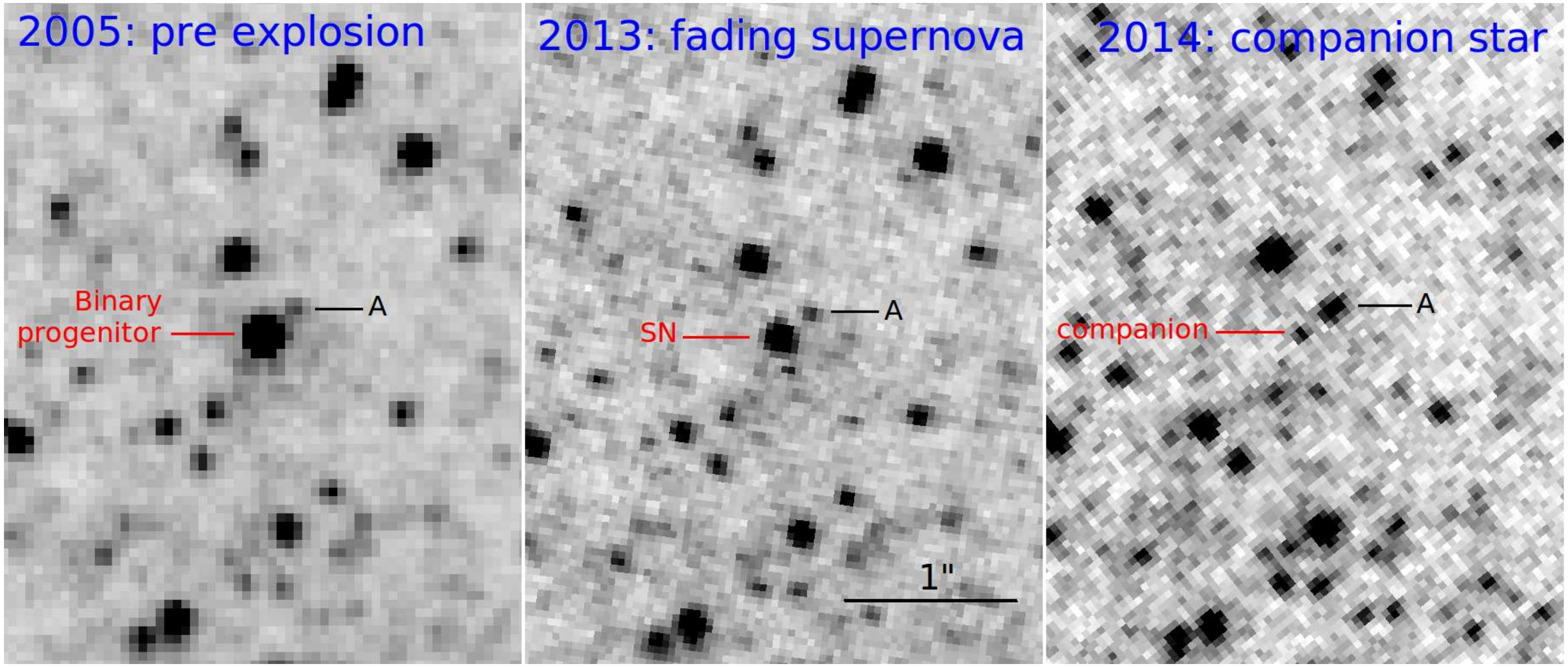


Binary-star mass-transfer



H-poor Supernovae

- Low ejecta masses ≈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