Newborn Black Holes and Explosive Transients

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A key (and old) question

What kind of massive star (RSG, BSG, WR) produces
what kind of compact object (NS or BH? B field, rotation, disk?)
and what kind of explosive transient (SN, GRB or else) ?

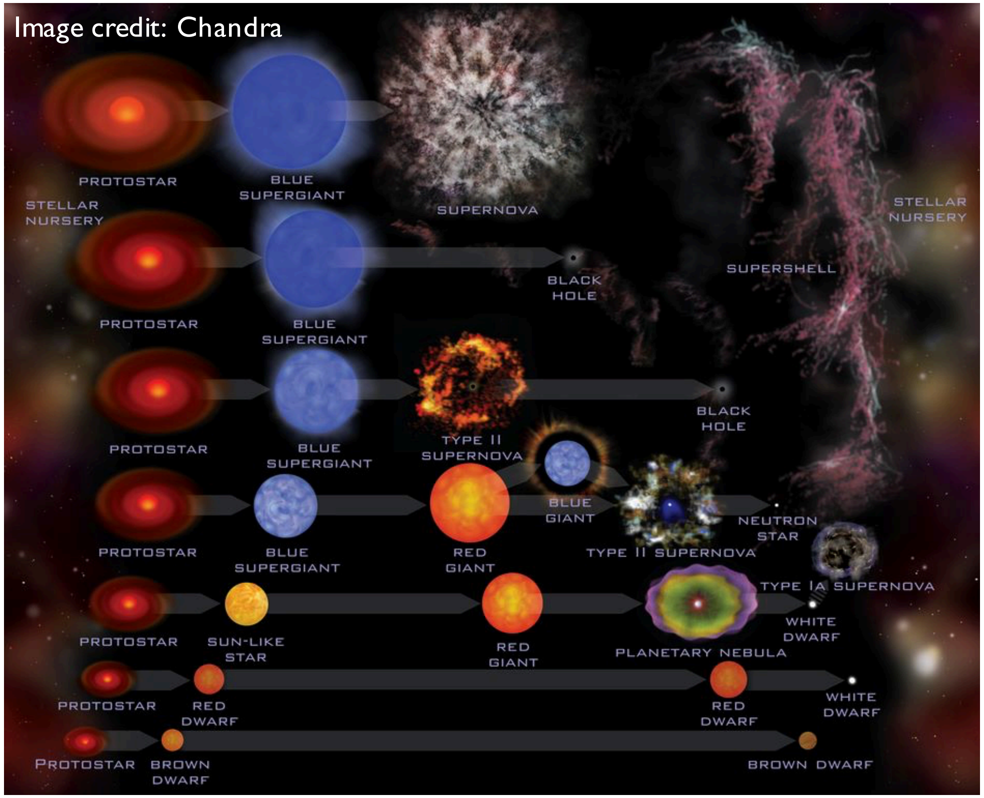
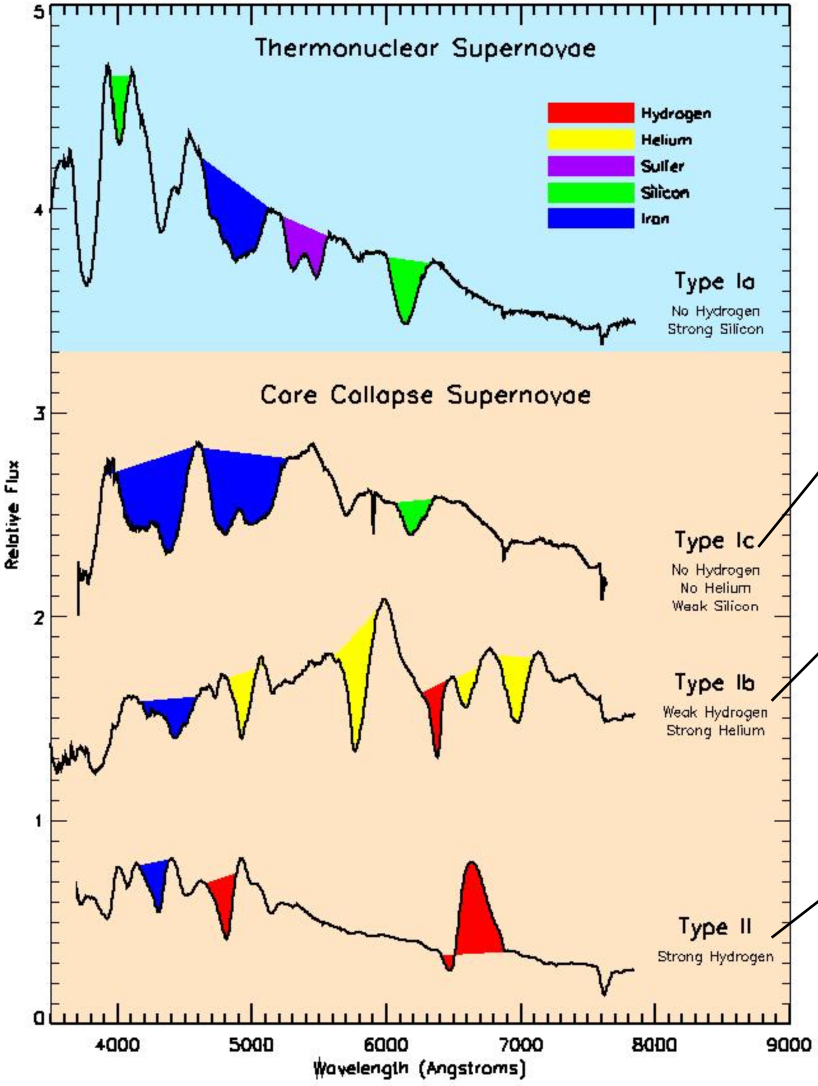
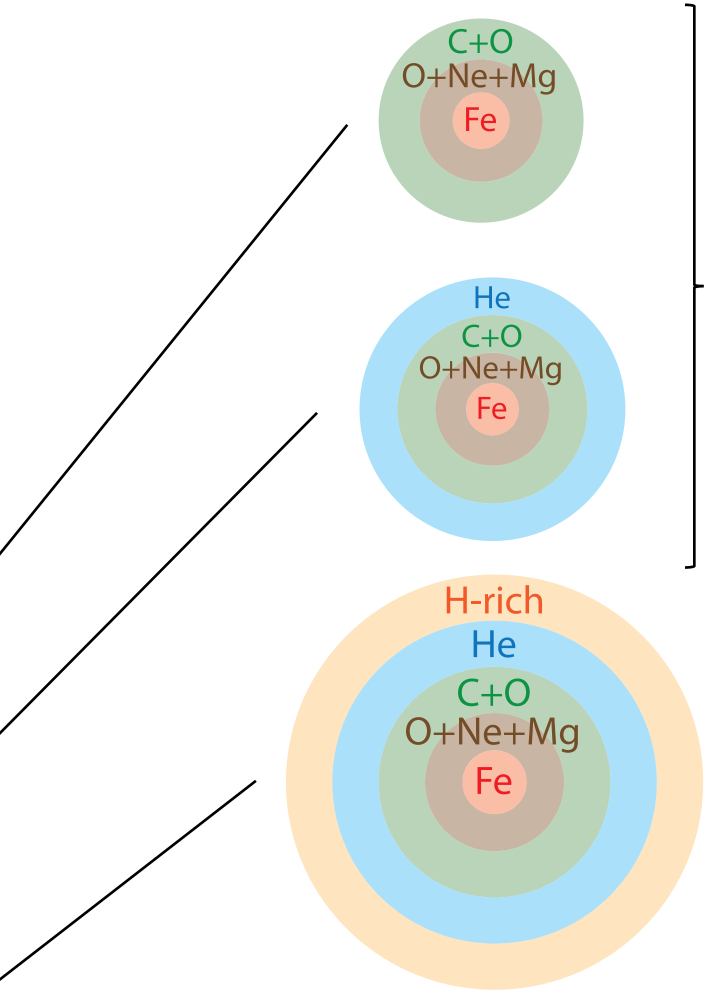


Image credit: Chandra

Legacy of supernova studies



http://supernova.lbl.gov/~dnkasen/tutorial/

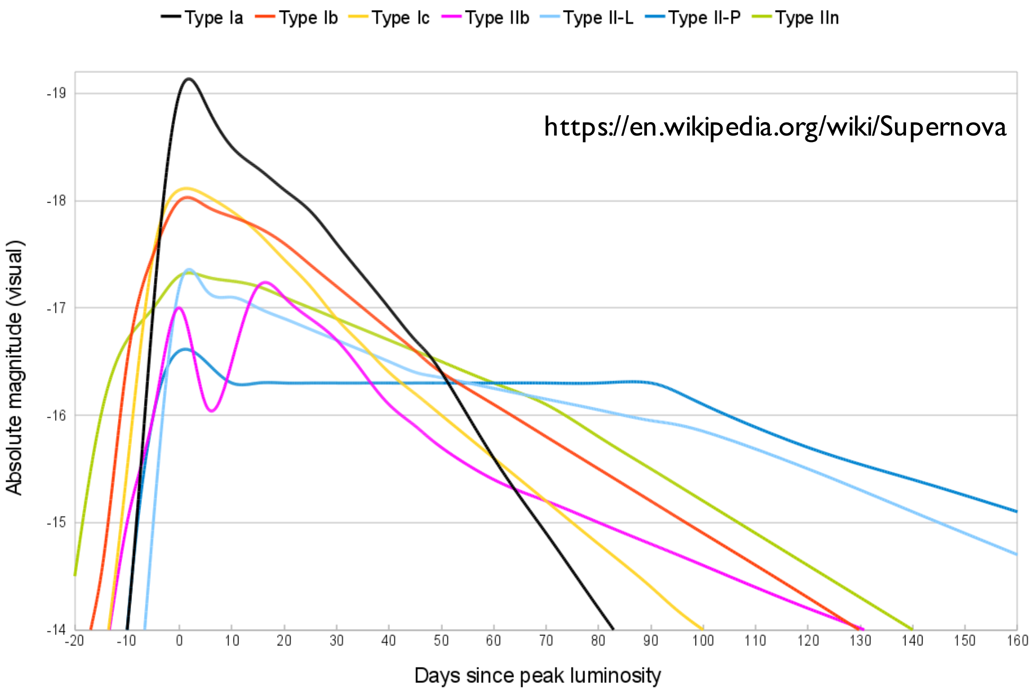


WRs

RSGs

- ✓ $v_{\rm ej} \lesssim 10,000\ {\rm km/s}$
- ✓ ^{56}Ni is a key rad. energy source.

Legacy of supernova studies



https://en.wikipedia.org/wiki/Supernova

light curve peak:

$$\frac{c}{\tau} \sim v_{\rm ej} \quad \tau \sim \frac{\kappa M_{\rm ej}}{4\pi r_{\rm ej}^2} \quad t_{\rm p} \sim \frac{r_{\rm ej}}{v_{\rm ej}}$$

$$\longrightarrow \quad M_{\rm ej} \sim 1 - 10 \ M_\odot$$

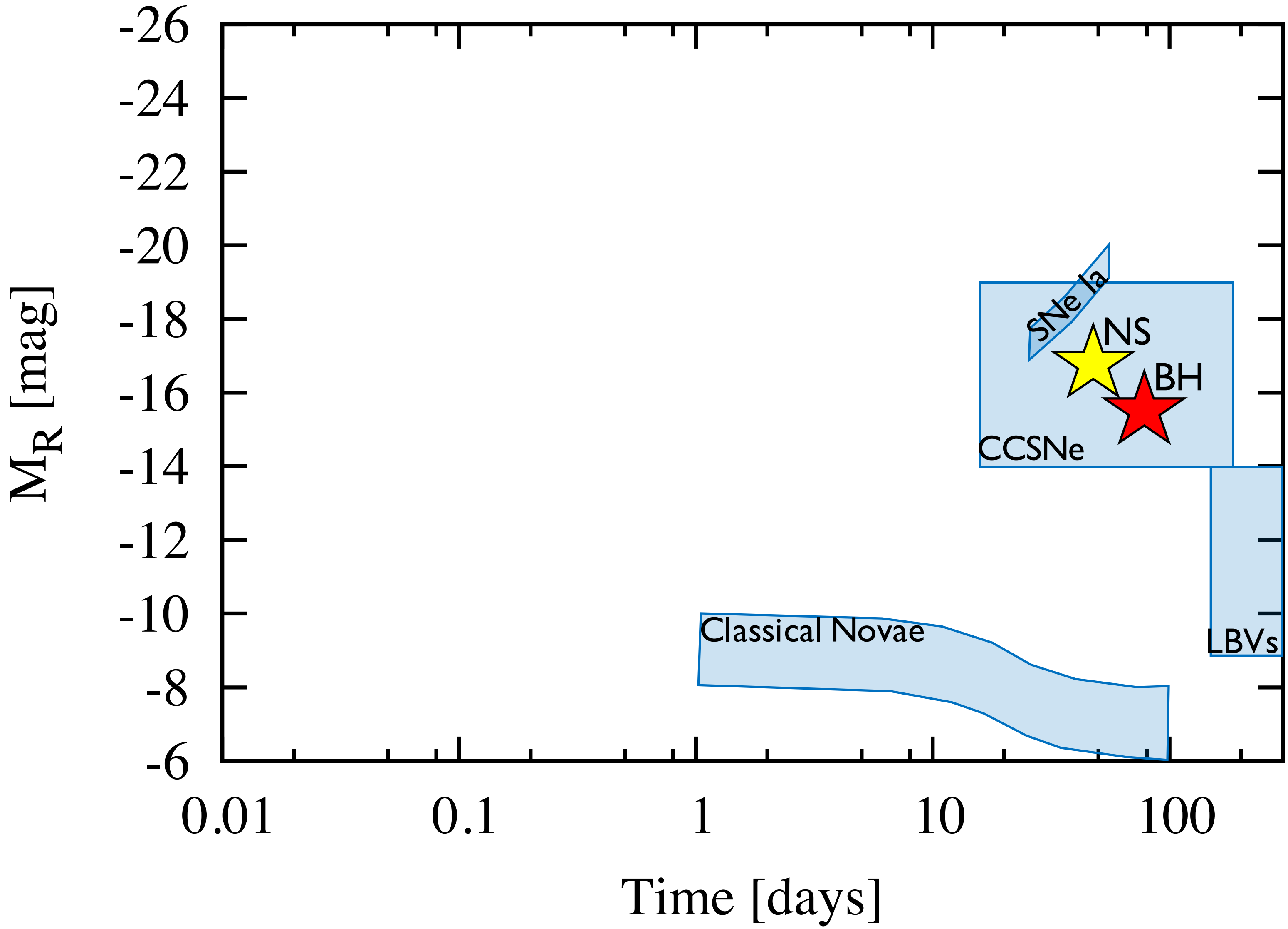
$$\longrightarrow \quad E_{\rm SN} \sim 10^{51} \ {\rm erg}$$

{ WR / RSG } → NS w/ $E_\nu \sim 10^{53}$ erg → ~1% of E_ν goes to $E_{\rm SN}$ → { SN Ibc / SN II }

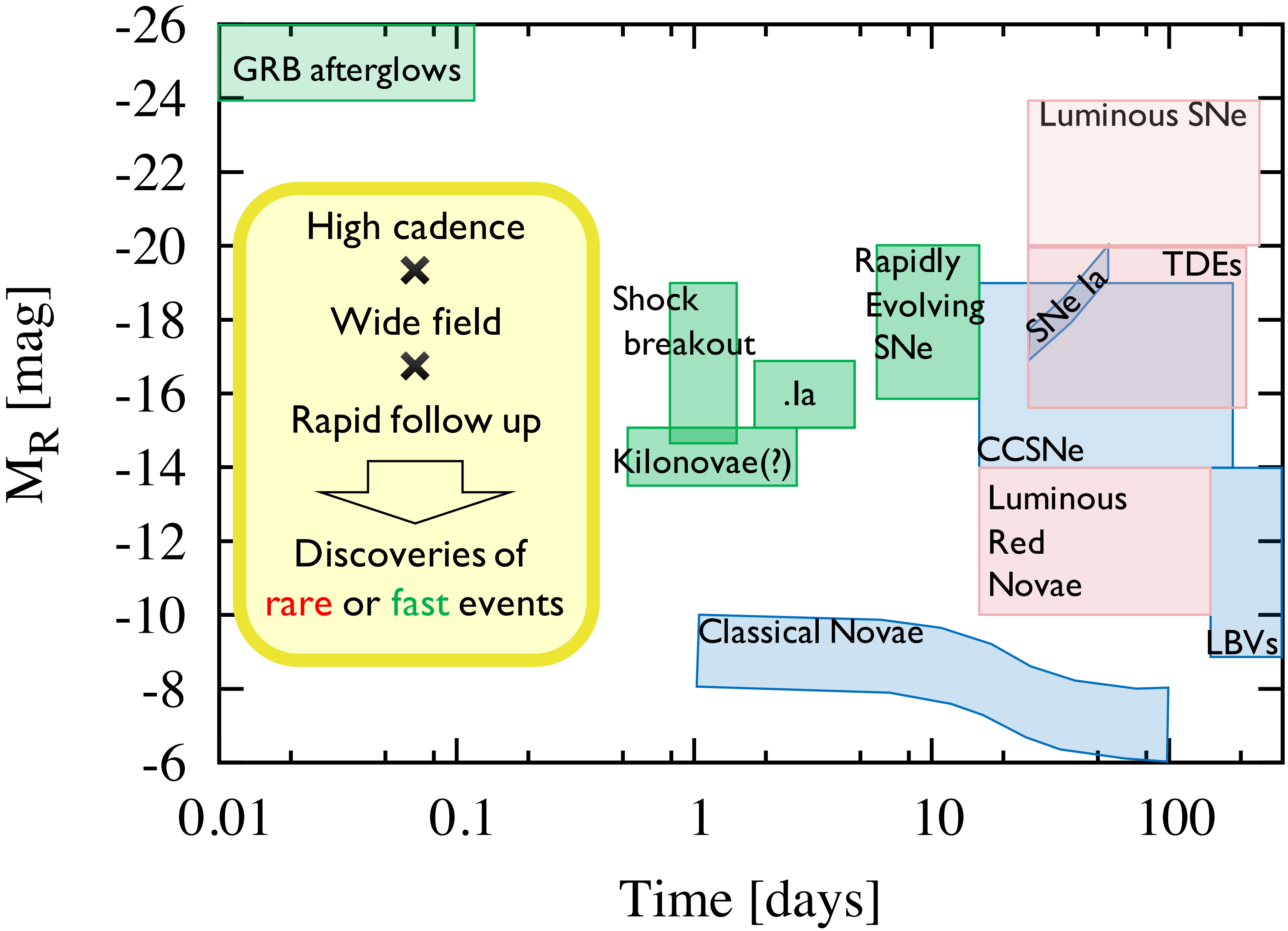
mass fallback - - → BH

Is that all??

Optical-transient zoo



Optical-transient zoo



High cadence

×

Wide field

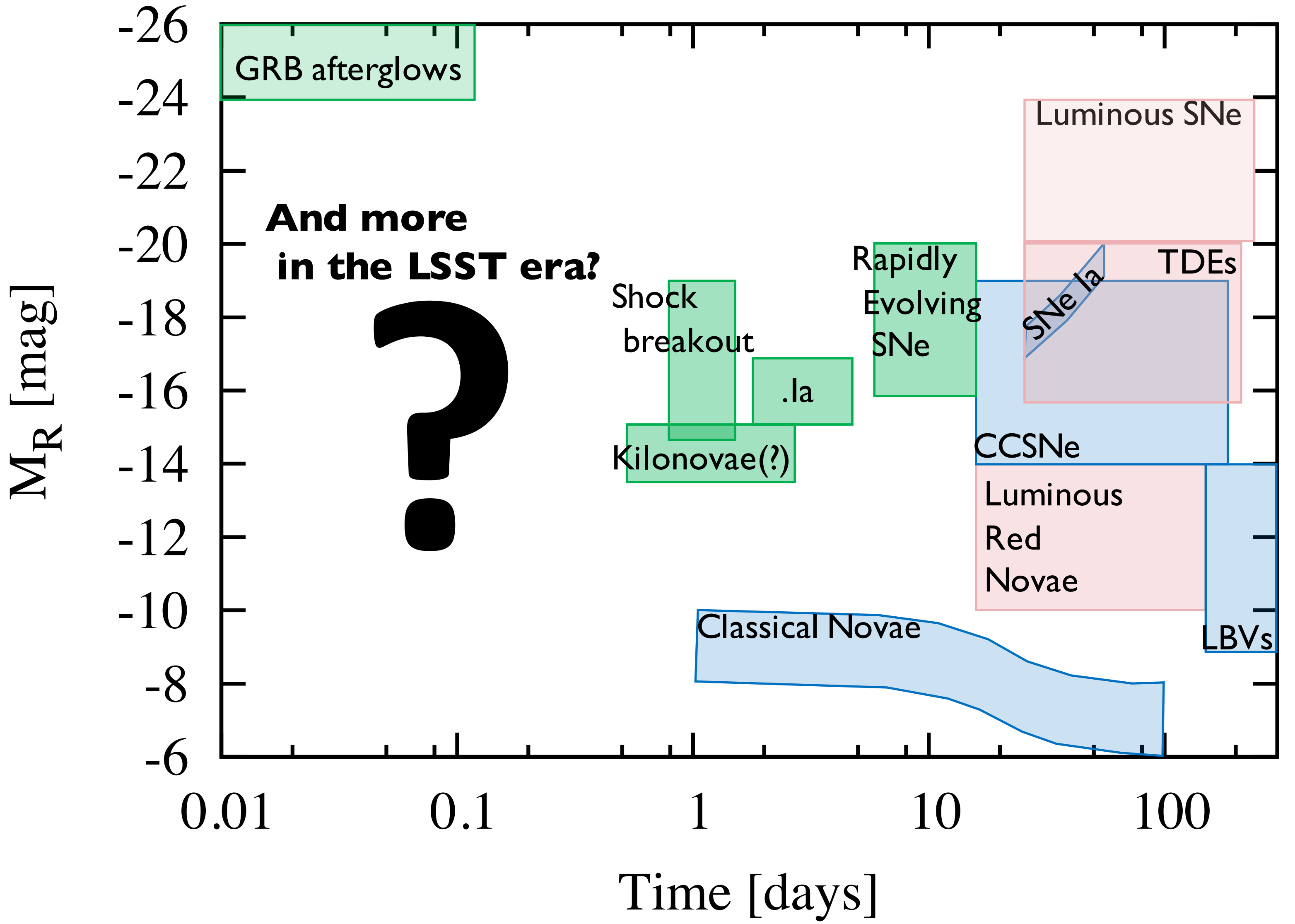
×

Rapid follow up

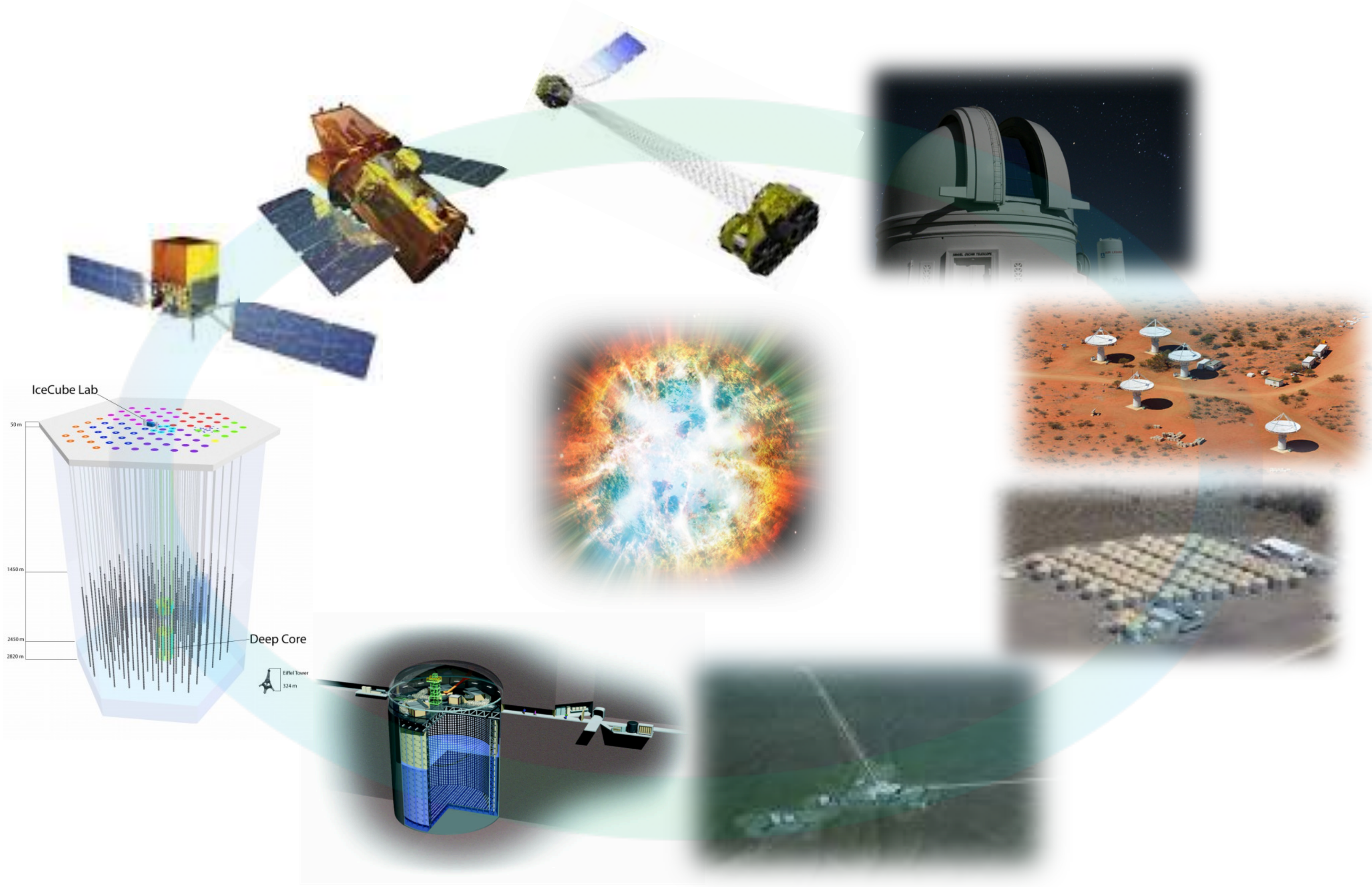
Discoveries of

rare or fast events

Optical-transient zoo



Multi-Messenger Time-Domain Astronomy



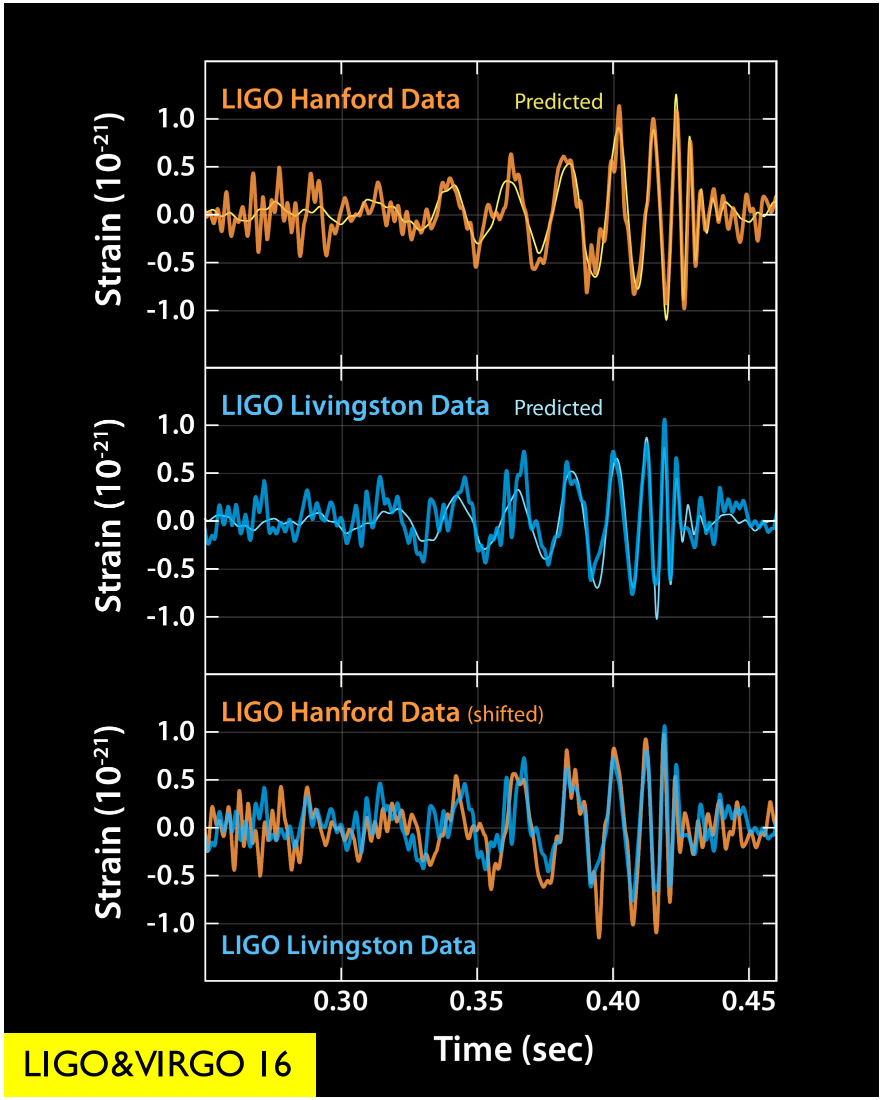
One needs a compelling scientific motivation and observational strategy

Today’s target

Newborn Black holes
(as observed in GW 150914)

How they are formed?
What is the associated explosive transients?
What is the observational strategy?

$M_{BH} >> M_{sun}$: How they are formed?



LIGO&VIRGO 16

✓ A barely successful SN explosion with a fallback onto a NS

M_{BH} ~ 5-10 Msun (c.f., X-ray binaries)

multiple mergers? (e.g., in dense star clusters)

✓ A failed SN explosion and direct collapse

M_{BH} ~ 10-100 Msun (e.g., massive PopIII)

The abundance could be well constrained by combining CMB and GWB in the O5 run.

Inayoshi, KK+16

Q1. When a SN shock totally fails, everything just falls?

A. Not really.

1. A weak explosion driven by core gravitational mass loss of the core through neutrino emission from a protoNS.
2. A minor fraction of the outer envelope has a sufficient angular momentum for forming a fallback disk.

Q2. How they look like?

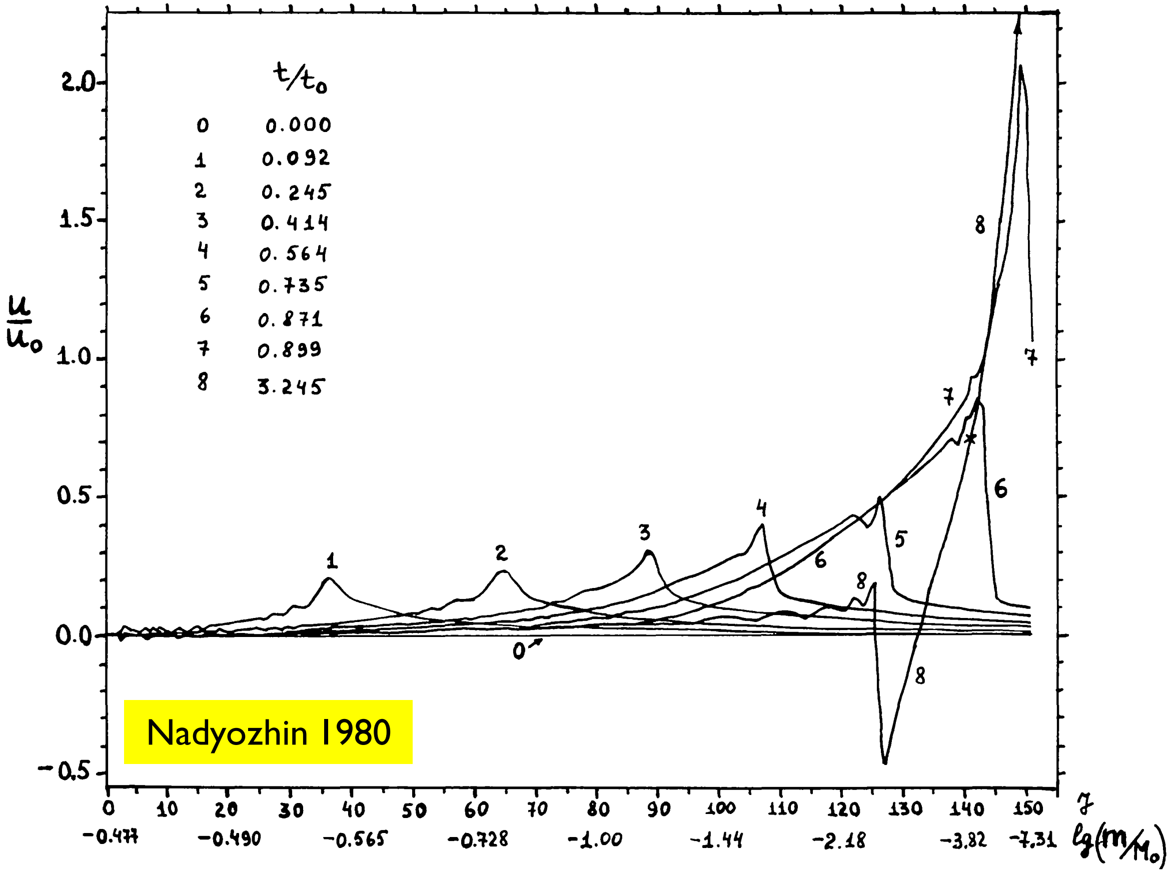
A. Let's see!

NOTE: they are probably not rare!

Practically no observational constrain; nu b.g. → < 70% of CCSNe
Theorists say ~ 10 % of CCSNe → ~ 1 per year within a few 10 Mpc

Progenitor id. is possible!

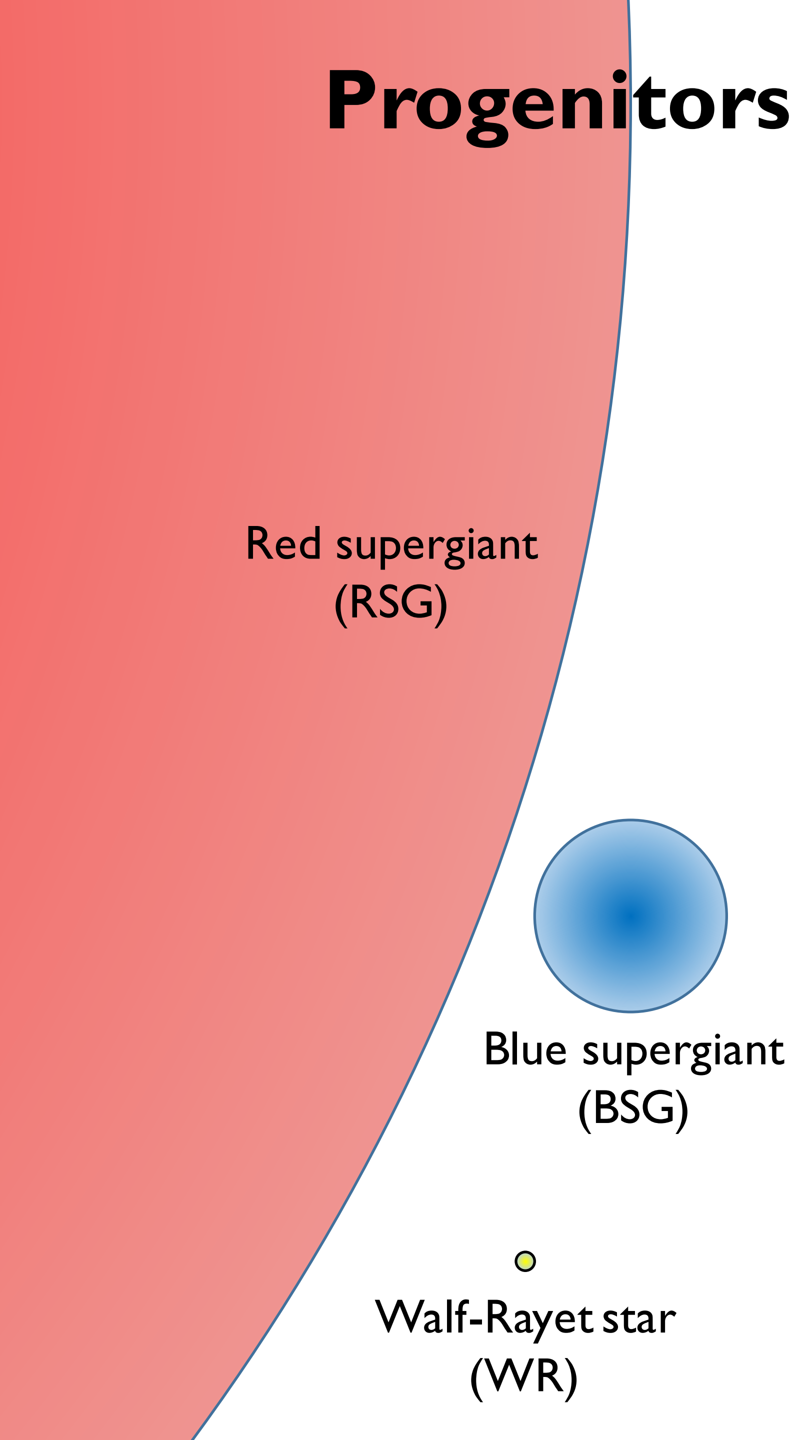
A weak shock driven by neutrino mass loss



Nadyozhin 1980

A fraction of outer envelope can be ejected due to a gravitational mass loss of the core through neutrino emission in the protoNS phase.

Progenitors of failed supernovae



Red supergiant
(RSG)

Blue supergiant
(BSG)

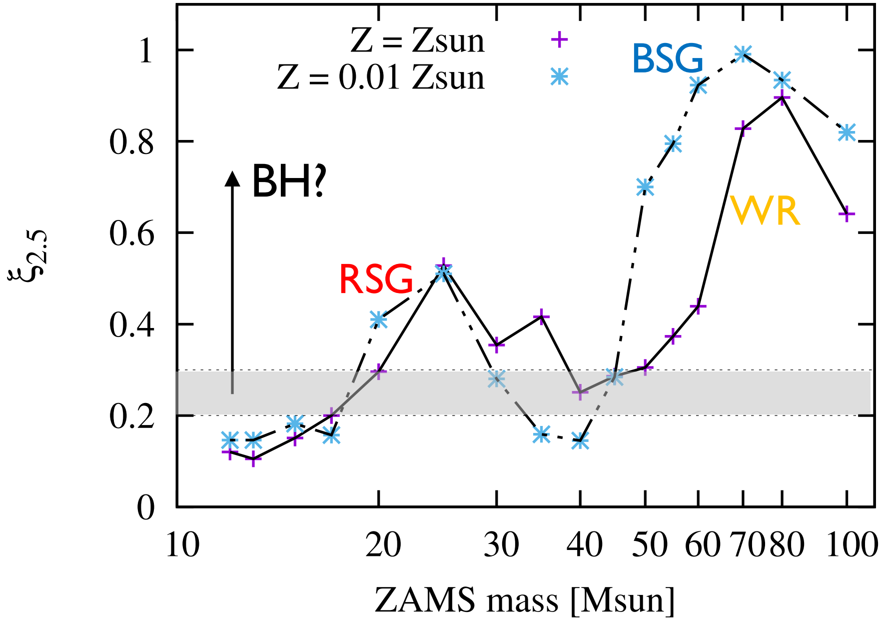
Walf-Rayet star
(WR)

Supernova shock is stalled or not?
How much material fallback on protoNS?

The key will be inner density structure within

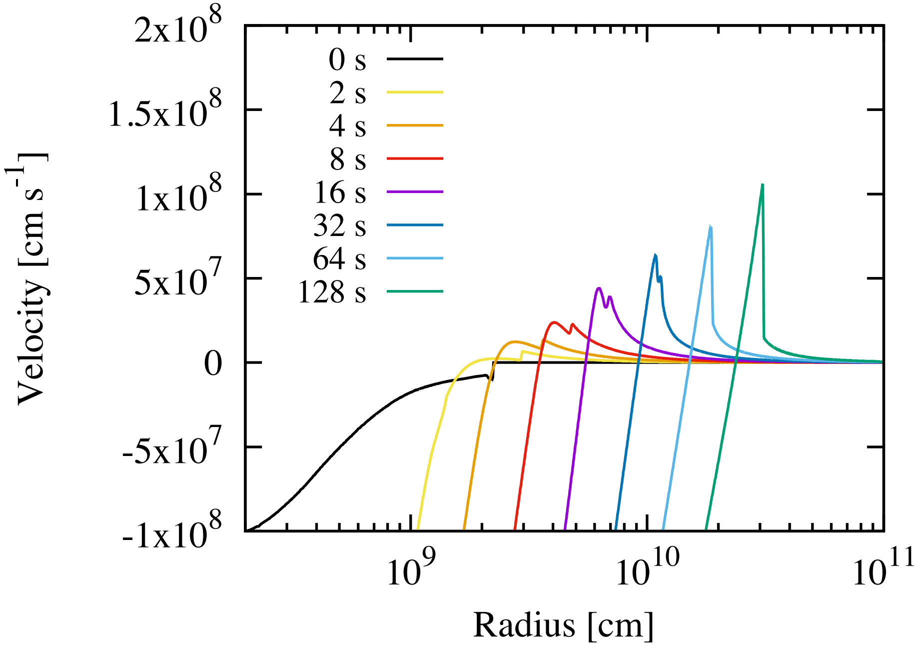
$$r \sim 1000\ \mathrm{km},\ Mr \sim 2\text{-}3\ M_\odot$$

O’Connor & Ott 2011; Ugliano et al. 2012;
Horiuchi et al. 2014; Pejcha & Thompson 2015

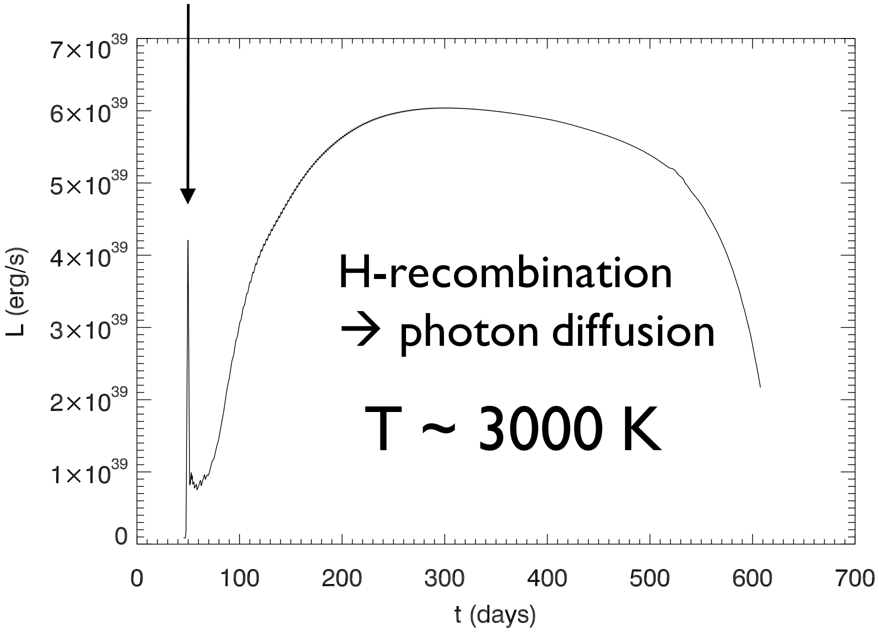


All types of massive star can form BHs.

Red supergiants



shock breakout



H-recombination
→ photon diffusion

T ~ 3000 K

E_{kin} ~ $10^{47\text{-}48}$ erg

comparable to the binding E of the hydrogen envelope → ejection!

"luminous red nova"

Lovegrove & Woosley 2013

KK, Fernandez, Quataert in prep

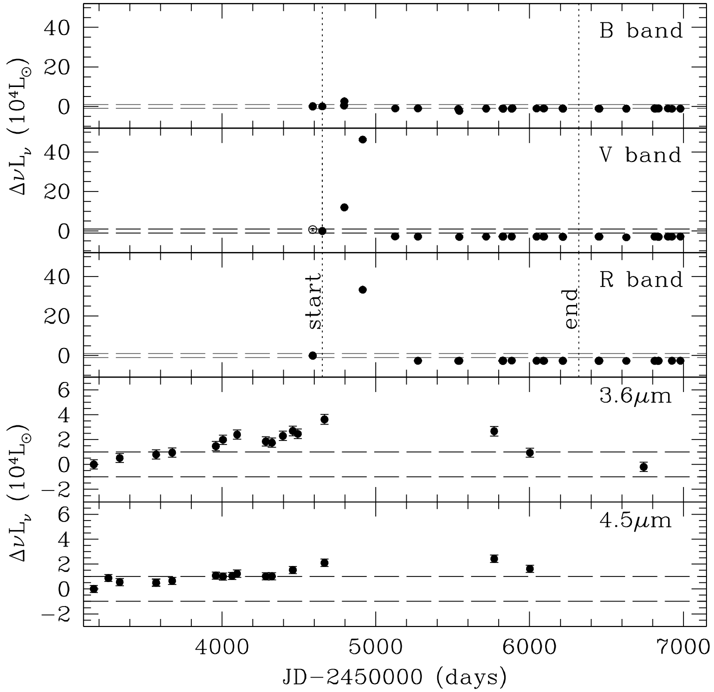
Searching for vanishing RSGs

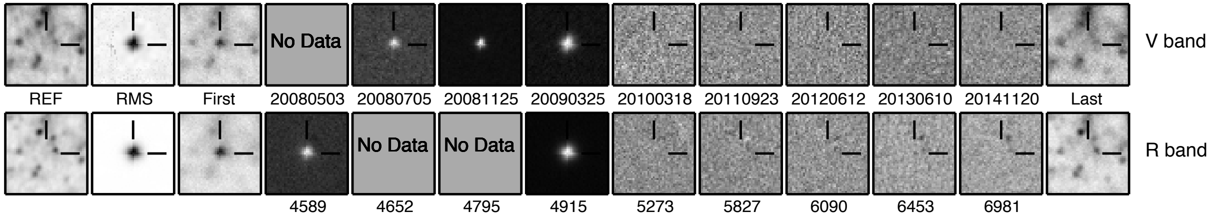
- Monitoring ~10^6 RSGs in ~25 Gal. within ~10 Mpc with ~0.5 yr cadence for ~5 yrs using the Large Binocular Telescope
- Examine sources with

$$\Delta(\nu L_\nu) \geq 10^4 L_\odot$$

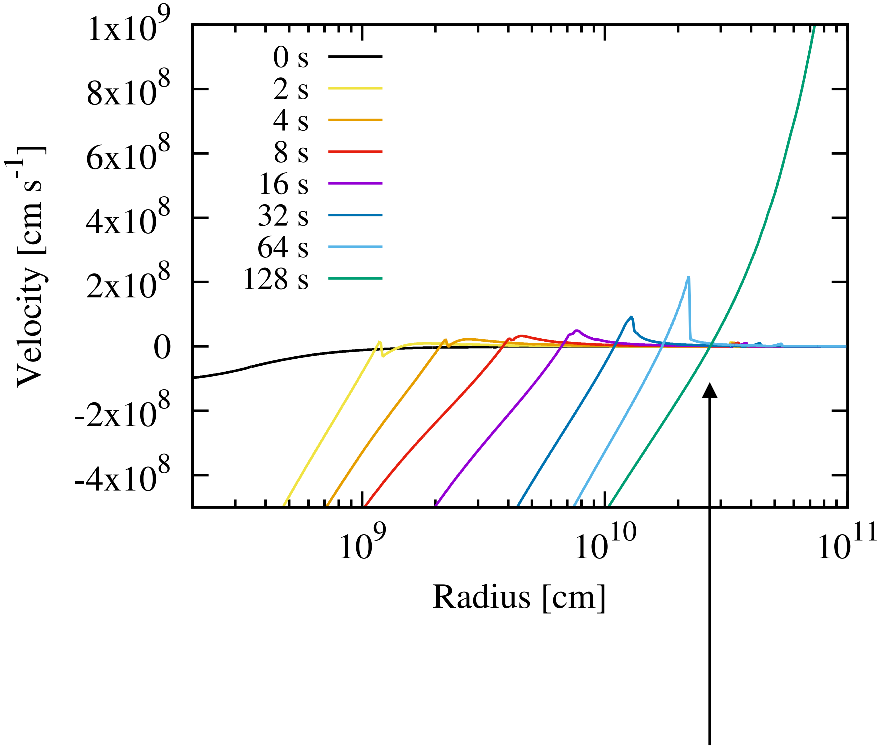
- 3 core collapse supernovae
- 1 candidate of vanishing RSG
- Continuous obs. will give meaningful constraints on failed SN rate.

Kochanek+08, Gerke+15



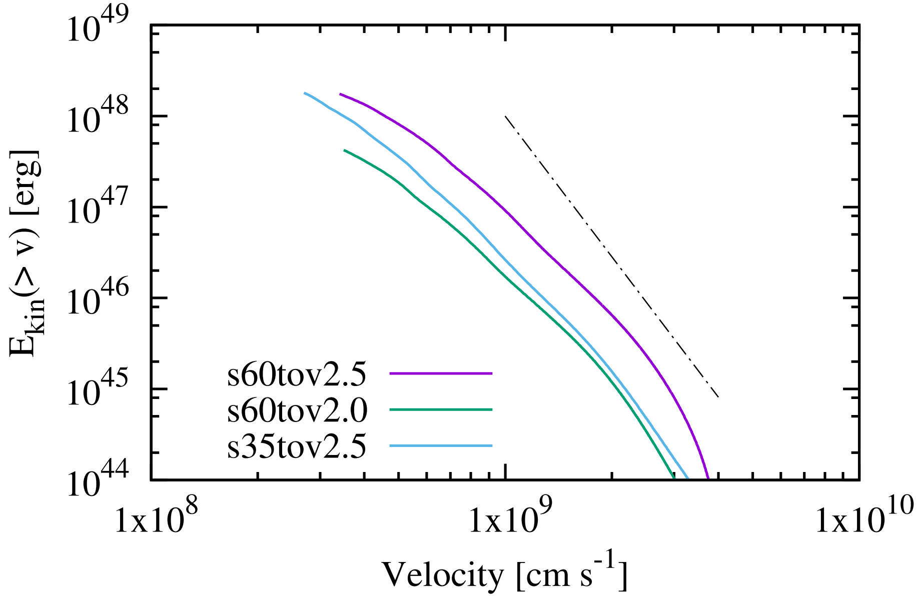


Wolf-Rayet stars



shock breakout

Cumulative kinetic-energy distribution



$E_{kin} \sim 10^{47\text{-}48}$ erg

$M_{ej} \sim 10^{-(2\text{-}3)} M_{sun}$

$\rho\, r^3$ ↓ → a fraction of mass is accelerated.

KK, Fernandez, Quataert in prep

Searching for vanishing WRs

✓ Optical

$$L_{\rm emi} \approx E_{\rm sbo} t_{\rm sbo}/t_{\rm emi}^2$$

$$\sim 1.5\times 10^{39}\ {\rm erg\ s^{-1}}\, E_{{\rm sbo},47.6} M_{{\rm ej},-2.3}^{-1}\kappa_{-1}^{-1} R_{*,10.5}$$

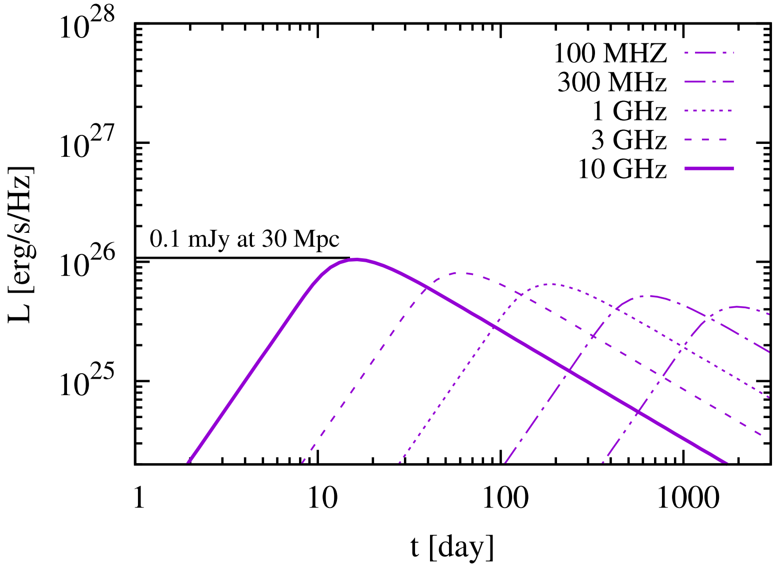
$$t_{\rm emi} \approx \left(\frac{3\kappa M_{\rm ej}}{4\pi c v_{\rm esc}}\right)^{1/2} \sim 1.9\ {\rm days}\ M_{{\rm ej},-2.3}^{1/2} v_{{\rm esc},8.5}^{-1/2} \kappa_{-1}^{1/2}.$$

$$T_{\rm emi} \sim 2.5\times 10^4\ {\rm K}\ T_{{\rm sbo},7.7} M_{{\rm ej},-2.3}^{-1/2} \kappa_{-1}^{-1/2} v_{{\rm esc},8.5}^{-1/2} R_{*,10.5}$$

c.f., $L_* \sim 10^{5-6} L_\odot$, $T_* \sim (3-9)\times 10^4$ K

"A blue twinkle in the very last day"
could be a target in the LSST era.

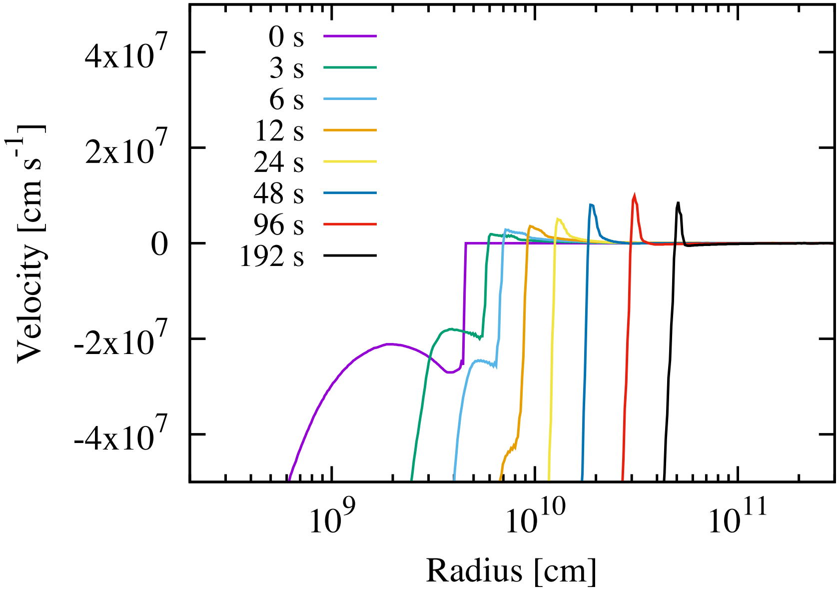
✓ Radio

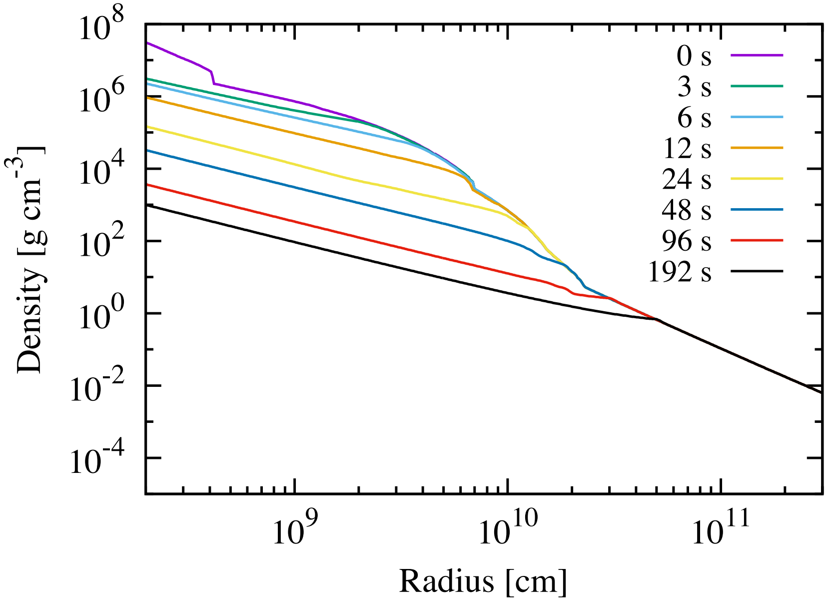


could be a target of
near future wide-field surveys
e.g., ASKAP and EVLA

KK, Fernandez, Quataert in prep

Blue supergiants





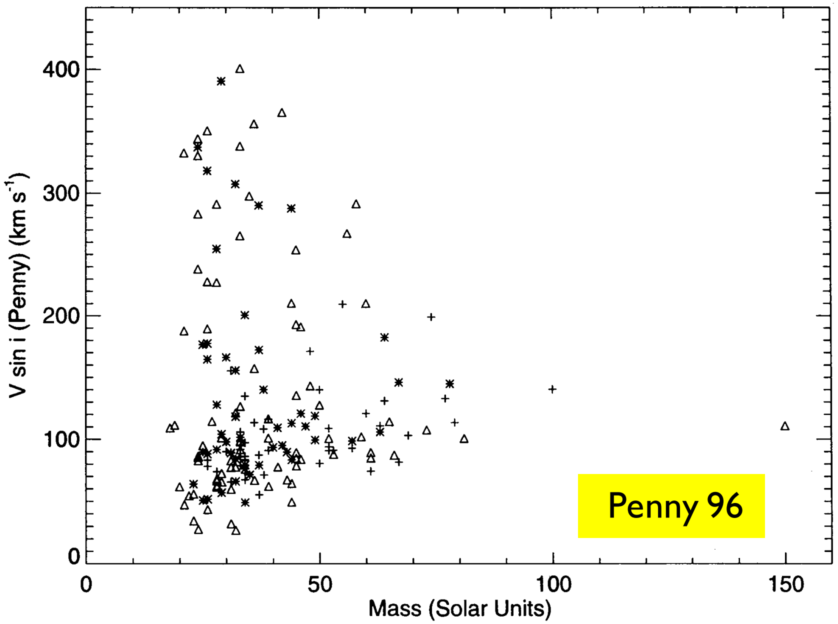
The shock fails to reach the outer edge (the core is too compact).

→ totally failed supernovae

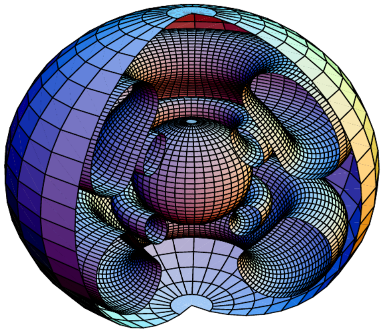
KK, Fernandez, Quataert in prep

Don’t forget the angular momentum!

- ✓ Rotation

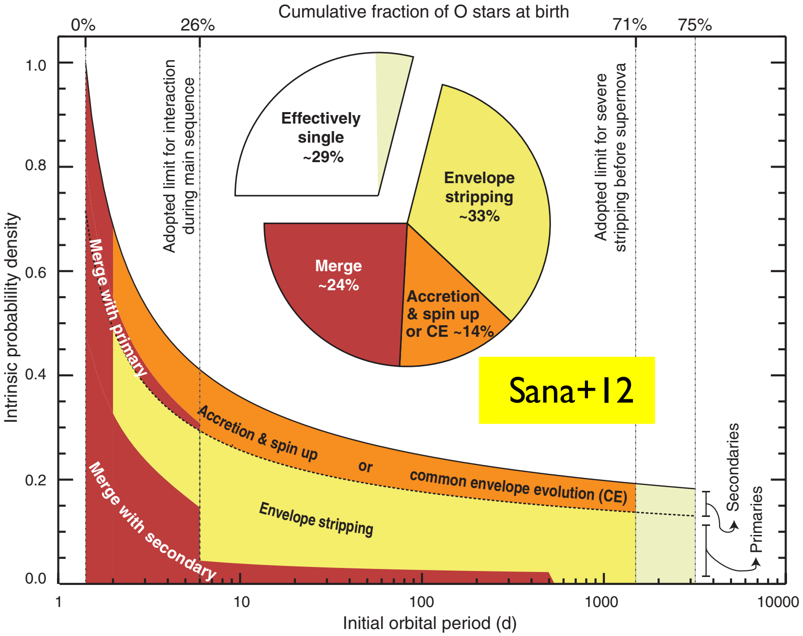


Penny 96



e.g., Meynet & Maeder 2002

- ✓ Binary interaction



Sana+12

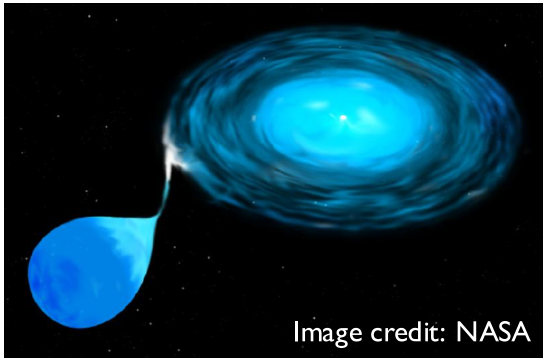
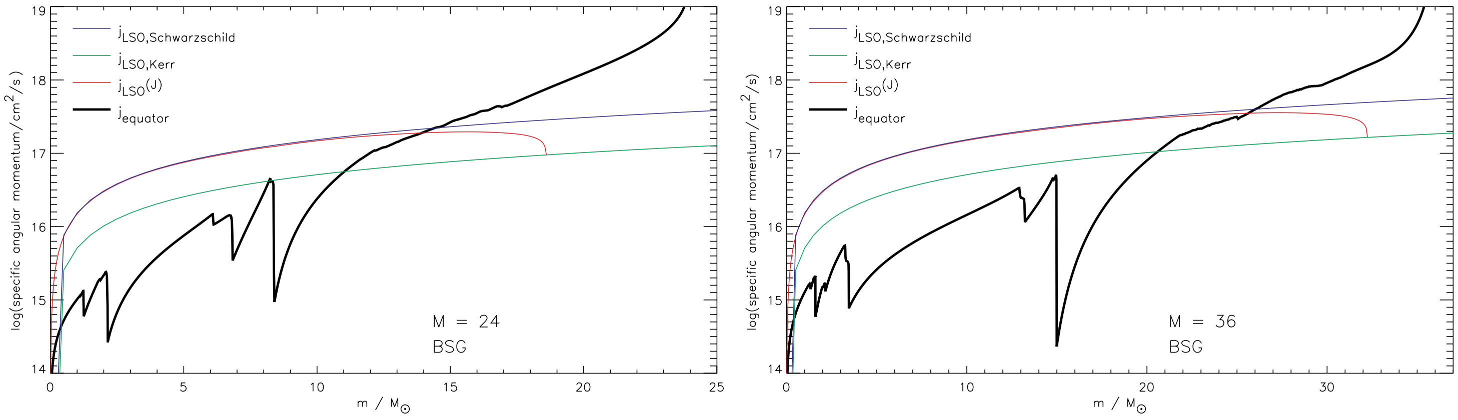


Image credit: NASA

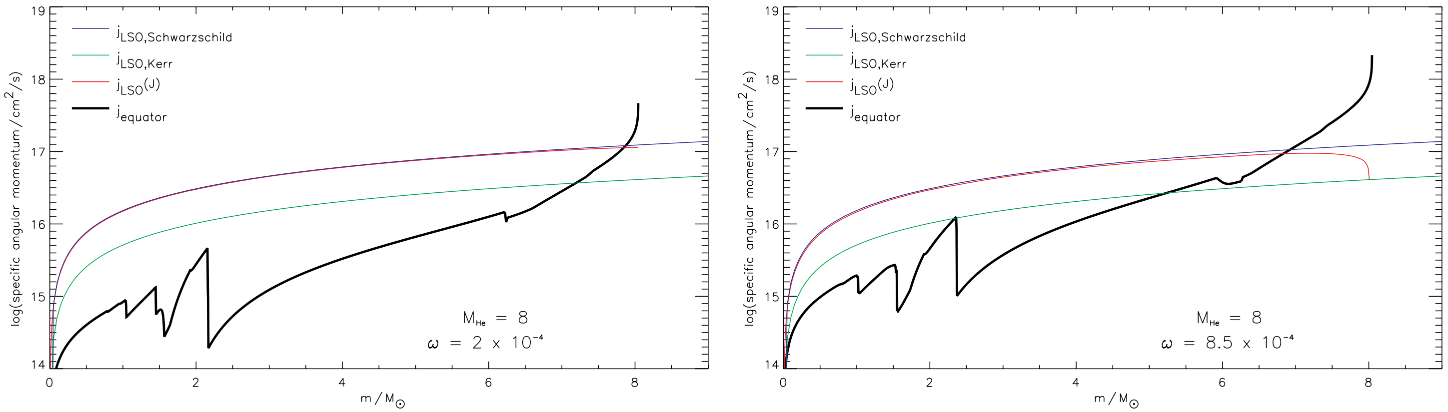
Rotation of pre-collapse massive stars

e.g., Woosley & Heger 12, Perna+14

BSG



WR
in binary



Outer layers of up to ~ a few $M_\odot$ may typically have sufficient j to form a disk.

Then, what will happen?

$$\dot{M}_{\rm d} \approx M_{\rm d}/t_{\rm acc},\ \text{or}$$

$$\dot{M}_{\rm d} \sim 3\times 10^{-5}\ {\rm M_\odot\ s^{-1}} \times \left(\frac{M_{\rm d}}{1\ M_\odot}\right)\left(\frac{R_*}{10^{12}\ {\rm cm}}\right)^{-3/2}\left(\frac{M_{\rm BH}}{10\ M_\odot}\right)^{1/2}, \gg \dot{M}_{\rm Edd} = 4\pi G M_{\rm BH}/c\kappa \sim 10^{-15}\ M_\odot\ {\rm s^{-1}}\ (\kappa/0.2\ {\rm cm^2\ g^{-1}})^{-1}(M_{\rm BH}/10M_\odot)$$

$$\text{where } t_{\rm acc} \approx \pi({R_*}^3/8GM_{\rm BH})^{1/2},\ \text{or}$$

$$t_{\rm acc} \sim 3\times 10^4\ {\rm s}\left(\frac{R_*}{10^{12}\ {\rm cm}}\right)^{3/2}\left(\frac{M_{\rm BH}}{10\ M_\odot}\right)^{-1/2}$$

Super-Eddington accretion!

& Outflows!

~ 10 % of the accreted mass

$$\bar{v}_{\rm out} \approx (2GM_{\rm BH}/r_0)^{1/2},\ \text{or}$$

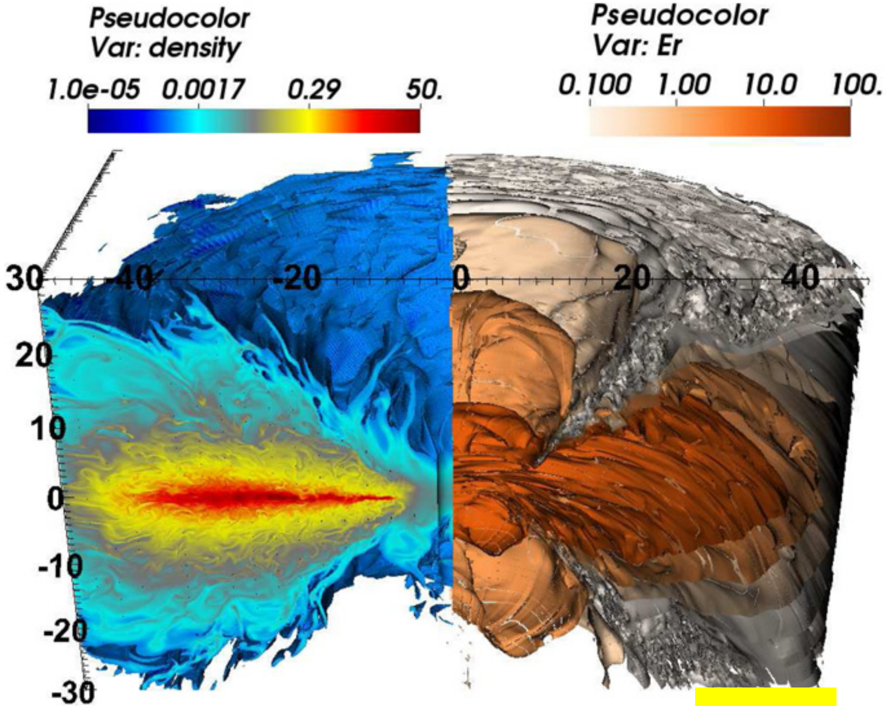
$$\bar{v}_{\rm out} \sim 1\times 10^{10}\ {\rm cm\ s^{-1}}\left(\frac{f_r}{10}\right)^{-1/2}.$$

Fast!

$$T_0 \approx (\dot{M}_{\rm out} v_{\rm out}/8\pi a r_0^2)^{1/4},\ \text{or}$$

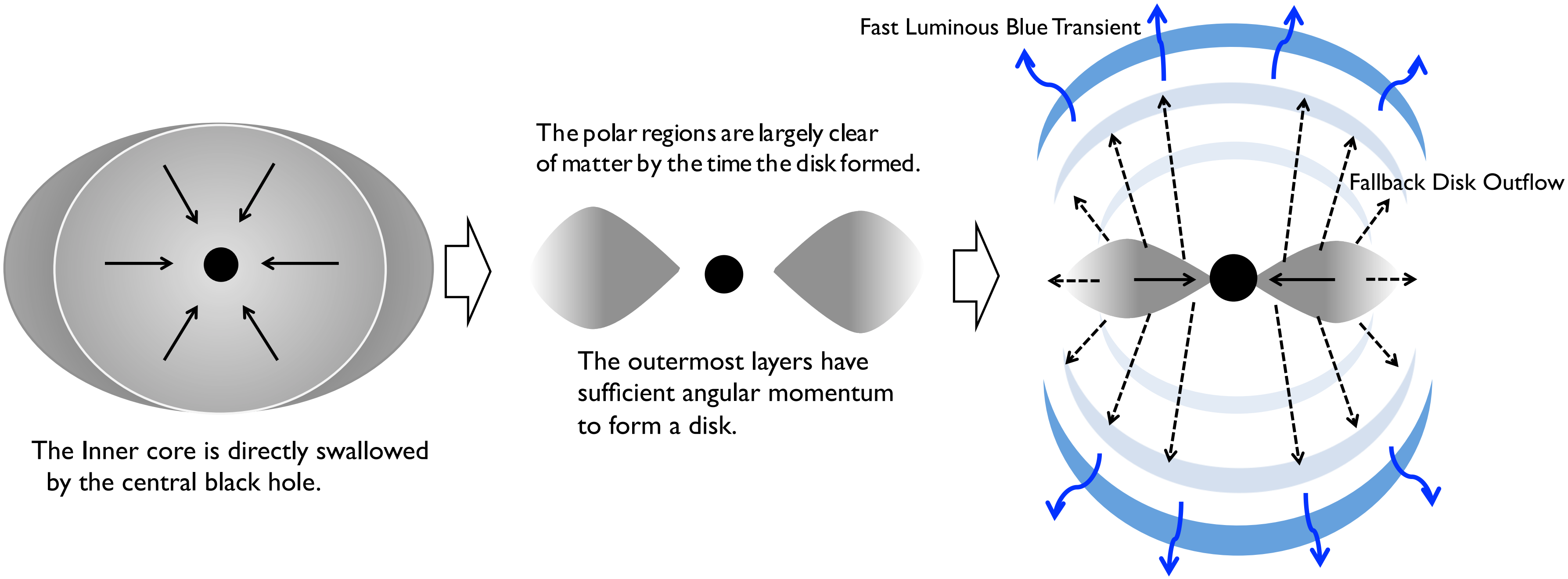
$$T_0 \sim 8\times 10^8\ {\rm K}\left(\frac{f_r}{10}\right)^{-5/8}\left(\frac{f_{\dot M}}{0.1}\right)^{1/4} \times \left(\frac{M_{\rm d}}{1\ M_\odot}\right)^{1/4}\left(\frac{R_*}{10^{12}\ {\rm cm}}\right)^{-3/8}\left(\frac{M_{\rm BH}}{10\ M_\odot}\right)^{-3/8}.$$

Hot!



Jiang+14

Schematic picture



The Inner core is directly swallowed
by the central black hole.

The polar regions are largely clear
of matter by the time the disk formed.

The outermost layers have
sufficient angular momentum
to form a disk.

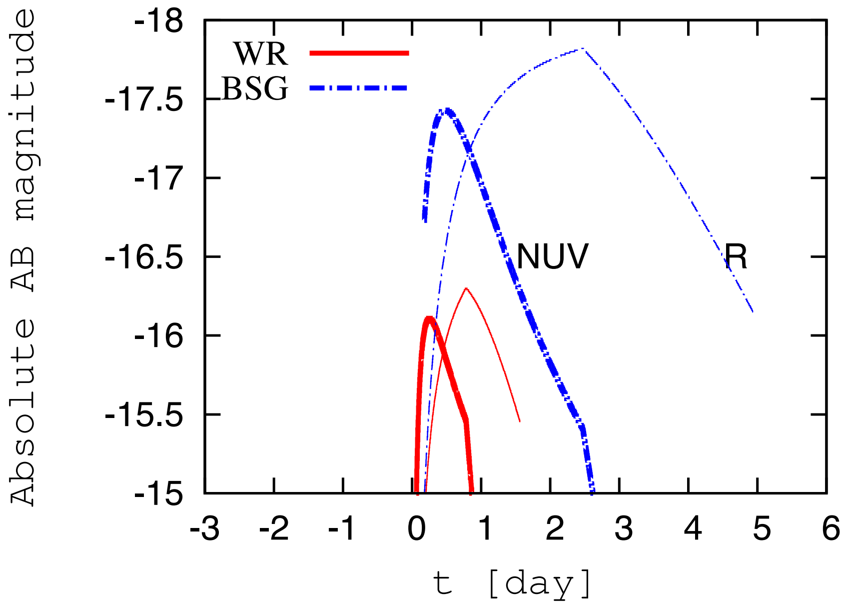
KK & Quataert 15

Fast luminous blue transients

Optically-thick hot wind → Adiabatic wind+homologous expansion → Diffuse thermal emission

$$t_{\rm p} \approx \left(\frac{3\kappa M_{\rm ej}}{4\pi \bar{v}_{\rm out}}\right)^{1/2} \sim 3\ {\rm days} \left(\frac{M_{\rm ej}}{0.1 M_\odot}\right)^{1/2} \left(\frac{\bar{v}_{\rm out}}{10^{10}\ {\rm cm/s}}\right)^{-1/2} \left(\frac{\kappa}{0.4\ {\rm cm^2/g}}\right)$$

$$L_{\rm bol,p} \approx \mathcal{C} \times E_{\rm int,0} \left(\frac{\bar{v}_{\rm out} t_{\rm acc}}{r_0}\right)^{-2/3} \left(\frac{t_{\rm p}}{t_{\rm acc}}\right)^{-1} \frac{1}{t_{\rm p}}, \quad T_{\rm p} \approx T_0 \left(\frac{\bar{v}_{\rm out} t_{\rm acc}}{r_0}\right)^{-2/3} \left(\frac{t_{\rm p}}{t_{\rm acc}}\right)^{-1}$$



✓ $L_{\rm bol} \sim 10^{41\text{-}43}$ erg s^{-1}

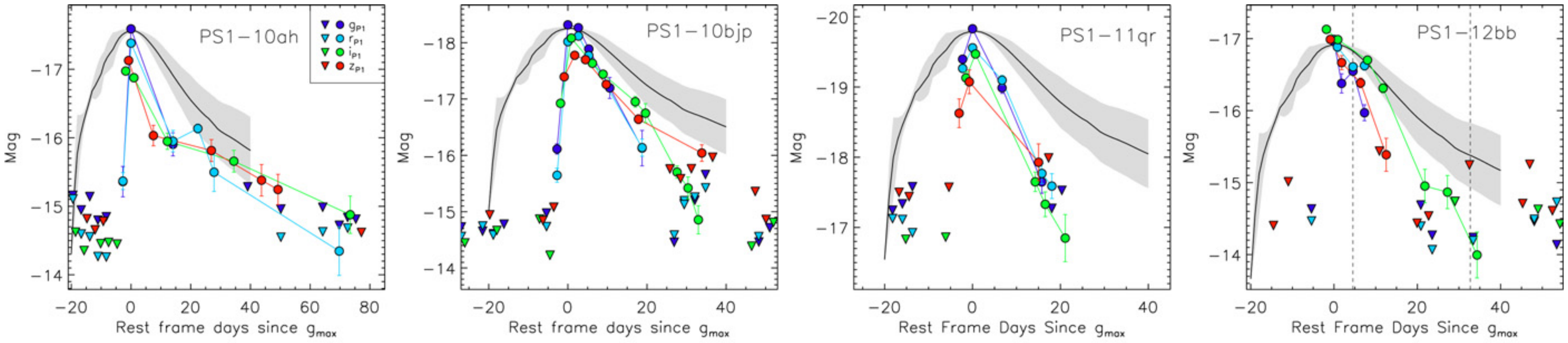
✓ blue continua with T ~10^4 K

KK & Quataert 15

The PS1-MDS Transients

Pan-STARRS1 Medium Deep Survey (PS1-MDS) for Rapidly Evolving and Luminous Transients

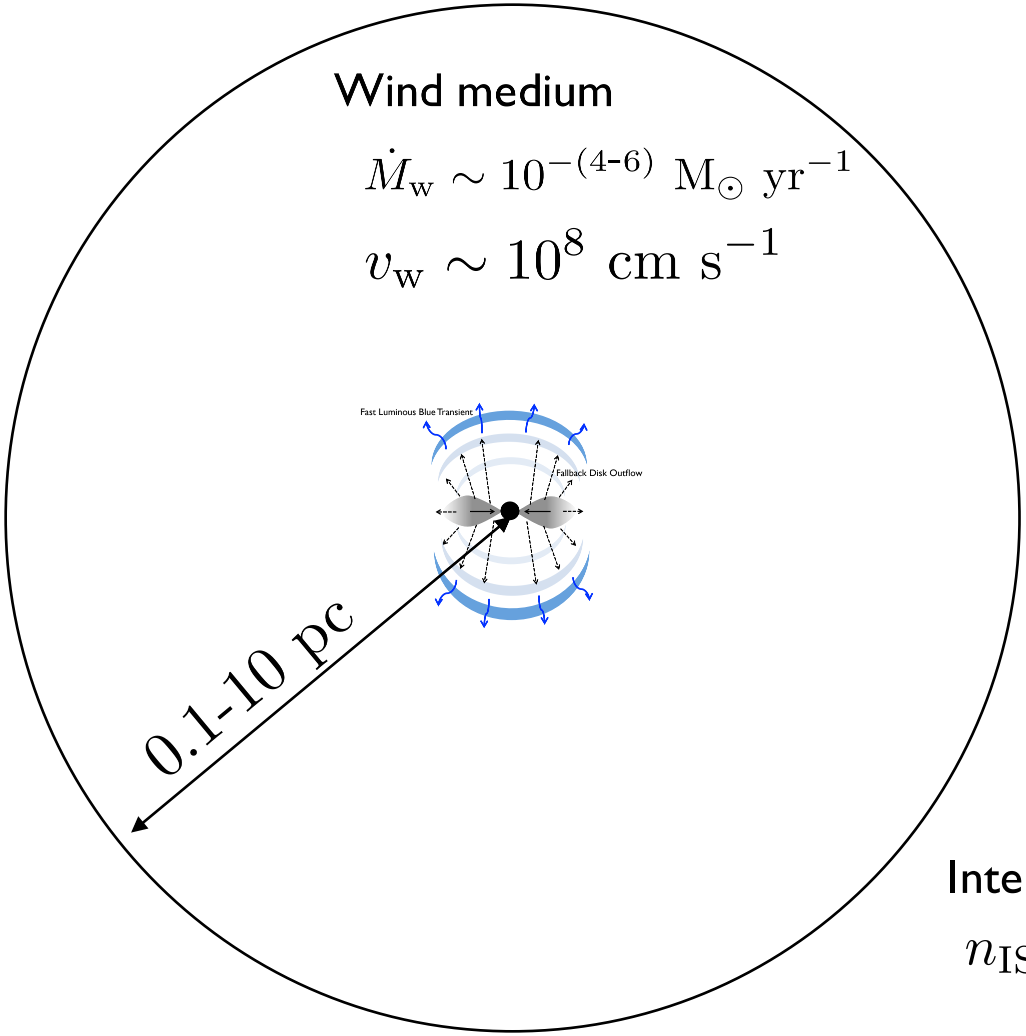
Drout+14



- ✓ $t_{1/2} < 12$ day --- rapidly evolving than any SN type
- ✓ $L_{peak} \sim 10^{42\text{-}43}$ erg s^{-1} --- luminous as bright SNe
- ✓ $T_{peak} \sim$ a few 10^4 K --- blue
- ✓ No line blanketing --- not powered by the radioactive decay
- ✓ Host Gal. = star forming Gal. --- related to massive stars
- ✓ Event rate ~ 4-7 % of core-collapse SN --- not rare

The afterglow

Decelerating disk outflow → Shock acceleration → Electron synchrotron emission



Wind medium

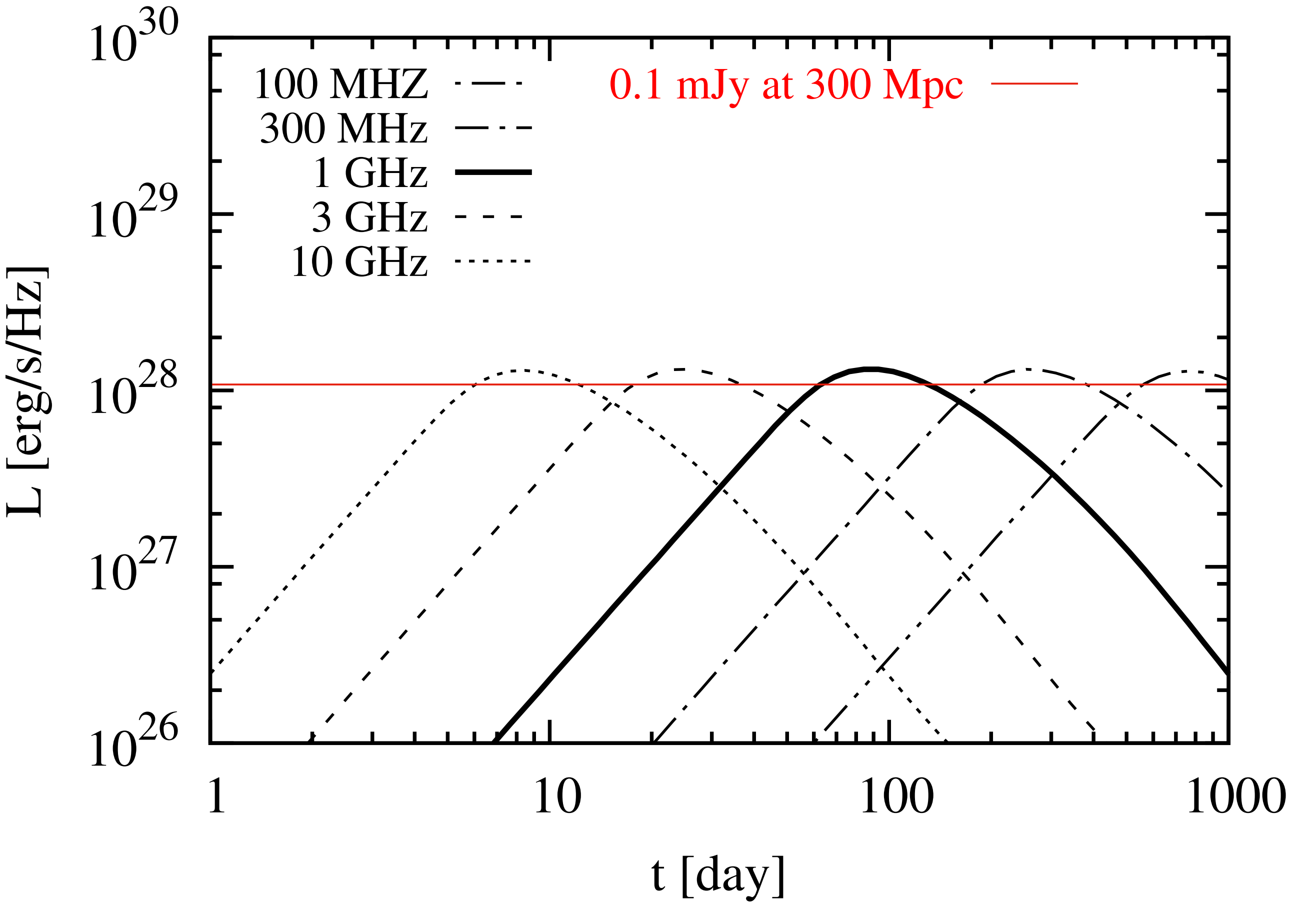
$\dot{M}_{\rm w} \sim 10^{-(4\text{-}6)}\ {\rm M_\odot\ yr^{-1}}$

$v_{\rm w} \sim 10^{8}\ {\rm cm\ s^{-1}}$

Interstellar medium

$n_{\rm ISM} \sim 1\text{-}100\ {\rm cm^{-3}}$

Radio counterparts



- ✓ Detectable by on-going and future surveys up to z > 1
- ✓ Good probe of collapsar environment

KK, Hotokezaka, Murase in prep

Q1. When a SN shock totally fails, everything just falls?

A. Not really.

Q2. How they look like?

1. with a negligible rotation

WR
RSG
BSG

→ DCBH w/ a weak shock driven by neutrino mass loss →

Blue twinkle w/ radio AG
Luminous red nova
Unnova

2. with a mild rotation

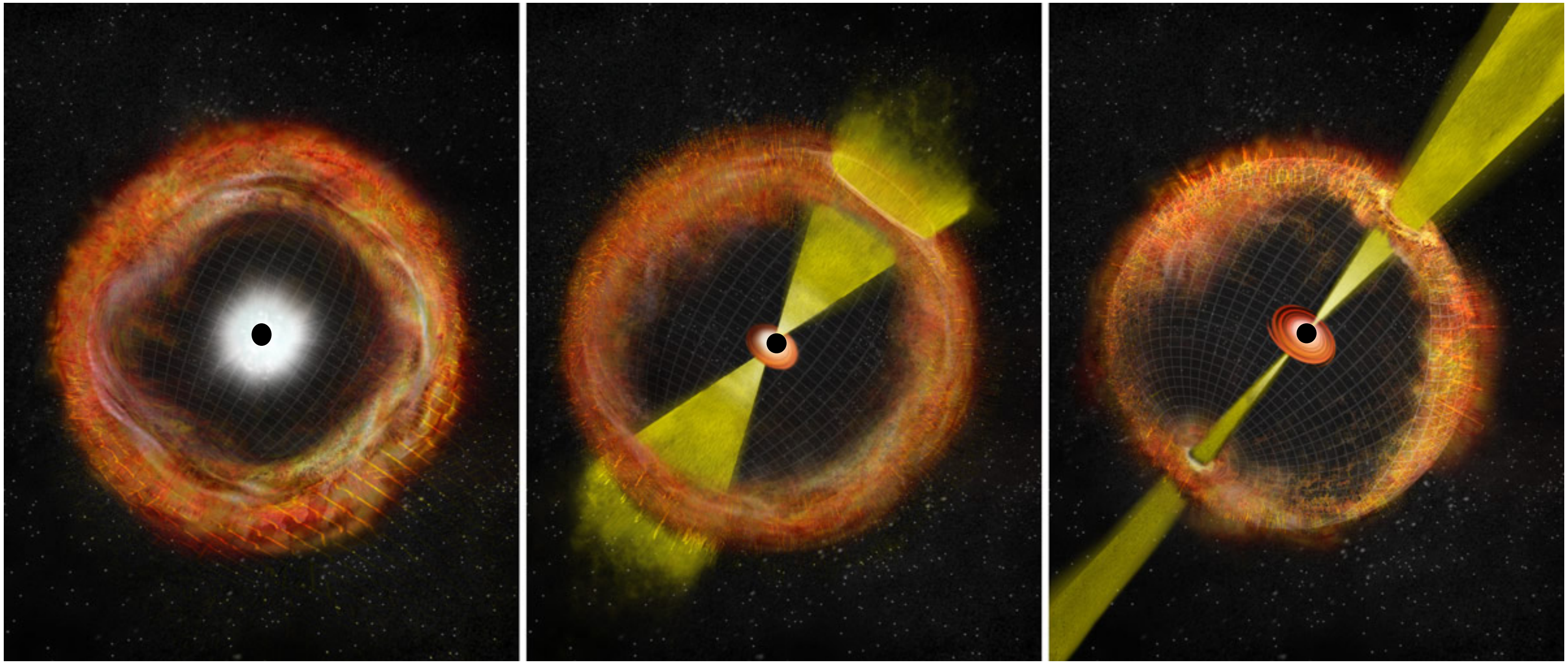
WR
BSG

→ DCBH w/ a minor fallback disk →

Fast luminous blue transient w/ bright radio AG

Diversity of BH formation

→ rotation

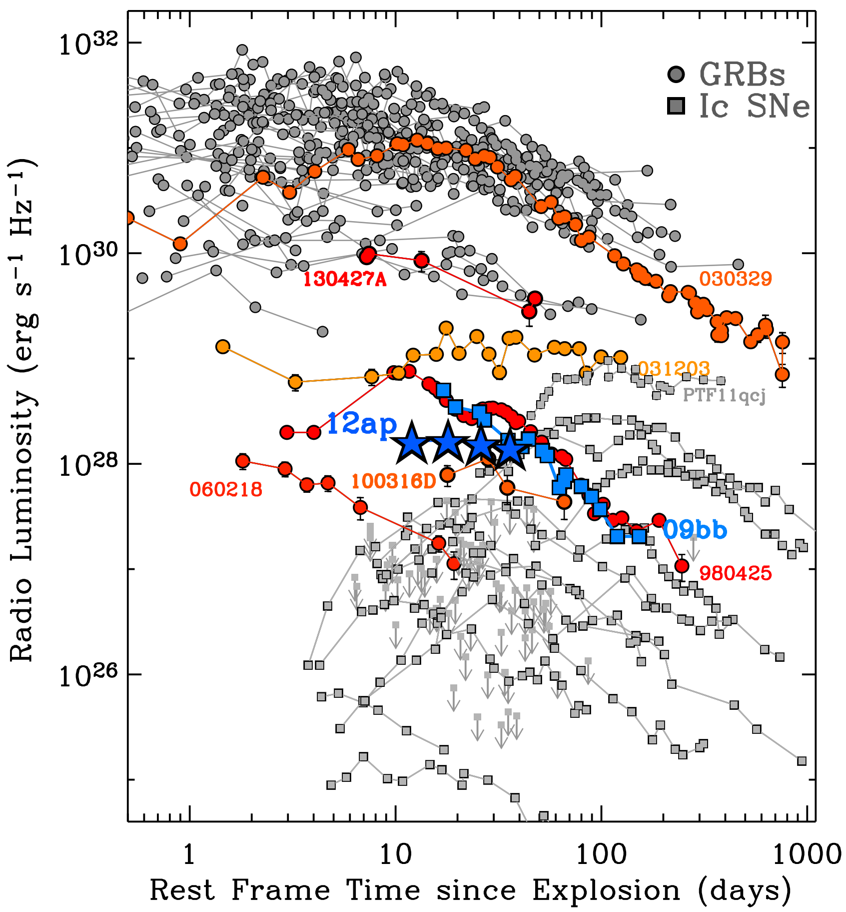


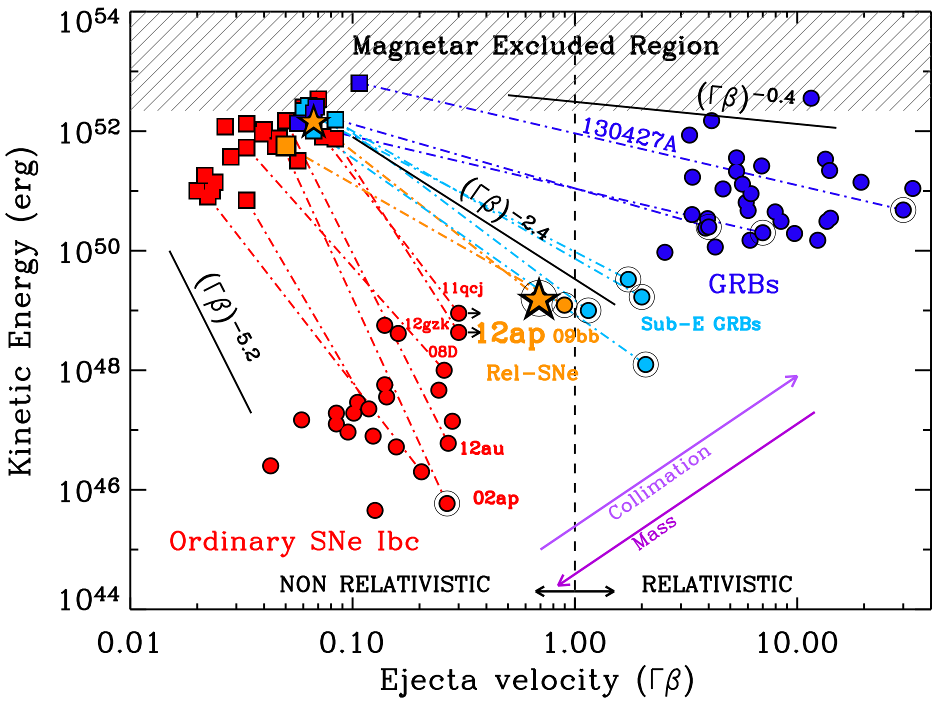
- ✓ Fallback SNe
- ✓ Weak explosions
  by ν mass loss
- ✓ Fallback disk wind

- ✓ Relativistic SNe?

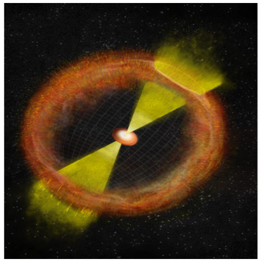
- ✓ Gamma-ray bursts

Relativistic SNe without GRB





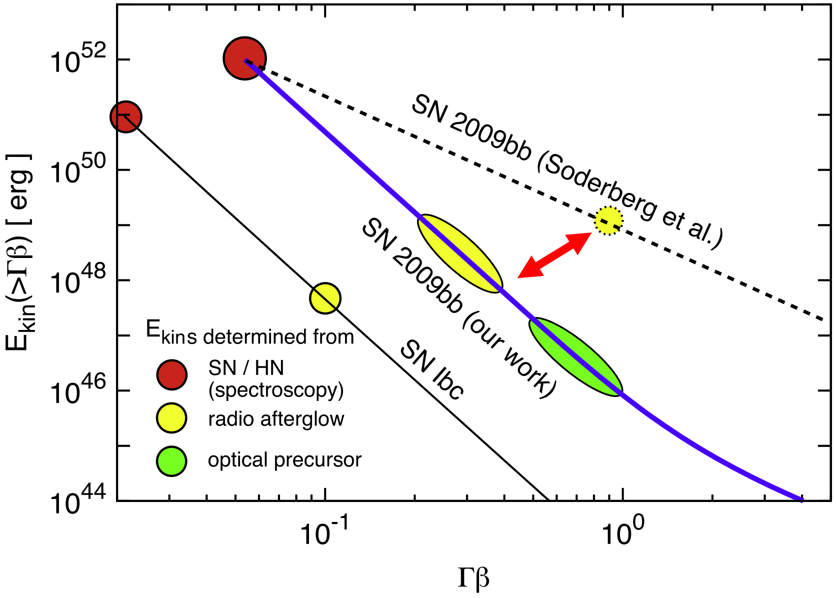
- ✓ Driven by a failed jet?
- ✓ Rate ~1% of SNe Ic

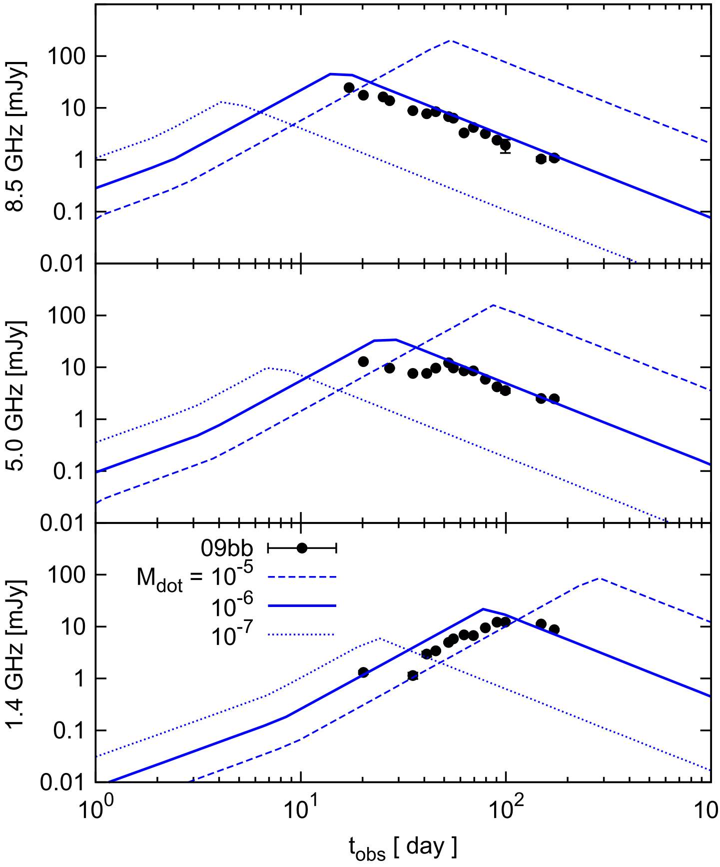


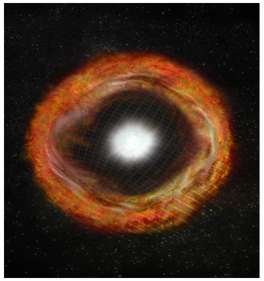
Soderberg+10; Chakraborti & Ray 11; Chakraborti+2014; Margutti+14; Milisavljevic+15

Spherical HN may also explain

hypernova shock breakout → A sufficient fraction of outer shells become trans-relativistic







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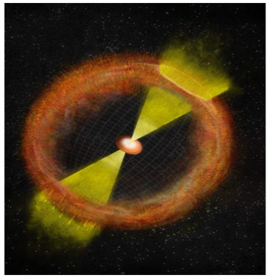
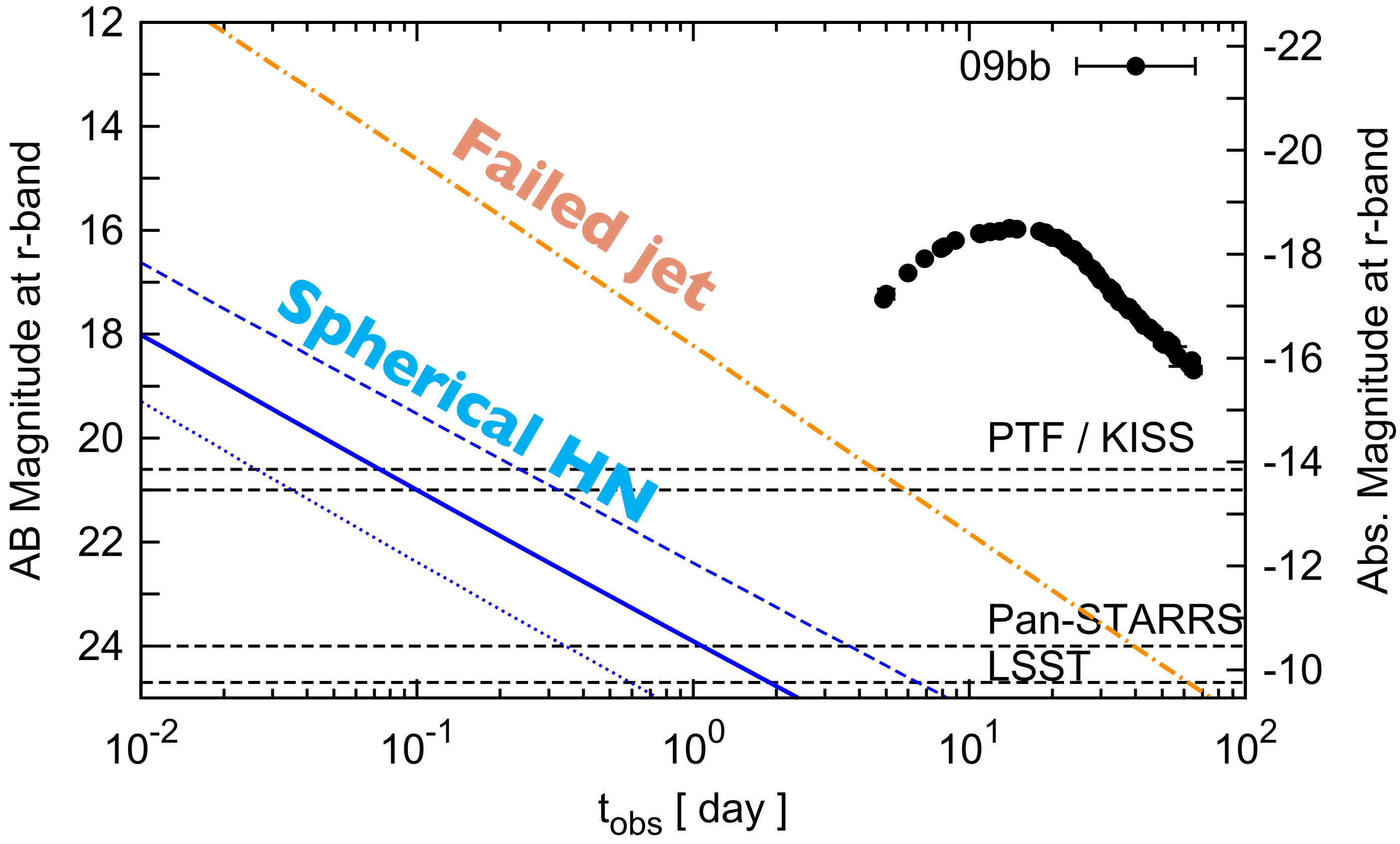


?

Nakauchi,KK+15

Optical synchrotron precursors

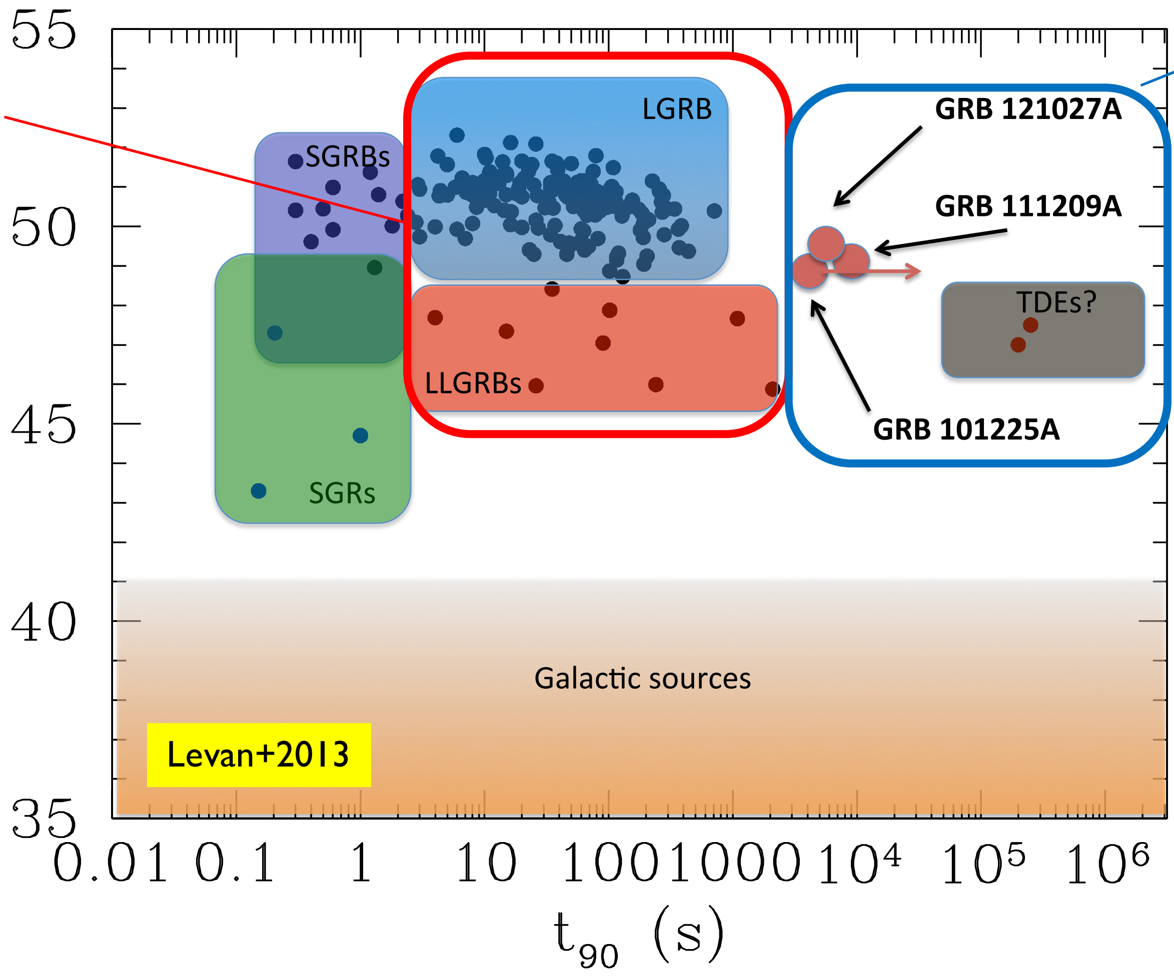


~sub-day cadence surveys can distinguish the explosion dynamics

Nakauchi,KK+15

Diversity of GRB

Observed with broad-line type Ibc SNe



γ-ray emission is much longer than accretion time of WRs

KK+13

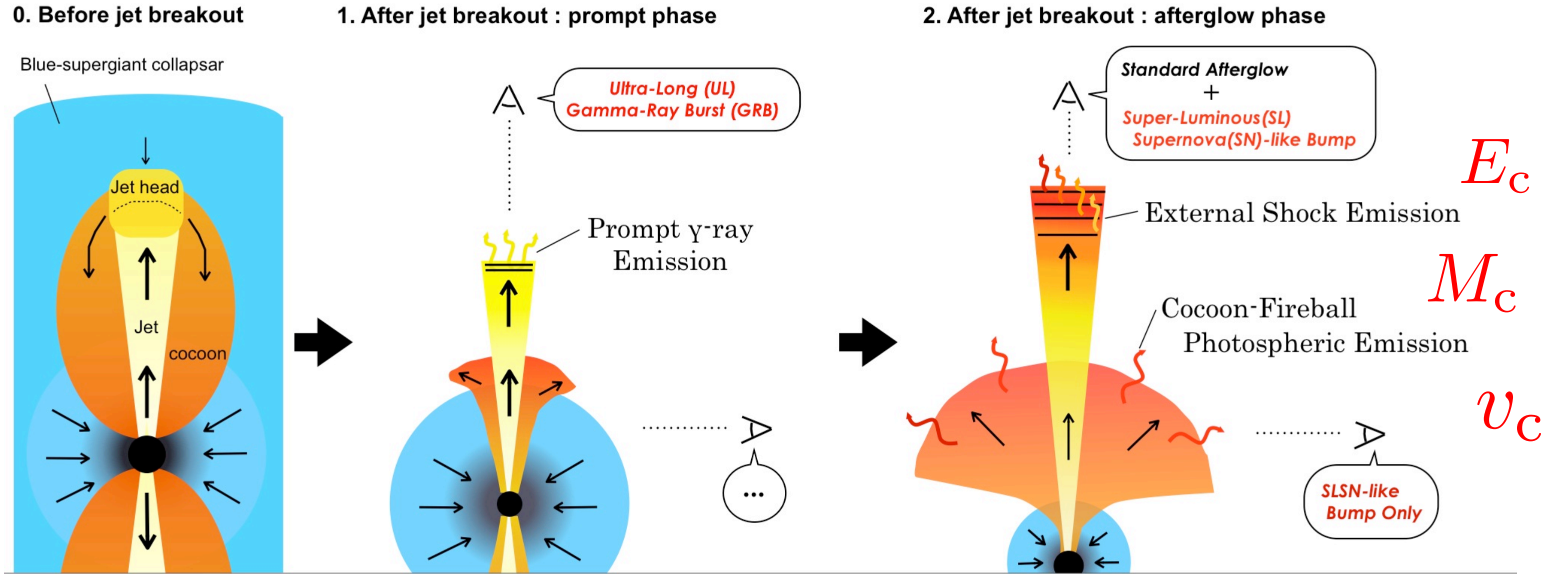
So as pop III GRBs?

↑

Unique probe of high-z universe!

Luminous SN like counterpart of BSG GRBs

KK+2013



$E_{\rm c} \sim 10^{53}$ erg

$M_{\rm c} \sim$ 5-10 $M_\odot$

$v_{\rm c} \sim 0.1\ c$

Predictions

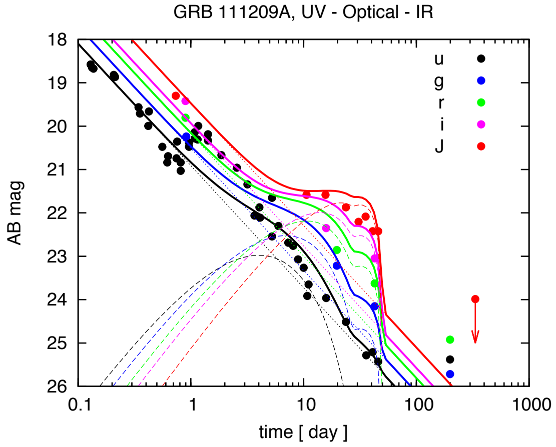
$$L \sim 10^{43-44}\ {\rm erg\ s^{-1}} {\rm E}_{\rm c,53}^{-1/4} {\rm M}_{\rm c,0.7}^{3/4}$$

$$t \sim 10\ {\rm days}\ {\rm E}_{\rm c,53}^{-1/4} {\rm M}_{\rm c,0.7}^{1/4}$$

broad H line features

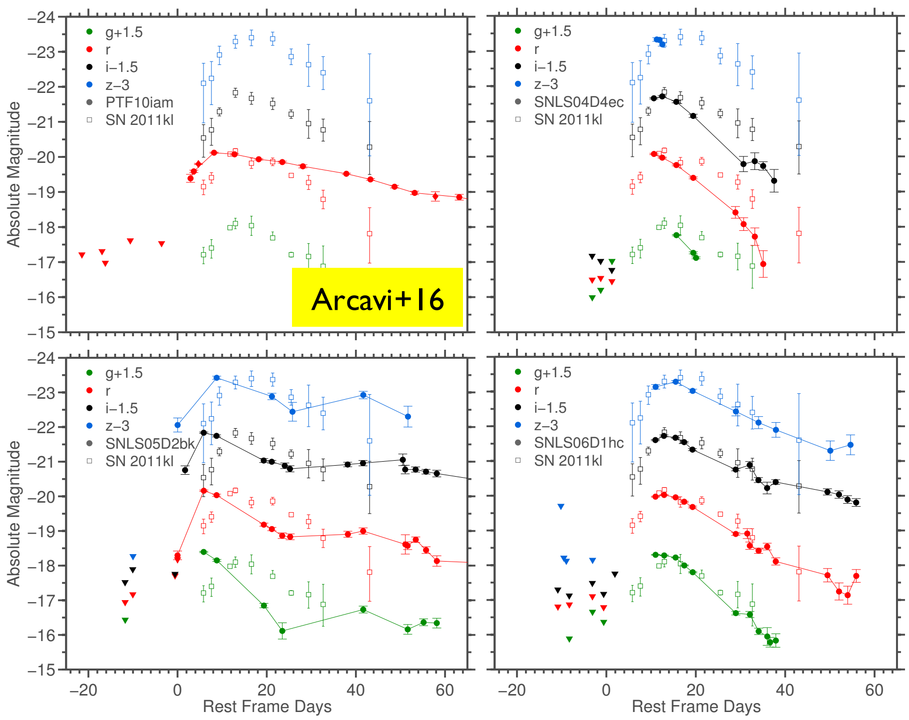
Already detected?

- ✓ With or without UL GRBs

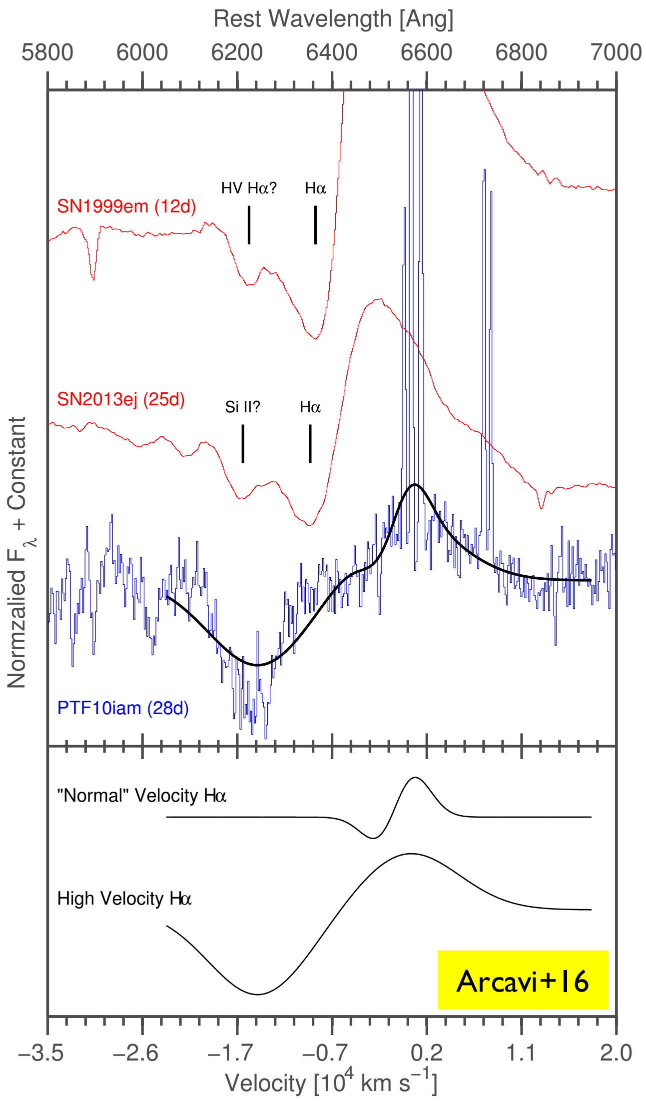


Levan+13

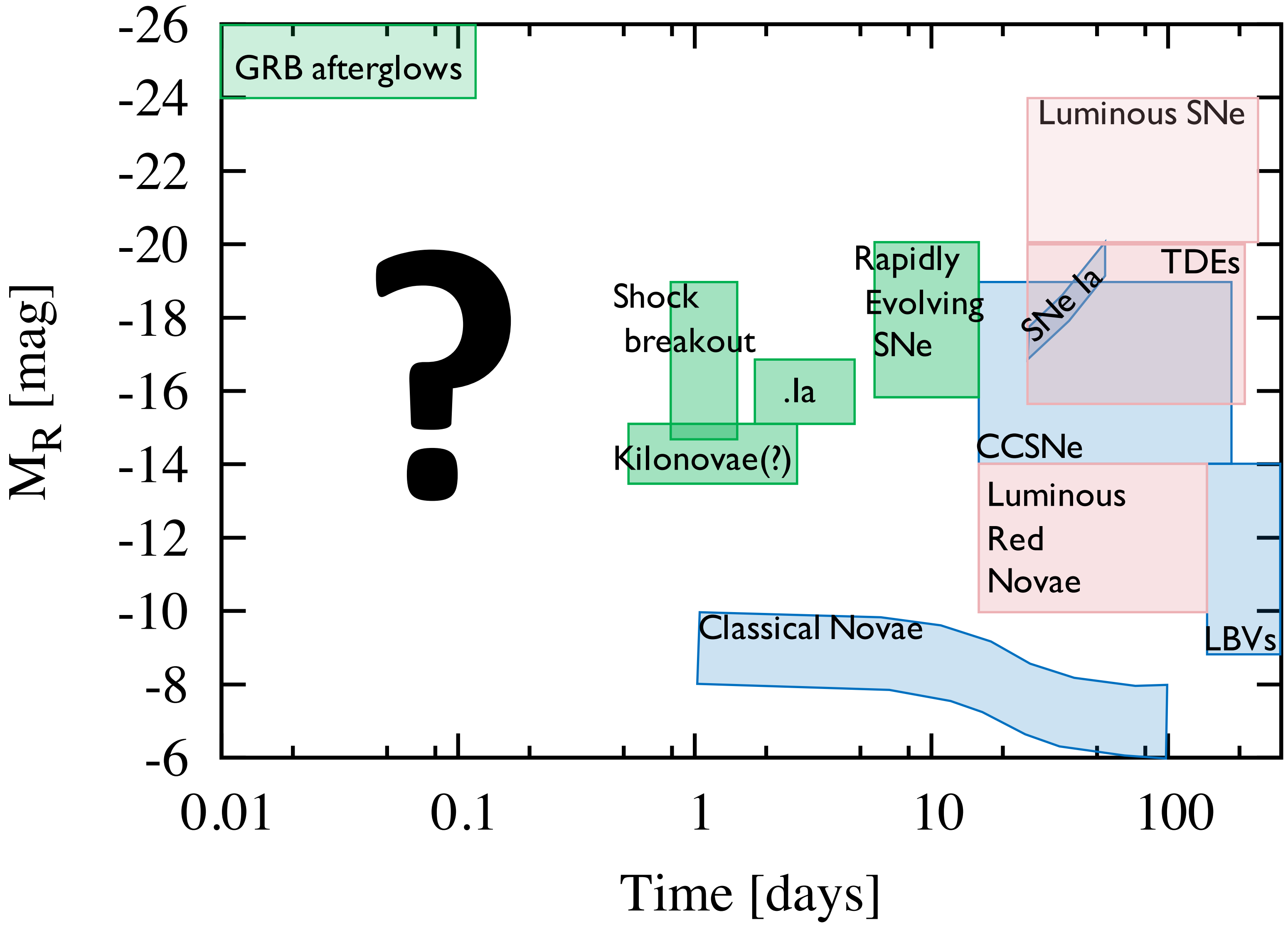
Nakauchi,KK+13



- ✓ With broad Hα line

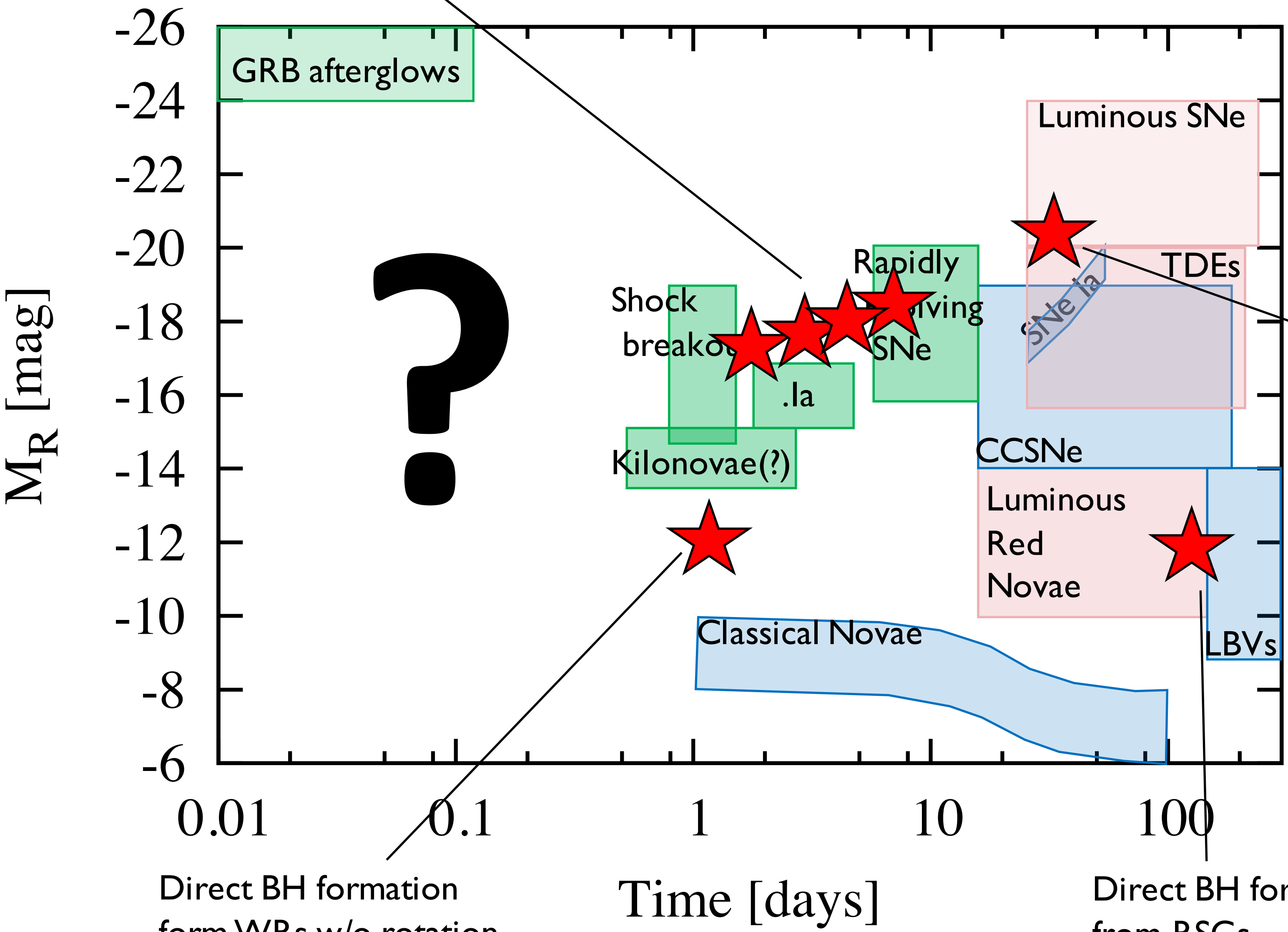


Summary


GRB afterglows
Luminous SNe
TDEs
SNe Ia
Rapidly Evolving SNe
Shock breakout
.Ia
Kilonovae(?)
CCSNe
Luminous Red Novae
LBVs
Classical Novae
?
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
M_R [mag]
0.01
0.1
1
10
100
Time [days]

Summary

Direct BH formation
from WRs and BSGs
+ **radio** (up to z ~ 1)



Off-axis
BSG GRBs

Direct BH formation
form WRs w/o rotation
+ **radio, vanished star**

Direct BH formation
from RSGs
+ **vanished star**

Backup

Computational setup

✓ Hydrodynamics

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho v_r\right) = 0,$$

$$\frac{D v_r}{D t} + \frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{G M(r,t)}{r^2} = 0,$$

$$\frac{D e_{\mathrm{int}}}{D t} - \frac{p}{\rho^2}\frac{D\rho}{Dt} = 0,$$

$$M(r,t) = \boxed{M_G(t)} + 4\pi \int_{R_{\mathrm{min}}}^{r} x^2 \mathrm{d}x\, \rho(x,t).$$

✓ Evolution of the inner core

Gravitational mass

$$\boxed{\dot{M}_{\mathrm{G}}} = \dot{M}_{\mathrm{B}} - \dot{\mathrm{BE}}_{\mathrm{c}} + \dot{M}_{\mathrm{th}},$$

baryon mass

$$\dot{M}_{\mathrm{B}} = 4\pi R_{\mathrm{min}}^2 \rho(R_{\mathrm{min}}, t) \min\left[v_r(R_{\mathrm{min}}, t), 0\right].$$

Binding energy

$$\mathrm{BE}_{\mathrm{c}} \simeq 0.084 \left(\frac{M_{\mathrm{G}}}{M_{\odot}}\right)^2 M_{\odot}.$$

thermal energy

$$\dot{M}_{\mathrm{th}} = \boxed{-\frac{M_{\mathrm{th}}}{\tau_c}} + \epsilon \frac{\mathrm{dBE_c}}{\mathrm{d}M_B} \dot{M}_B.$$

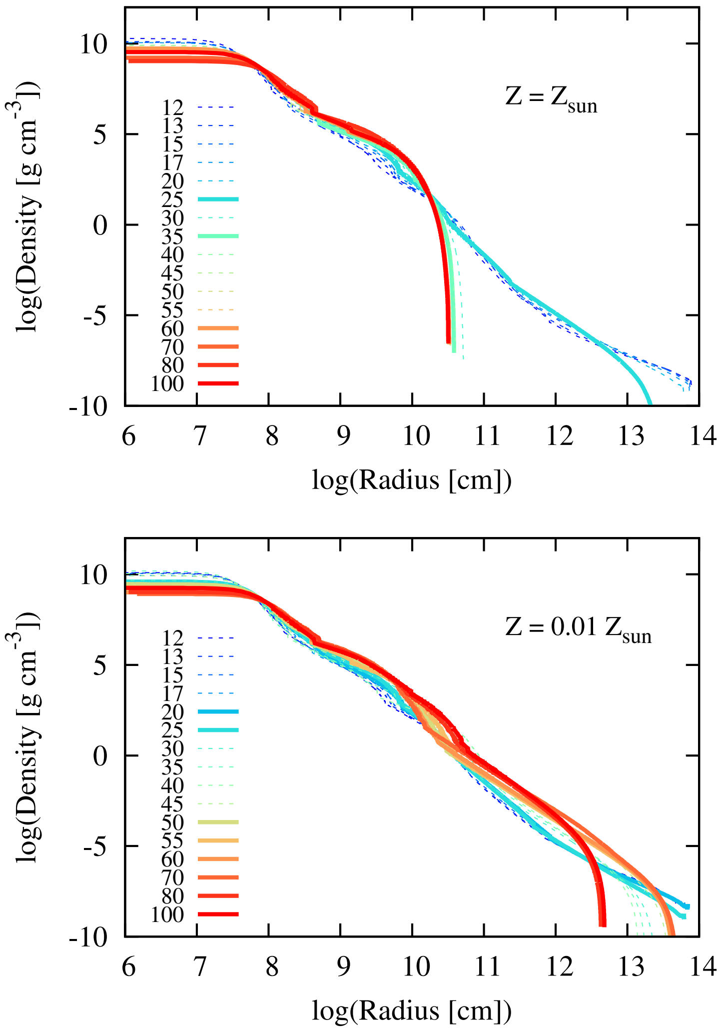
neutrino emission

while $M_{\mathrm{G}} < M_{\mathrm{TOV,max}}$

Lovegrove & Woosley 2013

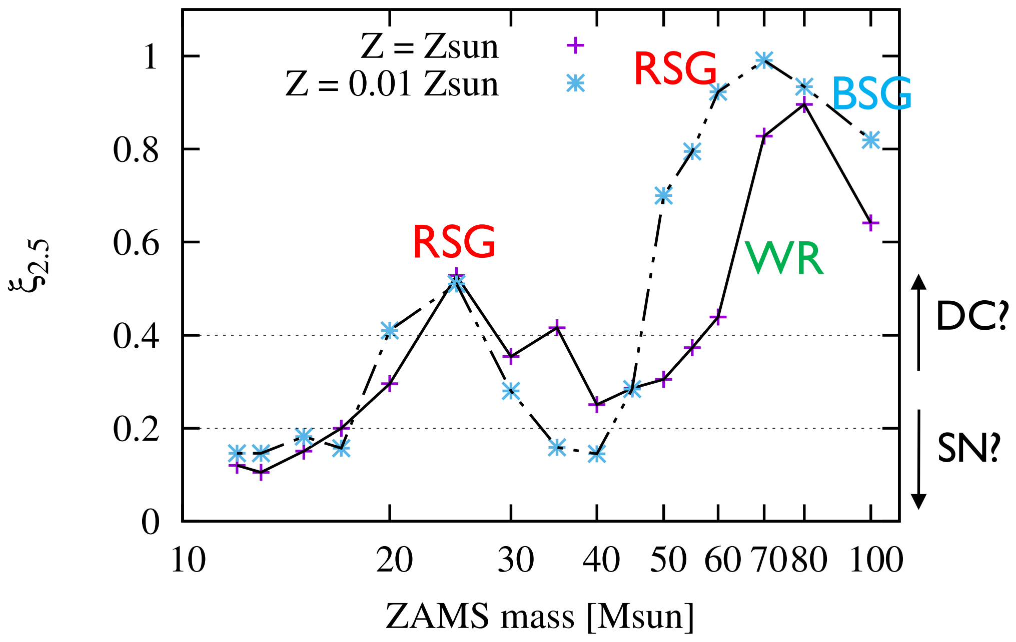
Initial condition and models evolved

MESA (massive star default, no rotation)



picking up stars with a compact core

$$\xi_{2.5} = \frac{M/M_\odot}{R(M_\mathrm{B} = M)/1000\ \mathrm{km}}$$



O'Connor & Ott 2011; Ugliano et al. 2012; Horiuchi et al. 2014; Pejcha & Thompson 2015