Fast Luminous Blue Transients from Newborn Black Holes

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with Eliot Quataert (UCB)

Reference: MNRAS, 451, 2656

The Diversity in Collapsar

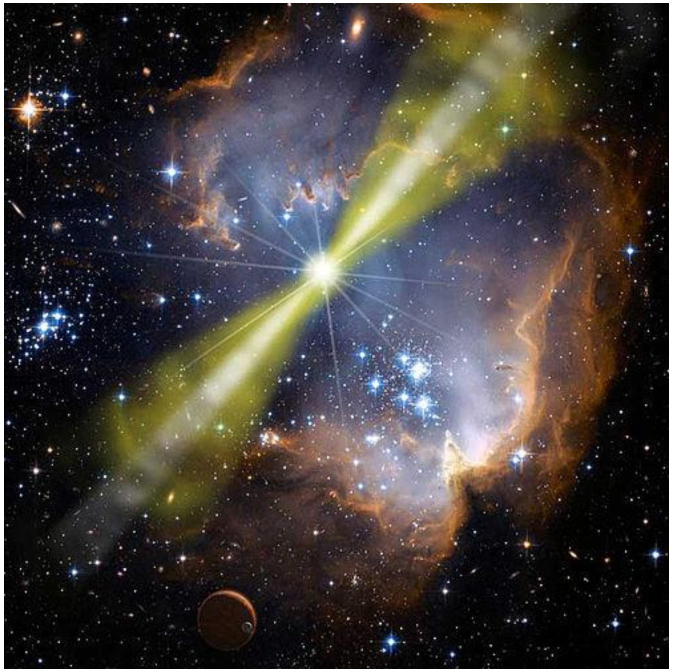
Slow rotation

Dim, but abundant
~1/100 yr

Fast rotation

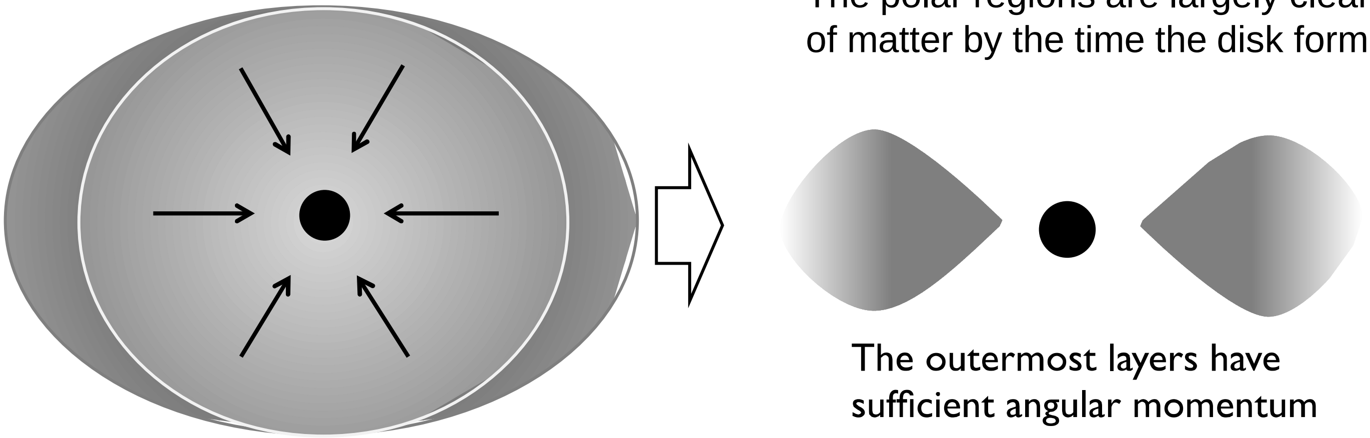
Maybe bright,
and not so rare

Extremely fast rotation
(with strong B field)



Very Bright, but very rare
$\sim 1/10^5$ yr

May be like this?



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

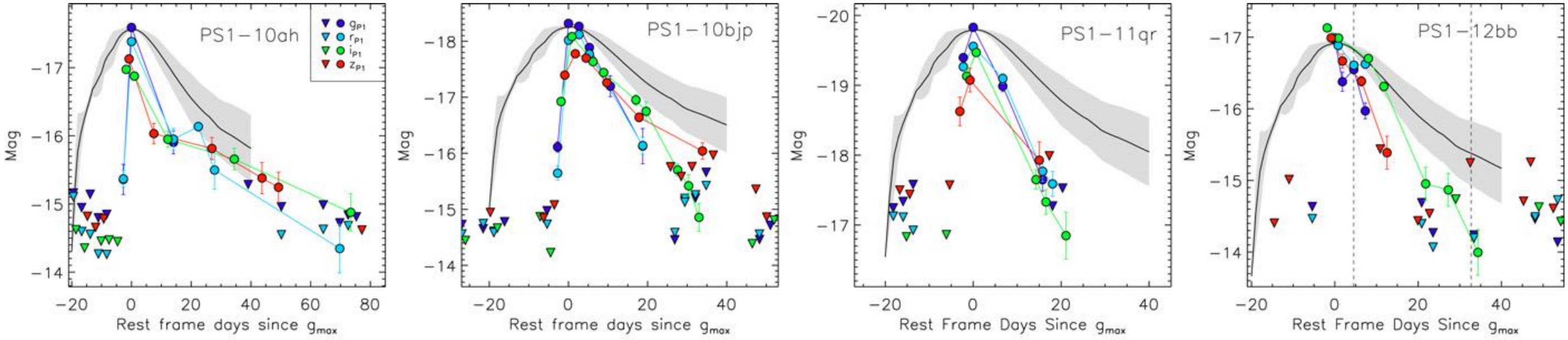
The outermost layers have
sufficient angular momentum
to form a disk.

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

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

Fast & Luminous & Blue = Difficult?

Optically-thick hot ejecta → Adiabatic (homologous) expansion → Diffuse thermal emis

$$\tau \propto t^{-2}, E_{\rm int} \propto t^{-1}, T \propto t^{-1} \qquad c/v_{\rm out} \approx \tau$$

$$t_{\rm p} \approx \left(\frac{3\kappa M_{\rm ej}}{4\pi v_{\rm out} c}\right)^{1/2} \sim 30\ {\rm days}\ \left(\frac{M_{\rm ej}}{M_\odot}\right)^{1/2} \left(\frac{v_{\rm out}}{10^9\ {\rm cm/s}}\right)^{-1/2} \left(\frac{\kappa}{0.4\ {\rm cm^2/g}}\right)$$

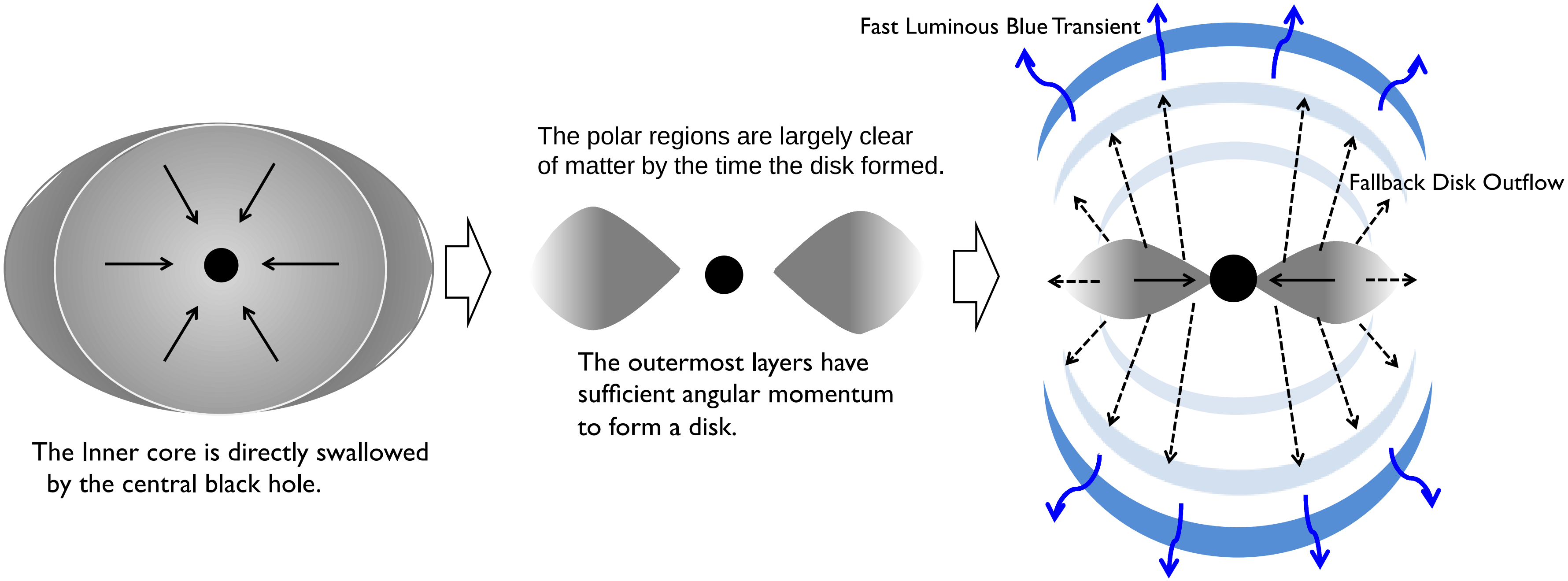
$$L_{\rm bol,p} \approx E_{\rm int,0} \frac{r_0}{v_{\rm out} t_{\rm p}} \frac{1}{t_{\rm p}} \qquad \leftarrow E_{\rm int,0} \approx \frac{1}{2} M_{\rm ej} v_{\rm out}^2$$

$$\sim 10^{40}\ {\rm erg/s}\ \left(\frac{M_{\rm ej}}{M_\odot}\right) \left(\frac{v_{\rm out}}{10^9\ {\rm cm/s}}\right)^2 \left(\frac{\kappa}{0.4\ {\rm cm^2/g}}\right)^{-1} \left(\frac{r_0}{10^{11}\ {\rm cm}}\right)$$

$$T_{\rm p} \approx T_0 \frac{r_0}{v_{\rm out} t_{\rm p}} \sim 3800\ {\rm K}\ \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1/2} \left(\frac{v_{\rm out}}{10^9\ {\rm cm/s}}\right)^{-1/2} \left(\frac{\kappa}{0.4\ {\rm cm^2/g}}\right)^{-1} \left(\frac{r_0}{10^{11}\ {\rm cm}}\right) \left(\frac{T_0}{10^9\ {\rm K}}\right)$$

It requires $M_{\rm ej}$ << $M_{\rm sun}$, $v_{\rm out}$ >> 10^9 cm/s, and somehow suppressed adiabatic cooling, bu

How about this?



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.

Fast Luminous Blue Transient

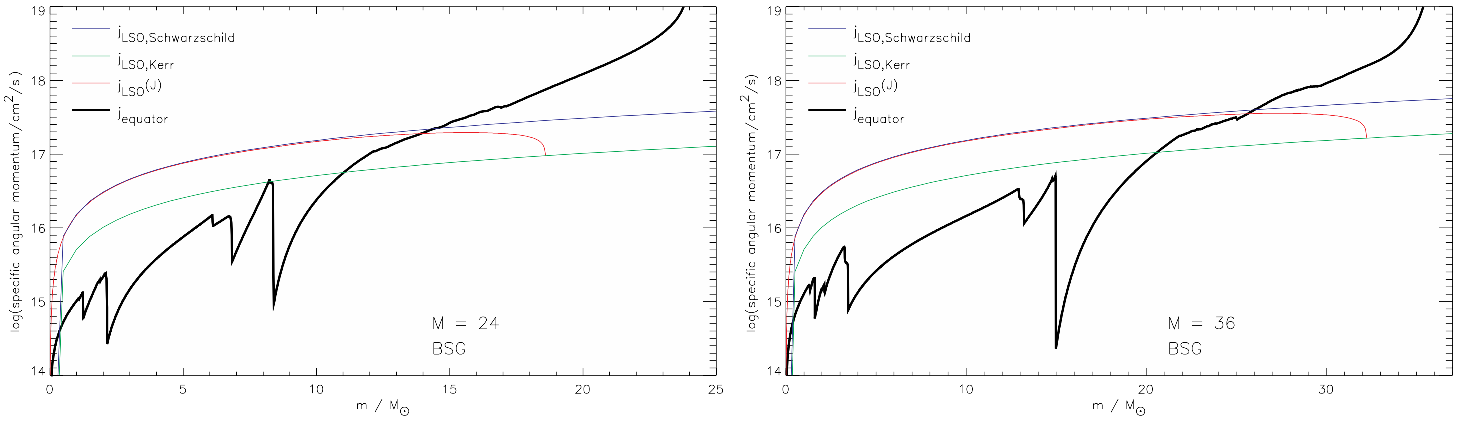
Fallback Disk Outflow

Fall back disk may be ubiquitous!

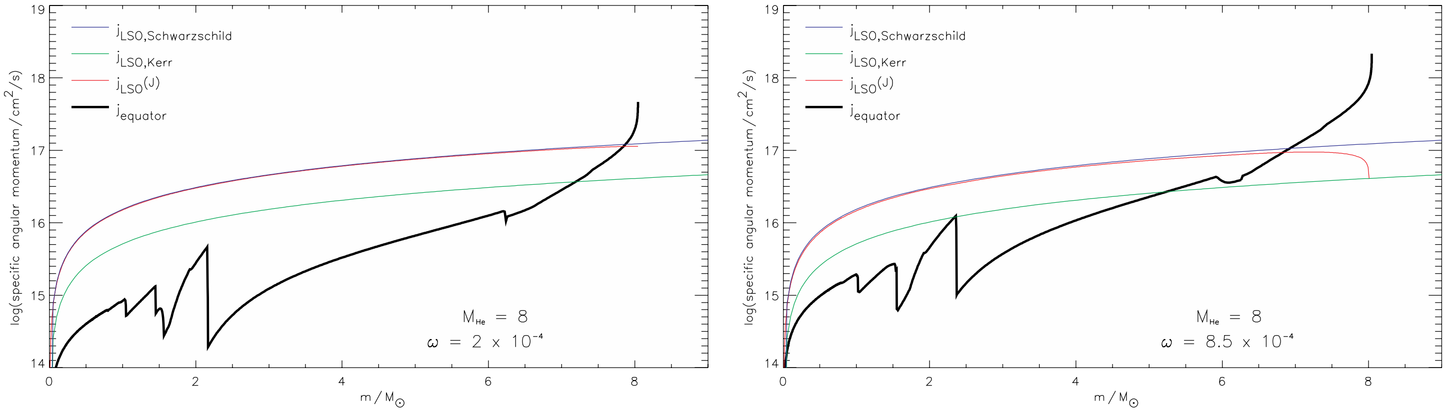
Woosley & Heger 12, Perna+14

e.g.,

BSG



WR
in binary



Outer layers of up to ~ a few $M_\odot$ can “naturally” have sufficient j

Then, what will happen?

$\dot{M}_d \approx M_d/t_{acc}$, or

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

$$\sim 10^{-15}\, M_\odot\, s^{-1}\, (\kappa/0.2\ cm^2\ g^{-1})^{-1}(M_{BH}/10 M_\odot)$$

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

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

Super-Eddington accretion!

& Outflows!

~ 10 % of the accreted mass

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

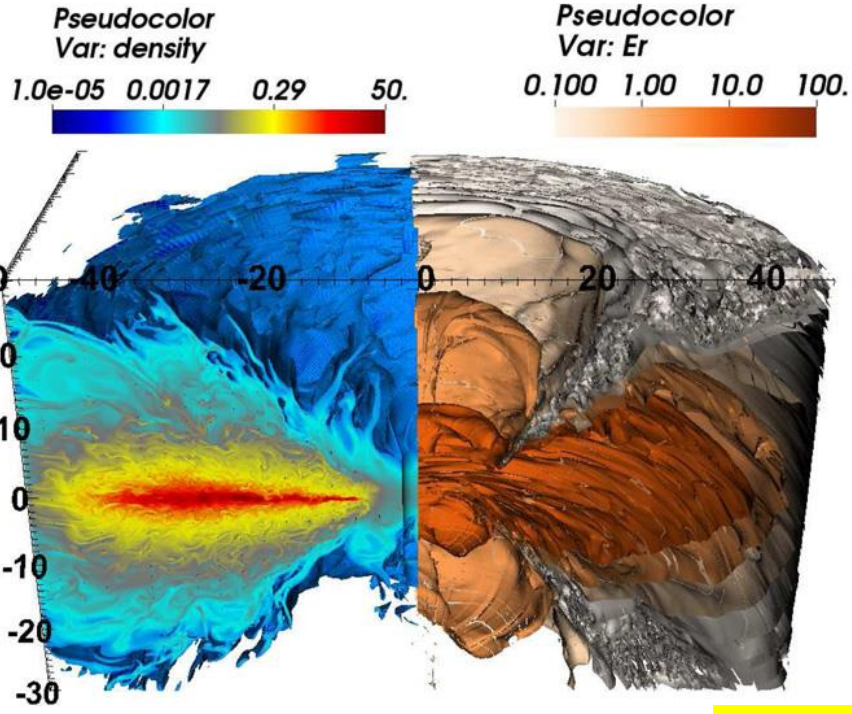
$$\bar{v}_{out} \sim 1\times 10^{10}\ cm\ s^{-1}\left(\frac{f_r}{10}\right)^{-1/2}.$$

Fast!

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

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

Hot!



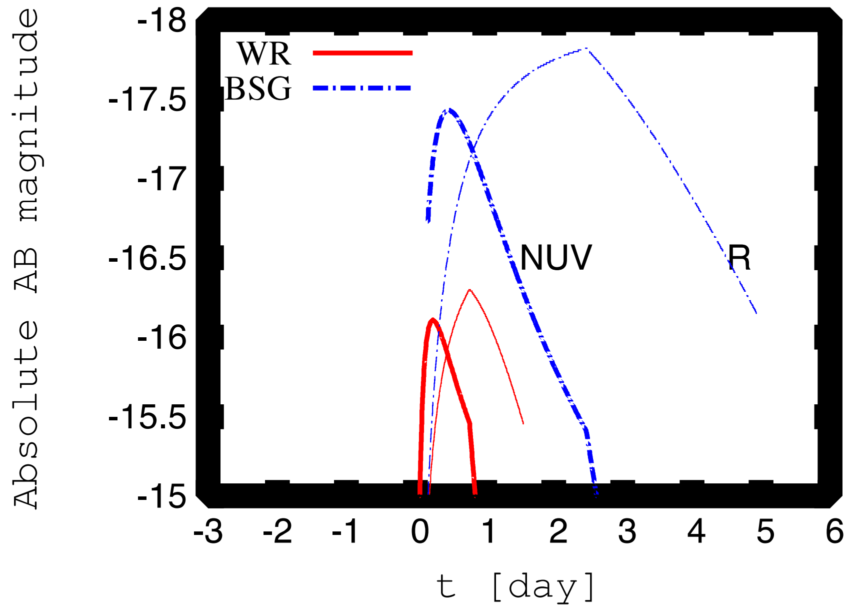
Jiang+14

Fast Luminous Blue Transients

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

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

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



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

✓ blue continua with T ~10^4 K

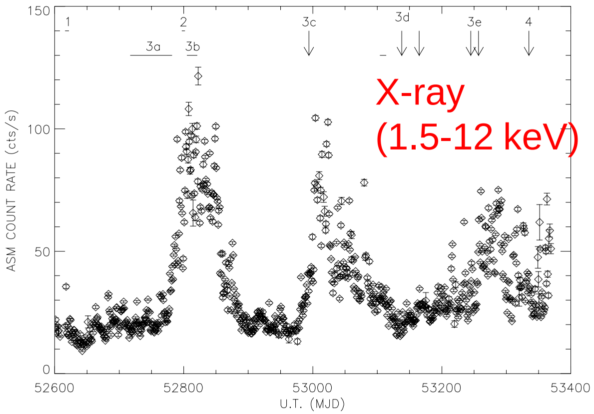
KK & Quataert 15

Summary and Discussion

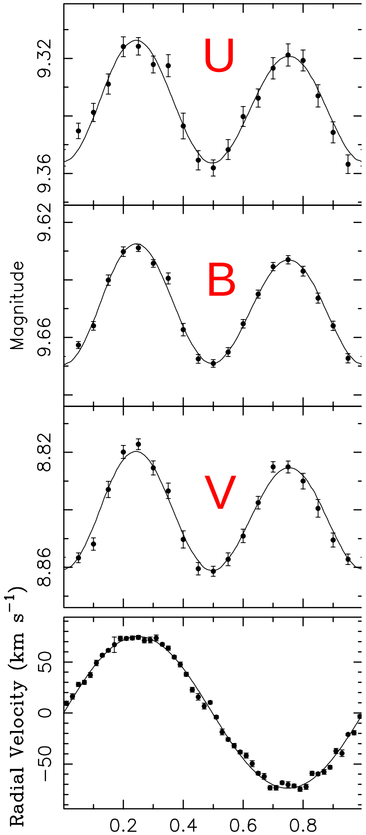
- Fast blue transients
  - ✓a day to 10 day depending on progenitor structure
  - ✓$L_{bol} \sim 10^{41\text{-}43}$ erg s^{-1}
  - ✓Blue continua with $T \sim 10^4$ K
  - ✓may not be rare (~5% of CCSNe).
- can be explained by the disk outflow from fast rotating collapsars, but not that fast as GRBs
- Multi-messenger approach
  - ✓(weak) jet?
  - ✓Radio?
  - ✓Gravitational wave?

Back up

Stellar-Mass Black Holes

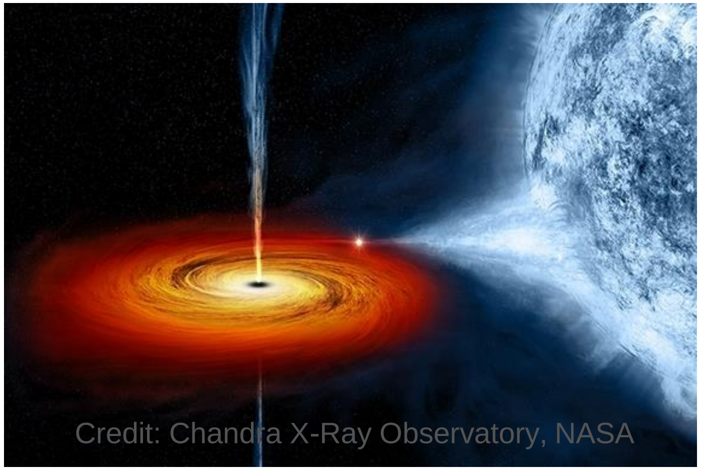


Cadolle Bel+06

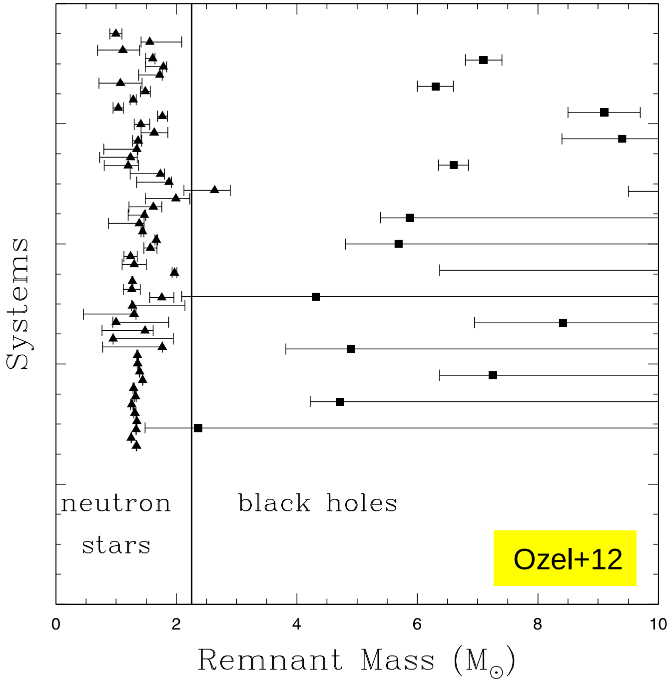


Orosz+11

$$f\,(m_1) \equiv \frac{m_1 \sin^3 i}{(1+\ q)^2} = \frac{P_{orb} V_2^2}{2\pi G}$$

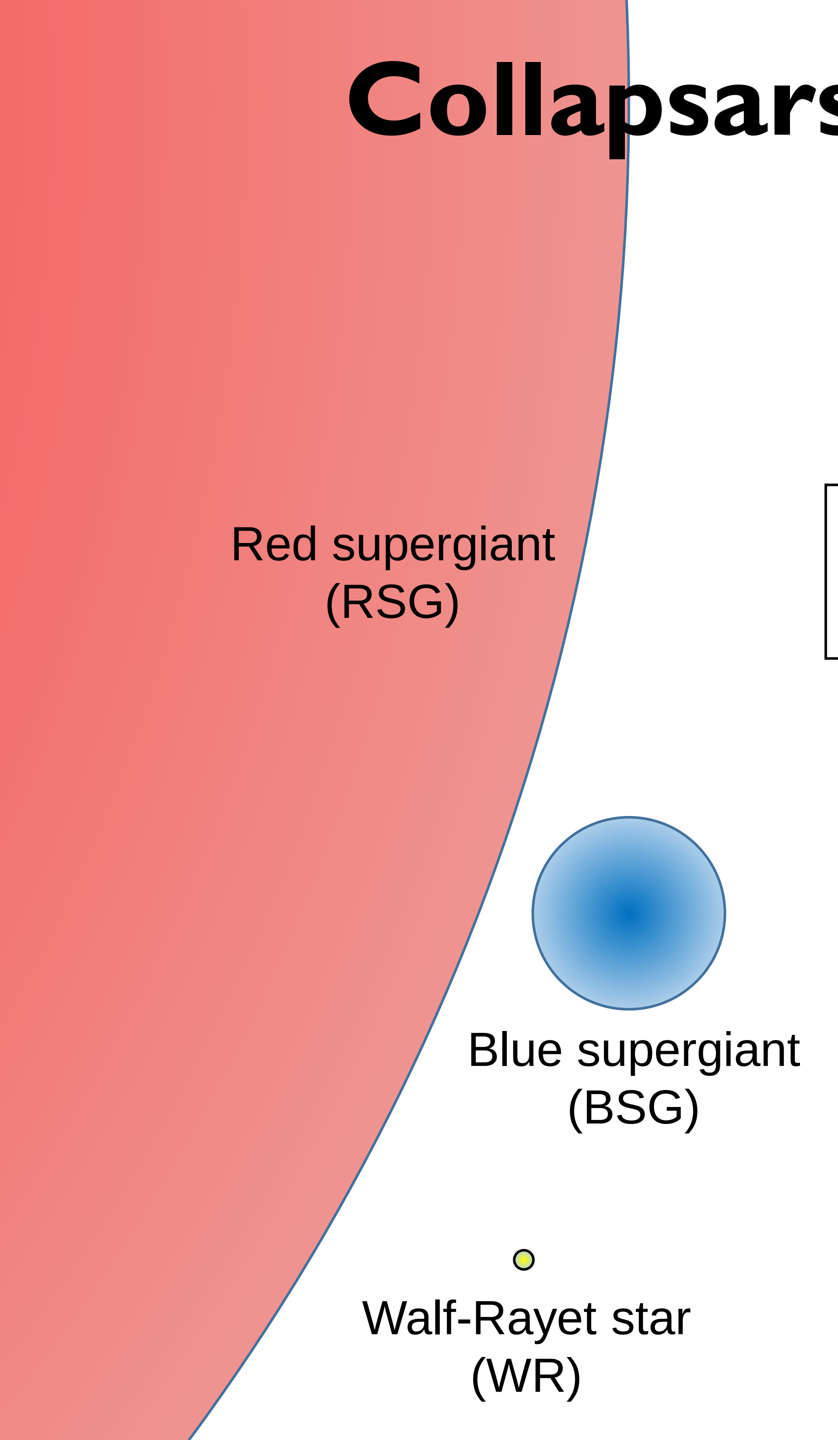


Credit: Chandra X-Ray Observatory, NASA



Ozel+12

Collapsars: BHs not NSs?



Red supergiant
(RSG)

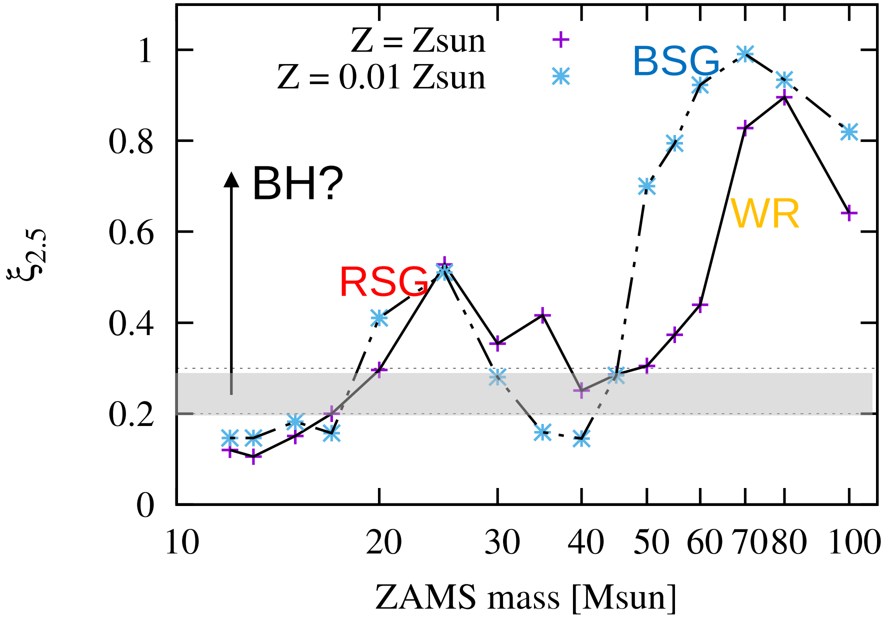
Blue supergiant
(BSG)

Walf-Rayet star
(WR)

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

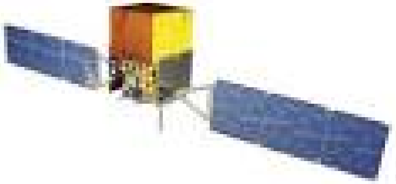
The key will be inner density structure within $r \sim 1000\ \mathrm{km},\, Mr \sim 2\text{-}3\ M_{\odot}$

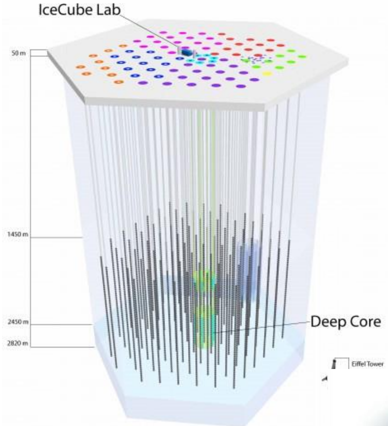
O’Connor & Ott 2011; Ugliano et al. 2012; Horiuchi et al. 2014; Pejcha & Thompson 2015

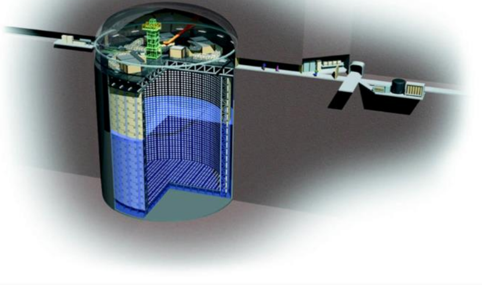


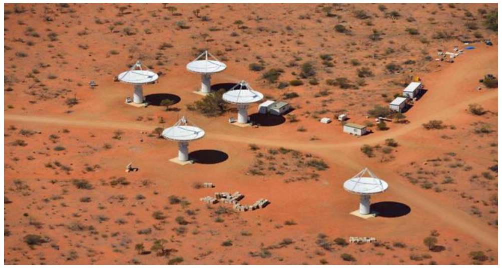
All types of massive star can form BHs

Now is the good timing









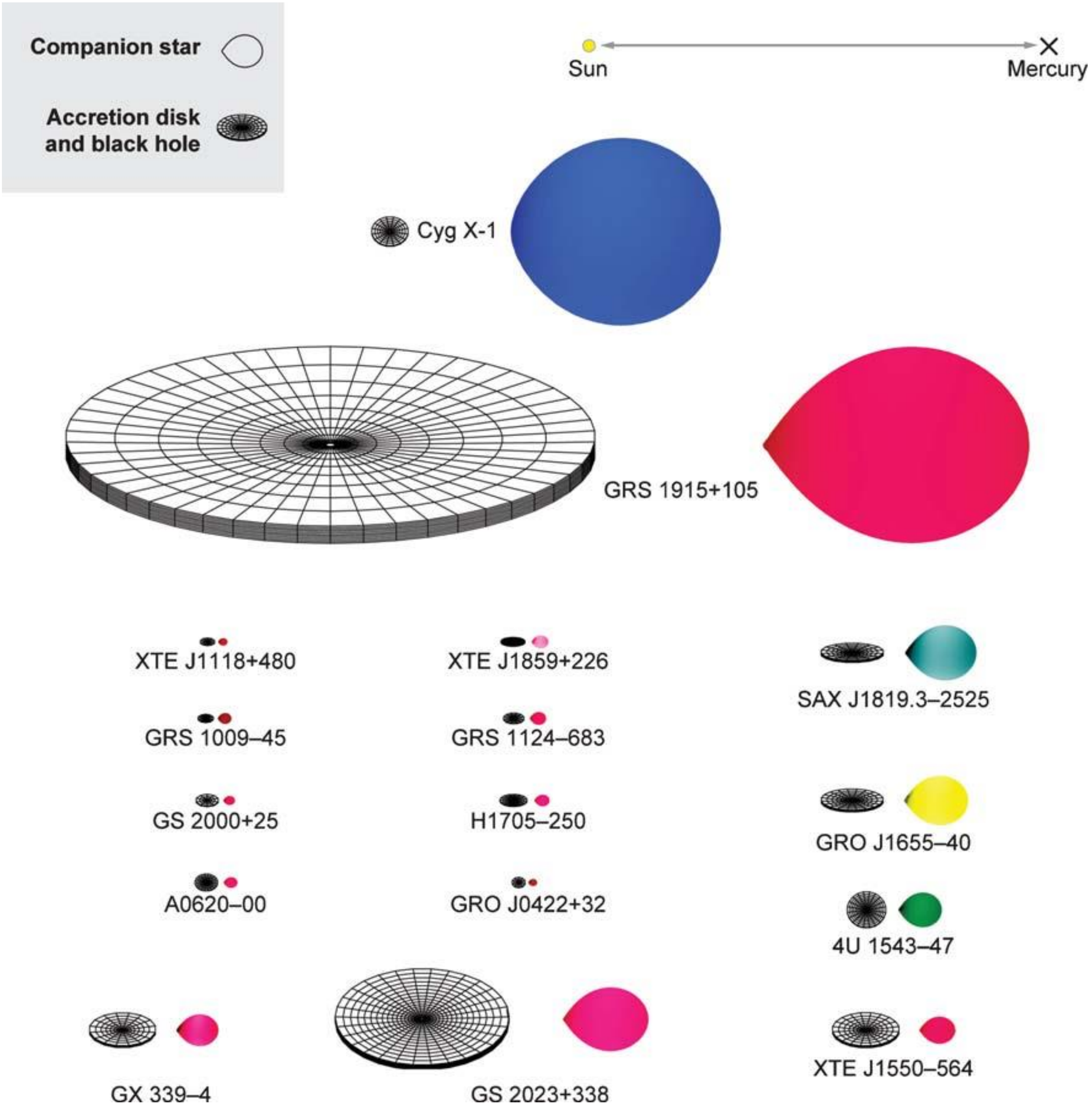
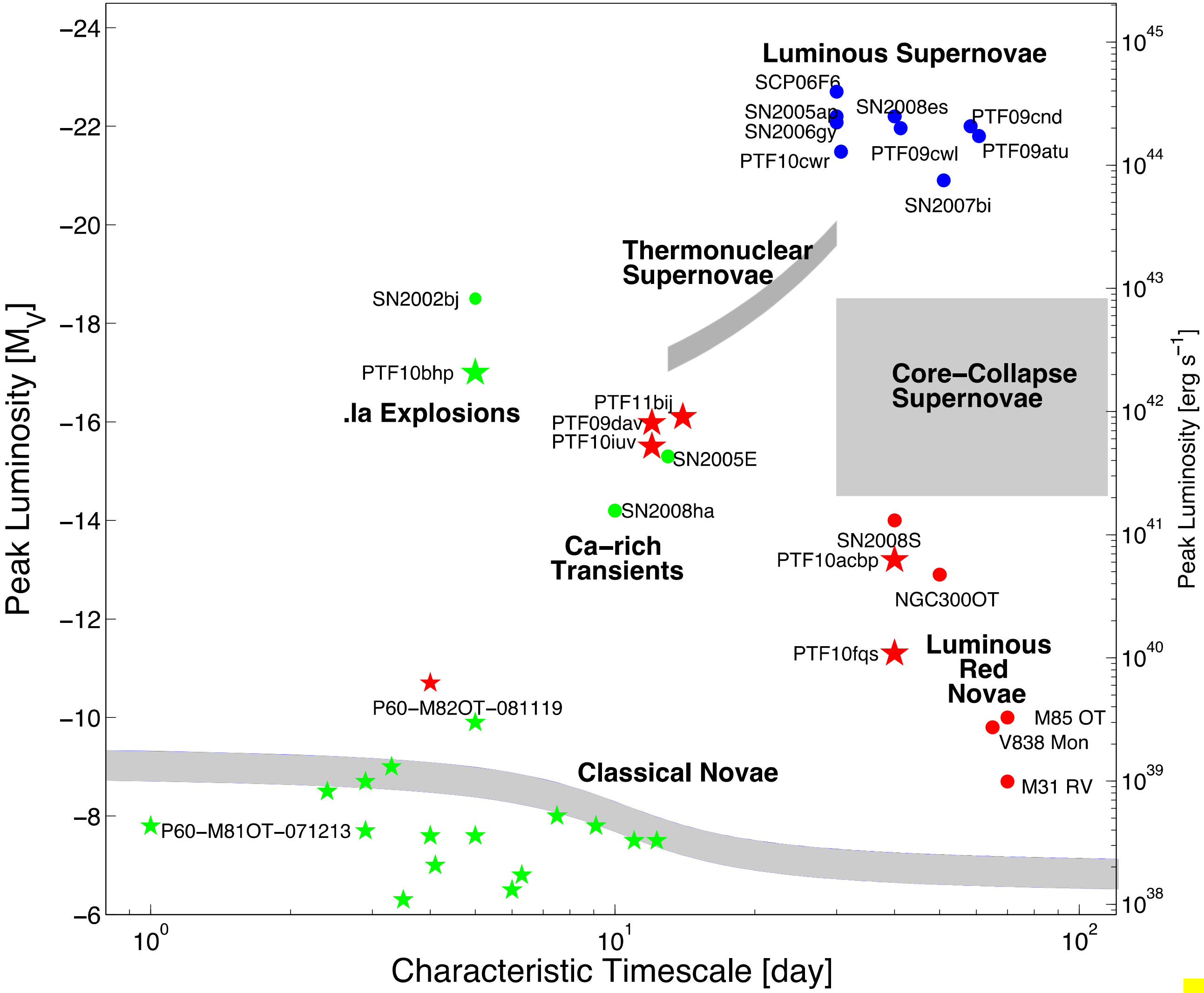


Figure 1

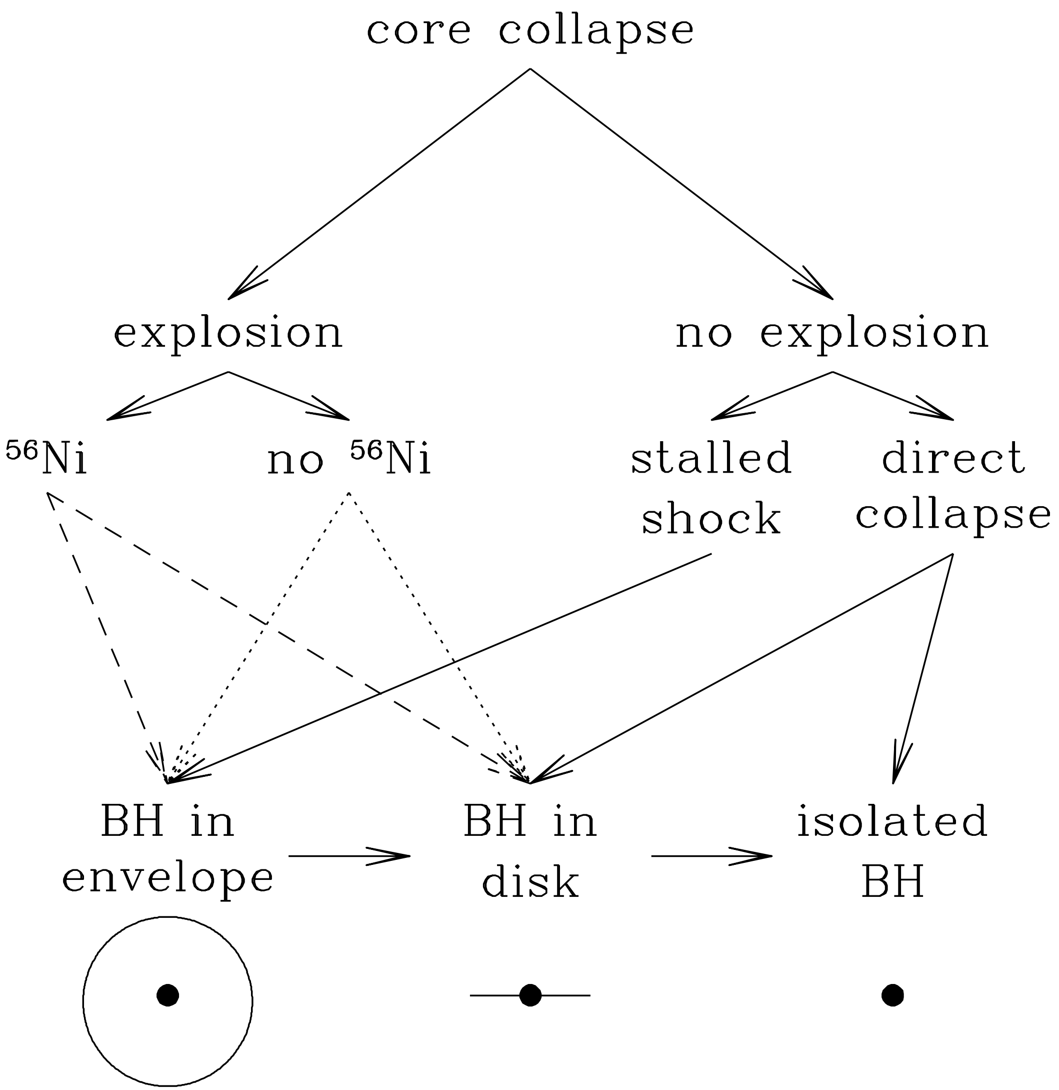
Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown at the top. The estimated binary inclination is indicated by the tilt of the accretion disk. The color of the companion star roughly indicates its surface temperature.

Optical Transients



Kasliwal 11

Possible Outcomes in a BH Formation



Kochanek+08

core collapse

explosion

no explosion

^{56}Ni

no ^{56}Ni

stalled shock

direct collapse

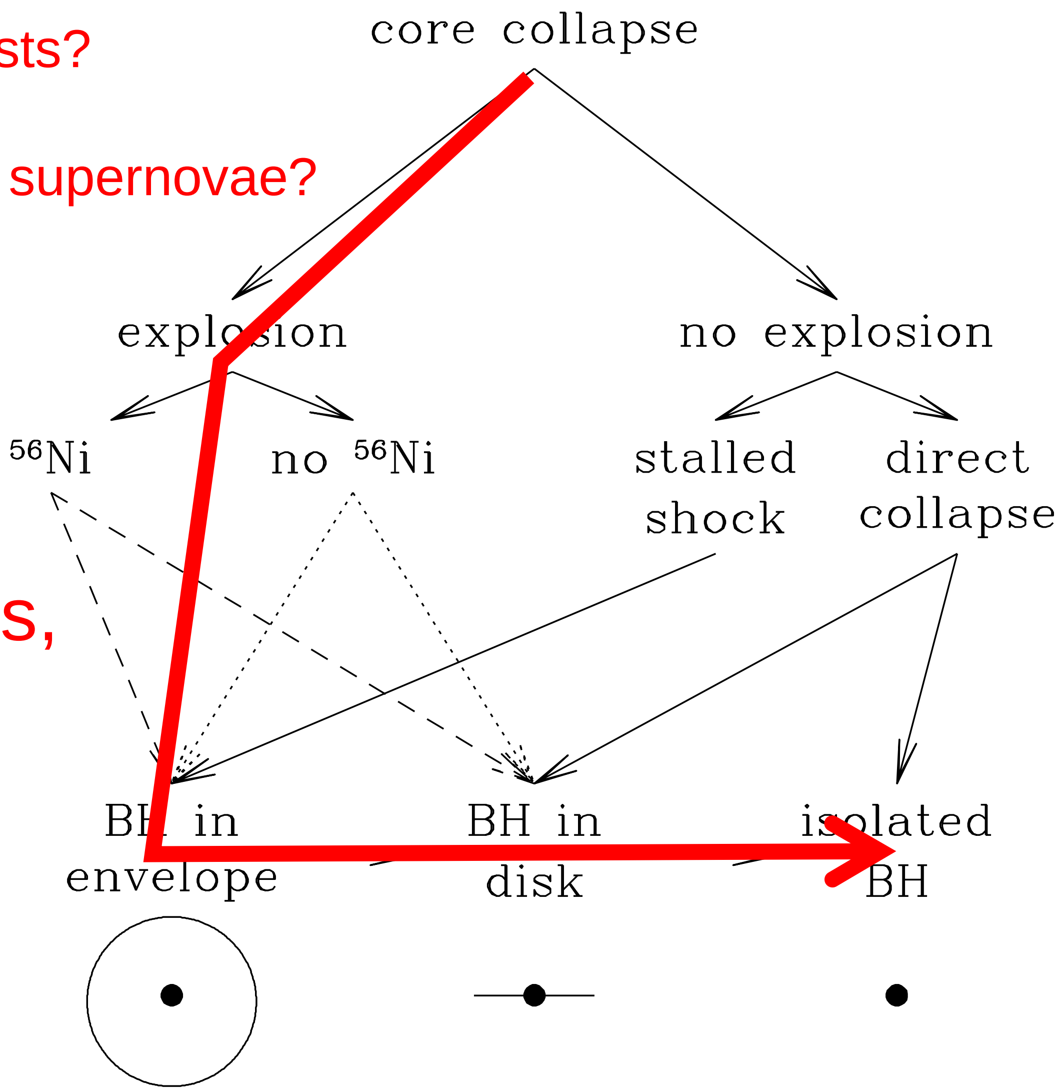
BH in envelope

BH in disk

isolated BH

Possible Outcomes in a BH Formation

Gamma-ray bursts?
Hypernovae?
Super-luminous supernovae?

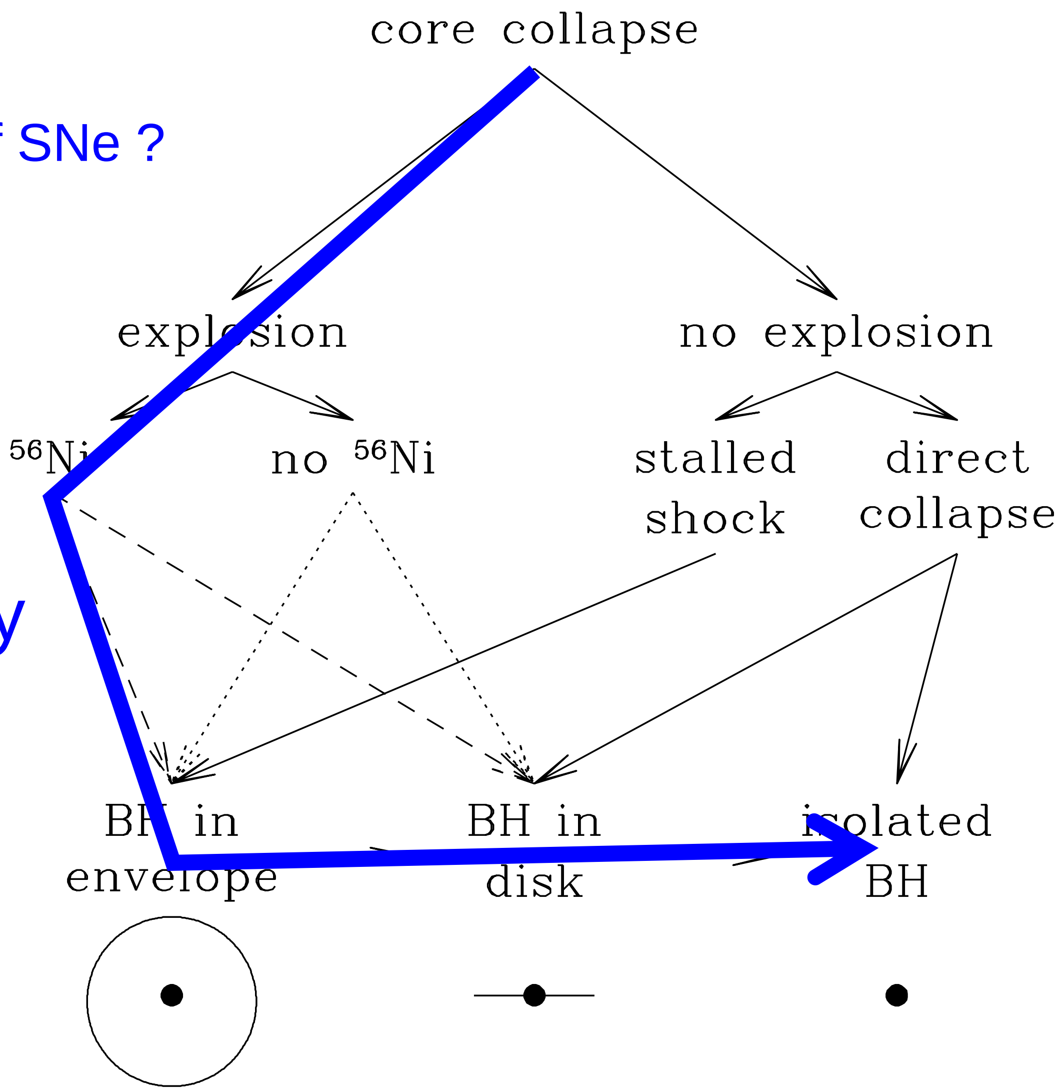


luminous,
but rare

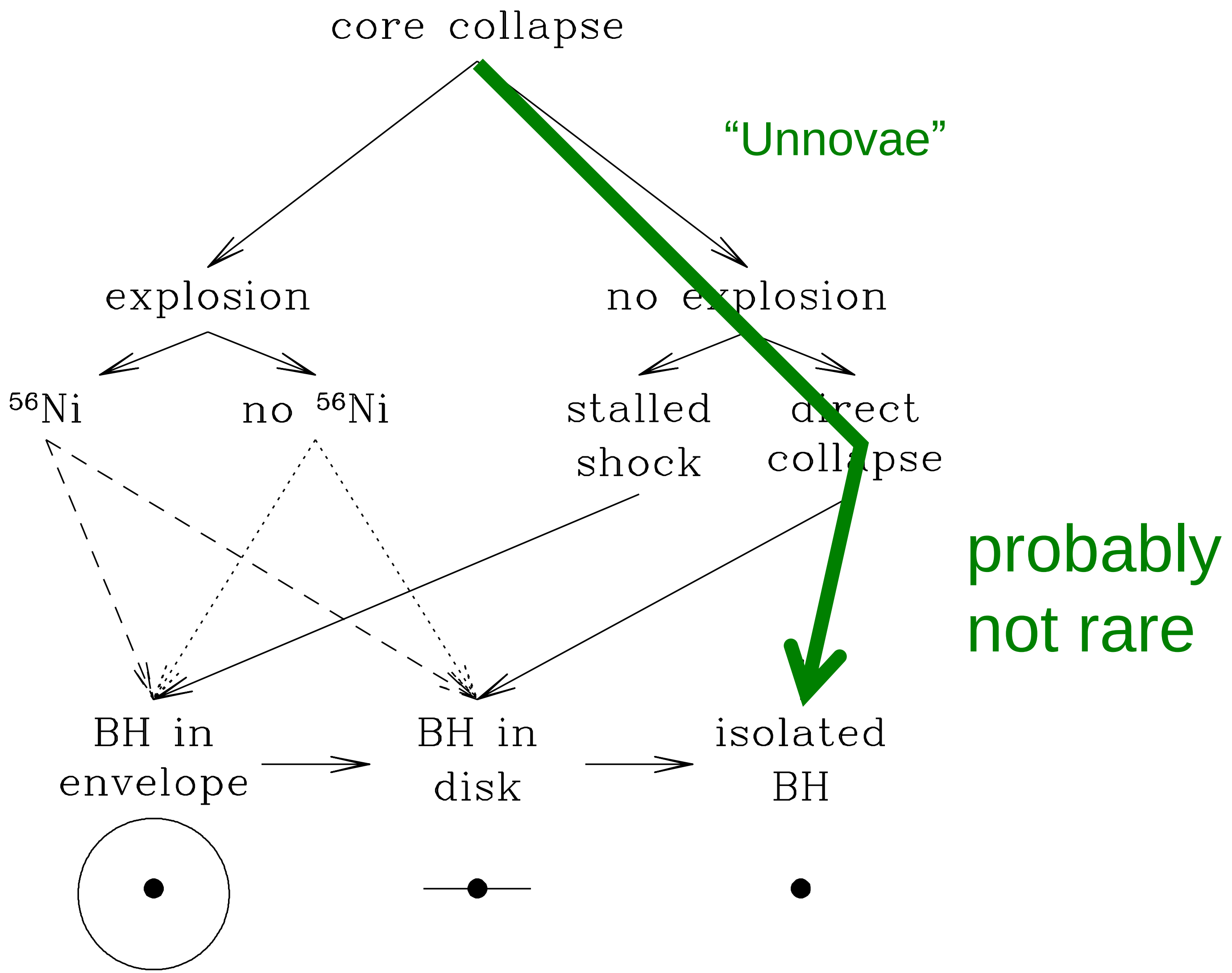
Possible Outcomes in a BH Formation

Dimer class of SNe ?
(e.g., 1987A)

probably
not rare



Possible Outcomes in a BH Formation



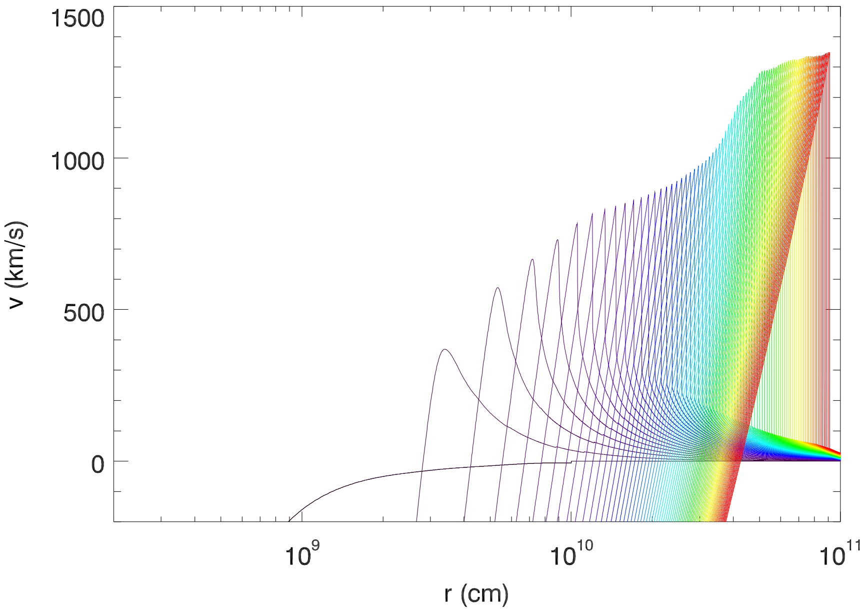
"Unnovae"

probably not rare

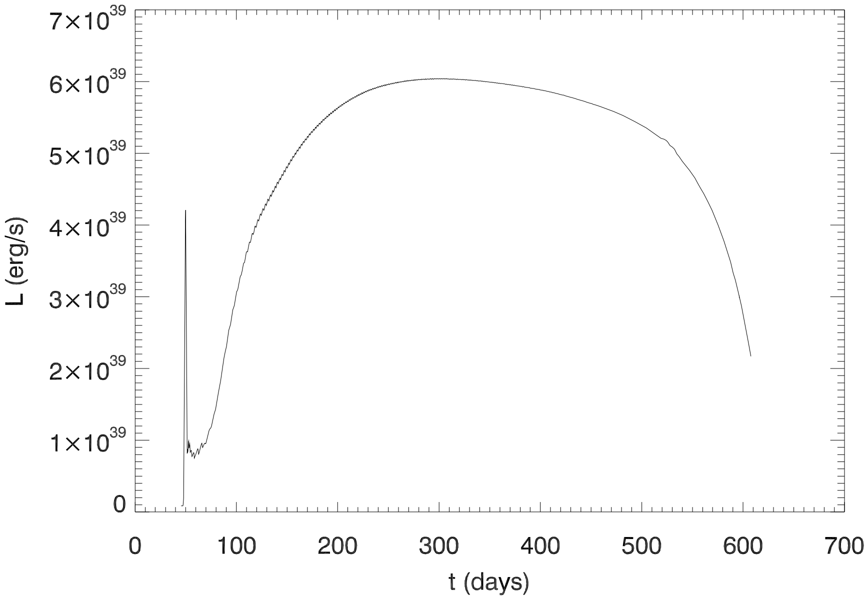
Very low energy supernovae from neutrino mass loss

Even if the SN shock is stalled,
a weak shock can be driven by
neutrino mass loss of the PNS.

Nadezhin 80, Lovegrove & Woosley 13



“Luminous red novae”



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

$\gtrsim$ Bind. E of H envelope of RSG

A significant part of the energy comes from H recombination.

$$T \sim 3000\ {\rm K}$$

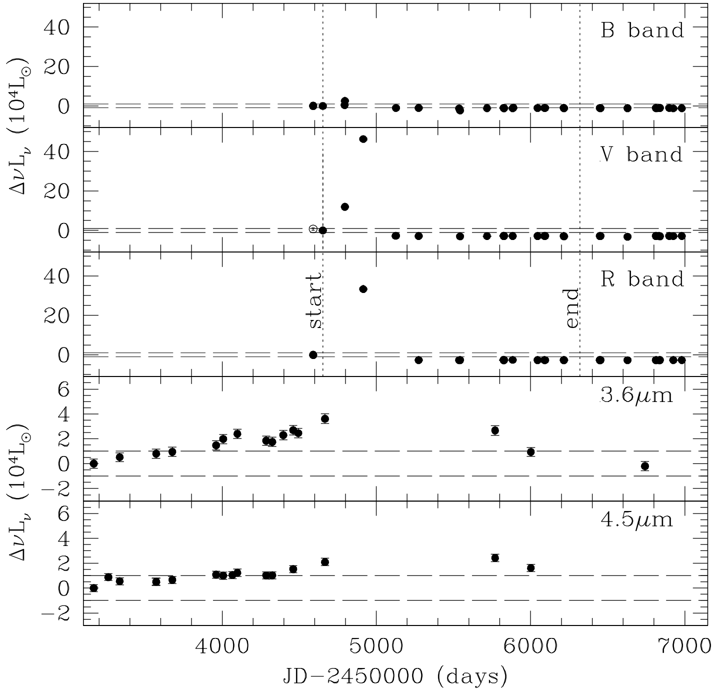
Searching for vanishing supergiants

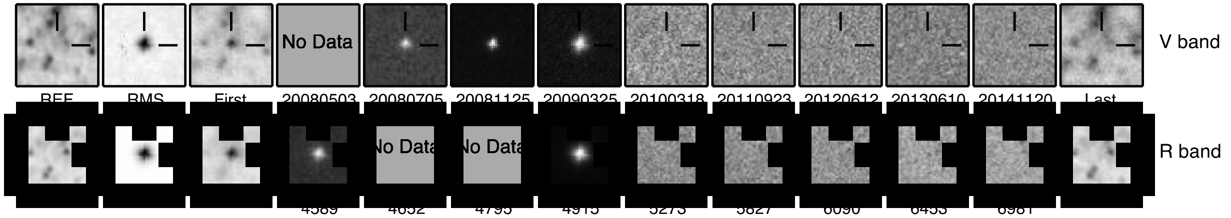
- Monitoring ~10^6 RSGs in ~25 Gal. within ~10 Mpc with ~0.5 yr cadence for ~5 yrs using the Large Binocular Telescope
- Examine sources with

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

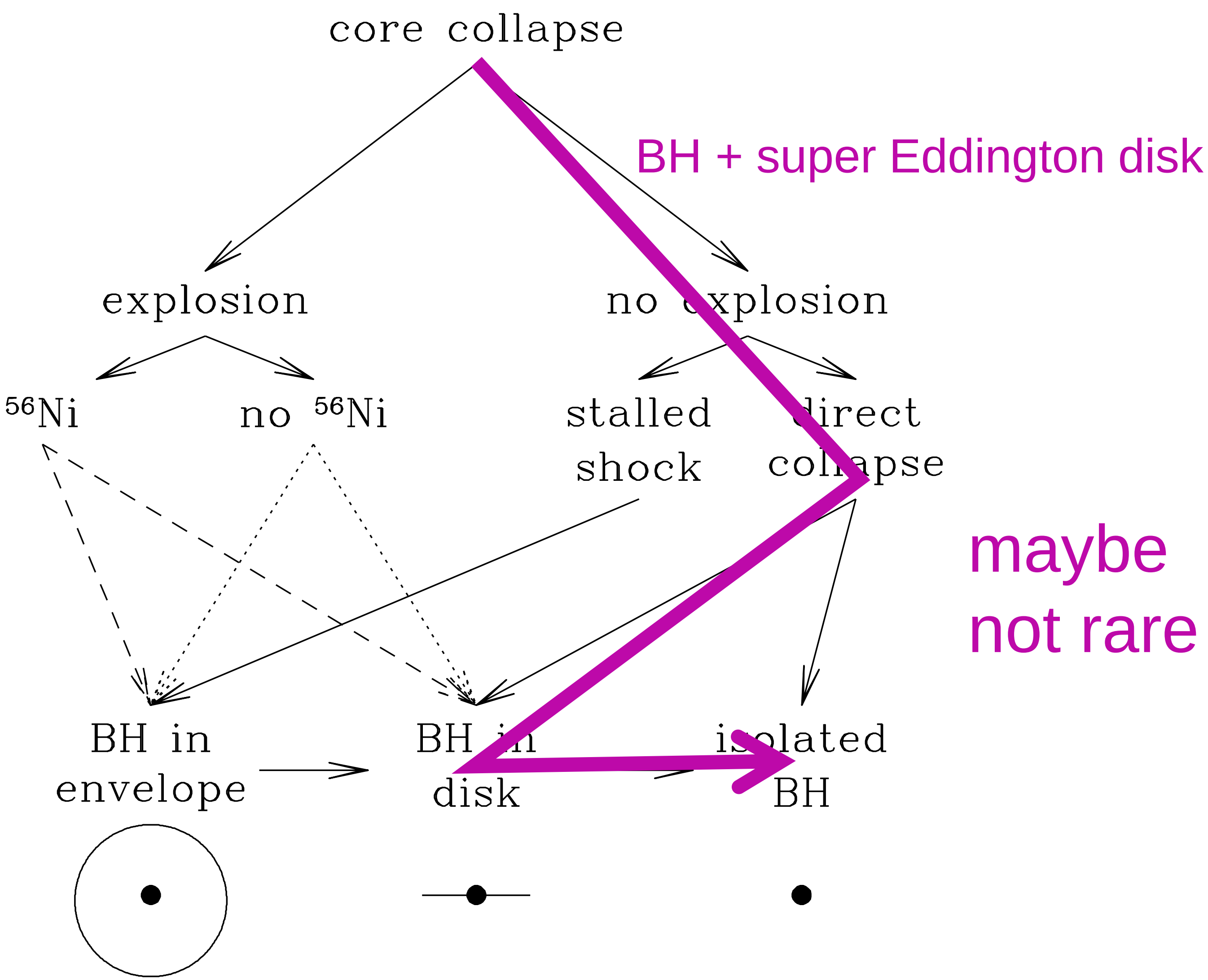
- 3 core collapse supernovae
- 1 candidate of vanishing RSG
- Continuous obs. will give meaningful constraints on failed SN rate.

Kochanek+08, Gerke+15





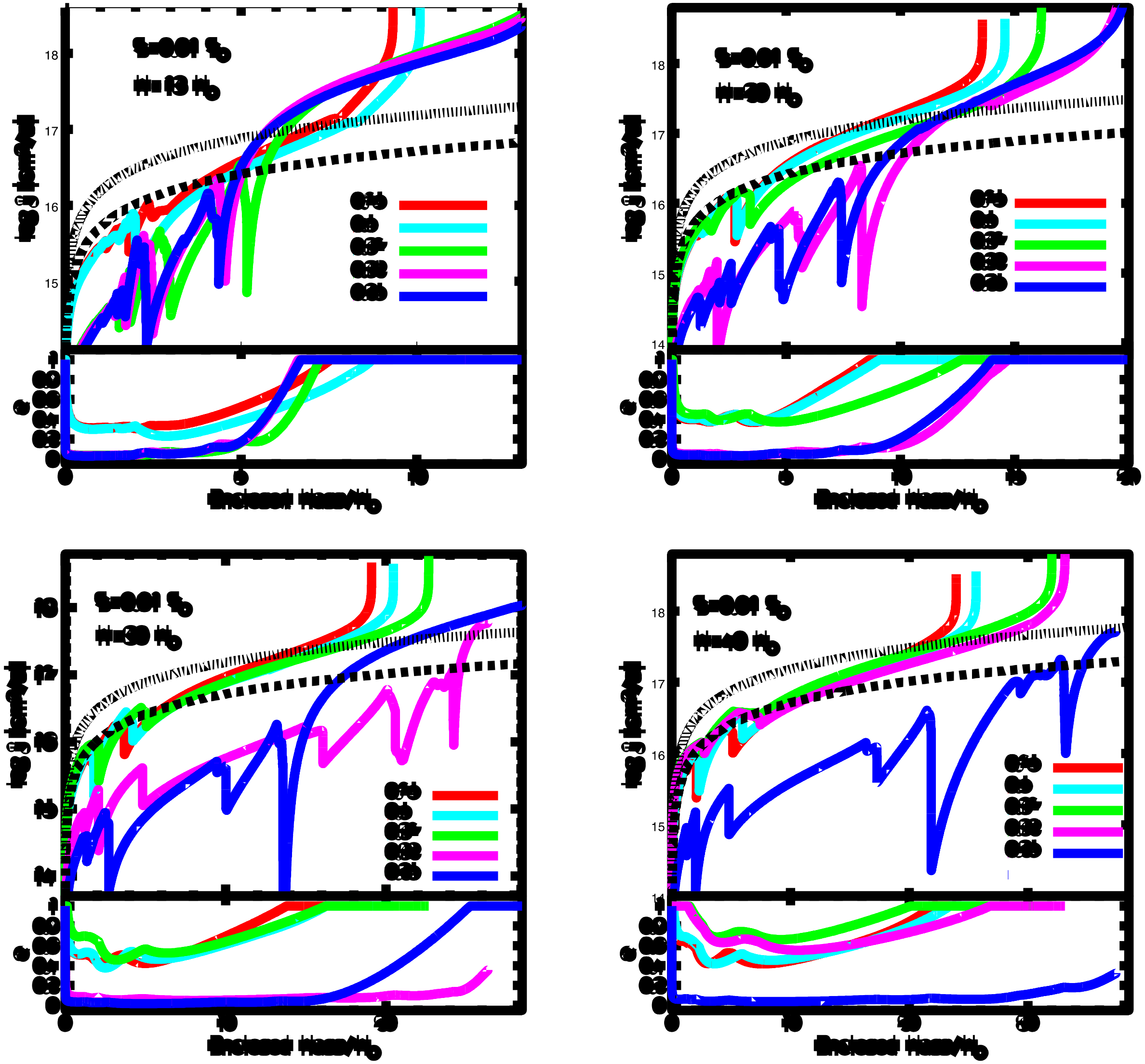
Possible Outcomes in a BH Formation



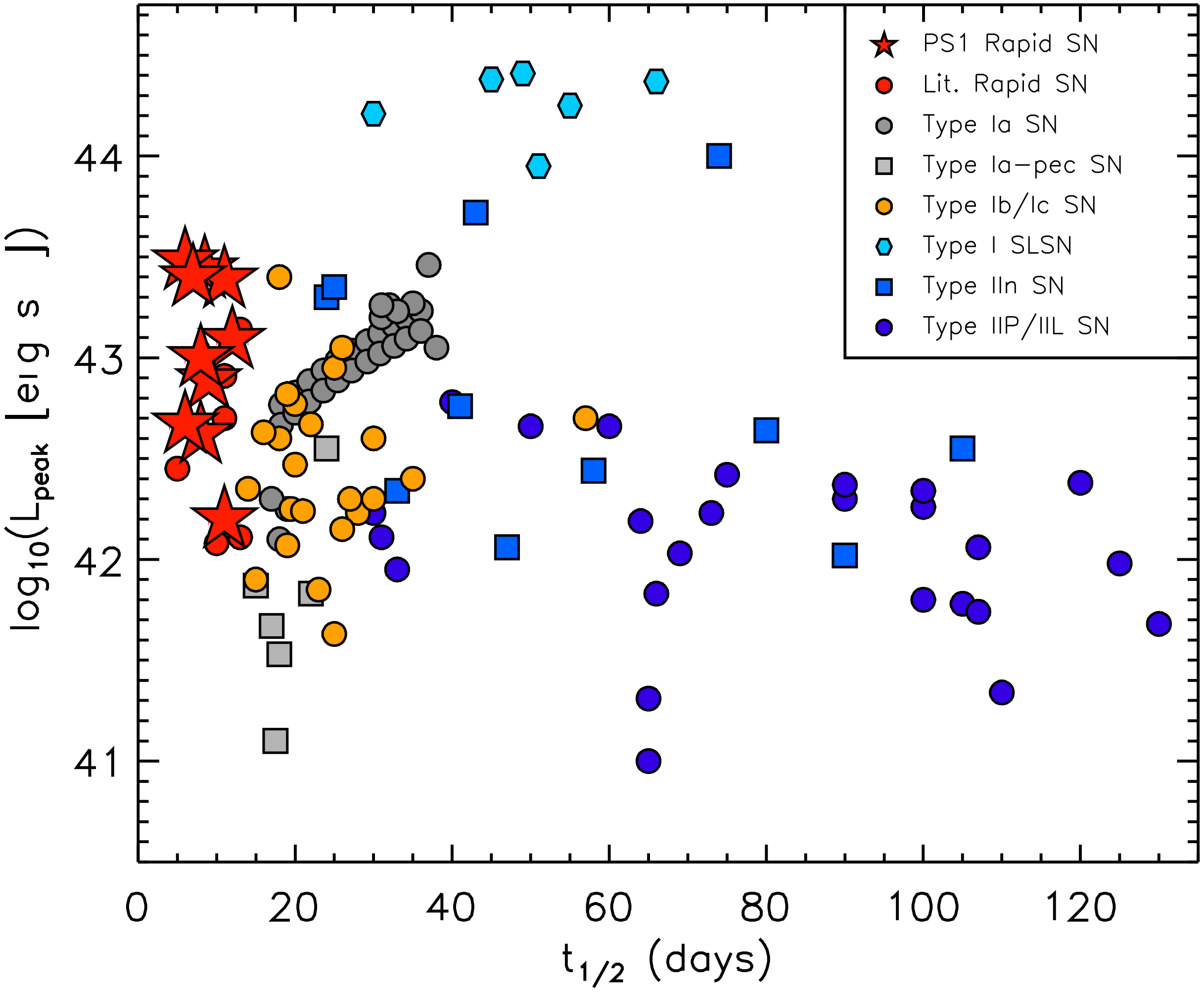
maybe not rare

Fall back disk may be ubiquitous

Perna+14

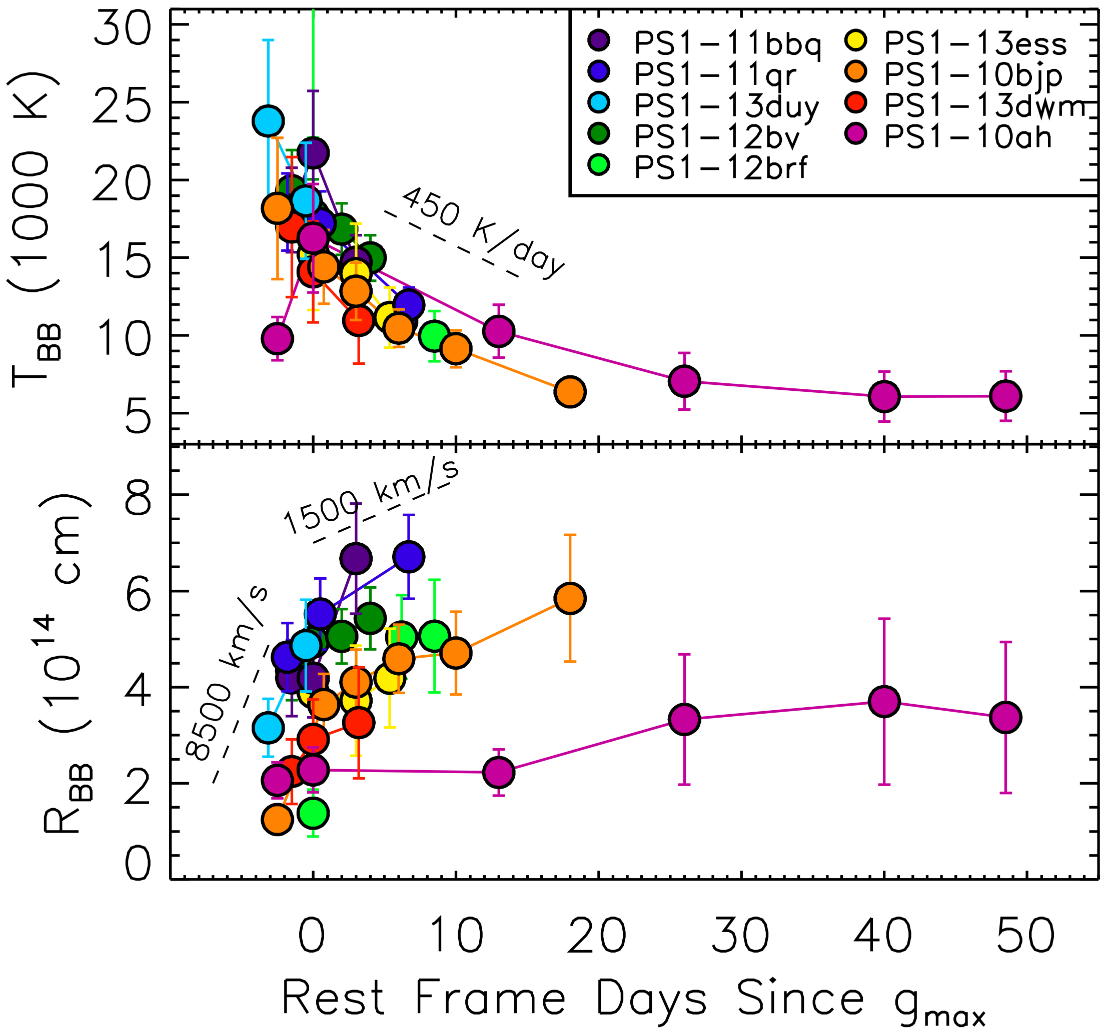


The PS1-MDS Transients



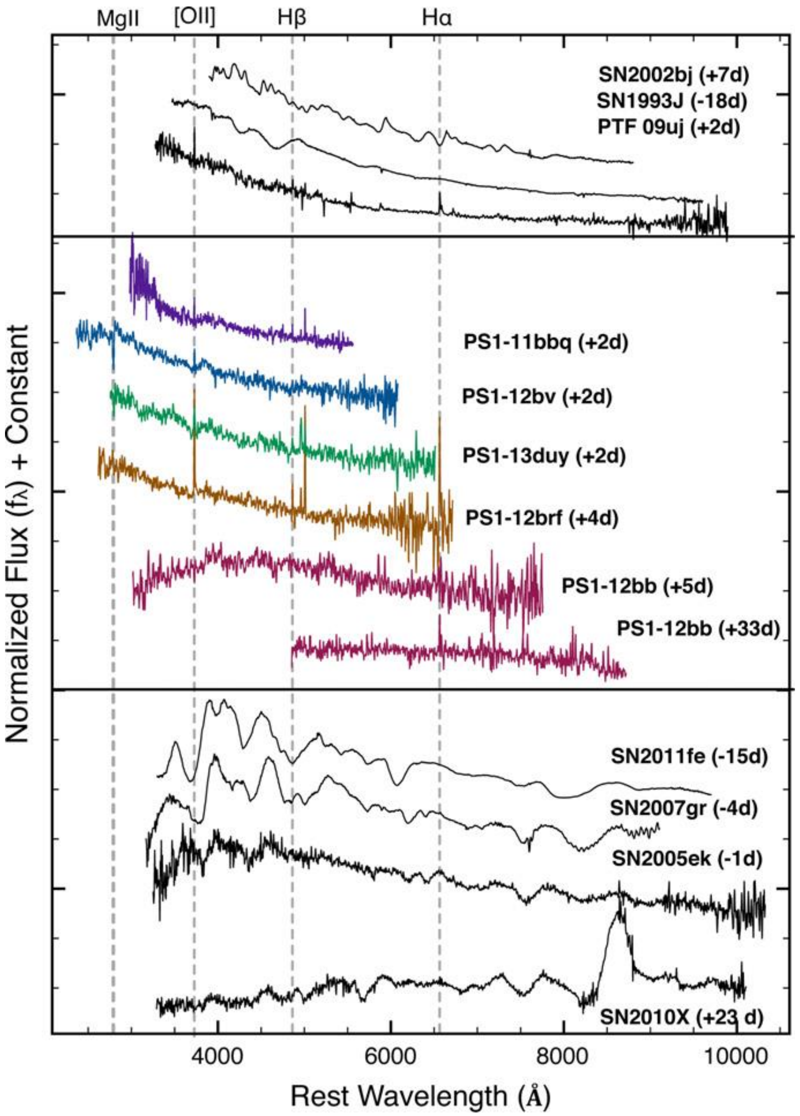
Drout+14

The PS1-MDS Transients



Drout+14

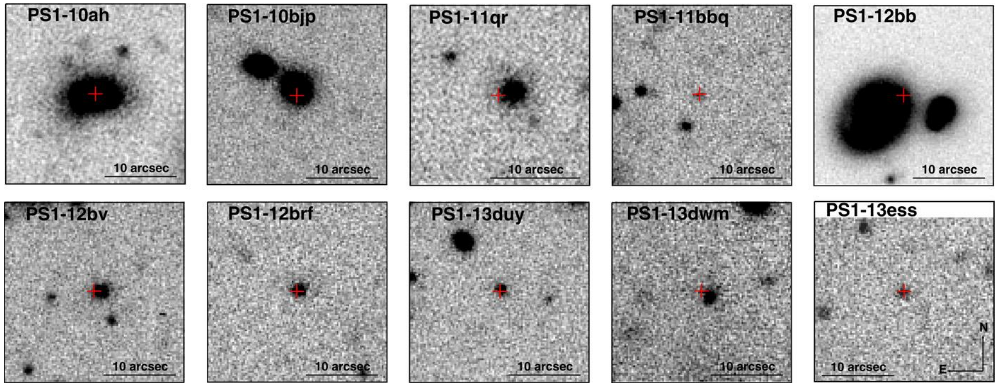
The PS1-MDS Transients

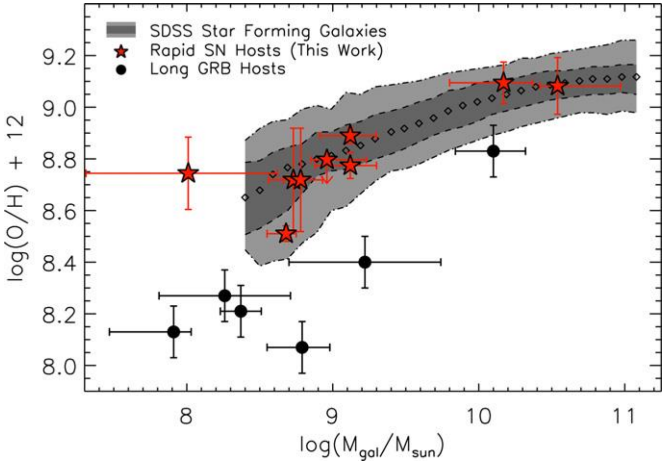


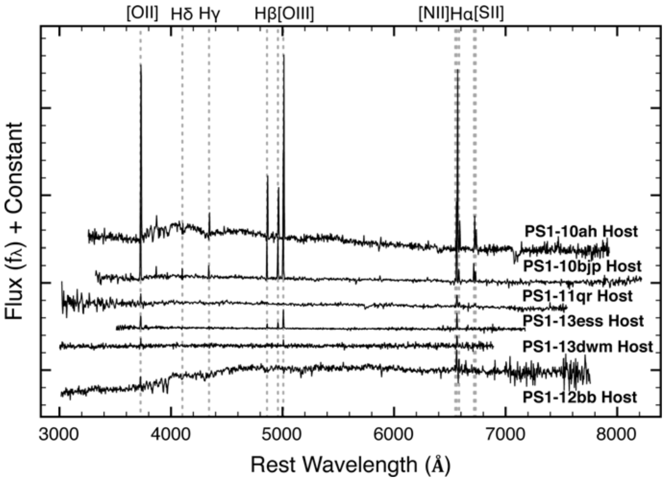
Blue Continua
No Line Blanketing

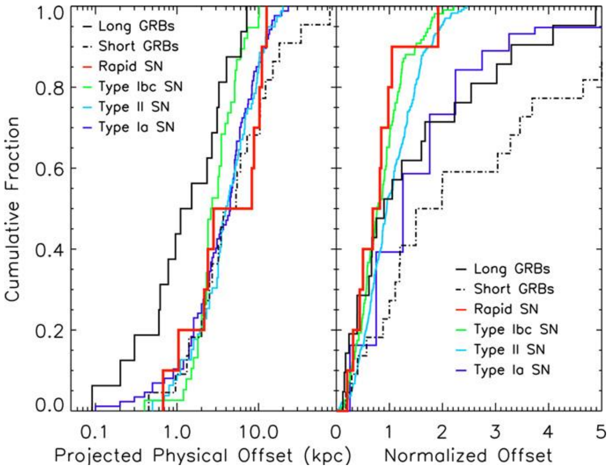
Drout+14

The PS1-MDS Transients





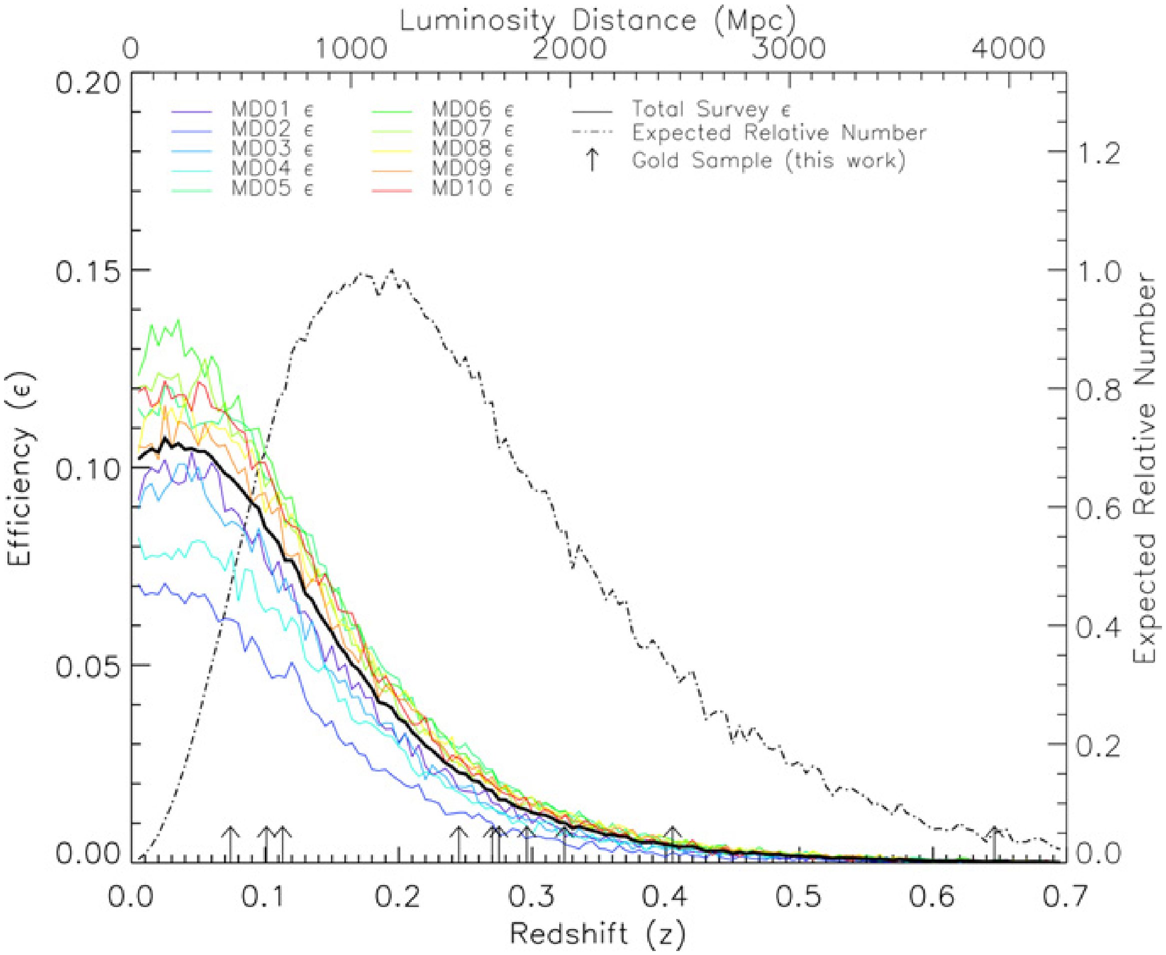




Host Gal. = SF Gal.

Drout+14

The PS1-MDS Transients



4%-7% of CCSN@z =0.2

Drout+14