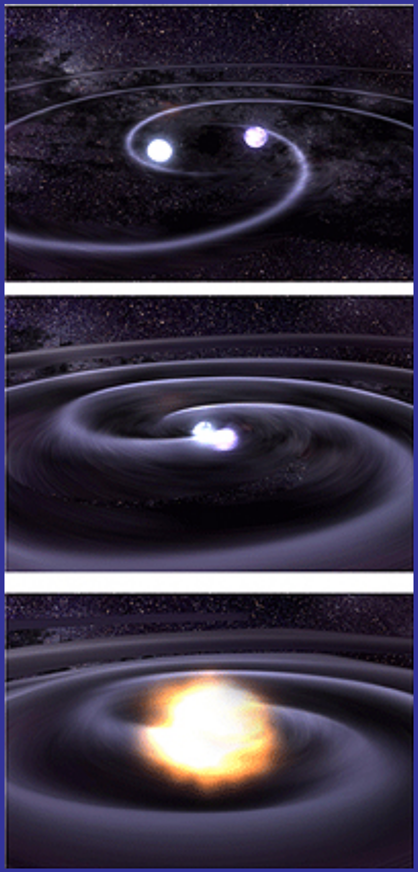
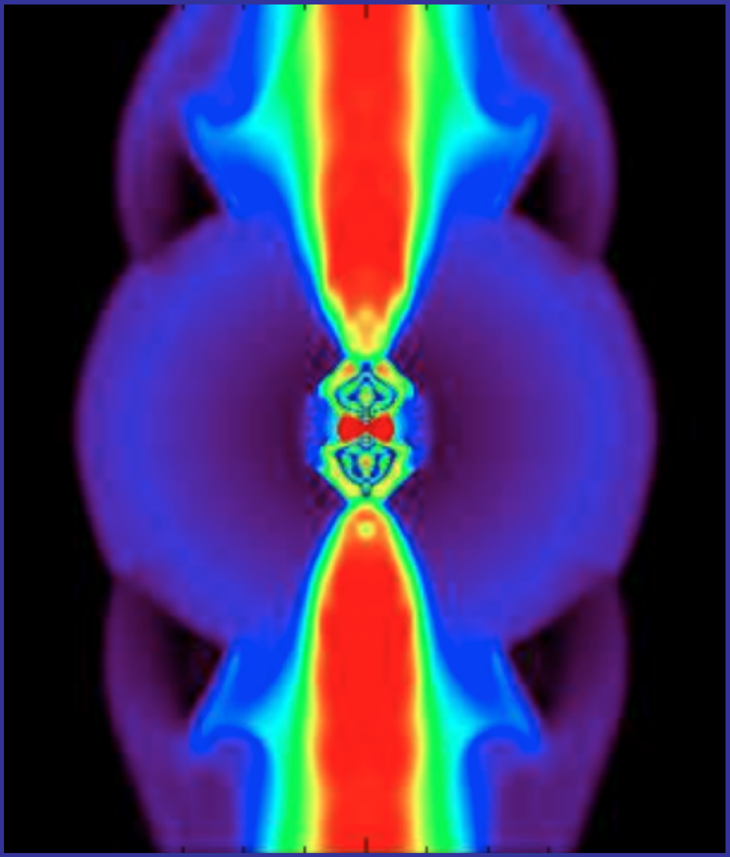
Gamma-Ray Bursts:

3. Short GRBs

Brian Metzger, Columbia University

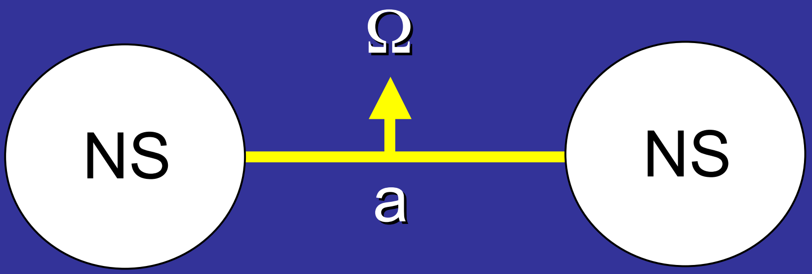


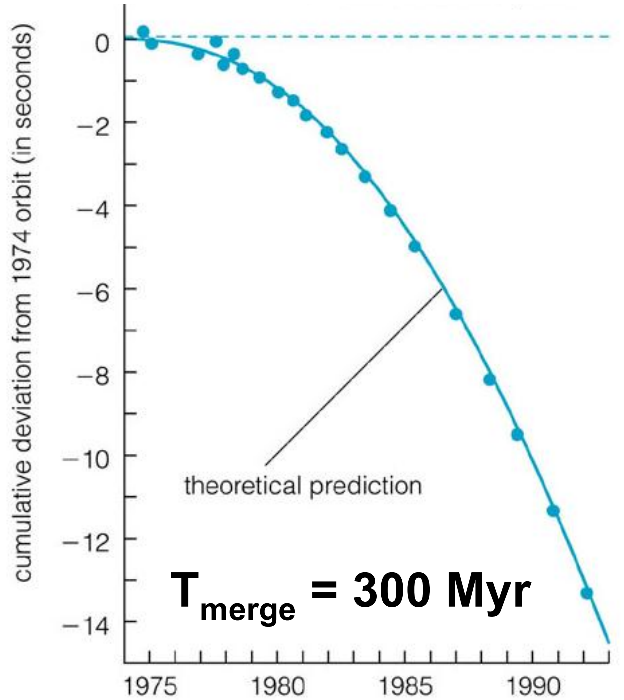


Binary Neutron Star Mergers

Gravitational Waves

$$-\frac{1}{P}\frac{dP}{dt} = \frac{48}{5}\frac{G^3}{c^5}\frac{M^2}{a^4}$$





Hulse-Taylor Pulsar

T_{merge} = 300 Myr

10 Known Galactic NS-NS Binaries

(Lorimer 2008)

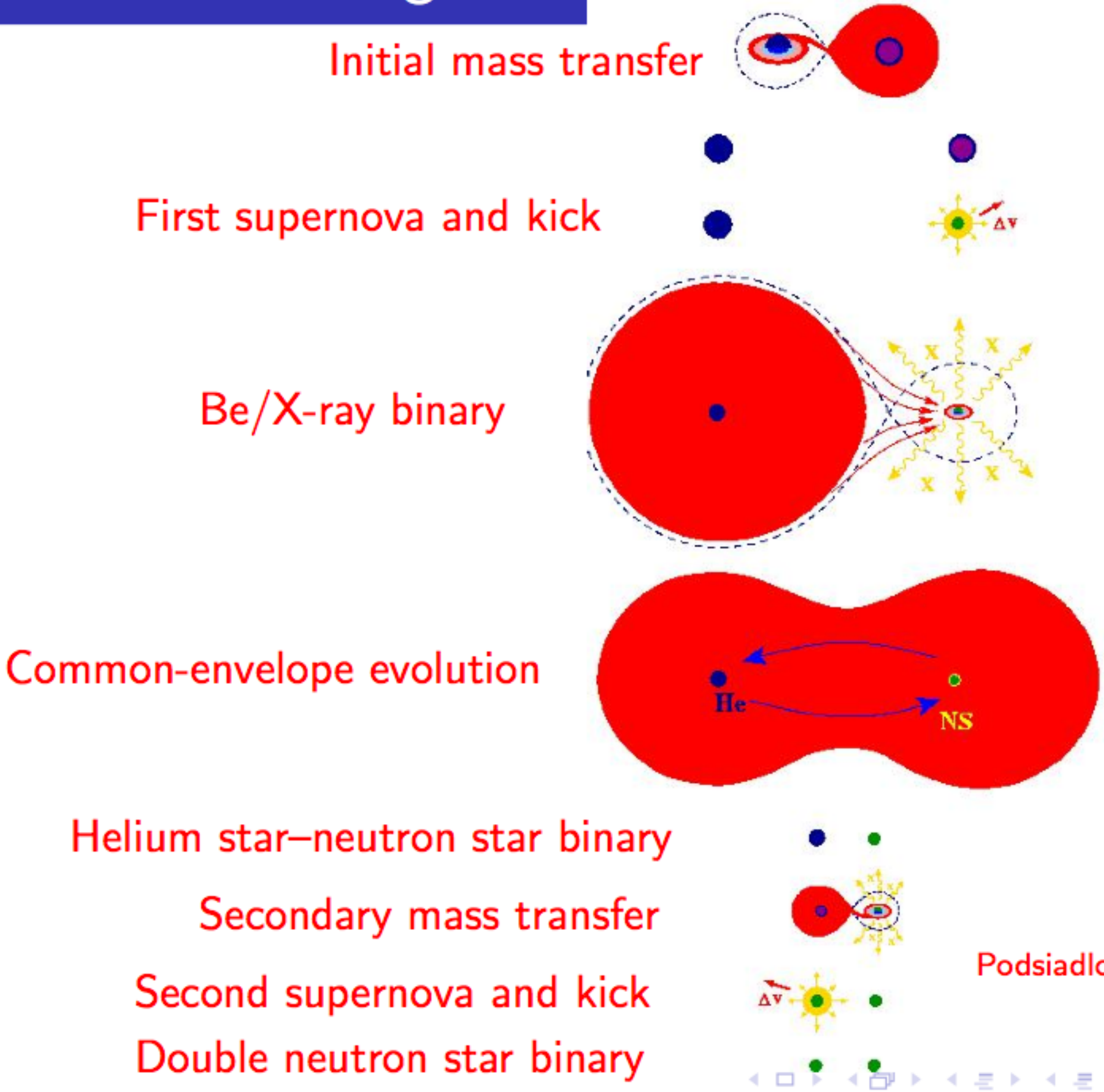
	J0737−3039	J1518+4904	B1534+12	J1756−2251	J1811−1736
P [ms]	22.7/2770	40.9	37.9	28.5	104.2
P_b [d]	0.102	8.6	0.4	0.32	18.8
e	0.088	0.25	0.27	0.18	0.83
$\log_{10}(\tau_c/[\mathrm{yr}])$	8.3/7.7	10.3	8.4	8.6	9.0
$\log_{10}(\tau_g/[\mathrm{yr}])$	7.9	12.4	9.4	10.2	13.0
Masses measured?	Yes	No	Yes	Yes	Yes

	B1820−11	J1829+2456	J1906+0746	B1913+16	B2127+11C
P [ms]	279.8	41.0	144.1	59.0	30.5
P_b [d]	357.8	1.18	0.17	0.3	0.3
e	0.79	0.14	0.085	0.62	0.68
$\log_{10}(\tau_c/[\mathrm{yr}])$	6.5	10.1	5.1	8.0	8.0
$\log_{10}(\tau_g/[\mathrm{yr}])$	15.8	10.8	8.5	8.5	8.3
Masses measured?	No	No	Yes	Yes	Yes

$$\dot{N}_{merge} \sim 10^{-5} - 10^{-4}\ \mathrm{yr}^{-1}$$

(Kalogera et al. 2004)

Double Neutron Star Mergers



Initial mass transfer

First supernova and kick

Be/X-ray binary

Common-envelope evolution

Helium star–neutron star binary

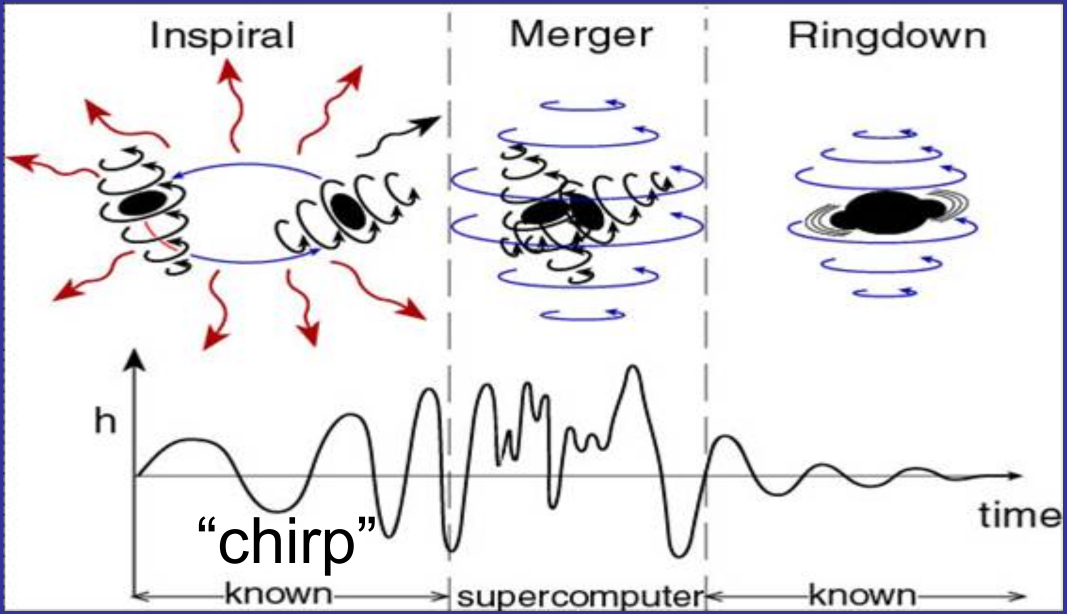
Secondary mass transfer

Second supernova and kick

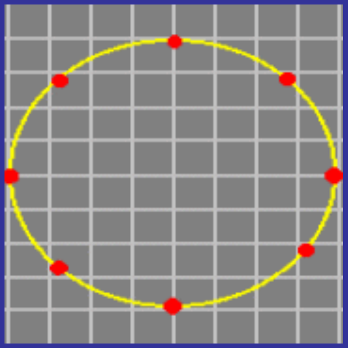
Double neutron star binary

Podsiadlowski

Gravitational Waves from Inspiral and Merger



Credit: Kip Thorne



Ground-Based
Interferometers

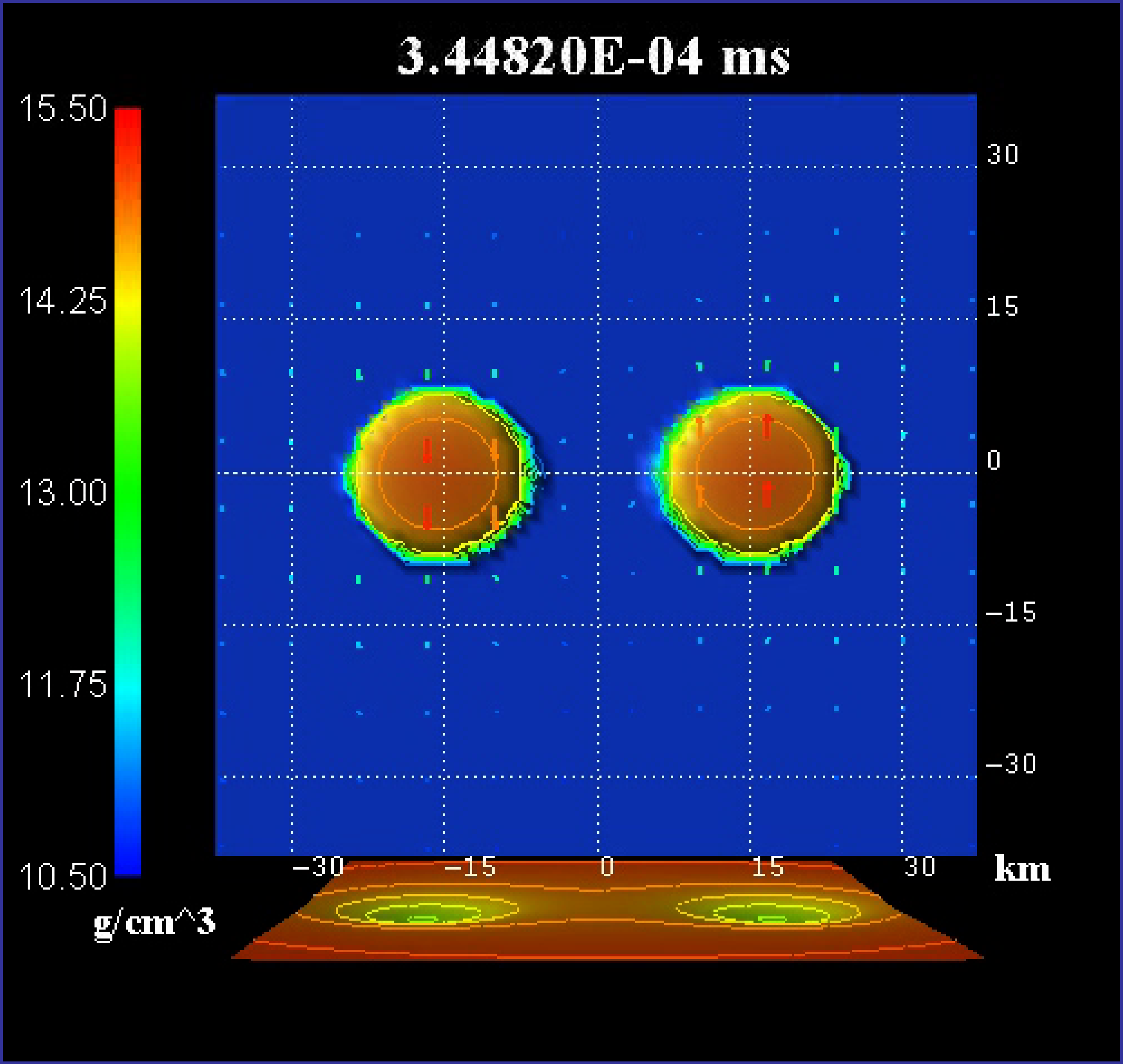
LIGO 6th Science Run
(2010) Range ~ 20-50 Mpc

**"Advanced" LIGO+Virgo
(~2016) Range ~ 300-600 Mpc**

LIGO (North America)

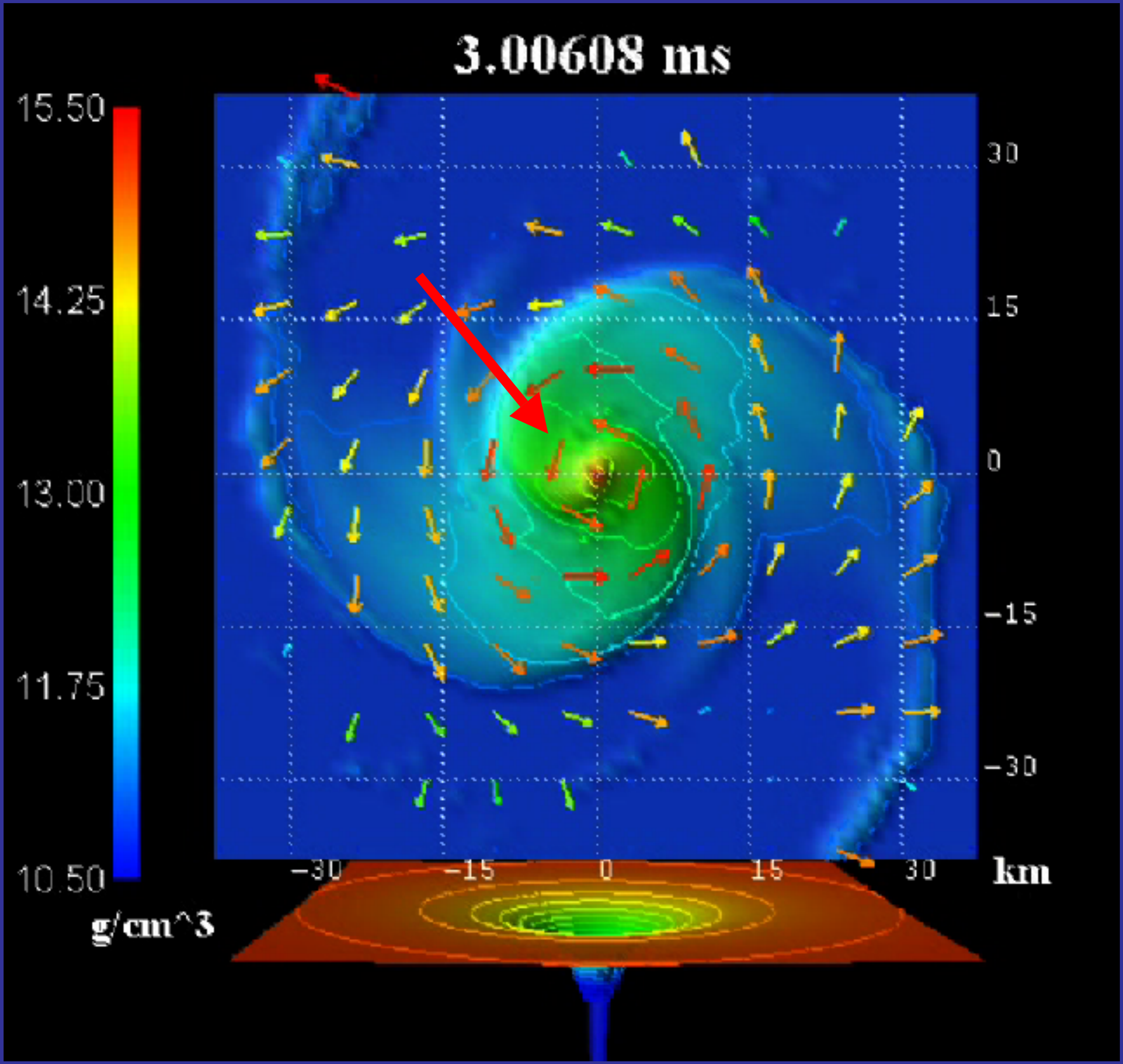
Virgo (Italy)

Numerical Simulation - Two 1.4 $M_\odot$ NSs



Courtesy M. Shibata (Tokyo U)

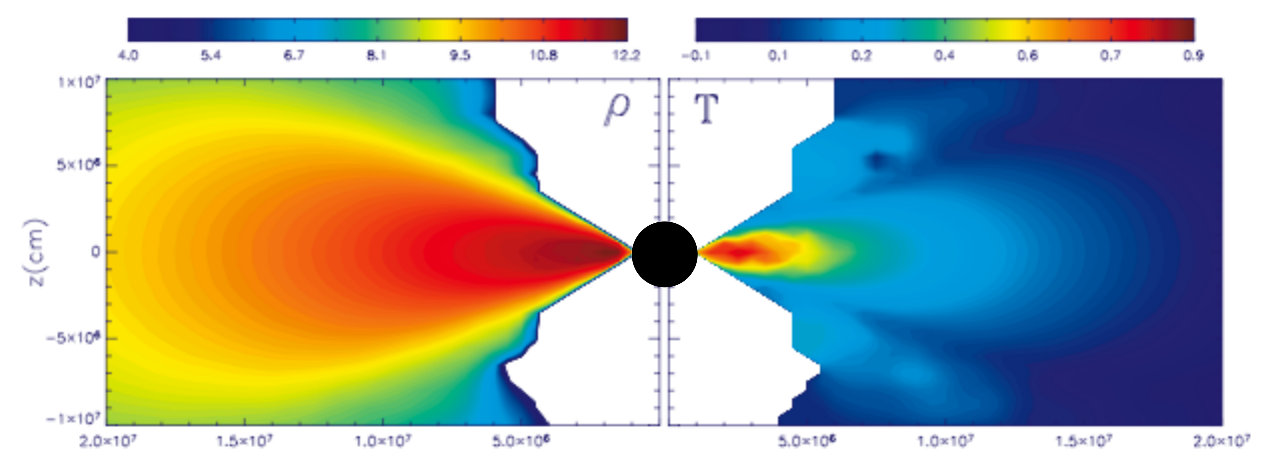
Numerical Simulation - Two 1.4 $M_\odot$ NSs



Courtesy M. Shibata (Tokyo U)

Remnant Accretion Disk

(e.g. Ruffert & Janka 1999; Shibata & Taniguchi 2006; Faber et al. 2006; Chawla et al. 2010; Duez et al. 2010; Foucalt 2012; Deaton et al. 2013)



Lee et al. 2004

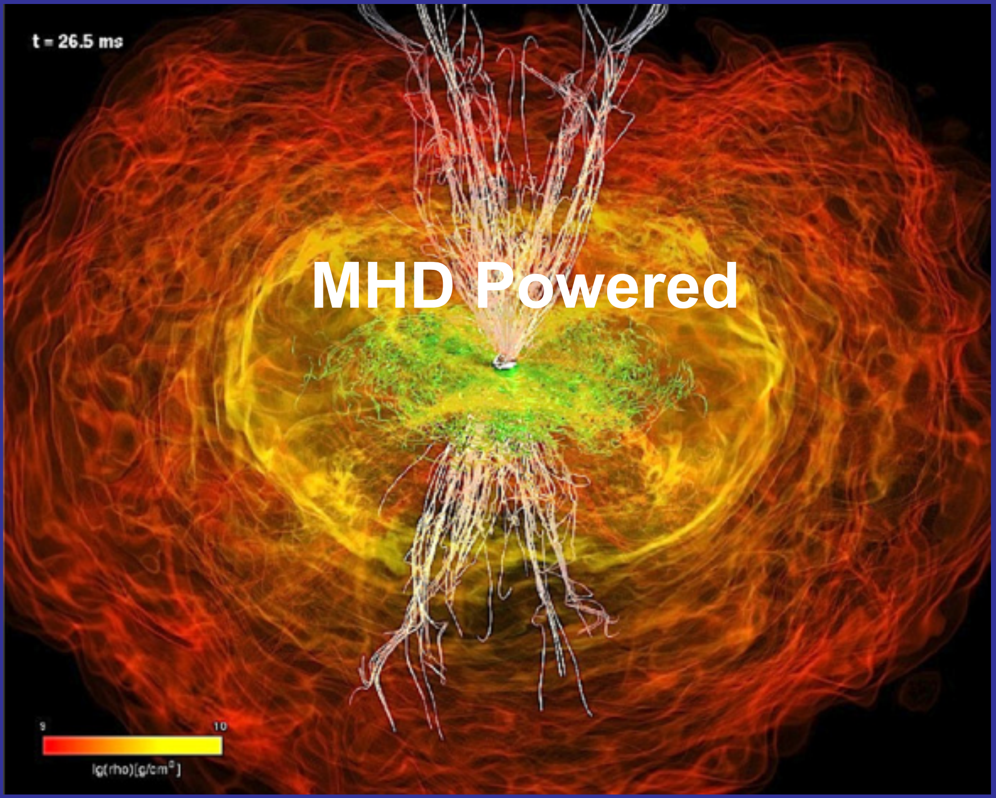
- Disk **Mass ~0.01 - 0.1 $M_\odot$** & **Size ~ 10-100 km**
- Hot (T > MeV) & Dense ($\rho \sim 10^8$-10^{12} g cm^{-3})
- Neutrino Cooled: ($\tau_\nu \sim$ 0.01-100)
- Equilibrium $e^+ + n \rightarrow \bar{\nu}_e + p$ vs. $e^- + p \rightarrow \nu_e + n$ $\Rightarrow Y_e \sim 0.1$

Accretion Rate $\dot{M} \sim 10^{-2} - 10\,M_\odot\ \mathrm{s}^{-1}$

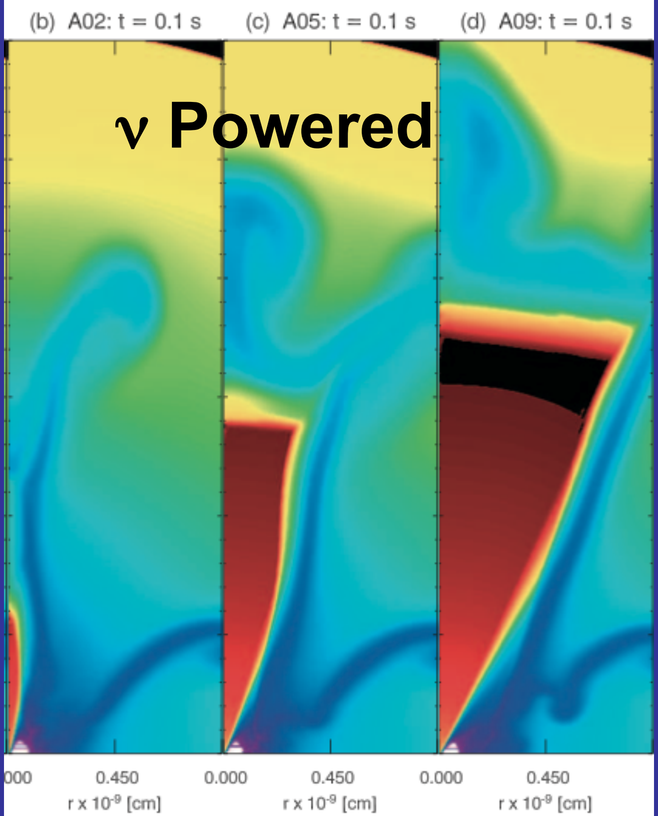
$$t_{\rm visc} \sim 0.1\left(\frac{M_\bullet}{3M_\odot}\right)^{1/2}\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{R_d}{100\ \mathrm{km}}\right)^{3/2}\left(\frac{H/R}{0.5}\right)^{-2}\ \mathrm{s}$$

Short GRB Engine?

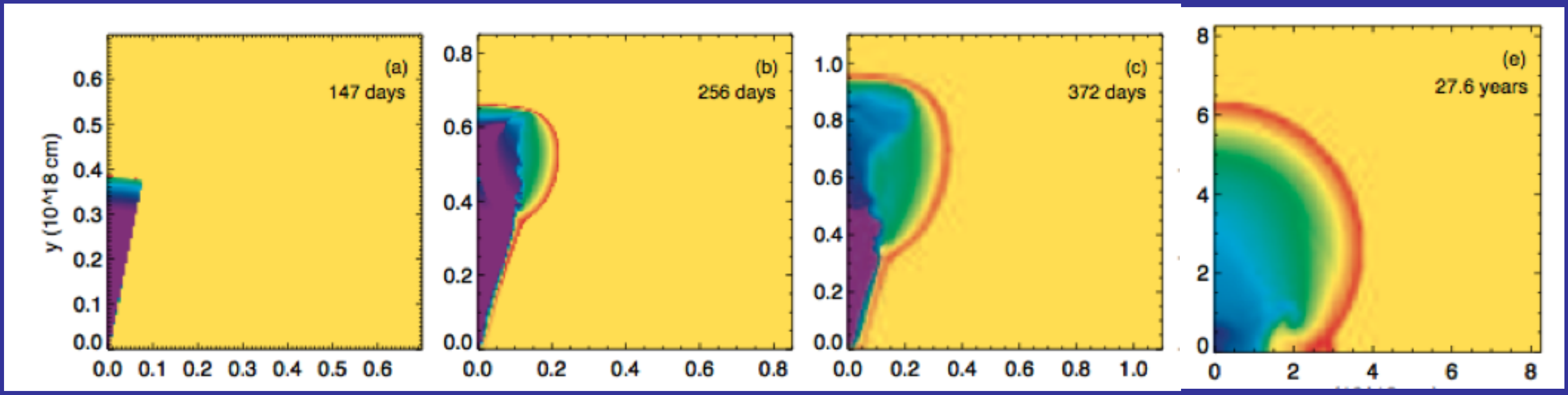
Relativistic Jets and Short GRBs



Rezzolla et al. 2010

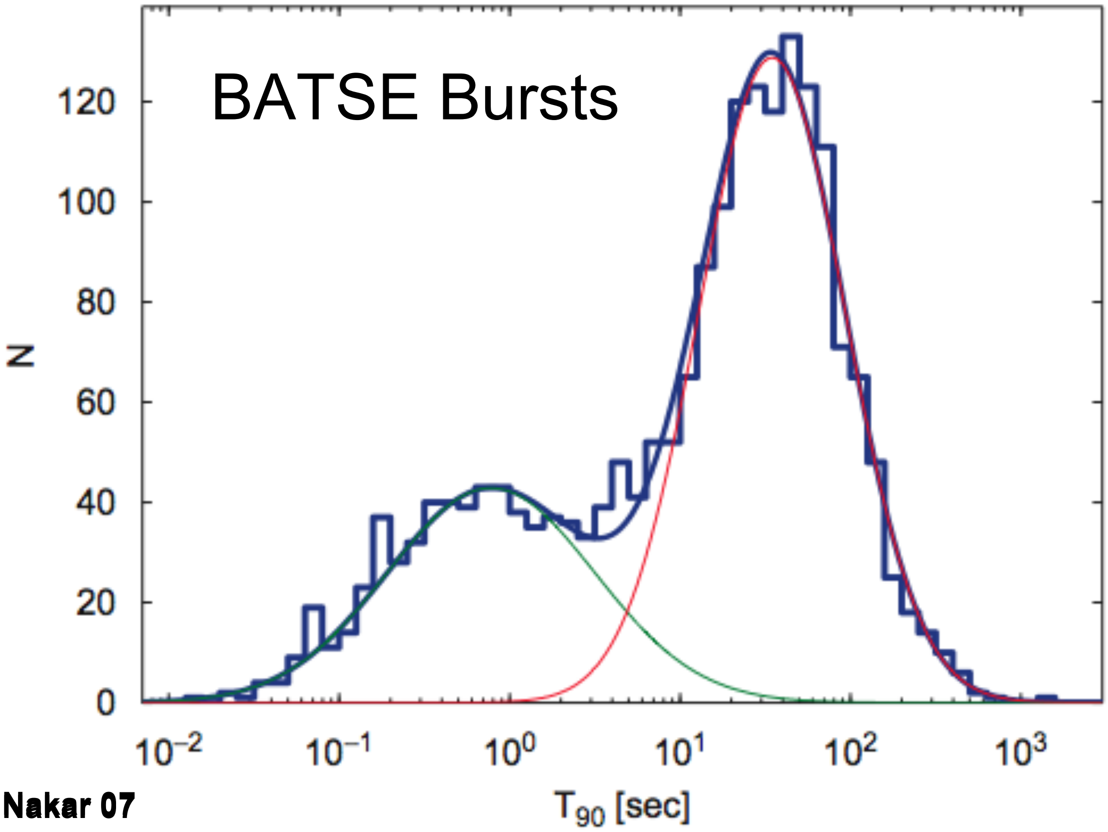


Aloy et al. 2005



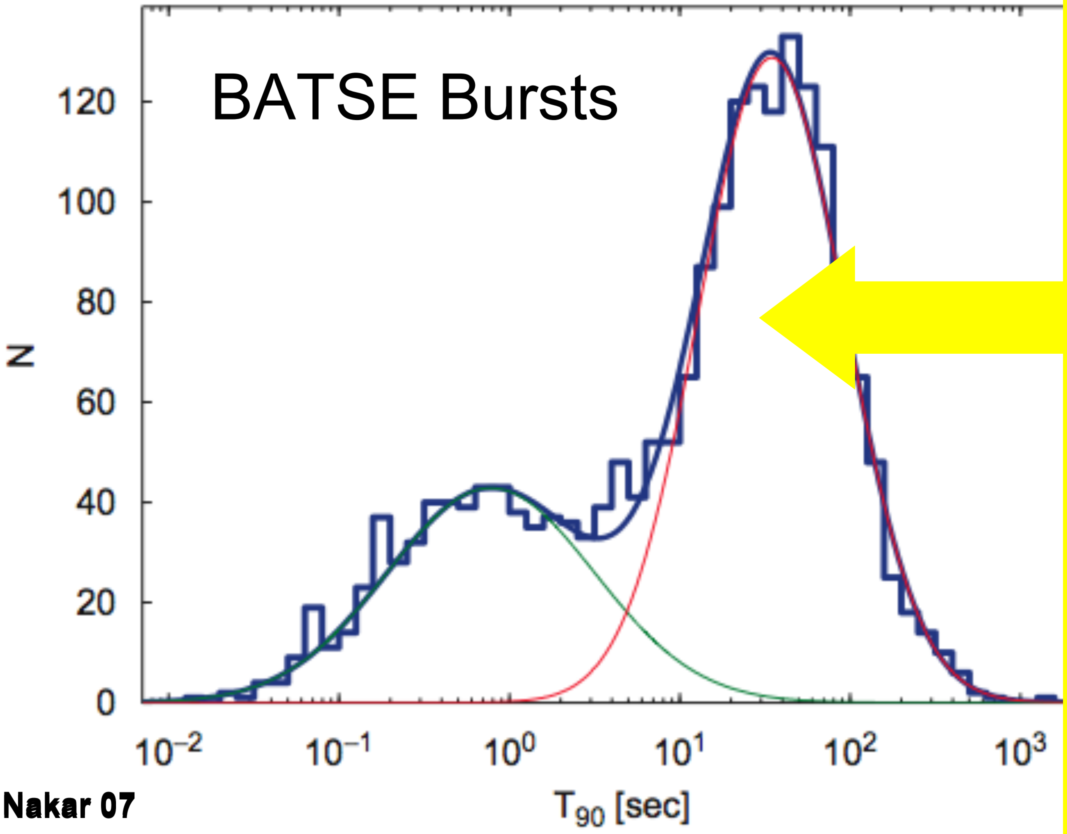
Zhang & MacFadyen 2009

Short & Long Gamma-Ray Bursts



Nakar 07

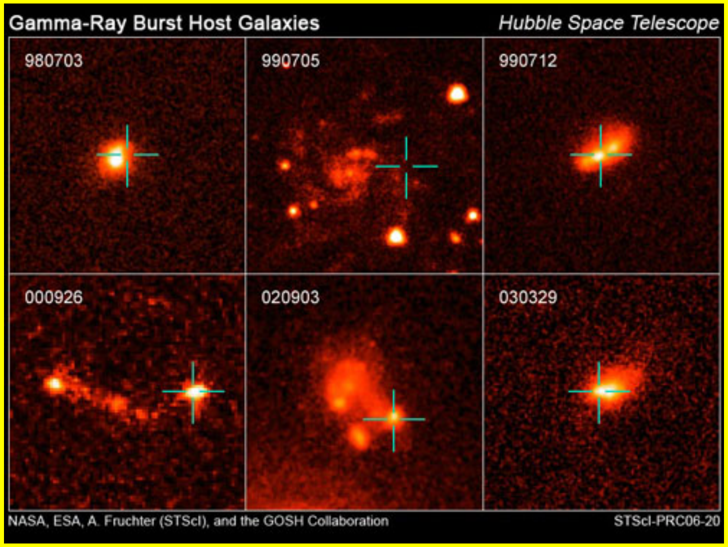
Short & Long Gamma-Ray Bursts



Nakar 07

Long GRBs = Death of Massive Stars

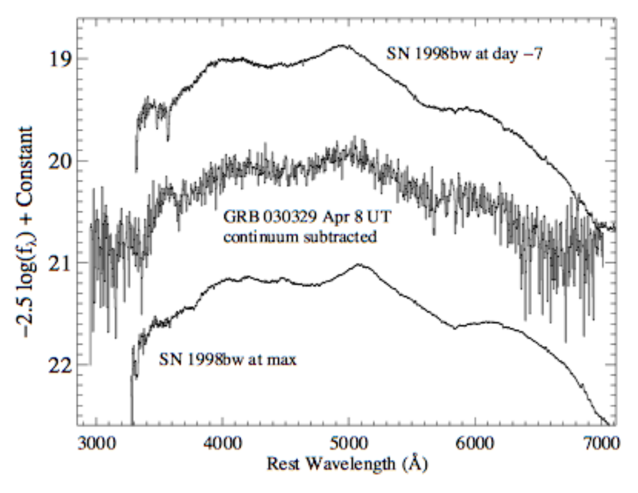
Star-Forming Host Galaxies (z_{avg}~2-3)



NASA, ESA, A. Fruchter (STScI), and the GOSH Collaboration

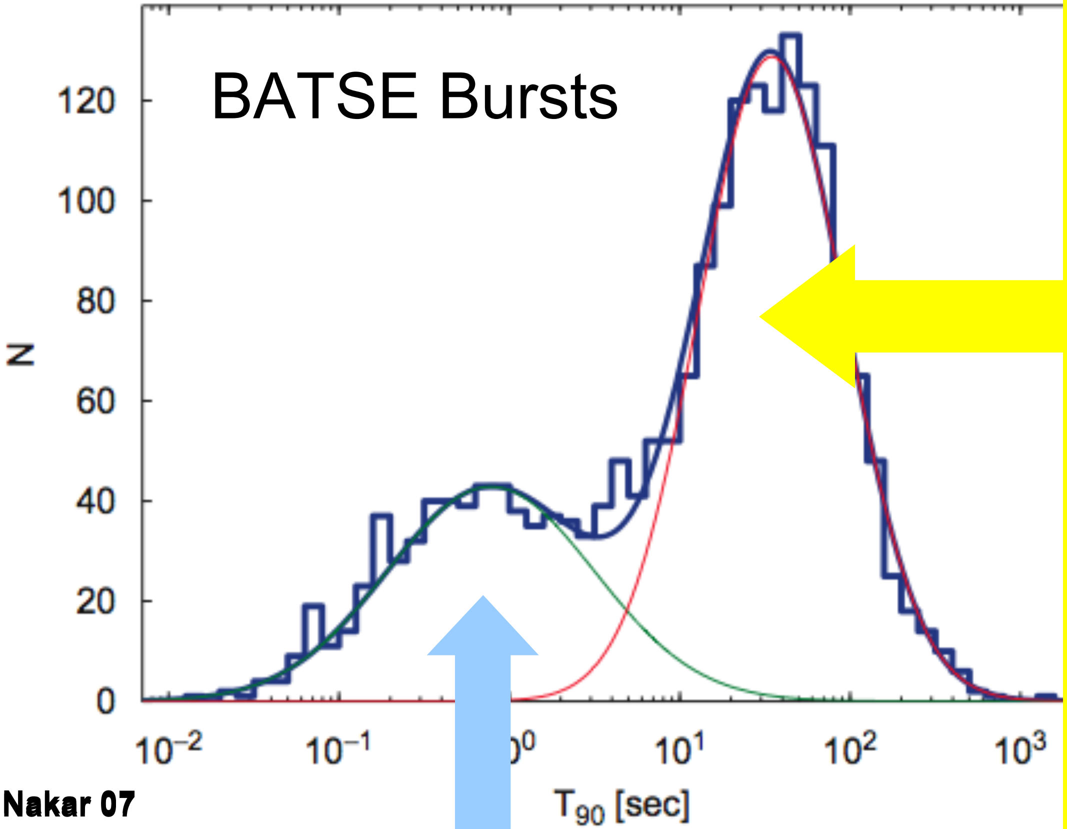
Supernova Connection

GRB 030329 ⇔ SN 2003dh

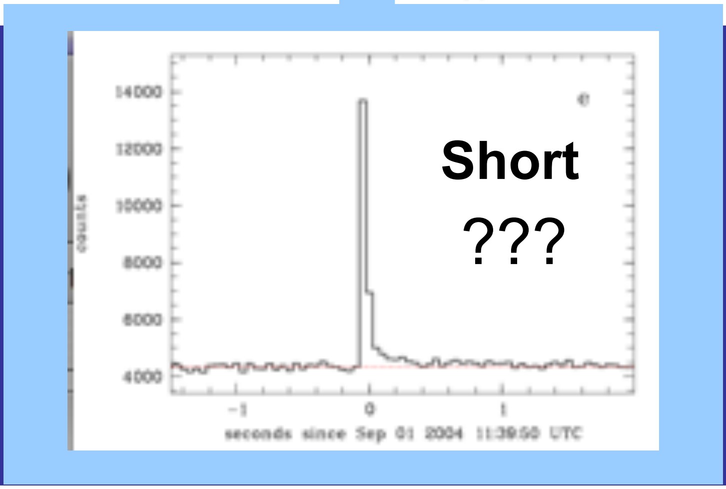


Stanek et al. 2003

Short & Long Gamma-Ray Bursts



Nakar 07

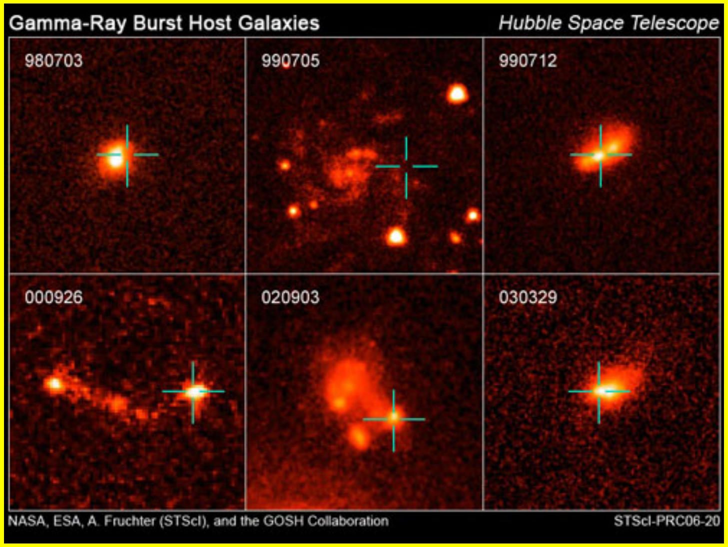


Short

???

Long GRBs = Death of Massive Stars

Star-Forming Host Galaxies (z_{avg}~2-3)



NASA, ESA, A. Fruchter (STScI), and the GOSH Collaboration

STScI-PRC06-20

Supernova Connection

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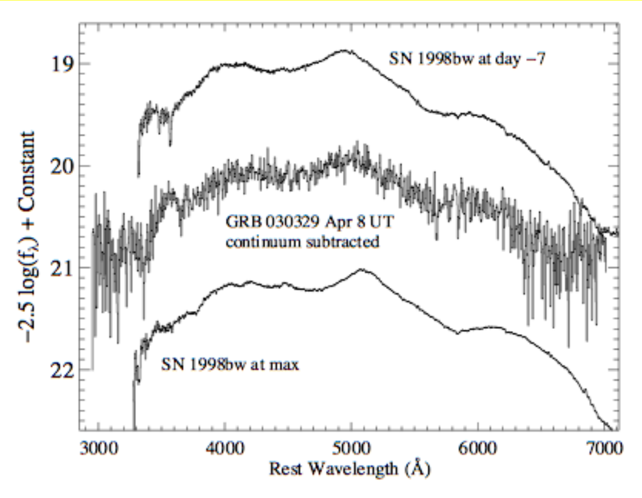
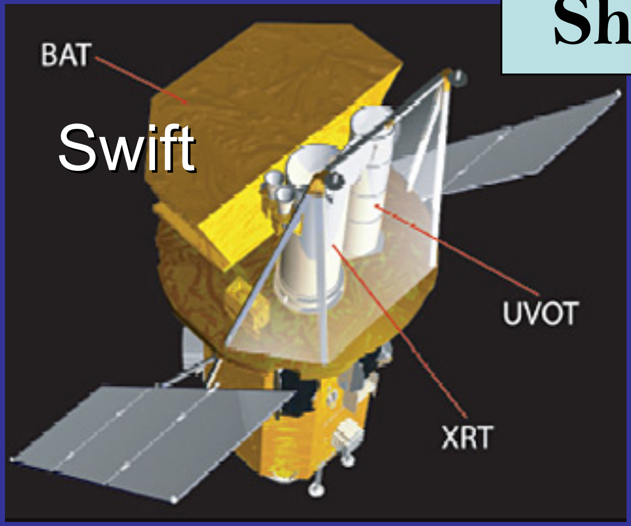
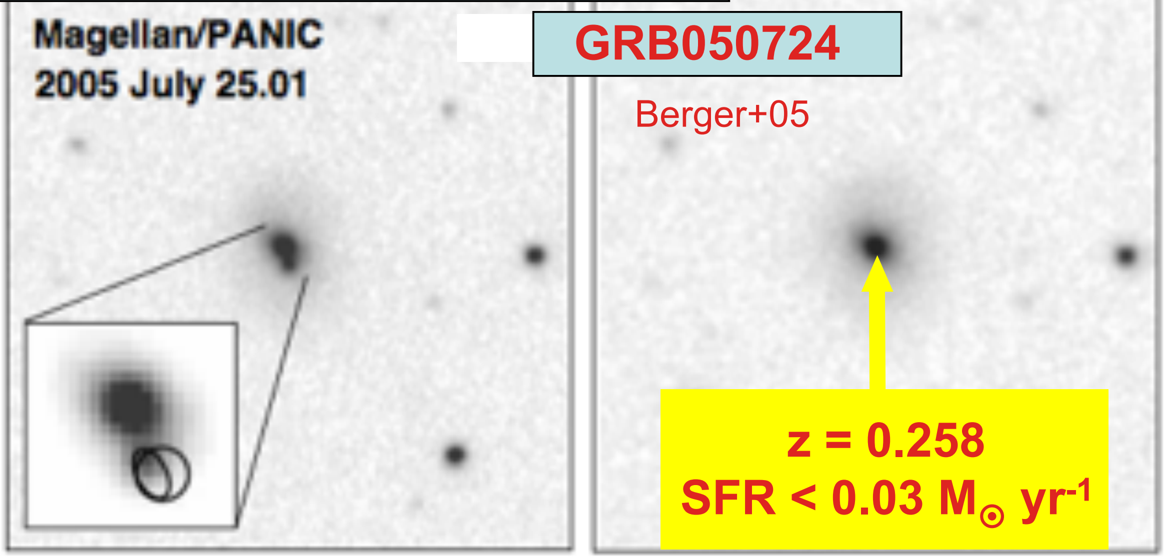


Stanek et al. 2003

Short GRB Host Galaxies



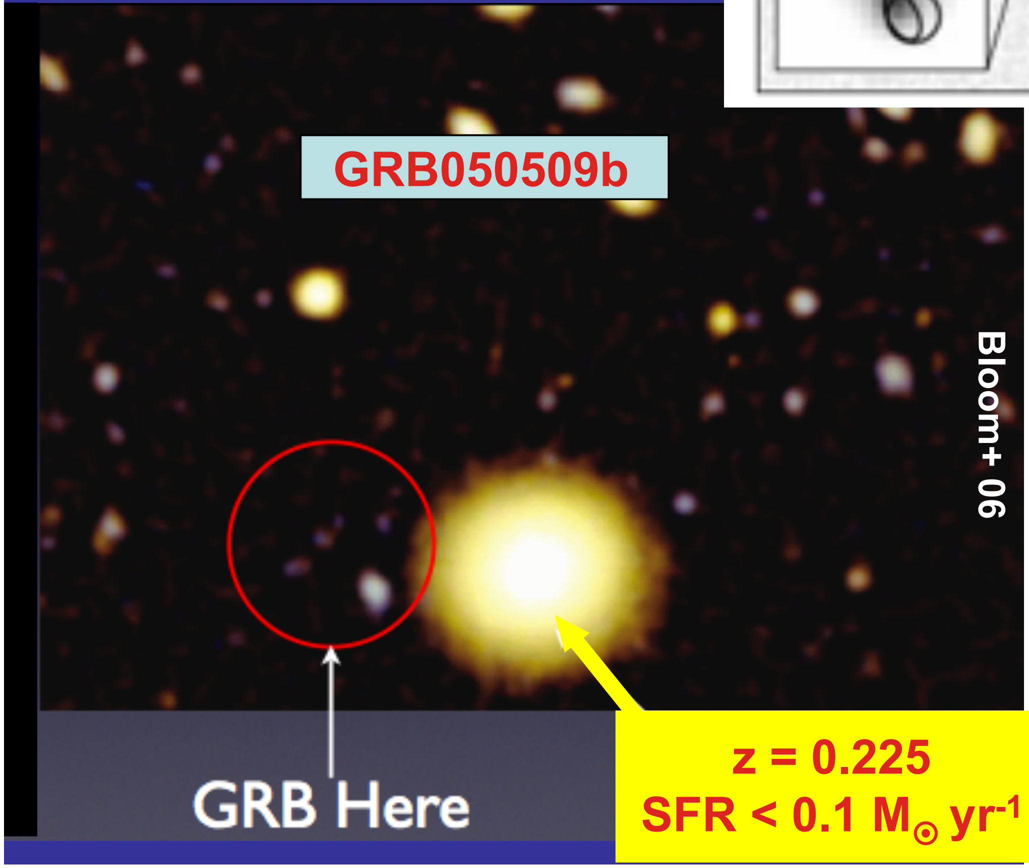


GRB050724

Berger+05

$z = 0.258$

SFR $< 0.03\ M_\odot\ yr^{-1}$

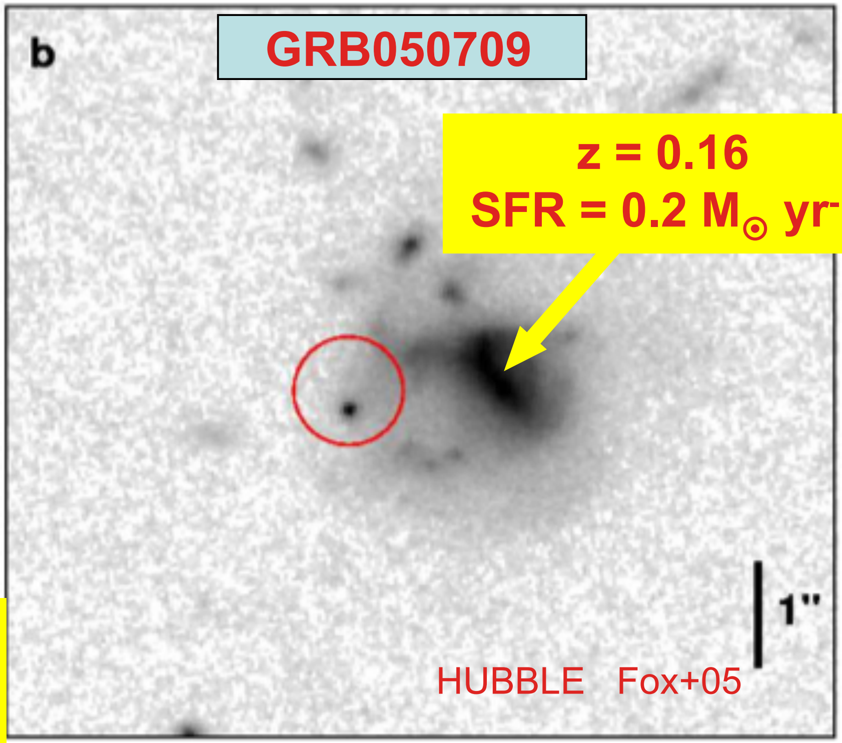


GRB050509b

Bloom+ 06

$z = 0.225$

SFR $< 0.1\ M_\odot\ yr^{-1}$



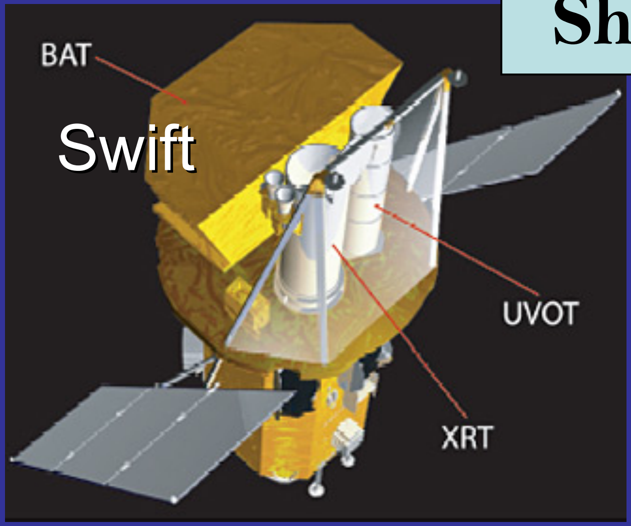
GRB050709

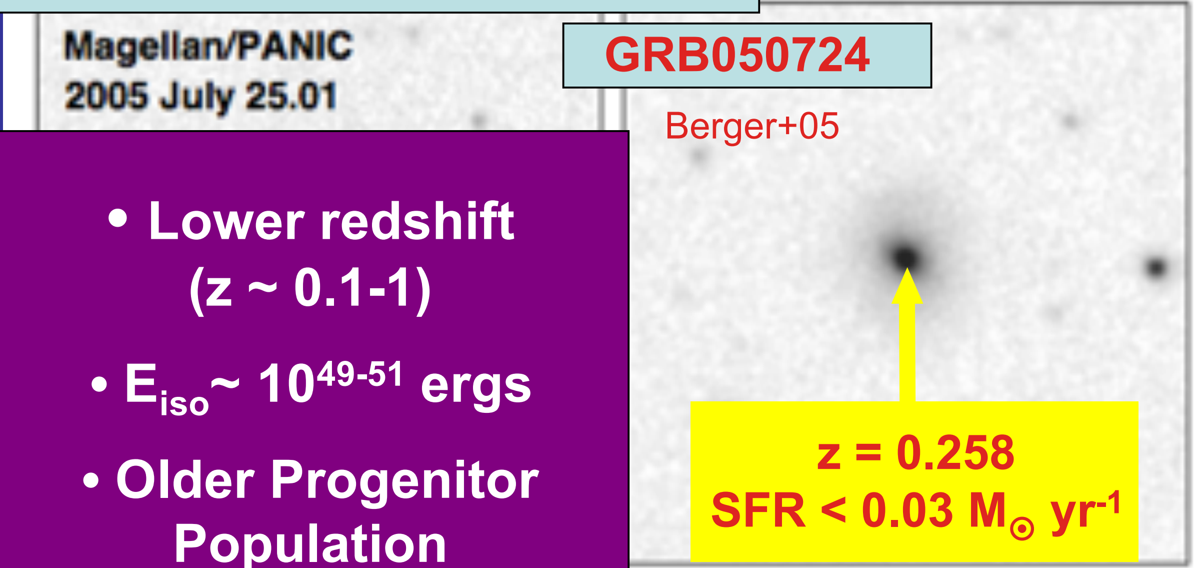
$z = 0.16$

SFR $= 0.2\ M_\odot\ yr^{-1}$

HUBBLE Fox+05

Short GRB Host Galaxies





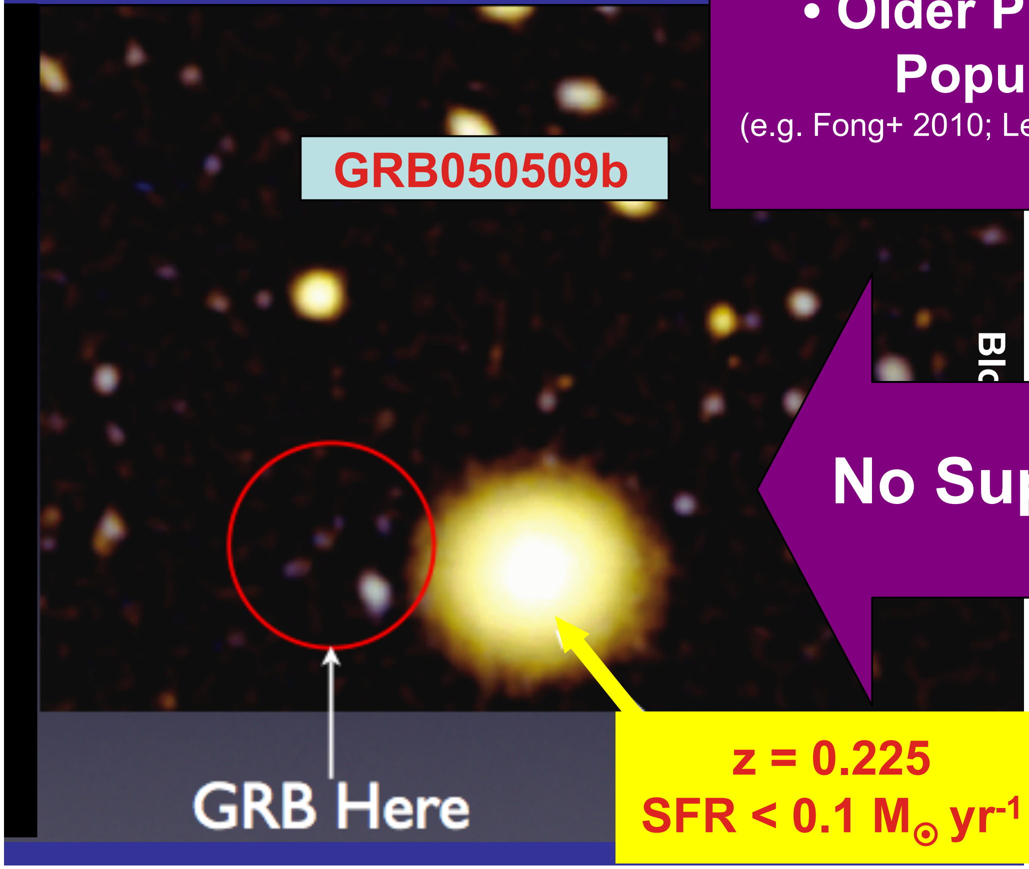
GRB050724

Berger+05

z = 0.258
SFR < 0.03 $M_{\odot}$ yr^{-1}

- **Lower redshift ($z \sim 0.1$-1)**
- **$E_{iso} \sim 10^{49-51}$ ergs**
- **Older Progenitor Population**

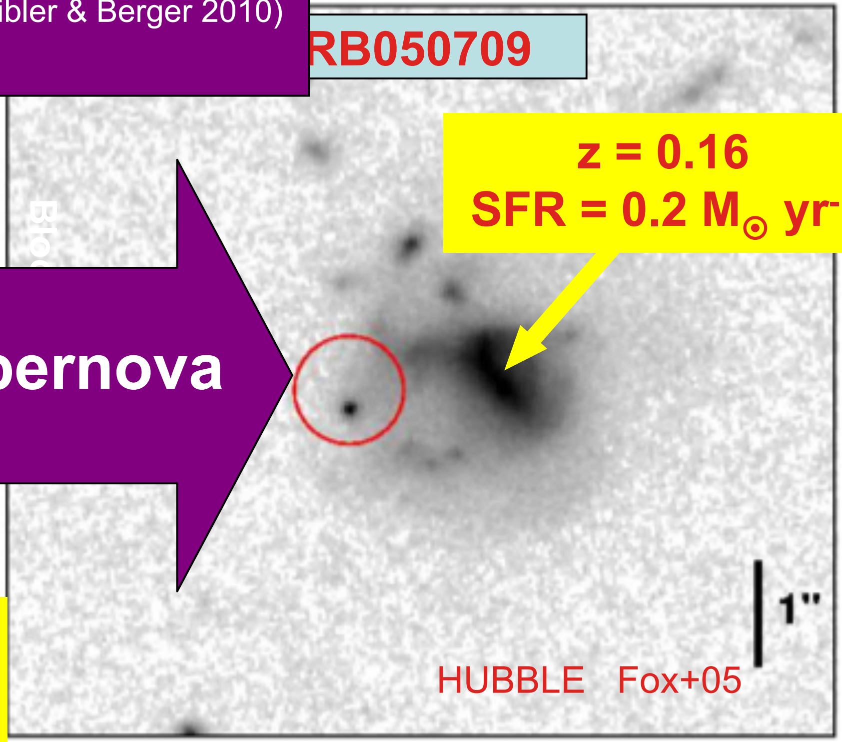
(e.g. Fong+ 2010; Leibler & Berger 2010)



GRB050509b

z = 0.225
SFR < 0.1 $M_{\odot}$ yr^{-1}

No Supernova

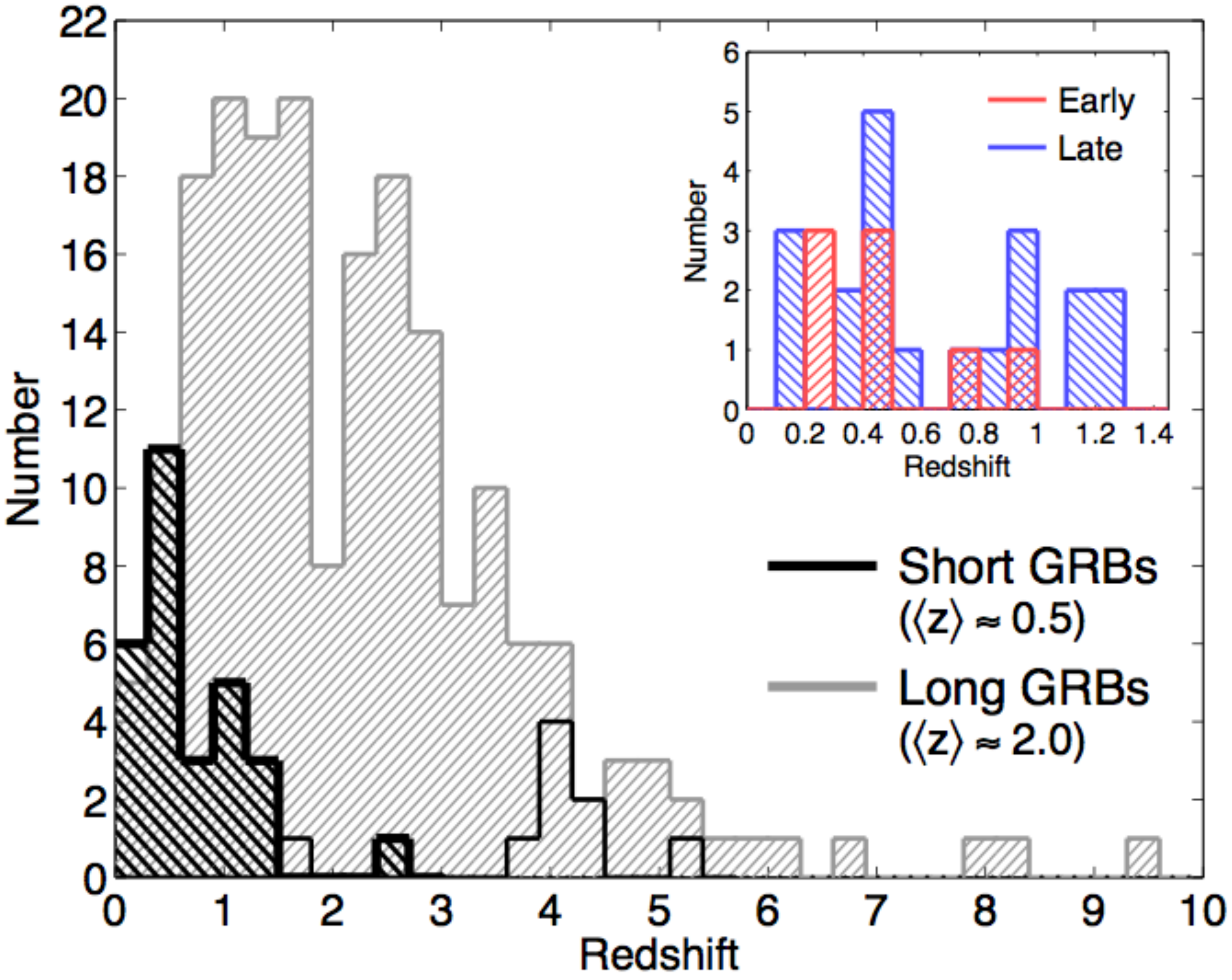


RB050709

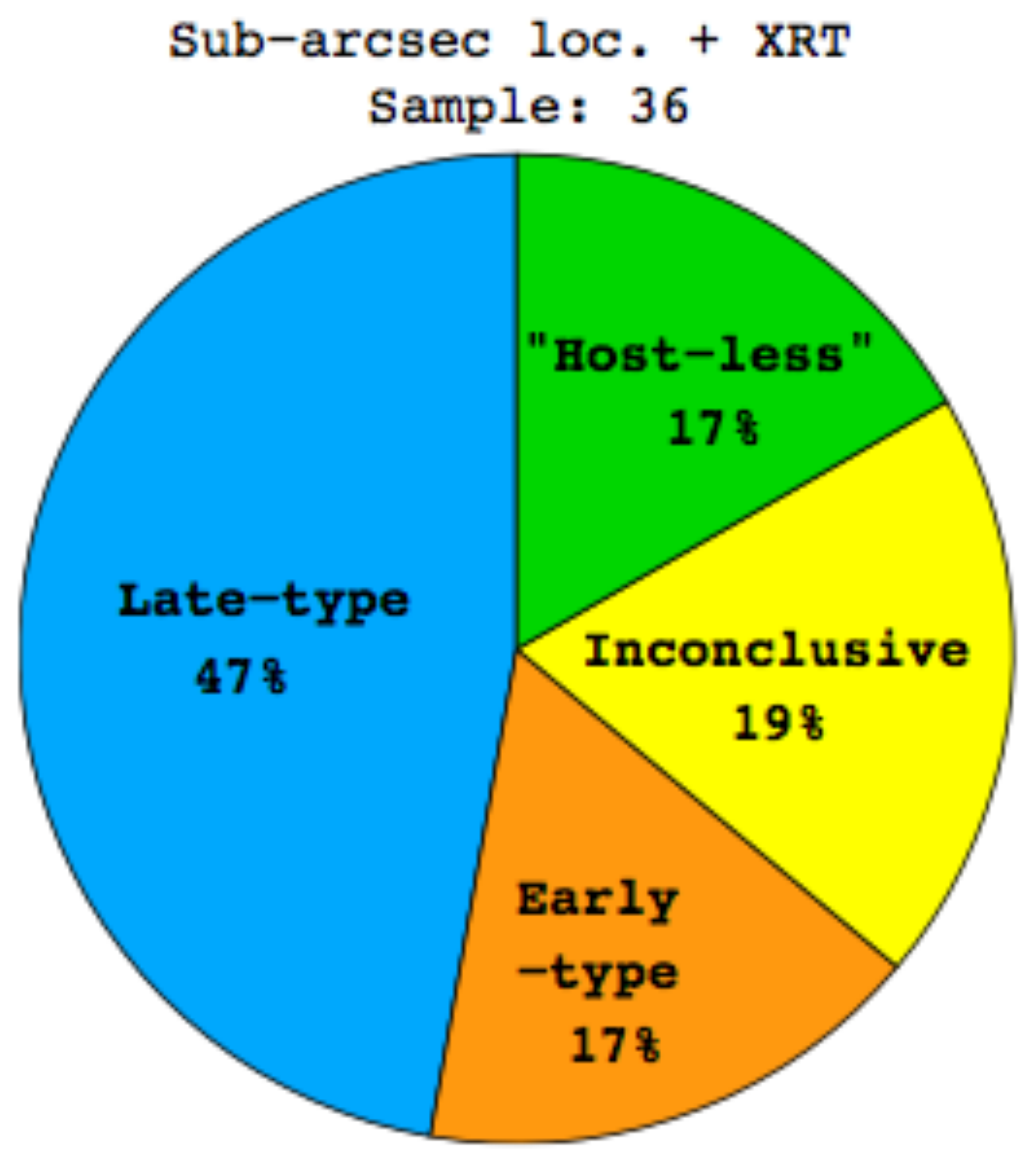
z = 0.16
SFR = 0.2 $M_{\odot}$ yr^{-1}

HUBBLE Fox+05

Berger 2013



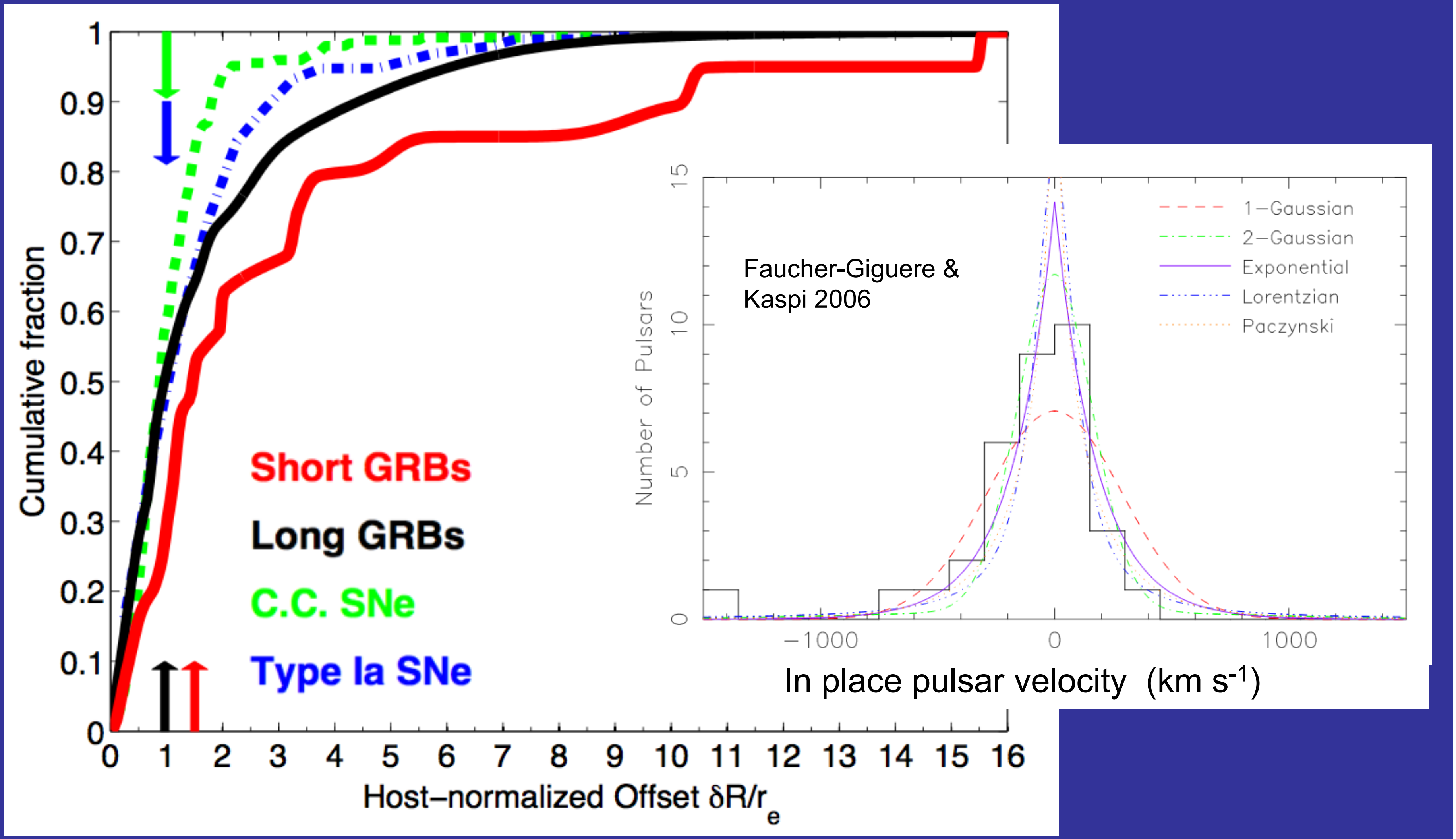
22
20
18
16
14
12
10
8
6
4
2
0
Number
0
1
2
3
4
5
6
7
8
9
10
Redshift
Short GRBs
(⟨z⟩ ≈ 0.5)
Long GRBs
(⟨z⟩ ≈ 2.0)
6
5
4
3
2
1
0
Number
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Redshift
Early
Late



Sub-arcsec loc. + XRT
Sample: 36

Radial Offsets from Host Galaxy

Berger 2013



Faucher-Giguere & Kaspi 2006

In place pulsar velocity (km s^{-1})

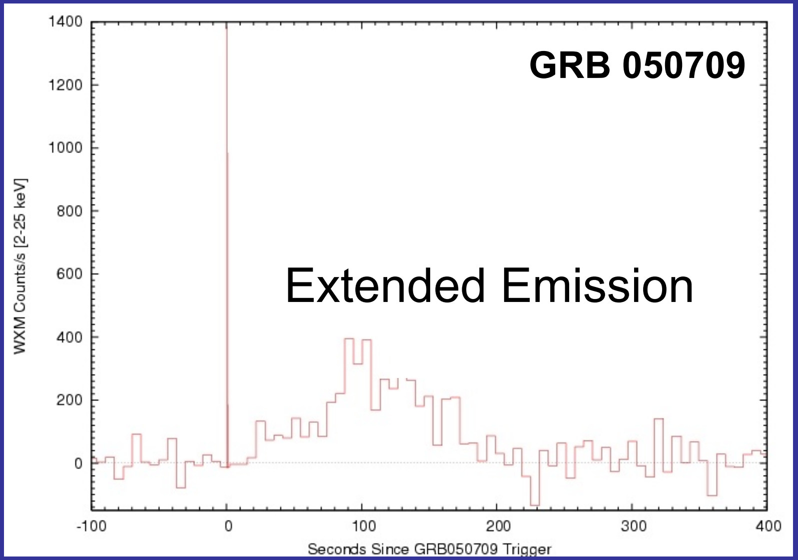
NS receive kick velocity $v_k \sim 100$ km s$^{-1} > v_{esc}$

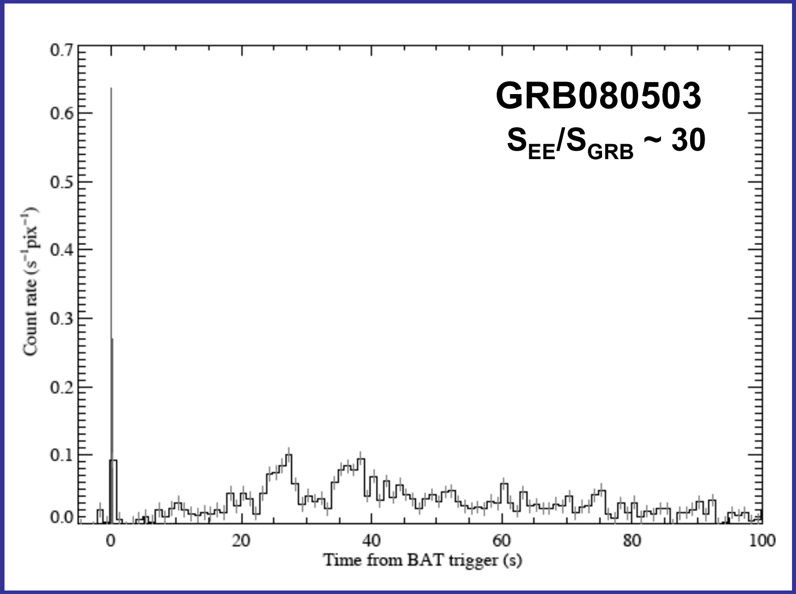
⇒ short GRBs may occur outside host galaxy

$$D = 100\ \mathrm{kpc}\left(\frac{v}{100\ \mathrm{km\ s^{-1}}}\right)\left(\frac{t}{\mathrm{Gyr}}\right)$$

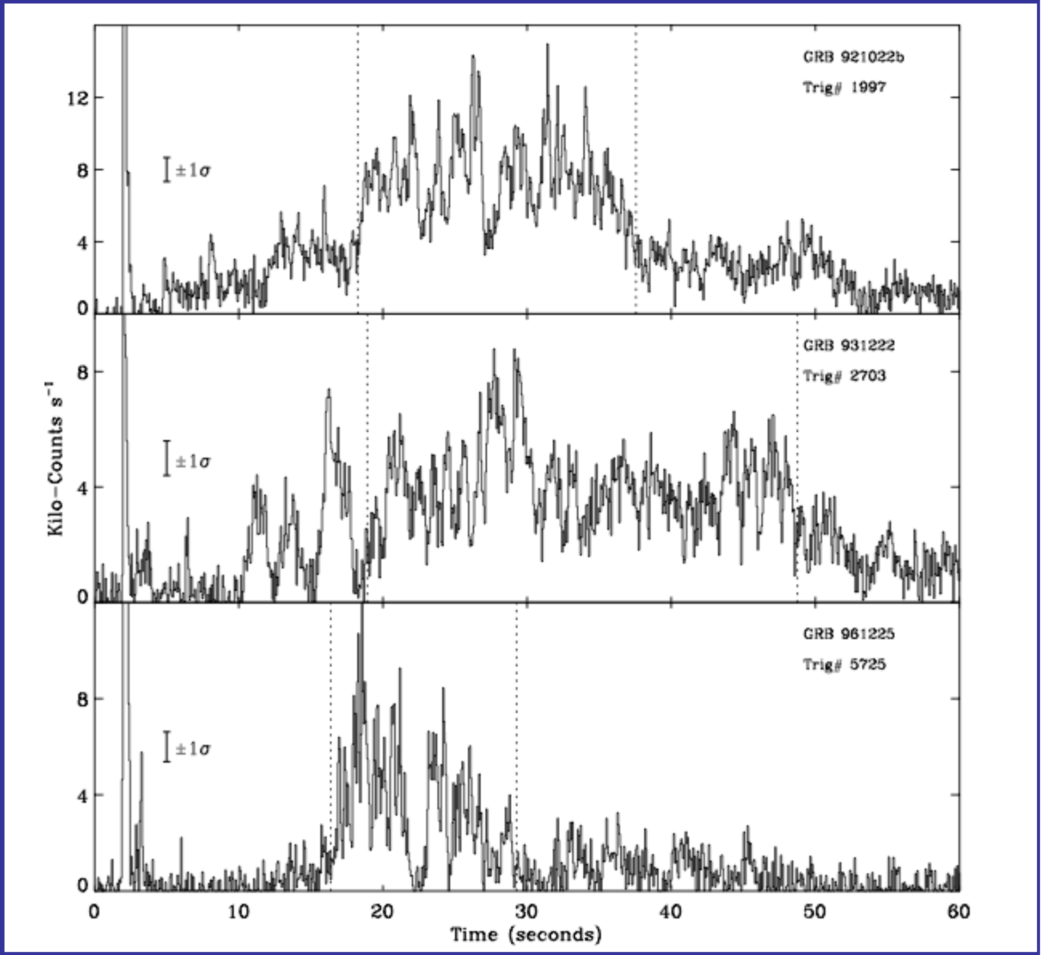
Not that Short After All….

- 1/4 Swift Short Bursts have X-ray Tails
- Rapid Variability ⇒ Ongoing Engine Activity
- Energy up to ~30 times Burst Itself!



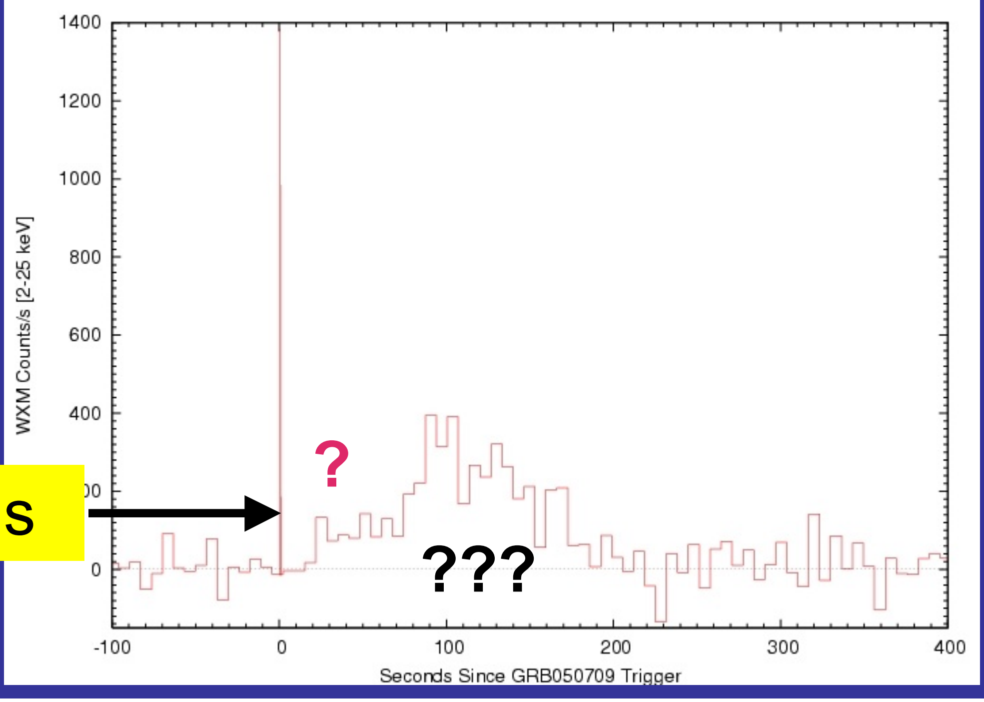


Perley, BDM et al. 2009

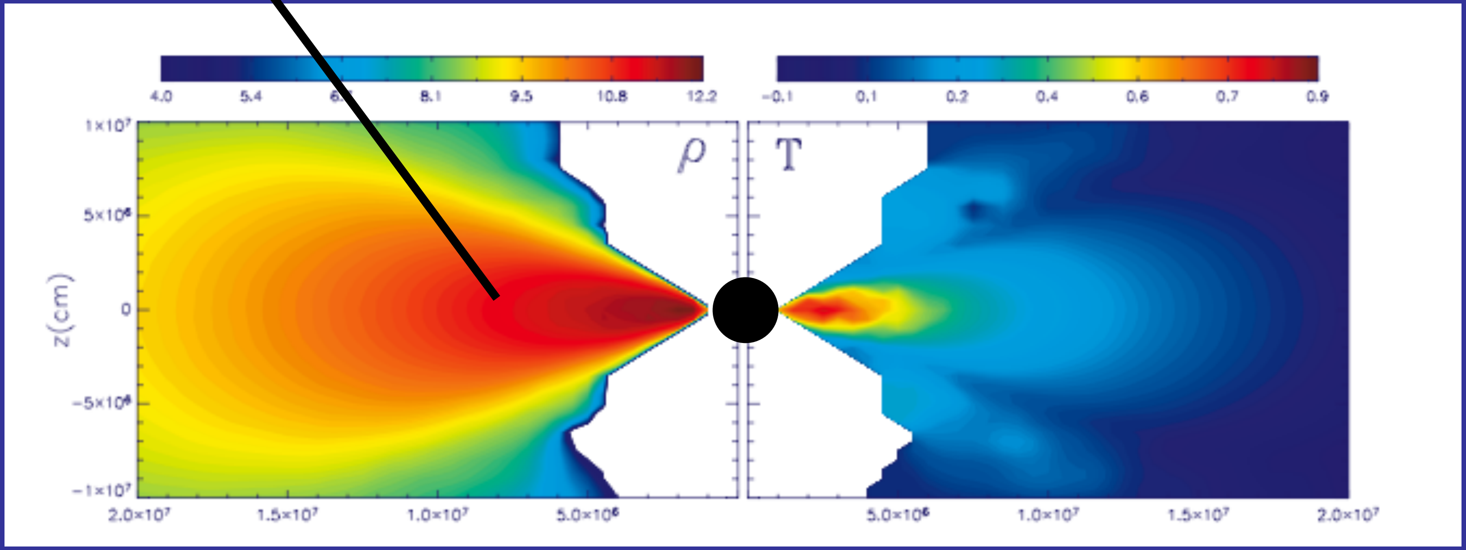


BATSE Examples (Norris & Bonnell 2006)

Why **Two** Timescales? Why the Delay?



$t_{accretion}$ ~ 0.1-1 s



Lee et al. (2004)

Viscous Evolution of the Remnant Disk

Metzger, Piro & Quataert 2008, 2009

Angular Momentum

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right]$$

$$J = M_d R_d v_K \propto M_d R_d^{1/2}$$

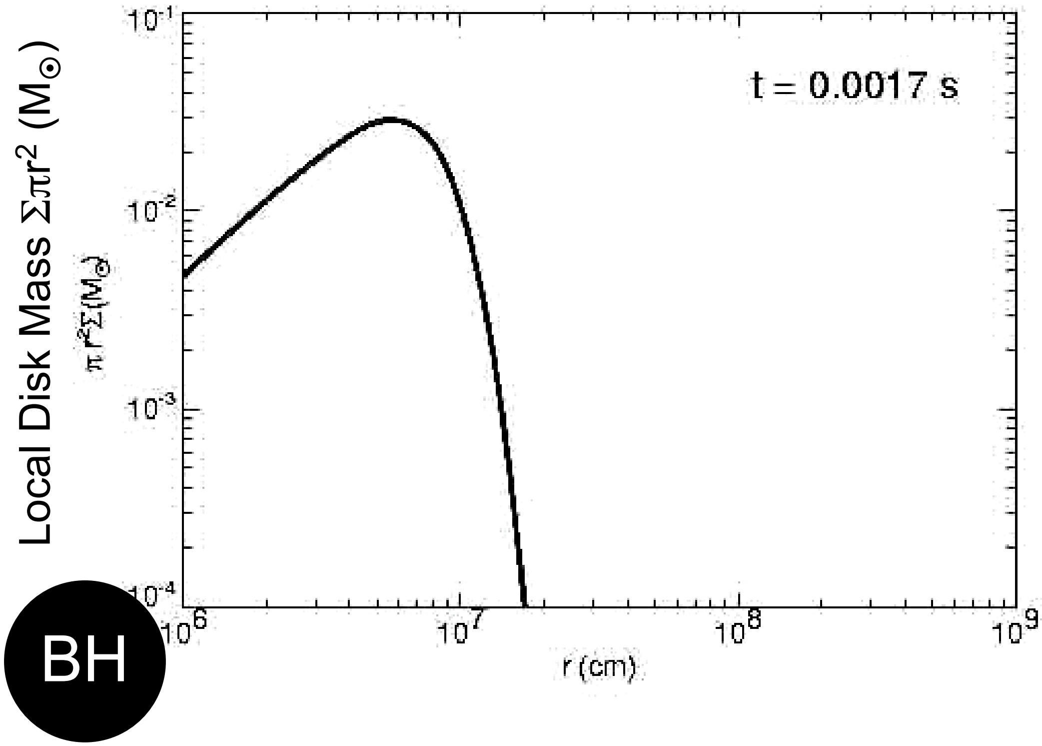
$$\Rightarrow R_d \propto M_d^{\;-2}$$

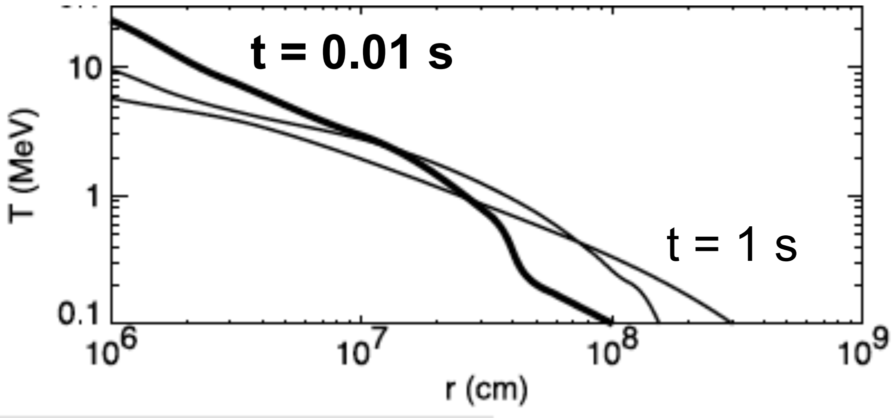
Entropy

$$T\frac{dS}{dt} = \dot{q}_{visc} - \dot{q}_{\nu}$$

Heating

Cooling





Late-Time Disk Outflows ('Evaporation')

After t ~ 1 seconds, R ~ 300 km & T < 1 MeV

- **Recombination: n + p ⇒ He**

  $E_{BIND} \sim GM_{BH}m_n/2R \sim 5$ MeV nucleon^{-1}

  $\Delta E_{NUC} \sim 7$ MeV nucleon^{-1}

- **Thick Disks Marginally Bound**

Late-Time Disk Outflows ('Evaporation')

After t ~ 1 seconds, R ~ 300 km & T < 1 MeV

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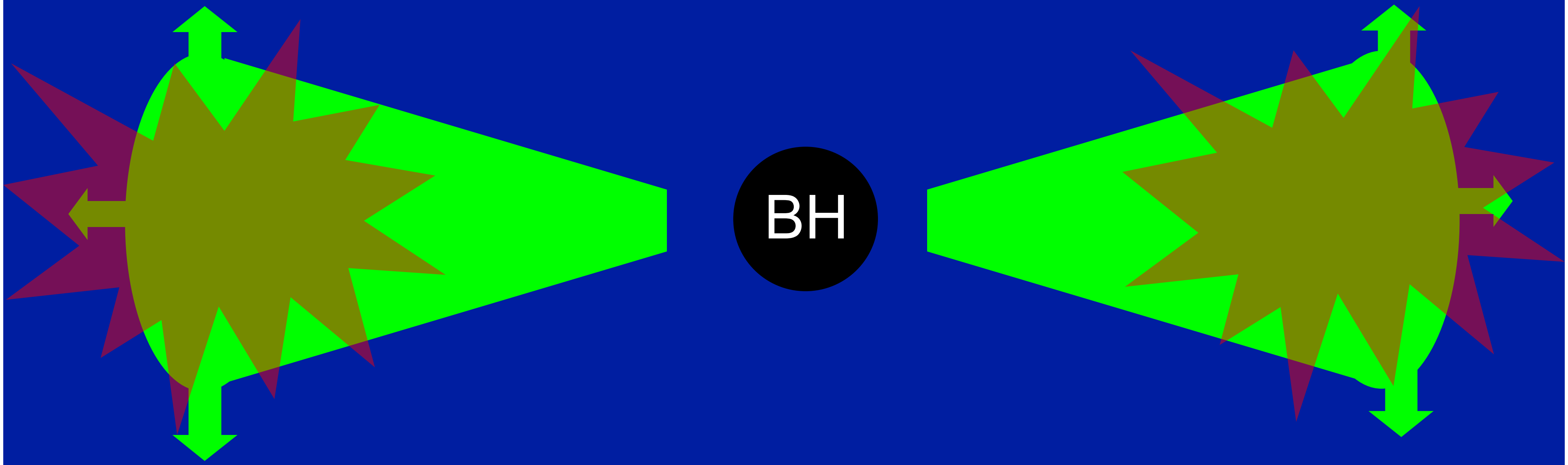
  $E_{BIND} \sim GM_{BH}m_n/2R \sim 5$ MeV nucleon^{-1}

  $\Delta E_{NUC} \sim 7$ MeV nucleon^{-1}

- **Thick Disks Marginally Bound**

} ⇒ **Disk Blows Apart**



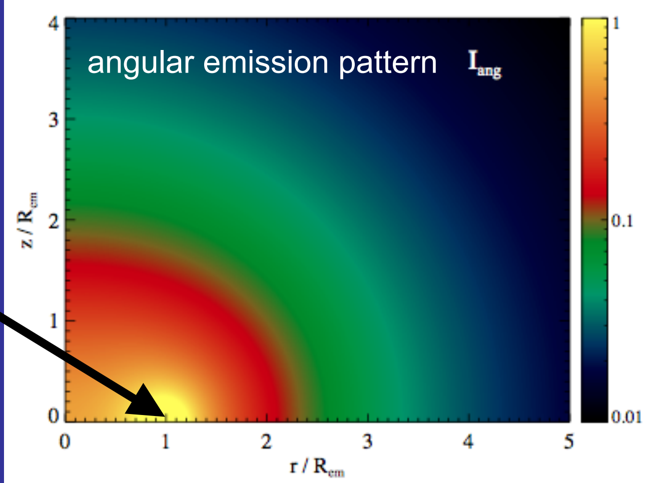
Sizable Fraction of Initial Disk Unbound!

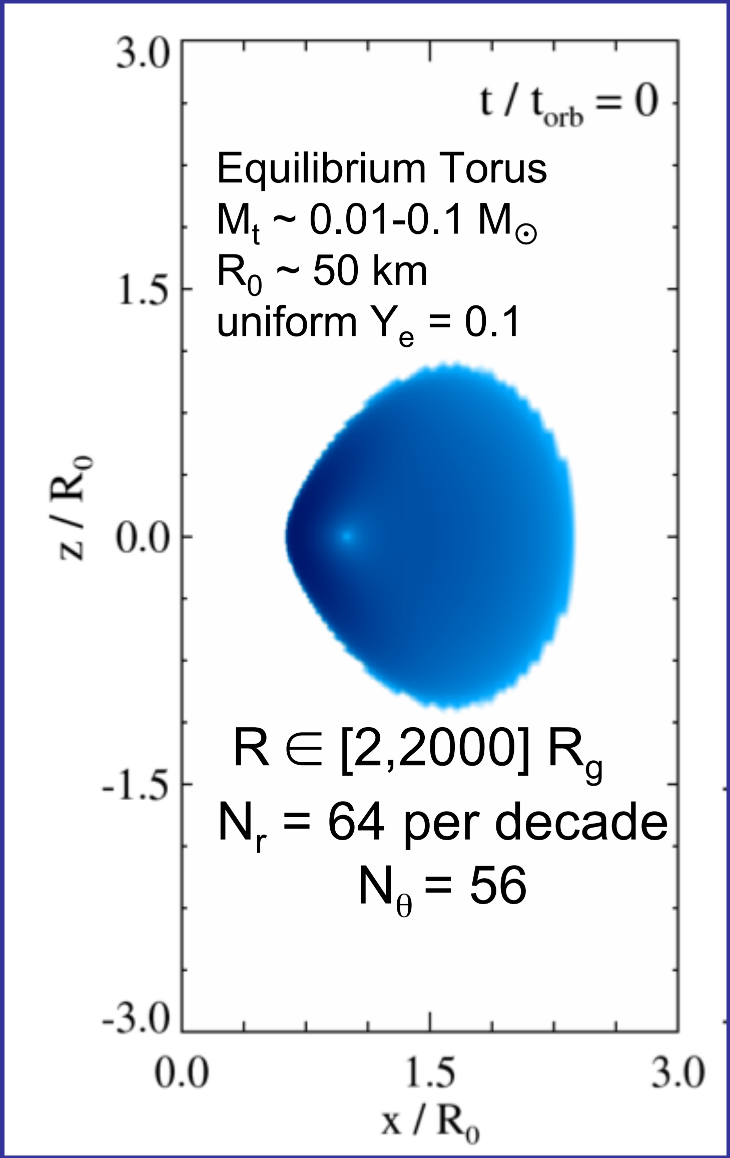
Axisymmetric Torus Evolution

(Fernandez & Metzger 2012, 2013)

- P-W potential with $M_{BH} = 3,10\ M_\odot$
- hydrodynamic α viscosity
- NSE recombination $2n+2p \Rightarrow {}^4He$
- run-time $\Delta t \sim 1000\text{-}3000\ t_{orb}$
- neutrino self-irradiation: “light bulb” + optical depth corrections:

peak emission radius

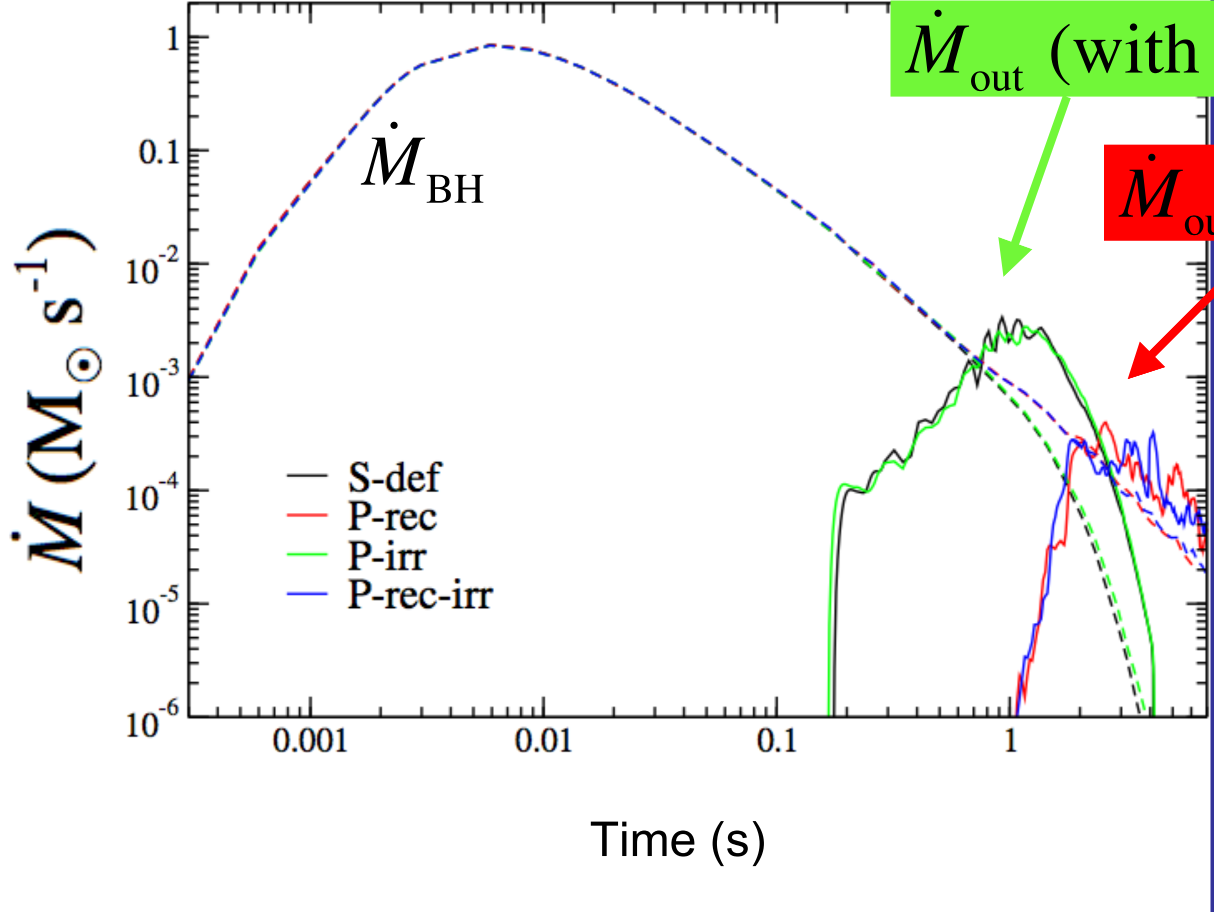




Equilibrium Torus
$M_t \sim 0.01\text{-}0.1\ M_\odot$
$R_0 \sim 50$ km
uniform $Y_e = 0.1$

$R \in [2,2000]\ R_g$
$N_r = 64$ per decade
$N_\theta = 56$

Late Disk Outflows (Evaporation)



$\dot{M}_{out}$ (with α recombination)

$\dot{M}_{out}$ (NO α recombination)

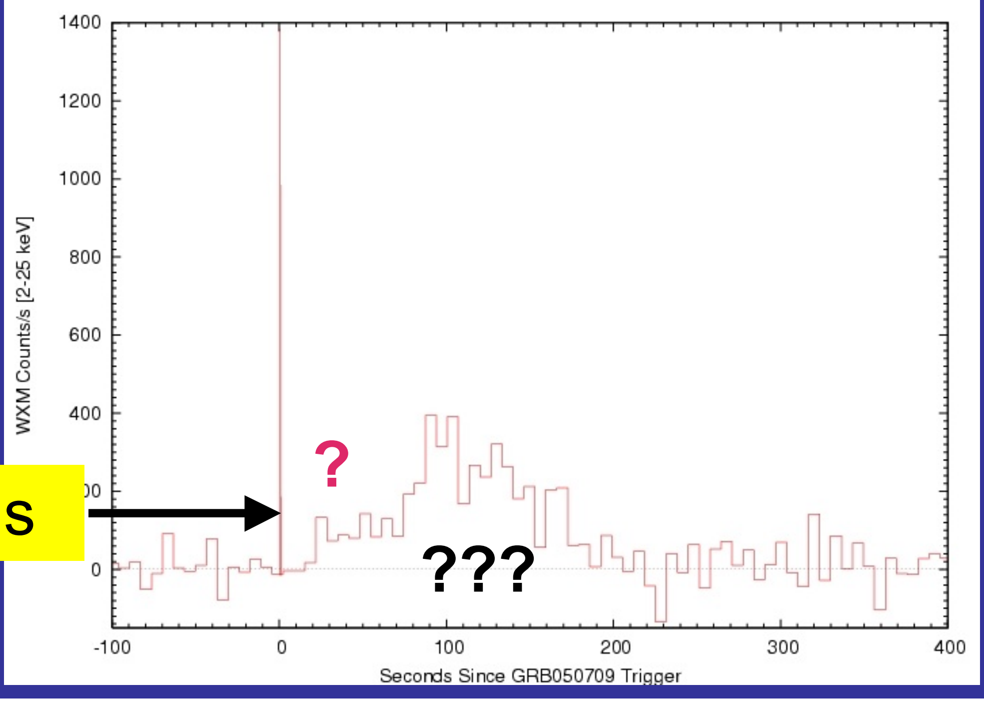
- unbound outflow powered by viscous heating and α recombination
- neutrino heating subdominant

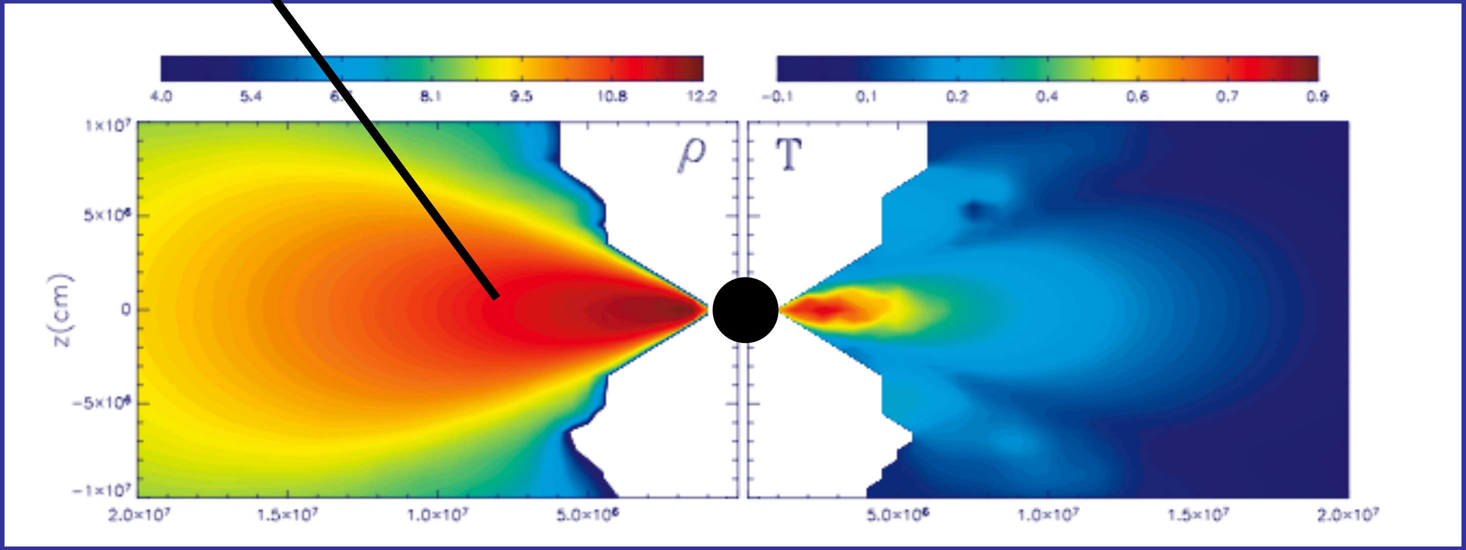
outflow robust

M_{ej} ~ 0.05 M_t V_{ej} ~ 0.1 c

Why **Two** Timescales? Why the Delay?

$t_{\mathrm{accretion}} \sim 0.1\text{-}1$ s





Lee et al. (2004)

Stable Neutron Star Remnant?

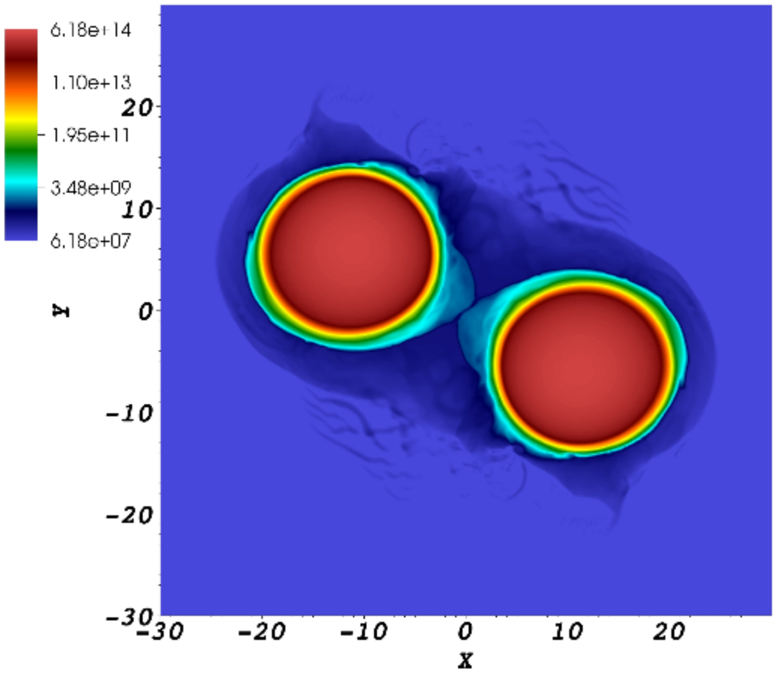
(e.g. Rasio 99; BDM+08; Ozel et al. 2010; Bucciantini et al. 2012; Zhang 13; Giacomazzo & Perna 13; Falcke & Rezzolla 13; Kiziltan 2013)

- Requires: low total mass binary, stiff EOS*, and/or mass loss during merger

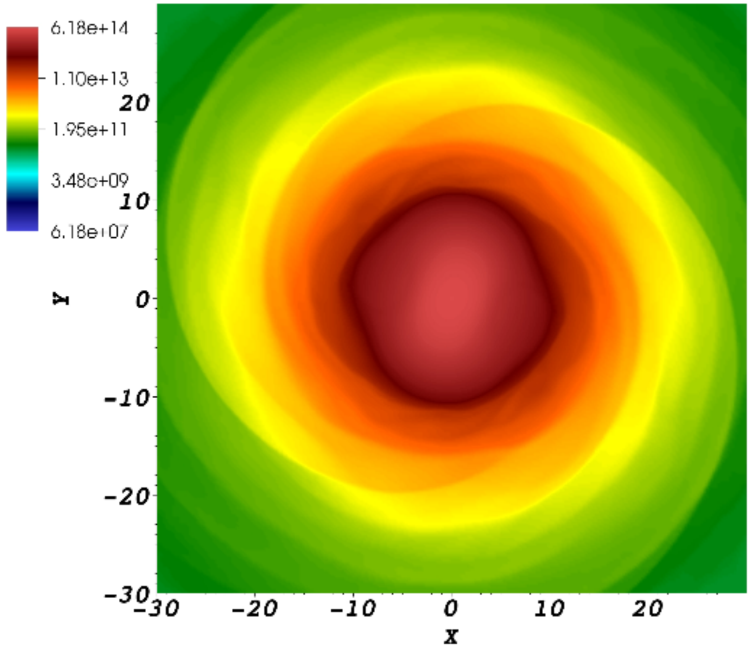
*supported by recent discovery of $2M_\odot$ NS by Demorest et al. 2011

- Rotating near centrifugal break-up with spin period P ~ 1 ms
- Magnetic field amplified by rotational energy ⇒ **"Magnetar" ?**

(e.g. Thompson & Duncan 92; Price & Rosswog 2006; Zrake & MacFadyen 2013)



t = 8.34 ms



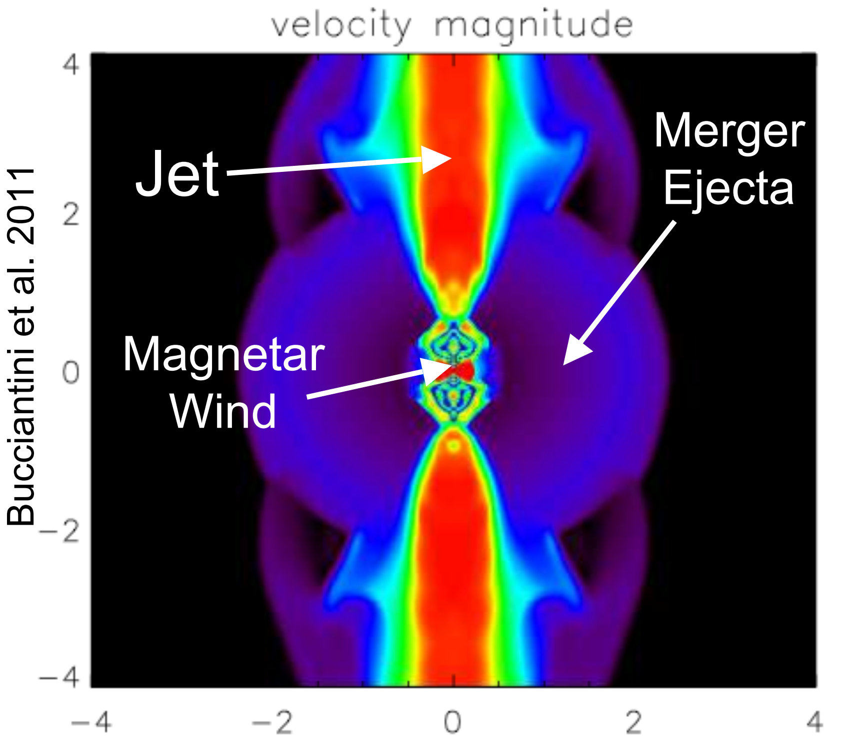
t = 66.0 ms

Giacomazzo & Perna 2013

Magnetar Spin-Down Powered Extended Emission

(BDM et al. 2008; Bucciantini, BDM et al. 2012)

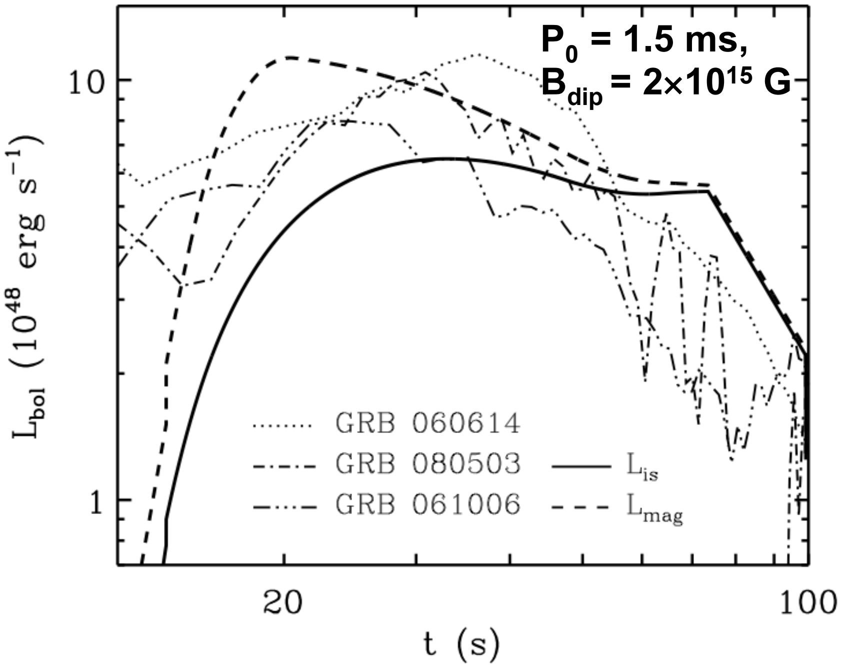
Magnetar wind confined by merger ejecta



Bucciantini et al. 2011

Theoretical Light Curves vs. observed X-ray tails

(magnetar outflow model from Metzger et al. 2011)



Jet may continue to inject energy into forward shock or produce lower level prompt emission

(Zhang & Meszaros 2001; Dall'Osso et al. 2011; Rowlinson et al. 2013; Gompertz et al. 2013)

Radio constraints on long-lived NS merger remnants

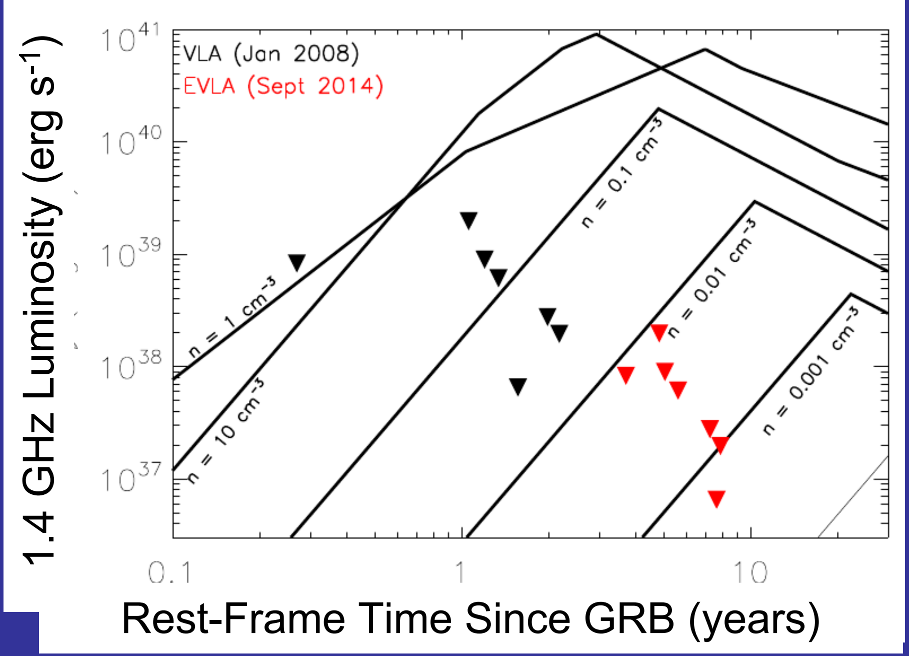
(BDM & Bower 2014)

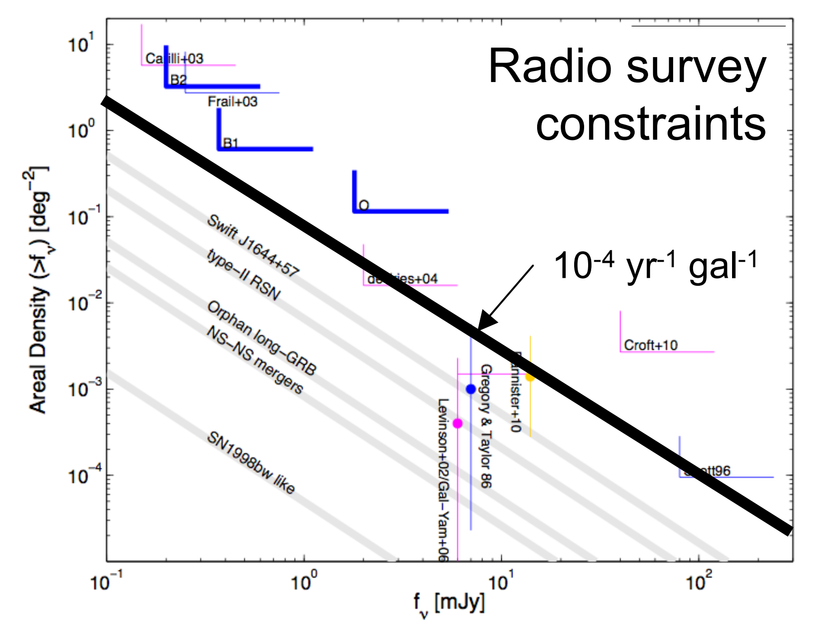
- Rotational energy

$$E_{\rm rot} = \frac{1}{2}I\Omega^2 \simeq 3\times10^{52}{\rm ergs}\left(\frac{P}{1\ {\rm ms}}\right)^{-2}$$

eventually transferred to ISM
⇒ bright radio emission

- Observed 7 short GRBs with VLA on timescales ~1-3 years after burst
- NO DETECTIONS ⇒ rules out stable NS remnant in 2 GRBs with known high ISM densities
- Additional EVLA observations *now* would be much more constraining
- Upcoming radio surveys (e.g. ASKAP) will strongly constrain population of stable NS merger remnants ⇒ indirectly probes EoS





Frail et al. 2012

Accretion-Induced Collapse (AIC)

(e.g. Nomoto & Kondo 1991)

- O-Ne WD built to $M_{chandra}$
- Collapse of rapidly-rotating WD ⇒ Disk around PNS: $M_{disk} \sim 10^{-2} - 0.3\ M_{\odot}$
- Evolution similar to NS merger disks (Metzger+ 08,09)

Nomoto & Kondo 1991

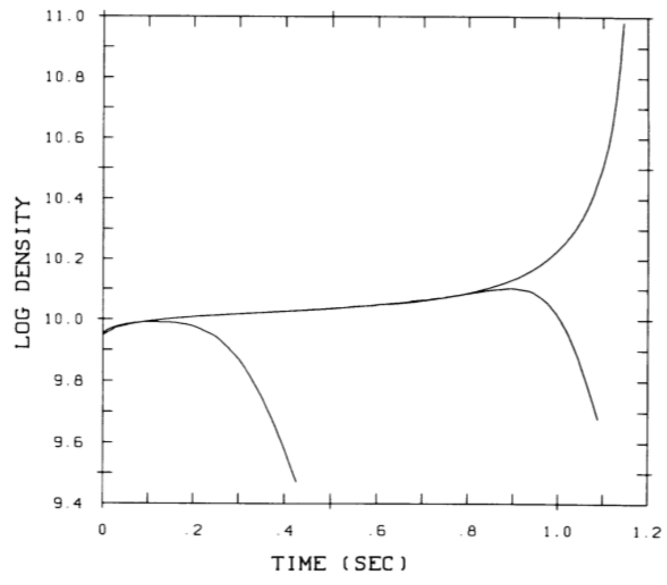
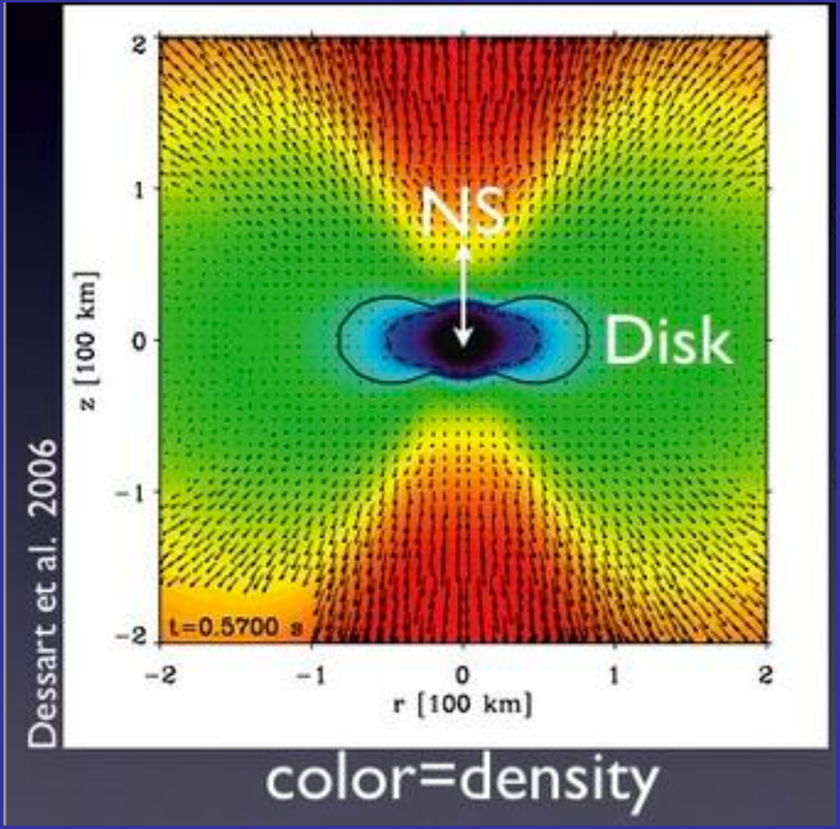
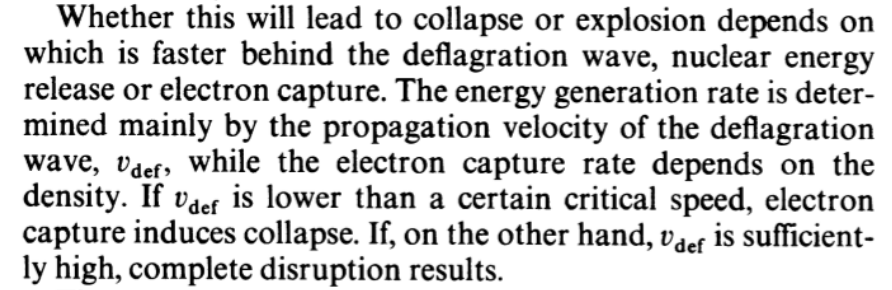


FIG. 1.—Change in the central density of the O + Ne + Mg white dwarfs following the propagation of the oxygen deflagration wave for three cases with l/min $(H_p, r) = 1.4$, 1.0, and 0.7. For the slowest case of $l/H_p = 0.7$, the central density (in units of g cm^{-3}) increases, i.e., the white dwarf undergoes collapse. Faster propagation induces an explosion of the white dwarf.



Dessart et al. 2006

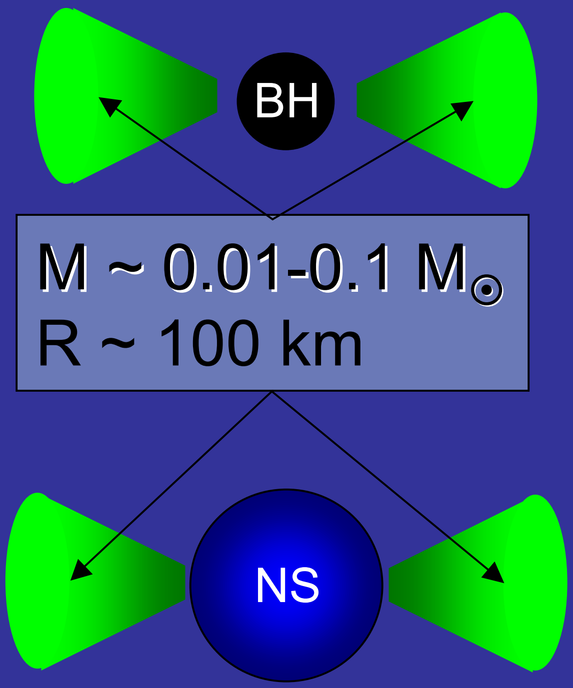
color=density



Whether this will lead to collapse or explosion depends on which is faster behind the deflagration wave, nuclear energy release or electron capture. The energy generation rate is determined mainly by the propagation velocity of the deflagration wave, v_{def}, while the electron capture rate depends on the density. If v_{def} is lower than a certain critical speed, electron capture induces collapse. If, on the other hand, v_{def} is sufficiently high, complete disruption results.

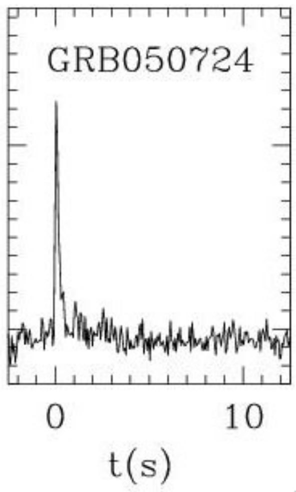
Similar Systems - Distinct Origins

NS-NS / BH-NS Mergers

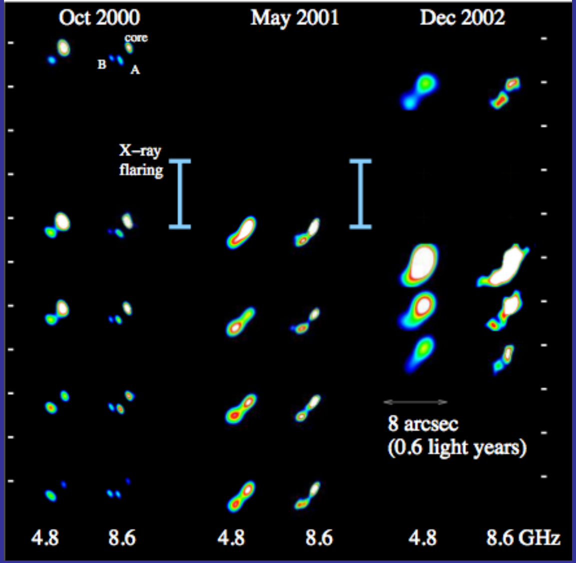


$M \sim 0.01\text{-}0.1\ M_\odot$
$R \sim 100$ km

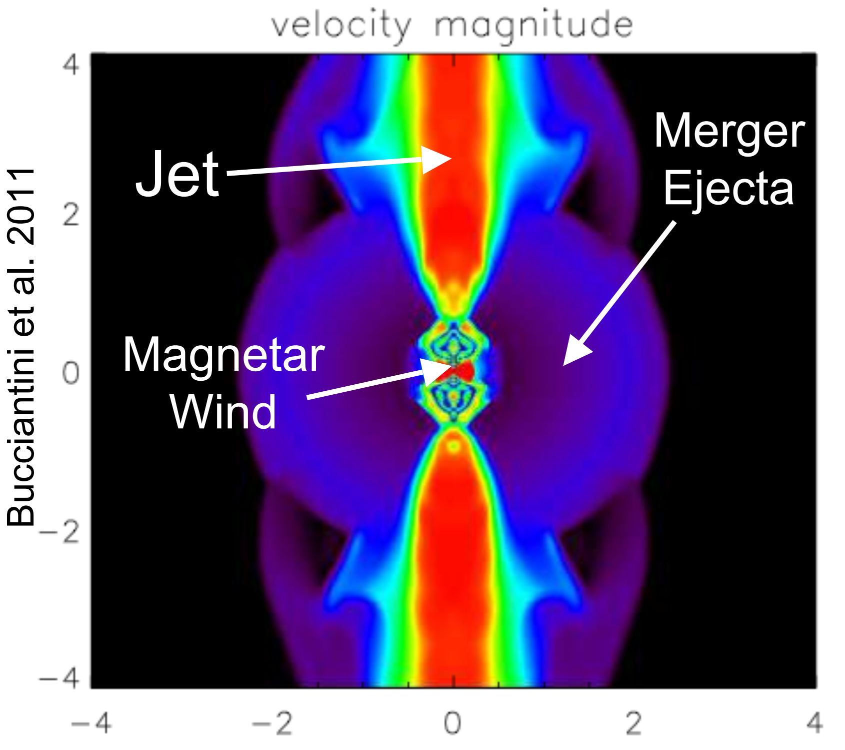
Accretion-Induced Collapse



Neutron Star Circinus X-1
$\Gamma > 15$! (Fender et al. 2004)



Magnetar wind confined by merger ejecta



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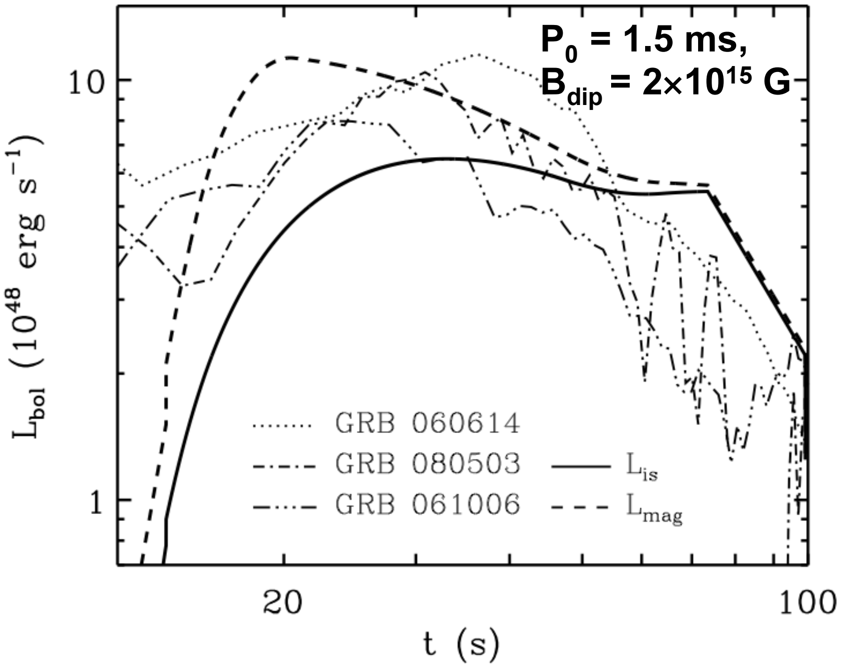
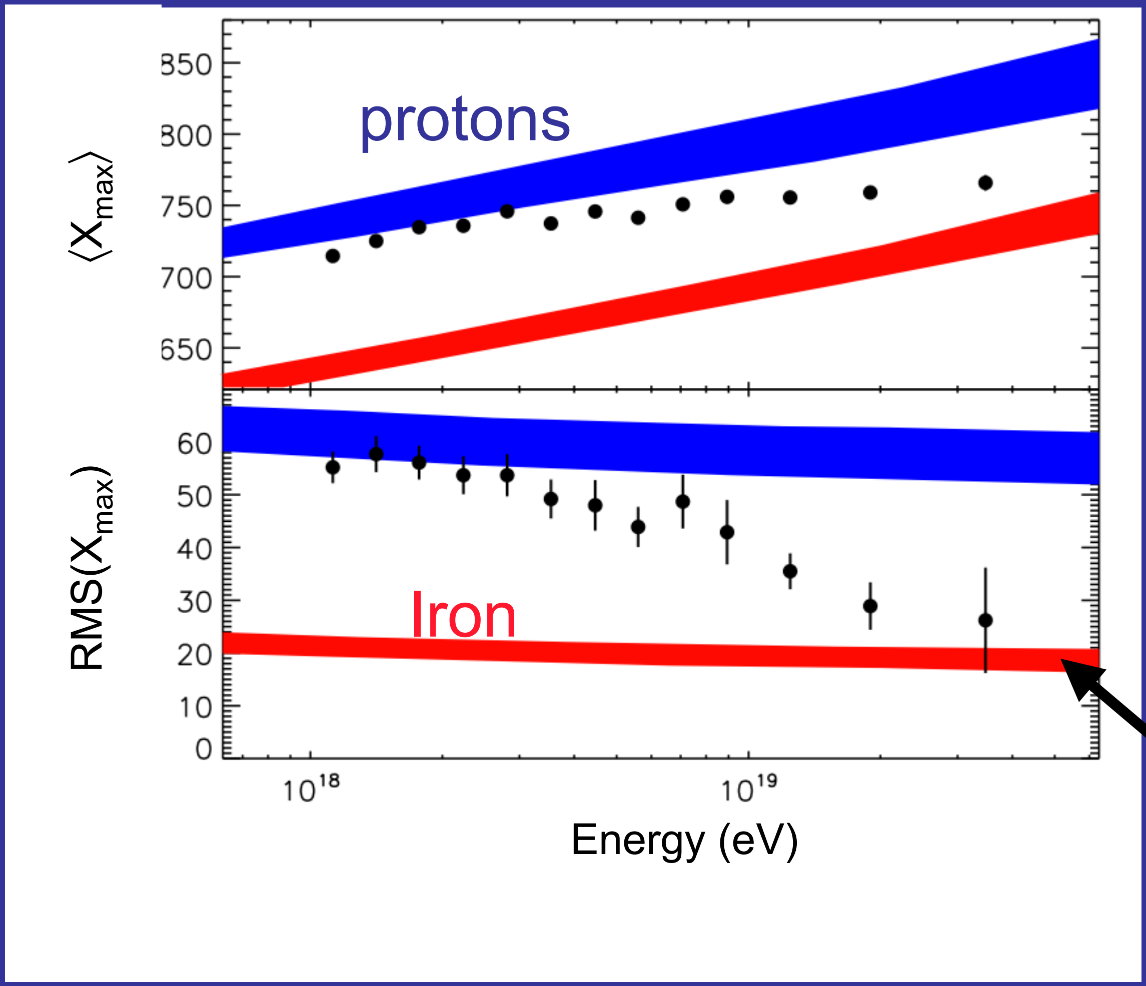
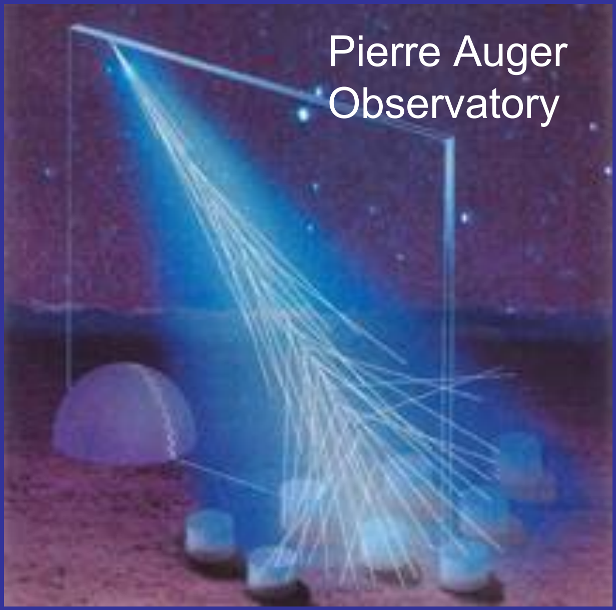


The Composition of
Ultra High Energy Cosmic Rays



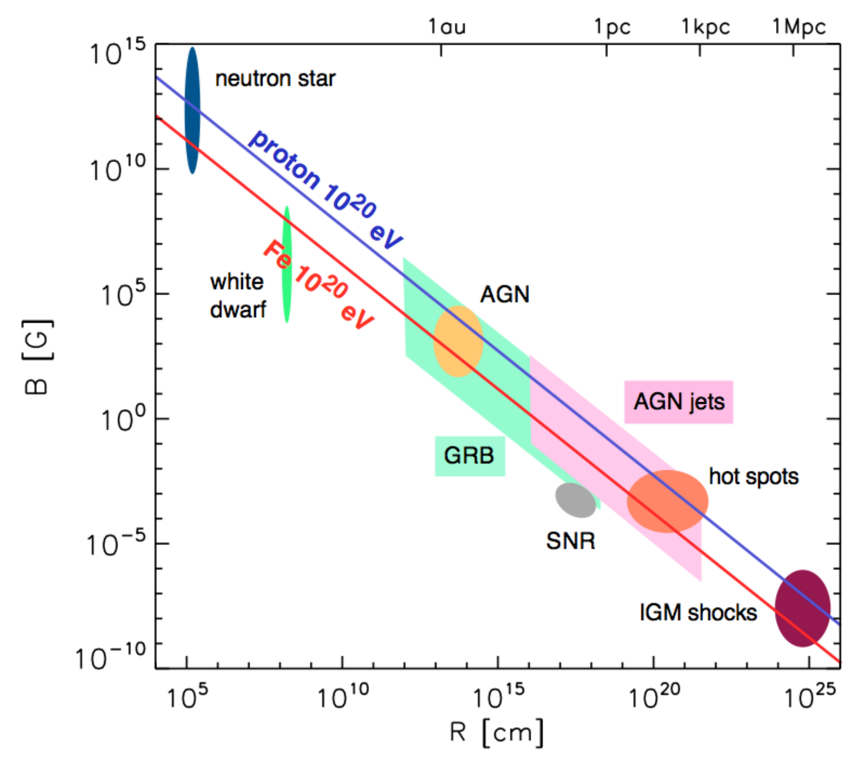
PAO Collaboration (review by Kotera & Olinto 2011)



Highest energy
UHECRs dominated by
heavy nuclei !

Candidate Astrophysical Sources

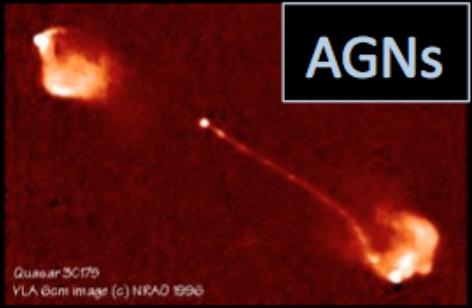
Hillas: $R_L = E/ZeB < R_{source}$



Magnetic Field Strength

Source Size

Most luminous explosions



Quasar 3C175
VLA 6cm image (c) NRAO 1996

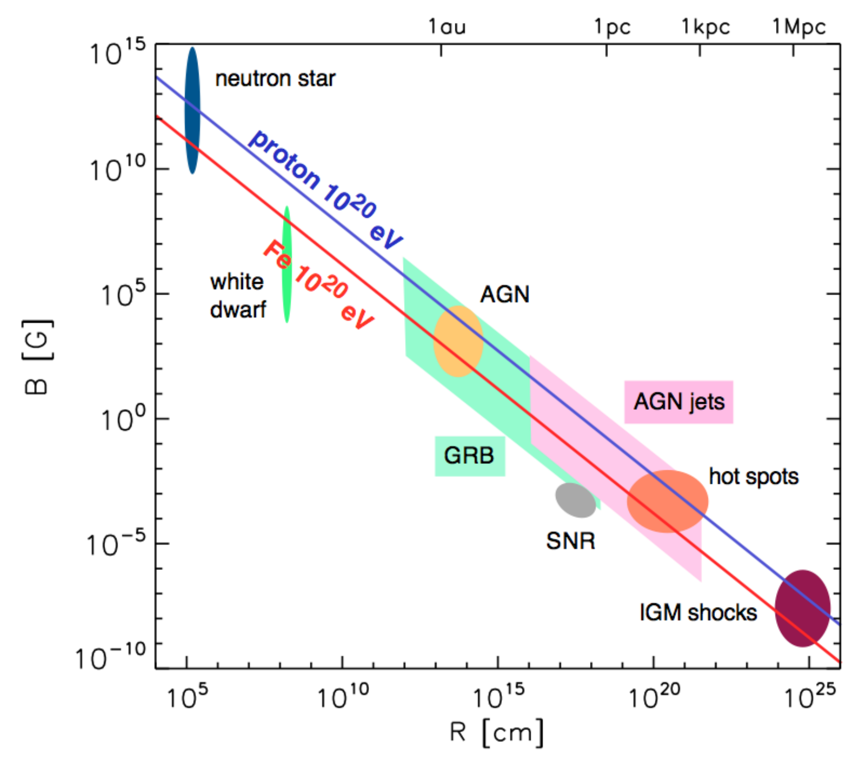
Most massive black holes

Largest bound objects

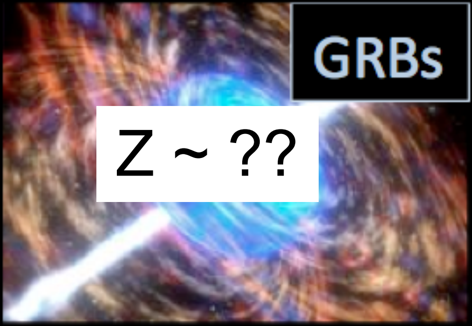
Candidate Astrophysical Sources

Hillas: $R_L = E/ZeB < R_{source}$

Magnetic Field Strength



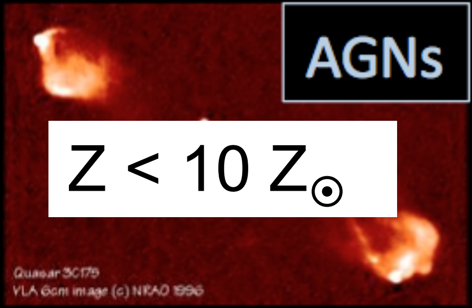
Source Size



GRBs

$Z \sim ??$

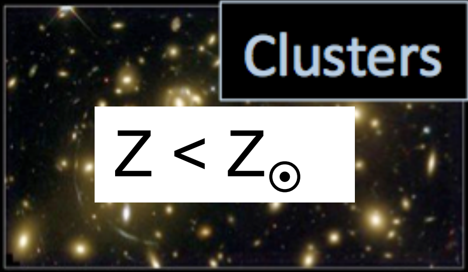
Most luminous explosions



AGNs

$Z < 10\,Z_\odot$

Most massive black holes



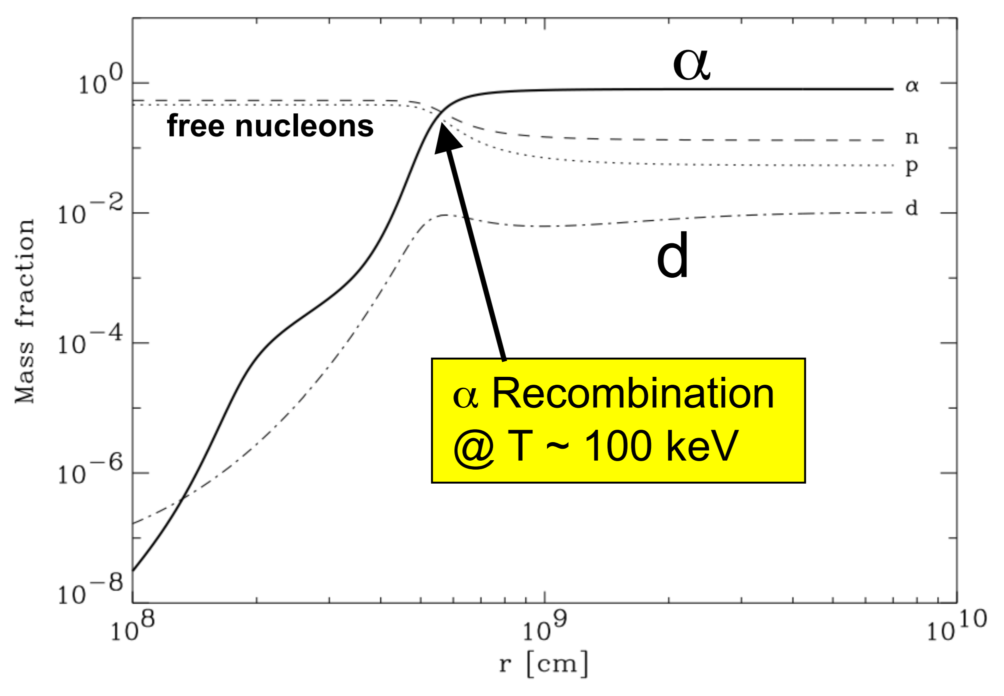
Clusters

$Z < Z_\odot$

Largest bound objects

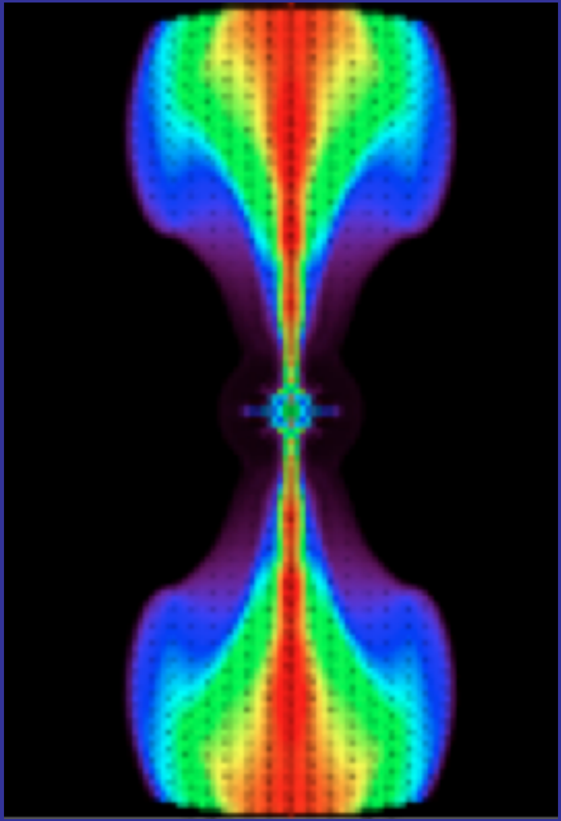
Nucleosynthesis in Thermally-Driven GRB Outflows

(Lemoine 2002; Pruet et al. 2002; Beloborodov 2003)



α Recombination
@ T ~ 100 keV

Lemoine 2002



GRB
Fireball

$$\frac{n_\gamma}{n_b} \sim 4 \times 10^4 \left(\frac{L_{j,iso}}{10^{52} \mathrm{erg\ s^{-1}}}\right)^{-1/4} \left(\frac{R_0}{10^7 \mathrm{cm}}\right)^{1/2} \left(\frac{\Gamma_j}{300}\right)$$

$$\Delta t_{exp} \sim \mathrm{ms}$$

vs. Big Bang Nucleosynthesis

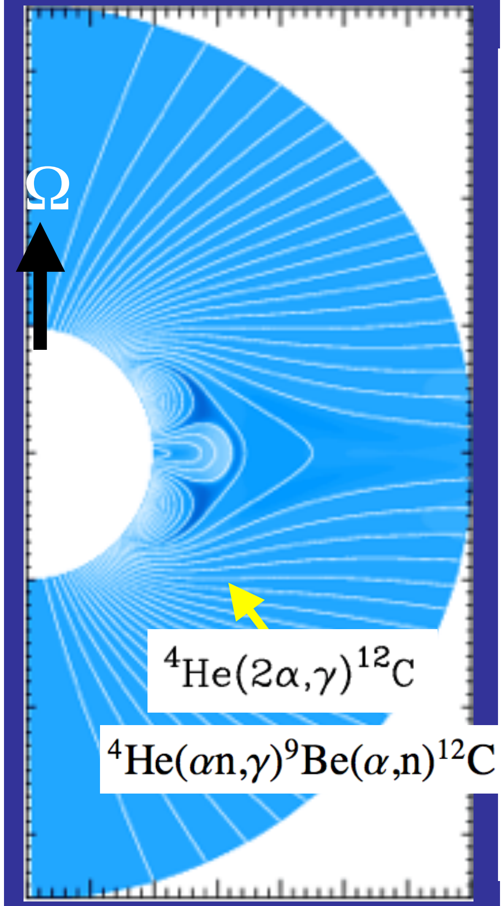
$$\frac{n_\gamma}{n_b} \sim 10^{10}$$

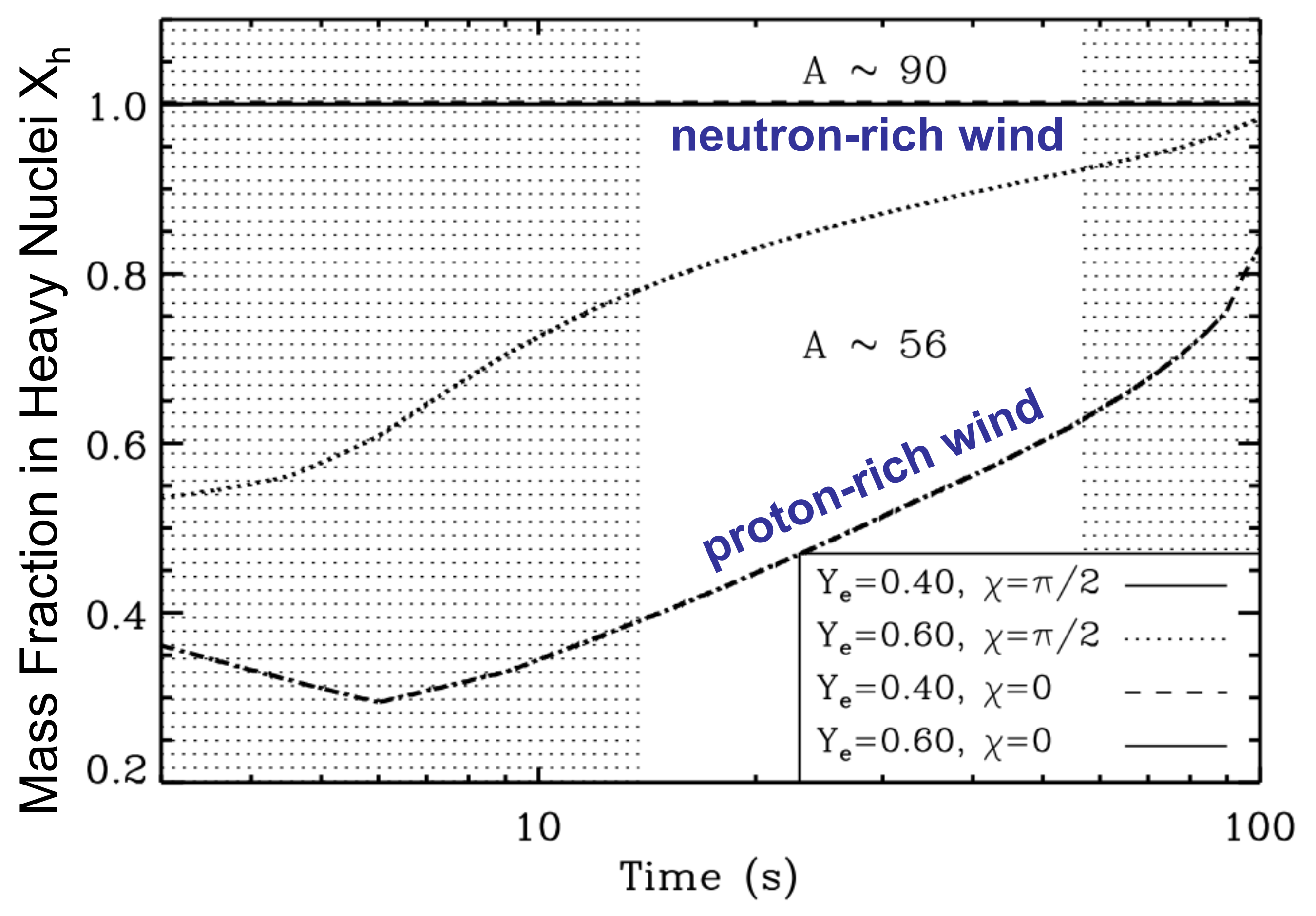
$$\Delta t_{exp} \sim \mathrm{min}$$

$\}$ High entropy ⇒
D bottleneck ⇒
mostly ^{4}He

Nucleosynthetic Yield of Proto-Magnetar Winds

Metzger, Giannios & Horiuchi 2011 (see also Kotera 2012)

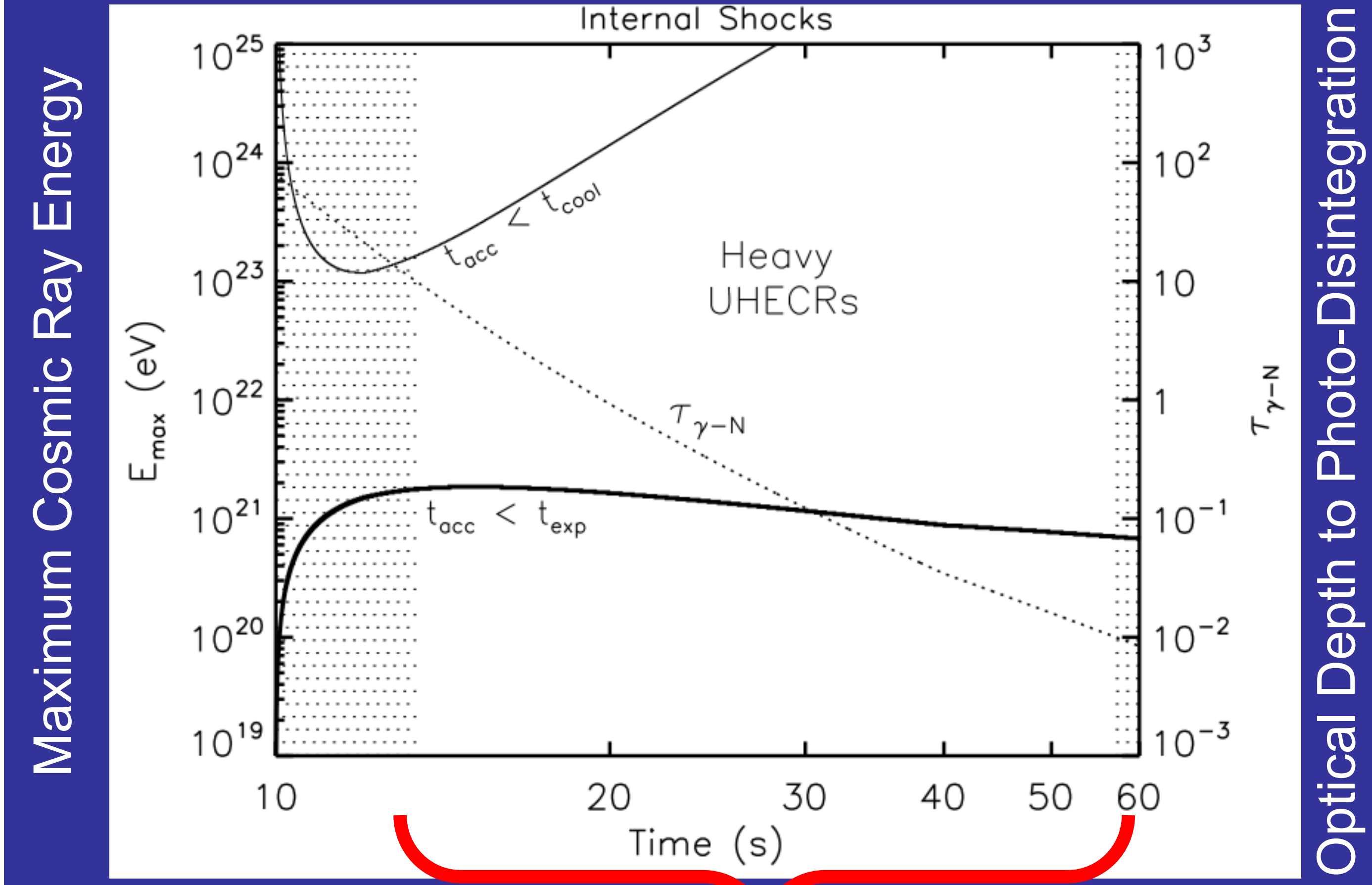


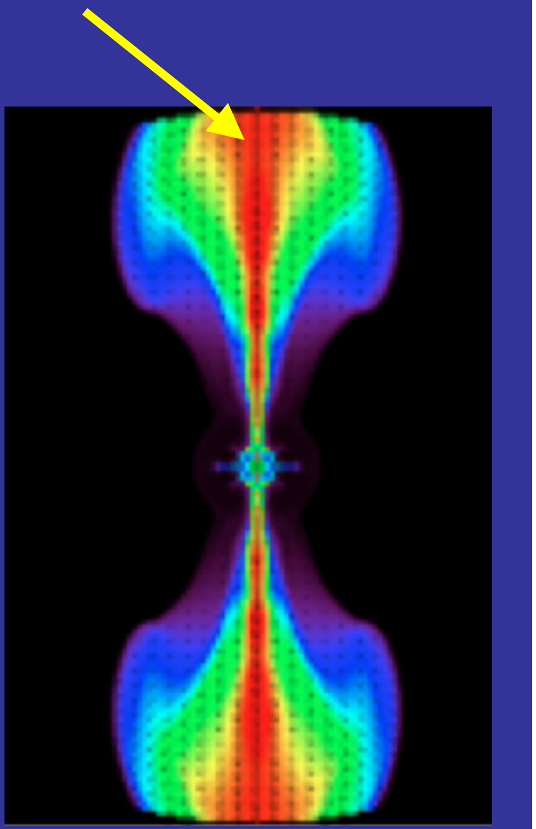


If proton-rich: X_h~ 0.3-0.8 (X_{He}=1-X_h) and ⟨A⟩ ~ 56 (Fe group)

If neutron-rich: X_h~ 1 and ⟨A⟩ ~> 90 (possibly r-process elements)

UHECR Acceleration by Internal Shocks



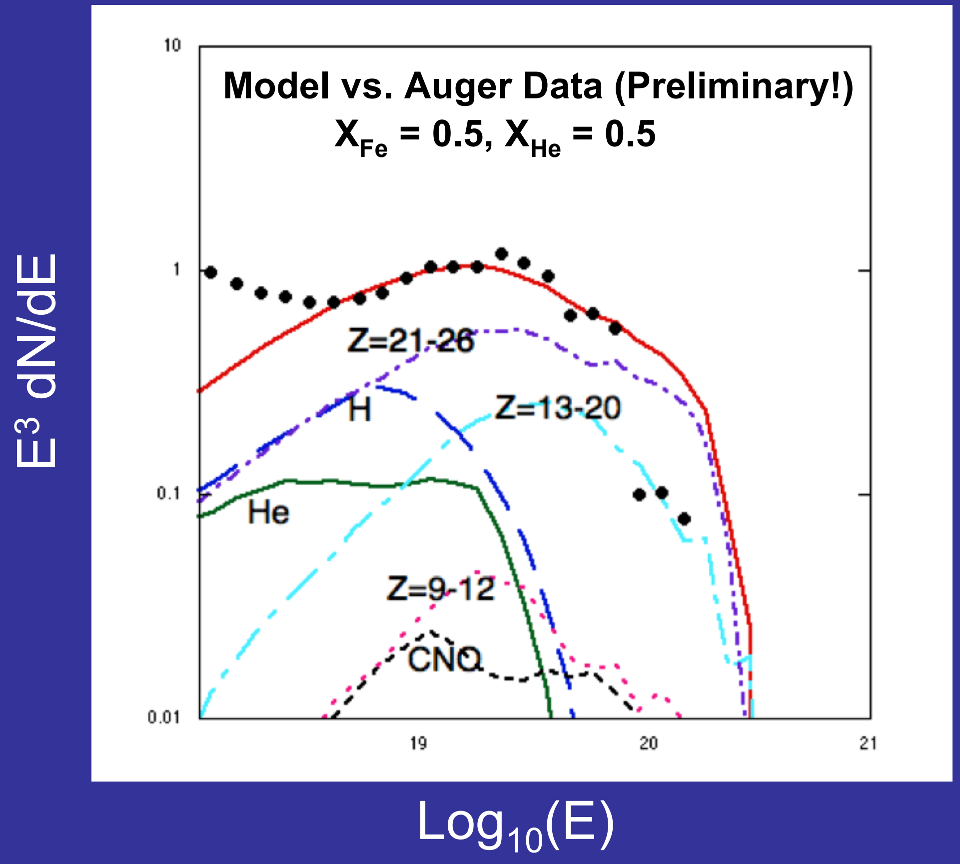


During this epoch, heavy nuclei can both reach energies $E > 10^{20}$ eV **and** survive destruction via $\gamma N \Rightarrow n\ N'$

Propagating Heavy Nuclei to Earth

Mean Free Path for
Photodisintegration by EBL/CMB:

$$\chi_{75} \approx 170 \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1.5} \left(\frac{A}{56}\right)^{1.3} \mathrm{Mpc}$$



(Calculation by D. Allard)

Accessible Volume $\propto \chi^3 \propto A^{3.9} \Rightarrow$ even a small fraction of ultra-heavy sources dominate composition at highest energies