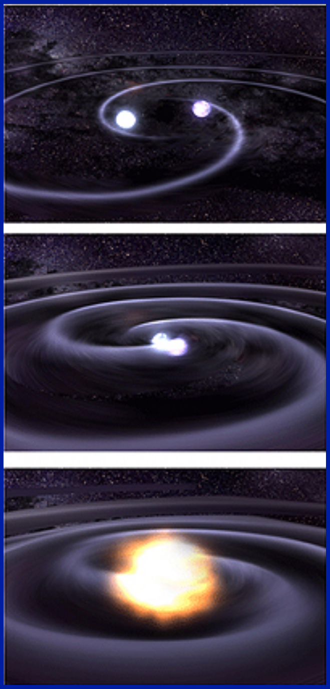
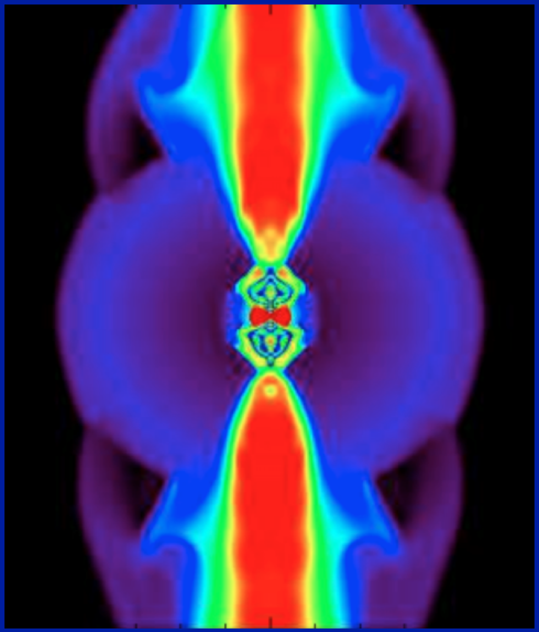
Electromagnetic Counterparts of Neutron Star Binary Mergers



NS ⇔ NS

NS ⇔ BH



Brian Metzger

NASA Einstein Fellow

Princeton University

In Collaboration with

Edo Berger (Harvard), Tony Piro (Caltech), Todd Thompson (OSU)

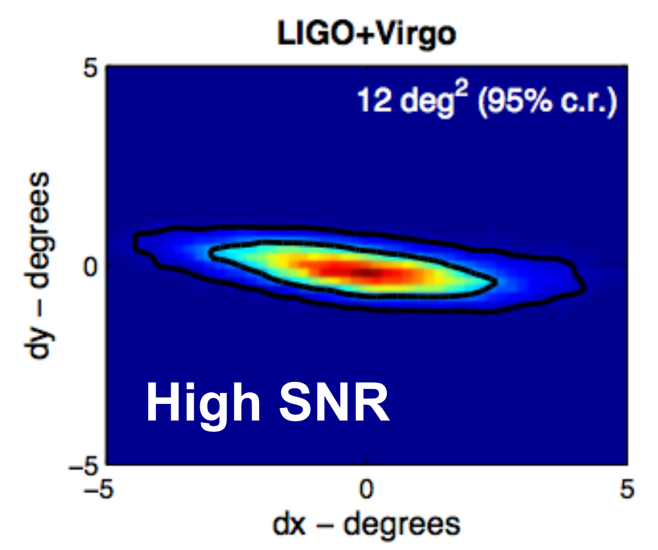
Almudena Arcones & Gabriel Martinez-Pinedo (GSI Darmstadt)

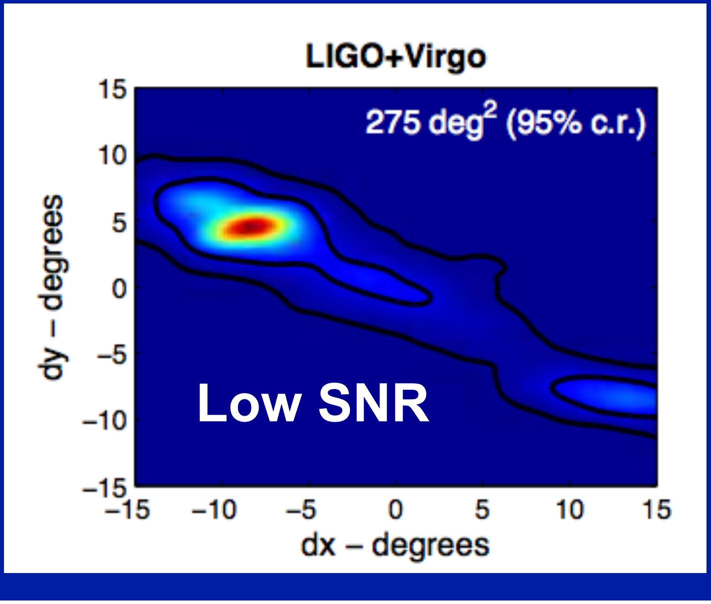
Eliot Quataert, Siva Darbha, Daniel Perley, Josh Bloom, Dan Kasen (UC Berkeley)

“Rattle & Shine,” KITP Santa Barbara, July 30, 2012

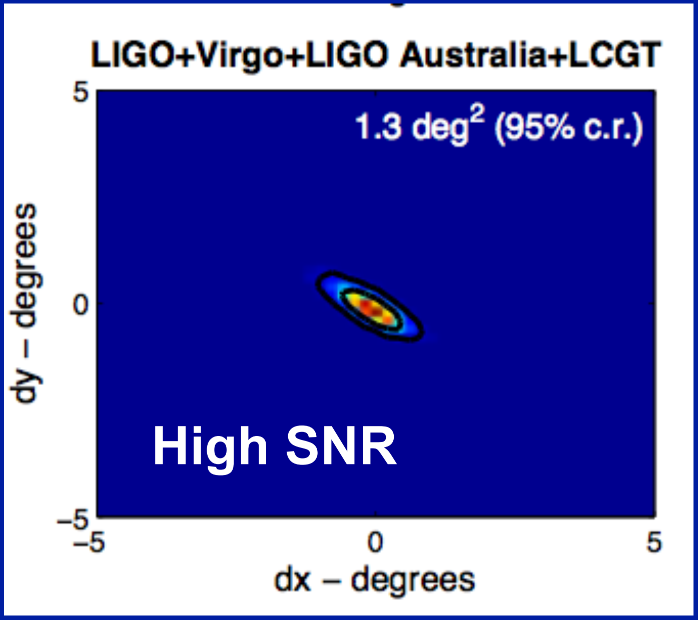
Sky Error Regions of Advanced GW Detector Arrays

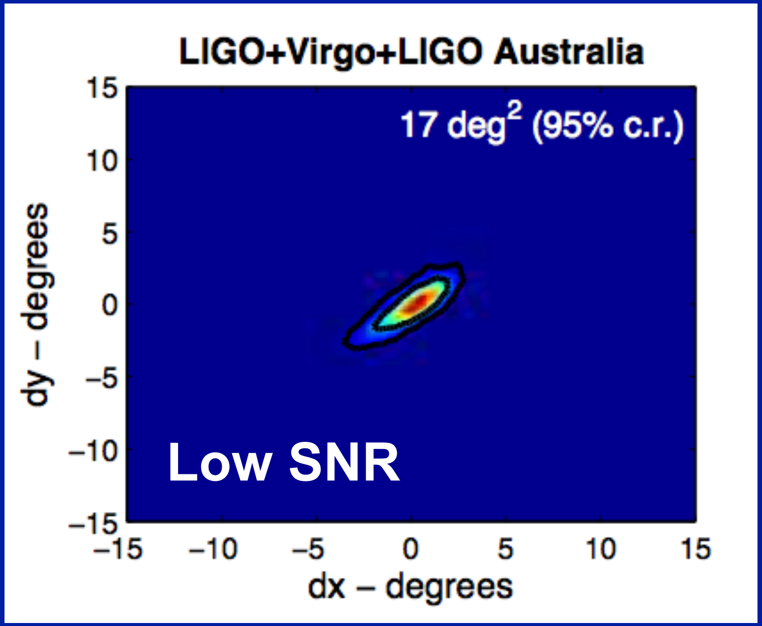
~2017


LIGO+Virgo


LIGO+Virgo

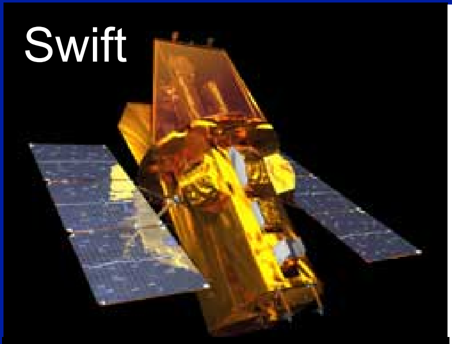
~2020


LIGO+Virgo+LIGO Australia+LCGT


LIGO+Virgo+LIGO Australia

Nissanke et a. 2011

Gamma-Rays



Swift

BAT FOV ~ 15%

XRT slews in ~min

Fermi

Gamma-ray Space Telescope

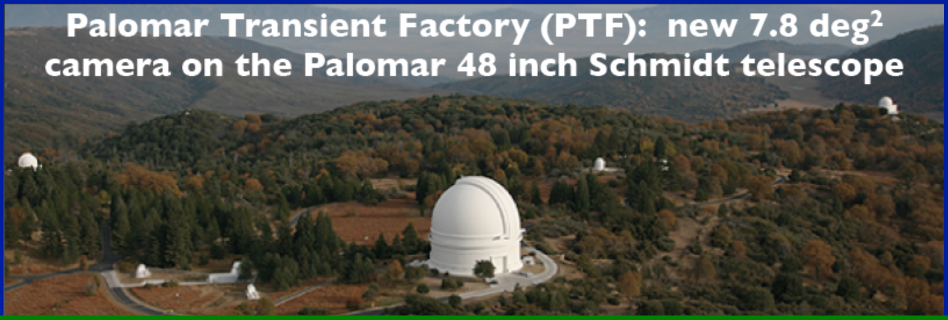
GBM FOV ~ 60%

Radio

LOFAR

FOV ~50%

Optical ("Now")



Palomar Transient Factory (PTF): new 7.8 deg^2 camera on the Palomar 48 inch Schmidt telescope

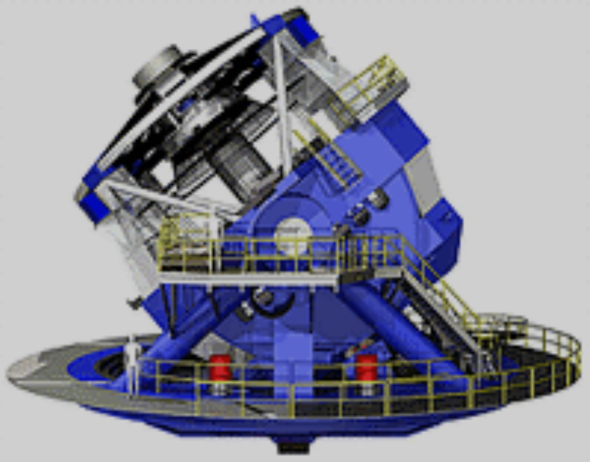
Quarter sky to $m_{AB} < 21$ every ~3 days

1 (ultimately 4) 1.8 m mirrors w/ Gigapixel Cameras

84 deg^2 "medium deep" survey to $m_{AB} < 25$ every few days

Optical (Future)

Large Synoptic Survey Telescope (LSST)



~All sky m_{AB}<24.5 every ~3 d

- Online >~2020

Importance of EM Detection:

- Improve “Confidence” in GW Detection; Dig Deeper into GW Data
- Independently Constrain Binary Parameters
- Astrophysical Context (e.g. Identify Host Galaxy & Environment)
- Other Science: e.g. Cosmology (Redshift $\Rightarrow H_0$), Test Strong-Field GR

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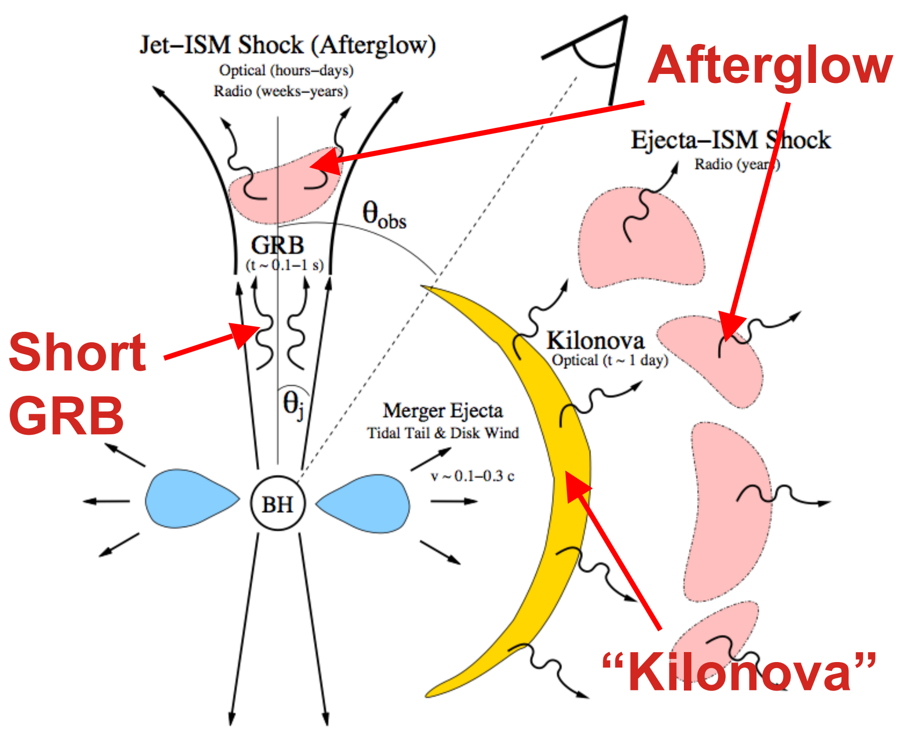

Metzger & Berger 2012

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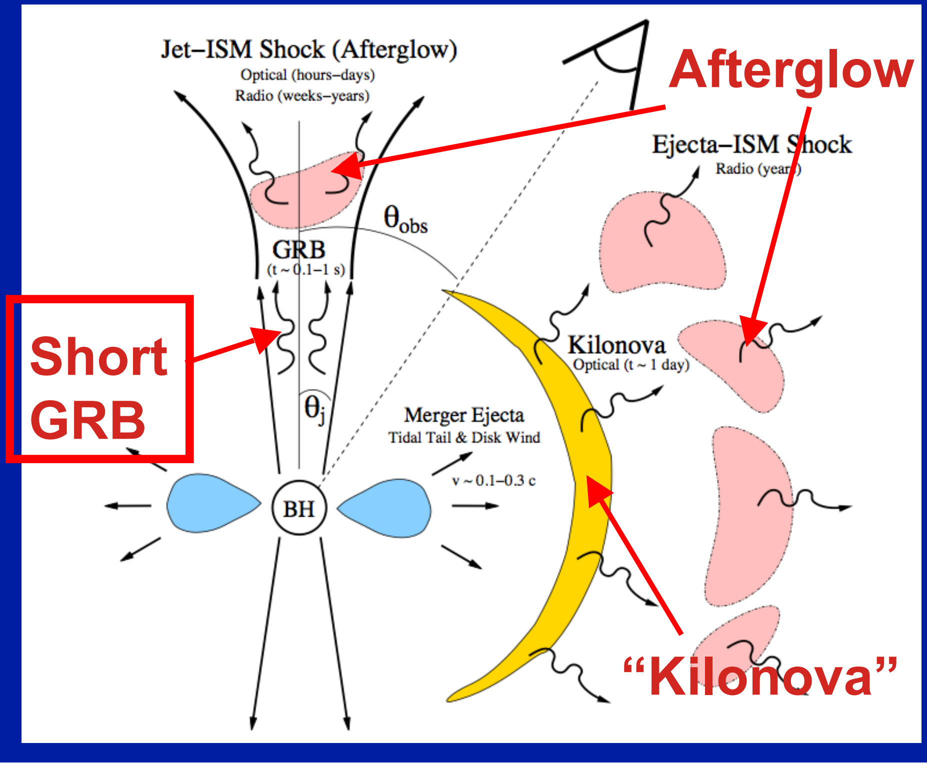
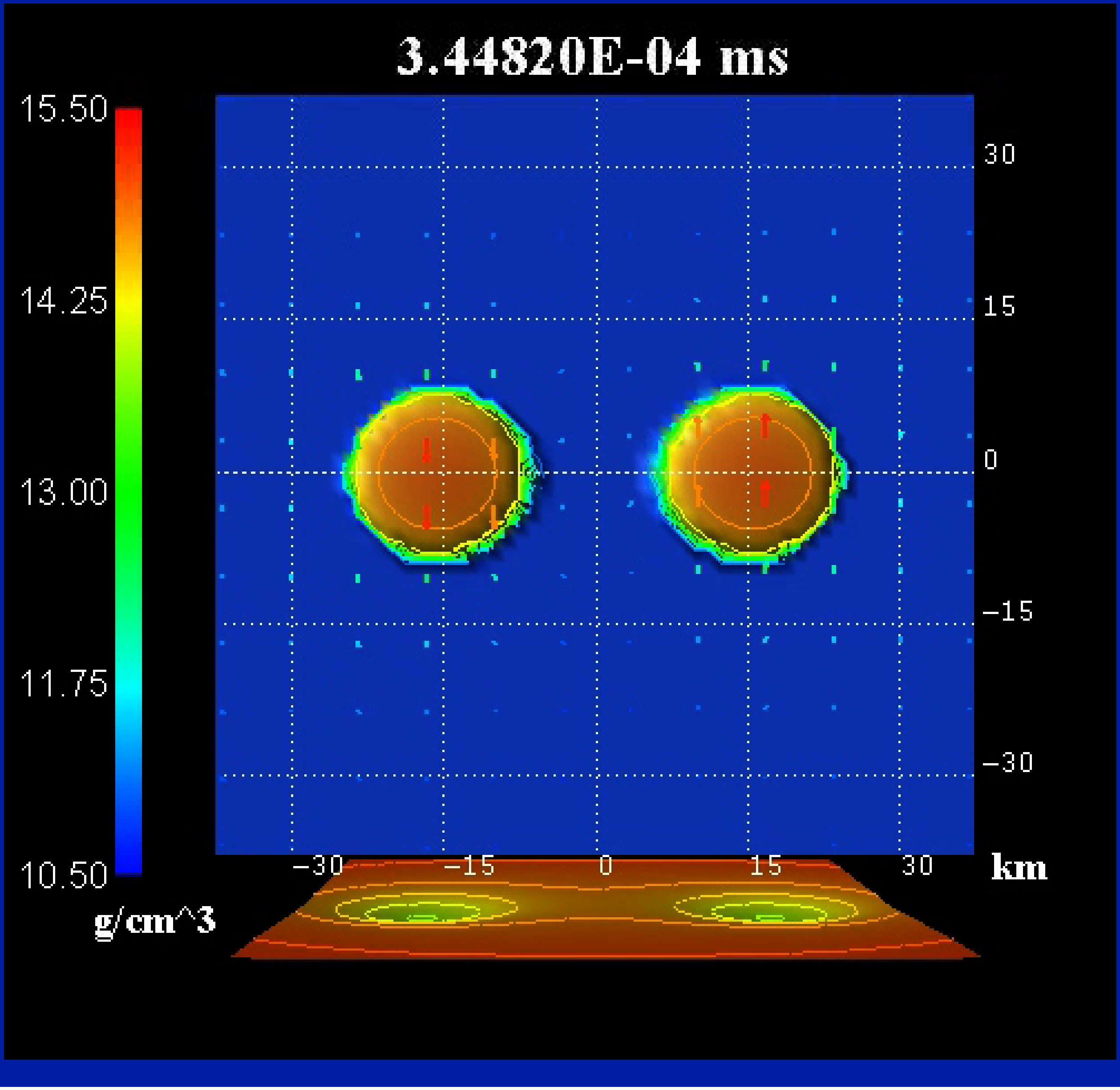


Metzger & Berger 2012

Numerical Simulation - Two 1.4 $M_\odot$ NSs

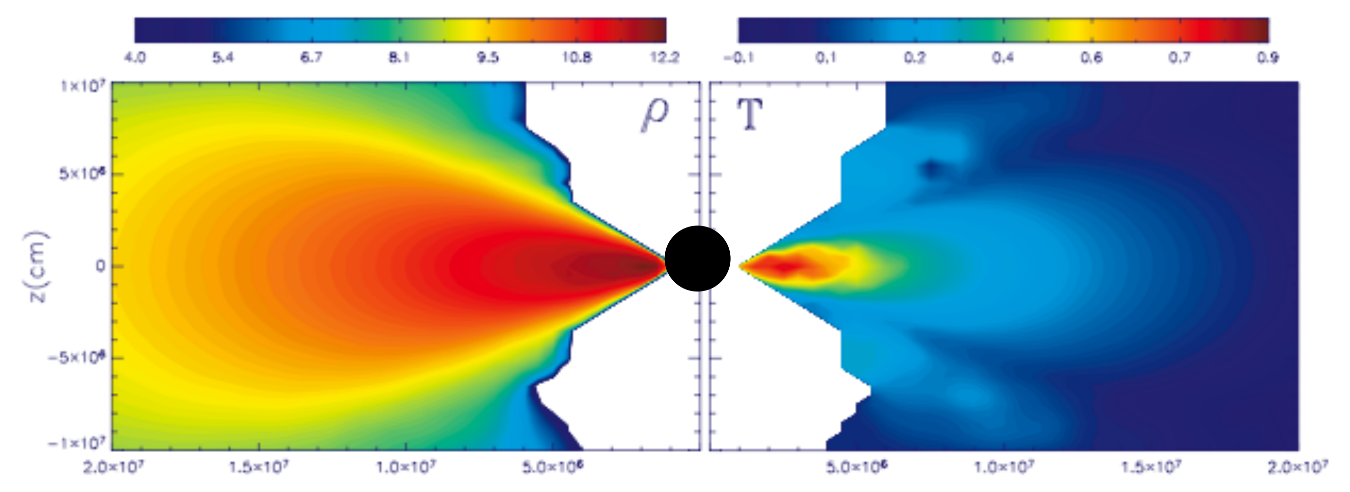
(see talks by Shibata, Rosswog, Etienne, Ramirez-Ruiz, Lovelace, Pretorius, Kiuchi, Foucart)



Courtesy M. Shibata (Tokyo U)

Remnant Accretion Disk

(e.g. Ruffert & Janka 1999; Shibata & Taniguchi 2006; Chawla et al. 2010; Duez et al. 2010; see talks by Ott, Reddy)



Lee et al. 2004

- Disk **Mass ~ 10^{-3} - 0.1 $M_\odot$** & **Size ~ 10-100 km**
- Midplane Hot (T > MeV) & Dense ($\rho \sim 10^{8}$-10^{12} g cm^{-3})
- Cooling via Neutrinos: ($\tau_\gamma >> 1$, $\tau_\nu \sim 0.01$-100)

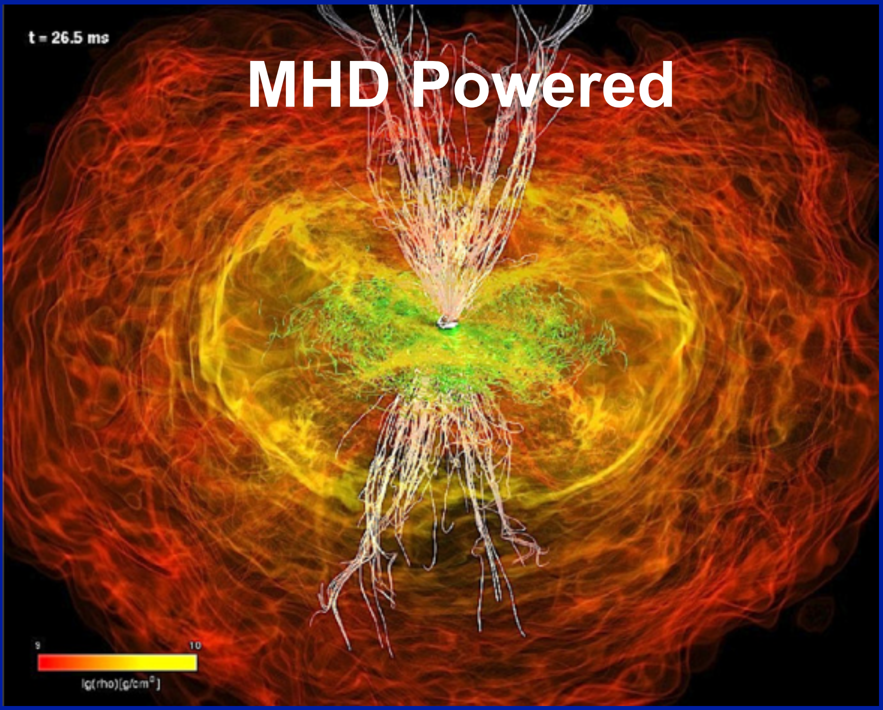
Accretion Rate $\dot{M} \sim 10^{-2} - 10\, M_\odot\ \mathrm{s}^{-1}$

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

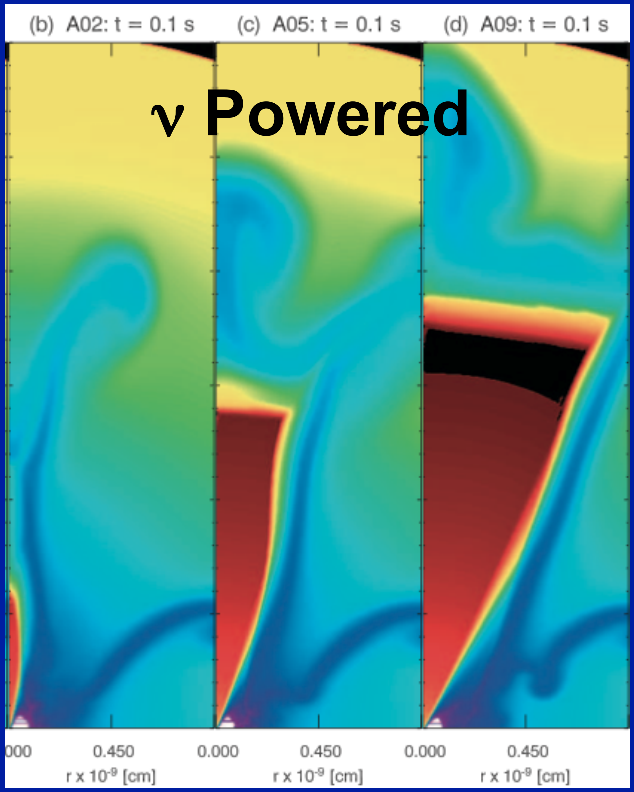
Short GRB
Central Engine?

(e.g. Narayan et al. 1992)

Relativistic Jets and Short GRBs



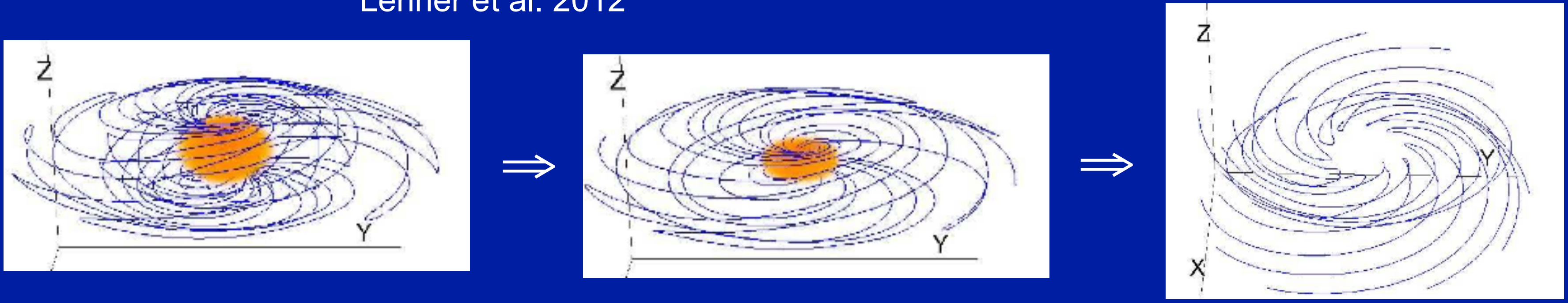
Rezolla et al. 2010



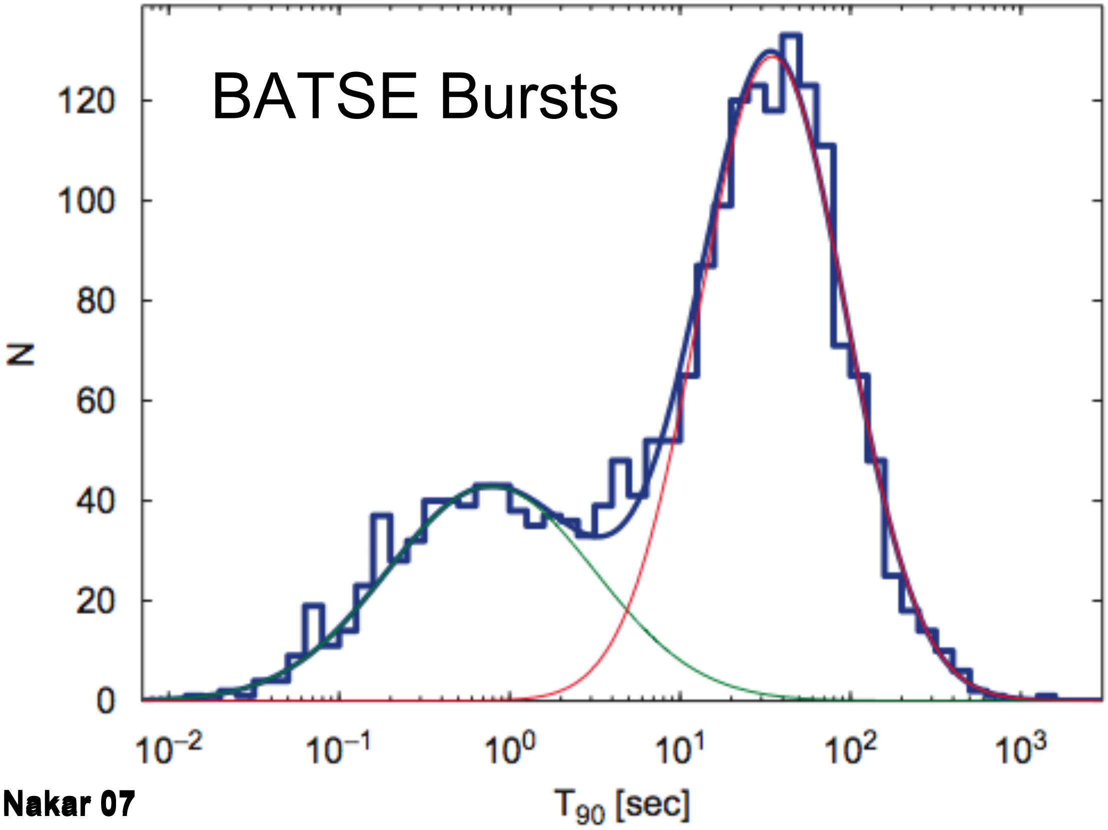
Aloy et al. 2005

Collapse of the Hyper-massive Magnetar

Lehner et al. 2012

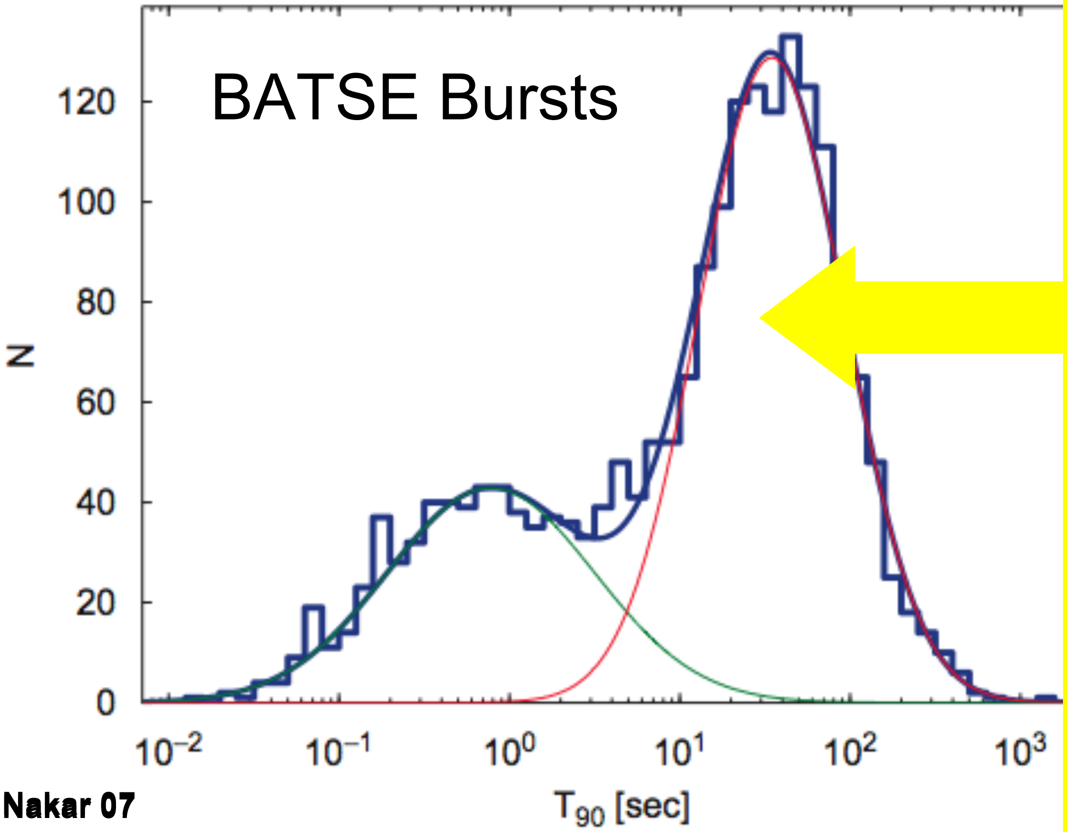


Short & Long Gamma-Ray Bursts



Nakar 07

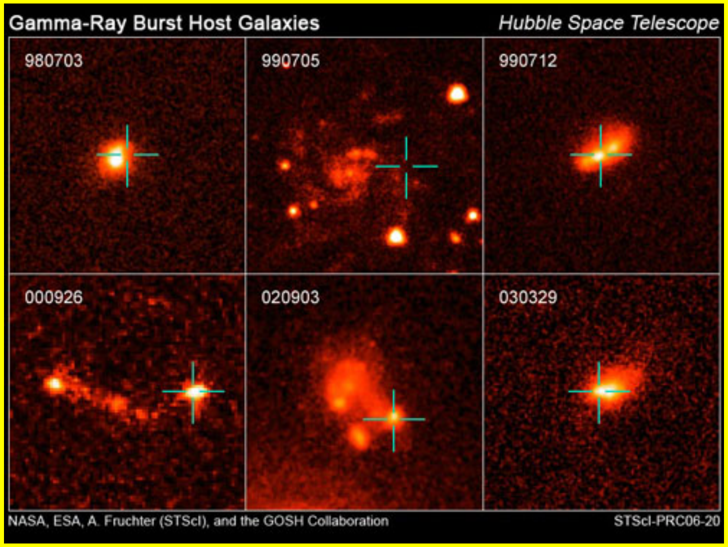
Short & Long Gamma-Ray Bursts



Nakar 07

Long GRBs = Death of Massive Stars

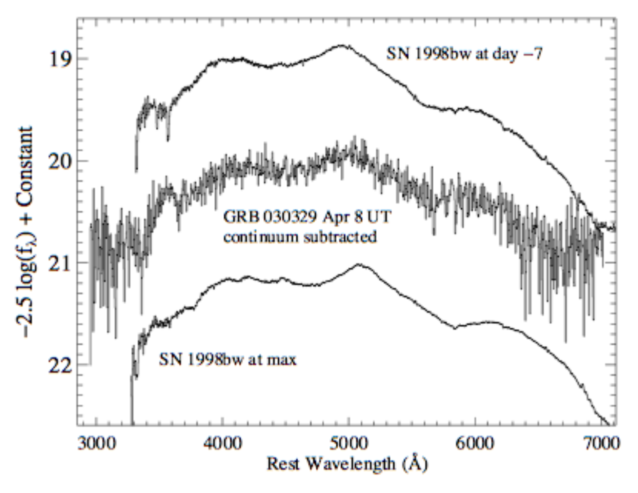
Star-Forming Host Galaxies (z_{avg}~2-3)



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

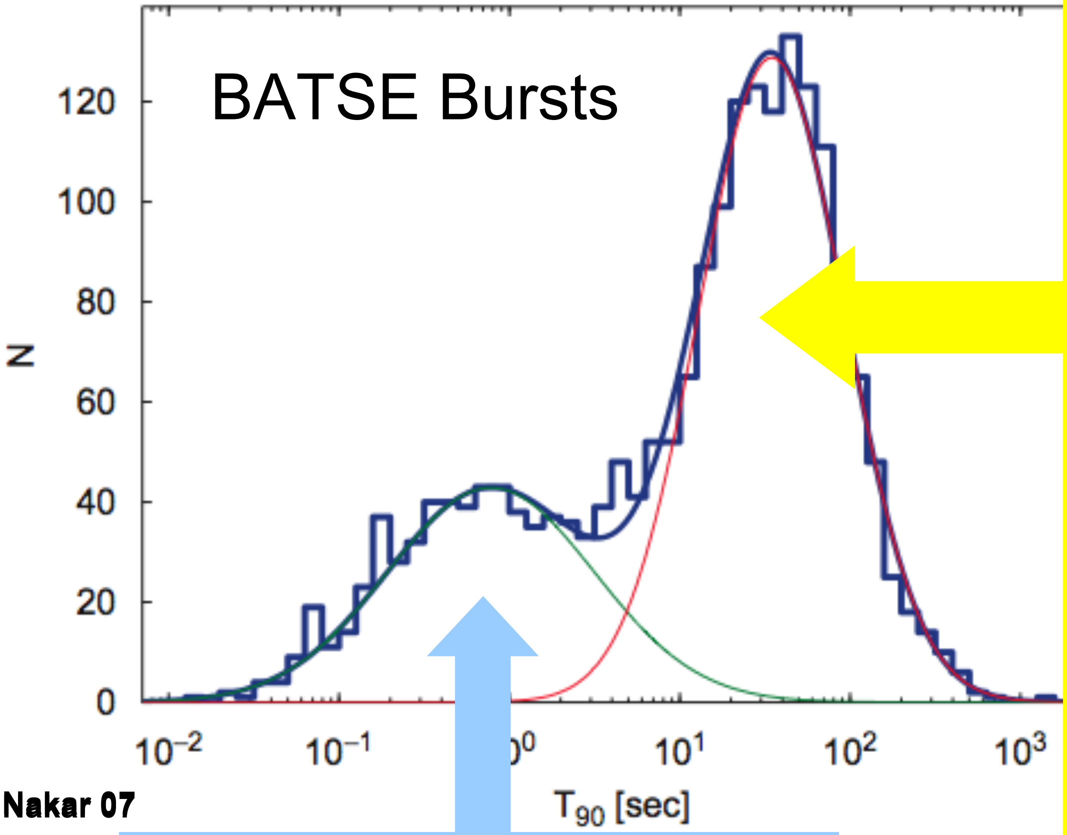
STScI-PRC06-20

Supernova Connection
GRB 030329 ⇔ SN 2003dh

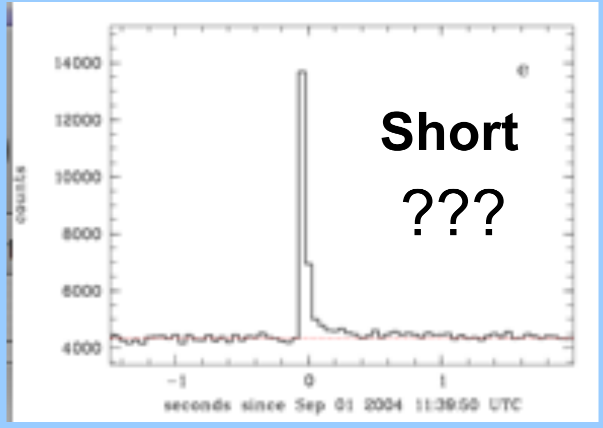


Stanek et al. 2003

Short & Long Gamma-Ray Bursts



Nakar 07

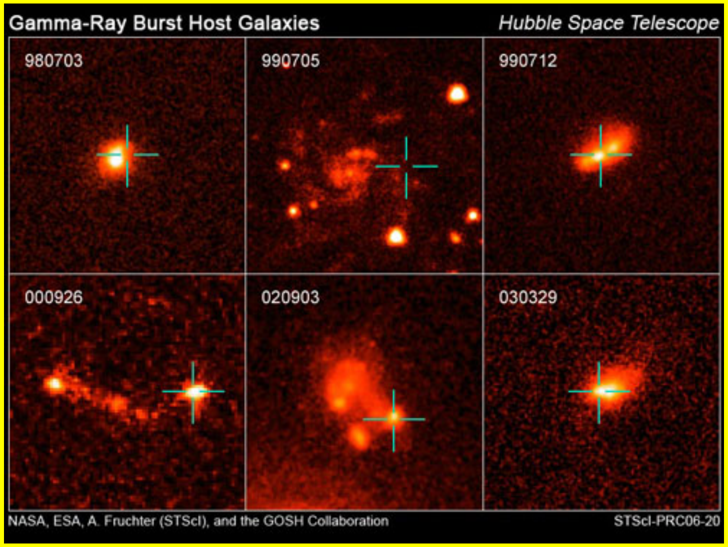


Short

???

Long GRBs =
Death of Massive Stars

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



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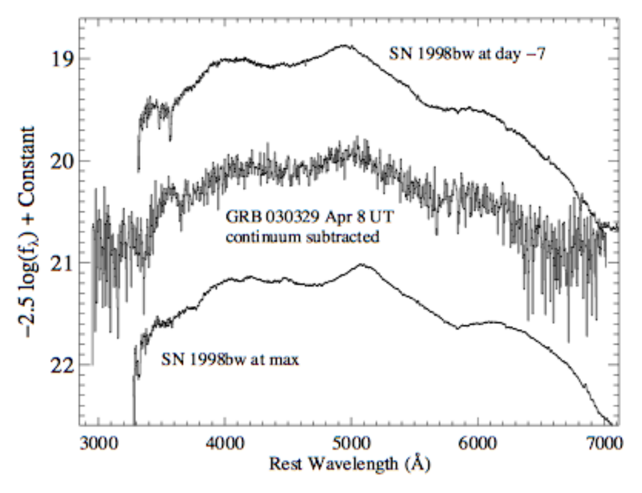
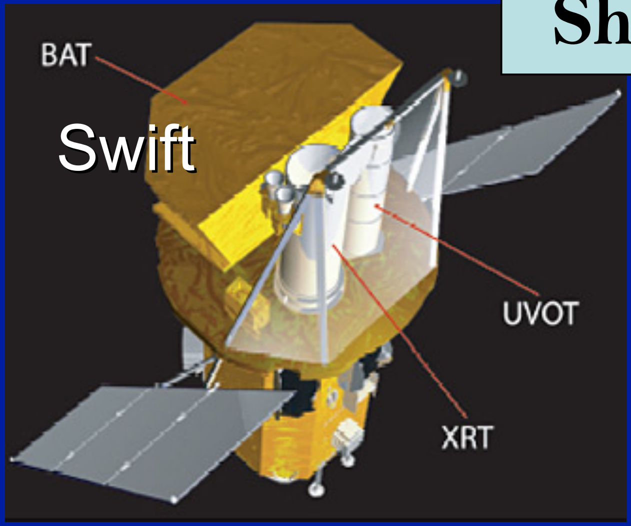
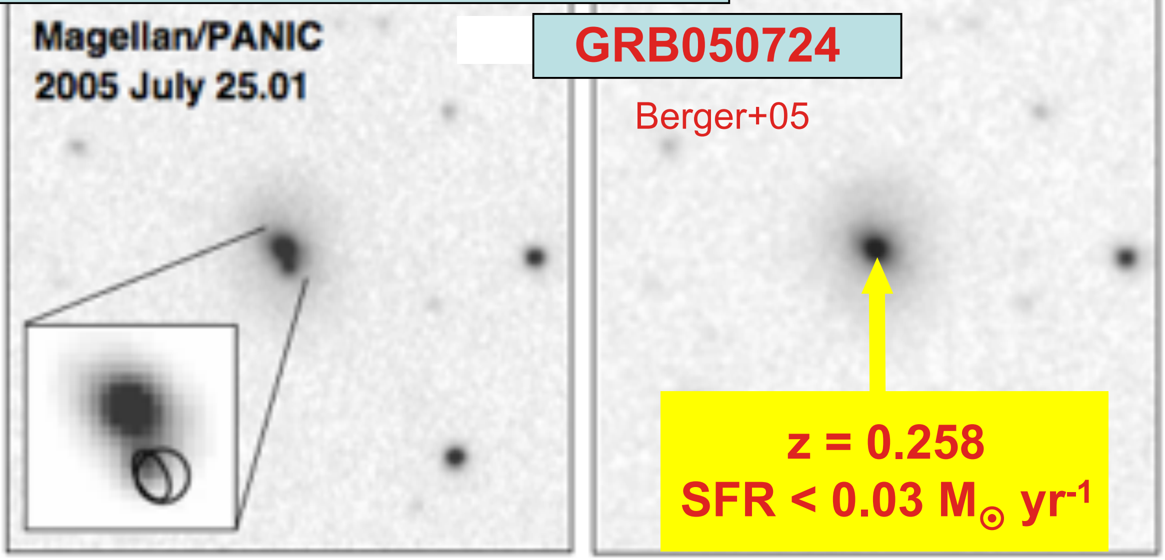


Stanek et al. 2003

Short GRB Host Galaxies

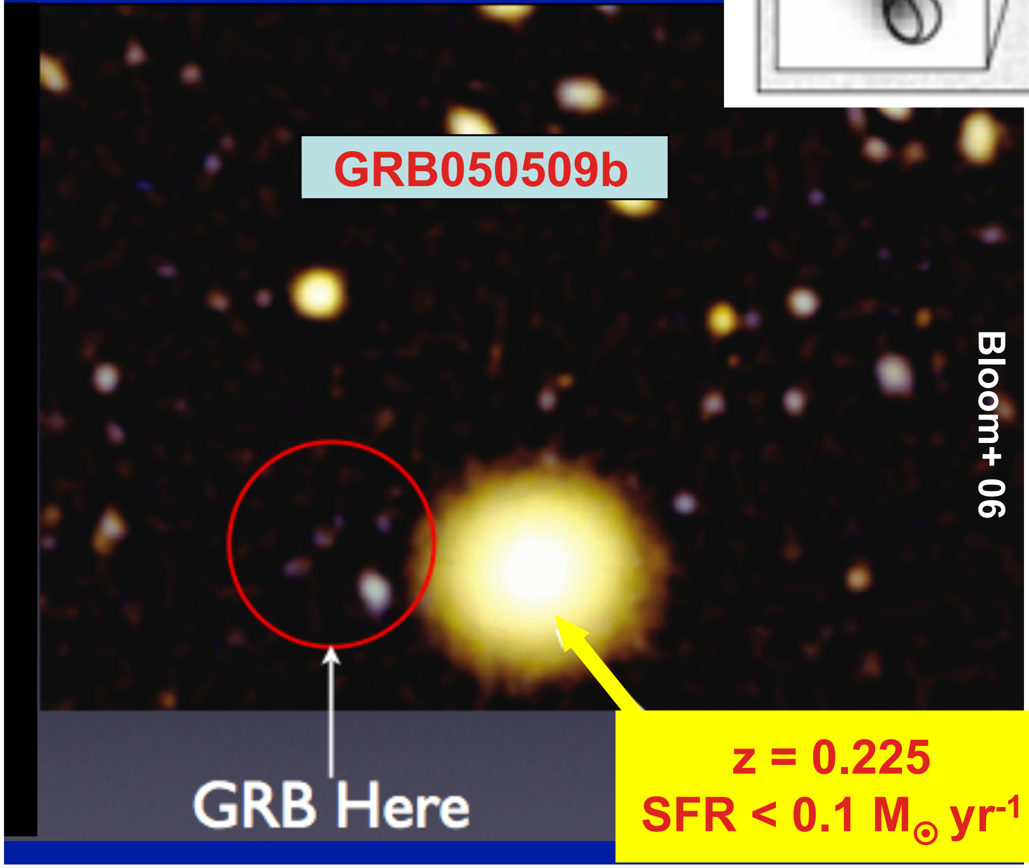




GRB050724

Berger+05

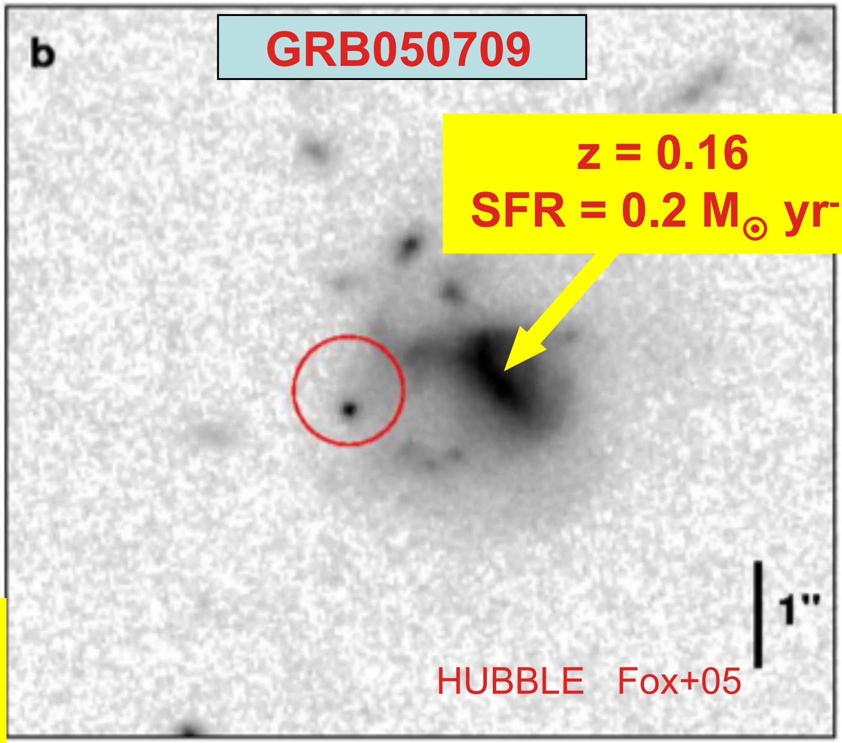
z = 0.258
SFR < 0.03 $M_\odot$ yr^{-1}



GRB050509b

Bloom+ 06

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

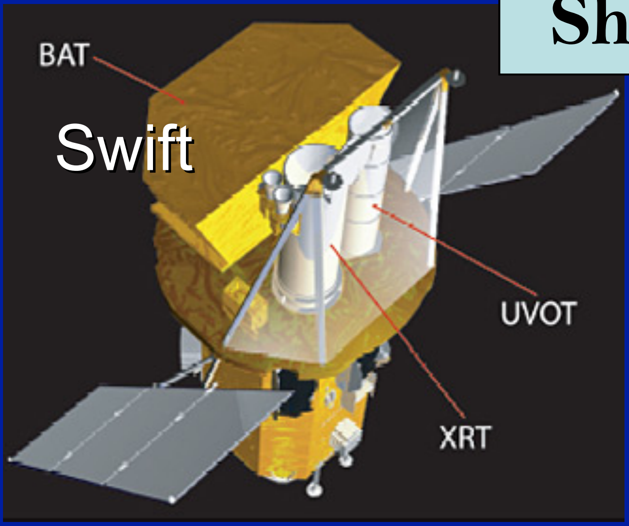


GRB050709

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

HUBBLE Fox+05

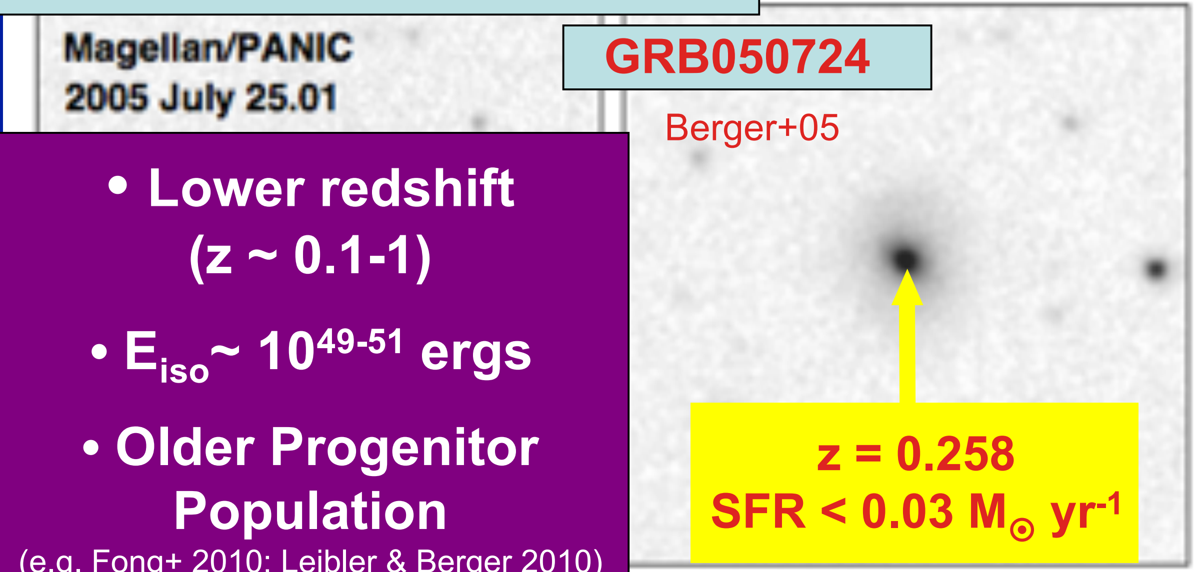
Short GRB Host Galaxies



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

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

see talk by Fong



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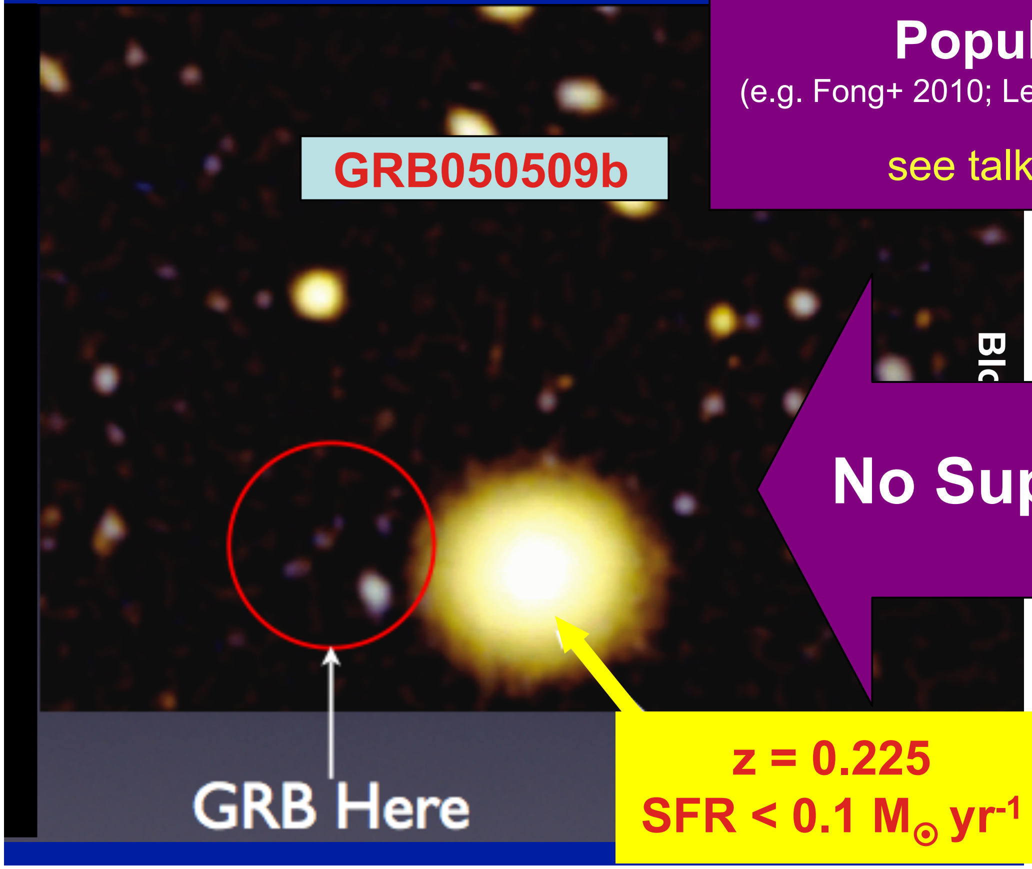

GRB050509b

z = 0.225
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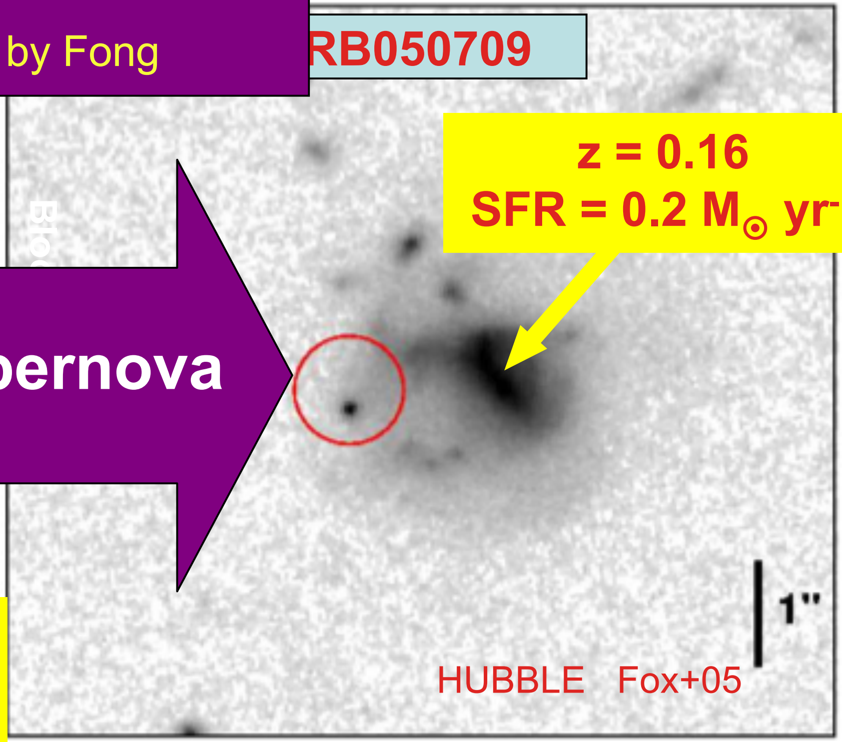
No Supernova



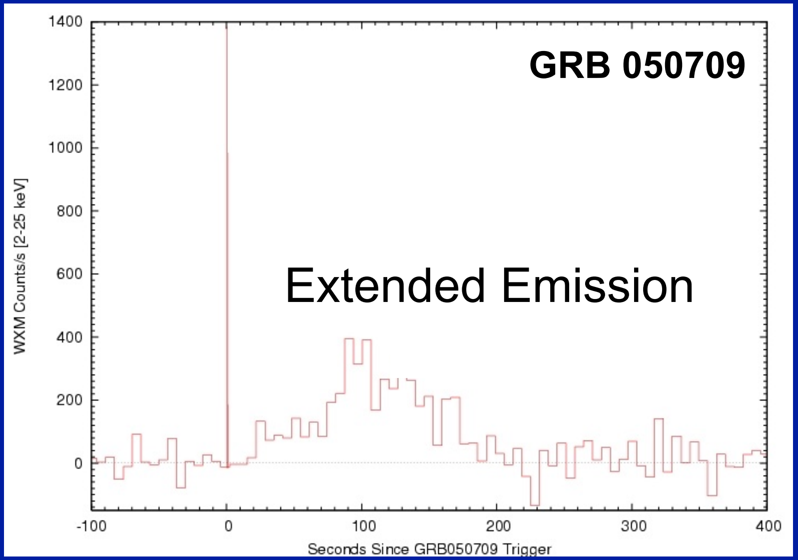
RB050709

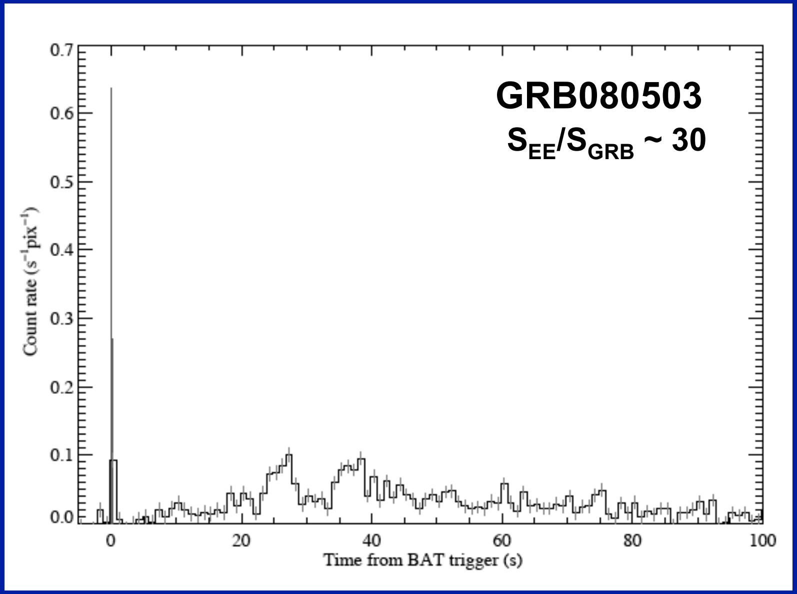
z = 0.16
SFR = 0.2 $M_\odot$ yr^{-1}

HUBBLE Fox+05

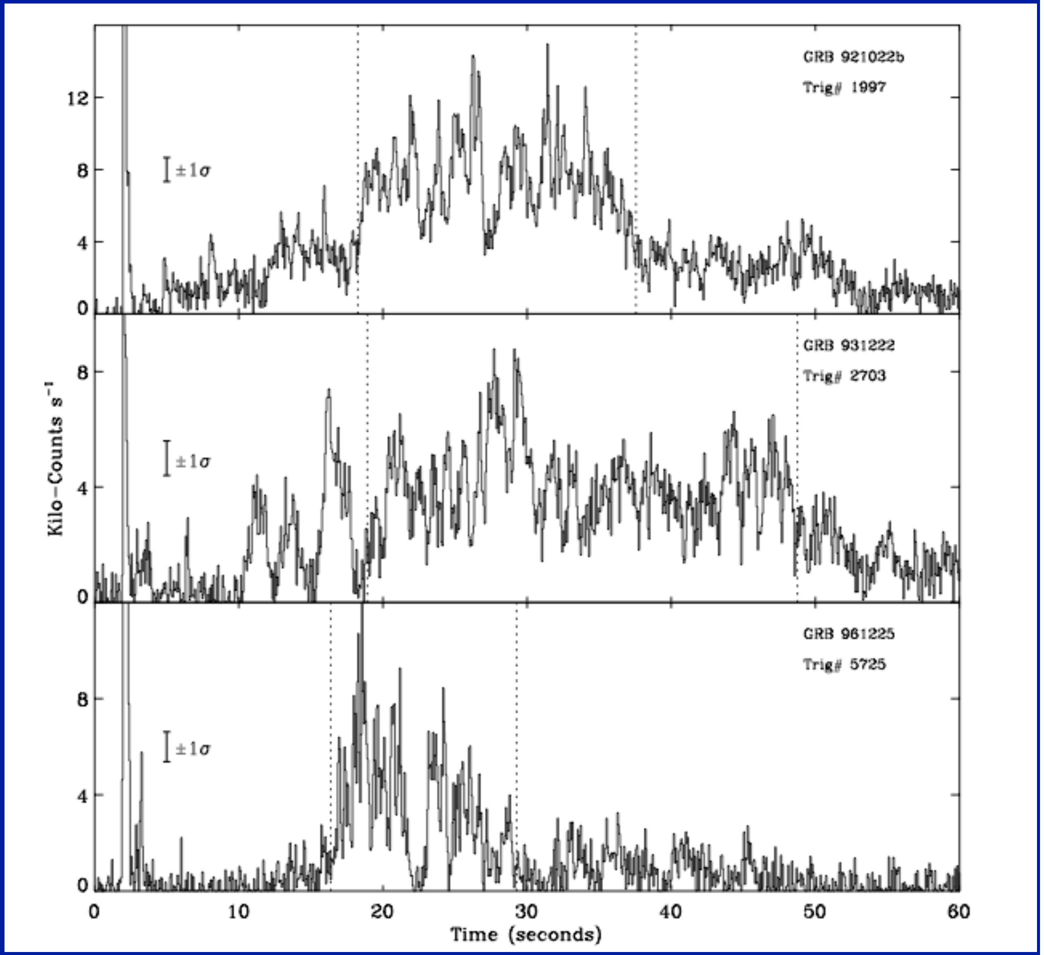
Not that Short After All….

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



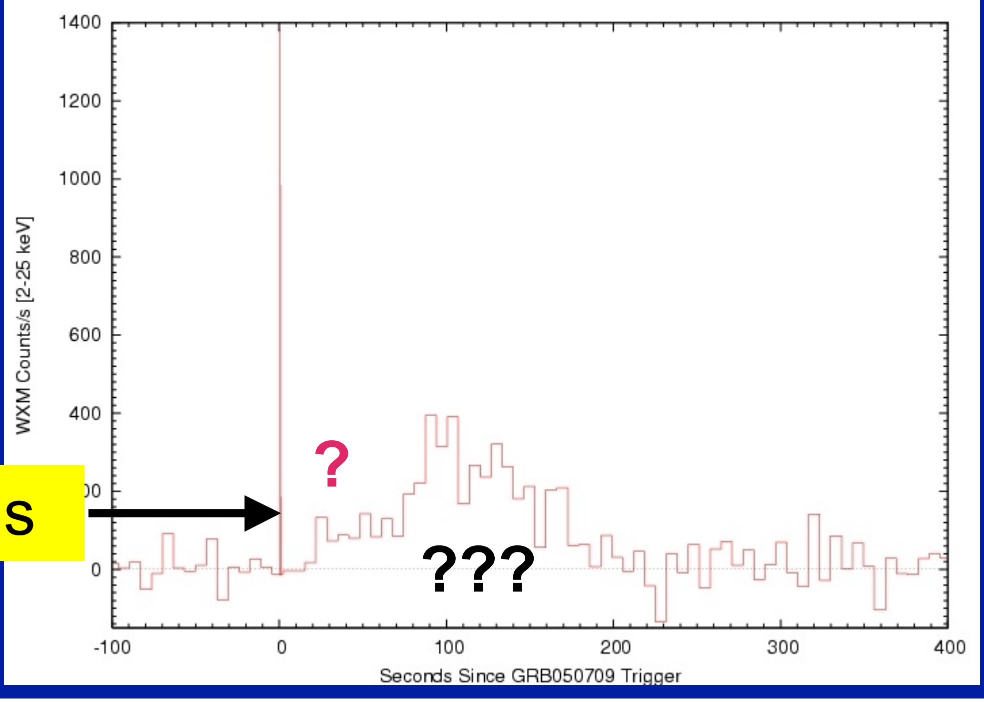


Perley, BDM et al. 2009

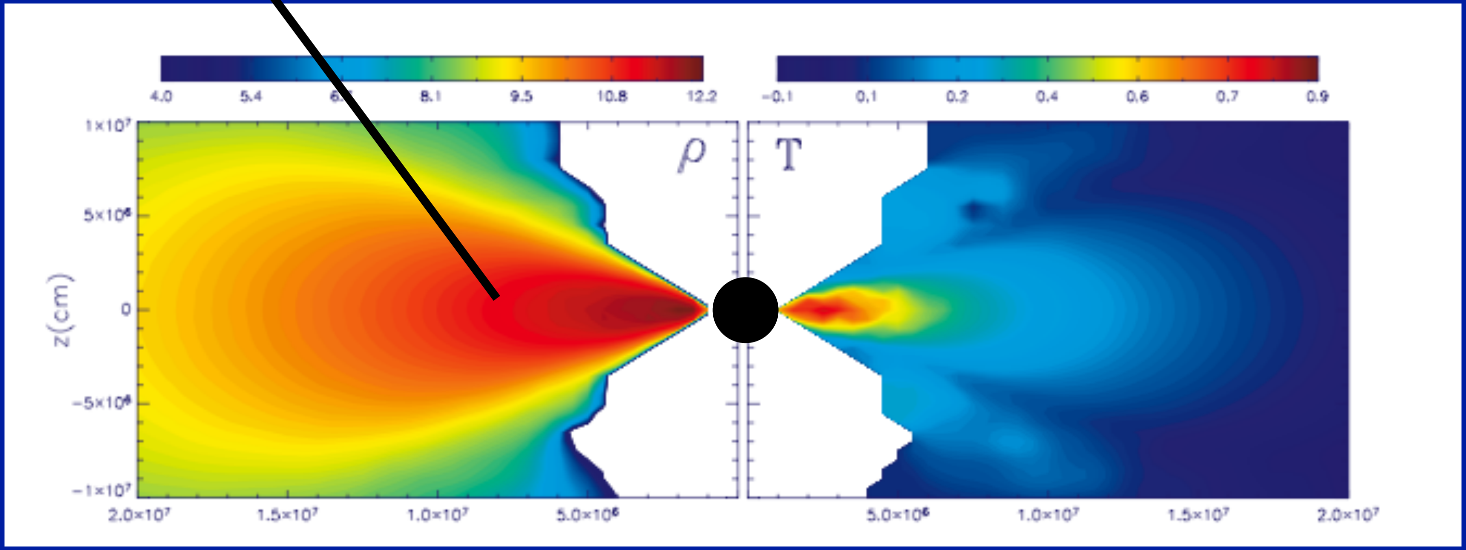


BATSE Examples (Norris & Bonnell 2006)

Why Two Timescales? Why the Delay?



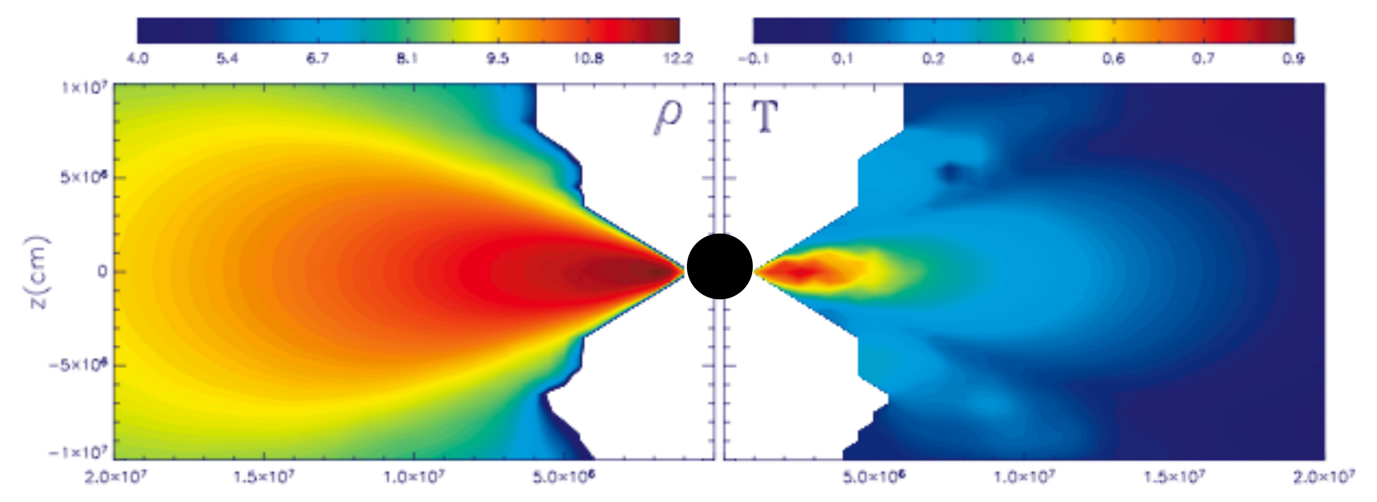
$t_{accretion}$ ~ 0.1-1 s



Lee et al. (2004)

Late Accretion from the Disk?

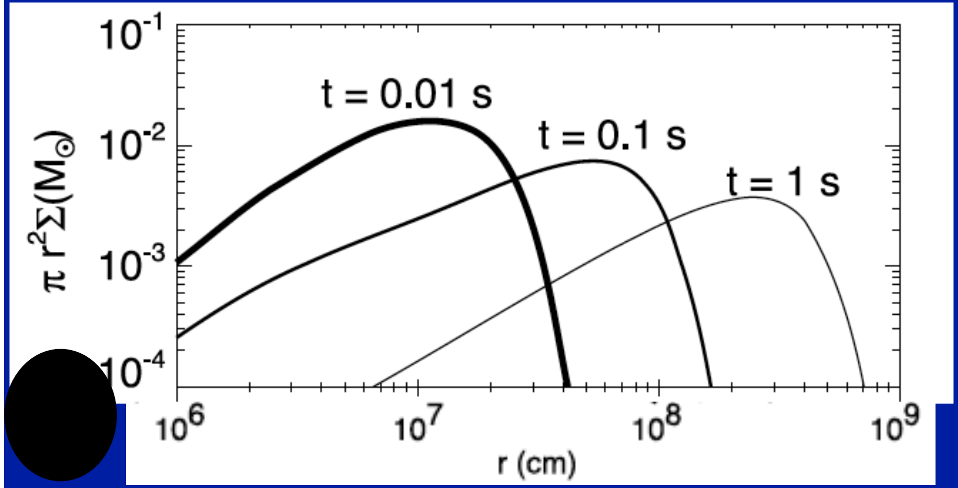
Popham et al. (1999); Narayan et al. (2001); Lee et al. (2004, 2005); Setiawan et al. (2004, 2006); Metzger et al. (2008, 2009)

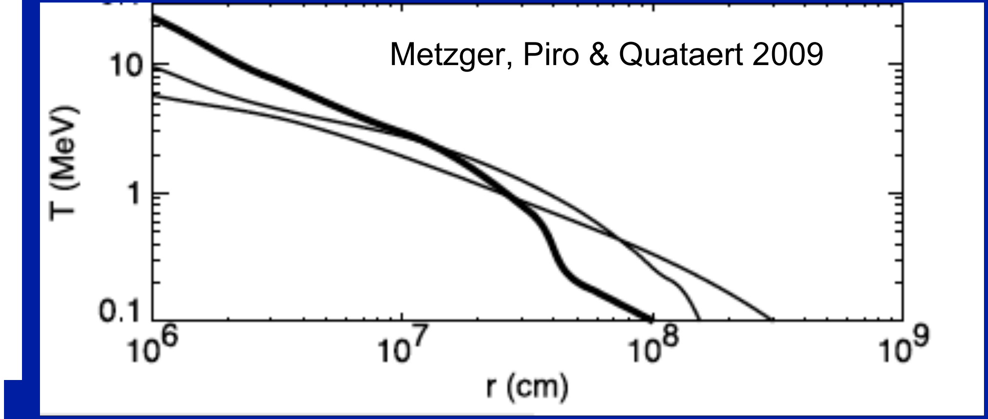


Lee et al. (2004)

As Disk Viscously Spreads…..

Its Temperature Decreases





Metzger, Piro & Quataert 2009

Late Time Disk Outflows

After t ~ 0.1-1 seconds, R ~ 500 km & T < 1 MeV

- **Recombination: n + p ⇒ He**

  $E_{BIND} \sim GM_{BH}m_n/2R \sim 3$ MeV nucleon^{-1}

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

- **Thick Disks Marginally Bound**

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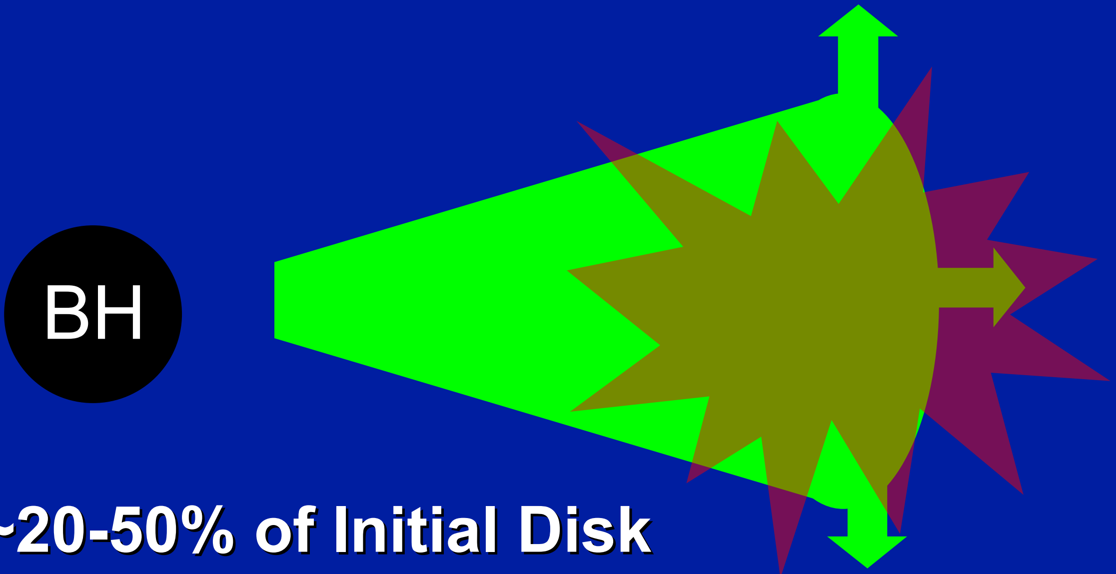
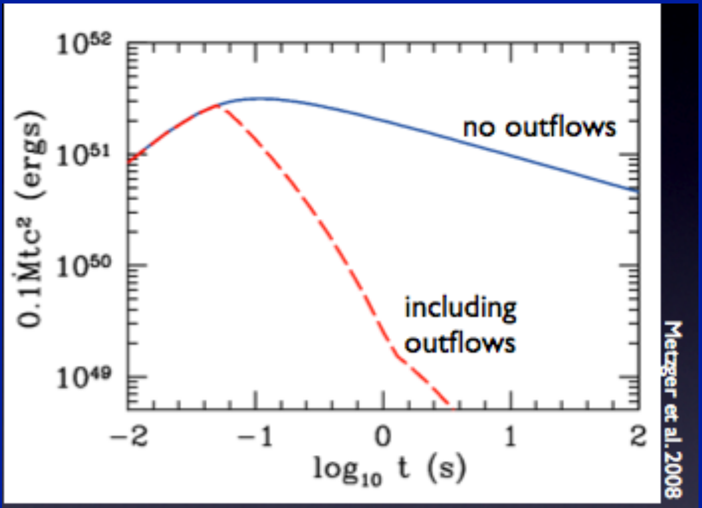
} ⇒ **Powerful Winds Blow Apart Disk**



~20-50% of Initial Disk Ejected Back into Space!

(agrees with full 2D sims - Lee et al. 2009)

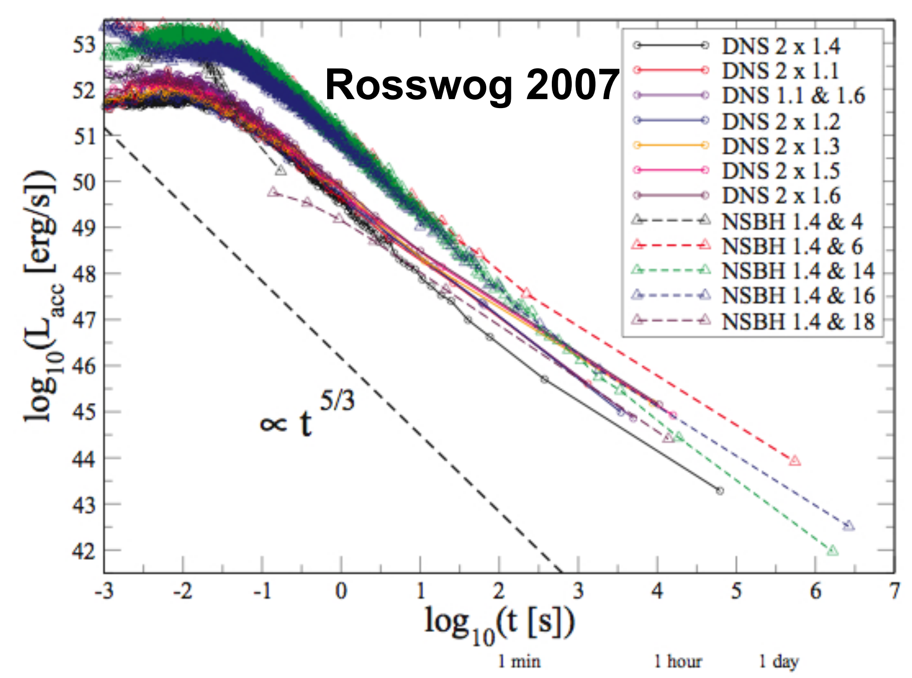


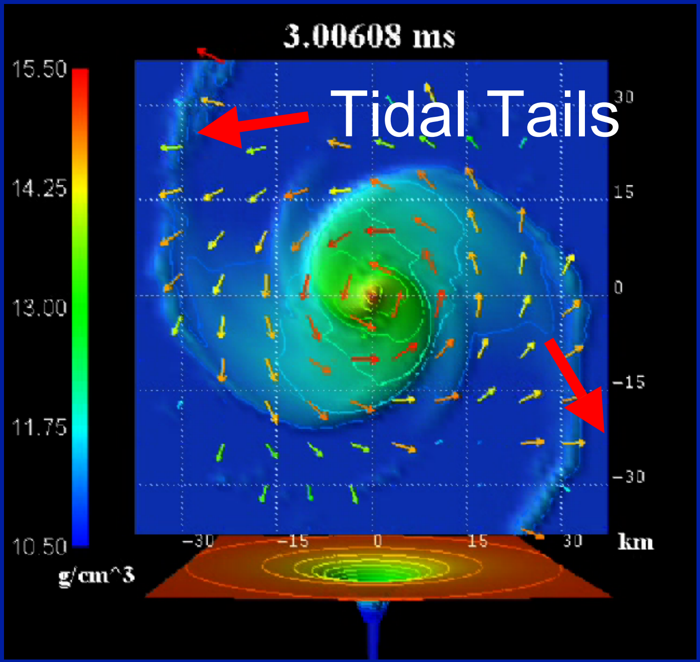
Accretion of the Initial Disk Cannot Power Late Time Activity in SGRBs

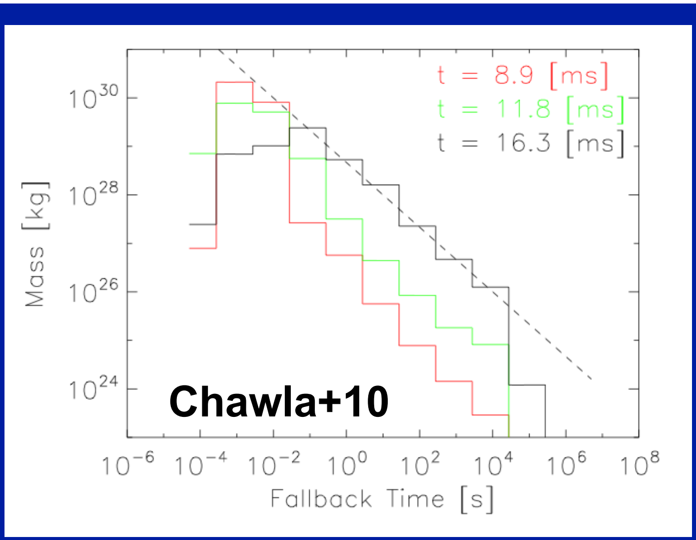
Late Fall Back Accretion?

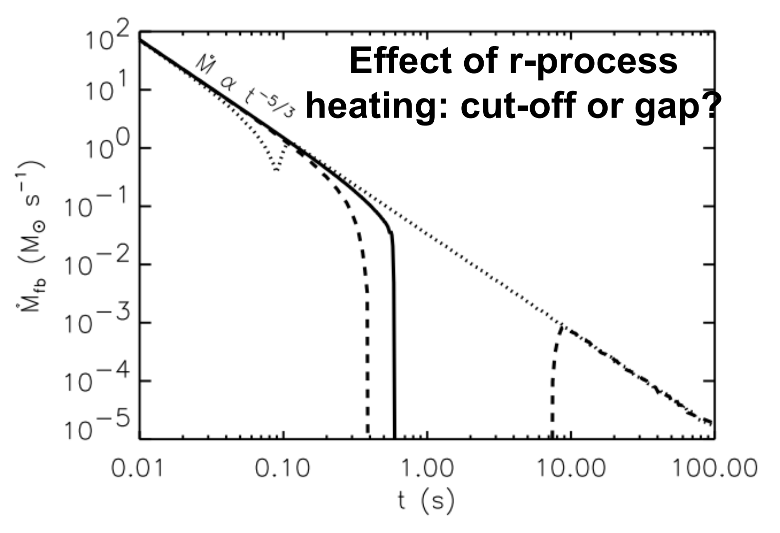
(e.g. Faber et al. 2006, Rosswog 2007; Lee & Ramirez-Ruiz 2007; Lee et al. 2009; Chawla et al. 2010)

Fallback Accretion Luminosity


Rosswog 2007


Tidal Tails


Chawla+10


Effect of r-process heating: cut-off or gap?

BDM et al. 2010

Alternative Explanation: Surviving Neutron Star Remnant?

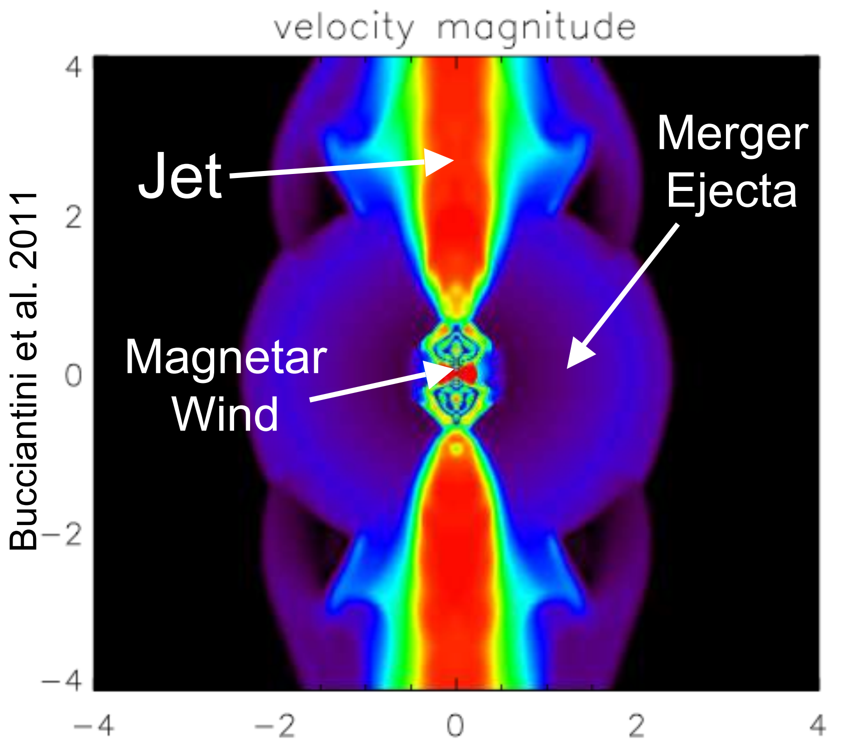
(Metzger et al. 2008; Bucciantini et al. 2011)

- 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

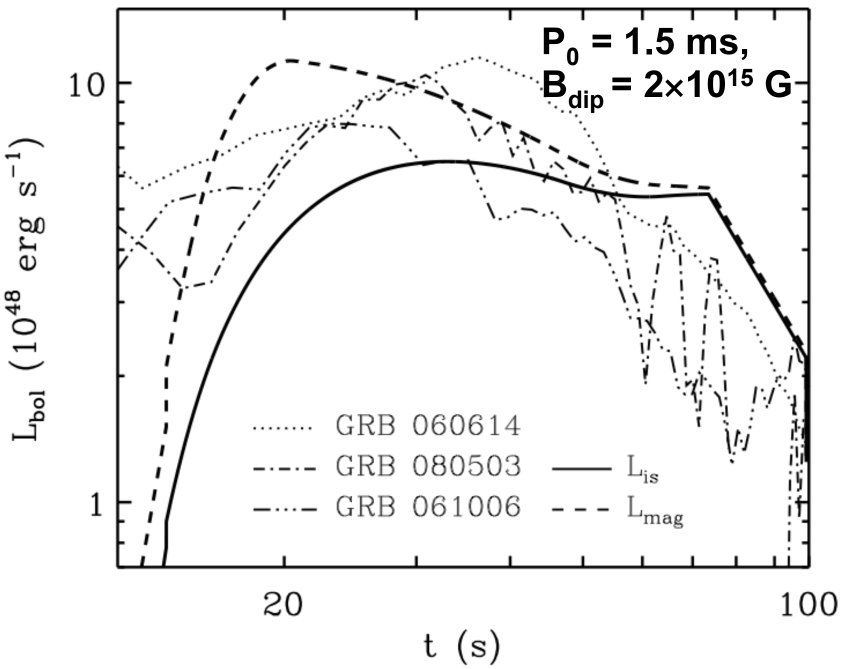
- Magnetic field amplified by rotational energy ⇒ **"Magnetar"**

Magnetar wind confined by merger ejecta

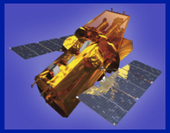


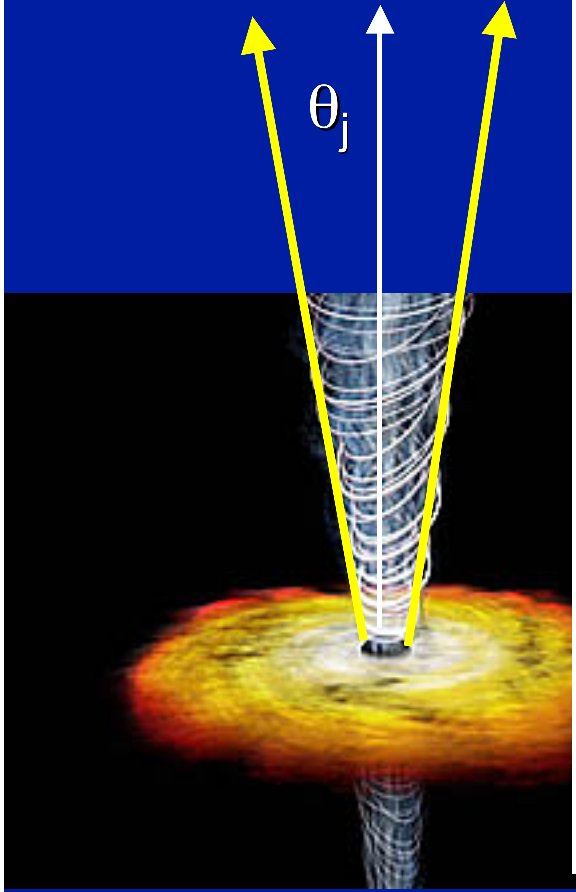
Theoretical Light Curves vs. Observed X-ray Tails

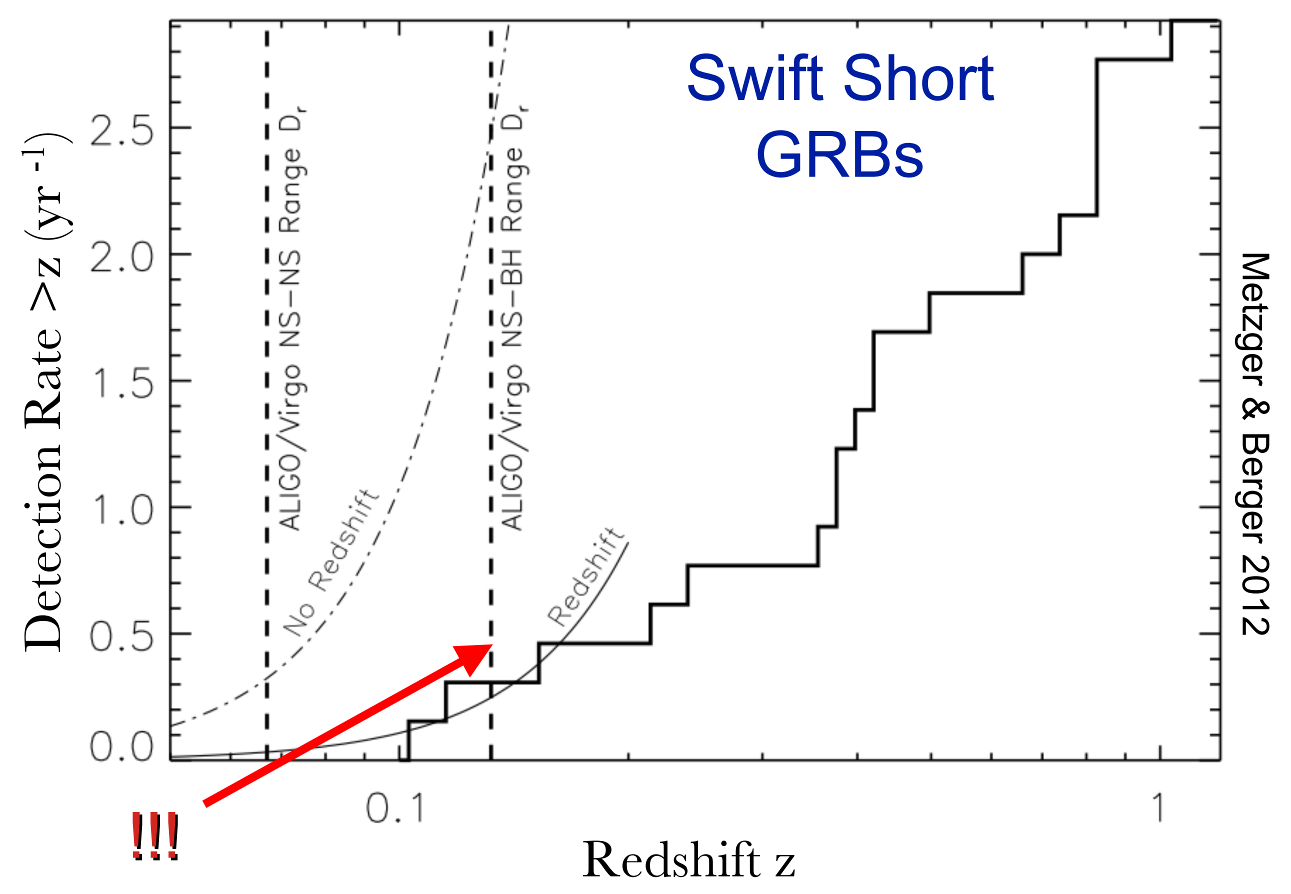
(magnetar wind model from Metzger et al. 2011)



Short GRBs are Rare within the A-LIGO Volume







Metzger & Berger 2012

Detectable fraction by all sky γ-ray telescope

$$f_\gamma \sim 3.4 \times \bar{\theta}_j^2 / 2 \sim 0.07 \left(\frac{\bar{\theta}_j}{0.2} \right)^2$$

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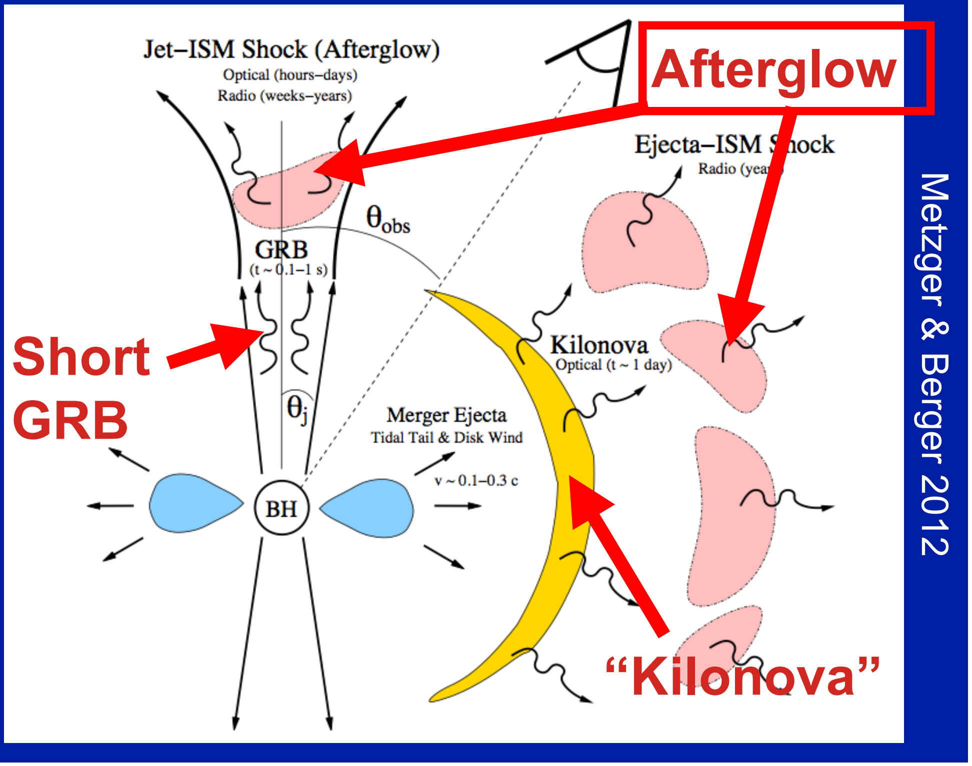
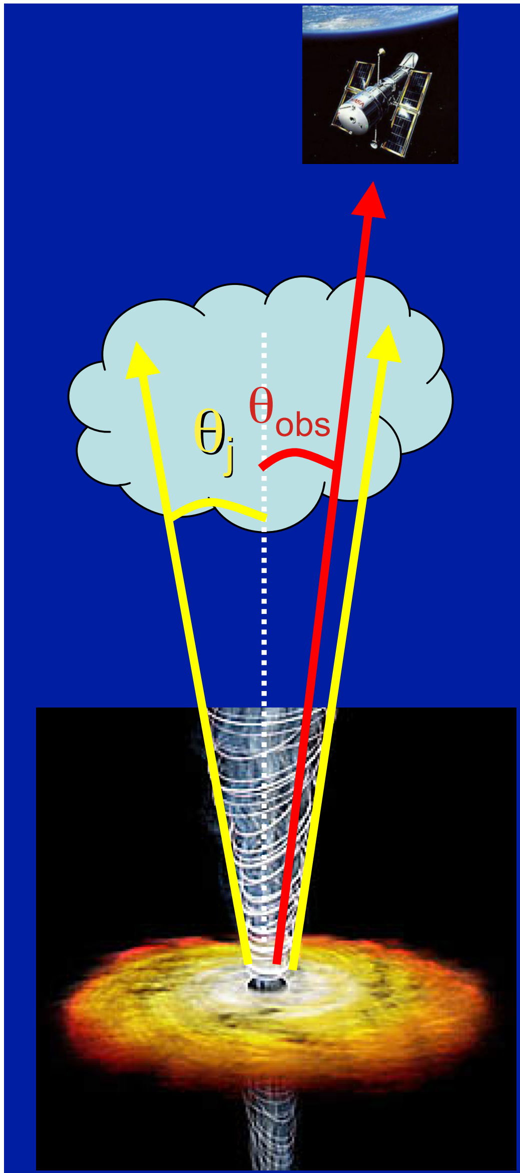
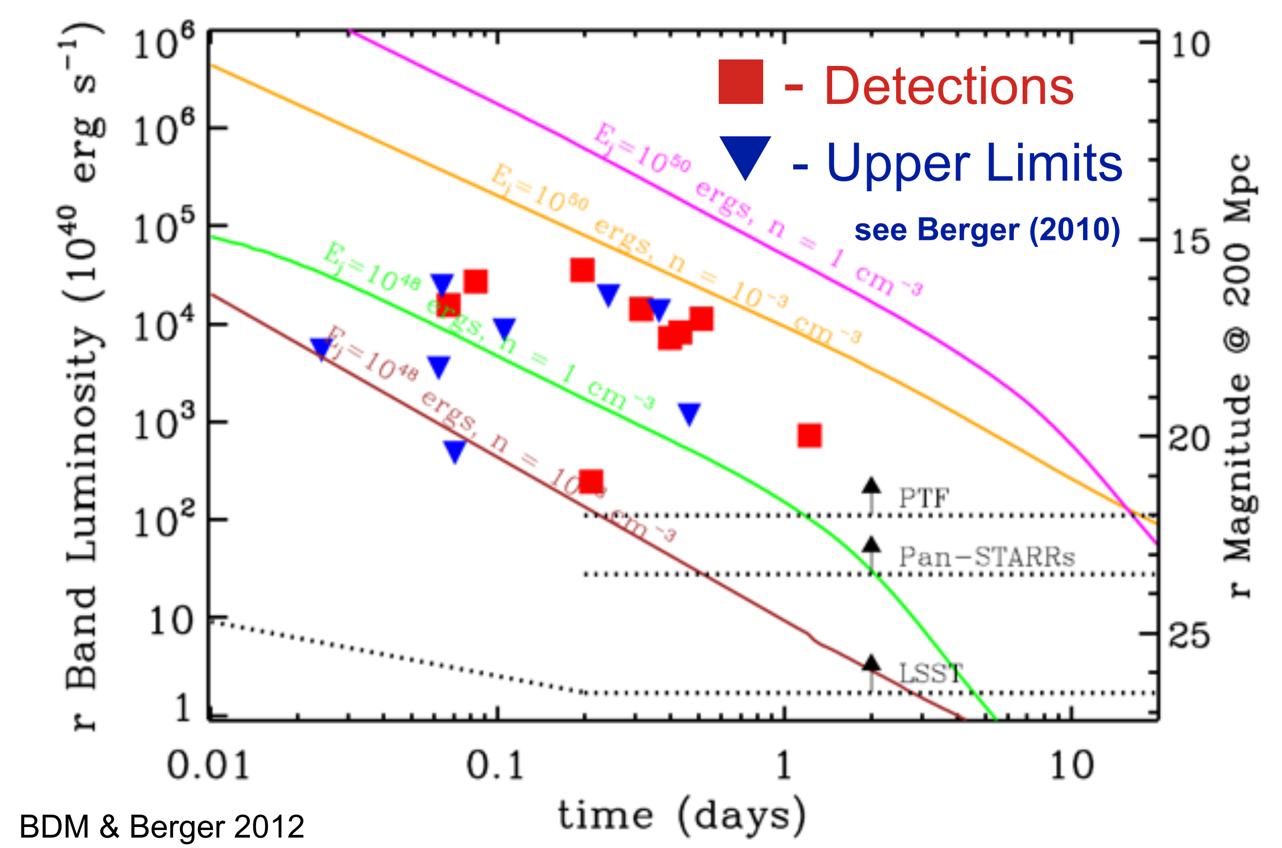


Metzger & Berger 2012

On Axis Optical Afterglow ($\theta_{obs} < \theta_j$)





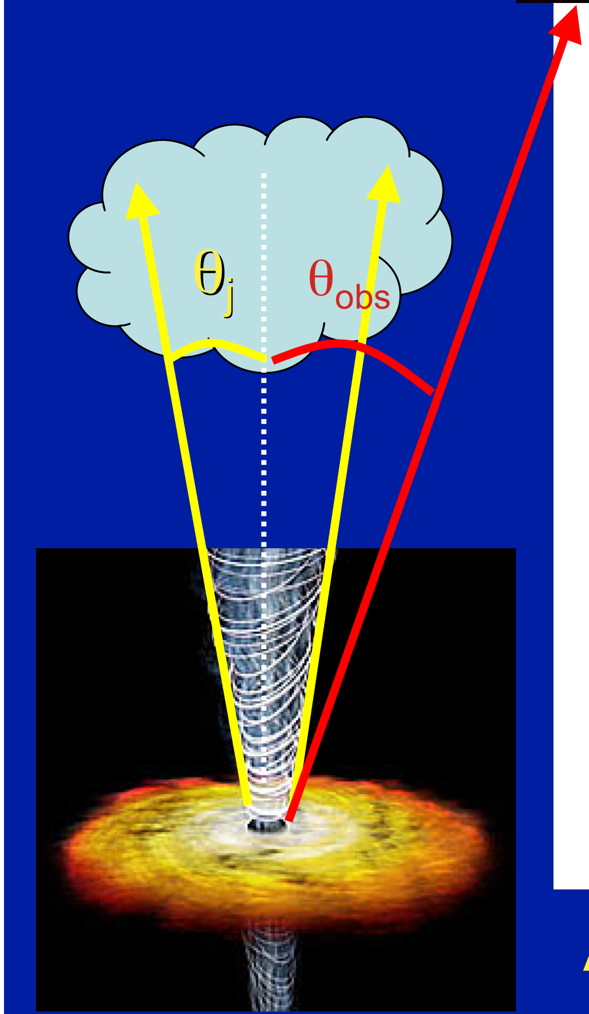
BDM & Berger 2012

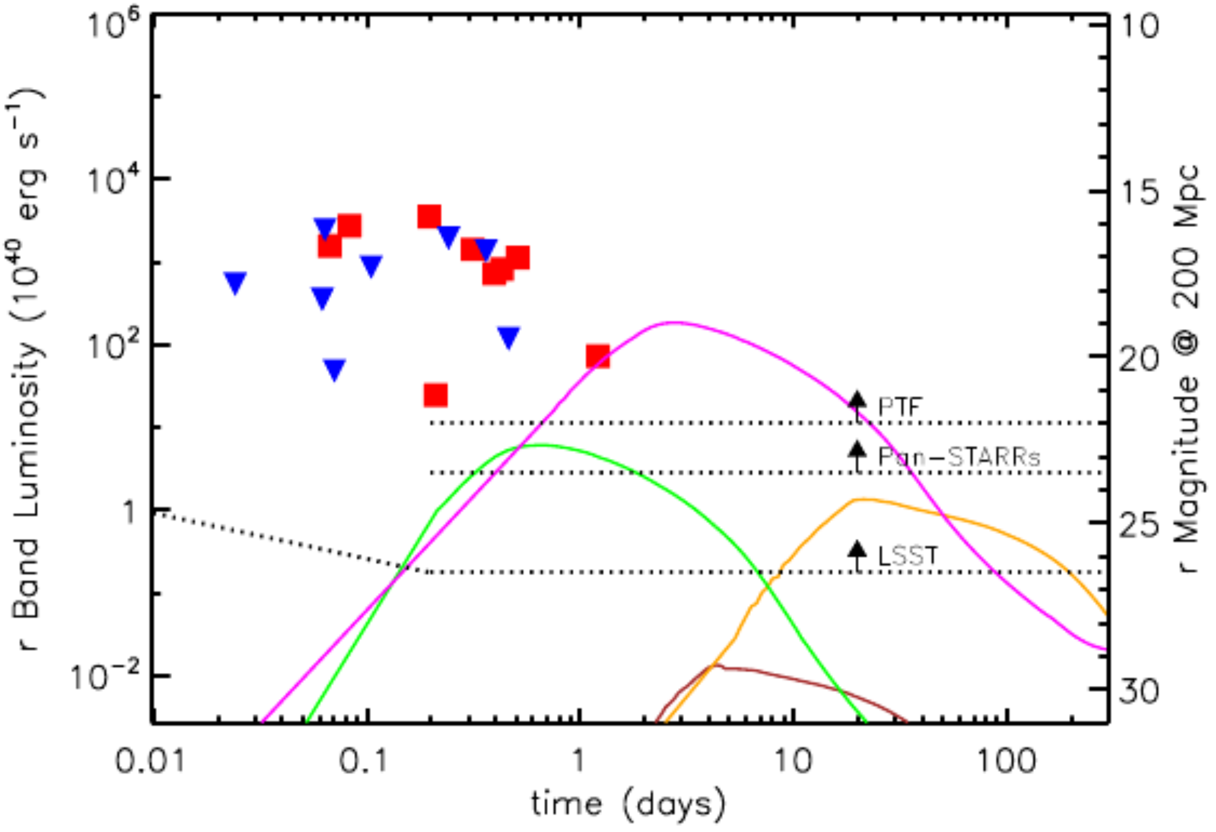
Afterglow models for different jet energy E_j and ISM density n (from van Eerten & MacFadyen 2011)

detections/upper limits constrain jet energy and ISM density:

$$\left(\frac{E_j}{10^{50}\ \text{ergs}}\right)^{4/3}\left(\frac{n}{\text{cm}^{-3}}\right)^{1/2} < 0.1\ (\text{avg } 0.01)$$

Off Axis Afterglow ($\theta_{obs} = 2\theta_j$)



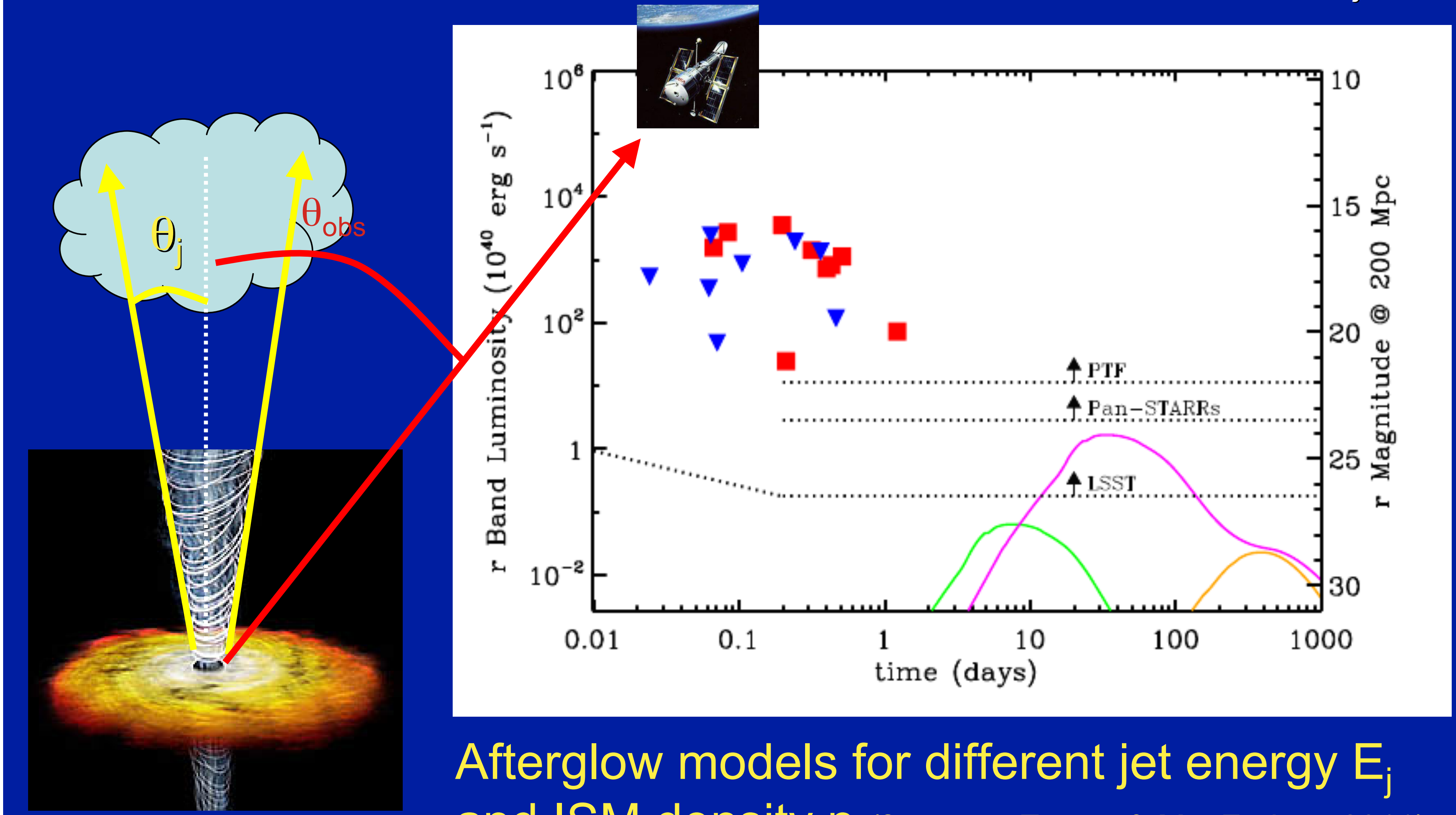


Afterglow models for different jet energy E_j and ISM density n (from van Eerten & MacFadyen 2011)

Detection fraction:

$$f_{opt} < 3.4 \times {(2\bar{\theta}_j)^2}/{2} \sim 0.25 \left(\frac{\bar{\theta}_j}{0.2}\right)^2$$

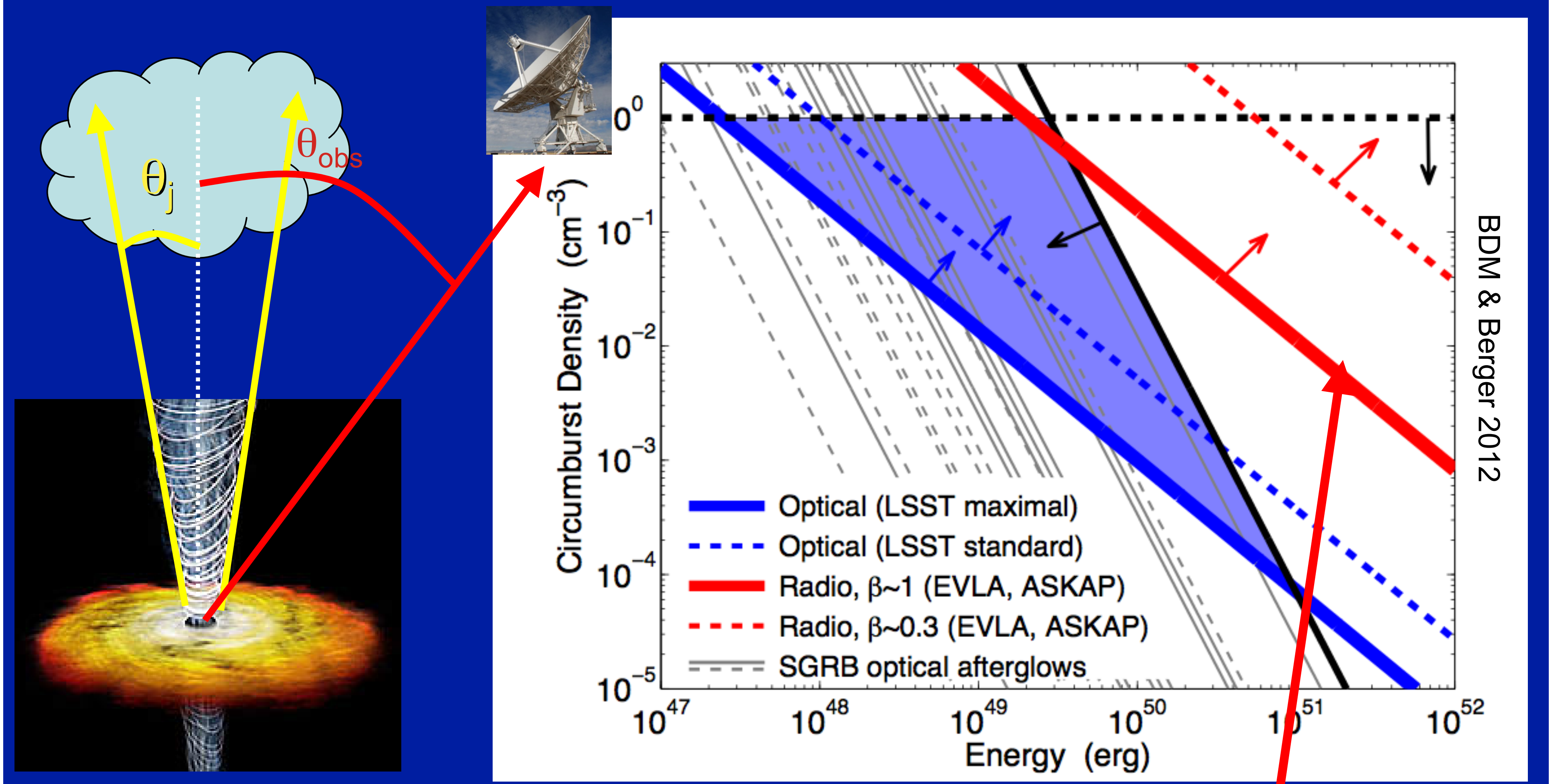
Far Off Axis Afterglow ($\theta_{obs} = 4\theta_j$)



Afterglow models for different jet energy E_j and ISM density n (from van Eerten & MacFadyen 2011)

Off Axis Radio Emission?

(Nakar & Piran 2012; see talks by Rosswog, Piran)



BDM & Berger 2012

Detection requires

Sky error region ~ tens degrees^2 ⇒ 100 pointings + 30 hrs EVLA ⇒ F_{min} ~ 0.5 mJy at 1 GHz ⇒

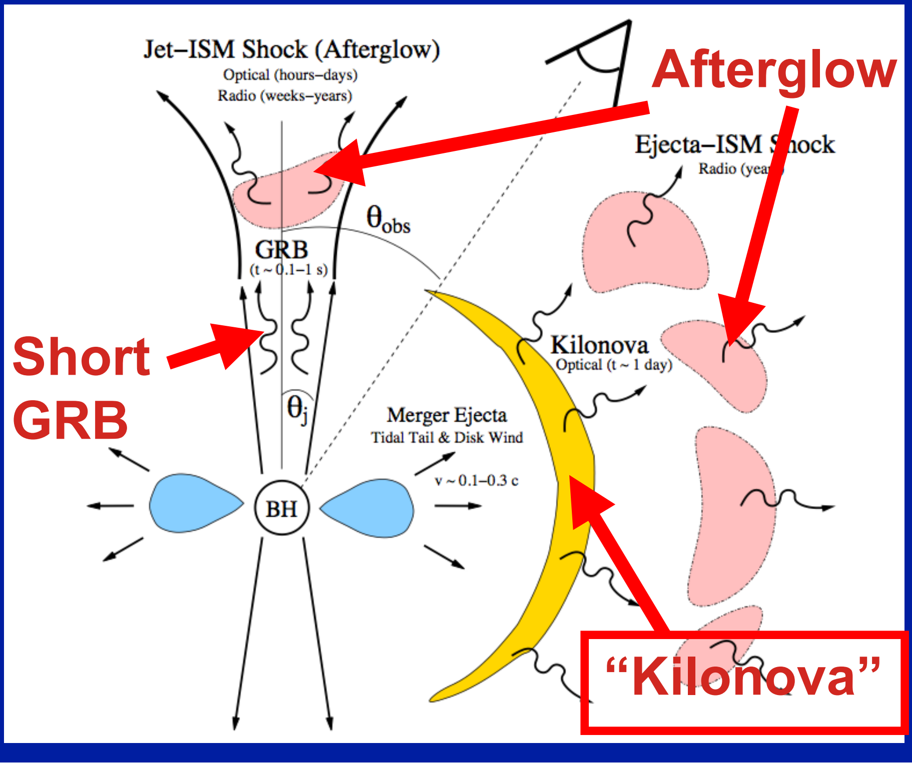
$$\boxed{\left(\frac{E_j}{10^{50}\ \mathrm{ergs}}\right) \times \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{7/8} > 0.2}$$

Importance of EM Detection:

- Improve "Confidence" in GW Detection; Dig Deeper into GW Data
- Independently Constrain Binary Parameters
- Astrophysical Context (e.g. Identify Host Galaxy & Environment)
- Other Science: e.g. Cosmology (Redshift $\Rightarrow H_0$), Test Strong-Field GR

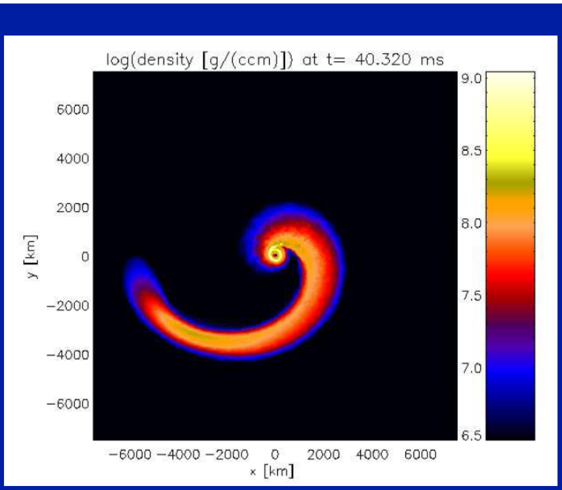
Four "Cardinal Virtues" of a Promising Counterpart

1) **Detectable** with present or upcoming facilities.
2) Accompany a **high fraction** of GW events.
3) Be unambiguously **identifiable** (a "smoking gun").
4) Allow for an accurate (~arcsec) sky **localization**.



Metzger & Berger 2012

Sources of Neutron-Rich Ejecta



Rosswog 2005

Tidal Tails (Dynamical Ejecta)

(e.g. Janka et al. 1999; Rosswog 2005; Giacomazzo et al. 2009; Rezzolla et al. 2010)

Accretion Disk Outflows

Neutrino-Driven Winds (Early)

(McLaughlin & Surman 05; BDM+08; Dessart et al. 2009; talk by McLaughlin)

Thermonuclear-Driven Winds (Late)

(BDM, Piro & Quataert 2008; Lee et al. 2009)

$M_{ej} \sim 10^{-3} - 10^{-1} M_{\odot}$

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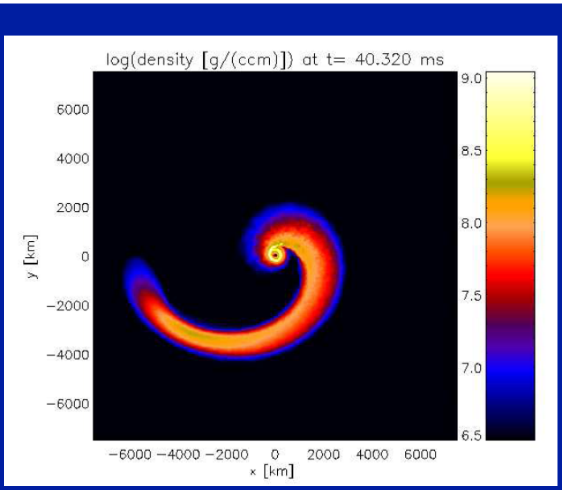

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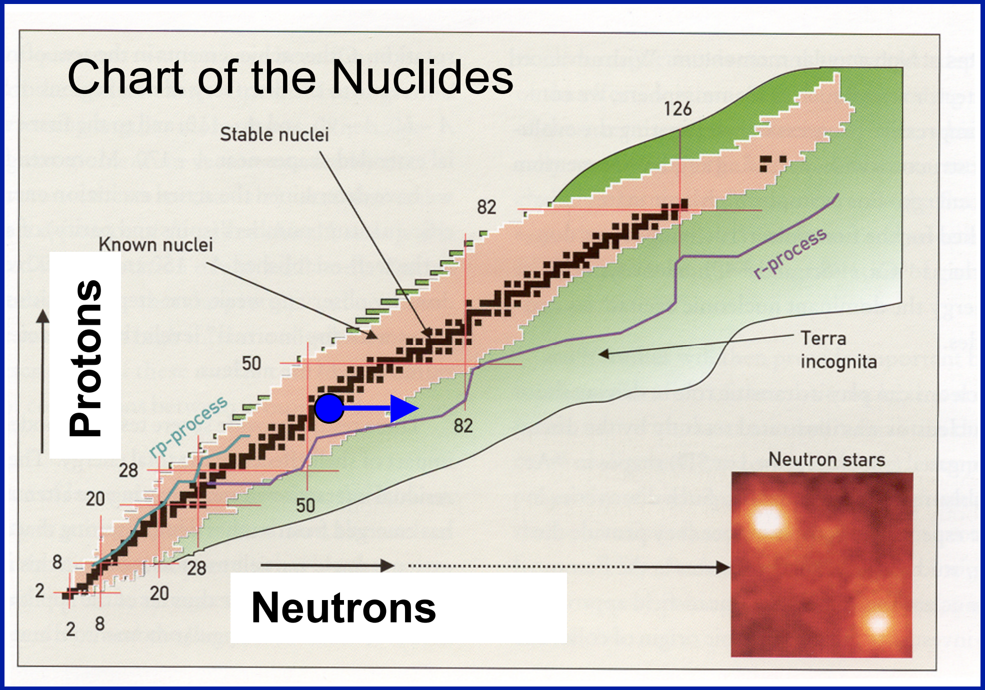


Rapid Neutron Capture (R-Process) Nucleosynthesis

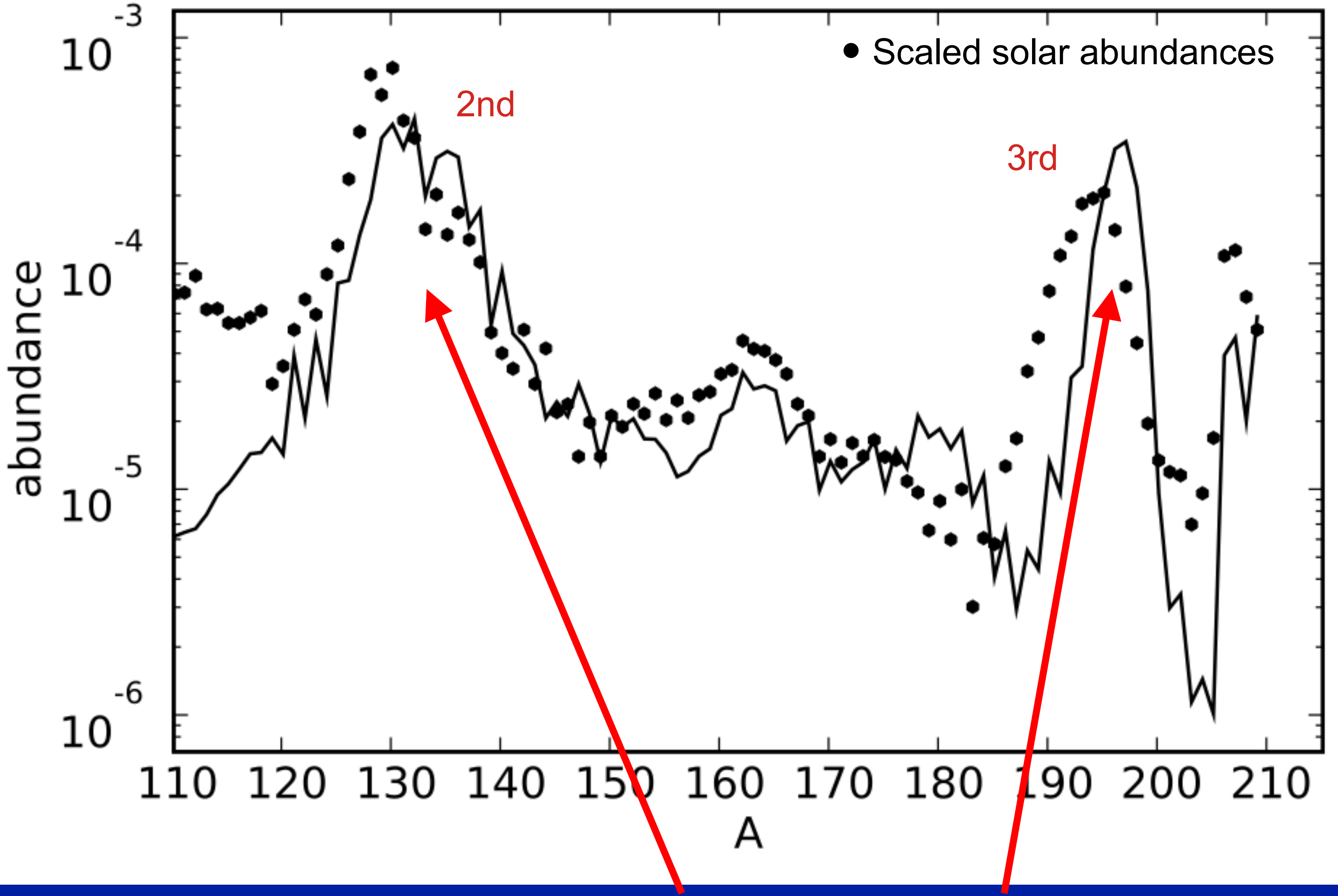
(Lattimer et al. 1977; Meyer 1989;
Freiburghaus et al. 1999; Goriely et al. 2005)

Decompressing NS Matter ⇒
A ~ 100 Nuclei + Free Neutrons

R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)

as used in Metzger et al. 2010 (movie courtesy of A. Arcones)

Final Abundance Distribution

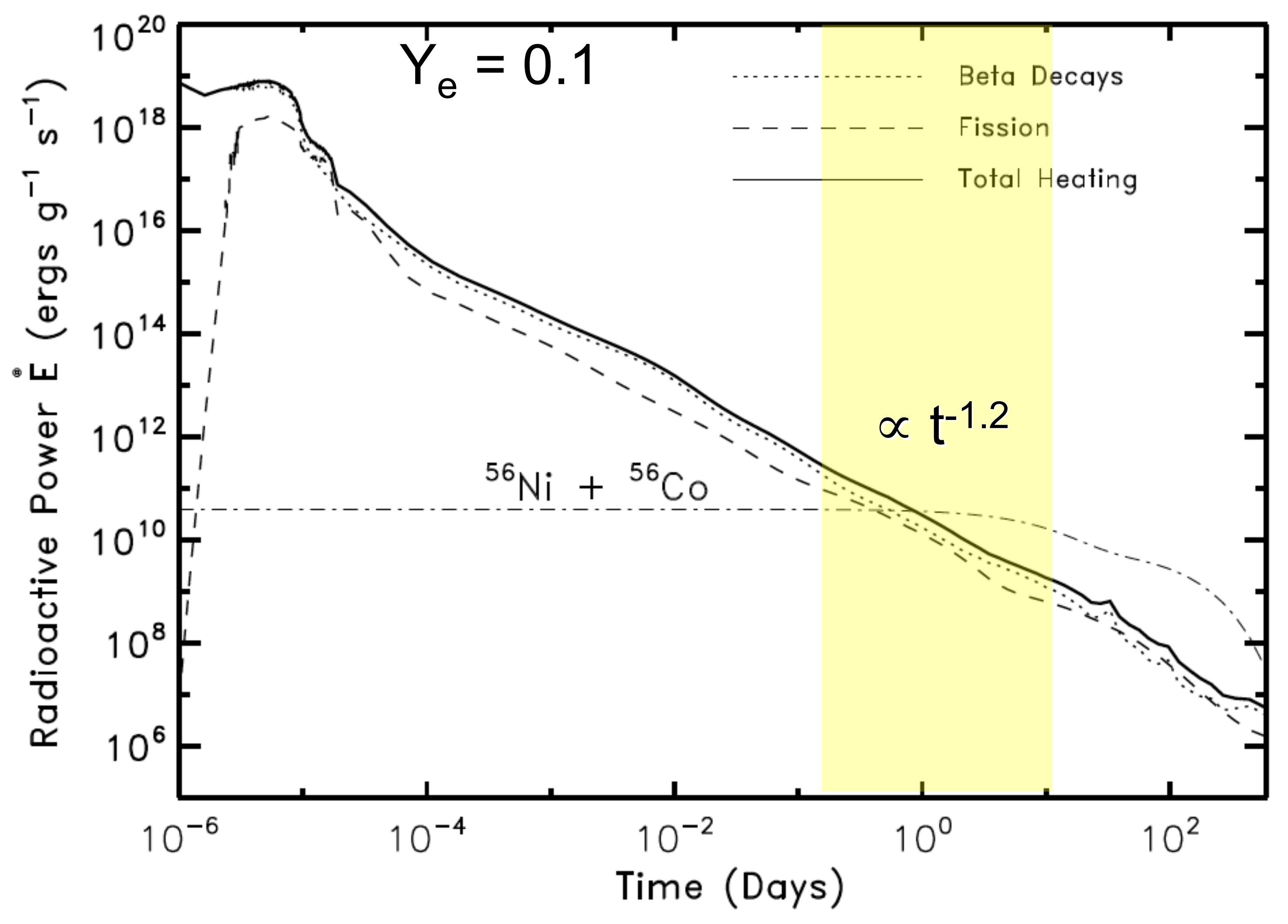


Peaks at A ~ 130 and A ~ 195

BDM et al. 2010

Radioactive Heating Rate in Merger Ejecta

(Li & Paczynski 1998; Kulkarni 2005; BDM et al. 2010; Roberts et al. 2011; Goriely et al. 2011)



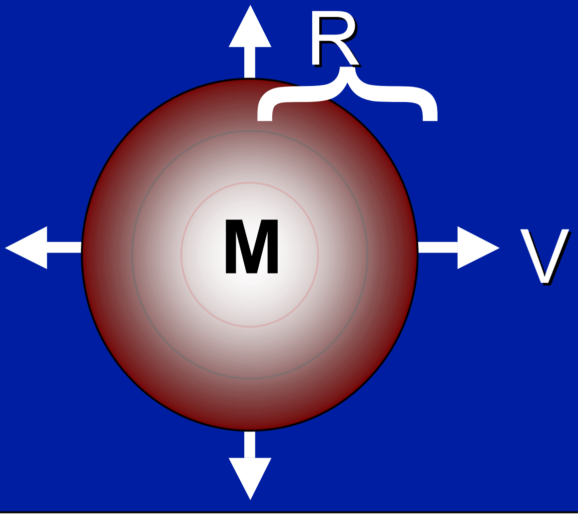
Metzger et al. 2010

Dominant β-Decays at t ~ 1 day: ^{132,134,135}I, ^{128,129}Sb, ^{129}Te, ^{135}Xe

$f = 3 \times 10^{-6}$

How Supernovae Shine (Arnett 1982)

Spherical ejecta w mass M, velocity v, thermal energy E = f Mc², & opacity κ



$$R = v\,t \qquad \rho = \frac{M}{4\pi/3\, R^3}$$

$$\tau \sim \kappa\rho R \qquad t_{\rm diff} \sim \tau R/c$$

Emission peaks when $t = t_{\rm diff} \Rightarrow \quad t_{\rm peak} \sim 2 \text{ weeks} \left(v/10^4 \text{ km s}^{-1}\right)^{-1/2} \left(M/M_\odot\right)^{1/2}$

$$L_{\rm peak} \sim E(t_{\rm peak})/t_{\rm peak} \sim 10^{43} \text{ ergs s}^{-1} \left(f/10^{-5}\right)\left(v/10^4 \text{ km s}^{-1}\right)^{1/2}\left(M/M_\odot\right)^{1/2}$$

Type Ia Supernova:

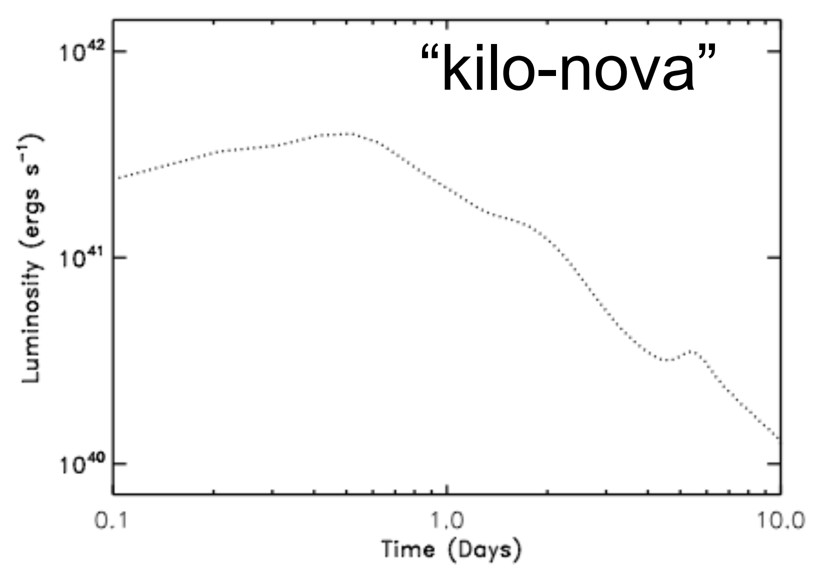
$v \sim 10^4$ km s^{-1}, $M_{ej} \sim M_\odot$, $f_{Ni \rightarrow Co} \sim 10^{-5} \Rightarrow t_{\rm peak} \sim$ week, $L \sim 10^{43}$ erg s^{-1}

NS Merger:

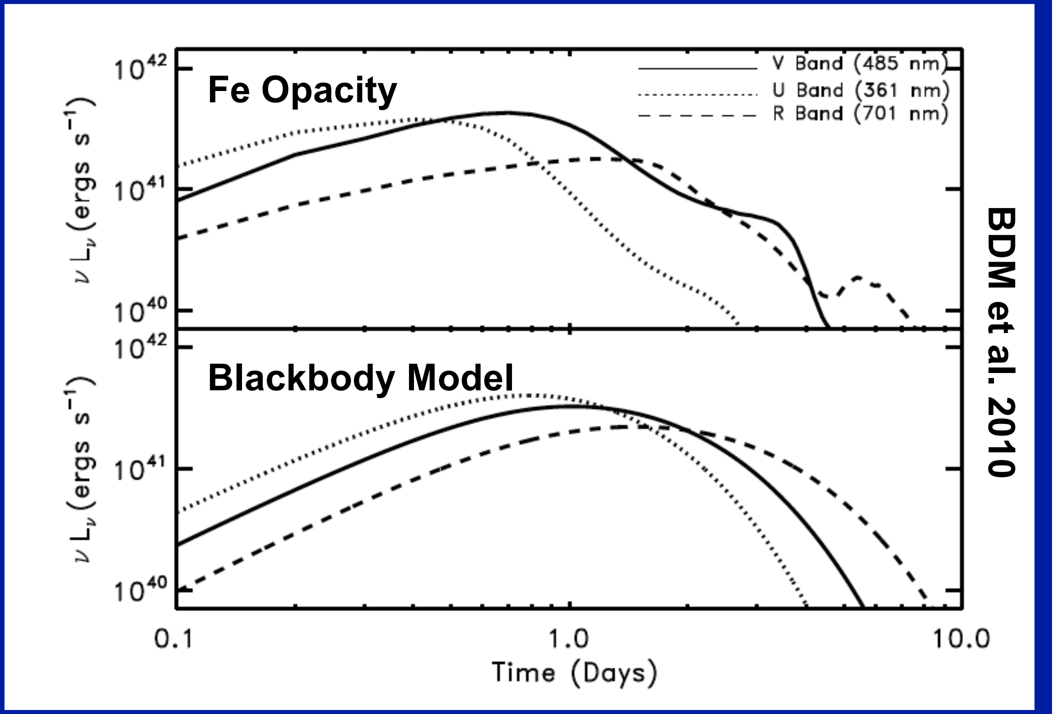
$v \sim 0.1$ c, $M_{ej} \sim 10^{-2} M_\odot$, $\boxed{f \sim 3\times10^{-6}}$ $\Rightarrow t_{\rm peak} \sim 1$ day, $L \sim 10^{42}$ erg s^{-1}

Light Curves

Bolometric Luminosity



Color Evolution



Monte Carlo Radiative Transfer (SEDONA; Kasen et al. 2006)

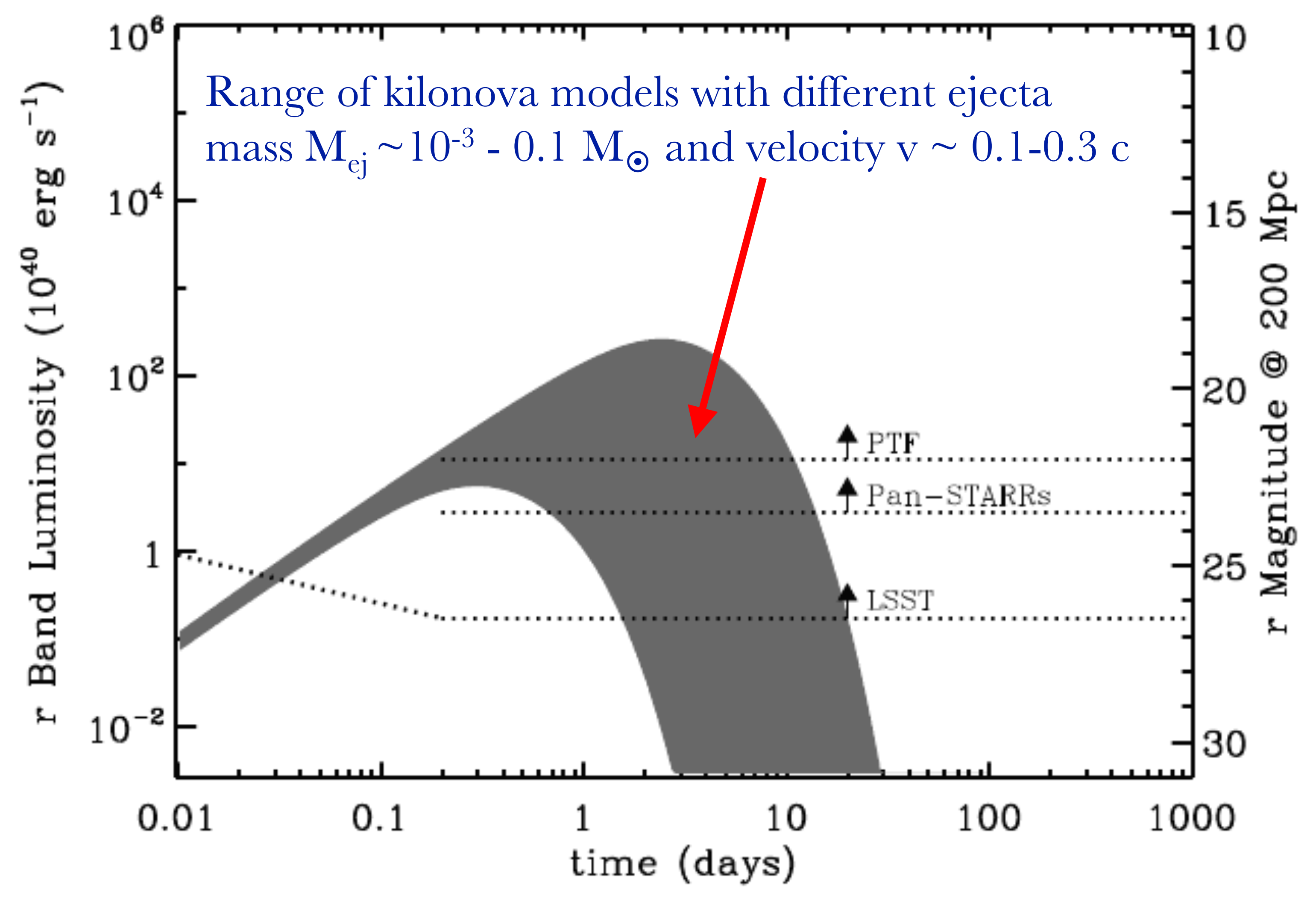
Peak Luminosity ~3×10^{41} erg s^{-1} @ t ~ 1 day for $M_{ej} = 10^{-2} M_\odot$

CAVEAT: Fe composition assumed for opacity

What *does* a pure r-process photosphere look like?

(see talks by Kasen, Hungerford, Rosswog, Piran)

Optical Search Following a GW Trigger



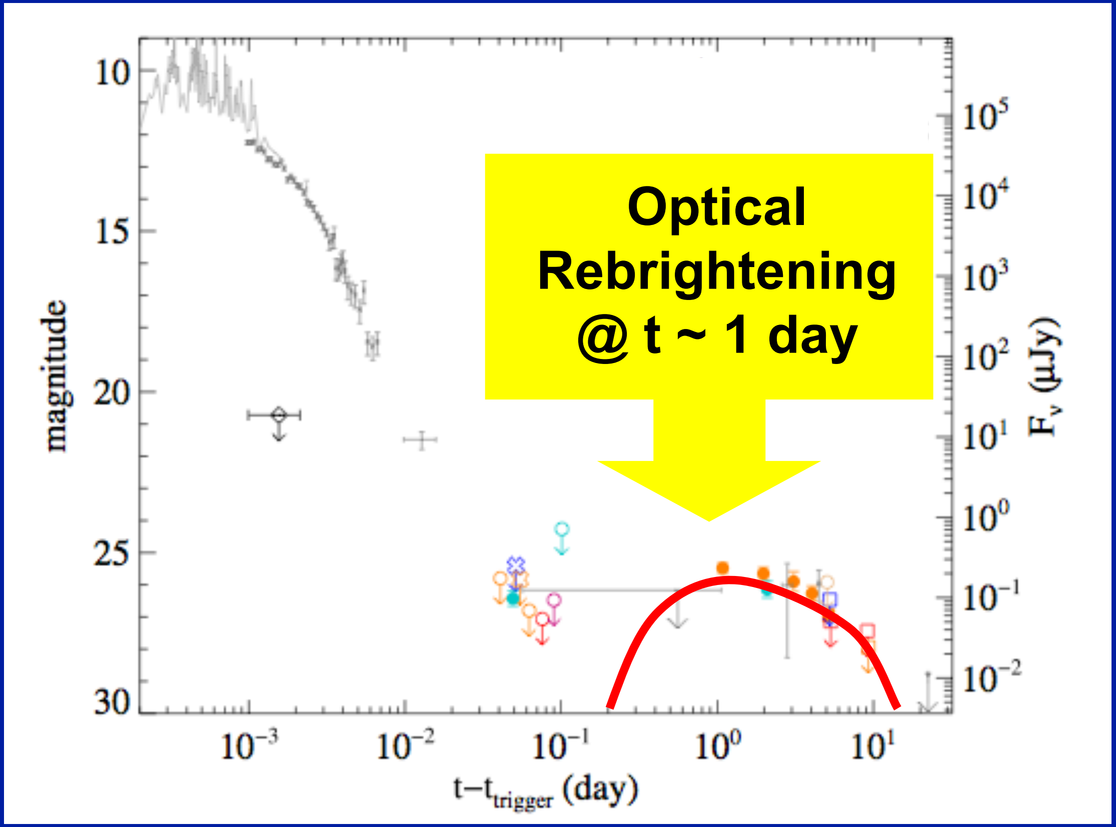
Range of kilonova models with different ejecta mass $M_{ej} \sim 10^{-3}$ - 0.1 $M_{\odot}$ and velocity $v \sim 0.1$-$0.3\,c$

⇒ **Requires search depth r ~ 22-24 and cadence <~ 1 day**

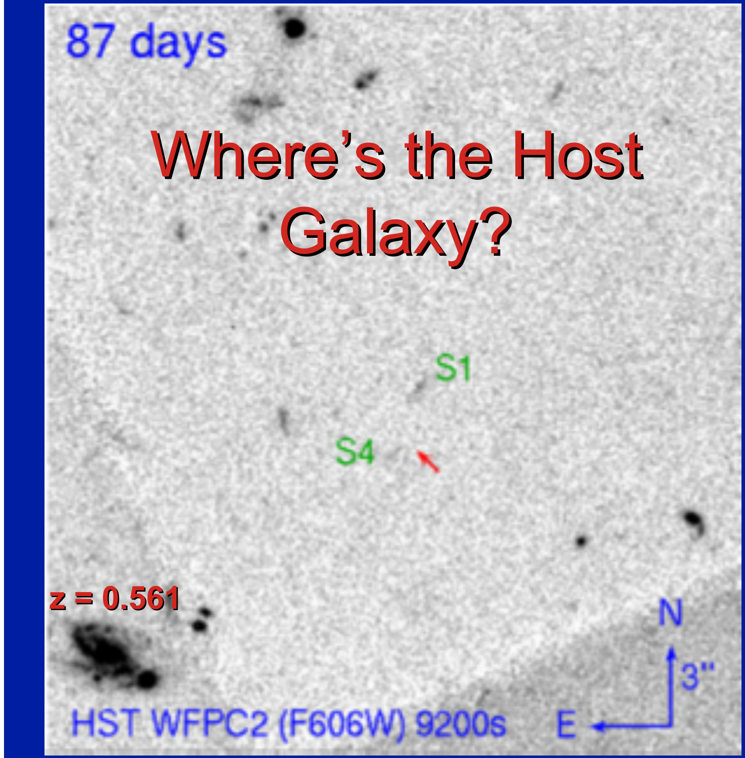
(see talk by Kasliwal)

GRB 080503: Candidate Kilonova

(Perley, BDM et al. 2009)



Optical Rebrightening @ t ~ 1 day



Where's the Host Galaxy?

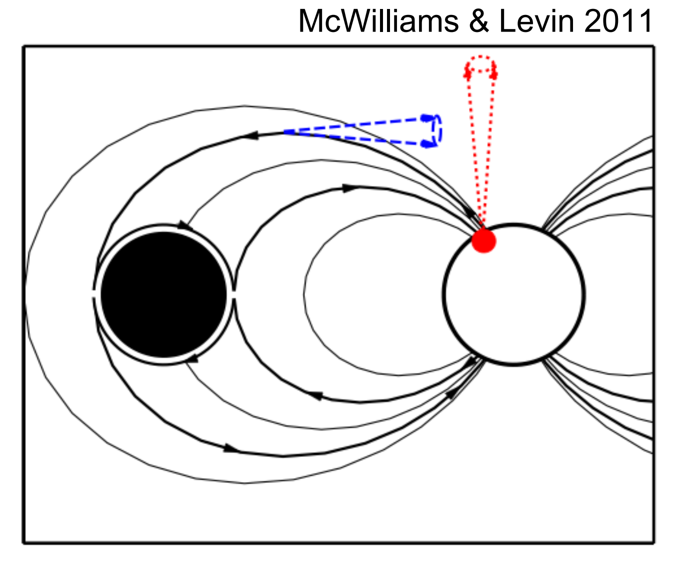
Best-Fit Kilonova Parameters:

$v \sim 0.1\,c$, $M_{ej} \sim$ few $10^{-2}\,M_\odot$, **$z \sim 0.2$**

Pre-Coalescence Counterparts?

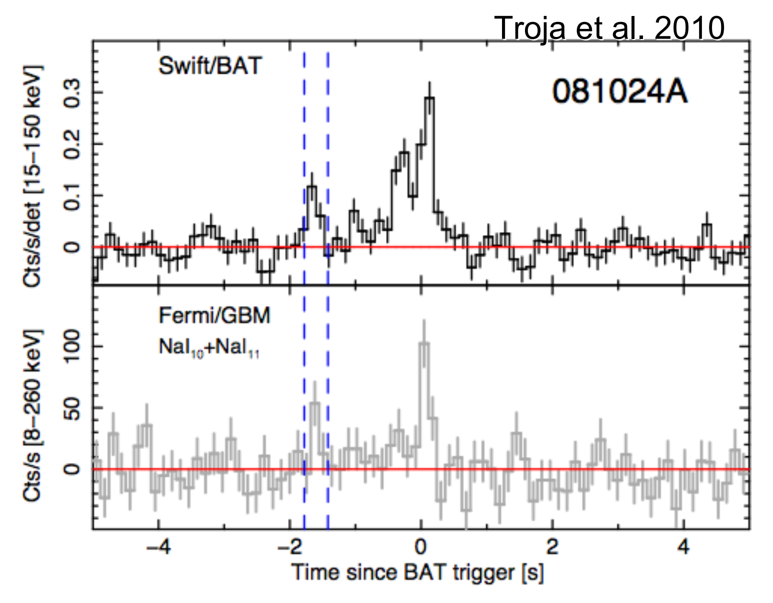
- Tidal Cracking of NS Crust
  (e.g. Troja et al. 2011; Tsang, Read, et al. 2012)
- NS Magnetosphere(s)
  Particle acceleration or Poynting Flux
  (e.g. Hansen & Lyutikov 2001; Postnov & Pshirkov 2009; Moortgat & Kuijpers 2004; McWilliams & Levin 2011; Piro et al. 2012).

  (see talk by Piro)
- Collapse of HyperMassive Magnetar
  (Lehner et al. 2012)


McWilliams & Levin 2011

What Wavelength?

- If γ-rays, should have been seen already.
  - Short GRB “precursors” seconds-minutes before burst. (Troja et al. 2010)
  - Local Isotropic Population of short GRBs?
- Coherent radio burst? (LOFAR)
  - Challenging to predict (cf. radio pulsars).
  - Easily self-absorbed by ambient plasma.


Troja et al. 2010

Timeline of NS-NS/NS-BH Mergers

1. Pre-Cursors: **X-ray / [Coherent] Radio** (crust cracking, NS B-field) **✓NS Crust Properties ✓Magnetospheric Plasma Physics**	t(minus) ~ hrs-ms
2. Chirp enters LIGO Bandpass	t(minus) ~ mins-hr
3. Last Orbit, Plunge & BH Formation (if prompt) **✓Dynamical GR ✓Nuclear-Density Equation of State**	t ~ 1-10 ms
4. Accretion of Remnant Disk, Jet Formation (**γ-ray** burst) **✓Weak Interactions, ✓Relativistic MHD, ✓Collisionless Shocks**	t ~ 0.1-1 s
5. He-Recombination + Disk Evaporation	t ~ 0.3-3 s
6. R-Process Nucleosynthesis in Merger Ejecta - **✓Nuclear properties far from β-stability**	t ~ few s
7a. Late "Fall-Back" Accretion (ongoing weaker jet, **X-rays**) 7b. Long-Lived Neutron Star (magnetar?, **X-rays)**	t >~ few s
8. Supernova-like Transient "Kilonova" (**Optical, UV-lines?**) **✓Radiative transfer through "exotic" heavy nuclei (opacities)**	t ~ 1 hrs-days
9. On[Off]-Axis GRB Afterglow (**X-ray, Optical, Radio**)	t ~ hrs-yrs

Comparison of EM Counterparts

Counterpart	λ	Telescope	Strengths	Weaknesses
Pre-cursors	X, R	Swift LOFAR	(1) Probes final in-spiral.	(1) Predictions uncertain. (2) Why not detected already?
Short GRB	γ	Fermi Swift	(1) They exist. (2) Smoking gun. (3) wide FOV of γ satellites.	(1) Merger association uncertain. (2) Hard to localize. (3) Small % of GW chirps.
Off-Axis Afterglow	X	Swift XRT A-STAR LobsterISS	(1) Detectable at 200 Mpc. (2) Fast slewing Swift XRT.	(1) Fade rapidly. (2) Lack of wide FOV instrument. (3) Small % of GW chirps.
	O	ZTF, Pan-Starrs, Subaru, LSST	(1) Detectable at 200 Mpc. (2) Detectable by small telescope (on-axis merger). (3) Good localization.	(1) Only % of GW chirps. (2) False positives.
	R	EVLA, ASKAP, Apertif	(1) ~Isotropic. (2) Slowly evolving. (3) Fewer false positives. (4) Good localization.	(1) Requires high ISM density. (2) Slowly evolving. (3) Source confusion.
R-Process Powered SN (kilonova)	O	PTF, Pan-STARRs, Subaru, LSST	(1) ~Isotropic. (2) Detectable at 200 Mpc. (3) Physics robust (thermal!) (4) Good localization. (5) Spectroscopic signature.	(1) Not detected yet. (2) False positives.

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This is Going to be Hard!