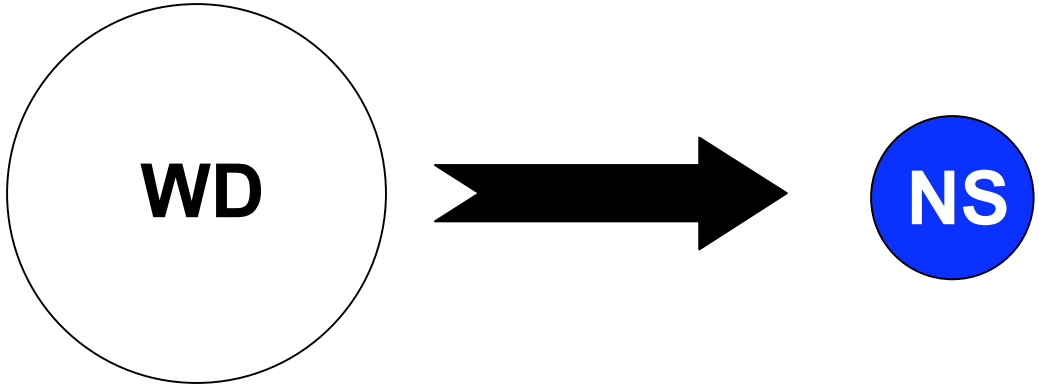
Observable Signatures of the Accretion-Induced Collapse of White Dwarfs

Brian Metzger, UC Berkeley

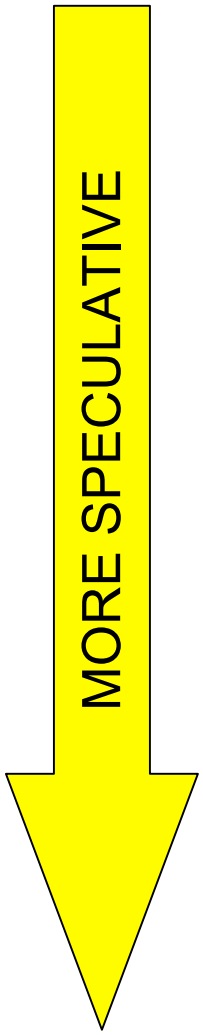
with Tony Piro, Eliot Quataert (UC Berkeley) & Todd Thompson (Ohio State)



Metzger, Quataert, & Thompson (2008) MNRAS, 385, 1455

Metzger, Piro, & Quataert (2008) arxiv.org/abs/0812.3656

Outline



- **Introduction to AIC**
- **Stages of AIC (as I see them)**
  - **Accretion Disks as Time Bombs**
- **Optical Transients**
  - **Connection to Sub-Luminous SNe**
- **High Energy Transients**
  - **Connection to Short Duration GRBs**
- **Summary**

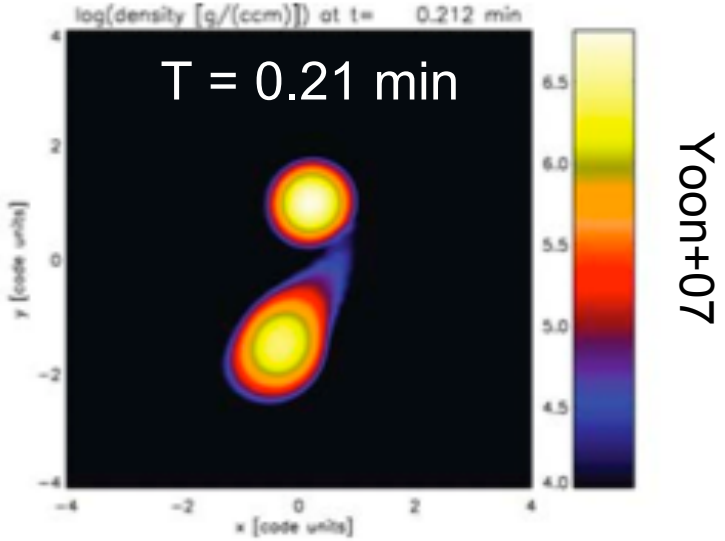
Accretion-Induced Collapse (AIC)

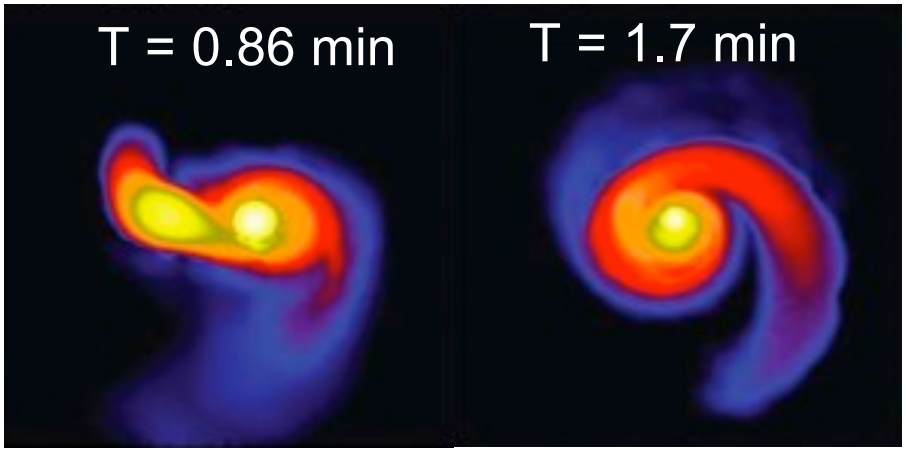
e.g. Miyaji+ 80, Nomoto & Kondo 91; Canal+ 92; Guitierrez+

- "Failed" Thermonuclear Explosion (otherwise Type Ia SN)
- Paths to AIC:

1) **Non-Degenerate Binary Accretion:** electron captures faster than nuclear burning
(e.g. O-Ne WDs)

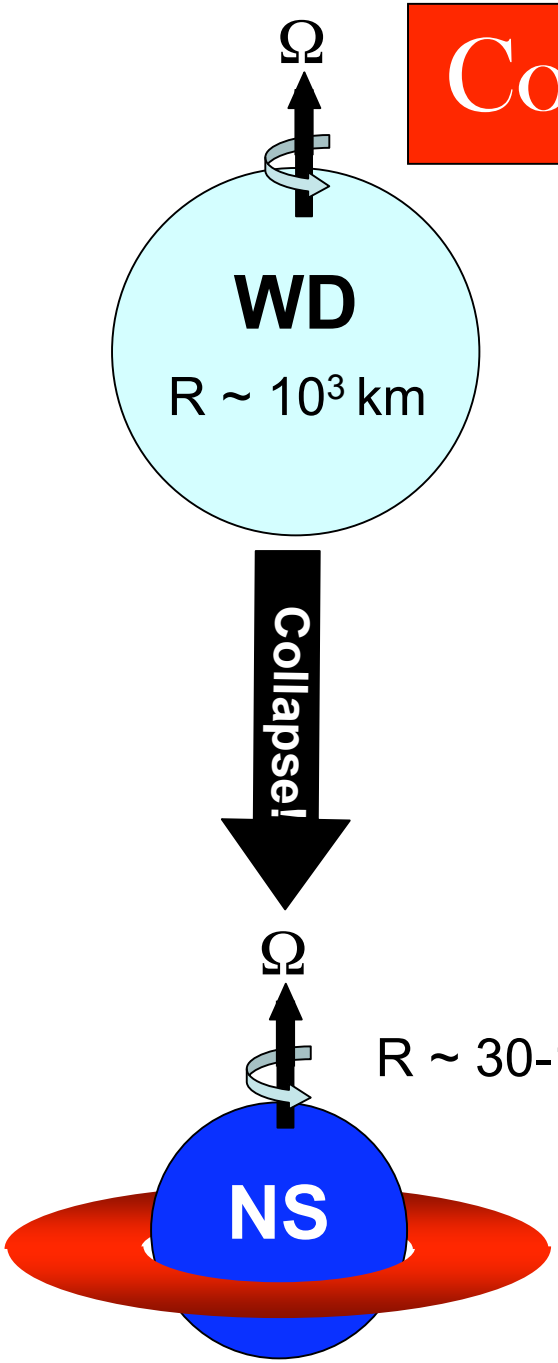
2) **Double White Dwarf Merger**:
⇒ Super-Chandrasekhar WD + Remnant Torus
(Candidates in SPY Survey; Napiwotzki+02)





- AIC Rate (Uncertain):
~10^{-6}-10^{-4} yr^{-1} $galaxy^{-1}$

Collapse to a Proto-Neutron Star

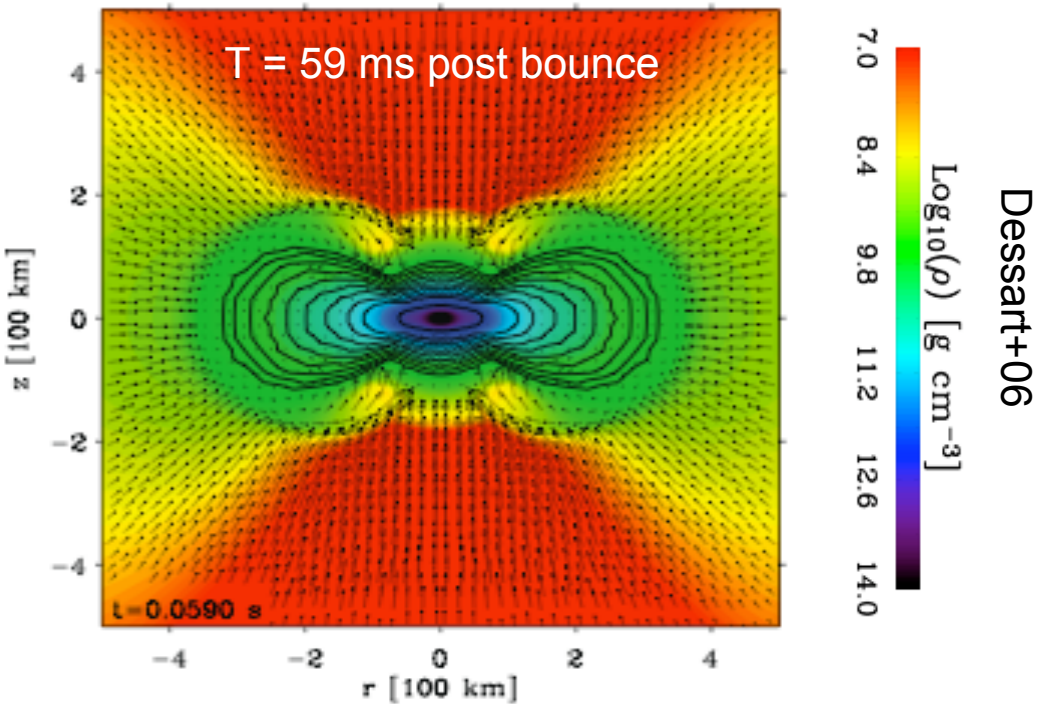


Wimpy Explosion ~10^{50} ergs, $M_{Ni} < 10^{-3}\ M_\odot$

(Woosley & Baron 92; Fryer+99; Dessart+06)

BUT with Rotation….

~ 0.1 $M_\odot$ Accretion Disk forms around NS



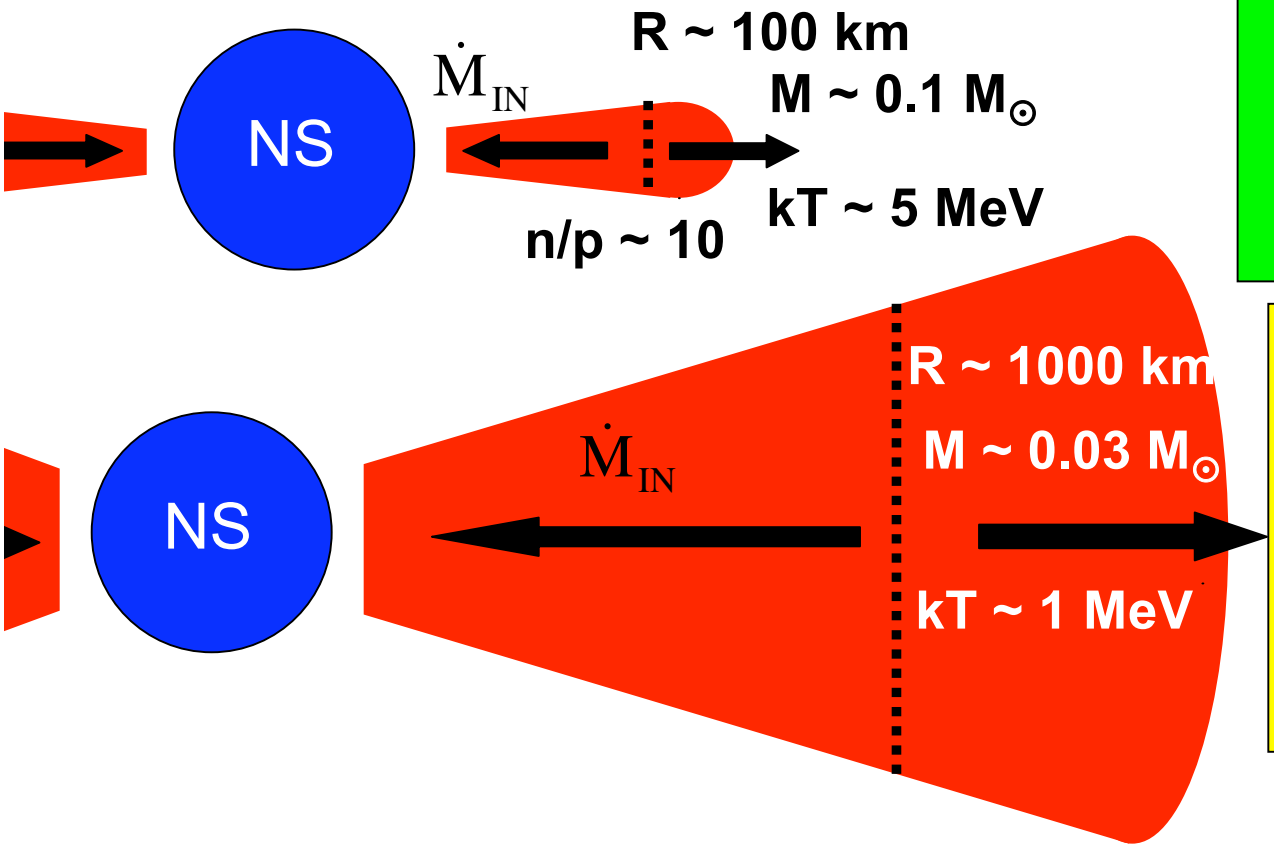
Disk Accretion and Viscous Spreading

Metzger, Piro, & Quataert 2008a,b

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

Entropy: $$T\frac{dS}{dt} = Q^{+}_{visc} - Q^{-}_{\nu}$$

Nuclear Composition: $$\frac{dY_e}{dt} = \text{Weak Interactions}$$



Initial $(t = 0)$

- Neutrino Cooled & Thin
- Neutron-Rich Equilibrium:

$$e^- + p \rightarrow \nu_e + n$$

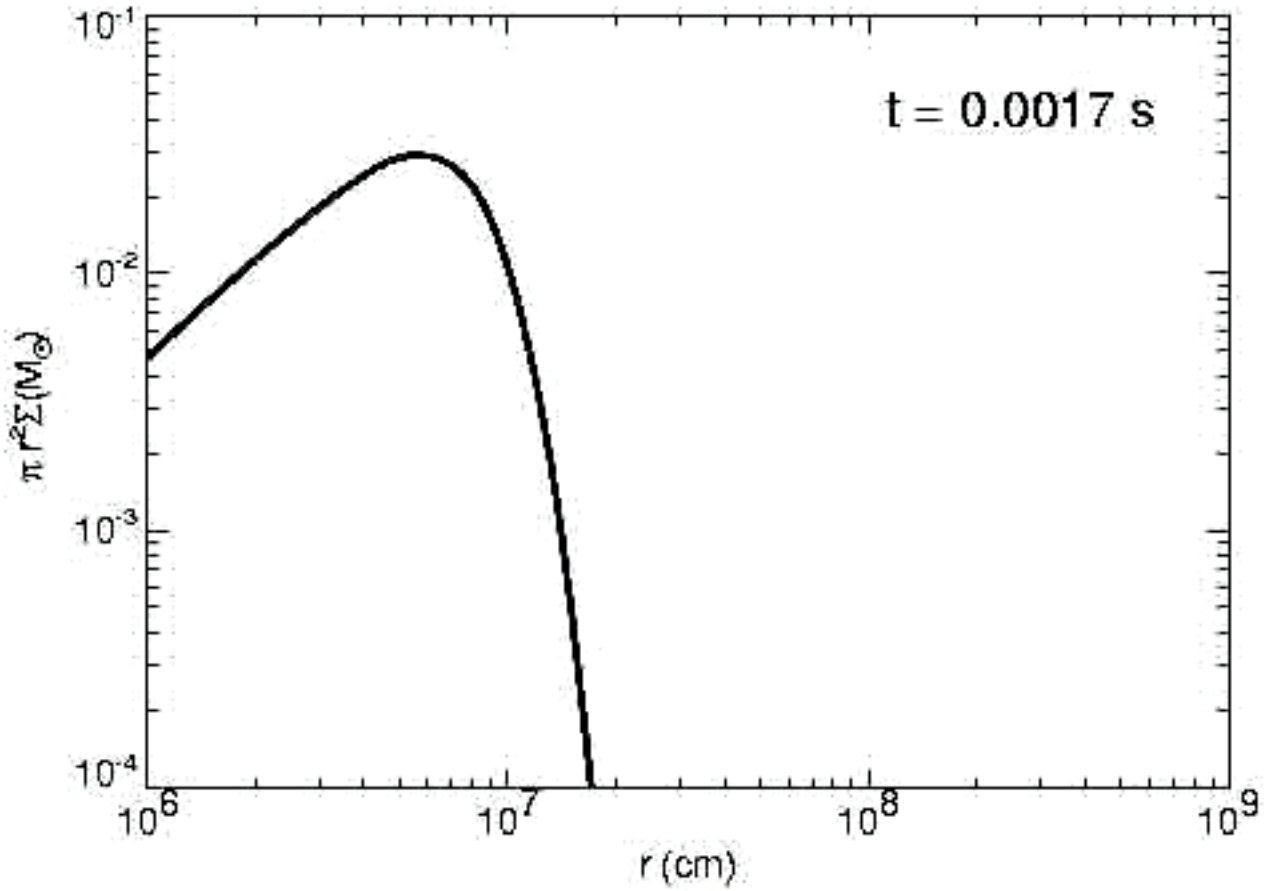
$$e^+ + n \rightarrow \bar{\nu}_e + p$$

Final $(t \sim 1\ s)$

- Inefficient Cooling (Thick)
- Neutron-Proton Ratio "Freezes Out"
- Disk Blown Apart

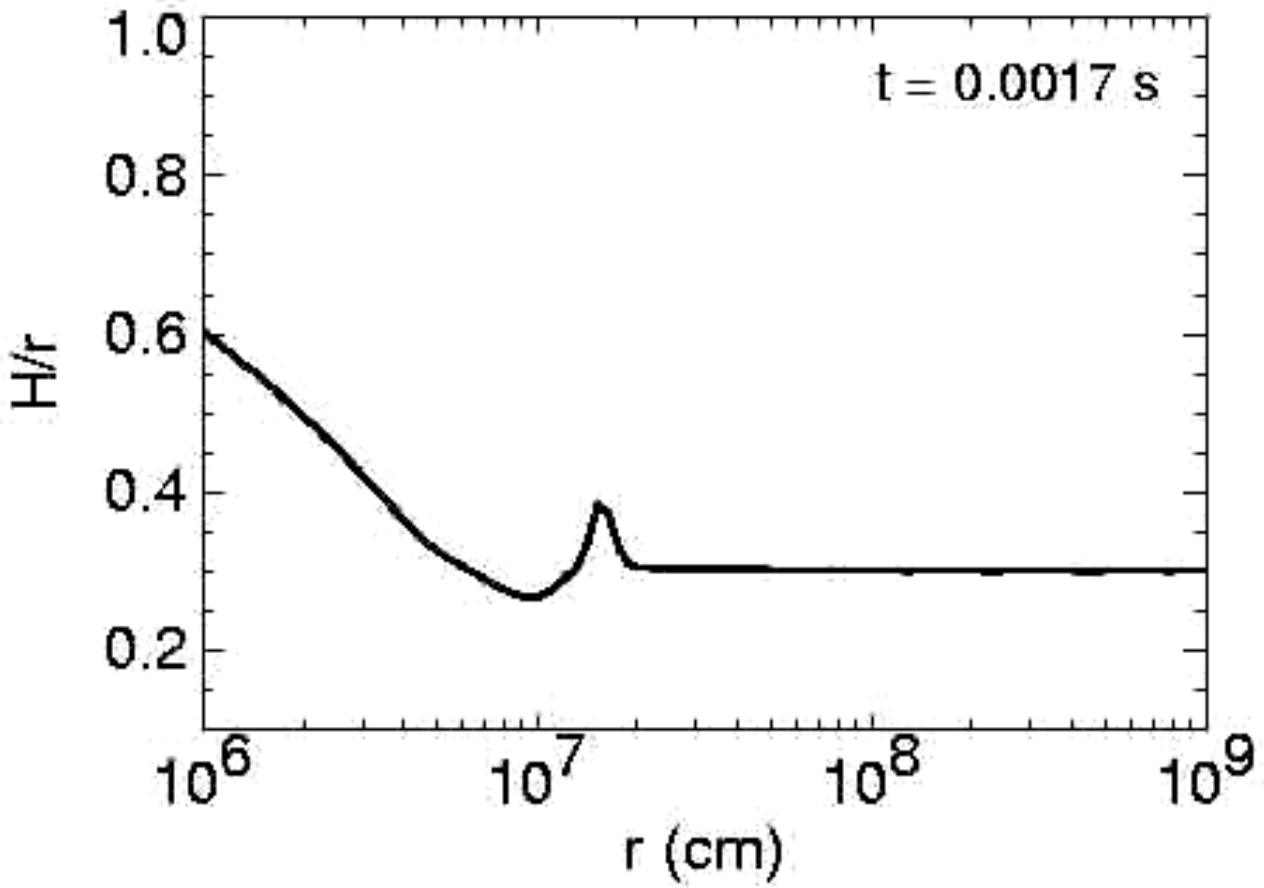
Spreading Disk Calculation

$M_0 \sim 0.1\ M_\odot$, $R_0 = 30$ km

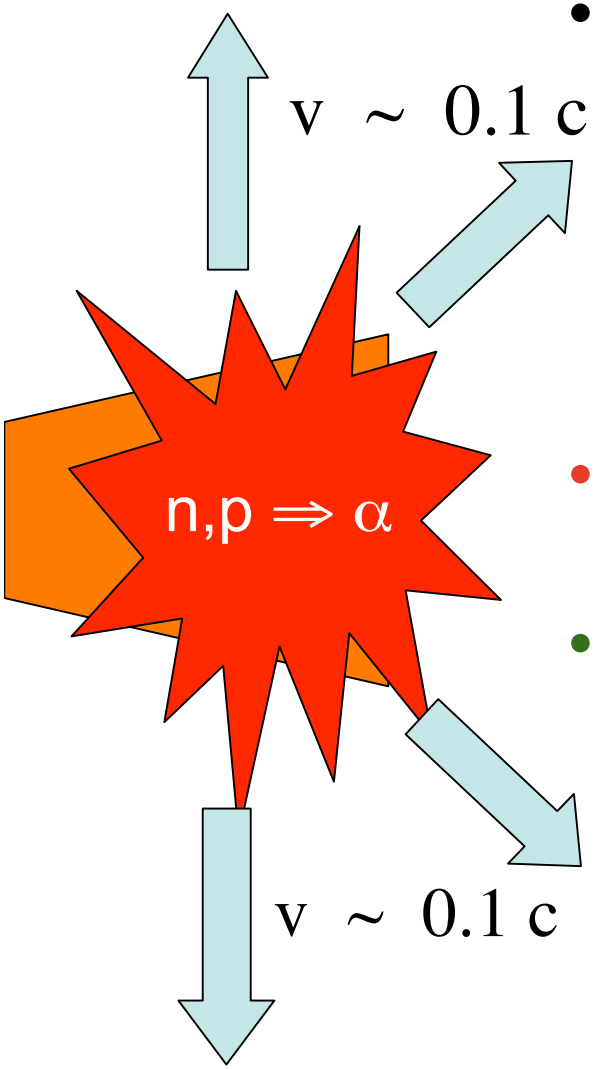


Metzger, Piro, & Quataert (2008b)

Disk Thickening



Stage III: Accretion Disks as Time Bombs



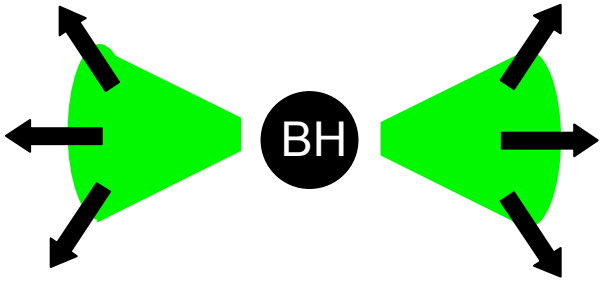
- Late-Time Outflows Disrupt Disk
  - Thick Disks Marginally Bound ⇒ **Powerful Winds**
    (Narayan & Yi '94; Blandford & Begelman '99)
  - **Nuclear Explosion** when α-Particles Form
    (~ 7 MeV released per nucleon)
  - ~30% of Initial Disk Mass Ejected
- Hot Ejecta (kT ~ 1 MeV)
  ⇒ Nuclear Statistical Equilibrium
- Adiabatic Expansion:
  ⇒ Fe-peak elements form

Weak Interactions Freeze-Out *in the Disk*
- **Critical Quantity: n/p at freeze out**

Weak Freeze-Out & Nucleosynthesis

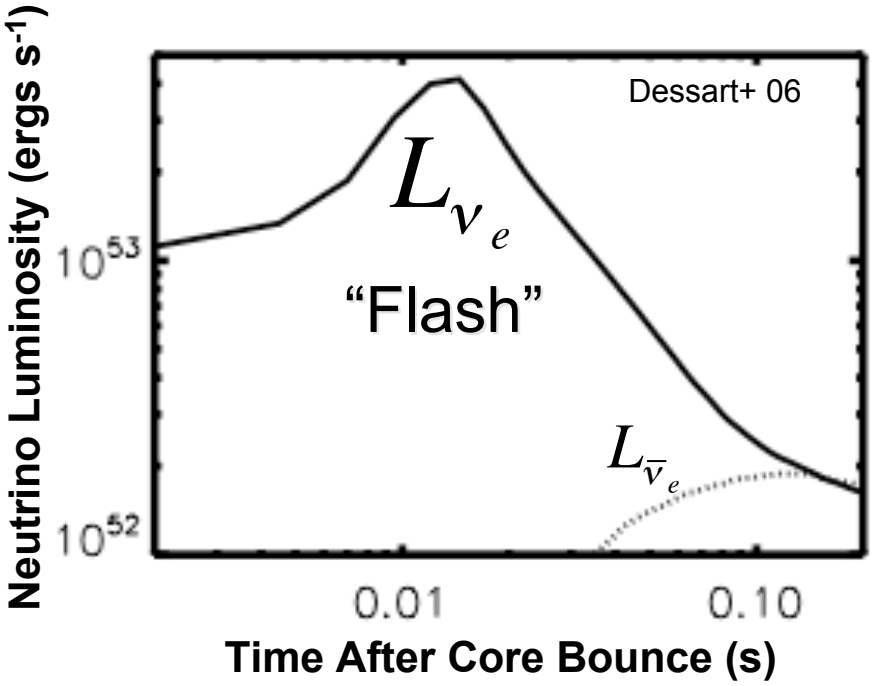
- BH Accretion (e.g. NS-BH mergers)
  - Neutron-Rich Freeze Out with **n/p ~ 2-3**;

    (Metzger, Piro, & Quataert 2008a,b)
  - *Products:* "Weird" Heavy Elements (e.g. Se, Br, Ag, Xe)



- NS Accretion
  - CRITICAL DIFFERENCE: ***Irradiation from Neutron Star***

    (SN Break-Out & De-Leptonization)



$\nu_e + n \rightarrow e^- + p$

competes with

$e^- + p \rightarrow \nu_e + n$

$\Rightarrow$ **n/p ~ 1**

$\Rightarrow$ ^{56}Ni

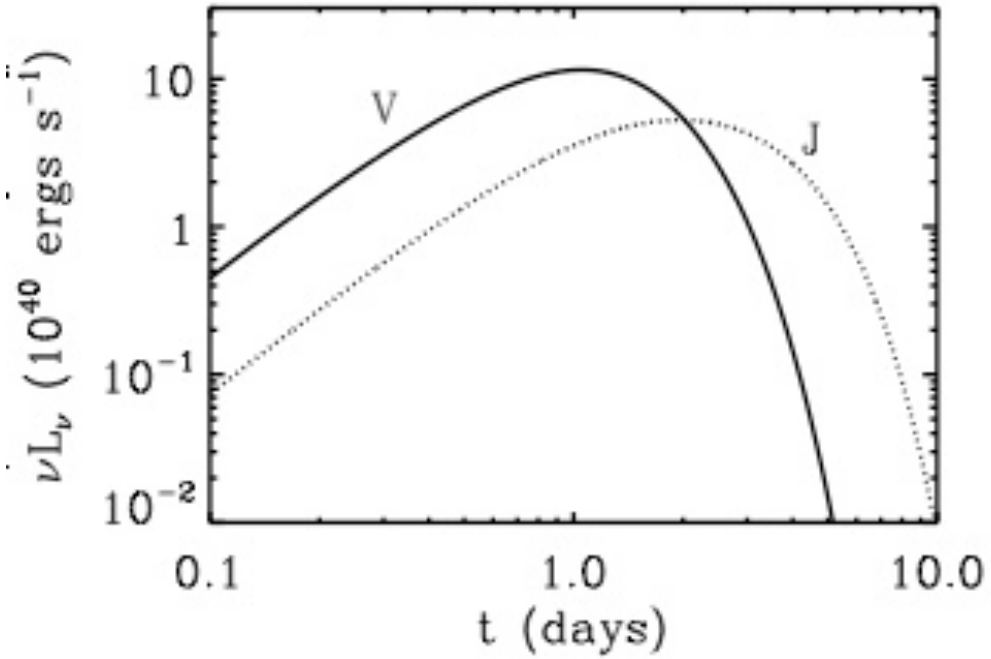
Stage IV: "Mini" SNe from Disk Outflows

- $^{56}Ni \Rightarrow {}^{56}Co + \gamma$ heats ejecta
- Photons diffuse out as ejecta expands

Naked AIC: $M_{Ni} \sim 10^{-2}\ M_\odot$, $M_{total} \sim 2 \times 10^{-2}\ M_\odot$, $v \sim 0.1$ c

$$T_{peak} \sim 1\ \text{day} \left(\frac{M_{total}}{10^{-2} M_\odot}\right)^{1/2} \left(\frac{v}{0.1\ c}\right)^{-1/2}$$

Metzger, Piro, & Quataert (2008c)



Optical Survey Rates

PanSTARRS / Palomar Transient Factory:

~ 1 yr^{-1} ($R_{AIC}/10^{-2}\ R_{Ia}$)

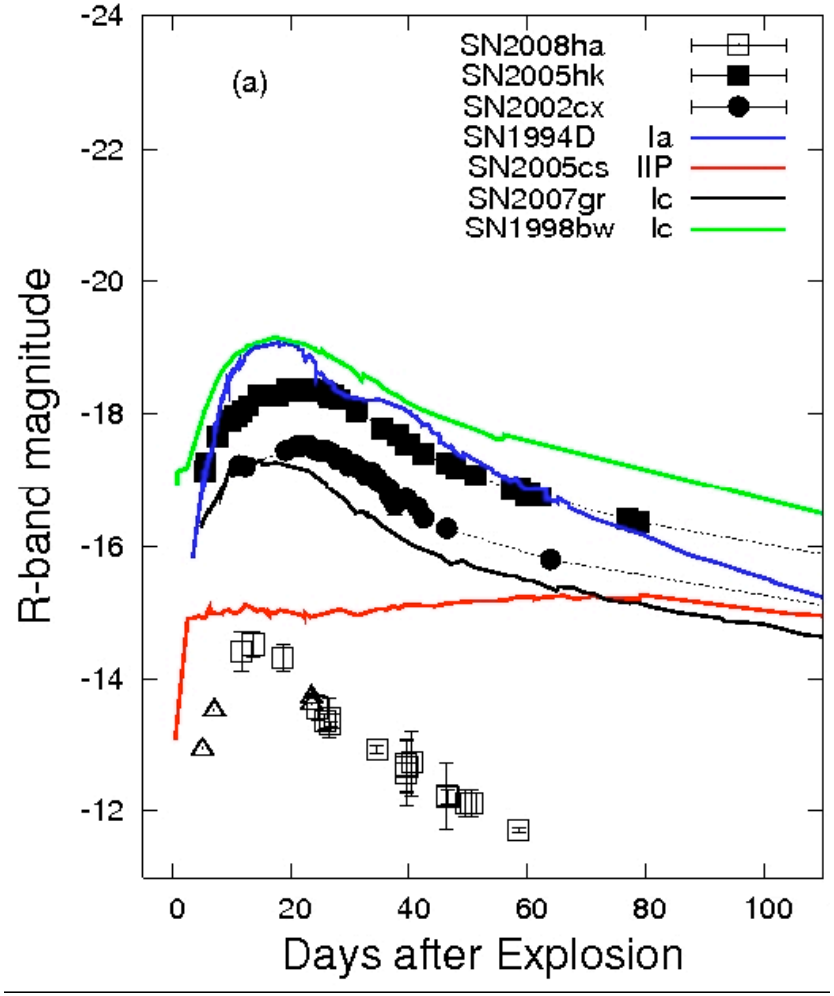
LSST:

~ 600 yr^{-1} ($R_{AIC}/10^{-2}\ R_{Ia}$)

Sub-Luminous, Sub-Chandrasekhar Type I SNe

e.g. SN 2008ha (Valenti+09 Nature; astro-ph/0901.2074)

- Small Inferred Ni Mass
  ($M_{Ni} \leq 10^{-2}\ M_{\odot}$)
- Low Velocity Ejecta
  (~2000 km/s)
- Intermediate Mass Elements
  (C, O, Ca, S, Si - but not H!)
- Sub-Chandrasekhar Mass
  $\Rightarrow M_{ejecta} \sim 0.1\ M_{\odot} << M_{Ch}$
  $\Rightarrow$ Rules Out "Pure Deflagration" Thermonuclear Models



Valenti +09: 2008ha = Core-Collapse of a Wolf-Rayet Star

"Enshrouded" AIC Supernovae

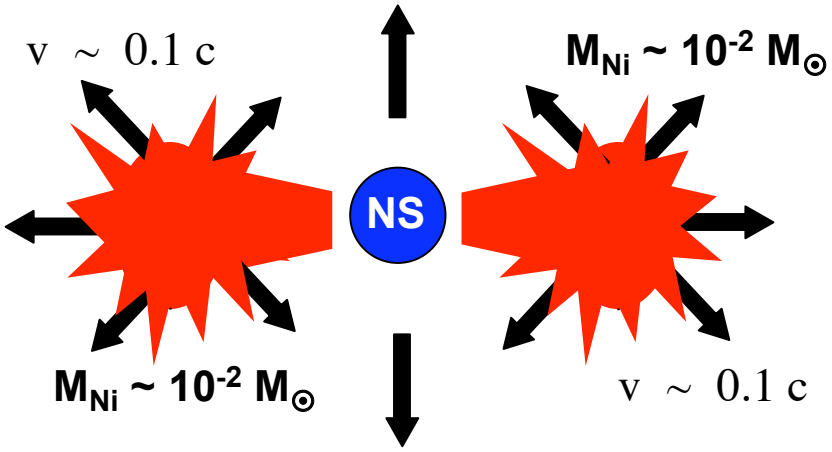
- Ni wind collides with WD-WD merger remnant torus
  ⇒ Shocks to ~ few 10^9 K; Intermediate mass elements produced
  (but some unburned C, O, He?)
- Remnant slows Ni wind:

$$v_f = \frac{M_{Ni} v_{Ni}}{M_{Ni} + M_{MR}} \approx 3000 \frac{km}{s} \left(\frac{M_{Ni}}{10^{-2} M_\odot}\right) \left(\frac{M_{MR}}{0.1 M_\odot}\right)^{-1} \left(\frac{v_{Ni}}{0.1\ c}\right)$$

- Higher opacity + lower velocity ⇒ Light curve extended to ~10 days

WD-WD Merger Remnant

$M_{MR} \sim 0.1\ M_\odot$



High Velocity Ni (Broad Nebular Fe Lines?)

WD-WD Merger Remnant

$R \sim 10^{3\text{-}4}$ km

AIC as a High Energy Source

- Accretion onto NS may produce relativistic jet
  - NS X-Ray Binary Circinus X-1 produces most relativistic micro-quasar jet known ($\Gamma > 25$; Fender +04)
- Accretion Timescale: $t_{\rm visc} \approx 1\,{\rm s} \left(\frac{M}{M_\odot}\right)^{-1/2} \left(\frac{0.1}{\alpha}\right) \left(\frac{R_0}{4R_{\rm NS}}\right)^{3/2} \left(\frac{H/R_0}{0.2}\right)^{-2}$

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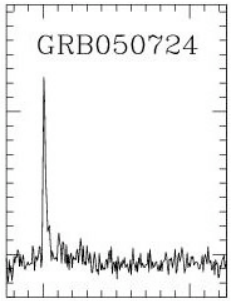
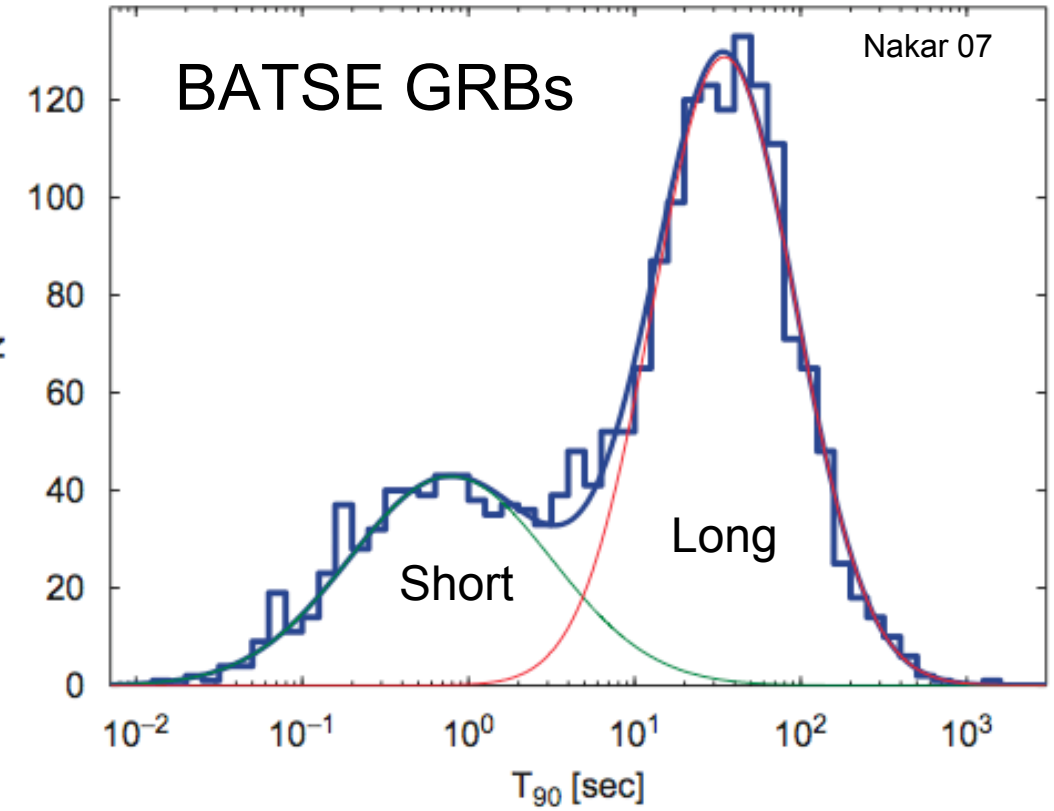
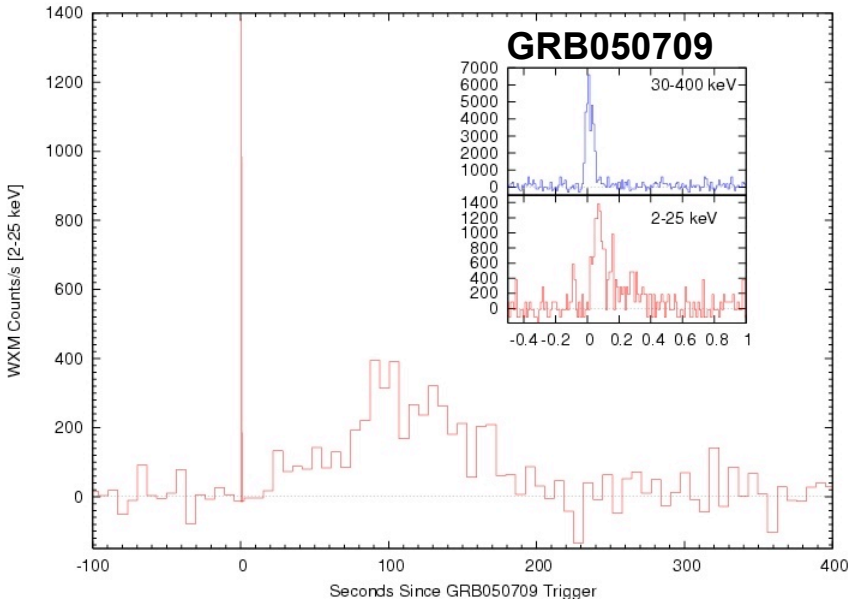


***Swift/HETE-2* Short GRBs**

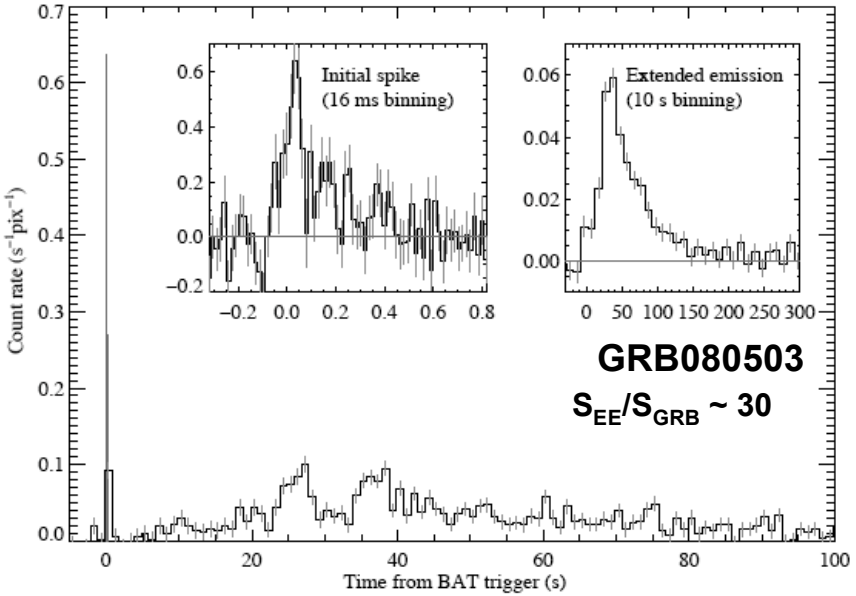


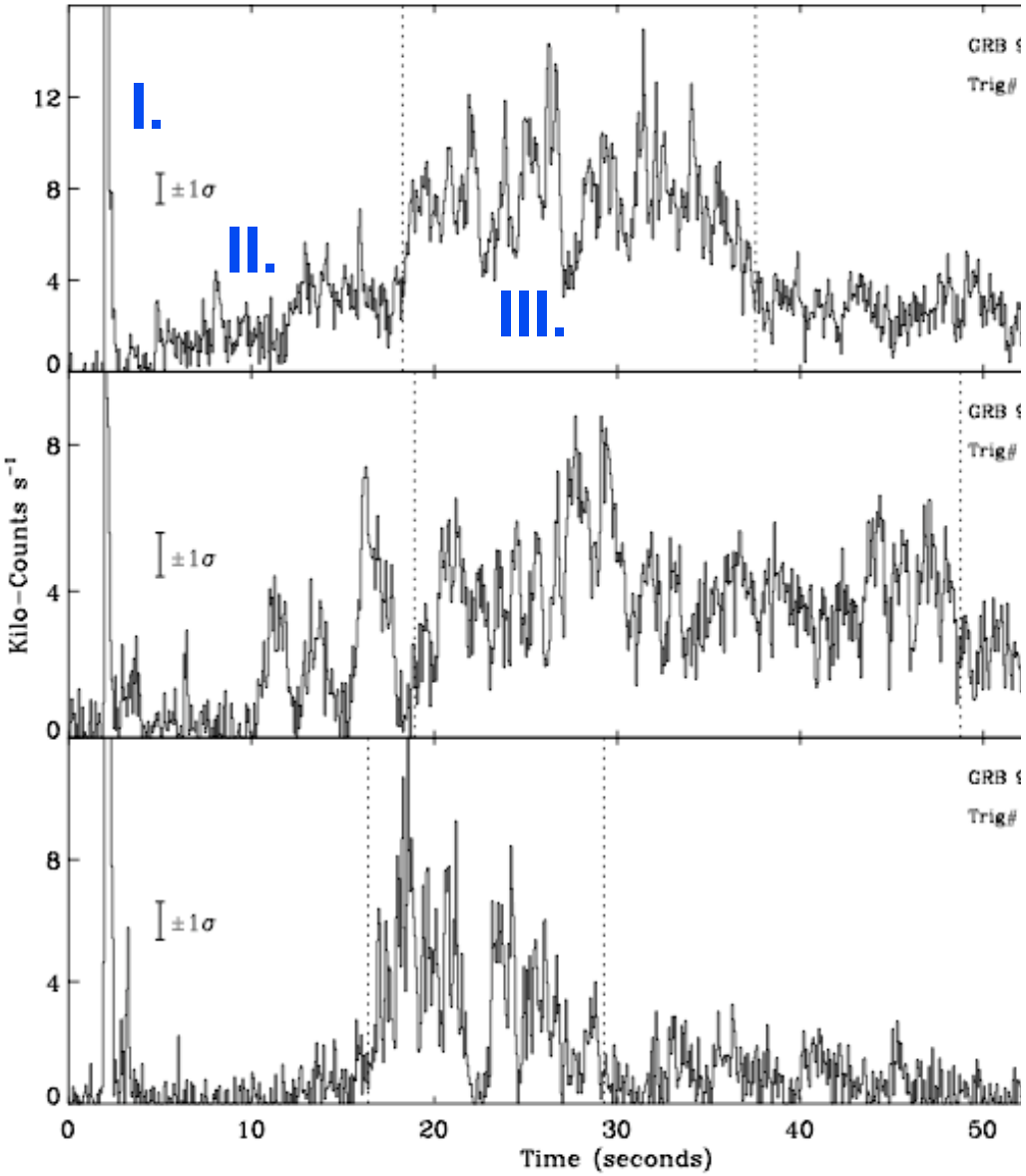
- Early & Late Type Host Galaxies; Low SFR
- No Bright Supernova
- Low Redshift (<z> ~ 0.4)

Short GRBs with Extended Emission



Perley et al. 2008



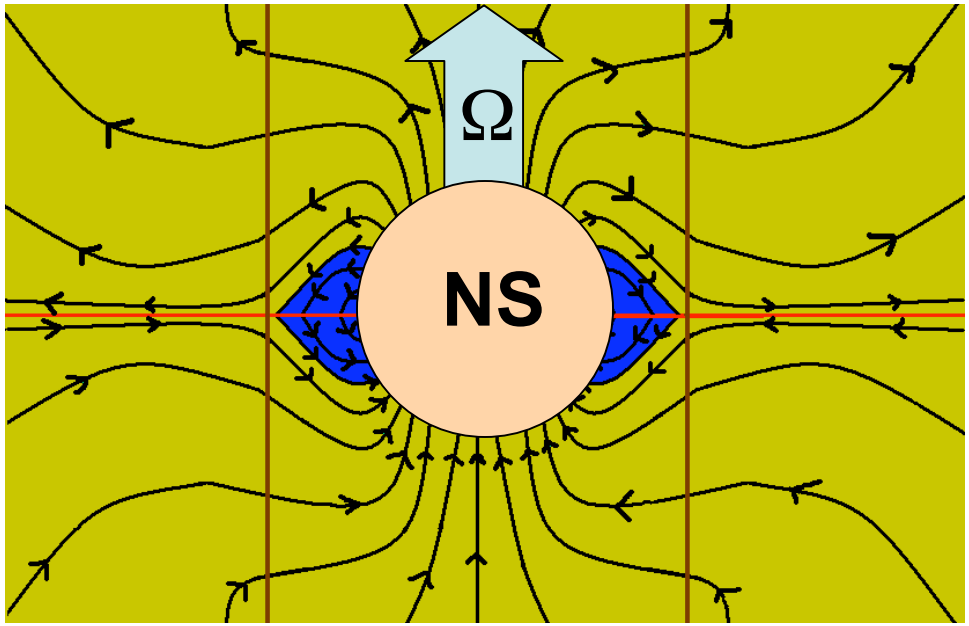


BATSE SGRBEEs (Norris & Bonnell 2006)

Extended Emission from Proto-Magnetar Spindown

(Metzger, Quataert, & Thompson 2008)

- **Energy:** Rotational Energy ~5 x 10^{52} erg for P ~ 1 ms
- **Duration ~ Spin-Down Time:** ~100 s for P ~ 1 ms, B ~ 10^{15} G.
- **Emission Lull:** Neutron Star Cooling Timescale (~10 s)



$$B_0, \Omega, \mathrm{L}_\nu, T_0 \Rightarrow \dot{M}, \dot{E}, \dot{J}$$

Evolutionary Calculations of Proto-Magnetar Winds
(Metzger, Thompson, Quataert 2007)

- 1D (Equatorial) Steady-State ν-heated MHD Wind Solutions
- Calibrated to 2D MHD Sims (Bucciantini+06)
- NS Neutrino Luminosity + Temperature Evolution

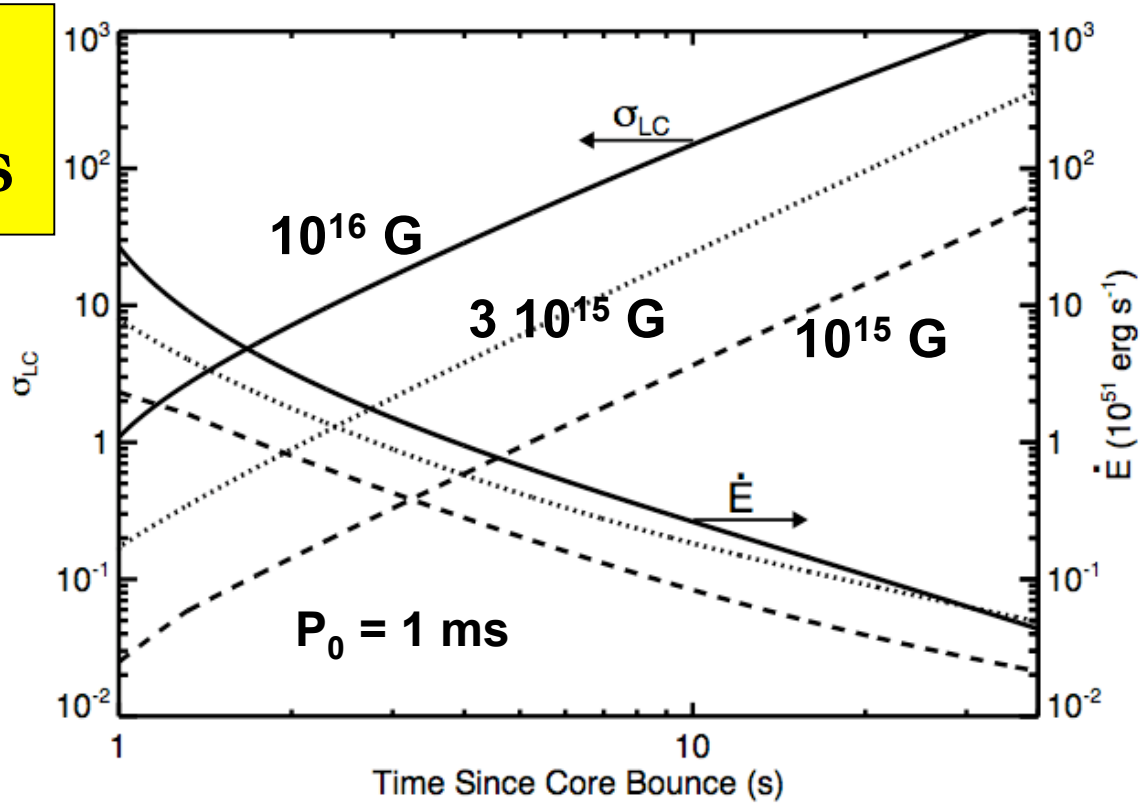
$$\mathrm{L}_\nu(t), T_0(t)$$

(e.g. Burrows & Lattimer 86; SN1987A)

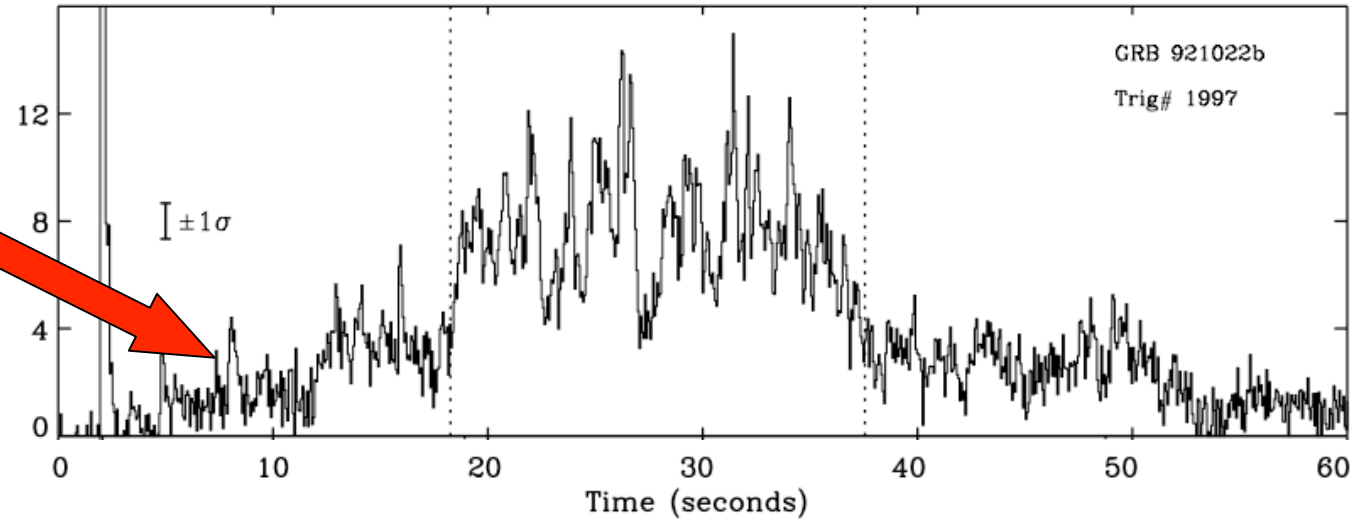
Time Evolving Proto-Magnetar Winds

Magnetization

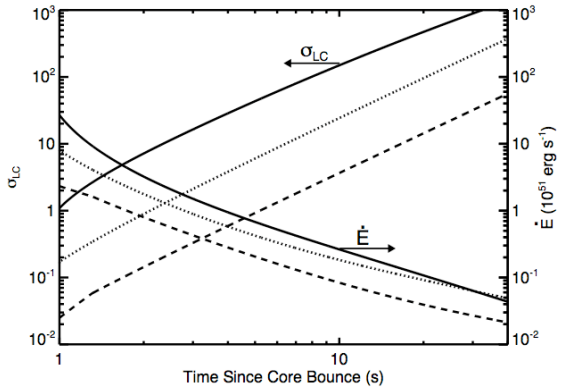
$$\sigma_{LC} \equiv \left.\frac{B^2}{4\pi\rho c^2}\right|_{R_L} \sim \Gamma$$

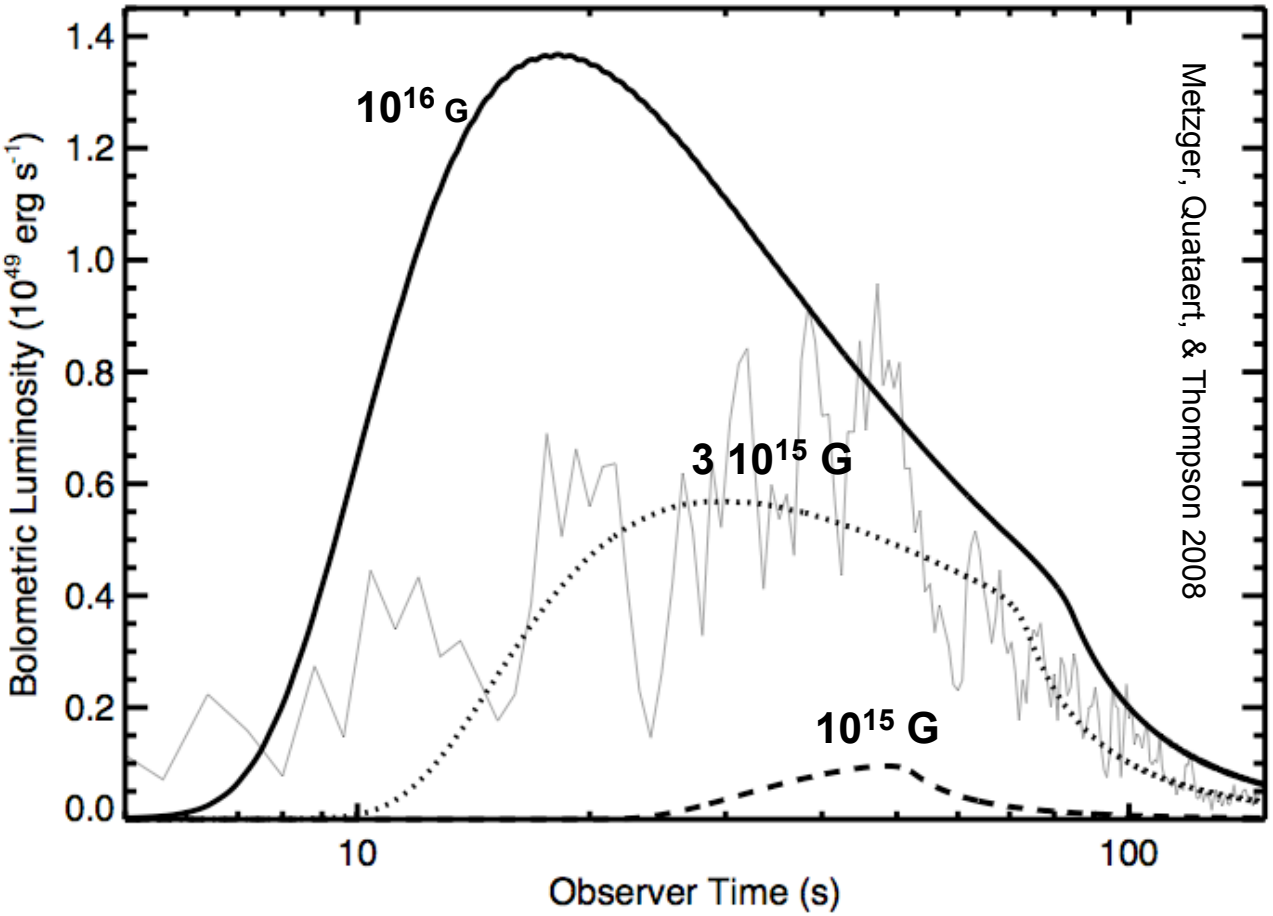


Cooling Delays Onset of Ultra-Relativistic Outflow



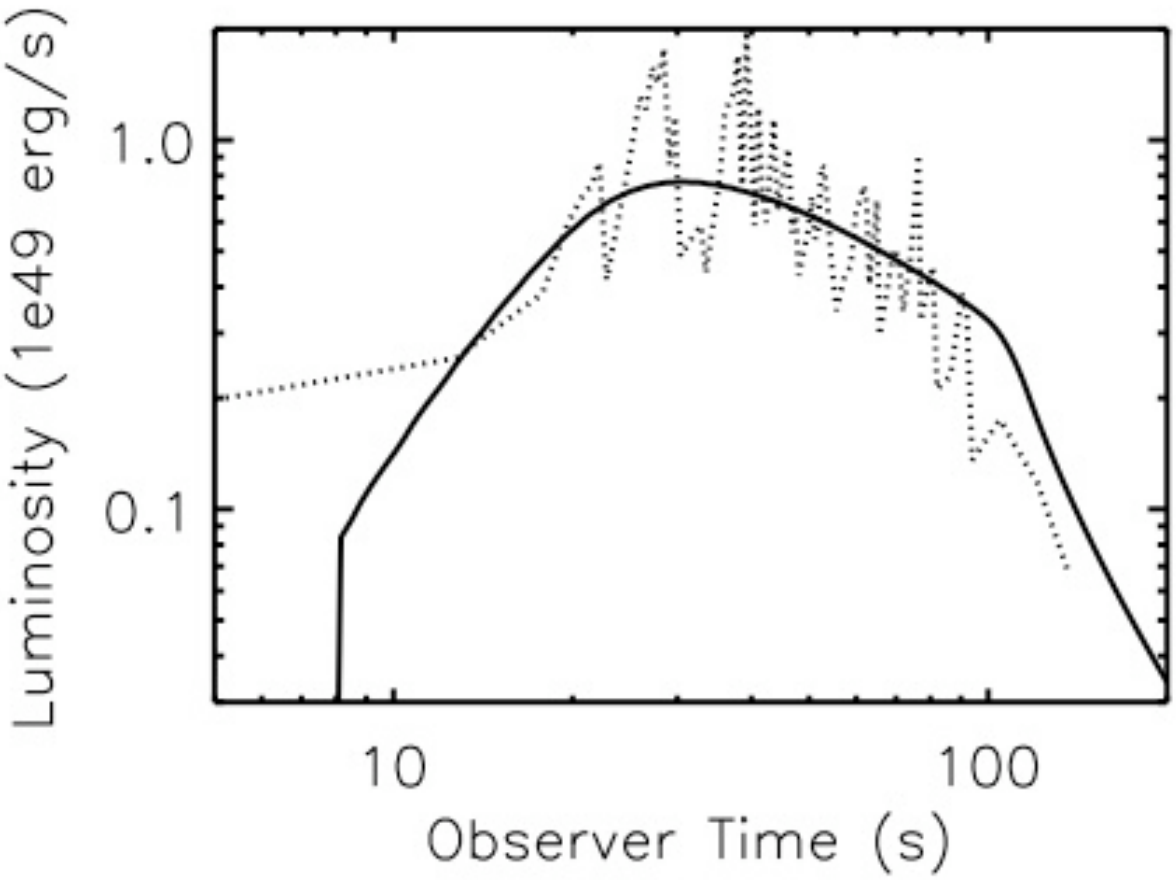
Magnetar Wind Internal Shock Light Curve





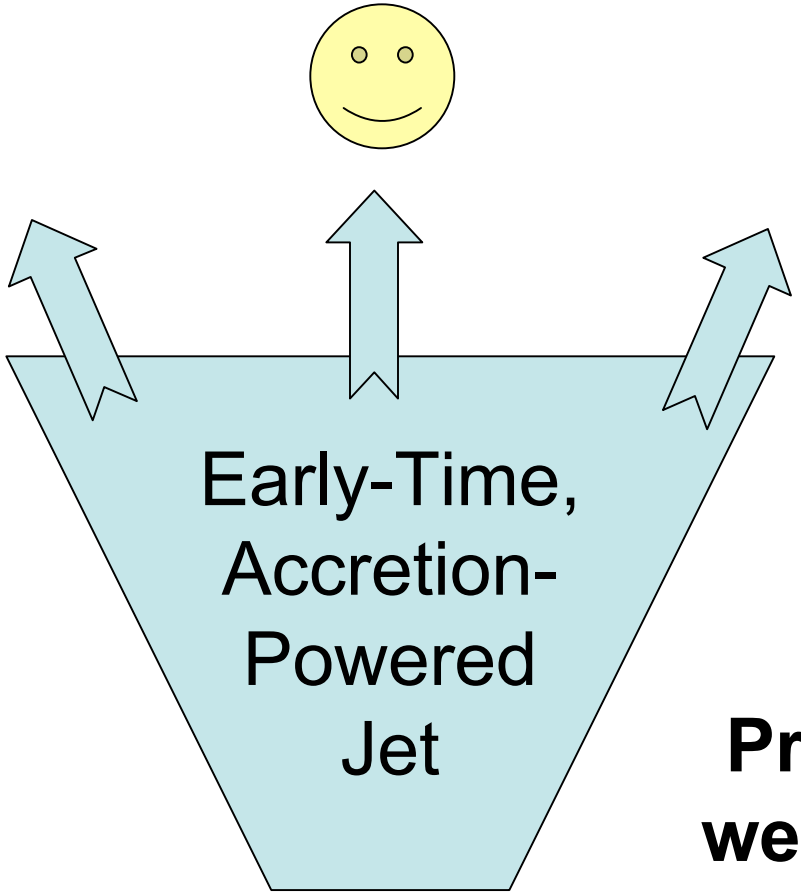
- ~ 10-20% Kinetic-to-Thermal Efficiency (consistent w/ observations)
- Stronger B ⇒ Shorter Duration & Faster Time to Peak
- 3 PHASES (I) Gradual Onset (Transparency), (II) Power Law Decline, (III) Rapid Decay (Onset of Ultra-High σ Prevents Strong Shocks?)

GRB080503



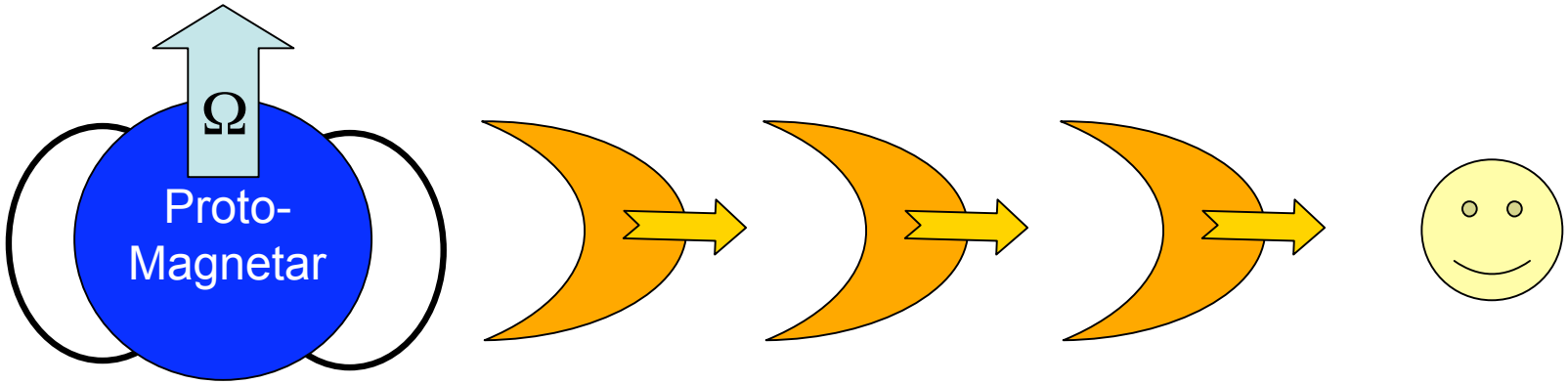
Data from Perley et al. (2008)

Off-Axis Viewers



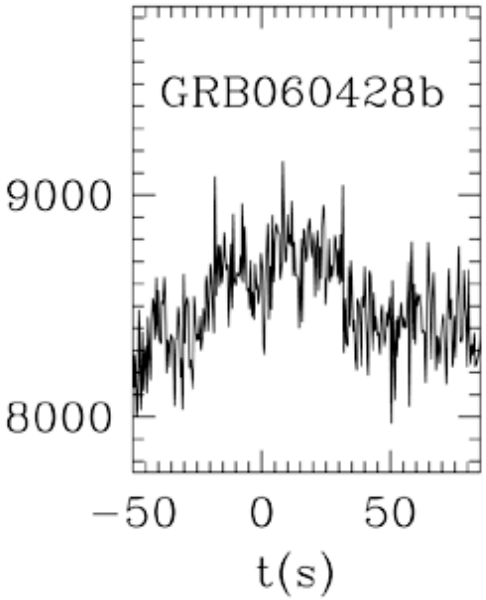
Magnetar Wind is Quasi-Isotropic: Equatorial Viewers see Extended Emission without Prompt Spike

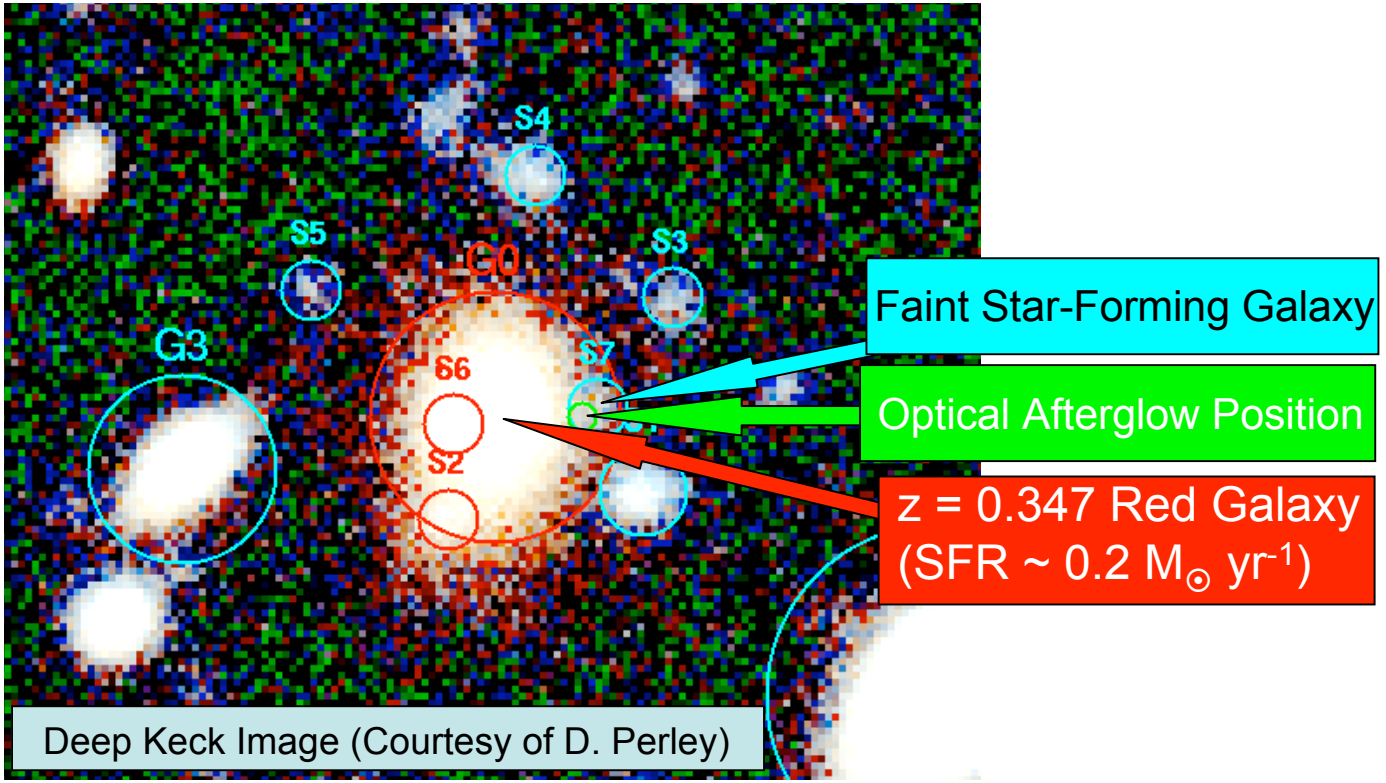
Prediction: X-ray flashes with weak SN + little star formation!



X-Ray Flash 060428B: Off-Axis SGRBEE?

- Light Curve Resembles Extended Hump (T_{90} ~ 50 s)
- Putative Red Host at z = 0.347; If confirmed:
  - SN < 20x as luminous as SN1998bw (Perley et al., in prep)
  - Energy of Burst ~2e50 ergs (roughly same as GRB060614)





- AIC + Rapid Rotation $\Rightarrow$ Proto-Neutron Star + Compact Accretion Disk
- Disk Accretes, Viscously Spreads and Cools
- Neutrino Irradiation from NS Drives n/p to ~ 1
- Disk "Explodes" $\Rightarrow$ ~ $10^{-2}\ M_{\odot}$ in ^{56}Ni Synthesized in Outflow

  1) "Naked" AIC $\Rightarrow$ "Mini-SN" with L_V ~ 10^{41} erg s^{-1} for ~ 1 day

  - Almost "pure" Ni explosion (spectroscopically distinct)
  - Detectable with transient surveys or as beacon to GW source

  2) "Enshrouded" AIC $\Rightarrow$ sub-luminous, sub-M_{Ch}, low velocity Type I SNe?

- Accretion Following AIC May Produce a Short GRB

  - "Magnetar" formation $\Rightarrow$ extended emission from internal shocks in proto-magnetar wind (first "first principles" GRB light curve calculation!)