重力波X線•ガンマ線対応天体

村瀬　孔大
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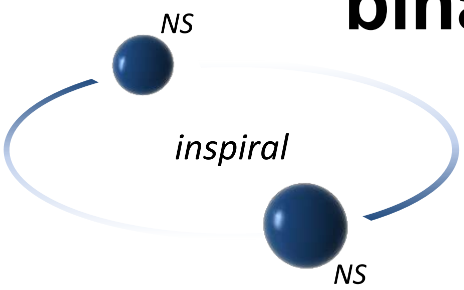
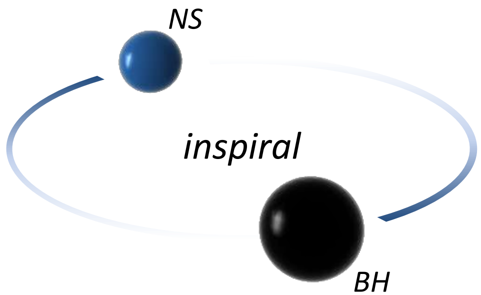
日本物理学会
3月 2014

Toward GW Astrophysics

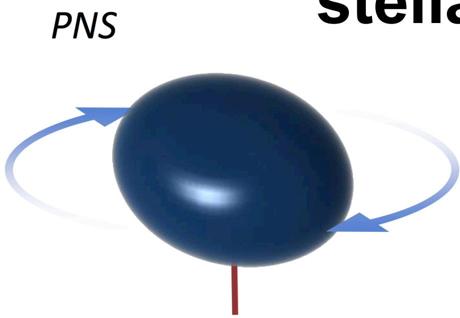
binary



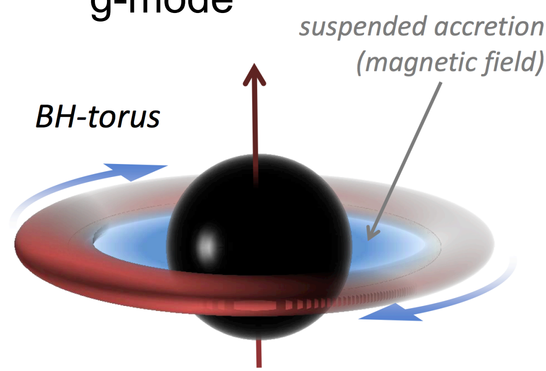


inspiral
merger
ringdown
etc.

stellar collapse



core-bounce
convection/SASI
anisotropic ν
g-mode



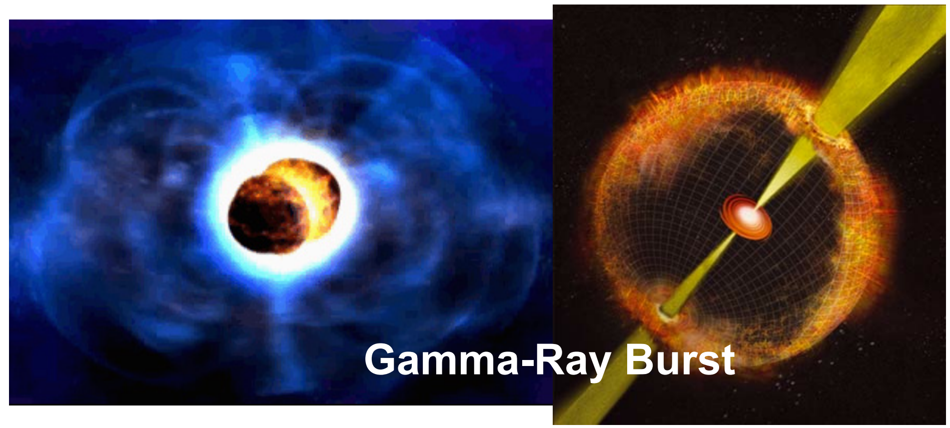
dynamical instability
secular instability
magnetic distortion
disk fragmentation

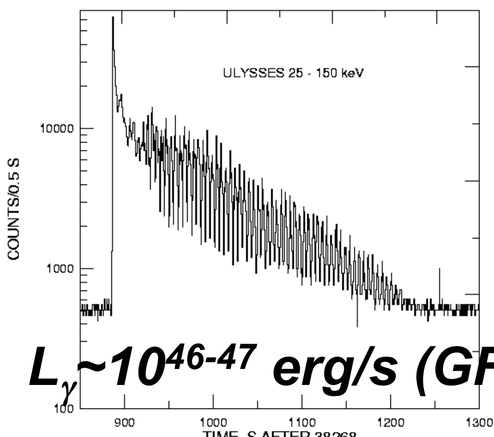
Promising: GWs have been indirectly detected so they should exist

Outline

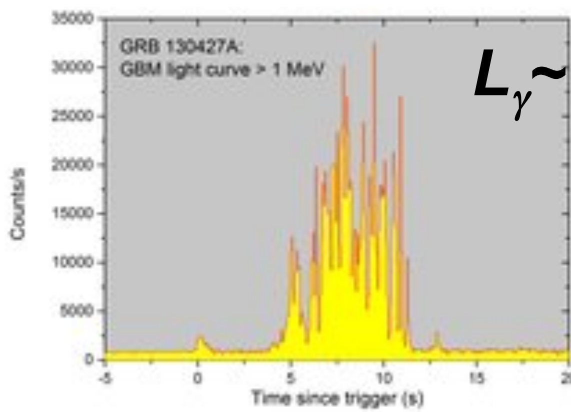
The next decade will be the multimessenger era

X/γ rays have provided powerful messengers

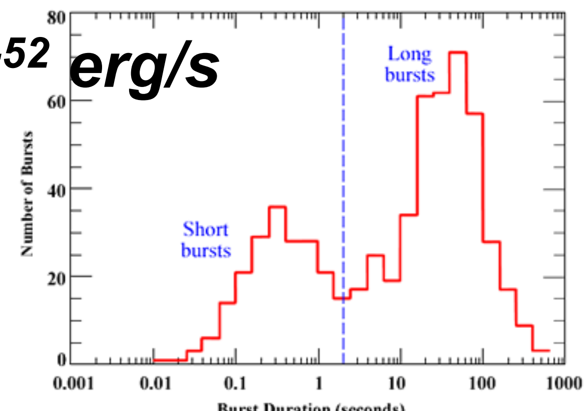




L_γ~$10^{46\text{-}47}$ erg/s (GF)



L_γ~$10^{51\text{-}52}$ erg/s



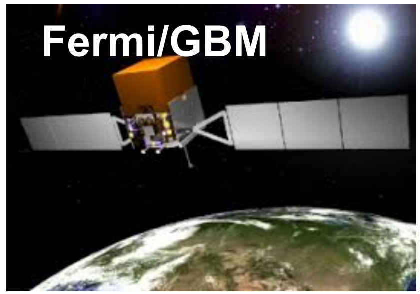
GRBs and related transients in the complimentary view

(apologizes: I decided not to cover SGRs, SMBH binaries)

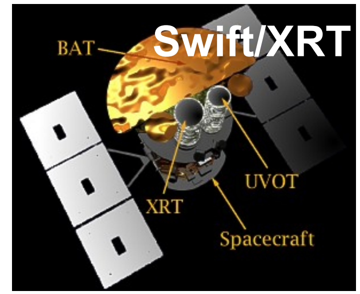
X-Ray and Gamma-Ray Detectors (Partial)

Monitor ← → follow-up

Energy: 0.02-300 GeV
FOV: ~2.4 sr
Localization: <1 deg



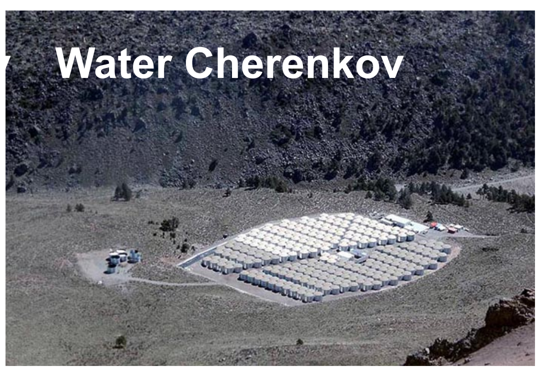
Energy: 8 keV-30 MeV
FOV: ~4π sr
Localization: <5-15 deg



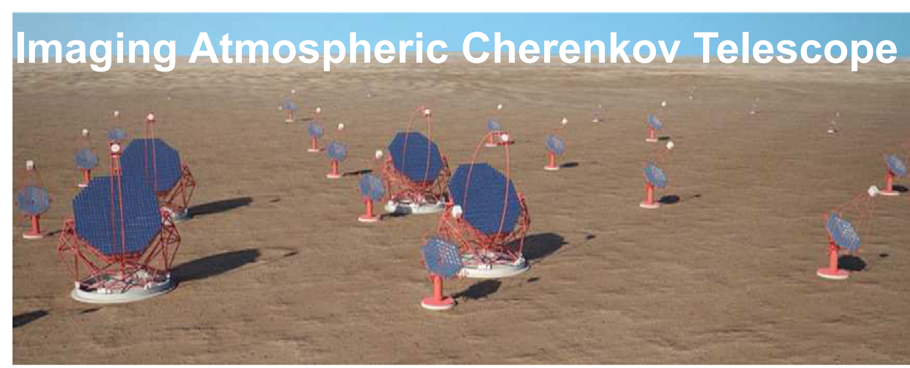
Energy: 0.2-10 keV
FOV: 23.6x23.6 arcmin
Ang. Res. ~20 arcsec
Follow-up: <100 s

Energy: 6-80 keV
FOV: 12x12 arcmin
Ang. res. ~45 arcsec
Follow-up: <24 hr

Energy range: >EeV
FOV: ~2π sr
Ang. res. ~1 deg
Duty cycle: ~100%

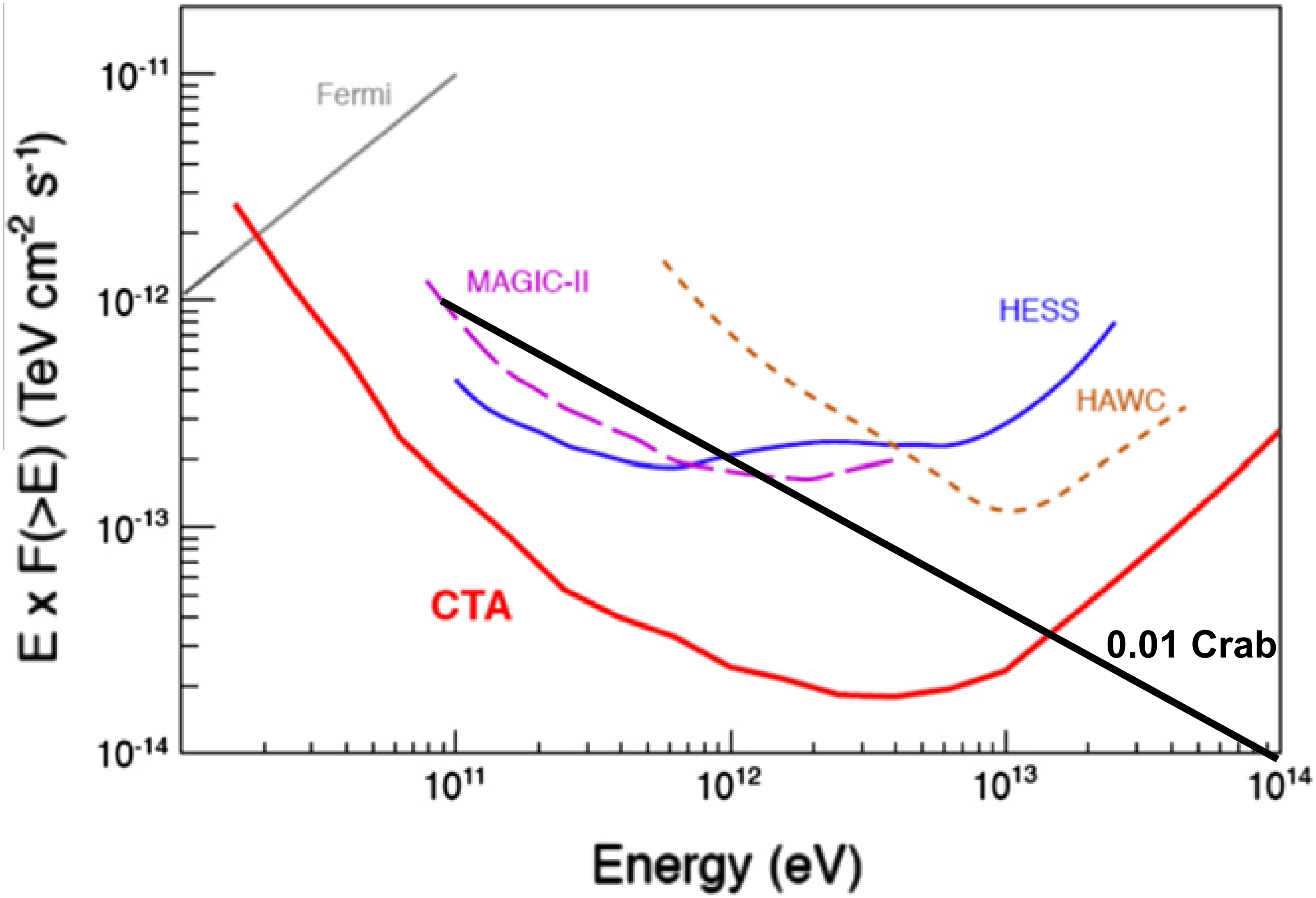


Energy range: 0.1-100 TeV
FOV: ~2π sr
Ang. res.: ~0.3-0.7 deg
Duty cycle: ~95%



Energy range: ~10 GeV-100 TeV
FOV: ~20 deg^2
Ang. res.: ~0.05 deg
Duty cycle: ~10%

Gamma-Ray Detectors: Sensitivity Comparison



cf. Swift/BAT: ~2×10^{-9} erg cm^{-2} s^{-1}, Swift/XRT: ~2×10^{-14} erg cm^{-2} s^{-1} (10^4 s),
WF-MAXI: 10^{-9} erg cm^{-2} s^{-1}, NuSTAR: 10^{-14} erg cm^{-2} s^{-1} (10^6 s)

Strategy & Outline

GW+EM – many motivations:
distance determination, host galaxy & source environments, explosion mechanism, outflow (jet) physics, nucleosynthesis

Localization by GW detectors ~ a few $degrees^2$

- wide-field monitor (ideal for bright transients: ex. GRBs)
  GW & X/γ rays: coincident detection

- detailed follow-ups (necessary for faint transients)
  GW → X/γ rays or GW → better local. w. optical/X → X/γ rays

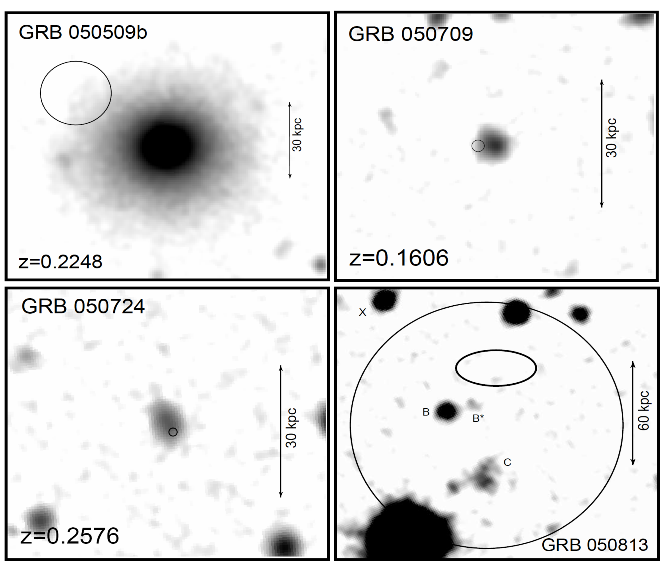
  cf. γ-ray detection by Fermi/Swift → CTA search
  ~1-2 long GRBs yr^{-1} (Kakuwa, KM+ 12 MNRAS)

Short GRBs: Questions and Motivations

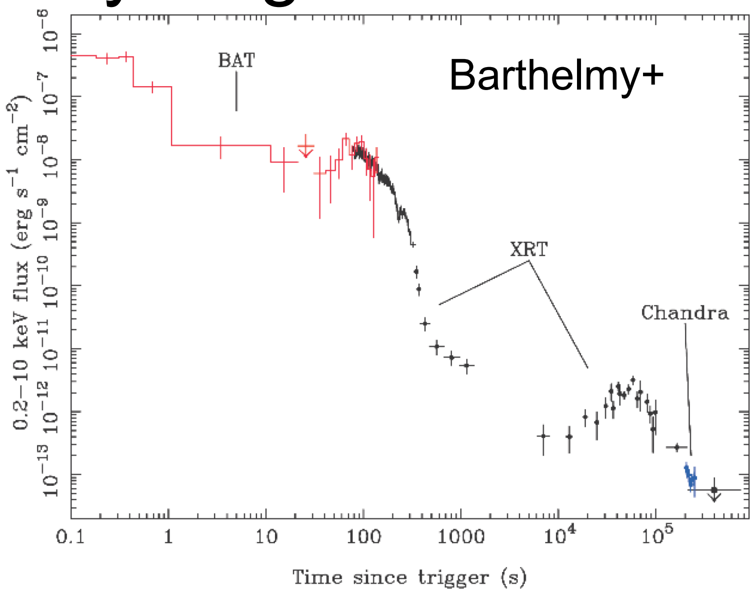
- E_{iso}~10^{49}-10^{51} erg << 10^{52-54} erg for long GRBs
- Various hosts including elliptical galaxies
- Leading candidates: NS-NS (or BH-NS) mergers

But some short GRBs show extended emission

Concerns about contamination by long GRBs

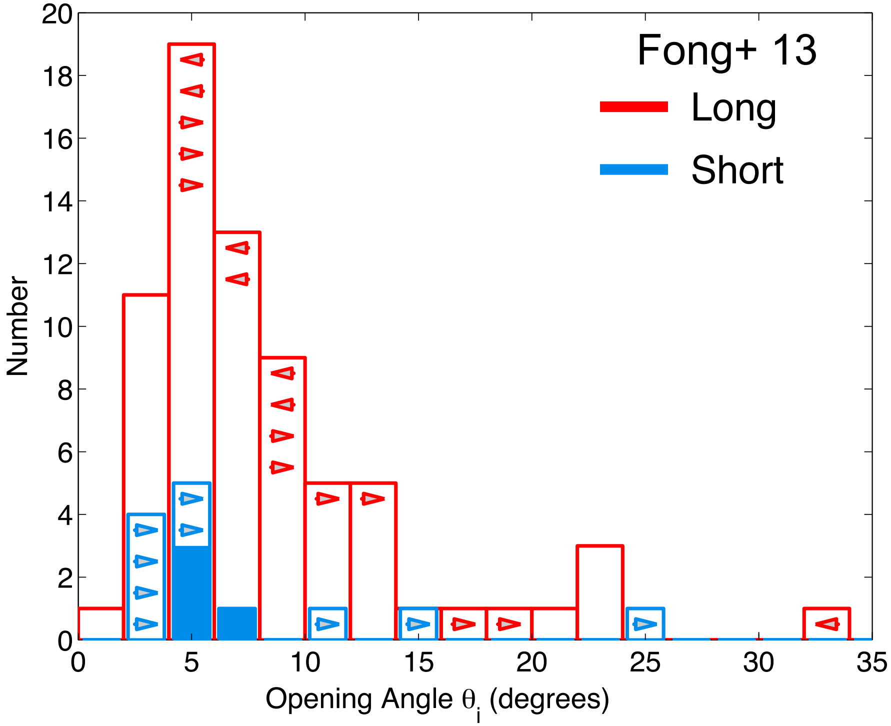


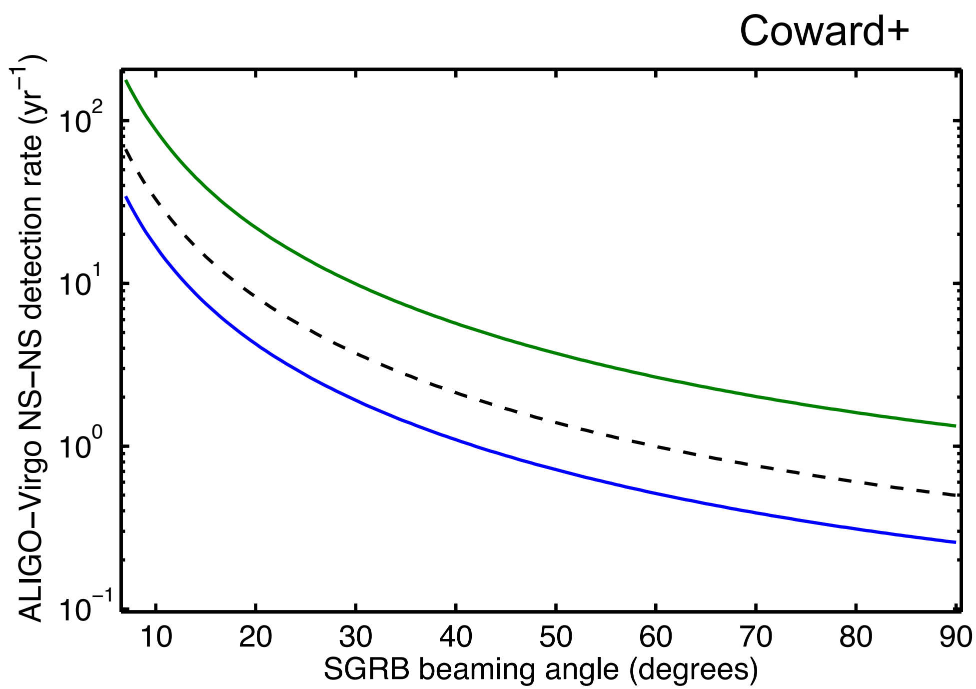
Prochaska+



Short GRBs: Emission from Relativistic Jets

Testing the meger paradigm for short GRBs





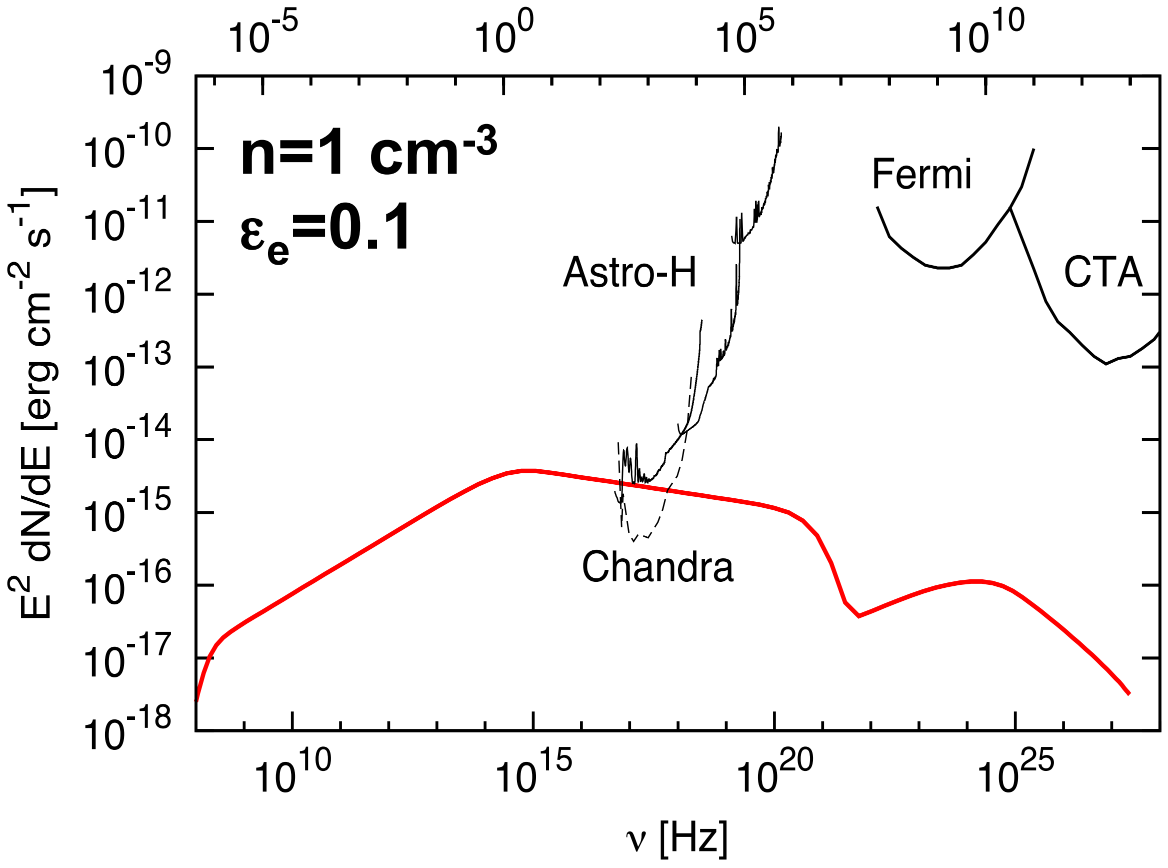
obs. rate ~10 $Gpc^{-3}\ yr^{-1}$ (~0.2 yr^{-1} within 200 Mpc)

true rate: ~1000 $Gpc^{-3}\ yr^{-1}\ (\theta/10\ deg)^{-2}$

Isotropic Mass Ejection: Merger Remnant

Takami, Kyutoku & Ioka 14 PRD

see Hotokezaka-san's talk



Sedov radius

$$R_{\rm dec} = \left(\frac{3M}{4\pi n m_p}\right)^{1/3} = 1 \times 10^{18} M_{-2}^{1/3} n_0^{-1/3} \quad {\rm cm}$$

Sedov time

$$t_{\rm dec} = \frac{R_{\rm dec}}{\beta c} = 5 M_{-2}^{1/3} n_0^{-1/3} \beta_{0.3}^{-1} \quad {\rm yr},$$

$E_{kin} \sim 10^{-2}\ M_{sun}\ (0.1c)^2 \sim 10^{51}$ erg << E_{GW}

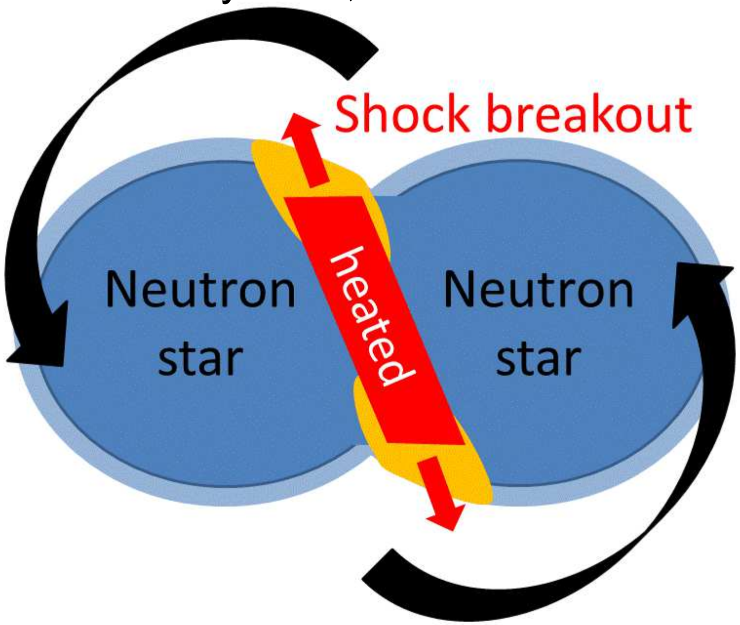
Detectable w. detailed X-ray follow-ups

DNS Mergers: Other Possibilities

Relativistic shock breakout

radiative acceleration of hot regions

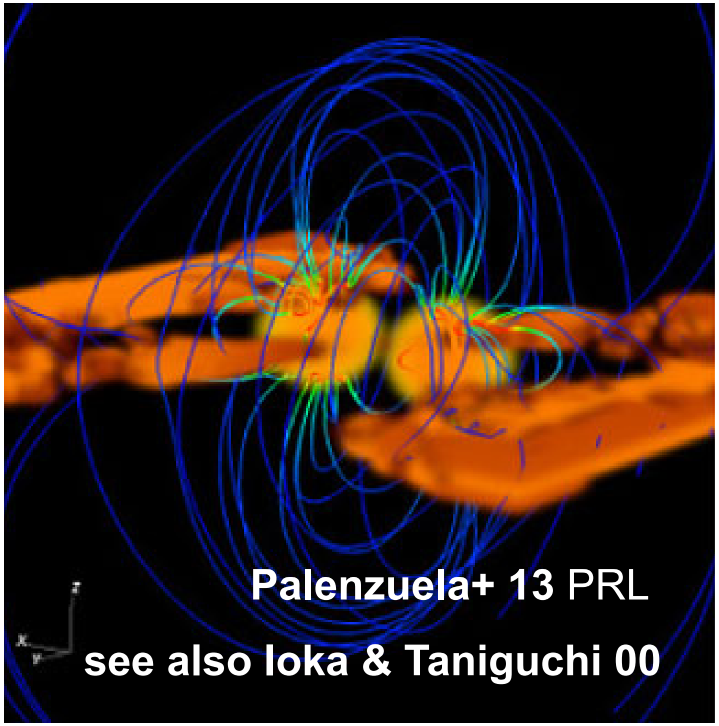
Kyutoku, Ioka & Shibata 14 MNRAS



E_{kin}~10^{47} erg → detectable w. Swift after ~0.1-1 day

Precursor

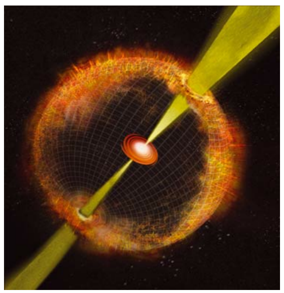
extraction via B field interactions



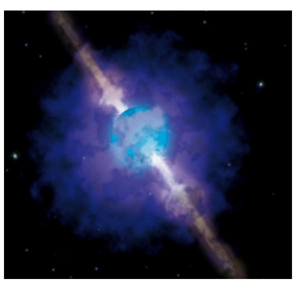
L_{EM}~$10^{40\text{-}43}$ erg/s $(B/10^{11}$ G$)^2$?

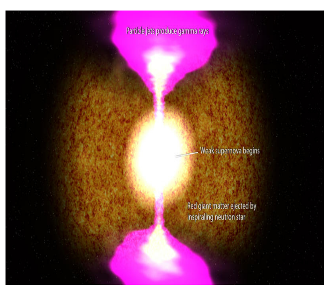
Long GRBs: Questions and Motivations

BH+disk or Pulsar?



WR star, Blue supergiant
BH/NS-He binary?

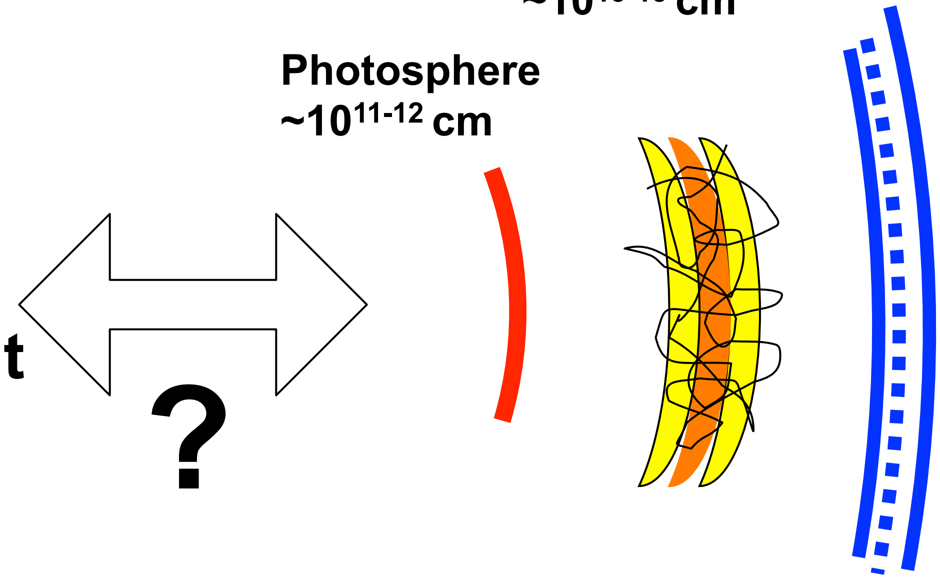




External shock
~10^{16-17} cm

Internal shock
~10^{13-15} cm

Photosphere
~10^{11-12} cm



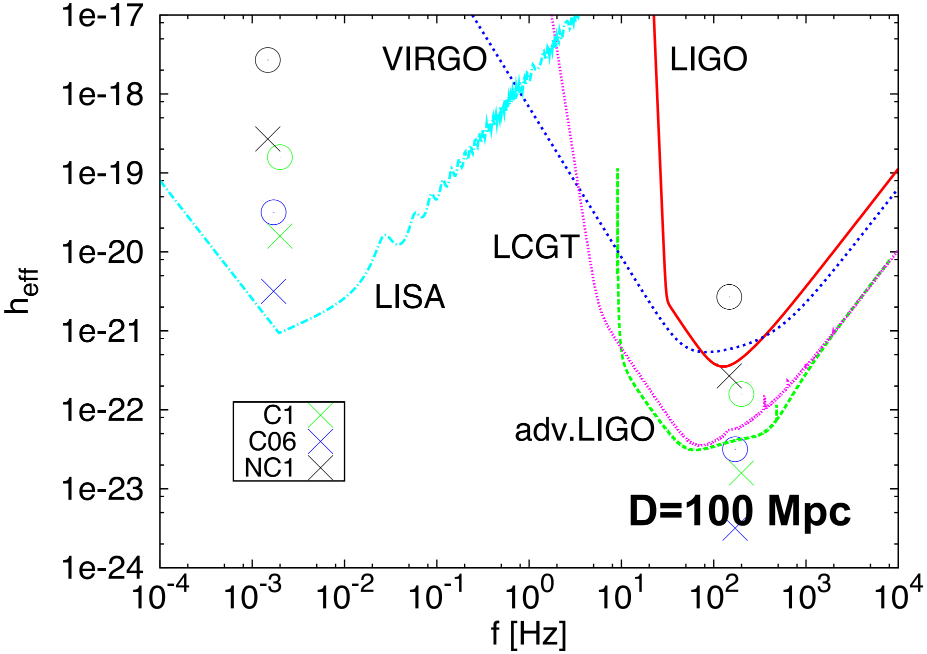
- **emission mechanisms?**
- **jet composition?**
  (magnetic, baryonic)
- **origins of flares/plateau?**

GWs can probe engines invisible by photons

Contd.

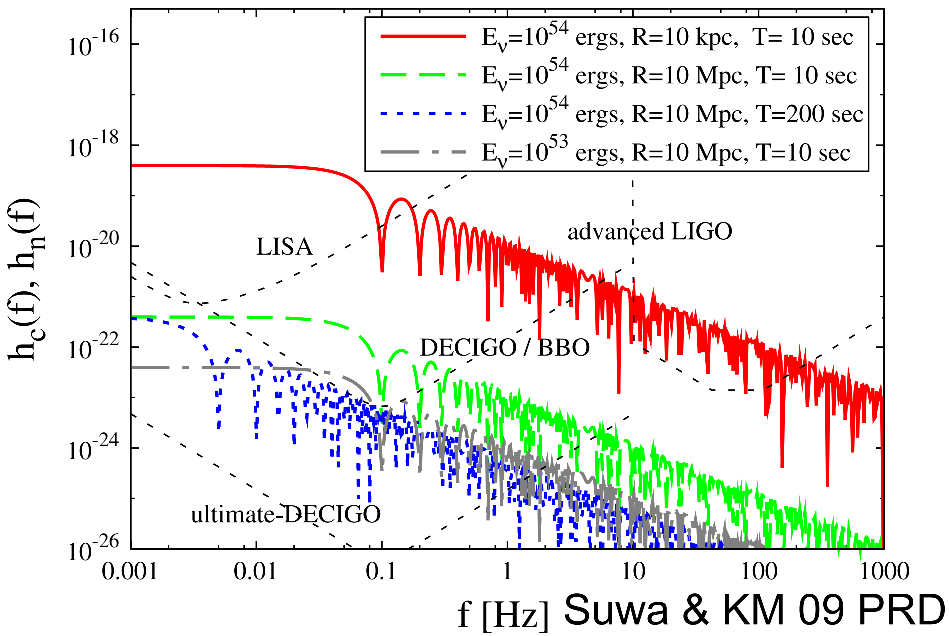
GWs from typical CCSNe: E_{GW}~10^{-9}-10^{-8} M_{sun} c^2 (Kotake-san)
Various stronger possibilities are suggested (but uncertain)

m=1 non-axisymmetric instability



Kiuchi, Shibata, Motero & Font 11 PRL

GW memory by ν from the disk

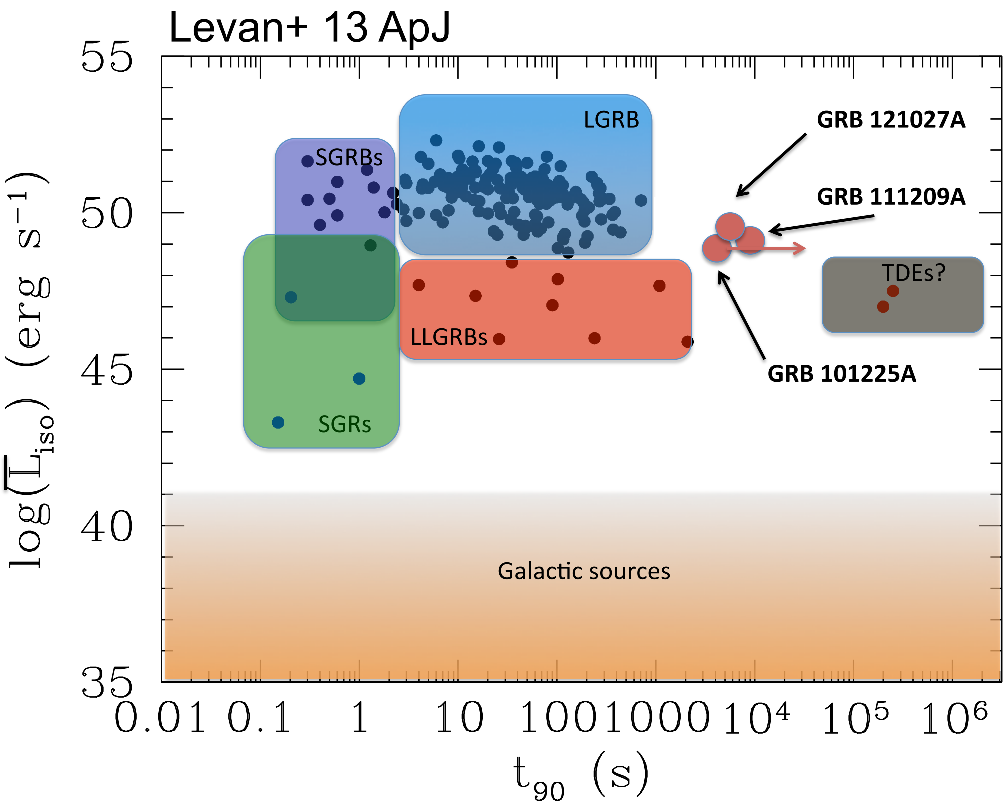


Suwa & KM 09 PRD

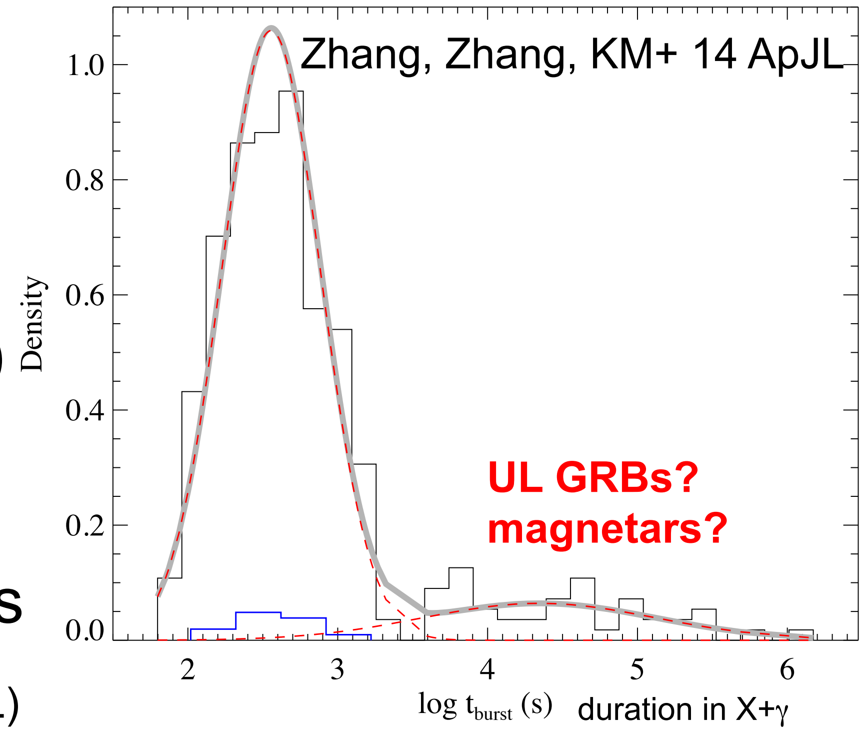
obs. rate ~1 Gpc^{-3} yr^{-1}, true rate ~100 Gpc^{-3} yr^{-1}

~0.3 yr^{-1} within 100 Mpc: rare but not the whole story

Diversity of GRBs

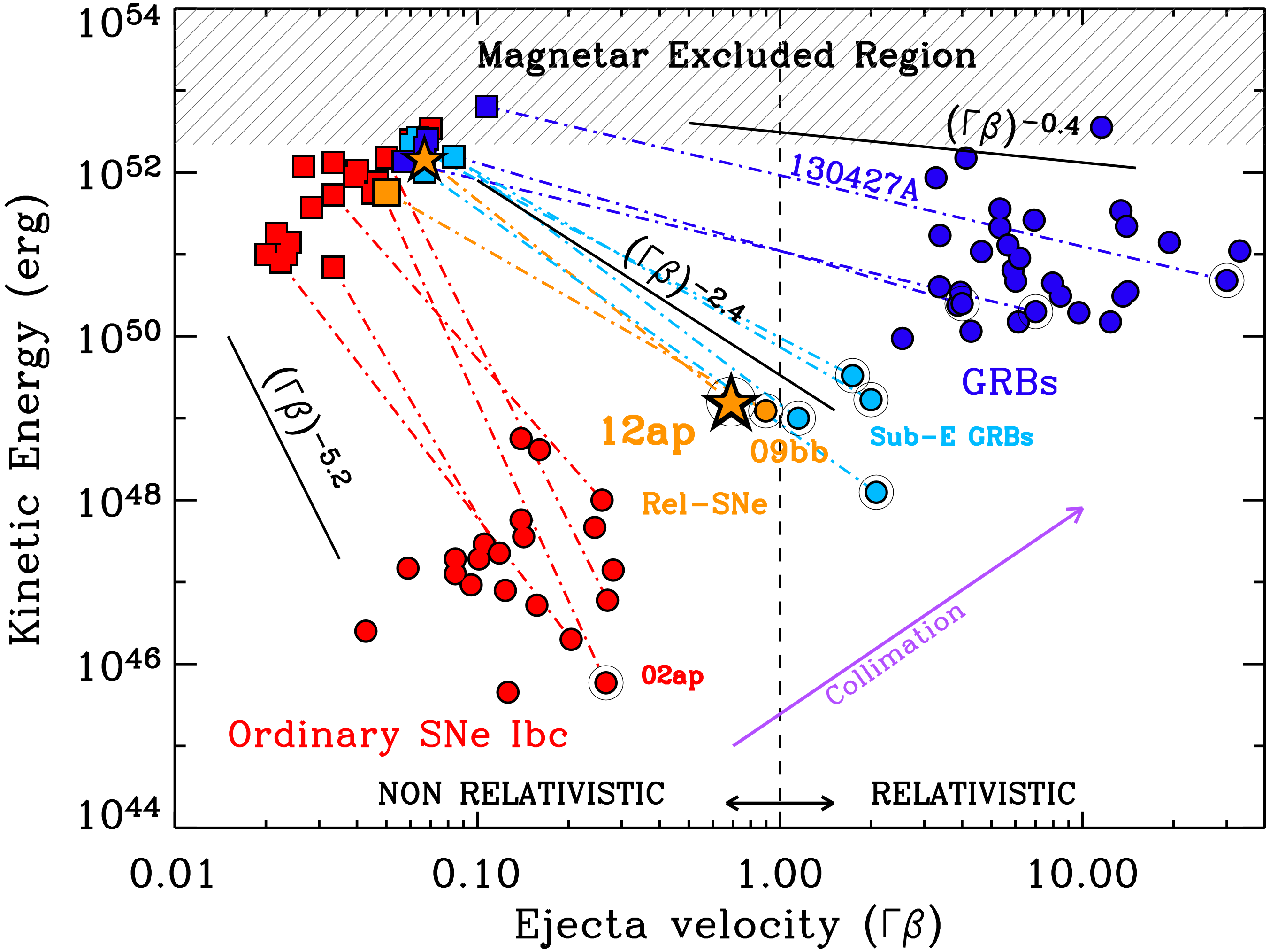


LL GRB rate ~ 1000 GRB rate (obs.)
UL GRB rate ~ GRB rate (possibly)



weaker jets and/or bigger progenitors
→ more chocked jets? (KM & Ioka 13 PRL)

GRB-SN Connection

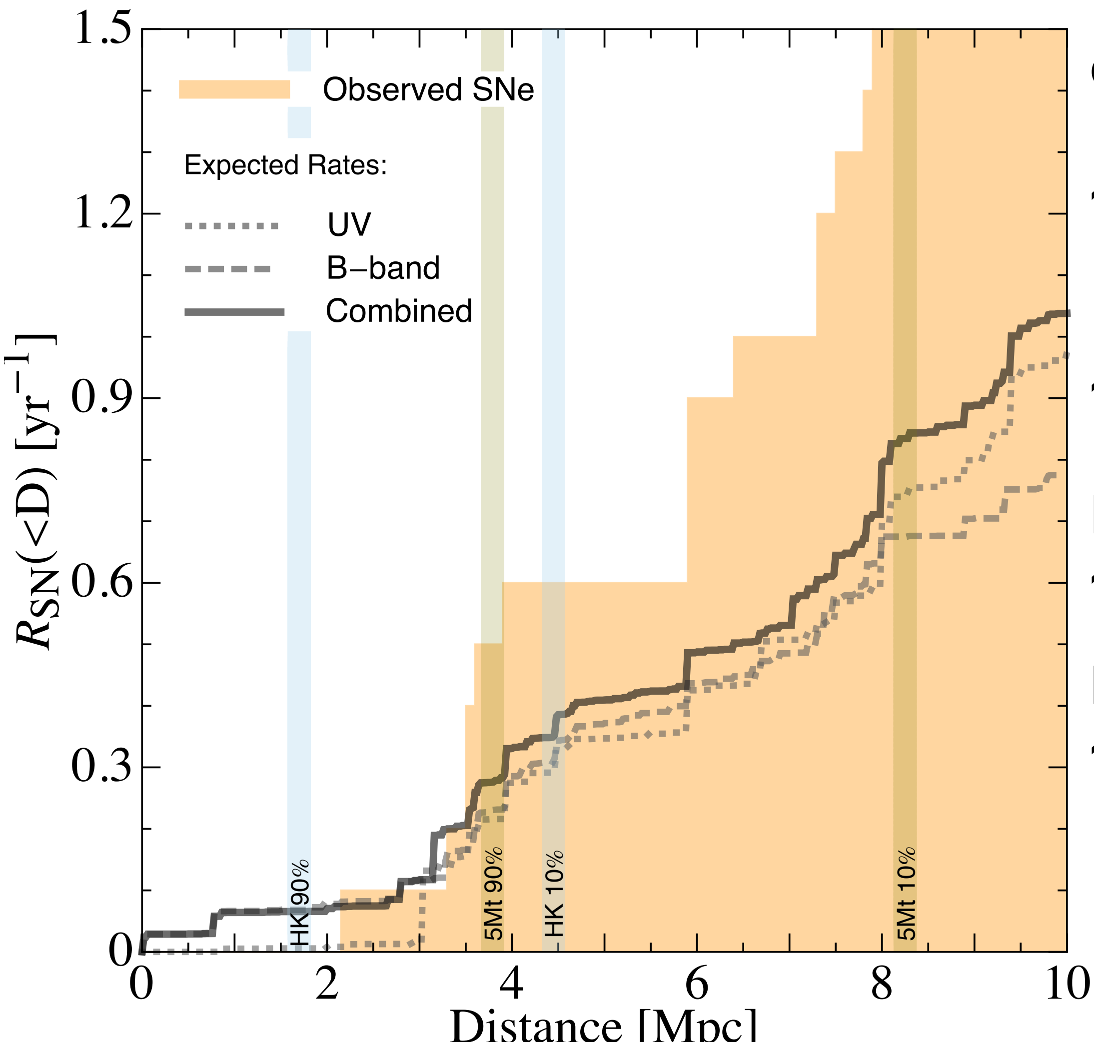


Margutti+ 14

LL GRBs, trans-rela. SNe: hints of engine-driven SNe?

Challenging But Not Bad

Kistler+ 13 ApJ



ex.

long GRB rate within 100 Mpc ~0.3 yr^{-1}

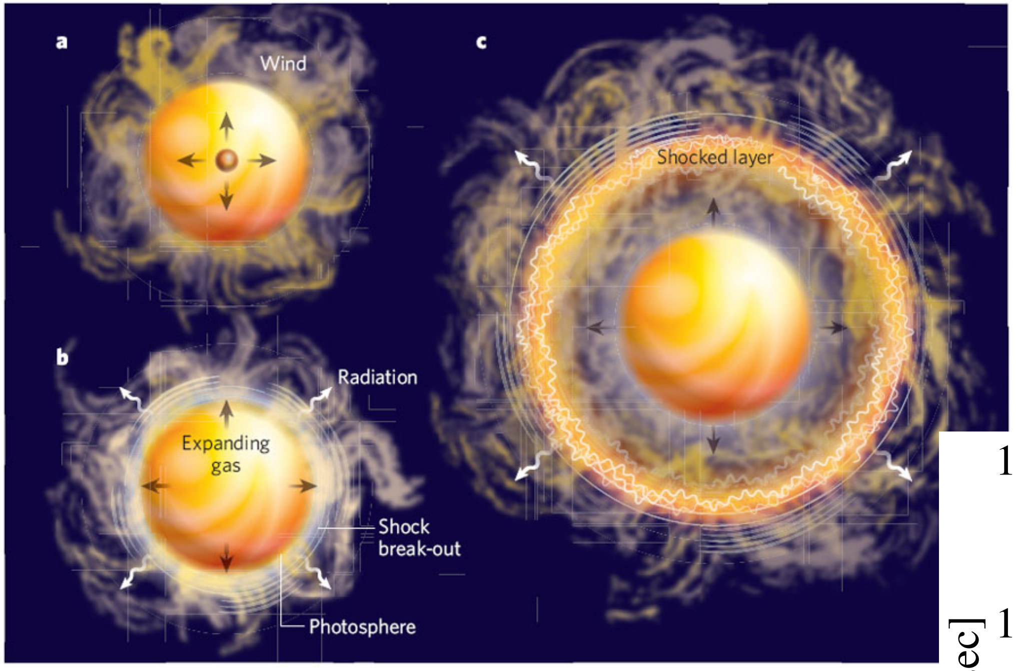
LL GRB rate within 100 Mpc ~1-3 yr^{-1}

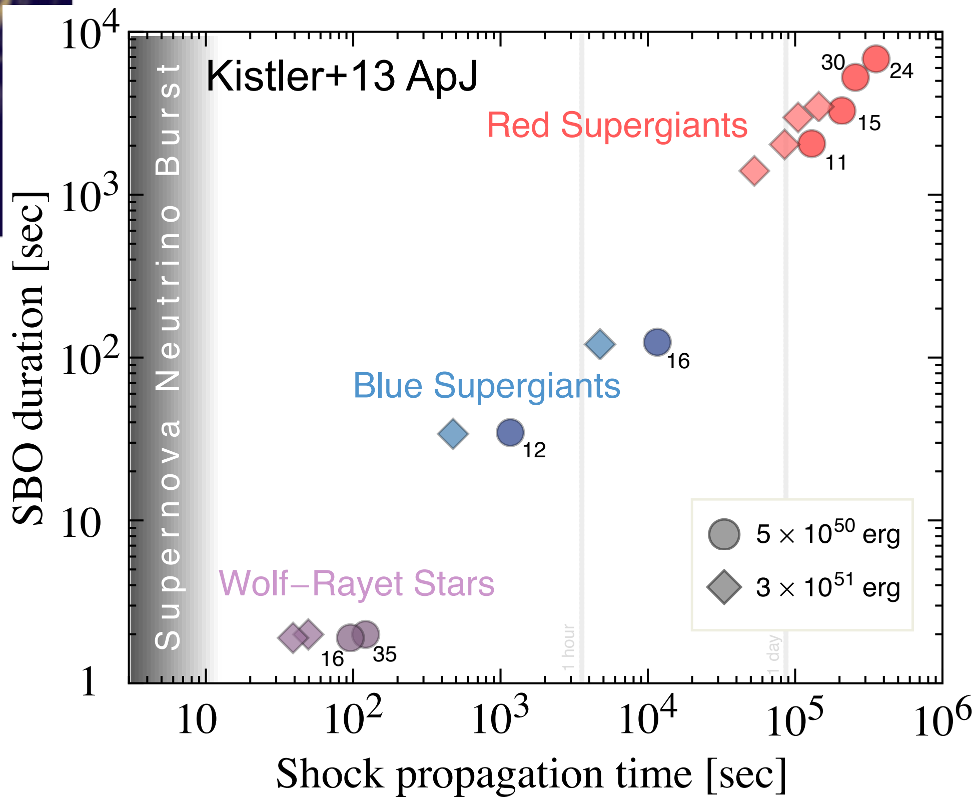
Hypernova rate within 100 Mpc ~10 yr^{-1}

Magnetar rate within 20 Mpc ~1 yr^{-1}

GW horizon can be larger than ν horizon

High-Energy Counterpart: Shock Breakout





UV/soft-X rays are released when $t_{diff} \sim t_{exp}$

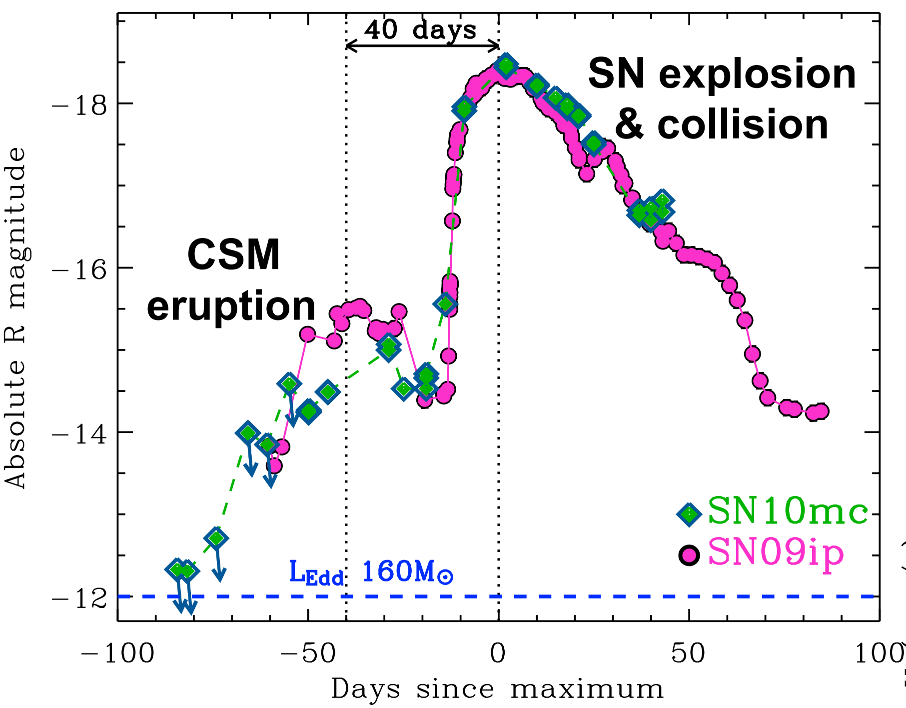
w. 10^{-12} erg cm^{-2} s^{-1}

up to ~100-200 Mpc

for BSGs/RSGs

~10% of CCSNe Have Dense Circumstellar Material

Margutti+ KM 14 ApJ

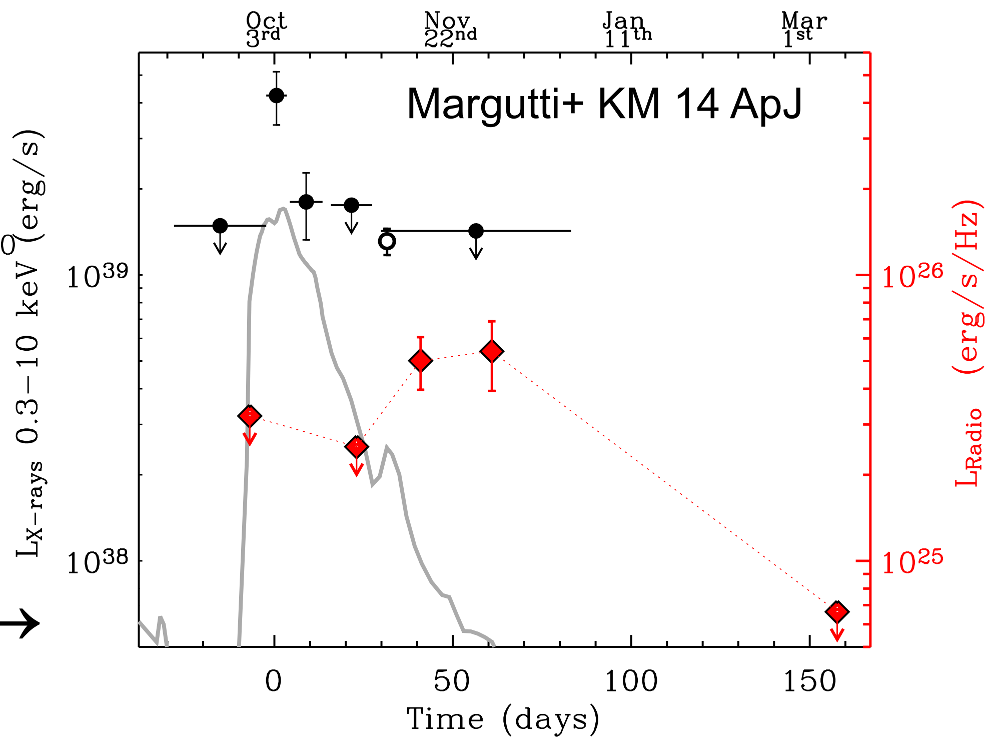


↑ **optical**

$$kT_p = \frac{2(\hat{\gamma}-1)}{(\hat{\gamma}+1)^2} m_p V_s^2$$

Comp. $kT_e \sim 40 \text{ keV } \tilde{\epsilon}_\gamma^{-2/5}$

eq. $kT_e \simeq 24 \text{ keV } (V_s/5000 \text{ km s}^{-1})^2$

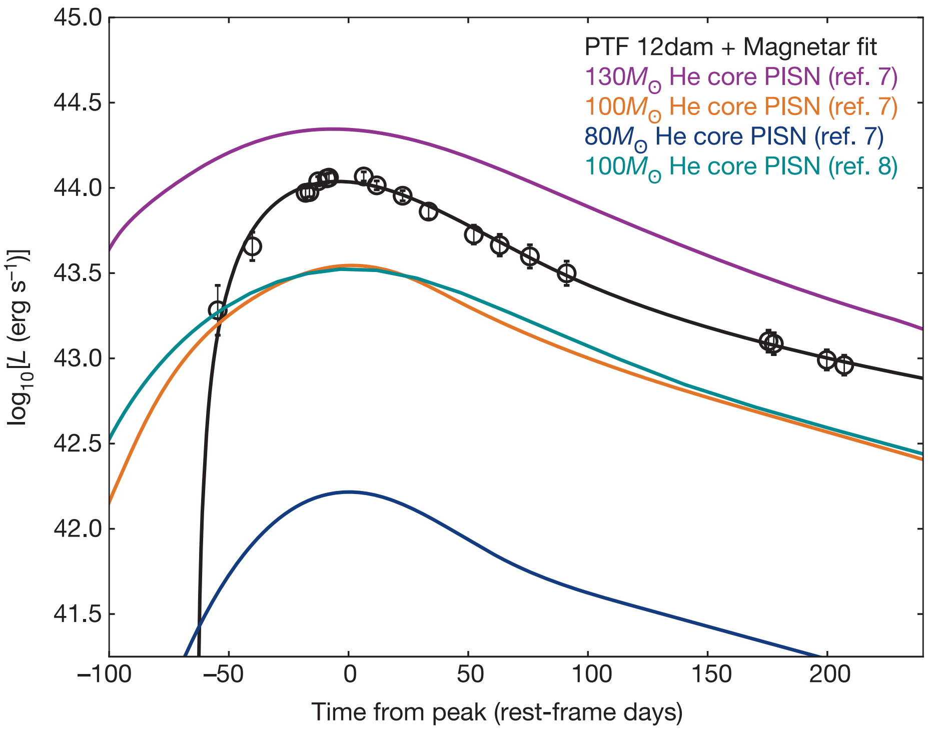


X & radio →

Interesting Case: Newborn Pulsar Scenario

- Possible origin of luminous SNe

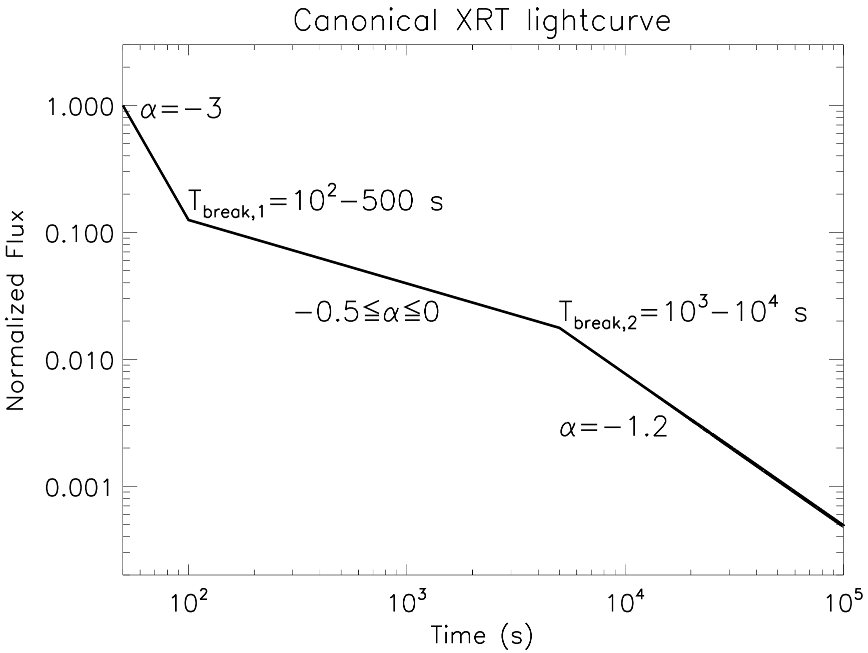
Nicholl+ 13 Nature



- Maybe origin of LL GRBs/GRBs

(Thompson+ 04 ApJ, Toma+ 07 ApJ)

- Possible origin of shallow decay



GW scenarios (uncertain)

ex1. mag. deform.: $\varepsilon_B=\Delta I/I\sim-10^{-3.5}(B_t/10^{16}\text{ G})^2 \rightarrow$ D<20 Mpc

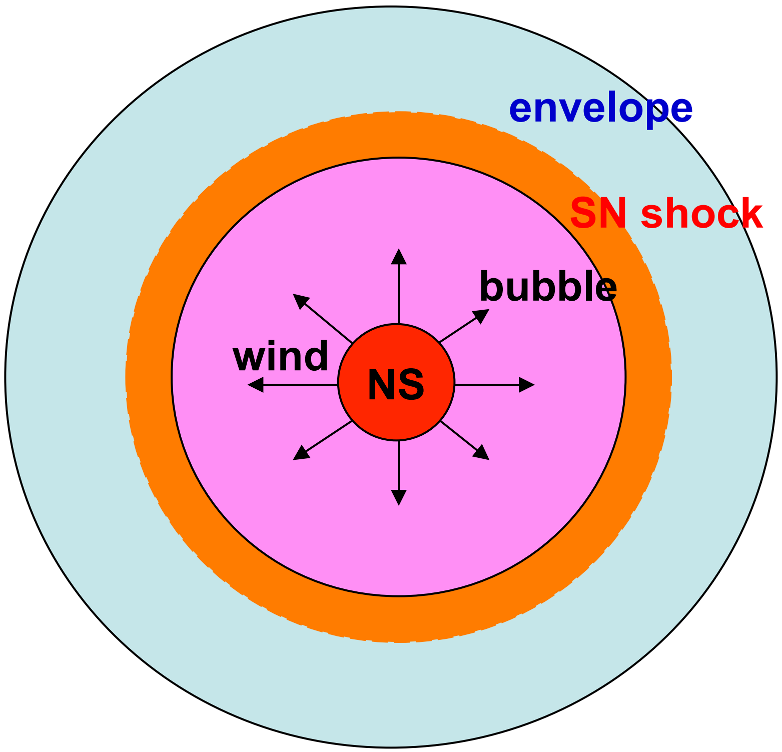
ex2. dyn./sec. instabilities → D<20-100 Mpc?

ex. Cutler 02, Stella+ 05, Corsi & Meszaros 09, Passamonti+ 13

Newborn Pulsar Scenario: Contd.

(Luminous) Supernovae

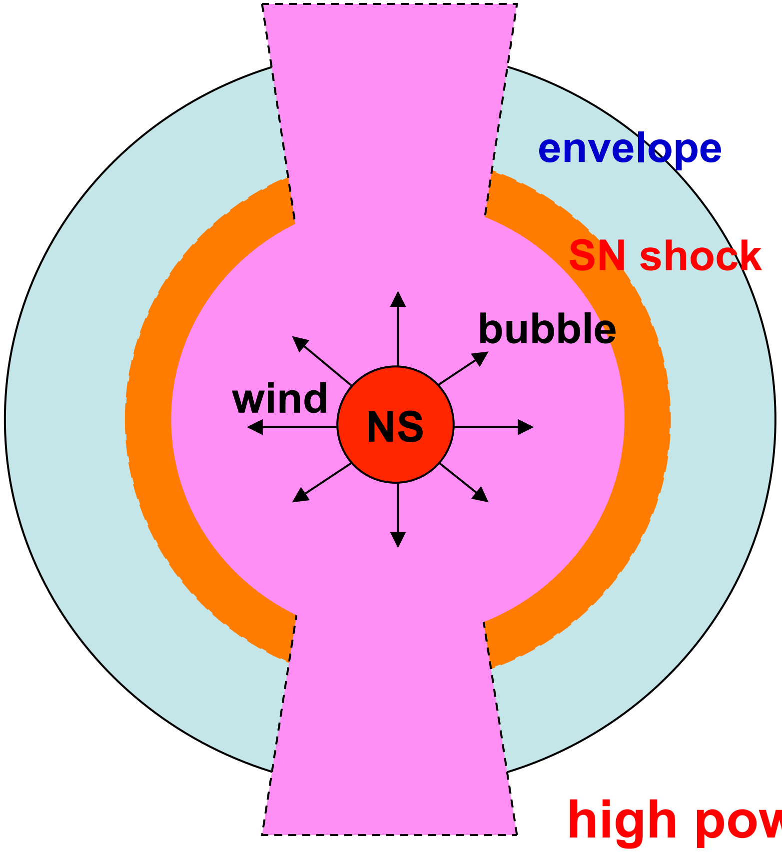
Near-spherical PNS wind



low power

GRBs/Jet-driven Supernovae

Collimated PNS wind



high power

diversity may be explained

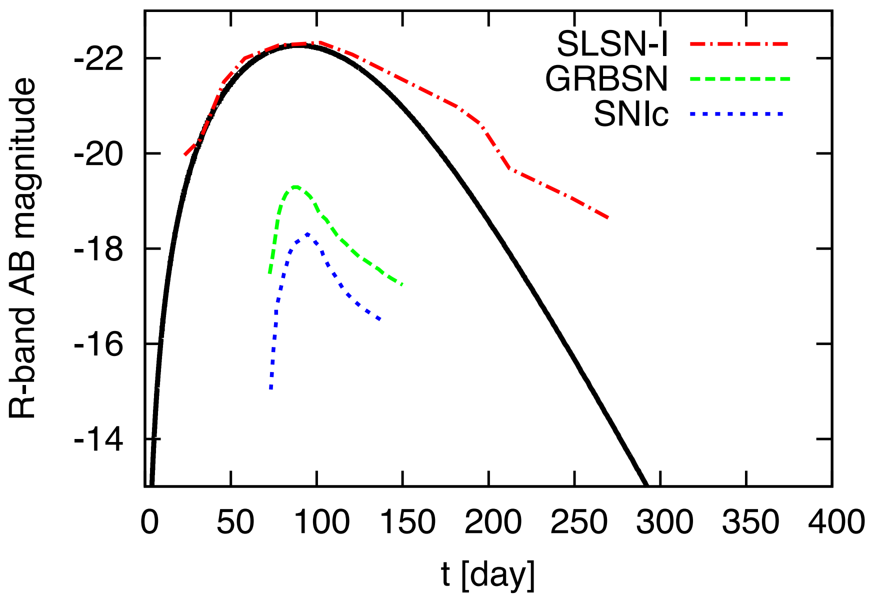
ex. Metzger+ 11 MNRAS

Application to Supernovae

$$\frac{dE}{dT} = -\frac{B_p^2 R^6 \Omega_{eff}^4}{6c^3} - \frac{32GI^2\epsilon^2\Omega^6}{5c^5} = L_{dip} + L_{GW} \quad \frac{1}{t}\frac{\partial}{\partial t}[E_{\rm int} t] = \eta_\gamma L_{\rm p}(t) - L_{\rm rad}(t)$$

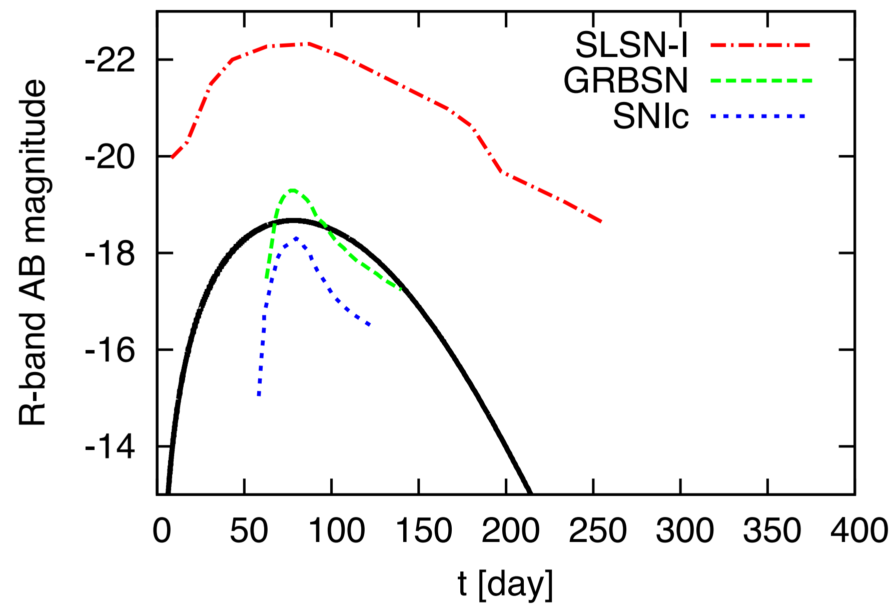
case A

$B_p = 8\times10^{13}$ G, $B_t = 2\times10^{15}$ G, $P_0 = 3$ ms, $M_{ej} = 10\ M_{sun}$



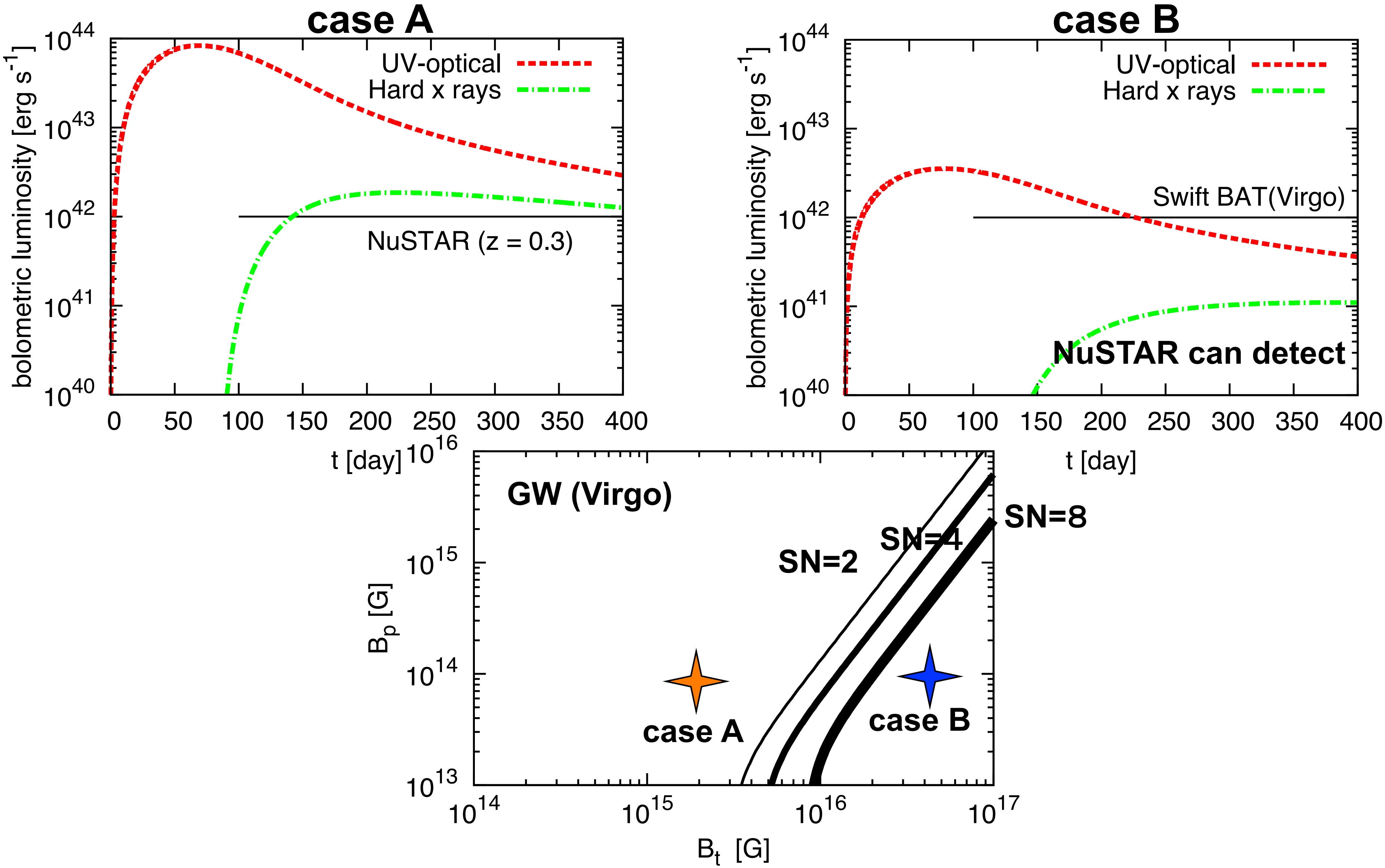
case B

$B_p = 1\times10^{14}$ G, $B_t = 4\times10^{16}$ G, $P_0 = 3$ ms, $M_{ej} = 10\ M_{sun}$



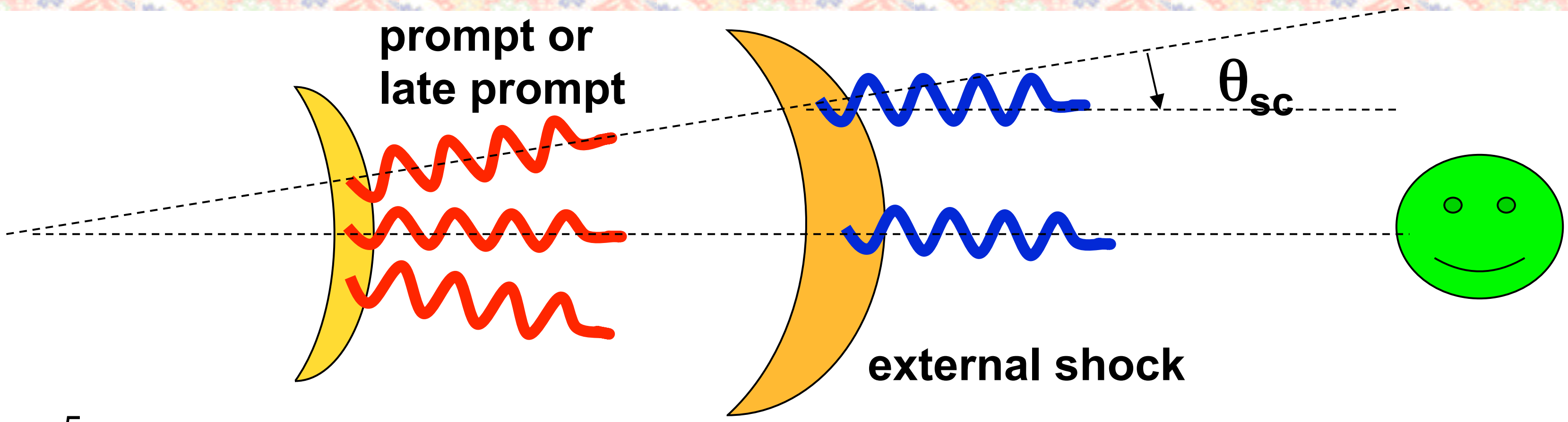
Kashiyama, KM+ in prep, KM, Kashiyama+ in prep.

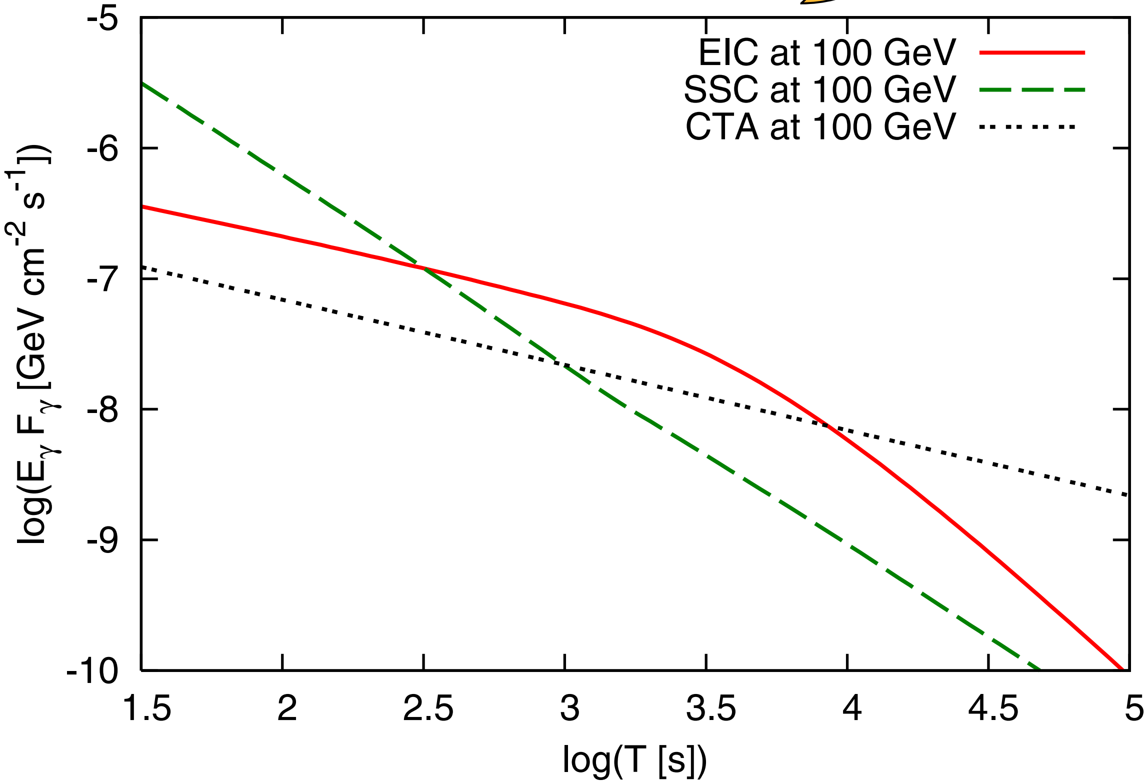
Contd.



case A
bolometric luminosity [erg s-1]
UV-optical
Hard x rays
NuSTAR (z = 0.3)
t [day]
case B
bolometric luminosity [erg s-1]
UV-optical
Hard x rays
Swift BAT(Virgo)
NuSTAR can detect
t [day]
GW (Virgo)
SN=2
SN=4
SN=8
case A
case B
Bp [G]
Bt [G]

Further Application: GRB Shallow-Decay





γ rays will support internal origins

KM, Toma, Yamazaki & Meszaros 11 ApJ

Implications

- GWs: detectable for P_0<3-4 ms, $B_p<10^{14}$ G, $B_t>10^{16}$ G for Virgo, SNe are dim so X/γ rays are relevant
- MeV, GeV, EeV νs & UHE γs might also be detected
- Successful GW & EM detections allow us to determine P_0, B_t, B_p $\rightarrow$ link between engines & emission
- Even only EM give clues to theoretical issues:
  σ problem - what happens in the early phase?
  roles of Rayleigh-Taylor instabilities etc.
- Origin of magnetic fields: dynamo vs fossil
  - Galactic magnetars are associated with non-HNRs.
  - SLSNe-Ic and GRBs are very rare
  GWs may help the dynamo scenario to be consistent

Summary

X/γ rays are powerful

- NS-NS, NS-BH: promising multimessenger sources
  - GW+EM $\rightarrow$ addressing short GRB origins
  - detailed X-ray follow-ups $\rightarrow$ remnant, precursor

- Long GRBs and related supernovae:
  potentially interesting GW sources
  and promising X/γ-ray counterparts
  - LL GRBs and peculiar SNe may be relevant
  - important not to miss nearby SNe (cf. ν)
  - shock breakout
  - example: newborn fast-rotating pulsars