Compact binary mergers and their electromagnetic counterparts

Albino Perego

Trento University & INFN, Milano-Bicocca

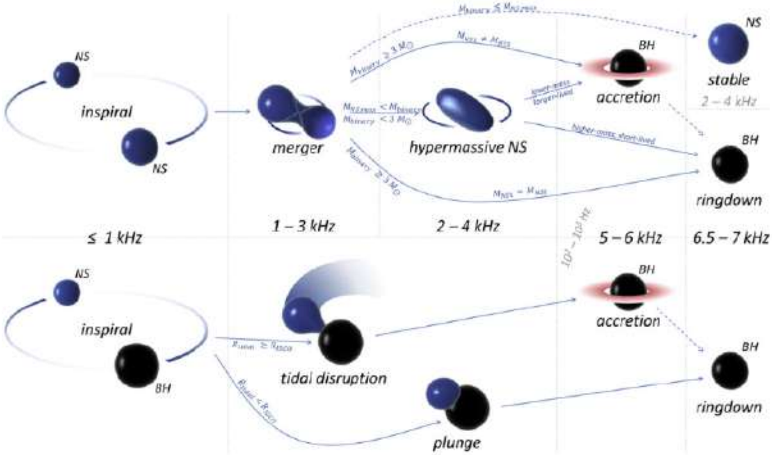
11-15 March 2019
Lecture at Pharos Doctoral School , Jena

Outline

- From compact binary merger to their EM counterparts
- (A bit of) Relevant Nuclear Astrophysics
    - Neutrinos
    - *r*-process nucleosynthesis
- Compact binary merger: the ejecta and its properties
- Kilonova: basic ideas and status of modeling
- GRB and relativistic jet
- Radio emission from expanding ejecta

From compact binary mergers to their EM counterparts

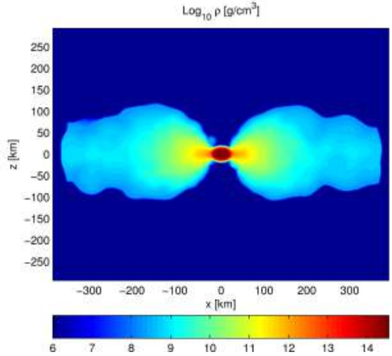
Compact binary (CB) mergers in a nutshell



Bartos+13, for reviews see: Rosswog IJMPD 2015, Shibata & Taniguchi LRR 2011 (BH-NS)

BNS merger remnants

Final stages of a compact binary merger: binary NS merger



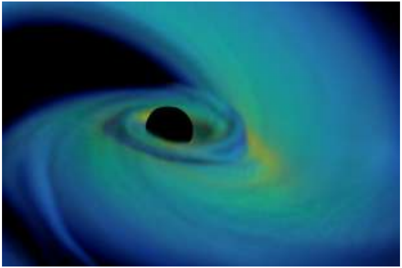
slice from 3D matter density

$\left(\mathrm{Y_e} = \mathrm{n_e}/\mathrm{n_B} \approx \mathrm{n_p}/\left(\mathrm{n_p} + \mathrm{n_n}\right)\right)$

- Massive NS ($\rightarrow$ BH)
  $M \sim 2.2 - 3.2 M_\odot$,
  $\rho \gtrsim 10^{13} \mathrm{g\,cm^{-3}}$
  $T \sim$ a few 10 MeV
- thick accretion disk
  $M \sim 10^{-2} - 0.2 M_\odot$
  $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
- highly magnetized system
  B in excess of 10^{14} Gauss
- intense ν emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$
  $E_\nu \gtrsim 10\,\mathrm{MeV}$

BH-NS merger remnants

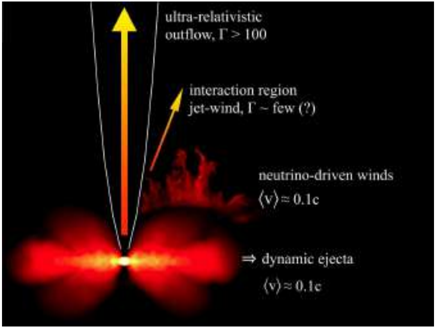
Final stages of a compact binary merger: BH-NS merger



Foucart+ 14,15 PRD

- (highly?) spinning BH
  $M \lesssim 10 M_\odot$,
  $\hat{a} \gtrsim 0.7$
- thick (warped?) accretion disk
  $M \sim 10^{-3} - 0.6 M_\odot$
  $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
  magnetized
- significant ν emission
  $L_{\nu,\mathrm{tot}} \lesssim 10^{53} \mathrm{erg\,s^{-1}}$
  $E_\nu \gtrsim 10\,\mathrm{MeV}$

Mass ejection in compact binary mergers

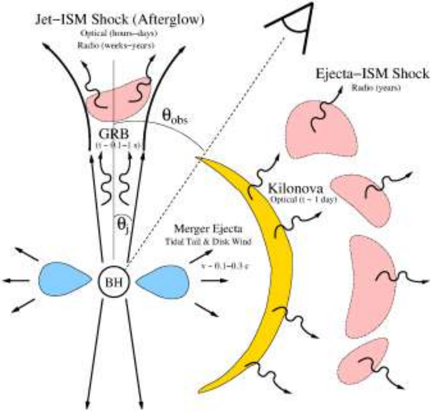


Rosswog RMPh 12

- most of matter gravitationally bound to central object
- tiny amount of matter (up to a few %) ejected into space (ejecta)
- possibly *n*-rich matter: synthesis of heavy elements via *r*-process mechanism

  e.g. Lattimer & Schramm 73 ApJL, Freiburghaus+ 99 ApJ and many more. See Thielemann+ 17 ARNPS for a recent review
- different ejecta types:
  - different ejection mechanisms
  - different ejecta properties

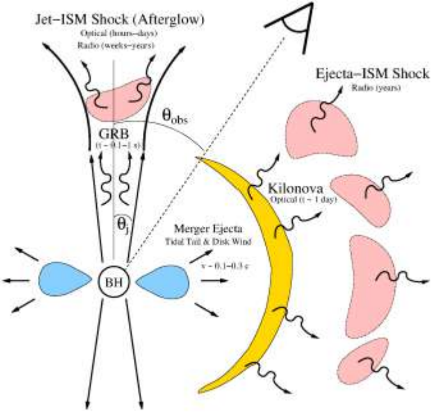
Electromagnetic counterparts: kilonova



Berger & Metzger ARAA 12

- radioactive decay of freshly sinthetized *r*-process elements in ejecta: release of nuclear energy
- thermalization of high energy decay products with ejecta
- diffusion of thermal photons during ejecta expansion
- quasi-thermal emission of photons at photosphere

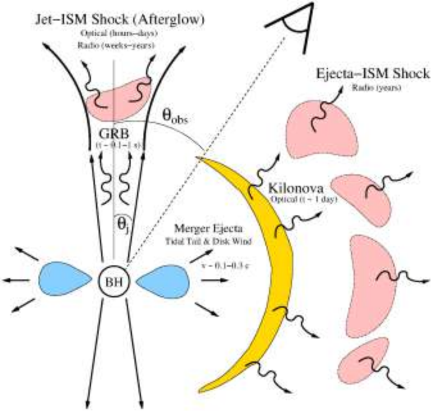
Electromagnetic counterparts: short-hard GRBs



Berger & Metzger ARAA 12

- production of a relativistic and collimated jet close to the merger remnant
- jet propagation, possibly inside expanding ejecta
- prompt non-thermal γ-ray emission: Gamma-ray burst (GRB)

Electromagnetic counterparts: synchrotron emission



Berger & Metzger ARAA 12

- jet-ISM interaction: GRB afterglow emission (non-thermal synchrotron)
- ejecta-ISM interaction: radio emission from merger remnant (non-thermal synchrotron)

Electromagnetic counterparts: a general comment

- all presented EM counterparts produced far from the central engine
- however, EM emission properties keep track of the strong field dynamics
- by observing EM counterparts we can learn something about strong field dynamics

(A bit of) Relevant Nuclear Astrophysics

Neutrino-matter interaction in hot and dense matter

- ν's are weakly interacting particles (NC & CC processes)
- production ($\rightarrow$, and possibly absorption, $\leftarrow$):

  $p + e^- \rightarrow n + \nu_e$ (EC)

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

  $e^- + e^+ \rightarrow \nu + \bar{\nu}$

  $N + N \rightarrow N + N + \nu + \bar{\nu}$
- scattering:

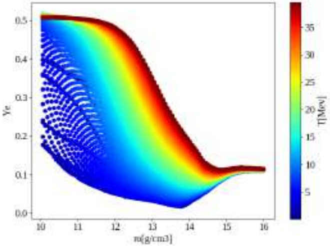
  $N + \nu \rightarrow N + \nu \qquad e^\pm + \nu \rightarrow e^\pm + \nu$

From cold NSs ($k_B T \lesssim 0.1$ MeV) …

- matter in weak equilibrium, neutrino reactions negligible
- $\rho > 10^{12}\mathrm{g/cm^3}$, very n-rich conditions

…to hot NS merger ($k_B T \lesssim 100$ MeV)

- kinetic $\rightarrow$ internal energy
- matter (de)compression and shocks
- activation of weak reactions for matter out of weak equilibrium



Equilibrium Y_e including ν's.

Courtesy of L. Branca, Milano-Bicocca university

Production rates in hot and dense matter

- plasma ($n, p, e^{\pm}, \gamma$) in thermal and NSE (NS matter EOS)

- ν production rates: boosted by high temperatures & densities

$$R_{\mathrm{e}^-} \propto n_p T^5 F_4(\mu_e/T) \qquad R_{\mathrm{e}^+} \propto n_n T^5 F_4(-\mu_e/T)$$

e.g.,

$$\begin{aligned} R_{\mathrm{e}-} &= \int \frac{\mathrm{d}^3 p_\nu}{(2\pi\hbar c)^3}\, j_{\nu_e}(E_\nu) \\ &\approx \left(\frac{n_n - n_p}{\exp\left(\frac{\mu_p - \mu_n + \Delta}{k_B T}\right) - 1} \right) \int_0^\infty \frac{4\pi\sigma_0 c}{(2\pi\hbar c)^3} \left(\frac{E+\Delta}{m_e}\right)^2 f_{e-}(E+\Delta)\, E^2 \mathrm{d}E \end{aligned}$$

$$\sigma_0 = \frac{4G_F^2 (m_e c^2)^2 (c_v^2 + 3c_a^2)}{\pi (\hbar c)^4} \approx 2.43 \times 10^{-44}\,\mathrm{cm}^2 \sim 2 \times 10^{-20} \sigma_{t,e}$$

$$F_k(\eta) = \int_0^\infty \frac{x^k}{1+\exp(x-\eta)}\,\mathrm{d}x$$

e.g. Bruenn ApJ 85; Rosswog & Liebendörfer MNRAS 03

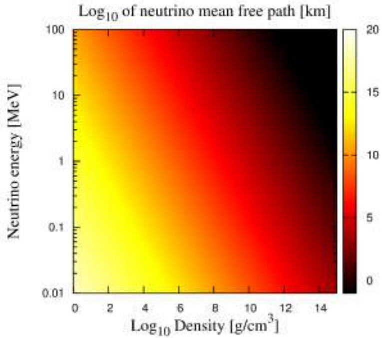
Neutrino opacity in merger remnants

ν absorption/scattering rates:

neutrino opacity ↔ neutrino mean free path, ℓ_ν

$$\ell_{\nu_e} = \frac{1}{n_{\rm B}\sigma_\nu} \approx 2.36 \times 10^3 {\rm cm} \left(\frac{\rho}{10^{14}\,{\rm g/cm^3}} \right)^{-1} \left(\frac{E_\nu}{10\,{\rm MeV}} \right)^{-2}$$

$$\rho \approx n_{\rm B} m_{\rm B} \quad \sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_{\rm e} c^2} \right)^2 \quad \sigma_0 = \frac{4 G_F^2 (m_e c^2)^2 (c_v^2 + 3 c_a^2)}{\pi (\hbar c)^4} \approx 2.43 \times 10^{-44}\,{\rm cm}^2 \sim 2 \times 10^{-20} \sigma_{t,e}$$



for a system of linear size R, ν absorption and scattering are dynamically relevant if

$$\lambda_\nu \lesssim R$$

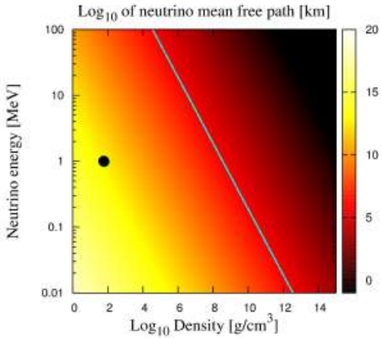
Neutrino opacity in merger remnants

ν absorption/scattering rates:

neutrino opacity $\leftrightarrow$ neutrino mean free path, ℓ_ν

$$\ell_{\nu_e} = \frac{1}{n_{\rm B}\sigma_\nu} \approx 2.36 \times 10^3 \mathrm{cm} \left(\frac{\rho}{10^{14}\,\mathrm{g/cm^3}} \right)^{-1} \left(\frac{E_\nu}{10\,\mathrm{MeV}} \right)^{-2}$$

$$\rho \approx n_{\rm B} m_{\rm B} \quad \sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_e c^2} \right)^2 \quad \sigma_0 = \frac{4G_F^2 (m_e c^2)^2 (c_v^2 + 3c_a^2)}{\pi (\hbar c)^4} \approx 2.43 \times 10^{-44}\,\mathrm{cm}^2 \sim 2 \times 10^{-20} \sigma_{t,e}$$



Sun:

- $R = R_\odot \approx 7 \times 10^5\,\mathrm{km}$
- $\rho_{\rm center} \approx 10^2\,\mathrm{g/cm^3}$
- $E_\nu \approx 1\,\mathrm{MeV}$

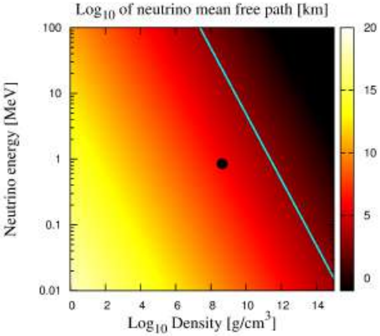
Neutrino opacity in merger remnants

ν absorption/scattering rates:

neutrino opacity ↔ neutrino mean free path, ℓ_ν

$$\ell_{\nu_e} = \frac{1}{n_\mathrm{B}\sigma_\nu} \approx 2.36 \times 10^3 \mathrm{cm} \left(\frac{\rho}{10^{14}\,\mathrm{g/cm^3}}\right)^{-1} \left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)^{-2}$$

$$\rho \approx n_\mathrm{B} m_\mathrm{B} \quad \sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_\mathrm{e}c^2}\right)^2 \quad \sigma_0 = \frac{4G_F^2 (m_e c^2)^2 (c_v^2 + 3c_a^2)}{\pi(\hbar c)^4} \approx 2.43 \times 10^{-44}\,\mathrm{cm}^2 \sim 2 \times 10^{-20} \sigma_{t,e}$$



Core massive star:

- $R = R_\odot \approx 10^3\,\mathrm{km}$
- $\rho_\mathrm{center} \approx 10^{10}\,\mathrm{g/cm^3}$
- $E_\nu \approx 0.5\,\mathrm{MeV}$

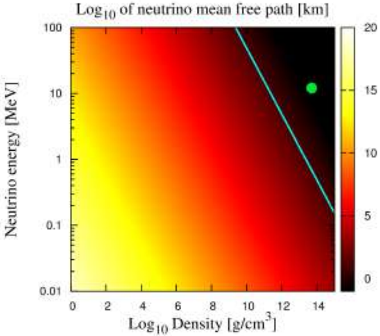
Neutrino opacity in merger remnants

ν absorption/scattering rates:

neutrino opacity ↔ neutrino mean free path, ℓ_ν

$$\ell_{\nu_e} = \frac{1}{n_B \sigma_\nu} \approx 2.36 \times 10^3 \mathrm{cm} \left(\frac{\rho}{10^{14}\,\mathrm{g/cm^3}} \right)^{-1} \left(\frac{E_\nu}{10\,\mathrm{MeV}} \right)^{-2}$$

$$\rho \approx n_B m_B \quad \sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_e c^2} \right)^2 \quad \sigma_0 = \frac{4 G_F^2 (m_e c^2)^2 (c_v^2 + 3 c_a^2)}{\pi (\hbar c)^4} \approx 2.43 \times 10^{-44}\,\mathrm{cm}^2 \sim 2 \times 10^{-20} \sigma_{t,e}$$



PNS/BNS merger remnant:

- $R \approx 10\,\mathrm{km}$
- $\rho_{\mathrm{center}} \approx 10^{14}\,\mathrm{g/cm^3}$
- $E_\nu \approx 10\,\mathrm{MeV}$

Role of ν's in CB mergers

- exchange energy and momentum with matter
- set n-to-p ratio $\rightarrow \mathrm{Y_e}$
  $p + e^- \leftrightarrow n + \nu_e$ (EC)
  $n + e^+ \leftrightarrow p + \bar{\nu}_e$ (PC)

ν luminosities

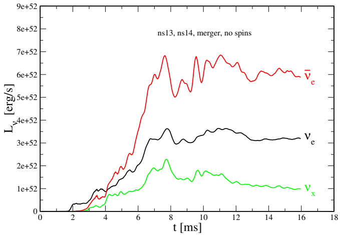
- n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$
- EOS dependence

e.g. Sekiguchi+15

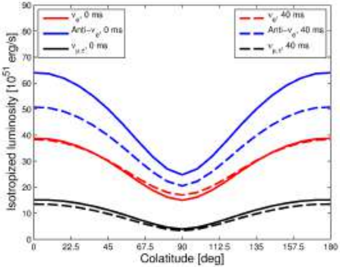
anisotropic ν emission

- due to presence of the disk
- $L_{\nu,\mathrm{pole}} \sim 3\, L_{\nu,\mathrm{equator}}$

e.g., Dessart+2009, Perego+14



Rosswog+13 (up), Perego+14 (down)



Relevant disk and neutrino scales

- disk lifetime:

$$t_{\rm disk} \sim \alpha^{-1} \left(\frac{H}{R}\right)^{-2} \Omega_K^{-1} \sim 0.31\,{\rm s} \left(\frac{\alpha}{0.05}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{-2} \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$$

α: viscosity coefficient
$R_{\rm disk}$: disk typical radius
H/R: disk aspect ratio
Ω_K: Keplerian angular velocity

$M_{\rm ns}$: MNS mass

Relevant disk and neutrino scales

- disk lifetime:

$$t_{\rm disk} \sim 0.31\,{\rm s} \left(\frac{\alpha}{0.05}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{-2} \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2} \left(\frac{M_{\rm ns}}{2.5\,M_{\odot}}\right)^{-1/2}$$

- disk L_{ν}:

$$L_{\nu,{\rm disk}} \sim \frac{\Delta E_{\rm grav}}{2\,t_{\rm disk}} \approx 8.35 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{M_{\rm ns}}{2.5\,M_{\odot}}\right)^{3/2} \left(\frac{M_{\rm disk}}{0.2\,M_{\odot}}\right) \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{-3/2} \times \left(\frac{\alpha}{0.05}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{2}$$

$\Delta E_{\rm grav}$: gravitational energy released during accretion

Relevant disk and neutrino scales

- disk lifetime:

$$t_{\rm disk} \sim 0.31\,{\rm s} \left(\frac{\alpha}{0.05}\right)^{-1} \left(\frac{H/R}{1/3}\right)^{-2} \left(\frac{R_{\rm disk}}{100\,{\rm km}}\right)^{3/2} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$$

- disk L:

$$L_{\nu,{\rm disk}} \sim 8.35 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{3/2} \left(\frac{M_{\rm disk}}{0.2\,M_\odot}\right) \ldots$$

- MNS L_ν:

$$L_{\nu,{\rm ns}} \sim \frac{\Delta E_{\rm ns}}{t_{\rm cool,ns}} \approx 1.86 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{\Delta E_{\rm ns}}{3.5 \times 10^{52}\,{\rm erg}}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2} \left(\frac{\rho_{\rm ns}}{10^{14}\,{\rm gcm^{-3}}}\right)^{-1} \left(\frac{k_{\rm B} T_{\rm ns}}{15\,{\rm MeV}}\right)^{-2}$$

$\Delta E_{\rm ns}$: thermal energy
$t_{\rm ns,cool} \sim 3\tau_{\nu,{\rm ns}}/\left(R_{\rm ns} c\right)$: diffusion time scale

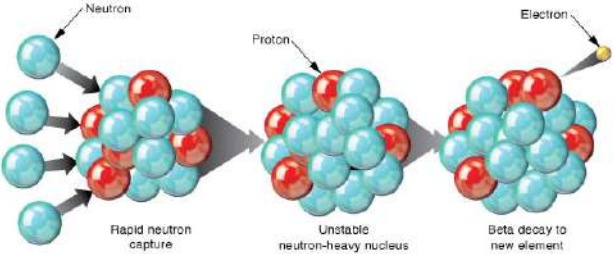
$\tau_{\nu,{\rm ns}}$: ν optical depth in MNS

r-process nucleosynthesis: basic ideas

- how do heavy elements (above Fe) form? n-capture processes

$$(A, Z) + n \leftrightarrow (A+1, Z) + \gamma$$

- hot, dense, n-rich matter: r-process nucleosynthesis
- high n_n: $t_{(n,\gamma)} \ll t_{\beta-\mathrm{decay}}$
- $(n,\gamma) \rightleftharpoons (\gamma,n)$ freeze-out $\rightarrow$ β-decays to stable nuclei

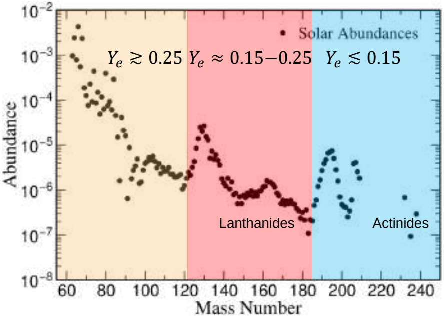


r-process nucleosynthesis: yields

at low entropy ($s \lesssim 40 k_b$/baryon), Y_e dominant parameter

Hoffman+ ApJ 98

- $Y_e > 0.5$: no r-process
- $0.25 \lesssim Y_e < 0.5$: weak r-process
- $Y_e \lesssim 0.25$: strong r-process



Courtesy of G. Martinez-Pinedo

Production of lanthanides dramatically changes photon opacity (κ_γ), because of electrons filling f-shell in ionized states

- no lanthanides: low opacity ($\kappa_\gamma \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$)
- presence of lanthanides: increased opacity ($\kappa_\gamma \gtrsim 10\,\mathrm{cm}^2/\mathrm{g}$)

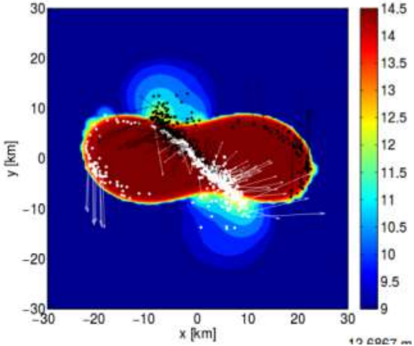
κ_γ: effective gray opacity

Ejecta from binary compact mergers

Dynamical ejecta from CB merger

- $t_{\mathrm{ej,dyn}} \sim$ few ms
- $v_{\mathrm{ej,dyn}} \sim 0.2 - 0.3\, c$
- BH-NS: $M_{\mathrm{ej,dyn}} \sim 0 - 10^{-1} M_{\odot}$, depending on q, NS EOS, M_{bh}, a_{BH}
- NS-NS: $M_{\mathrm{ej,dyn}} \sim 10^{-4} - 10^{-3} M_{\odot}$, depending on M_{NS}, q and NS EOS

e.g., Foucart+12,Korobkin+12,Hotokezaka+13,Bauswein+13,Wanajo+14,Sekiguchi+15,Radice+16,Kawaguchi+16,Bovard+17,...



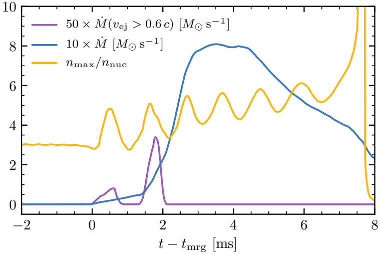
Dynamical ejected particles from NSNS merger, Bauswein+ ApJ 13

- tidal component
  - both in BH-NS and BNS mergers
  - first to develop
  - equatorial
  - cooler (lower entropy)
- shocked component
  - only for BNS mergers
  - due to (H)MNS bounces
  - equatorial & polar
  - higher entropy

Dynamical ejecta from CB merger

- $t_{\mathrm{ej,dyn}} \sim$ few ms
- $v_{\mathrm{ej,dyn}} \sim 0.2 - 0.3\,c$
- BH-NS: $M_{\mathrm{ej,dyn}} \sim 0 - 10^{-1} M_{\odot}$, depending on q, NS EOS, M_{bh}, a_{BH}
- NS-NS: $M_{\mathrm{ej,dyn}} \sim 10^{-4} - 10^{-3} M_{\odot}$, depending on M_{NS}, q and NS EOS

e.g., Foucart+12,Korobkin+12,Hotokezaka+13,Bauswein+13,Wanajo+14,Sekiguchi+15,Radice+16,Kawaguchi+16,Bovard+17,...

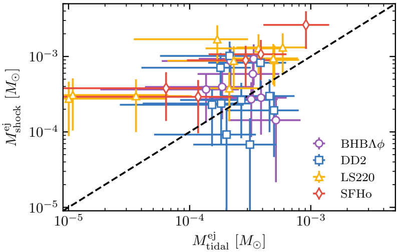


- tidal component
  - both in BH-NS and BNS mergers
  - first to develop
  - equatorial
  - cooler (lower entropy)
- shocked component
  - only for BNS mergers
  - due to (H)MNS bounces
  - equatorial & polar
  - higher entropy

Dynamical ejecta from CB merger

- $t_{\rm ej,dyn} \sim$ few ms
- $v_{\rm ej,dyn} \sim 0.2 - 0.3\, c$
- BH-NS: $M_{\rm ej,dyn} \sim 0 - 10^{-1} M_{\odot}$, depending on q, NS EOS, $M_{\rm bh}$, $a_{\rm BH}$
- NS-NS: $M_{\rm ej,dyn} \sim 10^{-4} - 10^{-3} M_{\odot}$, depending on $M_{\rm NS}$, q and NS EOS

e.g., Foucart+12,Korobkin+12,Hotokezaka+13,Bauswein+13,Wanajo+14,Sekiguchi+15,Radice+16,Kawaguchi+16,Bovard+17,...

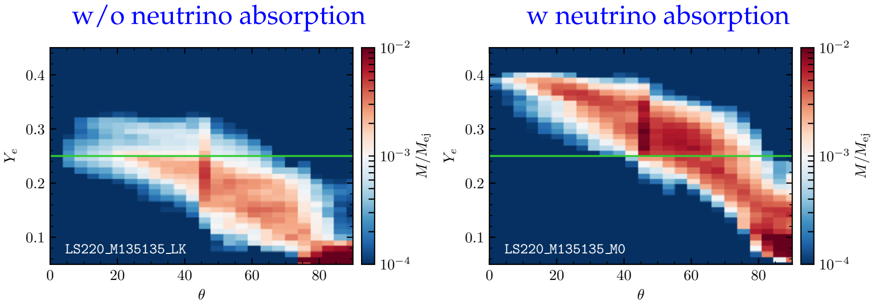


- tidal component
  - both in BH-NS and BNS mergers
  - first to develop
  - equatorial
  - cooler (lower entropy)
- shocked component
  - only for BNS mergers
  - due to (H)MNS bounces
  - equatorial & polar
  - higher entropy

← Radice+ ApJ 18 Tidal VS shocked dynamical ejecta, Radice+ ApJ 18 (35 BNS configurations, 49 different simulations in Numerical Relativity)

Impact of ν absorption on dynamical ejecta in BNS

- in the past, ν-matter interactions assumed to be negligile:
  - ejecta had always and everywhere $\mathrm{Y_e} < 0.1$
  - robust *r*-process
- however, ν-matter interactions increase $\mathrm{Y_e}$ at polar latitudes
  - most relevant reaction: $n + \nu_e \rightarrow p + e^-$
  - possible angular dependence in *r*-process nucleosynthesis
  - mass angular distribution $\propto \sin^2\theta$


w/o neutrino absorption

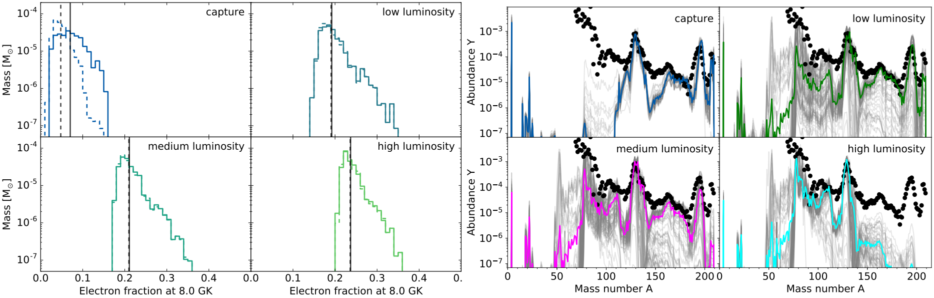
w neutrino absorption

2D histograms of $\mathrm{Y_e}$ of the dynamical ejecta, Perego+ ApJL 17; Radice+ *et al* ApJ 2018

see also Wanajo+ ApJL 2014, Sekiguchi+ PRD 2015, Foucart+ PRD 2016

Impact of ν absorption on dynamical ejecta in BNS

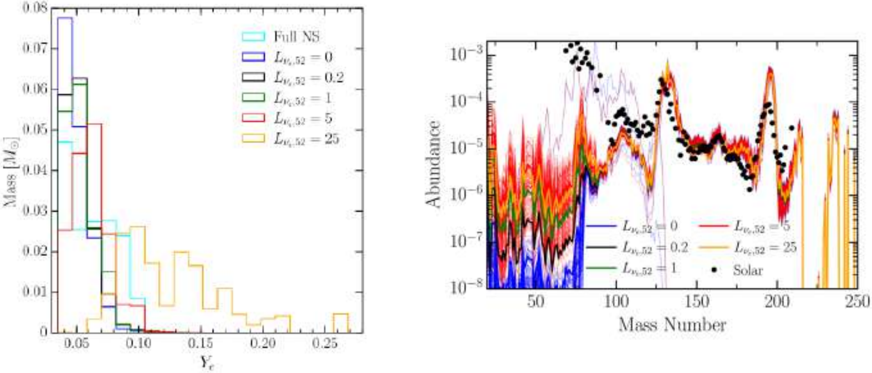
- in the past, ν-matter interactions assumed to be negligile:
  - ejecta had always and everywhere $Y_e < 0.1$
  - robust *r*-process
- however, ν-matter interactions increase Y_e at polar latitudes
  - most relevant reaction: $n + \nu_e \rightarrow p + e^-$
  - possible angular dependence in *r*-process nucleosynthesis
  - mass angular distribution $\propto \sin^2 \theta$



Y_e histograms and nucleosynthesis for dynamical ejecta for different neutrino luminosities, Martin+ CQG 2018

Impact of ν absorption on dynamical ejecta in BHNS

- small effect on Y_e
- negligible effect on nucleosynthesis
- lower luminosities and fast equatorial expansion



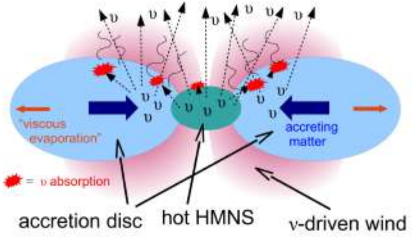
Y_e histograms and nucleosynthesis for dynamical ejecta for different neutrino luminosities, Roberts+ MNRAS 2016

Baryonic winds from CB merger

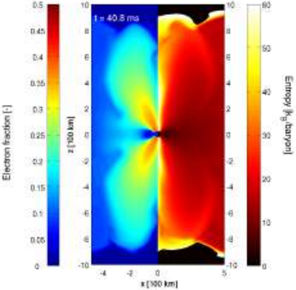
- due to neutrino absorption and/or magnetic pressure inside the remnant and the disk
- remnant expansion → nuclear recombination in the disk

$$(n,p) \rightarrow (\alpha,n) \rightarrow ((A,Z),n) \Rightarrow \dot{e} \approx 8\mathrm{MeV/baryon}$$

- $t_{\mathrm{ej,wind}}$ $\sim$few 10's ms and $v_{\mathrm{ej,wind}} \lesssim 0.1\,c$
- $M_{\mathrm{ej,wind}}$ up to $\sim 5\%$ of M_{disk} (BNS) or $\lesssim 1\%$ of M_{disk} (BH-NS)



Perego+ MNRAS 2014; Martin,Perego+ ApJ 2015, Perego+ JPhC 17

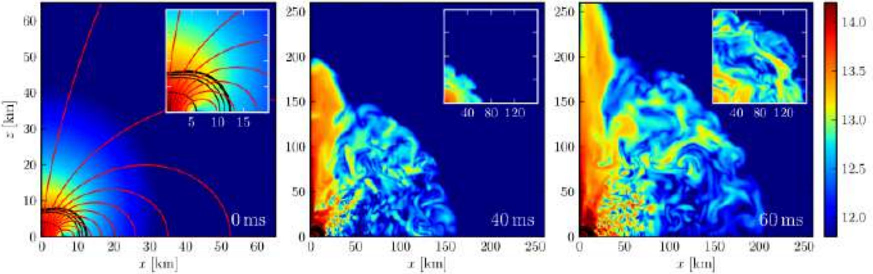


Baryonic winds from CB merger

- due to neutrino absorption and/or magnetic pressure inside the remnant and the disk
- remnant expansion → nuclear recombination in the disk

$$(n,p) \to (\alpha,n) \to ((A,Z),n) \Rightarrow \dot{e} \approx 8\mathrm{MeV/baryon}$$

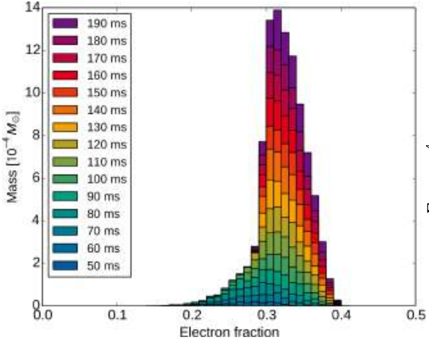
- $t_{\mathrm{ej,wind}} \sim$few 10's ms and $v_{\mathrm{ej,wind}} \lesssim 0.1\,c$
- $M_{\mathrm{ej,wind}}$ up to $\sim 5\%$ of M_{disk} (BNS) or $\lesssim 1\%$ of M_{disk} (BH-NS)

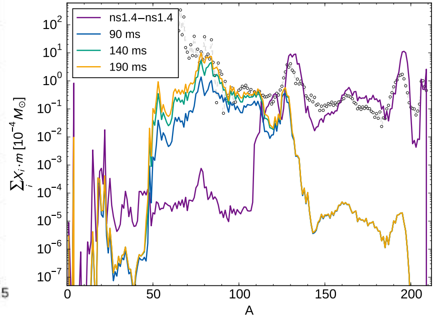


Siegel & Ciolfi ApJ 2014

Ejecta and nucleosynthesis from ν-driven winds

- wind intensity: strongly dependent on (H)MNS presence
- non-equatorial emission: $\theta < 60^o$
- larger Y_e in the polar regions
- nucleosynthesis: 1st *r*-process peak:
  - complementary to low-Y_e nucleosynthesis
  - low γ opacity, $\kappa_\gamma \lesssim 1\mathrm{cm}^2\mathrm{g}^{-1}$

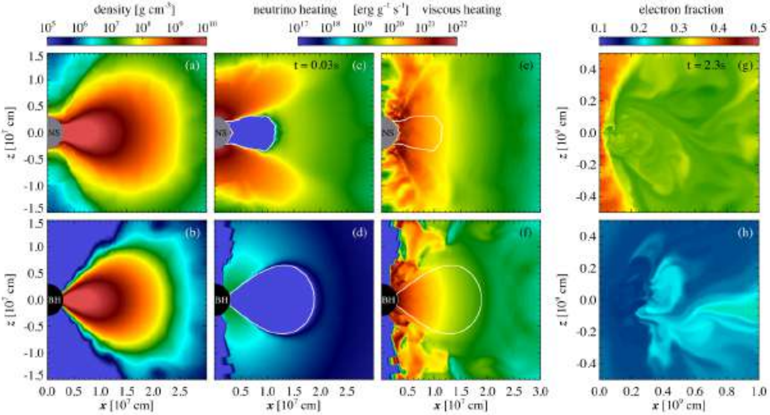




Martin+ ApJ 2015

Viscosity-driven ejecta from CB merger

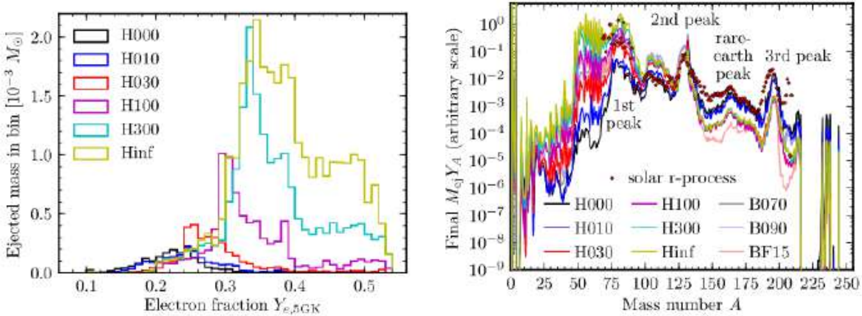
- due to viscosity and nuclear recombination in the disk
- $t_{\mathrm{ej,sec}} \sim$ few 100's ms and $v_{\mathrm{ej,sec}} \lesssim 0.1c$
- $M_{\mathrm{ej,sec}} \sim (0.1 - 0.4)\, M_{\mathrm{disk}}$



Figures from Metzger & Fernandez MNRAS 14, Wu+ MNRAS 16, see e.g. Just+ MNRAS 15, Siegel& Metzger PRD 17

Neutrino effect on viscosity-driven ejecta

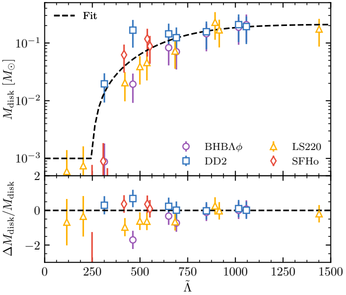
- ejecta: broad distribution of *n*-rich matter ($0.1 \lesssim \mathrm{Y_e} \lesssim 0.4$)
- all solid angle ejection, intermediate opacity $\kappa_\gamma \approx 1 - 10\,\mathrm{cm^2 g^{-1}}$
- key parameter: HMNS lifetime; long lived HMNS:
  - significantly larger ejecta
  - ejecta with larger $\mathrm{Y_e}$



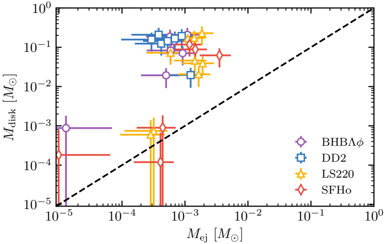
$\mathrm{Y_e}$ histograms (and nucleosynthesis) of viscous ejecta depending on HMNS lifetime. Lippuner+ MNRAS 2016

Disk masses from BNS mergers

winds & viscous ejecta: fraction of $M_{\rm disk}$



- $10^{-3} M_\odot \lesssim M_{\rm disk}[M_\odot] \lesssim 0.2$
- clear correlation with $\tilde{\Lambda}$
- relation with BH collapse time: presence of long-lived MNS VS BH formation
- BH formation from HMNS reduces mass (50 %) mass



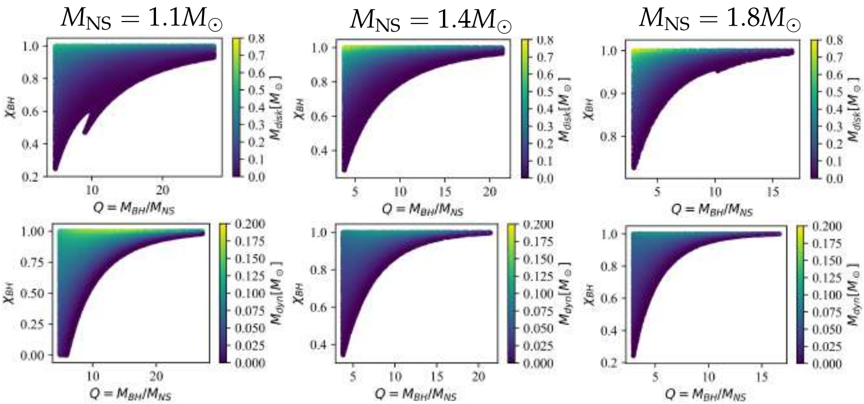
- viscous (as 20% of $M_{\rm disk}$) VS dynamical ejecta
- viscous ejecta dominant, unless prompt BH

Radice+ ApJ 18 (35 BNS configurations, 49 different simulations in Numerical Relativity)

Disk and ejecta from BH-NS mergers

Mass outside the BH horizon: only if $R_{\rm tidal} \gtrsim R_{\rm isco}$

$$\begin{aligned} R_{\rm tidal} &\sim R_{\rm NS}\left(2\frac{M_{\rm BH}}{M_{\rm NS}}\right)^{1/3} \\ R_{\rm isco} &= \frac{GM_{\rm BH}}{c^2} f(\xi_{\rm BH}) \qquad f(\chi_{\rm BH}=1)=1;\ f(\chi_{\rm BH}=0)=6;\ f(\chi_{\rm BH}=-1)=9 \end{aligned}$$

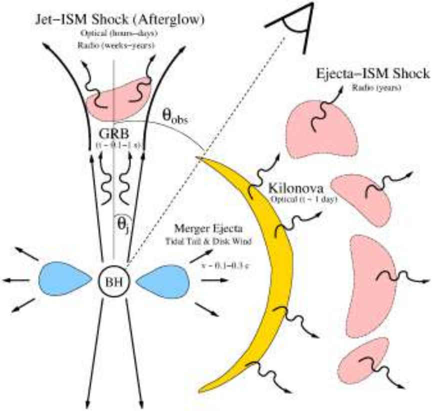


Mass in the disk and in dynamical ejecta after a BH-NS merger. NS EOS: SFHo. Fitting formulas from Foucart+ Arxiv 2018 & Kawaguchi+ PRD 2016.

Figures courtesy of Claudio Barbieri (PhD student Uni MiB).

Kilonova

Electromagnetic counterparts: kilonova



Berger & Metzger ARAA 12

- radioactive decay of freshly sinthetized *r*-process elements in ejecta: release of nuclear energy
- thermalization of high energy decay products with ejecta
- diffusion of thermal photons during ejecta expansion
- quasi-thermal emission of photons at photosphere

Nuclear heating rate

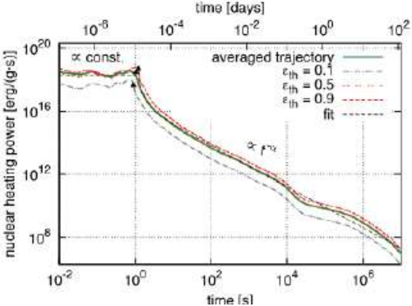
Radioactive decays of *r*-process elements release nuclear energy

$$\dot{e}_{r-\text{process}} = \sum_{i \in \text{reactions}} Q_i \, \lambda_i \qquad Q = M_{\text{initial}} - M_{\text{final}}, \ \lambda : \text{decay rate}$$

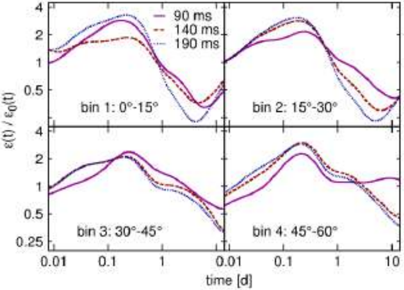
- nuclear heat computed by detailed nuclear network

  mainly $\beta - \text{decay} \Rightarrow \dot{e}_{r-\text{process}} = \dot{e}_0 t^{-\alpha} \qquad \alpha \approx 1.3, \, \dot{e}_0 \gtrsim 10^{16} \text{erg/g/s}$

- $Y_e \gtrsim 0.25$: weak *r*-process: shorter β decays lifetimes
- weak(strong) dependence on trajectory(mass model)



Korobkin+ 12; see also Metzger+ 10



Martin+ 15

Nuclear heating rate

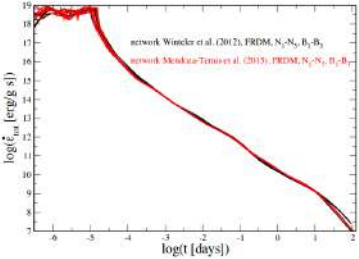
Radioactive decays of *r*-process elements release nuclear energy

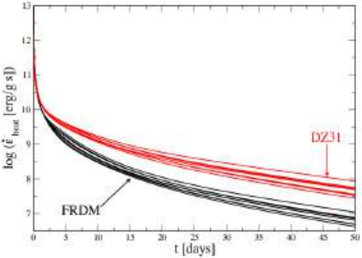
$$\dot{e}_{r-\mathrm{process}} = \sum_{i \in \mathrm{reactions}} Q_i \, \lambda_i \qquad Q = M_{\mathrm{initial}} - M_{\mathrm{final}}, \; \lambda : \text{decay rate}$$

- nuclear heat computed by detailed nuclear network

  mainly $\beta -$ decay $\Rightarrow \dot{e}_{r-\mathrm{process}} = \dot{e}_0 t^{-\alpha} \qquad \alpha \approx 1.3, \; \dot{e}_0 \gtrsim 10^{16}$erg/g/s

- $\mathrm{Y_e} \gtrsim 0.25$: weak *r*-process: shorter β decays lifetimes
- weak(strong) dependence on trajectory(mass model)



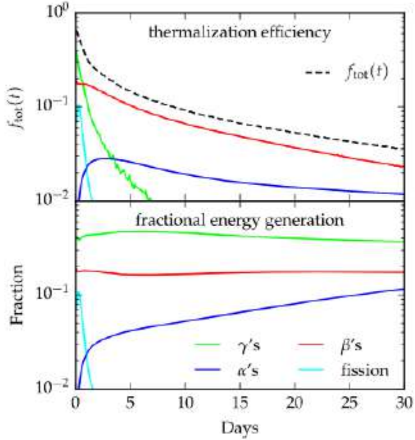


Rosswog+ JphG 2017

Thermalization efficiency

Not all the nuclear energy released by radioactive decay thermalize with ejecta:

$$\dot{e}_{\rm heat} = \dot{e}_{\rm r-process} f_{\rm th} \qquad 0 \leq f_{\rm th} \leq 1$$



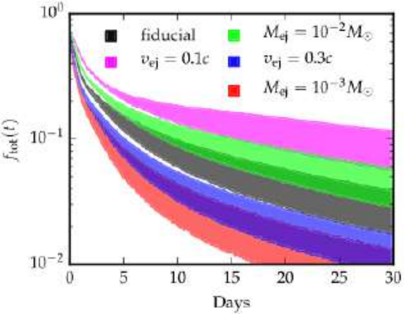
- $(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e + \gamma$
- $(A,Z) \rightarrow (A-4,Z-2) + \alpha + \gamma$
- $(A,Z) \rightarrow (A',Z') + (A'',Z'') + n's + p's + \gamma's$

Barnes+ ApJ 2016

Thermalization efficiency

Not all the nuclear energy released by radioactive decay thermalize with ejecta:

$$\dot{e}_{\rm heat} = \dot{e}_{\rm r-process} f_{\rm th} \qquad 0 \leq f_{\rm th} \leq 1$$



Barnes+ ApJ 2016

- thermalization efficiency depends on:
  - matter density
  - matter temperature
  - decay modes
  - decay product spectra
  - …

$$\Downarrow$$

both nuclear and astrophysical uncertainties

Fitting formulas derived from numerical results:

(fiducial: $m_{\rm ej} = 10^{-3} M_\odot$, $Y_e = 0.04$, $v = 0.2c$)

$$f_{\rm th}(t; m_{\rm ej}, v_{\rm ej})$$

A spherical model kilonova model

- $m_{\rm ej}$: amount of ejecta passing through a surface @ $R \gg R_{\rm NS}$
- radial, homologous expansion: we label each mass element by its velocity

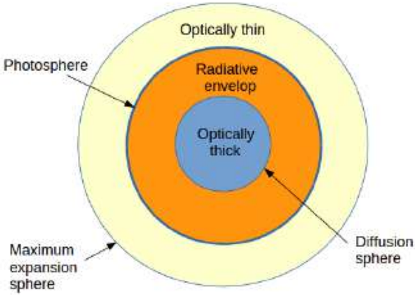
$$m_{\rm ej} = \int_0^{v_{\rm max}} \left(\int_{\Omega} \frac{1}{4\pi} \xi(v,\theta,\phi)\, {\rm d}\Omega \right) {\rm d}v$$

- spherical symmetry: $\xi(v,\theta,\phi) \Rightarrow \xi(v)$
- homologous expansion:

$$\begin{aligned}
\xi(v) &= \xi_0 \left(1 - \left(\frac{v}{v_{\rm max}} \right)^2 \right)^3 \\
v_{\rm rms} &= \left(\frac{1}{m_{\rm ej}} \int_0^{v_{\rm max}} v^2 \xi(v) {\rm d}v \right)^{1/2} = \frac{v_{\rm max}}{3} \\
m_{>v}(\tilde{v}) &= \int_{\tilde{v}}^{v_{\rm max}} \xi(v) {\rm d}v
\end{aligned}$$

e.g., Grossman+ MNRAS 2014; see Metzger LRR 2017, Fernandez & Metzger ARAA 2016 for good reviews

Photon diffusion model



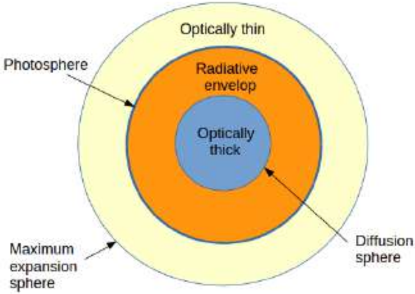
- let's suppose to consider a time $t = \tilde{t}$ after the merger
- the ejecta has maximally expanded up to $R_{\rm max} = v_{\rm max}\tilde{t}$
- diffusion radius $R_{\rm diff}(\tilde{t})$ (at which matter is moving at $\tilde{v}(\tilde{t})$):

$$t_{\rm diff} \approx t_{\rm dyn}$$

clearly

  - $R_{\rm diff}(\tilde{t}) = \tilde{v}(\tilde{t})\,\tilde{t}$
  - thermalizing photons outside this radius can be emitted at the photosphere carrying information about the present state of the system

Photon diffusion model



Diffusion radius:

$$t_{\rm diff} \approx t_{\rm dyn} \Rightarrow \tilde{v} = v_{\rm eff}$$

where

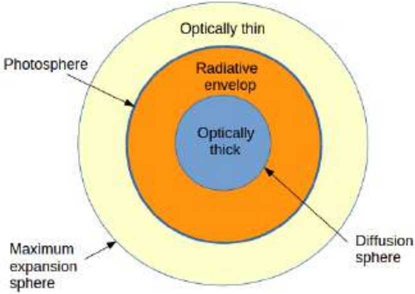
- $v_{\rm eff} = c/\tau$ is the photon effective (diffusion) speed
- τ is the optical depth:

$$\tau \approx \langle \rho \rangle \, \Delta R \, \kappa \approx \frac{m_{>v}(\tilde{v}) \, \Delta R \, \kappa}{4\pi (\tilde{v}\tilde{t})^2 \, \Delta R}$$

$\Rightarrow$ implicit equation for $\tilde{v}(\tilde{t})$

$$c = \frac{m_{>v}(\tilde{v}) \, \kappa}{4\pi \, \tilde{v} \, \tilde{t}^2}$$

Photon diffusion model



Photospheric radius:

- $R_{\rm ph}(\tilde{t})$ where

$$\tau(R_{\rm ph}) = 2/3$$

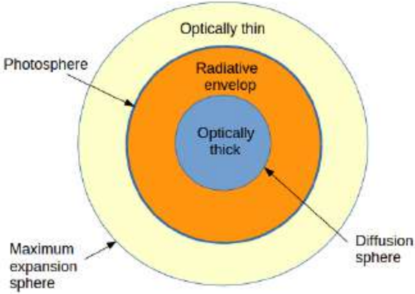
- matter at $R_{\rm ph}(\tilde{t})$ expands with velocity $v_{\rm ph}(\tilde{t})$:

$$R_{\rm ph}(\tilde{t}) = v_{\rm ph}(\tilde{t})\,\tilde{t}$$

$\Rightarrow$ implicit equation for $v_{\rm ph}(\tilde{t})$

$$\frac{m_{>v}(v_{\rm ph})\,\kappa}{4\pi\,\left(v_{\rm ph}\,\tilde{t}\right)^2} = \frac{2}{3}$$

Photon diffusion model



Photon luminosity:
emitted at the photosphere as a blacl body

$$\begin{aligned} L_\gamma(\tilde{t}) &= m_{\mathrm{rad,env}}(\tilde{t})\,\dot{e}_{r-\mathrm{proc}}(\tilde{t})\,f_{\mathrm{th}}(\tilde{t}) \\ m_{\mathrm{rad,env}}(\tilde{t}) &= \big(m_{>v}(\tilde{v}) - m_{>v}(v_{\mathrm{ph}})\big) \end{aligned}$$

Emission at the photosphere with black body temperature $T(\tilde{t})$

$$\frac{L_\gamma}{4\pi\,R_{\mathrm{ph}}^2} = \sigma_{\mathrm{SB}} T^4$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v})\,\kappa}{4\pi\,\tilde{v}\,\tilde{t}^2} \Rightarrow t_{\rm peak} \sim \sqrt{\frac{m_{\rm ej}\,\kappa}{4\pi\,v_{\rm ej}\,c}}$$

$$t_{\rm peak} \sim 4.9\,{\rm day}\left(\frac{\kappa}{10\,{\rm cm}^2{\rm g}^{-1}}\right)^{1/2}\left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{-1/2}$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v})\;\kappa}{4\pi\;\tilde{v}\;\tilde{t}^2} \Rightarrow t_{\rm peak} \sim \sqrt{\frac{m_{\rm ej}\;\kappa}{4\pi\;v_{\rm ej}\;c}}$$

$$t_{\rm peak} \sim 4.9\,{\rm day} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2}$$

$$L_\gamma = m_{\rm rad\,,env}\,\dot{e}_{r-{\rm proc}}\,f_{\rm th} \Rightarrow L_{\rm peak} \sim m_{\rm ej}\,f_{\rm th}\,\dot{e}_0\,t_{\rm peak}^{-\alpha}$$

$$L_{\rm peak} \sim 2.4 \times 10^{40}\,{\rm erg/s} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{-13/20} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{7/20} \left(\frac{v}{0.1c}\right)^{13/20} \left(\frac{\dot{e}_0}{5 \times 10^{16}{\rm erg/g/s}}\right) \left(\frac{f_{\rm th}}{0.5}\right)$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v})\,\kappa}{4\pi\,\tilde{v}\,\tilde{t}^2} \Rightarrow t_{\rm peak} \sim \sqrt{\frac{m_{\rm ej}\,\kappa}{4\pi\,v_{\rm ej}\,c}}$$

$$t_{\rm peak} \sim 4.9\,{\rm day} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2}$$

$$L_\gamma = m_{\rm rad,env}\,\dot{e}_{r-{\rm proc}}\,f_{\rm th} \Rightarrow L_{\rm peak} \sim m_{\rm ej}\,f_{\rm th}\,\dot{e}_0\,t_{\rm peak}^{-\alpha}$$

$$L_{\rm peak} \sim 2.4 \times 10^{40}\,{\rm erg/s} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{-13/20} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{7/20} \left(\frac{v}{0.1c}\right)^{13/20} \left(\frac{\dot{e}_0}{5\times 10^{16}{\rm erg/g/s}}\right) \left(\frac{f_{\rm th}}{0.5}\right)$$

$$R_{\rm ph,peak} \sim v_{\rm ej}\,t_{\rm peak}$$

$$R_{\rm ph,peak} \sim 1.26 \times 10^{15}\,{\rm cm} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{1/2}$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v})\,\kappa}{4\pi\,\tilde{v}\,\tilde{t}^2} \Rightarrow t_{\rm peak} \sim \sqrt{\frac{m_{\rm ej}\,\kappa}{4\pi\,v_{\rm ej}\,c}}$$

$$t_{\rm peak} \sim 4.9\,{\rm day} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2}$$

$$L_\gamma = m_{\rm rad,env}\,\dot{e}_{r-{\rm proc}}\,f_{\rm th} \Rightarrow L_{\rm peak} \sim m_{\rm ej}\,f_{\rm th}\,\dot{e}_0\,t_{\rm peak}^{-\alpha}$$

$$L_{\rm peak} \sim 2.4\times 10^{40}\,{\rm erg/s} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{-13/20} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{7/20} \left(\frac{v}{0.1c}\right)^{13/20} \left(\frac{\dot{e}_0}{5\times 10^{16}{\rm erg/g/s}}\right) \left(\frac{f_{\rm th}}{0.5}\right)$$

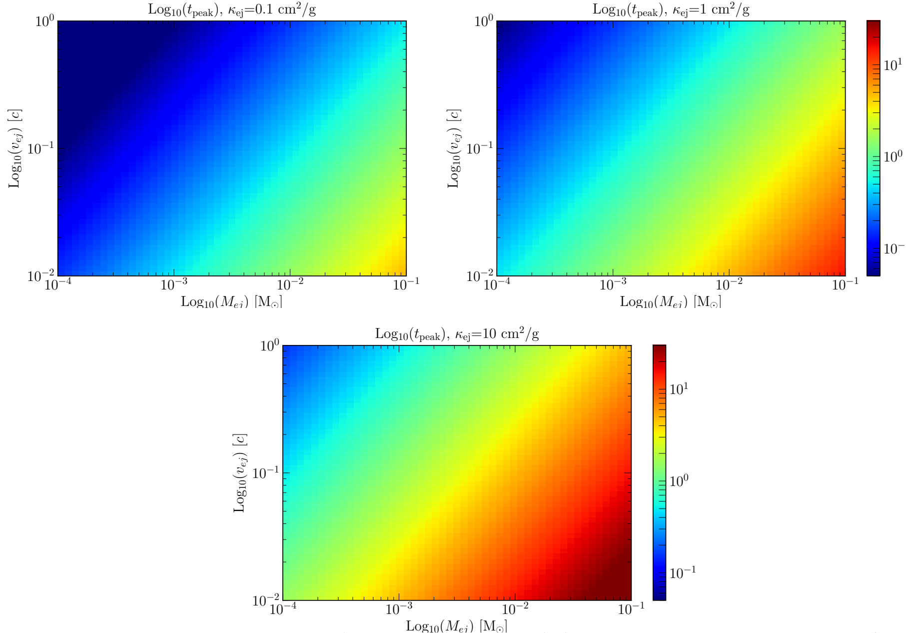
$$R_{\rm ph,peak} \sim v_{\rm ej}\,t_{\rm peak}$$

$$R_{\rm ph,peak} \sim 1.26\times 10^{15}\,{\rm cm} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{1/2}$$

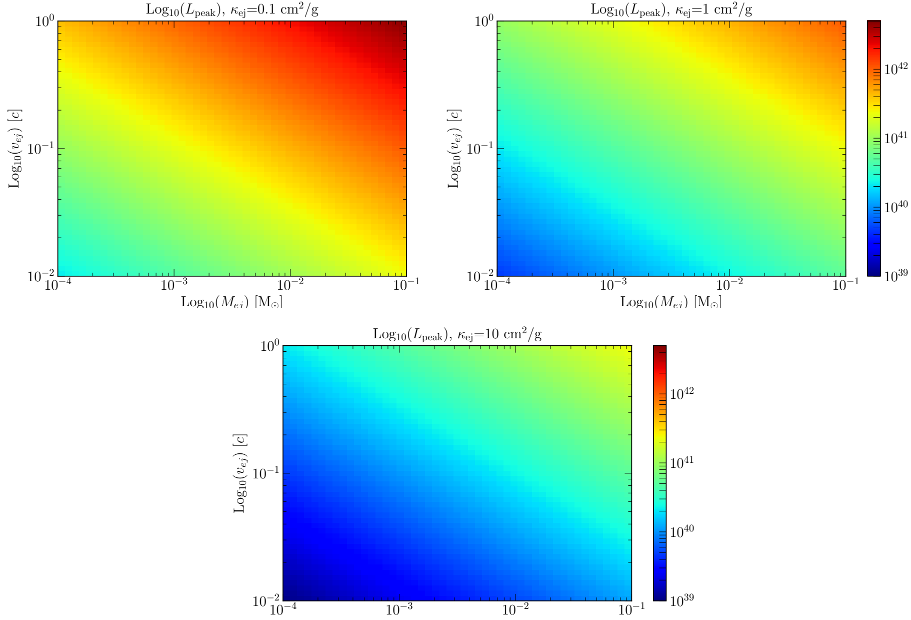
$$\frac{L_\gamma}{4\pi\,R_{\rm ph}^2} = \sigma_{\rm SB}T^4 \Rightarrow T_{\rm peak} \sim \left(\frac{L_{\rm peak}}{4\pi R_{\rm ph,peak}^2\,\sigma_{\rm SB}}\right)^{1/4}$$

$$T_{\rm peak} \sim 2.15\times 10^{3}\,{\rm K} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{-33/80} \left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{-13/80} \left(\frac{v}{0.1c}\right)^{-27/80} \left(\frac{\dot{e}_0}{5\times 10^{16}{\rm erg/g/s}}\right)^{1/4} \left(\frac{f_{\rm th}}{0.5}\right)^{1/}$$

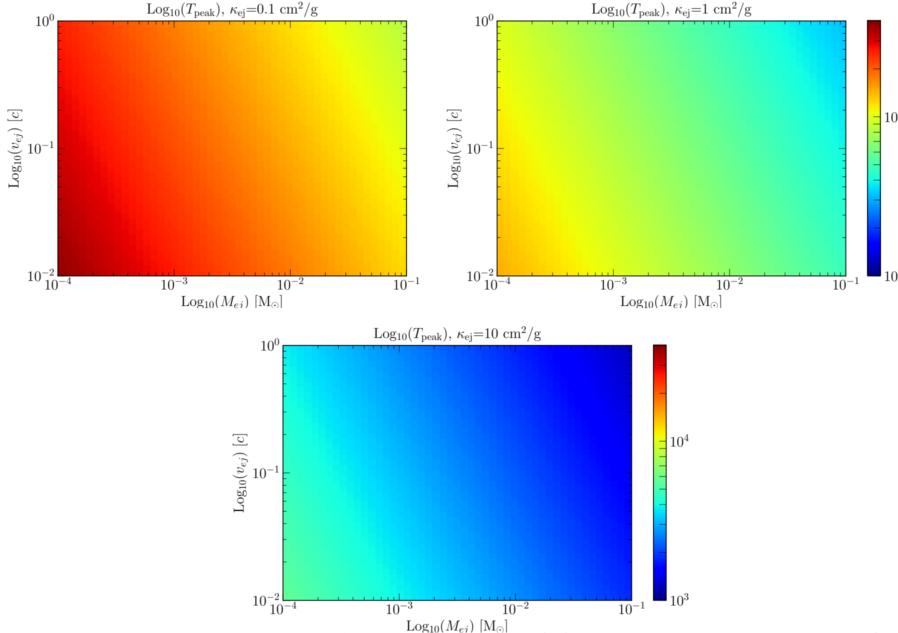
Peak properties: exploration of $t_{\rm peak}$(days)



Peak properties: exploration of $L_{\rm peak}$(erg/s)



Peak properties: exploration of $T_{\rm peak}$(K)



$\mathrm{Log}_{10}(T_{\rm peak})$, $\kappa_{\rm ej}$=0.1 cm^2/g

$\mathrm{Log}_{10}(T_{\rm peak})$, $\kappa_{\rm ej}$=1 cm^2/g

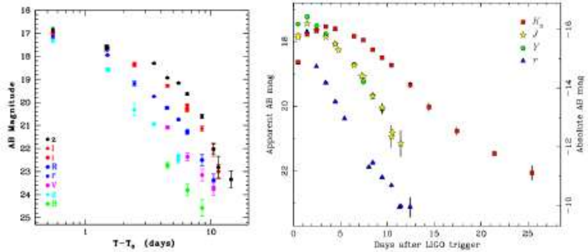
$\mathrm{Log}_{10}(T_{\rm peak})$, $\kappa_{\rm ej}$=10 cm^2/g

AT2017gfo: from spherical, one component models to anisotropic, multi-component models

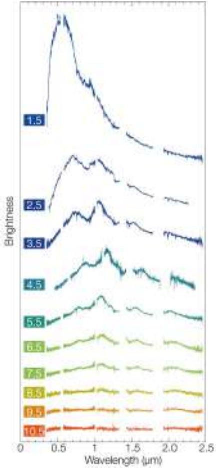
Properties of AT2017gfo

- 17/08/17, GW+EM detection of an event compatible with BNS merger ($\mathcal{M}_{\rm chirp} \approx 1.118 M_{\odot}$)

  LVC PRL 2017
- bright, UV/O component, with a peak @ $\sim$ 1day (blue component)
- rather bright, nIR component, with a peak @ $\sim$ 5day (red component)



Light curves; Pian, D'Avanzo+2017 (left); Tanvir+2017 (right)



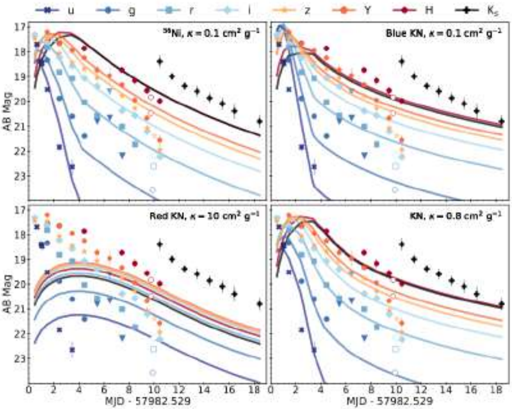
Xshooter spectra

VLT@EOS;

Pian, D'Avanzo+2017

The need for multicomponent models

- failure of model with a single component in reproducing AT2017gfo key features
- "component": spherically symmetric KN model labelled by $(M_{\rm ej}, v_{\rm ej}, \kappa)$
- "model": different levels of approximations ranging from semi-analitical to radiative transfert approaches



← Cowperthwaite+ 2017, ApJL

see also, e.g.,

Chornock+17,Drout+17,Nicholl+17,Tanaka+17,

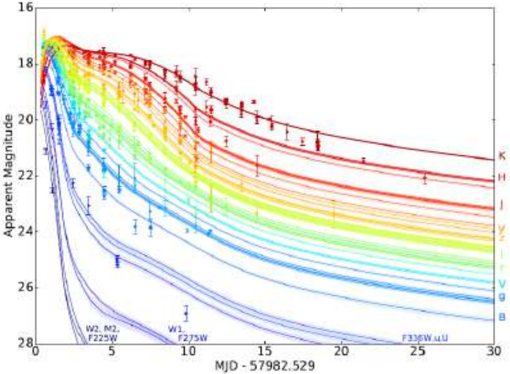
Villar+17, Waxman+17,Metzger+18.

For multi-D models, e.g., Tanvir+ ApJL 17, Kawaguchi+ ApJL 18

Cowperthwaite+ 2017, ApJL

Results from multicomponent models

- reasonable agreement of multicomponent models in reproducing AT2017gfo key features
- often, $(M_{\rm ej}, v_{\rm ej}, \kappa)$ still correlate in each component
- usually, multicomponent = combination of spherically symmetric single component models



← Villar+ 2017, ApJL

see also, e.g.,

Chornock+17,Cowperthwaite+17, Drout+17,

Nicholl+17,Tanaka+17,Waxman+17,Metzger+18.

For multi-D models, e.g., Tanvir+17, Kawaguchi+18

Results from multicomponent models

Esample of results from 2 or 3 components fits:

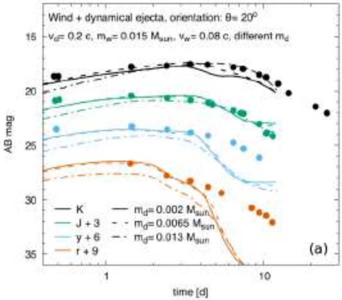
Table 2. Kilonova Model Fits

Model	M_{ej}^{blue}	v_{ej}^{blue}	κ_{ej}^{blue}	T^{blue}	M_{ej}^{purple}	v_{ej}^{purple}	κ_{ej}^{purple}	T^{purple}	M_{ej}^{red}	v_{ej}^{red}	κ_{ej}^{red}	T^{red}	σ	θ	WAIC
2-Comp	$0.023_{0.001}^{0.005}$	$0.256_{0.002}^{0.005}$	(0.5)	3983_{70}^{66}	-	-	-	-	$0.050_{0.001}^{0.001}$	$0.149_{0.002}^{0.001}$	$3.65_{0.28}^{0.09}$	1151_{72}^{45}	$0.256_{0.004}^{0.006}$		-1030
3-Comp	$0.020_{0.001}^{0.001}$	$0.266_{0.008}^{0.008}$	(0.5)	674_{417}^{486}	$0.047_{0.002}^{0.001}$	$0.152_{0.005}^{0.005}$	(3)	1308_{34}^{42}	$0.011_{0.001}^{0.002}$	$0.137_{0.021}^{0.025}$	(10)	3745_{75}^{75}	$0.242_{0.008}^{0.008}$		-1064
Asym. 3-Comp	$0.009_{0.001}^{0.001}$	$0.256_{0.004}^{0.009}$	(0.5)	3259_{306}^{302}	$0.007_{0.001}^{0.001}$	$0.103_{0.004}^{0.007}$	(3)	3728_{178}^{94}	$0.026_{0.002}^{0.004}$	$0.175_{0.008}^{0.011}$	(10)	1091_{43}^{29}	$0.226_{0.006}^{0.006}$	66_{3}^{1}	-1116

Villar+ ApJL 2017

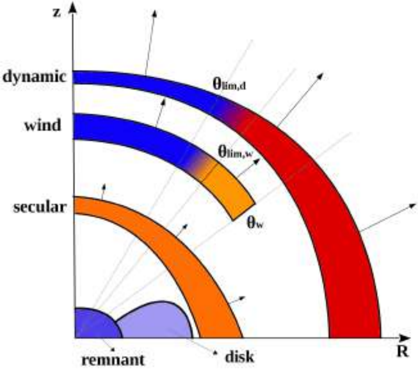
Example of light curves from 2 component, 2D radiative transfer models (`SuperNu`)

Tanvir+ ApJL 2017

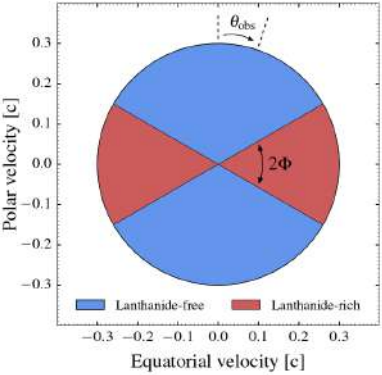


Multi-Component Anisotropic Kilonova Model

- kilonova model should include our present knowledge about ejecta
- different ejection channels → multi-component
- explicit dependency on polar angle → anisotropic
  - multi-angle (polar angle discretization)
  - explicit dependence on observer viewing angle

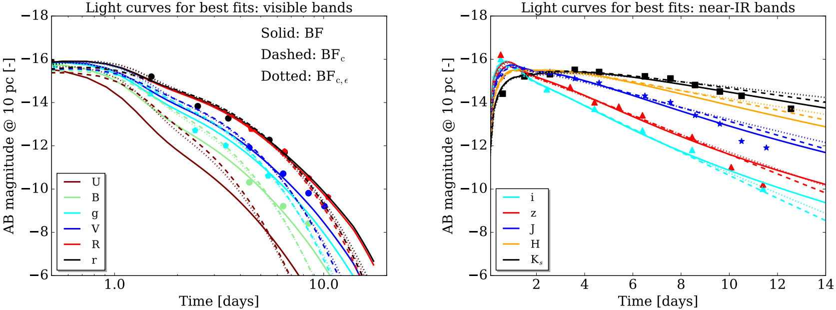


Perego, Radice, Bernuzzi 17, ApjL



Bulla+ 19, Nature

Application to AT2017gfo: best-fit models

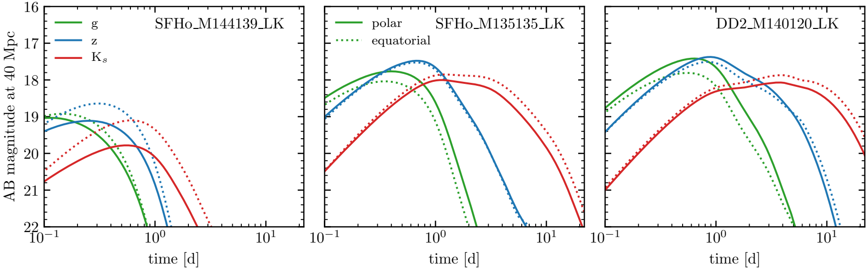


- multi-components (2 or 3) models reproduce major observed features of AT2017gfo
- fast ($v \sim 0.3c$), low opacity ($\kappa \sim 1\,\mathrm{cm}^2\mathrm{g}^{-1}$) material essential
- global properties for AT2017gfo
  - anisotropic and multicomponent ejecta
  - $M_{\mathrm{ej,tot}} \sim 0.05 M_\odot$, $\theta_{\mathrm{obs}} \approx 30^o$, $M_{\mathrm{disk}} \sim 0.1 M_\odot$
  - low-opacity material at high latitude: neutrinos @ work

Representative kilonova emission

- light curves in relevant photometric bands (UV, Optical, NIR) for a broad set of BNS
- dynamical ejecta directly extracted from simulations
- wind and viscous ejecta: fraction of the disk mass (0.03 and 0.20, respectively) with properties obtained from AT2017gfo best-fit model

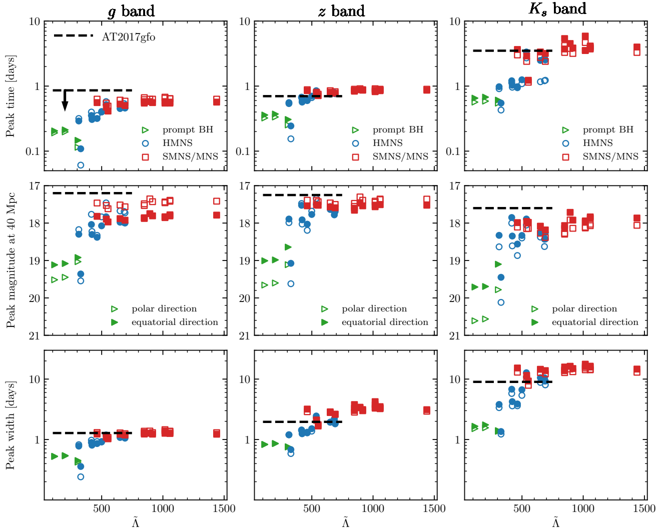
prompt BH short-lived MNS long-lived MNS



Radice+ 2018 ApJ

Systematics of kilonova peaks

Peak time, magnitude and time width ($\Delta M = 1\,\mathrm{mag}$) VS $\tilde{\Lambda}$

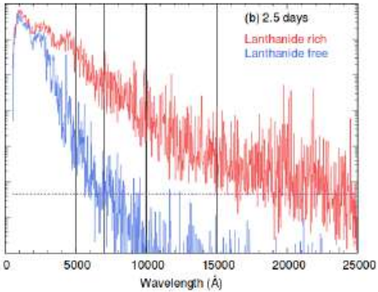


Radice+ 2018 ApJ (35 BNS configurations, 49 different simulations in Numerical Relativity)

Kilonova radiative transfers

- most appropriate approach to kilonova: photon radiative transfer
- usually MonteCarlo schemes
- *r*-process element opacity (very few experimental values!)
- detailed EOS: atomic and ionization abundances
- $\sim 10^6$ lines: effective approaches (e.g. Sobolev approx.)
- often 1D and with one component, multi-components in multi-D now also available

e.g. Kasen+ Nature 2017, Tanaka+ PASJ 2017, Smartt+ 2017, Wollaeger+ MNRAS 2018

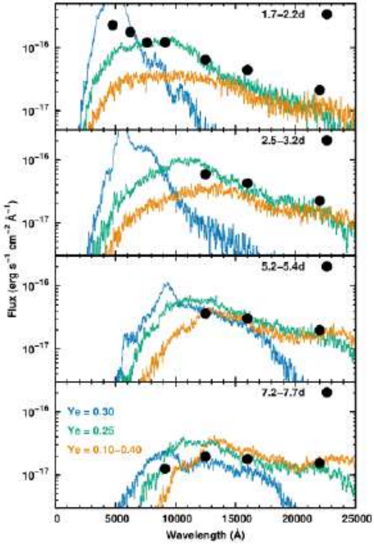


Bulla+ Nature 2019

Kilonova radiative transfers

- most appropriate approach to kilonova: photon radiative transfer
- usually MonteCarlo schemes
- *r*-process element opacity (very few experimental values!)
- detailed EOS: atomic and ionization abundances
- $\sim 10^6$ lines: effective approaches (e.g. Sobolev approx.)
- often 1D and with one component, multi-components in multi-D now also available

e.g. Kasen+ Nature 2017, Tanaka+ PASJ 2017, Smartt+ 2017, Wollaeger+ MNRAS 2018

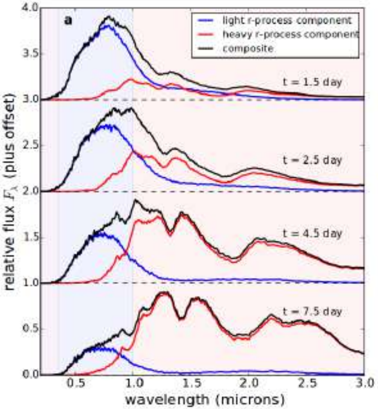


Tanaka+ PASJ 2017

Kilonova radiative transfers

- most appropriate approach to kilonova: photon radiative transfer
- usually MonteCarlo schemes
- *r*-process element opacity (very few experimental values!)
- detailed EOS: atomic and ionization abundances
- $\sim 10^6$ lines: effective approaches (e.g. Sobolev approx.)
- often 1D and with one component, multi-components in multi-D now also available

e.g. Kasen+ Nature 2017, Tanaka+ PASJ 2017, Smartt+ 2017, Wollaeger+ MNRAS 2018

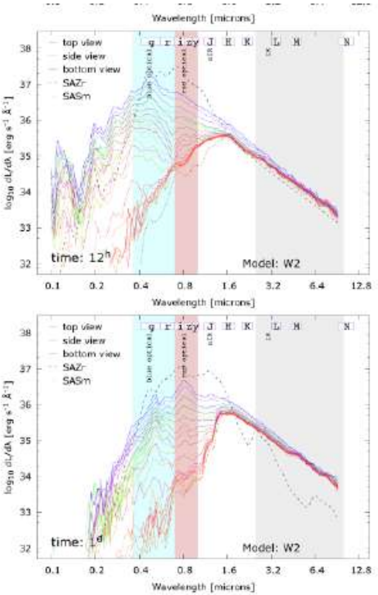


Kasen+ Nature 2017

Kilonova radiative transfers

- most appropriate approach to kilonova: photon radiative transfer
- usually MonteCarlo schemes
- *r*-process element opacity (very few experimental values!)
- detailed EOS: atomic and ionization abundances
- $\sim 10^6$ lines: effective approaches (e.g. Sobolev approx.)
- often 1D and with one component, multi-components in multi-D now also available

e.g. Kasen+ Nature 2017, Tanaka+ PASJ 2017, Smartt+ 2017, Wollaeger+ MNRAS 2018

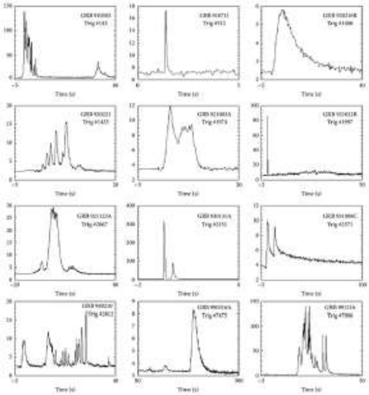


Wollaeger+ MNRAS 2018 (see also Tanvir+ ApJL 2017)

Short-hard Gamma-Ray burst

Observational properties

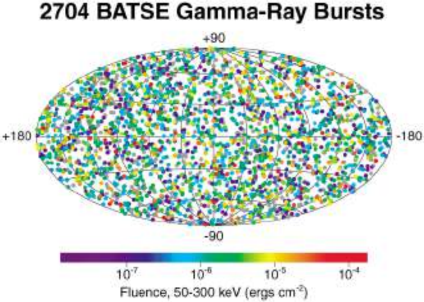
- non-thermal emissions associated with γ-ray flashes
- discovered in 1967 by Vela satellites
- now routinely observed by X and γ-ray satellites (1 every few days)
  - CGRO/BATSE (1991-2000)
  - INTEGRAL, IBIS+SPI (2002-)
  - SWIFT/XRT+BAT (2004-)
  - FERMI/LAT+GBM (2008-)



NASA/BATSE team & Pe'er+ 15

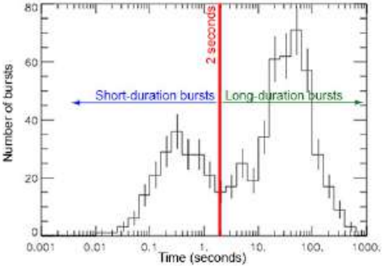
← large intrinsic variability

↓ isotropical (cosmological) distribution

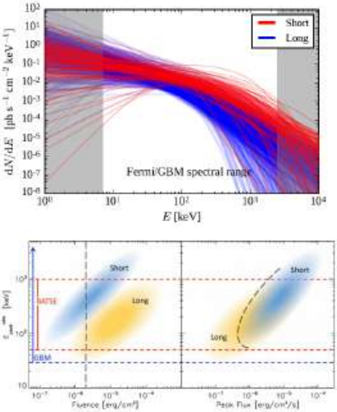


Short-hard VS long-soft GRBs

- 2 distinct classes based on burst duration (T_{90})
  - 25% short ($T_{90} < 2$ s)
- systematic spectral shift
  - short-hard VS long-soft
- indication of two distinct progenitors/central engines



NASA-BATSE team



Up: FERMI/GRB Team. Bottom: Nava+ 2010 A&A

Different progenitors and host galaxies

- 1997 BeppoSAX satellite detected first GRB afterglow:
  fainter X-ray, optical, radio emissions following a GRBs on timescale of hours to months
- afterglow observations → host galaxies studies

- long GRBs
  - galaxies with high star formation rate
  - 1998-2003: identification of SNIb/c & hypernovae with long GRBs (5-20 days after, SWIFT)
  - long GRBs peak: $z \sim 2$ (SWIFT)

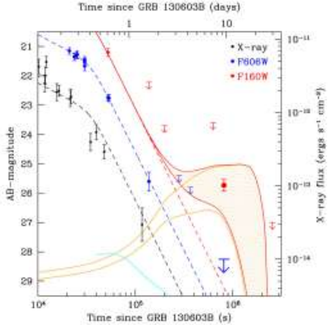
- short GRBs
  - 2005: first afterglow from short GRB (SWIFT)
  - all types of galaxies, also with old stellar population
  - often with significant displacement from host galaxy
  - systematically fainter and closer (smaller z)
  - $T_{90} \sim t_{\rm disk}$

  → all compatible with compact binary mergers

e.g. Berger 14 ARAA

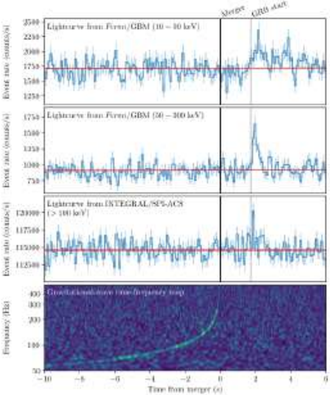
Short GRBs and compact binary mergers

Identification of IR excess (kilonova?) in sGRB afterglow (GRB130603B)



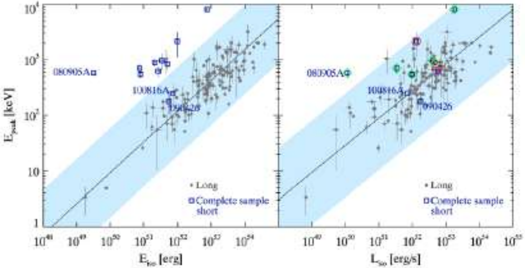
Tanvir+ 2013, Nature

Identification of BNS merger, short GRBs and kilonova (GW170817 + GRB170817A + AT2017gfo)



LVC+Fermi+Integral 2017 ApJL

Energetics and jets



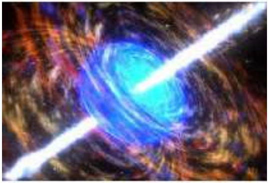
D’Avanzo+ 2014

$$E_{\rm iso} = 4\pi d_L^2 f \qquad L_{\rm iso} = 4\pi d_L^2 F$$

F flux VS f fluence (time-integrated flux)

cfr $M_\odot c^2 = 1.8 \times 10^{54}$erg

much lower energies required if outflow is collimated in a jet



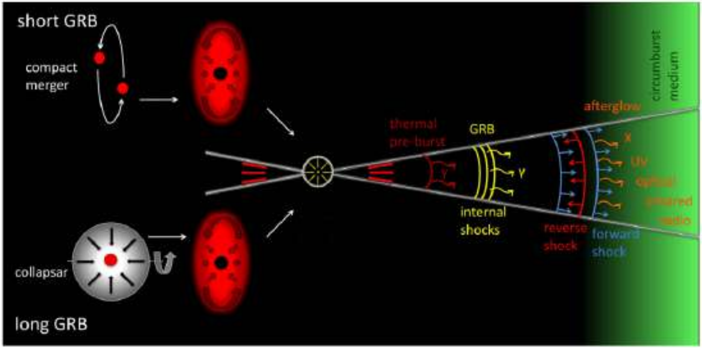
- half-opening angle: $\theta_{\rm jet}$

$$E_{\rm true} = E_{\rm iso}\frac{\Delta\Omega}{4\pi} = E_{\rm iso}(1-\cos\theta_{\rm jet}) \approx \frac{E_{\rm iso}}{65}\left(\frac{\theta_{\rm jet}}{10^o}\right)^2$$

- observational indications: $\theta_{\rm jet} \sim 6^o$ (e.g. achromatic break)

e.g. Fong+ 15 ApJ

How to produce a GRB? The fireball model

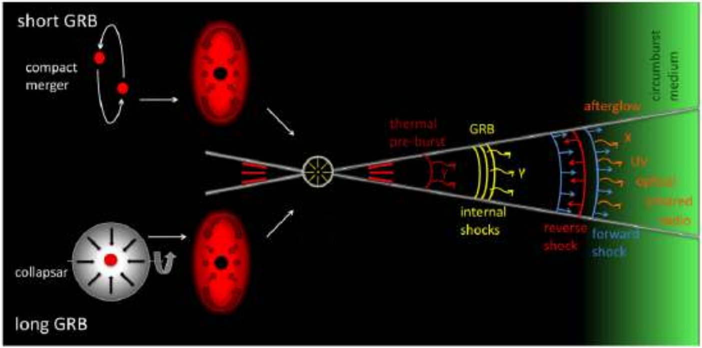


Gomboc 2011

1. energy injection:

- a stellar-size object undergoes a catastrophic event that deposits $E \sim$ a few times $E_{\rm true}$ within $\Delta t \sim T_{90}$ and $\Delta R \sim 10^6 - 10^7$cm
- E in form of heat, radiation or EM field, resulting in optically thick plasma of $e^{\pm}$, γ and baryons
- $\eta = E/Mc^2 \gg 1$

How to produce a GRB? The fireball model

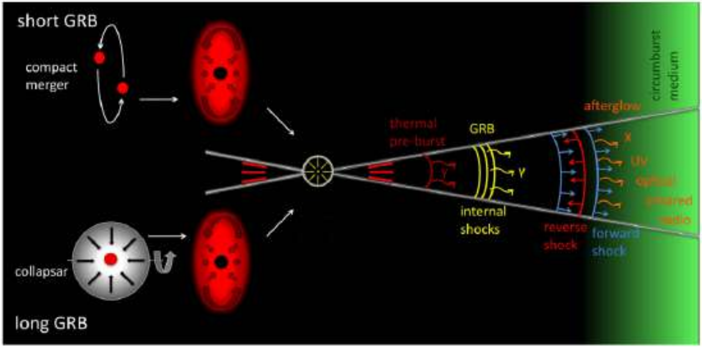


Gomboc 2011

2. expansion to UR speed:

- the fireball accelerates under its own pressure to UR velocities ($\gamma_{\rm asym} \approx \eta \sim 100$)
- matter dominated jet: $B^2/(4\pi\gamma\rho c^2) \ll 1$
- adiabatic expansion until the plasma becomes thin to γ, $R \sim 10^{13}{\rm cm} \sim 1{\rm AU}$

How to produce a GRB? The fireball model

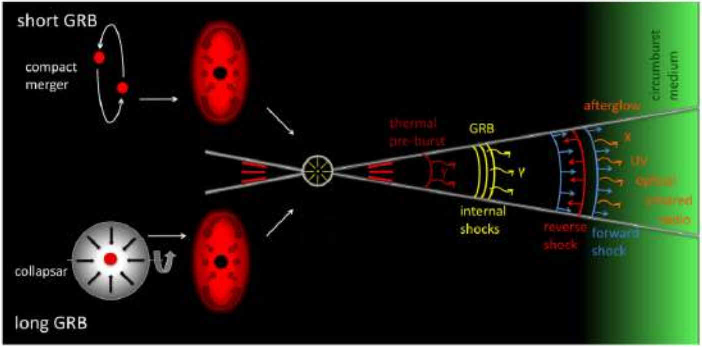


Gomboc 2011

3. pre-burst:

- thermal emission from photosphere (much weaker than GRB)

How to produce a GRB? The fireball model

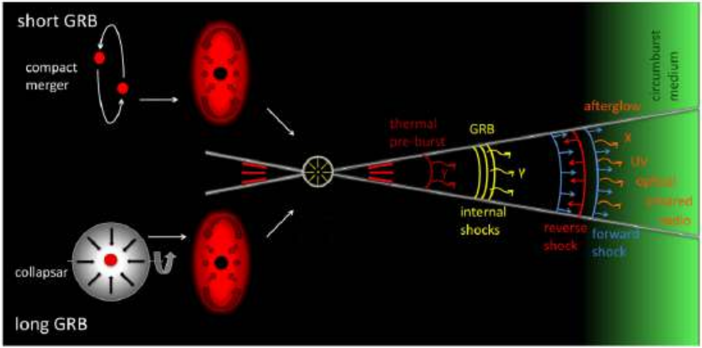


Gomboc 2011

4. GRB - prompt emission:

- dissipation of jet energy via internal shock due to matter expanding at different speed, at $R \sim 10^{13}$ cm Rees 78, Rees, Meszaros 94, Zhang+ 11
- collisionless plasma shocks: local amplification of magnetic field
- electrons: synchrotron radiation and possibly Compton processes

How to produce a GRB? The fireball model



Gomboc 2011

5. GRB - afterglow emission:

- significant fraction of bulk kinetic energy still available
- dissipated in external shocks with ISM at R $10^{14} - 10^{16}$cm $\sim 0.01 - 1$ ly
- electrons accelerated in power law distribution
- decellerating jet $\rightarrow$ lower γ's energy

Why a relativistic jet?

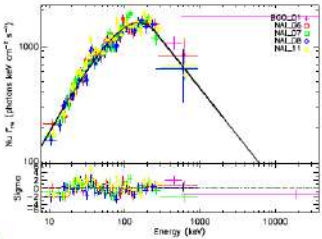
- GRBs show variability $\Delta t_{\rm obs} \gtrsim 1$ ms and $E_\gamma \lesssim 1$ MeV
- a non-relativistic sphere of size $D \sim \Delta t_{\rm obs} c \sim 10^7$cm populated by 1 MeV γ's ($\rightarrow e^{\pm}$) would be very optically thick → thermal spectrum how to reconcile with non-thermal spectrum (compactness problem)?

matter moving at relativistic speed

- γ's blueshifted by relativistic motion: $E_{\rm obs} = \Gamma E_{\rm rest}$
- $\Delta t_{\rm obs} \sim \Delta t_{\rm em}/(2\Gamma^2)$ and $D \sim \Delta t_{\rm em} c$
- $\Gamma \gtrsim 100 \rightarrow$ significant reduction of $e^{\pm}$ pairs and larger D

how easily $\Gamma_{\rm asym} \sim 100$ (baryonic pollution problem)?

- if $\gamma_{\rm asym} \approx \eta$ then $M_{\rm fb} \approx 6 \times 10^{-6} M_\odot \left(\frac{E}{10^{51}{\rm erg}}\right)\left(\frac{\Gamma}{100}\right)^{-1}$



Typical spectrum

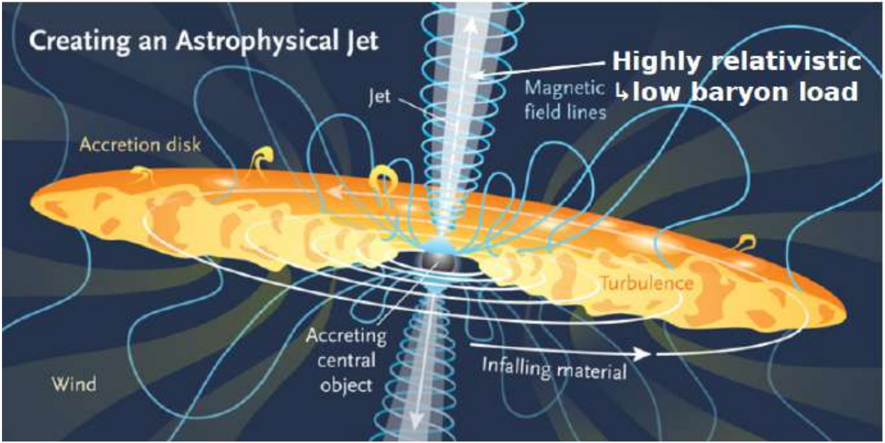
$$\frac{{\rm d}N}{{\rm d}t\,{\rm d}E} = A \begin{cases} E^{\alpha} \exp\left(\frac{-(2+\alpha)E}{E_p}\right) & E < E_b \\ E^{\beta}\left(\frac{E_b}{e}\right)^{\alpha-\beta} & E \geq E_b \end{cases}$$

How to produce a relativistic jet?

Still uncertain, with several possible mechanisms:

1. extraction of rotational energy from a BH through B field (Blandford-Znajek mechanism)

Blandford & Znajek MNRAS 77



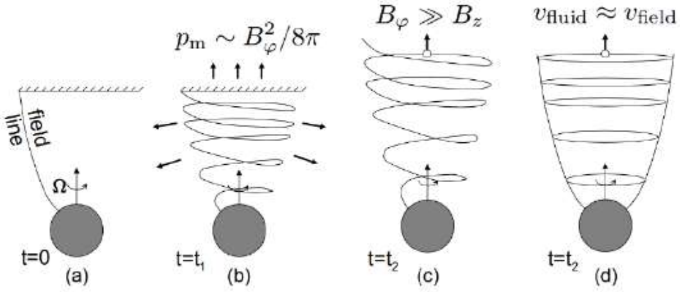
e.g. McKinney+ 12 MNRAS, Tchekhovskoy+ 2012 JPCS and references therein

How to produce a relativistic jet?

Still uncertain, with several possible mechanisms:

1. extraction of rotational energy from a BH through *B* field (Blandford-Znajek mechanism)

Blandford & Znajek MNRAS 77



Tchekhovskoy+ 2012 JPCS

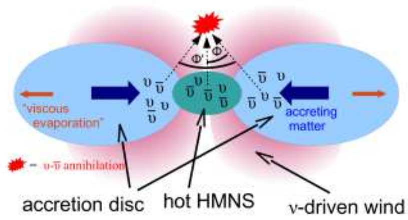
- BH formation: reduced baryon pollution
- BH-NS merger: always a BH in the center
  BNS merger: collapse of central MNS to a BH

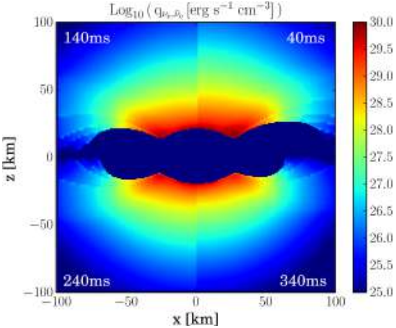
How to produce a relativistic jet?

Still uncertain, with several possible mechanisms:

2. neutrino-antineutrino pair annihilation

Eichler+ 89 Nature





Perego,Yasin,Arcones 18 CQG

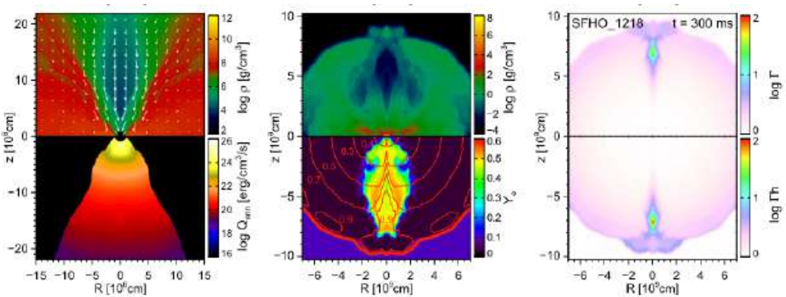
- $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$
- total energy marginally low
- more efficient if MNS is present
- potential problem: baryon pollution

How to produce a relativistic jet?

Still uncertain, with several possible mechanisms:

2. neutrino-antineutrino pair annihilation

Eichler+ 89 Nature



Just+ 16 ApJL

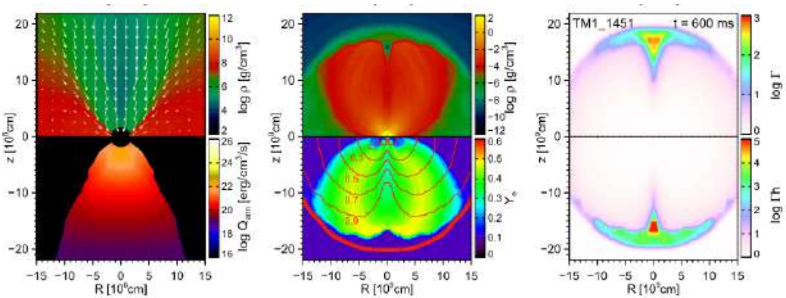
- $\nu + \bar{\nu} \rightarrow e^+ + e^-$
- total energy marginally low
- more efficient if MNS is present
- potential problem: baryon pollution

How to produce a relativistic jet?

Still uncertain, with several possible mechanisms:

2. neutrino-antineutrino pair annihilation

Eichler+ 89 Nature



Just+ 16 ApJL

- $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$
- total energy marginally low
- more efficient if MNS is present
- potential problem: baryon pollution

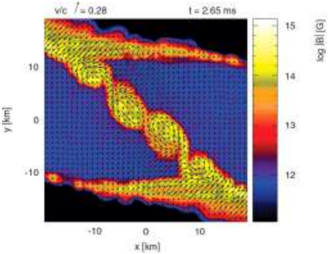
BZ mechanism: basic scaling relations

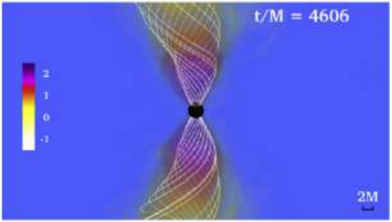
- *B* field amplification
  - magneto-rotational and Kelvin-Helmholtz instabilities
  - fast: over a few dynamical timescale

$$t_{\rm orb} \sim 2\pi\sqrt{\frac{GR^3}{M}} \lesssim 1\ {\rm ms}$$

  - at equipartition $B^2 \propto \dot{M} M_{\rm BH}^{-2}$
- *B* field large scale structure
  - less clear
  - Alfven timescale

$$t_{\rm Alf} \sim \frac{R}{v_{\rm Alf}} \lesssim 0.01 B_{16}^{-1}\ {\rm s}$$





Ruiz+ 18

Price & Rosswog 06 Science

BZ mechanism: basic scaling relations

- B field amplification
  - magneto-rotational and Kelvin-Helmholtz instabilities
  - fast: over a few dynamical timescale

$$t_{\rm orb} \sim 2\pi \sqrt{\frac{GR^3}{M}} \lesssim 1~{\rm ms}$$

  - at equipartition $B^2 \propto \dot{M} M_{\rm BH}^{-2}$
- B field large scale structure
  - less clear
  - Alfven timescale

$$t_{\rm Alf} \sim \frac{R}{v_{\rm Alf}} \lesssim 0.01 B_{16}^{-1}~{\rm s}$$

- BZ luminosity and jet energy

$$L_{\rm BZ} \propto \frac{G^2}{c^3}\, \epsilon\, M_{\rm BH}\, B^2\, \Omega_H^2 f(\Omega_H) \lesssim \epsilon \dot{M}\, c^2\, \Omega_H^2 f(\Omega_H)$$

$$E_{\rm kin} \approx L_{\rm BZ}\, t_{\rm disk} \approx \epsilon\, M_{\rm disk}\, c^2\, \Omega_H^2 f(\Omega_H) \lesssim 10^{51}~{\rm erg}$$

$$\Omega_H = \frac{\hat{a}}{2(1+\sqrt{1-\hat{a}^2})} \qquad f(\Omega_H) \approx 1 + 1.38\Omega_H^2 + 9.24\Omega_H^4 \qquad \epsilon \sim 0.01$$

ν annihilation mechanism: basic scaling relations

Energetics of ν-annihilation:

- annihilation rate formula

$$q_{\rm ann}(t,\mathbf{x}) \approx \frac{1}{6}\frac{\sigma_0\left(C_A^2+C_V^2\right)}{c\,(m_e c^2)}\int I_\nu I_{\bar\nu}\,(E_\nu+E_{\bar\nu})\,(1-\cos\Phi)^2\;{\rm d}\Omega_\nu {\rm d}\Omega_{\bar\nu}{\rm d}E_\nu {\rm d}E_{\bar\nu}$$

- $Q_{\nu,\bar\nu}(t) = \int_V q_{\nu,\bar\nu}(\mathbf{x},t)\,{\rm d}V$

$$Q_{\nu,\bar\nu} \approx \mathcal{C}\,L_\nu L_{\bar\nu}\left[\frac{\langle\epsilon_\nu^2\rangle}{\langle\epsilon_\nu\rangle}+\frac{\langle\epsilon_{\bar\nu}^2\rangle}{\langle\epsilon_{\bar\nu}\rangle}\right]G_{\nu,\bar\nu} \sim 10^{49-50}\,{\rm erg/s}$$

- $E_{\nu,\bar\nu}(t) = \int_t Q_{\nu,\bar\nu}(t')\,{\rm d}t' \sim 2\times10^{49}\,{\rm erg}$ (at $t \sim t_{\rm disk}$) i.e., energy on the low-side

Magnetic origin of prompt emission?

Alternative origin for GRB prompt emission: magnetic energy

- jet matter carries a globally ordered magnetic field: jet as Poynting-flux dominated outflow:

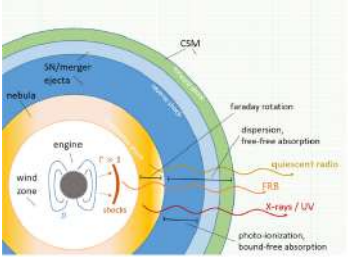
$$B^2/(4\pi\gamma\rho c^2) \gtrsim 1$$

- prompt emission energy from magnetic reconnection e.g. Zhang+ 11
- energy directly dissipated into energetic particles

source of magnetic field?

- rotational kinetic energy of massive NS extracted by B field

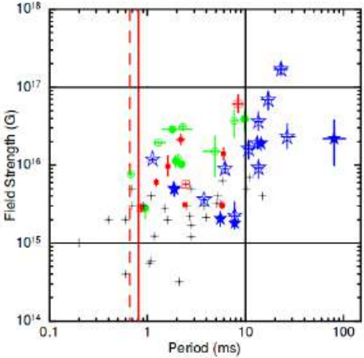
  e.g. Lyutikov 2006
- MHD models: B field produces a relativistic jet e.g. Drenkhahn & Spruit 02
- internal-collision-induced magnetic reconnection and turbulence model Zhang & Yan 11



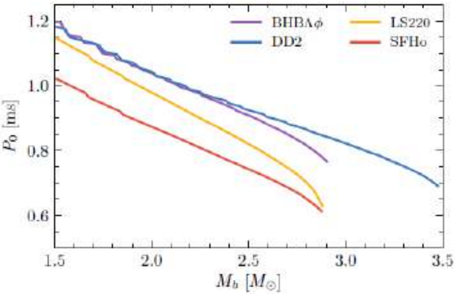
Metzger+ 2018

Magnetar Model for SGRBs?

how do MNS spins compare with spins required by magnerat models of SGRB?



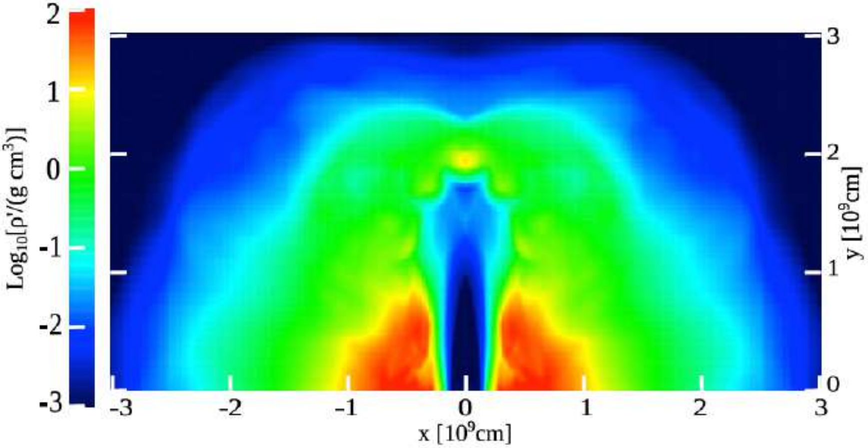
Gompertz+ 2013



Radice+ 2018 ApJ

Structured jet and cocoon

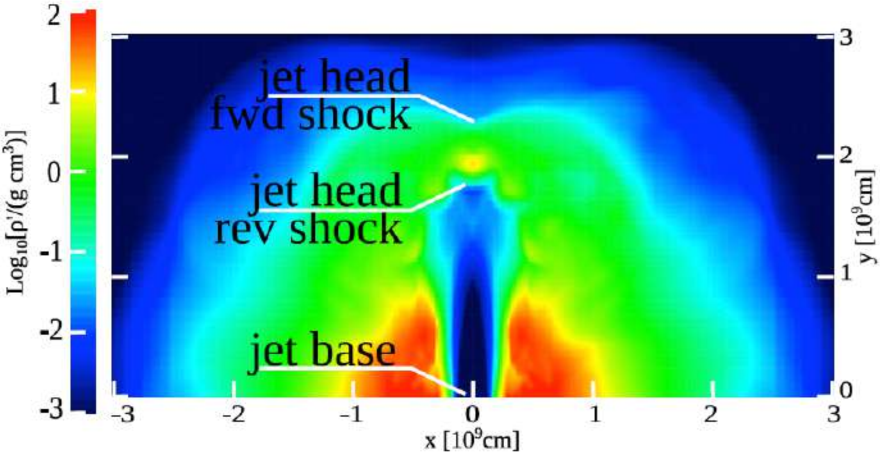
- jet moves in a polluted environment (ejecta)
- collimation but also jet structure and cocoon formation
- weaker and delayed X- and γ-ray emission



Lazzati+ 2017 MNRAS

Structured jet and cocoon

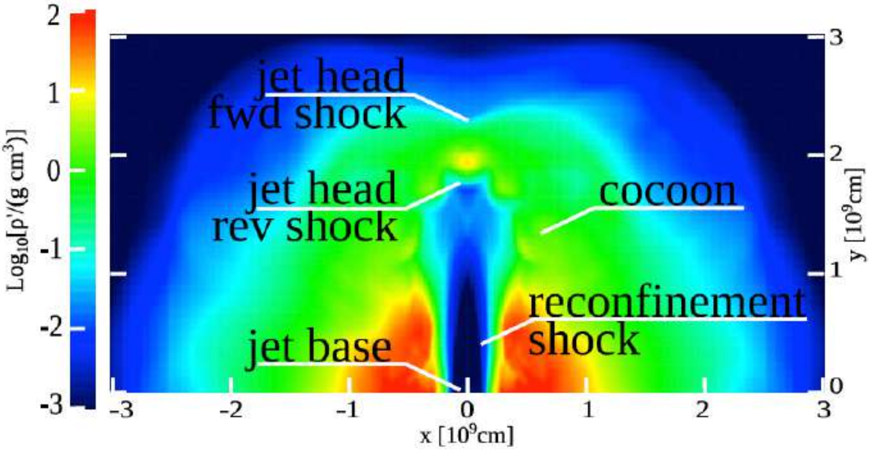
- jet moves in a polluted environment (ejecta)
- collimation but also jet structure and cocoon formation
- weaker and delayed X- and γ-ray emission



Lazzati+ 2017 MNRAS

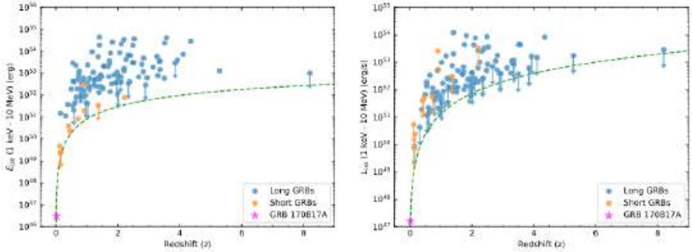
Structured jet and cocoon

- jet moves in a polluted environment (ejecta)
- collimation but also jet structure and cocoon formation
- weaker and delayed X- and γ-ray emission



Lazzati+ 2017 MNRAS

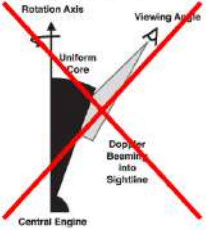
What did we observe in GRB170817A?



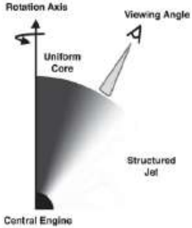
Abbott+ 2017 ApjL

A very weak GRB? No, an off-axis structured jet!

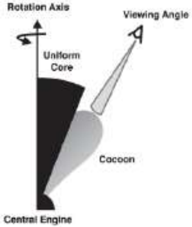
Scenario i: Uniform Top-hat Jet



Scenario ii: Structured Jet

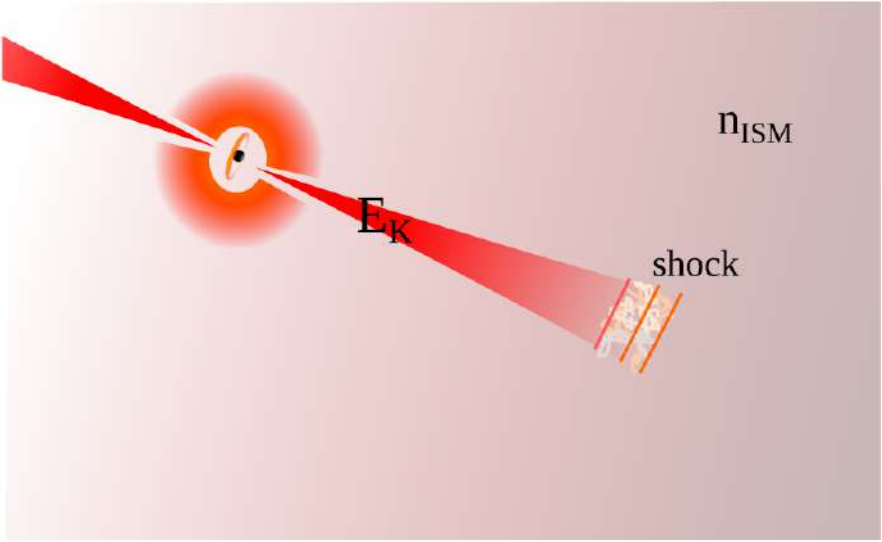


Scenario iii: Uniform Jet + Cocoon



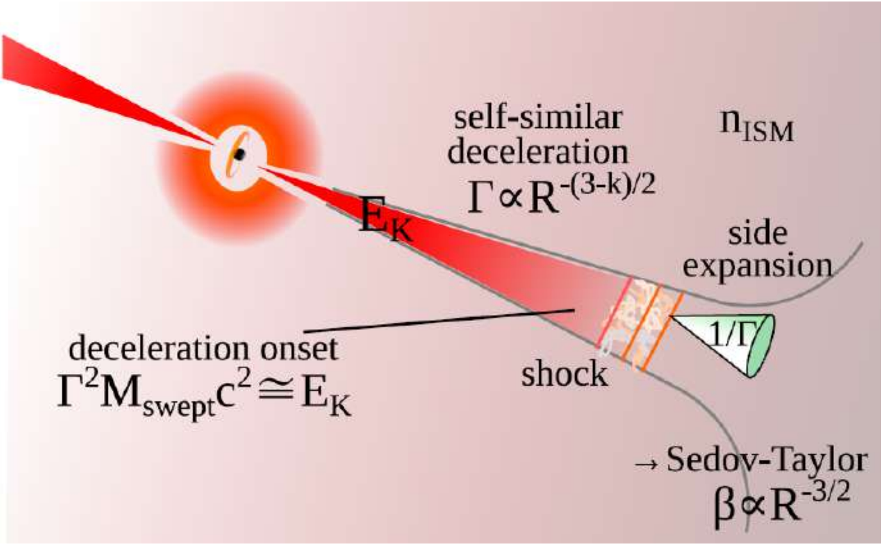
Emission from matter-interstellar medium interaction

Afterglow: basic ideas



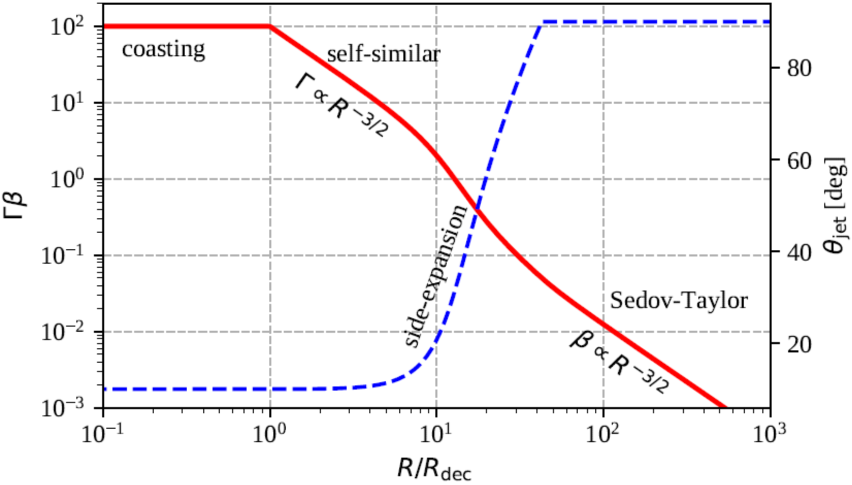
Courtesy of O. Salafia

Afterglow: basic ideas



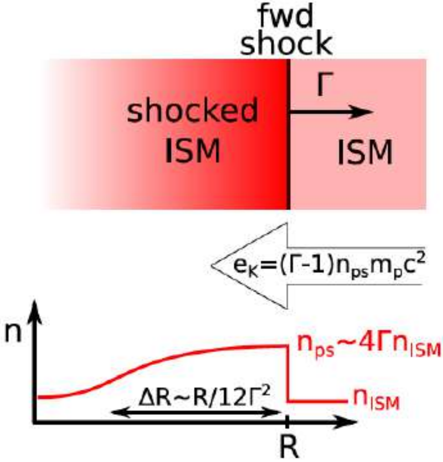
Courtesy of O. Salafia

Afterglow: basic ideas



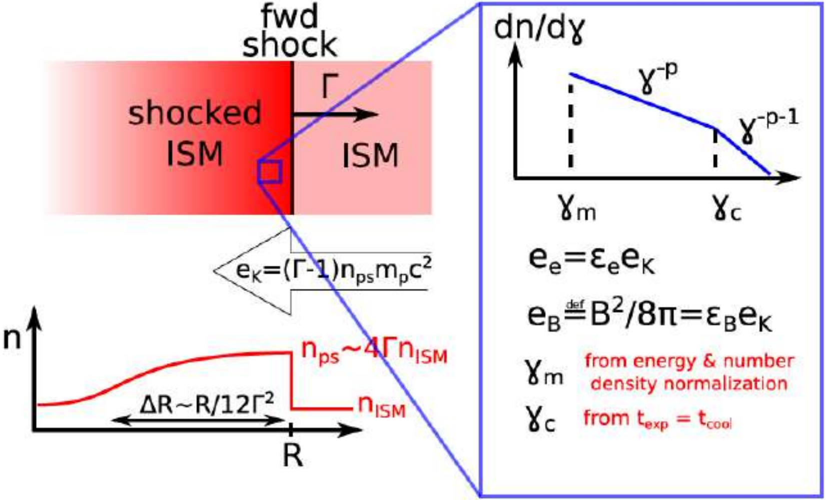
Courtesy of O. Salafia

Afterglow: emission mechanisms



Courtesy of O. Salafia

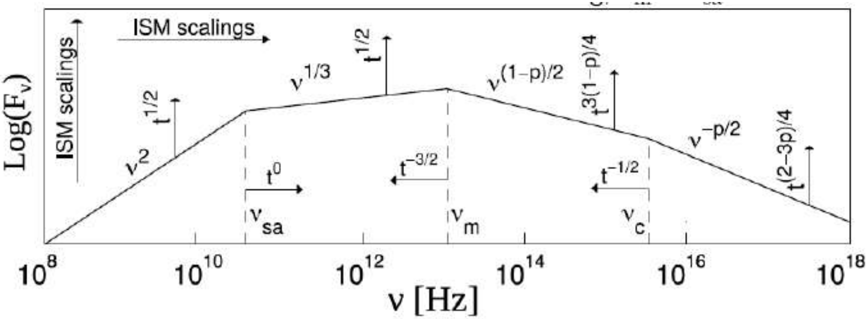
Afterglow: emission mechanisms



Courtesy of O. Salafia

Afterglow: emission spectrum

synchrotron radiation emitted from accelerated electrons moving in locally amplified magnetic field:



Synchrotron emission from fast dynamical ejecta

- expanding ejecta-ISM medium: shock that decellerates the ejecta
- synchroton emission from electrons accelerated in the shock

e.g., Hotokezaka & Piran 2015, Hotokezaka+ 2018

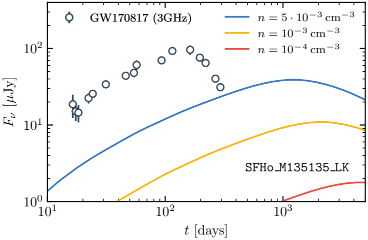
- high velocity tail provides most relevant contribution
- strong dependence on ISM density *n*

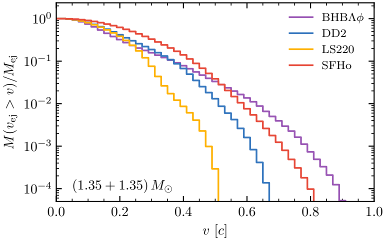
$$
\begin{aligned}
t_{\rm dec} &\sim 3 \cdot 10^3\,{\rm day} \left(\frac{E}{10^{50}{\rm erg}}\right)^{1/3} \\
&\quad \times \left(\frac{n}{10^{-3}}{\rm cm}^{-3}\right)^{-1/3} \left(\frac{v}{0.3c}\right)^{-5/3} \\
F_\nu &\sim 10\,\mu{\rm Jy} \left(\frac{E}{10^{50}{\rm erg}}\right) \left(\frac{n}{10^{-3}{\rm cm}^{-3}}\right)^{\frac{p+2}{4}} \left(\frac{\epsilon_B}{10^{-2}}\right)^{\frac{p+2}{4}} \\
&\quad \times \left(\frac{\epsilon_e}{10^{-1}}\right)^{p-1} \left(\frac{v}{0.3c}\right)^{\frac{5p-7}{2}} \left(\frac{D}{40\,{\rm Mpc}}\right)^{-2} \left(\frac{\nu}{3\,{\rm GHz}}\right)^{-\frac{p-1}{2}}
\end{aligned}
$$

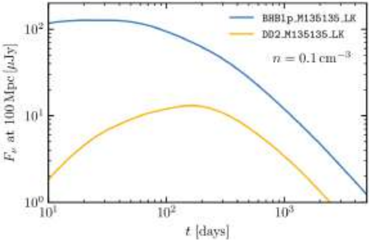
- characteristic peak time: deceleration time
- characteristic peak flux: synchrotron emission at peak time
- $2 \lesssim p \lesssim 2.5$

Synchrotron emission: EOS signature

- high velocity tail strongly depends on EOS
- synchrotron emission as EOS signature







Radice,Perego,Hotokezaka+ ApJ 2018

Conclusions

- large number of EM counterparts associated with compact binary merger
- large variety of properties, fingerprints of strong field dynamics
- modelling: good understanding, but substancial progresses needs to be done
- multimessenger era has opened unprecedent opportunities, also thanks to EM counterparts