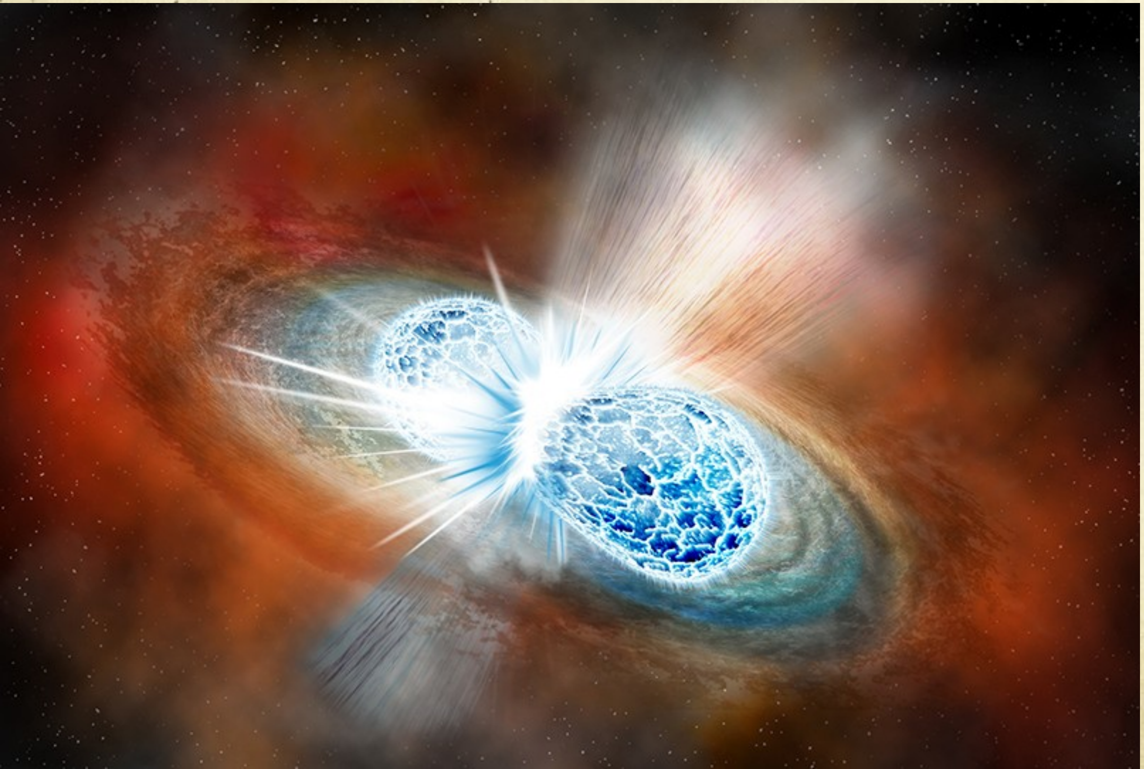
On the sGRB that accompanied GW170817



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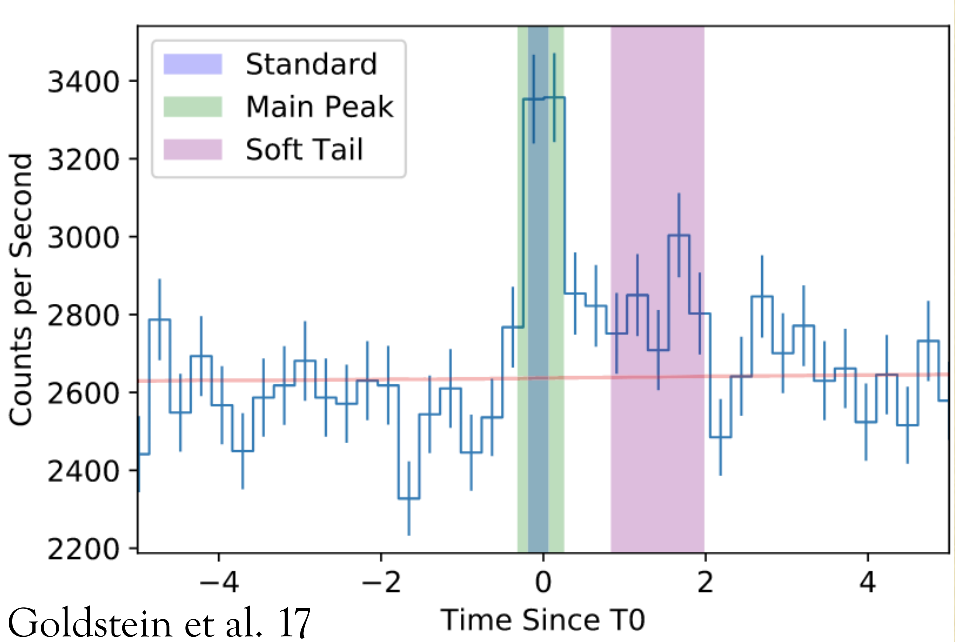
Sasha Tchekhovskoy (NW),
Ehud Nakar (TAU),
Ore Gottlieb (TAU),
Tsvi Piran (HUJI).

Introduction

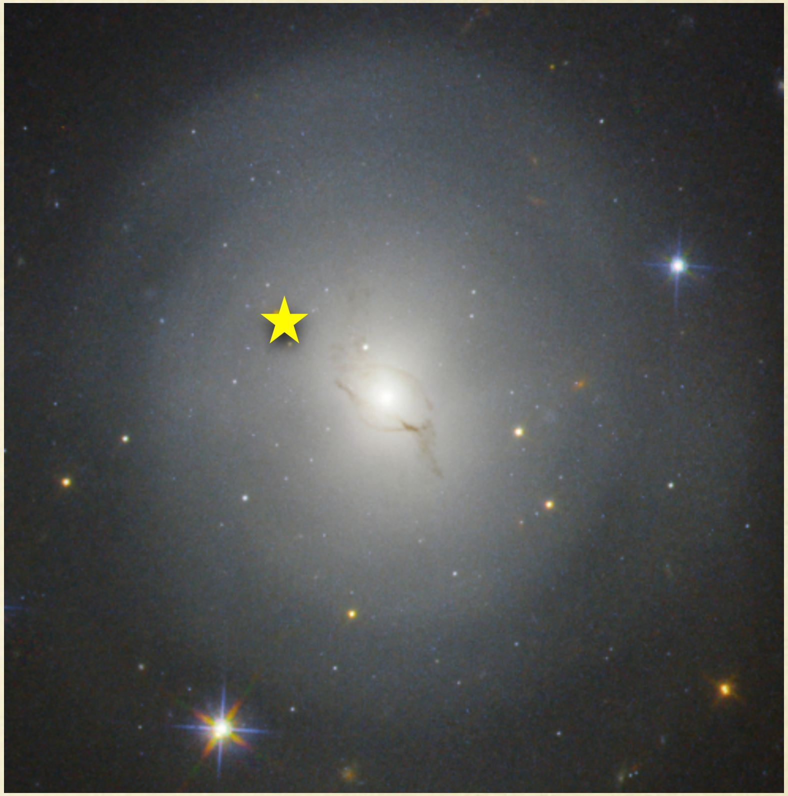
- The γ-ray event that accompanied GW170817 had sGRB characteristics:
  - $T_0 \sim 2$ after the merger
  - T90 ~ 2 sec



Goldstein et al. 17

Introduction

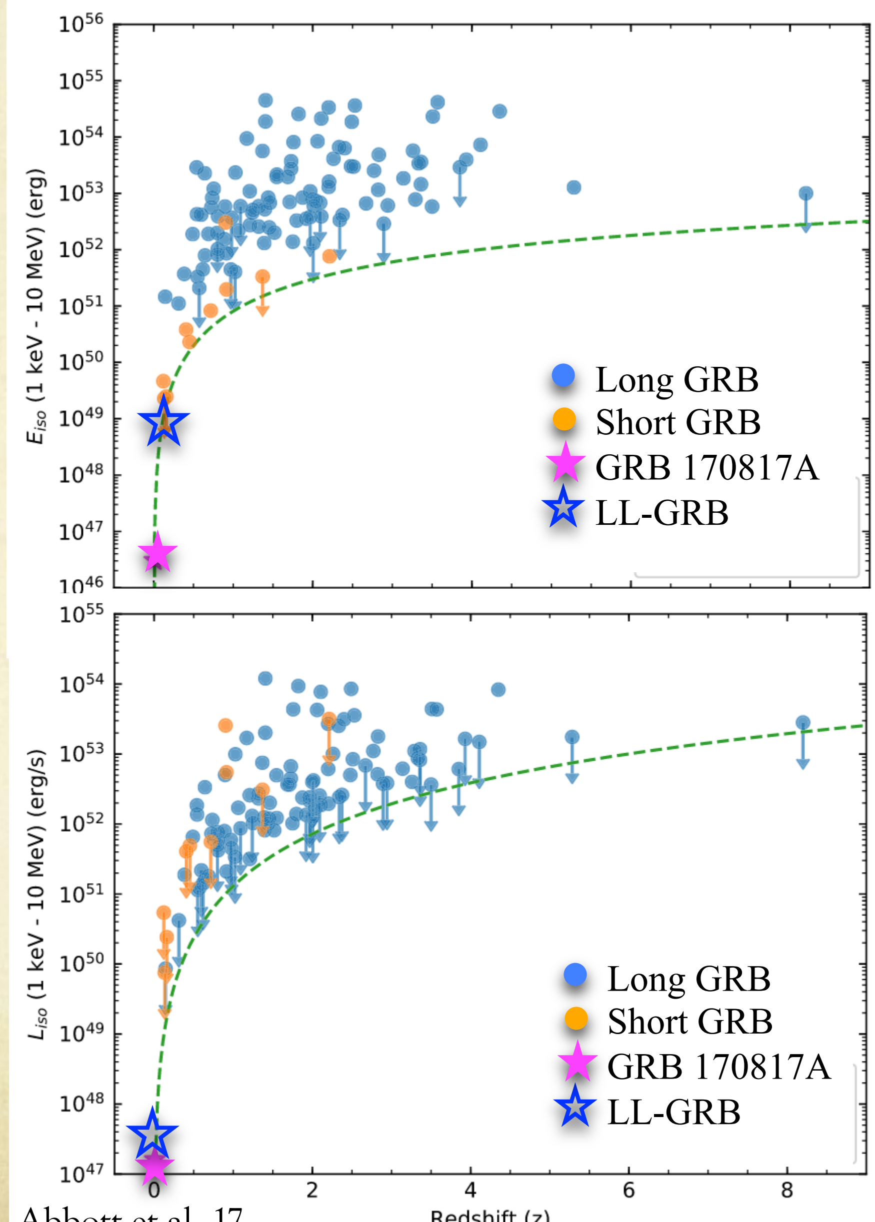
- The γ-ray event that accompanied GW170817 had sGRB characteristics:
  - $T_0 \sim 2$ after the merger
  - T90 ~ 2 sec
  - Red EG host with low SFR



Fong et al 2017

Introduction

- The γ-ray event that accompanied GW170817 had sGRB characteristics:
  - $T_0 \sim 2$ after the merger
  - T90 ~ 2 sec
  - Red EG host with low SFR
- On the other hand
  - $E_{iso}=6\times10^{46}$ erg
  - E_p=185 Kev
  - Soft spectral tail
- Similar properties in LL-GRBs attributed to shock breakout.
- Motivates us to explore this possibility.

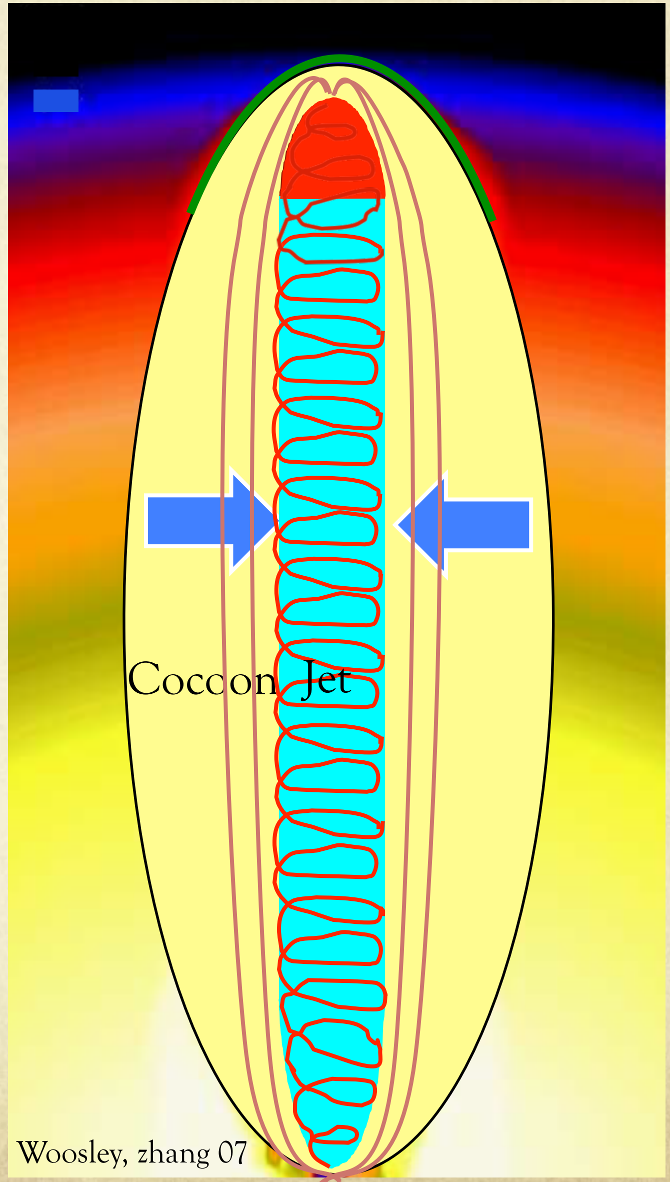


Abbott et al. 17

MHD jet in a medium

Jet propagation (stationary medium)

- Jet propagation forms a bow shock, and a slower moving head.
- The Shocked medium creates a cocoon.
- Collimation until $P_c = P_j$
- Cocoon pressure is roughly uniform in the z direction. Total energy comparable or greater than the jet.
- Jet's shape is close to a cylinder.
- MHD jets energy is carried by magnetic fields in the jet. Returning fieldlines are "dead".

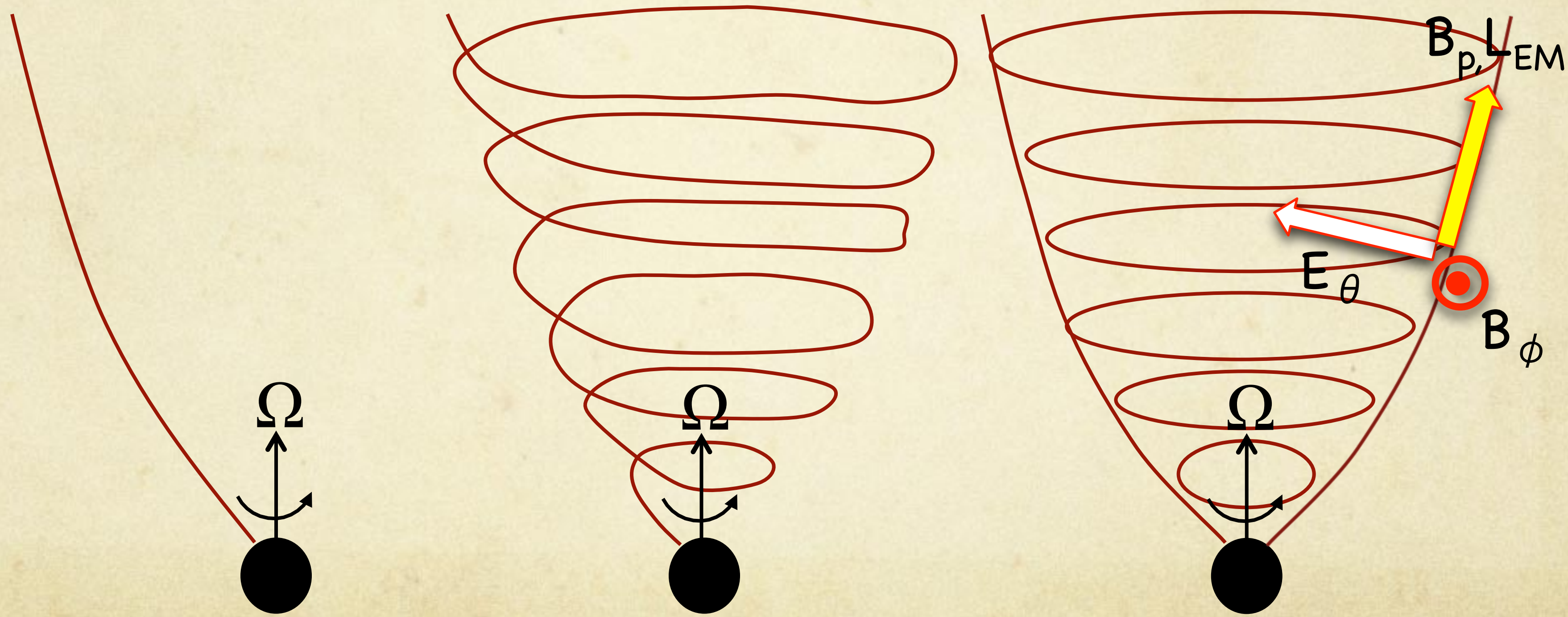


MHD Jet Launching – BZ

Poloidal field line connected to a central object

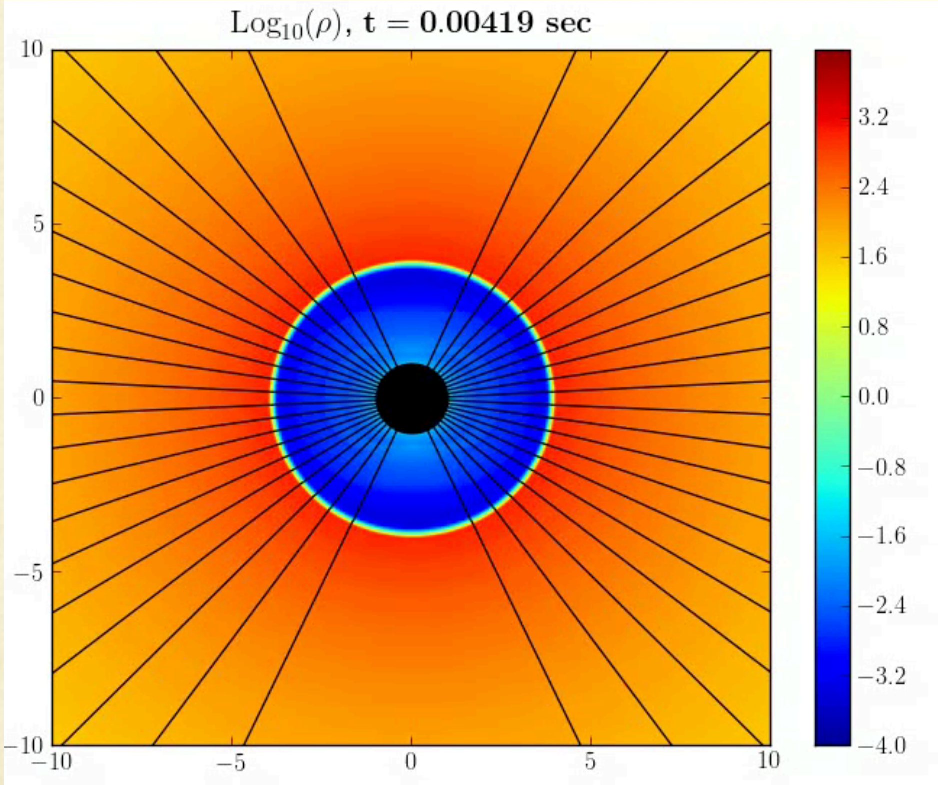
Rotation of the central object winds the field line creating azimuthal B_ϕ and E_θ

$E_\theta \times B_\phi$ gives Poynting flux in the direction of B_p.



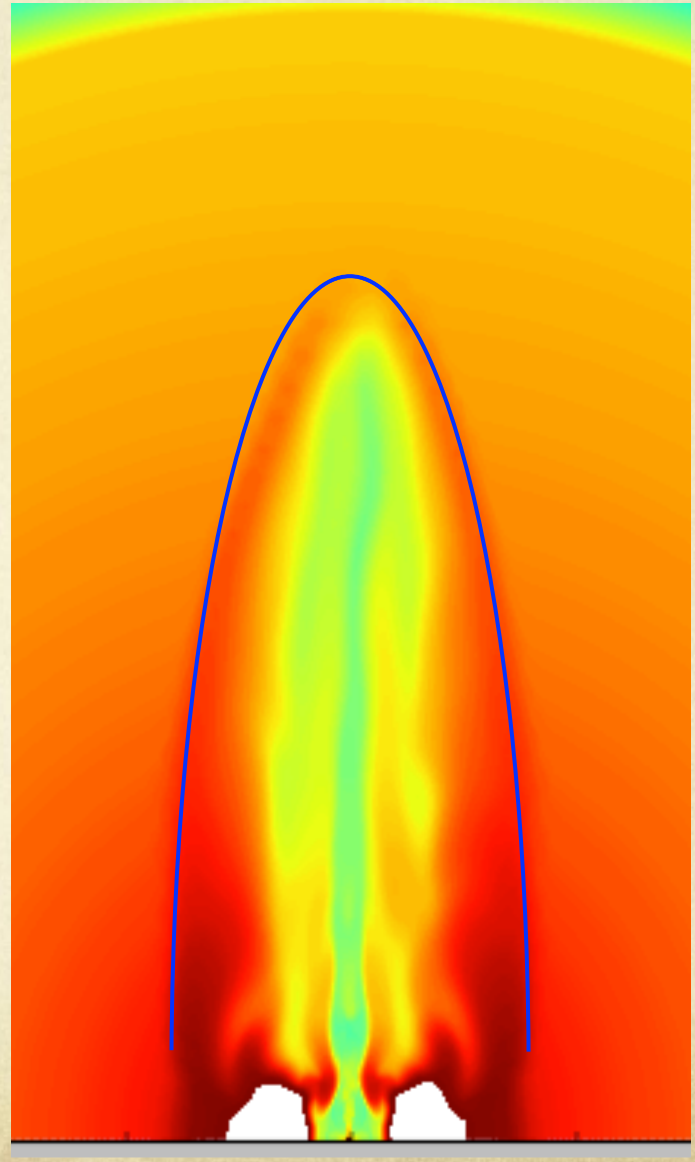
Jet Formation

- Helical field expands outwards radially carrying the jet energy.
- The medium blocks the free expansion.
- Toroidal pressure builds up from the rotation, and collimates the poloidal field lines (Uzdensky +06,07; Bucciantini+ 07,08,09).
- Poynting flux condenses to a smaller surface, paunches through.



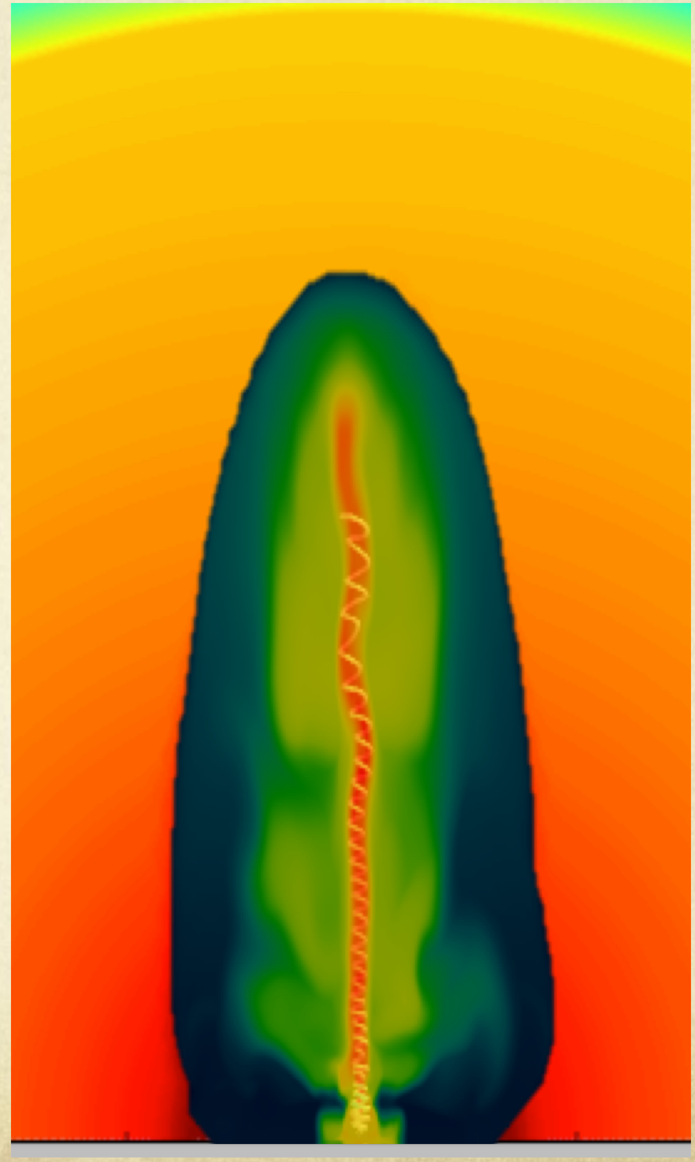
Propagation

- The jet pushes through the medium creating a cocoon which keeps it confined.
- Propagates at sub-mildly relativistic velocity.
- Jet matter that reaches the head is pushed sideways into the cocoon.



Cocoon energy composition

- Inner magnetized, and outer non-magnetized part.
- Lateral pressure balance.
- Mixing determines the properties of the two cocoon parts.
- Shape and pressure profile is dictated by the medium.



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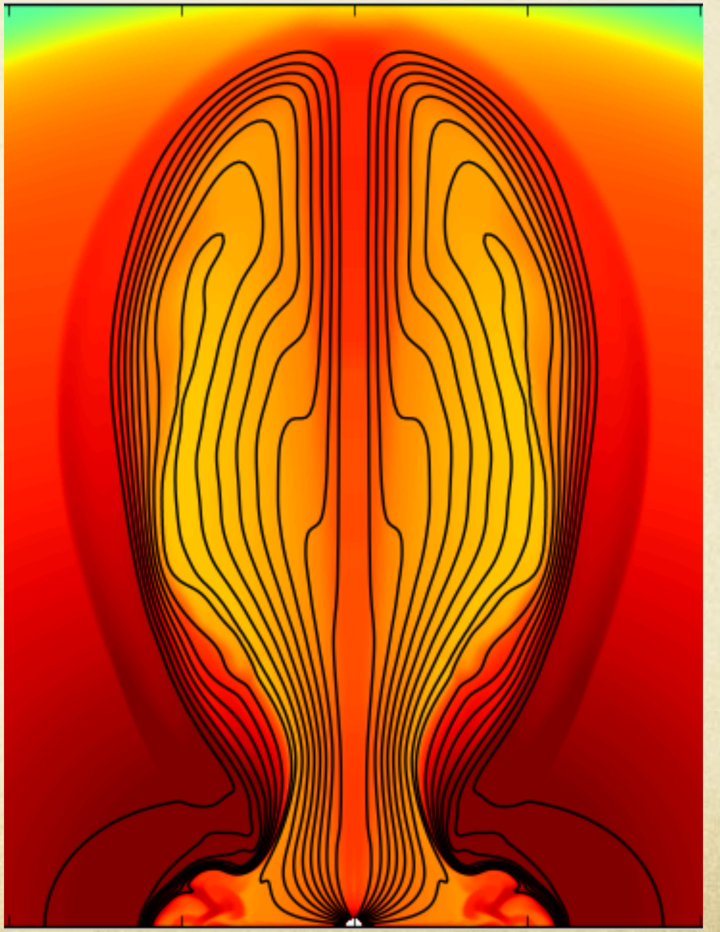
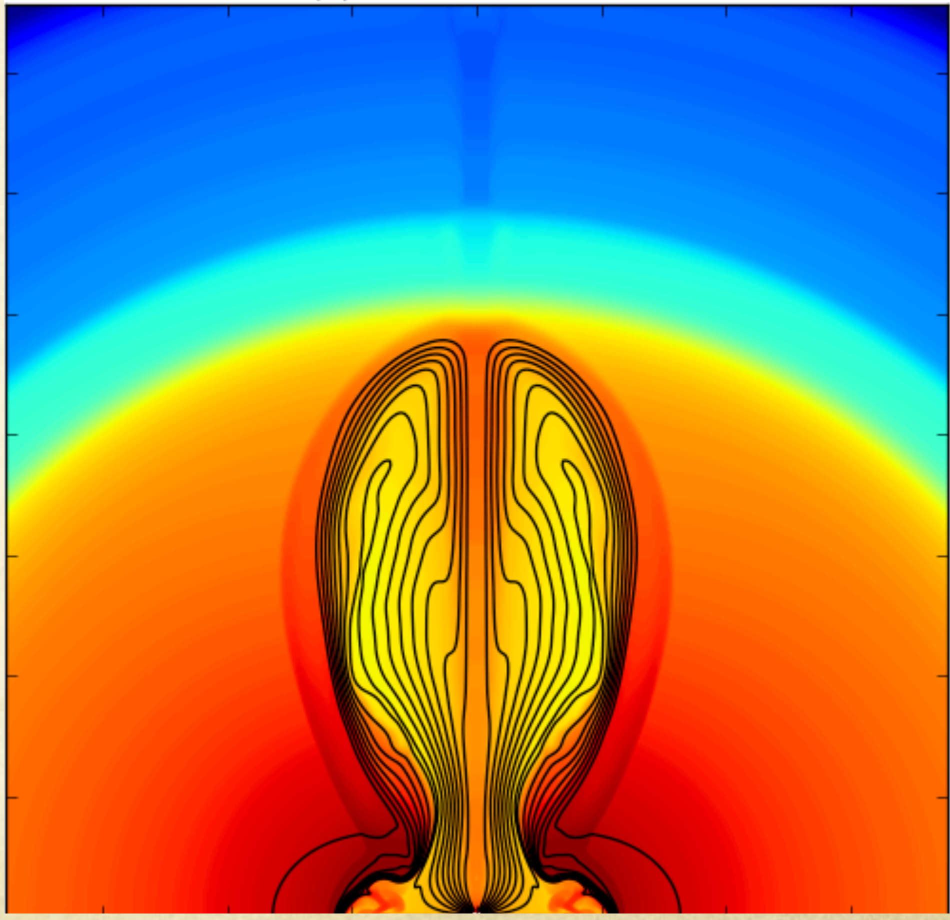


Breakout & acceleration

- Cocoon breaks out with the jet.
- Jet & cocoon matter accelerate and expand.
- Stratified shape: jet bounded by the inner and outer cocoon.
- Cocoon shock accelerates ahead and expands sideways as well.

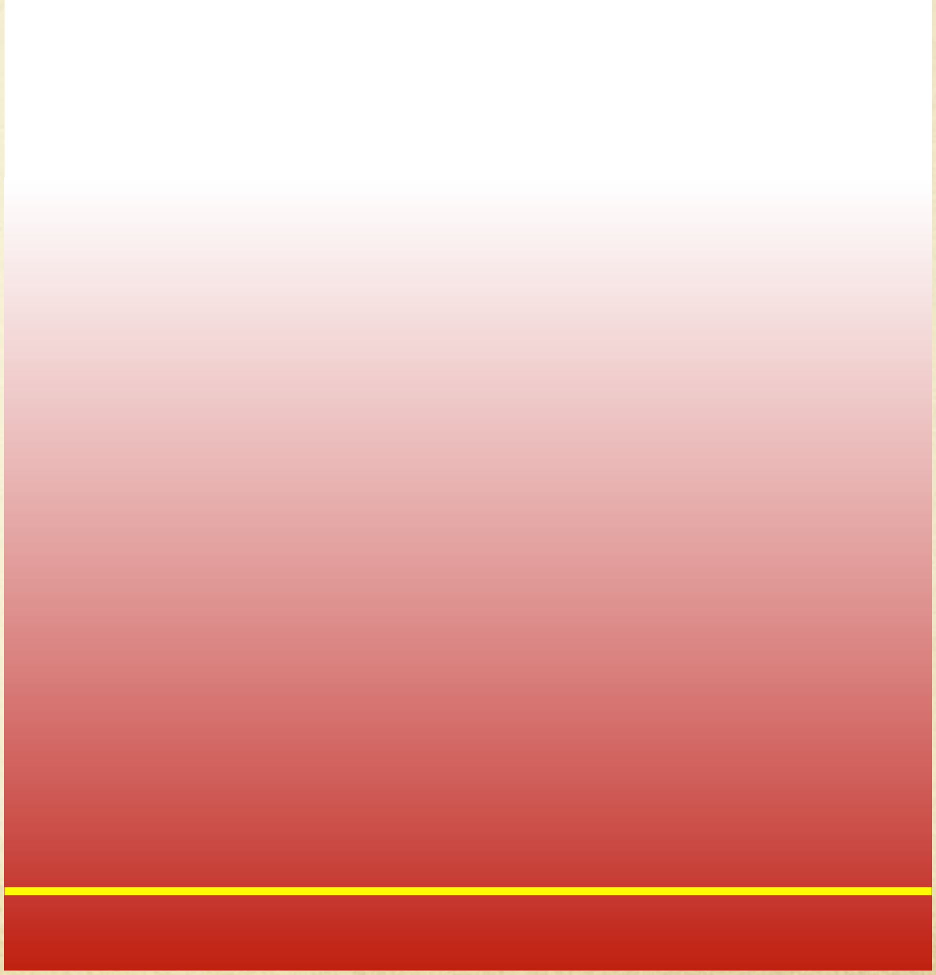


Shock breakout emission

(E. Nakar & R. Sari 2010, 2012)

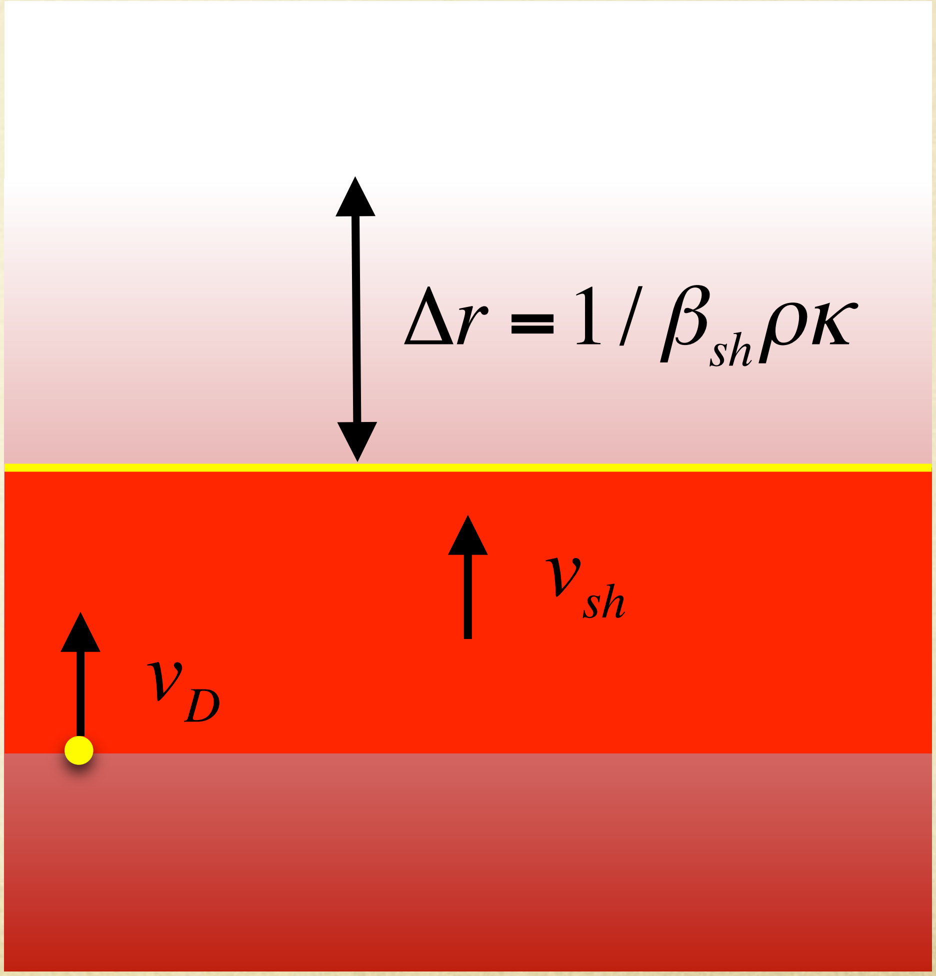
Physics of shock breakout

- Transition optically thick to optically thin medium.



Physics of shock breakout

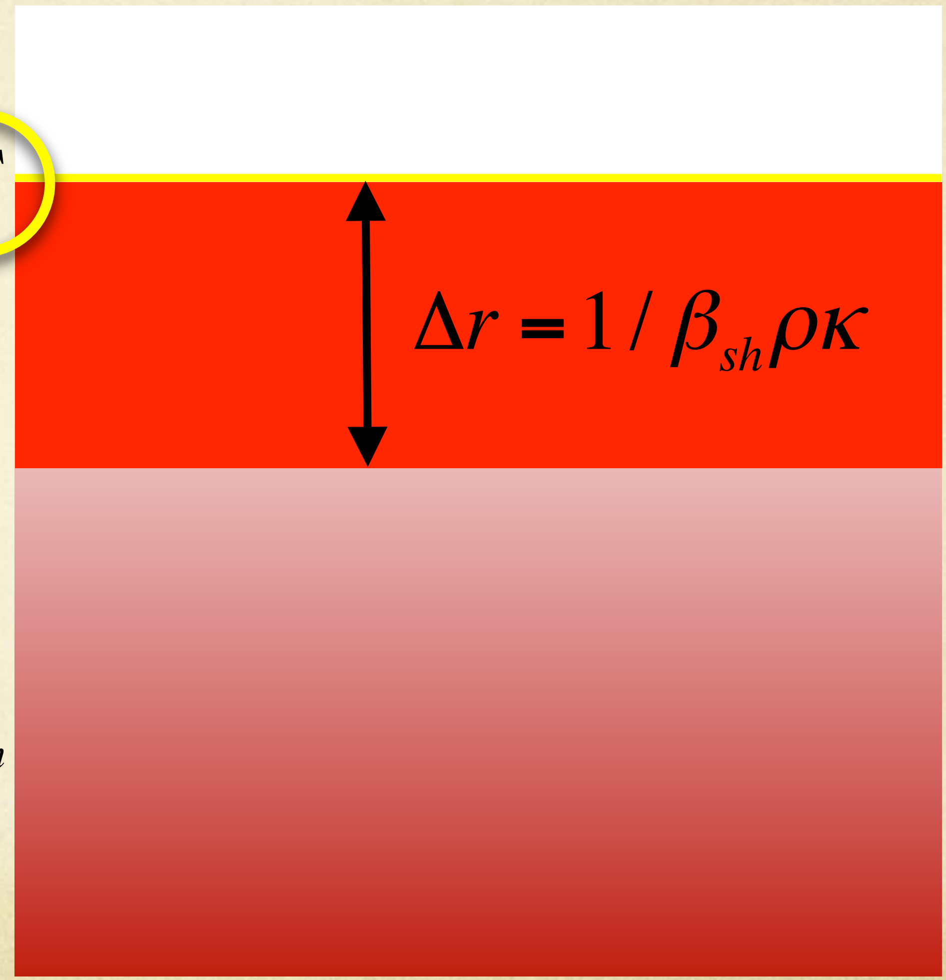
- Transition optically thick to optically thin medium.
- Shocked medium is hot, moves with velocity v_{sh}
- Radiation diffuses out at a velocity $v_D = c / \tau$
- Escapes from a layer in which $v_D = v_{sh}$ implying
  $\tau = \rho\kappa\Delta r = c / v_{sh}$
- Thickness of the layer -



Physics of shock breakout

- Available energy:

$$E = \underbrace{4\pi R^2 \Delta r}_{\Delta V} \cdot \underbrace{\rho c^2 (\Gamma_{sh} - 1)}_{e} \cdot \Gamma$$



- Typical "temperature":

$$kT \approx \frac{\varepsilon_e e}{n_{ph} + n_{\pm} + 2n_p} \approx \eta m_e c^2 \Gamma_{sh}$$

Granot et. al. 18

Breakout from dynamical ejecta

- Moving ejecta (NS merger):

$R_{bo} \approx ct_0 / (1 - \beta_{ej}) \approx 2 \times 10^{11}\,\mathrm{cm}$

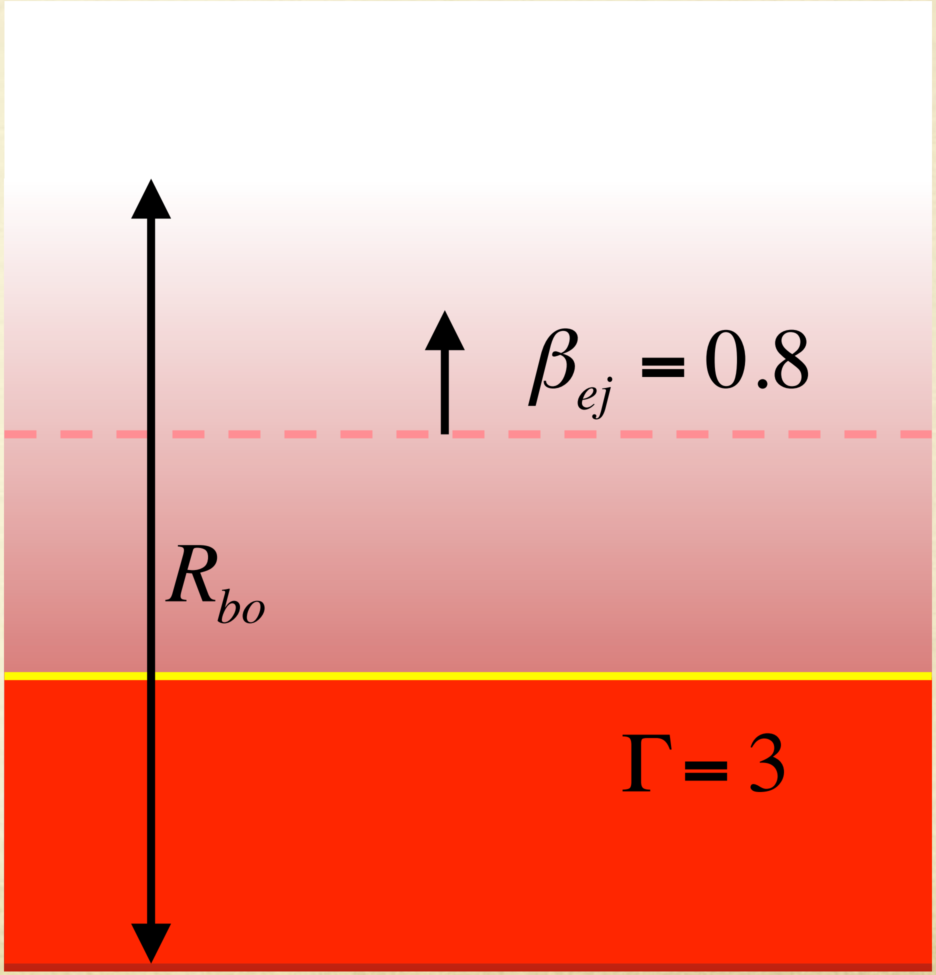
$\Gamma_{sh} \approx 1.3 < \Gamma$

$E \approx 10^{46}\, erg$

$kT \approx \eta m_e c^2 \Gamma_{sh} \approx 150\ \mathrm{KeV}$

$t_{GRB} \approx R_{bo}(1 - \beta_{ej}) / c \approx 1.5\,\mathrm{s}$

$\Delta t_{GRB} \approx R_{bo}(1 - \beta) / c \approx 0.5\,\mathrm{s}$

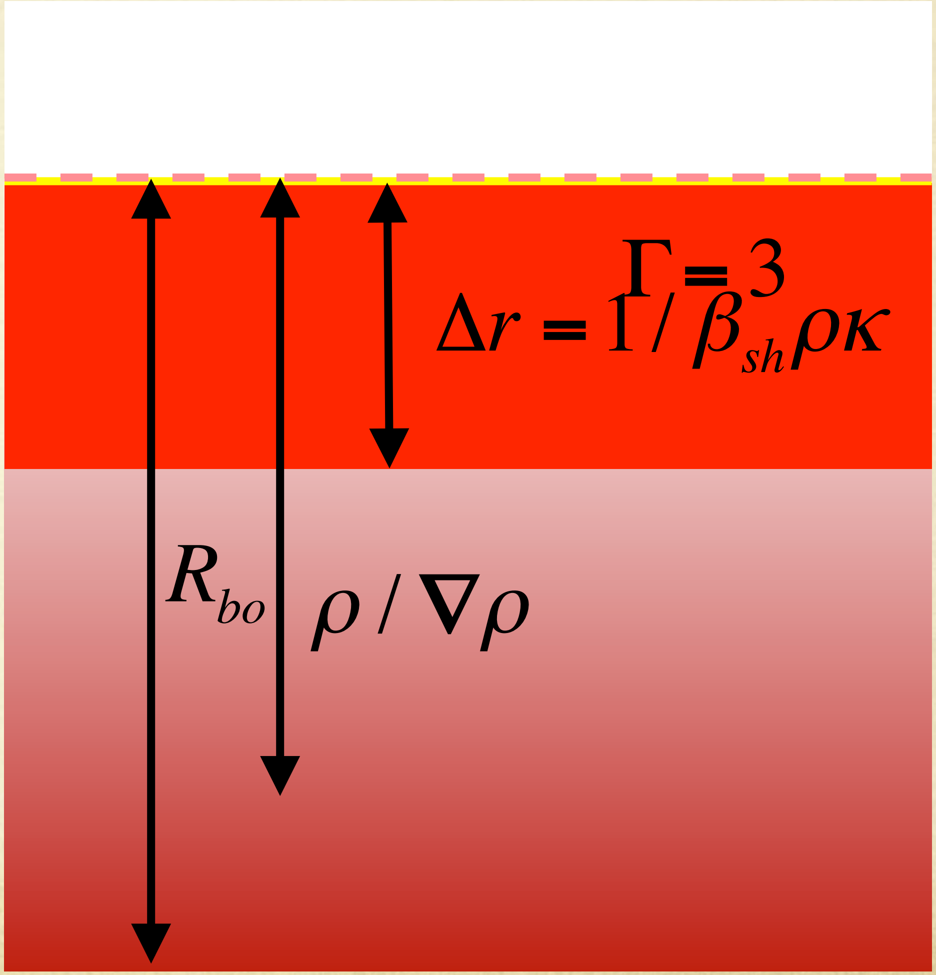


Post breakout evolution - planar

- Planar phase: $R_{bo} < R_{sh} < 2R_{bo}$

  $\rho / \nabla\rho >> \tau / \nabla\tau \sim \Delta r$

  - **Δr** nearly constant.
  - Photons diffuse from deeper shells, no adiabatic cooling.
  - **E** increases, Composite non-thermal spectrum.



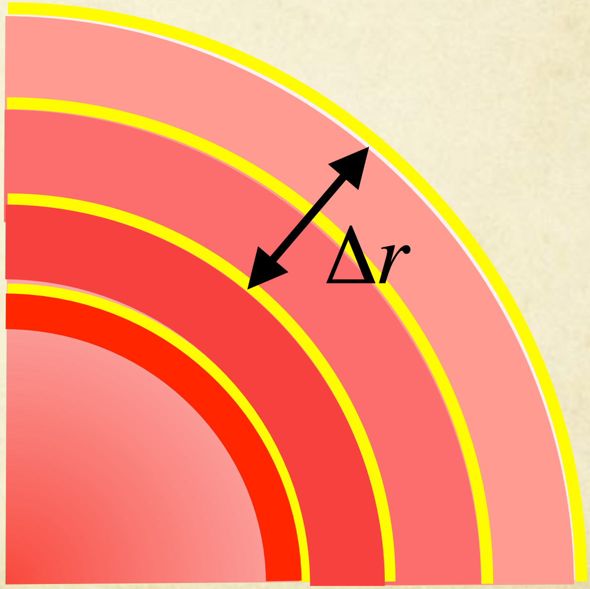
Post breakout evolution-spherical

- Planar phase: $R_{bo} < R_{sh} < 2R_{bo}$

  $$\rho / \nabla\rho >> \tau / \nabla\tau \sim \Delta r$$

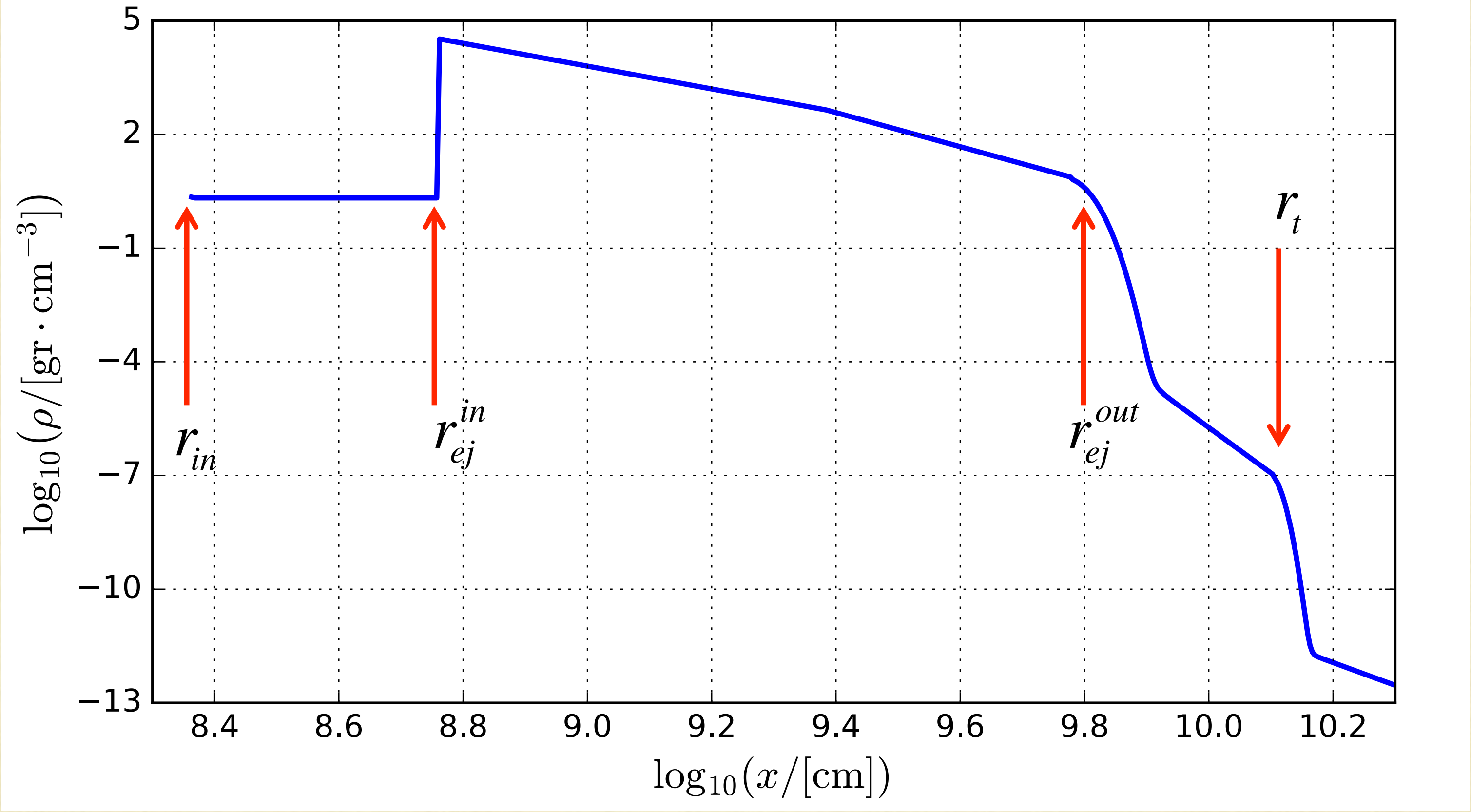
  - **Δr** nearly constant.
  - Photons diffuse from deeper shells, no adiabatic cooling.
  - **E** increases, Composite non-thermal spectrum.

- Spherical phase: $2R_{bo} < R_{sh}$
  - **Δr** increases with R, **τ** drops.
  - Photons diffuse out more efficiently from deeper cooler shells.
  - Quasi thermal spectrum.



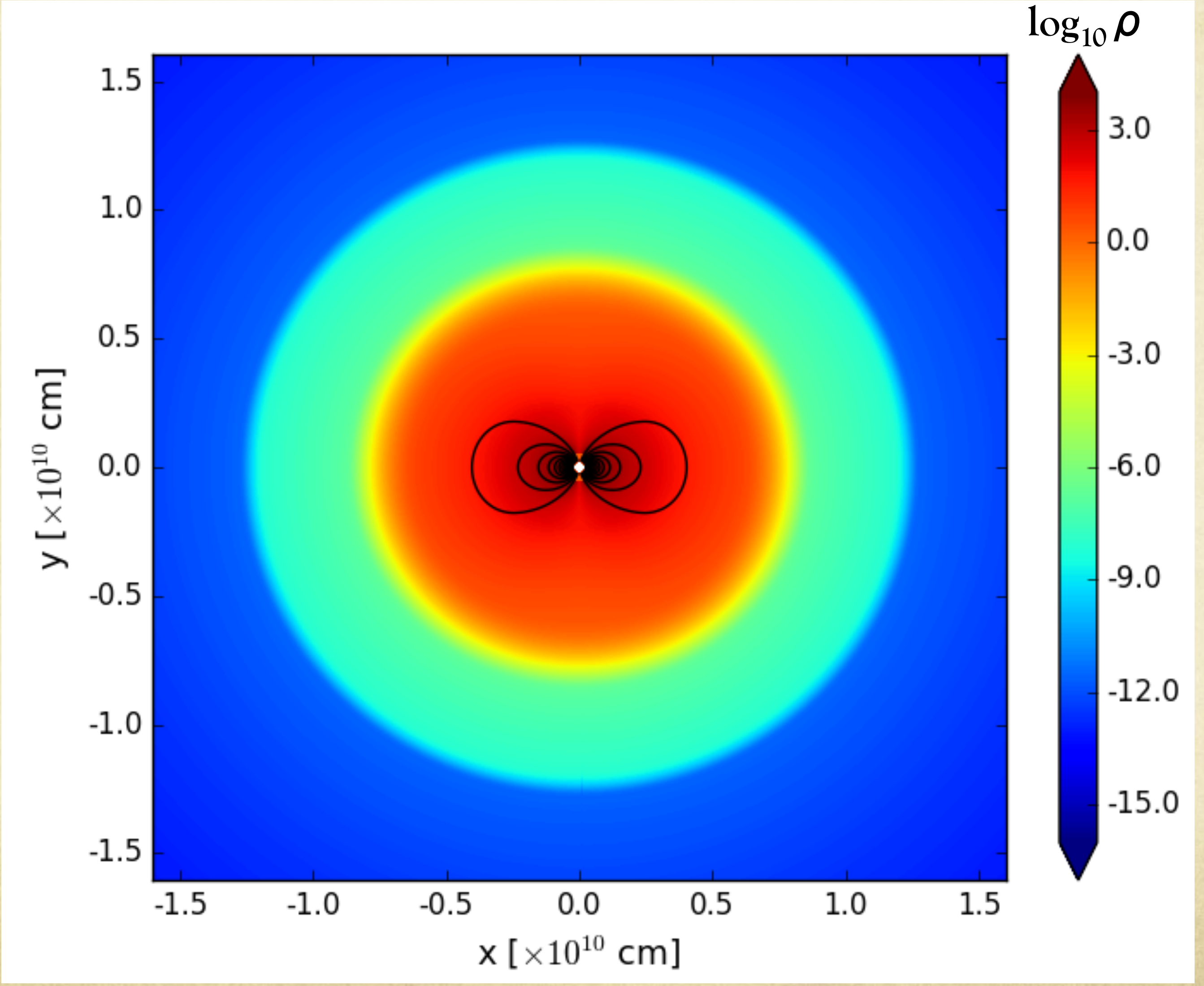
2D simulations of a MHD jet in dynamical ejecta

System setup

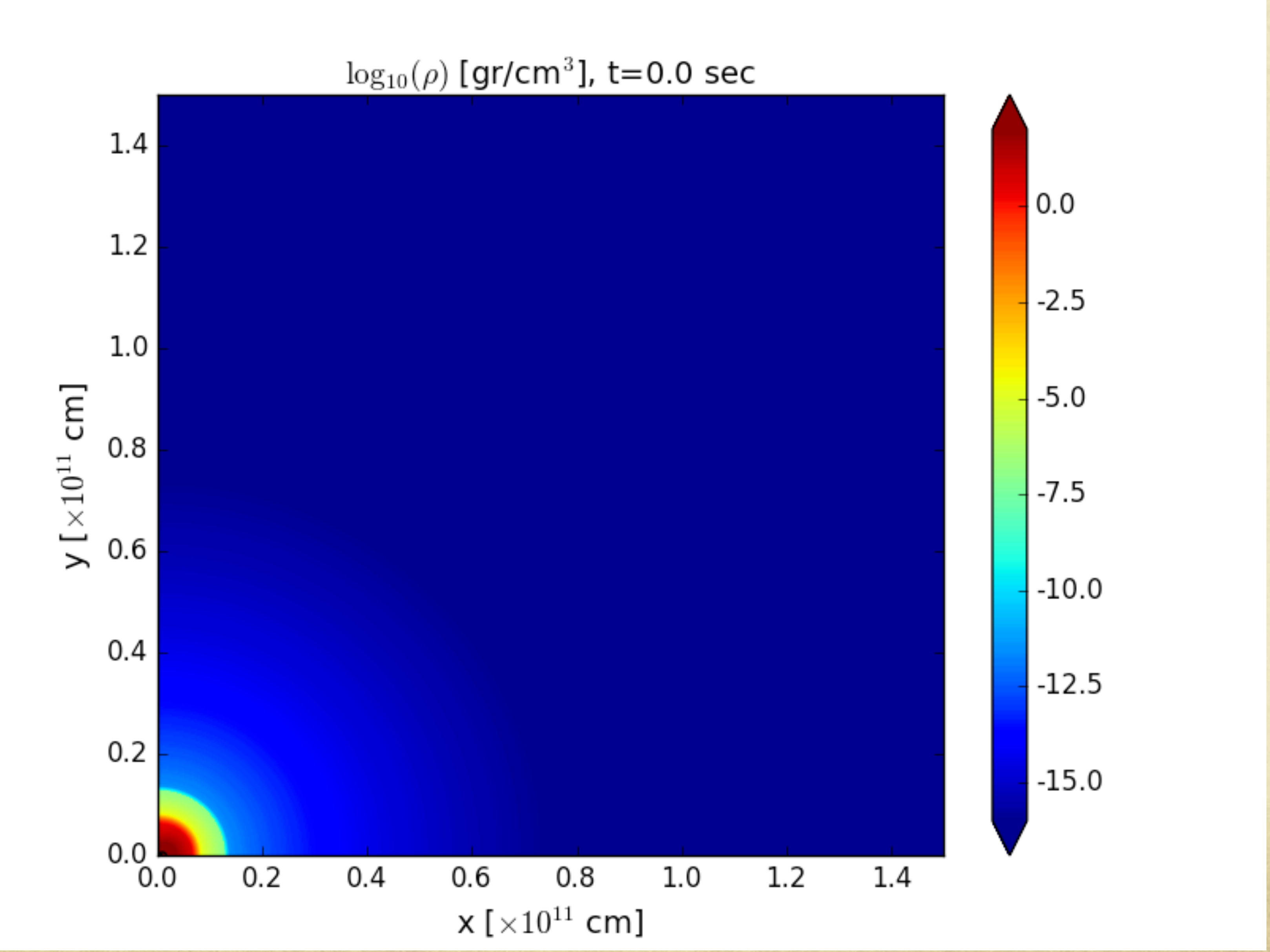


Hotokezaka et al 2014; 2018

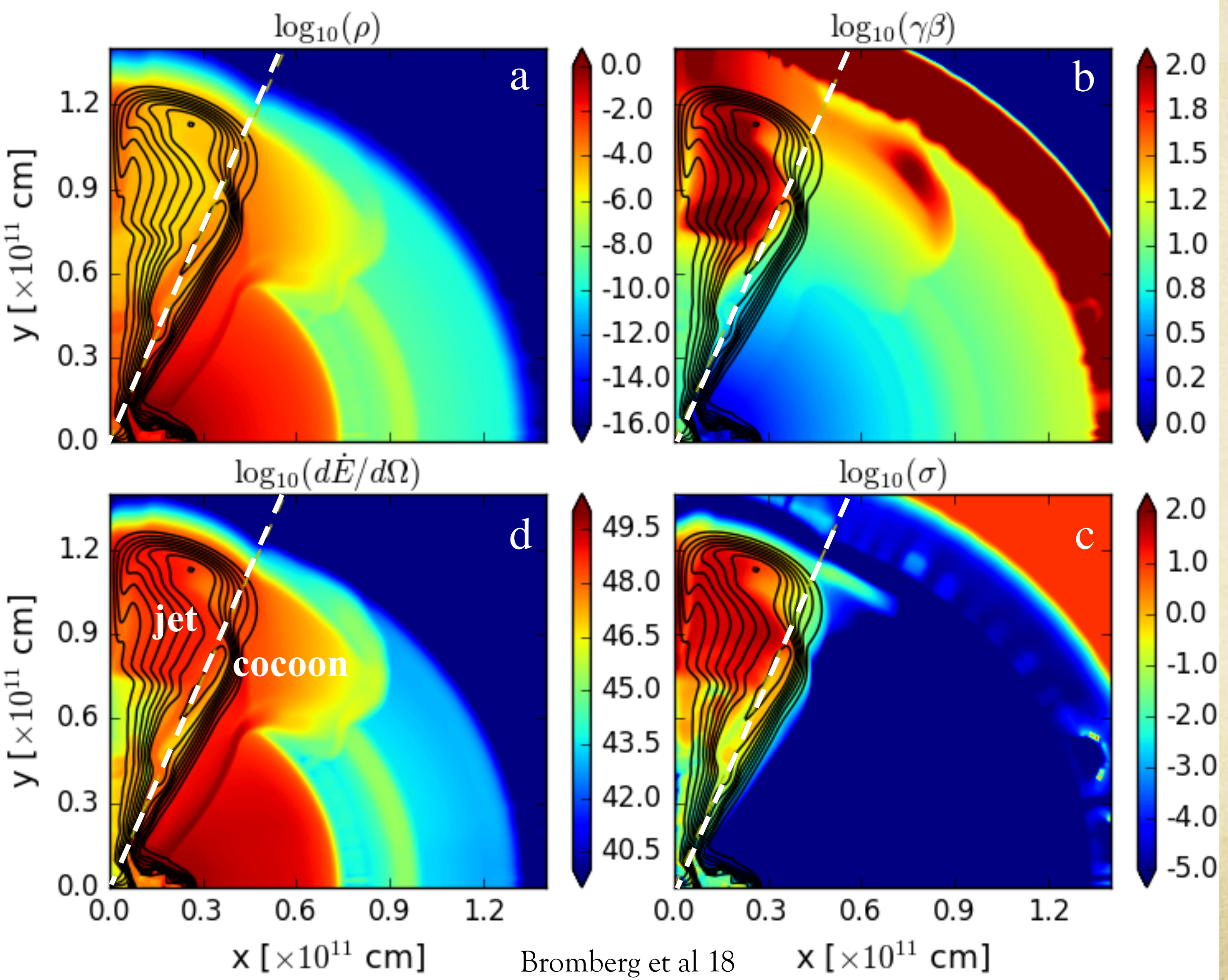
System setup



Jet propagation



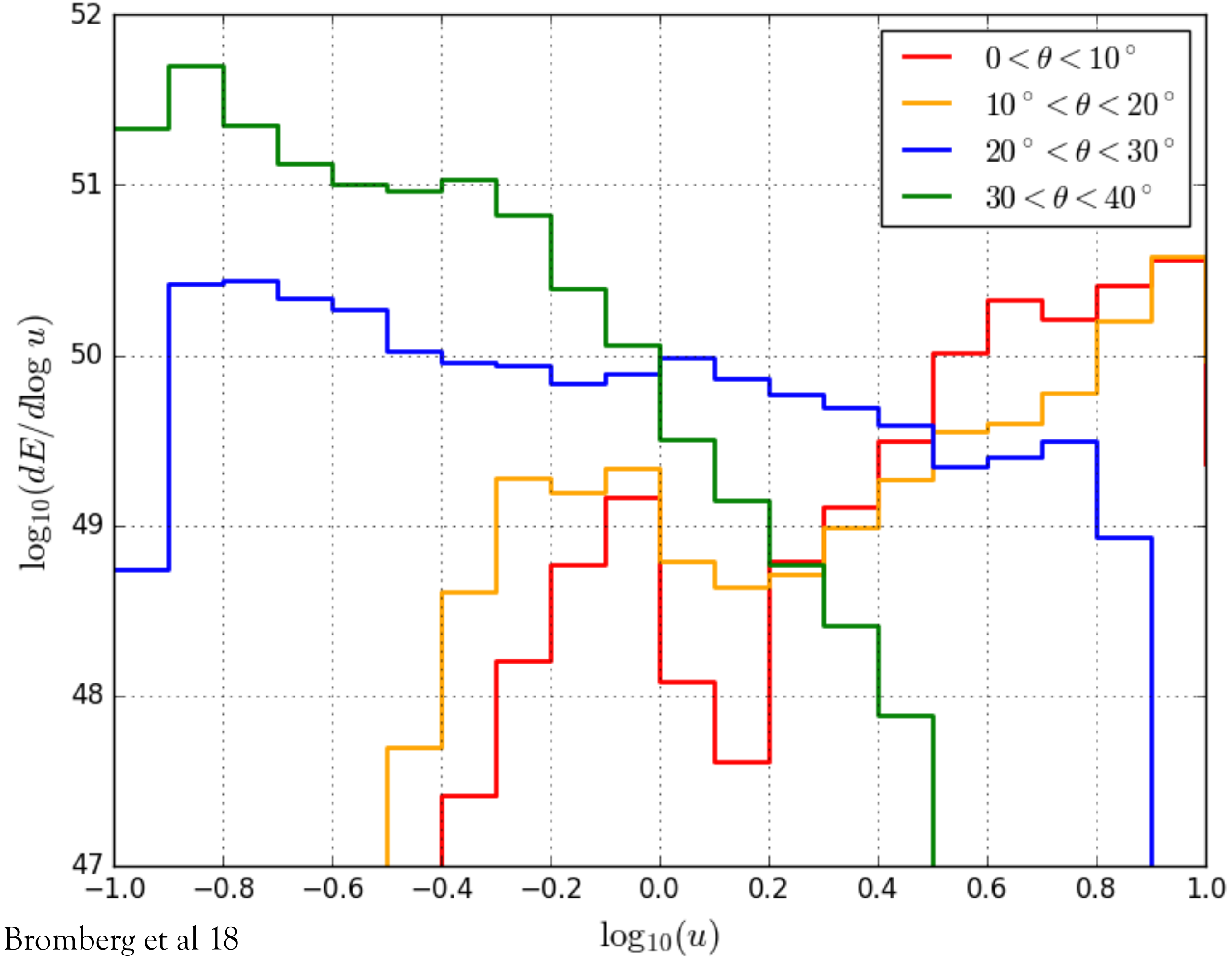
The shock breakout



Bromberg et al 18

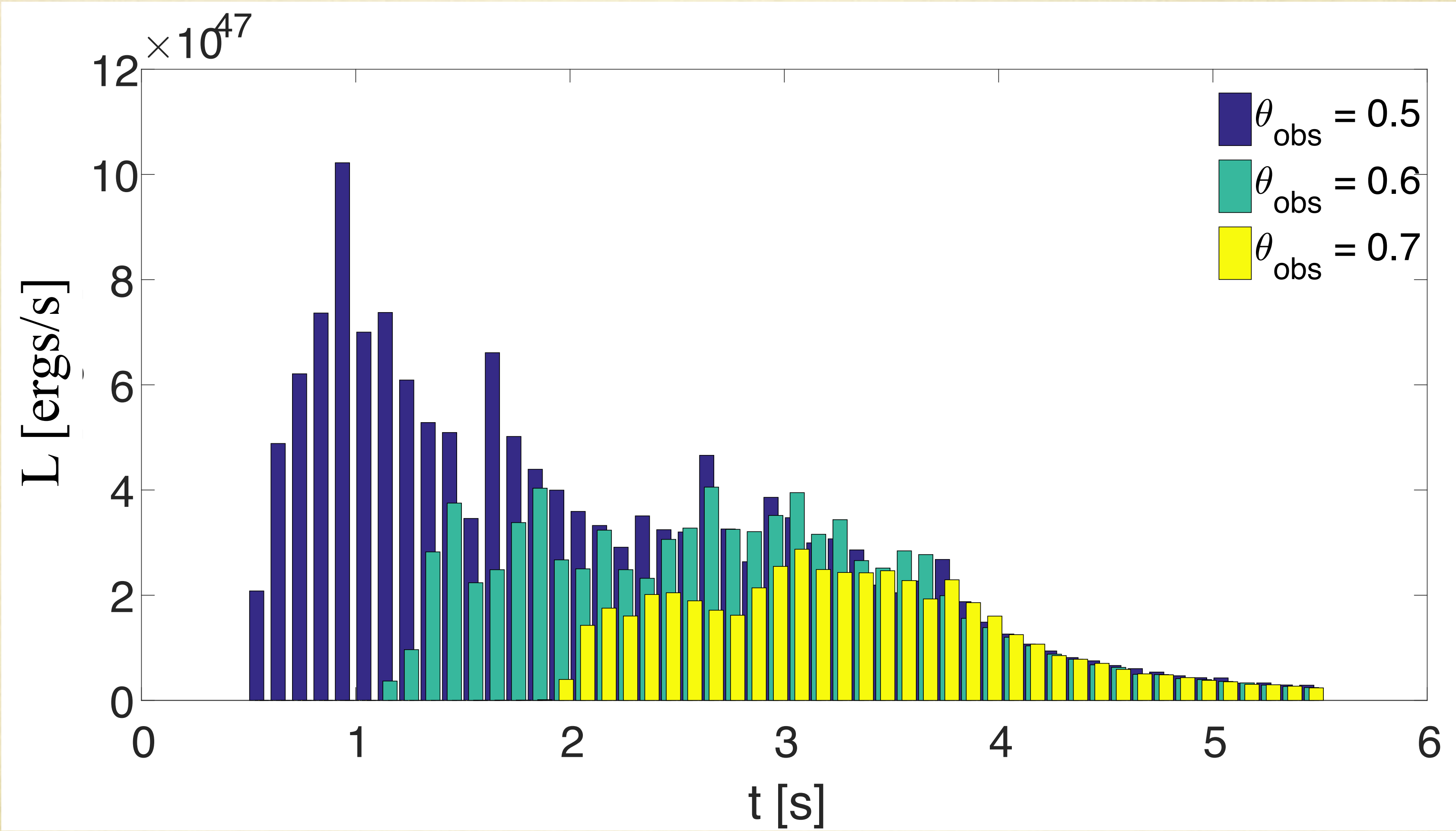
Energy per velocity bin

dE/dlog(u)



Bromberg et al 18

Synthetic lightcurves & Spectra



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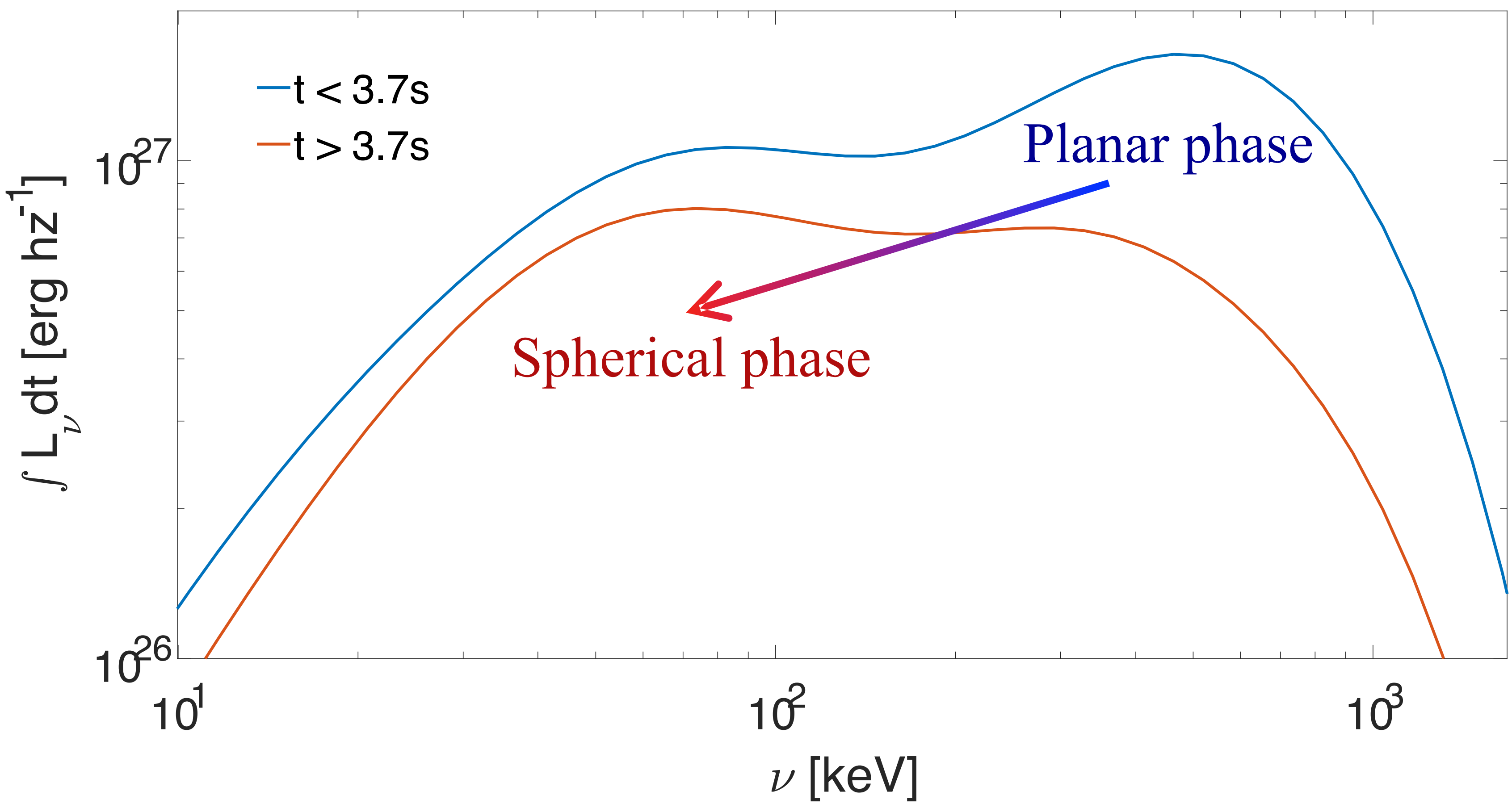
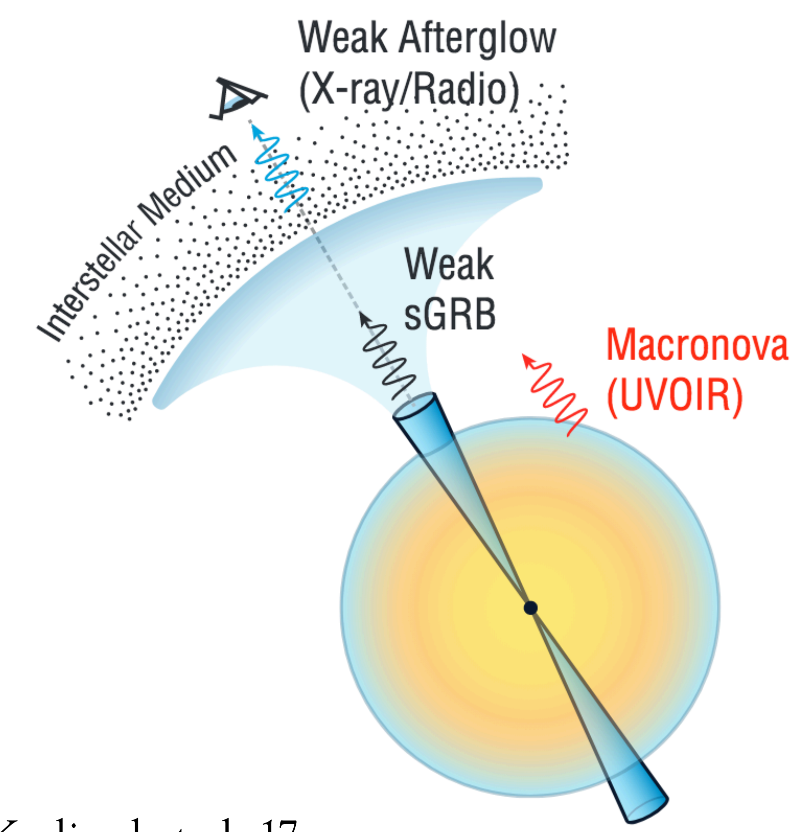


Where is the jet?

On axis jet emission

- $E_{\gamma,iso}$=3×10^{46} ergs
- $L_j = 2\times10^{44}\,\theta_j^2$ ergs/s
- For $M_{ej} \approx 10^{-2} M_\odot$
- Jet breakout time: $t_b \approx 15$ s
- Requires
  - Very low ejecta mass (<3×10^{-6} $M_\odot$).
  - More powerful jet (E_{iso}>3×10^{49} ergs).

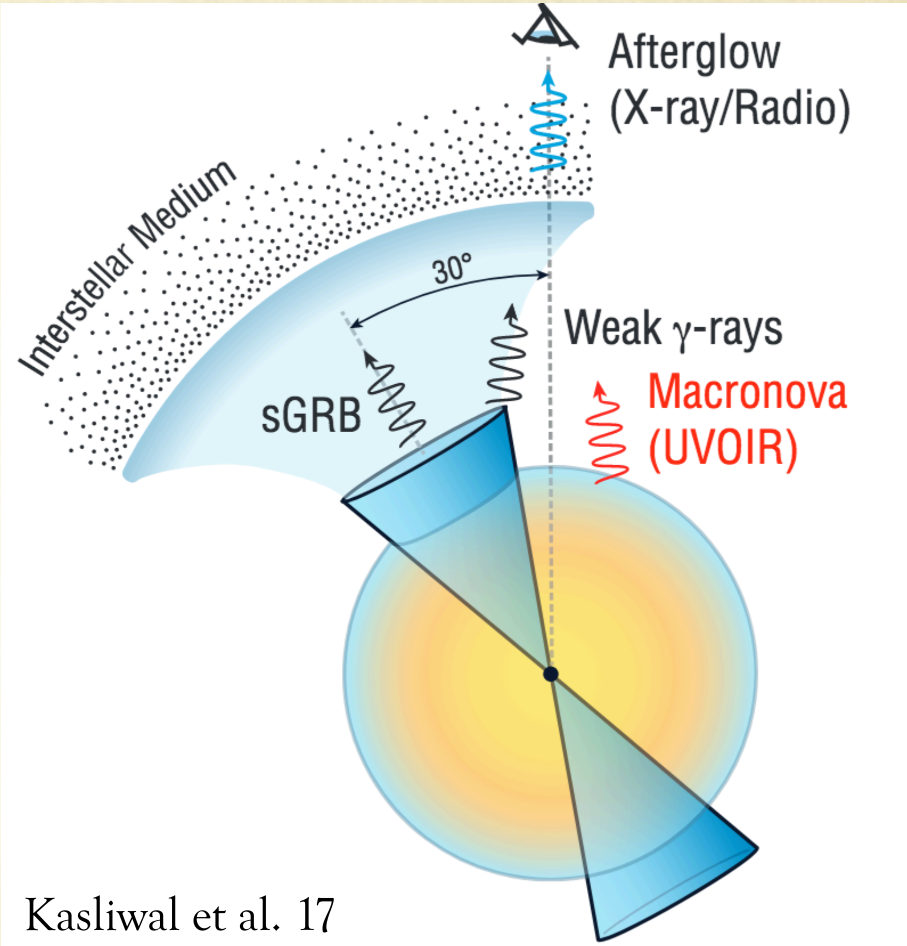


Kasliwal et al. 17

Off axis jet emission

- $E_{off} = E_{GRB} / (\Gamma \Delta\theta_{off})^4$
- Typical SGRB energies require boost

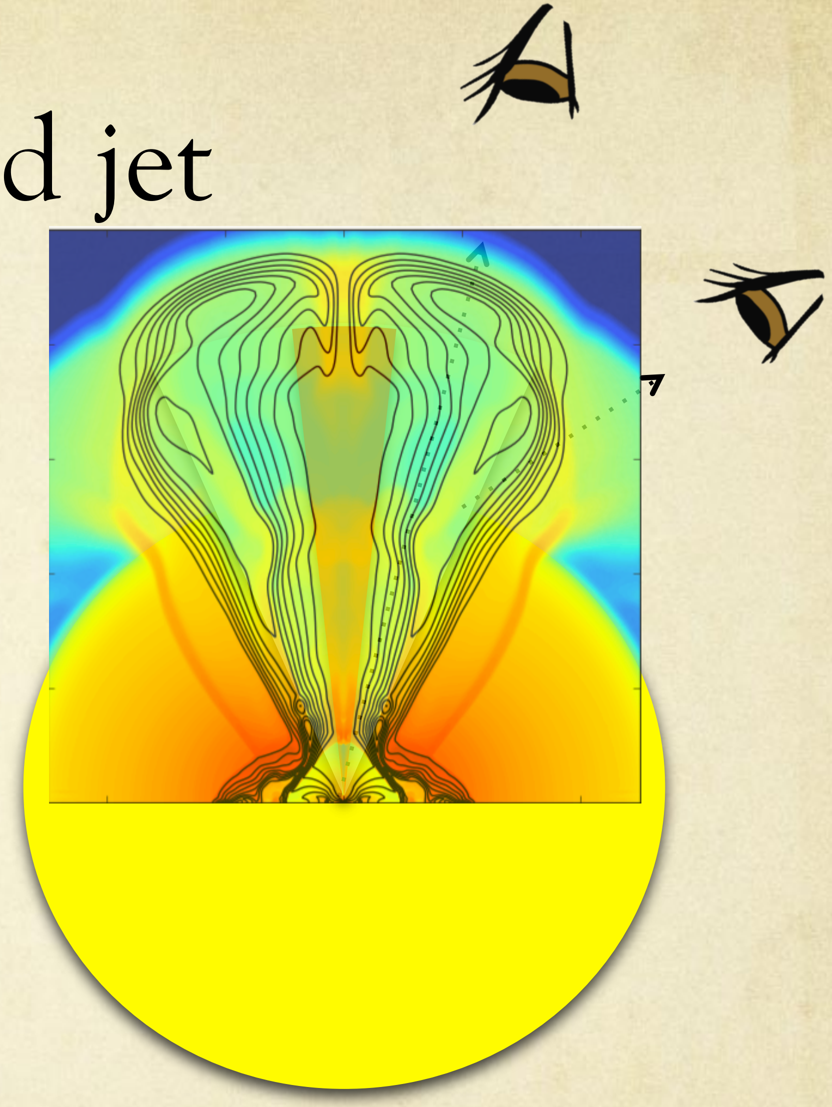
  $E_{GRB} / E_{off} = 10^3 - 10^6$
- Larger E_{GRB} requires larger Γ to avoid high τ.
- $\theta_{off} \leq 0.1$ rad.
- Bright AG (unless $n<10^{-6}$)
- Hard on-axis $E_{peak} \geq 10Mev$



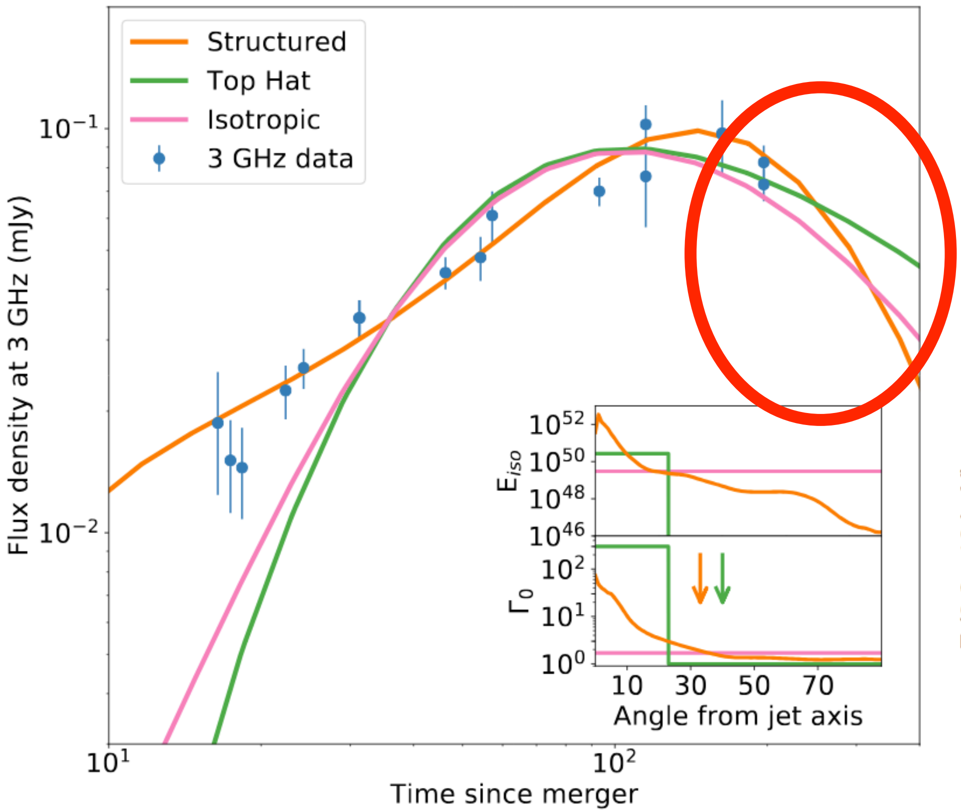
Kasliwal et al. 17

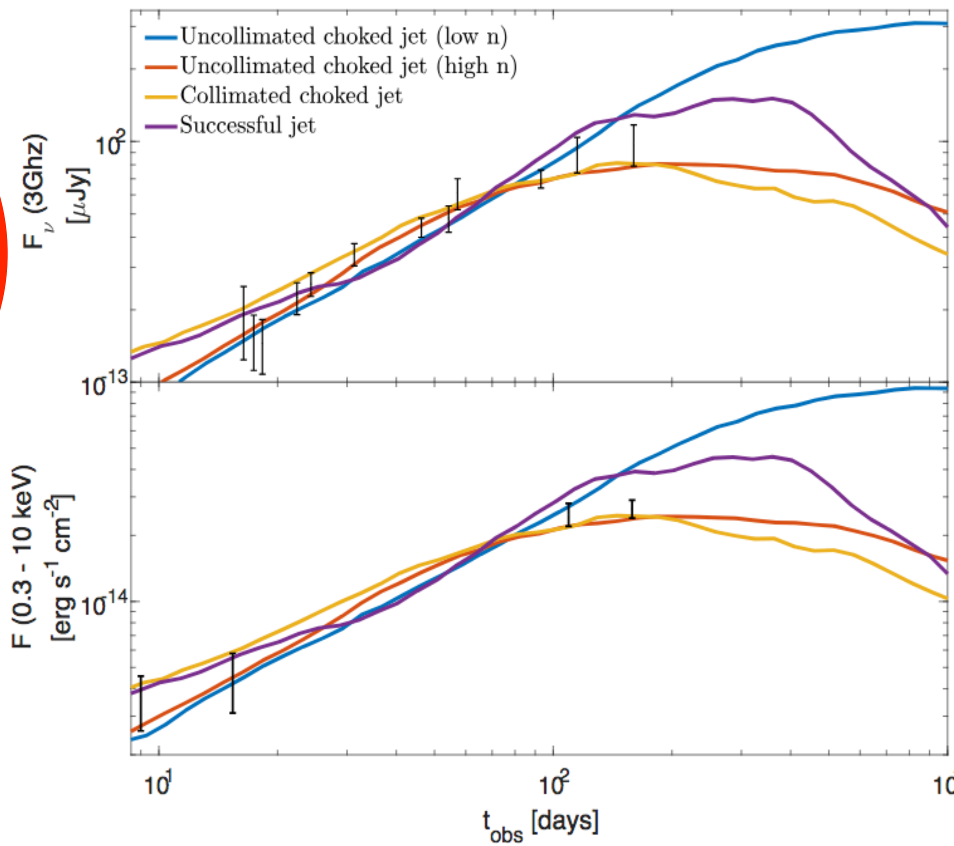
Structured jet

- "On axis" emission:
  - Low power & low **Γ**.
  - Quenched by the cocoon.
  - Cocoon too powerful.
- "Off axis" emission:
  - Moderate **Γ~10**
  - Moderate amplification $L_{iso}\sim5\times10^{47}$ ergs/s,
  - Inconsistent with sGRB observations.



Jet signature in radio AG



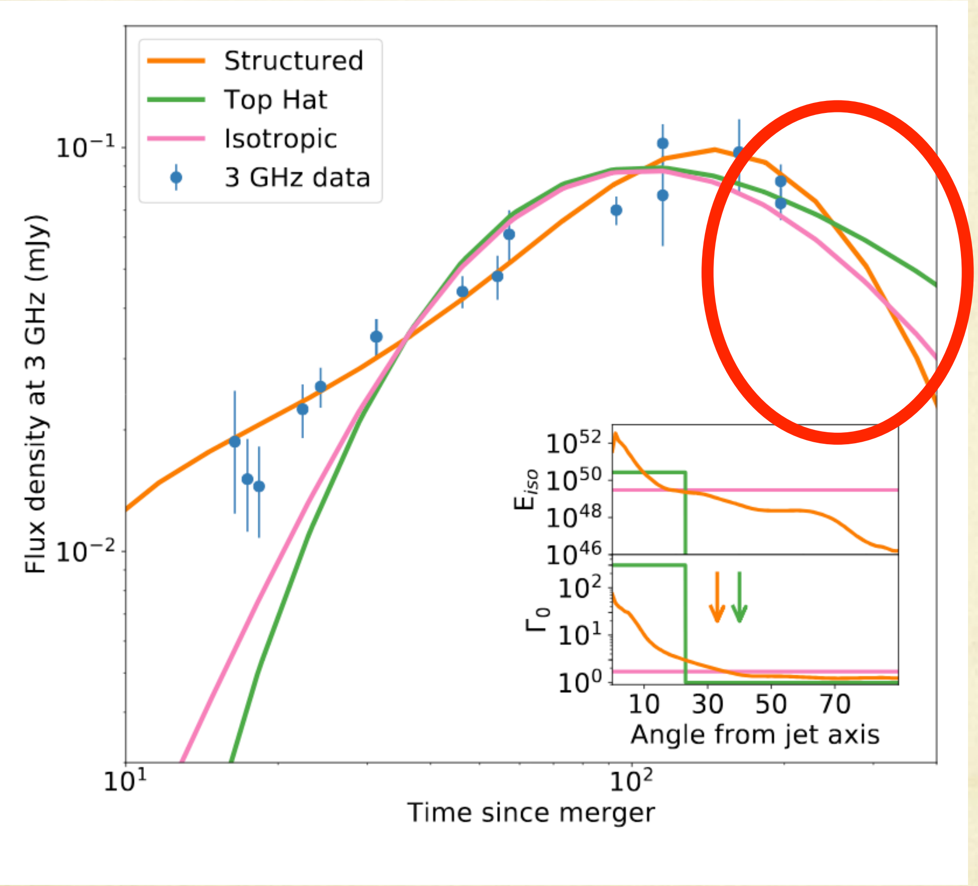


Lazzati et al 2018

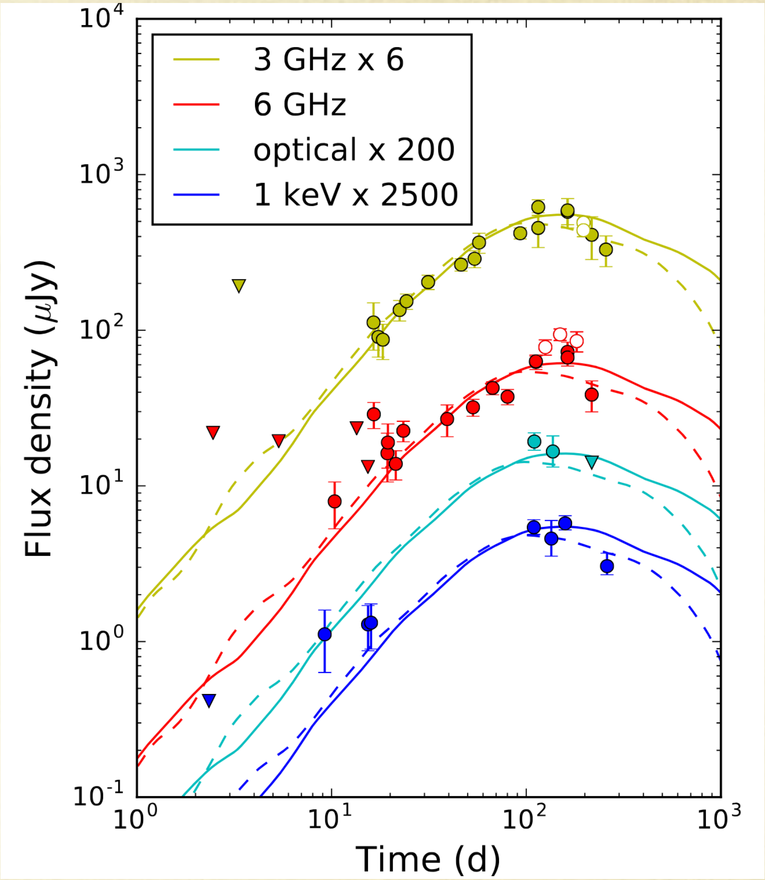
Nakar et al 2018

A signature of a successful jet is a steep drop in the AG lightcurve

Jet signature in radio AG



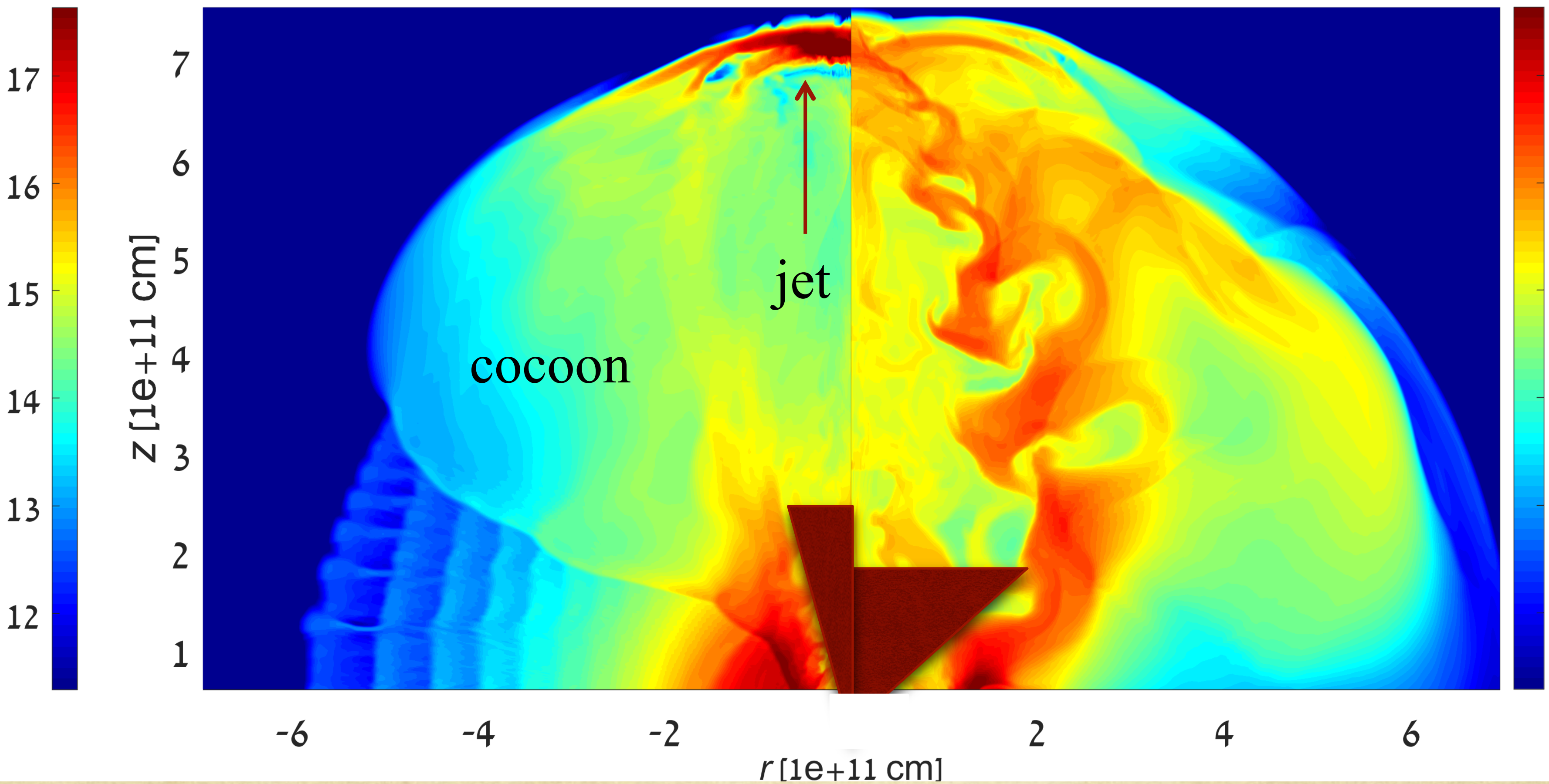
Lazzati et al 2018



Alexander et al 2018

A signature of a successful jet is a steep drop in the AG lightcurve

How can a jet fail?



O. Gottieb et. al. 17

Conclusions

- GRB 170817A had unusual characteristics for sGRBs: (low power, low E_p, soft spectrum)
- Similar to LL-GRBs in Long GRBs.
- Motivates the testing of shock breakout models.
- A jet propagating in an ejecta of NS merger produces a wide angle cocoon with comparable energy.
- The breakout of the cocoon shock from the ejecta can produce the observables.
- We may see a new low luminosity type of SGRBs,.
- Late time radio observations can be used to discriminate between off-axis jets and cocoon emission.