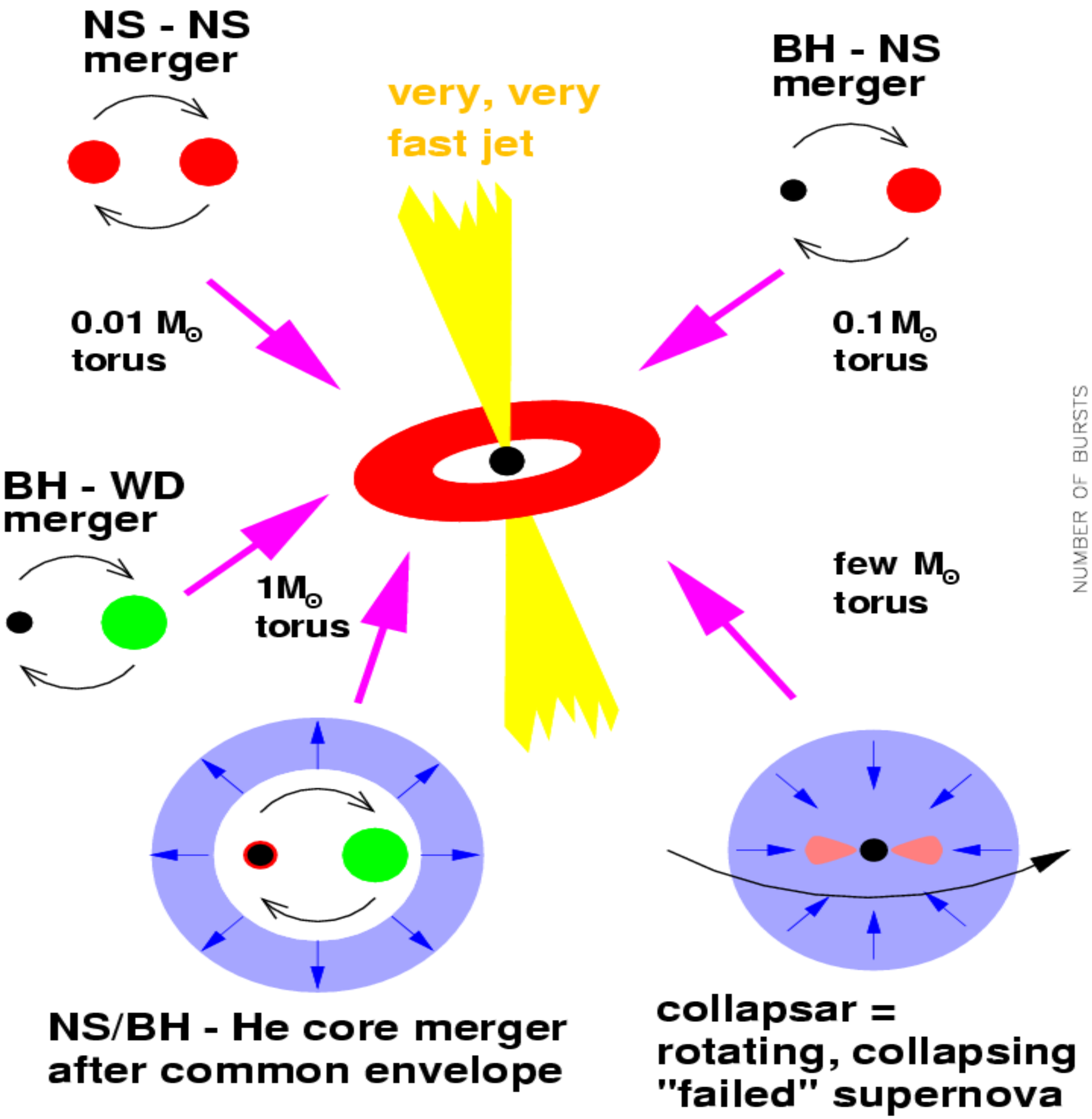
Central Engines and Jets of long GRB

Peter Mészáros,
Pennsylvania State University

Yukawa Inst. Workshop
Kyoto, Nov. 2013

GRB: standard paradigm

Hyperaccreting Black Holes

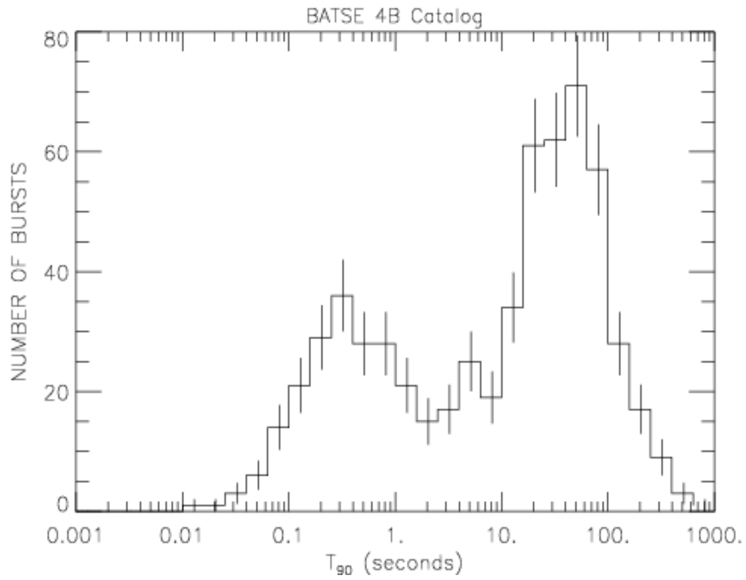


M. Ruffert, H.-Th. Janka, 1998

Bimodal distribution of $\mathbf{t}_\gamma$ duration

←↓**Short**

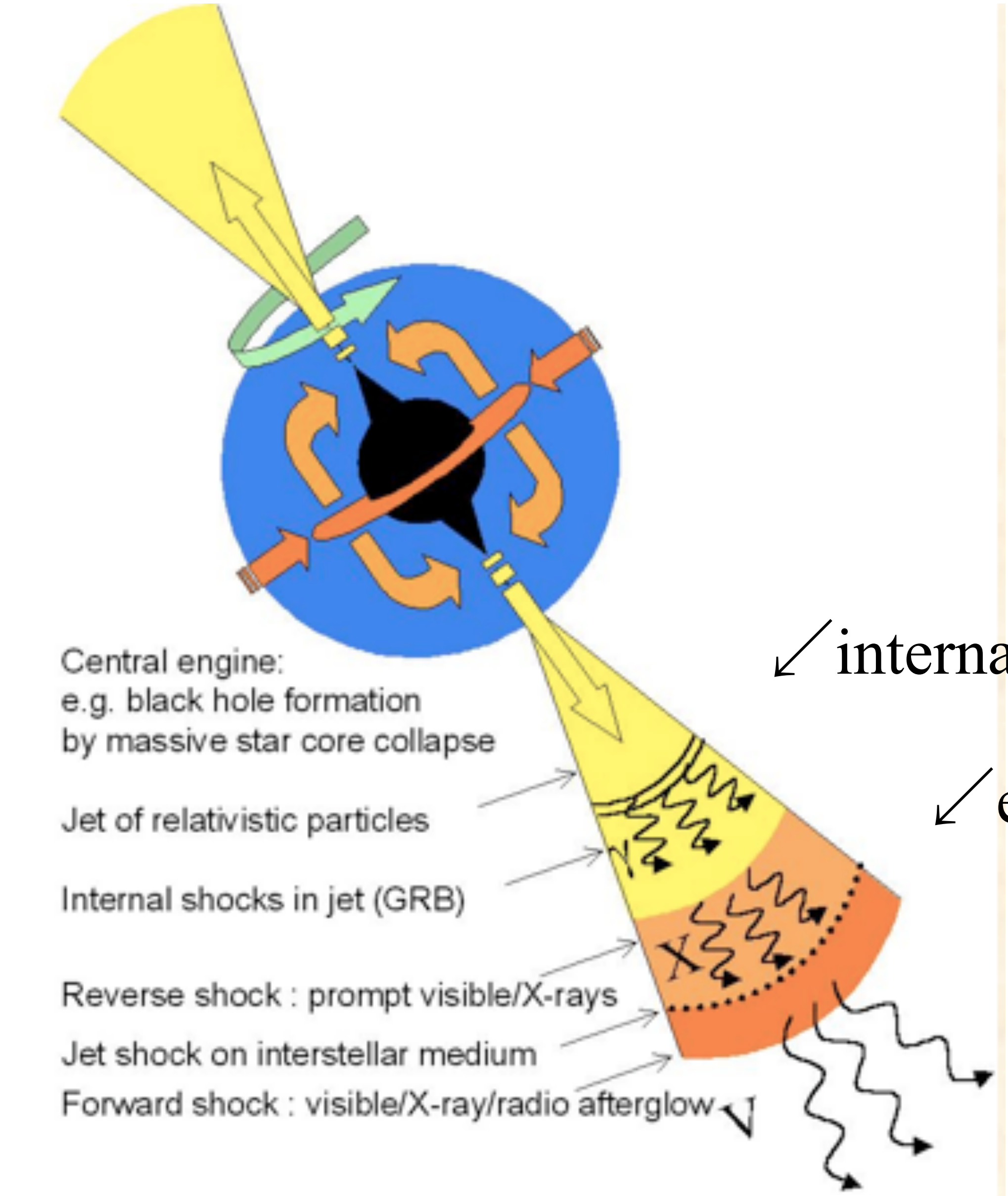
(t_g< 2 s)



→↑**Long**

(t_g >2 s)

Classical view of GRB Jet at work



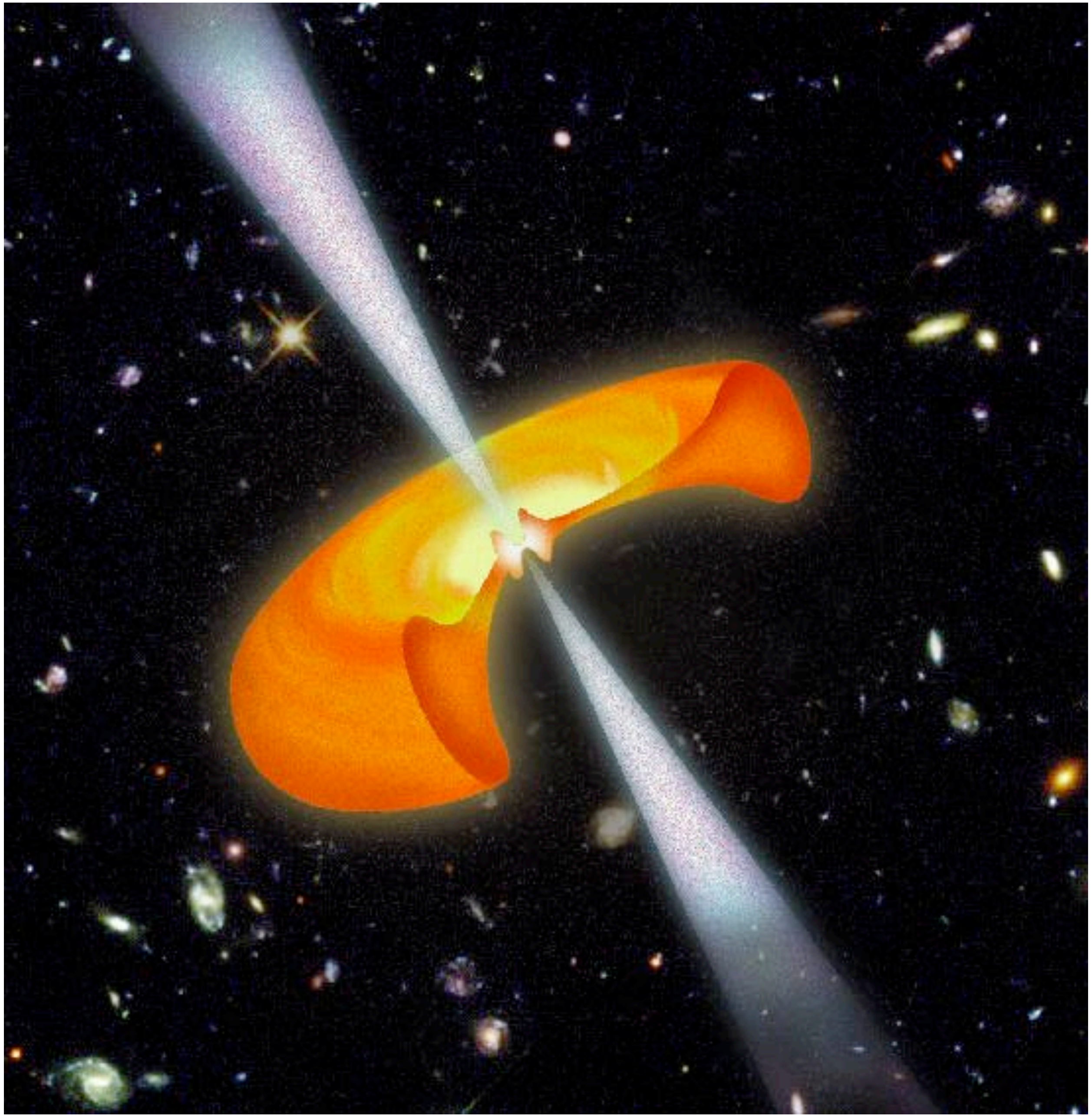
↙internal shocks

↙external shock

Int. & ext. shocks,
accelerate electrons
e,B →γ (***leptonic***);
and

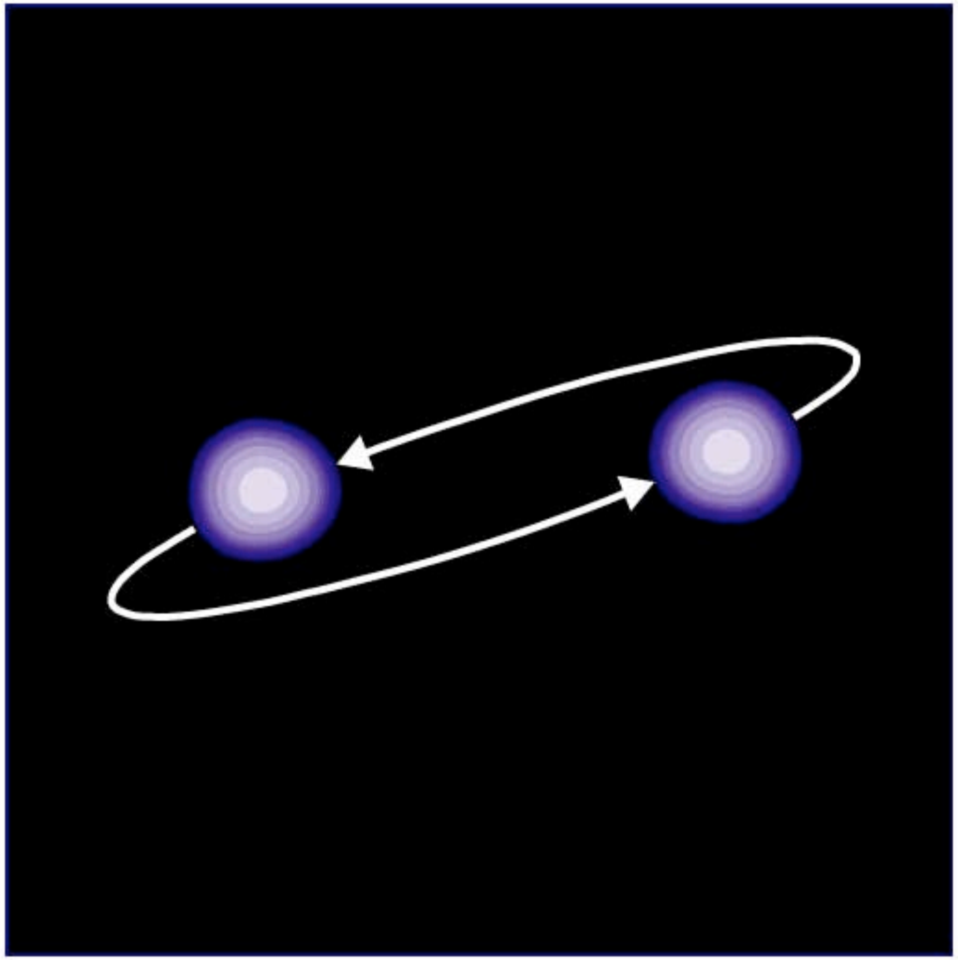
accel. protons too (?)
pγ→ν, γ (***hadronic***)

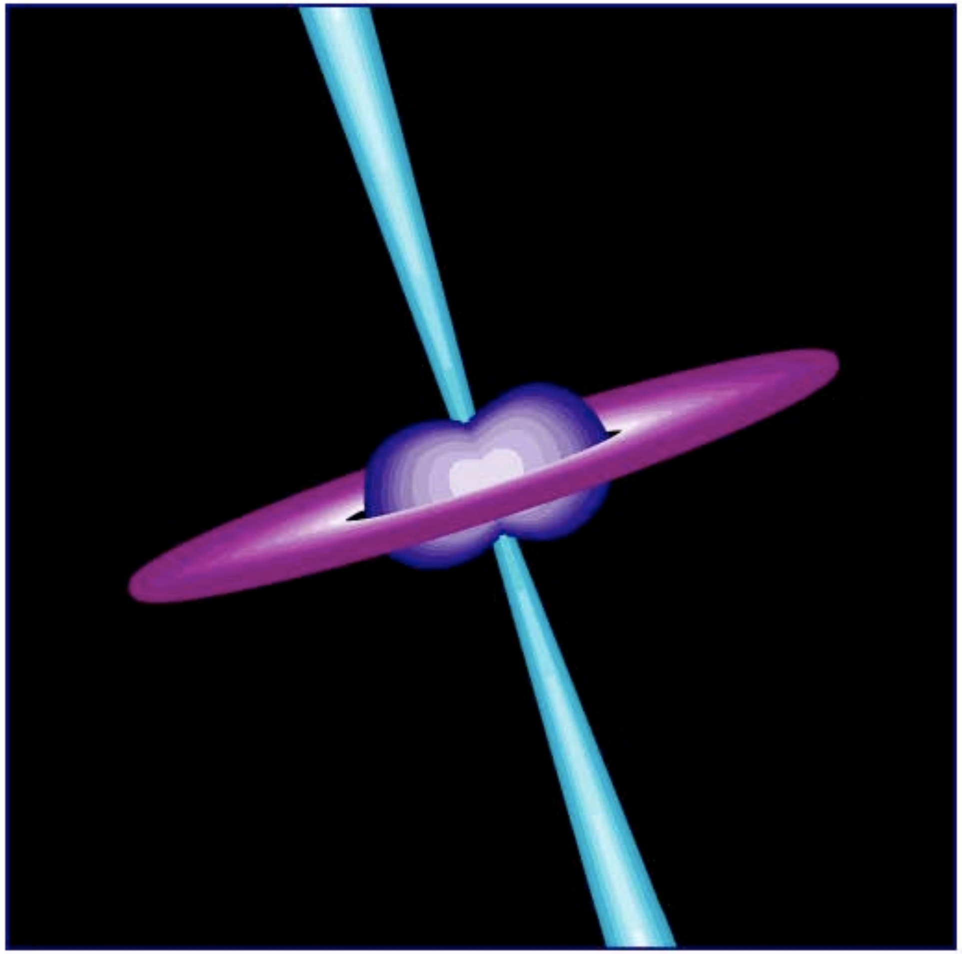
Idealized Jet & Disk



Numerical Hydro Jet (MacFadyen etal 99, Zhang et al, 03, ...)

DNS merger : → similar central engine

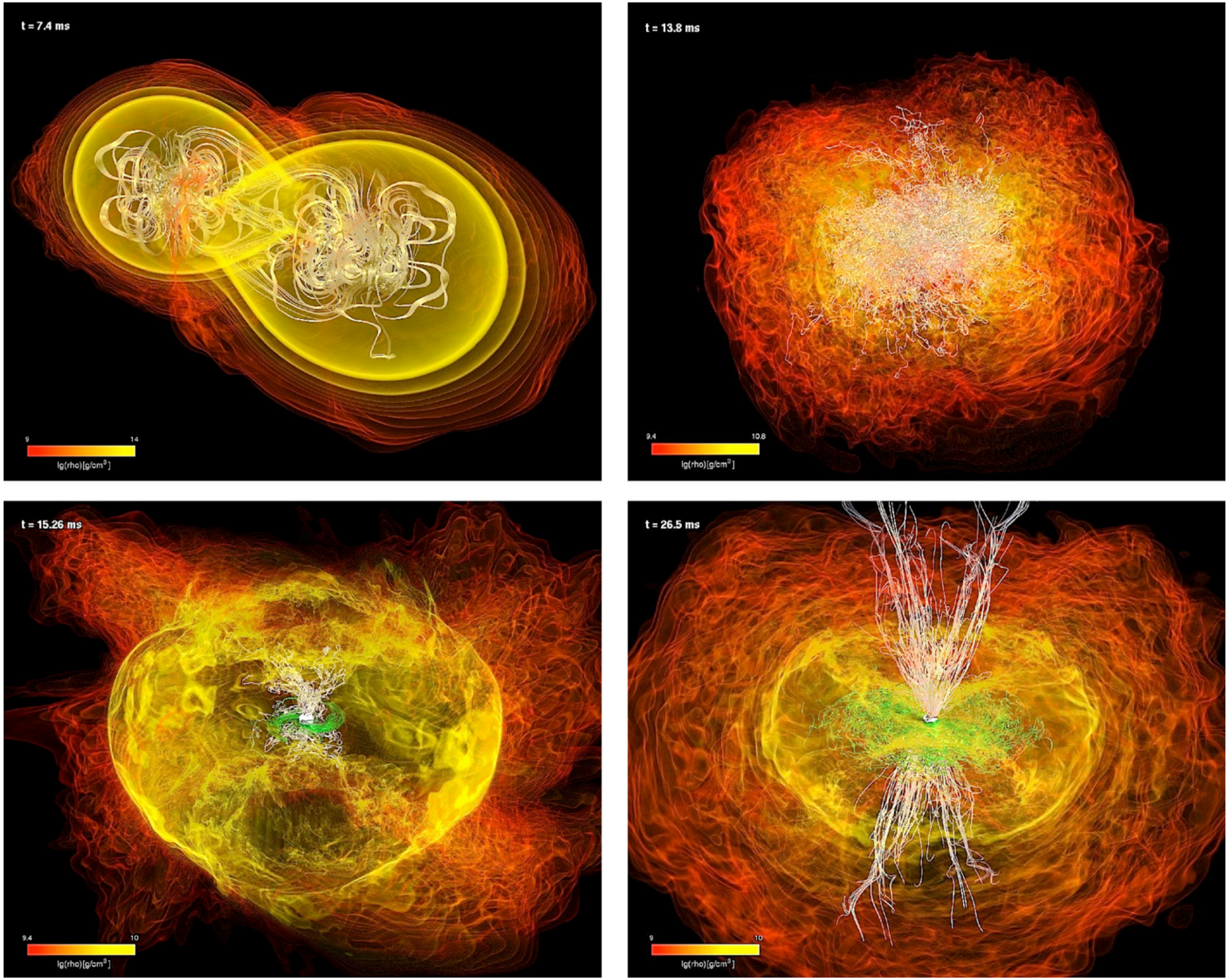




GR-MHD Jets from DNS Merger

Full GR, MHD, disruption, disk → jet

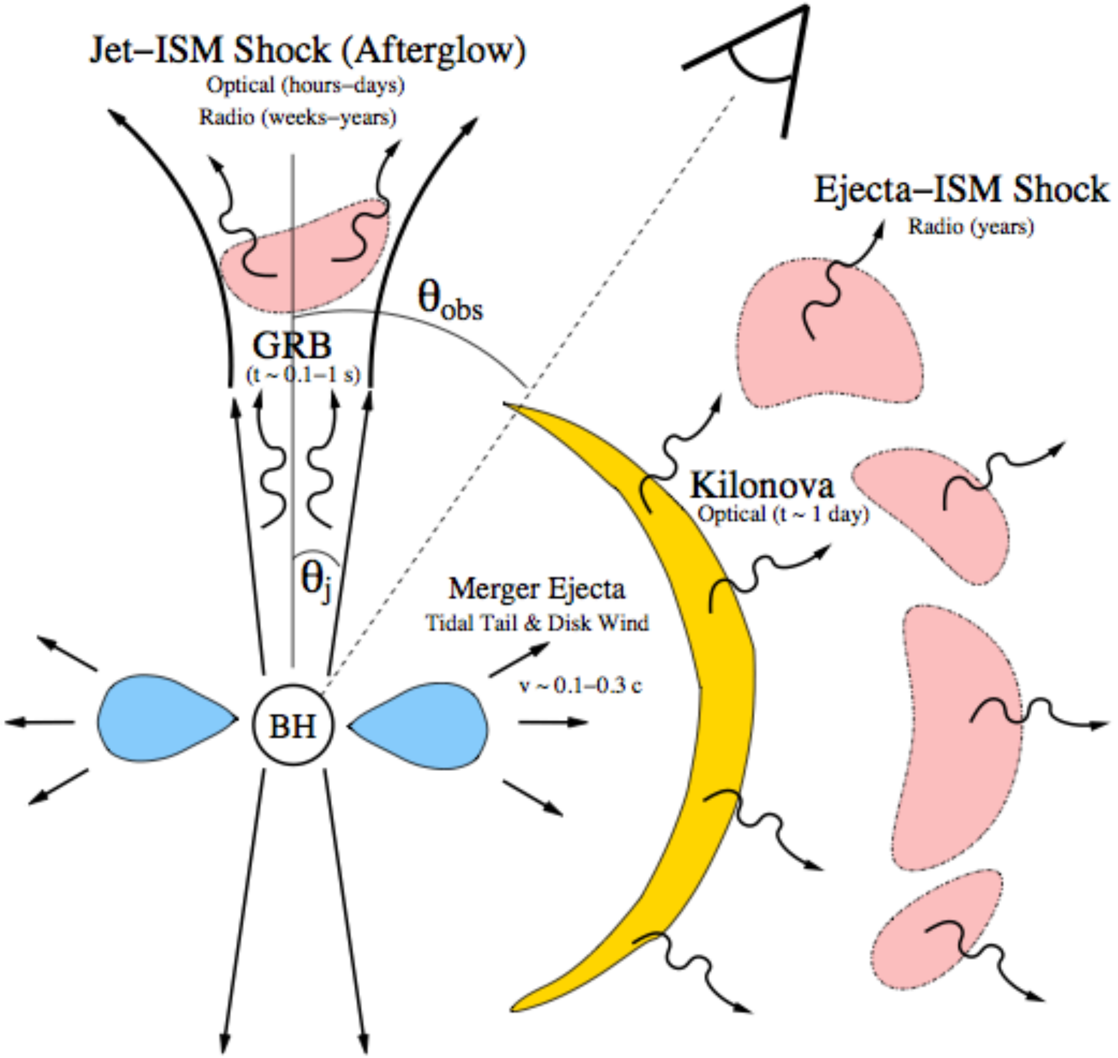
Rezzolla et al ’11, ApJL 762:L18



Trace out mag. field structure ←of jets, as well as that of disrupted ←disk

But: How Long?

SGRB↓ and/or ↓Kilonova?

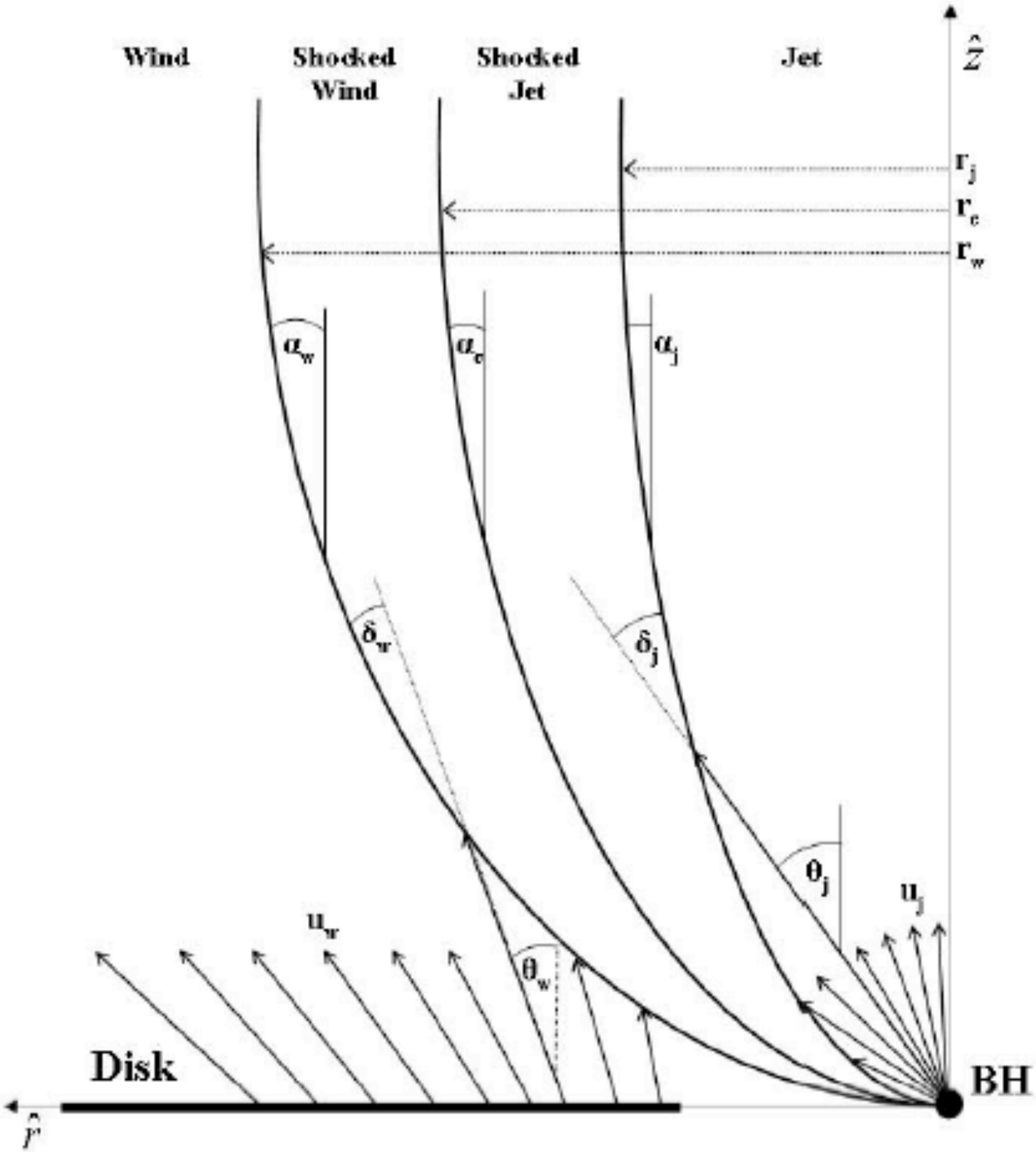


Metzger, Berger '12 ApJ 746:48

See talks by
Metzger
Zhang
Beloborodov
.....

QUESTION: if DNS accretion disk is MHD ⇒ "Long" GRB?

Whether BH or MGR: →



Hydro jet collimation by wind

Bromberg-Levinson '07,

← ApJ 671:678

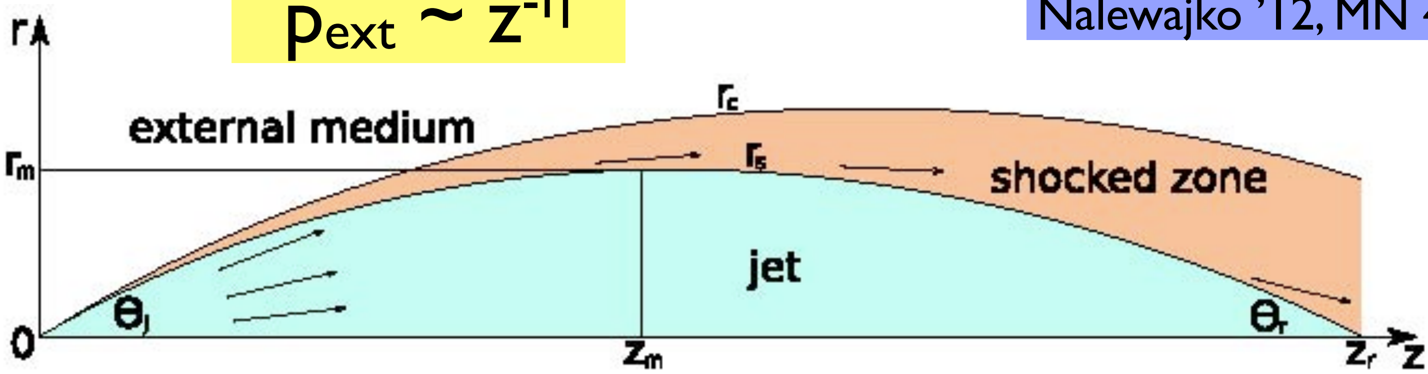
(early: Levinson-Eichler '00, PRL 85:236)

- External confinement either by pressure of envelope $p \sim z^{-\alpha}$
- Or confinement by external split monopole wind, ratio $\chi = L_w/L_j$

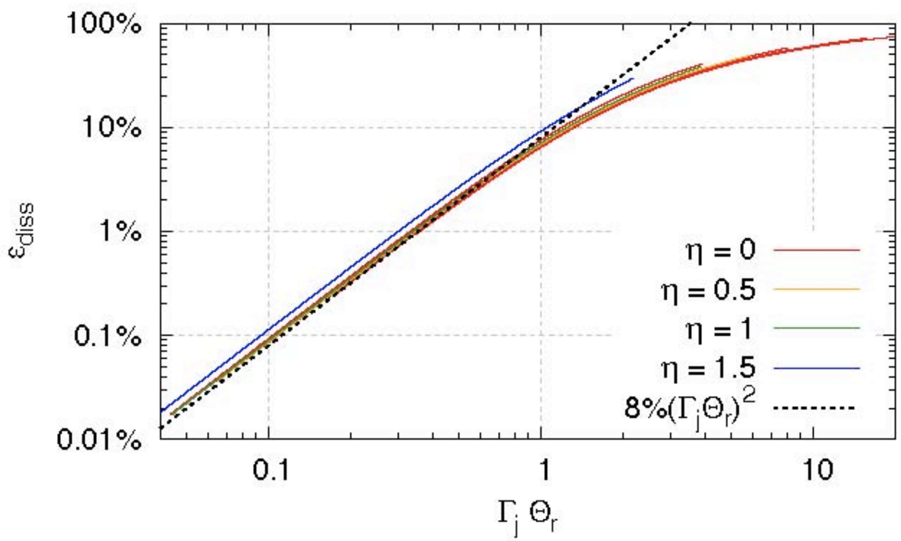
Hydro jet collimation: also by envelope pressure

$p_{ext} \sim z^{-\eta}$

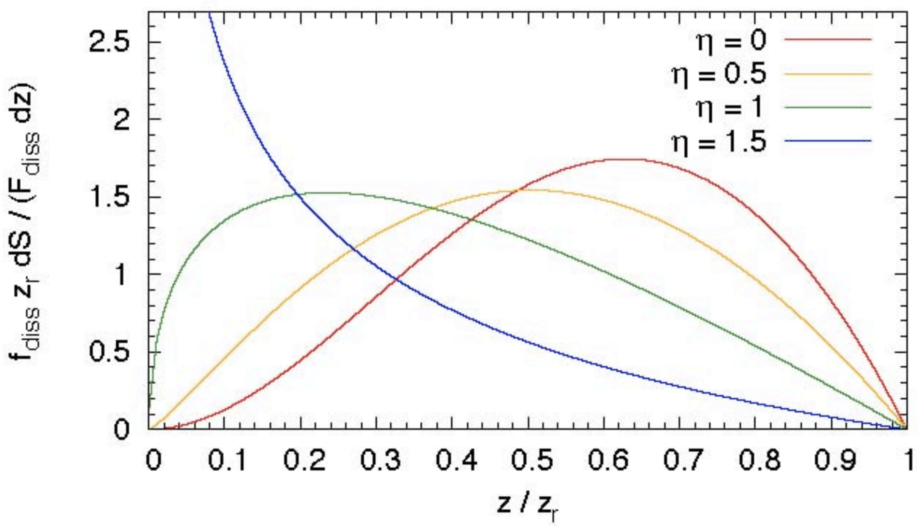
Nalewajko '12, MN 420:L48



Dissipation efficiency

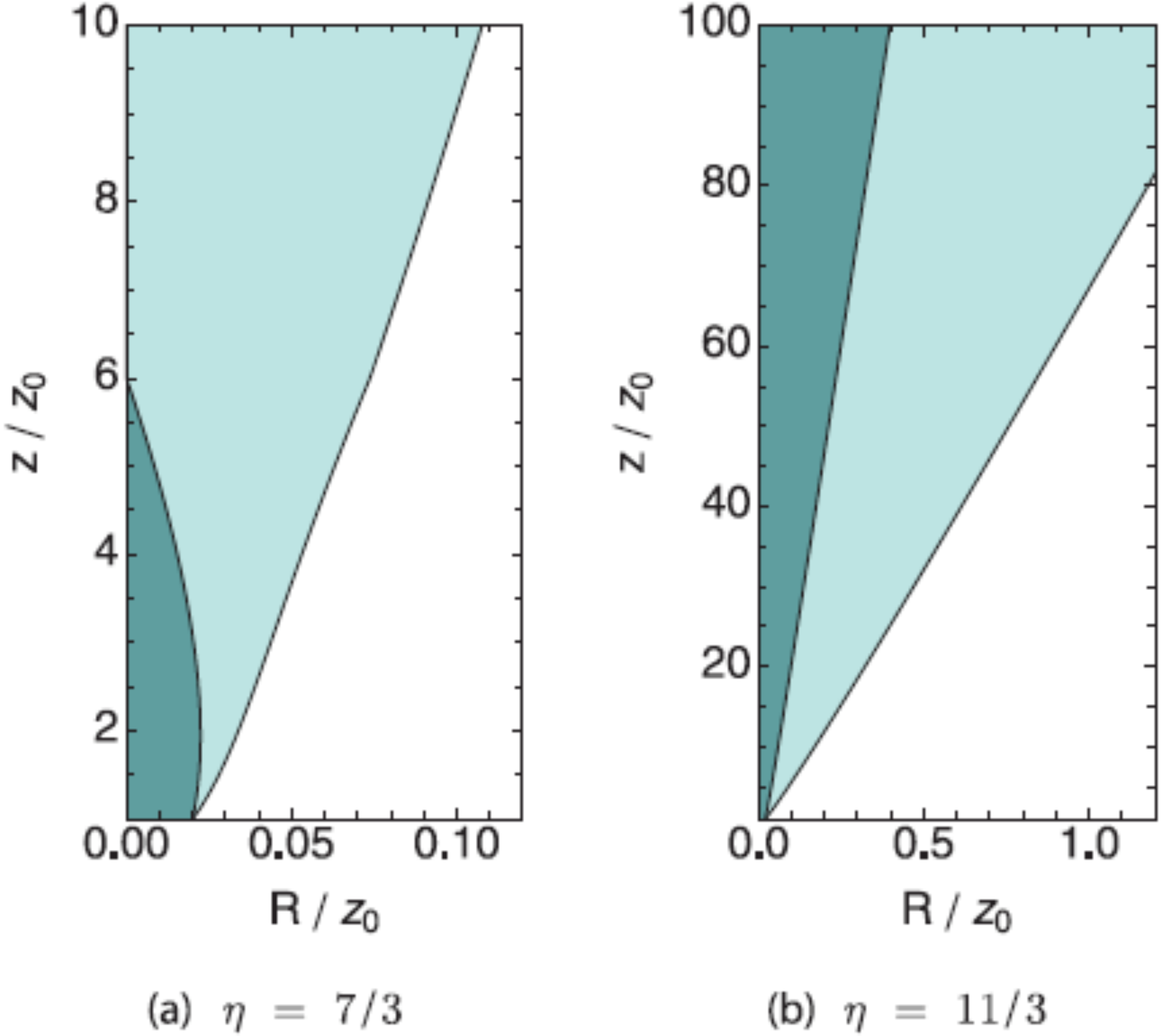


Dissipation rate per u. dist. z



Relativistic Jet hydro confinement

Kohler-Begelman '12 MN 422:2282



- For flat ext. pressure profile $p_{ext} \sim z^{-\eta}$, e.g. $\eta = 7/3$, jet re-collimates
- For steep ext. profile, e.g. $\eta = 11/3$, jet remains open

$p_{ext} \sim z^{-\eta}$, $p_{ext,0}/p_{j,0} = 1$, $\Gamma_{j,0} = 50$, $\theta_0 = 1/50$

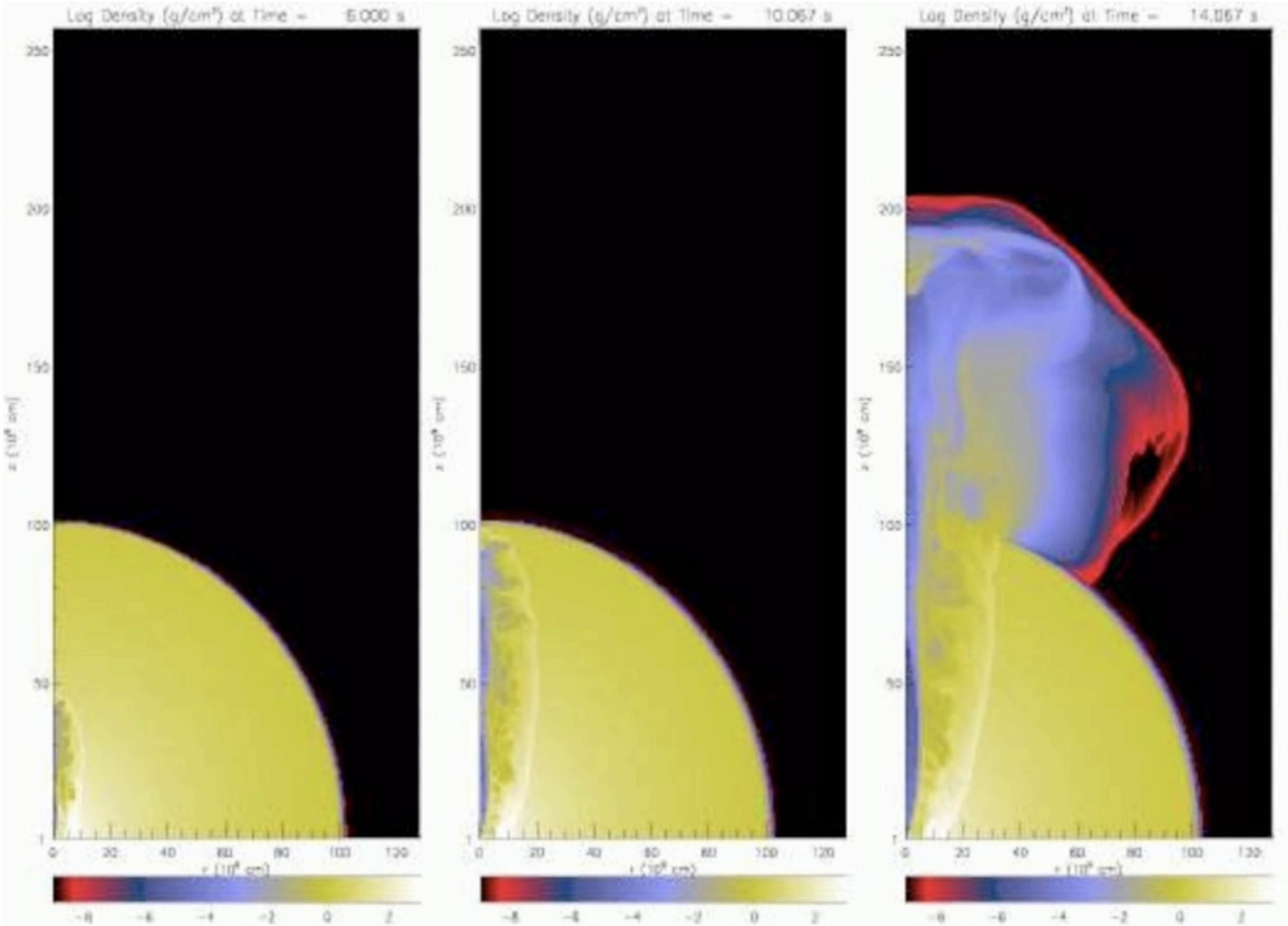
Collateral "benefit" : Cocoon accompanies jet penetration

(cocoon: beer foam spill-over analogue)

Earliest work in AGN (observationally motivated), e.g. Scheuer, Rees, Begelman-Cioffi, etc

Cocoons in GRB: →

Mészáros-Rees, '01, ApJL, 556:L37,
Ramirez-R et al, '02, MN 337:1349
Waxman+PM, '03, ApJ 584:390
Matzner '03, MN 345:575
Lazzati-Begelman '05, ApJ 629:903
Bromberg et al, '11, ApJ, 740:100
Mizuta-Ioka, arx:1304.0163,..... + others



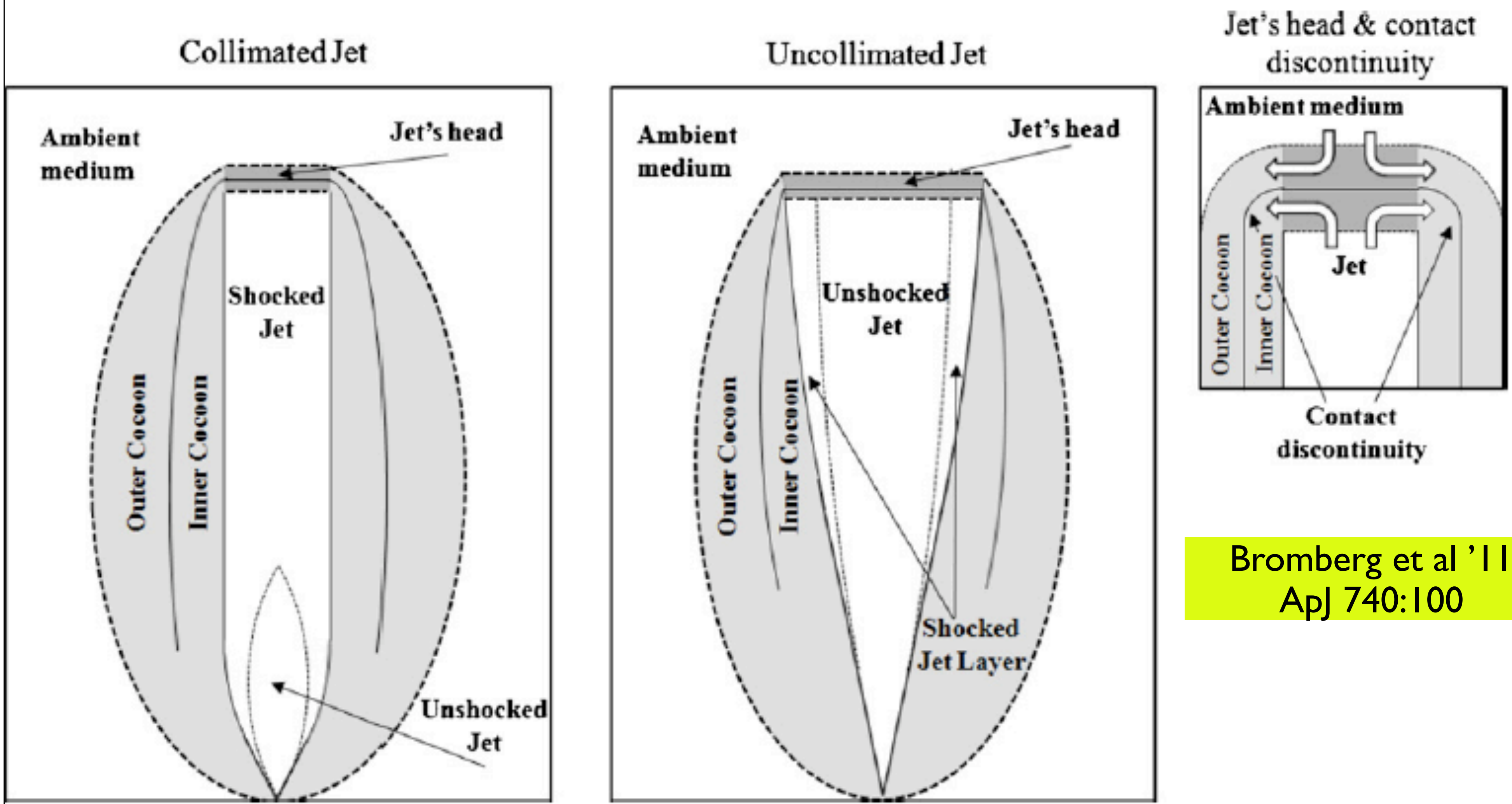
HYDRO simulation:
←Cocoon break-out

Morsony, et al, '07, ApJ 665:569

What's the point?

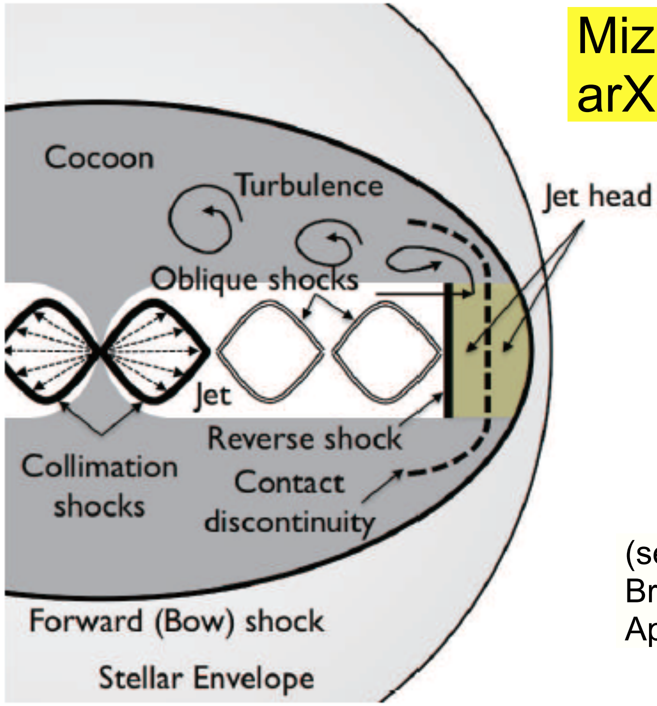
a) cocoon also constrains ***jet angle***
b) cocoon also ***radiates***

Hydro: cocoon pressure also → jet confinement



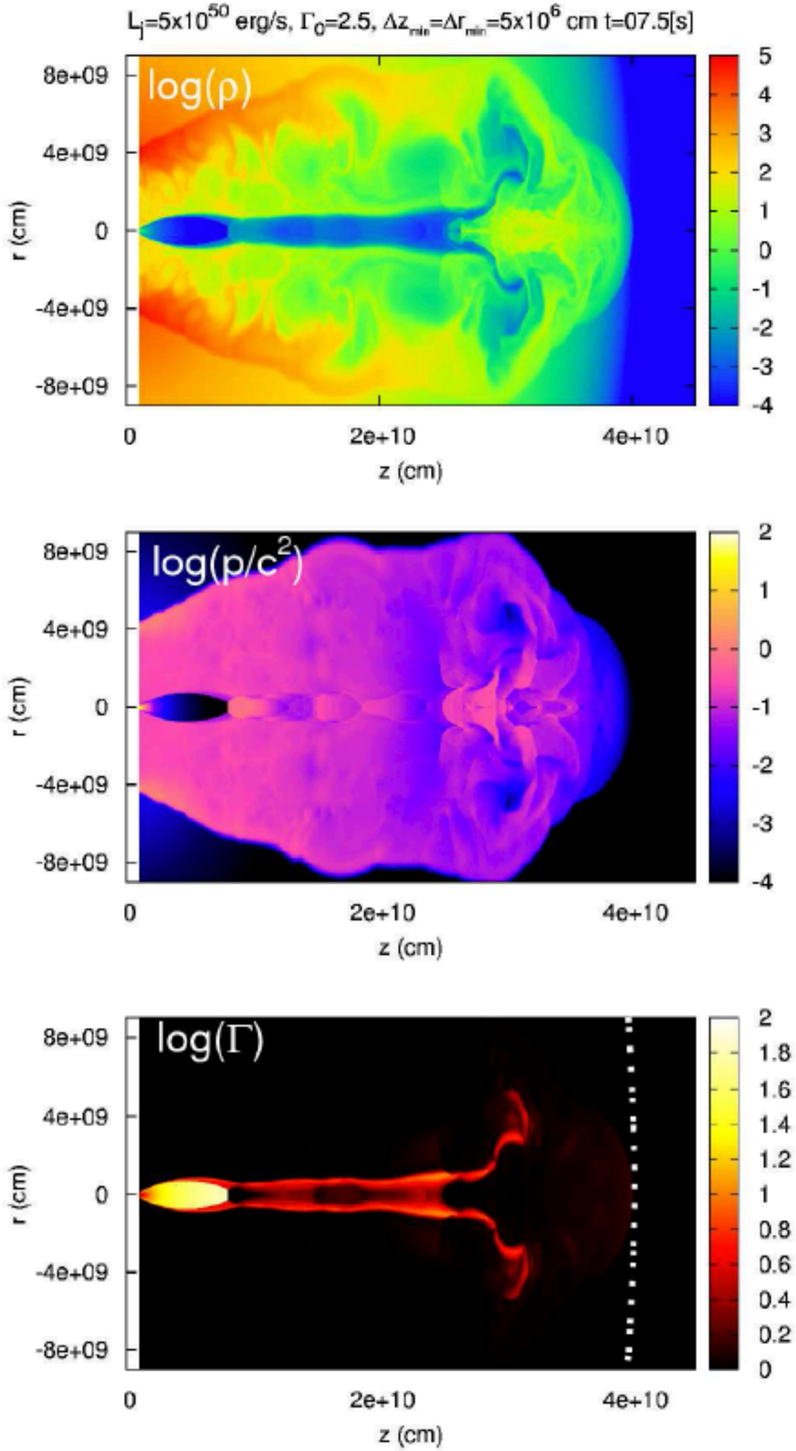
Bromberg et al '11
ApJ 740:100

Hydro jet-cocoon II



Mizuta & Ioka
arX:1304.0163

(see also
Bromberg et al '11
ApJ 740:100)



- Cocoon oblique shocks confine jet to ~cylindrical shape
- Escaping jet opening angle $\theta_j \sim 1/5\Gamma_0$, where Γ_0 -initial Γ at r_0 ; predict max. $\theta_{j,max} \sim 12^o$ (larger: 2-component jet? or some physics is missing)

MHD GRB Jets?

Early GRB Poynting jets:
Usov'94. MN 267:1035; Thompson'94, MN270:480; Mészáros-Rees'97 ApJ 482:L29

Important development work:

Lyutikov-Blandford,
'03, arXiv:/0312347
M. Lyutikov
'11 MN 411:422

Yu. Lyubarsky;
'09 ApJ 698:1570
'10, ApJ 725, L234
'10, MN 402:353
'11, PR E 83:016302

Drenkhahn-Spruit
'02, AA 387:714
'02, AA 391:1141
Spruit-Daigne-Giannios
'01, AA 369:694
'07, AA 469:1

J. Granot, Königl, et al
'11 MN 411:1323
'12 MN 421:244

S. Komissarov, et al
'99 MN 308:1069
'12 MN 422:326

Russo-Thompson
'13, arX:1303.1553,
'13, arX:1303.1554

(partial list...)

MHD dynamics scaling: similar to Hydro?

Generally, ***No***

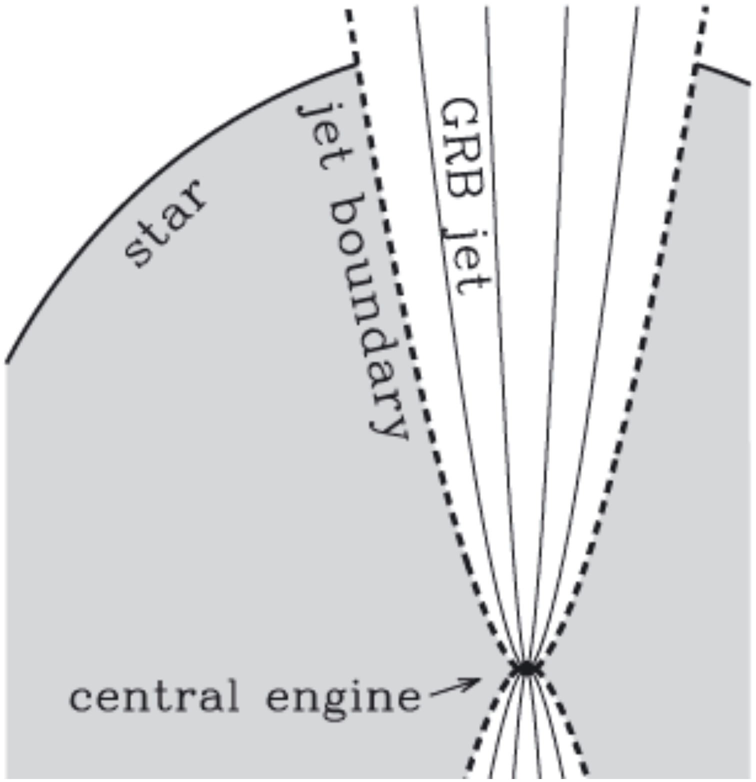
- If ***baryonic*** outflow ***(1-D)*** → $\Gamma \sim (r/r_0)$ up to $\Gamma_{max} \sim L/(dM/dt)$
- If ***magnetic, reconnection*** (e.g. "striped wind"), for 1-D cone outflow ***(1-D)*** → $\Gamma \sim (r/r_0)^{1/3}$, up to $\Gamma_{max} \sim L/(dM/dt)$ (Drenkhahn '72, AA 387:772, Drenkhahn& Spruit, '72, AA 391:1141)
- Why? Can use simple argument (PM & Rees '11, ApJL 733:L1)
- Comoving reconnection time $t'_r \sim \lambda'/v'_r \sim \Gamma \varepsilon r_0/c \sim \Gamma$;
- Comoving dynamic time $t'_d \sim r/c\Gamma$;
- Only two indep. timescales: t'_r, t'_d → determine γ'
- Since γ' must drop, suggest: $\gamma' \sim t'_r/t'_d \sim \Gamma^2/r$;
- energy conservation: $\gamma'.\Gamma \sim$ const.$\sim \Gamma^3/r \Rightarrow \Gamma \sim (r/r_0)^{1/3}$

However: things change if not 1-D ($\theta j \neq$ constant)

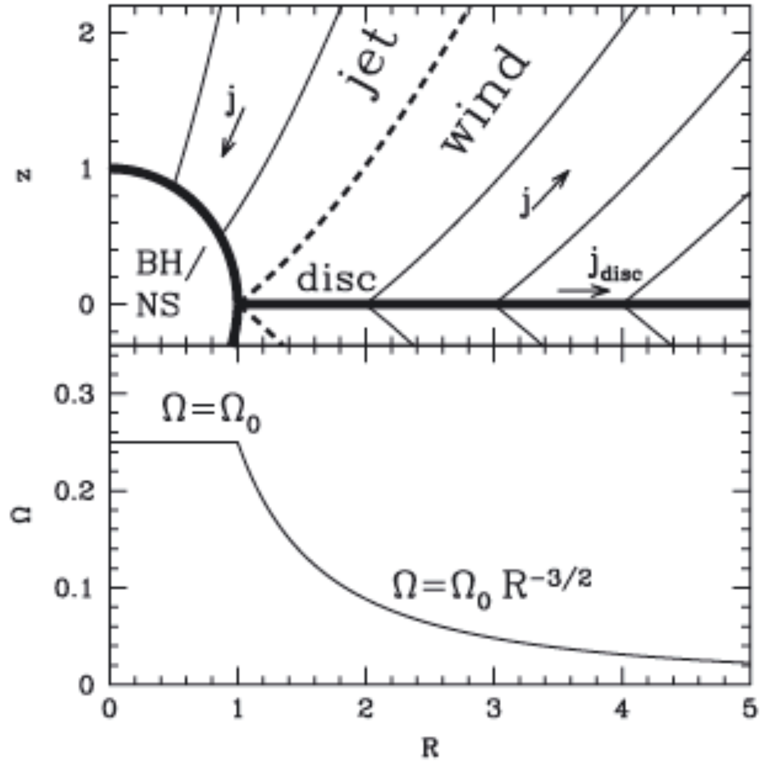
Non-reconnecting Mag. Jet dynamics

(here, $\theta_j(r) \neq$ const.)

Tchekhovskoy et al, 08, MN 388:551



R=cylindrical, r-radial

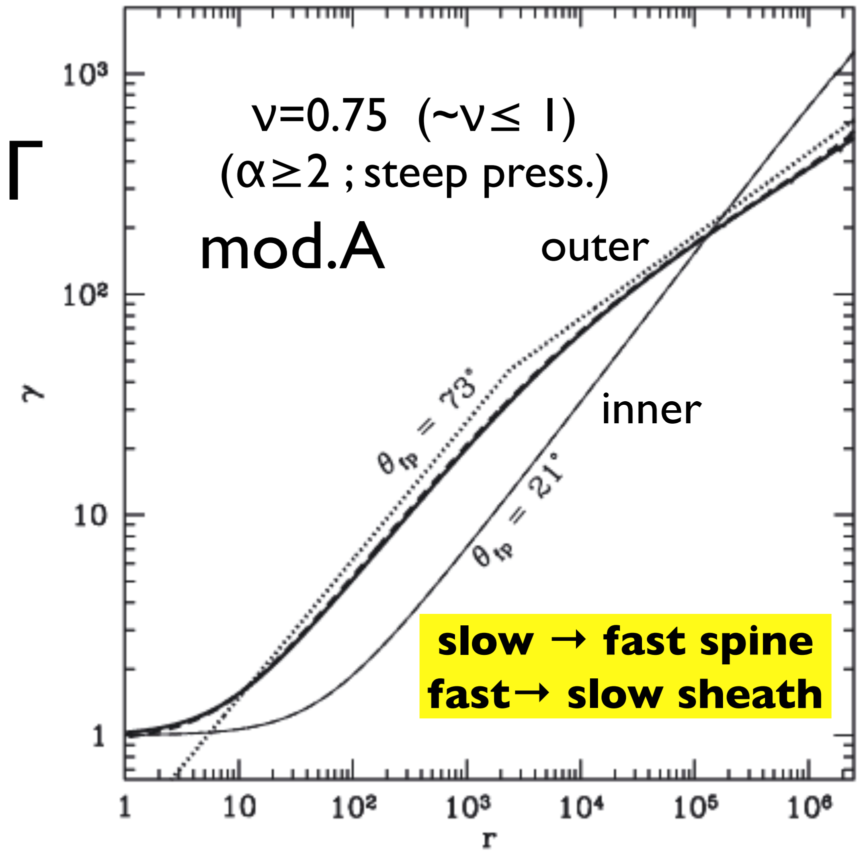


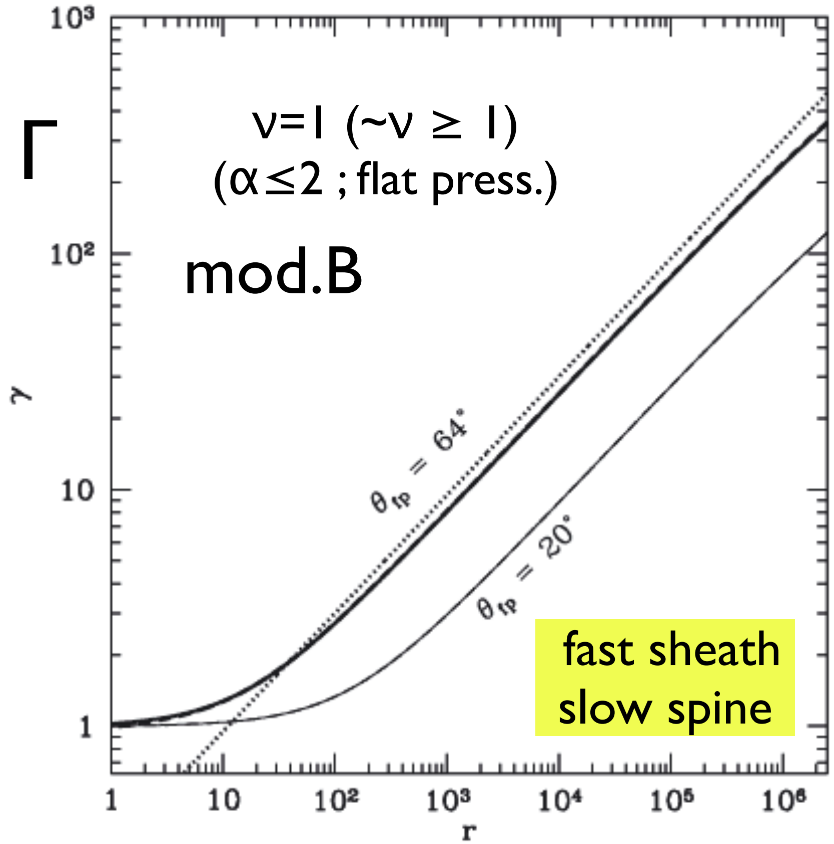
Jet external constraint: either stell. pressure or mag. wind pressure from disk

- $B_z(R) \sim R^{\nu-2}$, ν=const., when $p_{mag} \sim r^{-\alpha}$, where $\alpha=2(2-\nu)$ [R=cyl, r-radial]
- ν=1, α=2 : wind paraboloidal; ν=0, α=4 : wind split monopole
- MHD and Hydro simul. suggest $p_{amb} \sim r^{-\alpha}$, with $\alpha \sim 2.5$ ($\rightarrow \nu \sim 0.75$; mod. A)

Lorentz factor along field lines of ≠ footpoint θ_{fp}

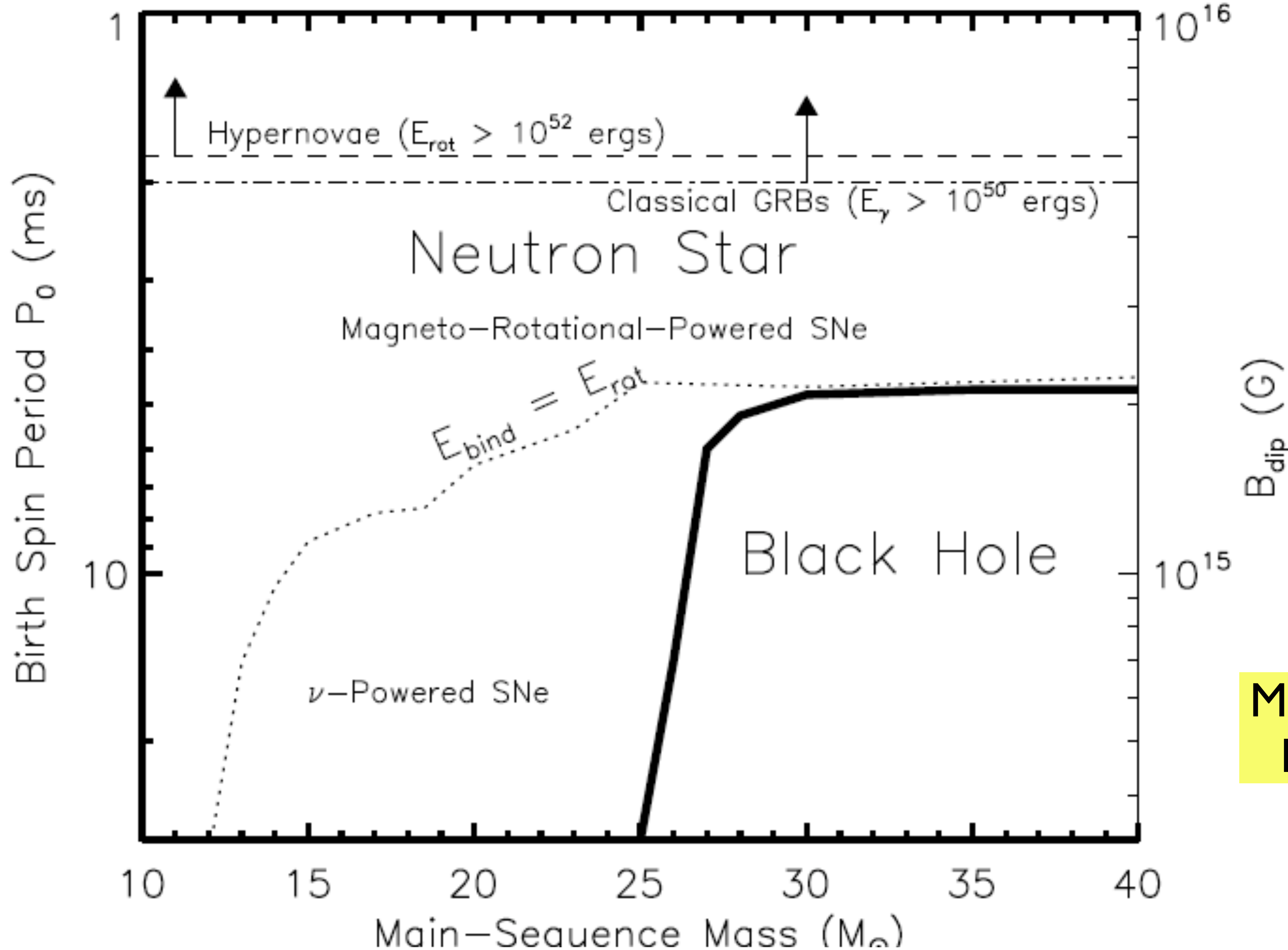
Tchekhovskoy et al, 08, MN 388:551





- Approx. analytical: $1/\Upsilon^2 = 1/\Upsilon_1^2 + 1/\Upsilon_2^2$ along field line ; $\Upsilon=\Gamma$: from drift velocity $v_d = E/B$
- (A) Typical behavior ($\nu \leq 1$): $\Upsilon_1 \sim r^{1-\nu/2} \sim r^{0.625}$, $p_{mag} \sim r^{2(\nu-2)}$; $\Upsilon_2 \sim r^{\nu/2} \sim r^{0.375}$, $p_{mag} \sim r^{-2}$
- (B) Typical behavior ($\nu \geq 1$): $\Upsilon_1 \sim r^{1-\nu/2} \sim r^{0.625}$, $p_{mag} \sim r^{2(\nu-2)}$; no Υ_2

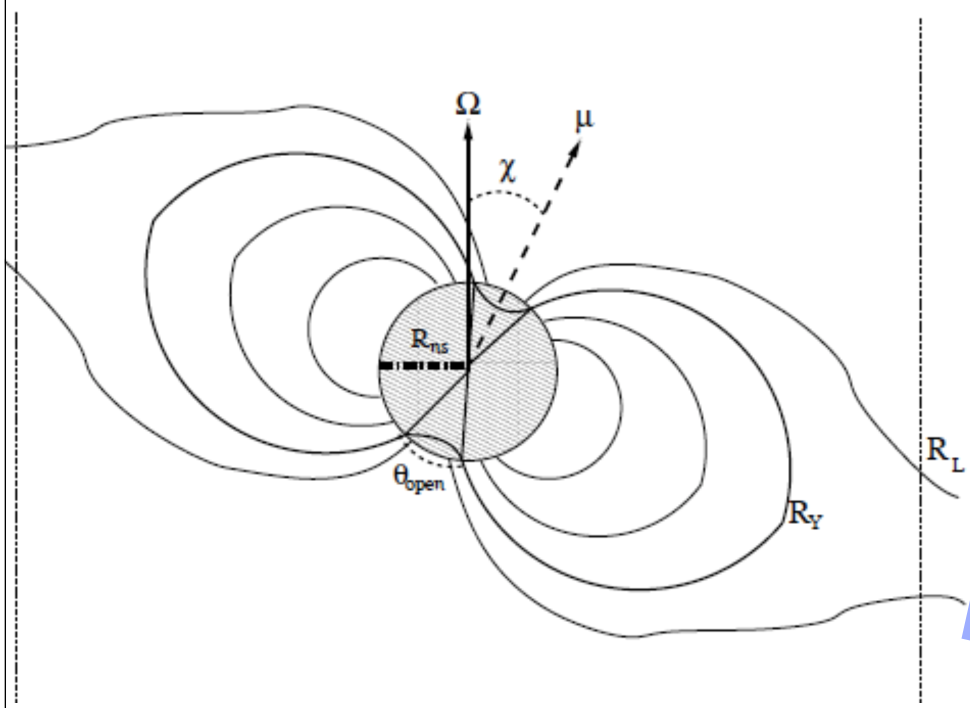
Proto-magnetar Central engine?



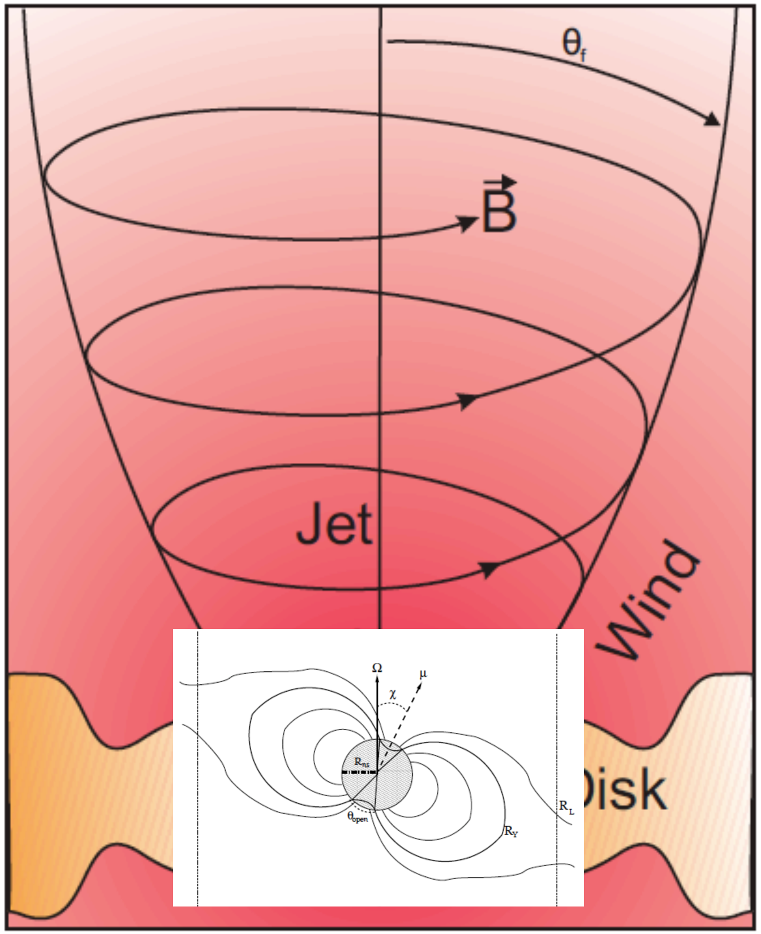
Metzger et al '11
MN 413:2031

Figure 1. Schematic diagram of the regimes of neutron star versus black hole formation in core collapse SNe at sub-solar metallicities (*solid line*) in the space of main sequence mass and initial proto-NS spin period P_0, taking into account the possible effects of rapid rotation and strong magnetic fields. The dotted line denotes the rotation rate above which the NS rotational energy $E_{\rm rot}$ (eq. [1]) exceeds the gravitational binding energy of the progenitor envelope. The dashed line denotes the rotational energy $E_{\rm rot} = 10^{52}$ ergs sufficient to power a 'hypernova'. The right axis shows the magnetic field strength $B_{\rm dip}$ that would be generated if the magnetic energy in the dipole field is $\sim 0.1\%$ of $E_{\rm rot}$ (eq. [4]). The dot-dashed line is the minimum rotation rate required for a magnetar with a field strength $B_{\rm dip}$ to produce a classical GRB with energy $E_\gamma > 10^{50}$ ergs, based on the model presented in §4.

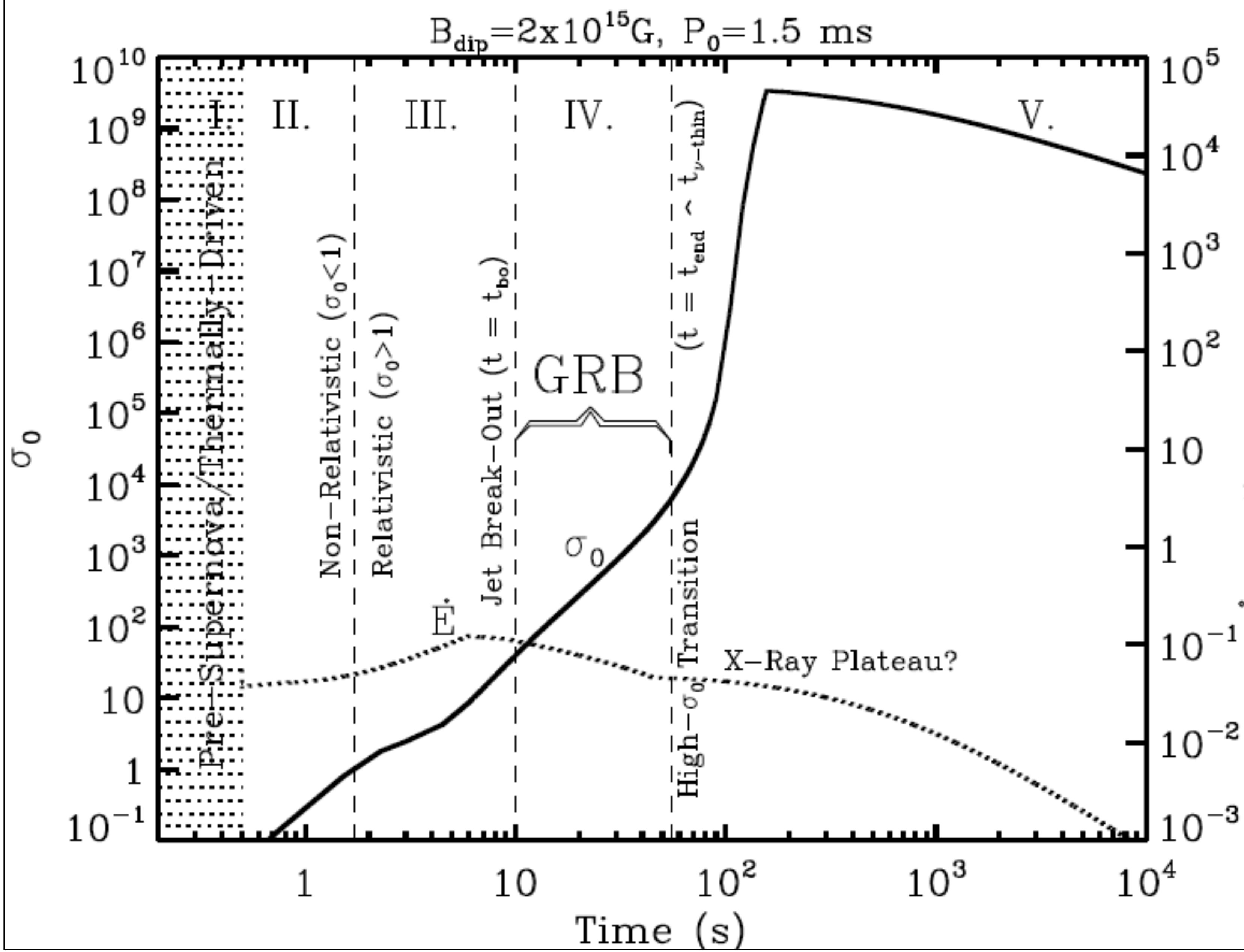
Proto-magnetar as initial remnant of core collapse: Central Engine ⇒ Pulsar Wind



⇒



Proto-magnetar model of GRB jet



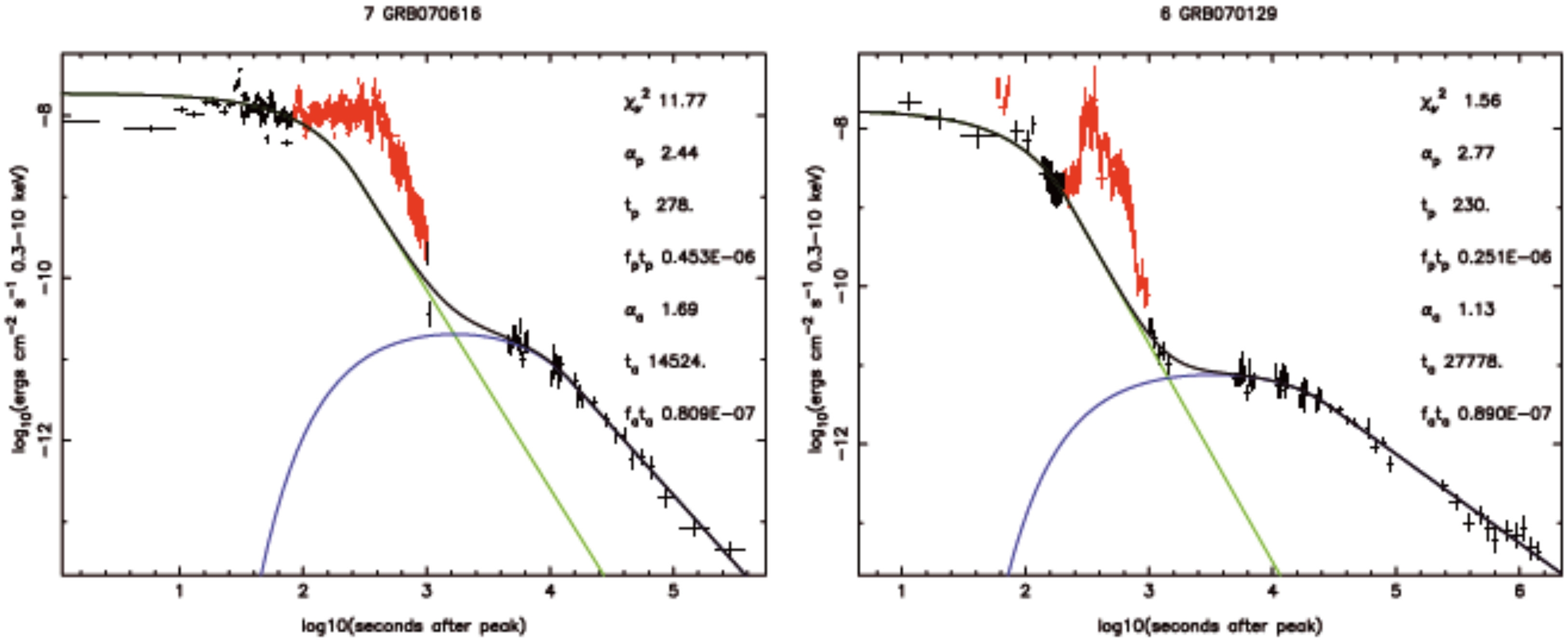
Metzger et al 11, MN 413:2031

where

Γ~σ₀

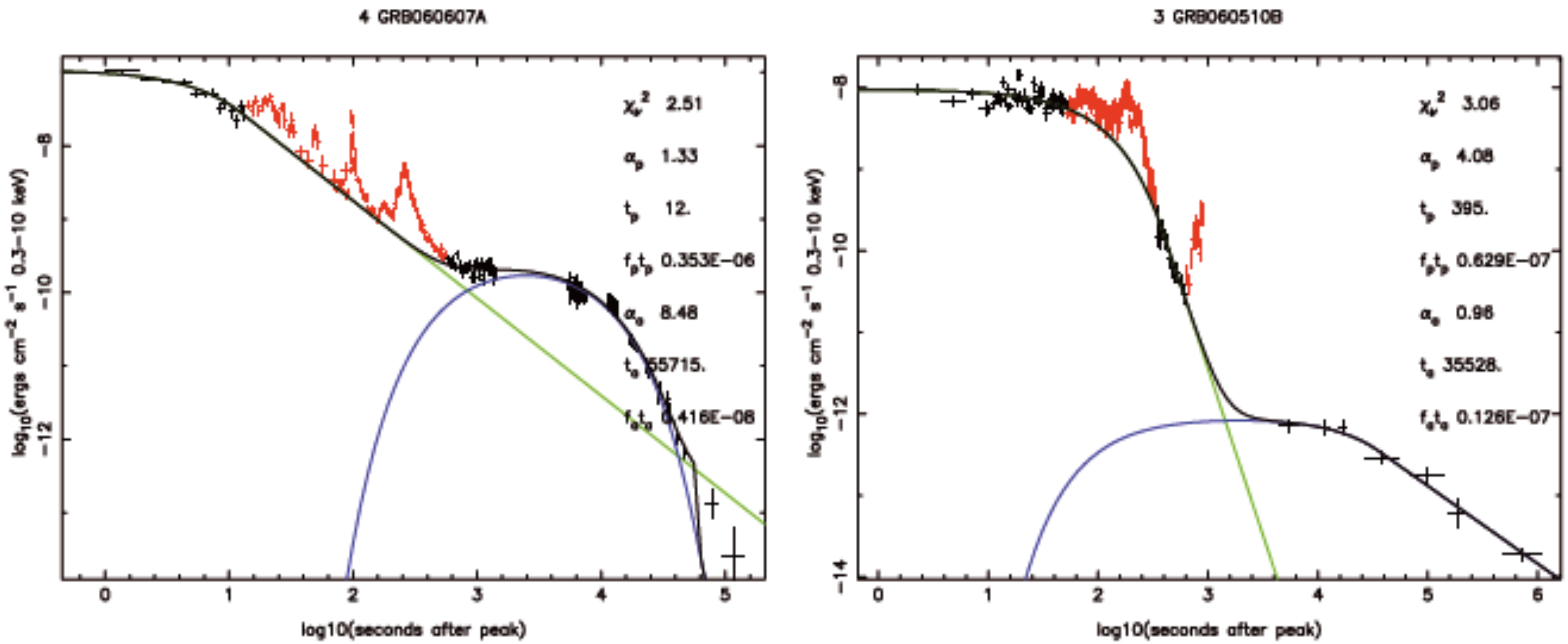
-CC→magnetar,
-rot. →MHD jet
-reconnect/dissip
→dynamics $\Gamma \sim r^{1/3}$
→dissip.photosph
+ also shocks

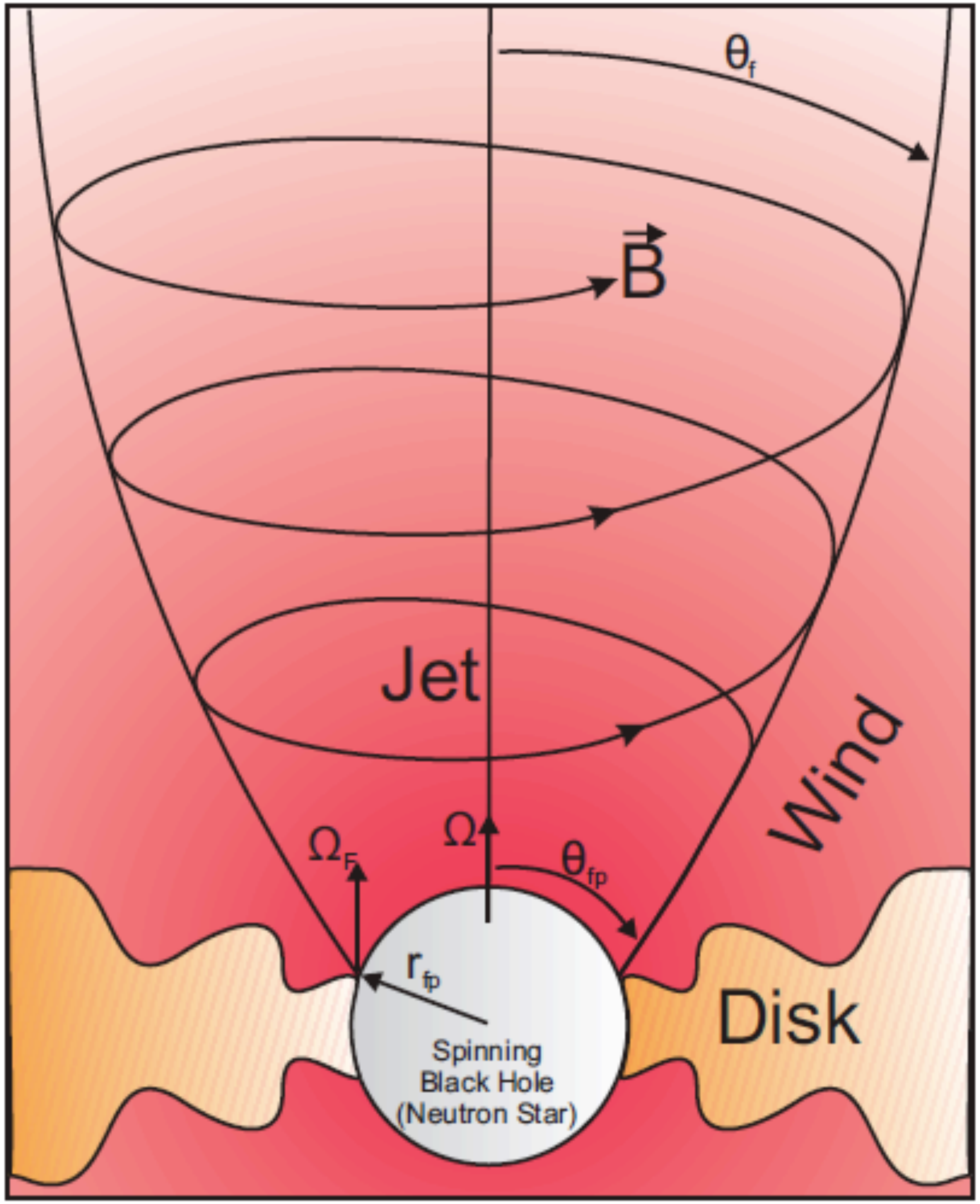
Magnetar effects: XR plateau in l.c.



(d) (e)

Lyons, O'Brien, Zhang et al, 10, MN 402:705



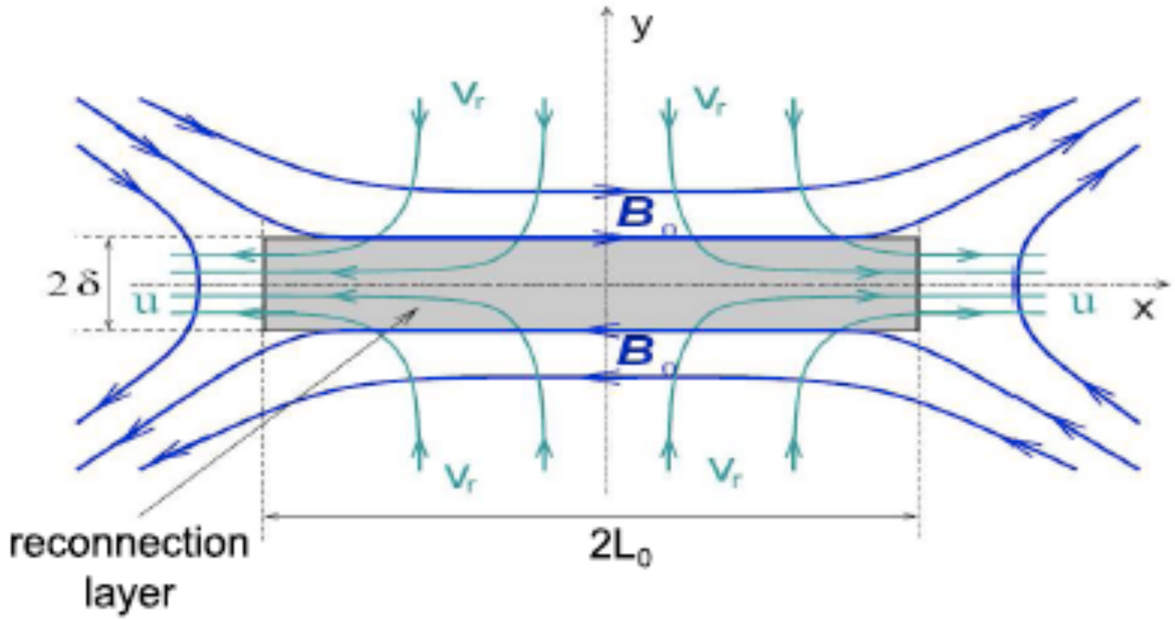


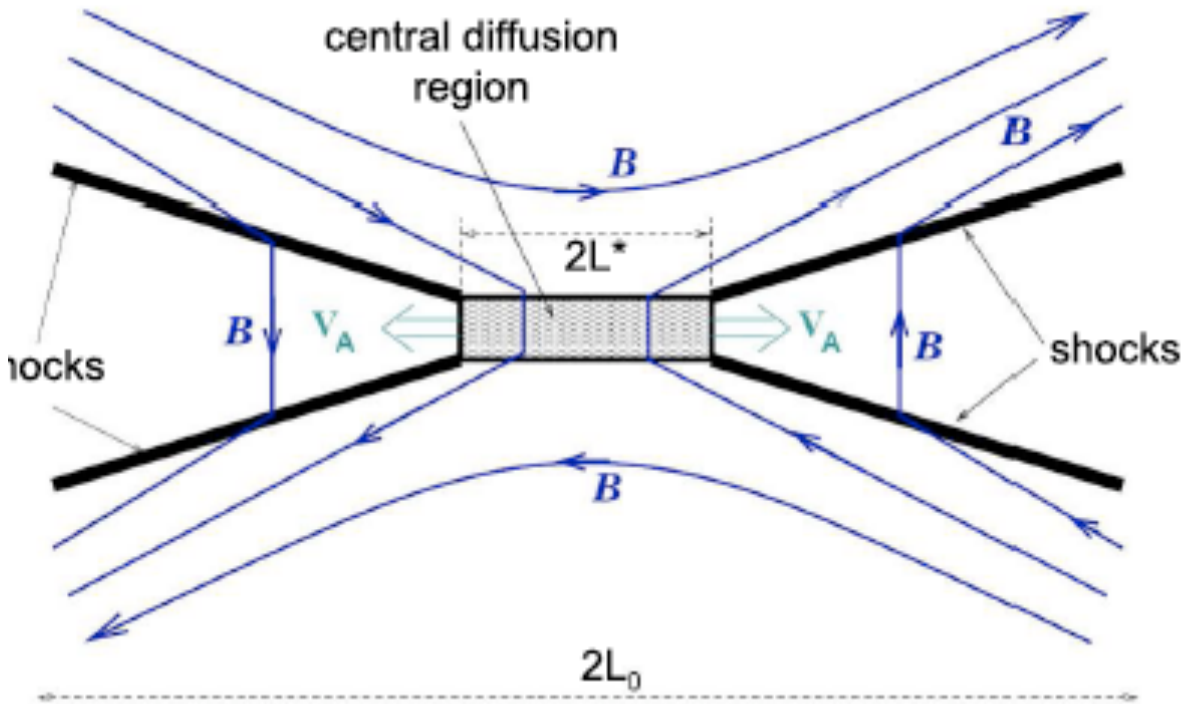
An MHD jet "reconnection switch" model

McKinney & Uzdensky '12
MN, 419:573

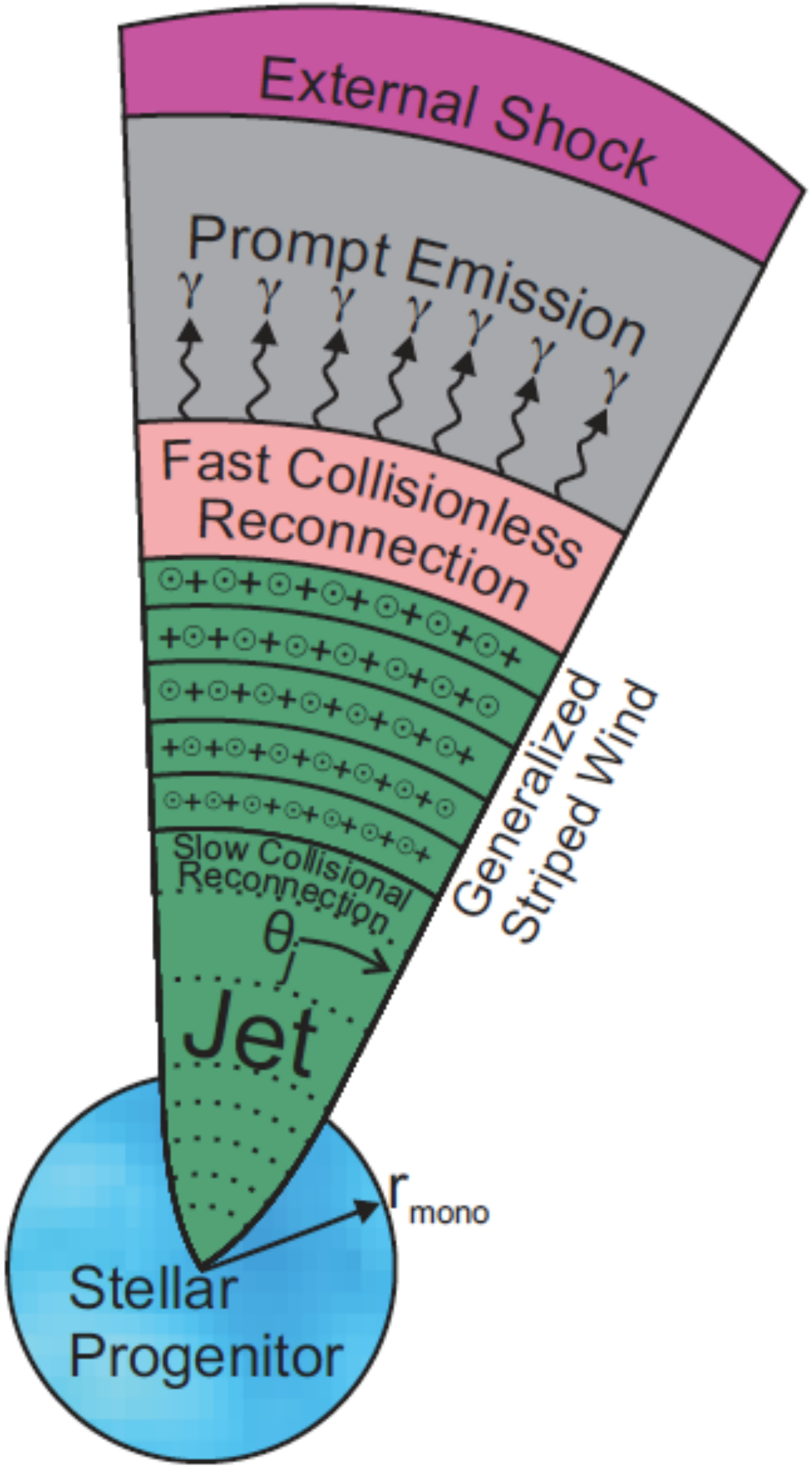
- Fast rot. collapsar→BH +disk →homopolar field (aligned rotator)
- Or, aligned rot. magnetar
- Reconnection in principle not easy (same polarity)

Reconn. Switch





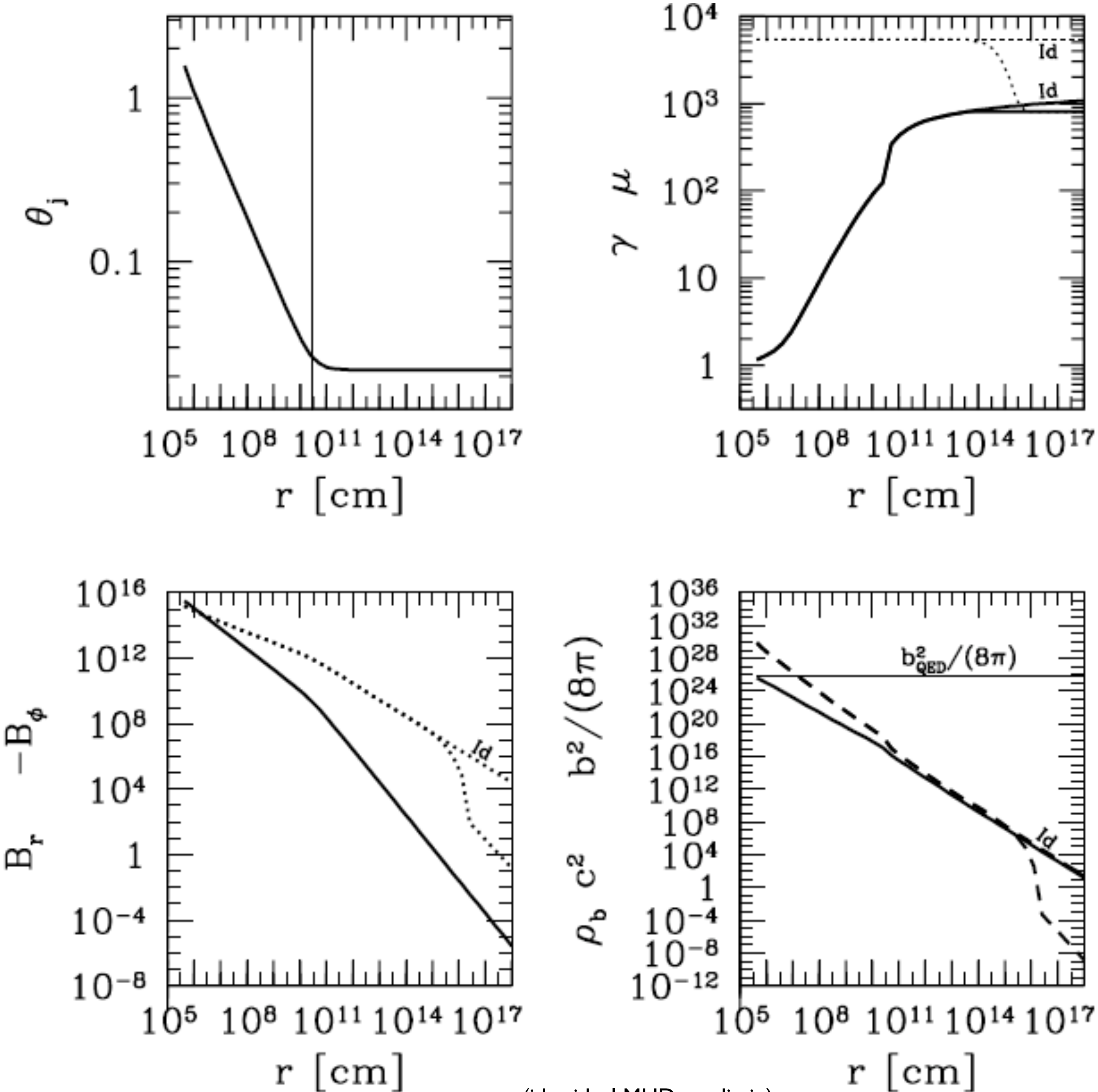
- When density drops low enough, switch from
- slow (Sweet-Parker, i.e. Spitzer resist.) reconnection to
- fast (Petschek, i.e. anomalous resist.) reconnection; occurs on fraction of Alfven timescale, beyond scatt. photosphere
- In this regime, not too diff. from Spruit et al (2001)



GRB "reconnection switch" mode

McKinney & Uzdensky '12, MN, 419:573

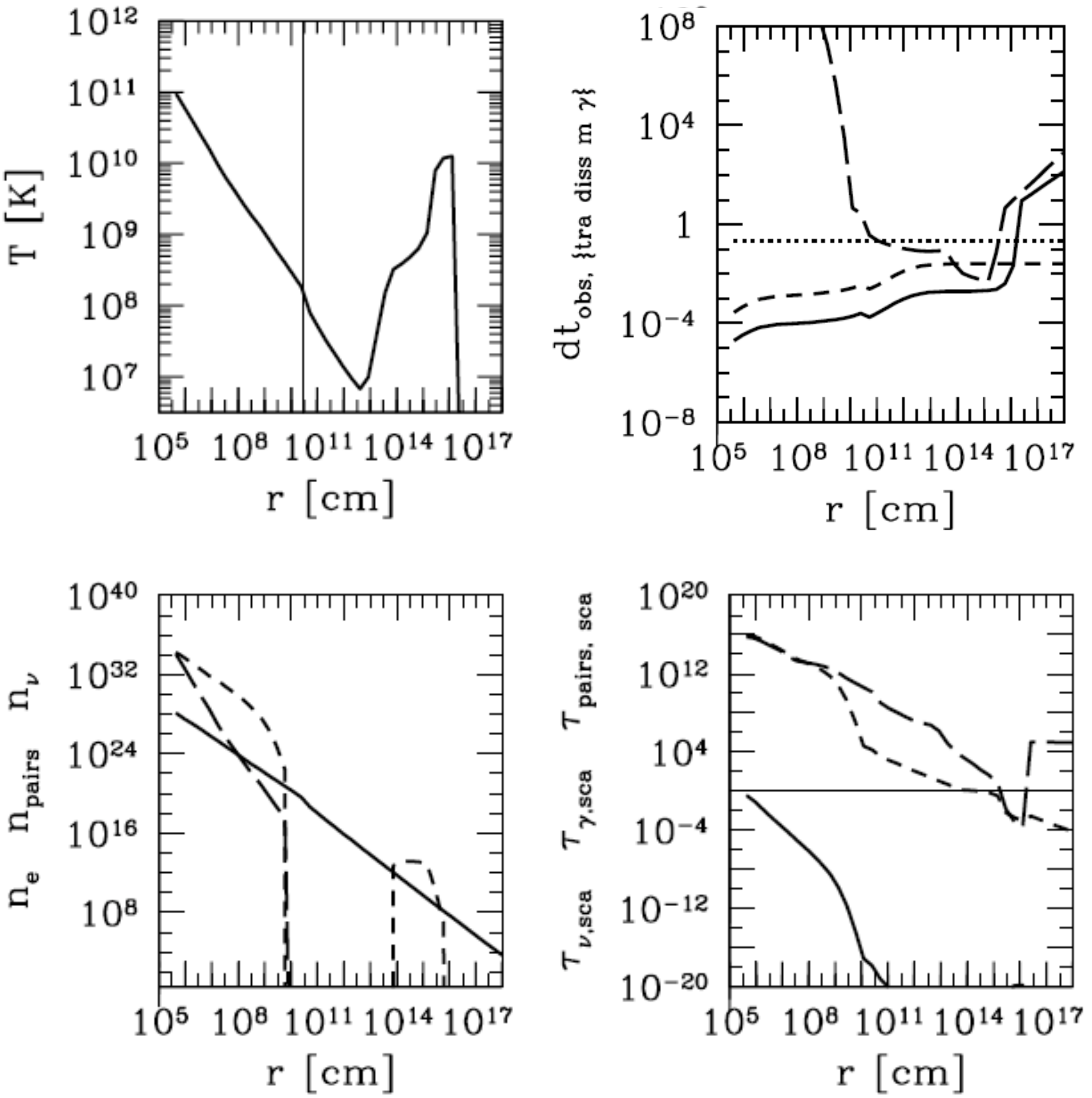
- Tangling →reversing of field lines leads:
- first (high density), to slow collisional reconnect/dissipation
- higher up (low density), to fast collisionless reconnection→ prompt emission



(id = ideal MHD, no dissip)

Jet structure and phys. quantities

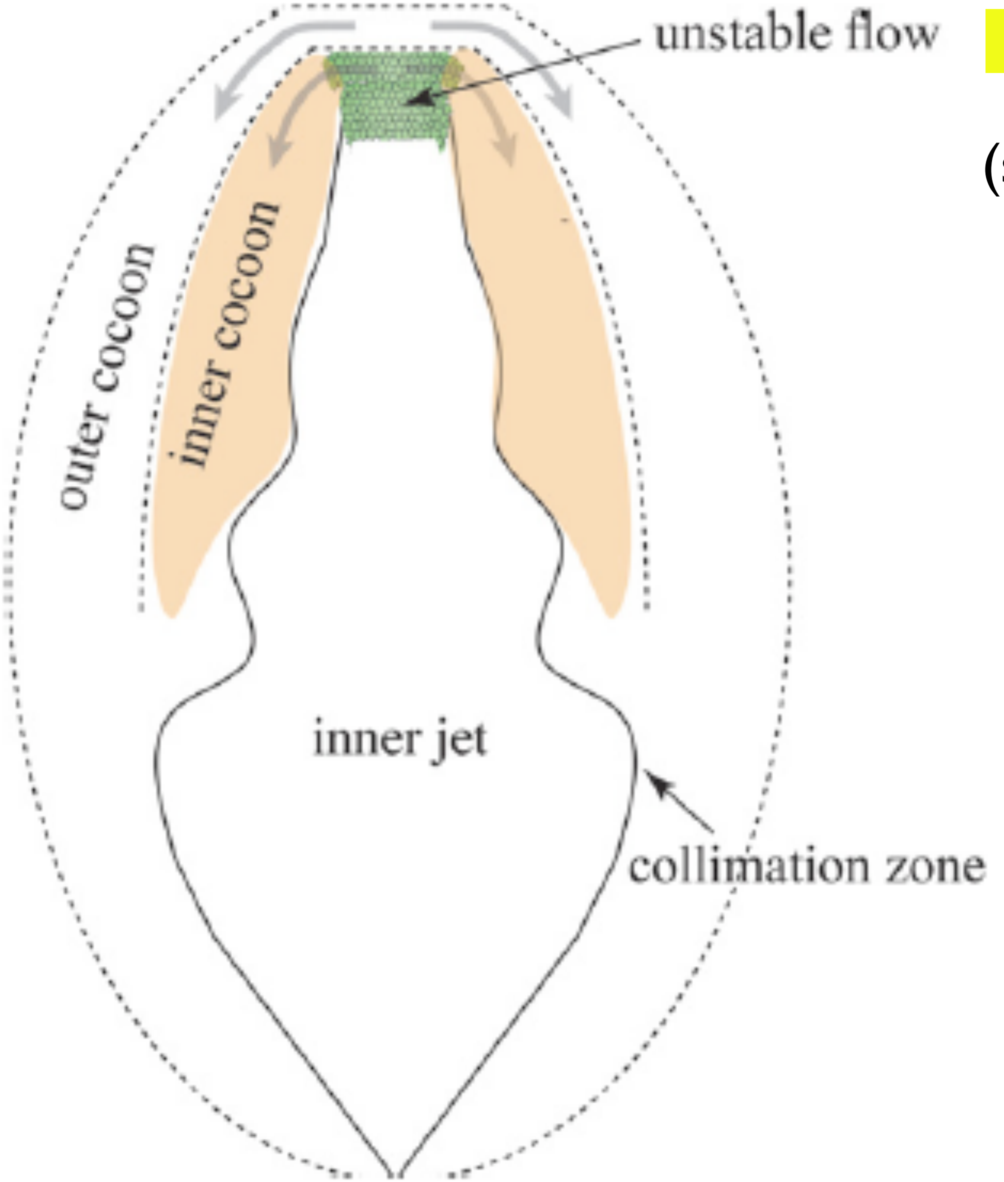
- Ideally, if all works right, get:
- Lorentz factor
- Jet angle
- Diissip at radius $r \sim 10^{15} - 10^{16}$ cm
- →"prompt emiss."
- →Usual afterglow
- But spectrum? Time variability?...



Jet structure and phys. quants., II

- Pair density and scatt. opt. depth large out to r~10^{15} - 10^{16} cm
- At 10^{15} - 10^{16} cm
  →fast reconnec
  →dissip/heat
- Fiducial variab. times are small enough (but wildly uncertain) at dissip radius

MHD: also jet + cocoon



Levinson-Begelman '13 ApJ 764:148

(similar results but diff. in details)

- Inner cocoon: jet spillover, outer cocoon: stellar envelope shoved aside.
- Estimate that instabilities dissipate magnetization of inner cocoon (→hydro)
- For WR star $M=10M_{\odot}$, $R_{\star}\sim R_{\odot}$ and $\rho_{\star}\sim z^{-\alpha}$ with $\alpha<3$, jet head becomes semi-relativistic near $R_{\star}$.
- Jet remains collimated inside star, and also well outside it by the cocoon.

Jet Radiation

in light of

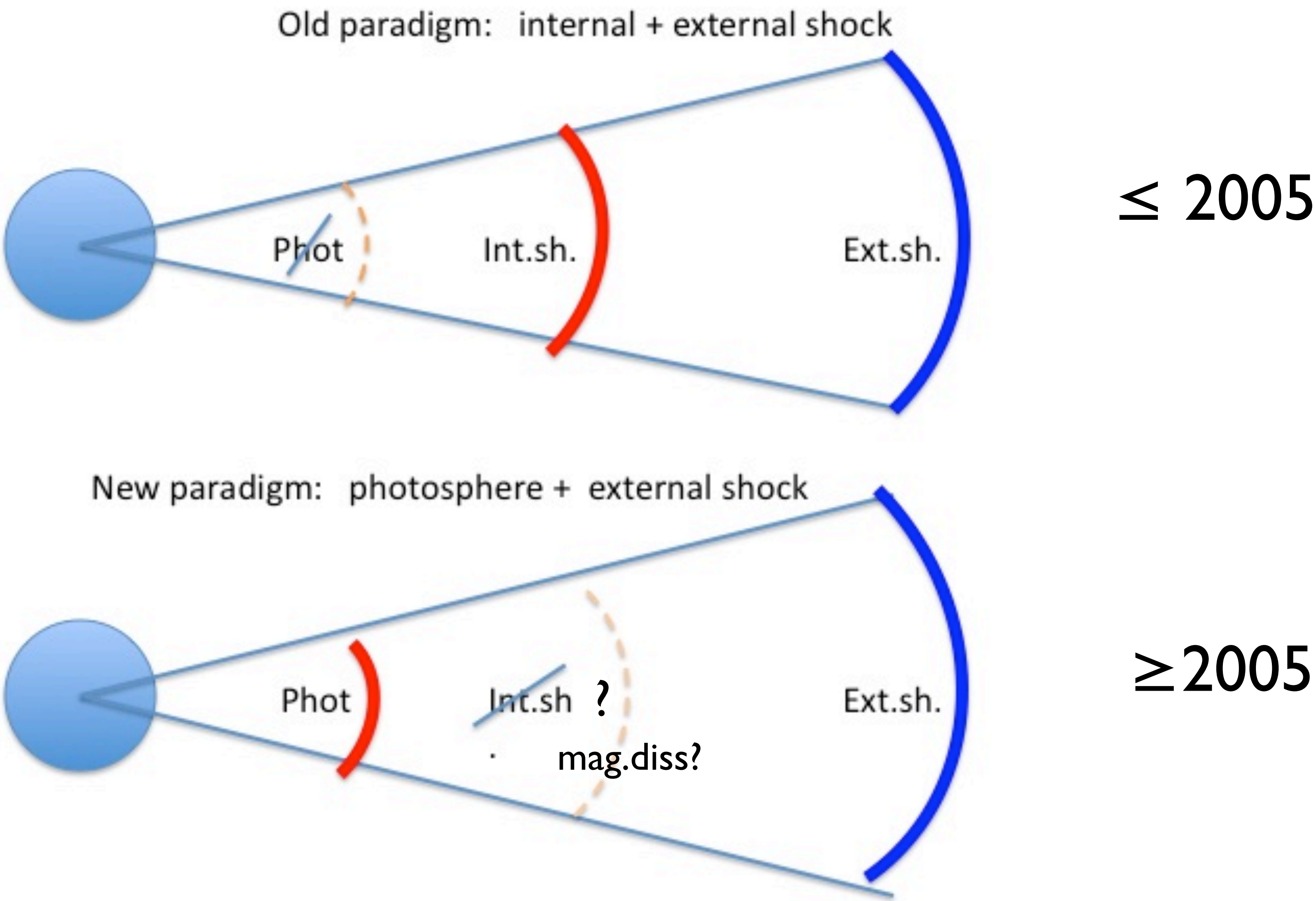
Swift & Fermi
and other instruments

Paradigm shift

- ***OLD:* *internal + external shock*** (weak phot.)
- Photosphere: low rad. effic., wrong spectrum
- Internal sh.: good for variability, *easy to model* ; but ***poor*** *radiative efficiency*
- External sh.: was, and is, *favored for afterglow model*

- ***NEW***: ***phot. + (int.sh? mag.diss?)+ext. shock***
- Photosphere: if dissipative, → **good** *rad. efficiency*
- **Int. sh**: if magnetic, may be absent; but ***mag. dissip***?
- ***External*** shock: most of GeV and soft afterglow

Evolving Fireball paradigm:



Mészáros

Photosphere radius

$$n' = \frac{\dot{M}}{4\pi r^2 m_p \Gamma c} = \frac{L}{4\pi r^2 m_p c^3 \eta \Gamma} \quad ; \quad \eta = \frac{L}{\dot{M} c^2}$$

$$\tau'_T = n' \sigma_T \Delta r' = n' \sigma_T \frac{r}{\Gamma}$$

Phot: $$\tau'_T = 1 = \frac{L \sigma_T}{4\pi r^2 m_p c^3 \eta \Gamma^2}$$

define $$\eta_{*b} = \left(\frac{L \sigma_T}{4\pi m_p c^3 r_0} \right)^{1/4} \quad \text{(baryonic } \eta_*\text{)}$$

$$\eta_{*m} = \left(\frac{L \sigma_T}{4\pi m_p c^3 r_0} \right)^{1/6} \quad \text{(magn. } \eta_*\text{)}$$

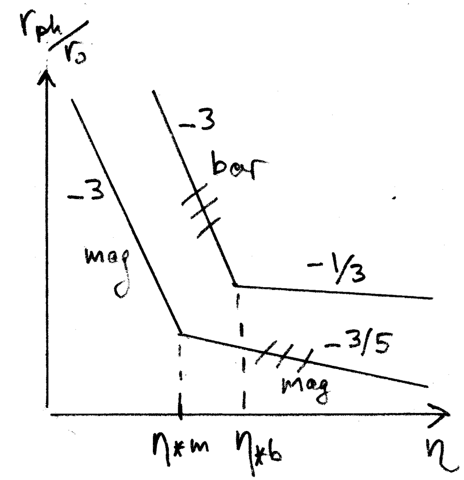
Bar. phot. $$\frac{r_{ph}}{r_0} = \eta_{*b} \begin{cases} (\eta_{*b}/\eta)^3 & \eta < \eta_{*b} \quad (r_{ph} > r_s) \\ (\eta_{*b}/\eta)^{1/3} & \eta > \eta_{*b} \quad (r_{ph} < r_s) \end{cases}$$

Mag. phot. $$\frac{r_{ph}}{r_0} = \eta_{*m}^{1/3} \begin{cases} (\eta_{*m}/\eta)^3 & \eta < \eta_{*m} \quad (r_{ph} > r_s) \\ (\eta_{*m}/\eta)^{3/5} & \eta > \eta_{*m} \quad (r_{ph} < r_s) \end{cases}$$

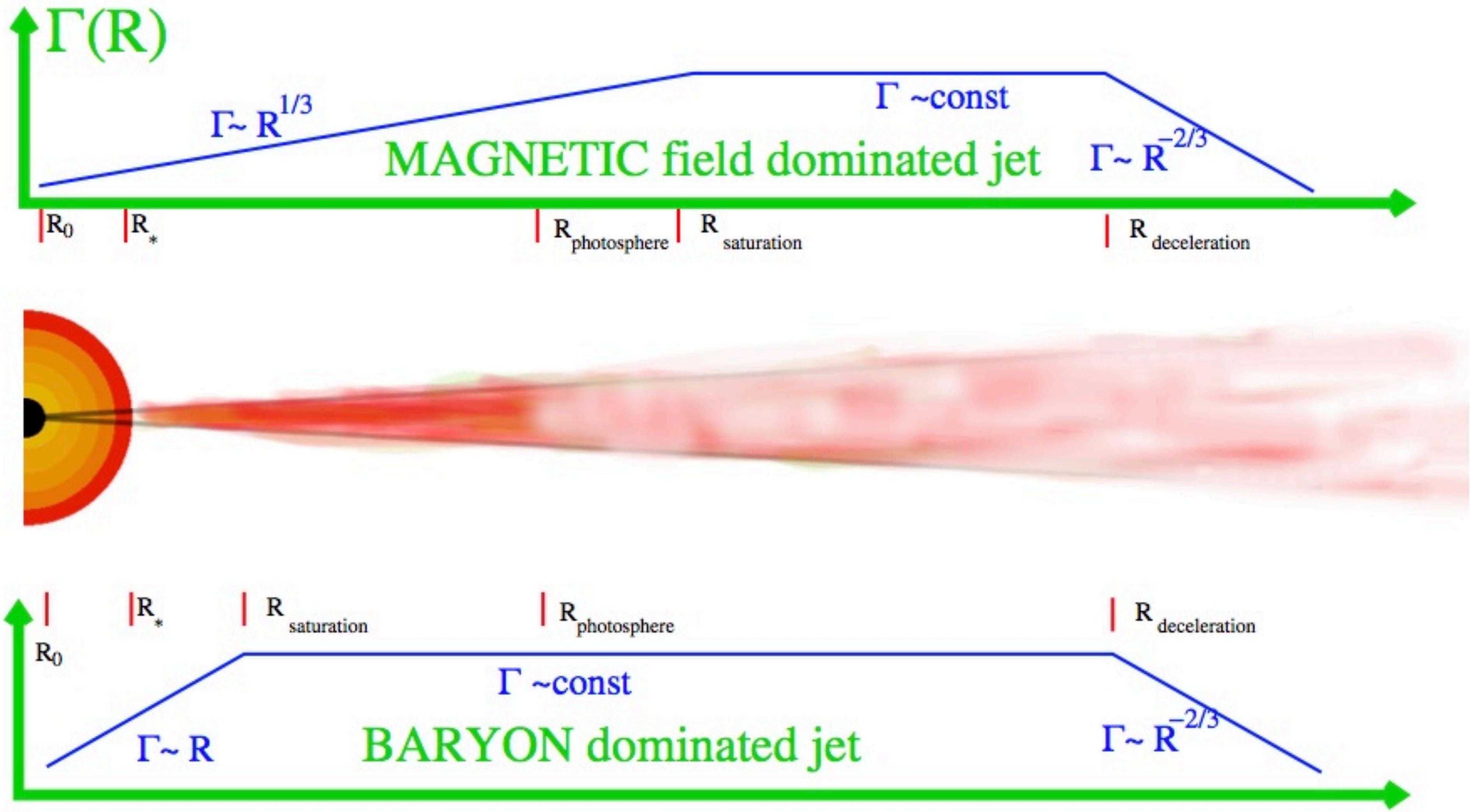
"Cold" (non-dissip.) photosphere

Mészáros-Rees' 00 ApJ 530:292
Mészáros-Rees '11, ApJ 733:L1

1) ***baryonic: phot.*** usually in **coasting** phase
2) ***magnetic: phot.*** usually in **accelerating** phase

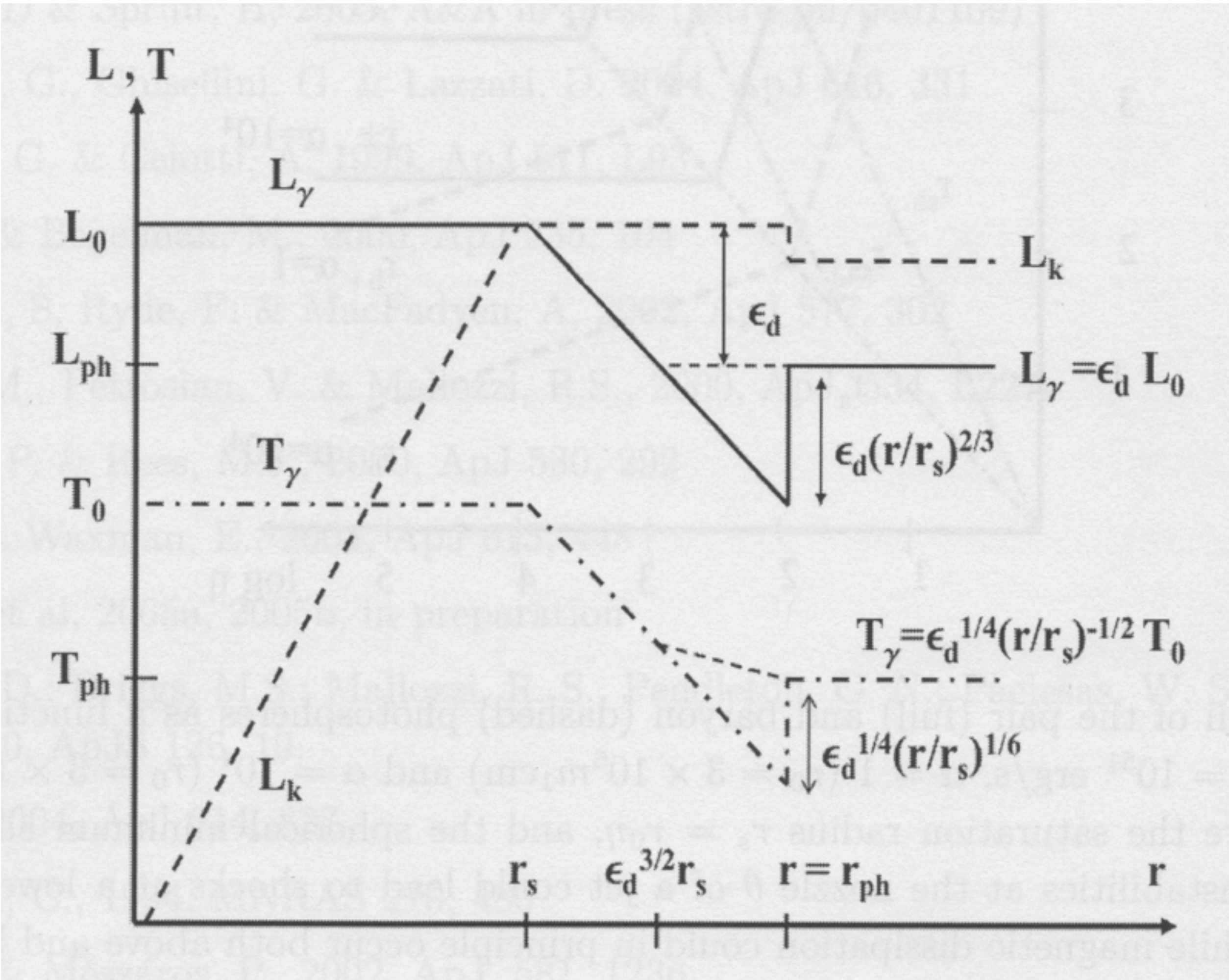


Mag. vs. baryonic jet dynamics



"Hot" (dissipative) photospheres

Rees-Mészáros 05, ApJ 628:847



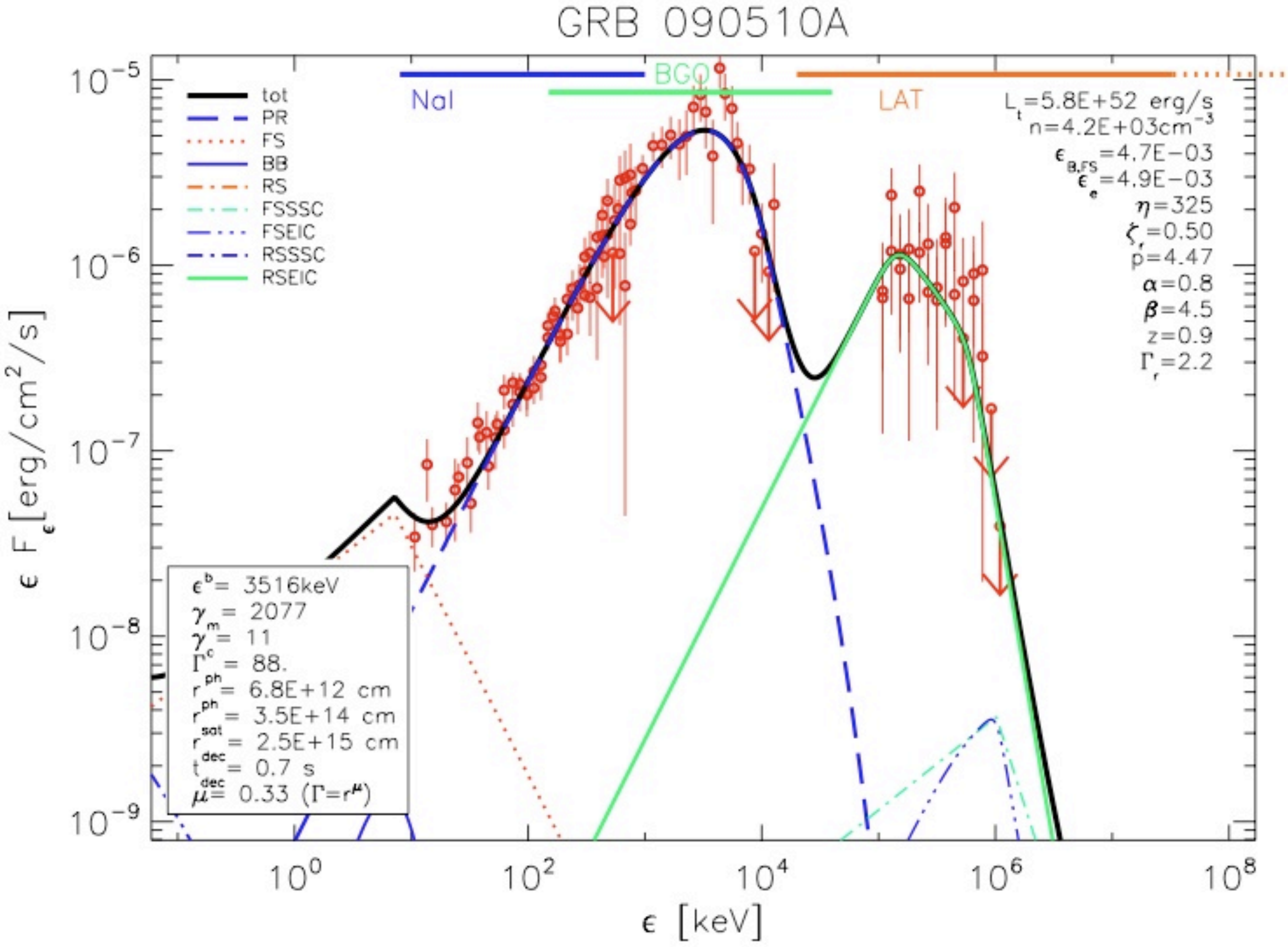
- If no dissipation, Temp: $T' \sim n'^{1/3}$, $n' \sim 1/r^2\Gamma \sim 1/r^2$ → $T = \Gamma T' \sim r^{-2/3}$
- Lum: $L_{ph} \sim r^2 \Gamma^2 T'^4$ → $L_{ph} \sim r^{-2/3}$
- ***But:*** if at some radius (e.g. phot.) dissipat. sets in (e.g. shocks, mag,reconn.,..)
- → **T_{ph}, L_{ph}** are ***higher !***

Photospheric Dissipation Mechanisms

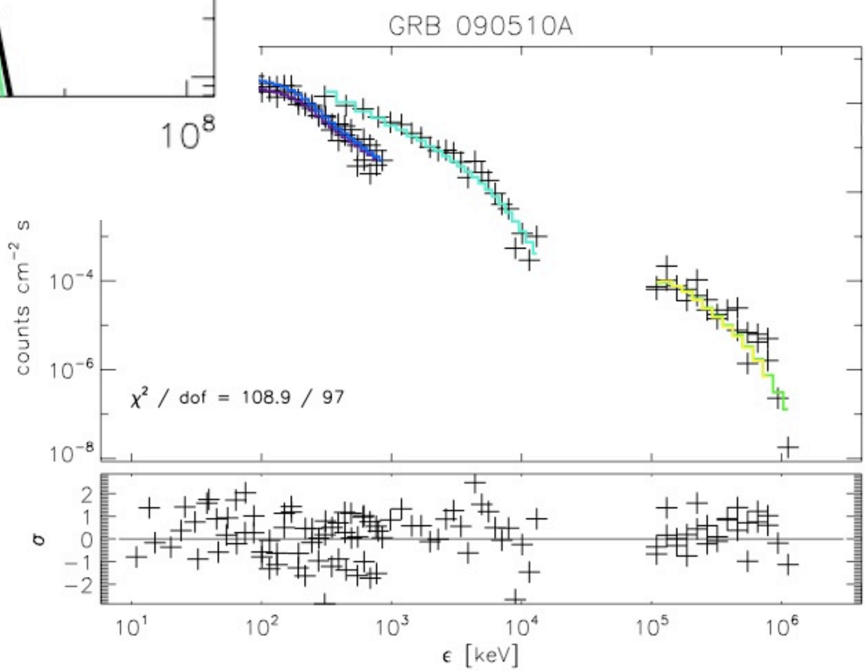
- p-n decoupling ($\perp$, $||$) $\rightarrow$ relativistic $e^{\pm}$, γ
- MHD reconnection, accel. $\rightarrow$ rel. $e^{\pm}$, γ
- Shocks @ photosphere (& below, above) $\rightarrow$same
- ....

Magnetic Photosphere (Leptonic) Fit Results

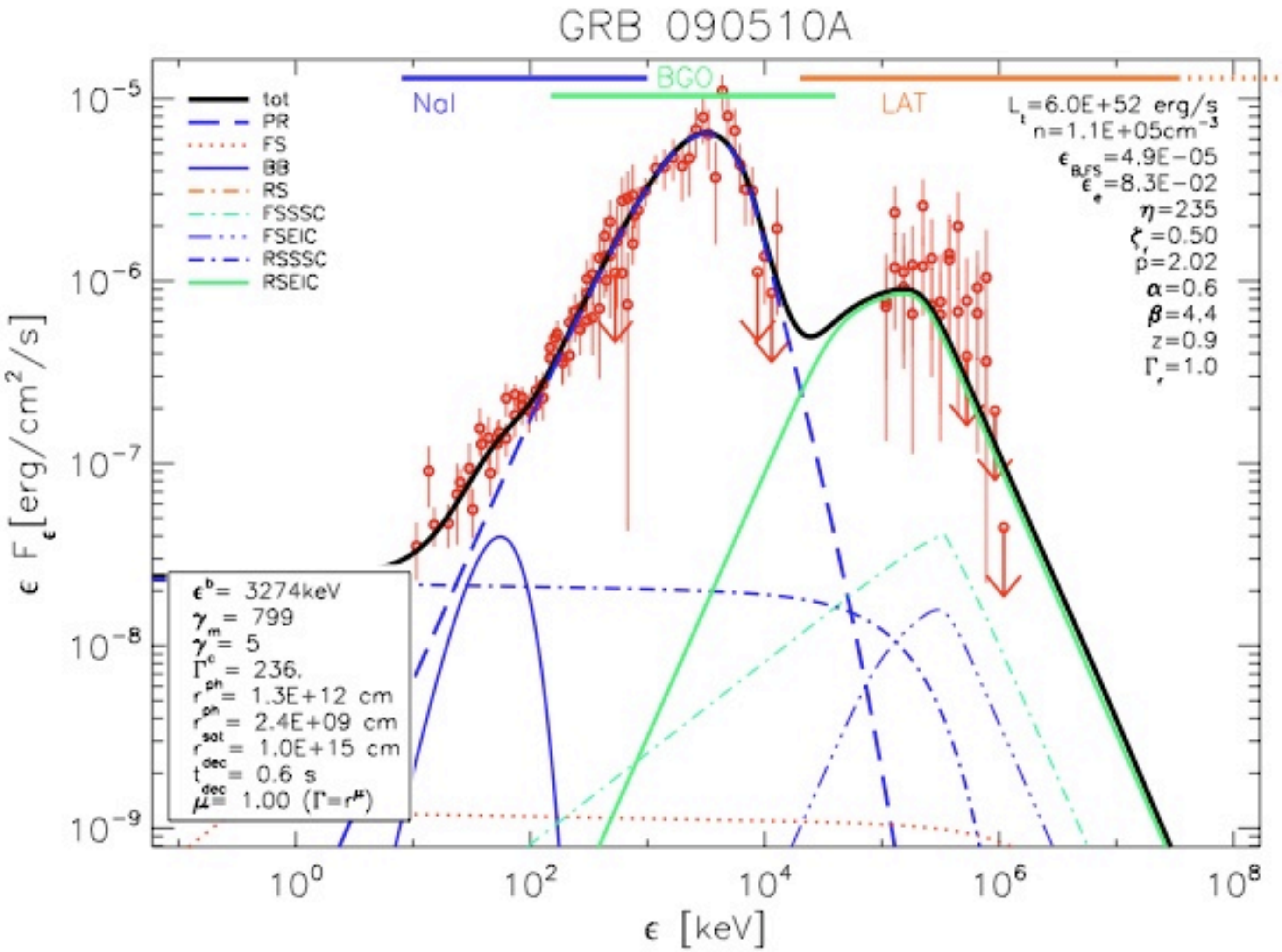
- ***Good fits*** obtained: can reproduce either ***1- or 2-*** component observed spectra with same model
- In some bursts (e.g. 080916C, where 2nd comp. is "absent" (or rather, possible evidence for it is $<2.5\ \sigma$), either a "single Band" or 2-component fit is possible
- Calculated model parameter error estimates
- Use GeV-MeV time delay as an additional constraint
- ***But,*** best fit parameters are generally not unique; and similar quality fits for ***both magn. and baryonic*** phot.



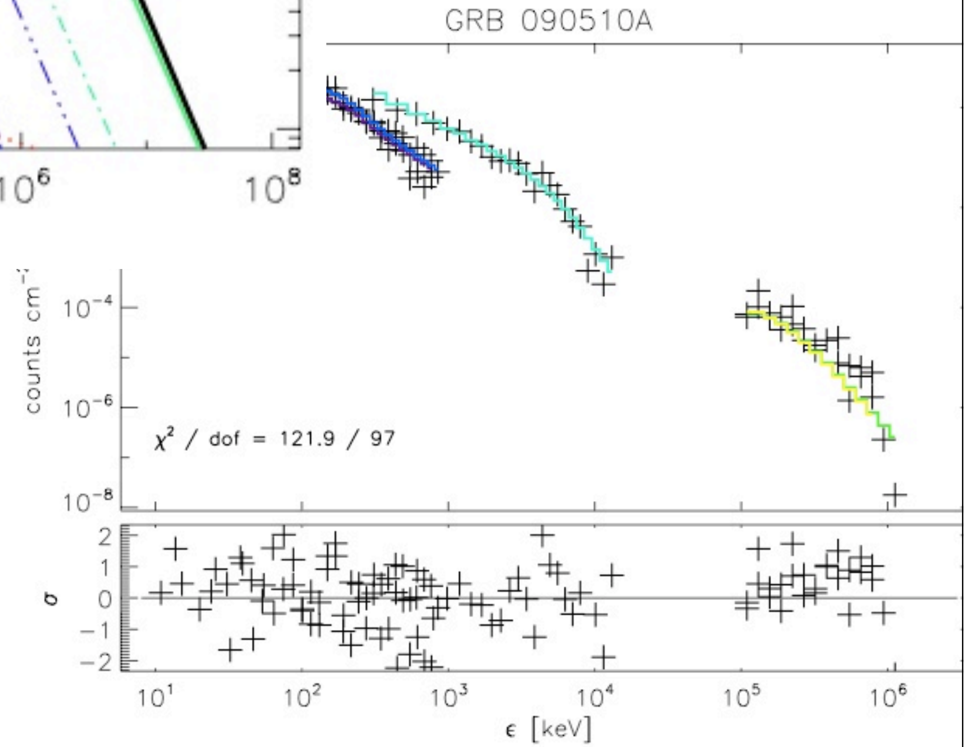
090510A magphot



Veres, BB Zhang & Mészáros '12, ApJ 764:94



090510A barphot



Veres, BB Zhang & Mészáros '12, ApJ 764:94

Upshot:

Can obtain similarly good fits to the
MeV - GeV spectrum with
either
baryonic or magnetic dissipative photospheres

Possible discriminant between them:
BB thermal peak energy/flux is $\neq$ for mag. and bar.

Test of $\Gamma \sim r^{\mu}$ now ***in progress***;
results suggest μ intermediate betw. 1/3 and 1

(Burgess, Veres, et al, 2013 in prep.)

Standard internal shocks: have well-known problems; so...

Internal Shocks Redux: modified internal shocks

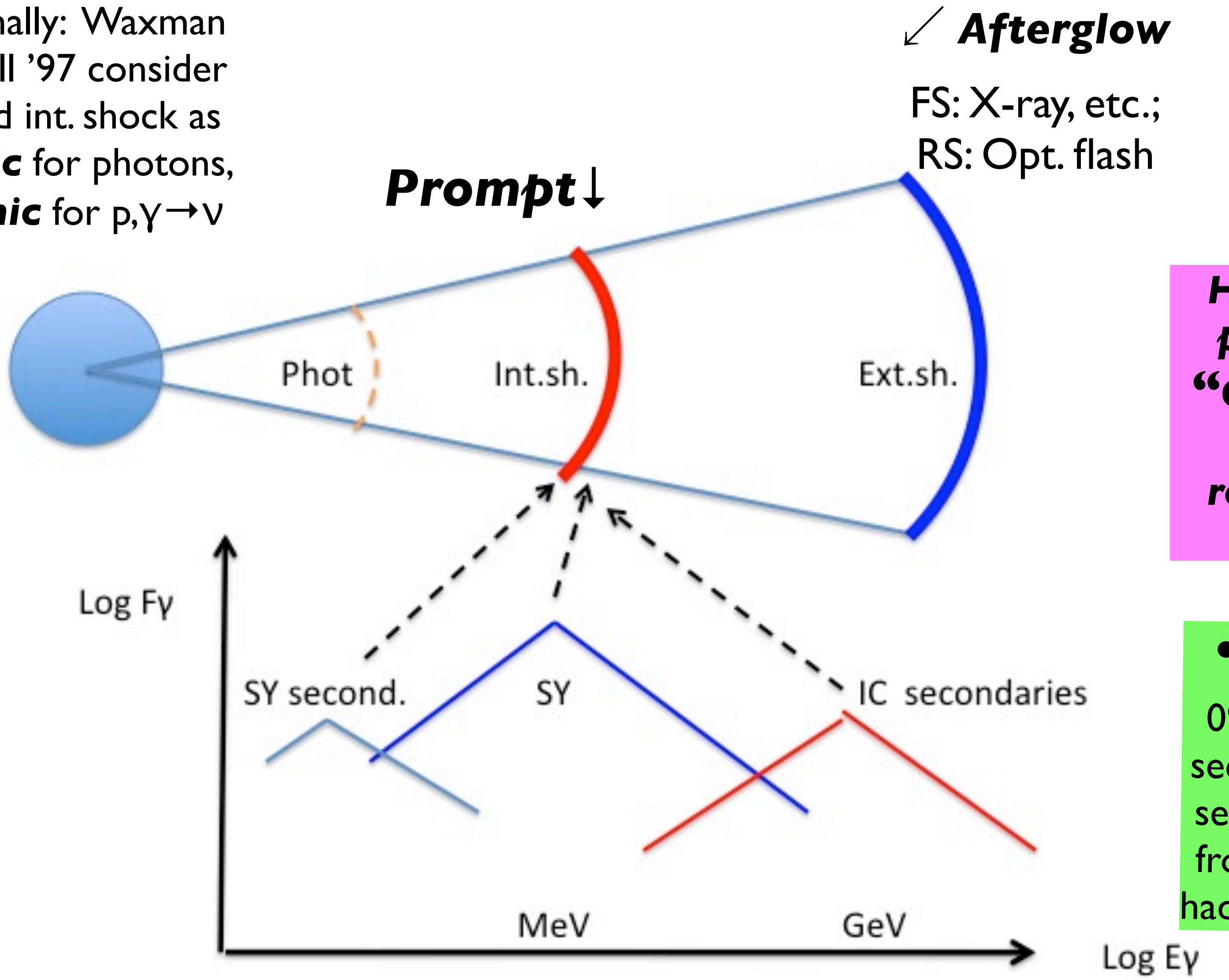
(address/mitigate/solve these problems)

Modifications currently of two main types:

- ***Magnetic dissipation*** in int.shock, R~ 10^{15} cm, allow GeV photons - but hard to calculate quantitatively details of reconnection, acceleration and spectrum, e.g. McKinney-Uzdensky '12, MN 419:573, Zhang & Yan '11, ApJ 726:90
- ***Hadronic internal shocks,*** protons are 1st order Fermi accelerated, and secondaries are subsequently re-accelerated by 2nd order Fermi ('slow heating"), e.g. Murase et al, 2012, ApJ 746:164 - more susceptible to quantitative analysis

Hadronic int. shock: more efficient

• Originally: Waxman & Bahcall '97 consider standard int. shock as ***leptonic*** for photons, ***hadronic*** for p,γ→ν



New Feature:

Hadron accel.* + *photomeson* → "dissipation"** →inject copious ***relativistic sec'y leptons

•↙ Asano & PM, 09-12 on, calculate second'y ***photons*** & second'y ***neutrinos*** from both original & hadronic sec'y leptons

also: Murase et al, 2012, ApJ 746:164

Questions

- *Increasing interest in whether the central engine is a prompt BH - or a magnetar → BH*
- *If so, what are timescale_mag vs. timescale_BH, and is jet emission any different in its power & baryon load?*
- *baryonic vs. magnetic* jets: how to distinguish them?
- Prompt emission: *hadronic or leptonic?*
- Are photospheres needed? *Magn. or baryon. phot?*
- Are modified internal shocks competitive? *Magnetized or hadronic* internal shocks?
- *Reconnection or Fermi* acceler'n? *Pairs*: important?
- *Combined Swift + Fermi obs. crucial for above*

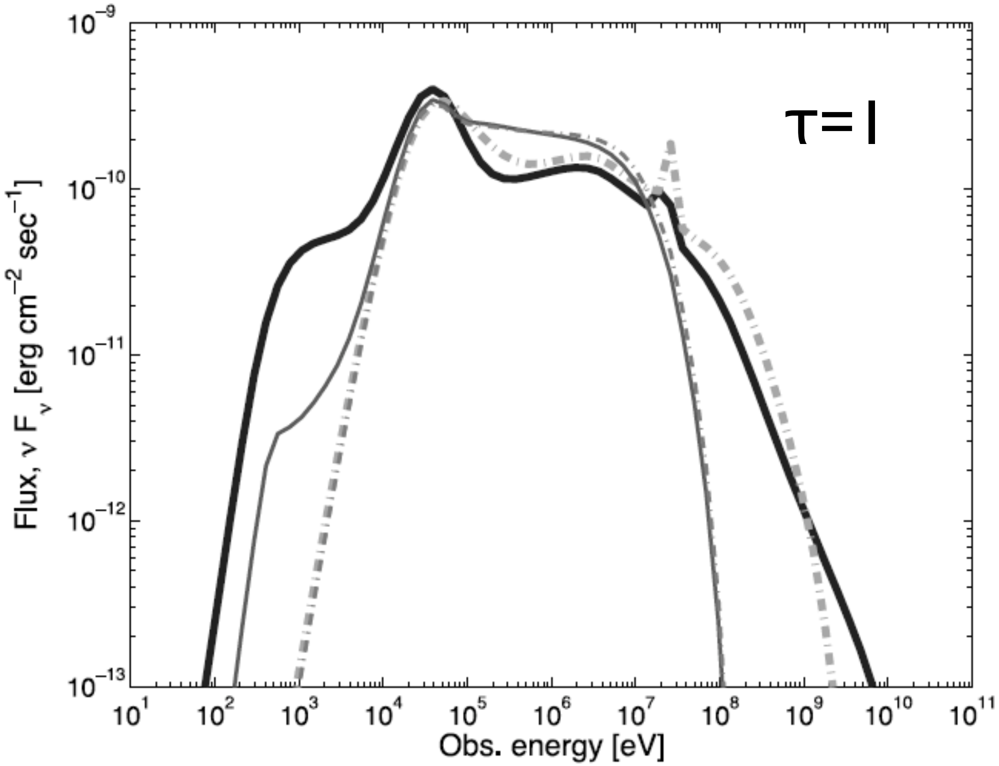
Some Theoretical Issues:

- Are "single Band" spectra at GeV due to ***internal*** or ***external*** shocks? - or ***magnetic dissipation***? or a ***photosphere***, ..?
- Is ***2nd*** component always present at some level? Is it a ≠ ***zone/rad.mech.*** than ***1st***? Do we need ***two-zone*** models?
- Are photons ***leptonic***, ***hadronic***, or ***mixed?***
- What are ***astrophysical*** causes of ***GeV-MeV delay?*** (aside from posible QG effects)

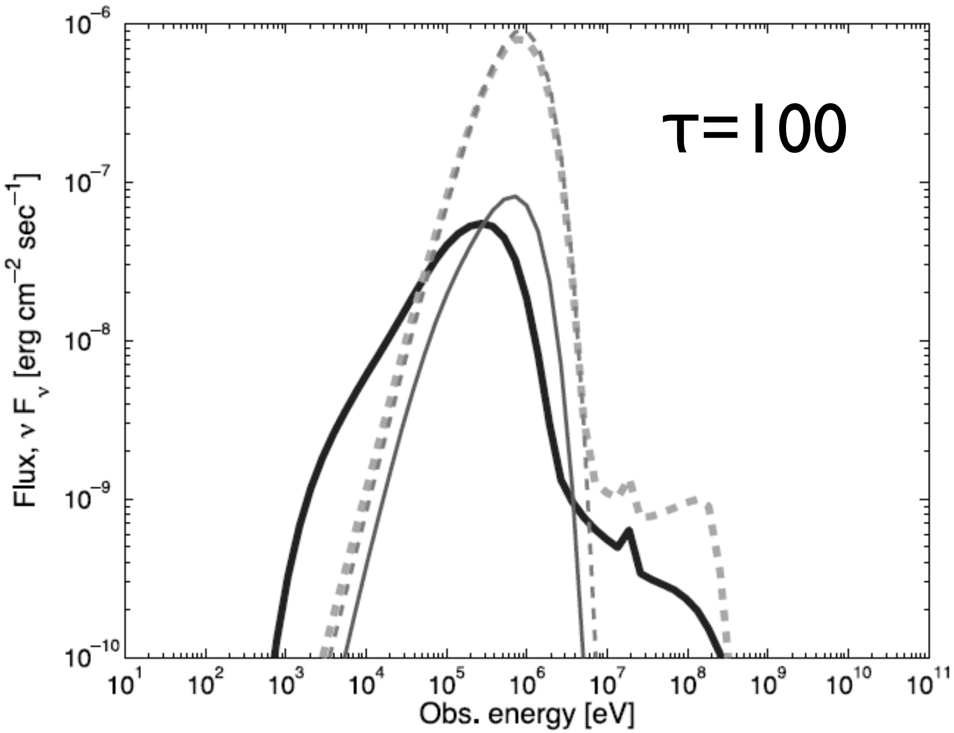
Numerical dissip. photospheres

- 2 scenarios: slow dissip. and shock dissip.
- Incl. synchro+ Compton, pair form+annih

Pe'er et al 06 ApJ 642:995



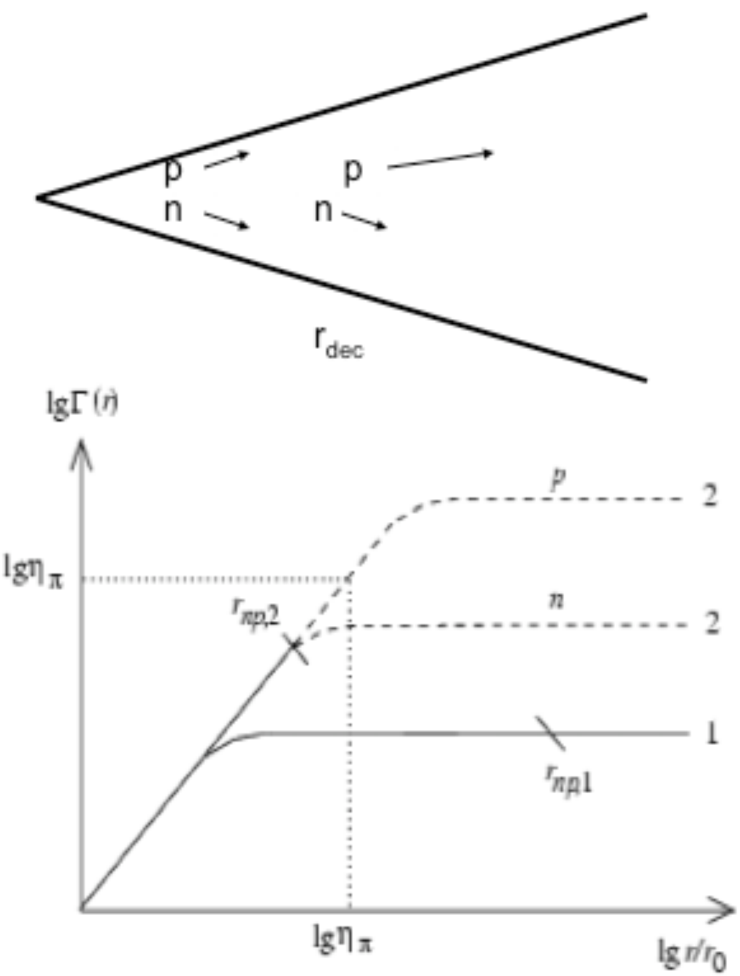
Left: synch peak, middle: thermal peak
Right: Comptonized spectrum + annih. peak



Slow dissipation: thin lines, shock dissipation: thick lines
Solid lines: high ε_B=0.3, dot-dashed lines: low ε_B=10^{-6}

Hadronic GRB Fireballs:

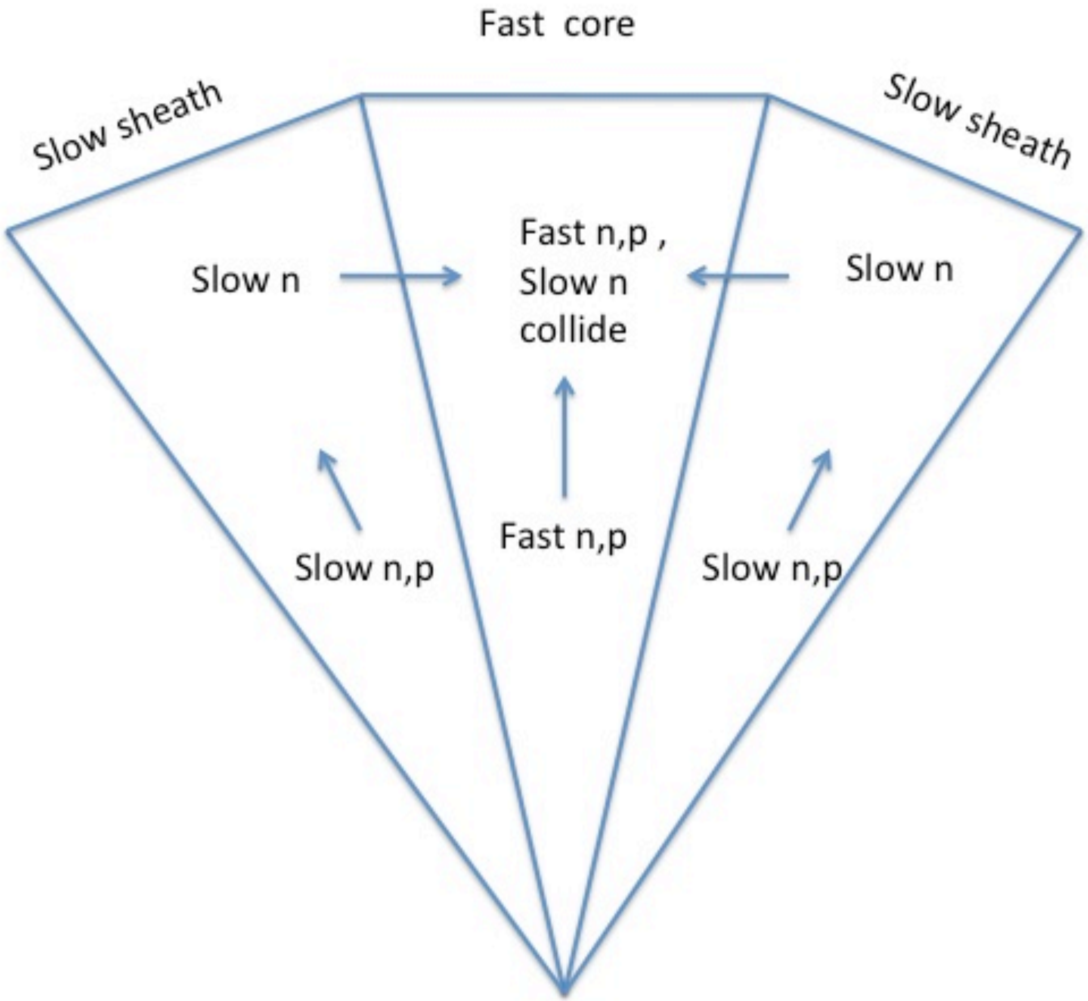
p,n decouple $\rightarrow$ VHE ν, γ



Bahcall & Mészáros 2000

- Radiation pressure acts on e^-, with p^+ coming along (charge neutrality)
- The n scatter inelastically with p^+
- The p,n initially expand together, while $t_{pn} < t_{exp}$ (p,n inelastic)
- When $t_{pn} \sim t_{exp} \rightarrow$ p,n decouple
- At same time, $v_{rel} \geq 0.5c$ $\rightarrow$ p,n becomes inelastic $\rightarrow \pi^+$
- Decoupling important when $\Gamma \geq 400$, resulting in $\Gamma_p > \Gamma_n$
- $\Rightarrow$ ***dissipation***
- Decay $\rightarrow \nu$, of $E_\nu \geq$30-40 GeV
- **And ALSO: γ-rays !**

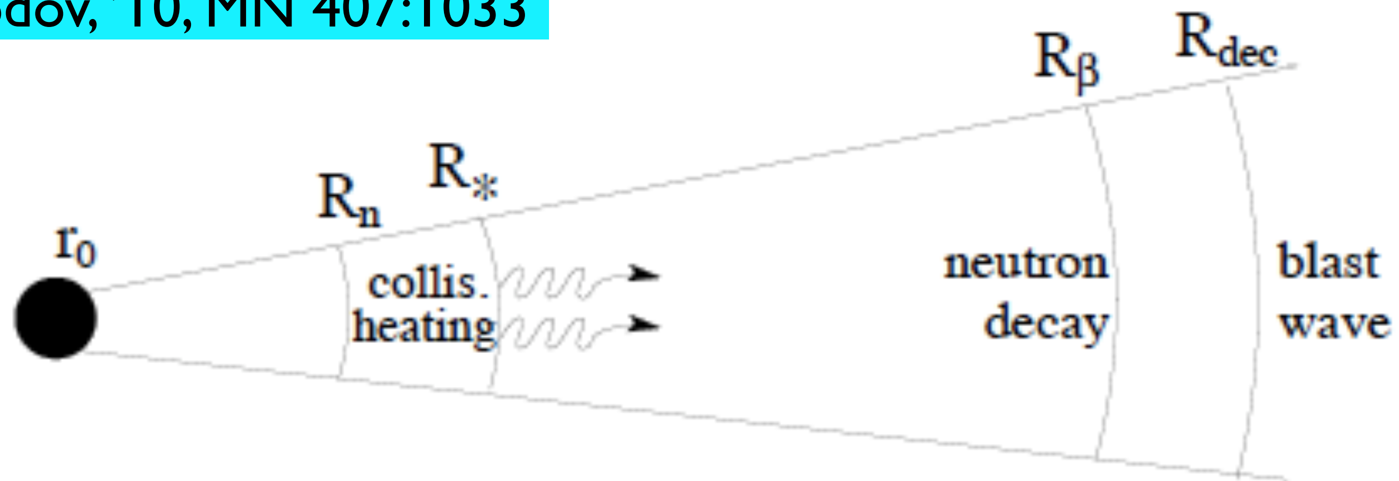
Decoupling of p-n also possible transversally



A hadronic “thermal” photosphere PL spectrum?

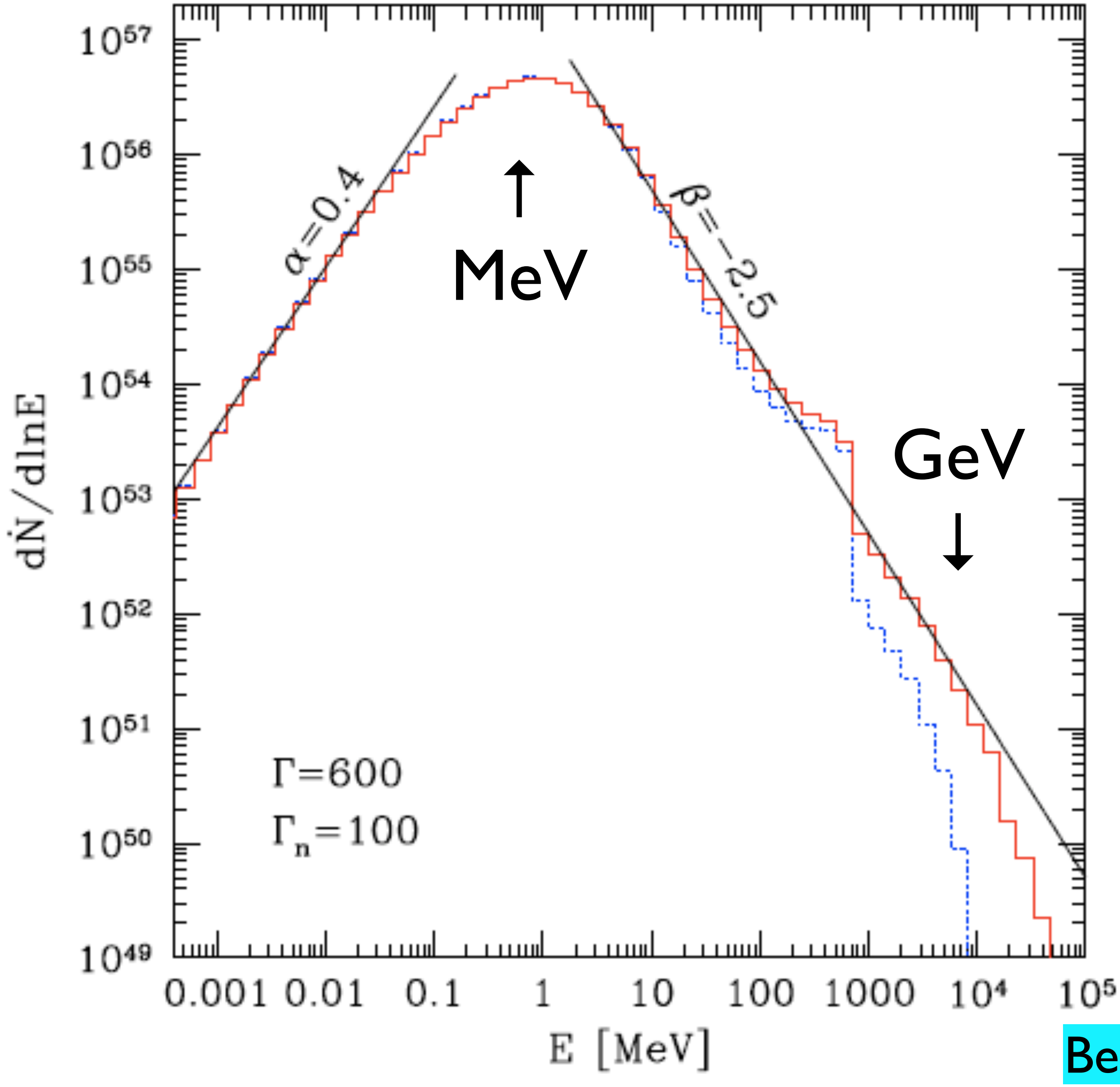
p-n collisions in sub-photosphere

Beloborodov, ’10, MN 407:1033



- Long history: Derishev-Kocharovsky 89, Bahcall-Meszaros 00, Rossi et al 04, etc
- Either p-n decoupling or internal colls. → relative p-n streaming, inelastic colls.
- Highly ***effective dissipation*** (involves baryons directly)- can get >50% effic’y
- Sub-photospheric dissipation can give strong photospheric component

p-n coll.→e±→ *photosphere γ-spectrum*

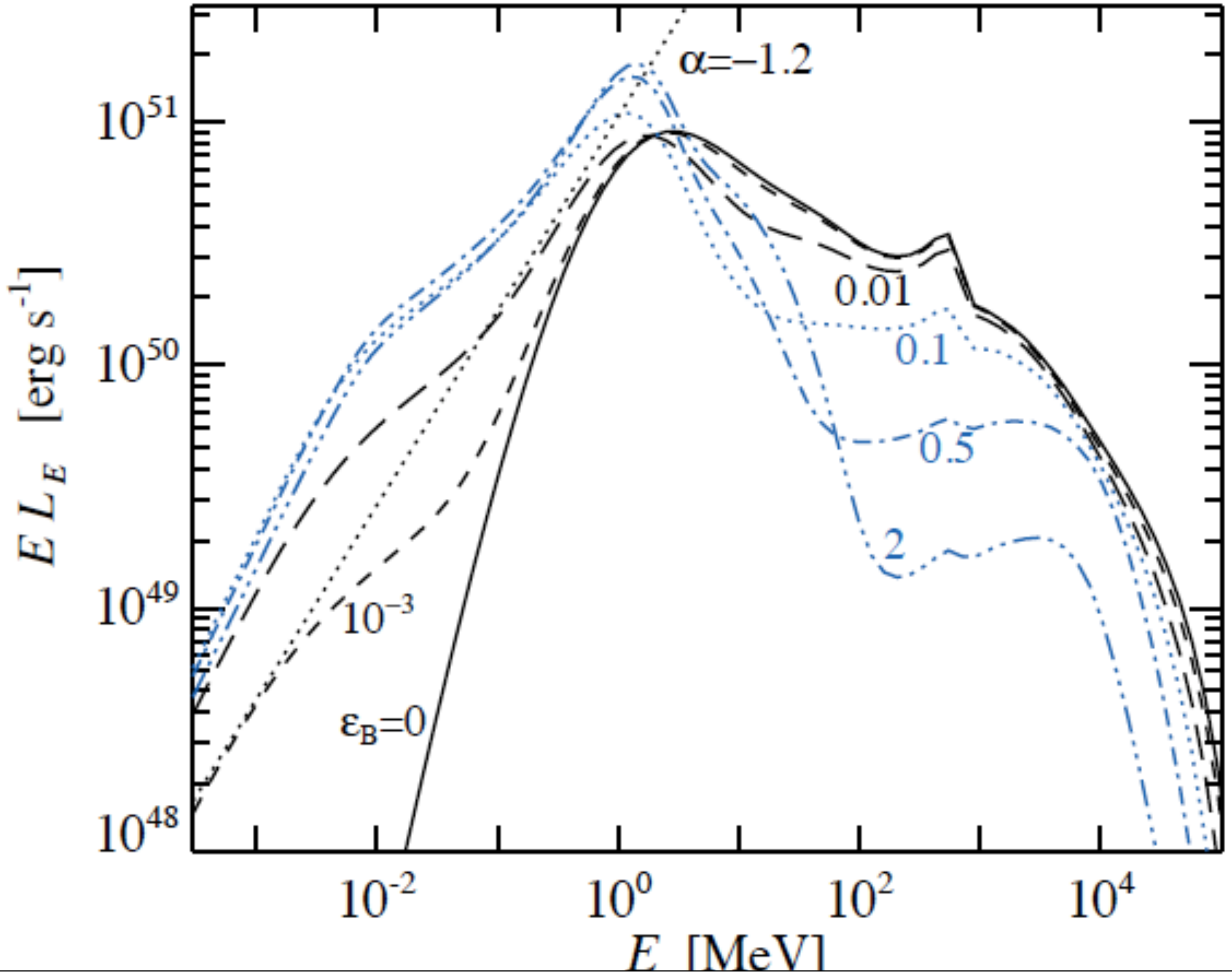


- The result is a thermal peak at the ~MeV Band peak, plus
- a high energy tail due to the non-thermal $e^{\pm}$, whose slope is comparable to that of the observed Fermi bursts with a "single Band" spectrum
- The "second" higher energy component (when observed) must be explained with something else

Beloborodov, '10, MN 407:1033

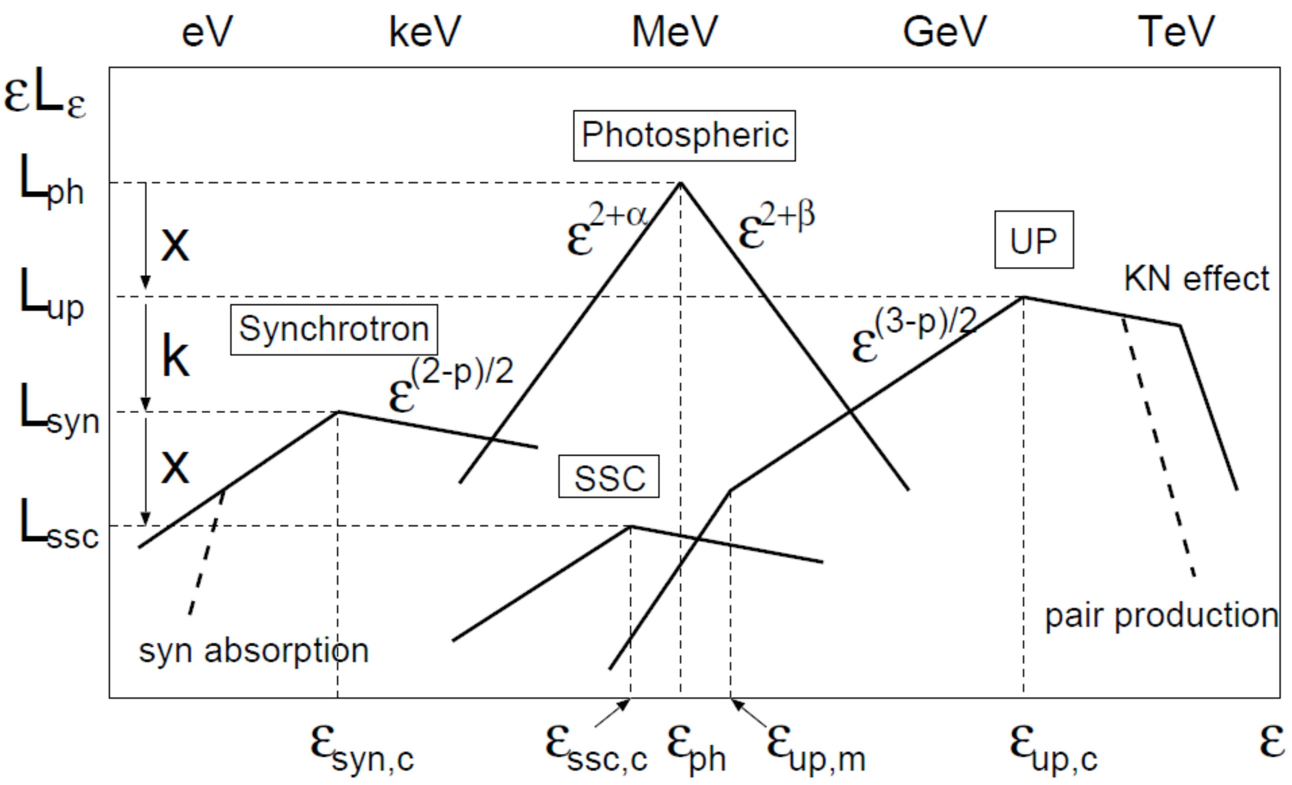
pn sub-photosphere w. mag.fields

Wurm et al, '11 ApJ 738:77



Mag. fields => synchr, get a partial 2nd component, to ~<10 GeV

Photosphere + Internal Shock leptonic model, cont.



$$x \simeq \frac{\epsilon_d \epsilon_e}{(\eta/\eta_*)^{8/3}} \left(\frac{\gamma_c}{\gamma_m} \right)^{2-p} .$$

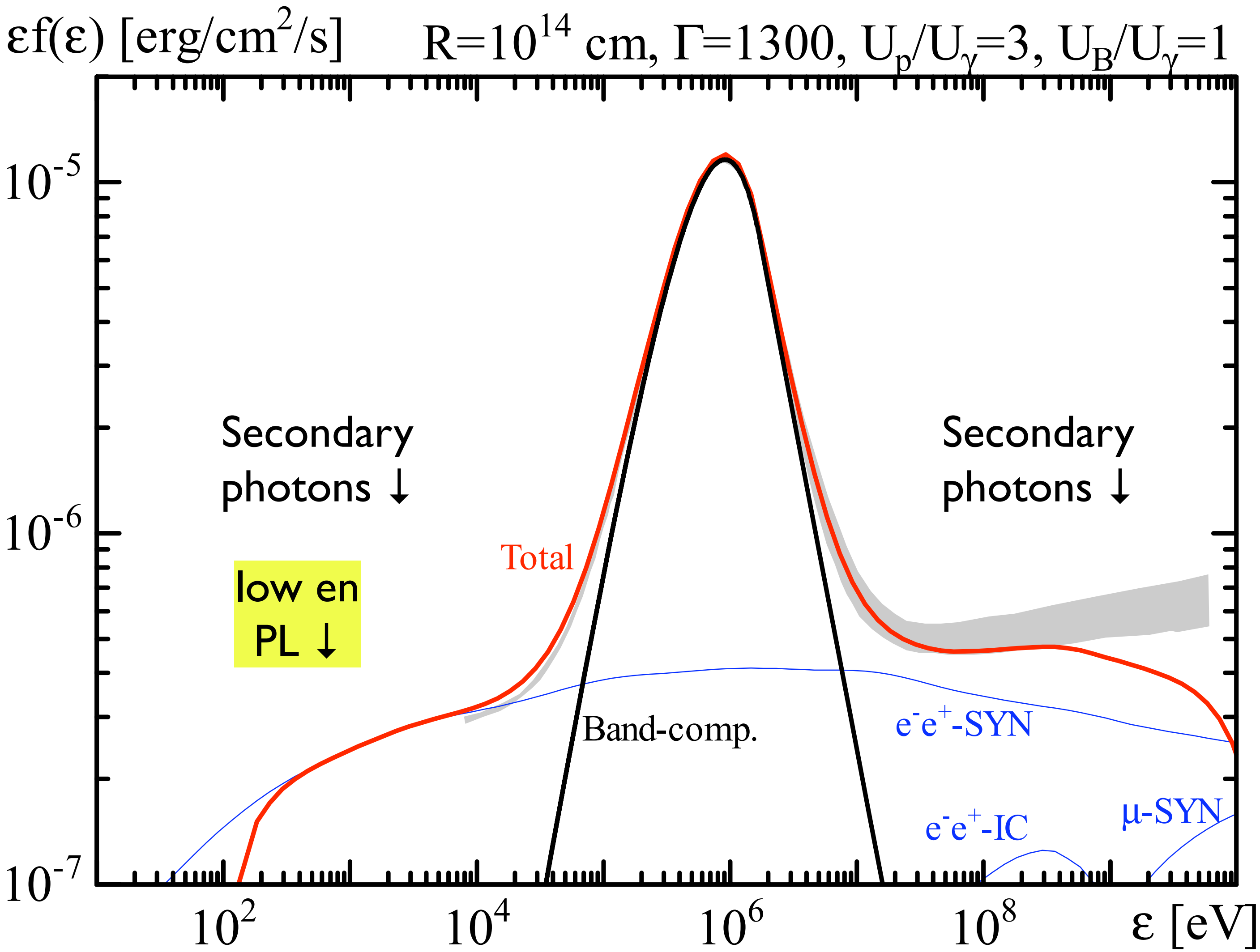
$$k \equiv \frac{L_{\rm syn}}{L_{\rm up}} = \frac{U'_B}{U'_{\rm ph}} = \frac{\epsilon_d \epsilon_B}{(\eta/\eta_*)^{8/3}},$$

$$L_{\rm up} = L\epsilon_d \epsilon_e \left(\frac{\gamma_c}{\gamma_m} \right)^{2-p}$$

$$\varepsilon_{{\rm up},c} = \varepsilon_{\rm ph} \gamma_c^2$$

Generic shape comparable to Fermi observations ✔

a **hadronic** model: 090902B



Assume phot. makes Band function & shock or mag. dissip. at $r \sim 10^{15}$ - 10^{16} cm accelerates p^{+}, $e^{\pm}$

Also explain presence of low energy power law spectral component

Asano, Inoue, Mészáros, 2010, ApJL 725:L121

MHD / Poynting jets?

ICMART model

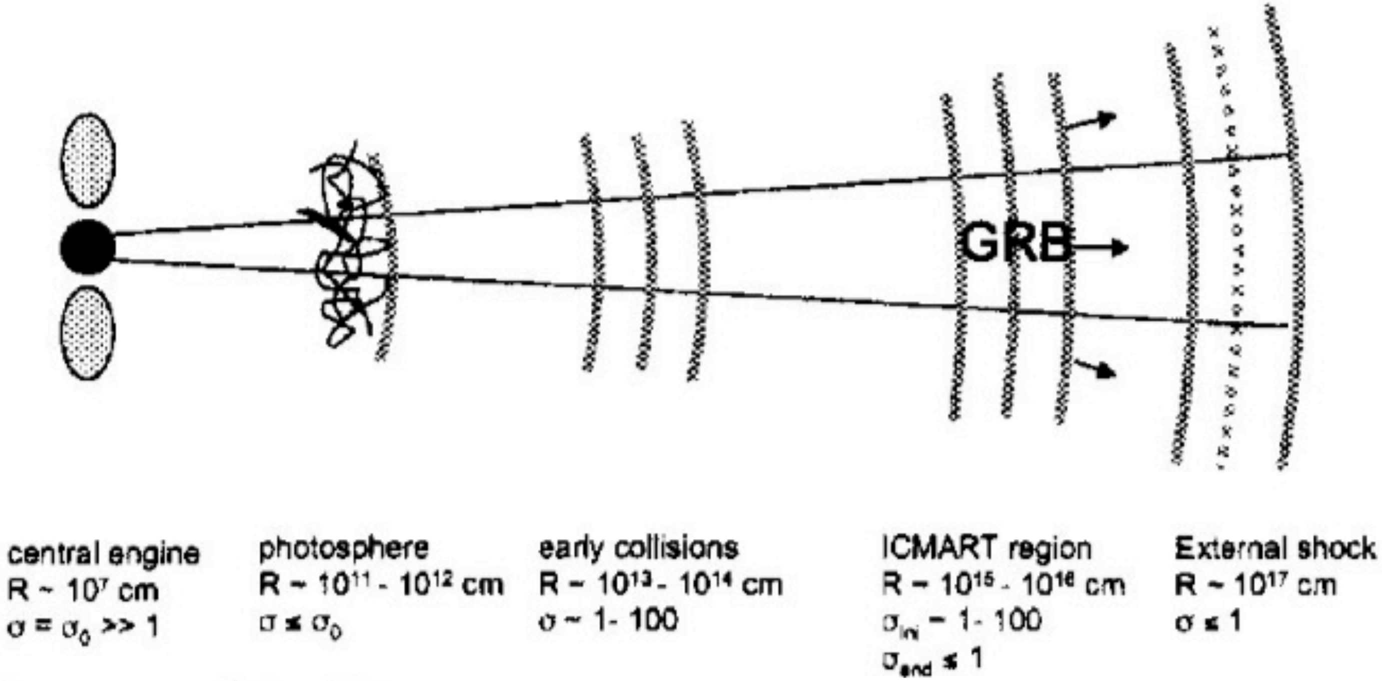
("Internal Collision Magnetic Reconnection Transient")

B. Zhang & H. Yan '11, ApJ, 726:90

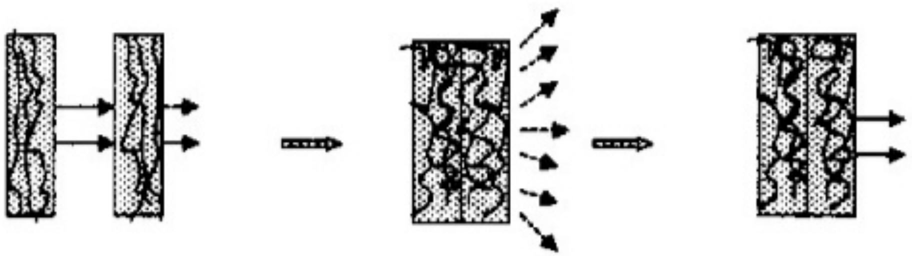
- Int. coll. w. $1 \lesssim \sigma \lesssim 100$, where $\sigma = B'^2/4\pi\rho' c^2$ (MHD)
- Magn. reconn. in intern. shock (aided by turbulence)
- Accel e^- : direct (recon.) or stochast. turb. $\rightarrow$ rad: SY
- Need reconn. over $\lambda_{par} \leq 10^4$ cm lengths , envisage blobs w. same directions spiral but staggered, have $\downarrow\uparrow$ regions of B_{perp} $\rightarrow$ turb. resist. $\rightarrow$ reconn. (early colls. distort B, at large r much distort., recon)

ICMART model

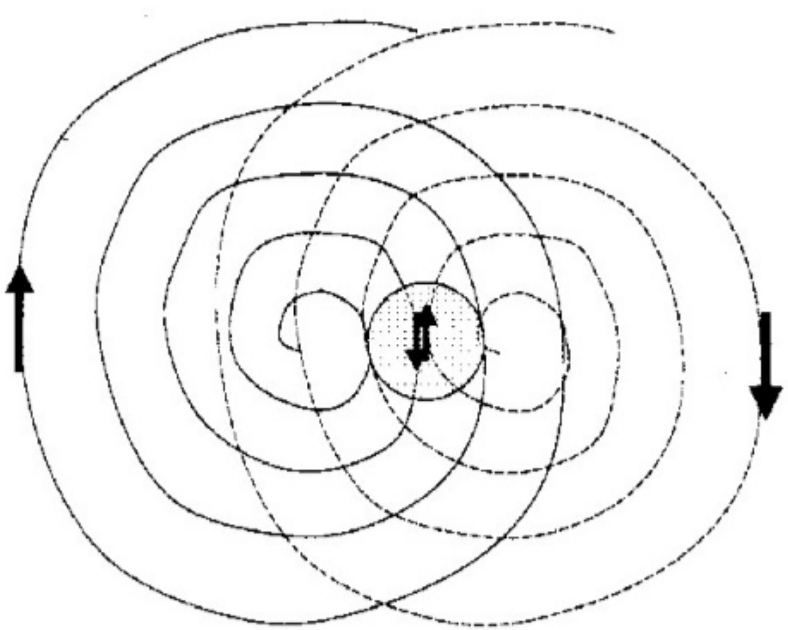
B. Zhang & H. Yan '11, ApJ, 726:90



(a) Initial collisions only distort magnetic fields



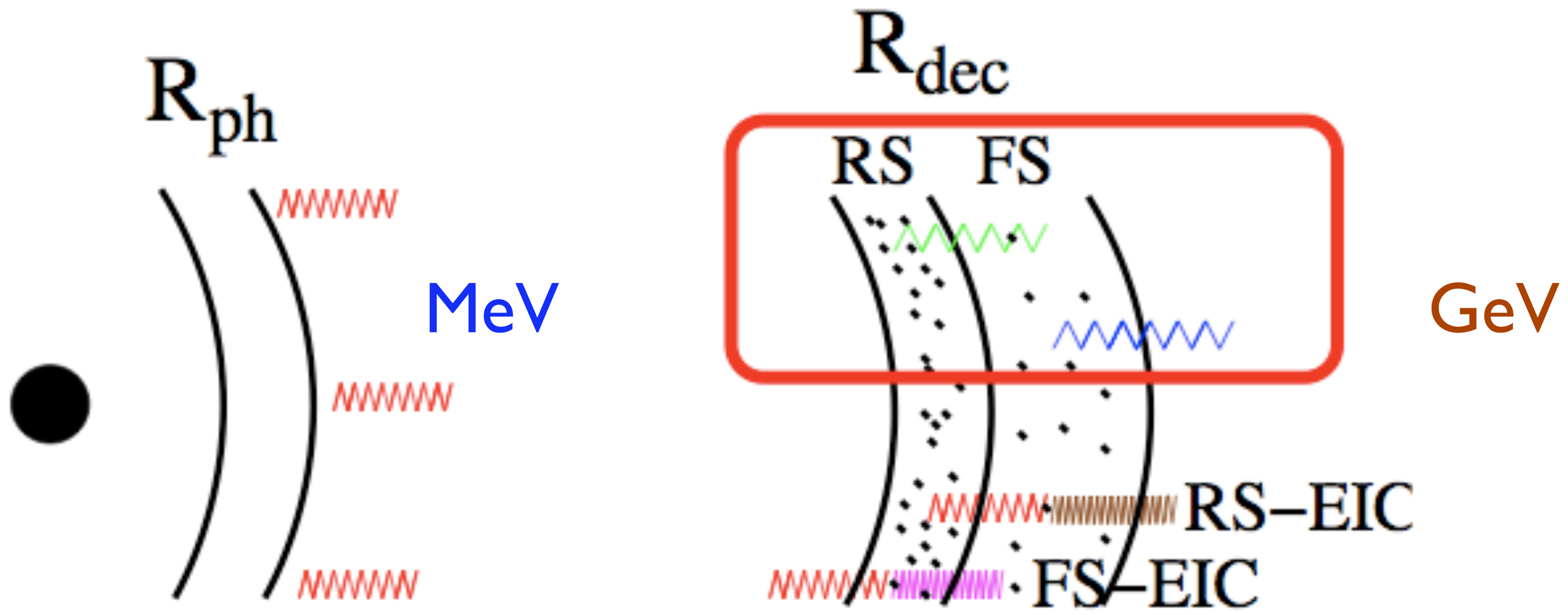
(b) Finally a collision results in an ICMART event



Non-magnetic leptonic “first response” models to Fermi, concentrating mainly on GeV

- Kumar & Barniol-Duran 2010: adiabatic external shock synchrotron (low B)
- Ghisellini et al 2010: radiative (pair-enriched) external shock synchrotron
- Wang et al, He et al & Corsi et al, 2010-11: external shock synchrotron + IC

A leptonic magnetic photosphere + external shock model



- Leptonic photosph. spectrum extend to $\Gamma_{ph}\, m_e$ ~50-100 MeV
- Ext. shock upscattering spectrum extend to $\Gamma_{es}\, \gamma_{e,KN}\, m_e \rightarrow$ TeV

Veres & Mészáros '12, ApJ 755:12

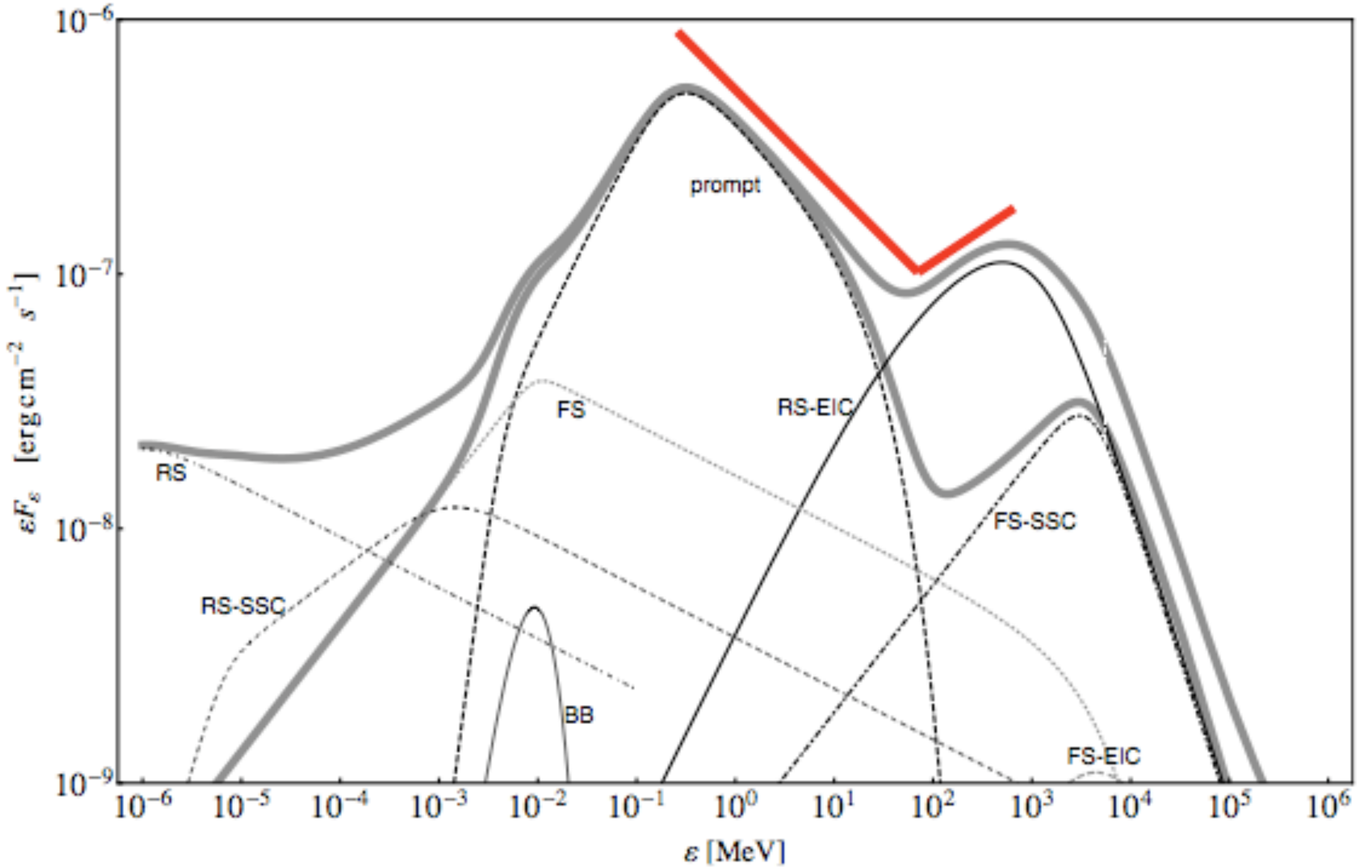
Magnetized GRB jet radiation

- Dynamics of expansion $\Gamma \sim r^{1/3} \rightarrow \Gamma \sim$ const
- Dissipative (magn. or baryon.) scattering photosphere → broken PL MeV spectrum
- No internal shocks expected
- Magnetiz. param. σ drops to ~ o(1) at r_{decel}
- External shock present (forward; +reverse?)
  →both shocks up-scatter photospheric MeV
  →to GeV -TeV range

Veres & Mészáros, 2012, ApJ 755:12

Phot+ExtSh : Band + 2nd comp.

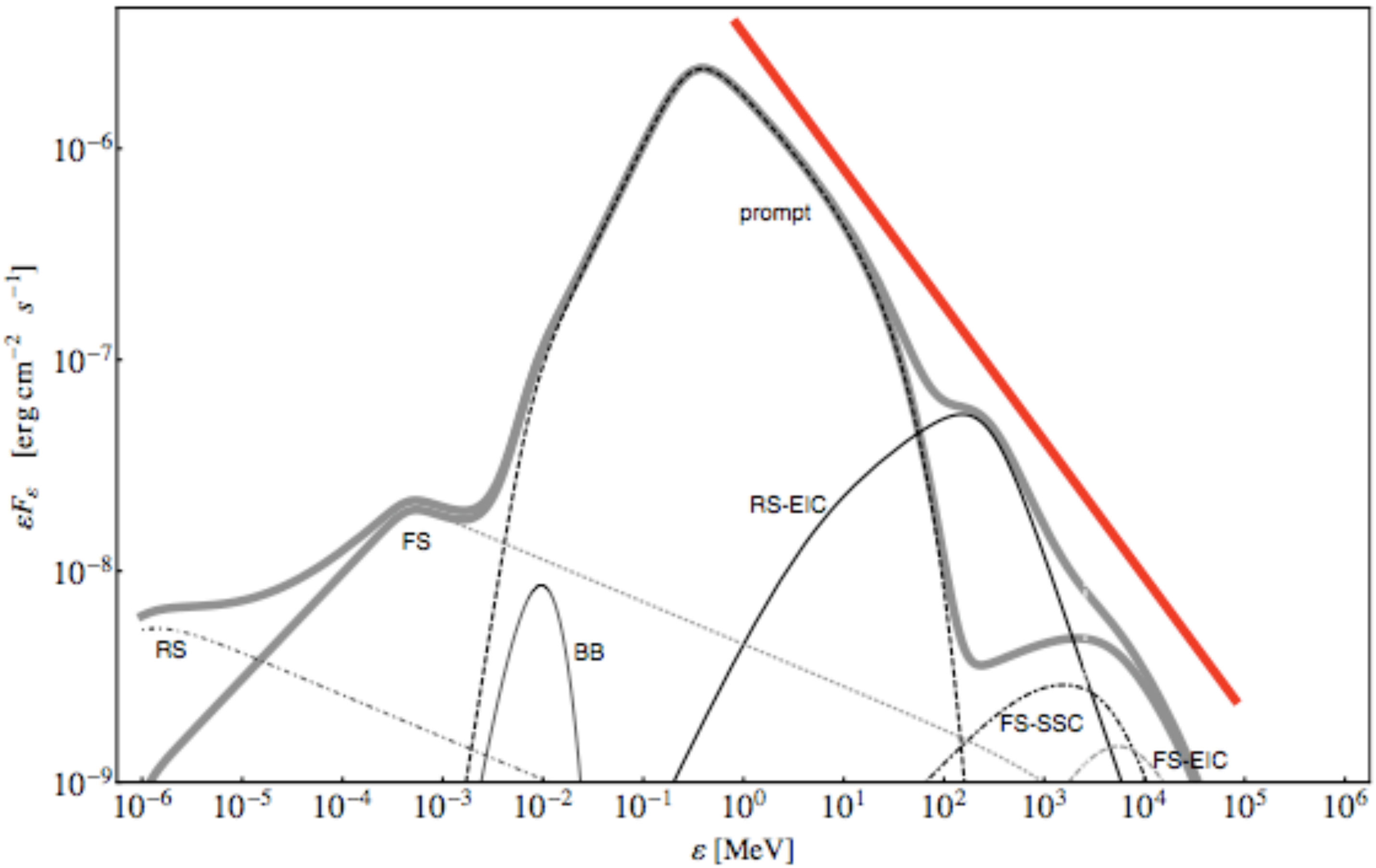
Veres & Mészáros '12, ApJ 755:12



$L_t = 5 \times 10^{52}$ erg/s, $\zeta_r = 0.6$, $n = 10^2$ cm^{-3}, $\eta = 400$, $\epsilon_{B,pr} = 0.9$, $\epsilon_{B,FS} = 10^{-2}$, $\epsilon_{e,FS} = 2 \times 10^{-2}$, $r_0 = 10^7$ cm, $z = 1$, $\beta = 2.4$, $p = 2.4$

Phot+ExtSh : Single (Band) PL

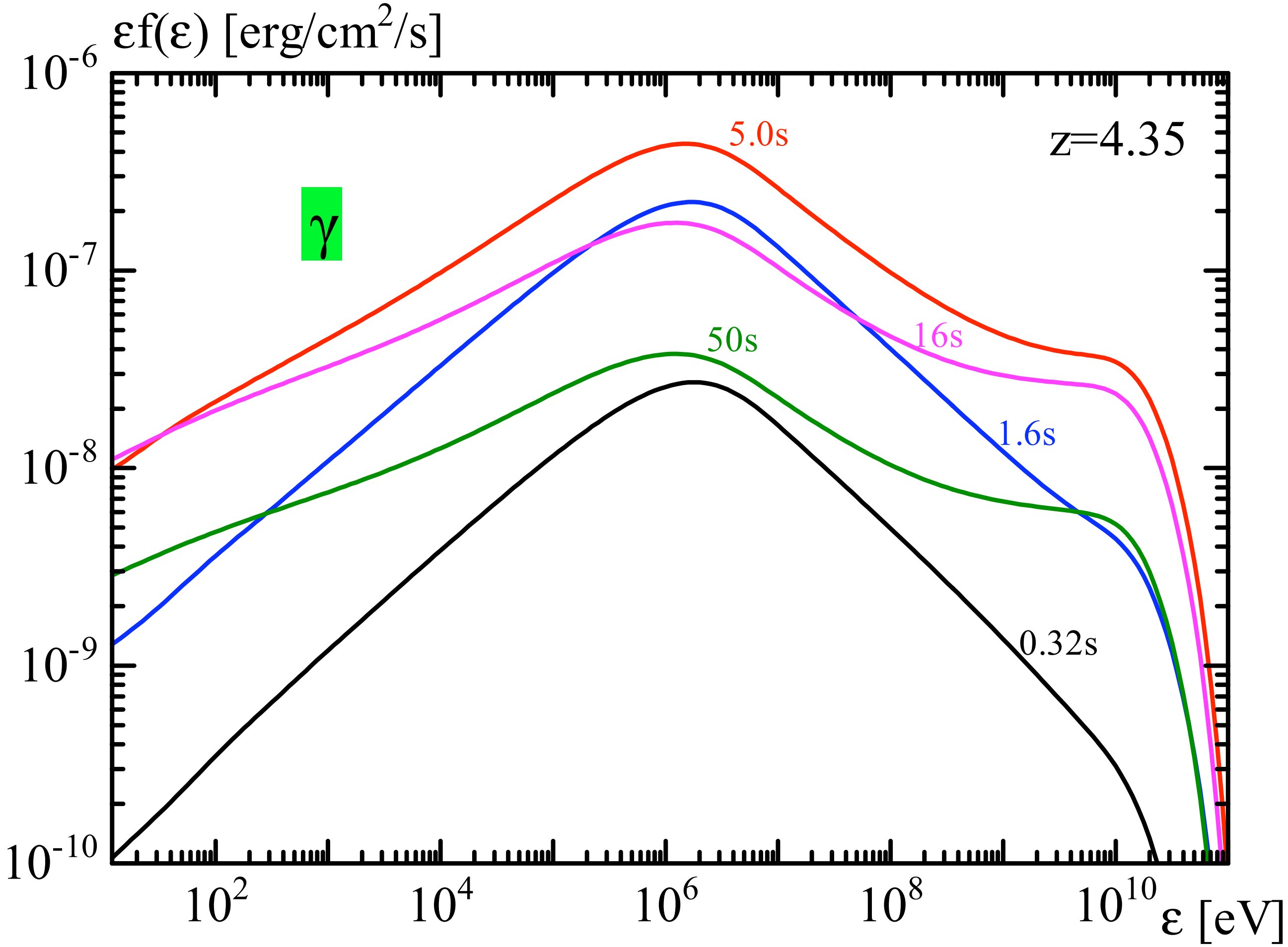
Veres & Mészáros, '12, ApJ 755:12



$L_t = 10^{53}$ erg/s, $\zeta_r = 0.5$, $n = 30$ cm^{-3}, $\eta = 400$, $\epsilon_{B,pr} = 1$, $\epsilon_{B,FS} = \epsilon_{B,RS} = 2 \times 10^{-2}$, $\epsilon_{e,FS} = \epsilon_{e,RS} = 5 \times 10^{-3}$, $r_0 = 10^7$ cm, $z = 1$, $\beta = 2.5$, $p = 2.4$

Numerical time dependence of photon & neutrino secondaries

(Asano & PM '12, ApJ 757:115)

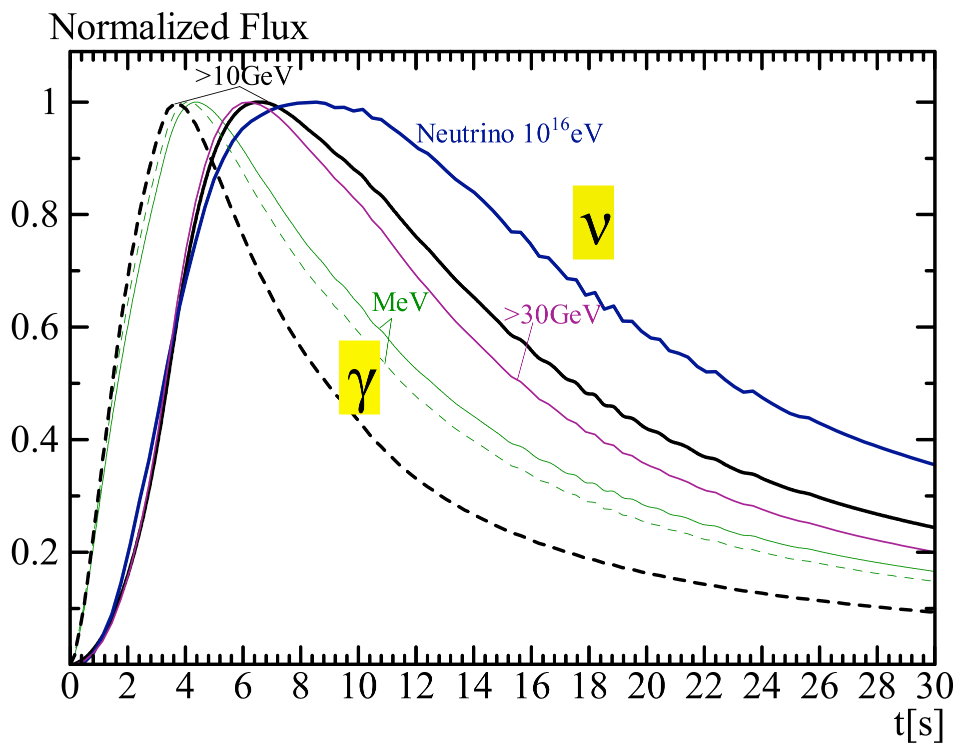


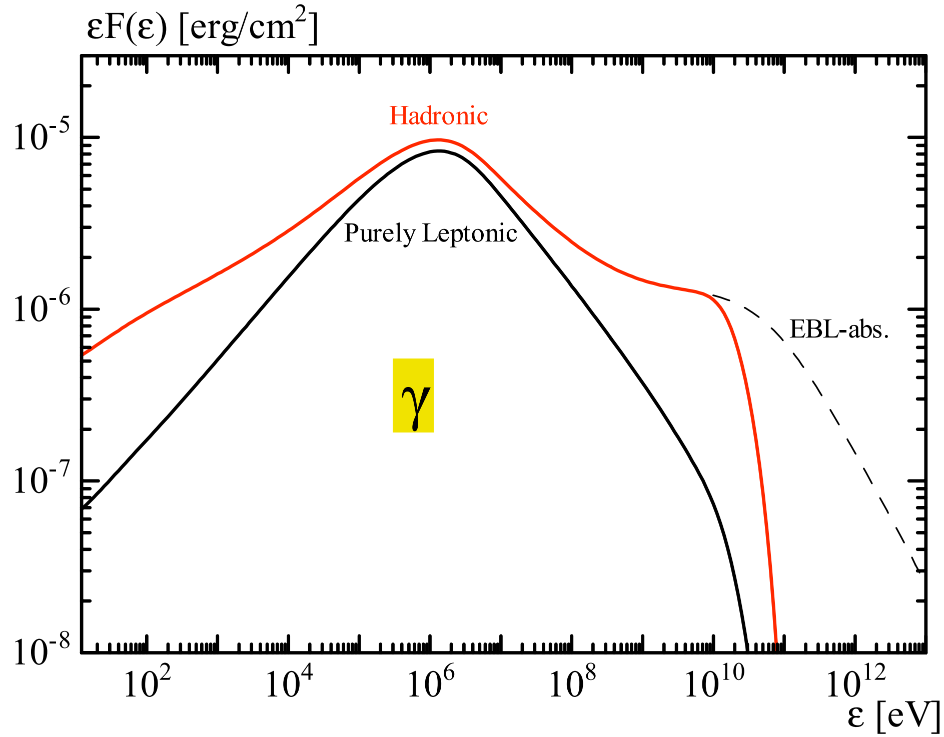
- Generic dissipation region at a radius $R \sim 10^{14}$-10^{16} cm (could be Int.Sh. or mag. diss. region, etc.)
- Numerical Monte Carlo one-zone rad. transfer model with all EM & ν physics
- ←Fermi/LAT param. $E_{\gamma iso} \sim 2.10^{54}$, $L_p/L_e=20$, $\Gamma=600$, $R \sim 10^{16}$cm, z=4.5

Fermi/LAT hadronic case

- For very bright, rare bursts (<10% of all cases)
- Get 2nd GeV γ- comp. & its delay
- Predict complying ν-flux, but on rare LAT bursts and at > 10^{16} eV
- Predict substantial nu-gamma delay

Asano & PM ’12, ApJ 757:115)





To pair or not to pair (e±)?

- Pair-loaded fireballs proposed 10+ years ago
- For high L_{MeV}, pair cascade almost inevitable
- With advent of Fermi GeV detections, new interest in such models (e.g. Ghisellini etal, 10, MN403:926)
- → ***Beloborodov*** (arX:1307.2663) addresses various features of early GeV emission (+opt)

Outlook

- **Prospects for *multi-waveband* astrophysics of GRB are encouraging - have enough bursts w. good photons statistics!**
- **New discovery space: high-redshift → cosmology impact**
- **Major theoretical issues: 1) *baryonic vs. magnetic* jets: how to distinguish them? 2) Prompt emission: *hadronic or leptonic?* 3) Are photospheres needed? *Magn. or baryon.* photospheres? 4) Are modified internal shocks competitive? *Magnetized or hadronic* internal shocks? 5) *Reconnection or Fermi* acceler'n? 6) *MeV-GeV delay*: astrophysical cause? 7) *Pairs*: important?**
- ***Combined Swift + Fermi obs. are crucial for above questions***
- ***TeV* spectra→new constraints on hadronic vs. leptonic models**
- **Would constrain particle acceleration / shock parameters, emission region compactness (dimension, mag.field), etc.**