Central engines and radiation mechanisms of gamma-ray bursts

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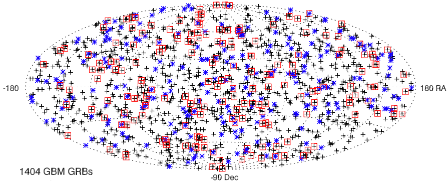
Gamma-ray Bursts - Overview

- Random directions on the sky ($\sim$ few per week)
- Short/long divide in duration
- Broad non-thermal spectrum emerging complex picture
- Afterglow visible for $\sim$ week(s)
- Prompt: keV to $\lesssim$ MeV, AG: radio to $\lesssim$TeV
- Deduce: compact object, $\Gamma > 100$, $\theta_{\rm jet} \approx$few $^\circ$, $E_{\rm iso} = 10^{51} - 10^{55}$ erg



$3^{\rm rd}$ GBM GRB catalog Bhat+16

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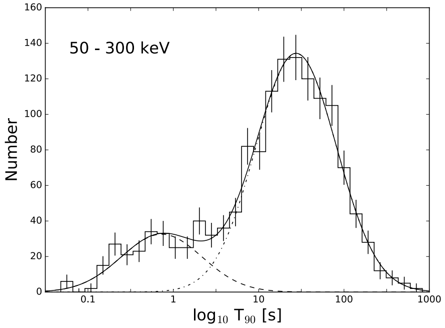

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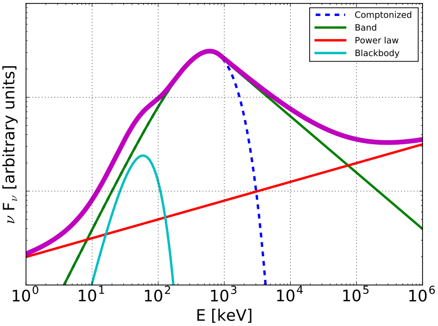

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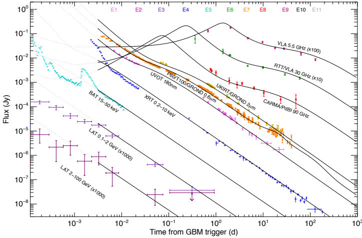

Perley+14

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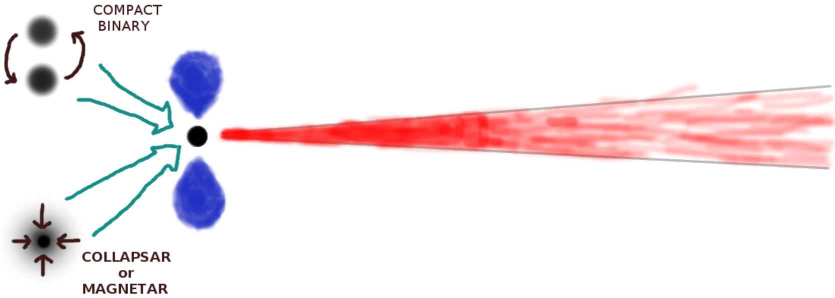
credit: NASA/Swift/deWilde

Outline

- Central engine [Black hole and/or neutron star]
- Emission mechanism [thermal, synchrotron, Compton]
- Case studies [GRB 130427A, GW 150914-GBM]
- Jet composition [baryonic, magnetic]



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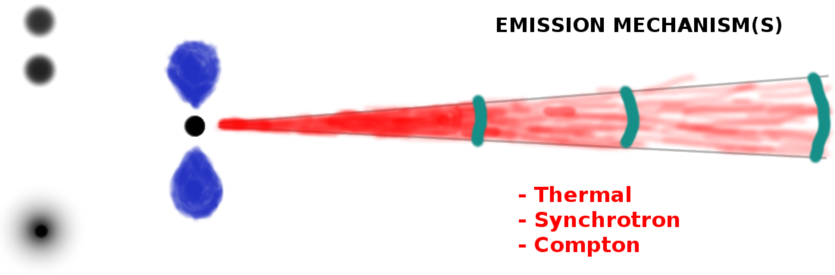

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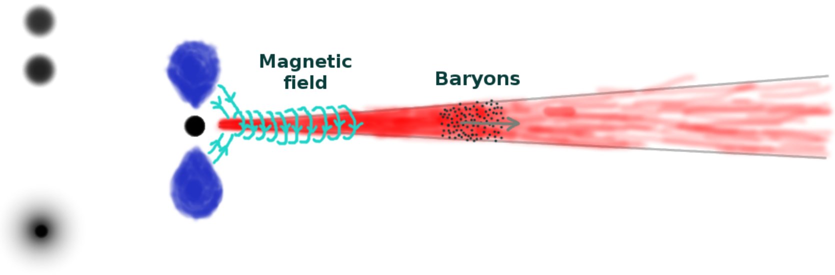
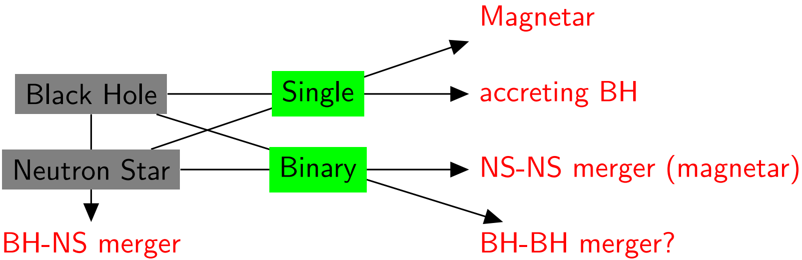


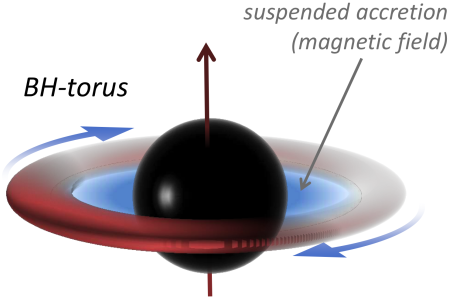
Central engine sources



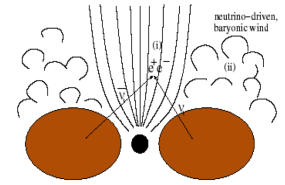
- (Indirect) evidence:
  - Long GRB progenitor: collapsar
  - Short GRB progenitor: compact binary
- Invisible central engine: black hole + disc or magnetar
- (?) direct observations near $\rightarrow$ GW [see also talk by Bing Zhang]

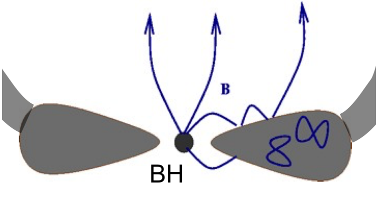
Central engines: Black hole + accretion disk

- Hyper-accreting BH
  - Neutrino annihilation: $\nu\bar{\nu} \rightarrow e^{\pm}$ powers jet along rot axis. E budget: disk material $\lesssim 10^{54}$ erg
  - Blandford Znajek: E budget: BH rotation $\sim 10^{54}$ erg



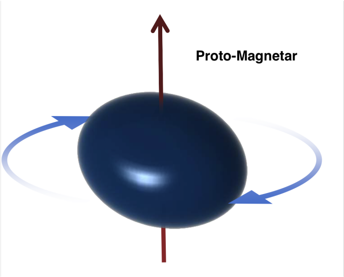
credit: Bartos+13





Magnetars

- Rapidly rotating (P$\sim$ 1 ms) NS (near breakup speed)
- Highly magnetized (B$\sim10^{15}$ G) - to transfer NS energy to jet
- Observational signature: X-ray plateau + break / extended emission
- Possible issue: $E_{\rm max} = E_{\rm rot} = 2\times10^{52} R_6^2 P_{\rm ms}^{-2} \frac{M}{1.4 M_\odot} {\rm erg} \lesssim E_{\rm GRB}$ (talk by Fruchter)

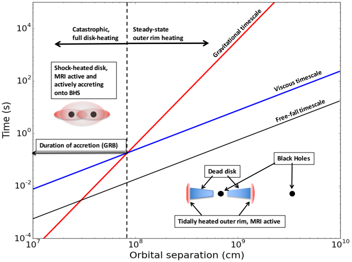


credit: Bartos+13

Binary Black hole mergers - unlikely progenitors

- For EM: mass stripped form NS to form acc. disk to tap BH energy $\rightarrow$ need at least a NS component.
- Difficult to keep disk around BH binary for long time

- Considered after GW 150914-GBM
- Loeb15: Star /w massive He core forms 2 BHs
- Woosley16: need binary/ EM delay problematic
- Perna+16: dead disk around one BH, re-energized by merger
- Zhang16: norm. charge: $\sim 10^{-5}$, links to FRB
- Lyutikov16: unreasonable magn. field required.
- ... and many more: Li+16, Yamazaki+16, Janiuk+16, Murase+16, Kimura+16, Veres+16

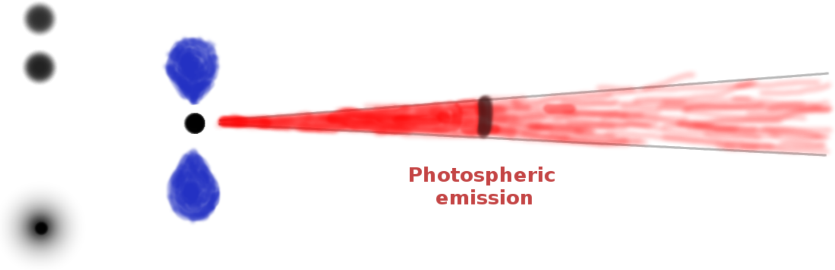


Perna+16

- Are BBH mergers (short)GRB sources? $\rightarrow$ need more observations

Scenarii for GRB prompt emission

- Photospheric models (dissipative/non-dissipative)
    - Blackbody / shocks + synchrotron / geometry / $\tau \gg 1$ dissipation
- Internal shocks
    - Shocks + Synchrotron / Self-Compton / magnetic fields
- External shock (?)
    - Synchrotron / Self-Compton



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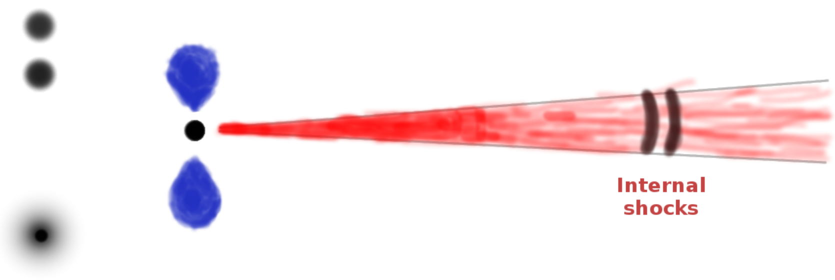

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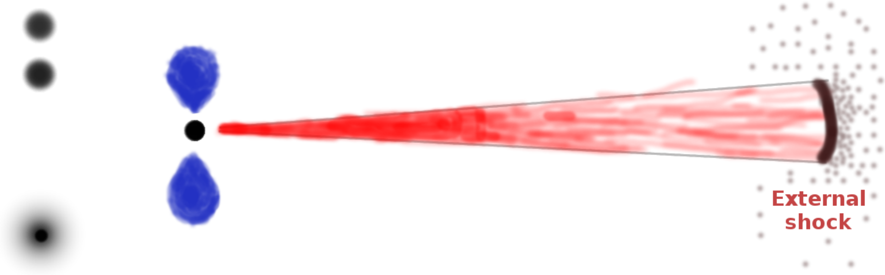
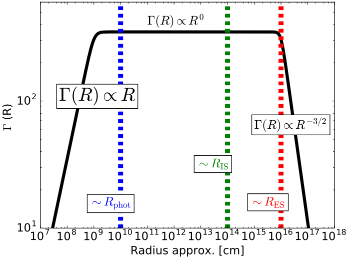


GRB dynamics and **prompt** emission models

Energy ($\Gamma_0 = E/Mc^2 \gg 1$) released in a volume $\sim R_0^3$.
$\rightarrow$ Jet expands/accelerates
$\rightarrow$ Reaches $\Gamma \sim \Gamma_0$
$\rightarrow$ Dissipates (kinetic/magnetic) energy
$\rightarrow$ Decelerates

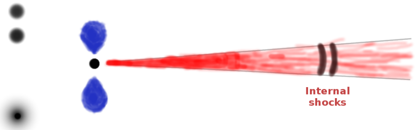
$$\Gamma(R) = \begin{cases} R/\mathbf{R_0} & \text{if} \quad R < R_{\rm sat} \\ \Gamma_0 & \text{if} \quad R_{\rm sat} < R < R_{\rm dec} \\ (R/R_{\rm dec})^{-3/2} & \text{if} \quad R_{\rm dec} < R. \end{cases}$$

- Photospheric models
  $\rightarrow$ Dissipative photosphere ($\lesssim 10^{10}$ cm)
  $\rightarrow$ Non-dissipative photosphere ($\sim 10^{10}$ cm)
- Internal shocks ($\sim 10^{14}$ cm)
- External shocks ($\sim 10^{16}$ cm)



Prompt emission models - Internal shocks

- Unsteady outflow $\rightarrow \Gamma \gtrsim 100$ shocks ($\tau \ll 1$)$\rightarrow$ accelerated particles, magnetic field, synchrotron
- Explains variability, broad nonthermal spectrum
  $\rightarrow$ easy to calculate analytically
- Radiation from $R_{\rm IS} \approx t_{\rm var} c \Gamma_0^2 \approx 3 \times 10^{14} t_{\rm var,0} \Gamma_{0,2}^2 \,{\rm cm}$
- But: low efficiency, spectral index, dim photosphere $\rightarrow$ problems
- Zhang+11: ICMART: 2 step: highly magnetized $\sim R_{\rm IS}$ coll., then magnetic reconn. at $\lesssim R_{\rm ES}$



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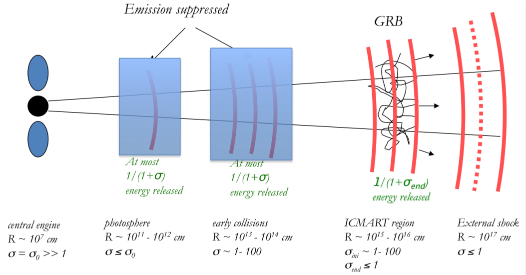
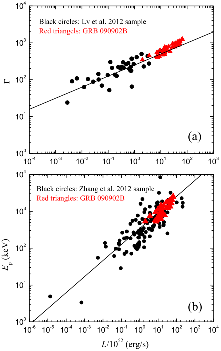
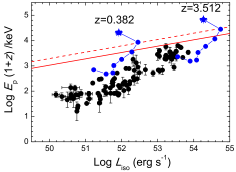


Credit: Bing Zhang

Prompt emission - photospheric models

- Energy released <u>at</u> the photosphere: $\tau = 1 \Rightarrow$ $R_{\rm phot} = 6 \times 10^{12} L_{52} \Gamma_{0,2}^{-3}\,\rm cm$
- **Non** dissipative: geometry, Γ profile, fuzzy $\rightarrow$ broadened Planck
- Fan+12: explains correlations
- Zhang+13: GRB 110721A: line of death $E_p \lesssim 3.92 k_B T_0 \approx 4.7 L_{52}^{1/4} R_{0,7}^{-1/2} \rm MeV$
- Rees+05: **Dissipation** below the photosphere ($\tau \gg 1$)
- High efficiency, explains high $E_{\rm peak}$ & distr.
    - Giannios08: magnetic dissipation
    - Beloborodov10, Vurm+11: n-p collisional heating (+magnetic)
    - Meszaros+11: shocks @photosphere
- Jet simulations (Lazzati16) include more refined physics e-γ decoupling [see poster by Parsotan].
- **Most likely model**, but potentially violates emission radius constraints $R_{\rm dissip.} > 10^{15-16}$ cm.





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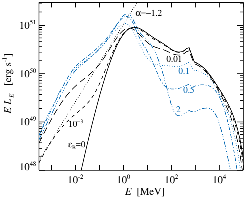
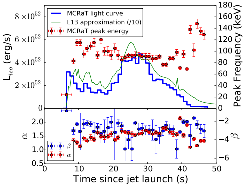


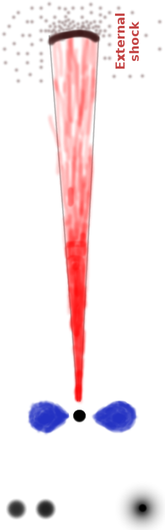
Vurm+11



Lazzati+16

Prompt emission models - External shocks?

- Jet plows into ISM, decelerates, shocks form, B field enchanced, synchrotron
- Radiation from $R_{\rm dec} \approx 6 \times 10^{16}\, E_{53}^{1/3} n_0^{-1/3} \Gamma_{0,2.5}^{-2/3} {\rm cm}$
- Peak energy $E_p \sim 800\, \epsilon_{e,-1}^2 n_0^{1/2} \epsilon_{B,-1}^{1/2} \Gamma_{0,2.5}^4 {\rm keV}$
- Invoked for afterglow
- Strong variability ($t_v \sim 10^{-2}$ s) in prompt is difficult to explain
- May be relevant in unique cases (see talk by Yu)



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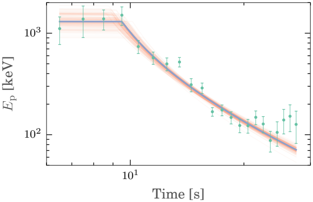
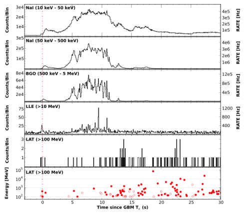
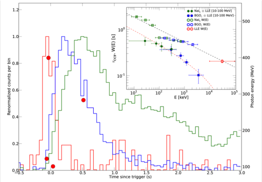


Burgess+15

Case study 1 - GRB 130427A

- Preece+14: first pulse -synchrotron lab
- $E_p \propto t^{-1}$ curvature: OK, $L \propto E_p^{1.5}$ not OK
- $L \propto E_p^{1.5}$ expanding shell synch.: OK, $\Rightarrow$ $E_p \propto t^{-4}$ not OK
  $\rightarrow$ no single model can explain these relations
- Kouveliotou+13: synchrotron/ no SSC, but $E_{\rm max}^{\rm synch.}$ violated
  Ackermann+14: no SSC
  Aliu+14: VHE upper limits
  Liu+13, Fraija+16: FS/RS + SSC
  Vurm+14: pairs: synch. + external Compton
  de Pasquale+16: long term obs.





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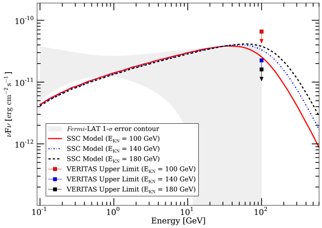

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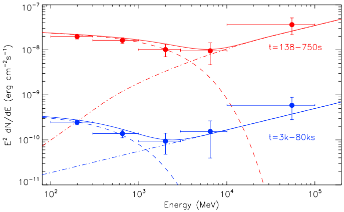
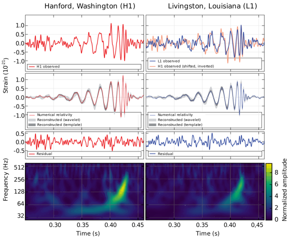
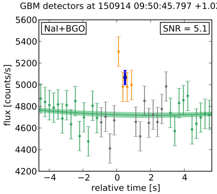


Case study 2. - GW 150914-GBM

Assume: GW 150914 and GW 150914-GBM are related.
A binary black hole merger produced a GRB.
Ask: What can we learn about GRB prompt emission models? Veres+16

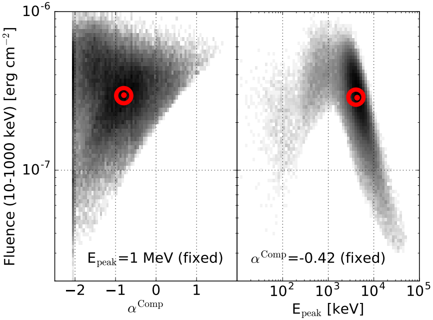
- M_1=36 $M_\odot$, M_2=29 $M_\odot$, $M_{\rm BH}$=62 $M_\odot$
- a $\approx$ 0.67, z $\approx$ 0.09
- Gravitational radius:
  $R_G = GM_{\rm BH}/c^2 = 9.2 \times 10^6$ cm
- **Innermost stable radius → GRB launching radius:** $R_0 \approx 3.5 R_G = 3.2 \times 10^7$ **cm.**
- Best explanation: untriggered, short GRB [see talk by Goldstein]
- Best fit spectrum: power law
- T $\approx$ 1 s, $\Delta T_{\gamma-{\rm GW}} \approx$ 0.4 s





GW 150914-GBM - Spectrum

- Fluence 2.4×10^7 erg/cm^{-2} (40 precentile of short GBM GRBs)
- Weak signal: only 2 spectral parameters can be constrained
- Spectrum: power law $\rightarrow$ needs a cutoff (3 param.)
- Fix 1 out of 3 parameters
- MC sim. spectral parameters consistent with data
- **Conclusion: $\mathbf{E_{peak}} \gtrsim$ 1 MeV ($\sim$ 95%)**



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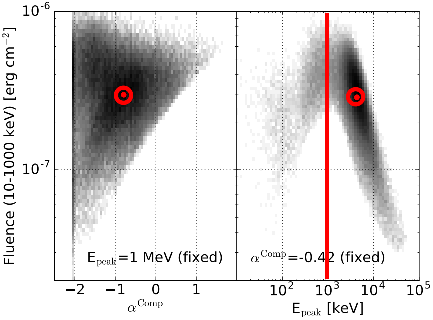
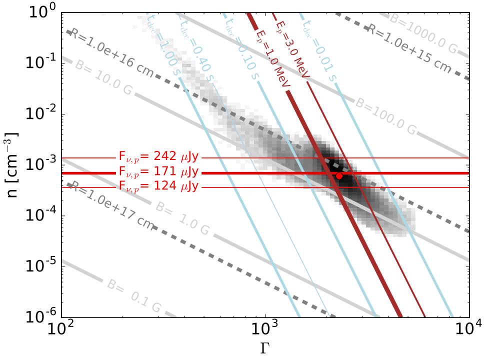


GW 150914-GBM - testing prompt emission models

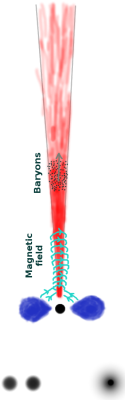
- Non-dissipative photosphere:
  $E_{\rm pk}^{\rm PH} \lesssim 3.92 \times kT_0 \approx 0.6 \left(\frac{L}{L_{\rm obs}}\right)^{1/4} \left(\frac{R_0}{R_*}\right)^{-1/2}$ MeV ~not OK
- Diss. phot. $E_{\rm pk} \lesssim 10$ MeV (for $L_{\rm obs}$) OK
- Int. sh.: $E_{\rm pk}^{\rm IS} \lesssim 0.1 \left(\frac{L}{L_{\rm obs}}\right)^{1/6} \left(\frac{\Delta}{R_0}\right)^{-5/6} dt_{-3}^{1/6} \epsilon_B^{1/2} \epsilon_e^{4/3}$ MeV. ~not OK

- External shocks: Synchrotron emission, at $R_{\rm dec}$ assuming ϵ_B, $\epsilon_e(=0.5)$ get: $n \sim 10^{-3}$ cm^{-3} and $\Gamma \sim 2000$



Jet composition - What carries the energy?

- Multiple methods for hints on jets components
- Bromberg+14: T_{90} plateau $\rightarrow$ jet breakout timescale $\sim$ 10s $\rightarrow$ baryon dom.
- Zhang+10: BB non-detection in GRB 080916C $\rightarrow \sigma \gtrsim 20$ [see also talk by Ryde]
- Veres+14: modified initial acceleration: $\Gamma \propto R^{\mu}$, $\mu = 1/3$-magnetic $\rightarrow$ $\mu = 1$-baryonic jets



Jet composition - What carries the energy?

- Multiple methods for hints on jets components
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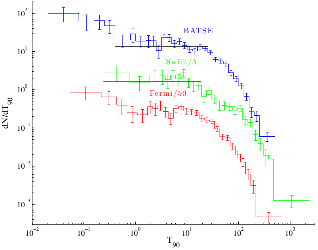

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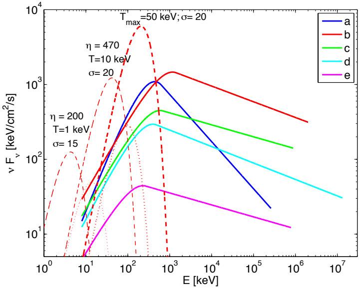

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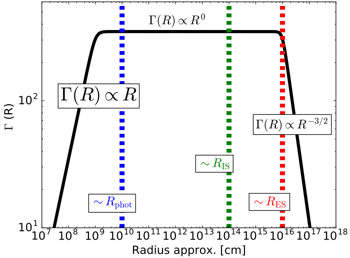

Drenkhahn+02, Meszaros+11, Bošnjak+12, McKinney+12, Gao+15

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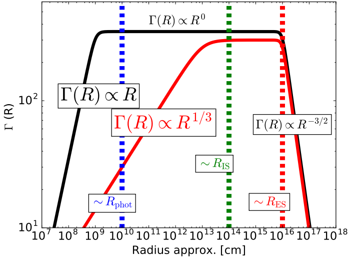

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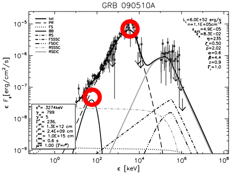
Jet composition from E_{peak}-T correlation

Observations:



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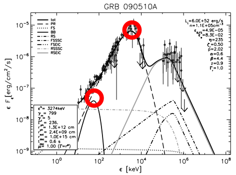

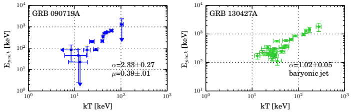

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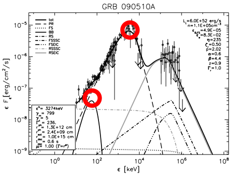

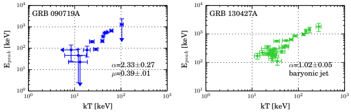

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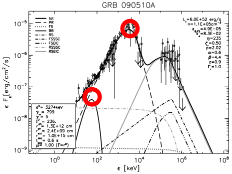

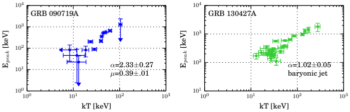

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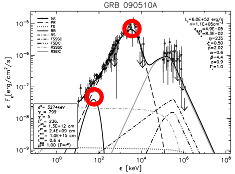

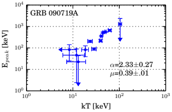

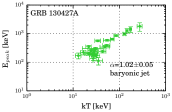

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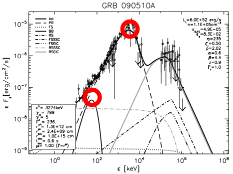

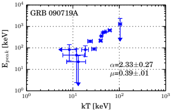

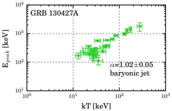

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GRB Name	α ($E_p \propto T^{\alpha}$)	Jet Type	μ
081224A	1.01 ± 0.14	baryonic	–
090719A	2.33 ± 0.27	magnetic	0.39±0.01
100707A	1.77 ± 0.07	magnetic	0.42±0.01
110721A	1.24 ± 0.11	baryonic	–
110920A	1.97 ± 0.11	magnetic	0.4±0.01
130427A	1.02 ± 0.05	baryonic	–

Veres+13, Burgess+14

Conclusion

- Exciting times for GRB studies
- Direct information on central engine
- Confirm/reject binary BH CE
- GW obs. will constrain GRB models
- Jet composition