Energies of GRB blast waves and prompt efficiencies as implied by modeling of X-ray and GeV afterglows

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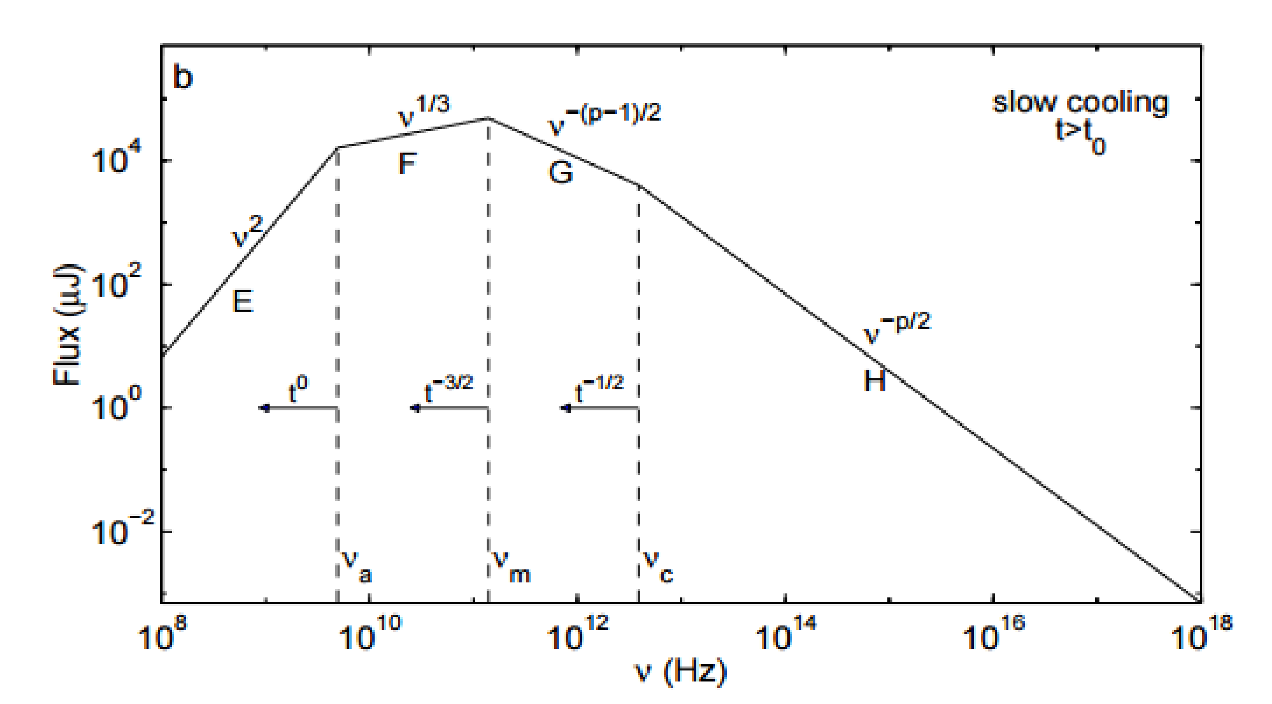
- The late time afterglow is well modelled and described by synchrotron radiation
- At sufficiently large frequencies, the synchrotron flux provides a "clean" estimate for the kinetic energy left at the afterglow stage:

$$E_{0,kin} \sim F_{\nu}^{0.9} \epsilon_B^{\frac{1}{9}} \epsilon_e^{-\frac{4}{3}} t^{\frac{11}{9}} \text{ (p=2.5)}$$



Sari, Piran, Narayan (1997)

- Previous studies with X-ray afterglows at ~1day have found low kinetic energies implying large efficiencies:

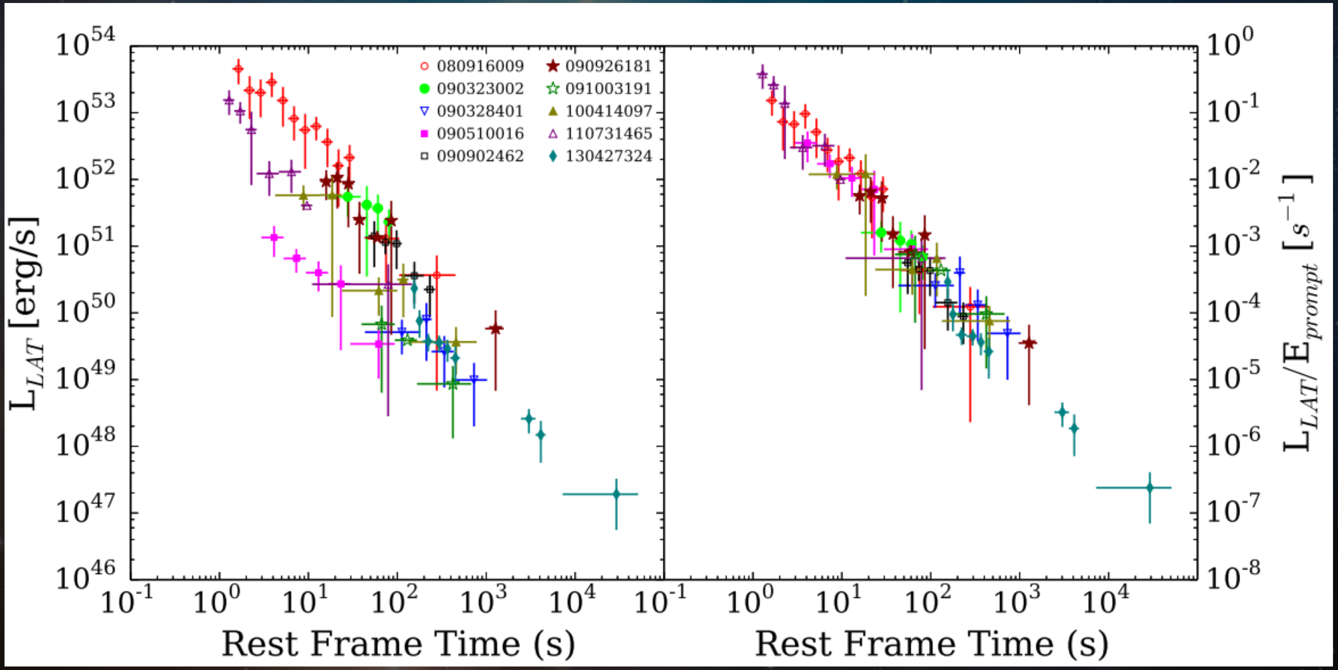
$$\varepsilon_\gamma = \frac{E_\gamma}{E_\gamma + E_{0,kin}} > 0.5$$

- Large efficiencies are very challenging for many prompt emission models, such as internal shocks where ε≈0.1-0.2 (Kobayashi et al. 1997, Daigne & Mochkovitch 1998, Beloborodov 2000, Guetta et al. 2001)

- Two implicit assumptions have been made to arrive at these estimates:

1. Electrons emitting at X-rays are fast cooling
2. The X-ray flux is not suppressed by Inverse Compton (IC)

- If GeV radiation is of external shock origin (Kumar & Barniol Duran 2009, 2010, Ghisellini et al. 2010, Wang et al. 2013, Nava et al. 2014), LAT observations could constrain the location of the synchrotron cooling frequency, ν_c, and assess the importance of IC
- 10 of the GRBs detected with extended GeV emission, have also been detected in X-rays



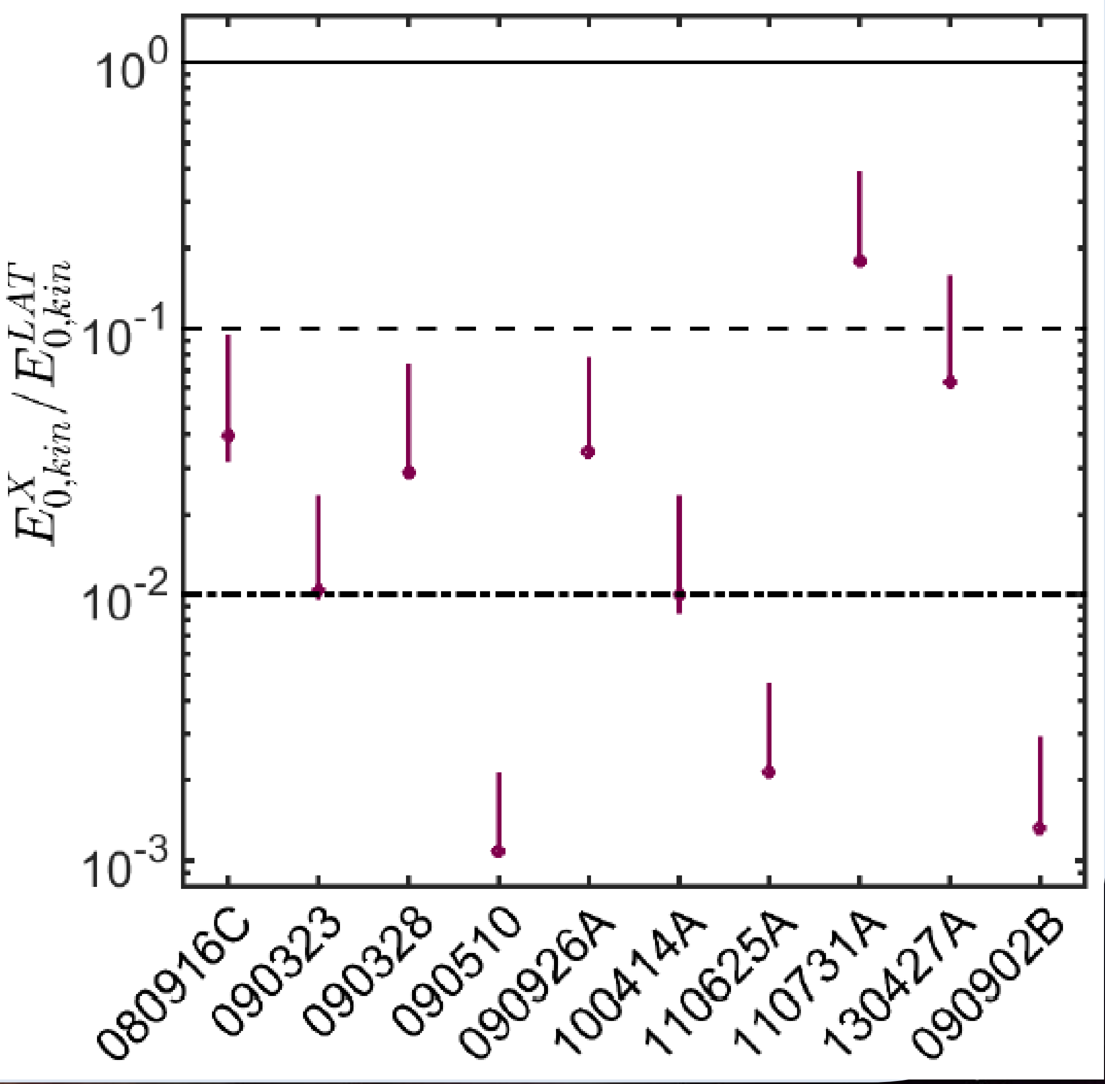
Nava et al. (2014)

Kinetic energy of the Blast wave

$$E_{0,kin} = F_{\nu}^{\frac{4}{2+p}} \epsilon_B^{\frac{2-p}{2+p}} \epsilon_e^{\frac{4(1-p)}{2+p}} t^{\frac{3p-2}{2+p}}$$

BP et al. (2015)

- X-rays (at ~day) & GeV (at ~300sec) are inconsistent
- $\frac{E^{X}_{0,kin}}{E^{GeV}_{0,kin}}$ - **independent of microphysical parameters**
- Energies from GeV are 5-1000 times larger



Efficiency of the prompt phase

BP et al. (2015)

$$\varepsilon_\gamma = \frac{E_\gamma}{E_\gamma + E_{0,kin}}$$

- Using the GeV fluxes:

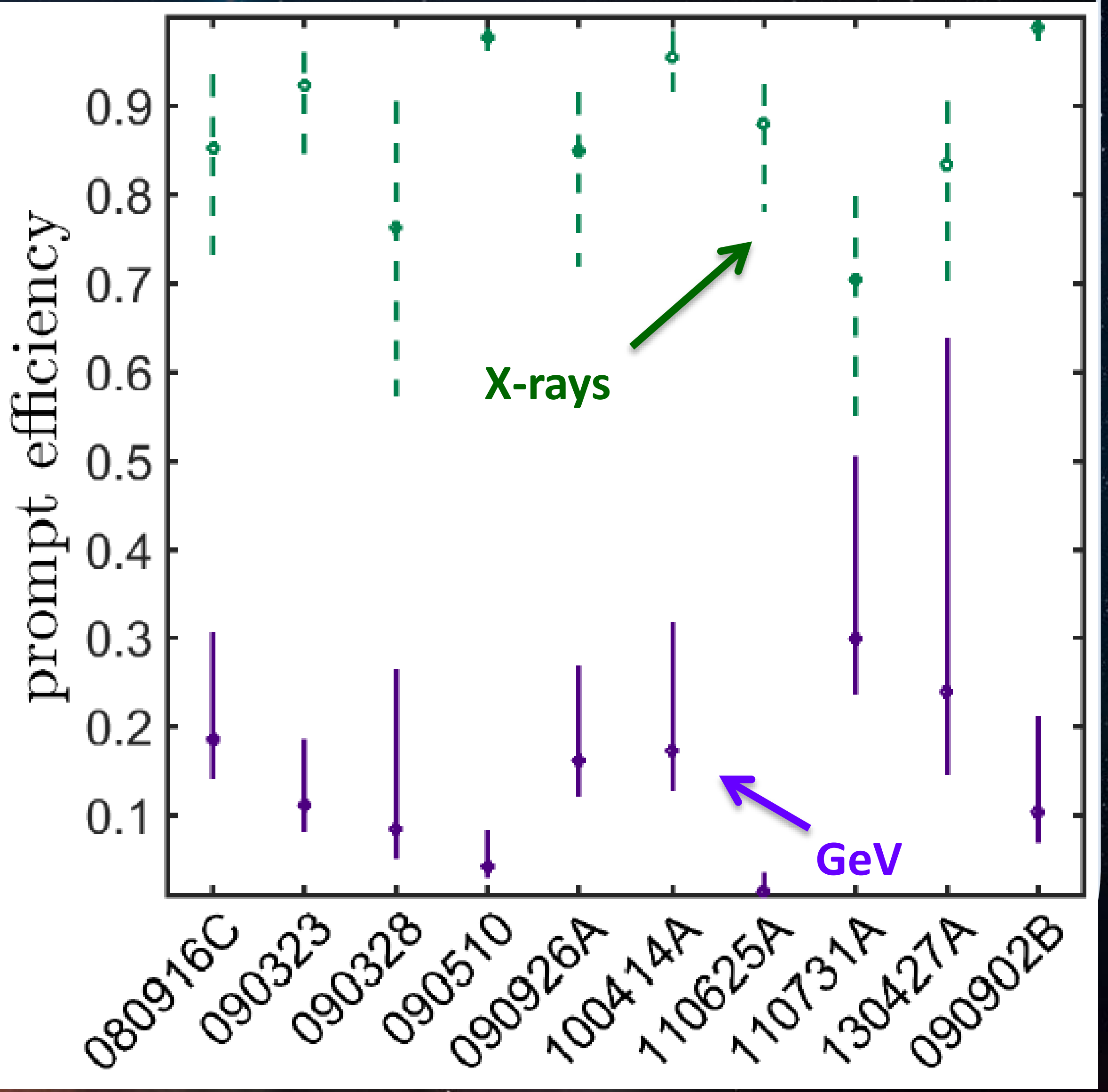
$$\langle \varepsilon_{\gamma,GeV} \rangle = 0.14$$

whereas with X-rays

$$\langle \varepsilon_{\gamma,X} \rangle = 0.87$$

and in some cases

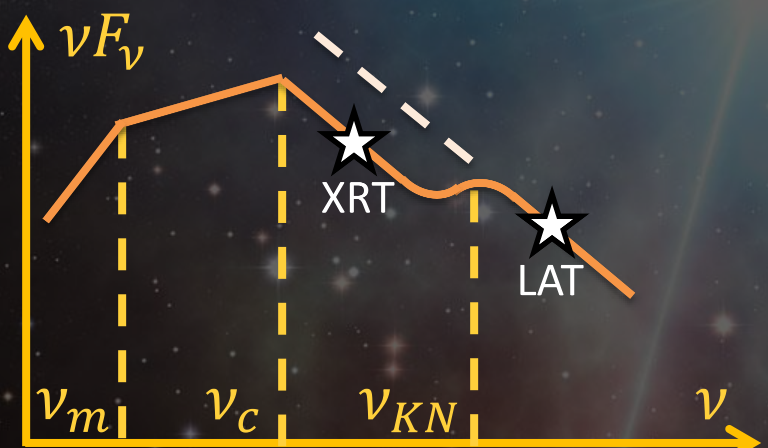
$\varepsilon_{\gamma,X} \approx 0.99$



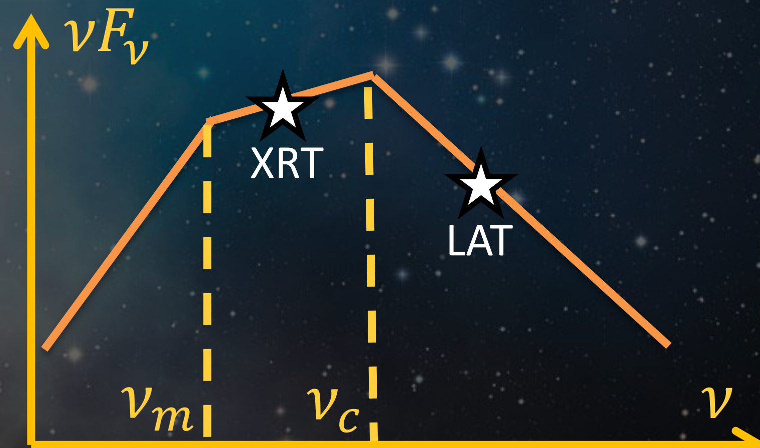
Resolving the apparent contradiction

- The X-ray flux is “too low”:

1. Both X-rays and GeV photons are above ν_c but X-rays are suppressed by IC while GeV emitting electrons are in the KN regime



2. The X-ray band is below ν_c (Here the X-ray flux depends strongly on ε_B, n)



In both cases the X-rays are not a good proxy for the kinetic energy!

Resolving the apparent contradiction

1. Large energy ratio -> Large Y_X -> small ε_B

$$\frac{E_{0,kin}^{X}}{E_{0,kin}^{GeV}} \propto \left(\frac{1+Y_X}{1+Y_{GeV}}\right)^{\frac{4}{2+p}} \approx \left(\frac{\varepsilon_e}{\varepsilon_B}\right)^{\frac{2}{2+p}}$$

2. **In this case ε_B should be low in order for ν_c to be above X-rays**

$$\nu_c \propto \varepsilon_B^{-\frac{3}{2}}(1+Y_X)^{-2}$$

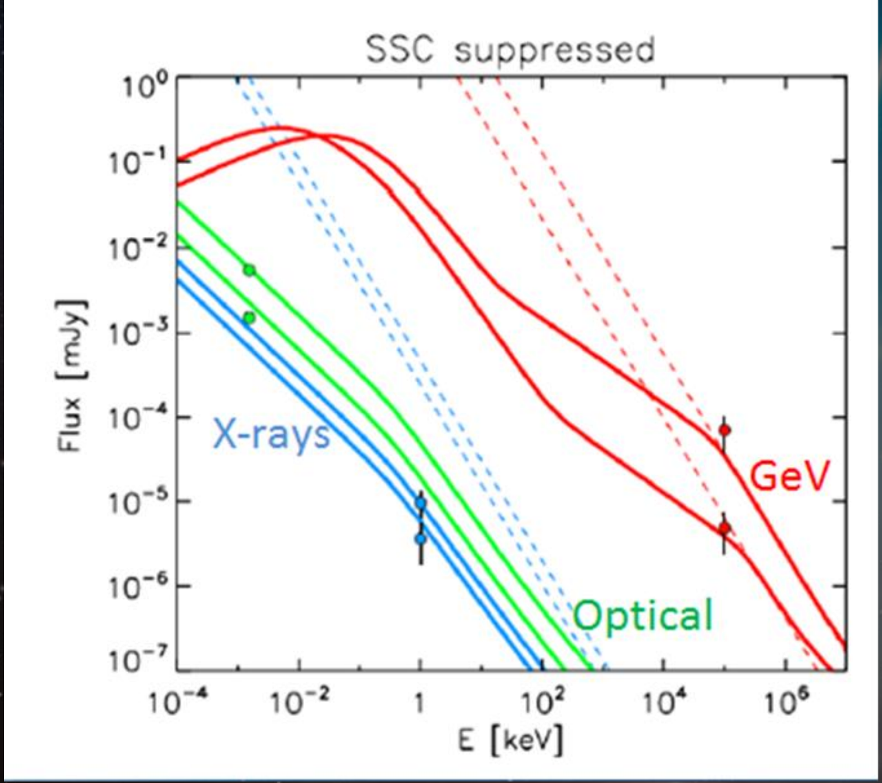
Both cases require very low values of ε_B

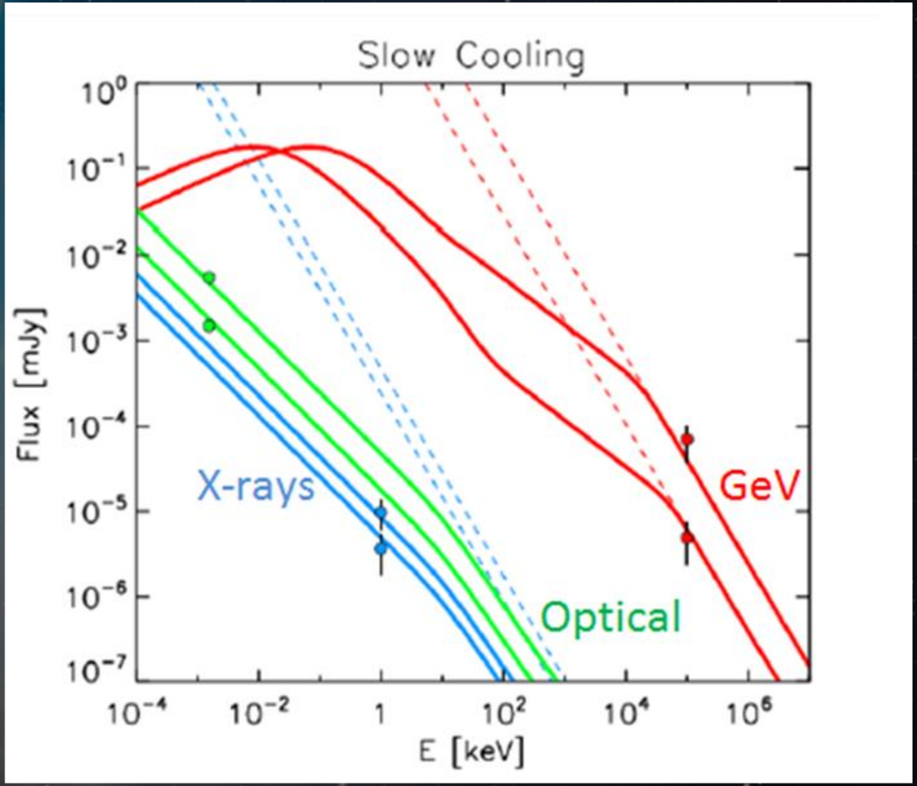
$$10^{-6} < \varepsilon_B < 10^{-3}$$

See also similar results by: Kumar & Barniol Duran 09,10, Lemoine 13, Barniol Duran 14, Santana et al. 14, Zhang et al. 15, Wang et al. 15

Numerical modelling

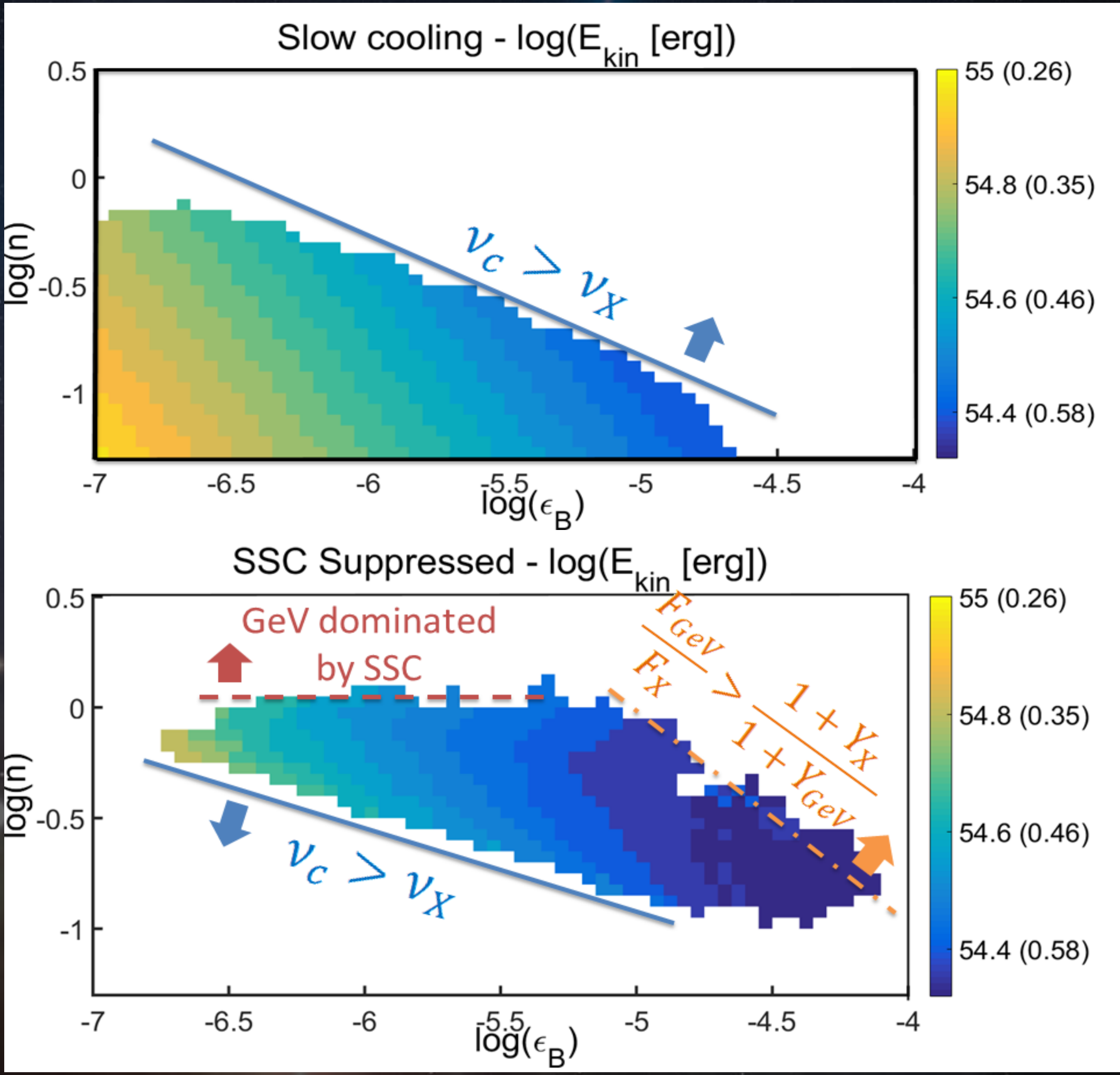
- synchrotron + IC SEDs including KN corrections (Nakar et al. 2009)
- For all GRBs we can reproduce the observed fluxes with the model





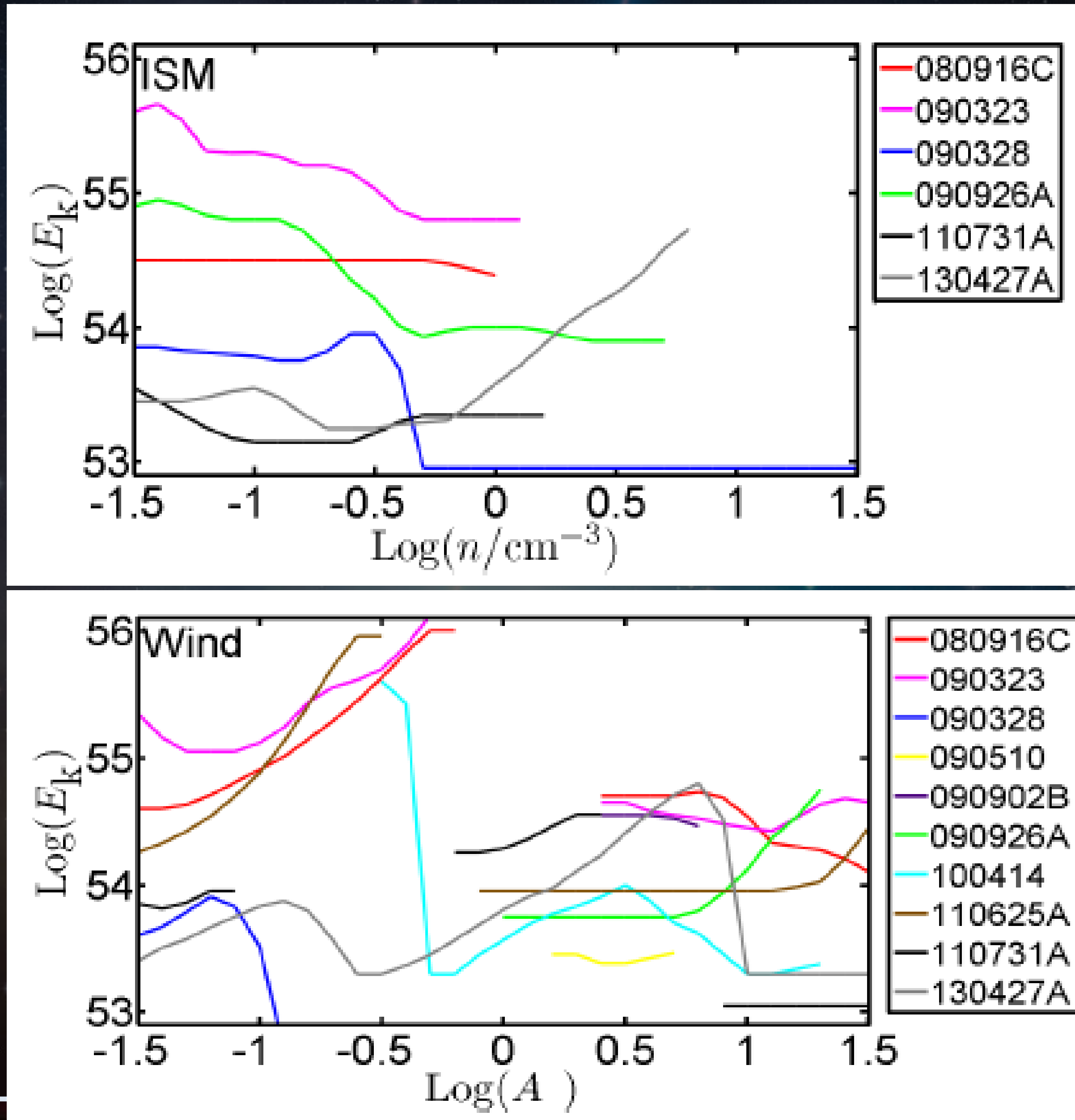
GeV is well described by fast cooling synchrotron (and is a good proxy for the kinetic energy) while X-rays are not

Numerical modelling – 080916C (ISM)

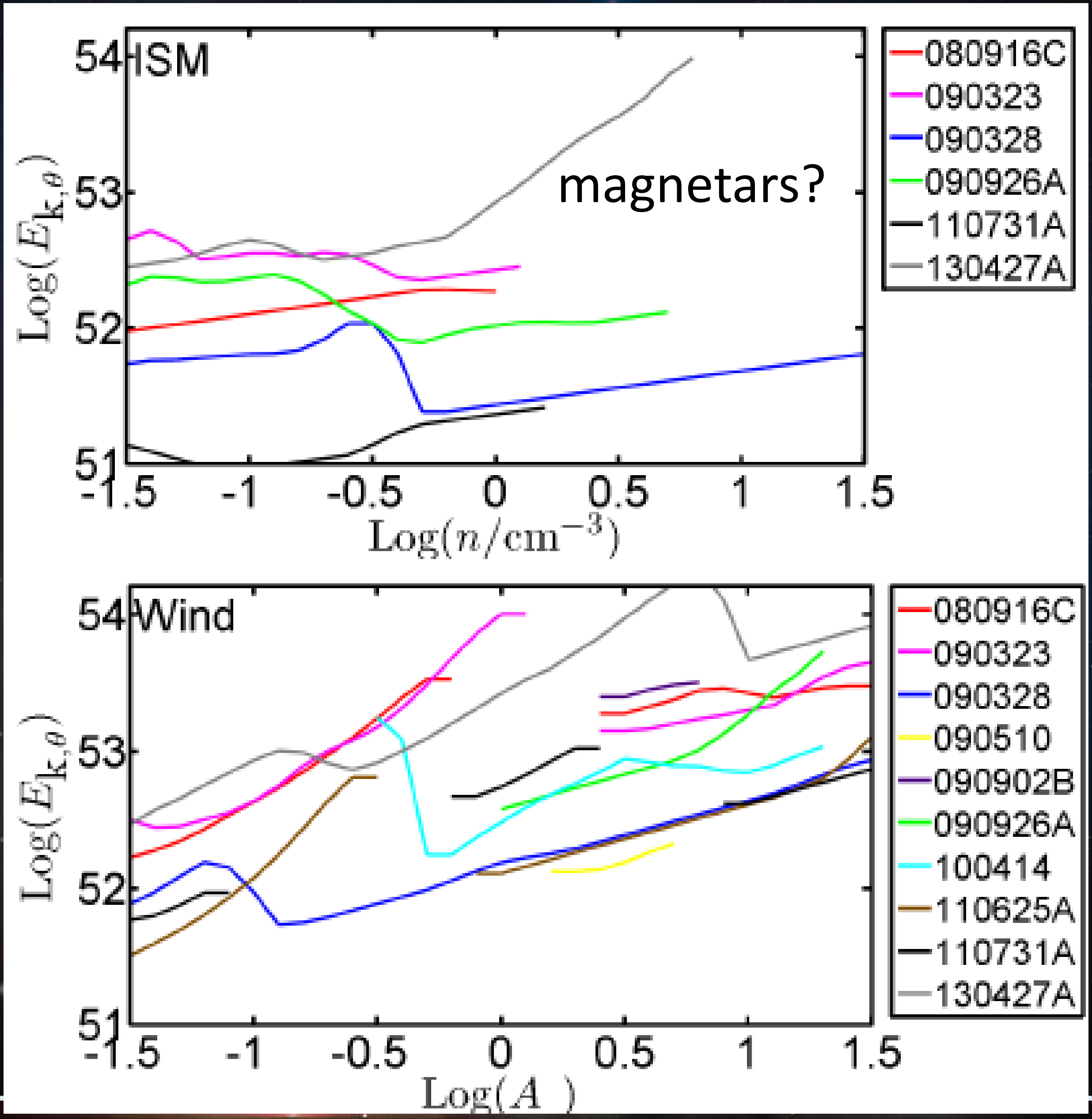


$3 \times 10^{-2} cm^{-3} < n < 3 cm^{-3}$ ➡ $\varepsilon_\gamma < 0.55$, $E_{0,kin} > 3 \times 10^{54} erg$, $\varepsilon_B < 5 \times 10^{-5}$

Lower limits on isotropic Energies



Lower limits on collimated energies

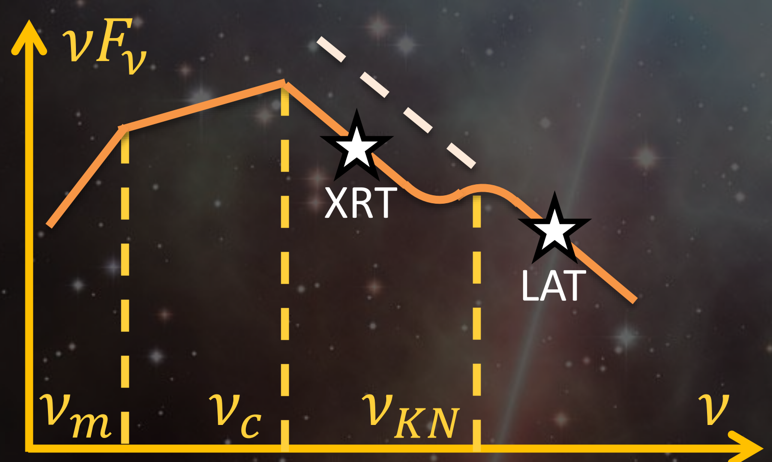


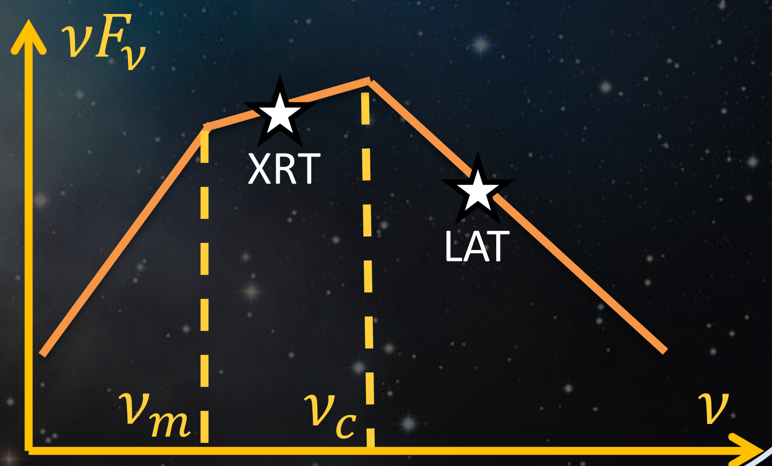
Summary

- For GRBs with long lasting GeV emission and X-ray afterglows, broad-band observations consistent with the forward shock scenario
- The GeV flux is a good proxy for the kinetic energy but X-rays are not
- Two types of solutions: “SSC suppressed” (at larger densities) and “slow cooling” (at smaller densities).

Both require: $10^{-6} < \varepsilon_B < 10^{-3}$ and $E_{0,kin} > 10^{53} ergs$ (collimated energy $E_{\theta,kin} > 10^{52} - 5 \times 10^{52} ergs$)

- GRB efficiencies are large (~20%) but not huge (>90%) – internal shocks cannot be ruled out by this argument





Thank You!

Backup slides

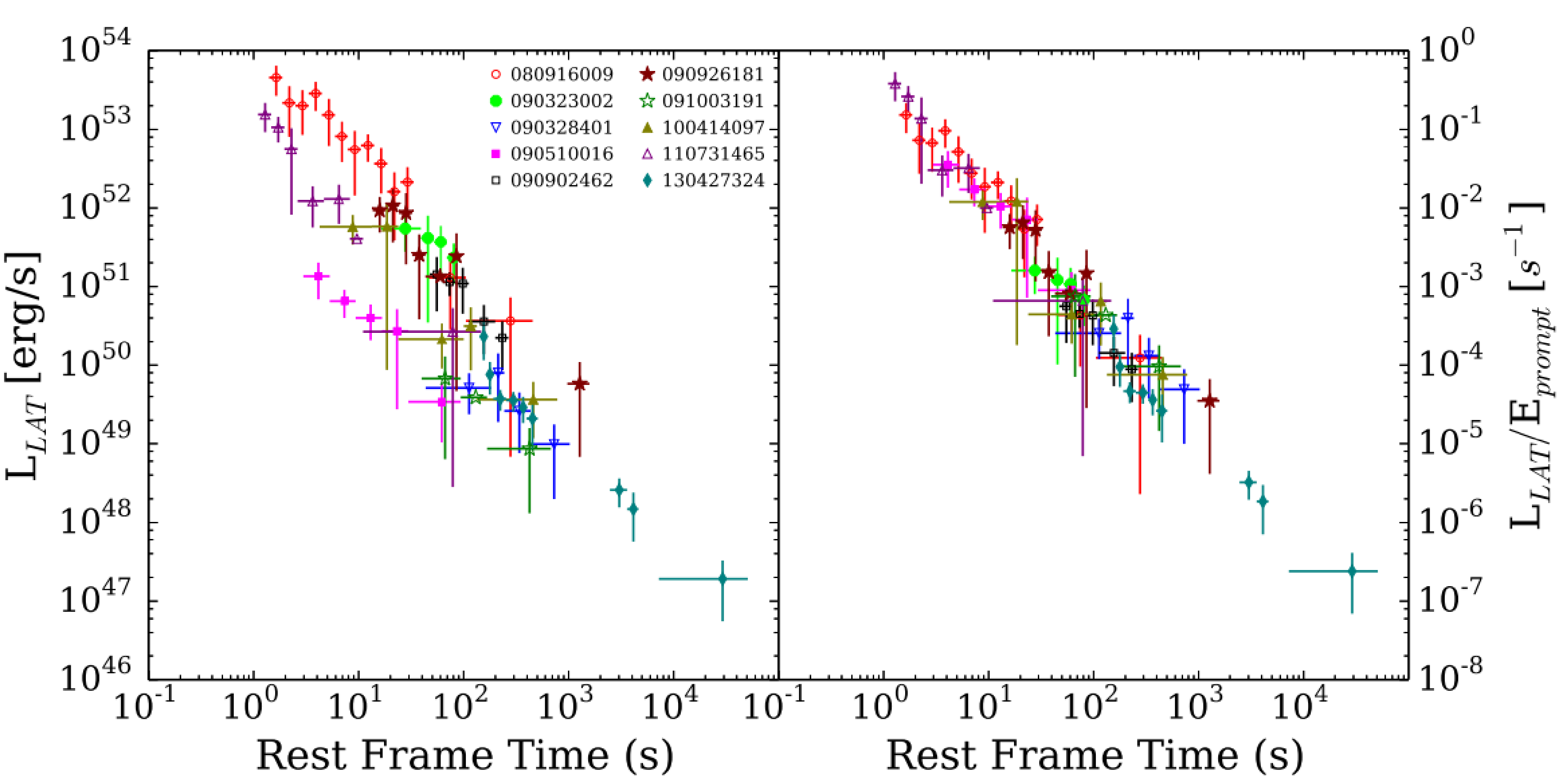
The Sample

- X-rays: for each burst we use two observation times at ~day, that are after the plateau phase and before the jet break
- GeV: for each burst we use two observation times as removed in time as possible but given that they are after T_{90}
- Optical: In 8/10 bursts (when they are available) we also take two optical observations subject to the same requirements as the X-rays

Burst	$t_{GeV,1}$ 10^{-3}days	$F_{GeV,1}$ nJy	$t_{GeV,2}$ 10^{-3}days	$F_{GeV,2}$ nJy	$t_{X,1}$ days	$F_{X,1}$ nJy	$t_{X,2}$ days	$F_{X,2}$ nJy	$t_{opt,1}$ days	$F_{opt,1}$ μJy	$t_{opt,2}$ days	$F_{opt,2}$ μJy	z	t_{jet} days	ref.
080916C	4.6	4.9	1	72	6.94	9.7	11.57	3.6	1.39	5.5	3.47	1.5	4.35	> 15.3	1
090323	4.3	14	1.6	54	2.495	23	5.78	6.3	1.85	14	5.1	2.7	3.57	> 10	2
090328	14	1.2	2	8.1	3.47	20	6.9	11	1.63	25	2.6	11	0.73	> 10	2
090510	1.3	16	0.1	210	0.14	22	0.062	100	1.16	1.8	0.14	9	0.9	> 0.75	3
090902B	7.6	15	0.2	400	0.928	21	2.38	3.7	1.43	10	2.52	5.7	1.822	20	4
090926A	3	15	0.4	42	2	80	11.57	5.4	3	37	6.1	14000	2.1	10	2
100414	3.2	7.1	0.5	66	2.3	7.6	7.17	0.33	-	-	-	-	1.37	> 7.4	-
110625A	5	38	3	42	0.46	130	0.139	1300	-	-	-	-	*	> 0.47	-
110731A	3.5	0.75	0.2	350	1.22	61	3.84	12	0.026	70	0.012	240	2.83	> 7.5	5
130427A	63	2	3	110	1.19	2600	11.54	100	1.15	130	0.22	1000	0.34	> 180	6

Afterglow origin for GeV emission

- Delayed onset
- Extended emission
- The long lasting emission decays as a single power law in time



Nava et al. (2015)

Energy and efficiency estimates

Burst	$E_{\gamma,54}$	$E^{X}_{0,kin,54}$	$E^{GeV}_{0,kin,54}$	$\epsilon_{\gamma,X}$	$\epsilon_{\gamma,GeV}$
080916C	3.48	0.6 (1.38)	15.2 (20.1)	0.85 (0.71)	0.19 (0.14)
090323	3.44	0.28 (0.61)	27.4 (37.3)	0.92 (0.85)	0.11 (0.08)
090328	0.1	0.03 (0.07)	1.08 (1.71)	0.77 (0.58)	0.08 (0.05)
090510	0.04	0.001 (0.002)	0.88 (1.12)	0.98 (0.96)	0.04 (0.03)
090902B	2.53	0.03 (0.06)	21.4 (32.1)	0.99 (0.98)	0.1 (0.07)
090926A	1.75	0.3 (0.67)	9 (12.3)	0.85 (0.72)	0.16 (0.12)
100414	0.49	0.023 (0.05)	2.3 (3.2)	0.95 (0.9)	0.17 (0.13)
110625A	0.18	0.02 (0.05)	11.4 (16.6)	0.88 (0.78)	0.015 (0.01)
110731A	0.49	0.2 (0.4)	1.1 (1.5)	0.7 (0.54)	0.3 (0.24)
130427A	0.8	0.15 (0.35)	2.5 (4.6)	0.83 (0.7)	0.24 (0.15)

Results for all bursts

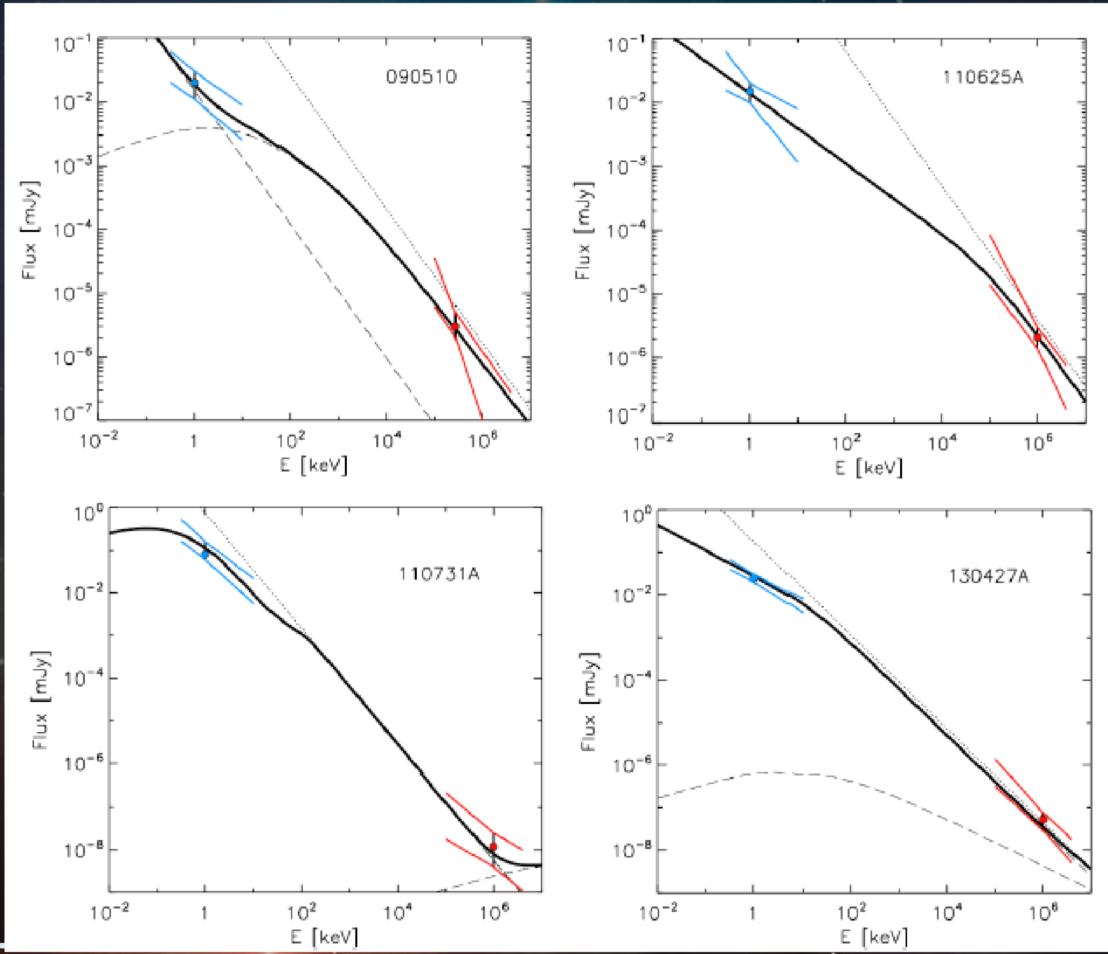
- For a constant ISM four bursts have both “SSC suppressed” and “slow cooling” solutions, while one has only an “SSC suppressed” solution and another only a “slow cooling” solution

- For a wind medium no bursts have “SSC suppressed” while seven bursts have “slow cooling” solutions. Three bursts have solutions in which the GeV is dominated by SSC emission and X-rays are synchrotron emission from fast cooling electrons

Results with simultaneous observations

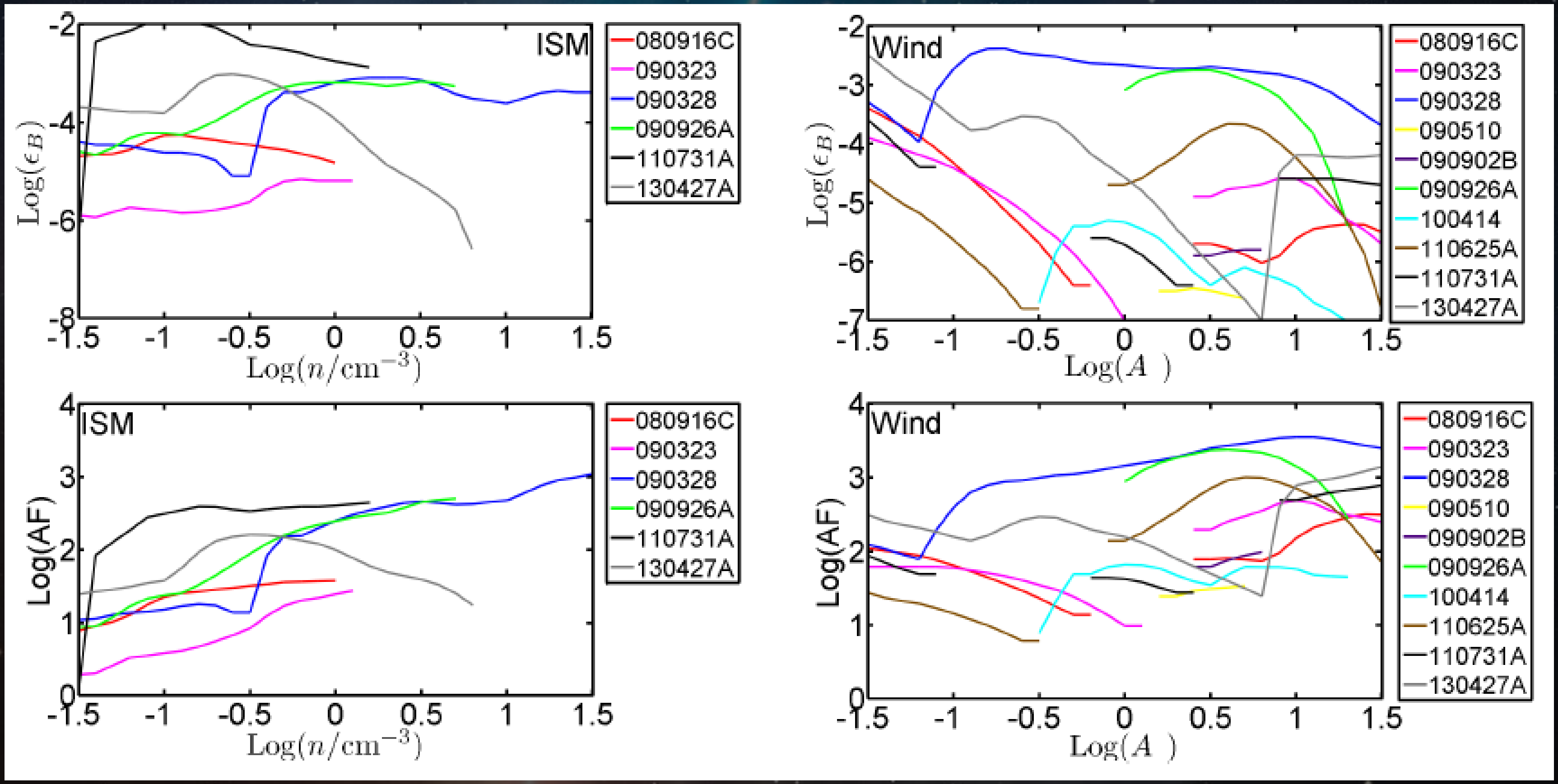
For four bursts have simultaneous X-ray and GeV data

The parameter space overlaps with that from late time observations



Results for all bursts – magnetic field

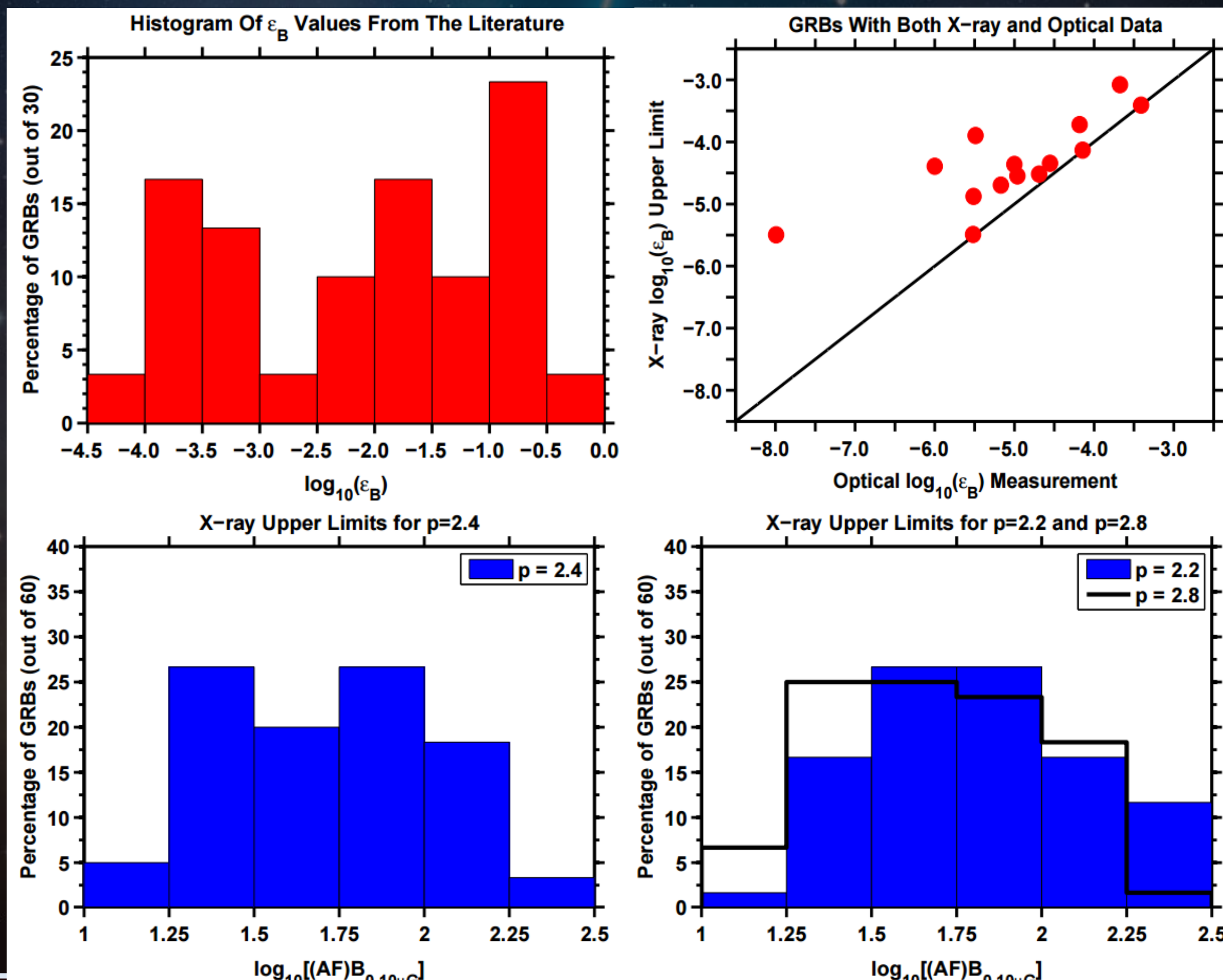
Upper limits on ε_B and amplification factors (AF) beyond shock compression assuming a seed magnetic field of 10 μG



Low values of the magnetization

Many studies (with and without LAT observations) find small ε_B and AF

(Kumar & Barniol Duran 09,10, Lemoine 13, Barniol Duran 14, Santana et al. 14, Zhang et al. 15, Wang et al. 15)



Santana et al. (2015)

Low values of the magnetization

Our results are consistent with the possibility that ε_B is decreasing with the distance from the shock front (Lemoine et al. 2013)