Very-high-energy GRB events in novel Fermi-LAT photon data and their emission mechanism

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Overview

- ✦ Introduction
- ✦ Emission processes
- ✦ Fermi-LAT CalOnly classes
- ✦ Search for new GRB photon candidates
- ✦ Likelihood analysis
- ✦ Prospect of CTA
- ✦ Conclusions

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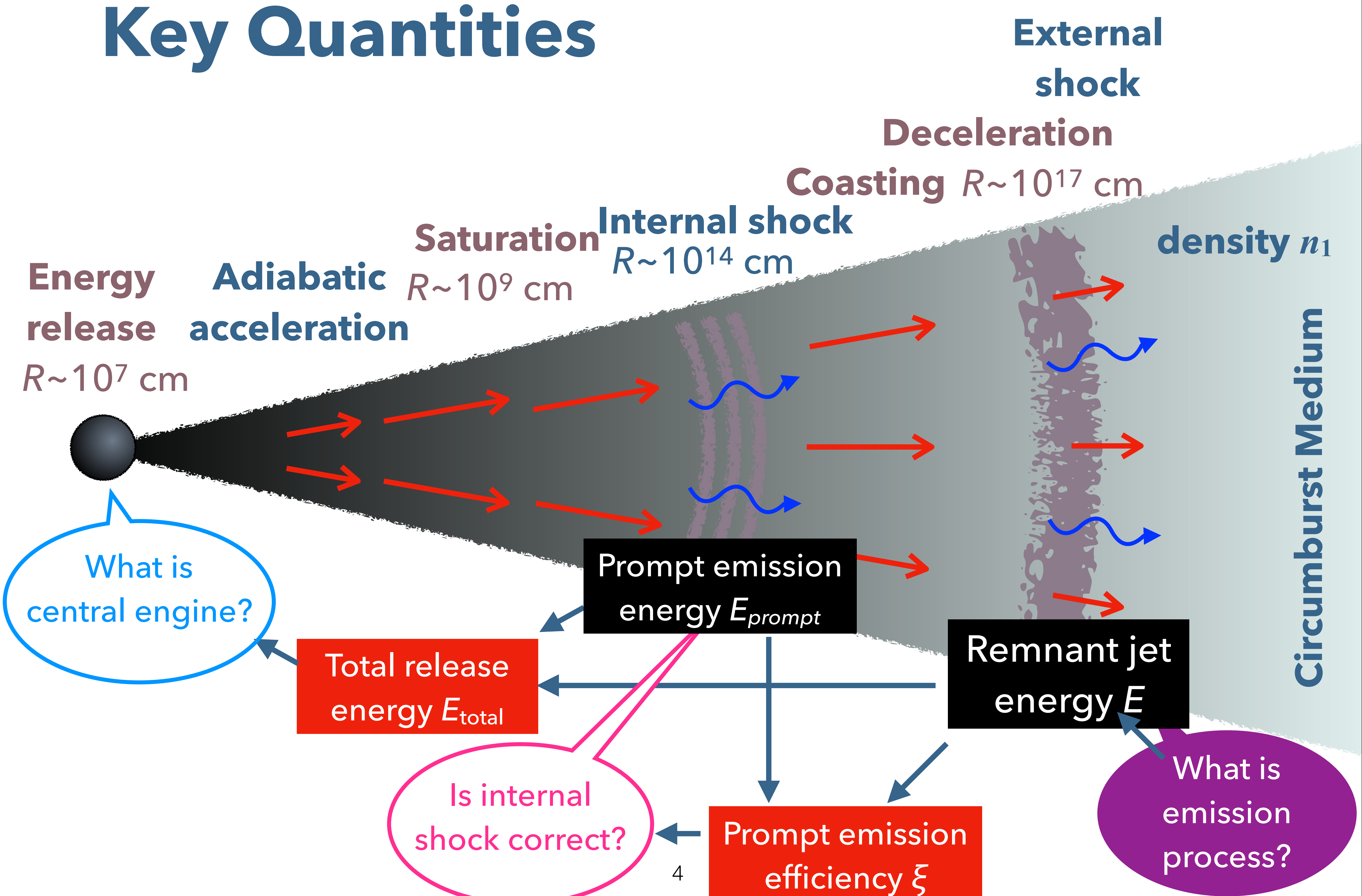
Key Quantities



Emission processes

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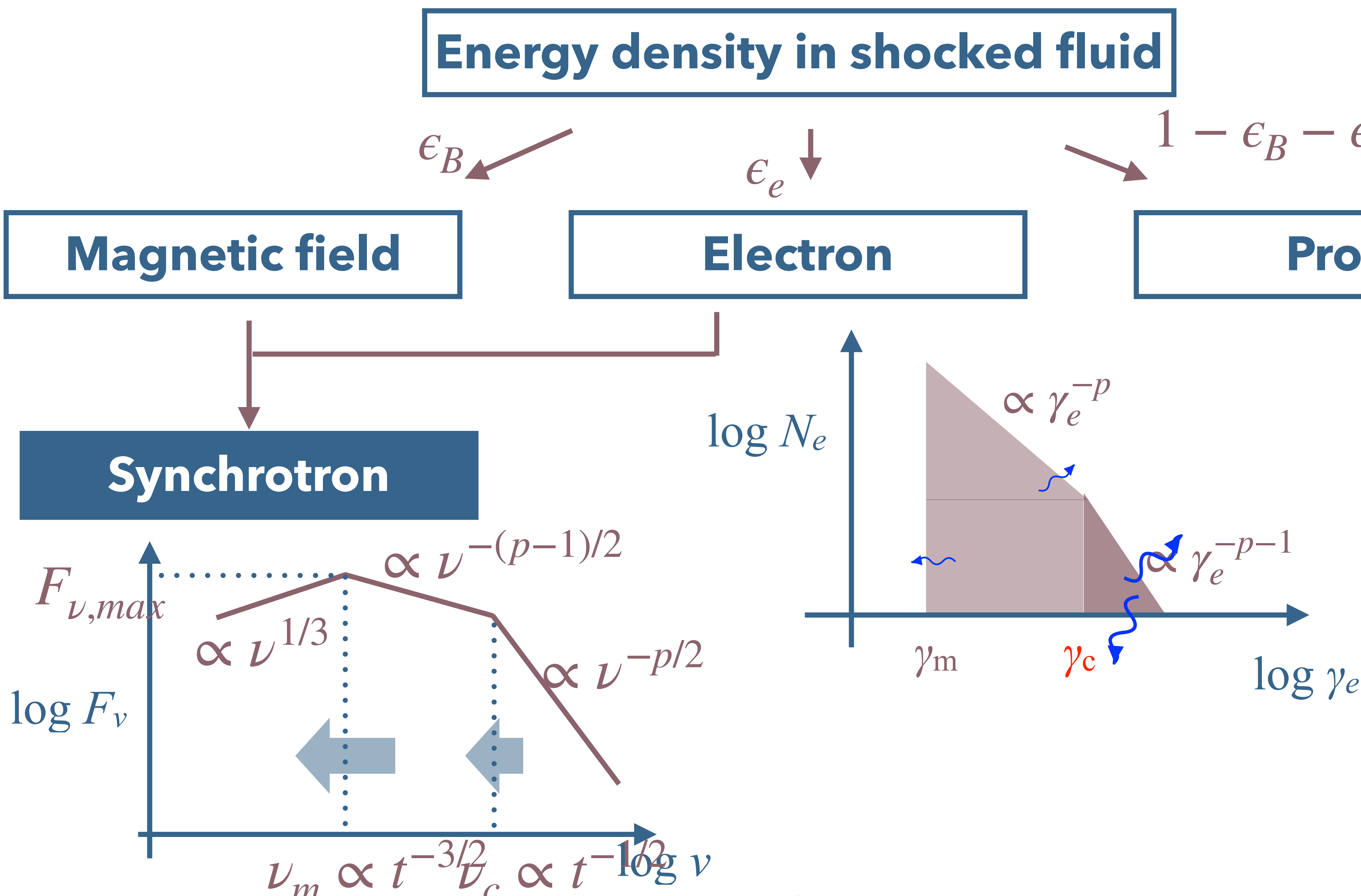
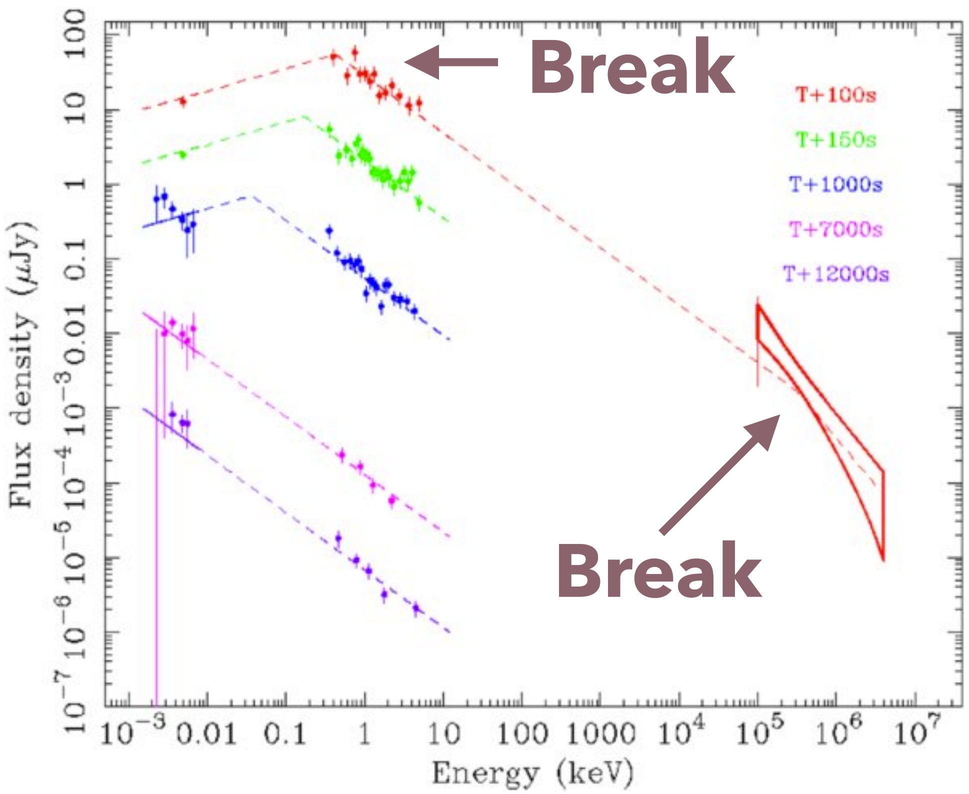
Synchrotron Emission from External-Shocked Fluid



Synchrotron Model

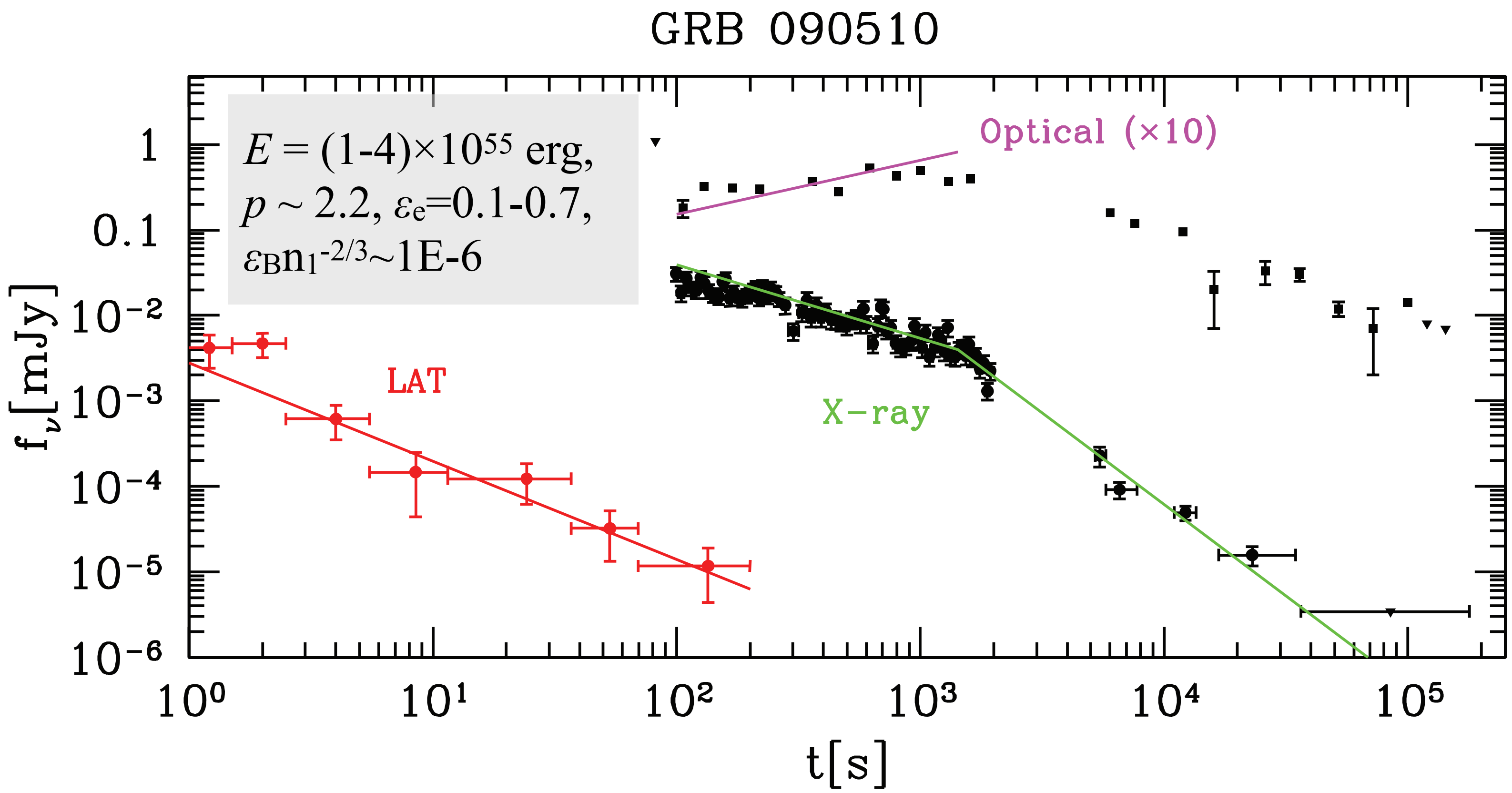
GRB 090510A

Spectra



[De Pasquale+ 10]

Light curves

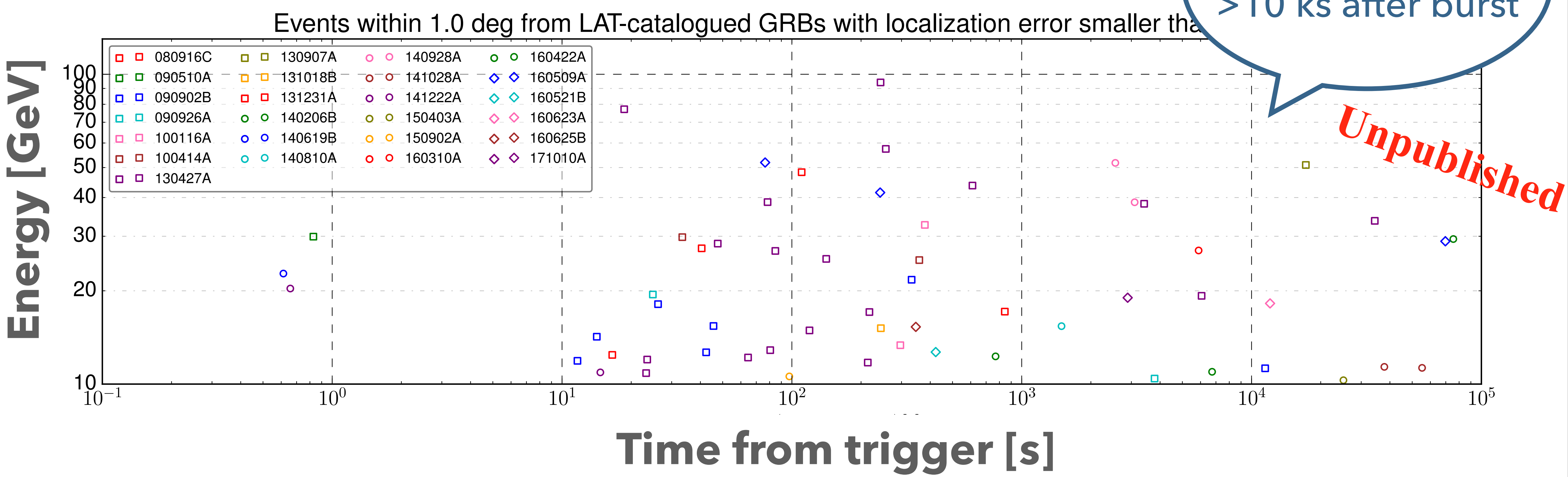


[Kumar+ 10]

- ✦ Observations were well explained by synchrotron from external shocks

Photon Energy Challenging for Synchrotron

Extend up to >10 ks after burst

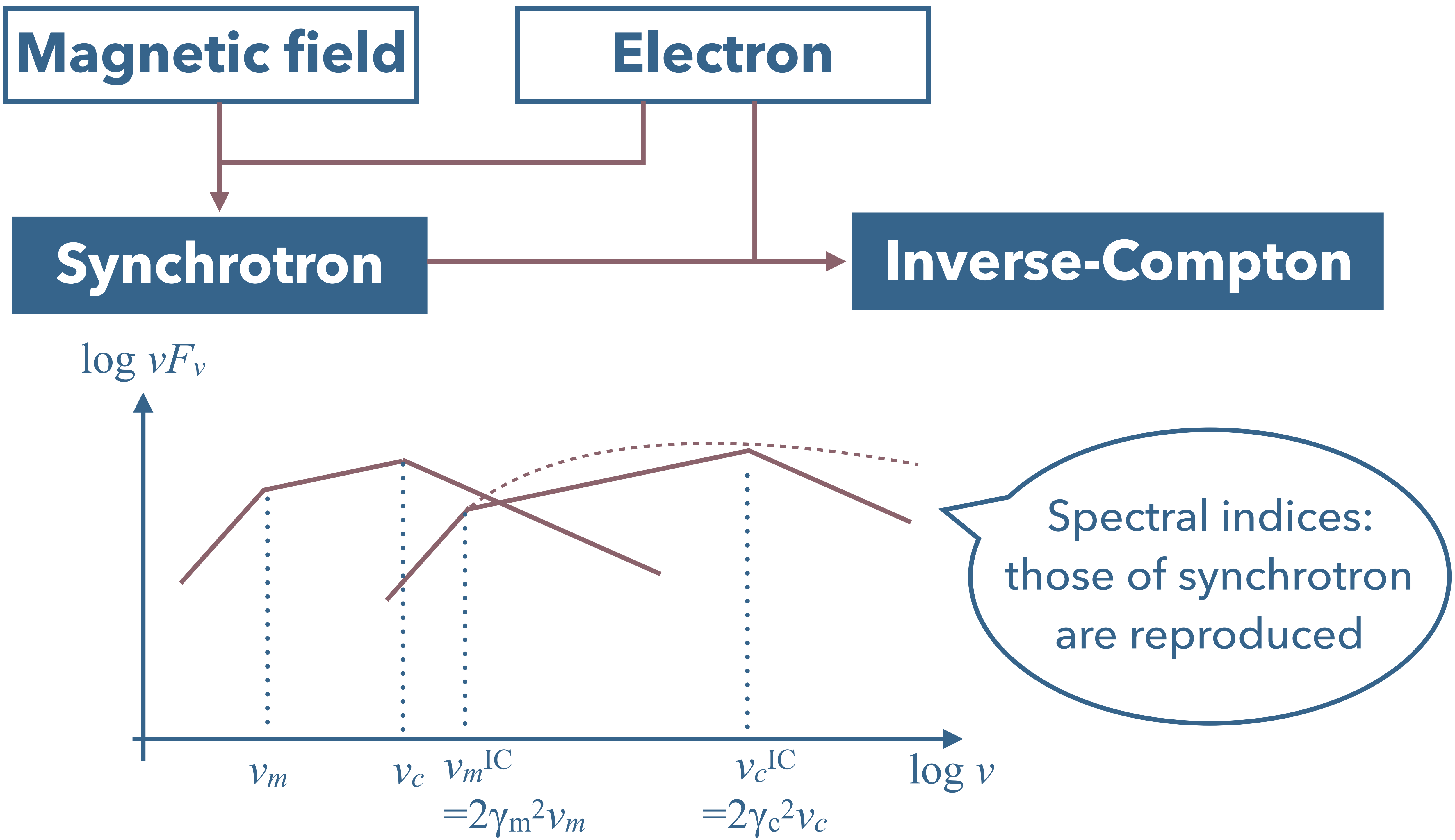


Maximum synchrotron energy

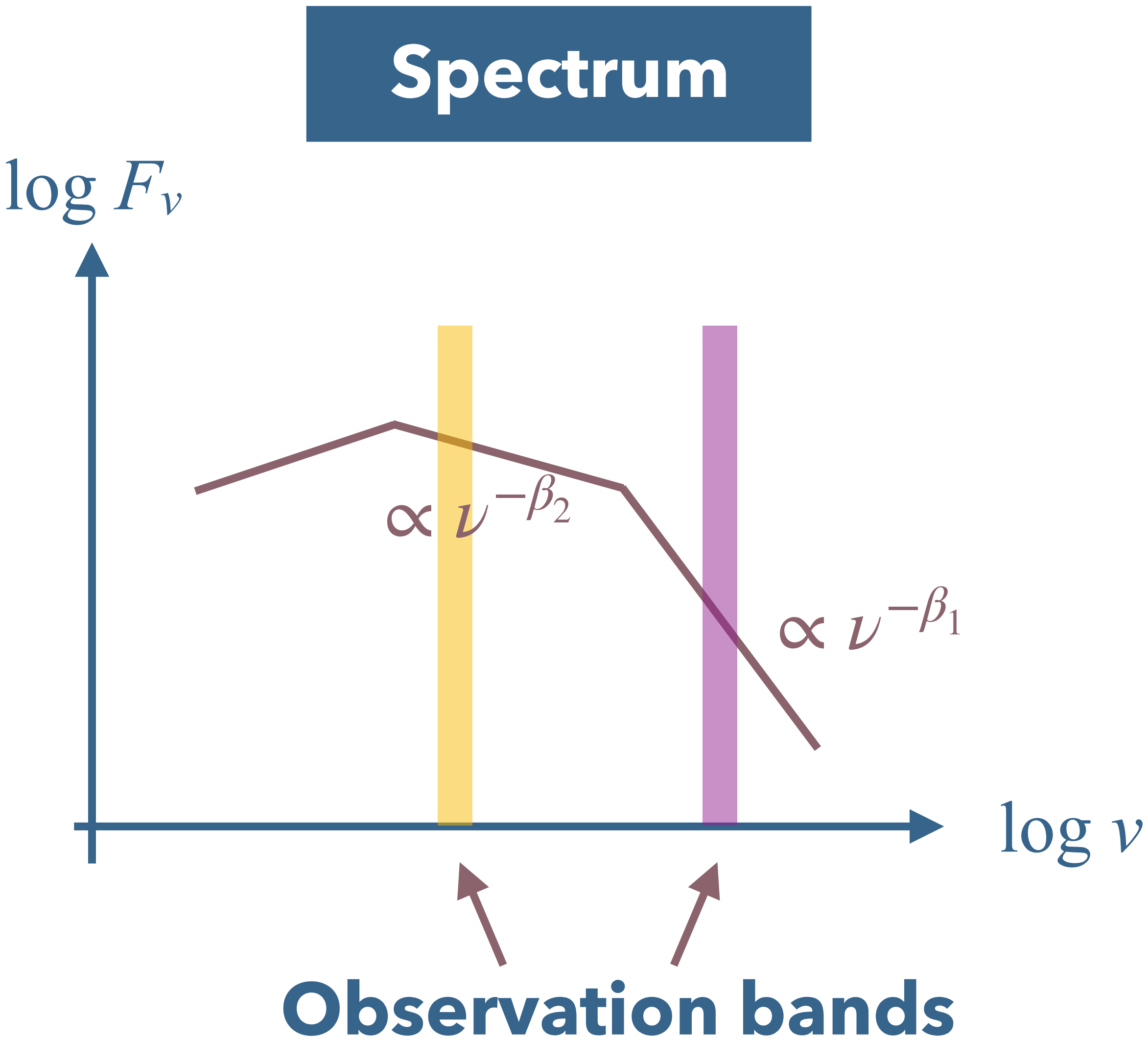
$$h\nu_{sync} \lesssim 50\Gamma\,\mathrm{MeV}$$

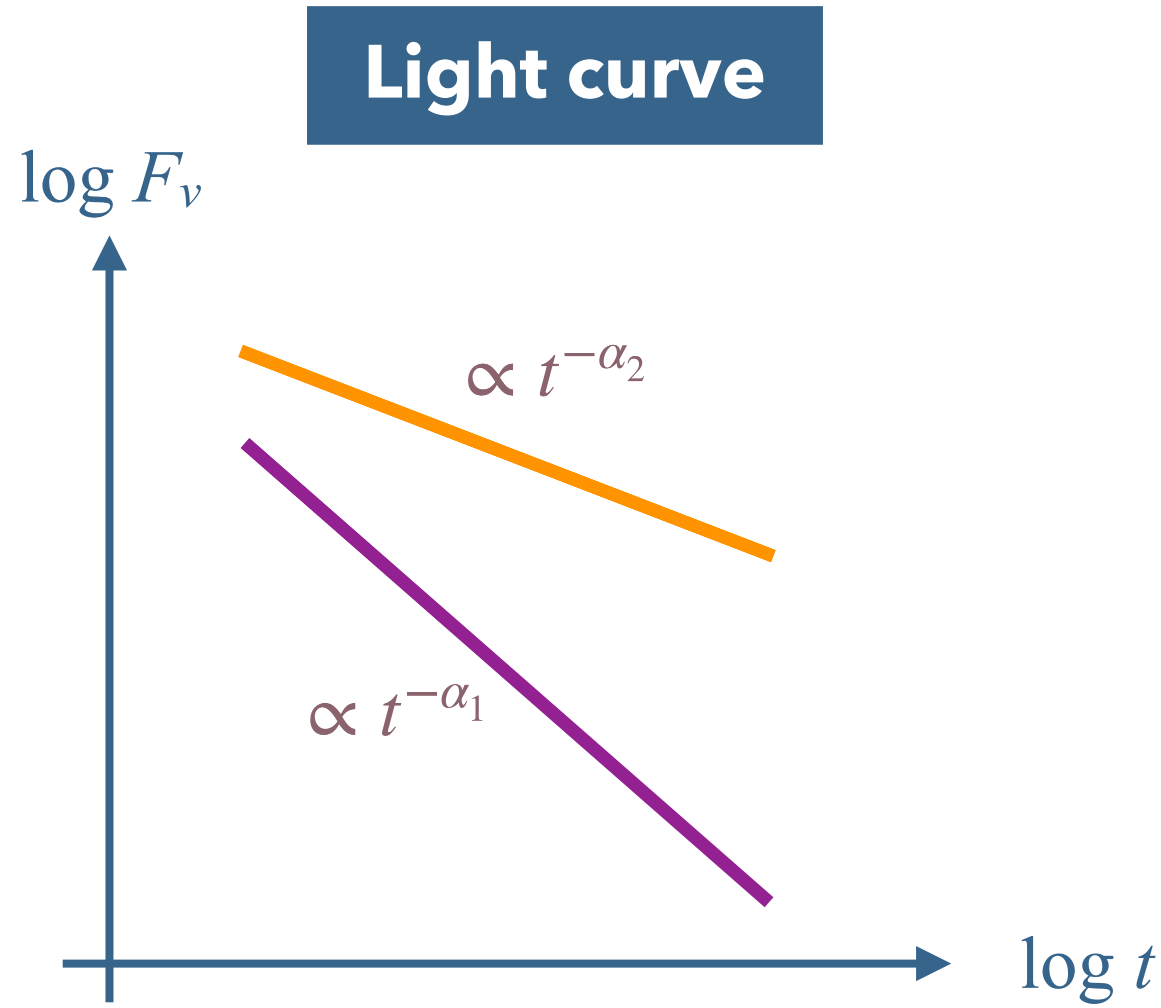
$$\lesssim 3\left(\frac{E}{10^{53}\mathrm{erg}}\right)^{1/8}\left(\frac{n_1}{\mathrm{cm}^3}\right)^{-1/8}\left(\frac{t}{\mathrm{ks}}\right)^{-3/8}\ \mathrm{GeV}$$

Synchrotron Self-Compton Emission



Closure Relations





$\alpha_i = f_i(\beta_i)$ for every component, scenario, and spectral segment

Fermi-LAT CalOnly classes

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- ✦ Fermi-LAT CalOnly classes
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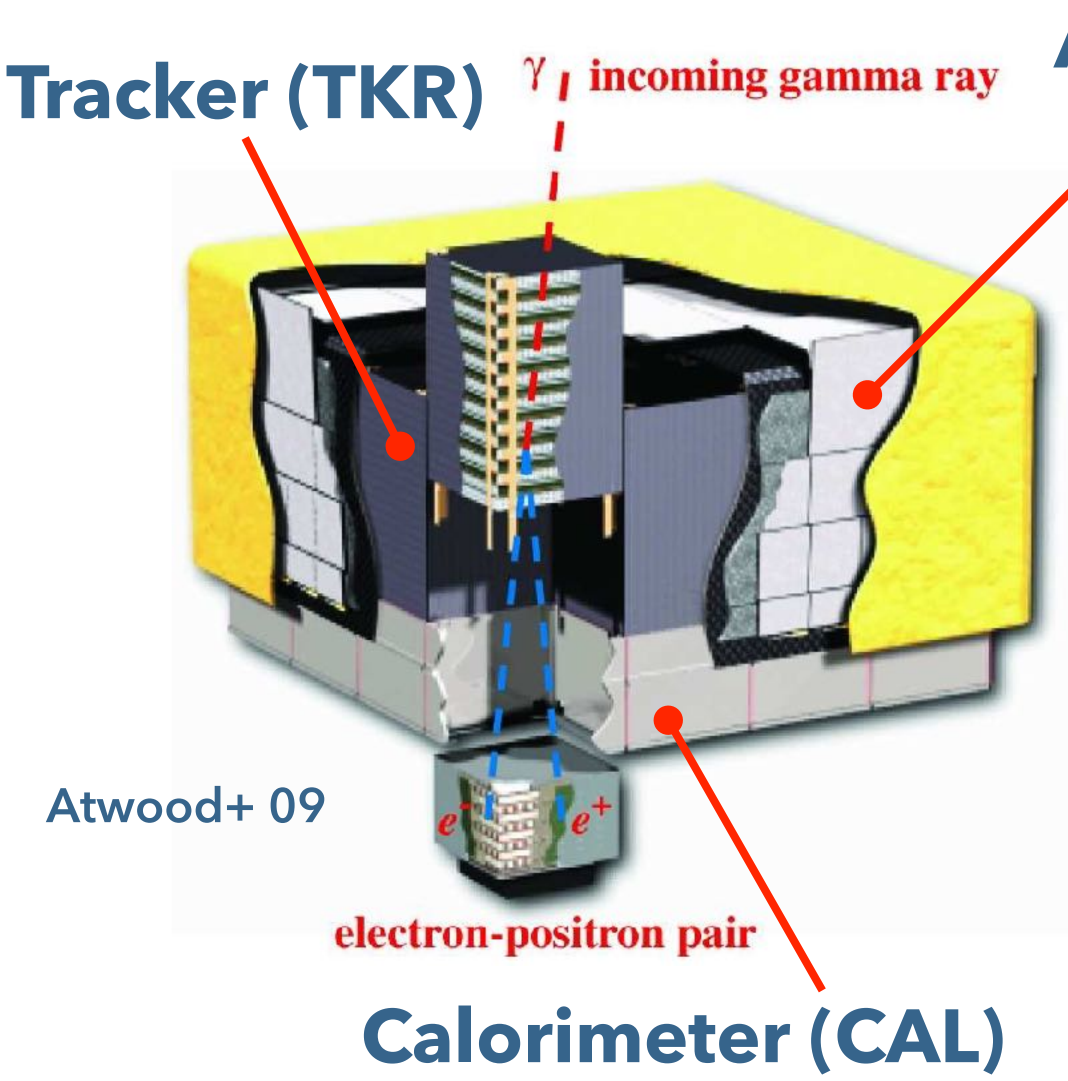
Fermi Large Area Telescope (LAT)



Atwood+ 09

- ✦ Energy range
  - from ~20 MeV to > 300 GeV
- ✦ Effective area
  - >0.8 m^2 for normal incidence
- ✦ Field of view
  - 2.4 sr for 1 GeV

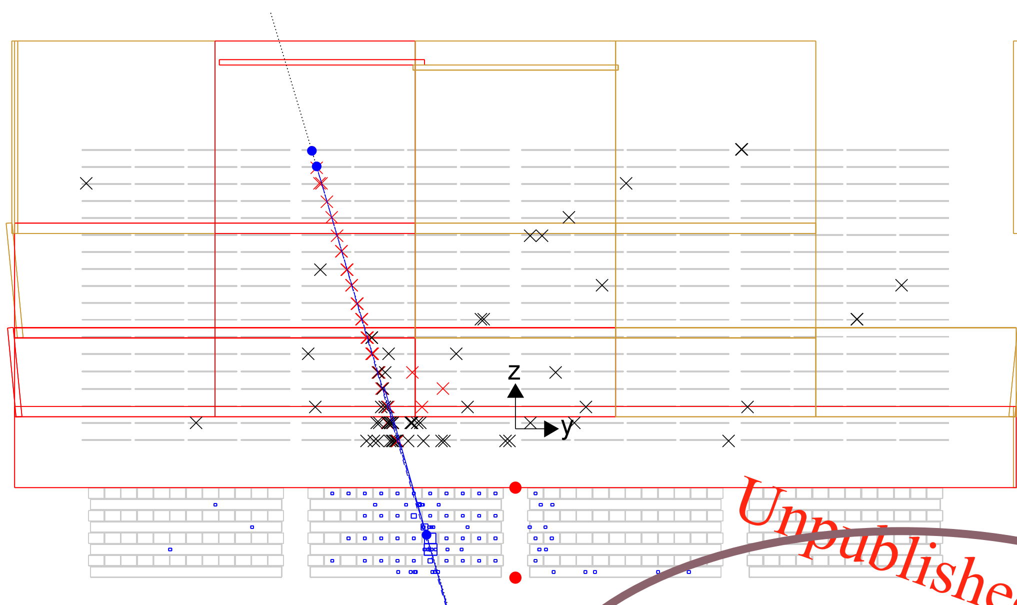
Sensitivity is limited by signal statistics above 10 GeV

Calorimeter-Only Classes

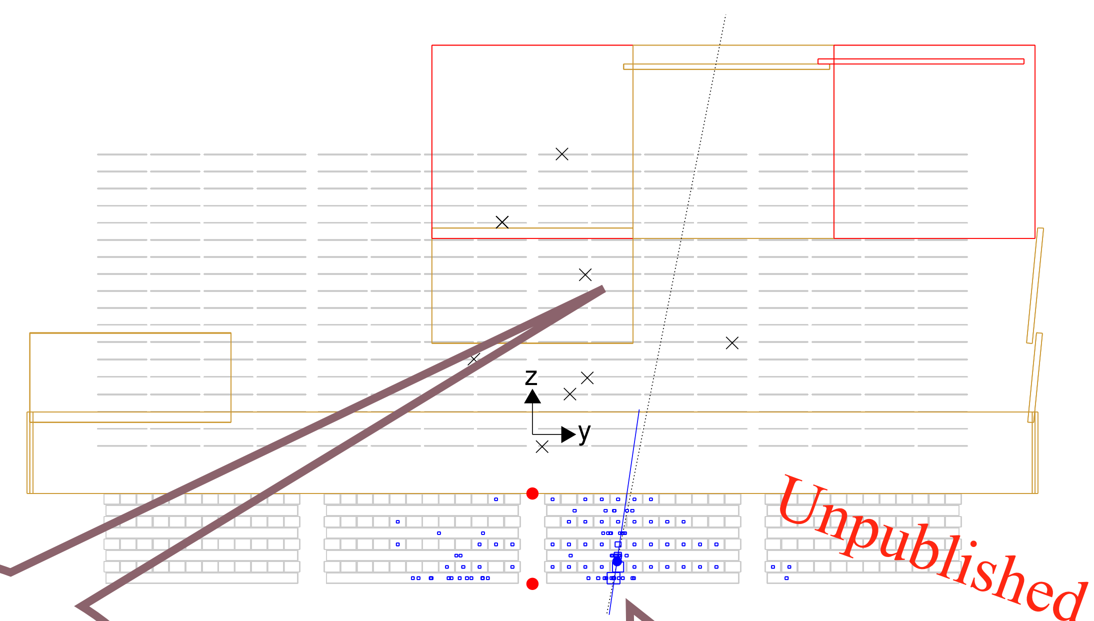
Standard event

TKR
~1X_0

CAL
~8.6X_0



CalOnly event



No usable TKR information

Arrival direction is determined by a few degrees

Make CalOnly events with energy >20 GeV usable for analysis

Improve in statistics

Background Rejection

Event data

↓

Boosted Decision Tree

↙ ↘

Gamma-ray-like | Cosmic-ray-like

- Veto of ACD
  - ACD hit count, correlation with shower axis, *etc.*
- Shower profile in TKR and CAL
  - Transversal RMS, longitudinal maximum, *etc.*

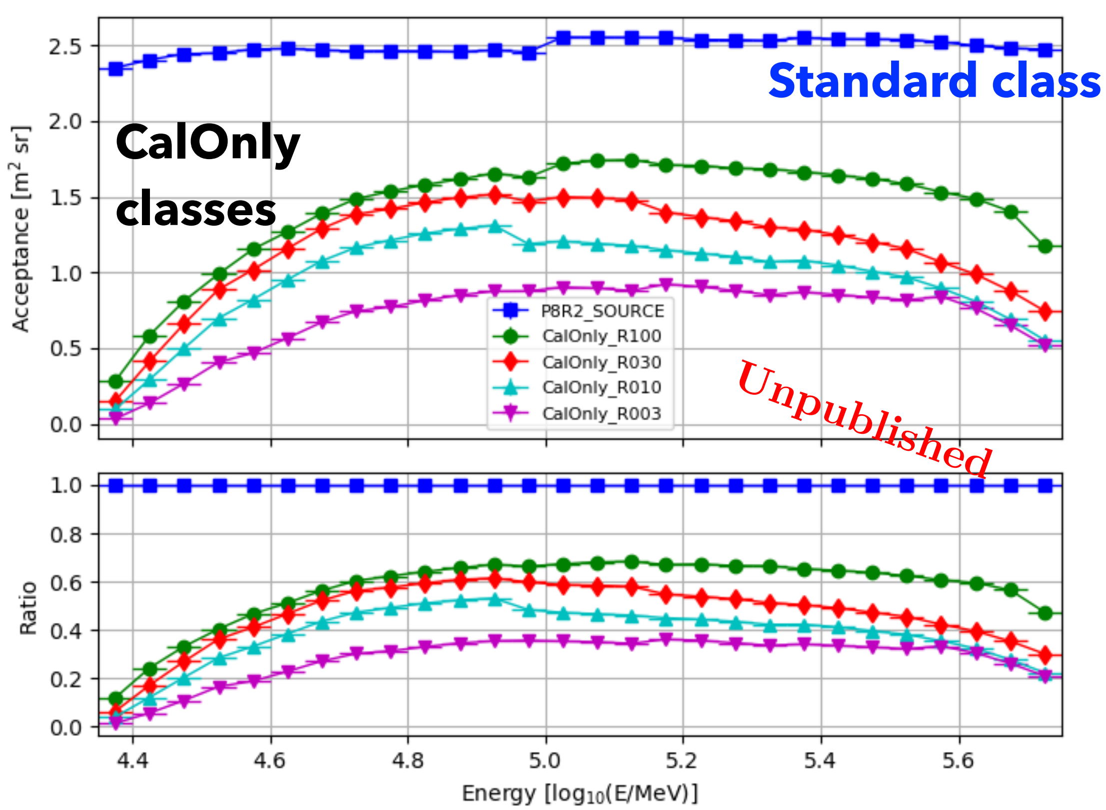
Optimize for CalOnly events

- Find best combination of separators
- Tune configuration
- Introduce new separators

Performance evaluated with MC

Acceptance

Fig. 6.7 (P85)

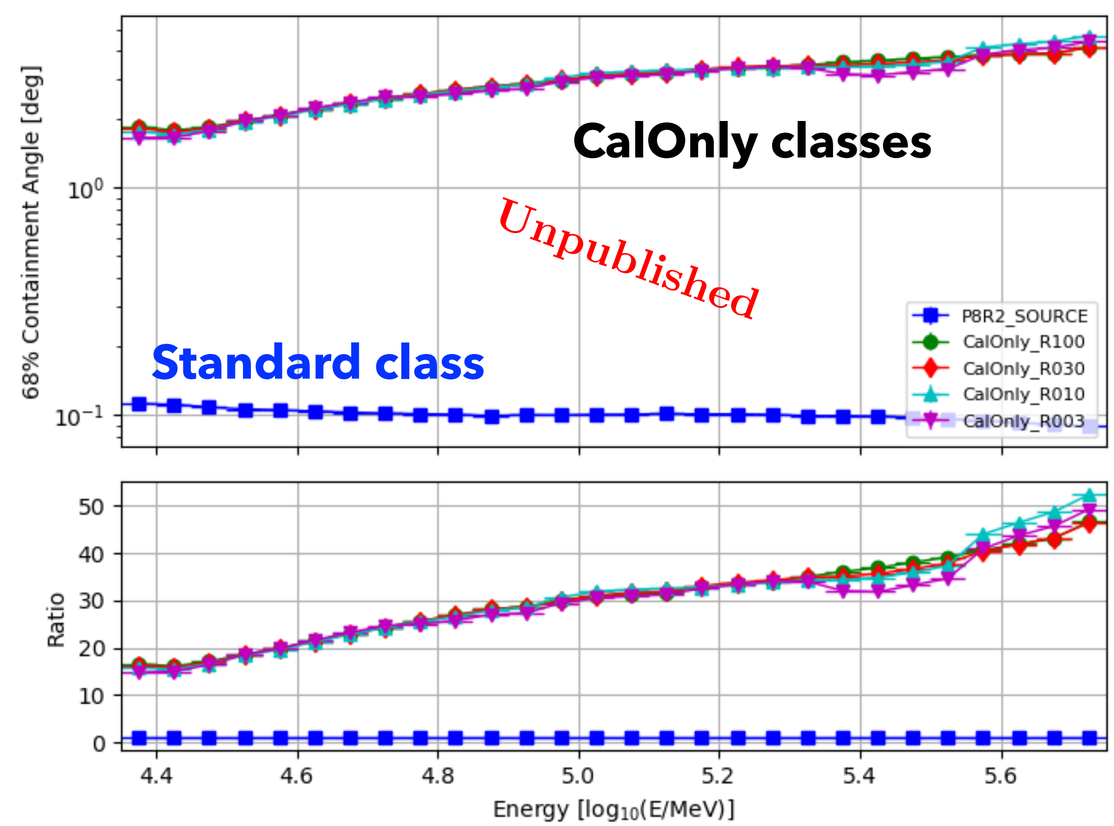


22GeV 100GeV 562GeV

~50% increase in statistics from ~50 to ~300 GeV

PSF

Fig. 6.10 (P87)



22GeV 100GeV 562GeV

~30 times worse PSF

Search for new GRB photon candidates

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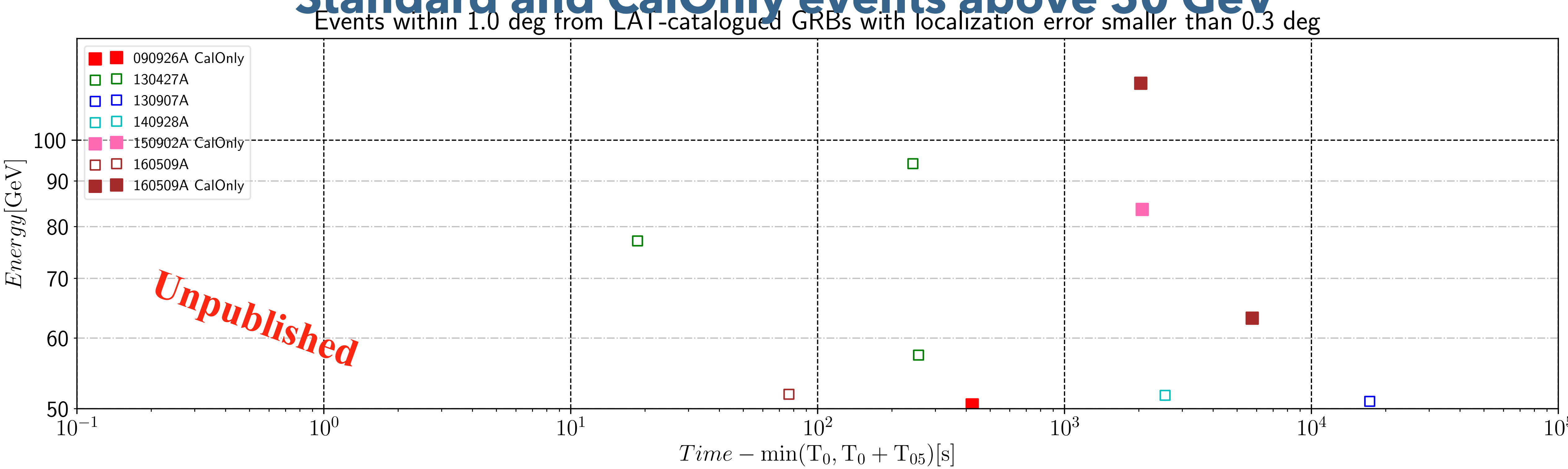
GRB Photon Search in CalOnly class

Analyze CalOnly data of 24 GRBs with standard events above 10 GeV

→

Four photon candidates coincident with GRBs

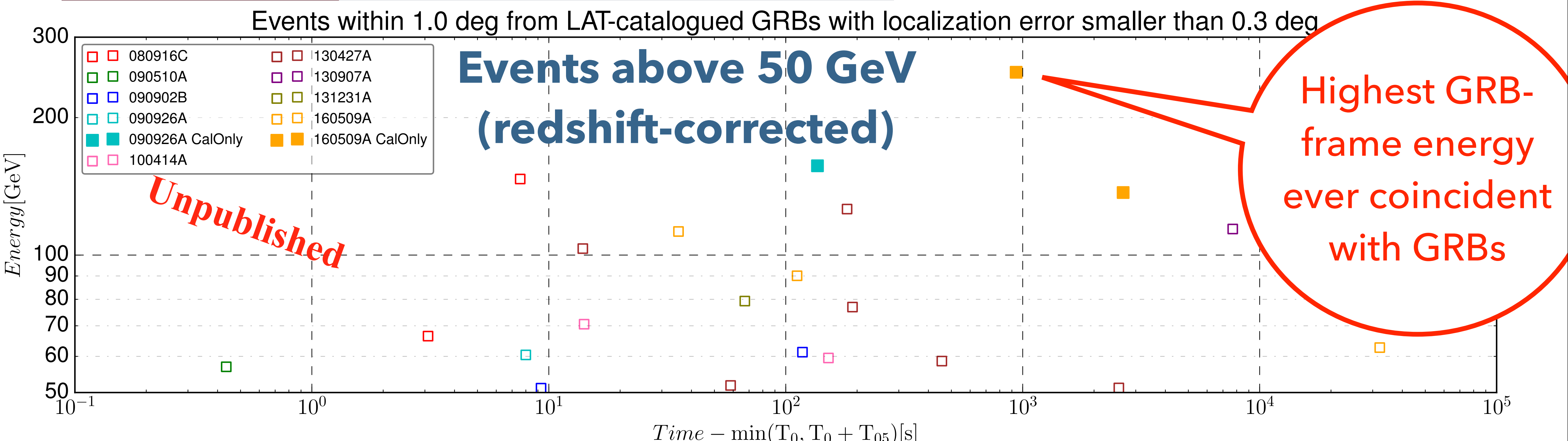
Standard and CalOnly events above 50 GeV



GRB Photon Candidates

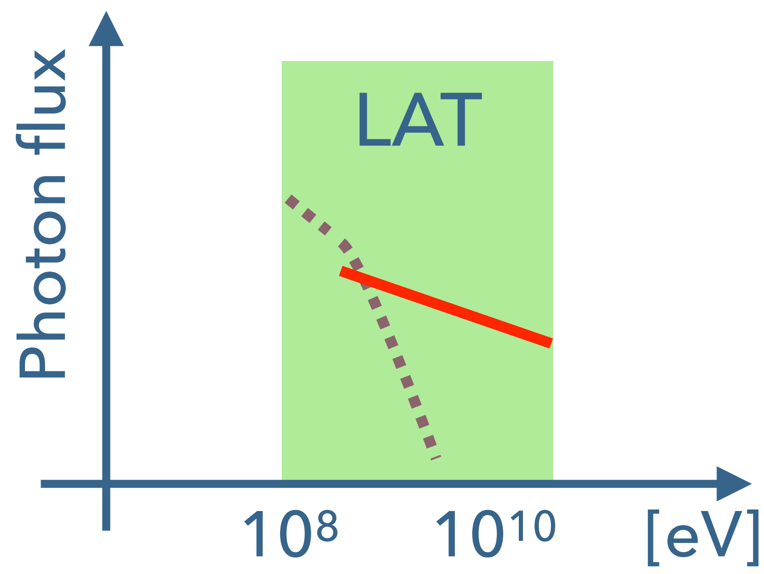
Focus on these two GRBs

GRB	090926A	150902A	160509A	
Arrival time [s]	424	2064	2057	5779
Energy [GeV] (in GRB-frame)	50 (157)	84 (?)	116 (252)	63 (137)
Separation [°] (cf. PSF68%)	0.8 (1.7)	3.6 (5.2)	4.6 (5.6)	3.7 (5.0)
Background probability	~0.02%	-	p(≥1 bkg): ~7% p(≥2 bkg): ~0.2%	



Synchrotron Energy Limit

GRB	090926A	160509A	
Arrival time [s]	424	2057	5779
Energy [GeV]	50^{+3}_{-2}	116^{+18}_{-13}	63^{+5}_{-4}
Synchrotron energy limit [GeV]	~11	~7	~5



Clearly higher than limit

$E=100E_{\mathrm{prompt}}$ and $n_1=10^{-3}/\mathrm{cm}^3$ are used

Harder component exists in LAT band

- SSC from external shock

$$h\nu_{sync} \lesssim 3 \left(\frac{E}{10^{53}\mathrm{erg}}\right)^{1/8} \left(\frac{n_1}{\mathrm{cm}^3}\right)^{-1/8} \left(\frac{t}{\mathrm{ks}}\right)^{-3/8} \mathrm{GeV}$$

Constraints on spectral vs. temporal indices

Likelihood Analysis

- ✦ **Time-joint analysis**
  - Combine likelihood in time bins after T95 of Fermi-GBM
  - Scan over normalization at 100 s vs. spectral index β vs. temporal index α
- ✦ **Spectral model**
  - Power-law with EBL
- ✦ **Temporal model**
  - Normalization: Power-law decay

Scan whether each parameter set explains both spectrum and light curve

⇩

Constraints on β vs. α for comparison with closure relations

GRB 090926A
Power-law Spectrum Model

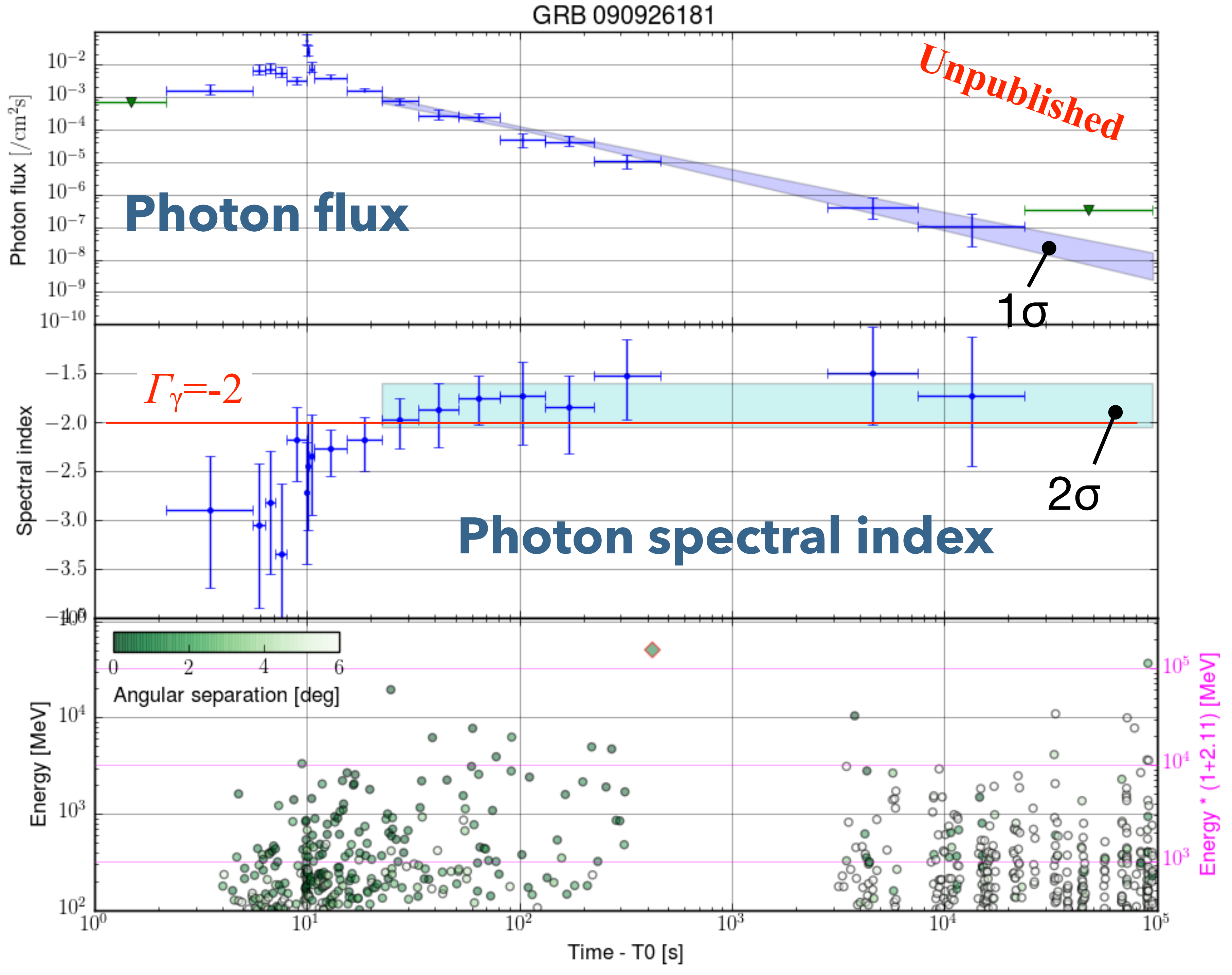
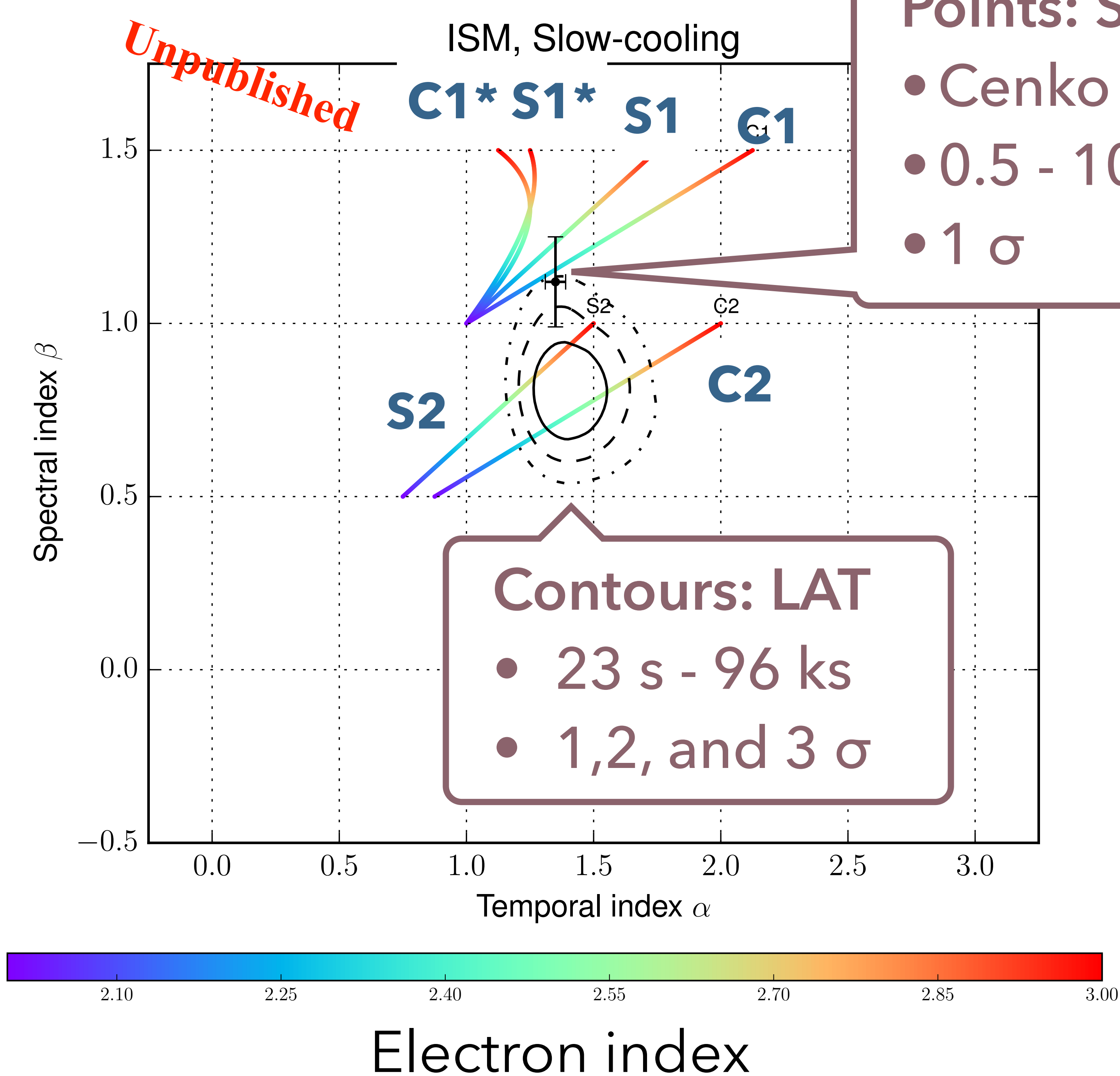
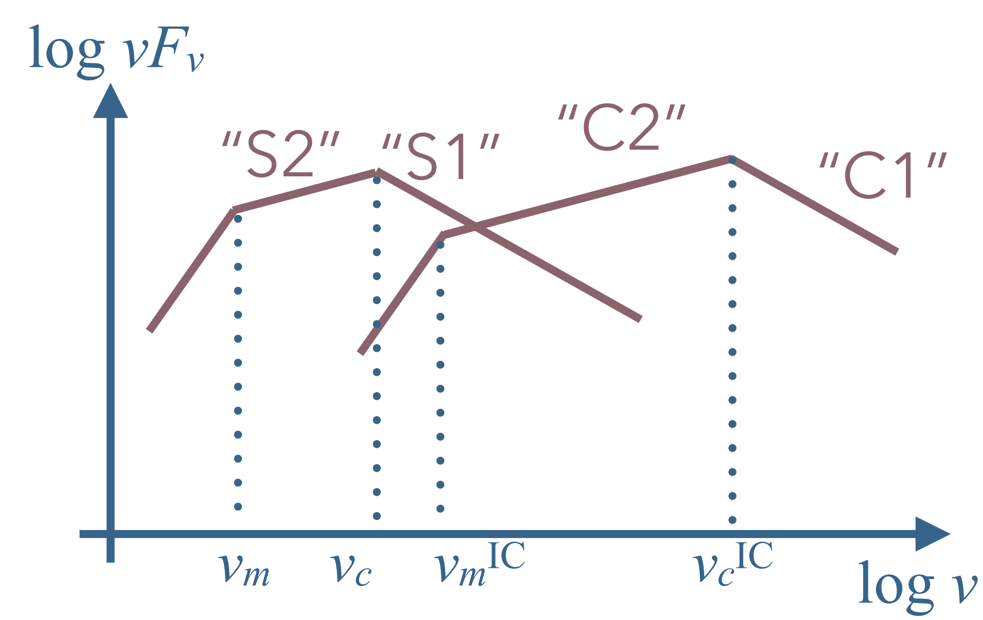


Fig. 8.1 (P119)

Comparison with Closure Relations

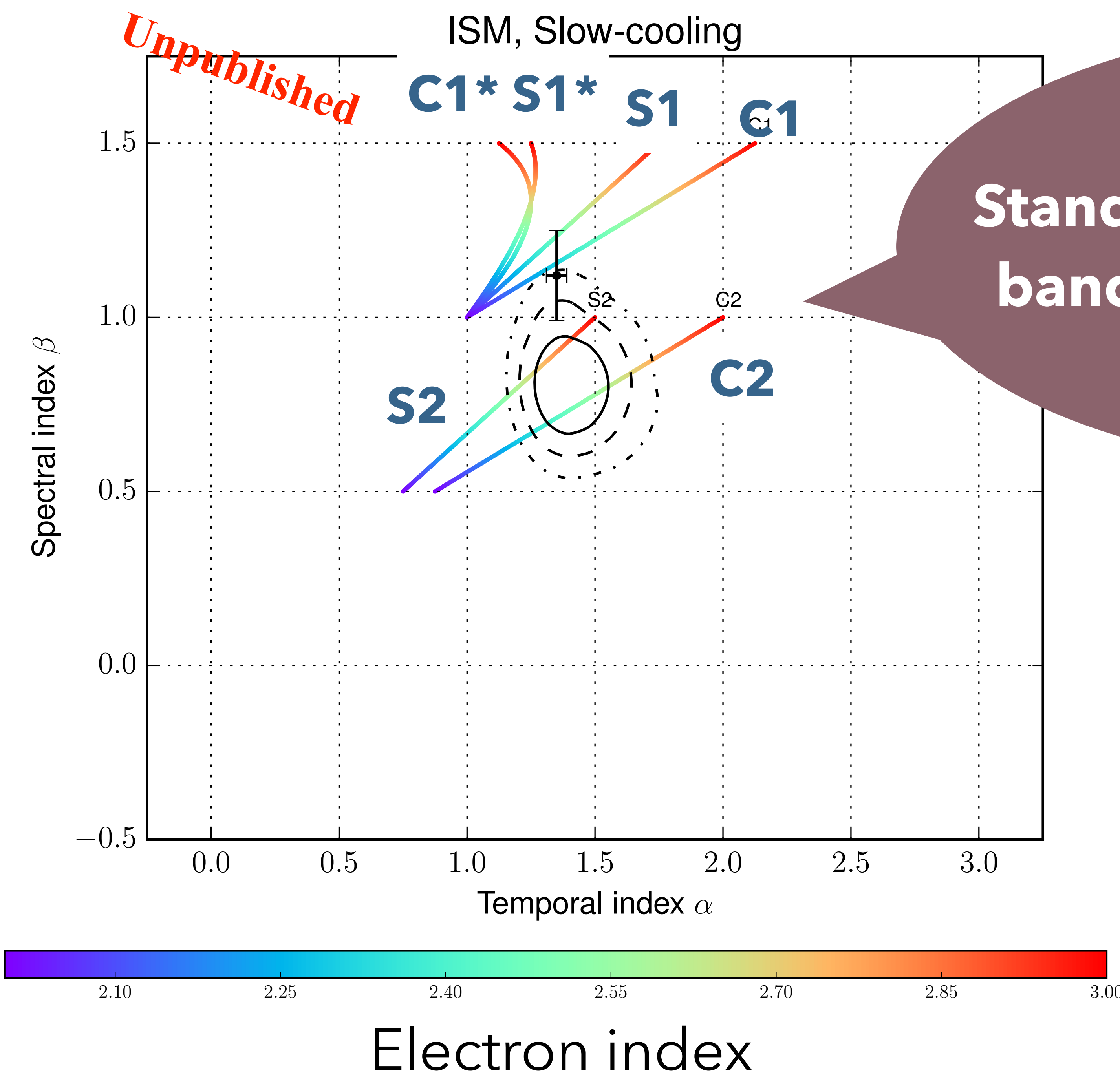




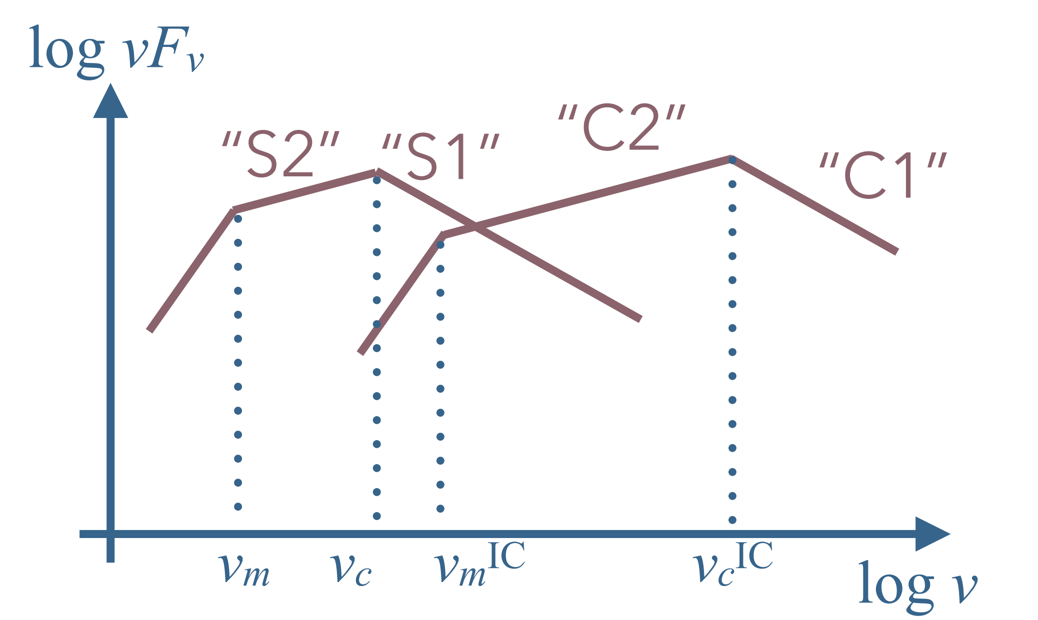
"S1*" and "C1*" are cases when cooling is dominated by SSC, rather than synchrotron

Model: Sari+ 98, Panaitescu+ 00, Sari+ 01

Comparison with Closure Relations



Standard explanation for LAT band "S1" is rejected by 3σ



"S1*" and "C1*" are cases when cooling is dominated by SSC, rather than synchrotron

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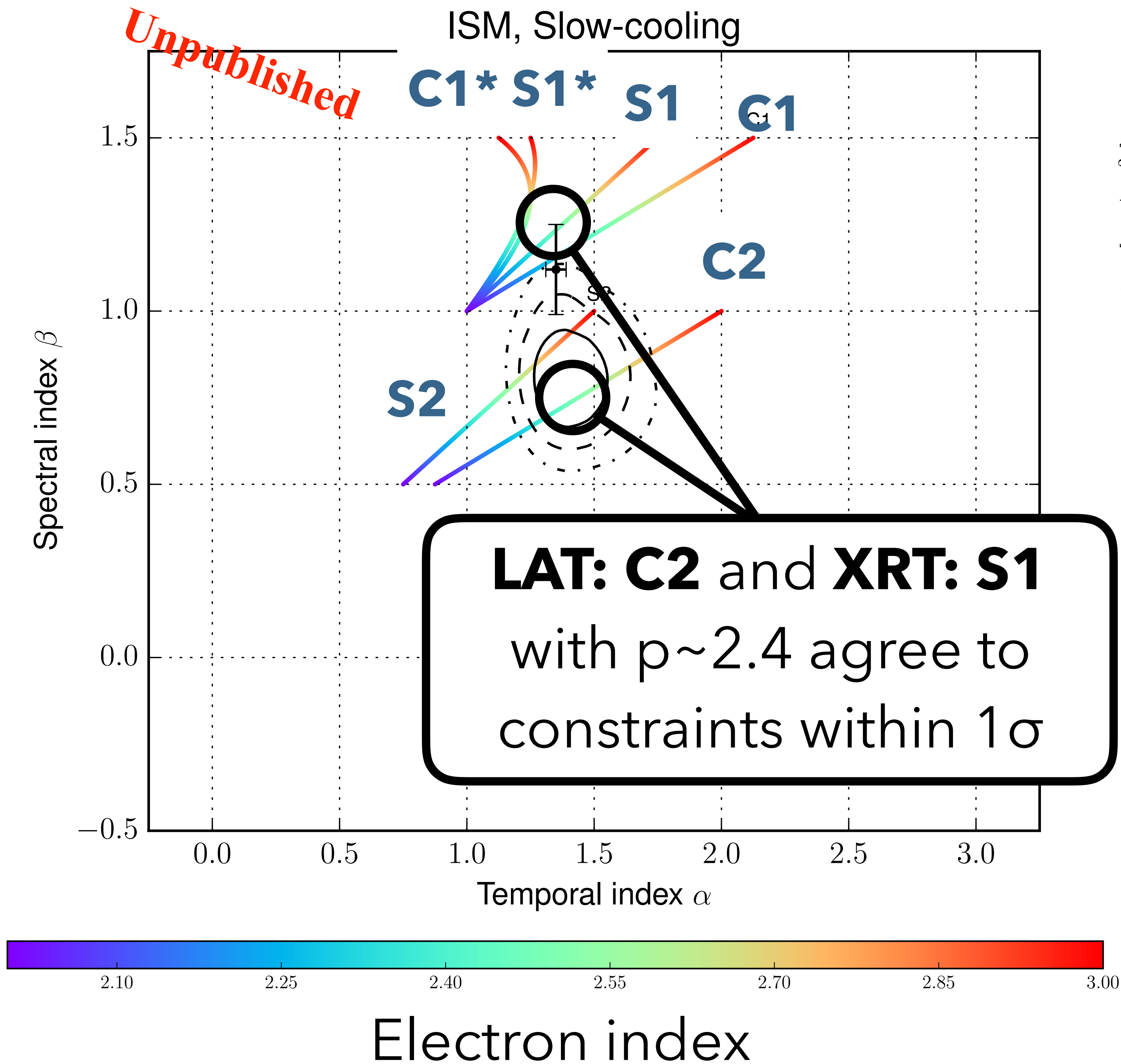
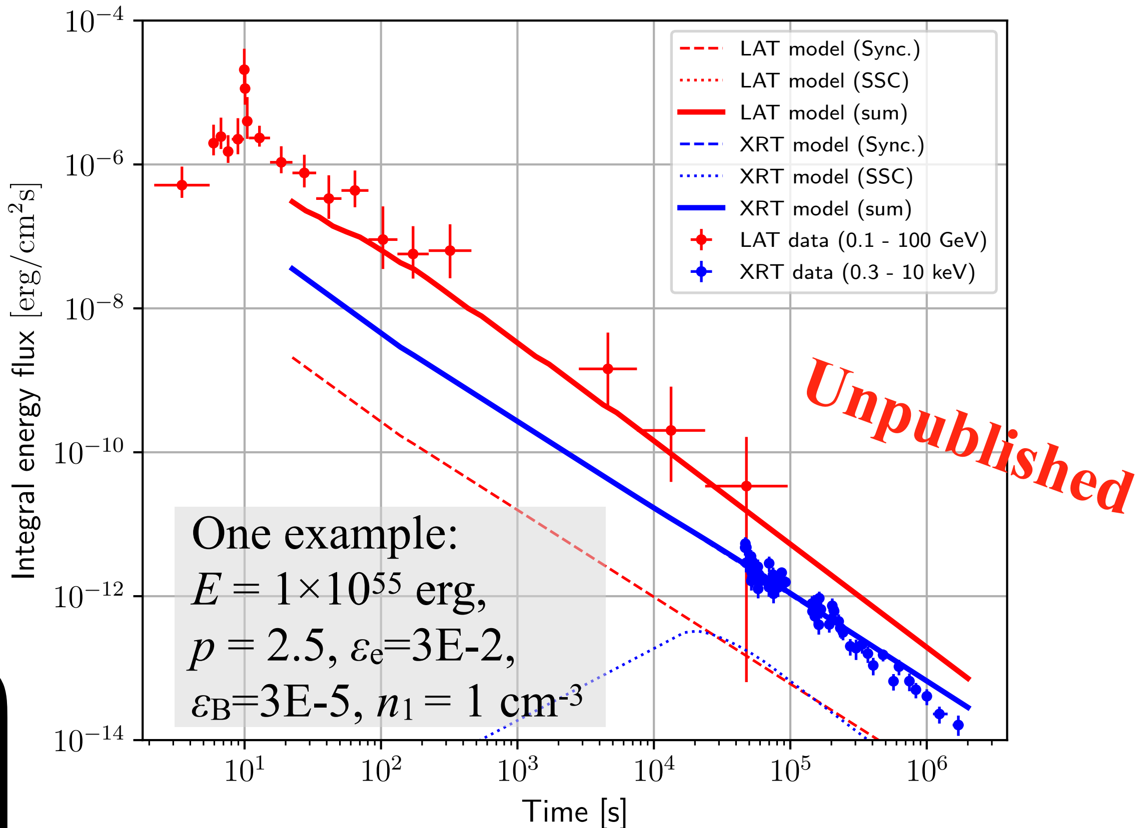
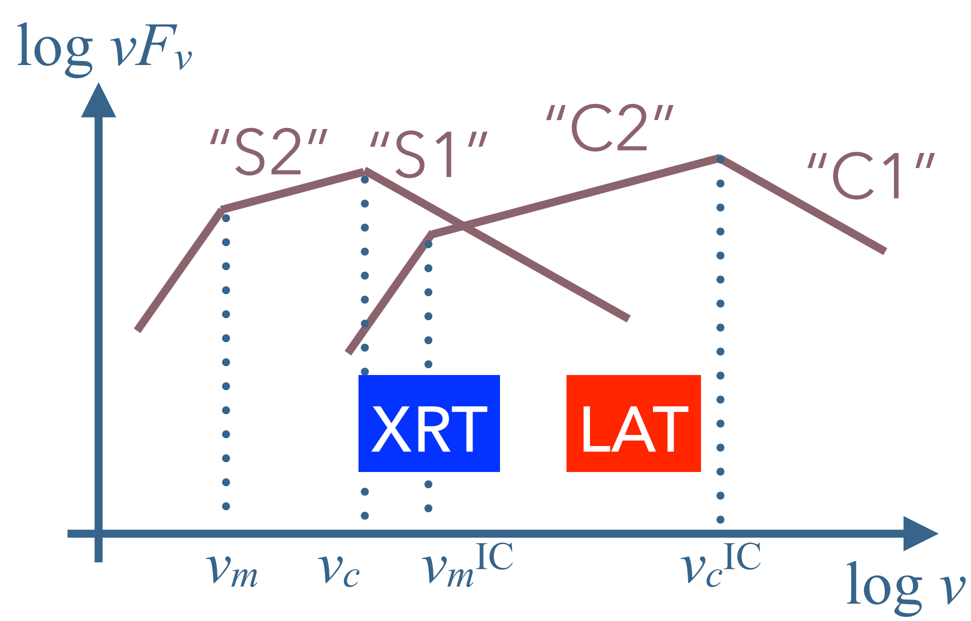
Interpretation: C2-S1

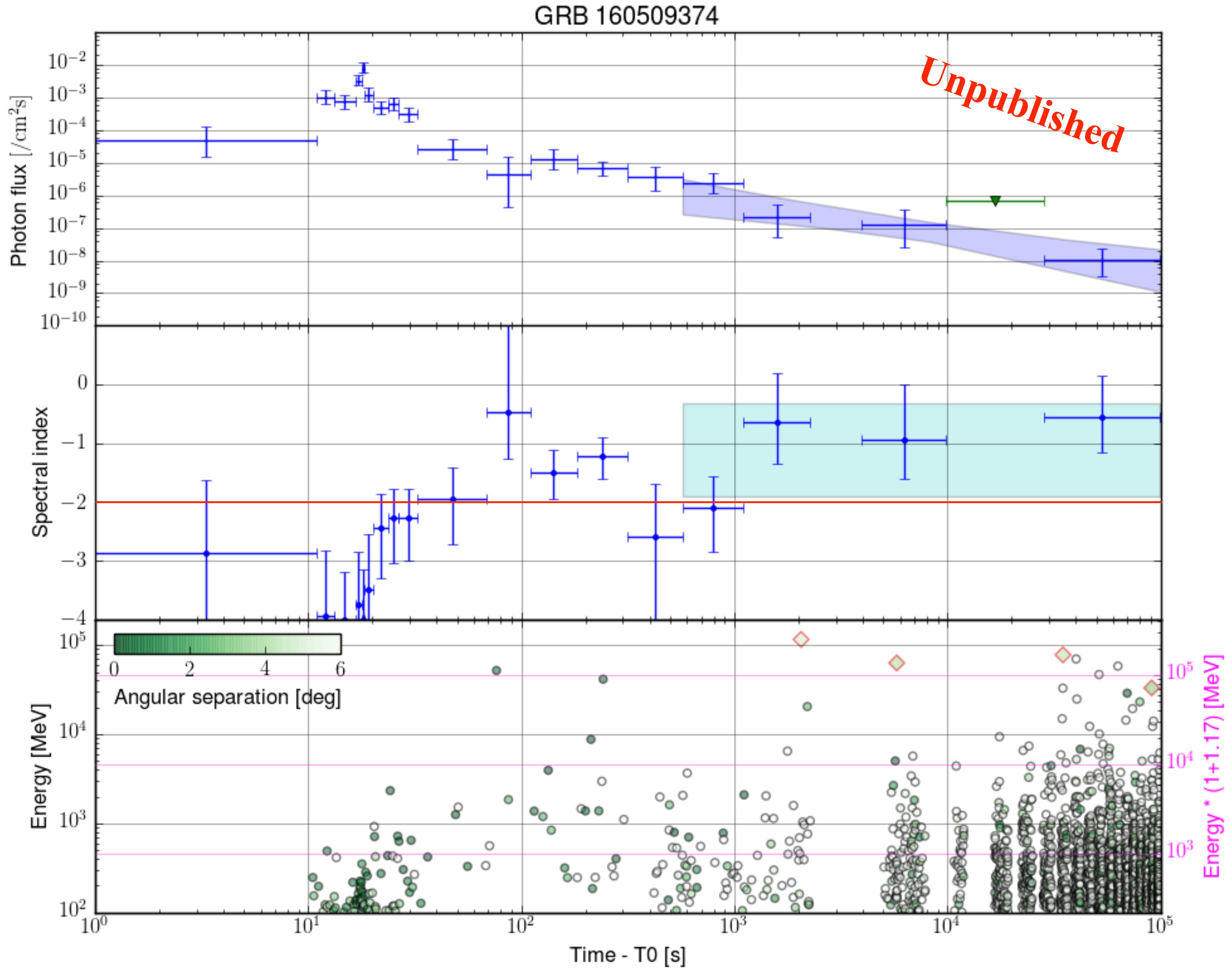




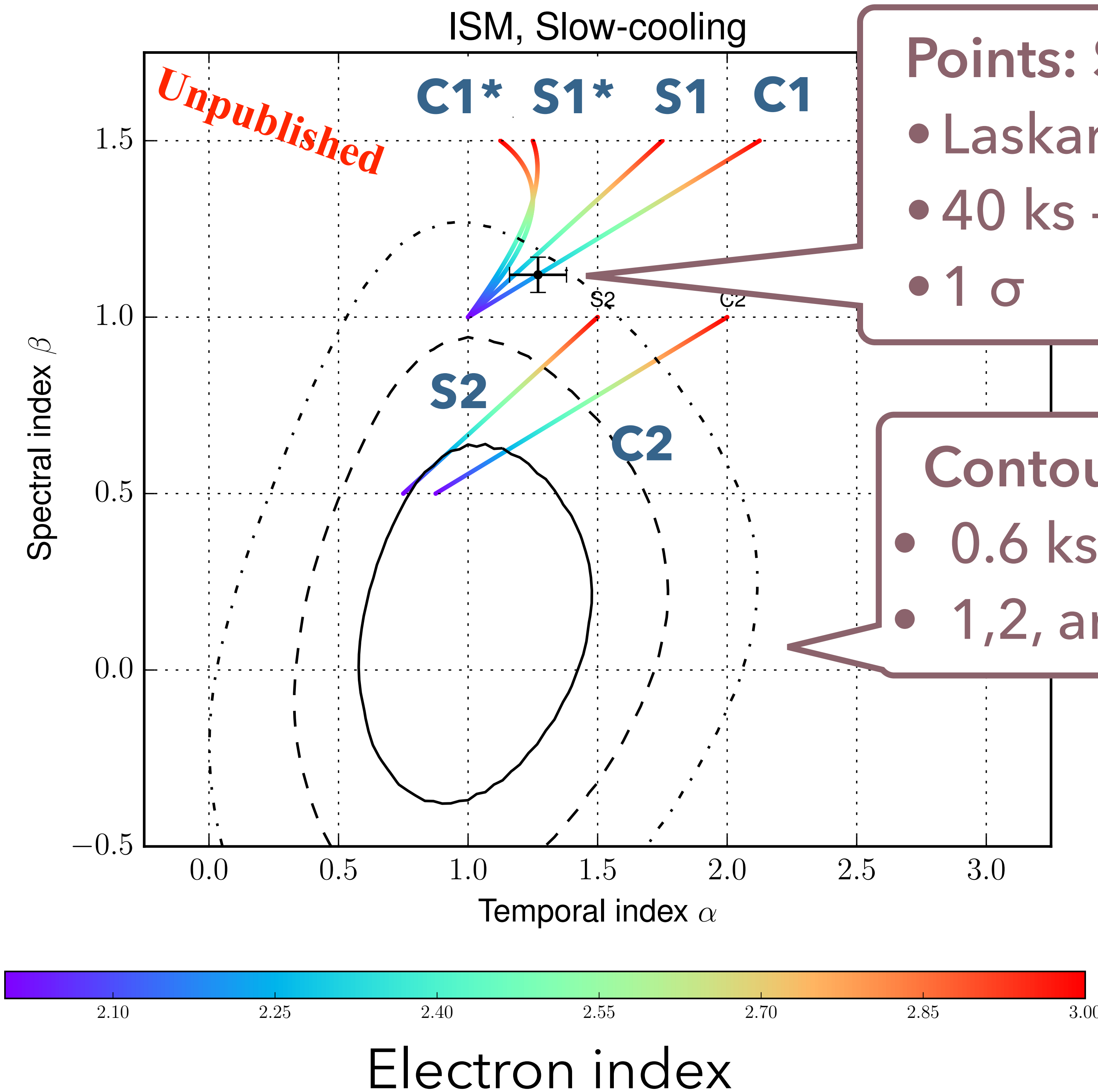


Model: Sari+ 98, Panaitescu+ 00, Sari+ 01

GRB 160509A
Power-law Spectrum Model



Comparison with Closure Relations

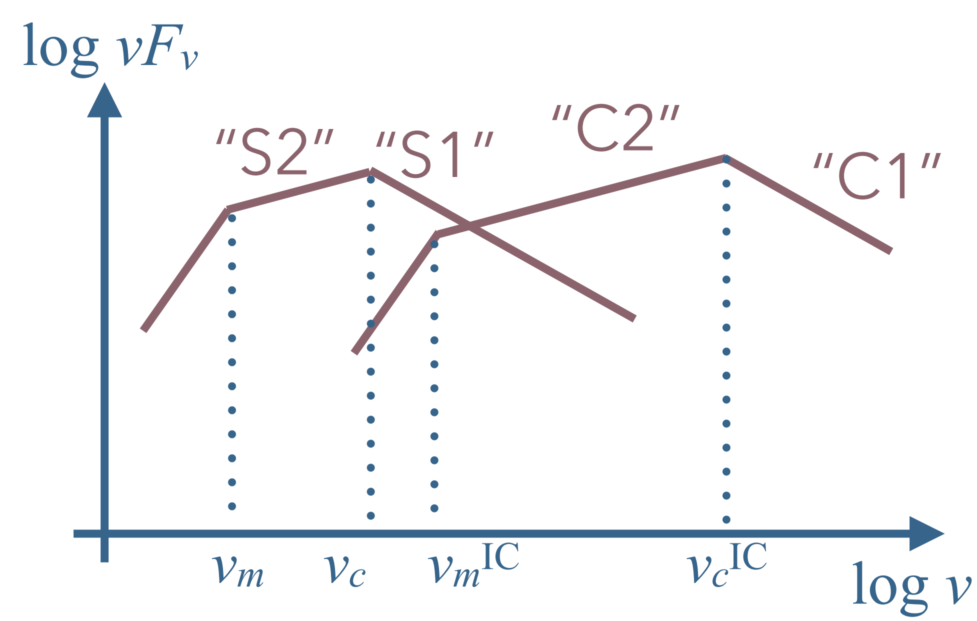


Points: Swift-XRT

- Laskar, *et al.* 16
- 40 ks - 360 ks
- 1 σ

Contours: LAT

- 0.6 ks - 100 ks
- 1,2, and 3 σ



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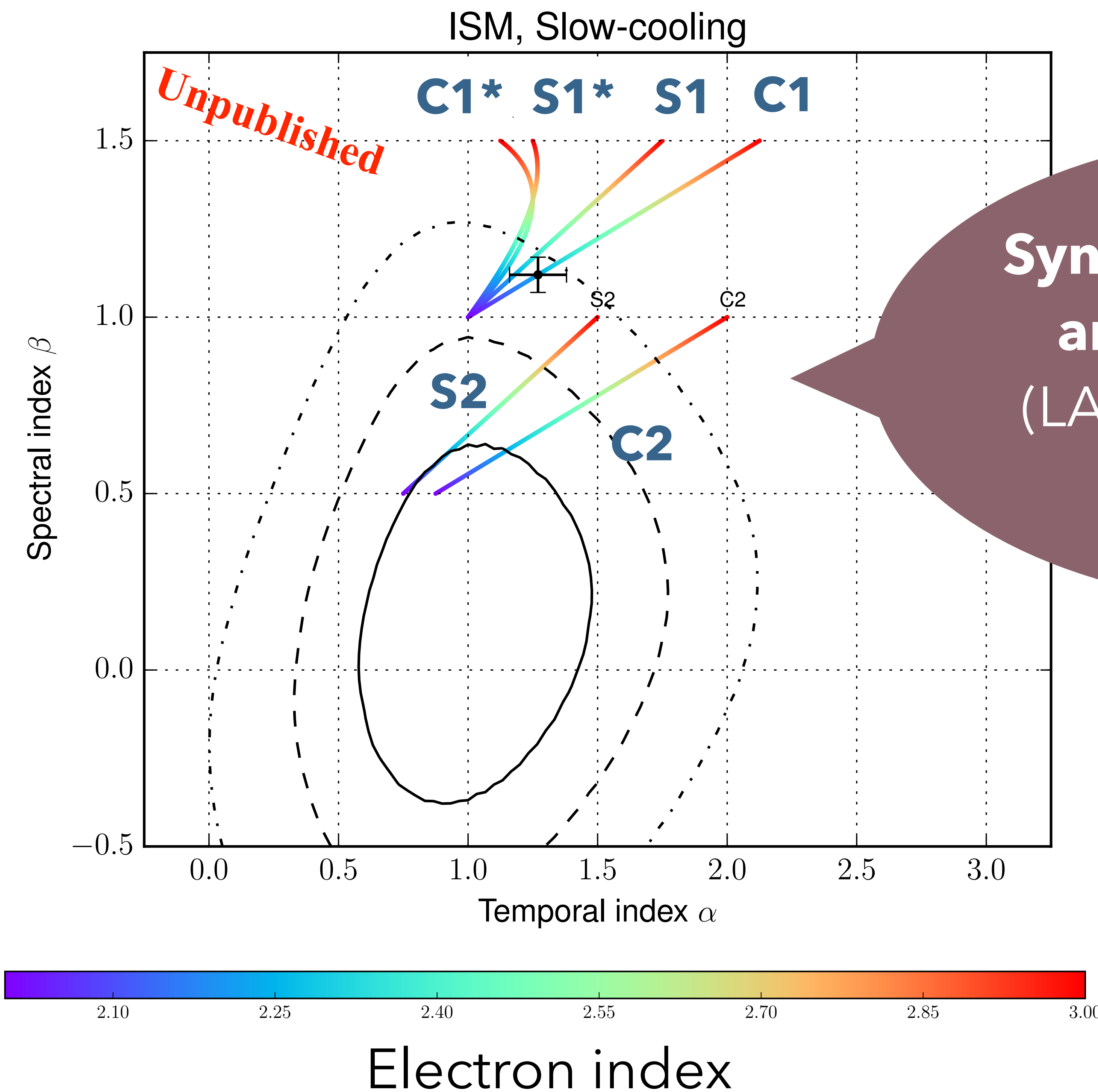
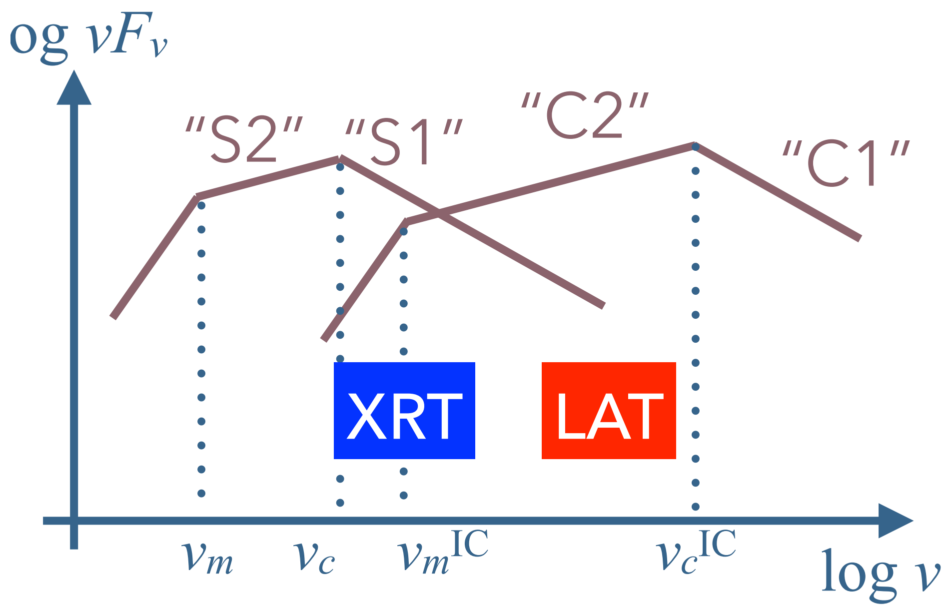
Comparison with Closure Relations

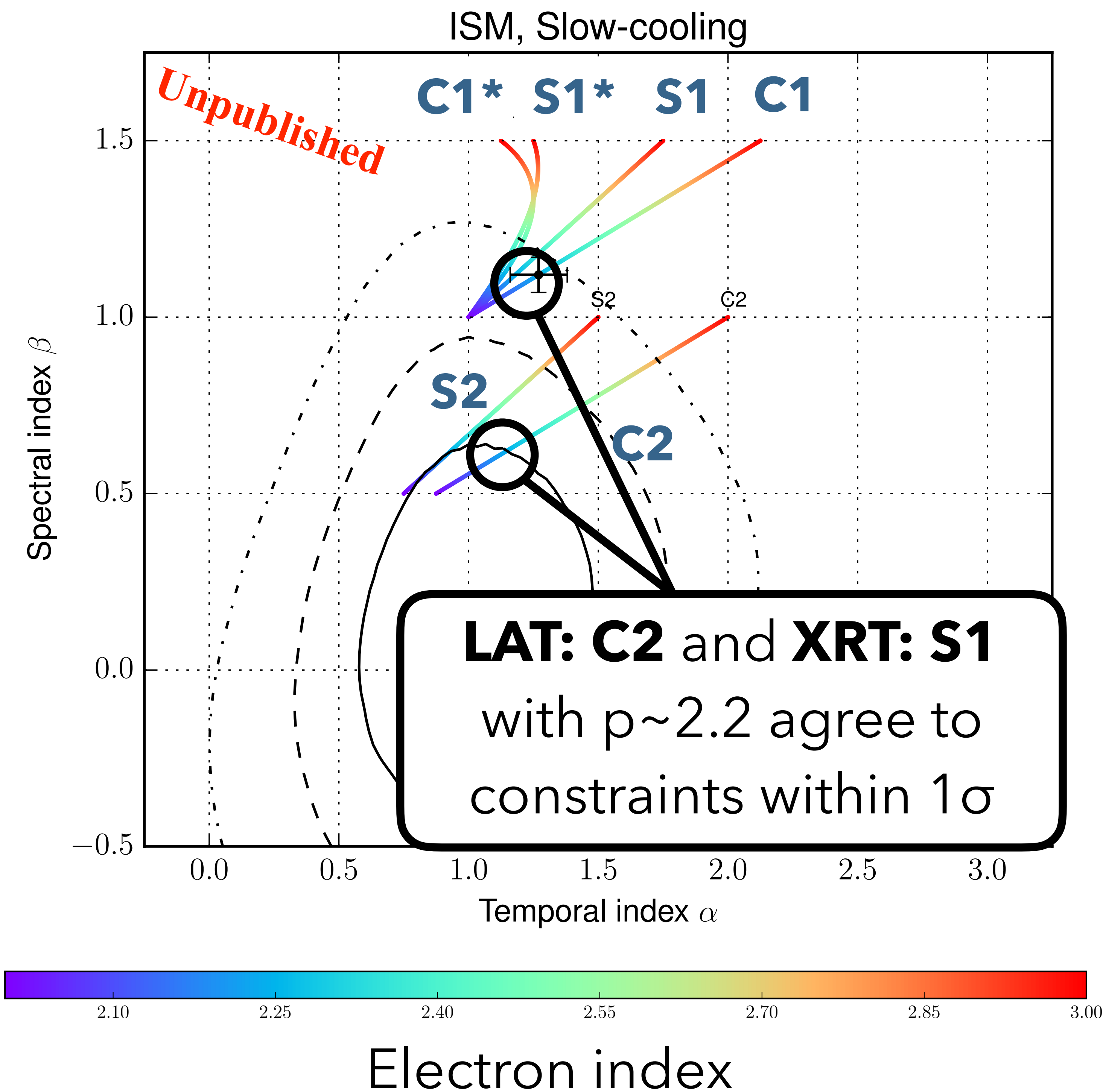


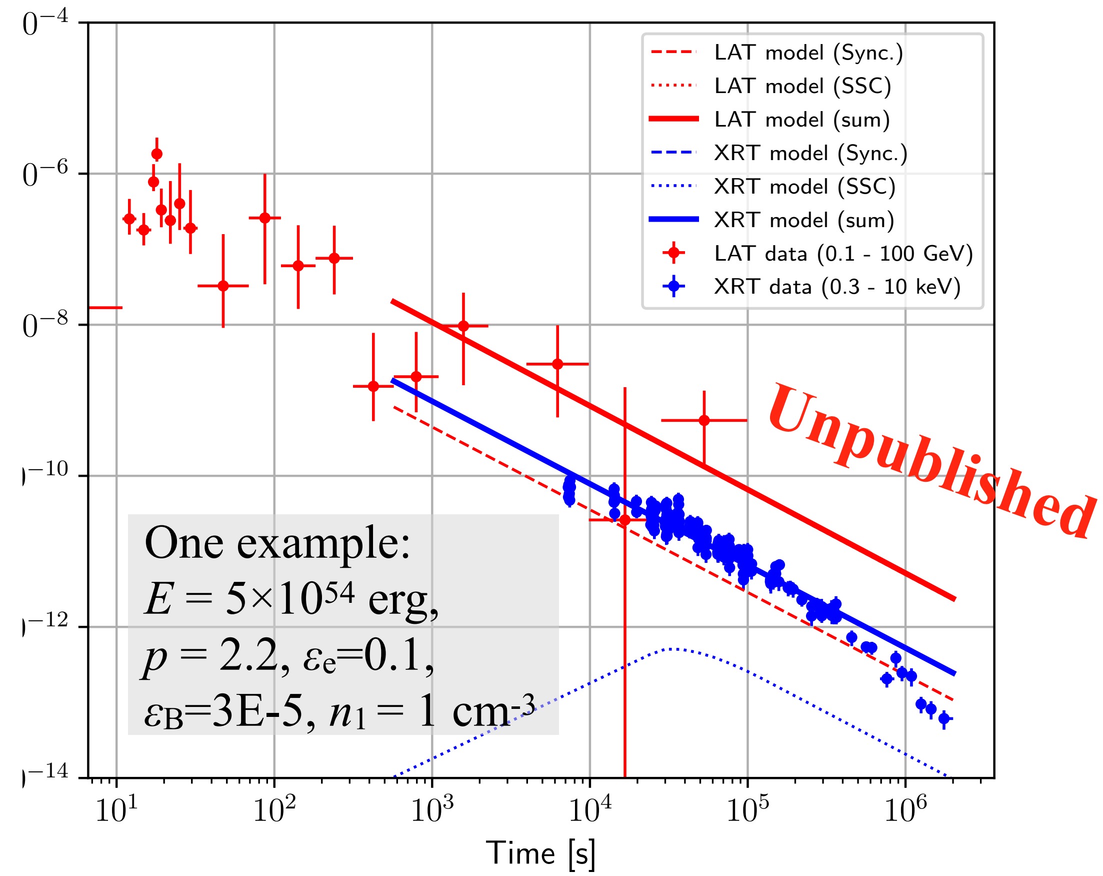
Synchrotron scenarios are rejected by 2σ
(LAT:S2 and XRT:S1) is unreasonable

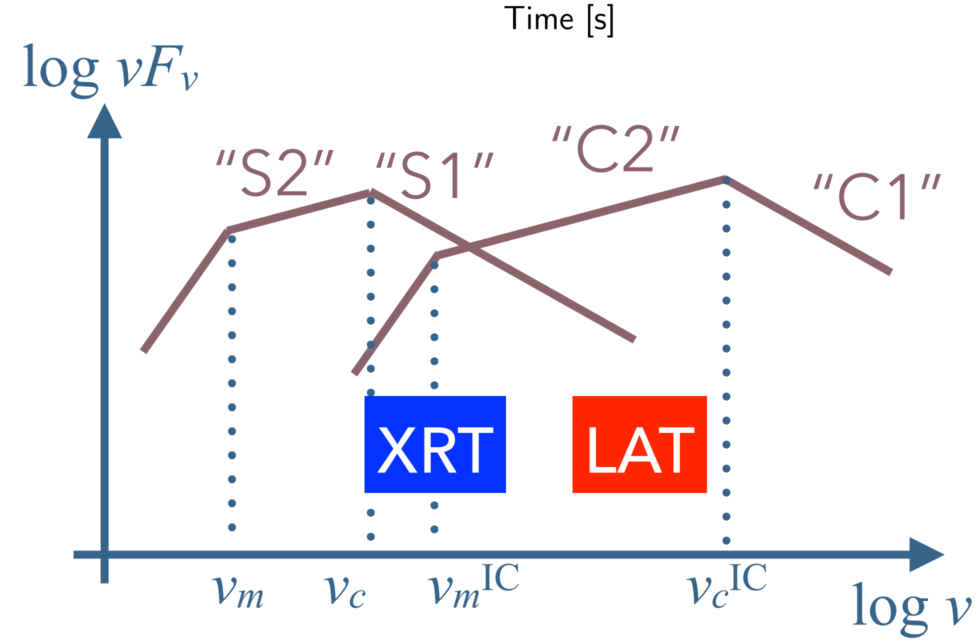


Model: Sari+ 98, Panaitescu+ 00, Sari+ 01

Comparison with Closure Relations







Model: Sari+ 98, Panaitescu+ 00, Sari+ 01

Prospect of CTA

Cherenkov Telescope Array

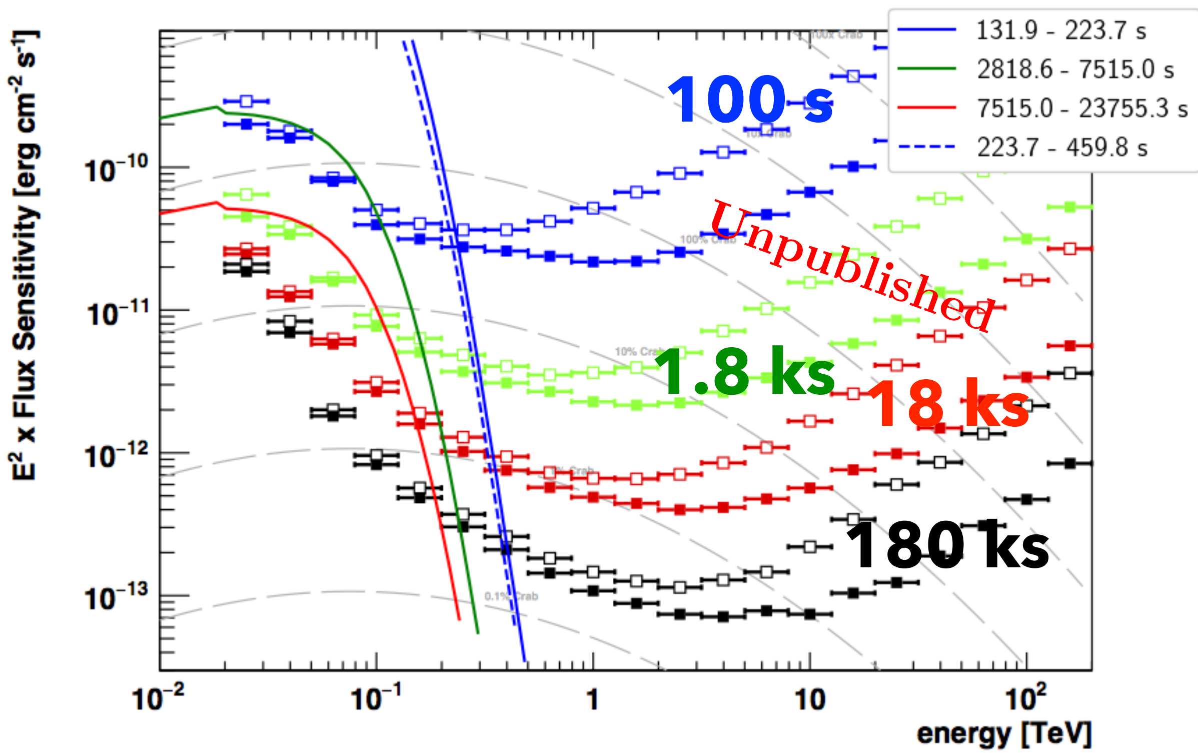
- ✦ Imaging Atmospheric Cherenkov Telescope in next-generation
- ✦ Sites: La Palma, Spain (North) and Paranal, Chille (South)
- ✦ Three telescope sizes
  - Large-Sized Telescope (LST)
    - Mirror: 23 m in diameter
    - Responsible for 20 GeV- 200 GeV
    - Repositioning time: <20 seconds
  - Medium-Sized Telescope (MST)
  - Small-Sized Telescope (SST)

Energy threshold: 20 GeV

Effective area: ~3×10^4 m at 20 GeV
More than four orders of magnitude larger than LAT

Extrapolation to CTA energy range

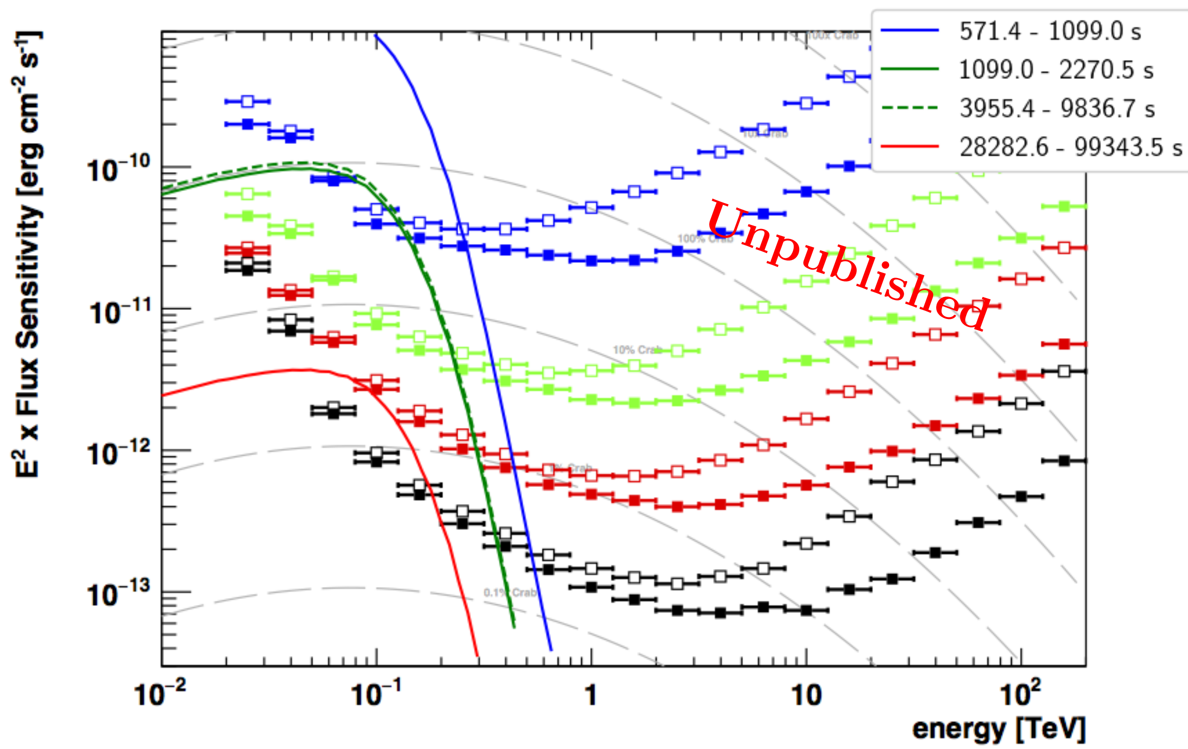
090926A



$\Gamma_\gamma = -1.7$

Fig. 9.10 (P144)

160509A



$\Gamma_\gamma = -1.6$

Fig. 9.11 (P145)

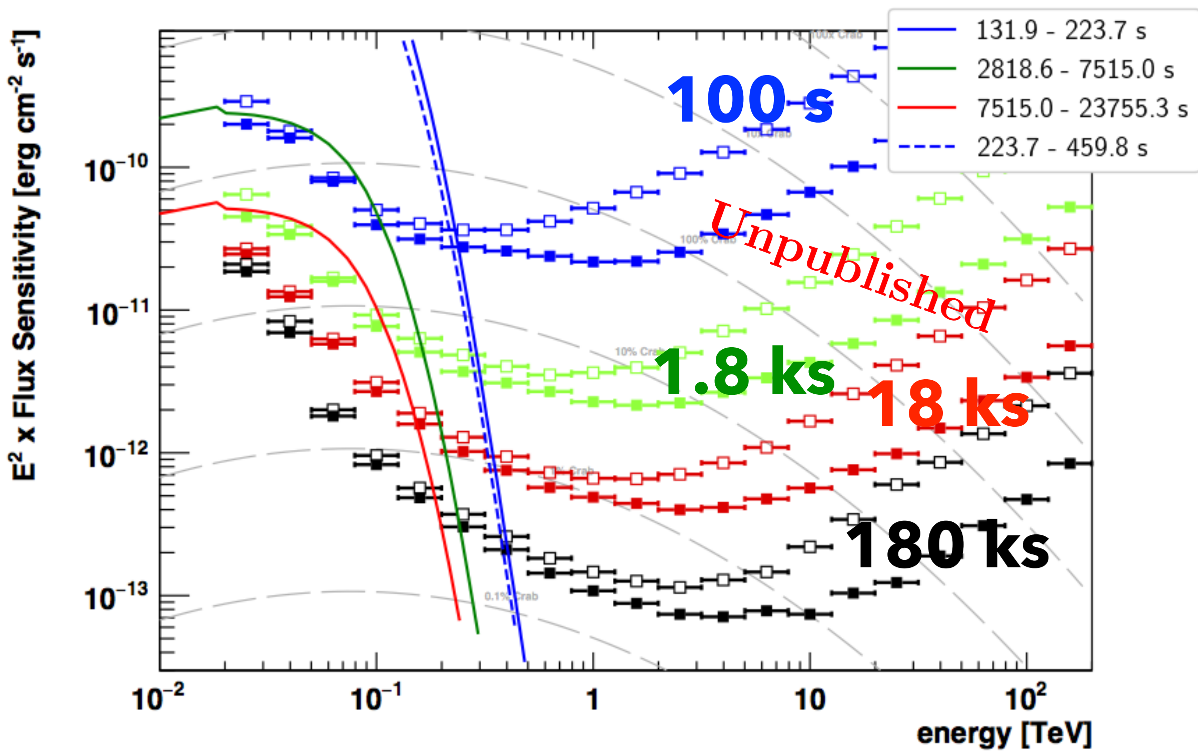
✦ Extrapolate SSC spectrum with most plausible p from 1 GeV to CTA energy range

- EBL model: Franceschini *et al.* 2008

✦ Sensitivity curve: Maier *et al.* 2017

Extrapolation to CTA energy range

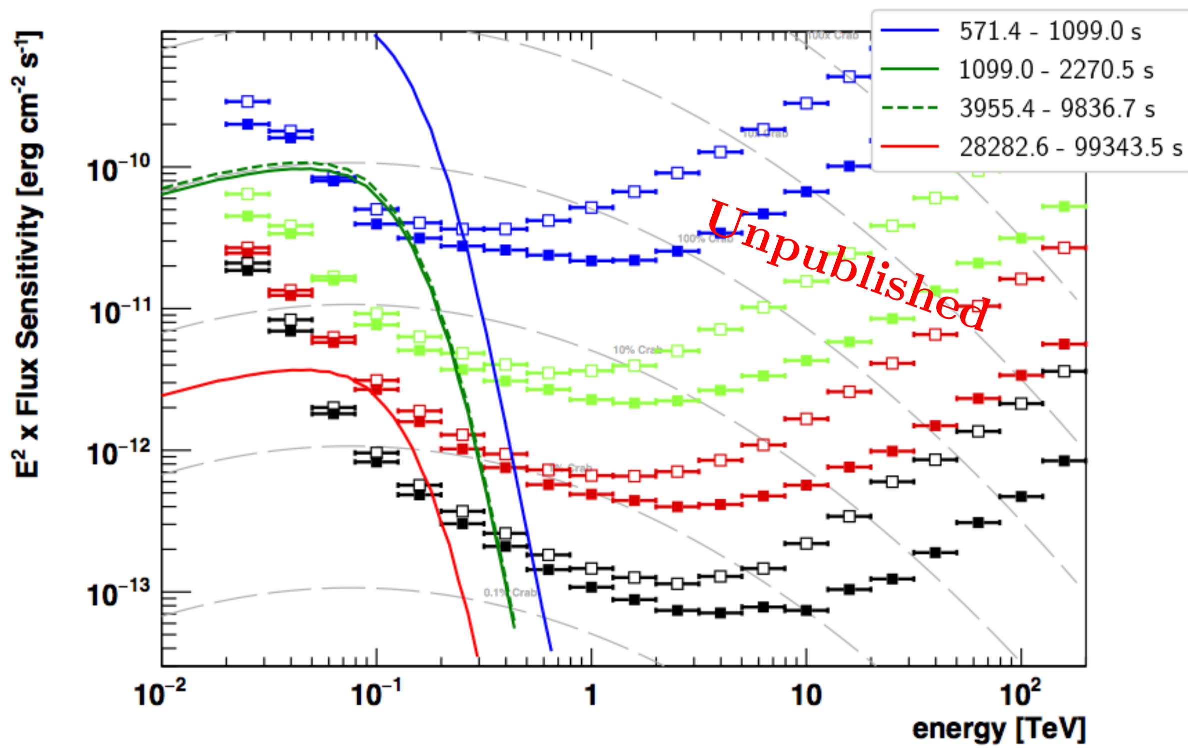
090926A



$\Gamma_\gamma = -1.7$

Fig. 9.10 (P144)

160509A



$\Gamma_\gamma = -1.6$

Fig. 9.11 (P145)

✦ Extrapolate SSC spectrum with most plausible … y range

- EBL model: Franceschini *et al.* 2008

✦ Sensitivity curve: Maier *et al.* 2017

Detailed spectrum and long-term light curve will be obtained

Conclusions

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Conclusions

- ✦ **LAT data without TKR information (CalOnly classes) was proved to be usable for transients**
  - Residual background is one order of magnitude suppressed by optimization
  - ~50% increase in statistics above 50 GeV
- ✦ **Four photon candidates coincident with GRBs were detected**
  - Including event with 252 GeV in GRB-frame, which is highest ever detected
- ✦ **GRB 090926A and GRB 160509A**
  - Too high energy for synchrotron from simple external shock
  - First detailed quantification of consistency between observed LAT (α,β) vs. closure relations
  - SSC dominating LAT band is only one consistent and natural solution
  - Most clearly described evidences of SSC emission from afterglow ever
- ✦ **Jet energy estimation based on synchrotron-alone model turned out to be doubtful**
- ✦ **CTA will provide long-term light curve with little uncertainty and enable us to test SSC decisively**