On the direct correlation between γ-rays and neutrinos from blazars

Shan Gao

Collaborators: Martin Pohl, Walter Winter

arXiv: 1610. 05306

Dec. 9, 2016
HAP workshop,
Cochem, Germany

Outline

- Motivation

  Why blazars / MWL & Multi-Msg. / $L_\nu \sim L_\gamma$?

- Methods and modeling

  What's special on PKS B1424-418 / our analysis ?

- Results and implications

  What's new to consider in a future analysis ?

Blazars

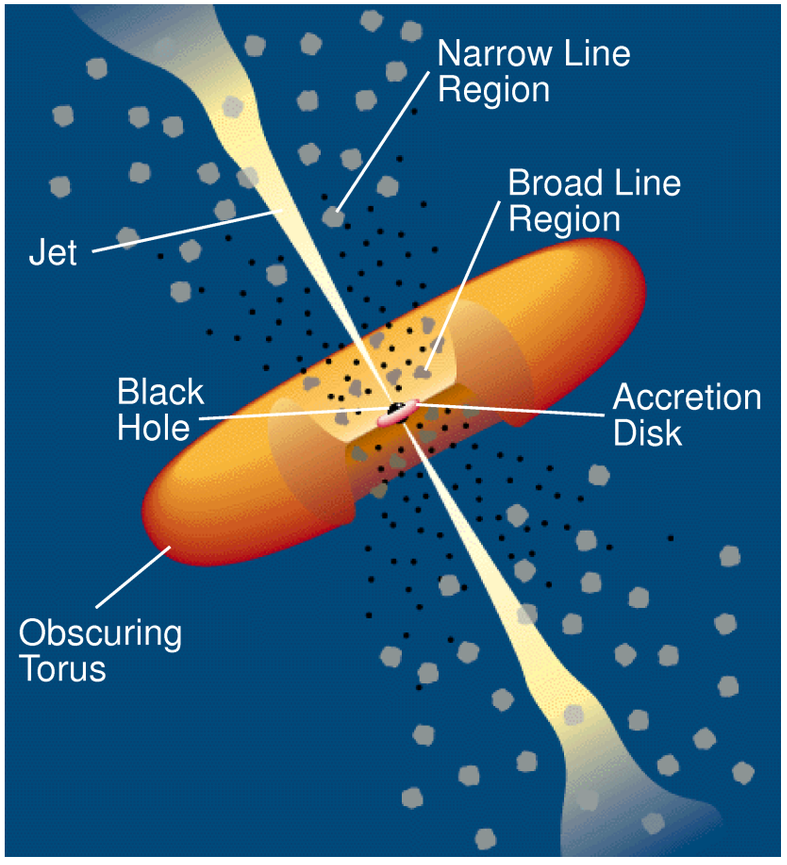
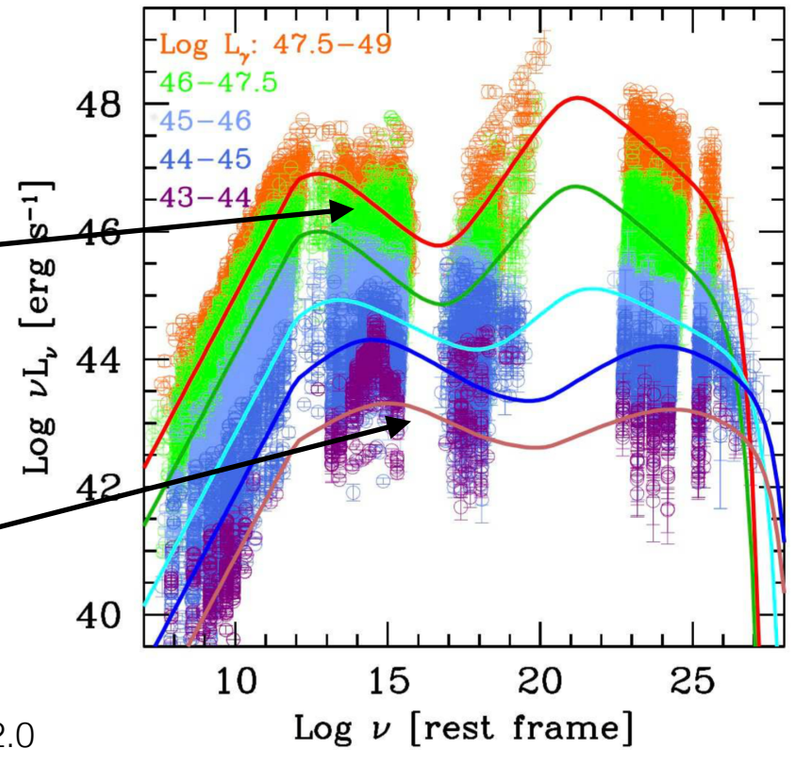


Figure: blazar, Urry & Padovani 95

- Relativistic jets & Doppler boosting;
- Power from SMBH
- Spectrum: non-thermal double hump
- Variable on all time scales
- Population: 745 (3LAC catalog)
- Distribution: isotropic
- Luminosity range ~$10^{44\text{-}49}$ erg/s.
- Jet Component: unknown - leptonic, hadronic, magnetic, …

FSRQ, LBL
e.g. PKS B1424-418

HBL
e.g. Mrk 421



Ghisellini, 2016
blazar sequence 2.0

neutrino production

Dissipation in the jet

↓

Proton acceleration (Diffusive shock acc., stochastic acc., mag. reconn. …)

see talks by Asano, Nalewajko

↓

Interacting with a target photon or another proton

↓

γ-rays and neutrinos

$$p+\gamma(p) \rightarrow \pi + p(n)$$

$$\pi^0 \rightarrow \gamma + \gamma$$

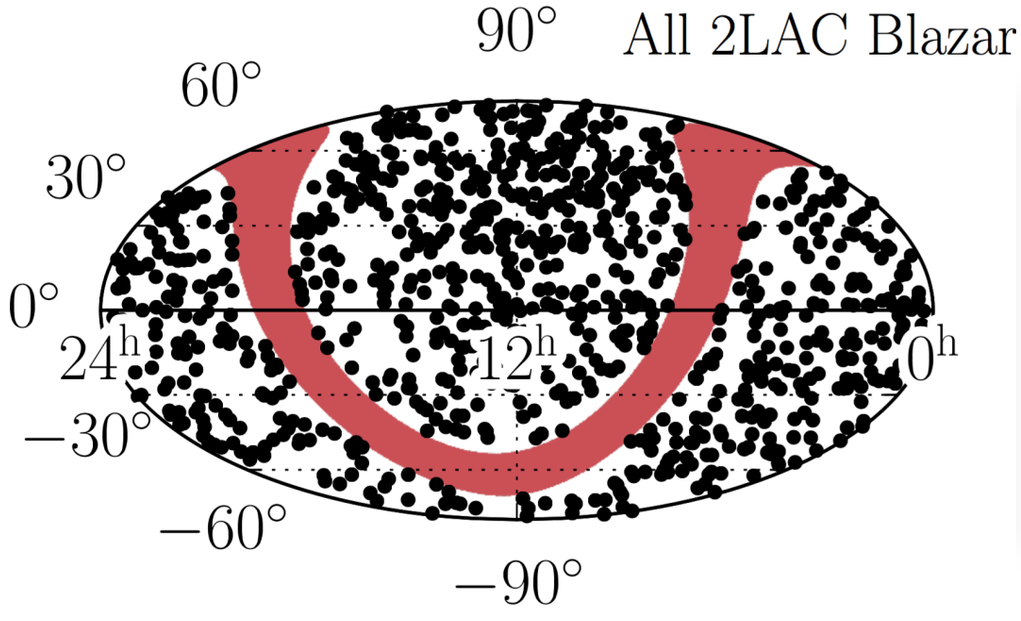
$$\pi^+(\pi^-) \rightarrow \nu_\mu(\bar{\nu}_\mu) + \mu^+(\mu^-) \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e\,(\bar{\nu}_e) + e^+(e^-)$$

They have comparable energy budgets

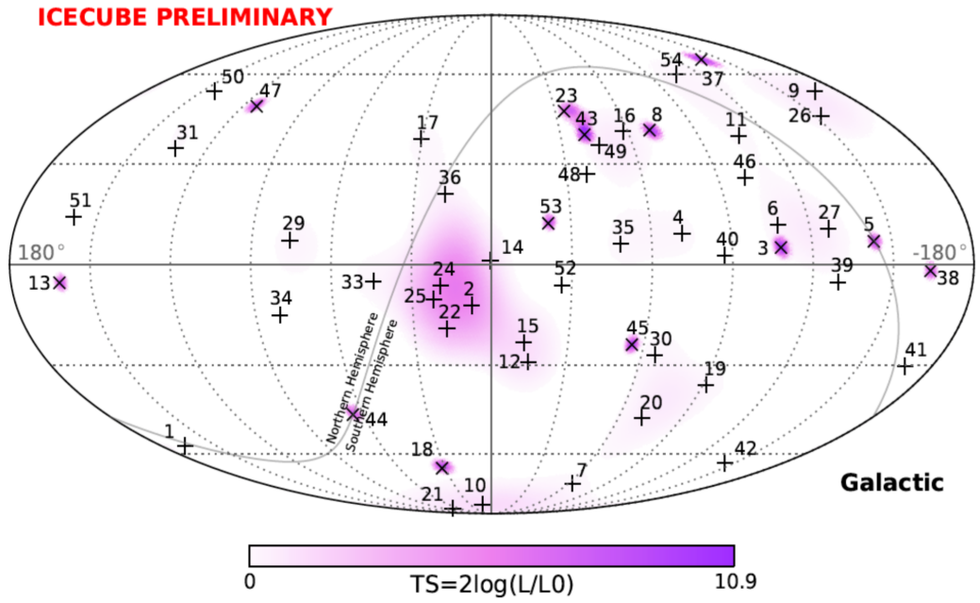
Blazars significantly contribute to EGRB* → promising candidate as IceCube neutrino source

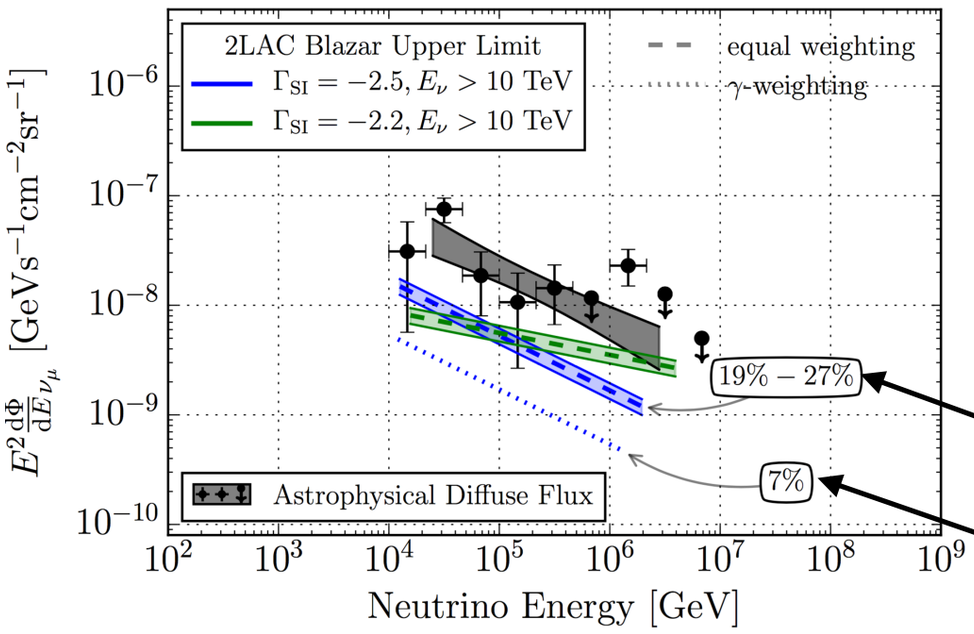
*Ajello et al. Astrophys.JL 2015

IceCube analysis 2LAC blazars



IceCube collaboration, arXiv: 1611.03874





All 2LAC blazars (862 objects, FSRQ,LBL,IBL,HBL)

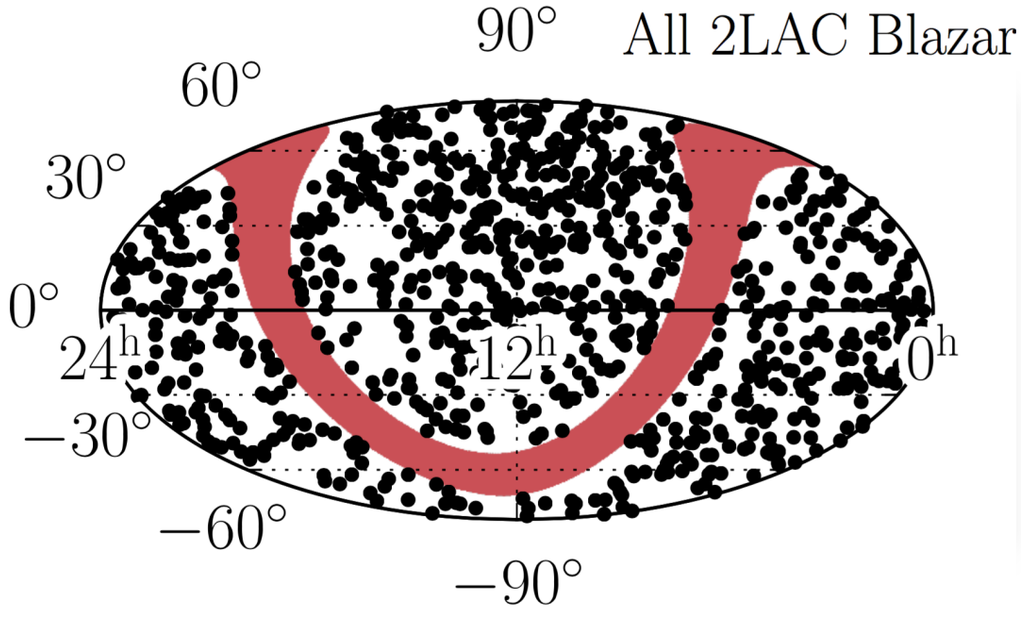
equal weighting

γ-weighting

γ-weighting: L_ν=L_γ for each source

equal weighting: dN/dS follows the same as γ-rays; No correlation for individual source

IceCube analysis 2LAC blazars



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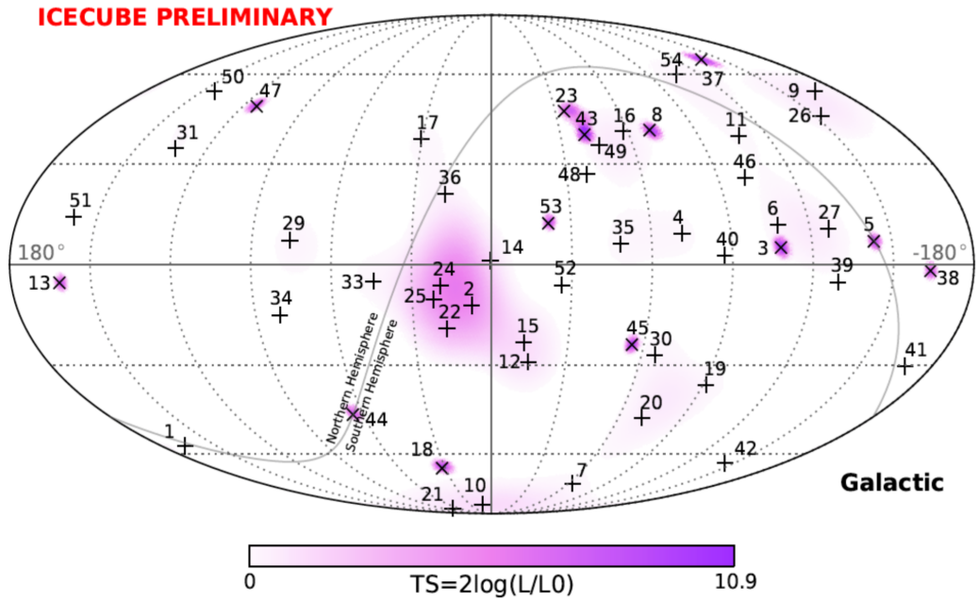

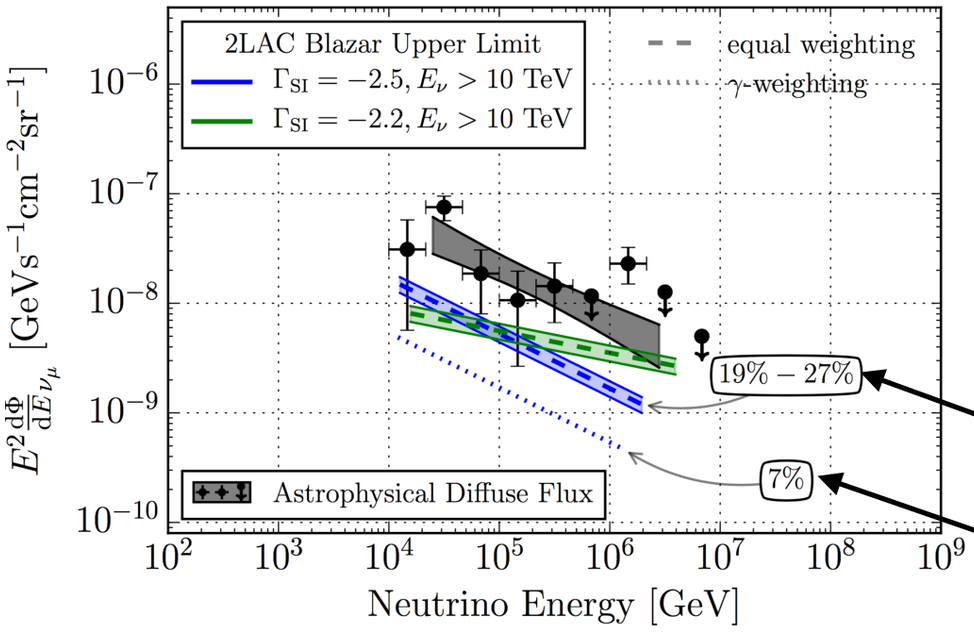

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$L_\nu \sim L_\gamma$ relation is crucial for any kind of analysis

γ-weighting: $L_\nu = L_\gamma$ for each source

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One central issue: tension between
No. of para. & No. of data points

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	Group	Symbol	Definition
Parameters	Global	$R'_{\rm blob}$	Comoving radius of blob, fixed to 7.5×10^{17} cm
		$f_{\rm esc}$	$e^{\pm}$ and p escape fraction, fixed to $1/10$
		$\Gamma_{\rm bulk}$	bulk Lorentz factor of the blob fixed to 35
	Leptonic	B'	Magnetic field strength, blob frame
		$L_{\rm e,inj}$	Injection luminosity of primary e^-, AGN frame
		$\gamma'_{\rm e,min}$	Minimum Lorentz factor of primary e^-, blob frame
		$\gamma'_{\rm e,max}$	Maximum Lorentz factor of primary e^-, blob frame
		$\alpha'_{\rm e,idx}$	Power law index of injected primary e^-
	Hadronic	$\alpha'_{\rm p,idx}$	Power law index of injected protons, fixed to -2.0
		$\eta_{\rm b}$	Luminosity ratio p to e^- at injection, *i.e.*, $\eta_{\rm b} \equiv L_{\rm p,inj}/L_{\rm e,inj}$
		$E^{ob}_{p,max}$	Maximal energy of injected protons, observer frame

big blazar parameter table for the simplist hadronic model :
one-zone + single power-law injections

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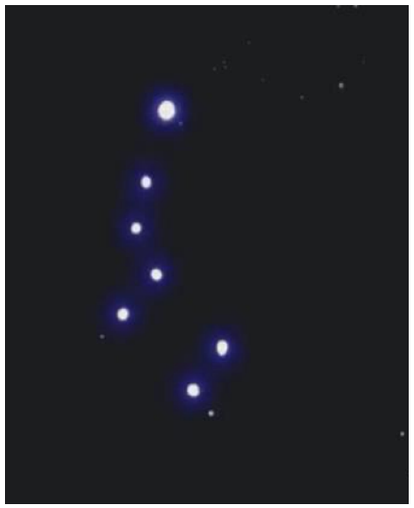
data (e.g. γ-ray)



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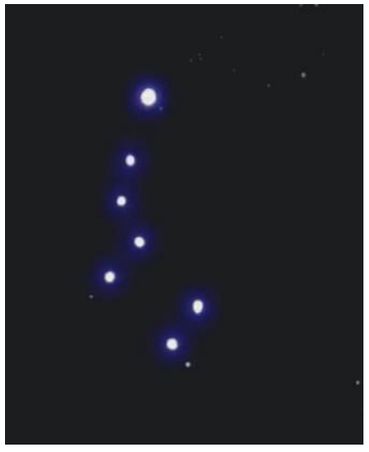

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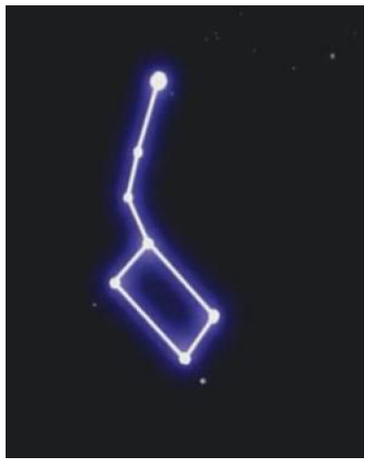

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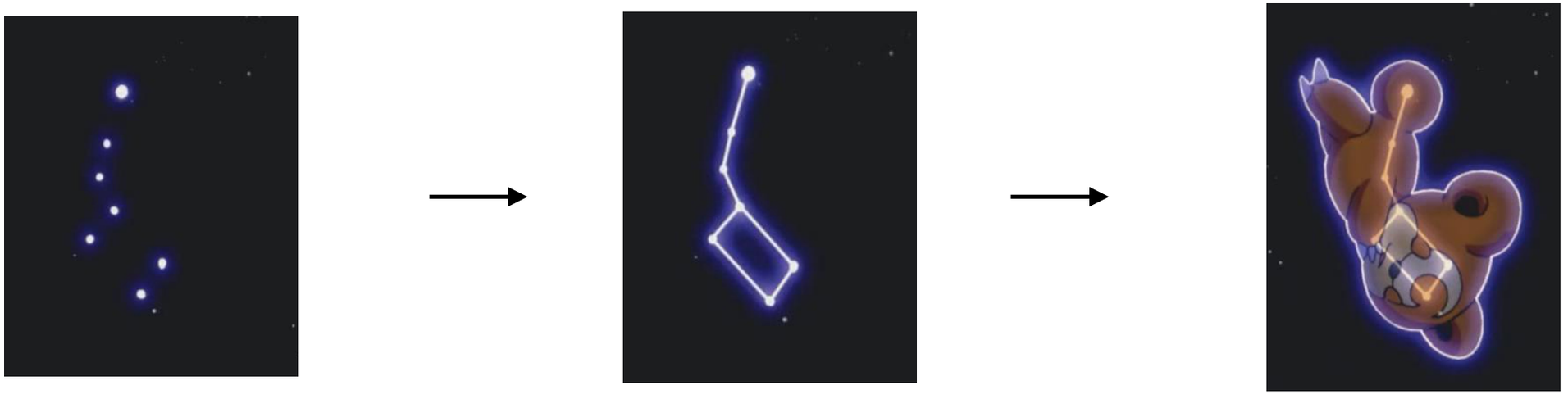
data (e.g. γ-ray) fitting serious over-fitting



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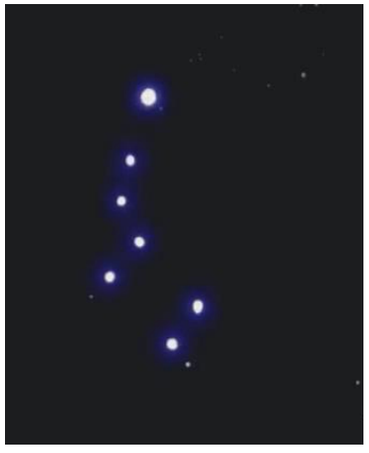

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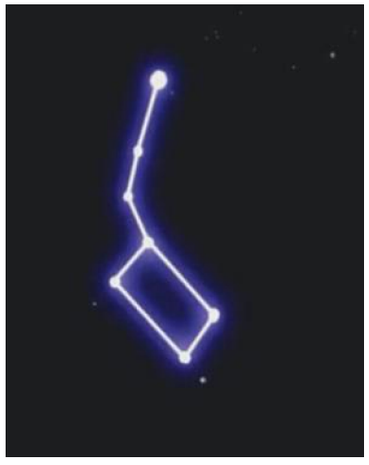

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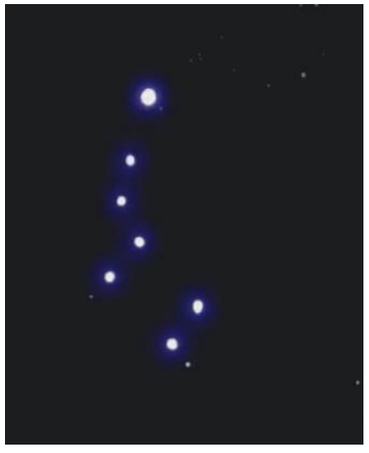

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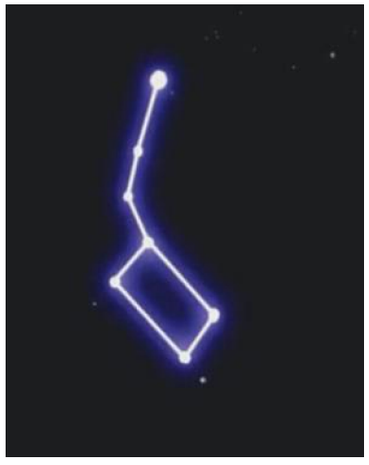

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Answer: MWL + MM

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besides, there are other novel observables:

- time series — PSD , PDF … See 8 talks presented in “variability” section
- polarization See talk by Böttcher
- …

model & methods

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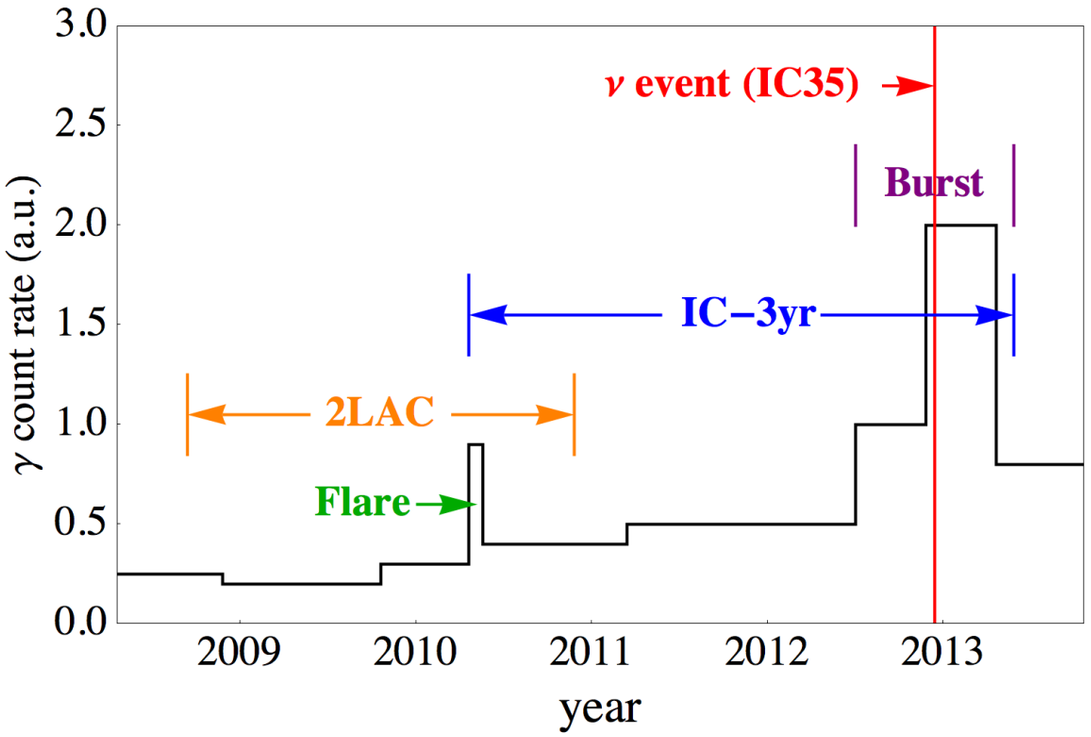
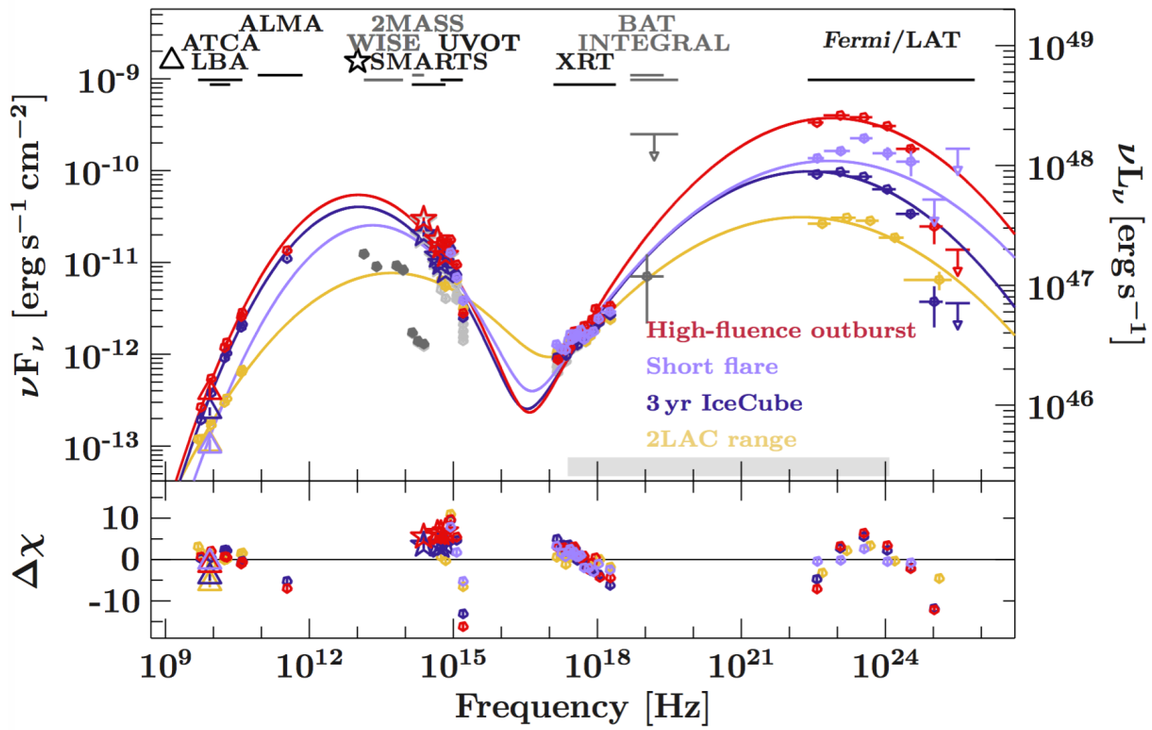
   t-dependent, full particle interactions (syn + IC + pg + BH …), coupled diff-int Fokk-Plk eqn., and efficiency

PKS B1424 418

z=1.522 FSRQ



SG,Pohl,Winter arxiv:1610.05306



Kadler et al. NatPhys 2016

—Positional and temporal correlation with “big-bird” event (IC35, 2PeV)

—Sufficient energy in γ-rays → if all converted to ν → multiple events

—Low background coincidence probability

for PKS B1424 418

	1st peak (eV-keV)	middle range	2nd peak (MeV-TeV)	Example
Pure Leptonic	**L** primary e-syn	**L** Synchrotron-Self Compton (**SSC**)	**L** SSC or External-IC	can explain most blazars
LH-SSC	**L** primary e-syn	**H** secondary lep emission	**L** SSC	PKS B1424-418
LHπ	**L** primary e-syn	**H** secondary lep emission	**H** π^0 decay or secondary lep	Mrk 421
LHs	**L** primary e-syn	**H** secondary lep emission	**H** proton syn	3C 279
Pure Hadronic	**H** proton-syn	**H** secondary lep emission	**H** π^0 decay or secondary lep	postulated

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Analytical calculation: E_{peak}, L_{peak}, E_ν must be consistent with observation;
BH, psyn not overshooting SED, etc.

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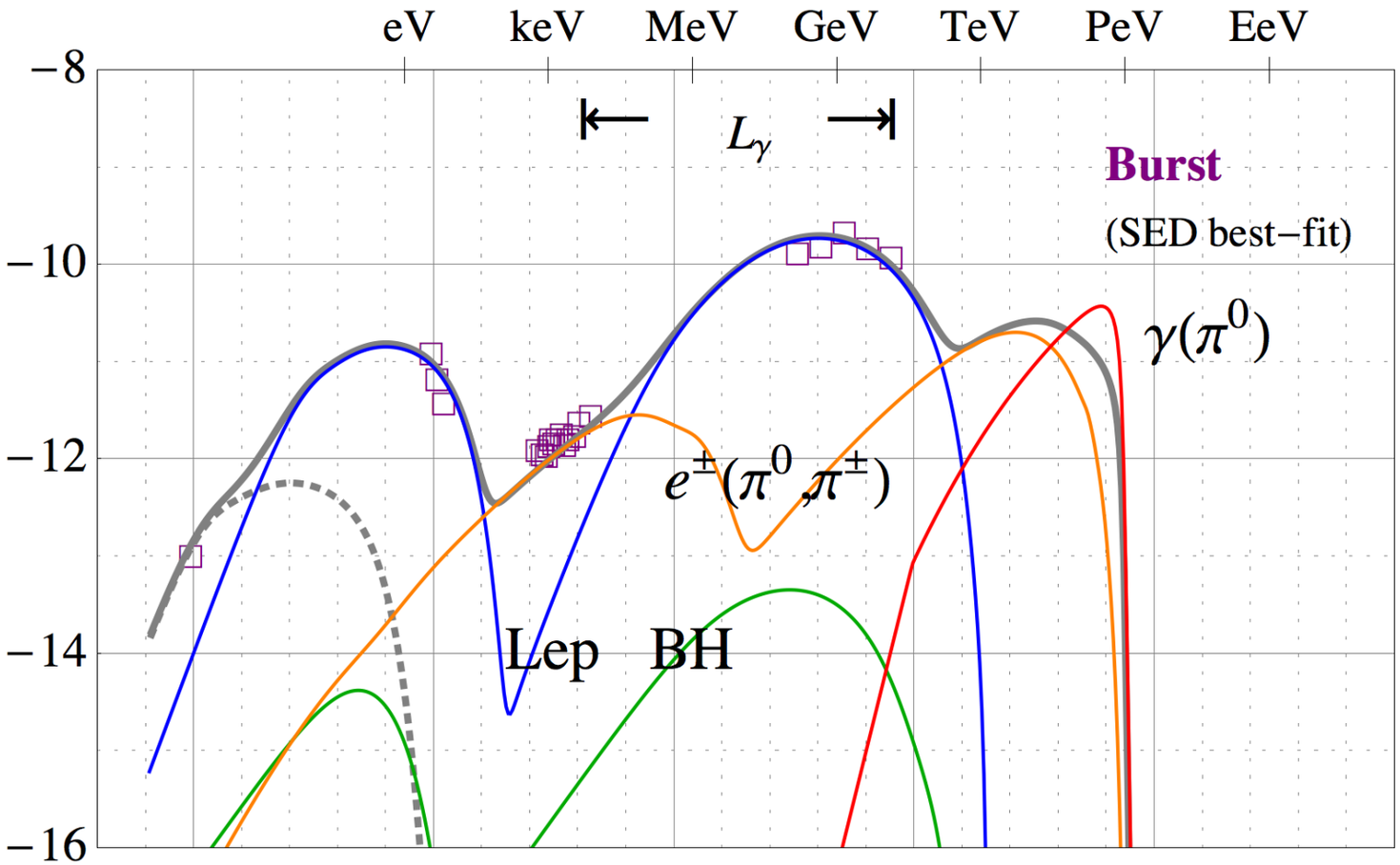
Components of the SED

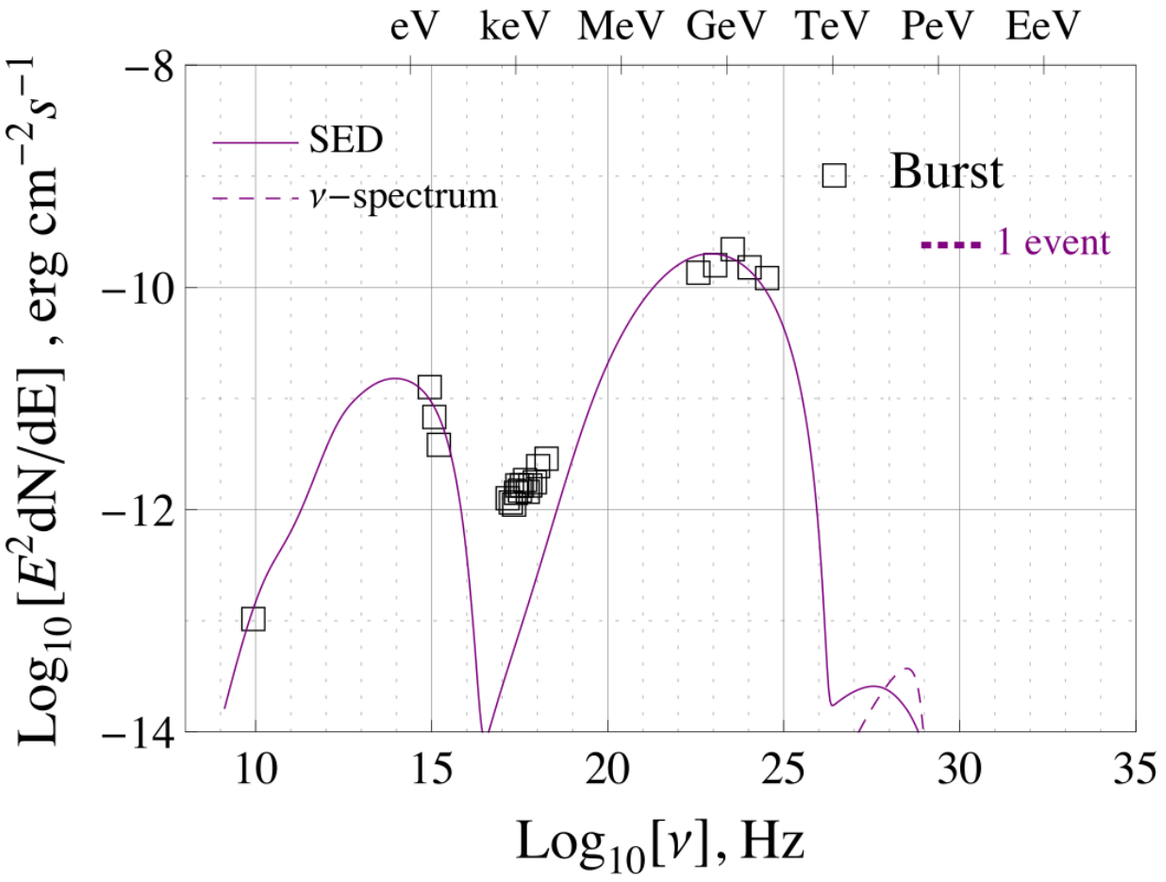


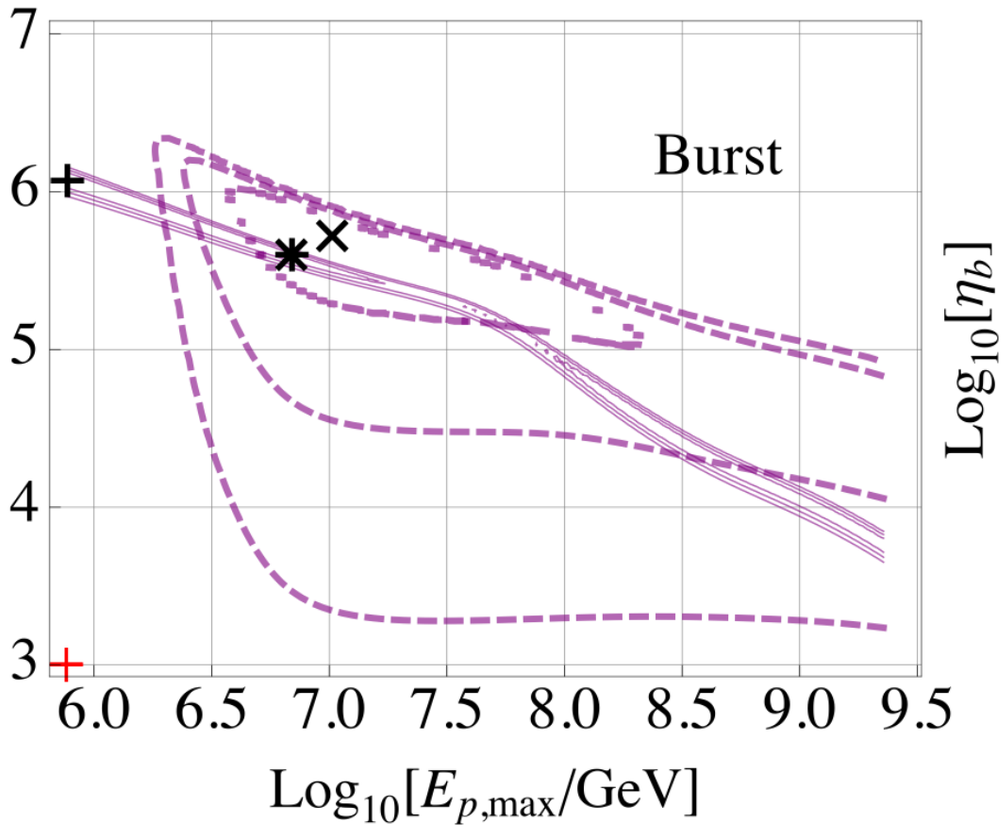
Hadronic X-rays

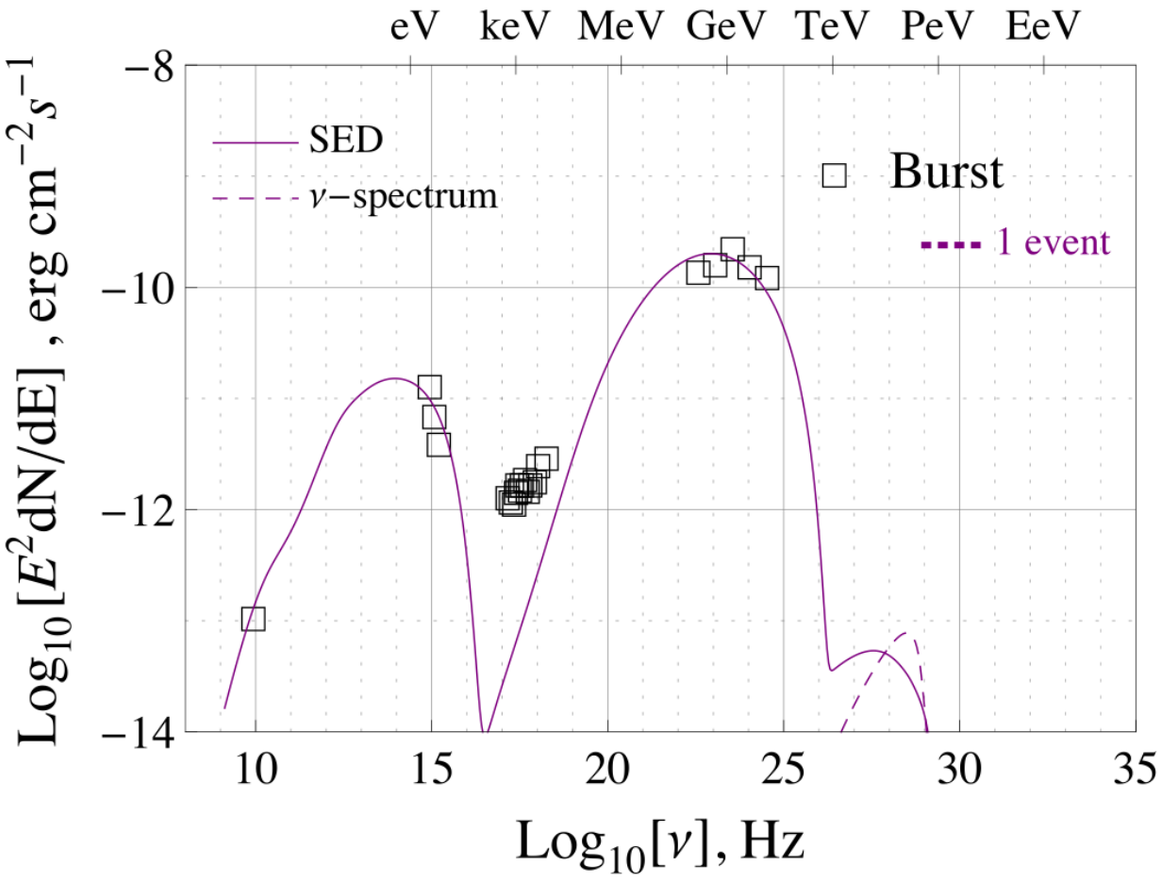
SG,Pohl,Winter arxiv:1610.05306

Suggesting $L_\nu \neq L_\gamma$

parameter space scan



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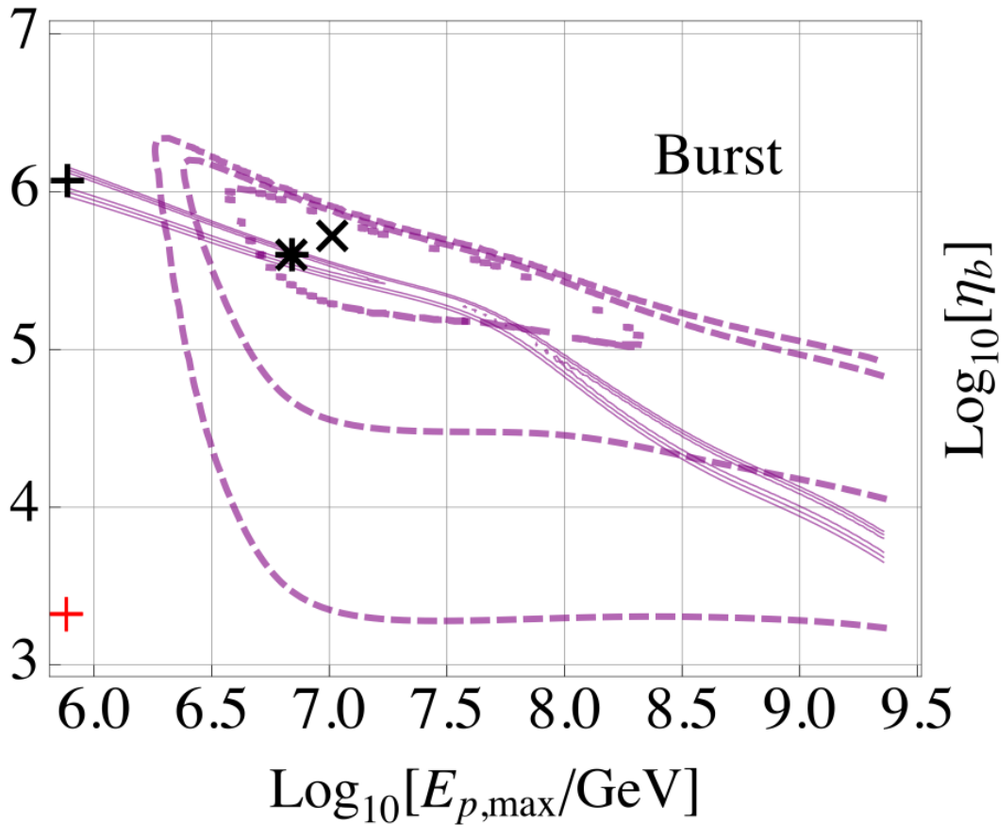
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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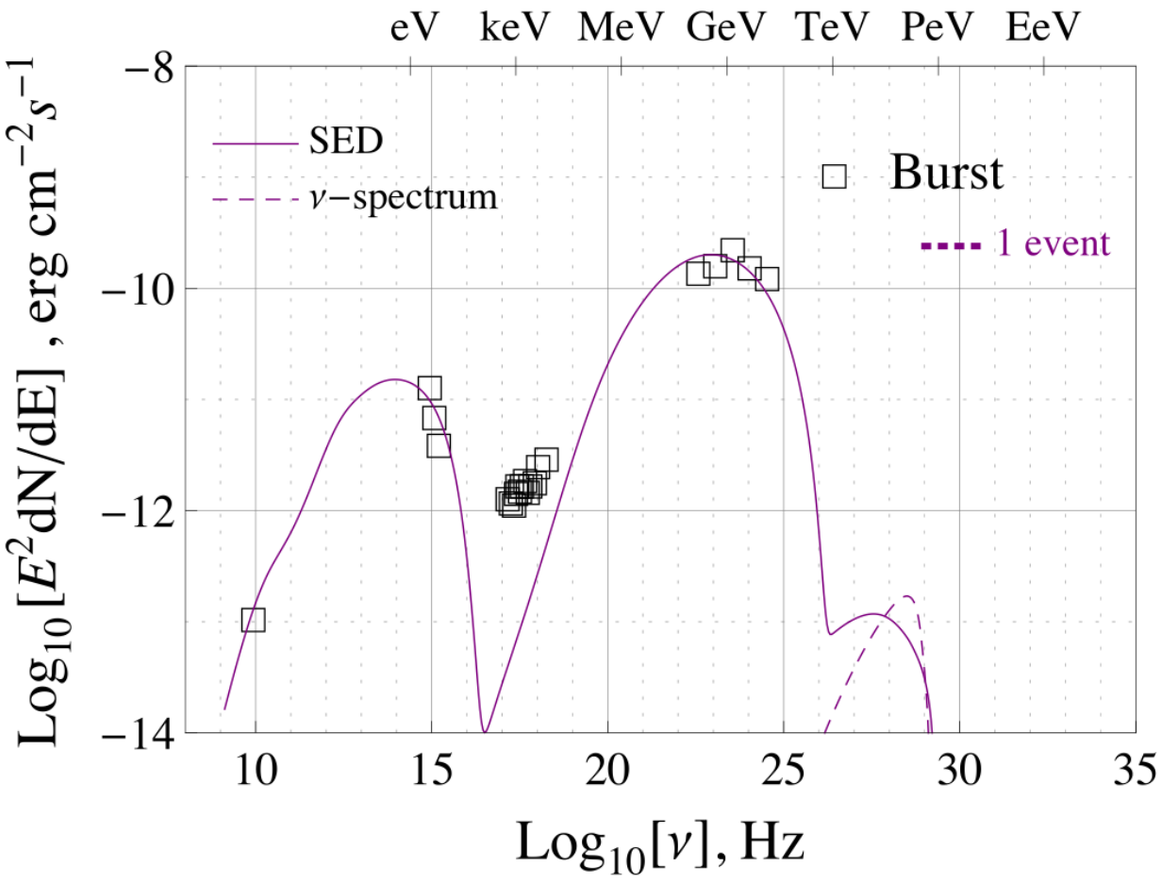
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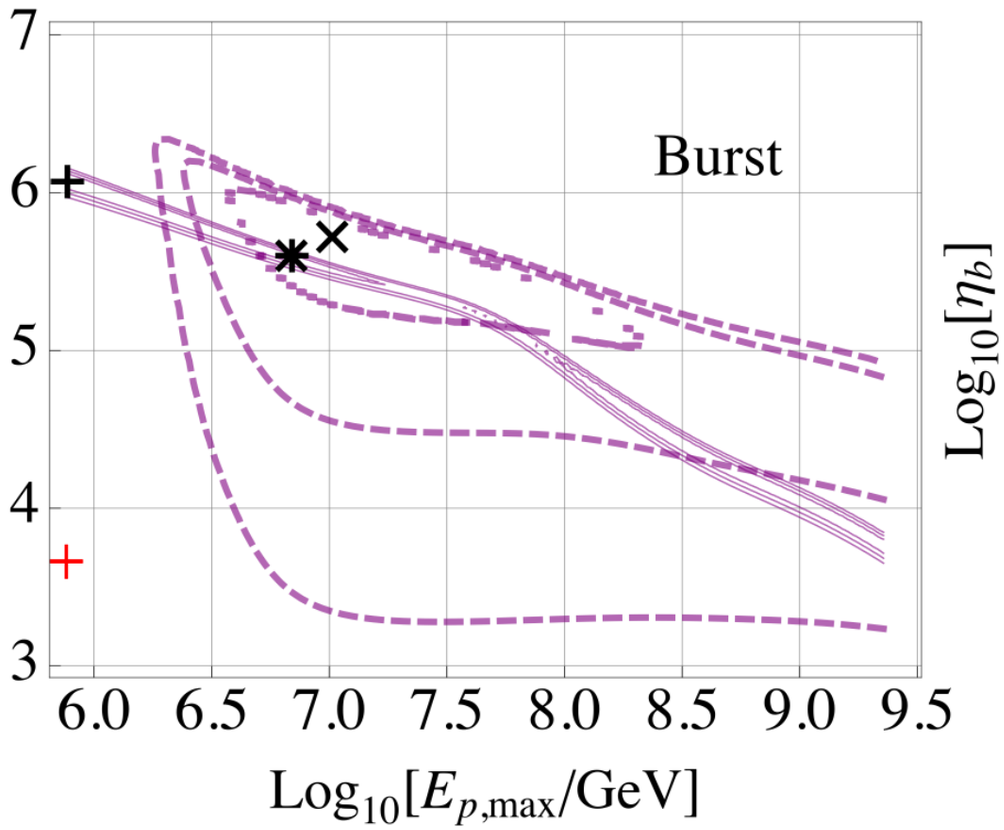
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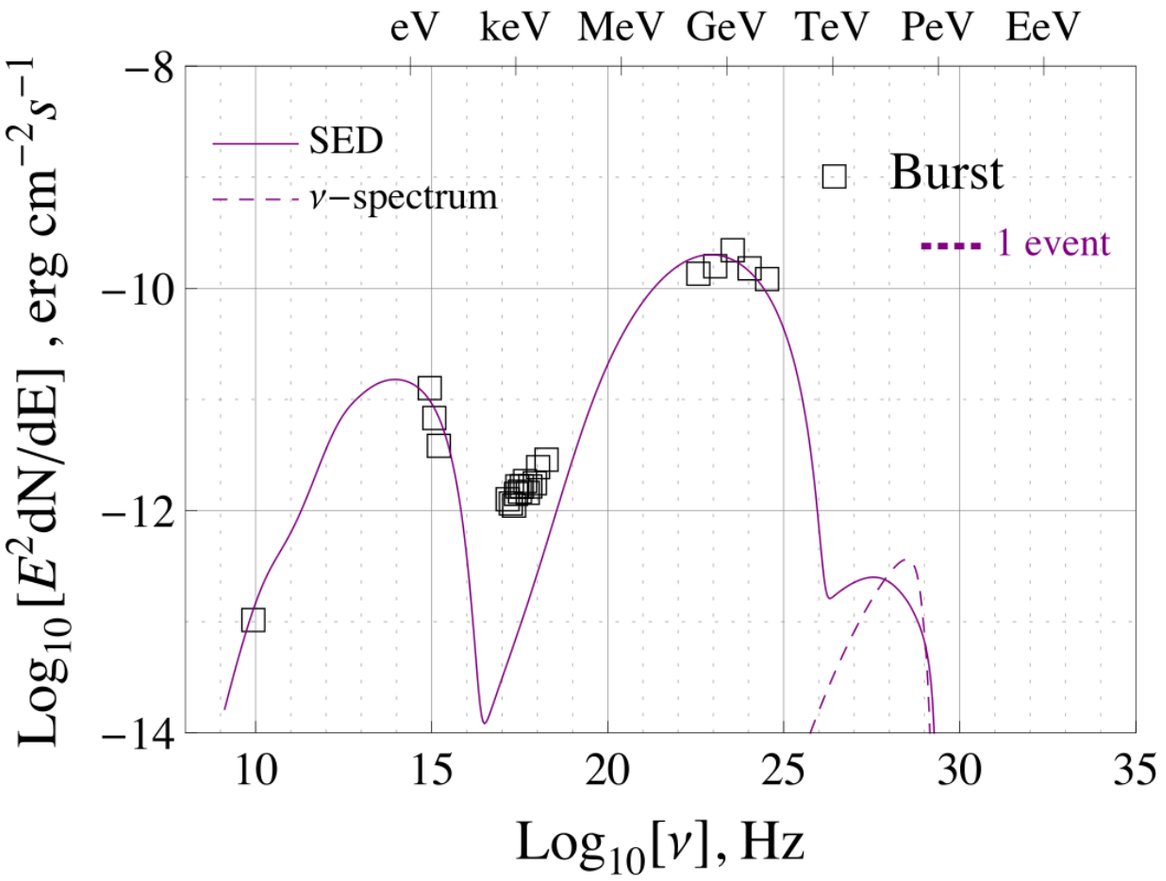
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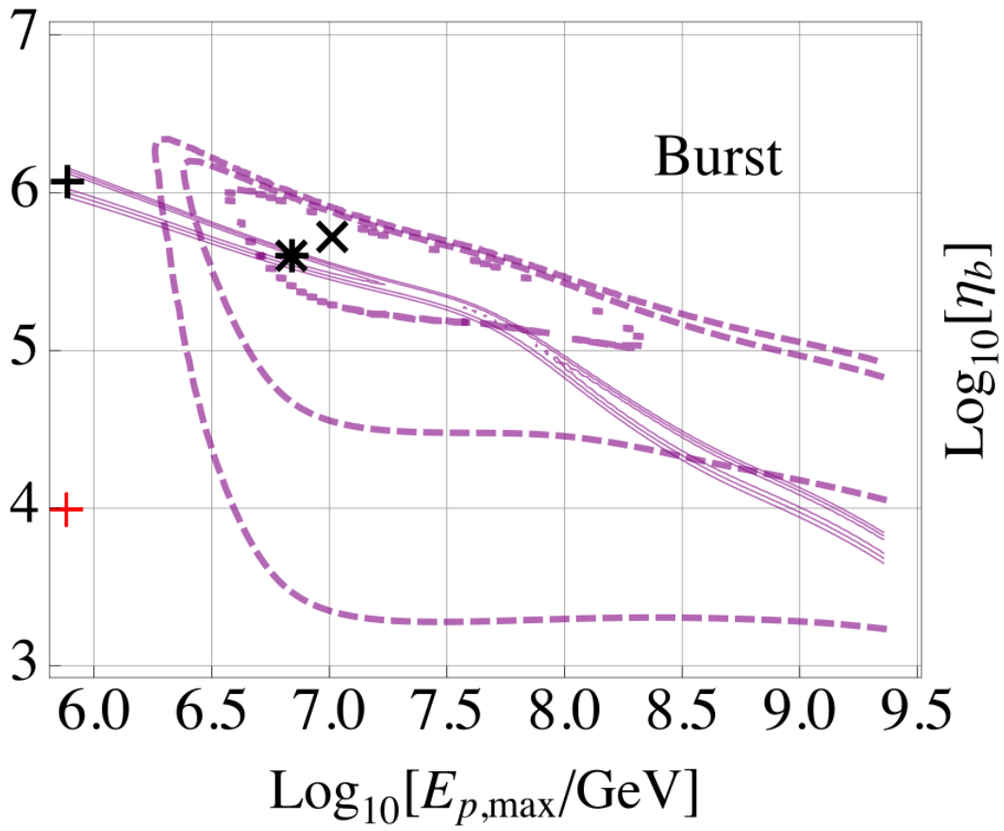
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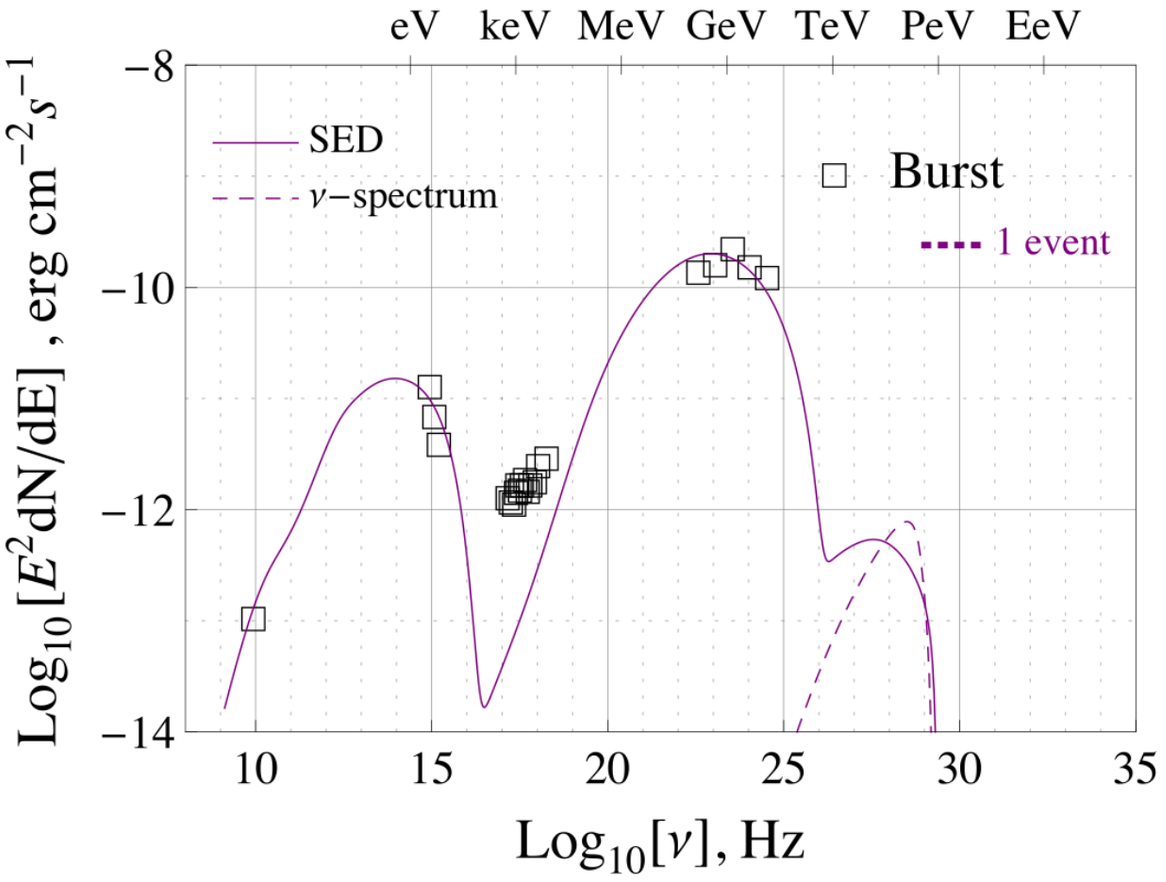
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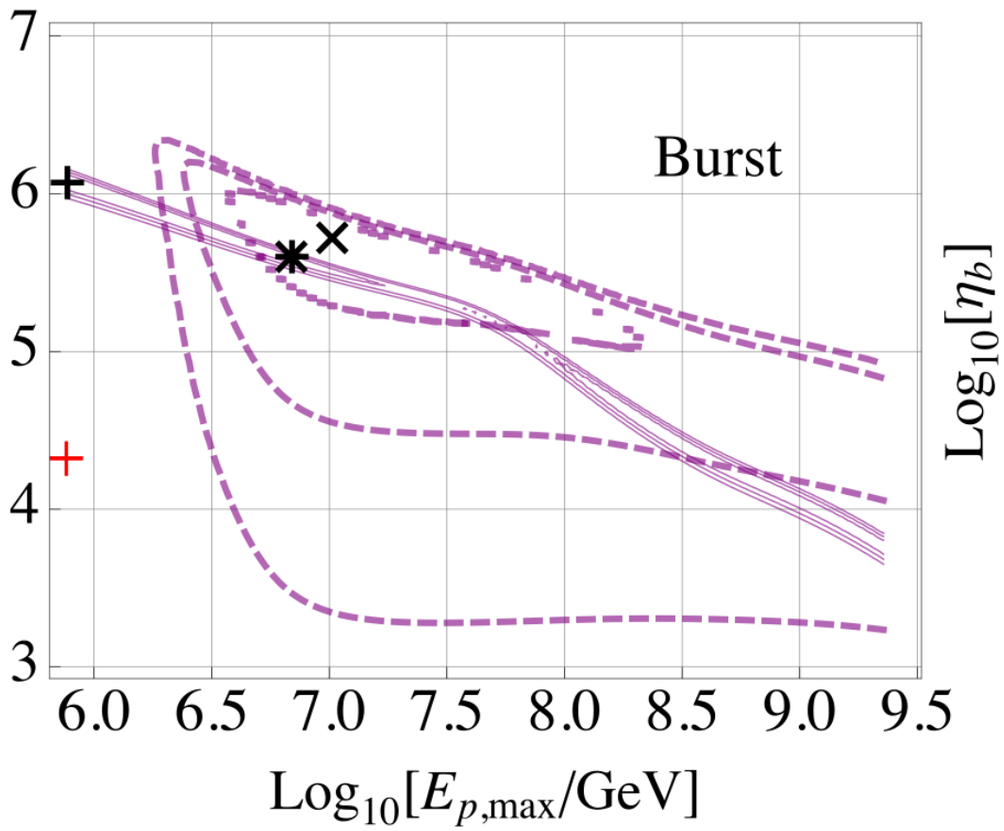
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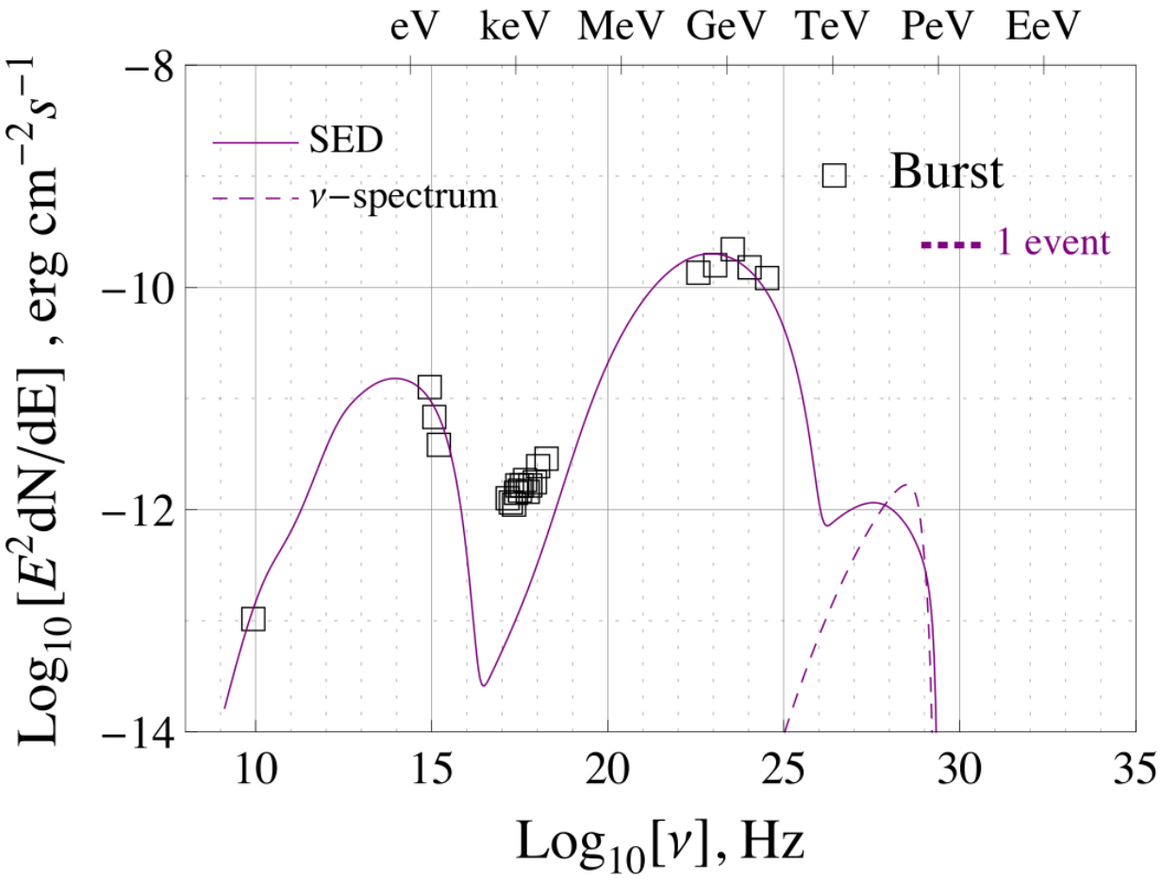
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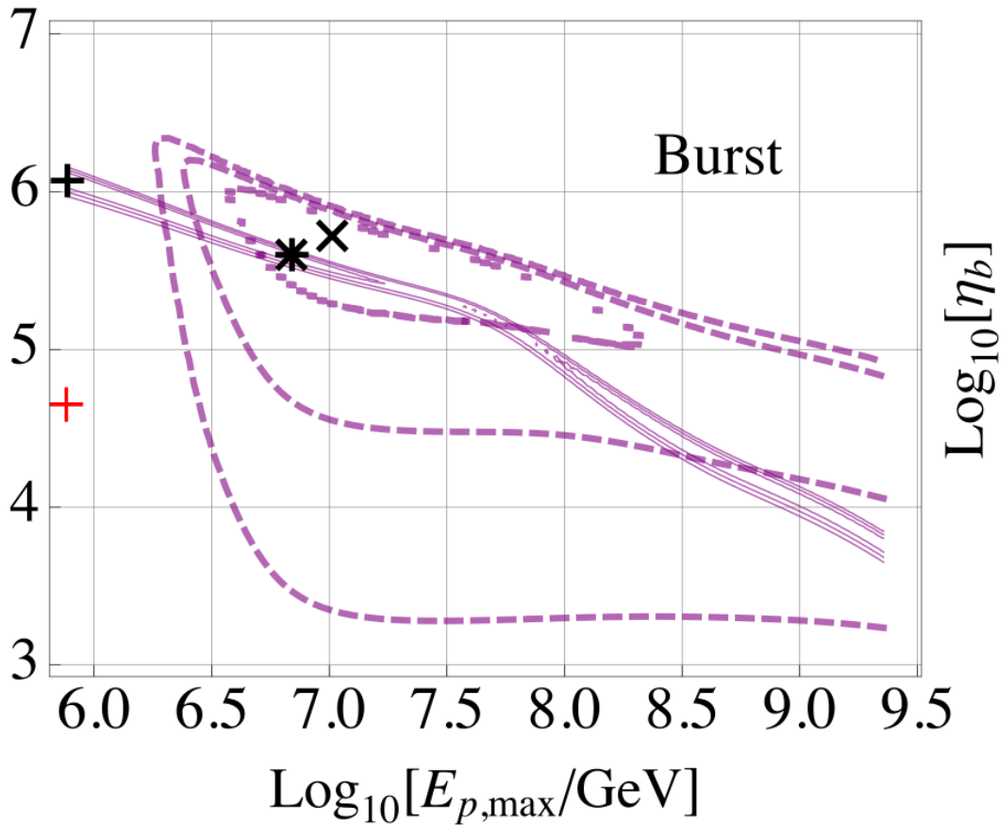
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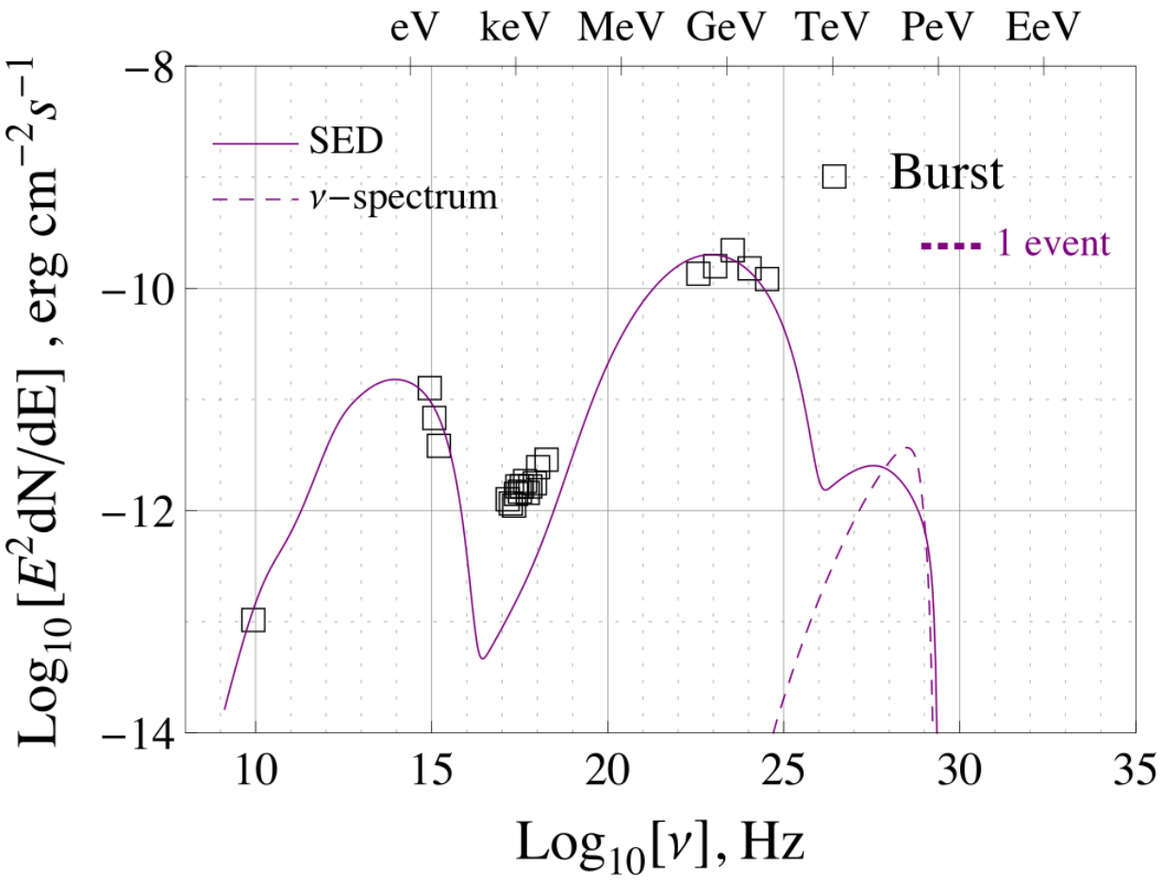
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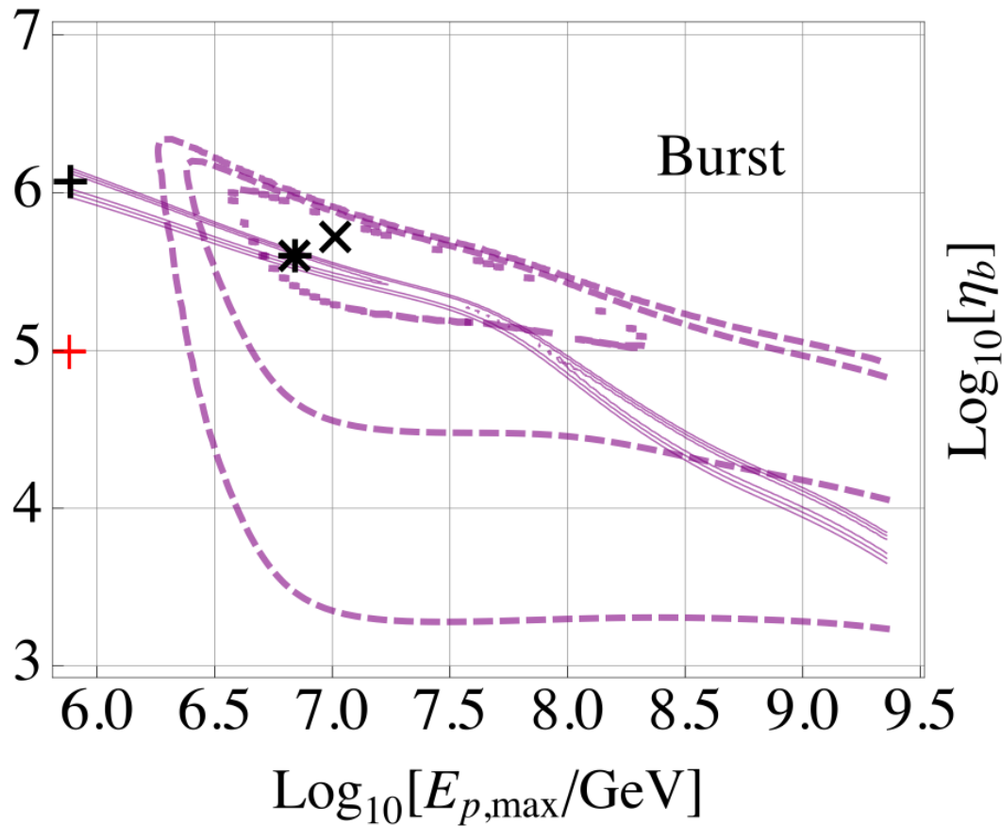
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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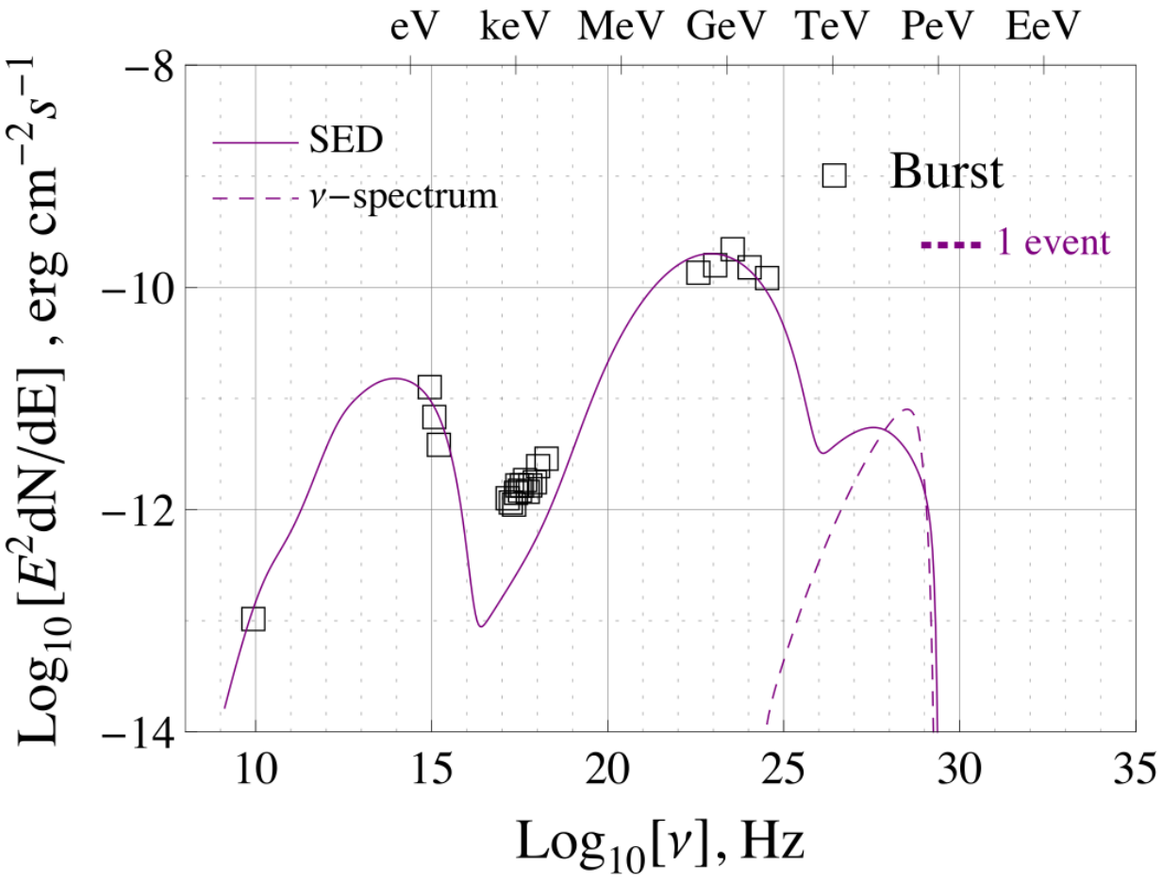
Log10[Ep,max/GeV]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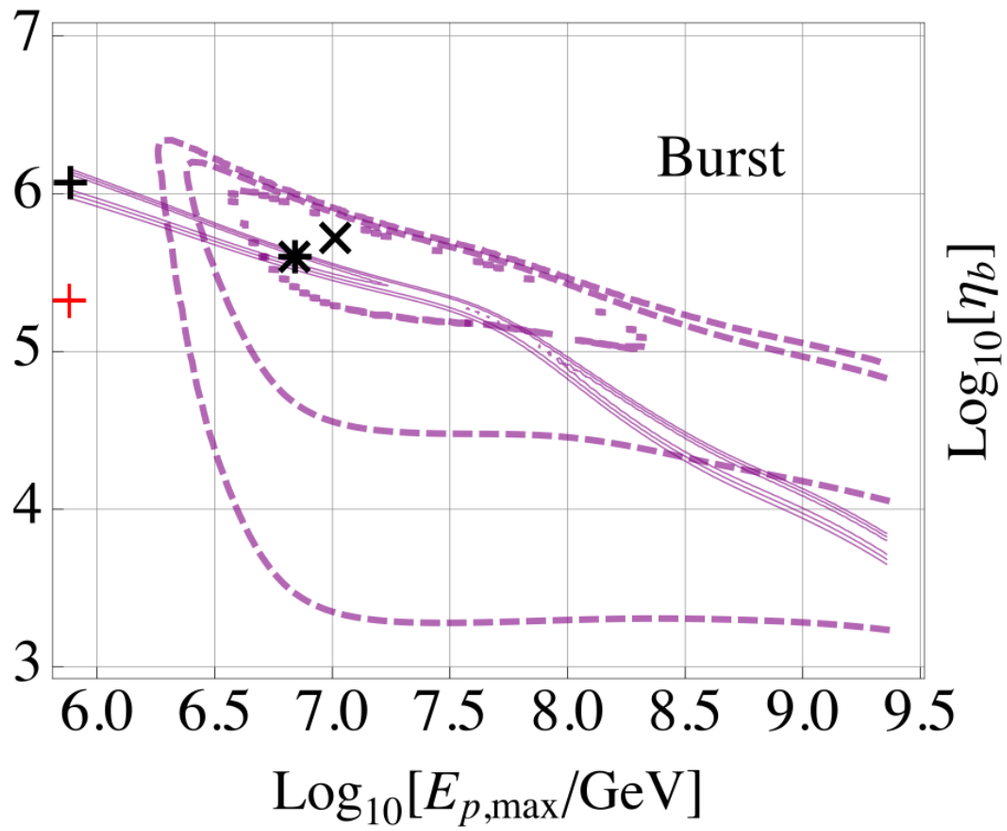
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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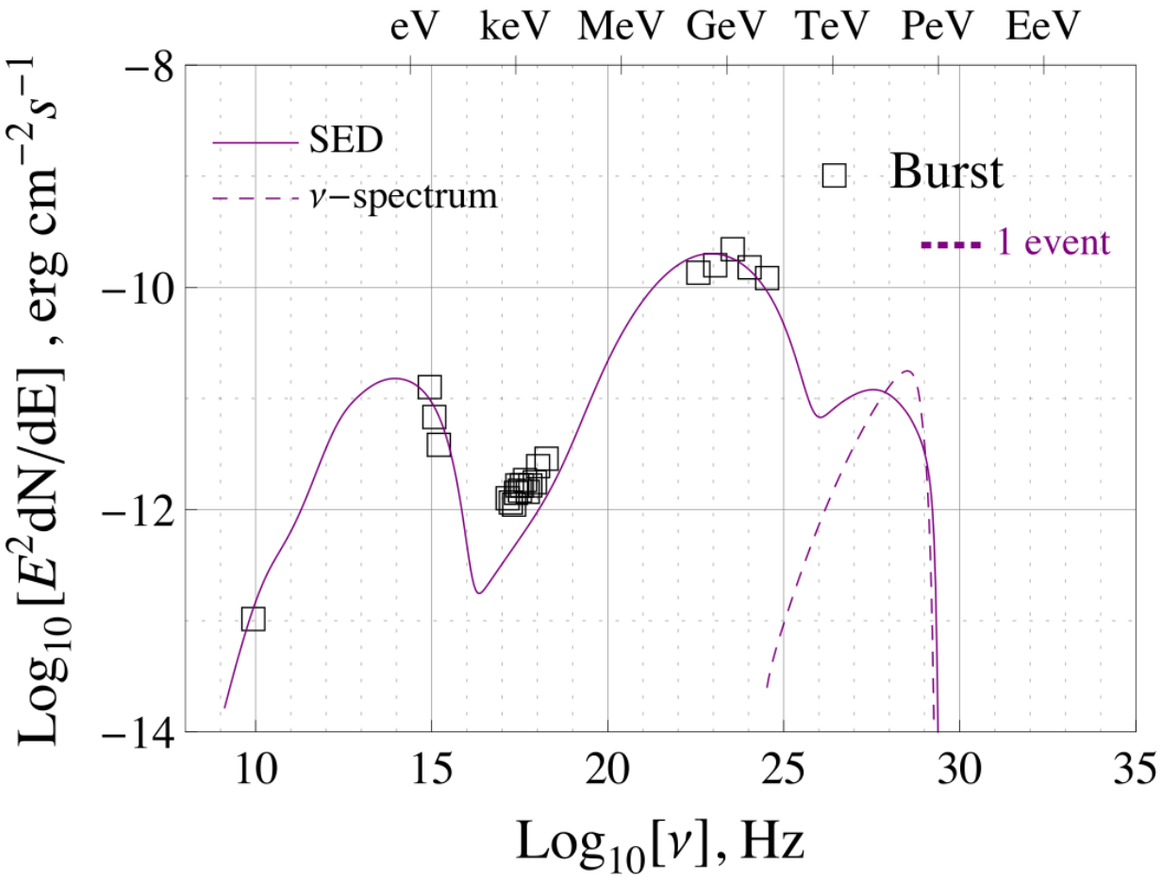
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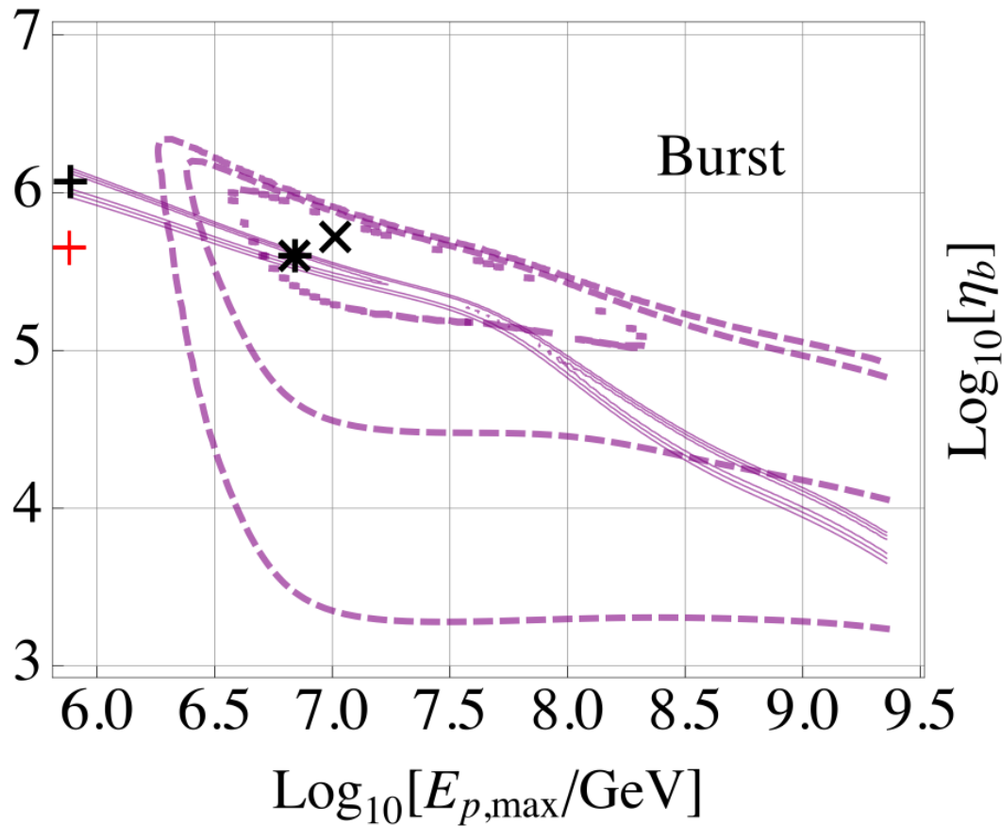
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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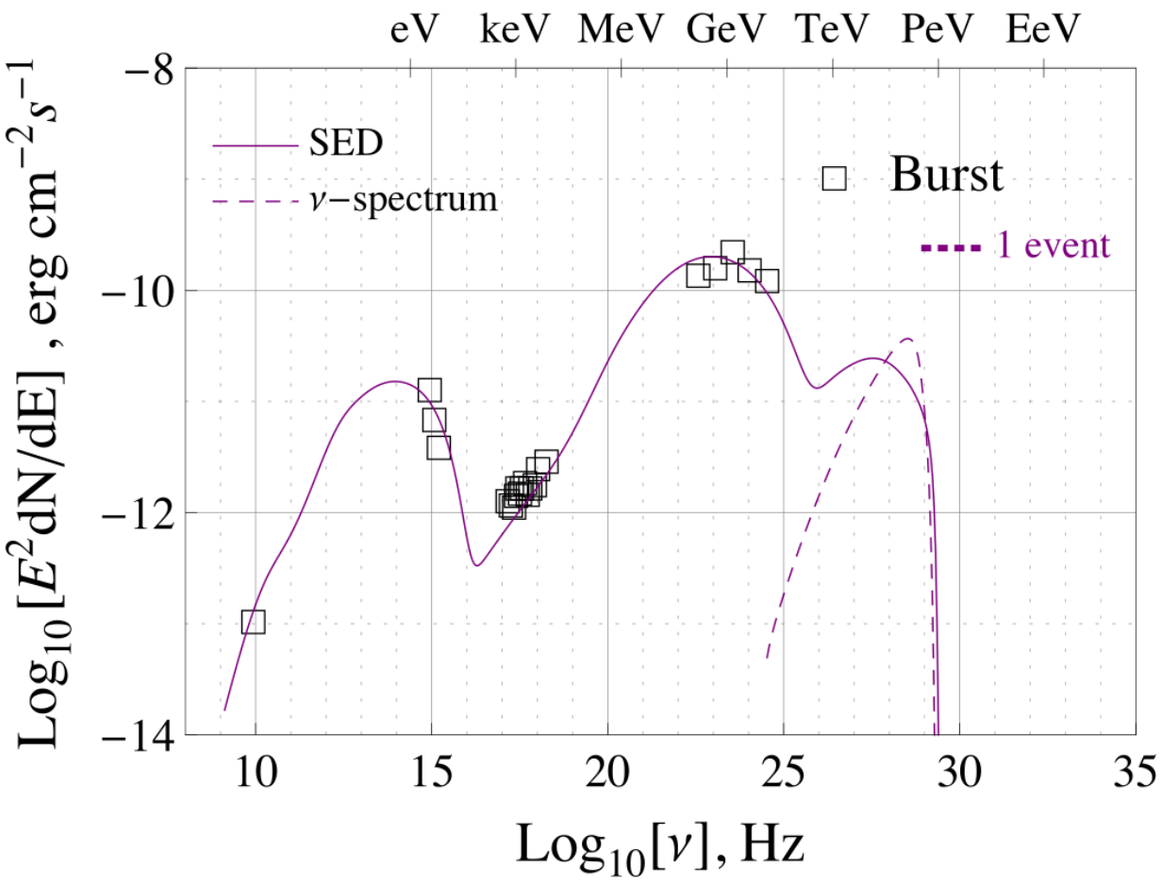
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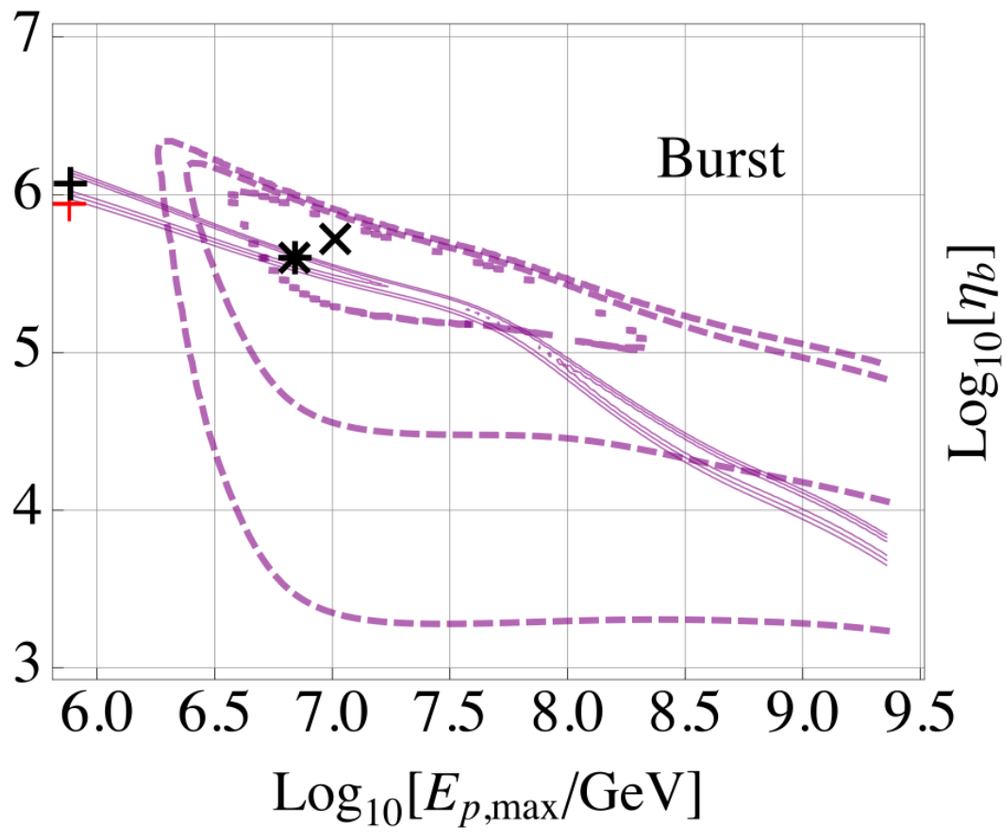
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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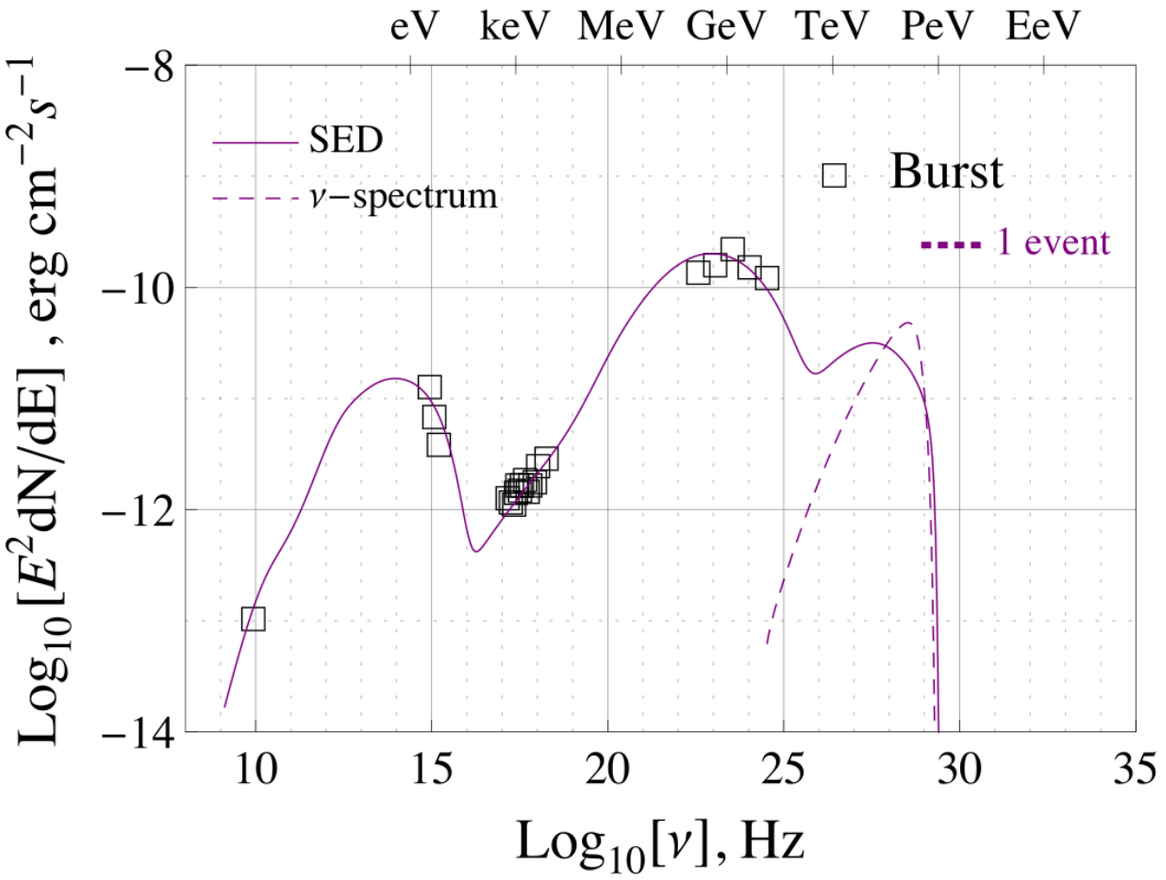
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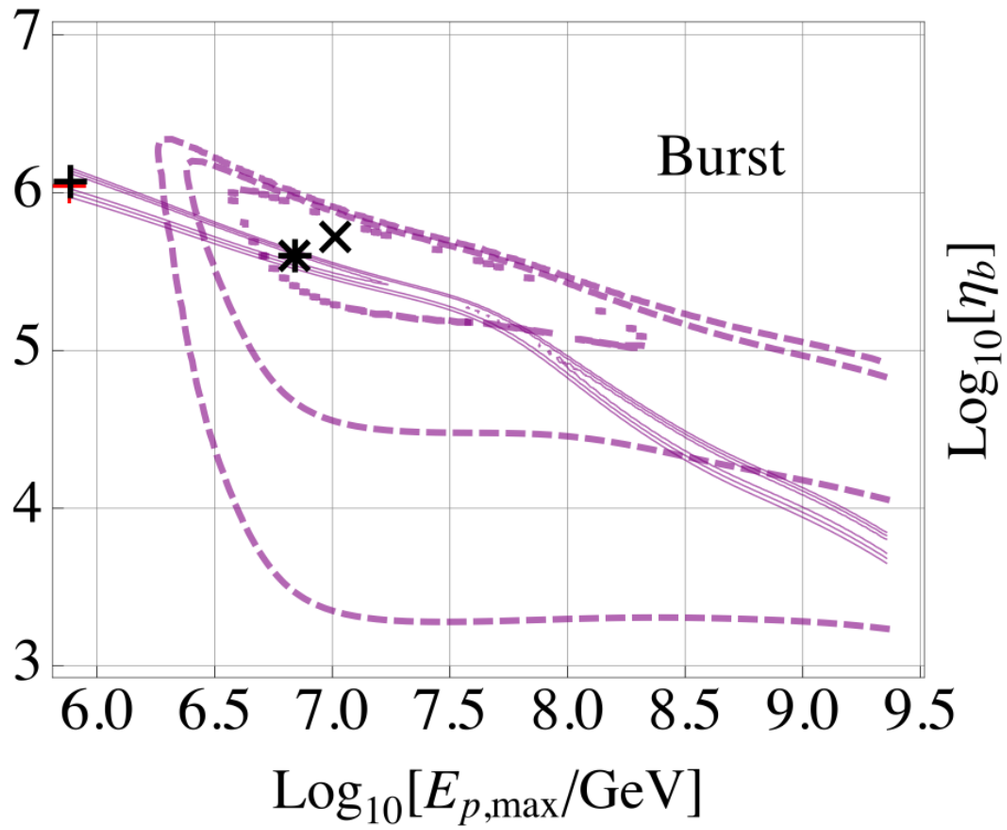
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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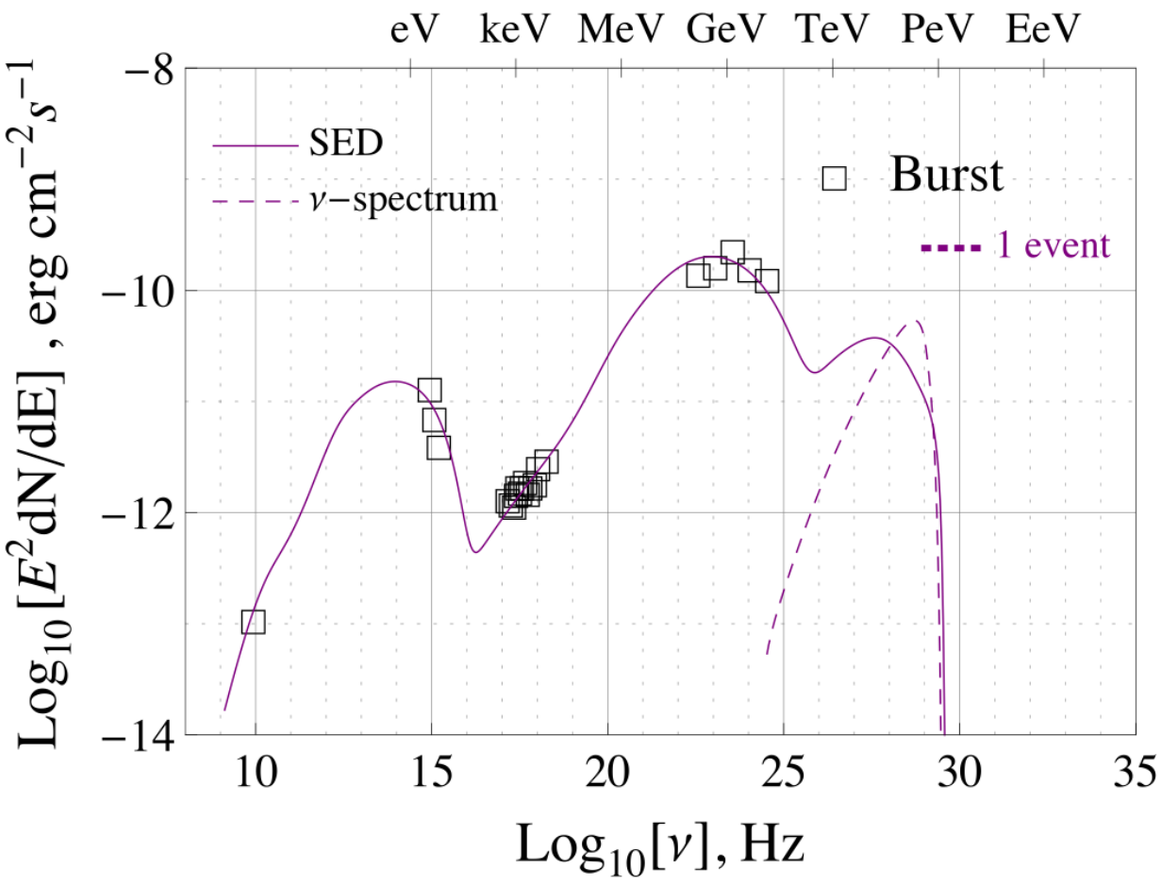
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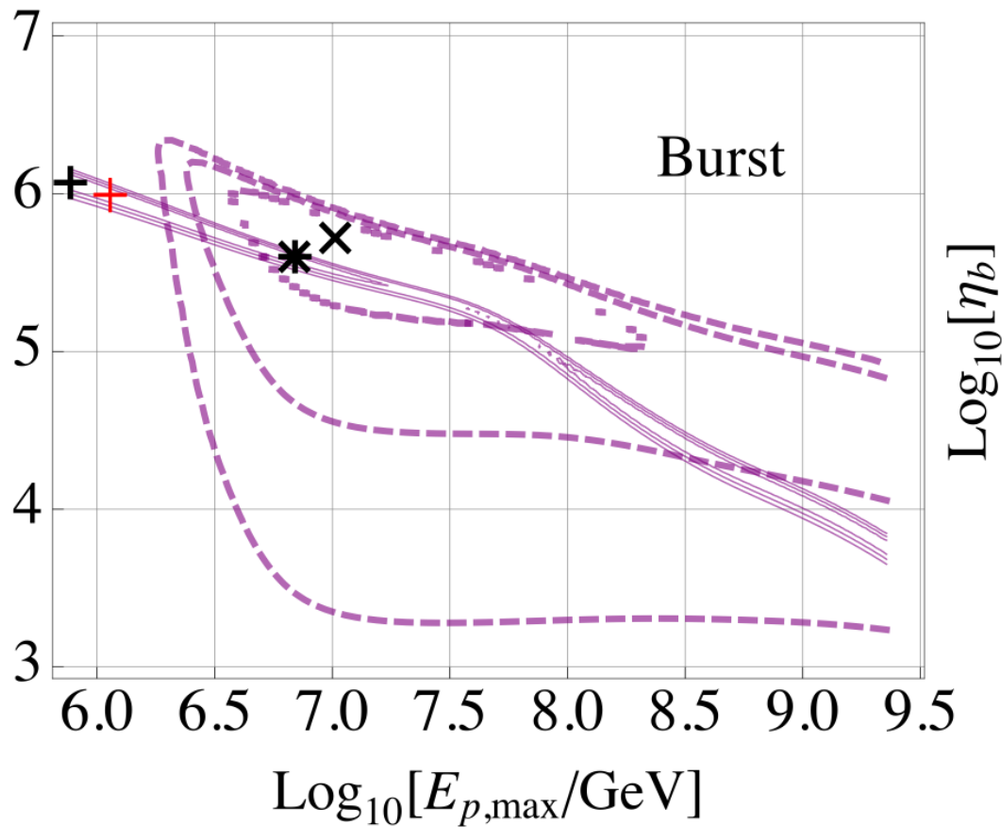
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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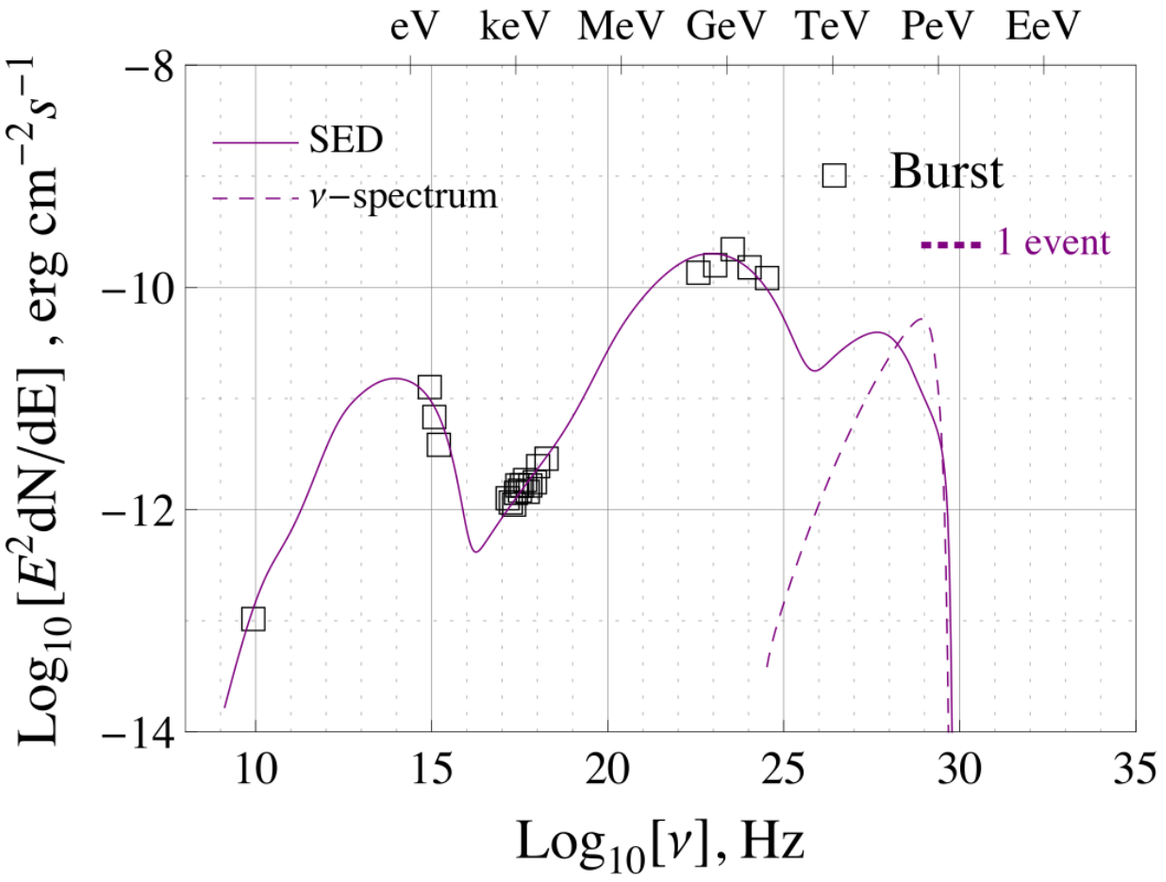
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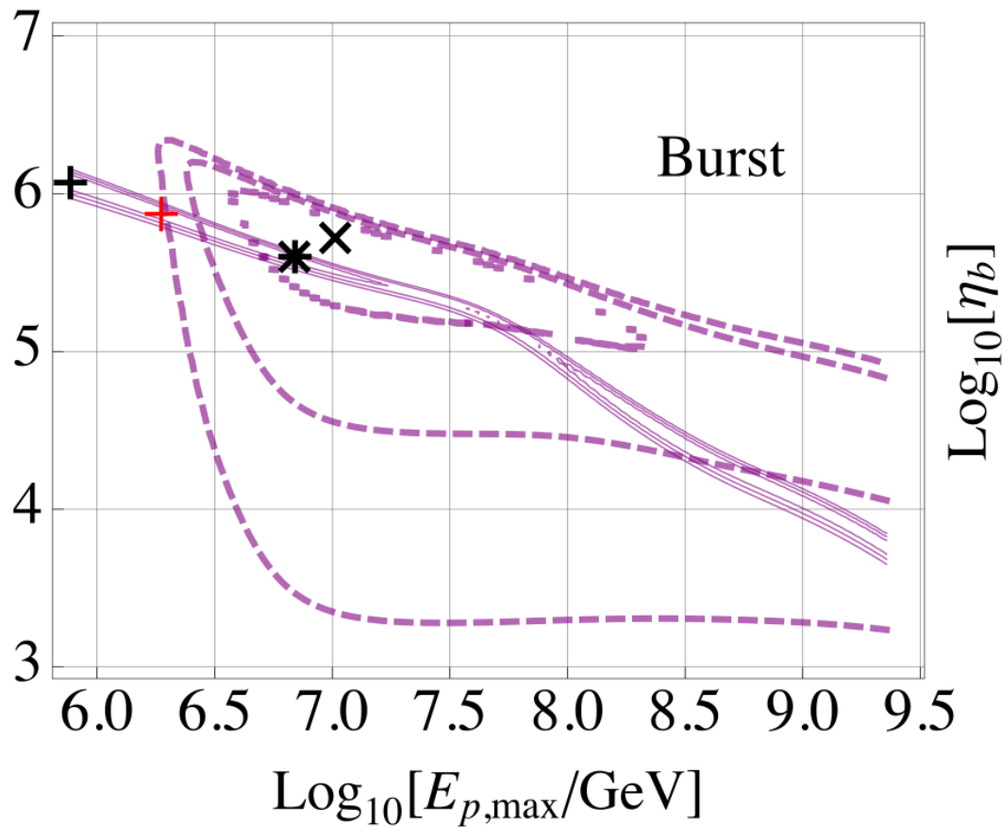
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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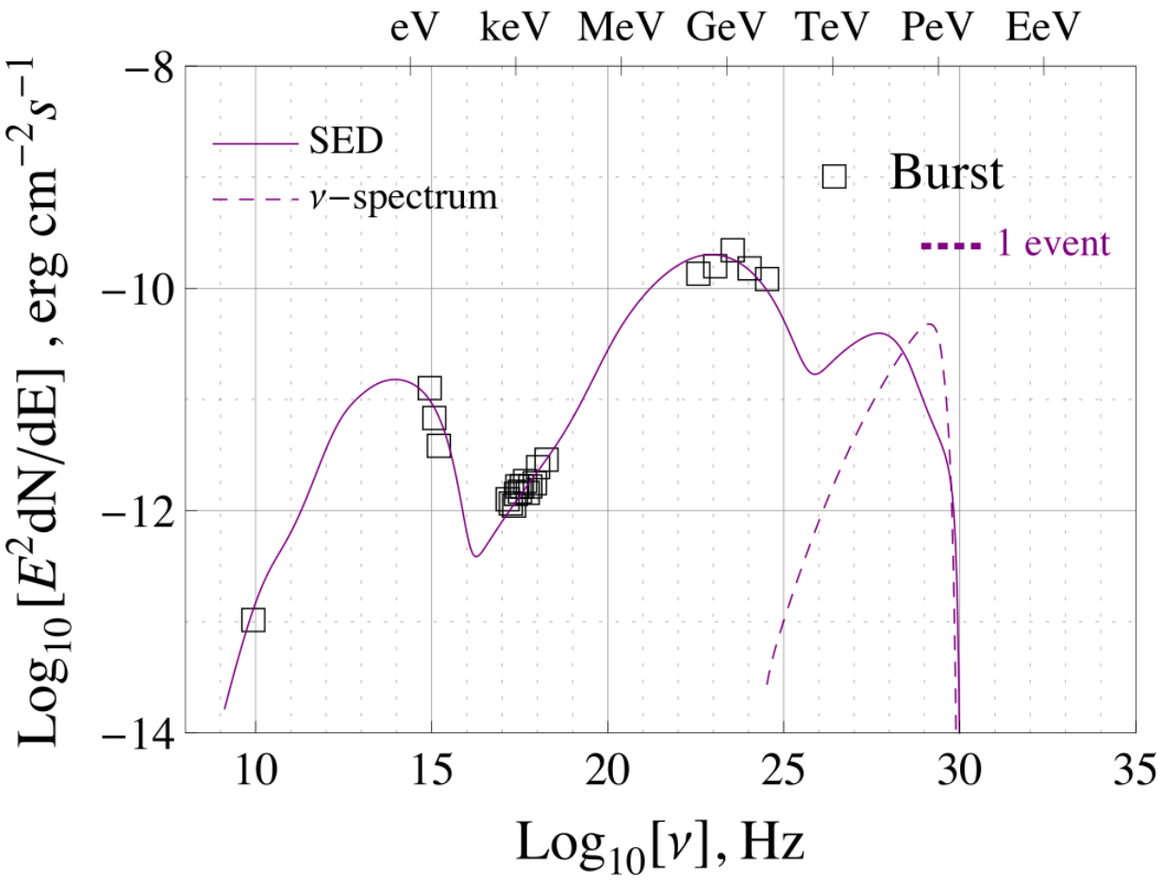
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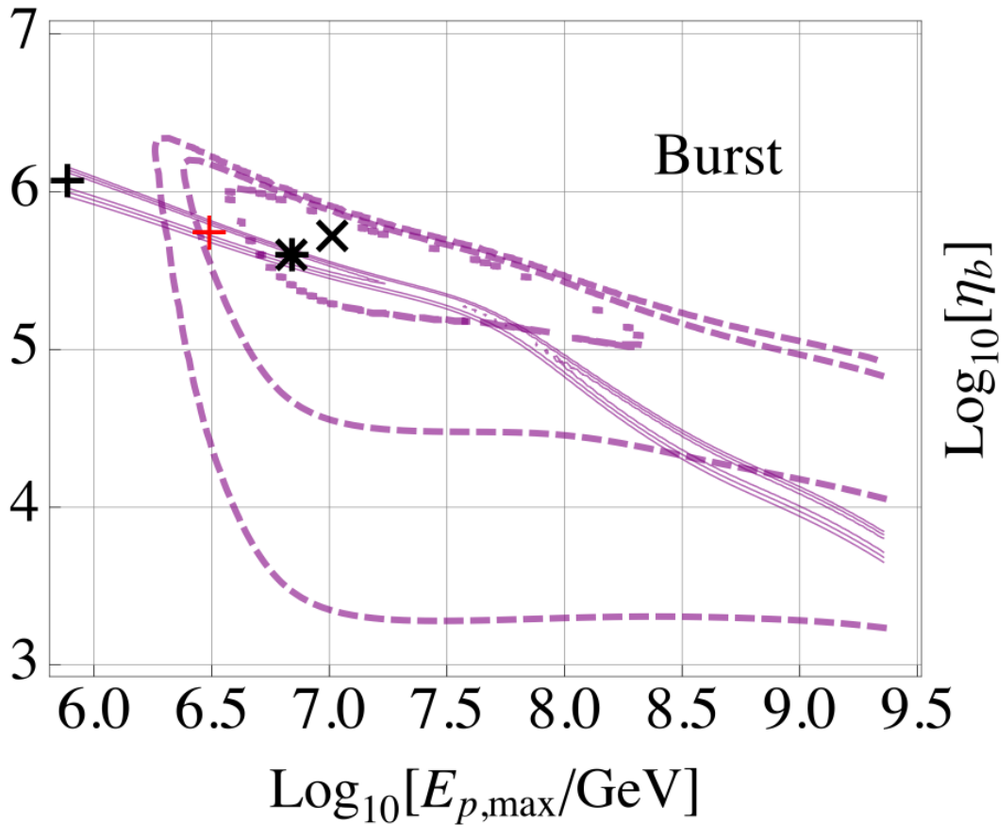
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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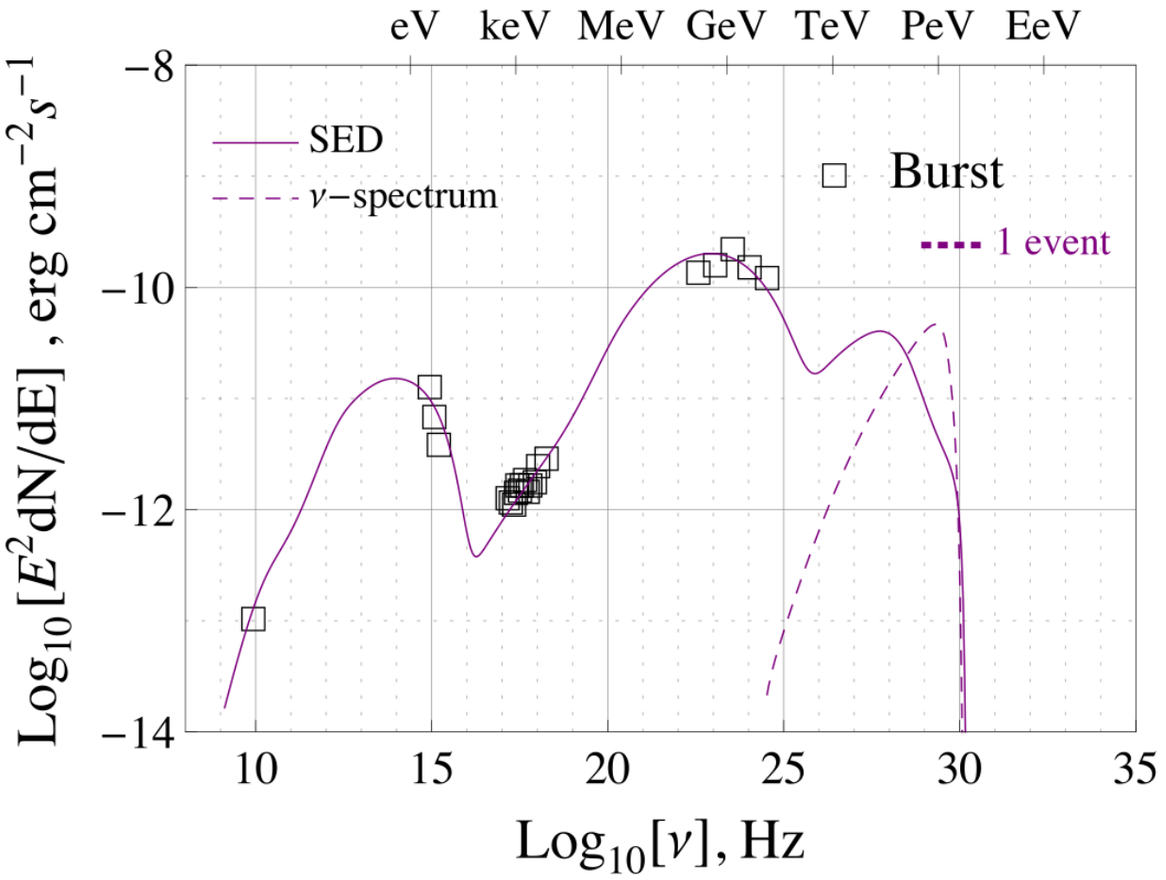
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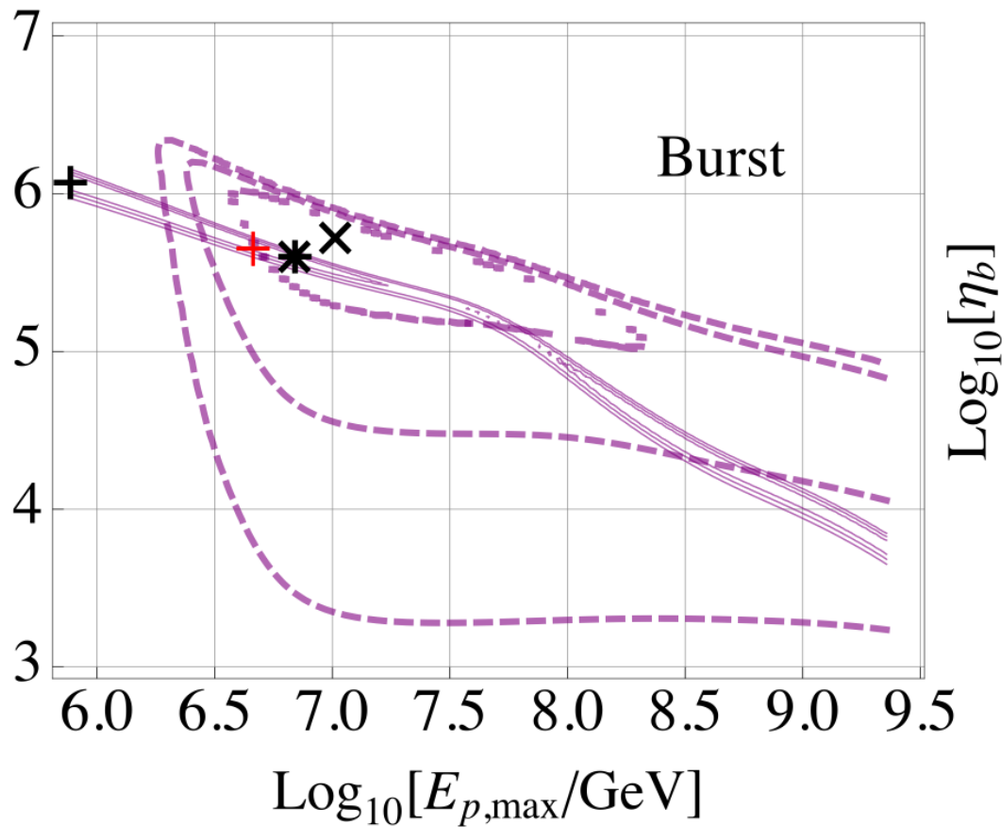
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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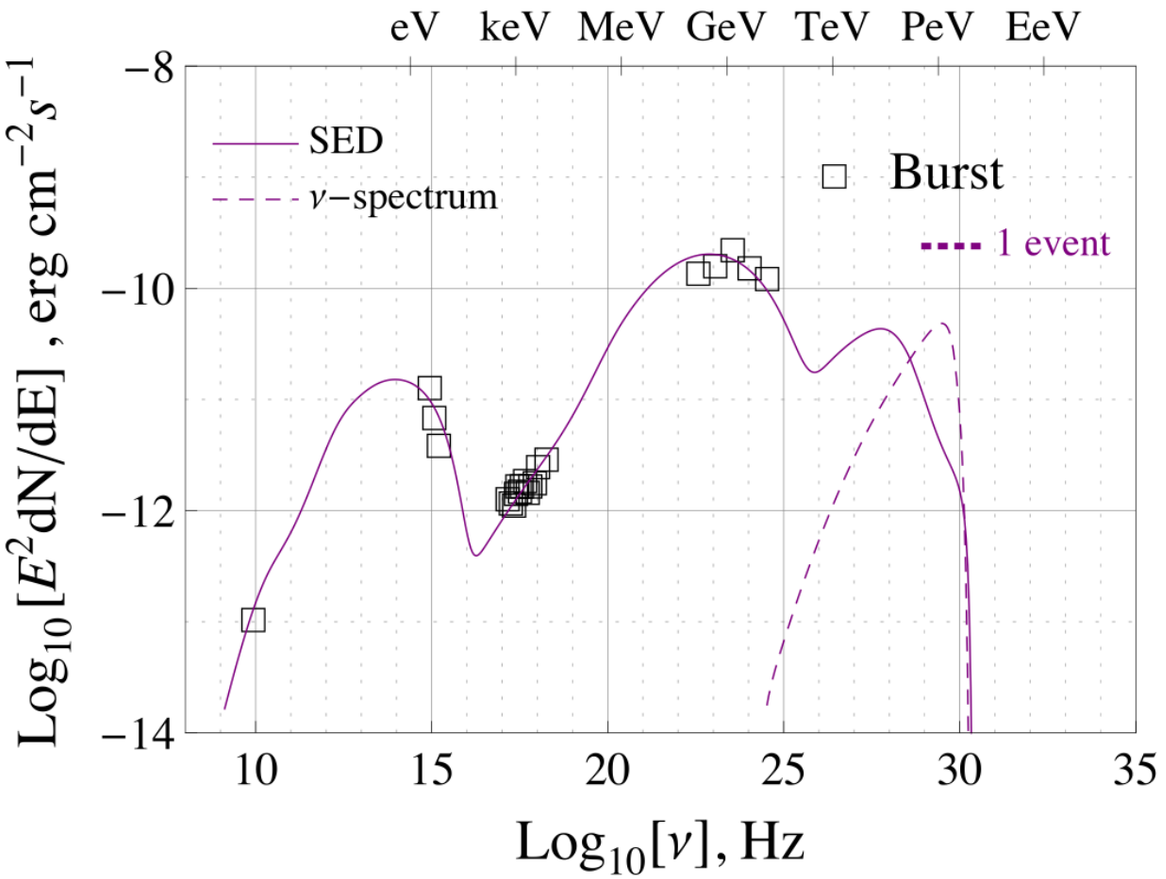
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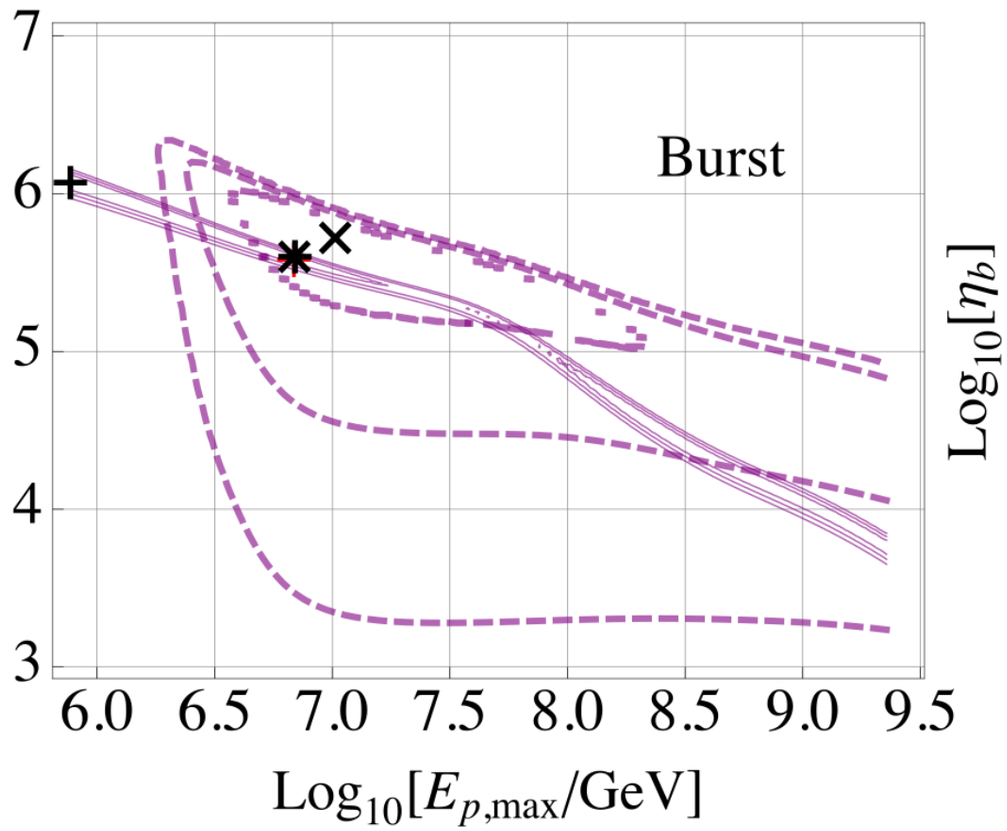
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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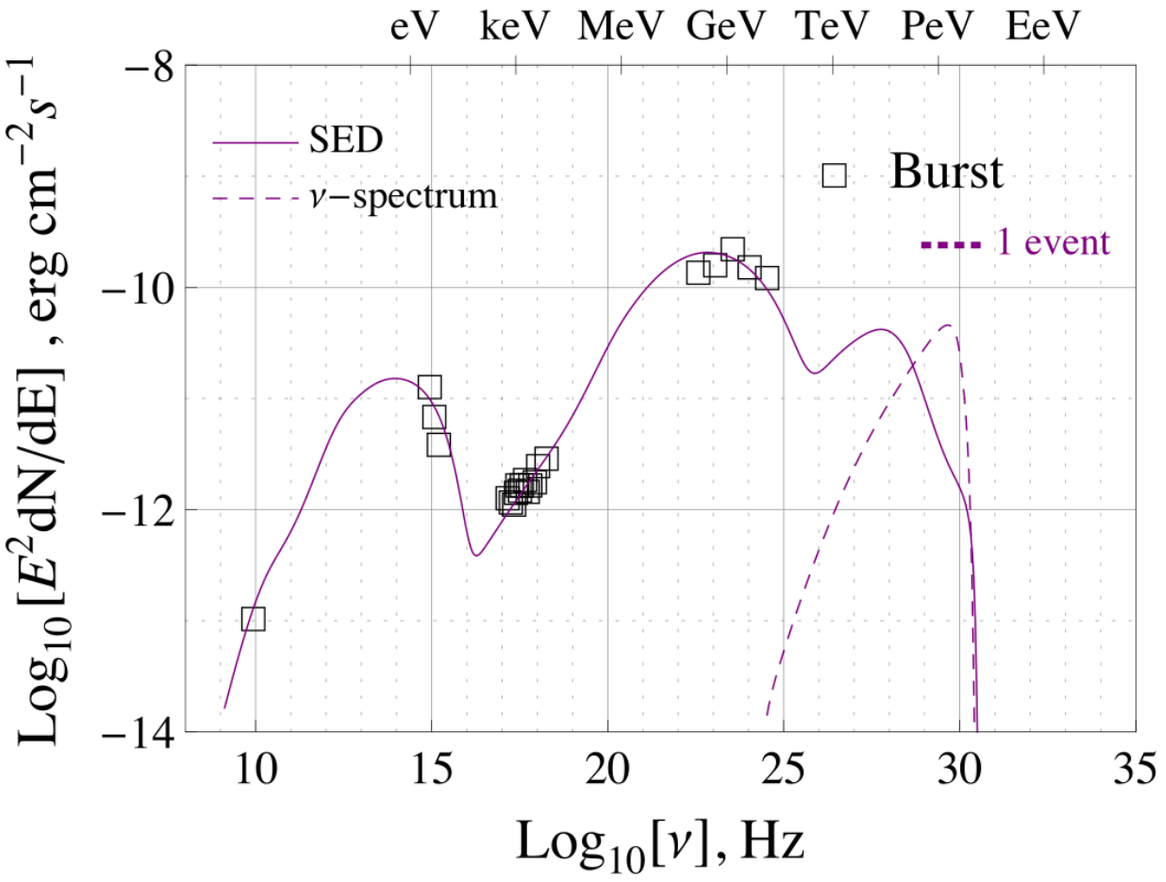
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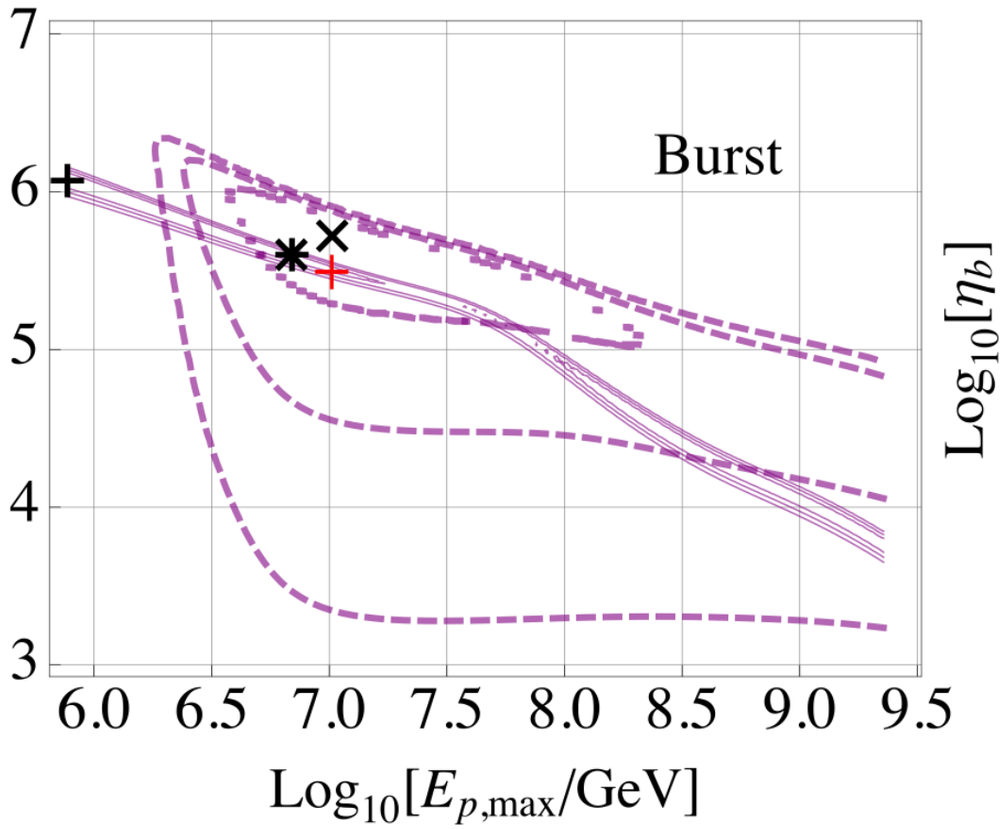
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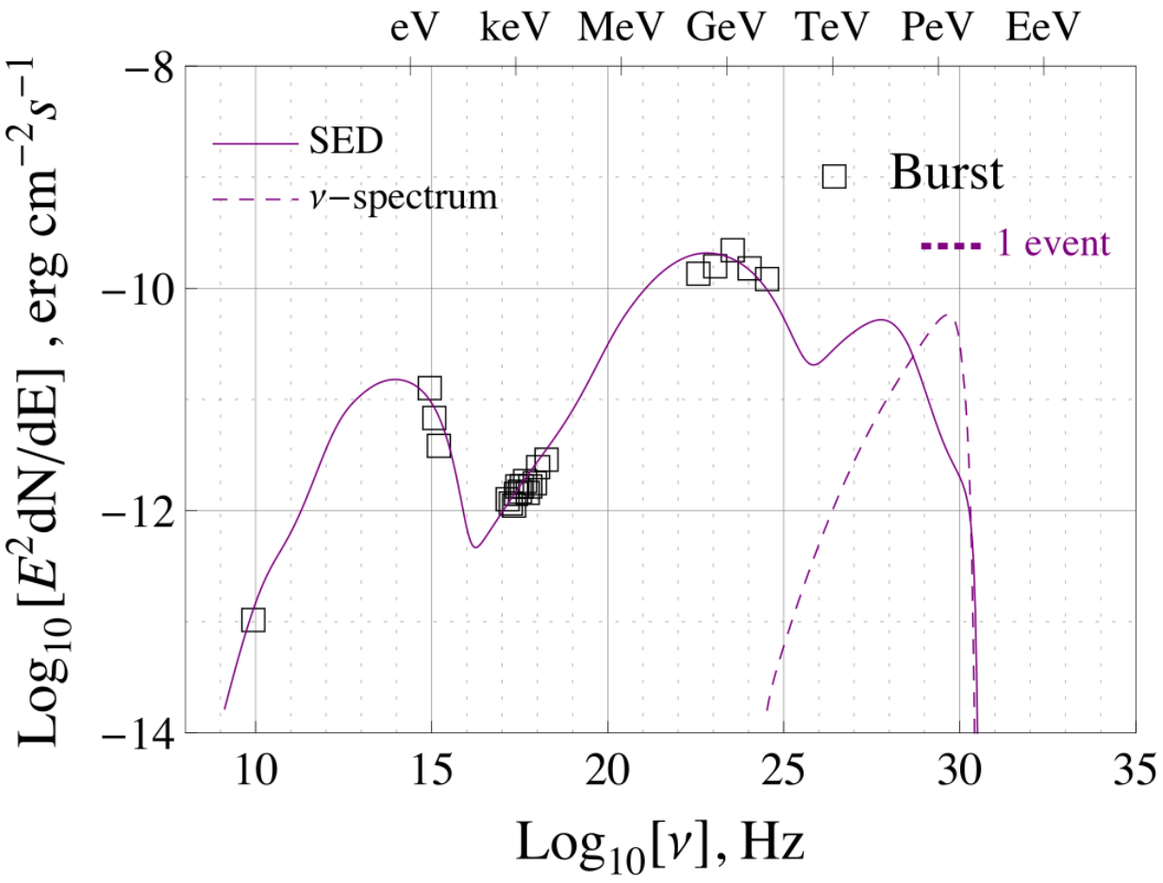
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Log10[E²dN/dE] , erg cm⁻² s⁻¹
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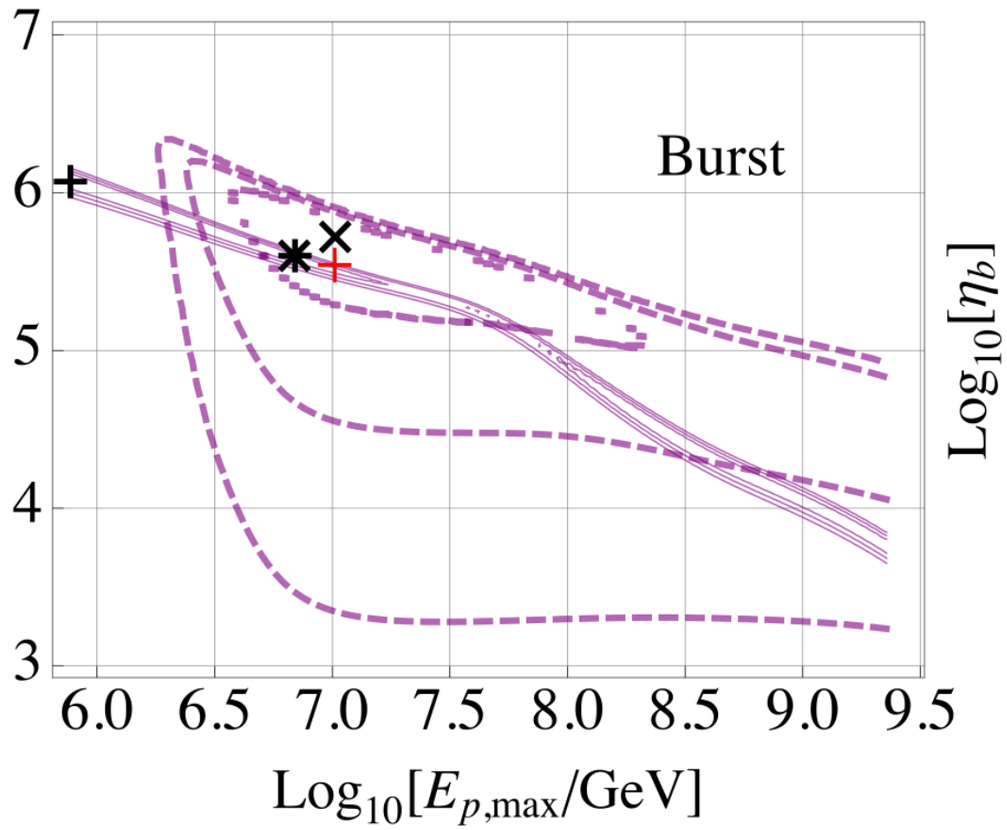
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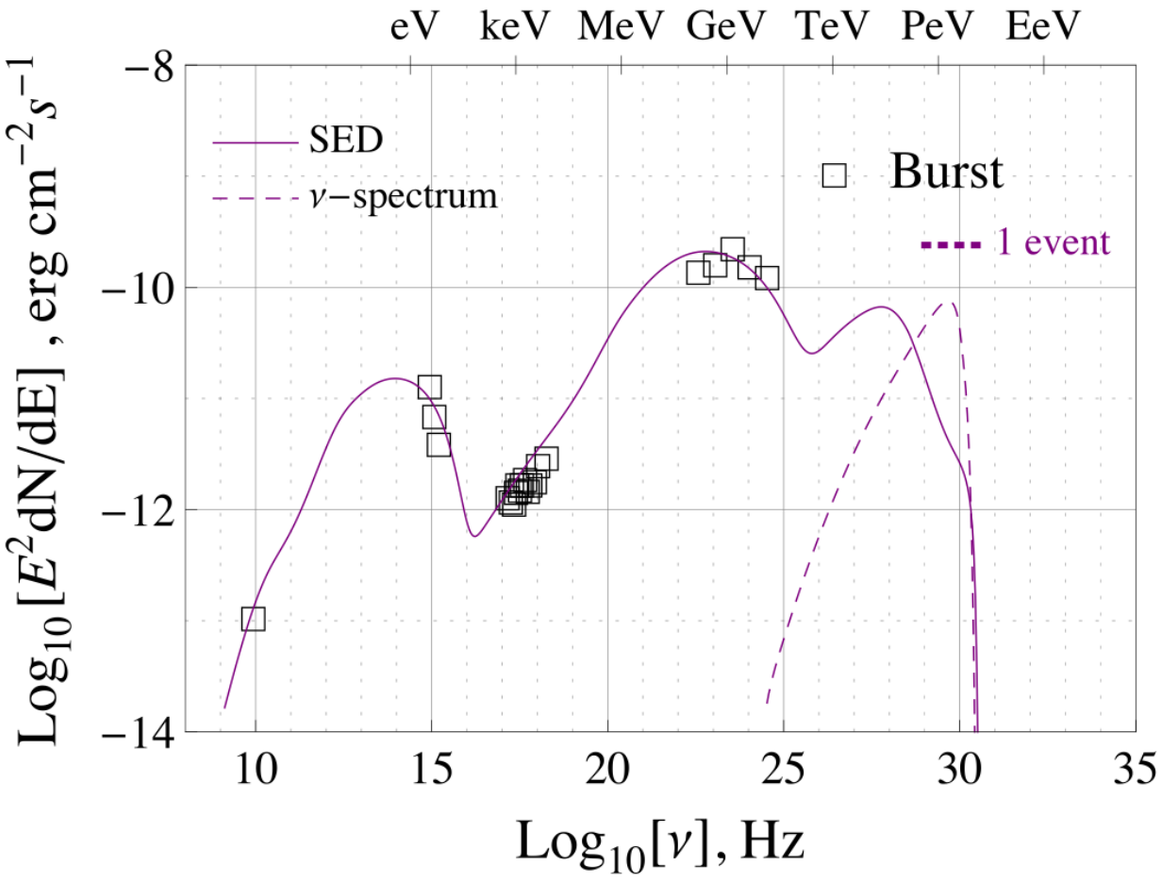
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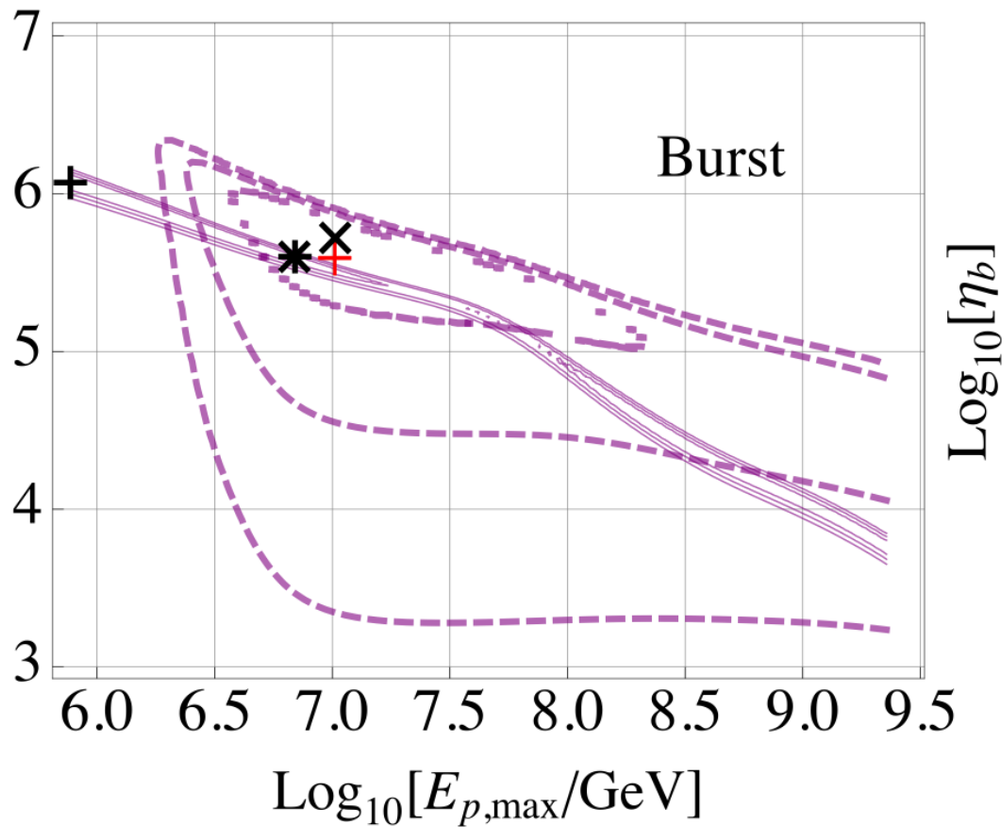
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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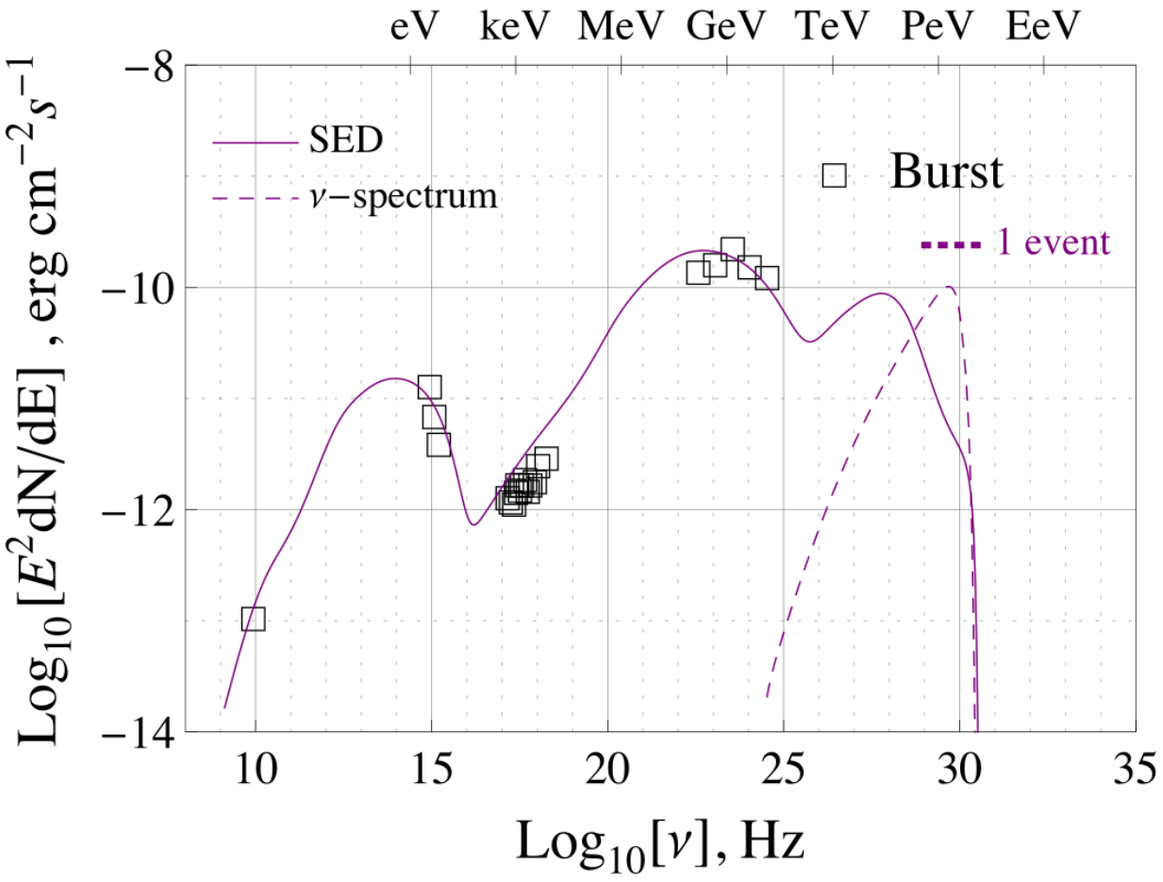
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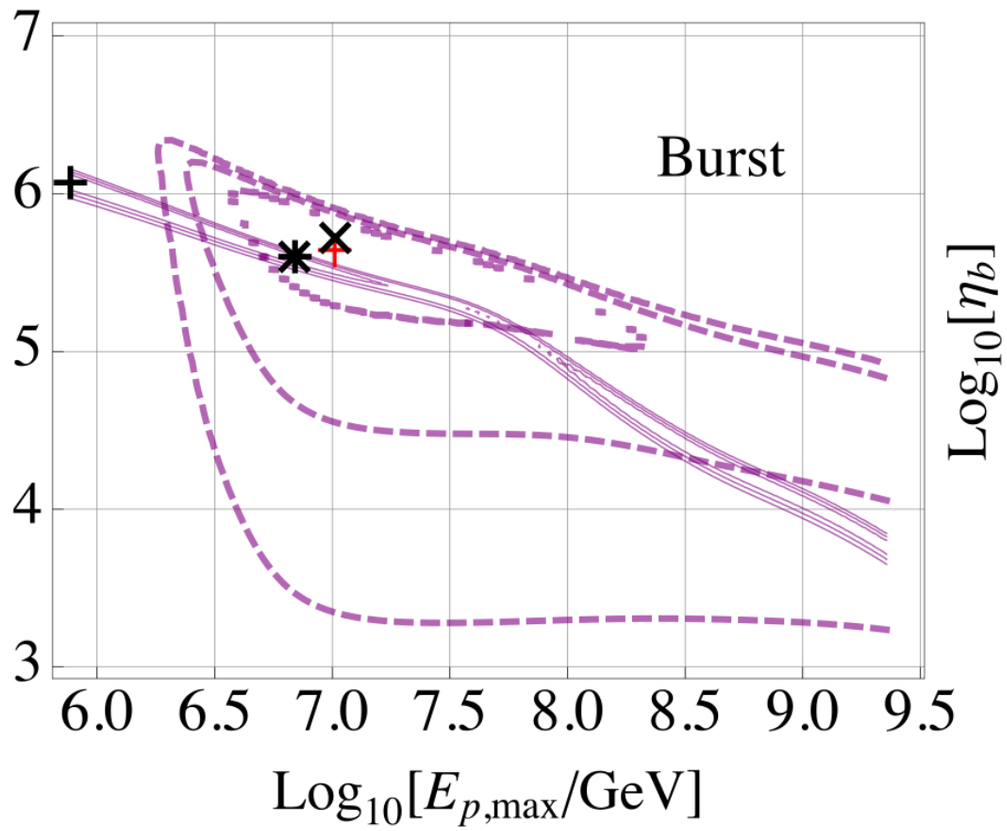
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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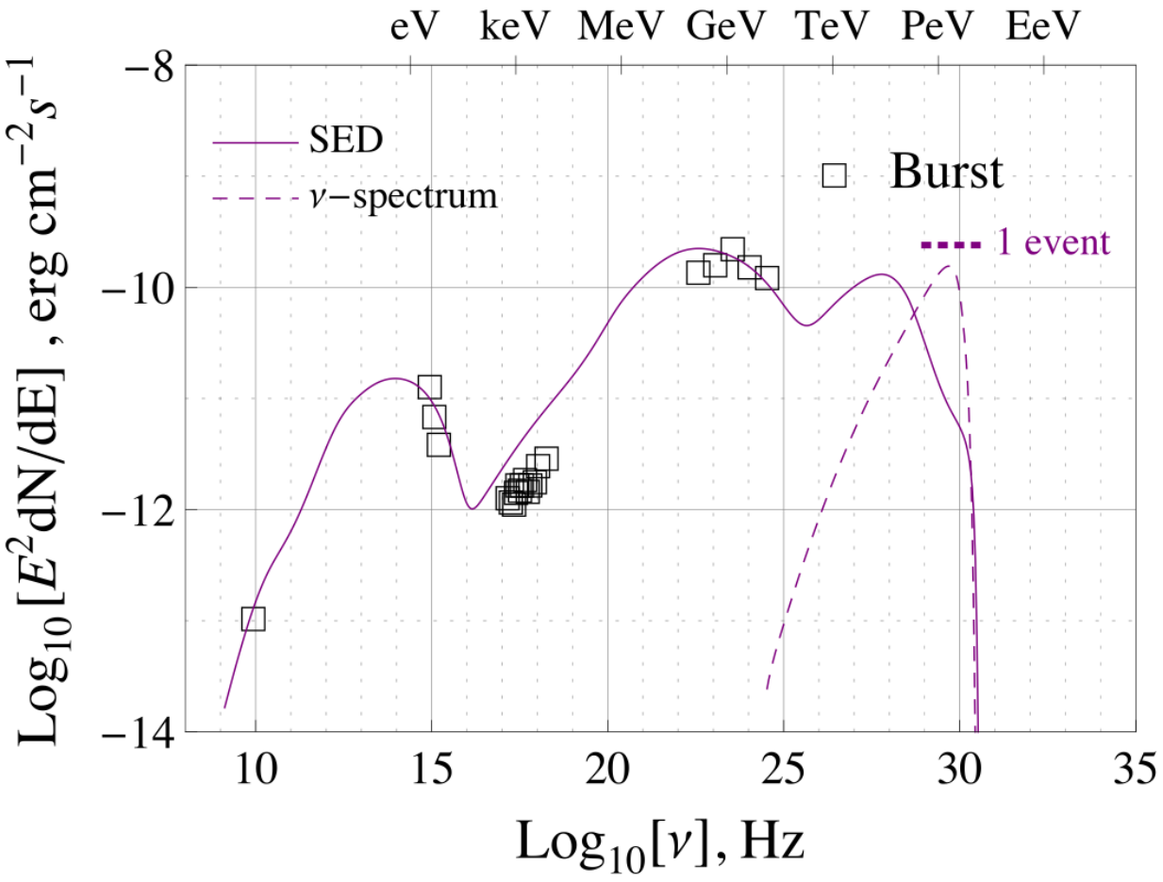
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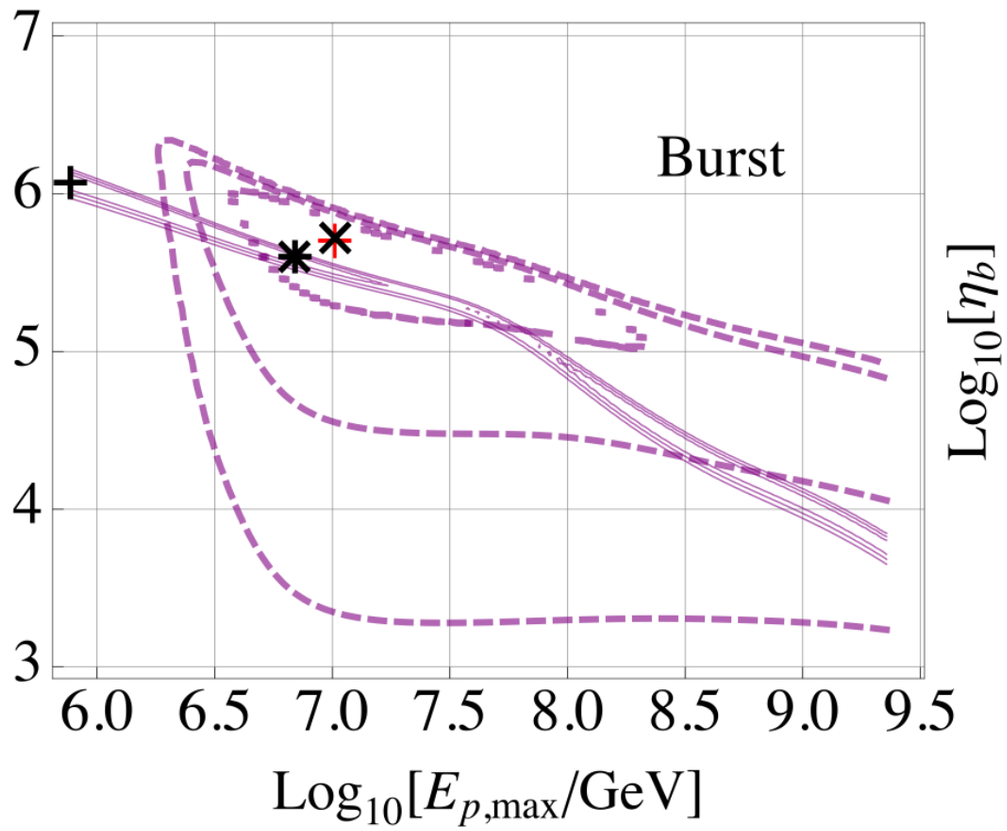
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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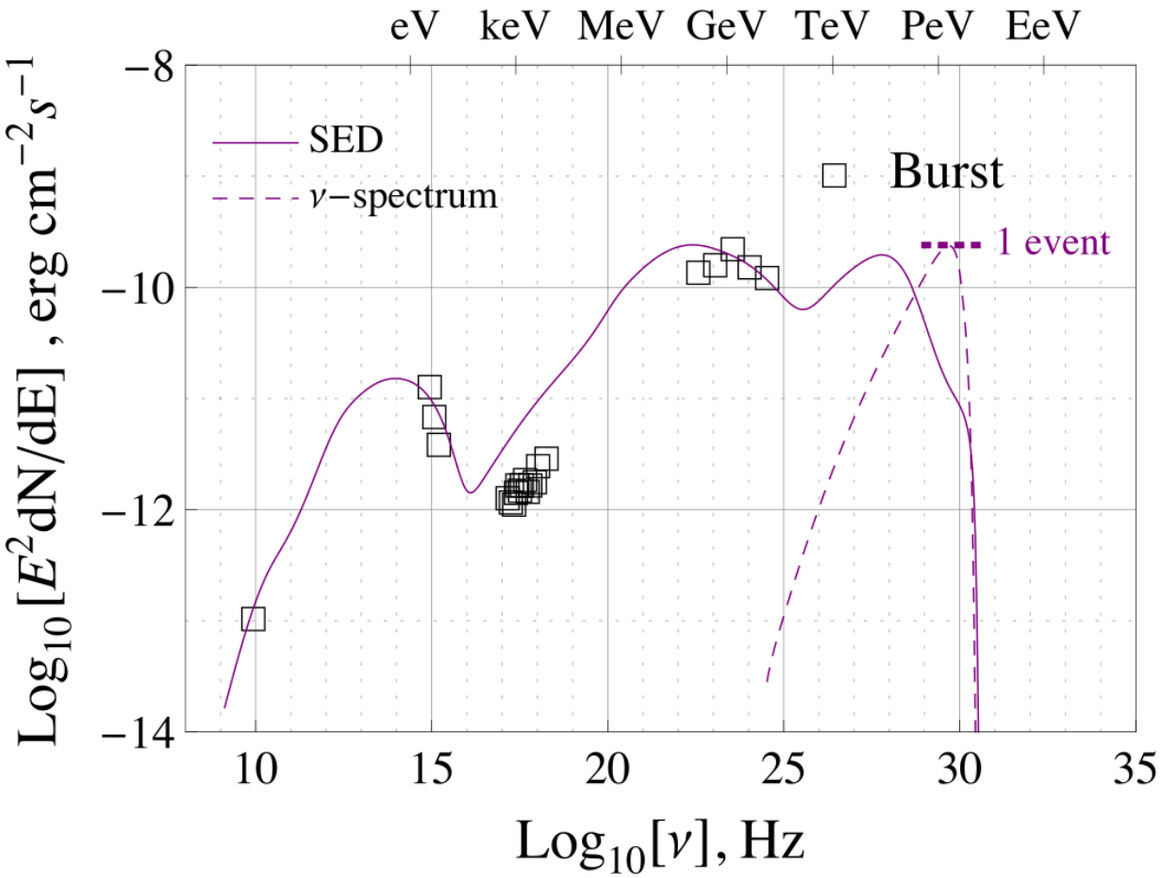
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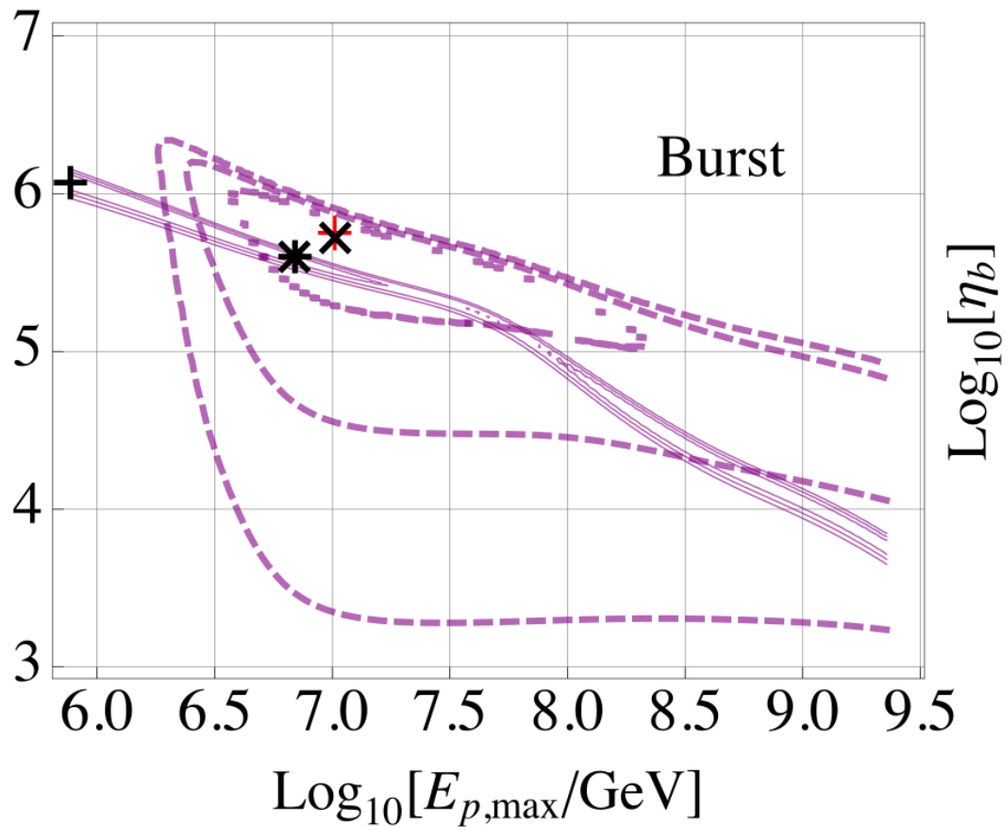
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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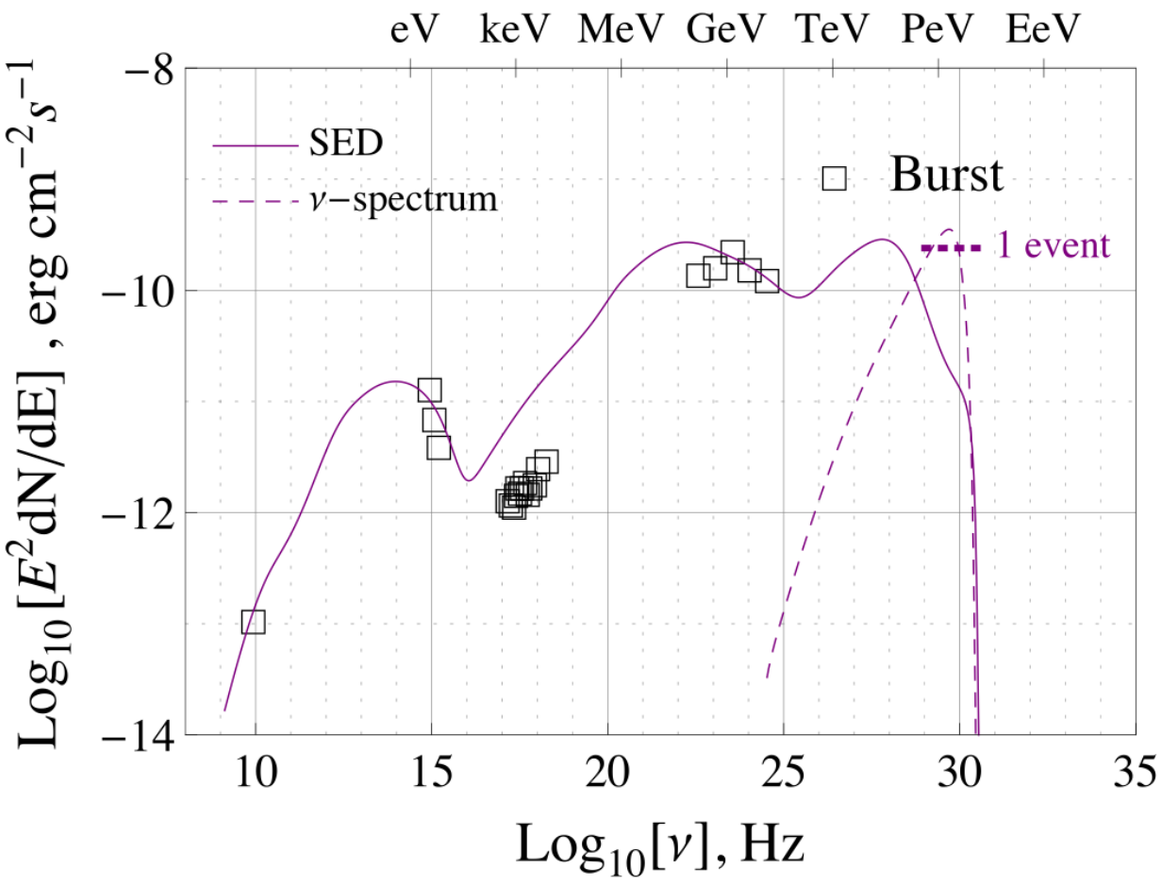
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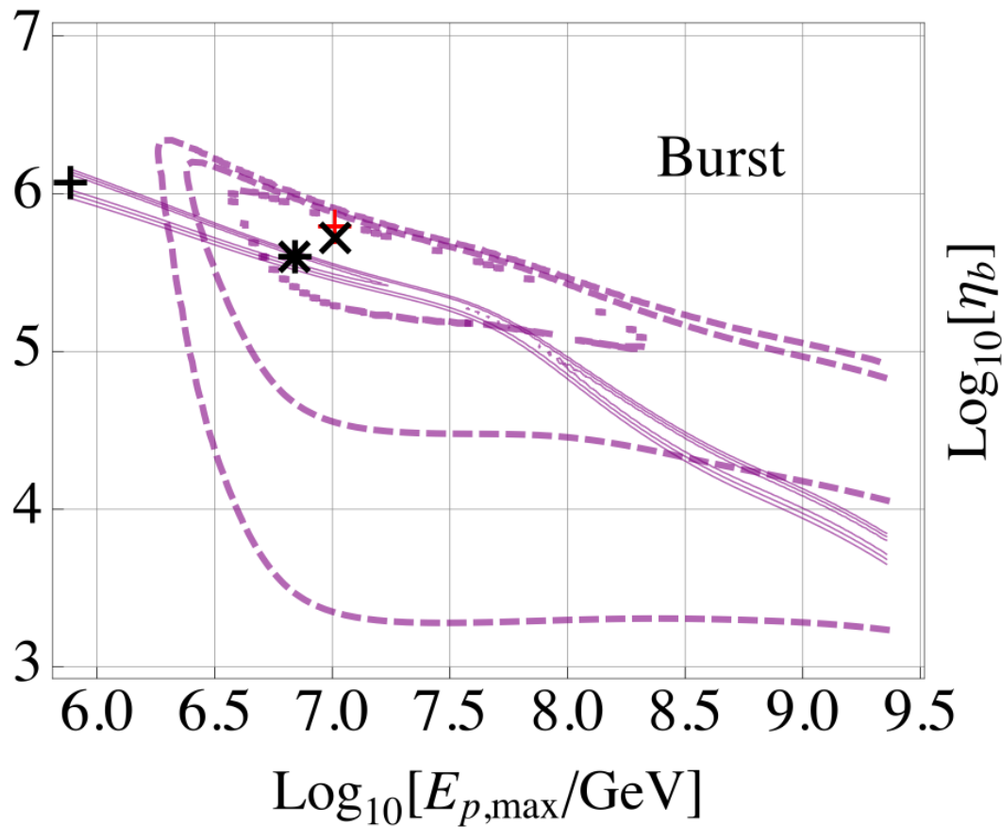
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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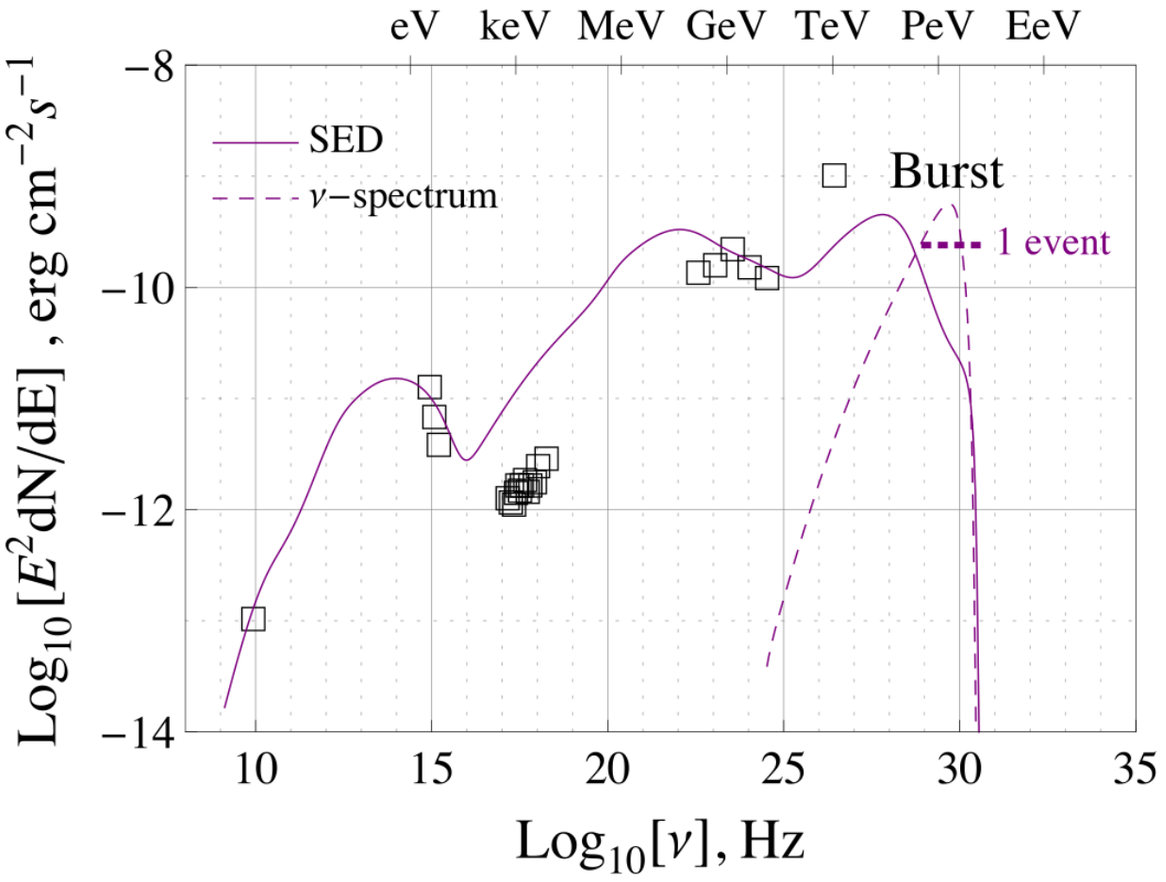
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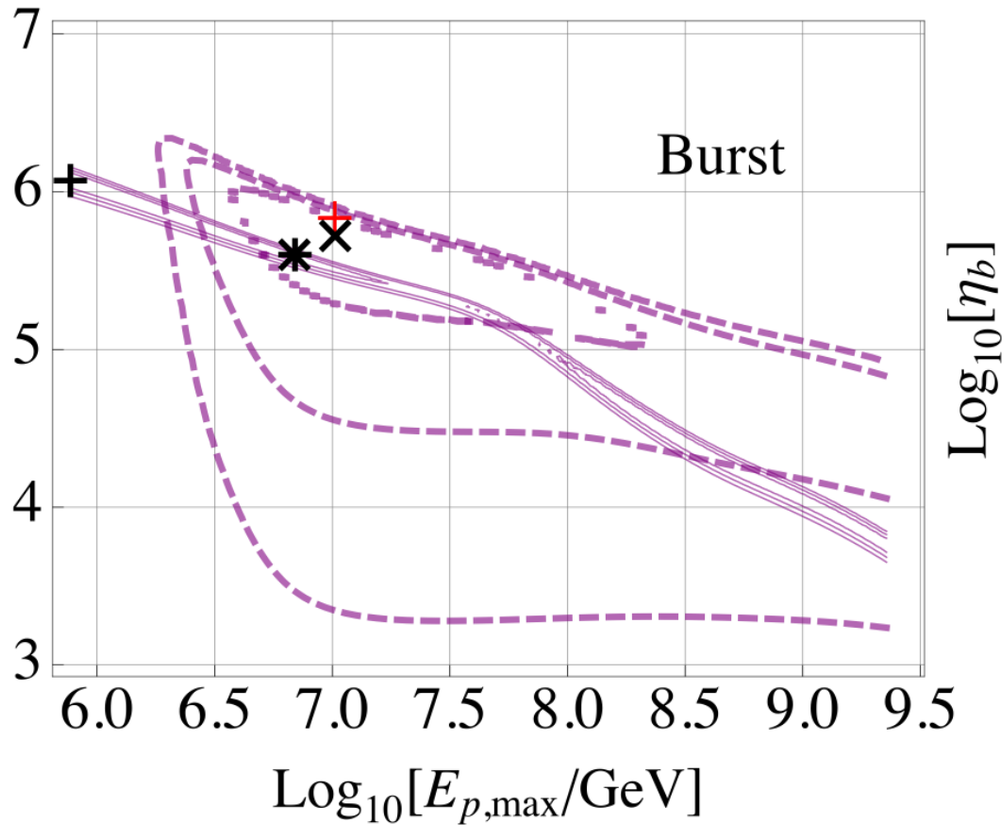
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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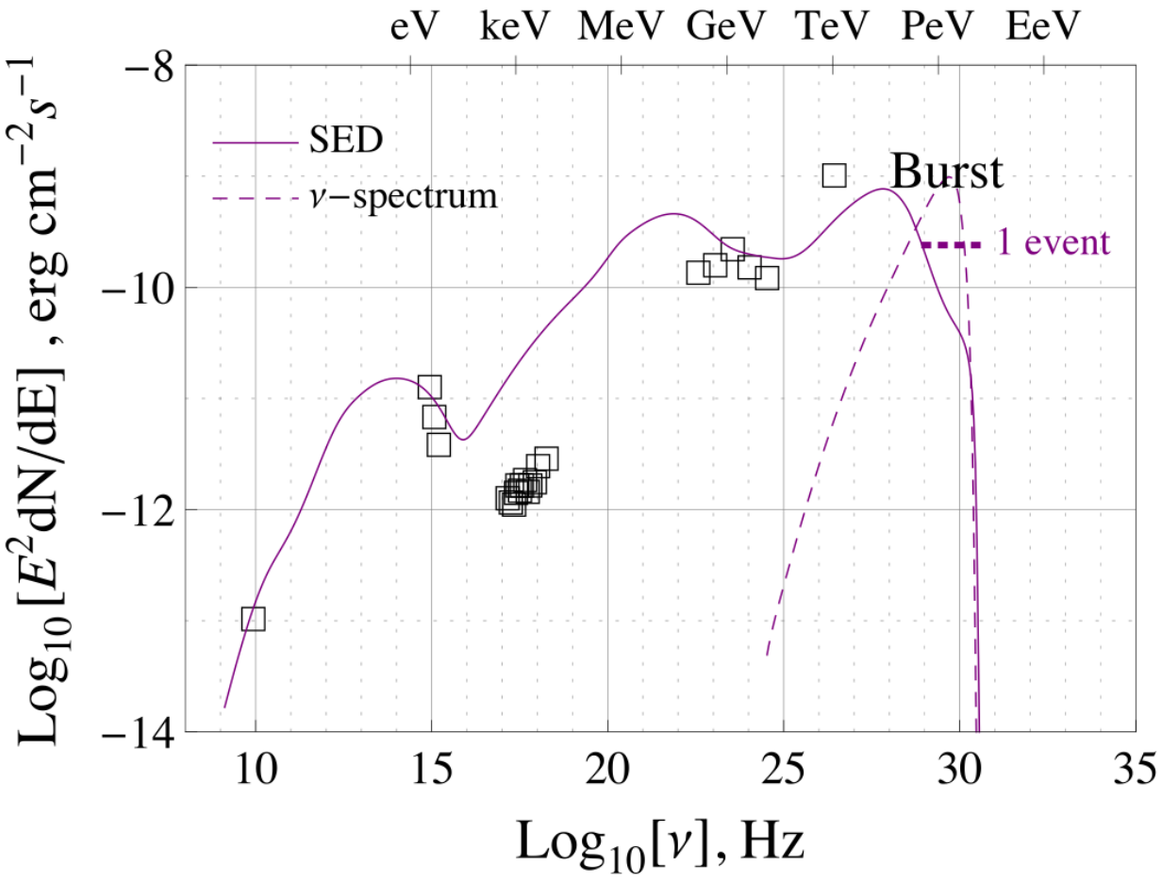
Log10[ηb]
Log10[Ep,max/GeV]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Burst
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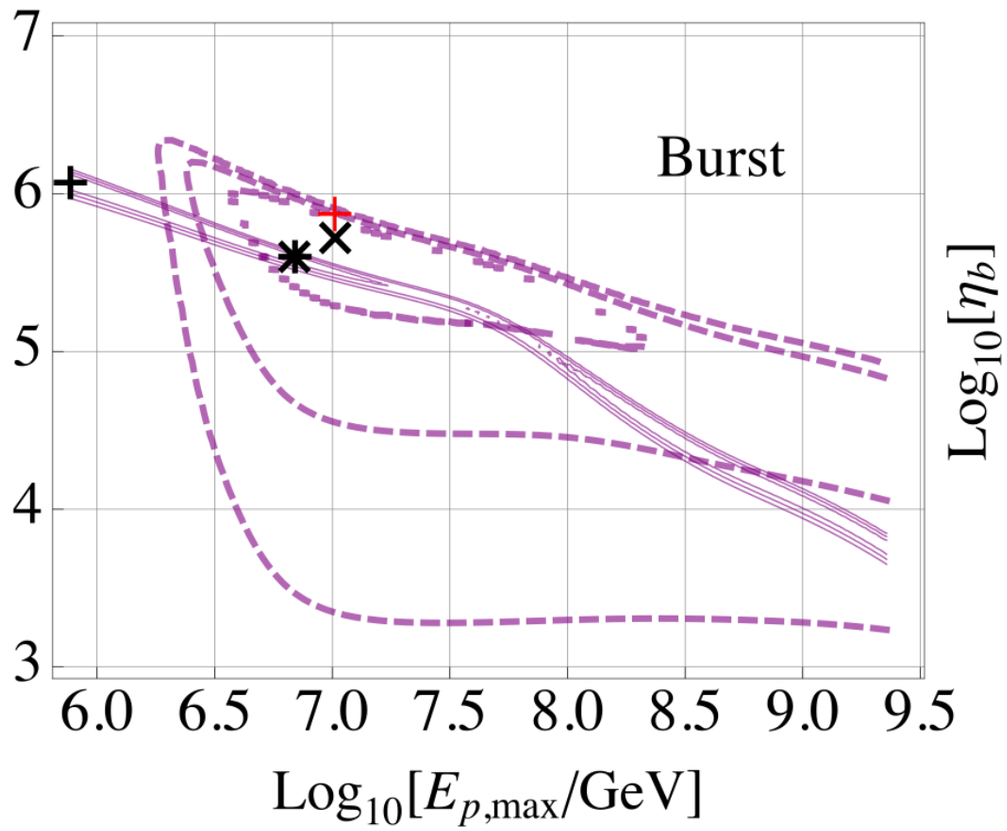
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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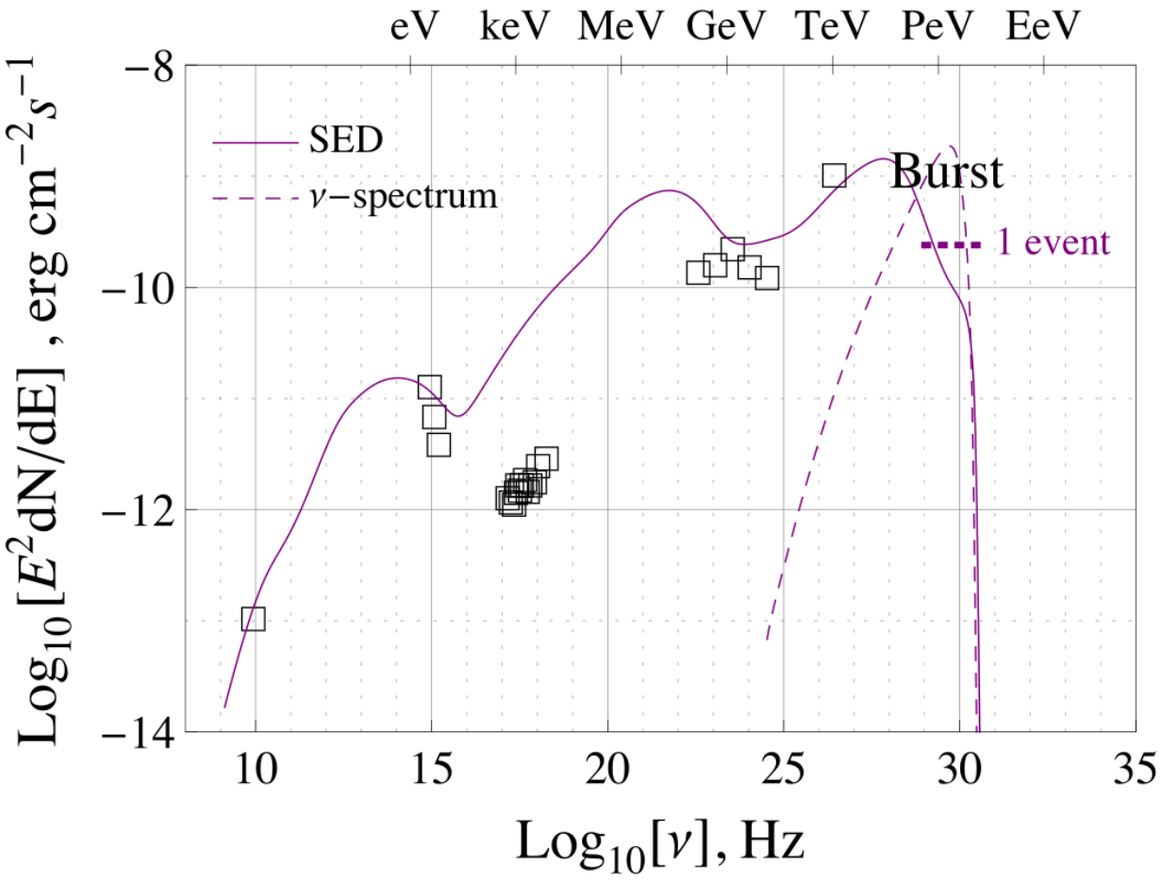
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Log10[E²dN/dE] , erg cm⁻² s⁻¹
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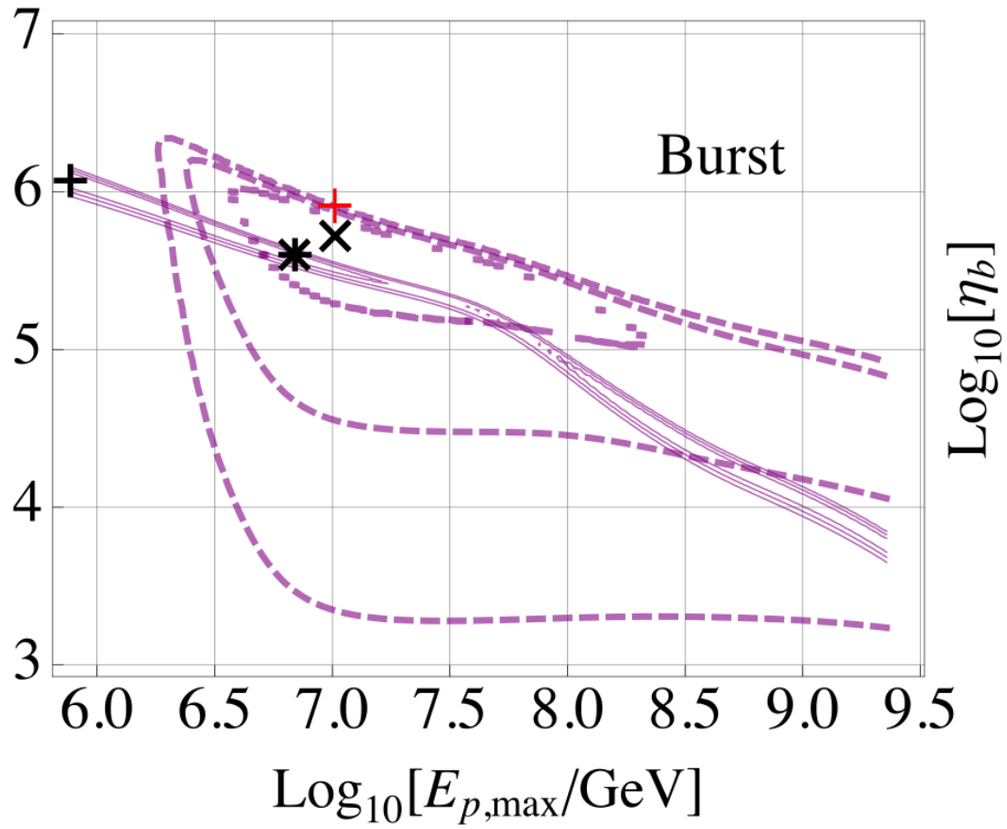
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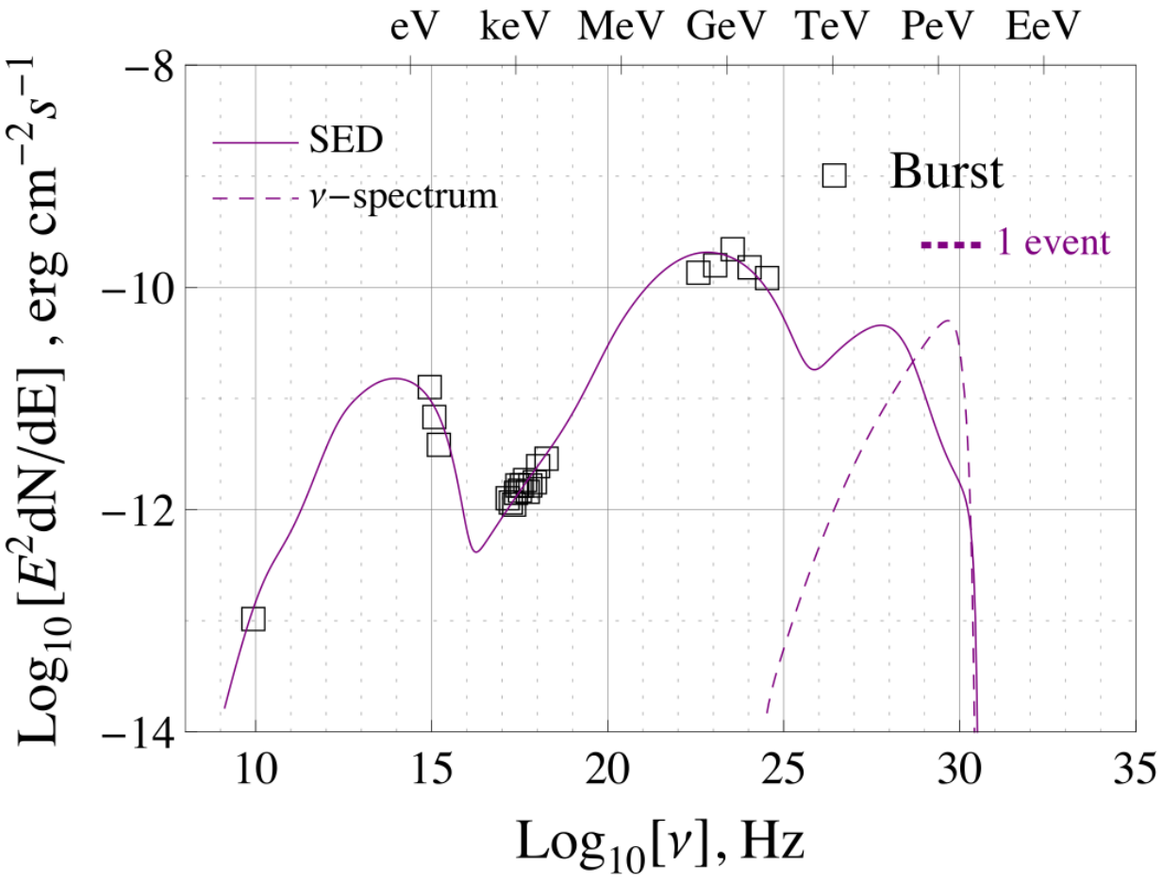
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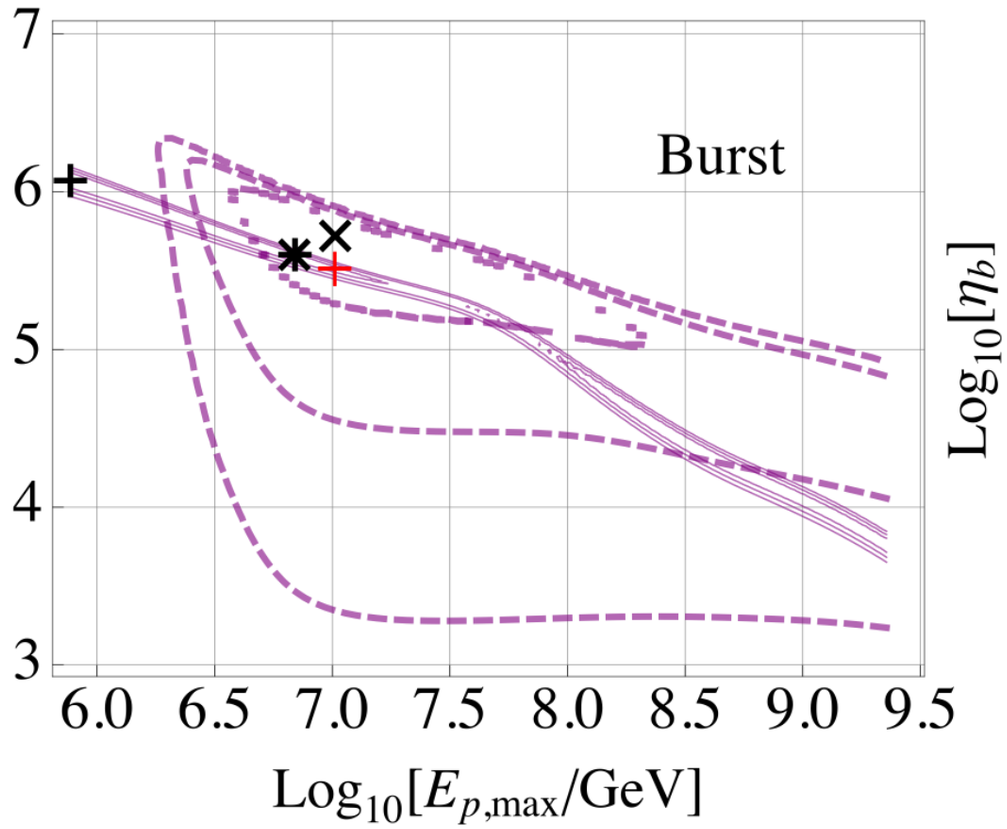
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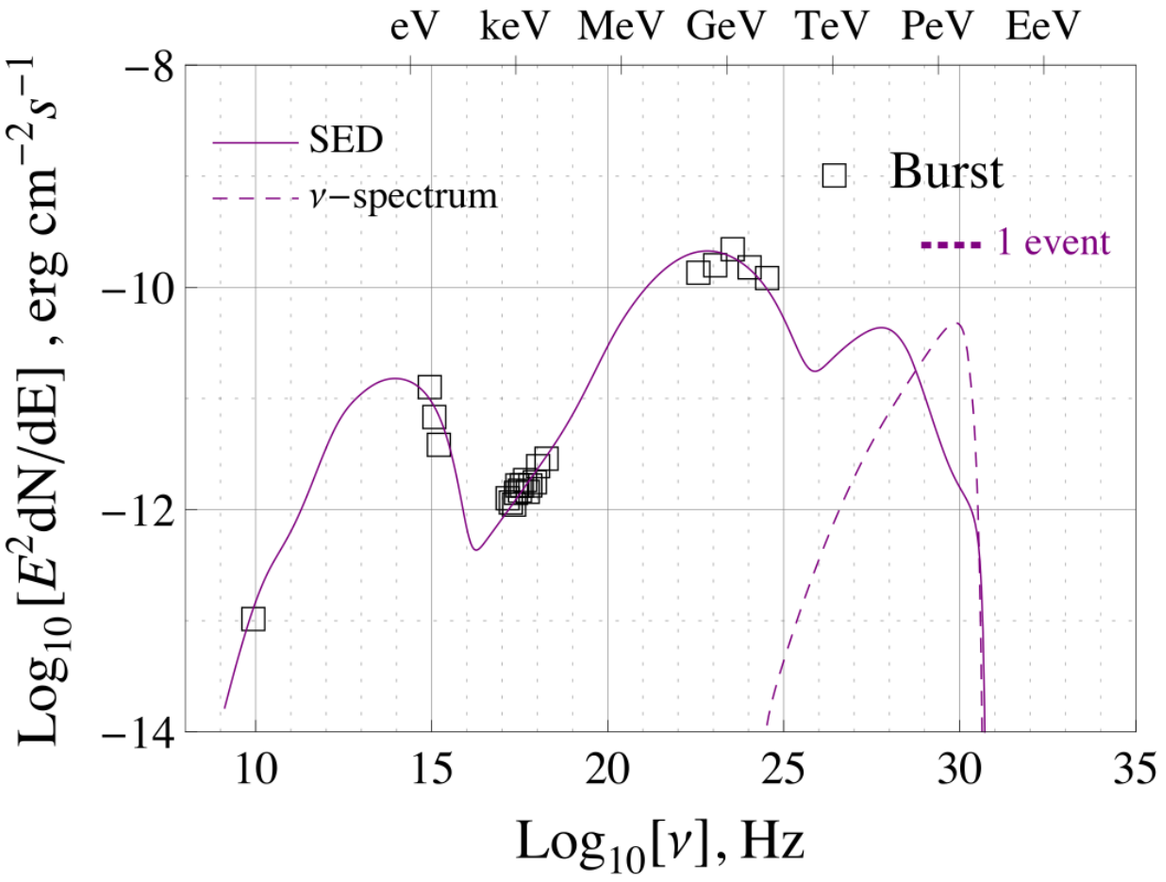
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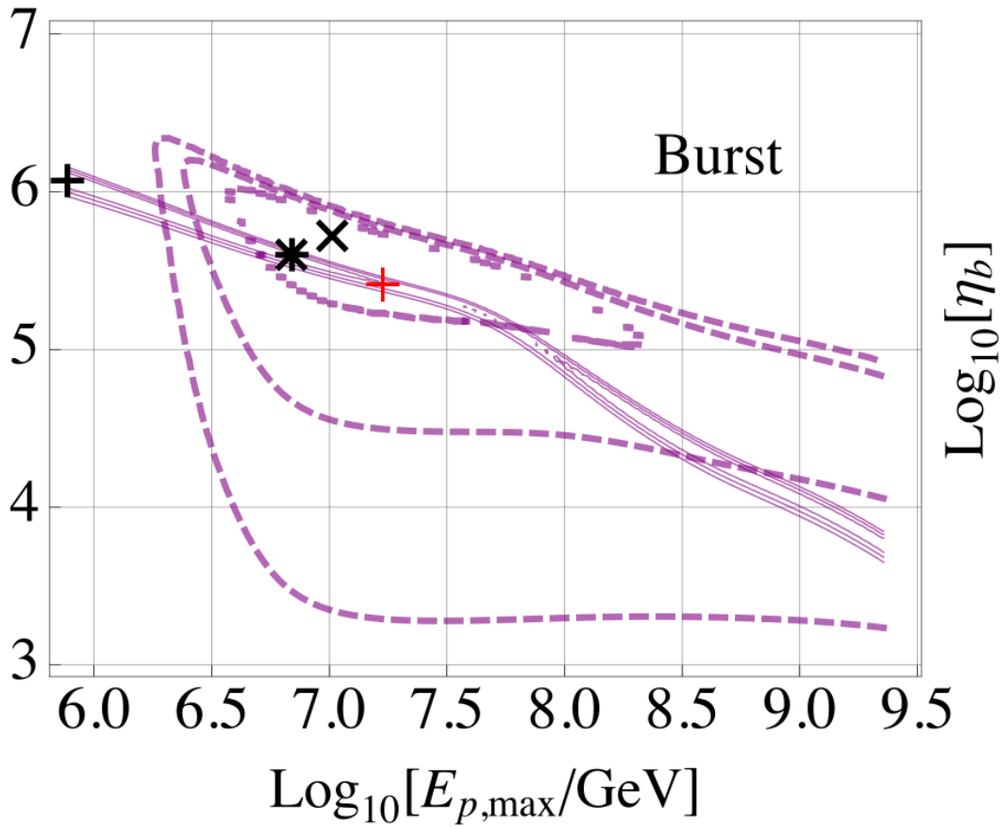
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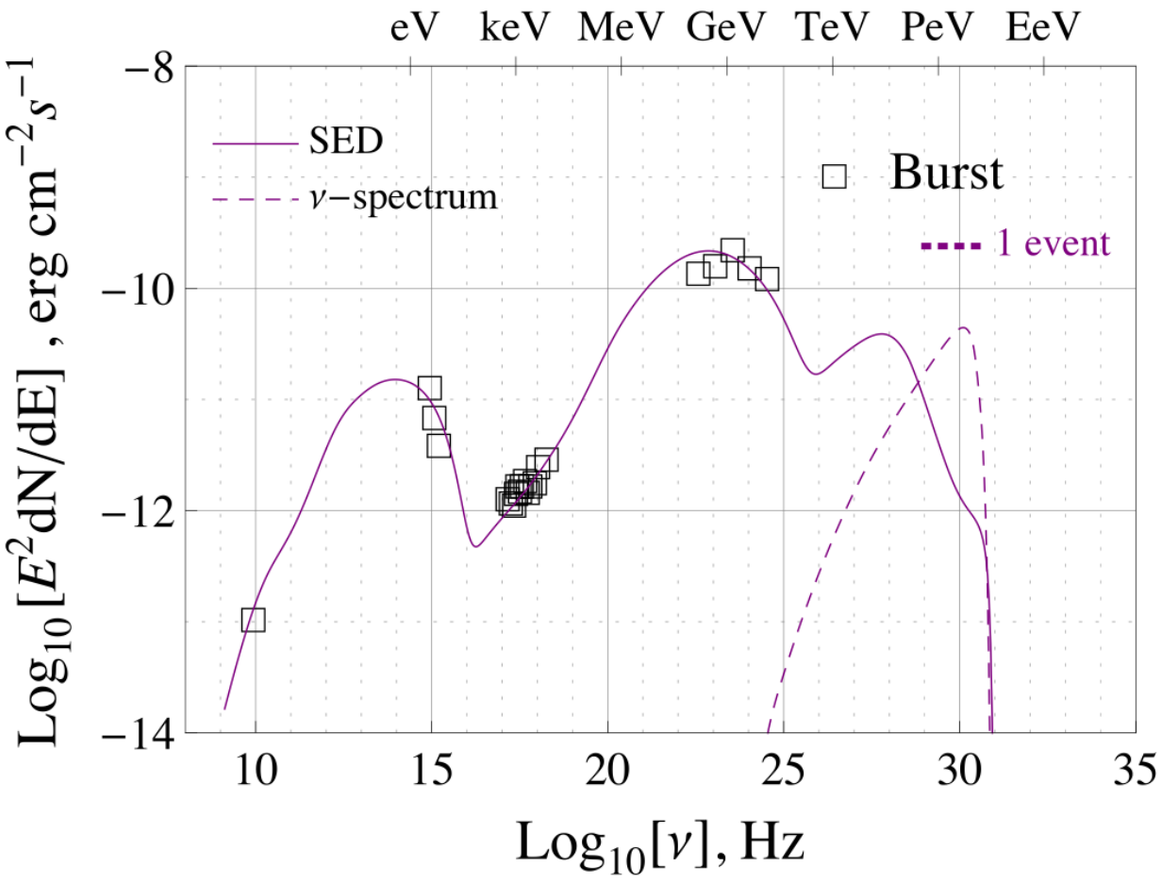
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Log10[E²dN/dE] , erg cm⁻² s⁻¹
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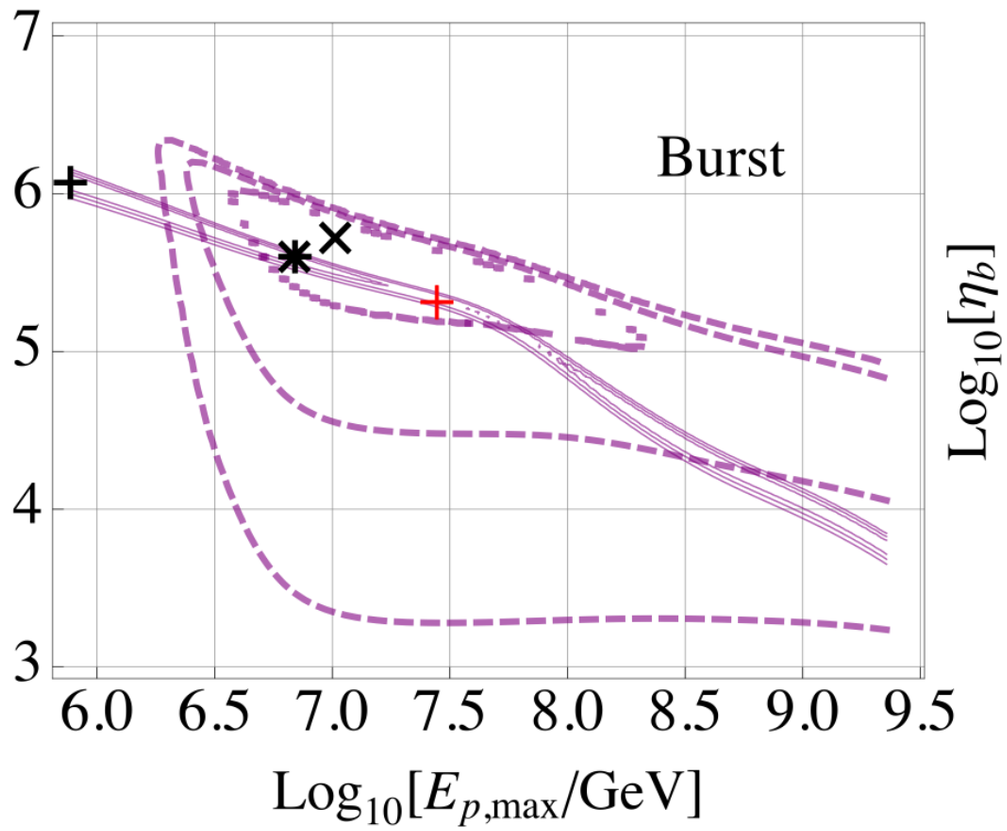
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Log10[ηb]
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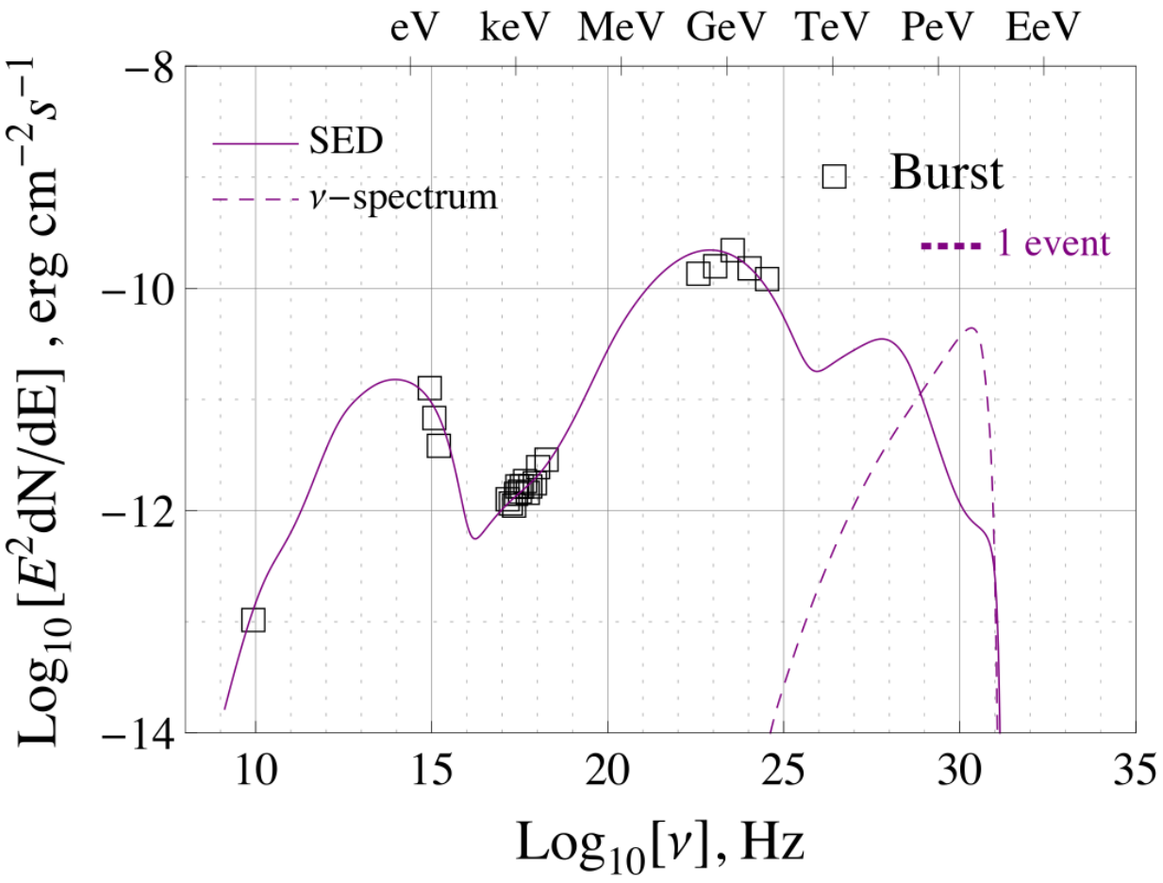
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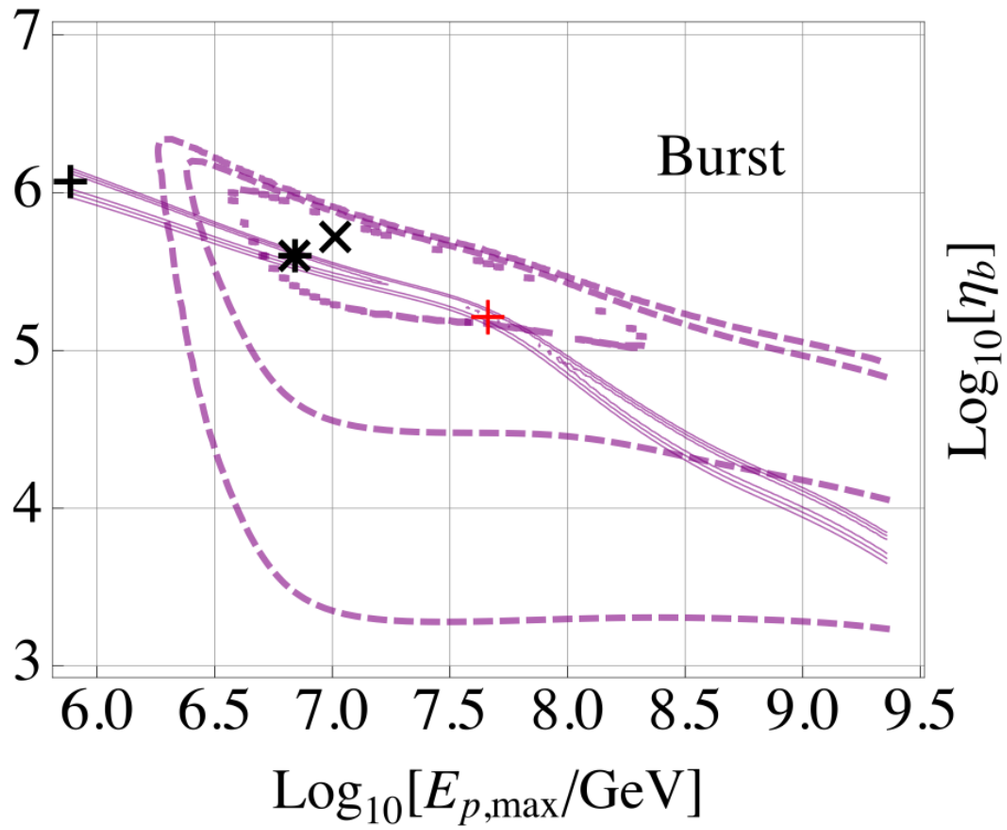
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz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Log10[ηb]
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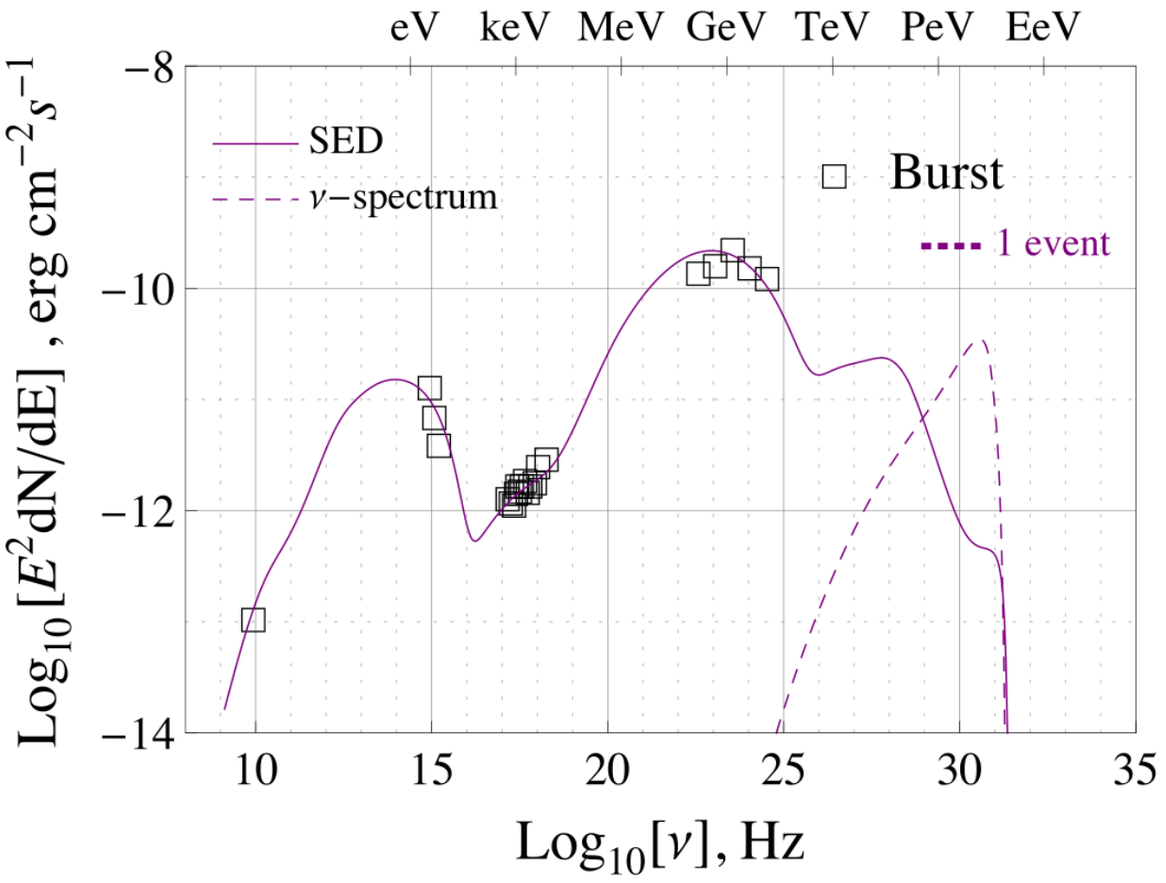
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Log10[E²dN/dE] , erg cm⁻² s⁻¹
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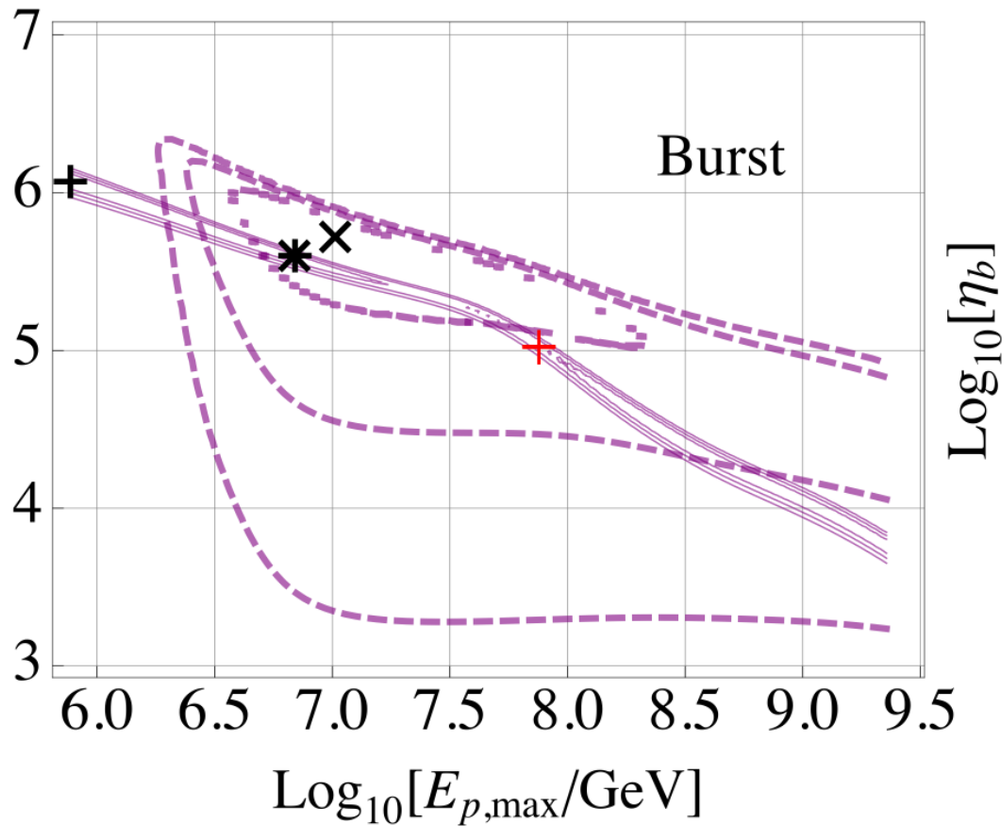
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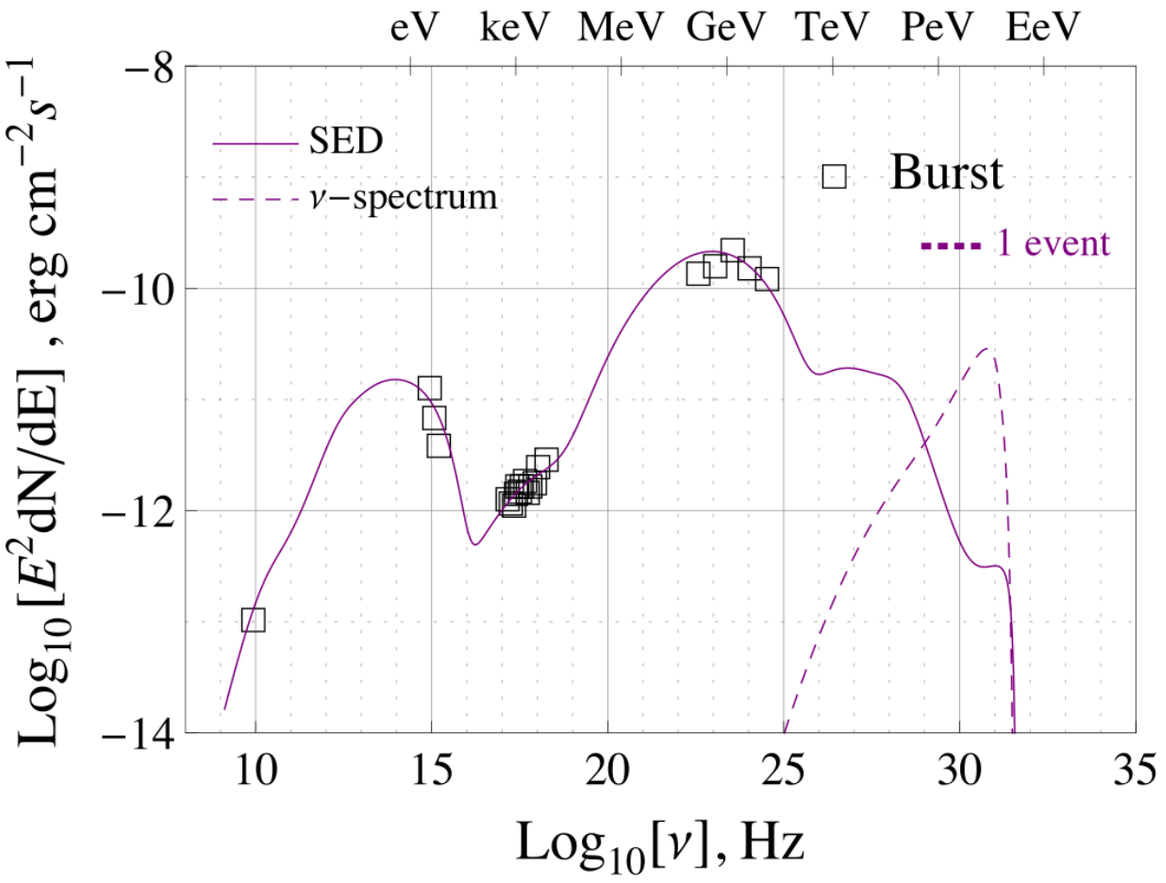
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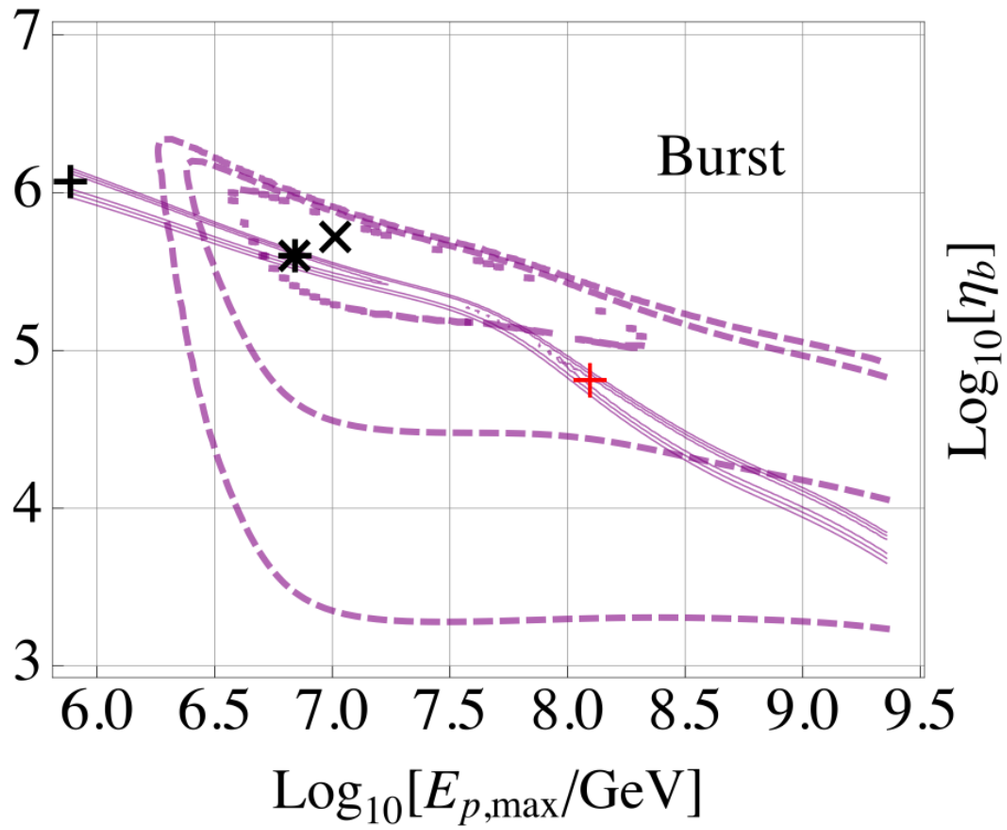
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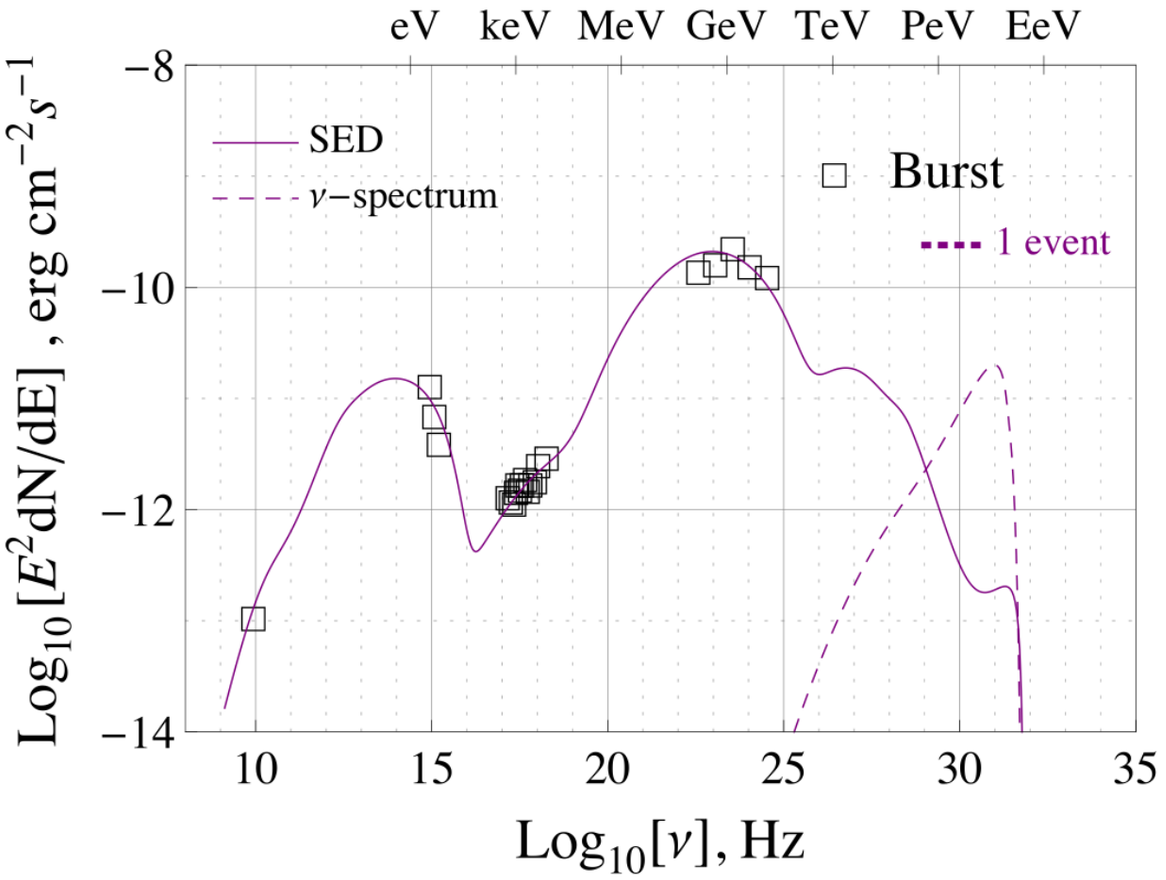
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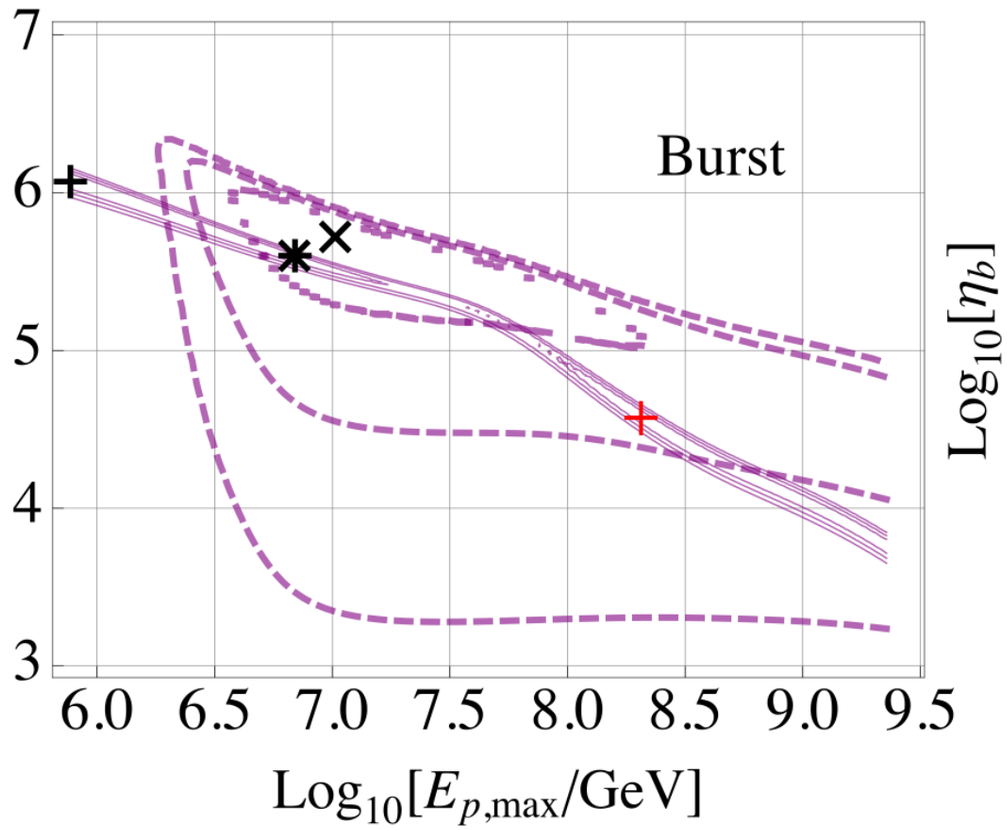
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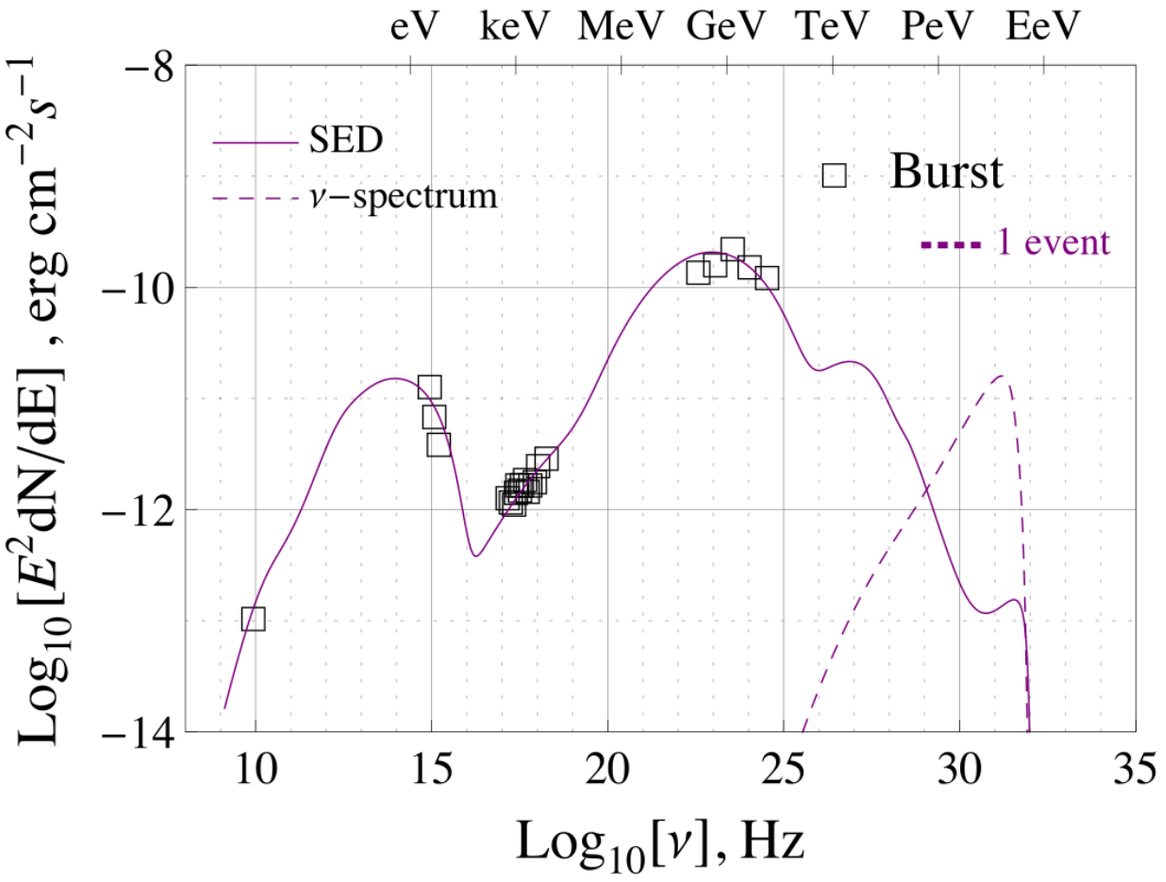
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Burst
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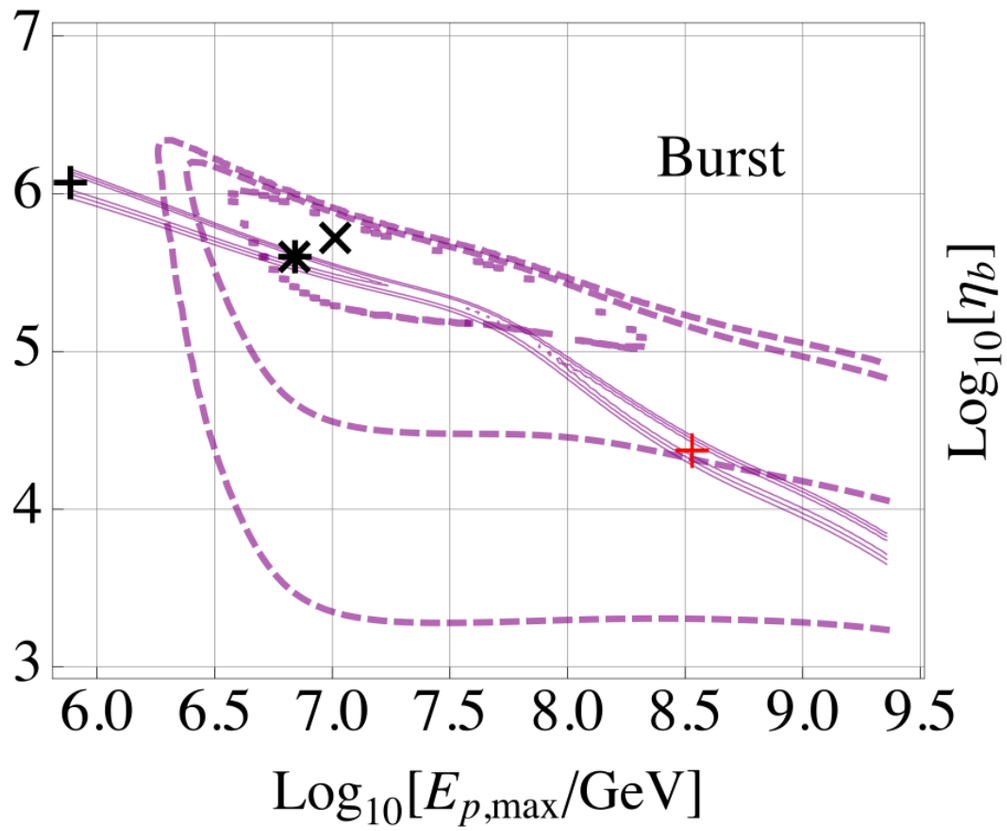
Log10[E²dN/dE] , erg cm⁻² s⁻¹
Log10[ν], Hz


Burst
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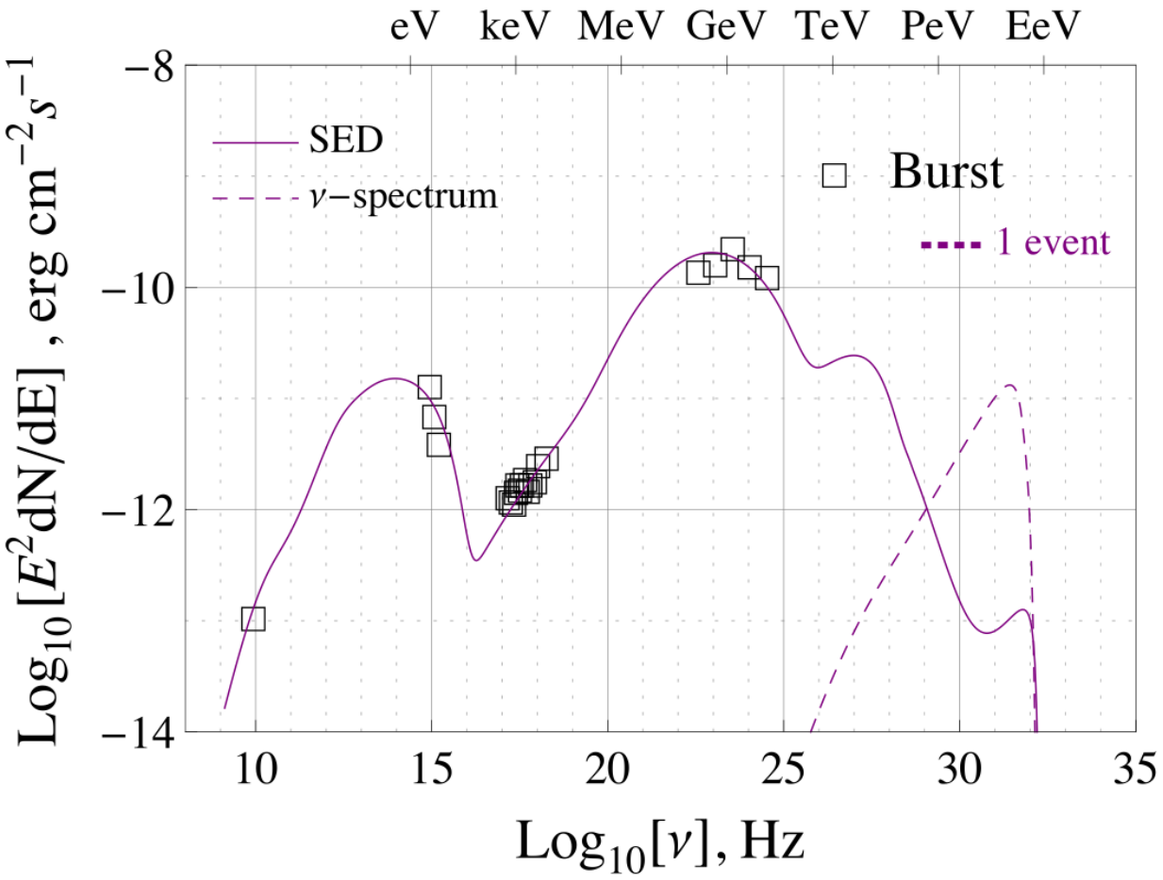
eV
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Log10[E²dN/dE] , erg cm⁻² s⁻¹
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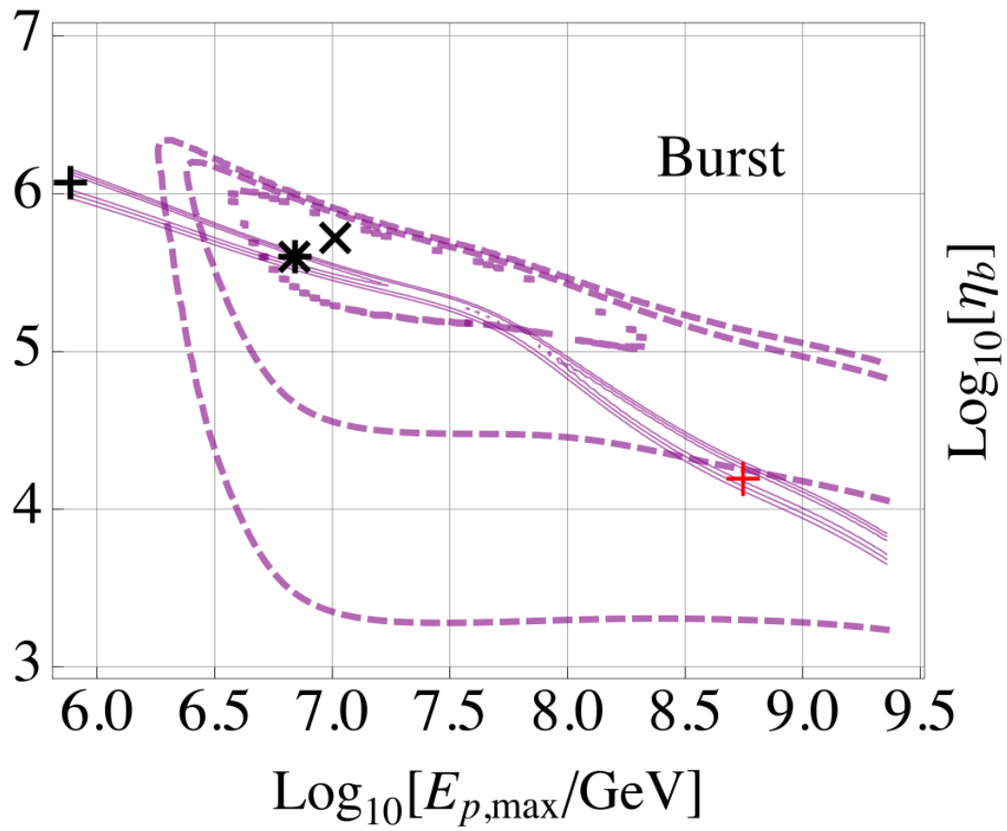
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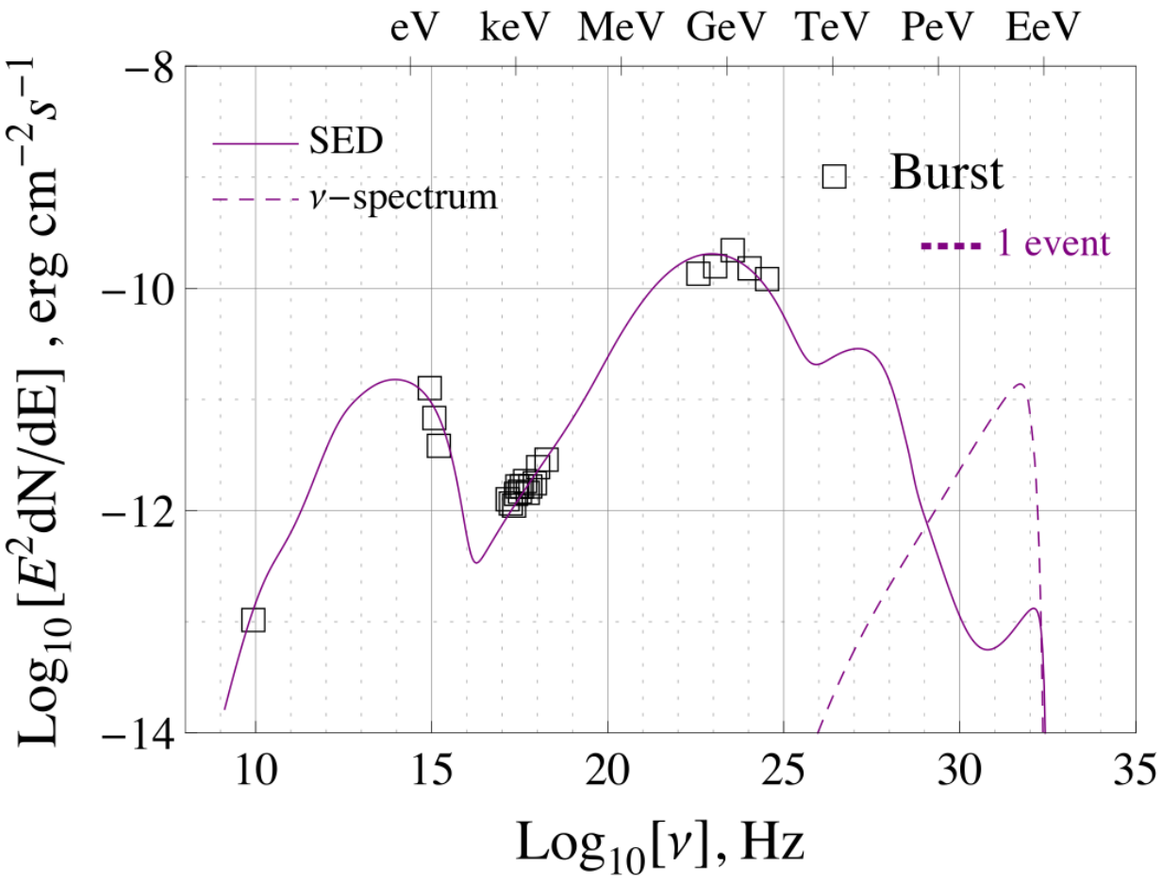
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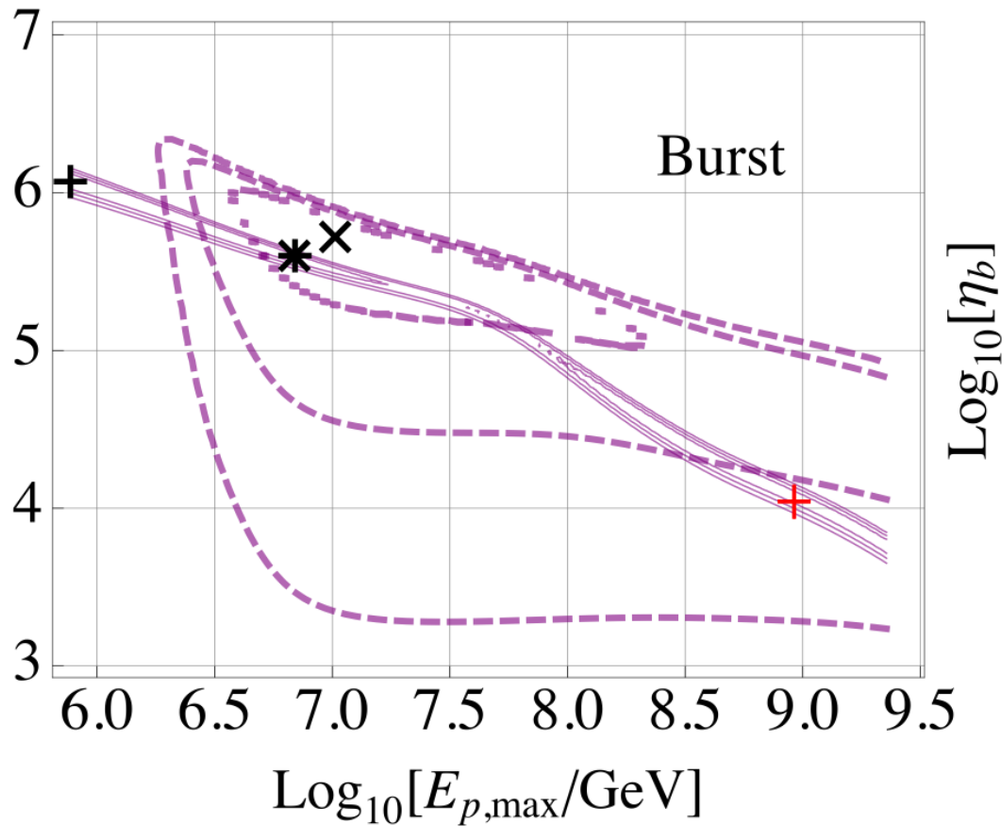
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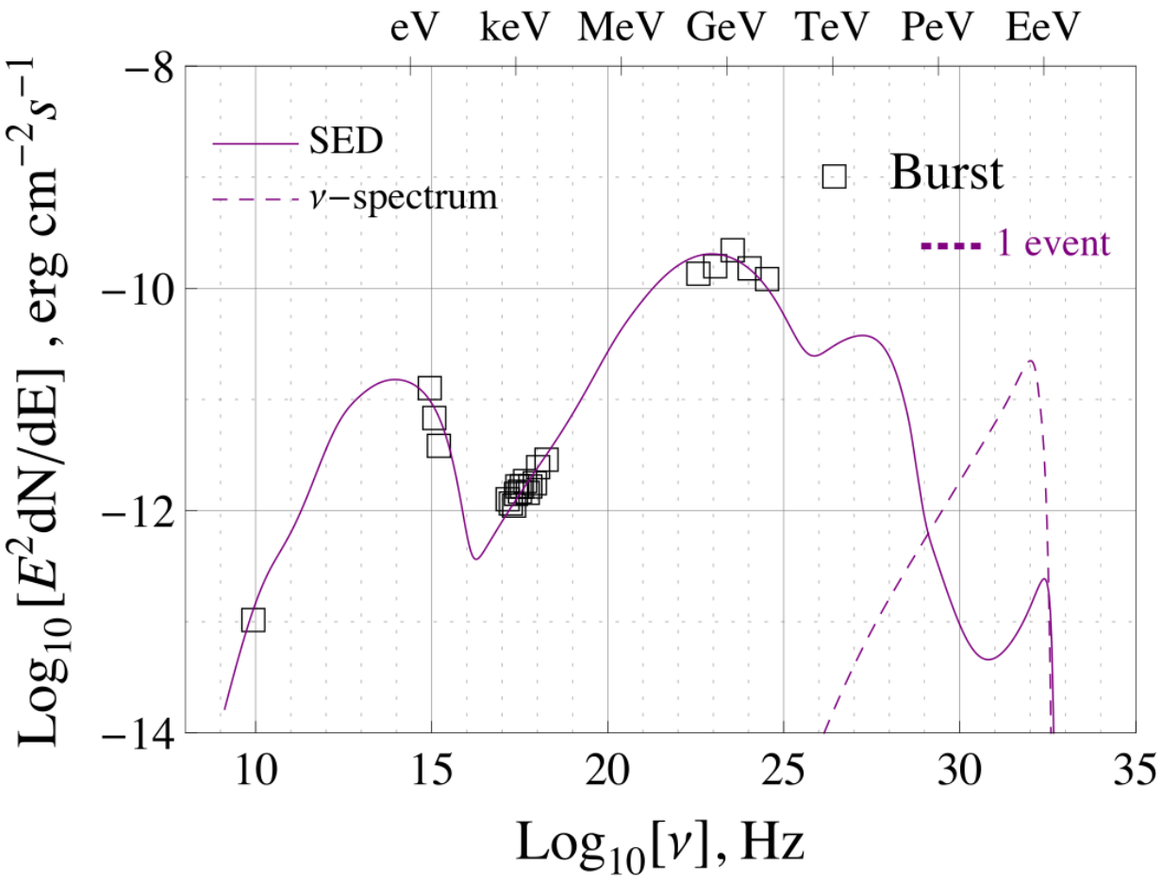
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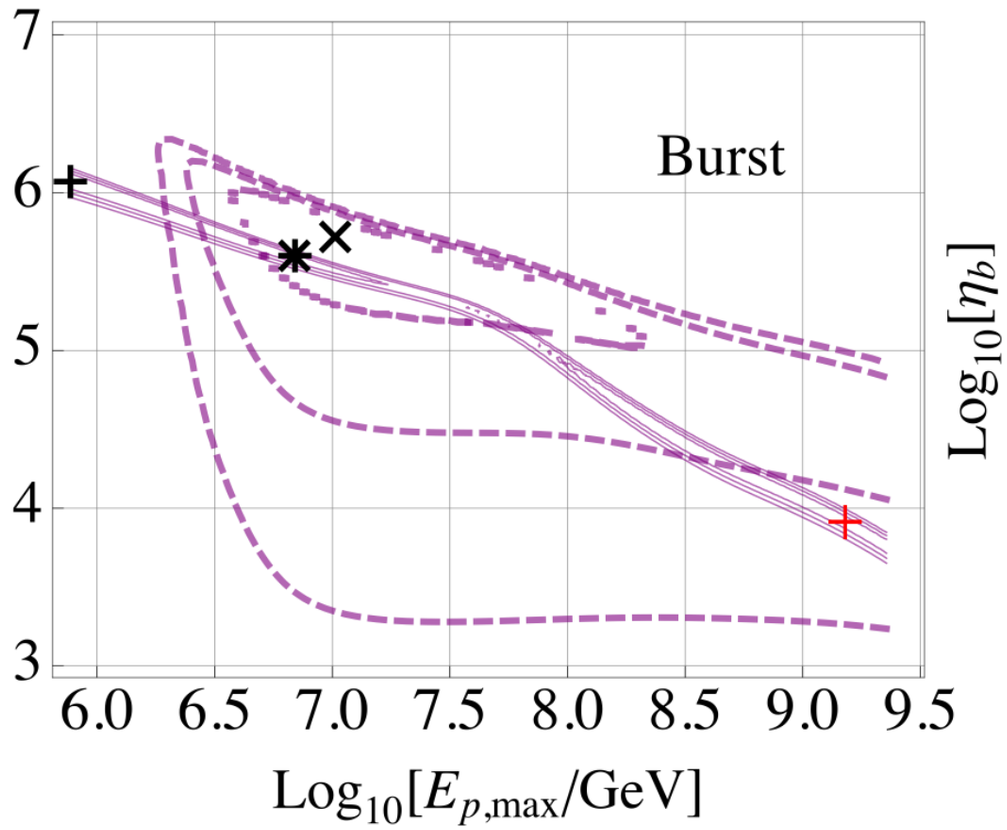
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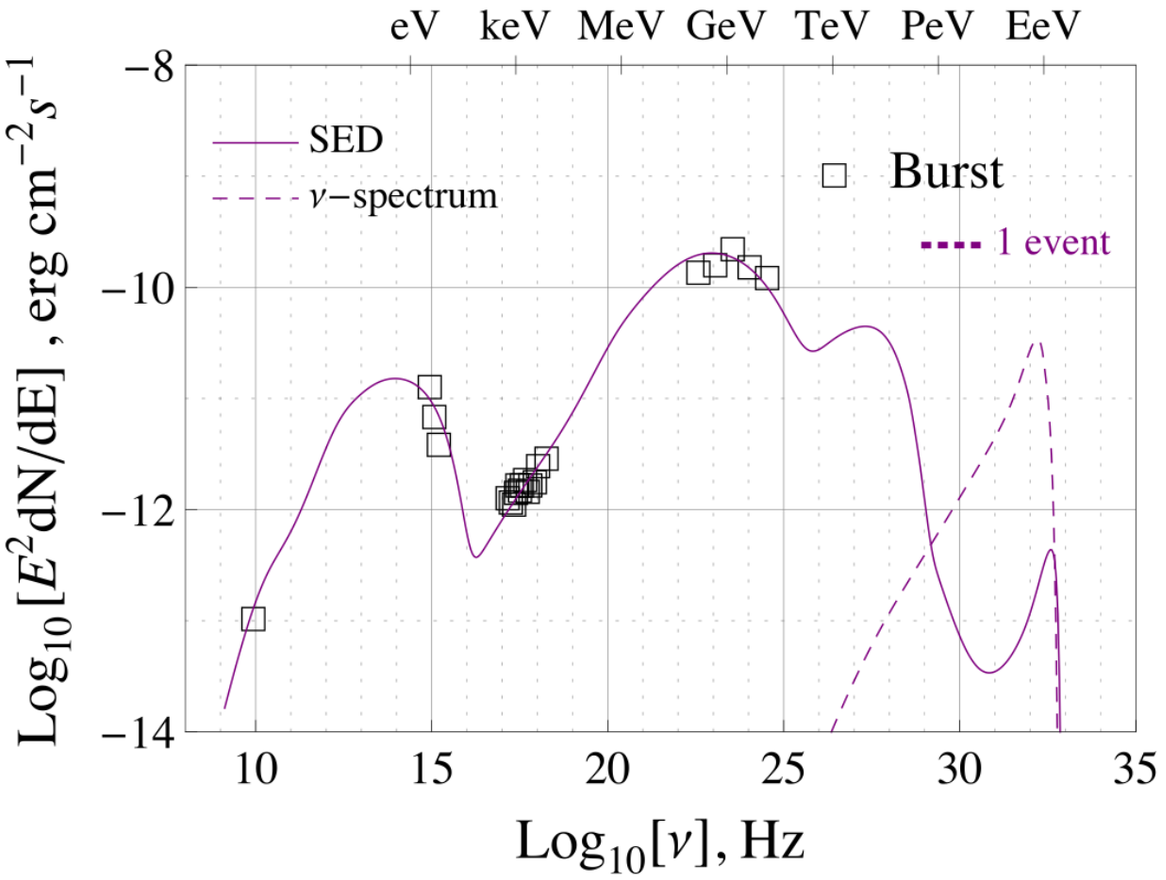
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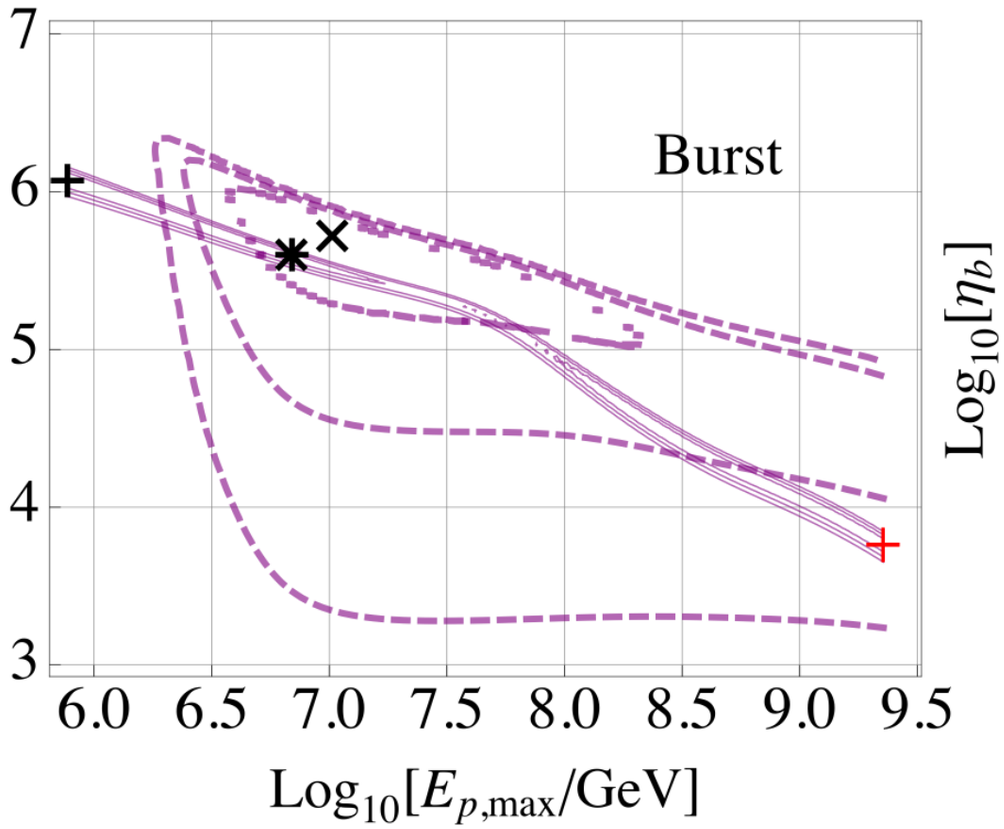
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Log10[ηb]
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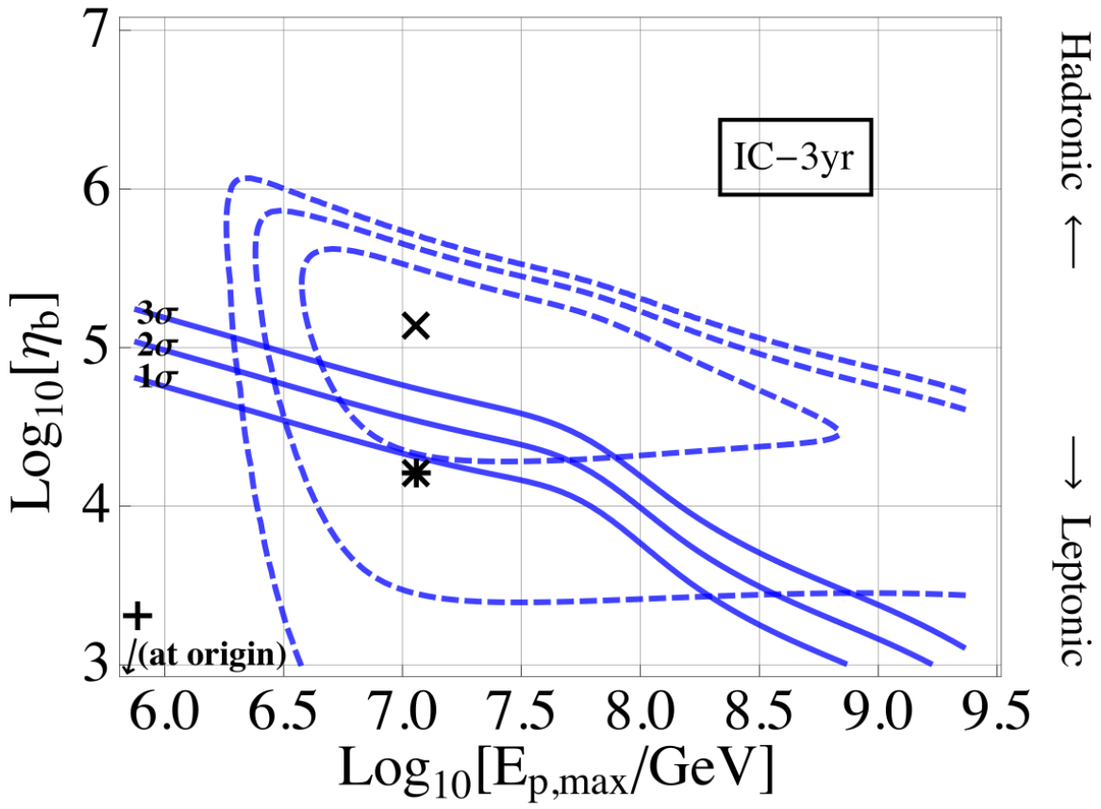
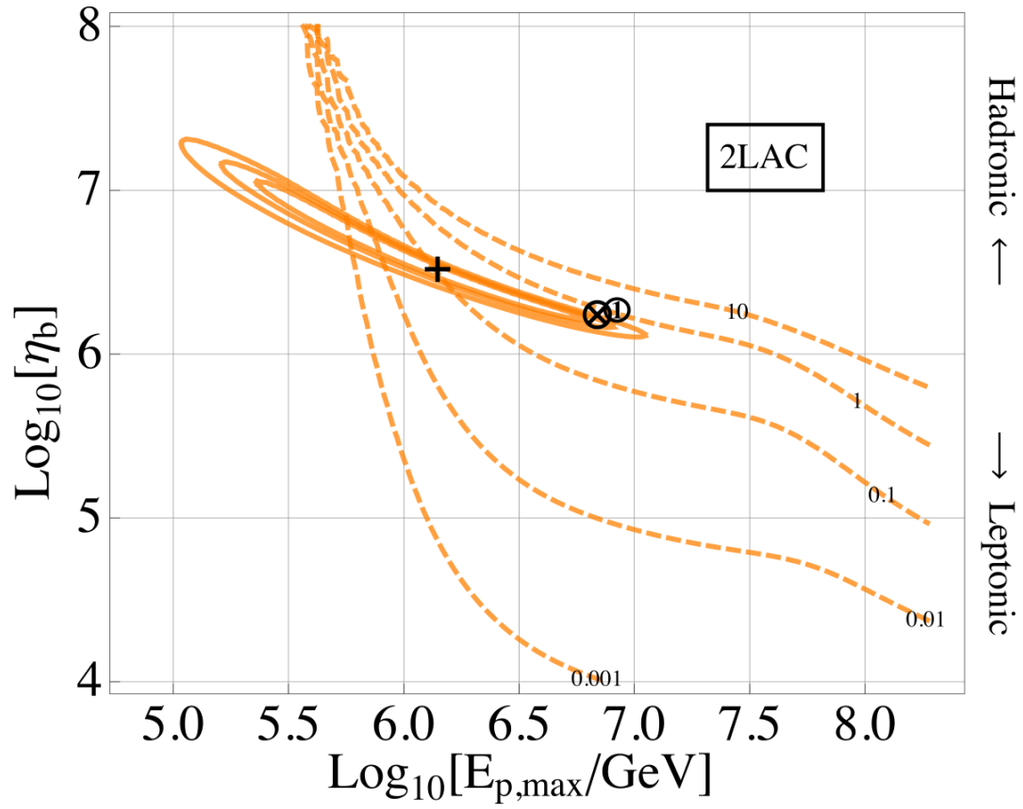
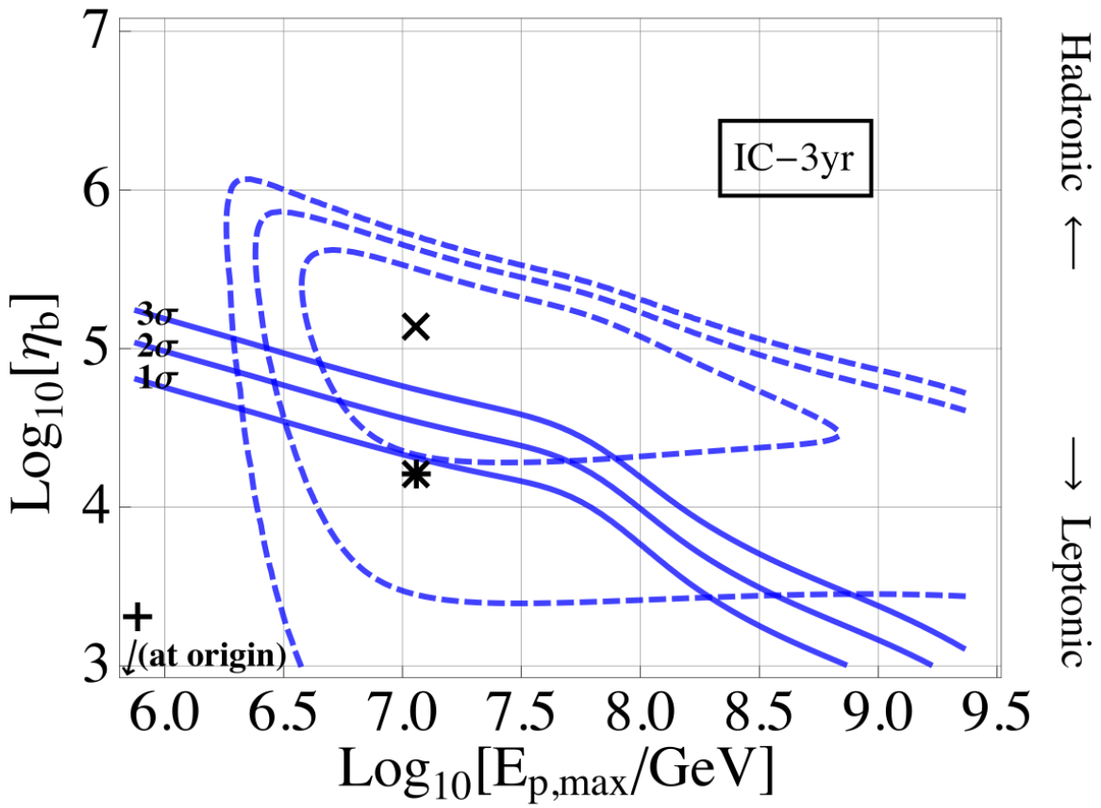
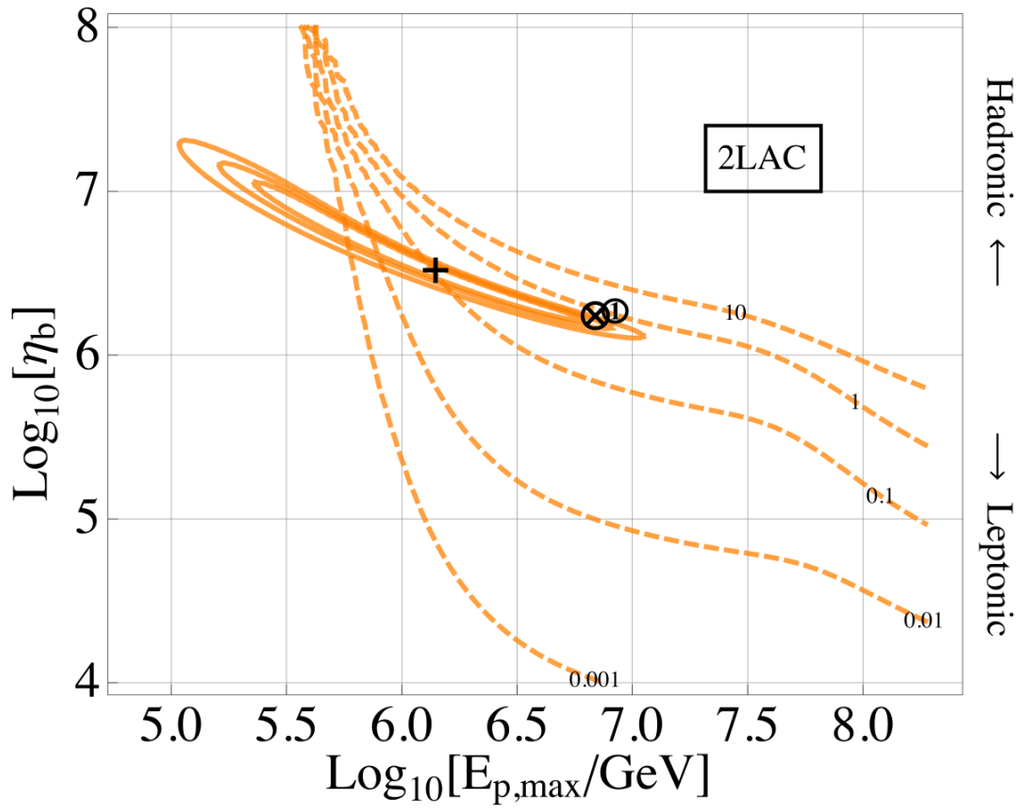
Other phases





Other phases





SED best-fit: Leptonic SSC

Question of how many protons it can tolerate.

ν best fit in tension with SED

IC 40 + 59 strings

No neutrinos

SED best fit consistent with this

Conclusions

- Caution: $L_\gamma \sim L_\nu$ OK for $\mathbf{LH\pi}$; Invalid for $\mathbf{LHs}$ or $\mathbf{LH\text{-}SSC}$ models — additional correction factor from theory.

- Degeneracy is large; ν + more MWL observation breaks it significantly.

- PKS B1424-418: able to reproduce “big-bird” event (P~5%) during both burst & IC-3yr phase.

- backup

Phase	2LAC	IC-3yr	Burst
Time	2008.9–2010.9	2010.5–2013.5	2012.5 – 2013.5
$R_{\rm blob}/{\rm cm}$		7.5×10^{17}	
$\Gamma_{\rm bulk}$		35	
$B'/{\rm mG}$	3.0	3.7	2.5
$L_{\rm e,inj}/L_{\rm edd}$	5.9×10^{-6}	1.7×10^{-5}	1.7×10^{-5}
$\gamma'_{\rm e,min}$	1.6×10^{3}	1.5×10^{3}	3.3×10^{3}
$\gamma'_{\rm e,max}$	1.5×10^{5}	1.1×10^{5}	1.6×10^{5}
$\alpha'_{\rm e,idx}$	-2.2	-2.3	-2.1
$\alpha'_{\rm p,idx}$		-2.0	

Fit symbol	+	$\otimes$	①	+	✳	×	+	✳	×
Fit	SED	Tab. 2	Tab. 2	SED	joint	ν	SED	joint	ν
$\eta_{\rm b}/10^5$	32	17	18	0	0.16	1.3	12	3.9	5.1
$E^{\rm ob}_{\rm p,max}/{\rm PeV}$	1.67	8.3	10.1	-	13.7	13.7	0.92	8.3	12.4
N_ν, 0.5 – 1.6 PeV	0.11	0.51	0.74	0	0.066	0.69	0.008	0.25	0.68
N_ν, 1.6 – 2.4 PeV	0	0.10	0.18	0	0.017	0.18	0	0.050	0.19
N_ν, $>$ 2.4 PeV	0	0.038	0.10	0	0.071	0.17	0	0.017	0.15
$P_{0,1,0}(E_{\rm p,max},\eta_{\rm b})$, %	-	-	-	0	1.6	6.4	0	3.6	6.7
photon SED χ^2/d.o.f.	1.0	1.6	5.6	1.0	1.09	3.9	1.0	1.06	33

Pure Hadronic Model

$$E_\nu \approx 0.05\, E_p$$

NU E is ~5% of parent proton

$$\gamma'_p = 5\times10^{6}\,\Gamma_{10}^{-1}\,E^{\rm ob}_{\nu,\rm PeV}$$

Derived p Lorentz factor

$$h\,\nu'_{\rm pk1}\,/\,m_e\,c^2 = \left(m_e\,/\,m_p\right)\left(B\,/\,B_{\rm crit}\right)\gamma'^{\,2}_p$$

Freq. of 1st peak by p-syn

$$B = 7\times10^{-4}\left(\frac{\nu_{\rm pk1}}{10^{14}\ {\rm Hz}}\right)\left(\frac{\Gamma}{10}\right)\left(\frac{E^{\rm ob}_\nu}{\rm PeV}\right)^{-2}$$

Required B field

$$\gamma'_{e|{\rm p}\gamma}\,m_e \approx 0.05\,m_p\,\gamma'_p$$

Secondary e+- E is ~5% of parent proton

$$h\,\nu'_{\rm pk2}\,/\,m_e\,c^2 = \left(B\,/\,B_{\rm crit}\right)\gamma'^{\,-2}_{e|{\rm p}\gamma}$$

2nd peak by synchrotron emission of secondaries

$$B = 3\times10^{-2}\left(\frac{\nu^{\rm ob}_{\rm pk2}}{10^{23}\ {\rm Hz}}\right)\left(\frac{\Gamma}{10}\right)\left(\frac{E^{\rm ob}_\nu}{\rm PeV}\right)^{-2}$$

Required B field

Requires contradictory B field values >> Pure Hadronic Model not viable

Leptonic and LH-SSC model

$$\gamma^2\,\nu_{\rm sy} = \nu_{\rm IC}$$

$$\gamma_{\rm KN}\,h\,\nu'_{\rm sy} = m_e\,c^2$$

Thomson to KN scattering transition

$$\frac{\gamma}{\gamma_{\rm KN}} = 0.006\left(\frac{\nu_{\rm sy}}{10^{14}\,{\rm Hz}}\,\frac{\nu_{\rm IC}}{10^{23}\,{\rm Hz}}\right)^{1/2}\left(\frac{\Gamma}{10}\right)^{-1}$$

2nd peak by Th. , not KN

Cutoff due to $E_{e,max}$, or absorption by EBL (not discussed)

$$l_* \equiv \left(\frac{L'}{R}\right)\Big/\left(\frac{4\,\pi\,m_e\,c^2}{\sigma_T}\right) \approx 0.03\left(\frac{L_{\rm ob}}{10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}}}\right)\left(\frac{\Gamma}{10}\right)^{-4}\left(\frac{R}{10^{15}\,{\rm cm}}\right)^{-1}$$

compactness for gamma-rays

GeV - TeV γ can escape source

Leptonic and LH-SSC model

$$\gamma_e'^{\,2} \approx \nu'_{\rm sy} \Big/ \nu'_{\rm IC}$$

Thomson scattering

$$h\,\nu'_{\rm sy} = m_e\,c^2 (B'/B_{\rm crit})\,\gamma_e'^{\,2}$$

Synchrotron, ~ 1st peak

$$\nu' = \nu^{\rm ob}(1+z)\Big/\Gamma$$

$$u'_{\rm ph} = \left(\frac{d_{\rm pks}}{R_{\rm blob}}\right)^2 \left(\frac{1+z}{\Gamma^2}\right)^2 \frac{\nu F_\nu}{c}$$

comoving phot density

$$Y_{\rm SSC} \approx \frac{u'_{\rm ph}}{u'_B} \approx \frac{L(\nu_{\rm sy})}{L(\nu_{\rm IC})}$$

Y_{SSC} related to relative heights of the two peaks of SED

$$X = 10^i\, X_i$$

$$R_{18}\,\Gamma_{10} \approx 1.4 \left(\frac{L(\nu_{\rm sy})}{10^{-11}\ {\rm erg\,cm^{-2}}\ s^{-1}} \Big/ Y_{\rm SSC}\right)^{1/2} \left(\frac{\nu_{\rm sy}^{\rm ob}}{10^{14}\ {\rm Hz}}\right)^{-2} \left(\frac{\nu_{\rm IC}}{10^{23}\ {\rm Hz}}\right)$$

Expressed in all observed quantities

Requires either large R or Γ values

Numerical Calculation

Diff-integral Equations

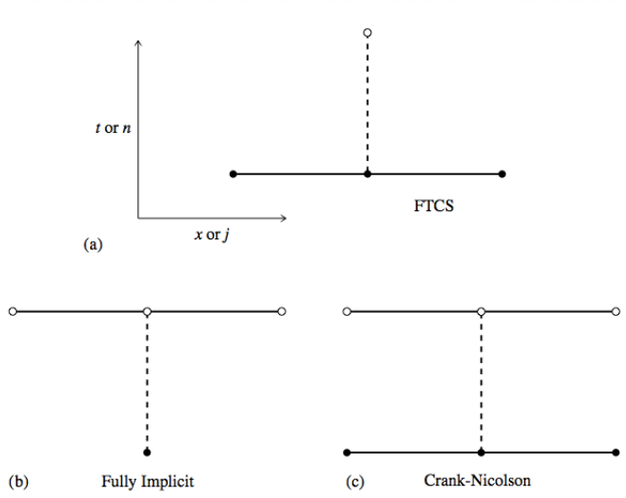
$$\frac{\partial n(E)}{\partial t} = -\frac{\partial}{\partial \ln E}\left[A(E) - B(E)\,\frac{\partial}{\partial \ln E}\right] n(E) - \alpha\, n(E) + \epsilon$$

Solving time-dependent coupled kinematic equations for e^-, e^+, p, n, γ, ν

$$n(E) \equiv \frac{d\,N}{d\,V\,d\ln x} = x\,\frac{d\,N}{d\,V\,d\,E}$$
$$\alpha(E) = \sum_{\rm IT} \int c\,\sigma_{\rm IT}\; n_{\rm IT}(E_1)\,{\rm dE}_1$$
$$\epsilon(E) = \sum_{\rm IT}\; \int R(E \leftarrow E_1)\,d\,n_{\rm IT}(E_1)$$

Coefficients derived from physics

Numerical Scheme : Finite Difference



Chang & Cooper for E

Crank & Nicohlson for t

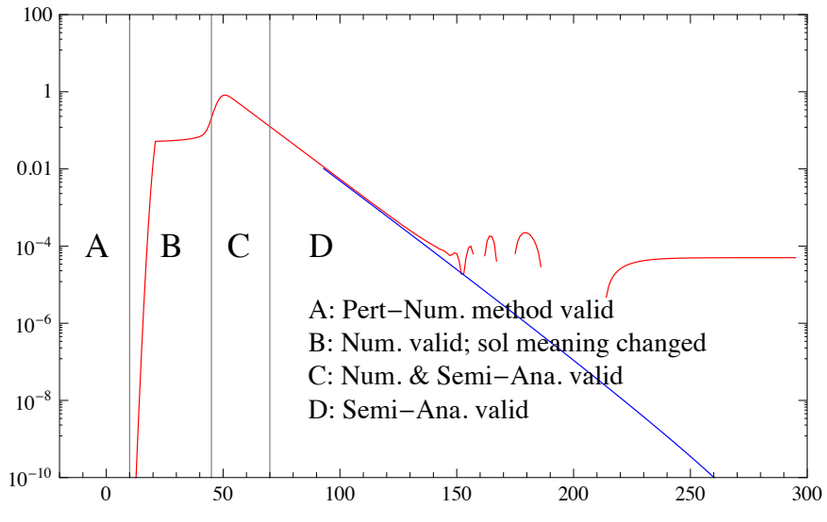
Stability + Energy conservation + Positive spectrum (even when dt and dN/dE is large)

Approximation

Semi-analytical solution for VHE e quasi-steady states within a step Δt

>> reasonable Δt and high efficiency

resolving the stiffness problem at VHE



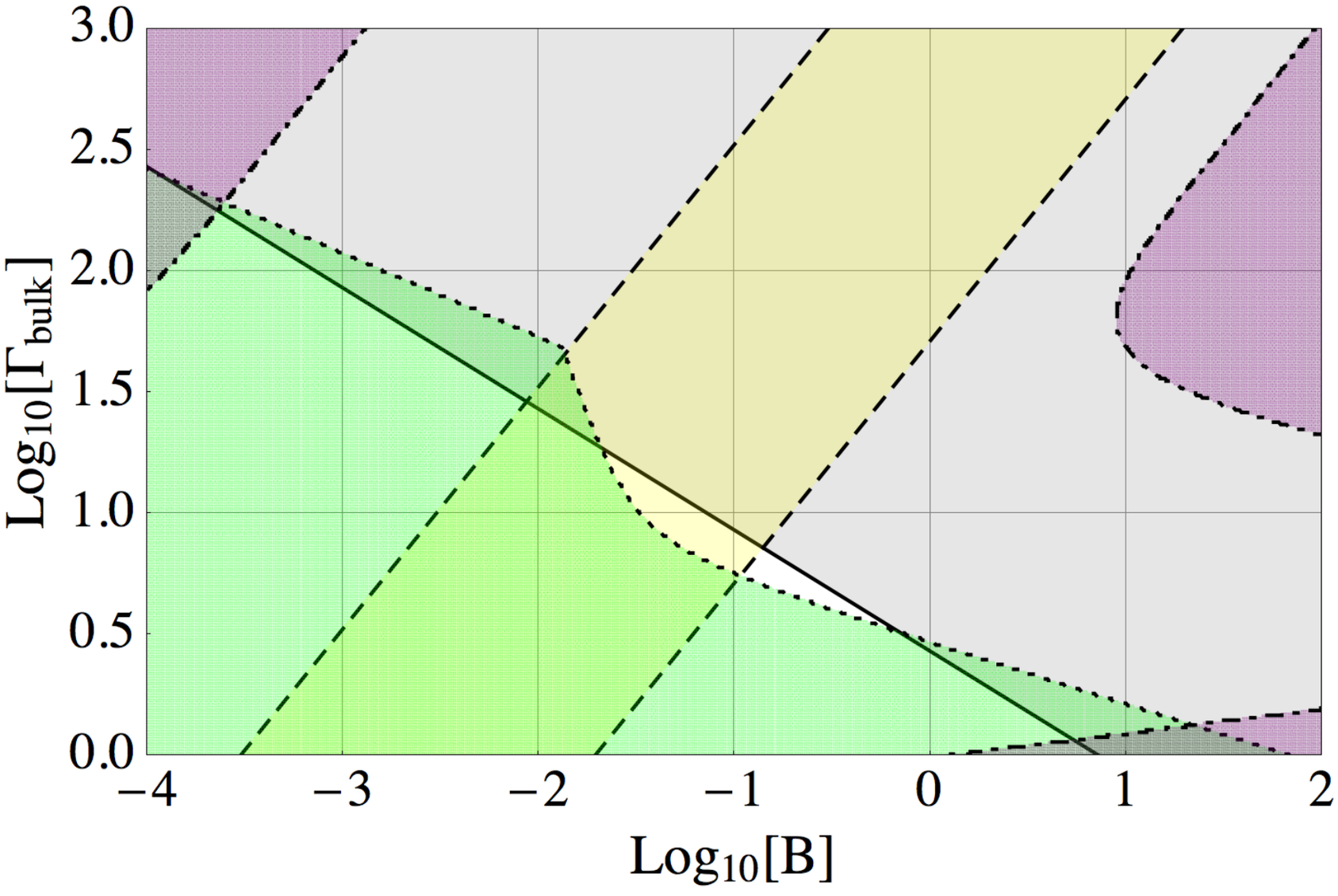
LHπ model

Allowed region : $F_{psyn} < SED$

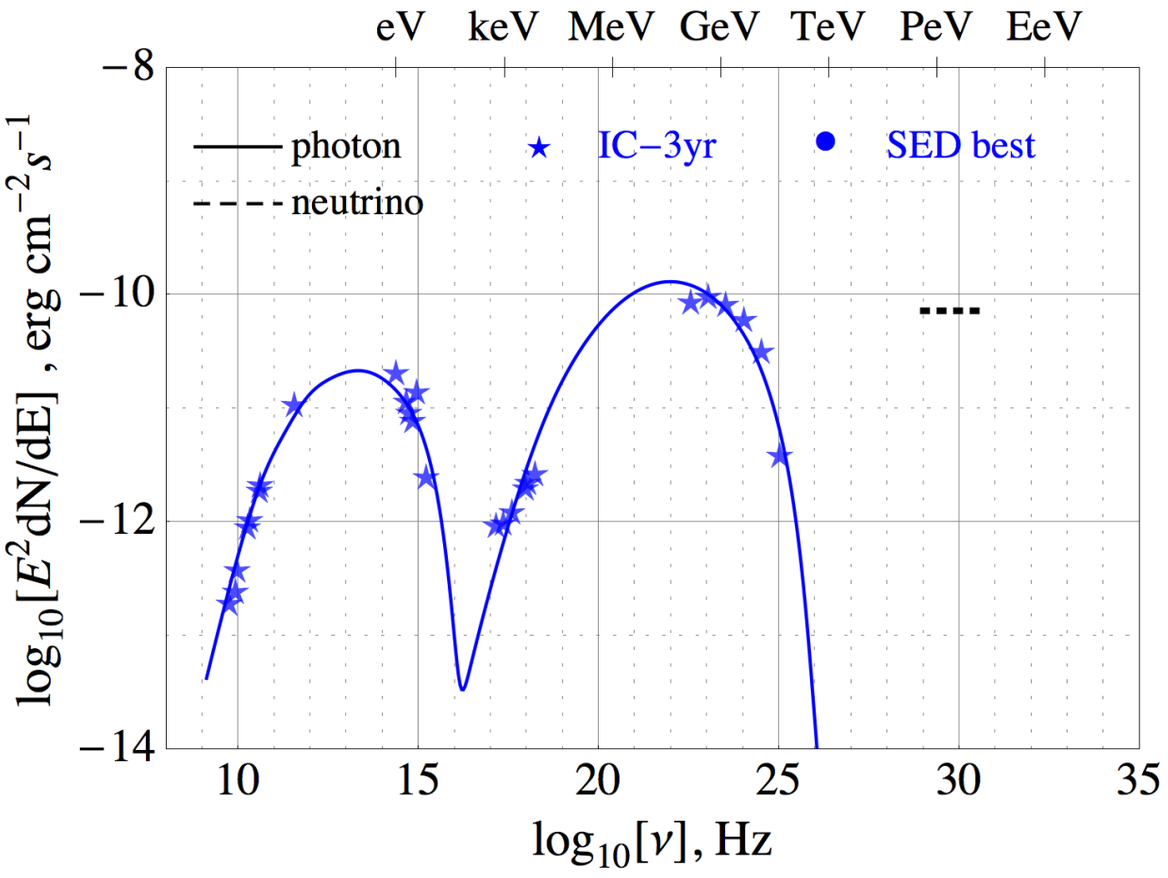
Allowed region : $Y_{SSC} < 1$ (otherwise SSC model)

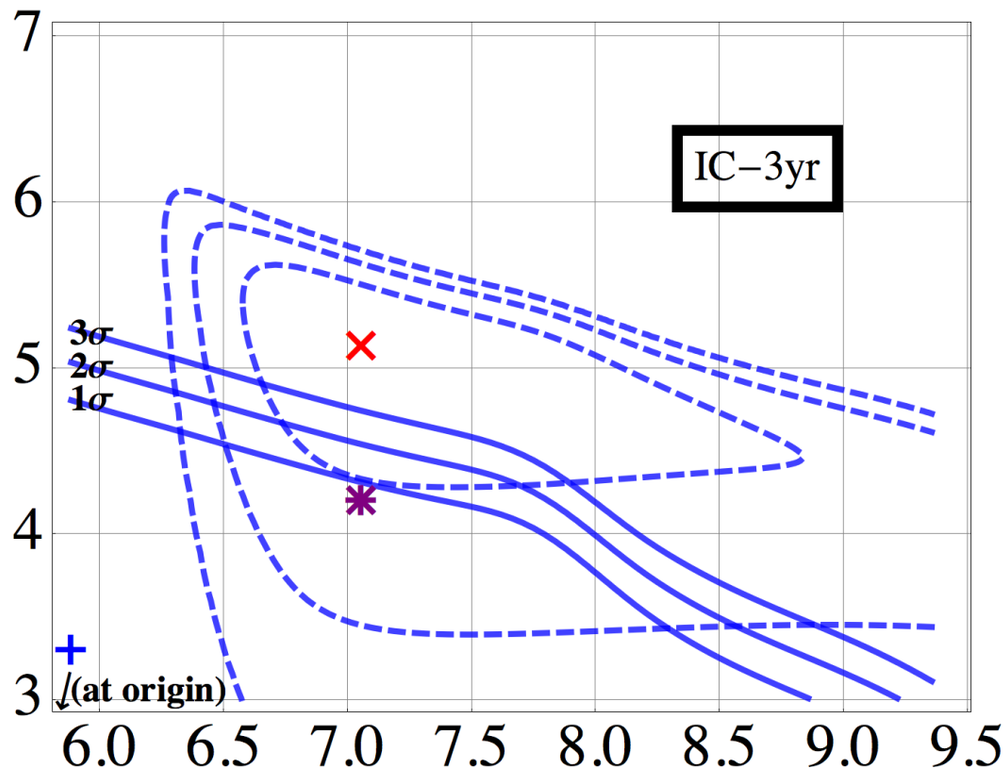
Allowed region : $F_{BH} < SED$

Allowed region where $E_{syn,VHE\ Lep} \sim E_{pk2,obs}$



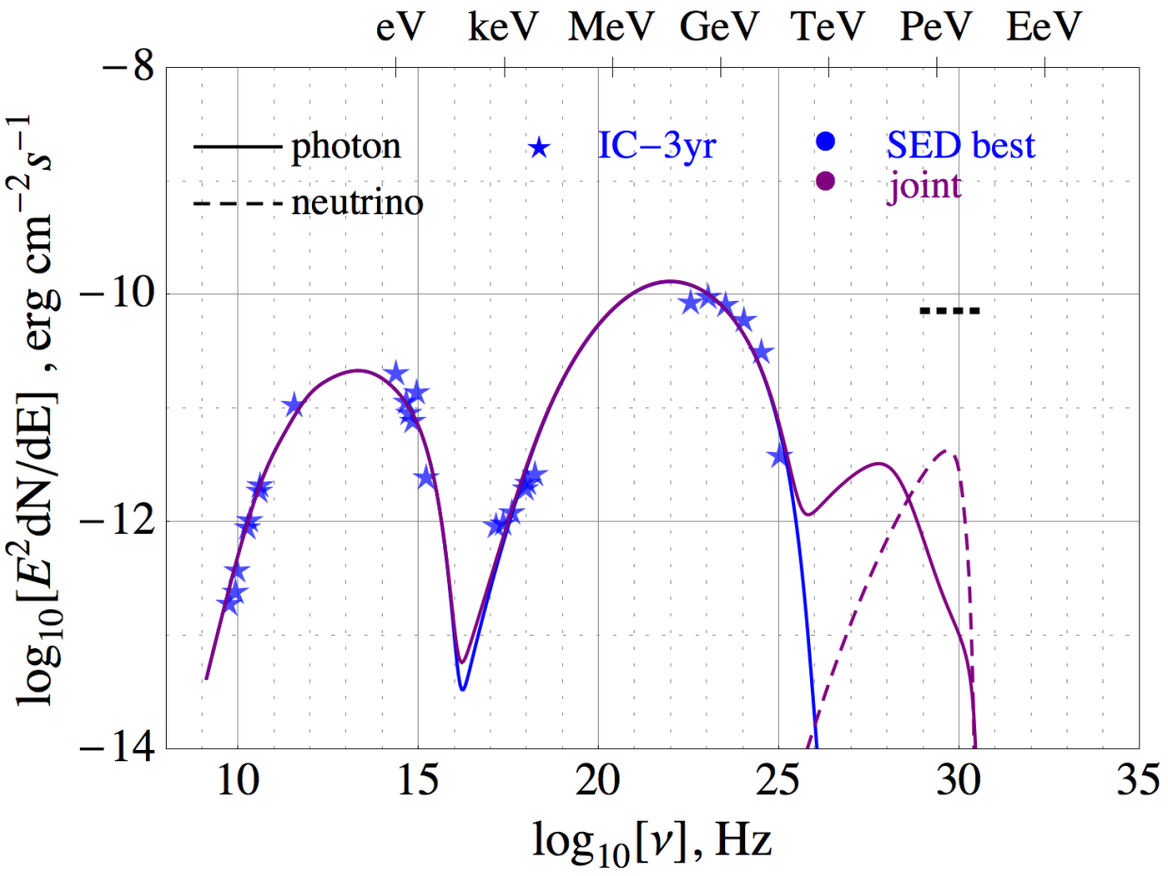
IC-3yr phase

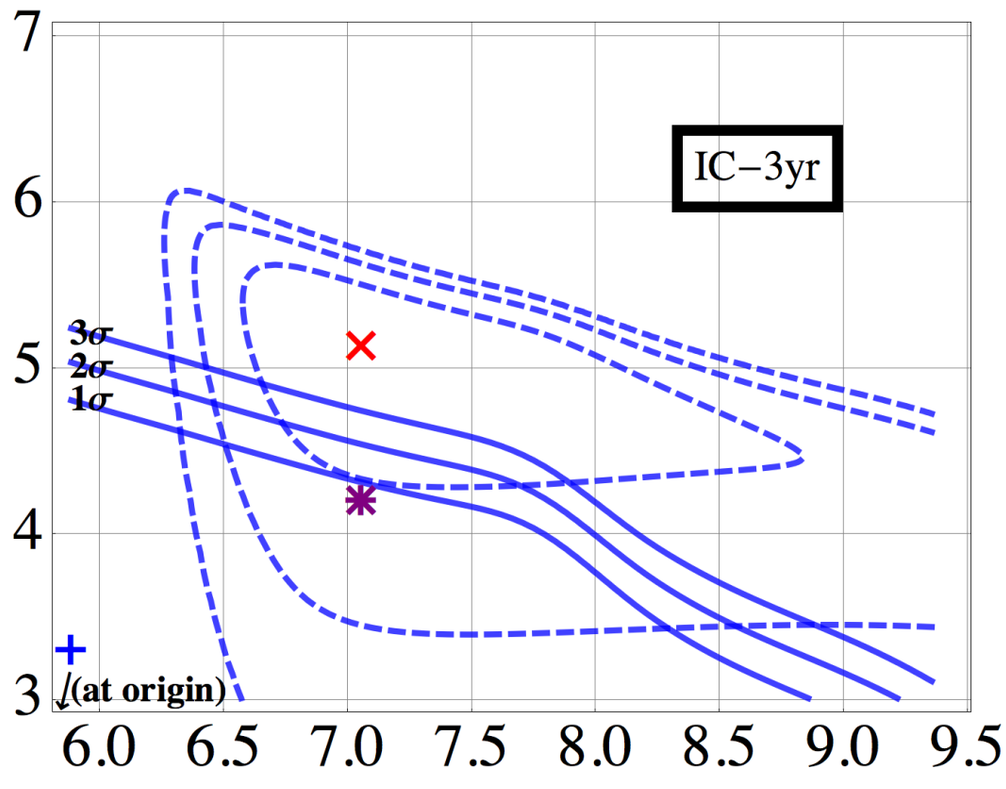




SED best fit, a leptonic SSC-model

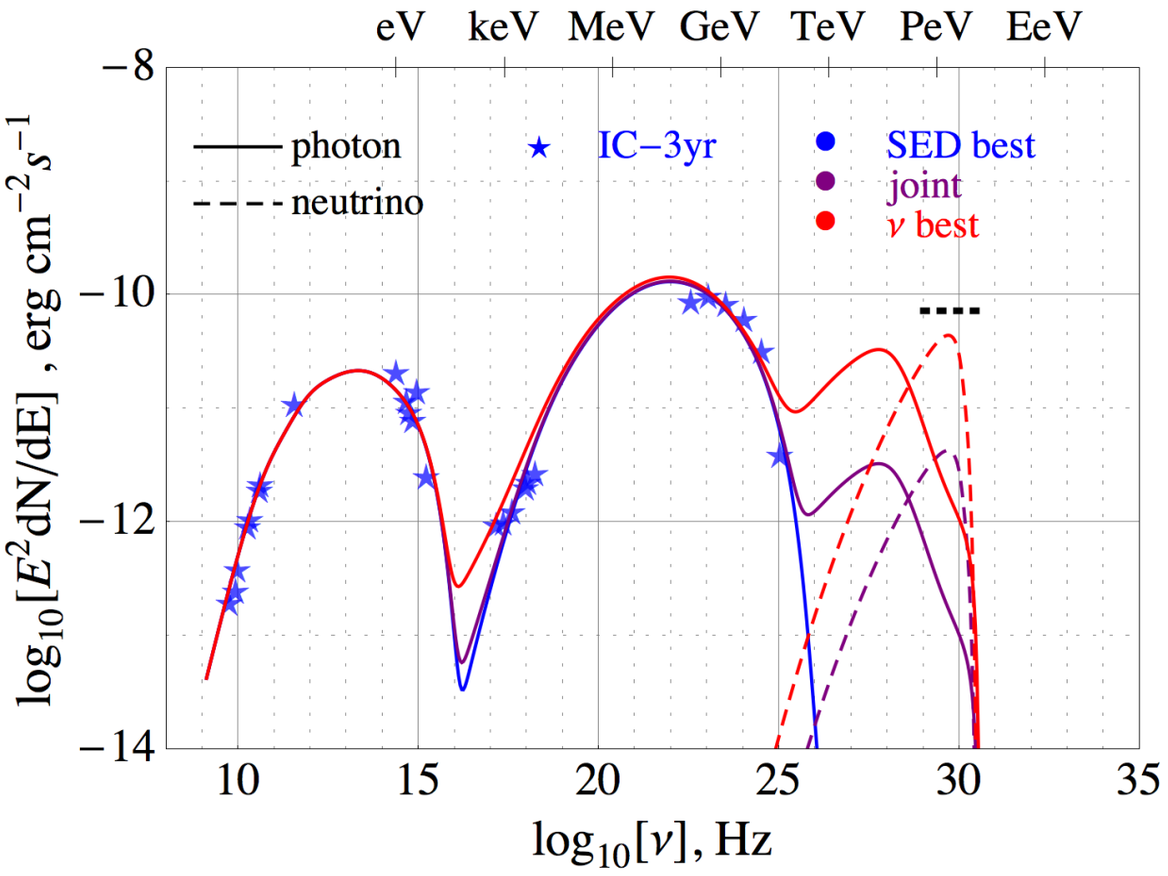
IC-3yr phase

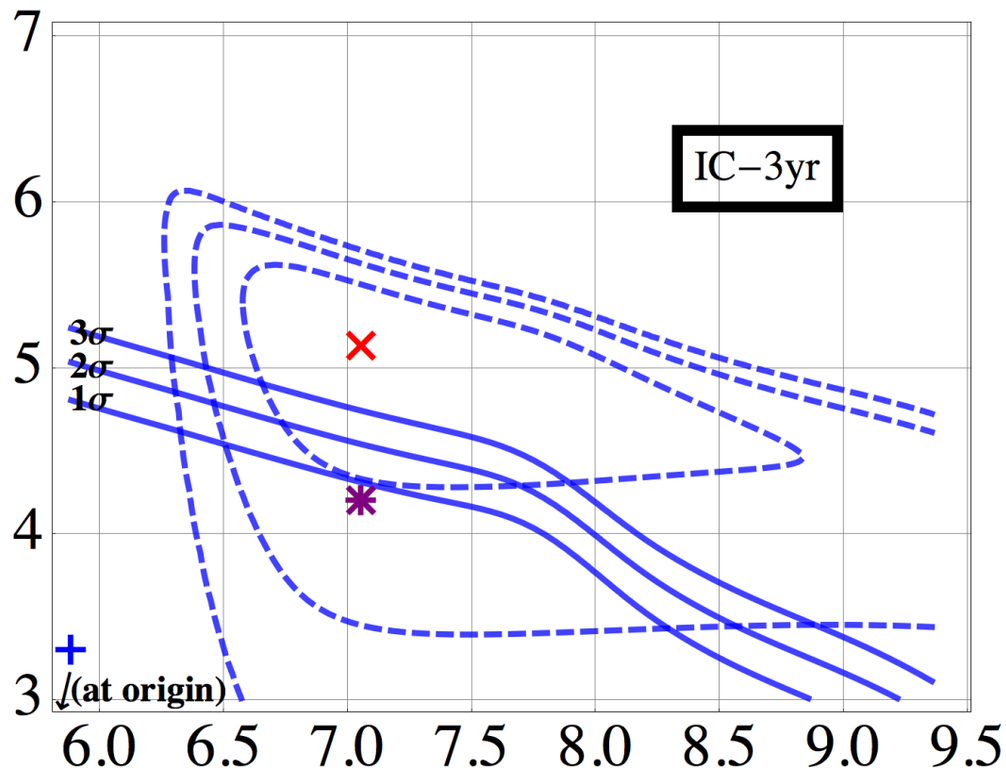




SED - neutrino joint best-fit, $L_p/L_e \sim 10^4$

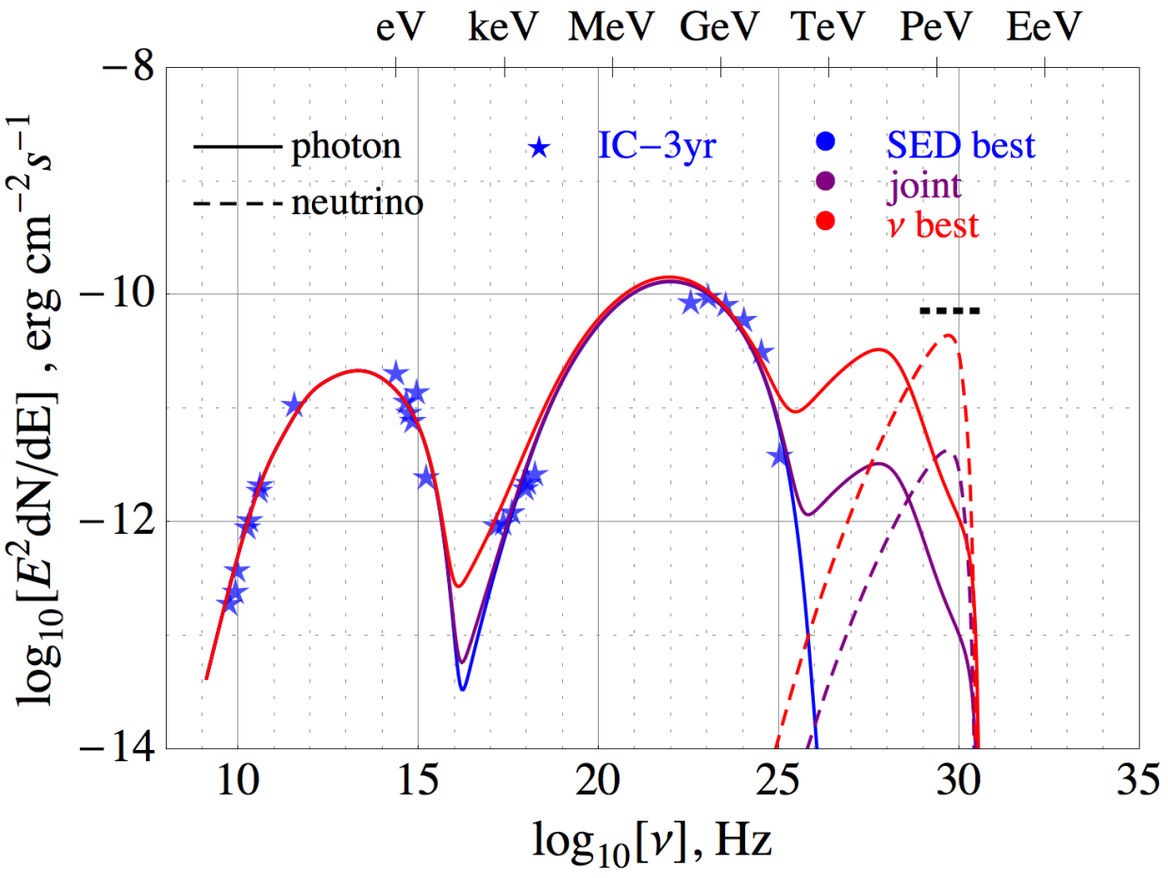
IC-3yr phase

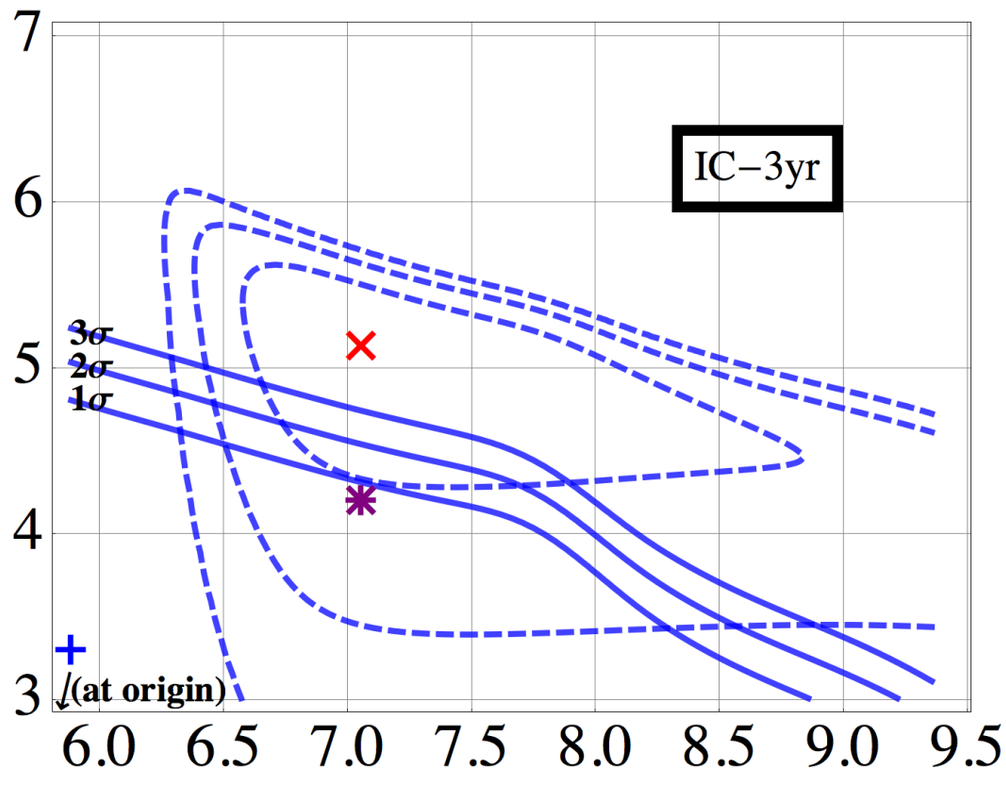




neutrino best-fit, $L_p/L_e \sim 10^5$

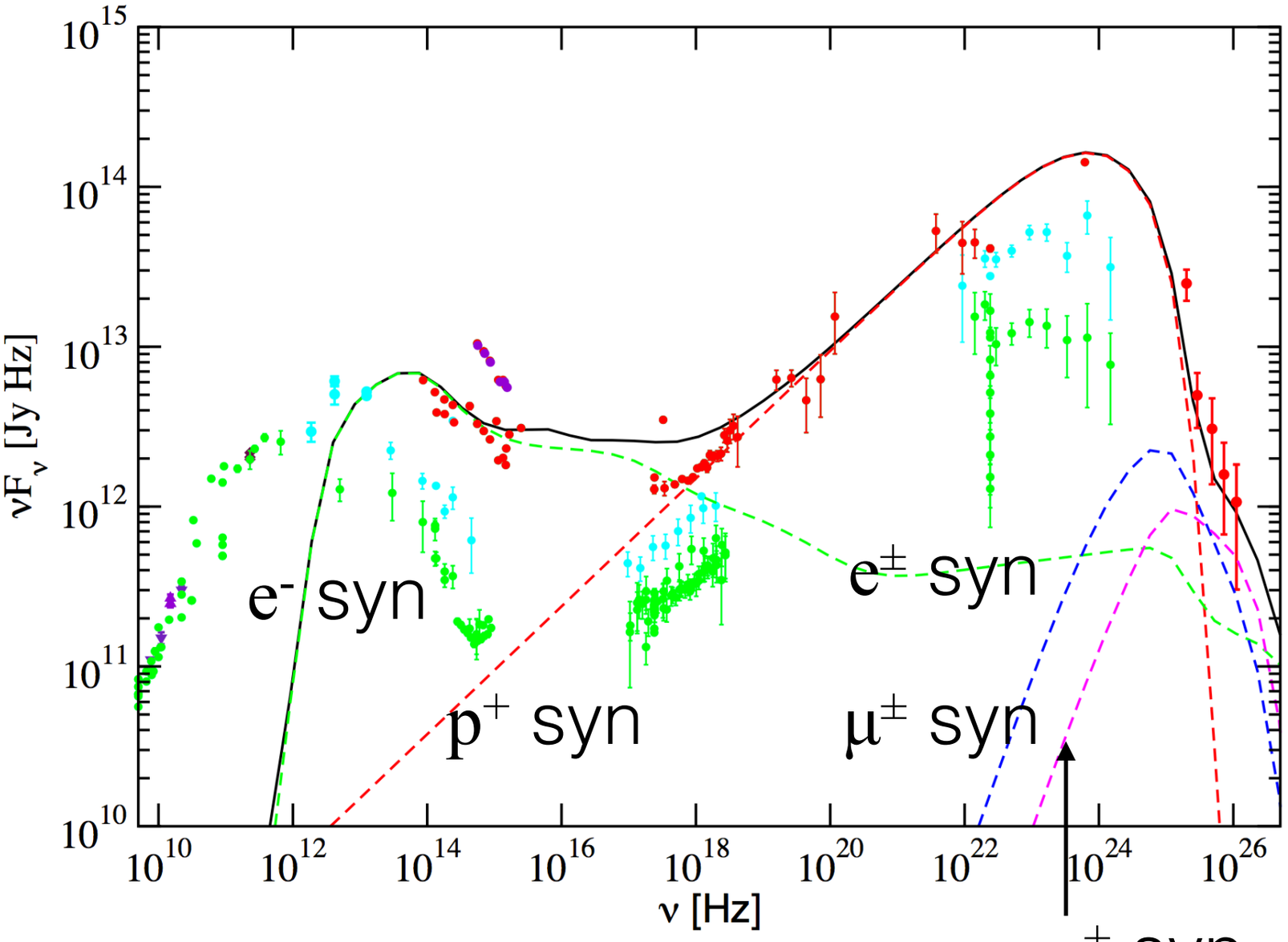
IC-3yr phase





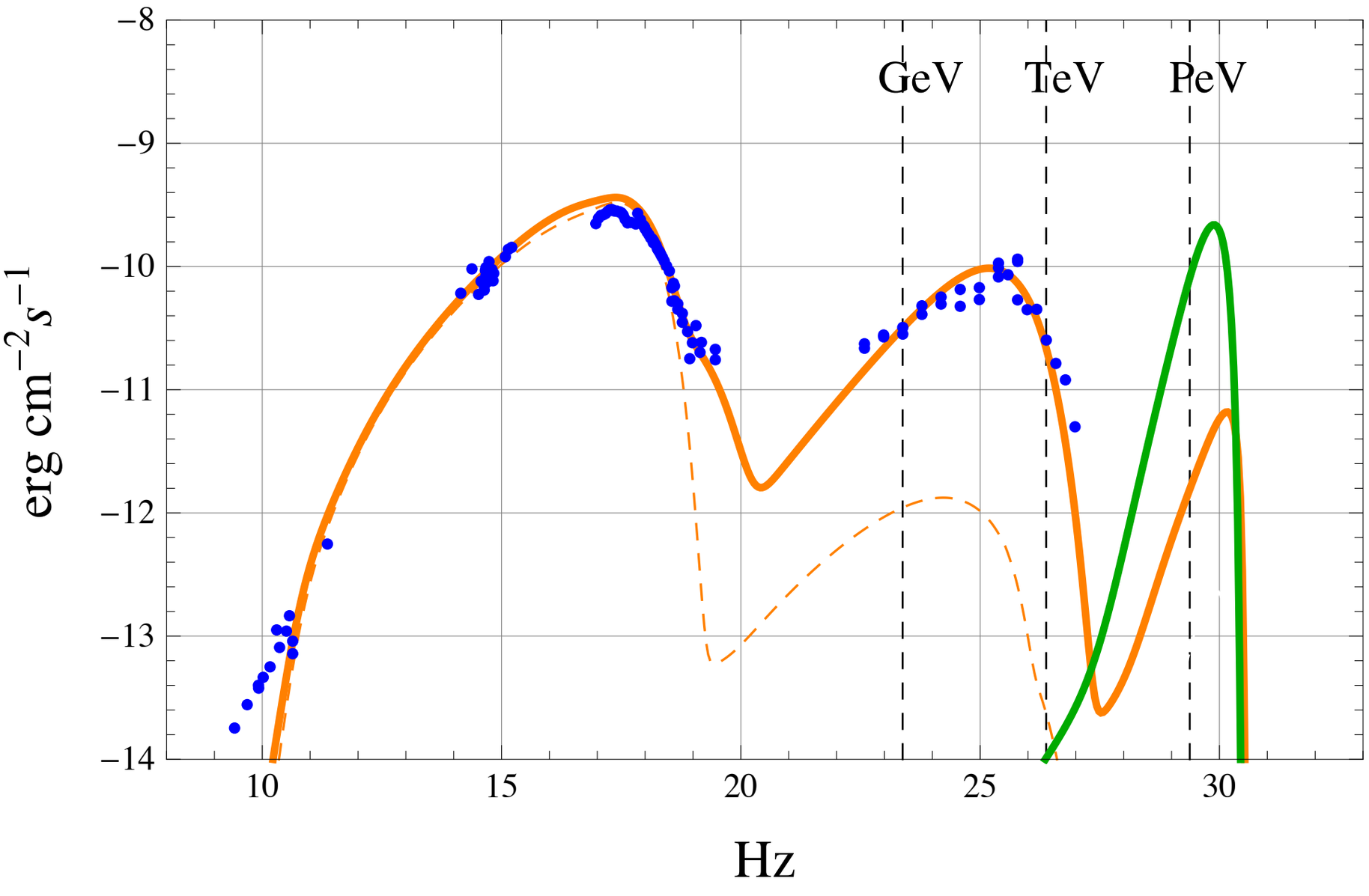
Max amount hadrons can a leptonic model tolerate
NU best-fit is in tension with SED best-fit (overshooting X-ray band)
Joint-fit gives ~5% probability to reproduce “big-bird” within this phase

3C 279, Steady-state, proton-synchrotron model



$B = 150$ G
$L_e = 10^{41.9}$ erg/s
$L_p = 10^{46.5}$ erg/s
$\Gamma_{bulk} = 21$
$R = 10^{15.9}$ cm

$E_\nu \sim 300$ PeV

Diltz,Böttcher,Fossati 2015 ApJ

Mrk 421