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The Multimessenger Approach

Julia Tjus

For a review, see

J.K. Becker, Phys. Rep. 458:173(2008) [arXiv:0710.1557]

FAKULTÄT FÜR PHYSIK & ASTRONOMIE
Theoretische Physik IV

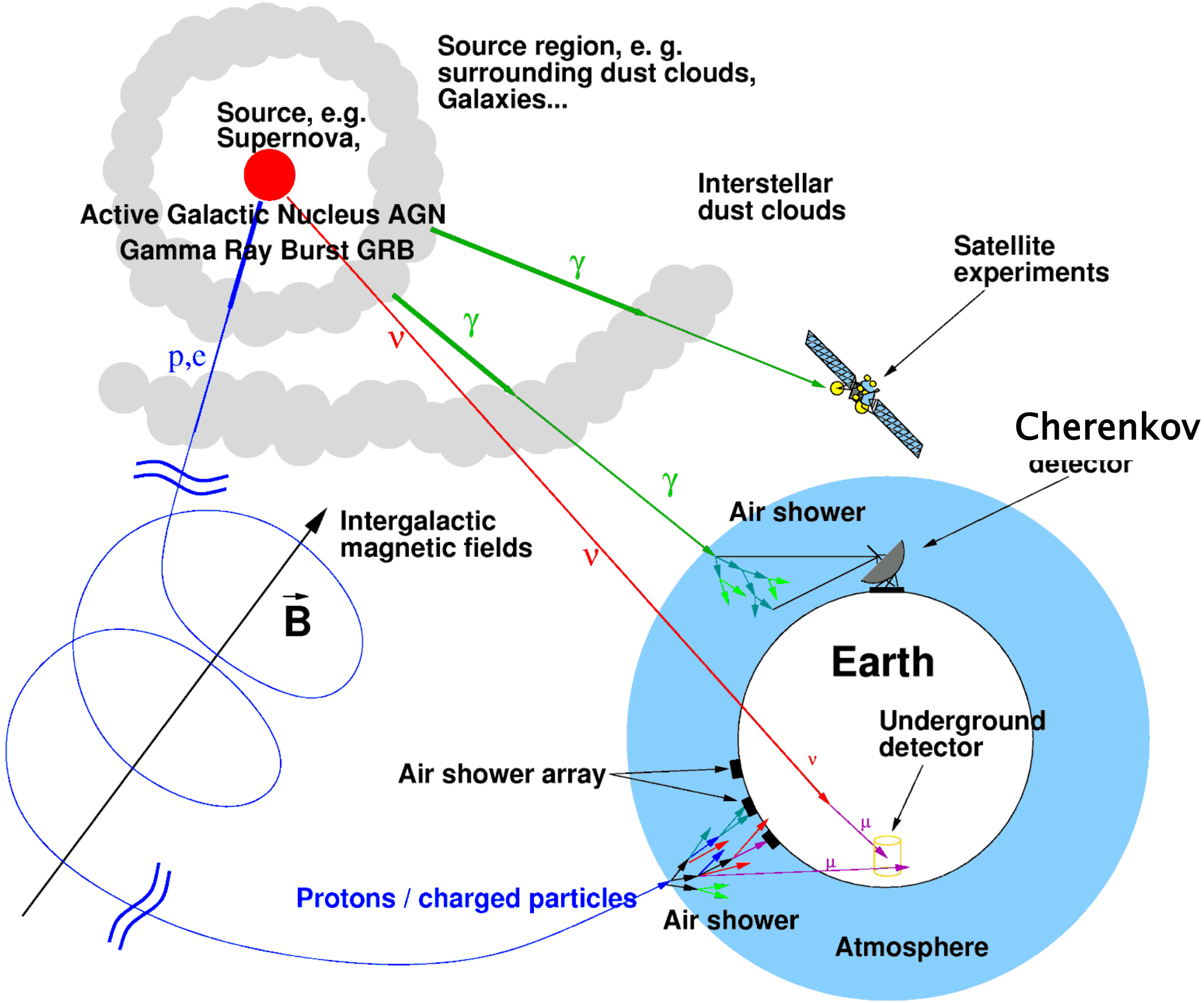

Figure: Wolfgang Wagner, PhD, TU Dortmund, Germany (2004)

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Theoretische Physik I | Julia Tjus (born: Becker)

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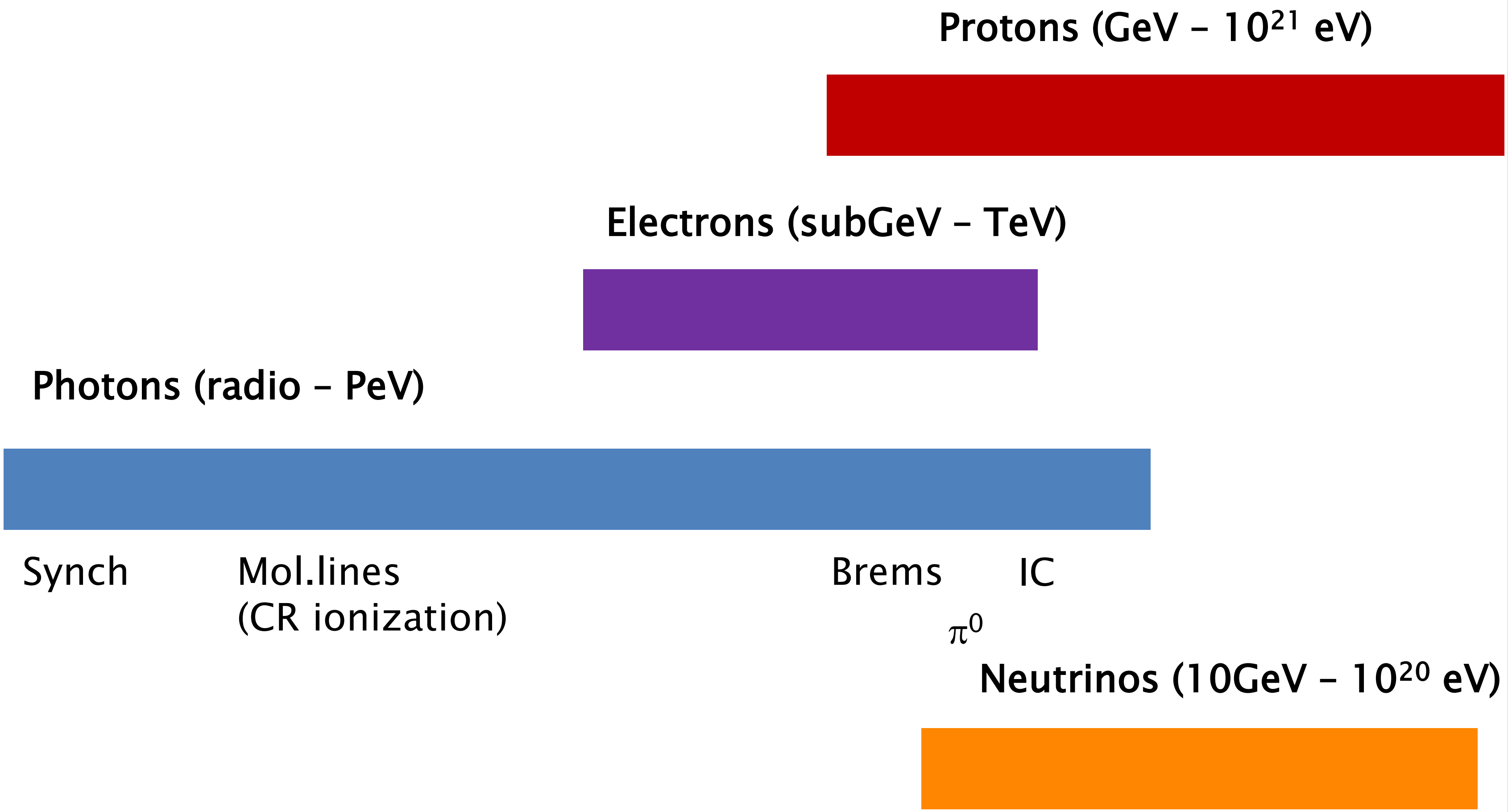
Energy range
Detection of non-thermal processes



Contents

- Supernova Remnants:
  - Spectral energy distribution for photons & neutrinos
  - Ionization signatures

- Gamma-ray bursts:
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SNRs: available information from observations

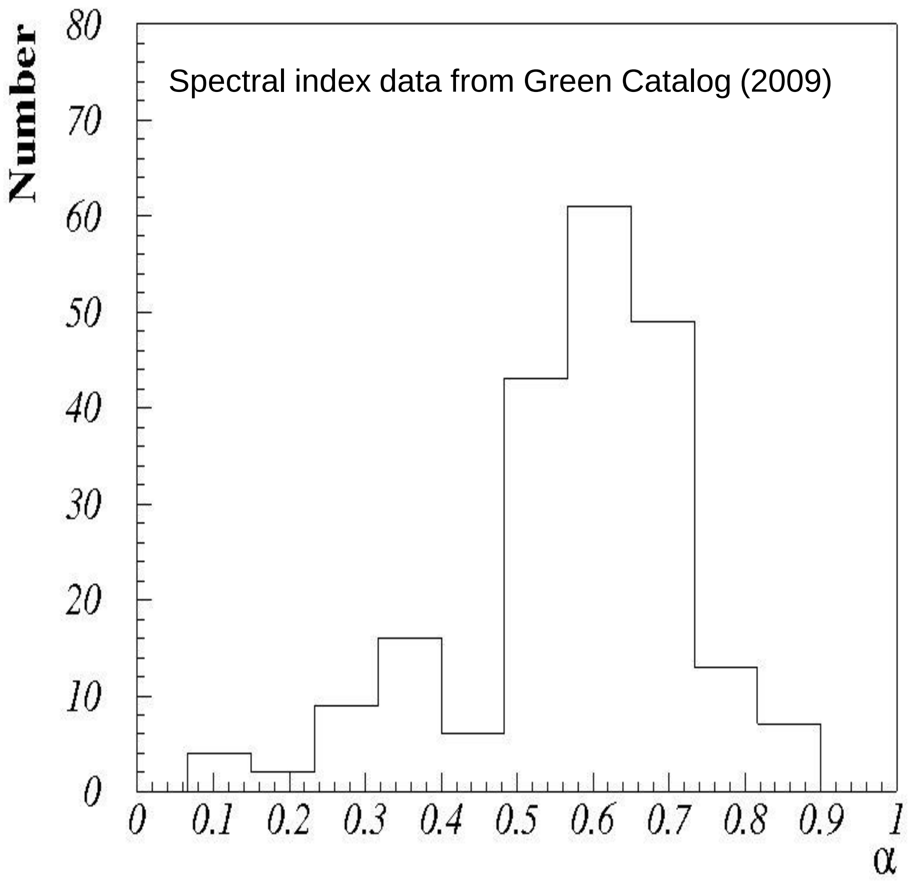
- **Radio observations → non-thermal electrons**
- **Gamma-ray radiation → hadrons/leptons**
  - π^0-decays, IC, brems
- **Molecular ions: lines**
  - Cosmic ray ionization
  - *Difficulty:* CR spectrum at low energies not known

Electron spectral index
(Radio measurements)

- Details of spectral behavior complex
- Distribution of SNR radio spectral indices, $S_\nu \sim \nu^{-\alpha}$
- **p = 2*α+1, dN/dE ~ E^{-p}**

- Green's catalog:
- **<α> ~ 0.6 ➔ $\langle p_e \rangle$ ~ 2.2**

- **Same true for protons?**



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The SNR high-energy component
Modeling with IC/brems/π0

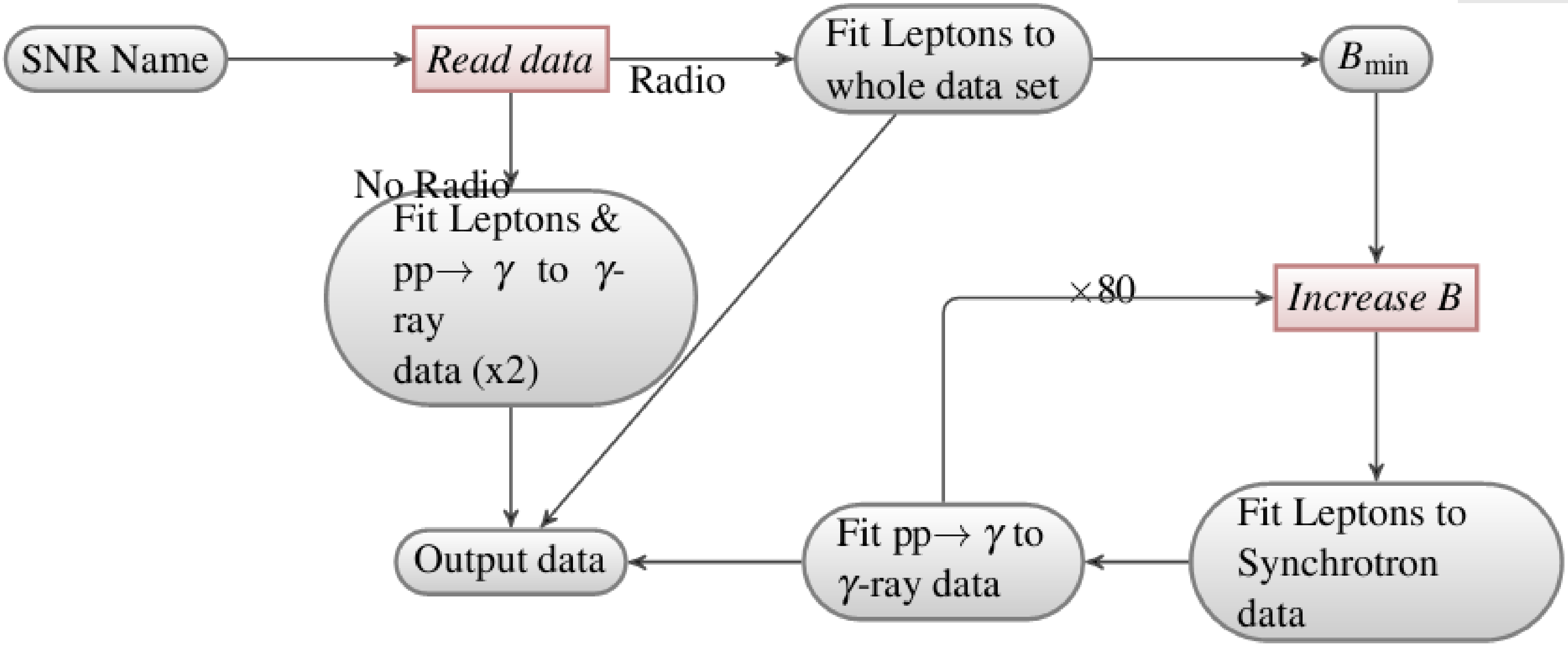
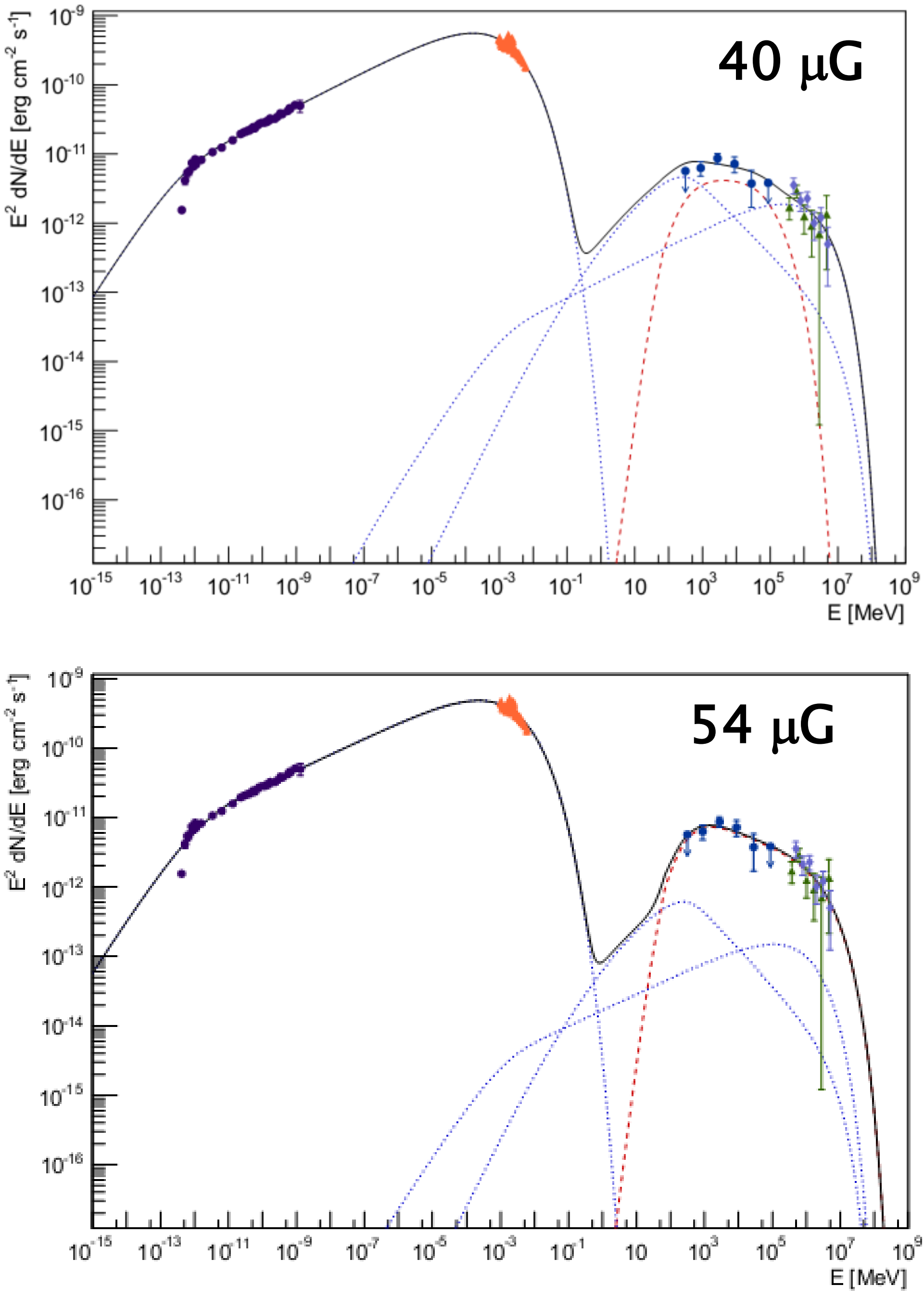


Figure 3.3: Schematic of the routines work flow.

Example: CasA
IC + brems + $\pi 0$

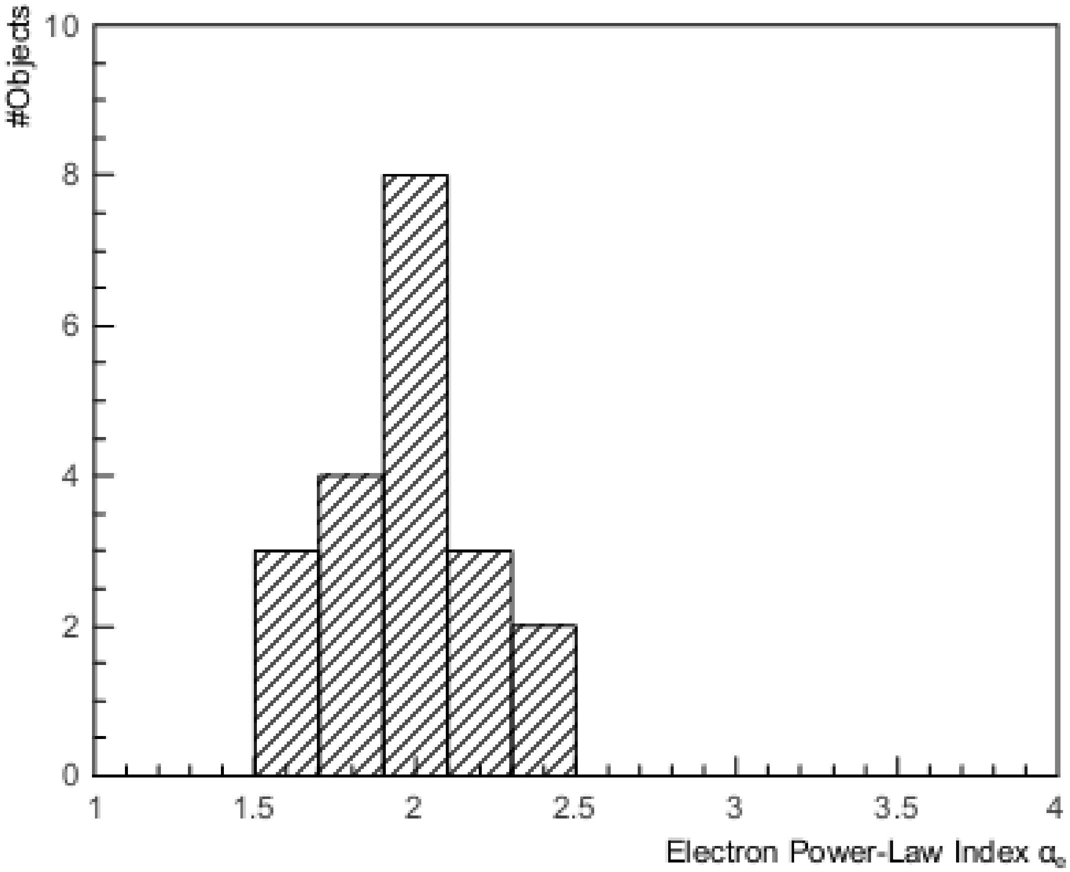
- Brems + IC works with current data
- $\pi 0$ works as well
- → discrimination of models:
  - high-energy cutoff (hadronic models > IC)
  - Low-energy cutoff (hadronic models > brems)
- → extension of detected energy range will help to distinguish models (→CTA)



Mandelartz & Becker Tjus, to be submitted

SNR	Distance [kpc]	Age [yr]	B_{min} [μG]	B_{eq} [μG]	MeV–GeV	GeV–TeV	En
W28	1.9	33000+	500	620	P	B(P)	
W28C	1.9	?	40	40	B(P)	B(P)	M
W30	4	25000	100	110	P	B+C	
W33	4	1200	18	18	B?(P)	B(P)	
W41	4.2	100000	9	9	B(P)	B(P)	
3C391	7.2	4000	27	130	P	P	
W44	3	10000	40	130	P	B	
G40.5–0.5	3.4	30000	90	159	P	P	
W49B	10	1000+	100	307	P	P	
W51C	7.2	26000	20	<20	B	B	
Cygnus Loop	0.58	14000	35	100	P	P	
Cassiopeia A	3.5	332	37	?	B(P)	C(P)	
Tycho	3.5	440	45	100	P	P	
IC443	1.5	3000+	35	40	B	B+P	
Puppis A	2	4500	33	33	B(P)	B+C(P)	M
Vela Jr	1.3	2500	9	9	C(P)	C(P)	
MSH 11–62	6.2	1300+	10	21	P	–	E
RCW 86	2.3	1827	13	13	?	C	
SN 1006	2.2	1006	29	30	?(P)	C(P)	
RX J1713.7–3946	3.5	1619?	27	10	C	C	
CTB 37A	7.9	2000	138	?	P	P/B?	
CTB 37B	13.2	1750	30	30	C(P)	C(P)	
G349.7+0.2	18.3	3500	45	>100	P	P	
G359.1–0.5	7.6	10000+	41	41	B	B	

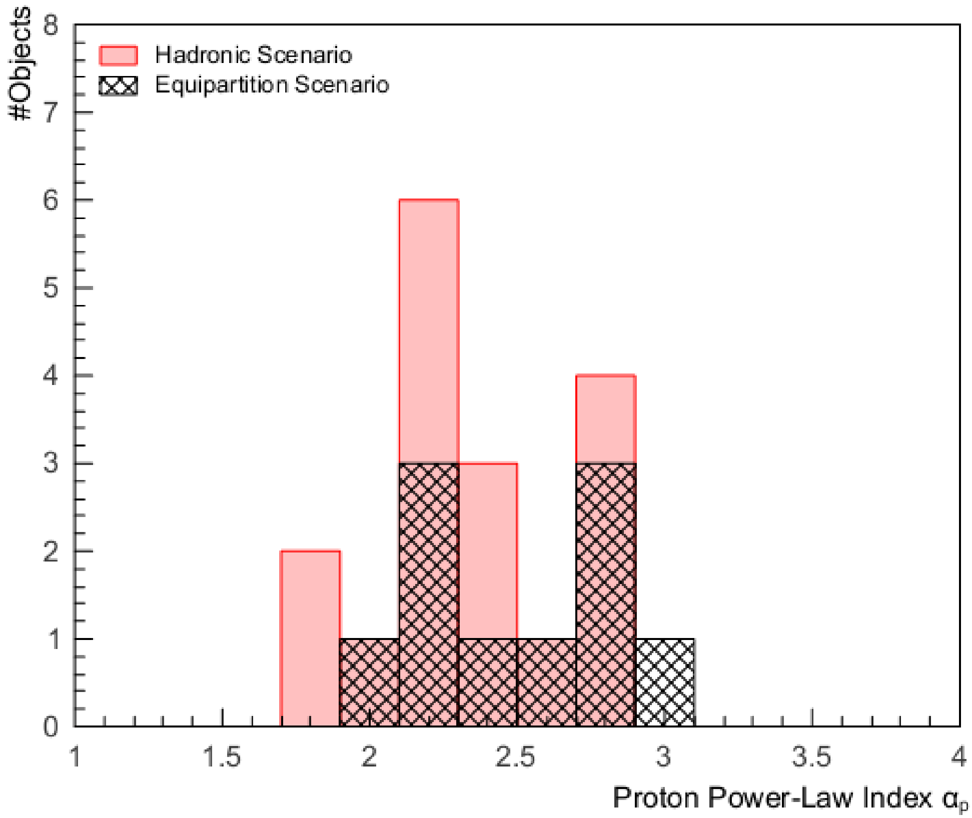
Electron spectral index
(full SED fit)



Mandelartz, Becker Tjus, to be submitted

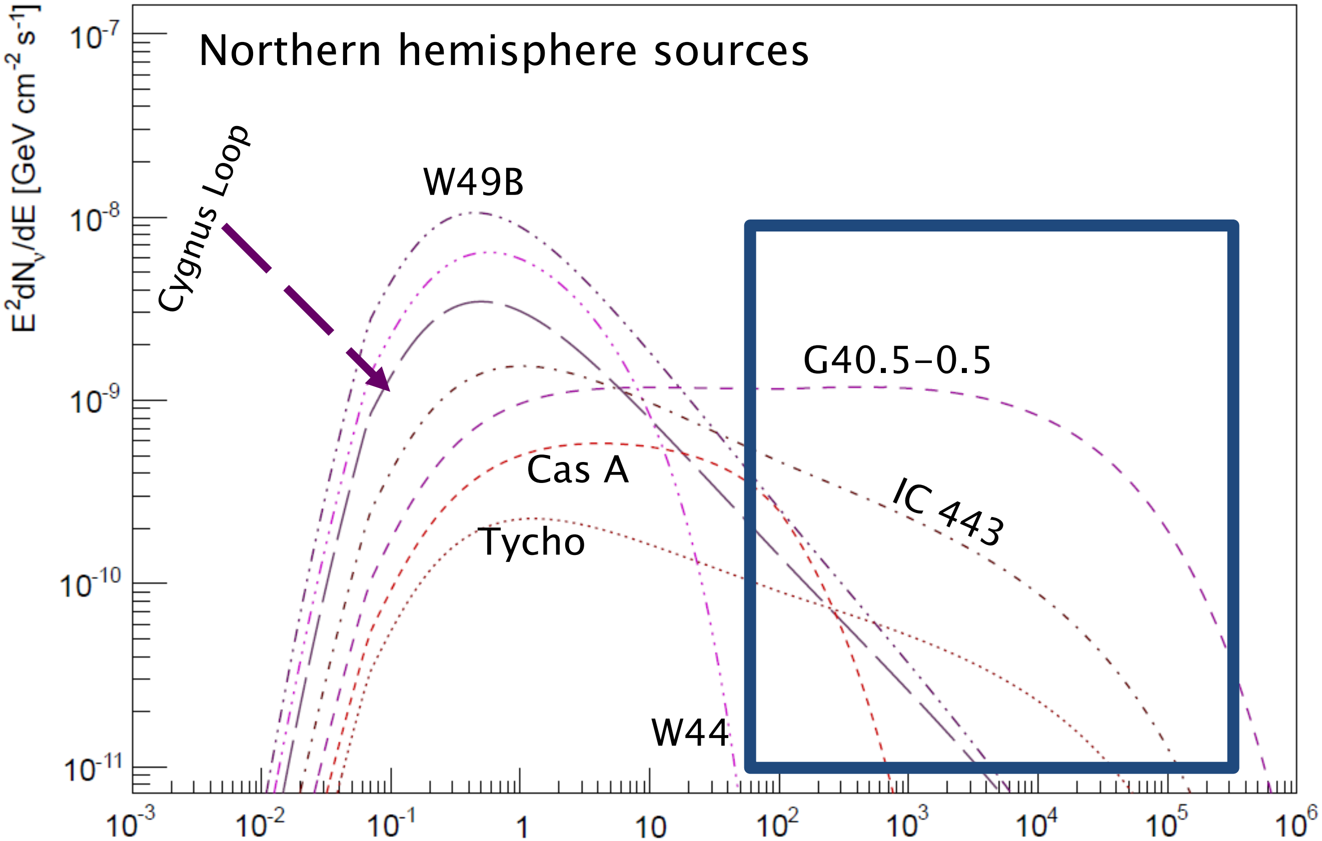
Proton spectral index

- Improvement of spectral behavior investigation:
  - Larger number of sources
  - Better discrimination between leptonic VS hadronic mode



Mandelartz, Becker Tjus, to be submitted

SNRs:Neutrino emission



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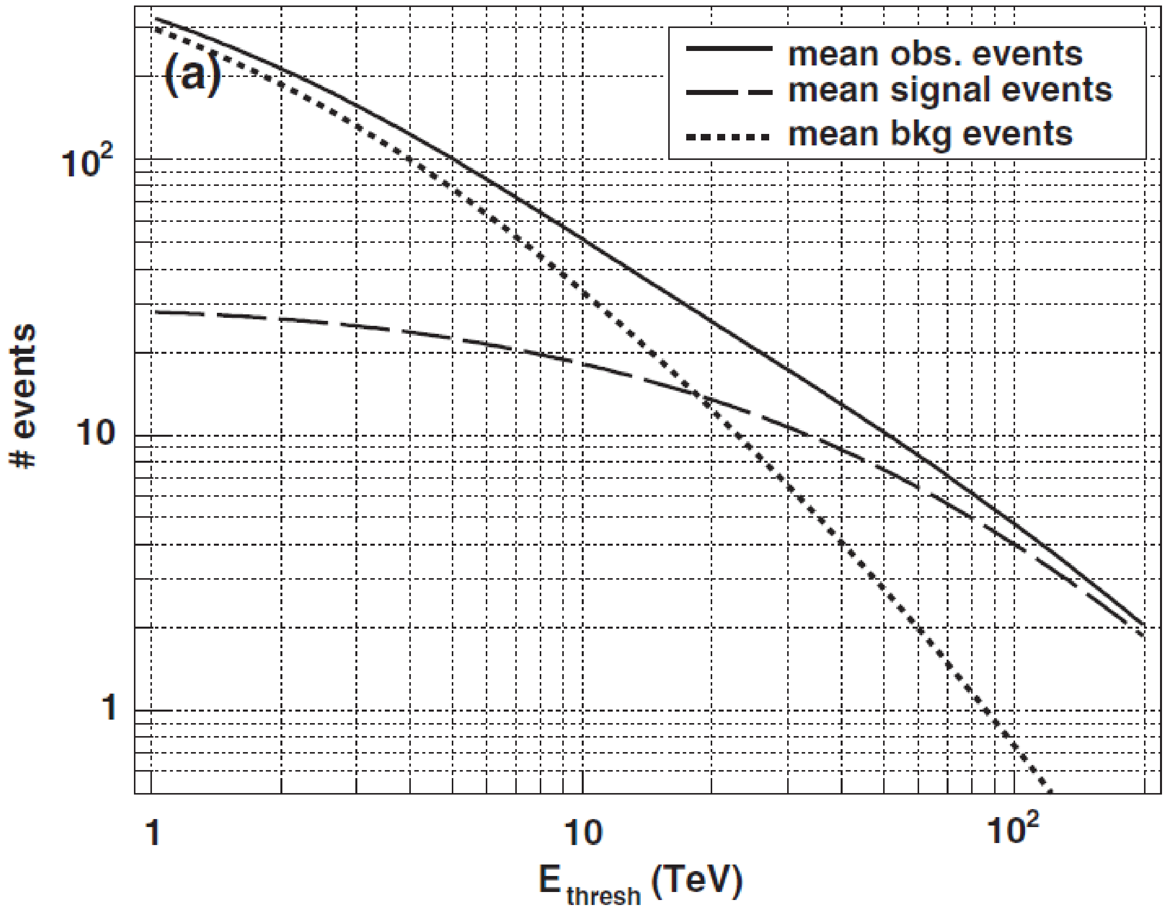
Measurement of SNR Neutrinos possible within a few years of IceCube for sources
Cutoff at high-energies ➔ measurements from CTA/HAWC to identify Pevatrons

SNRs:Neutrino emission



Measurement of SNR Neutrinos possible within a few years of IceCube for sources
Cutoff at high-energies ➔ measurements from CTA/HAWC to identify Pevatrons

Halzen, Kappes, Ó Murchadha, PRD (2008)

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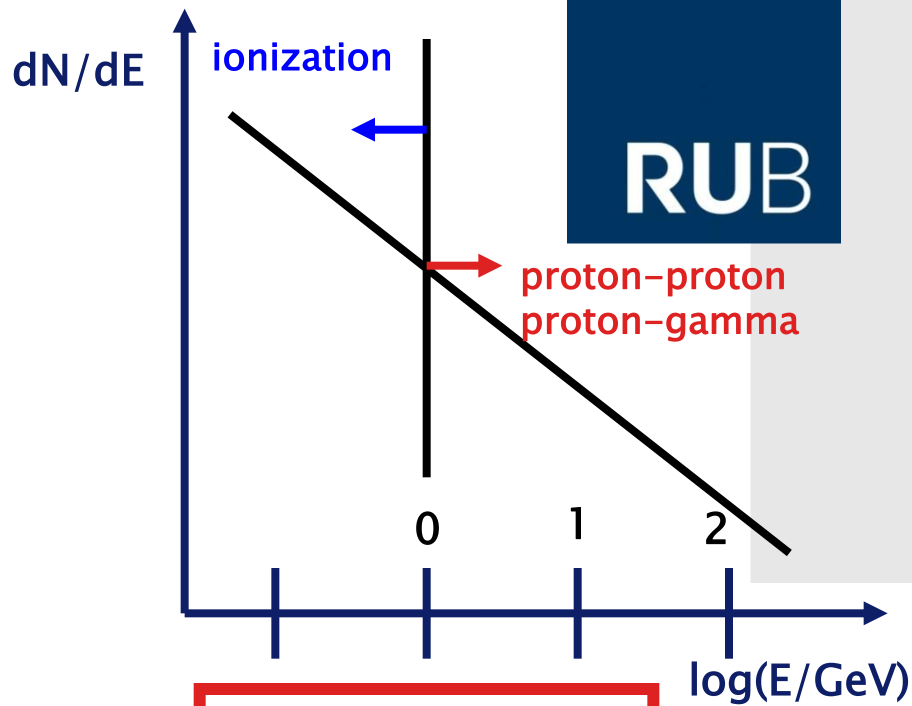
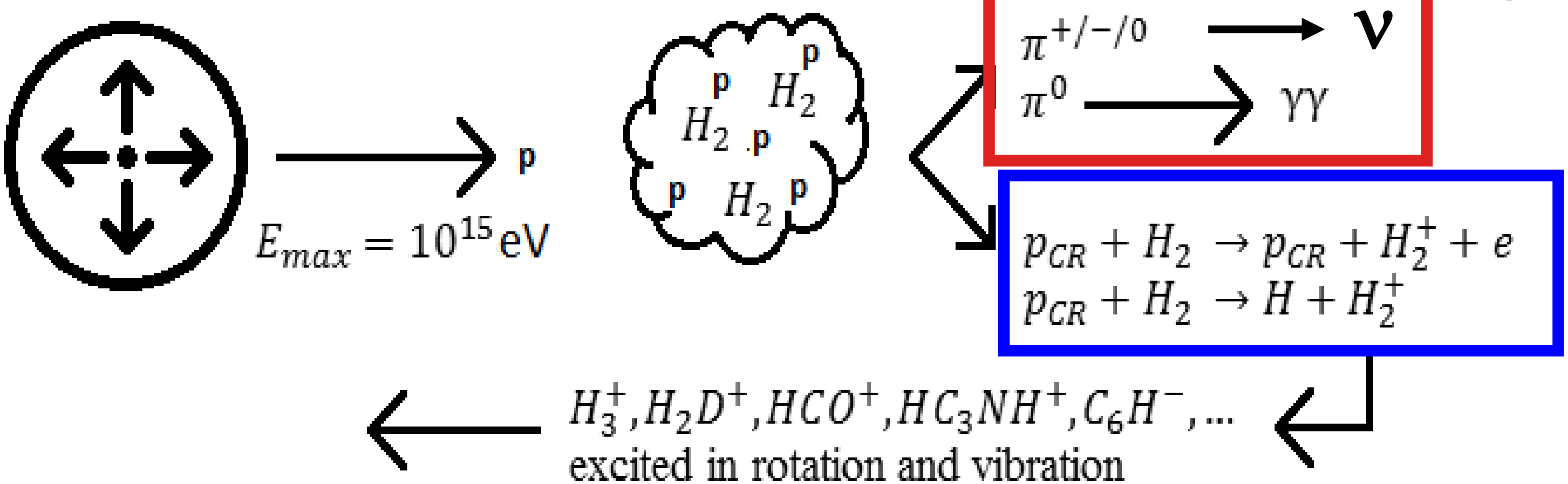
Low-energy signatures In coincidence with high-energy signals

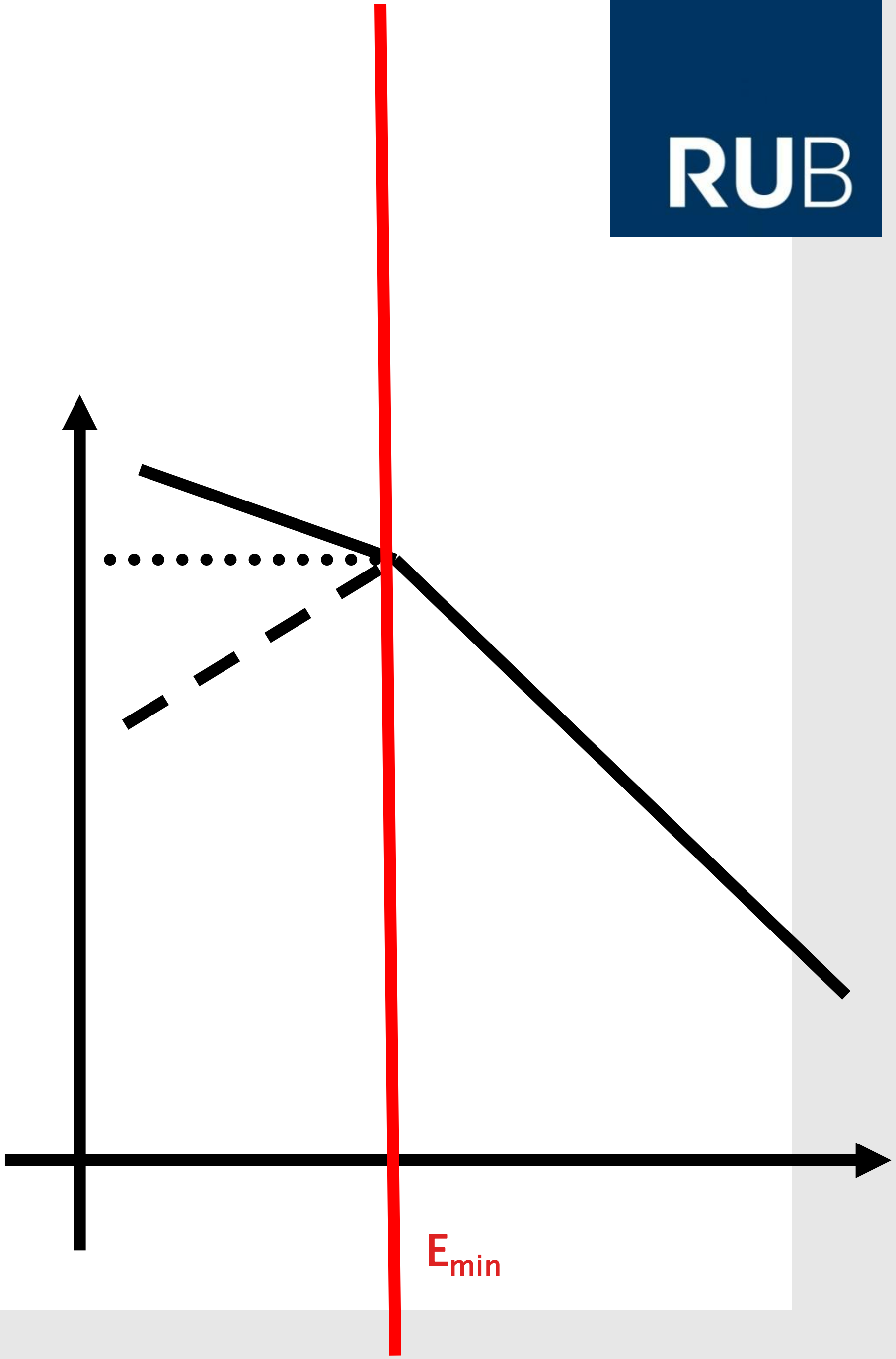




Signatures: gamma-rays; neutrinos; ionization-induced molecules

The primary spectrum

- Assumption that low- and high-energy cosmic rays are accelerated at the same site
- Spectrum might be different at lower energies (e.g. Blasi 2005, Drury 2011)
- → Testing different spectral indices at lower energies
- → or simpler: using a low-energy cutoff E_{min}



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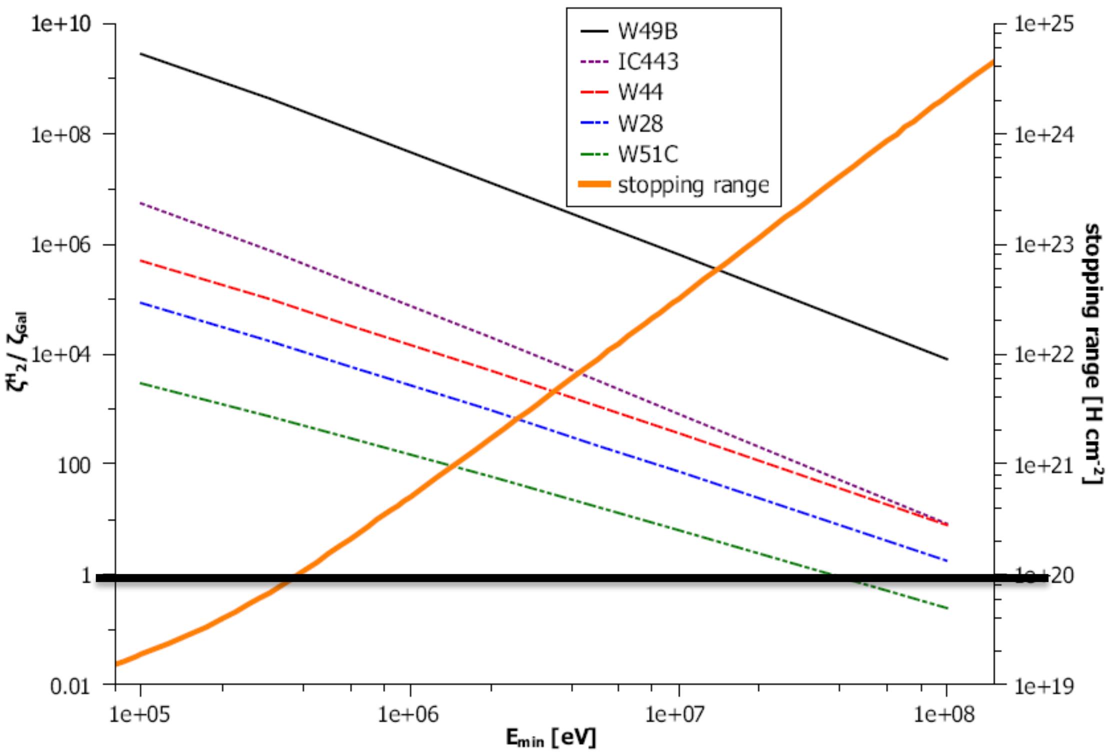
Ionization rates for five SNRs

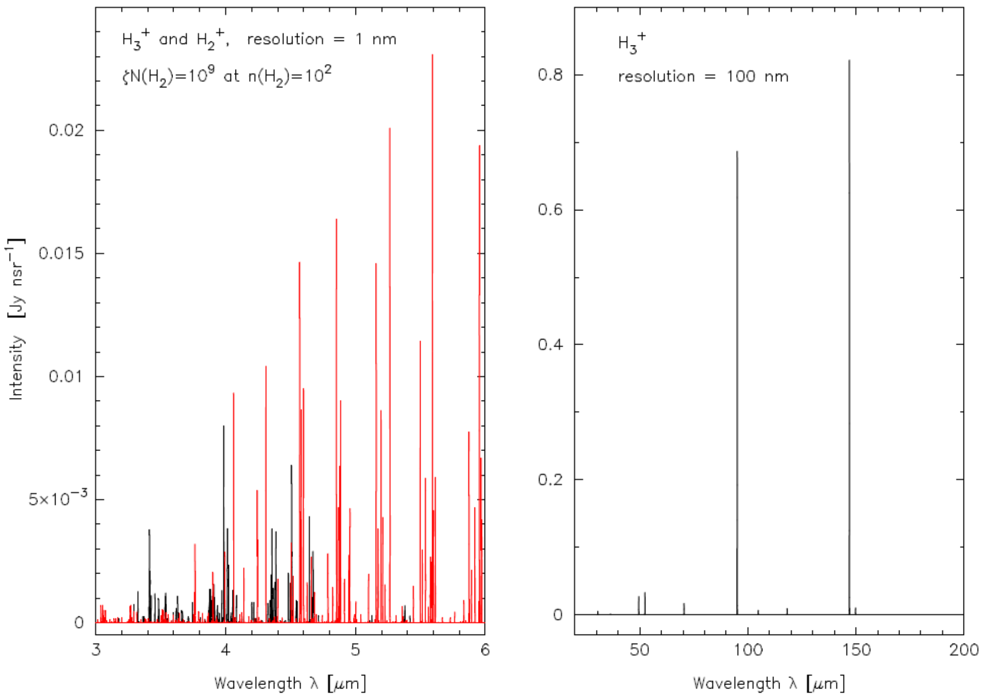


Expectations can be far above Galactic average

Becker, Black, Safarzadeh & Schuppan, ApJL (2011)
Schuppan, Becker, Black, Casanova, ApJ (2012)

Molecule spectra at SNR: H_2^+ and H_3^+

- First prediction of an observable H2+ spectrum
- Coincident observations with significant spatial resolution → submm arrays + IACTs
- Low-energy part of the photon spectrum extremely important!



Becker, Black, Safarzadeh & Schuppan, ApJL (2011)
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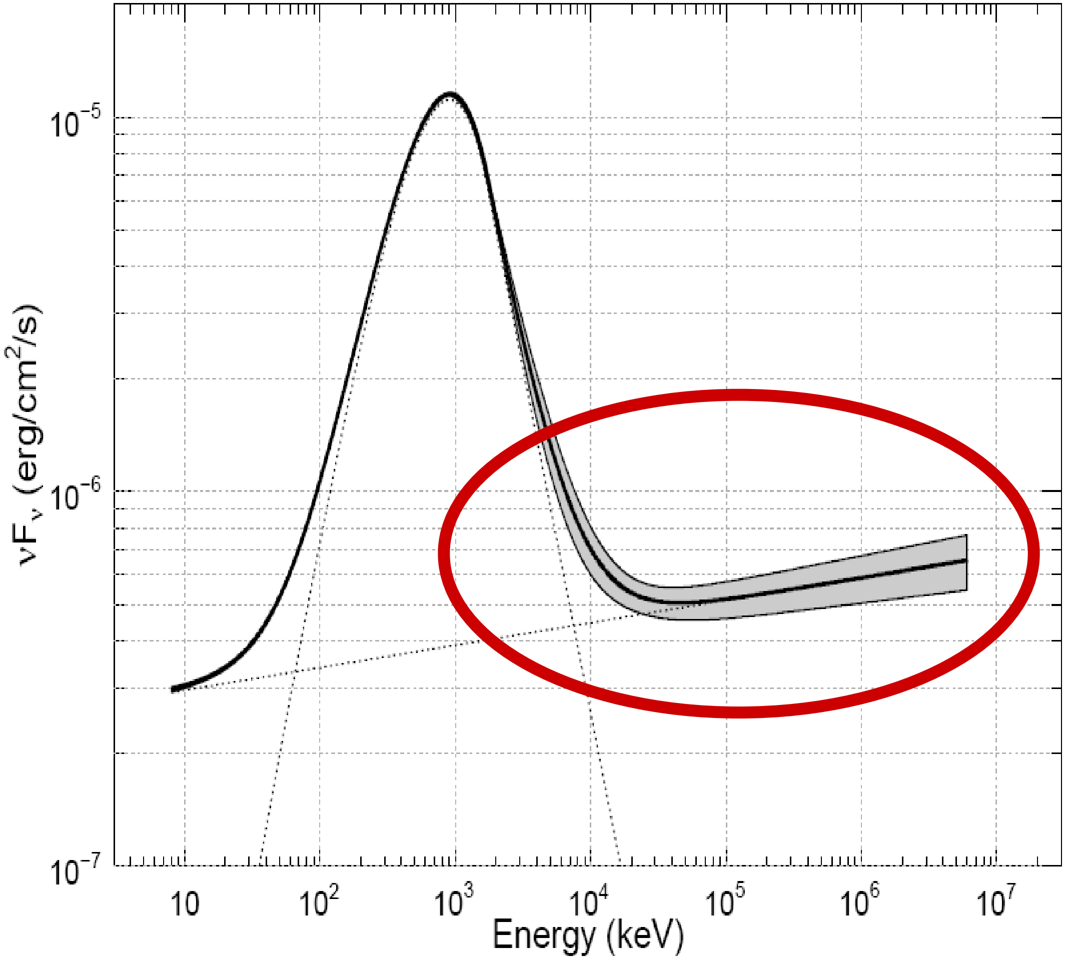
High-energy component GRBs:
Prospects for single bursts

- **GRB941017** – high-energy component (BATSE & EGRET) Gonzalez et al, Nature 2003
- **GRB090510 & GRB090902b** – high-energy component, most likely from π^0 decays (Ackermann et al, ApJ 716 (2010); Abdo et al, ApJL 706 (2009))



Abdo et al, Nature 462:331 (2009)

Test: interpretation as π^0-decay

- $\gamma\gamma$-interactions in GRB environment

- → cascading of photons down to energies at which they can escape

- → "bolometric method":

$$\int \left.\frac{dN_\gamma}{dE_\gamma}\right|_{obs} \cdot E_\gamma \cdot dE_\gamma = \int \left.\frac{dN_\gamma}{dE_\gamma}\right|_{theory} \cdot E_\gamma \cdot dE_\gamma \Rightarrow \int \left.\frac{dN_\nu}{dE_\nu}\right|_{theory} \cdot E_\nu \cdot dE_\nu$$

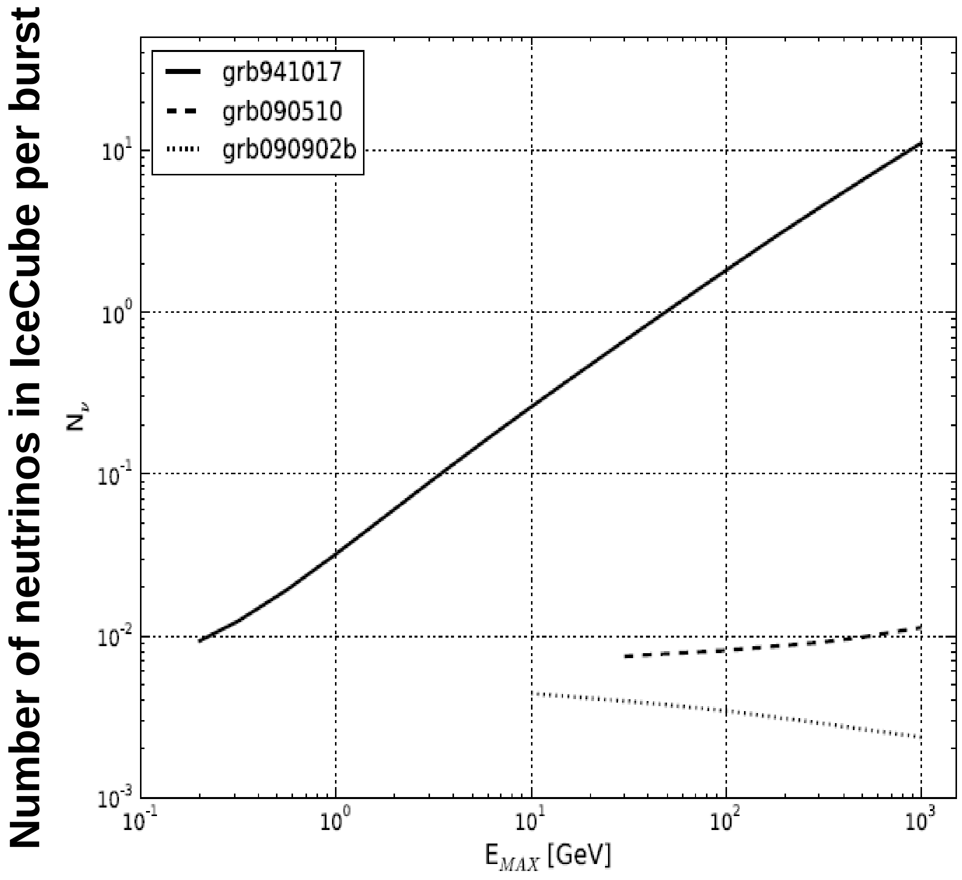
Alvarez-Muñiz, Halzen, Hooper, ApJL 604:85 (2003)

Neutrinos from high-energy compontent GRBs

- **GRB941017**: possibly event rates >10 → corresponds to clear detection in IceCube

- **GRB090510/GRB090902b** → average burst with ~ 1e-2 events ➔ only visible through stacking of sources

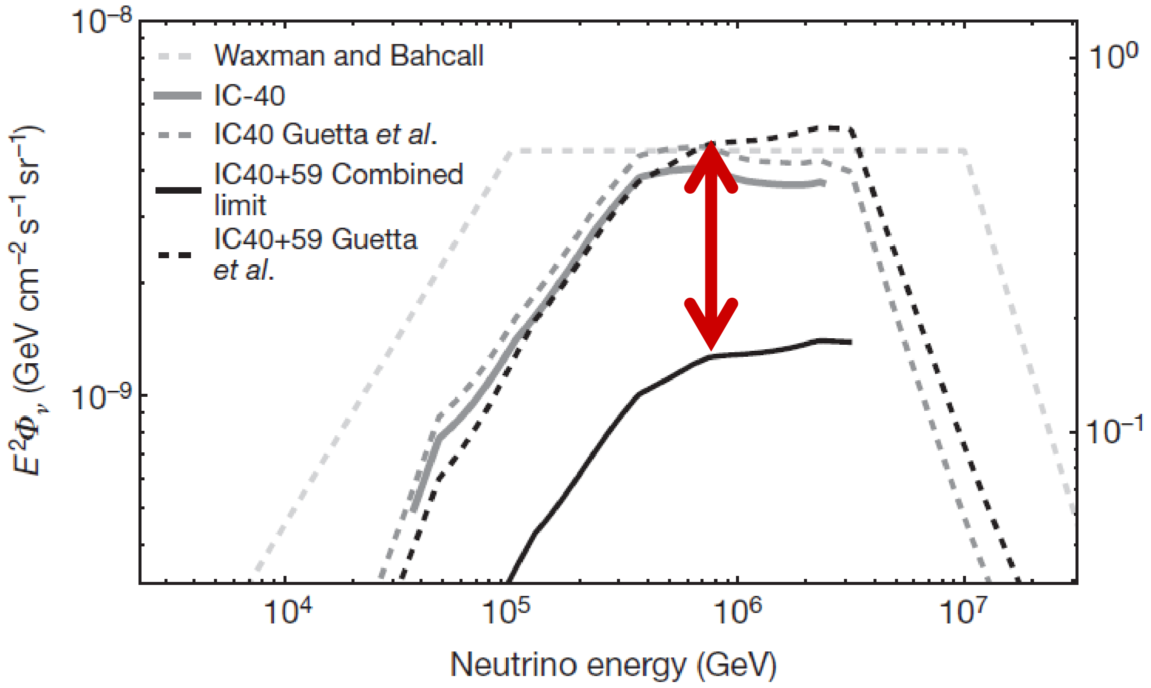
- **➔ high boost factors in gamma-ray bursts are bad for neutrino production (reduces true photon density at the source)**



Becker, Halzen, O'Murchadha, Olivo, ApJ 721:1891 (2010)

GRBs: constraints on acceleration

- **Limits violate flux estimate**

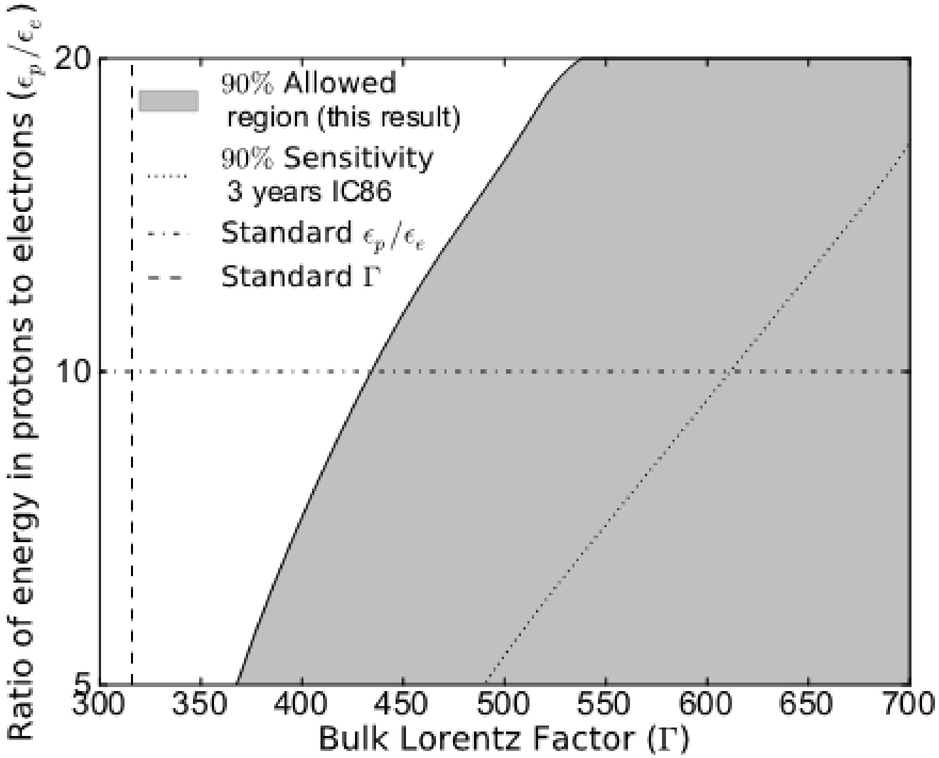


- **Model-optimized search (few hour time window)**
- **Model-independent search (24hour time window)**

Abbasi et al, Nature 484:351 (2012)

Proton-to-electron ratio

- Standard model assumes K ~ 10
- Theory (same spectral index) predicts ~ 100
  - Would lead to enhancement of prediction by factor 10



Abbasi et al, Nature 484:351 (2012)

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Flaring behavior via time-dependent transport equation

$$\frac{\partial n_{e,p}}{\partial t} = q_1(\gamma,\, t)\, q_2(r) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D(\gamma)\frac{\partial n_{e,p}}{\partial r}\right) + \frac{\partial}{\partial \gamma}\left[|\dot{\gamma}|\, n_{e,p}\right]$$

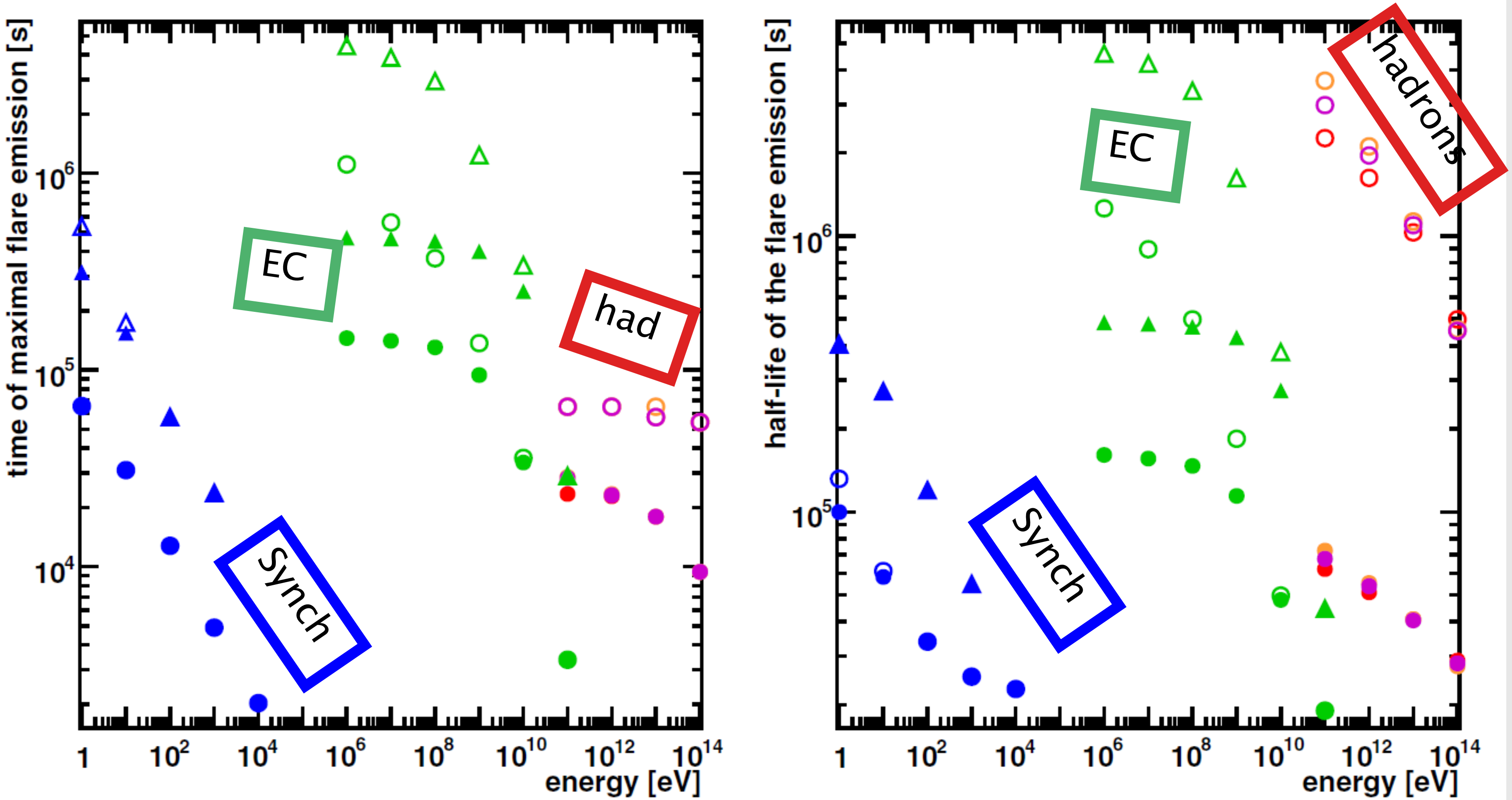
Injection | Diffusion | Loss processes (cont.)

- Loss processes:
  - Leptons → Coulomb losses, Synchrotron, inverse Compton, brems
  - Hadrons → proton-proton, proton-gamma, Coulomb
- Radiation at surface of object: Retarding effect → propagation depends on density distributions

Eichmann, Schlickeiser, Rhode, ApJ (2012)

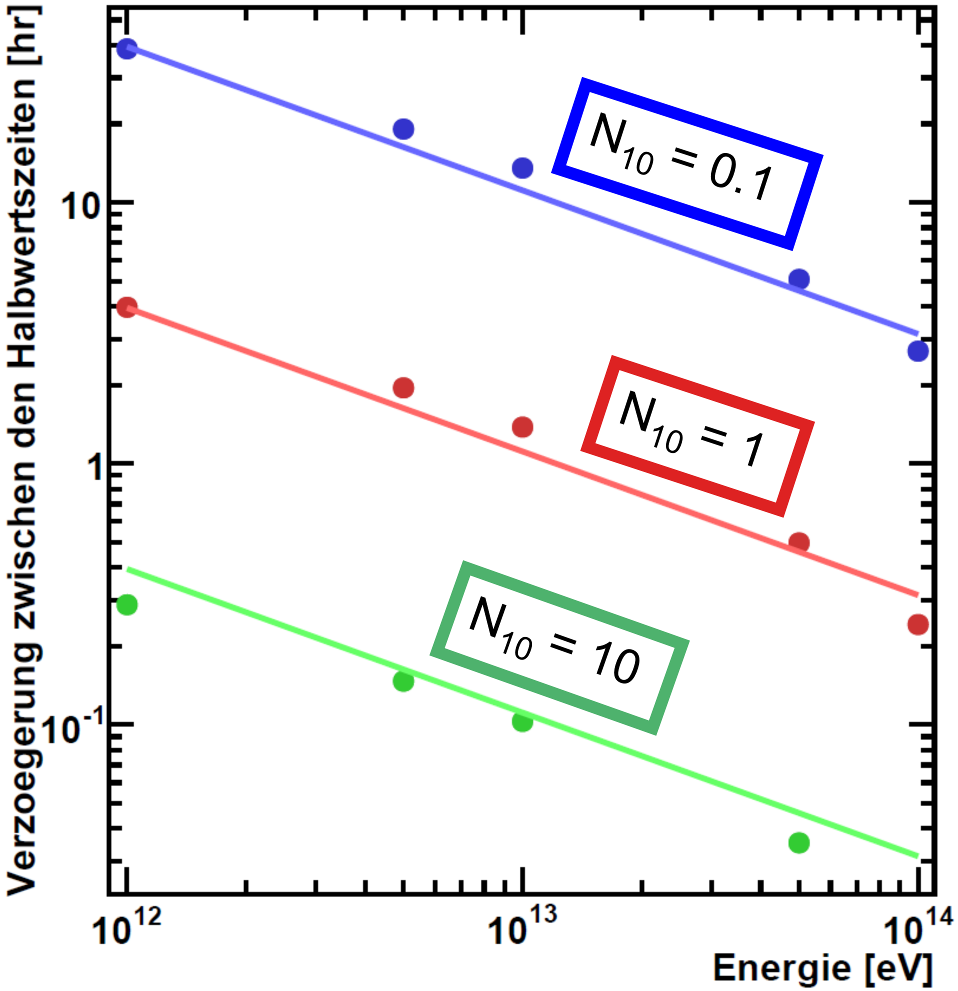
Emission time and half lives

EC/Synch: B-dependent; Hadrons: N-dependent



Eichmann, Schlickeiser, Rhode, ApJ (2012)

Delay between hadronic ν–γ flare half lives



- Density: $N_{10} = N^* \, 10^{10}$ cm^{-3}

- Analytic approximation for correlation:

$$\Delta t^*_{1/2}(E^*) = 3.9\, N_{10}^{-1}\, (E^*/1\,\mathrm{TeV})^{-0.55}\ \mathrm{hr}$$

*: observer‘s frame

Eichmann, Schlickeiser, Rhode, ApJ (2012)

Summary

- Ionization signatures and high-energy photons
  - → provide additional method to distinguish hadronic and leptonic scenarios
  - **Low-energy part of the CR spectrum** most important → low-energy component of photon spectrum needs to be well-known.

- High-energy photons and neutrinos:
  - Neutrinos would be unambiguous proof for CR acceleration
  - High-energy photons: measurements at the highest energies important → best detection chances with IceCube if spectrum extends to **PeV energies**

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Thank You!

Questions?

abstract

- Identifying the origin of high-energy cosmic rays is only possible with a multimessenger approach due to the ambiguity of the individual signal components. In this talk, different possibilities of multiwavelength astronomy are presented, focussing on supernova remnants as the possible sources of galactic cosmic rays and on gamma-ray bursts as a candidate for extragalactic cosmic rays. In particular, spatially and temporally coincident signatures between low- and high-energy photons as well as high-energy photons and neutrinos will be discussed.

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Gamma-gamma Optical depth GRBs

$$\tau = \frac{4\pi d_L^2 \delta t}{4\pi(\Gamma^2 c\delta t)^2} \int_{-1}^{1} d(\cos\theta)\, \frac{(1-\cos\theta)}{2} \times \int_0^{E_{\max}} dE_\gamma\, \sigma_{\gamma\gamma}\left(\frac{(1+z)E_\gamma}{\Gamma}, \frac{(1+z)E_{\max}}{\Gamma}, \cos\theta\right) \frac{dN_\gamma}{dE_\gamma}(E_\gamma),$$

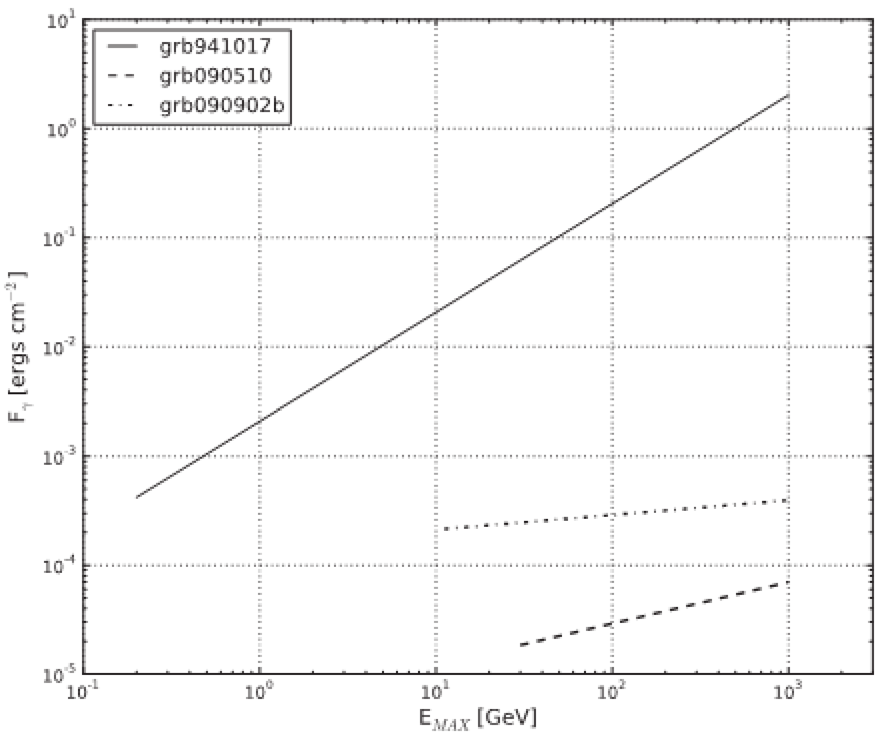


Figure 2. Fluence of the high-energy component above 30 keV as a function of the maximum energy $E_{\max}$ for GRB941017, GRB090510, and GRB090902b.

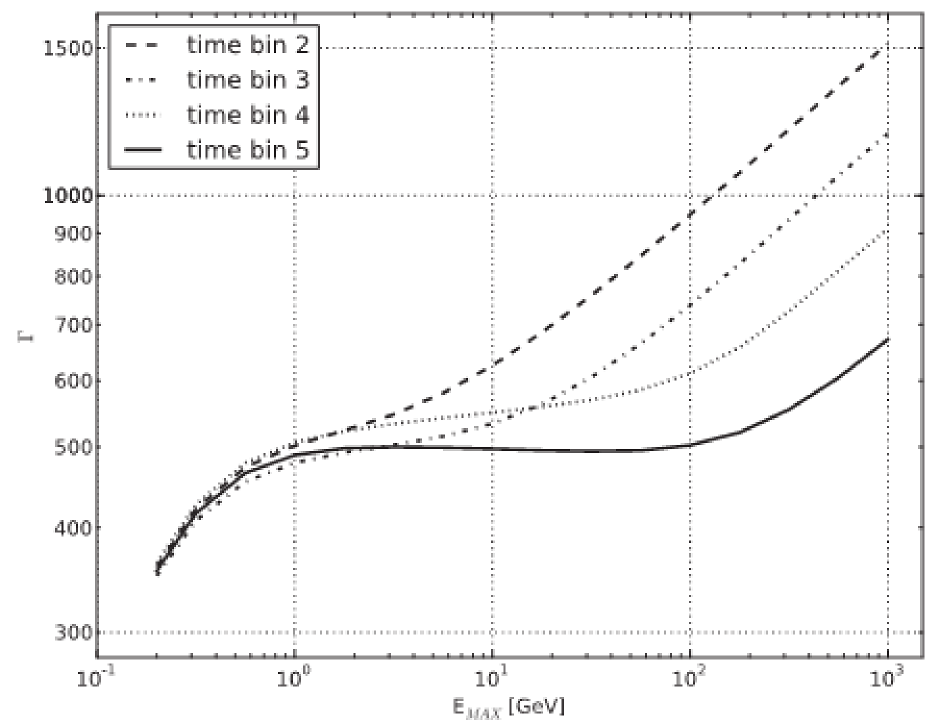
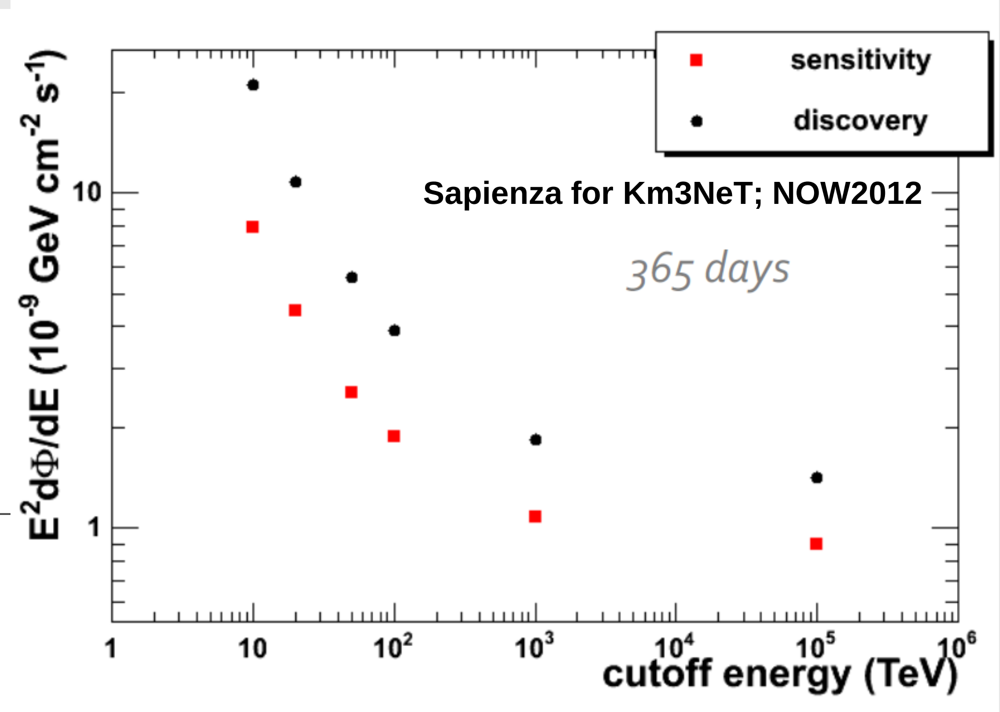
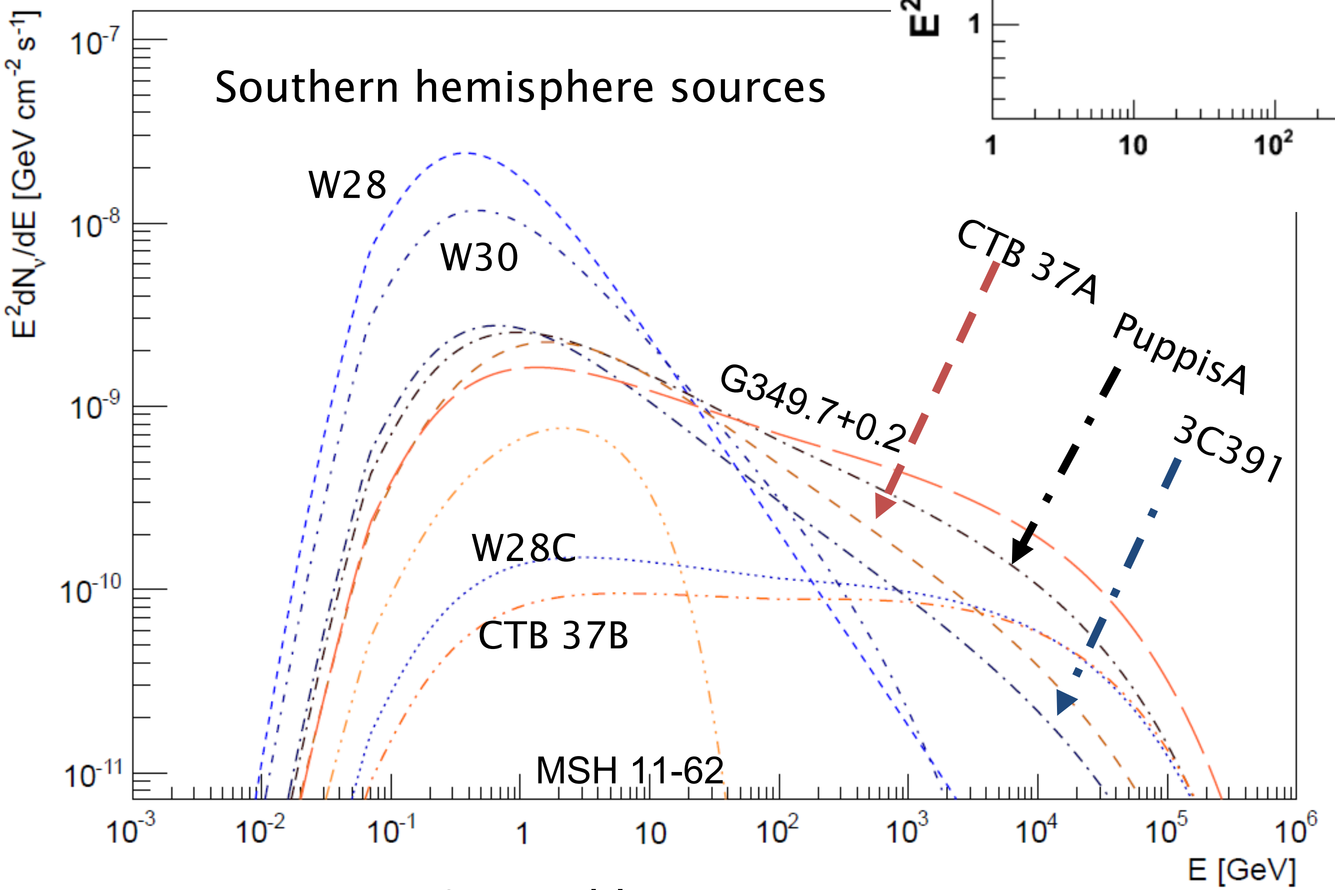


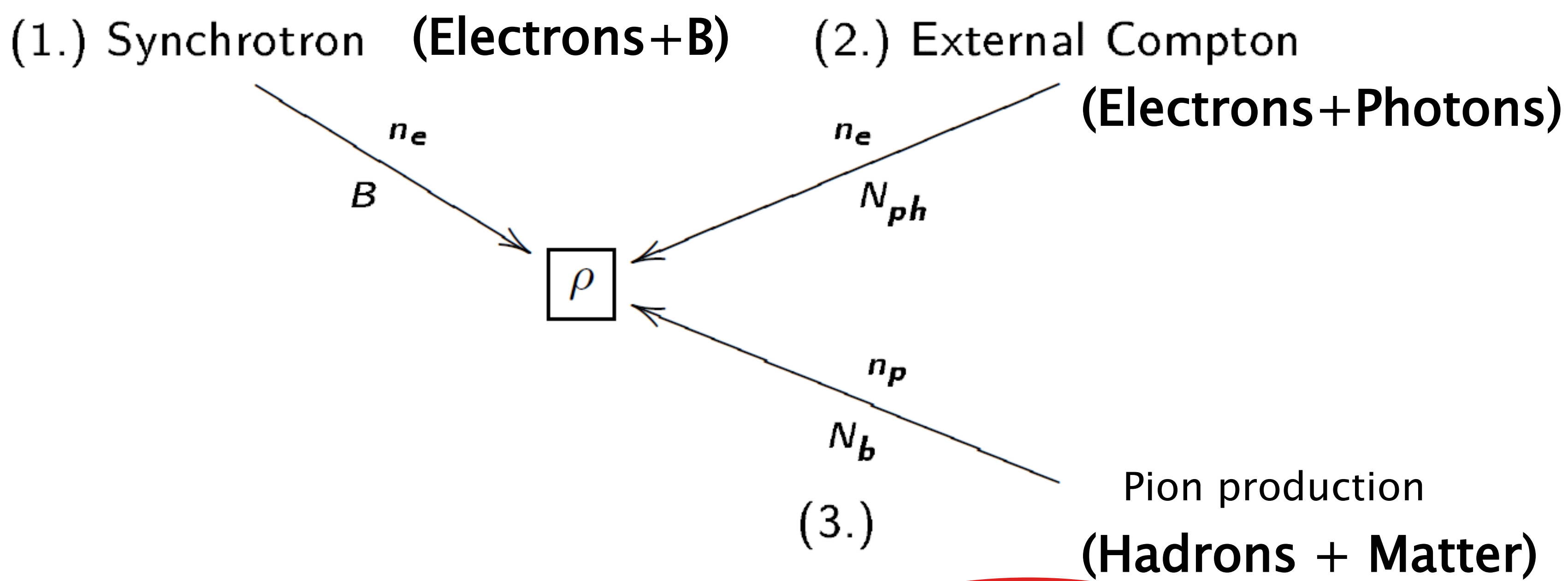
Figure 1. For time bins 2–5 of GRB941017, values of Γ such that $\tau_{\gamma\gamma} = 1$ for a photon of energy $E_{\max}$ ($\Gamma_{\min}$).

Neutrino emission from SNRs





Radiated intensity at surface R



$$I(R,E,t) = \frac{1}{2R}\int_0^R \mathrm{d}r'\, r' \int_{R-r'}^{R+r'} \frac{\mathrm{d}s}{s}\, \rho(r', E, t - s/c)\, \exp(-g\, s/R)$$

Eichmann, Schlickeiser, Rhode, ApJ (2012)