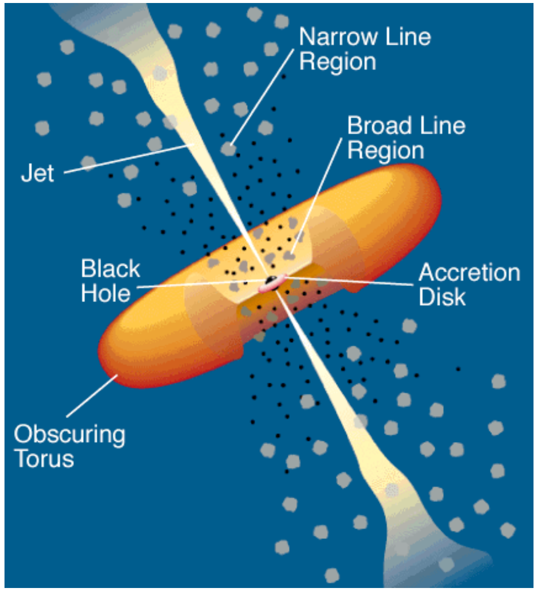
UHENU and GRB

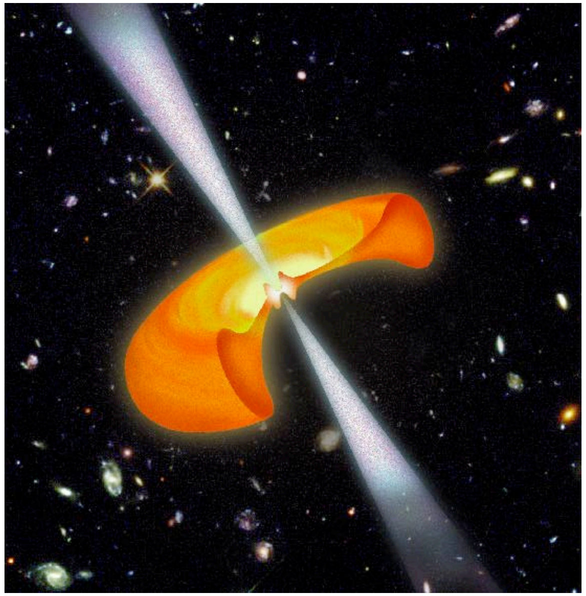
Péter Mészáros
Pennsylvania State University

Albanova 2011

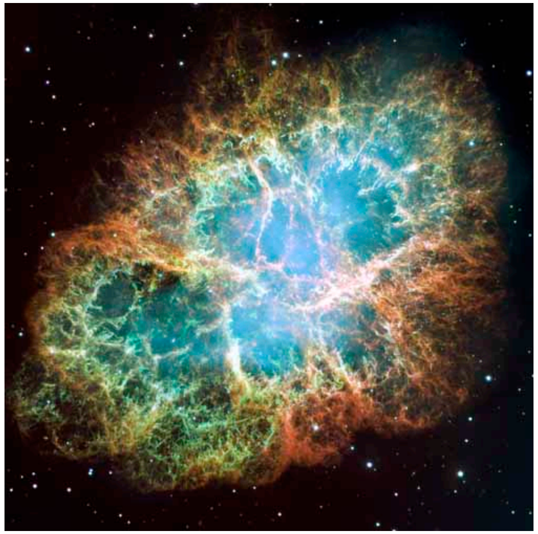
Astrophys. UHECR/NU Sources ?



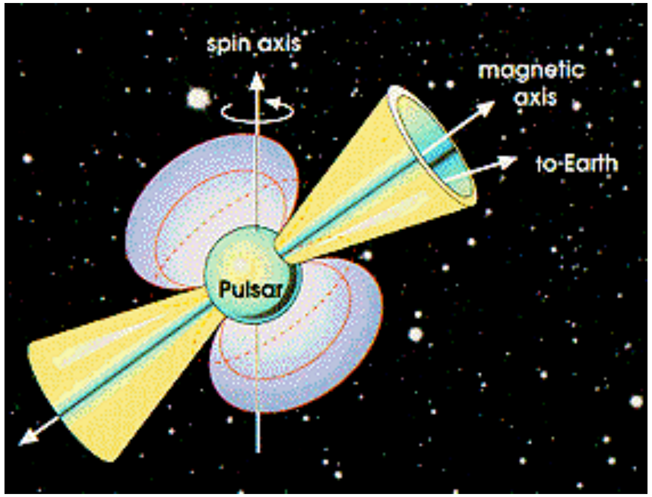
AGN
Active Galactic Nucleus



GRB
Gamma Ray Burst



HN
Hypernova

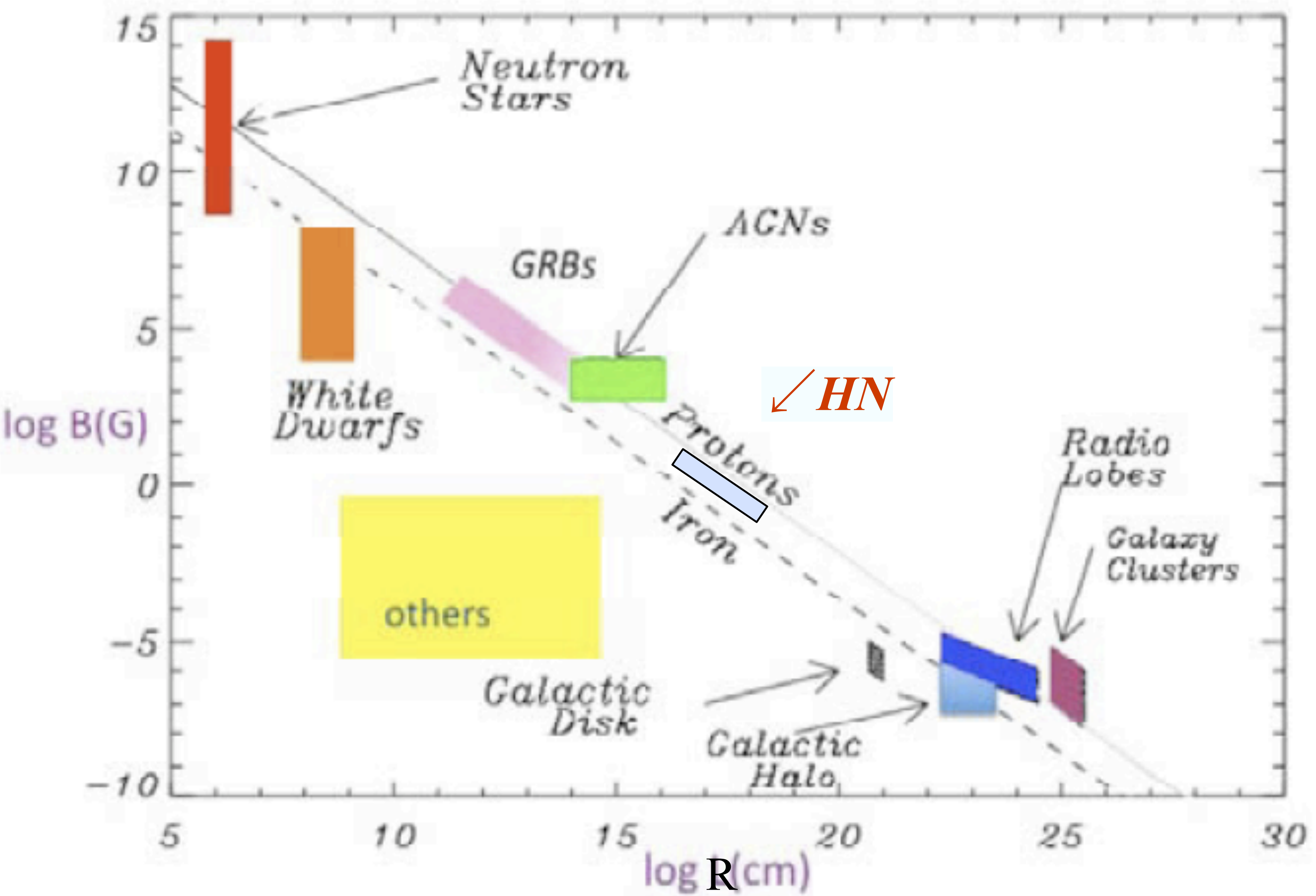


MGR
Magnetar

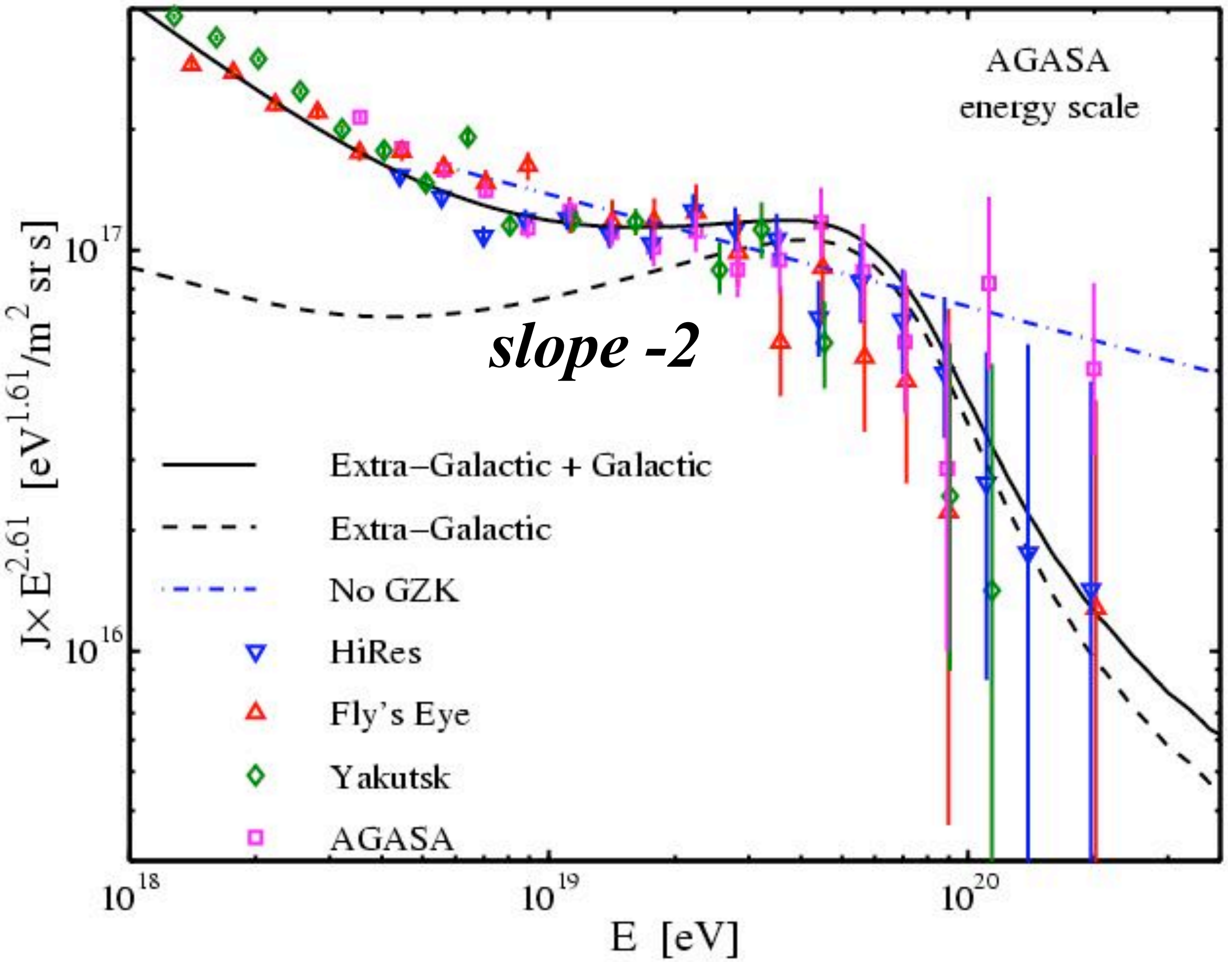
CR acceleration: shocks?

- Shocks present in HE non-thermal γ-ray sources (or else: magnetic reconnection).
- Electrons are definitely accelerated
- γ-rays usually attributable to leptonic mechanisms (synchrotron, inv. Compton)
- But: UHECR ***must be*** accelerated somewhere; likely (?) in the same shocks of one of these HE γ-ray sources- but which?

Maximum E_p for various sources from DSA



UHECR spectrum vs. Extragal. (GRB, AGN, other astrophys.) model



Waxman 06

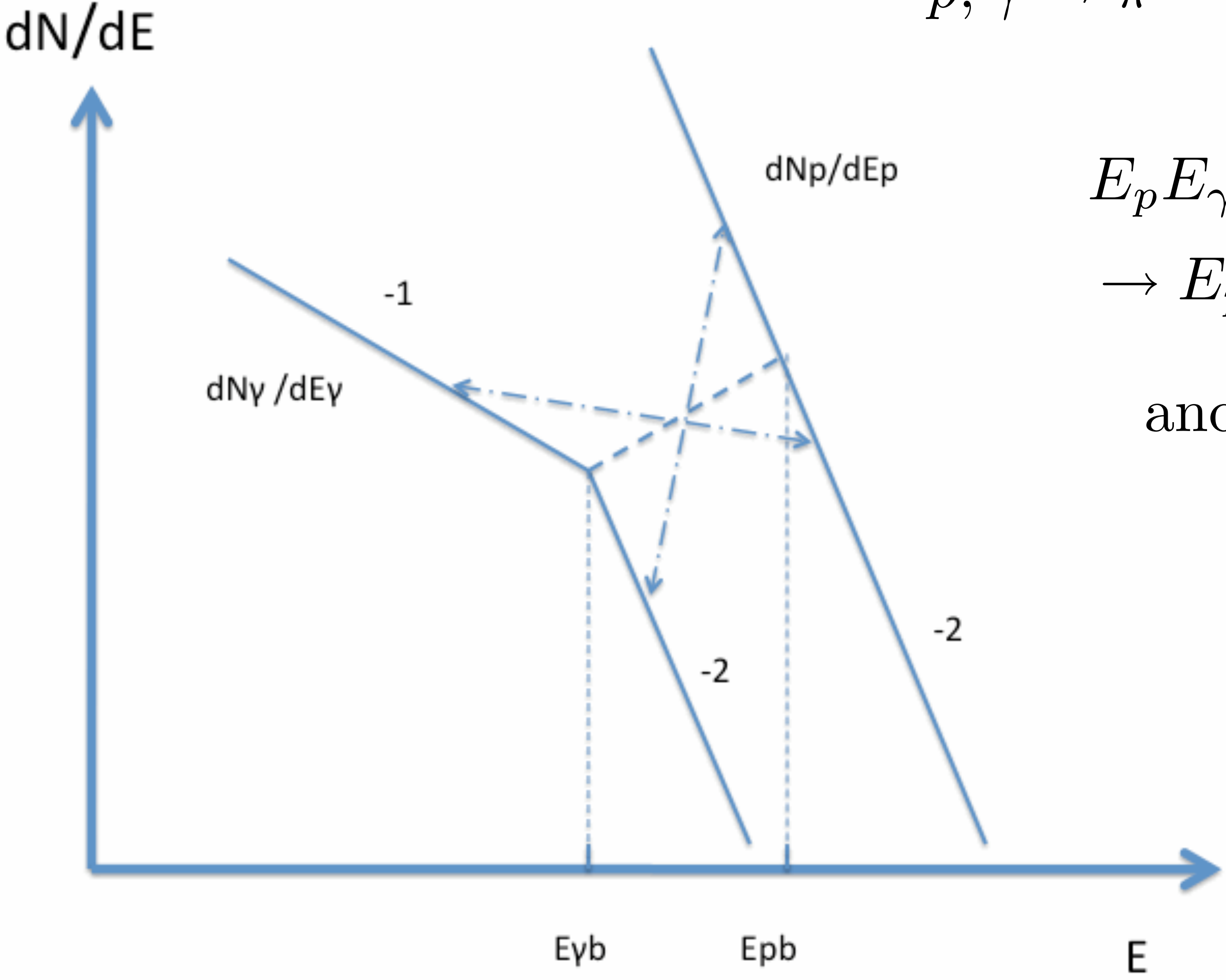
Can neutrinos be used as a test?

- *If* have protons in jet $\rightarrow$ p^+ are Fermi accelerated too
- **p,**γ $\rightarrow$ $\pi^{\pm} \rightarrow \mu^{\pm}, \nu_\mu \rightarrow e^{\pm}, \nu_e, \nu_\mu$
- **Δ**-resonance: $E_p\, E_\gamma \sim 0.3\ \mathrm{GeV}^2$ in jet frame
- Depending on target photon energy, the typical observer frame neutrino energies in the ***E_ν ~ GeV- EeV*** range
- Potentially, can detect with **ICECUBE, KM3NeT**
- Also: **p,**γ $\rightarrow \pi^0 \rightarrow 2\gamma \rightarrow$ $\gamma\gamma$ cascade **: Fermi , ACTs..**
- Test content of jets (are they pure MHD/$e^{\pm}$, or baryonic …?)

UHE neutrinos from GRB

- Need baryon-loaded relativistic outflow
- Need to accelerate protons (as well as e^-)
- Need target photons or nuclei with $\tau \gtrsim 1$ (generally within GRB itself or environment)
- Need $E_{rel,p} \gtrsim$ 10-20 $E_{rel,e}$
- Might hope to detect individual GRB if nearby ($z \lesssim 0.15$), or else cumul. background
- If detected, can identify hadronic γ in GRB?

Photomeson Neutrino Spectrum



$p, \gamma \to \pi^+$: dominated by

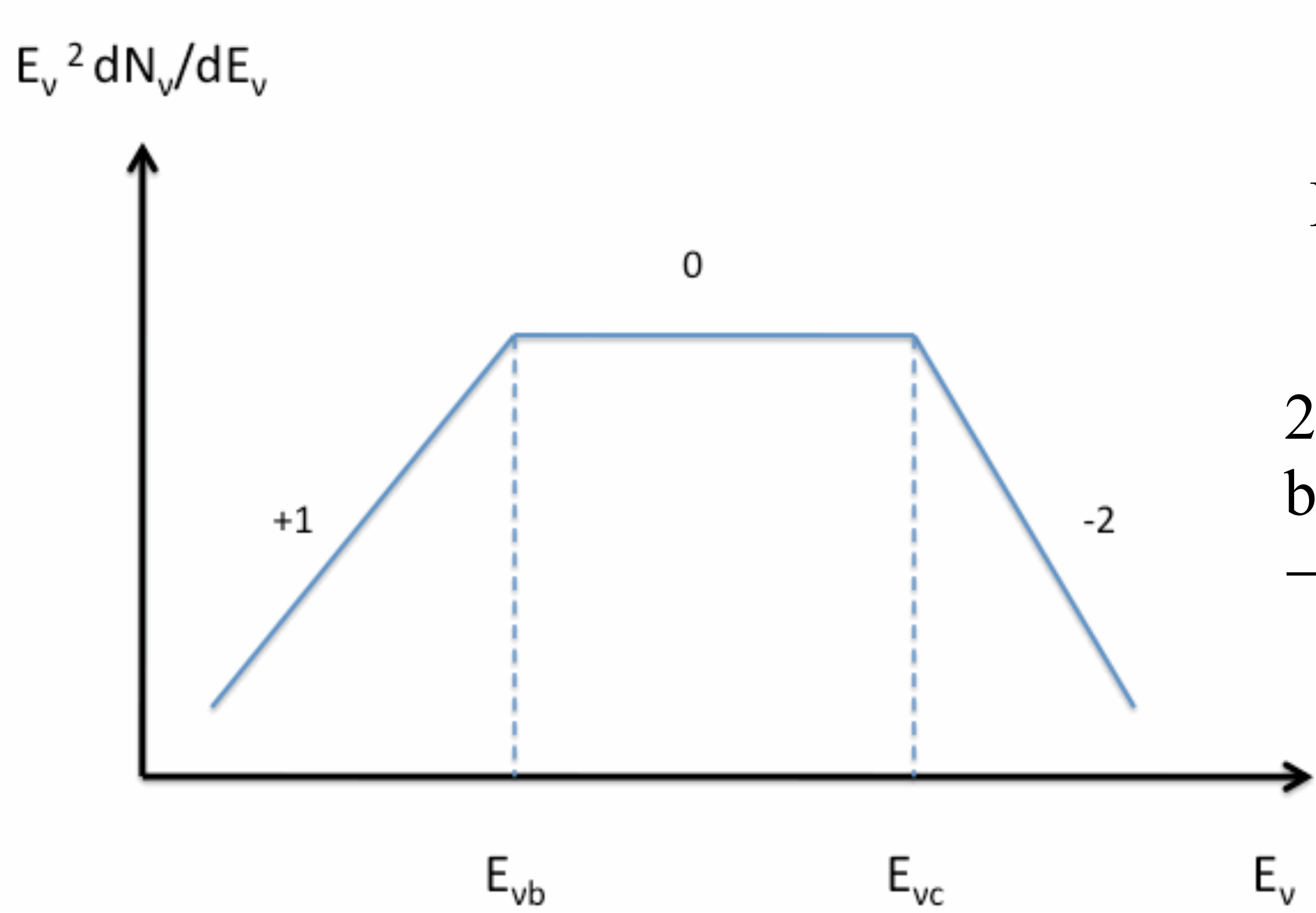
Δ − resonance :

$$E_p E_\gamma \sim 0.3\ \Gamma^2\ \mathrm{GeV}^2$$

$$\to E_{pb} \sim 0.3\ \Gamma^2\ E_{\gamma b}^{-1}$$

and $\quad E_{\nu b} \simeq \dfrac{1}{20} E_{pb}$

GRB pγ Neutrino Spectrum



1st break: Δ-reson.:
For $E_{\gamma b} \sim 1$ MeV
$\rightarrow E_{\nu b} \sim 100$ TeV

2nd break: muon cools before it can decay
$\rightarrow E_{\nu c}$: $t_{\mu d} \sim t_{\mu c}$
$t_{\mu d} \sim 2.10^{-6}$ s
$t_{\mu c} \sim 5.10^{12} / (\gamma_\mu B^2)$
$(t_{\mu c} / t_{\mu d})_{lab} \propto 1/E_\mu{}^2$
$\rightarrow E_{\nu c} \sim 10$ PeV

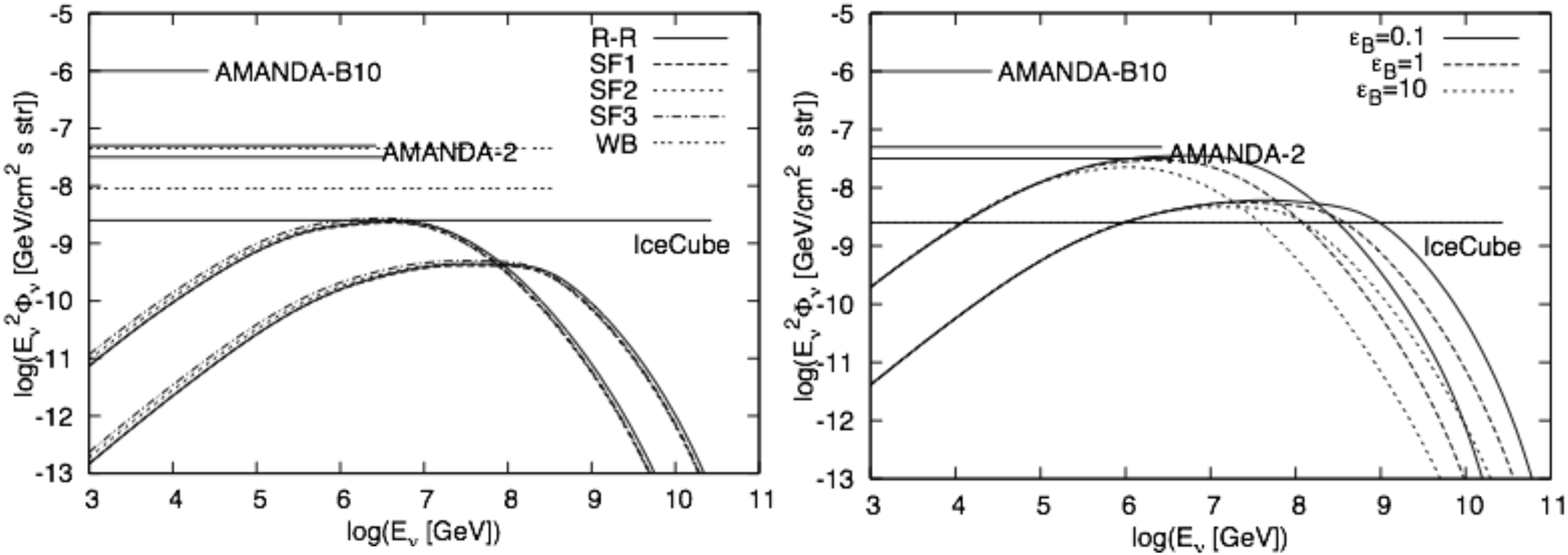
Traditional "Waxman-Bahcall" GRB ***internal shock*** pγ neutrino spectrum

(All tests so far are done on tweaks of this IS model)

However: there are other possible neutrino sources in GRB !..

Internal shock ν's contemp. with γ's

Detailed ν_μ diffuse flux incl. cooling, using GEANT4 sim., integrate up to z=7, U_p/U_γ=10 (left) ; z=20, U_p/U_γ=100 (right)



Asano 05, ApJ 623:967; Murase & Nagataki 06, PRD 73:3002

Flavor composition at source

- Pionic:

$$p, \gamma(p, p) \rightarrow \pi^+ \rightarrow \mu^+, \nu_\mu \rightarrow e^+, \bar{\nu}_\mu, \nu_e \rightarrow [1;2;0]_{src}$$

- Damped muons :

$$\pi^+ \rightarrow \mu^+, \nu_\mu \quad (+cooled\ muons) \rightarrow [0;1;0]_{src}$$

- Prompt :

$$\pi^+ \ (dense:\ interact\ before\ decay) \ \rightarrow [1;1;0]_{src}$$

- Beta beam :

(neutron decay) $n \rightarrow p^+, e^-, \bar{\nu}_e \rightarrow [1;0;0]_{src}$

Flavor oscillations in vacuum

Vacuum oscillations: $[i,j,k]_{obs} = P_{osc} \, . \, [i,j,k]_{src}$,

where $P_{osc} \sim$ "tri-bi-maximal" vac. osc. prob. matrix

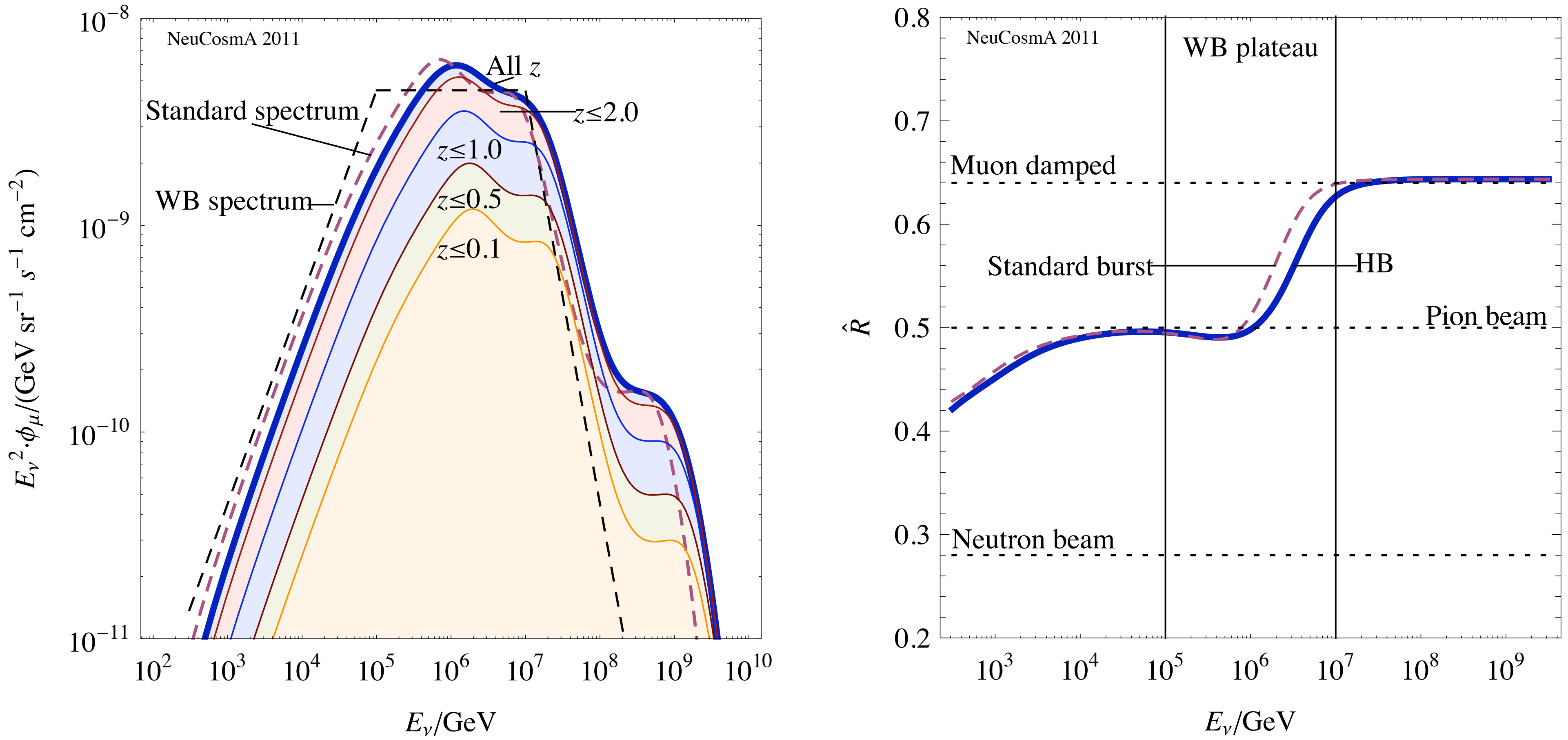
$$P_{TBM} \simeq \frac{1}{18} \begin{bmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{bmatrix}$$

Thus, approximate flavor composition observed is:

- Pionic: $P_{TBM} \, .[1,2,0]_{src} = [1 \; ; \; 1 \; ; \; 1]_{obs}$
  Damped muons: $P_{TBM} \, .[0,1,0]_{src} = [1 \; ; \; 1.8 \; ; \; 1.8]_{obs}$,
  Prompt (dense): $P_{TBM} \, .[1,1,0]_{src} = [1 \; ; \; 0.6 \; ; \; 0.6]_{obs}$,
  Beta beam: $P_{TBM} \, .[1,0,0]_{src} = [5 \; ; \; 2 \; ; \; 2]_{obs}$

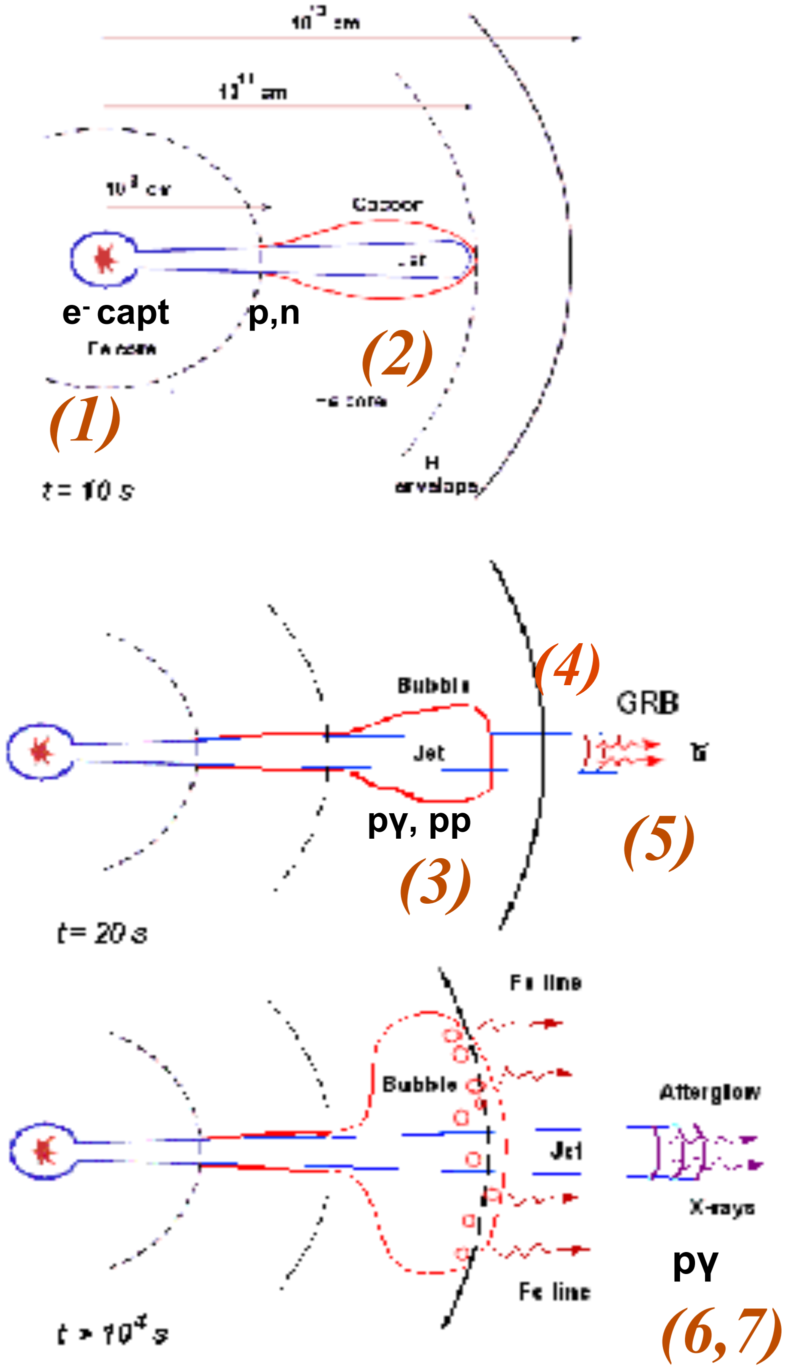
Flux & Flavor

more accurately, from a distrib. of GRBs (int.shocks):



Cumulative diffuse flux using Hopkins-Beacom (HB) z-distribution

(Baerwald, Huemmer & Winter, arXiv:1107.5583)



UHE ν from GRB

7 possible (long) GRB ν-sites:

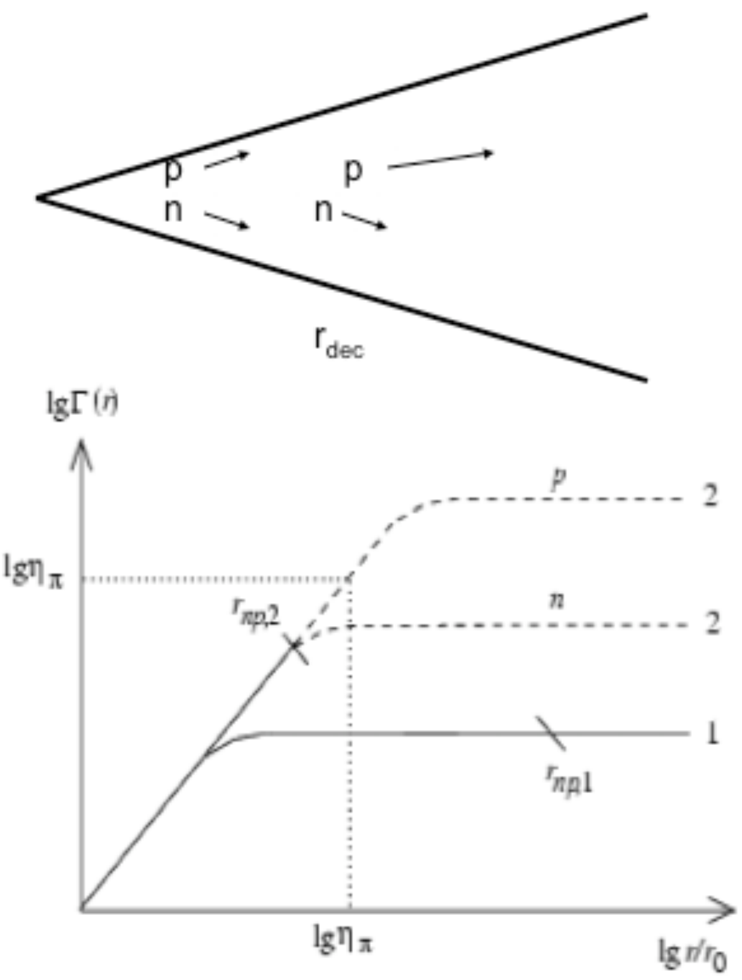
- ***1)*** at collapse, make gravitational waves + → **thermal ν (MeV)**
- ***2)*** If jet outflow is baryonic, have p,n,
  → p,n relative drift, **pp/pn** collisions
  → **VHE ν (*GeV)***
- ***3)*** Int. shocks while jet is inside star can accel. protons → **pγ, pp/pn** collisions
  → **UHE ν *(TeV)***
- ***4)*** Photospheric shocks/mag. reconn. → **pγ** collisions → **UHE ν (~ *TeV)***
- ***5)*** Int. shocks outside star, accel. protons
  → **pγ** collisions → **UHE ν *(100 TeV)***
- ***6)*** Ext. rev. shock → **EeV ν (10^{18} eV)**
- ***7)*** External forward shock? can accelerate CRs, but unless there is a reverse shock, photon field too dilute for effective **pγ** . ***May not produce UHENU, nor neutrons which escape***

1) Initial core collapse or double NS merger: →"thermal" ν's

- Core density increases dramatically
- inverse beta-decay, $p^+ + e^- \rightarrow n + \nu_e$
- **Thermal** neutrinos ("low energy"), with $k_B T_{vir} \sim G m_p M_{core}/R_{core} \sim$ ***10-30 MeV***
- Detectable by ***Super-K***, or by ***IceCube***,
- no directionality, but clear timing,
- ***BUT*** only det. if distance ***D≲ 50 kpc***

2) Hadronic GRB Fireballs:

At r $\gtrsim$400 r_0, **p,n** decouple $\rightarrow$ **VHE ν, γ**

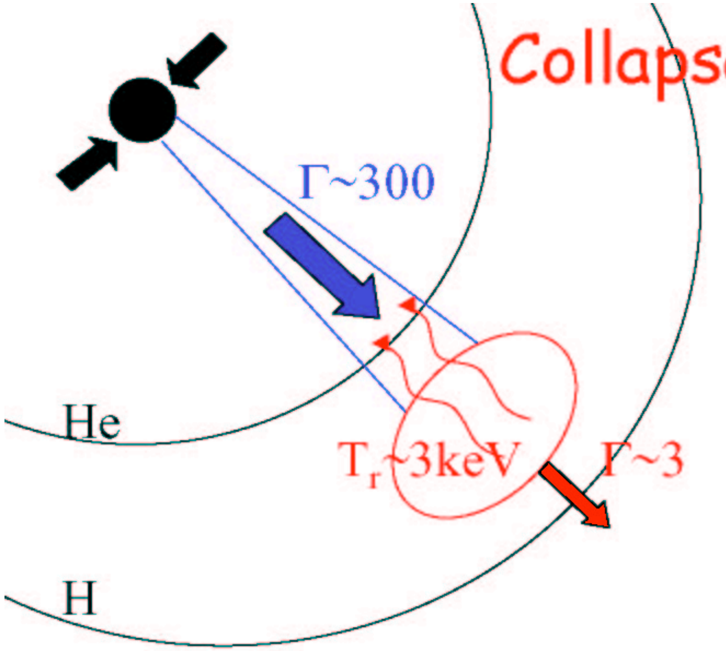


Bahcall & Mészáros 2000

(Well inside collapsing star, or only few hundred inner radii outside merging double neutron star)

- Radiation pressure acts on e^-, with p^+ coming along (charge neutrality)
- The n scatter inelastically with p^+
- The p,n initially expand together, while $t_{pn} < t_{exp}$ (p,n inelastic)
- When $t_{pn} \sim t_{exp} \rightarrow$ p,n decouple
- At that time, $v_{rel} \geq 0.5c$ $\rightarrow$ p,n becomes inelastic $\rightarrow \pi^+$
- Decoupling important when $\Gamma \geq 400$, resulting in $\Gamma_p > \Gamma_n$
- Decay $\rightarrow \nu$, of $E_\nu \geq$30-40 GeV
- **Motivation for DEEP-CORE !**

3) Later: While Jet is still inside Progenitor Star:



$$\frac{\varepsilon_p}{\Gamma}\Gamma\varepsilon_\gamma \geq 0.3\,\mathrm{GeV}^2$$

$$\Rightarrow \quad \varepsilon_p \geq 100\,\mathrm{TeV}$$

- $\varepsilon_\nu \geq 10^{12.5}$ eV

  $N_{\nu\to\mu} \approx 0.2\,/\,\mathrm{km}^2/\mathrm{Collapse}$ (10^3 GRBs/yr)

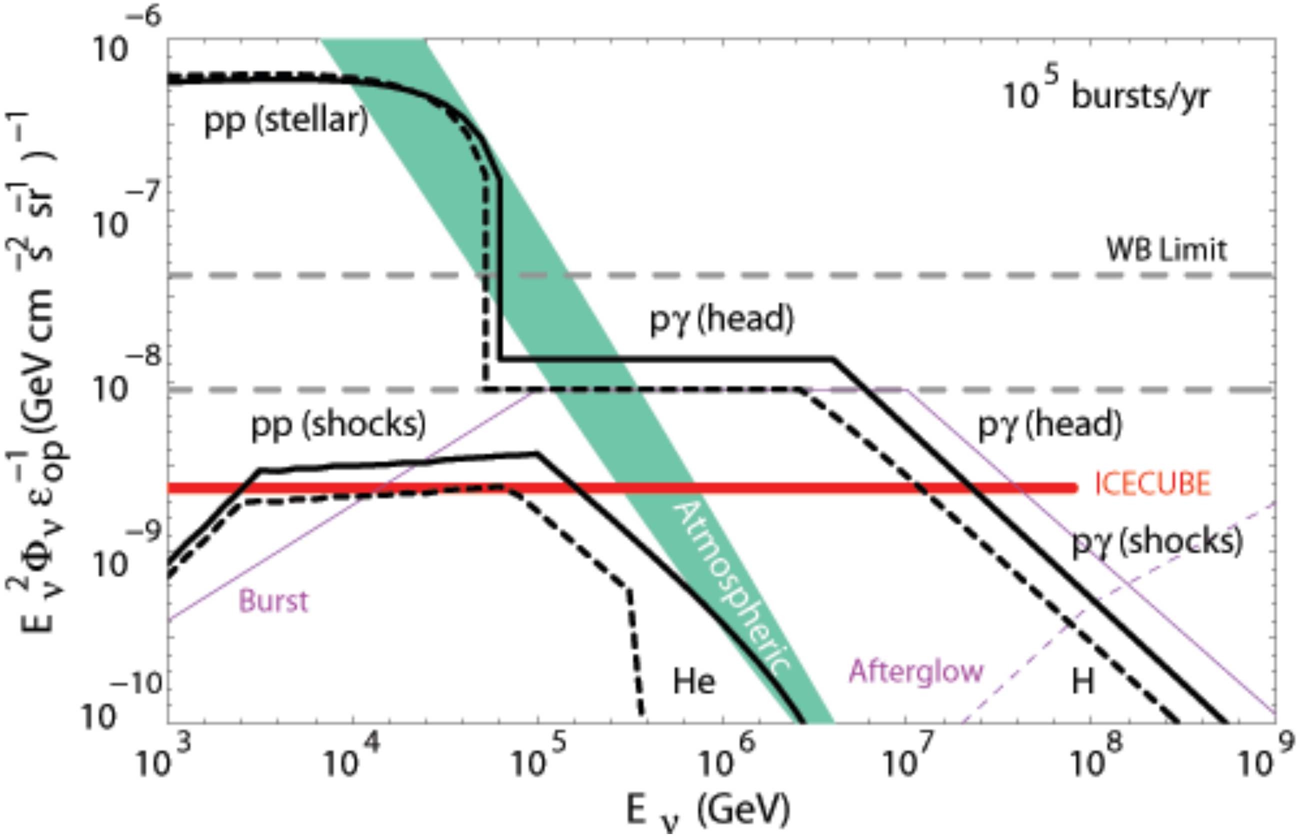
- Both "Chocked" and "successful" jets

Choked jets $\Rightarrow$ ***ν-burst (γ-dark)***
Succesful jets $\Rightarrow$ ***precursor ν (before γ)***

Mészáros & Waxman 01

Precursors & stellar tomography

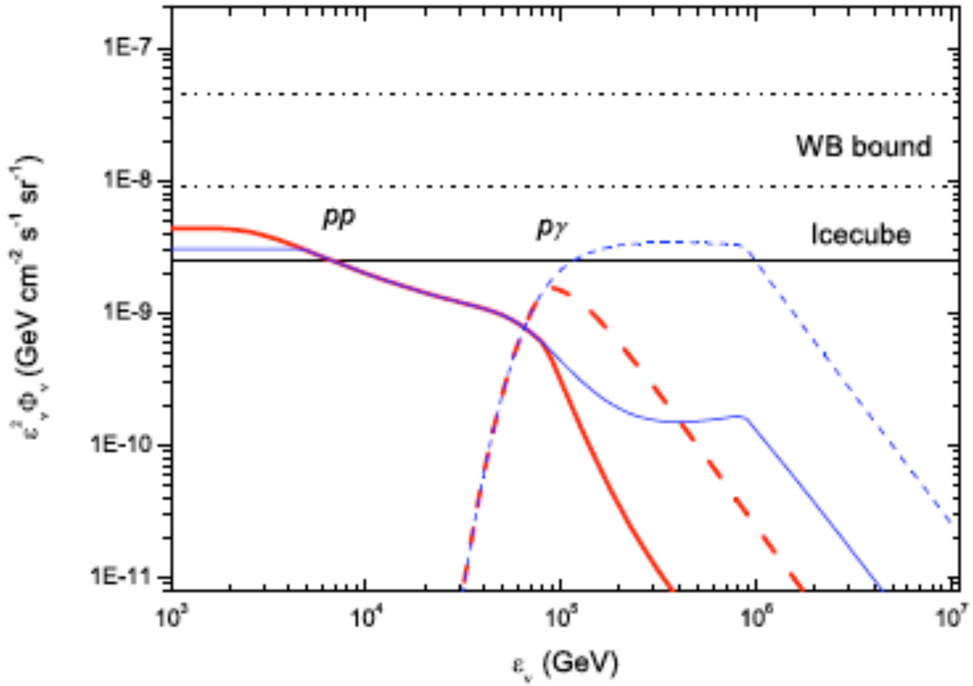
Razzaque, Mészáros, Waxman, 2003, PRD 68:3001



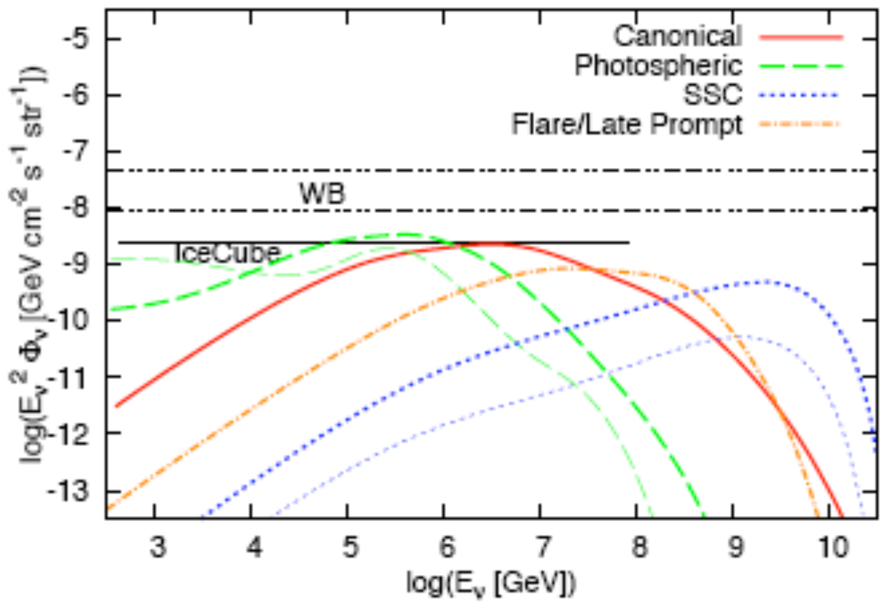
- Precursor ν-burst, both pp and pγ, leads by $\Delta t_{adv} \sim$ 10-100s, spectra depend on R_{*}
- Spectrum depends on size of stellar envelope - i.e., diagnostic for progenitor

4) GRB ‘Photospheric’ Neutrinos

- GRB relativistic outflows have a Thomson scattering $\tau_T \sim 1$ “photosphere” , below which photons are quasi-thermal
- Shocks and dissipation can occur below photosphere.
- Acceleration of protons occurs, followed by pp and pγ interactions → neutrinos
- Gas and photon target density higher than in shocks further out.
- Characteristics resemble precursor neutrino bursts, but contemporan. with prompt gamma-rays

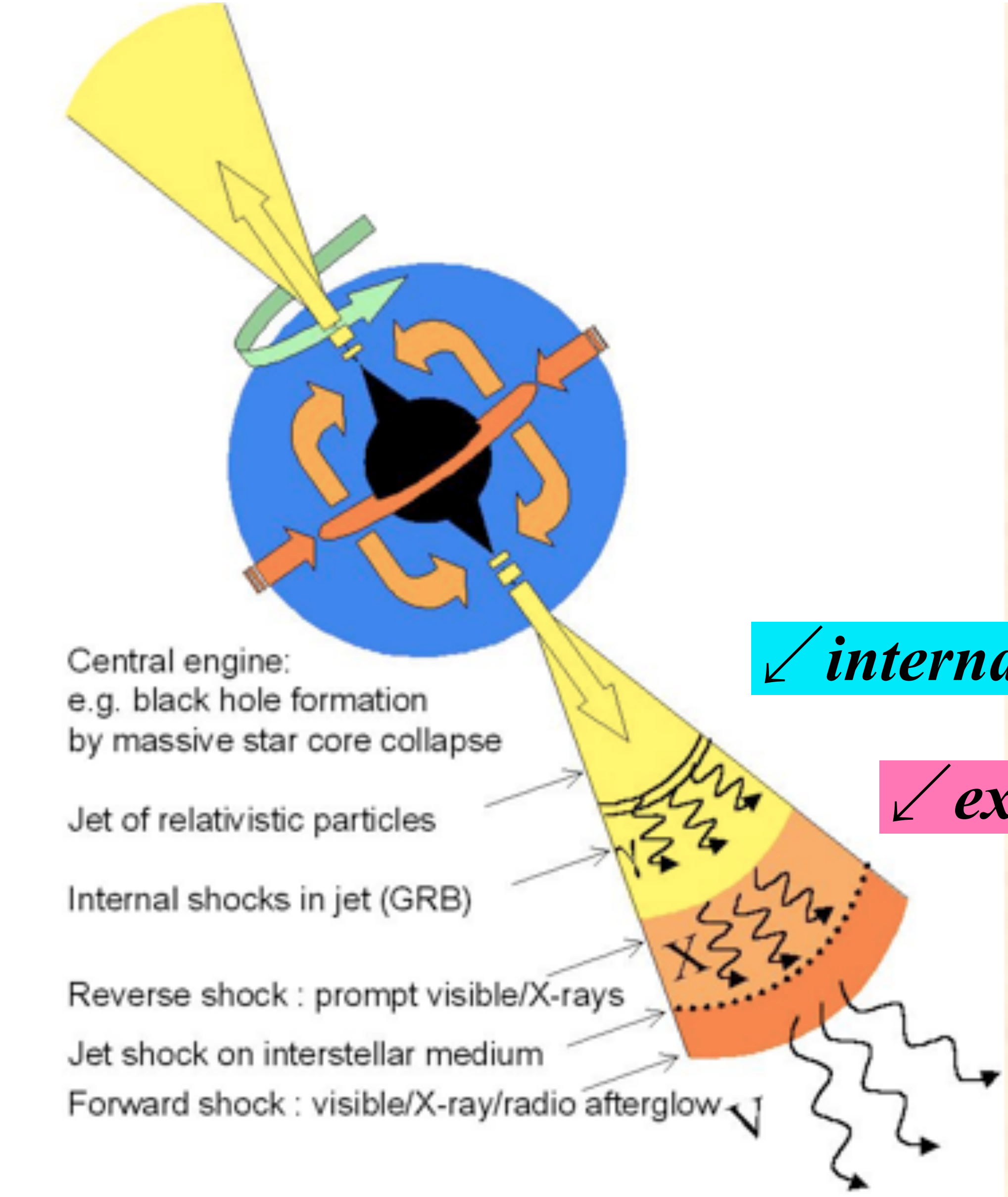


Wang, Dai, 2009, ApJL, 691:L67 (0807.0290)



Murase, 2008, PRD 78:1302 (0807.0919)

5, 6) Even Later (10-100 s after collapse): Jet emerged from Progenitor Star, int. & ext. shocks

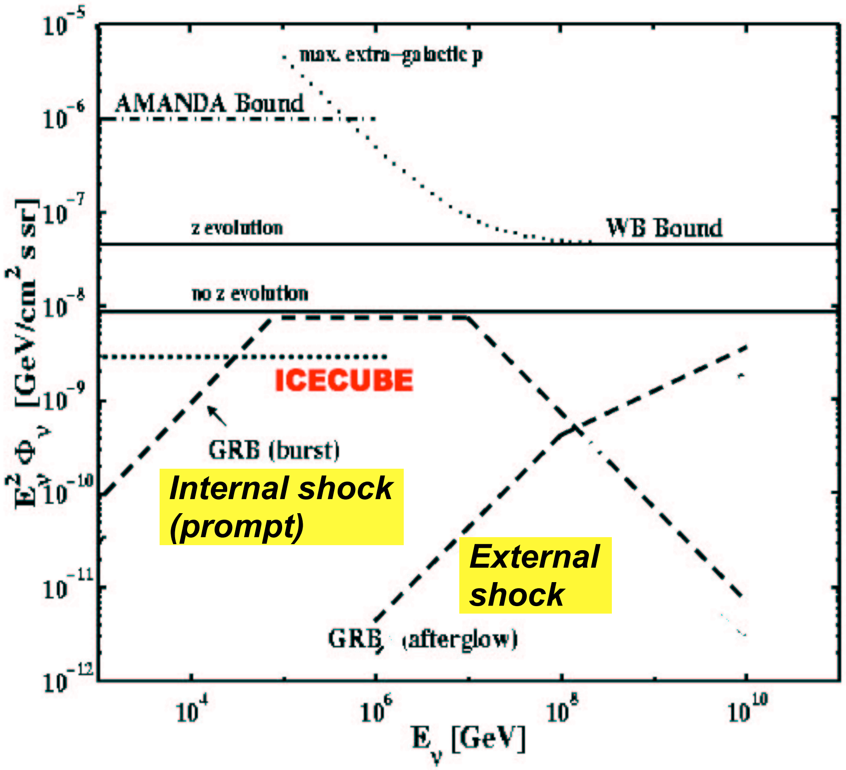


Int. & ext. shocks,
accelerate protons
and electrons,
e,B $\longrightarrow\gamma$,
p$\gamma\longrightarrow\nu$
(contemporaneous)

↙ ***internal shocks***

↙ ***external shock***

νs from pγ in internal & external shocks in GRB (5,6)



Waxman, Bahcall 97 & 99 PRL

- Δ-res.: $E'_p E'_\gamma \sim 0.3\,\mathrm{GeV}^2$ in comoving frame, in lab:

  $\rightarrow E_p \geq 3\mathrm{x}10^6\, \Gamma_2^2$ GeV

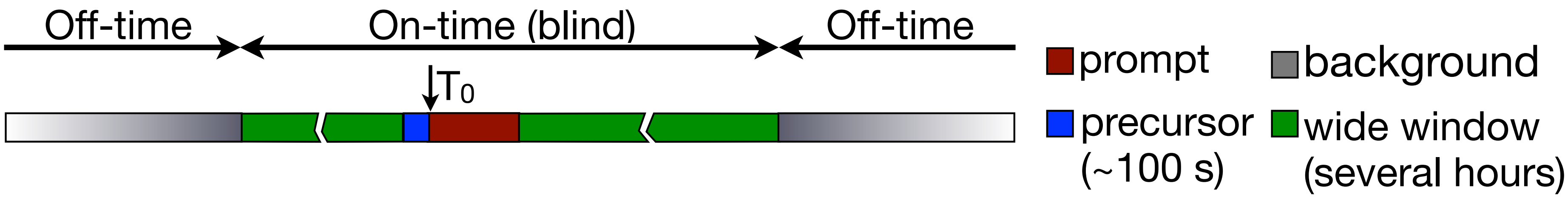
  $\rightarrow E_\nu \geq 1.5\mathrm{x}10^2\, \Gamma_2^2$ TeV
- Internal shock p$\gamma_{MeV} \rightarrow$ ~100 TeV ν s
- (External shock p$\gamma_{UV} \rightarrow$ ~ 0.1-1 EeV ν s)
- Diffuse flux: det. w. km^3

GRBs with IceCube

(Kappes et al, NUSKY, June 2011)

Being tested here **: internal shock** prompt ν-burst (WB 97) model (5)

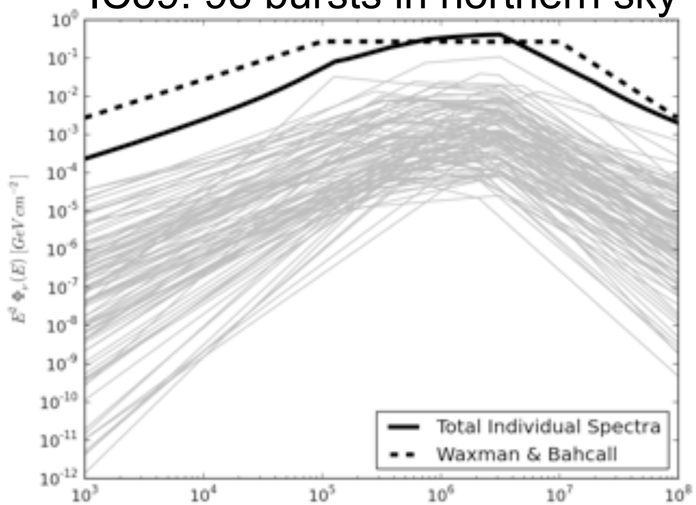
- GCN-satellite triggered searches



very low background → 1 event can be significant !

- Individual modeling of neutrino fluxes (fireball model)
- Measured parameters: γ spectrum, (redshift)
- Average parameters: Γ_{jet} (316), t_{var} (10 (1) ms), L_{iso} ($10^{52\,(51)}$ erg), ε_B *(0.1)*, ε_e *(0.1)*, $f_{e/p}$ (0.1)

IC59: 98 bursts in northern sky

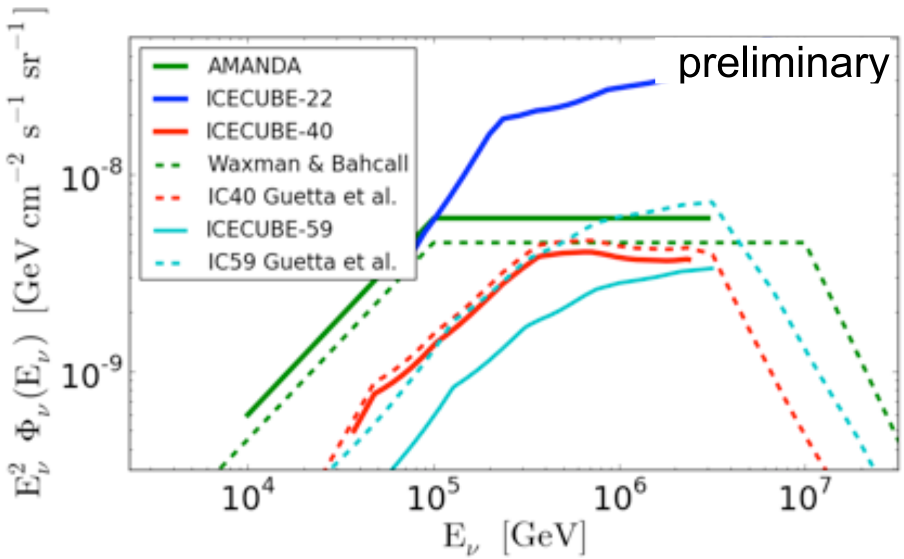


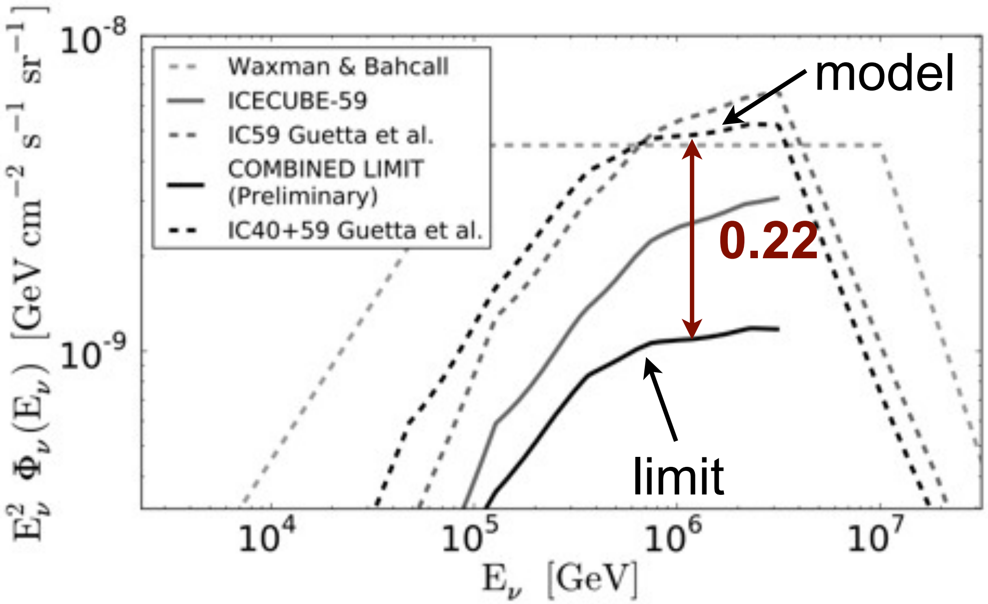
GRBs: Limits on prompt emission

- 1.9 evts needed for ≥5σ (50% cases)
- IC59: No signal-like events found (expected 5.8)

  → limit (90% CL) factor 2 below model

(Kappes et al, NUSKY, June 2011)





- Combination with upper limits from IC40

  → limit factor 5 below model

Reality check: sobering...

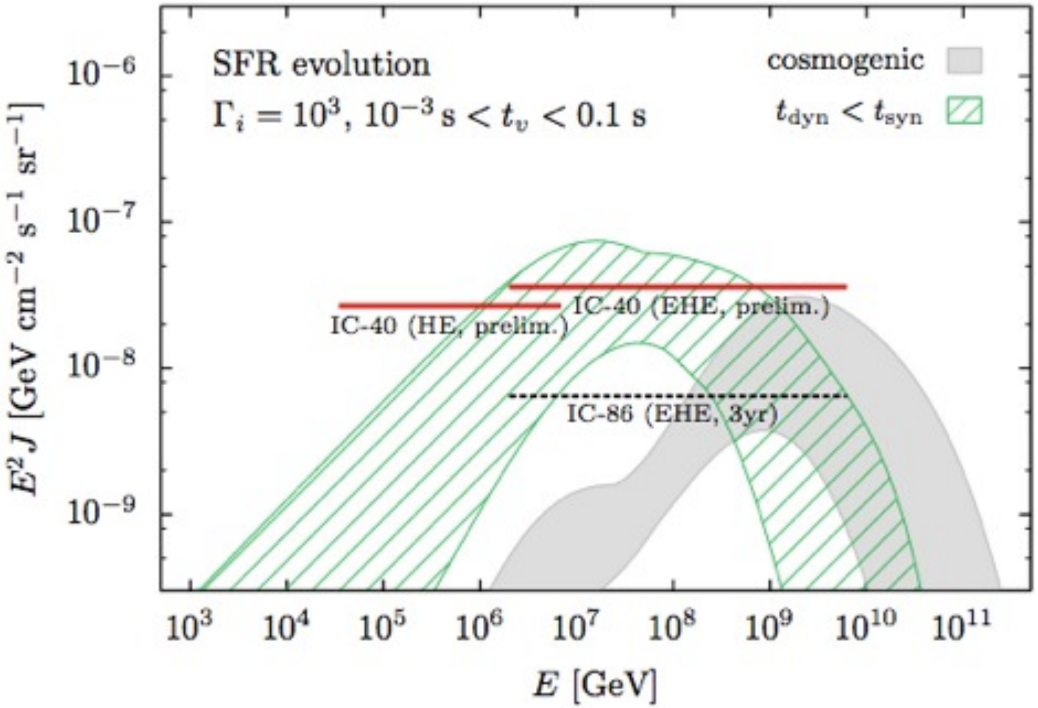
Internal shock proton acceleration model (using nominal parameters) constrained

GRBs and UHECRs

(Kappes et al, NUSKY, June 2011)

- Up to now no hint for neutrinos from GRBs
- Diffuse IC40 limit starts to disfavor GRBs as major sources of UHECR (see M. Ahlers' talk) *(… from the internal shock model, 5)*

Ahlers et al. 2011



- But GRBs could still be neutrino sources !

Note :

GZK GRB model *used for IC58 limits is based on* ***internal shock*** *prompt* **ν**-*burst (WB 97) model (with more liberal choice of proton spectral index)*

- Internal shock model of gamma prompt emission is easy to calculate, and for this reason has been used preferentially
- But internal shocks have been known to have difficulties even for gamma-ray phenomenology (efficiency, spectrum, etc)
- Internal shock proton models with index -2 are less constraining than steeper ones (but they still push the IC58 limits)
- Injection rate of protons vs. electrons is unknown; protons are not injected into the acceleration process as efficiently as electrons?
- Alternatives to internal shock gamma-ray emission region: they are being investigated - but so far are much less "calculable"

Model-dependence of predictions & detectability of GRB ν

- E_ν ~100 TeV (IS, simult.) would be least model dependent, provided assume IS - but the latter may not be justified (see BAT gamma-ray modeling)

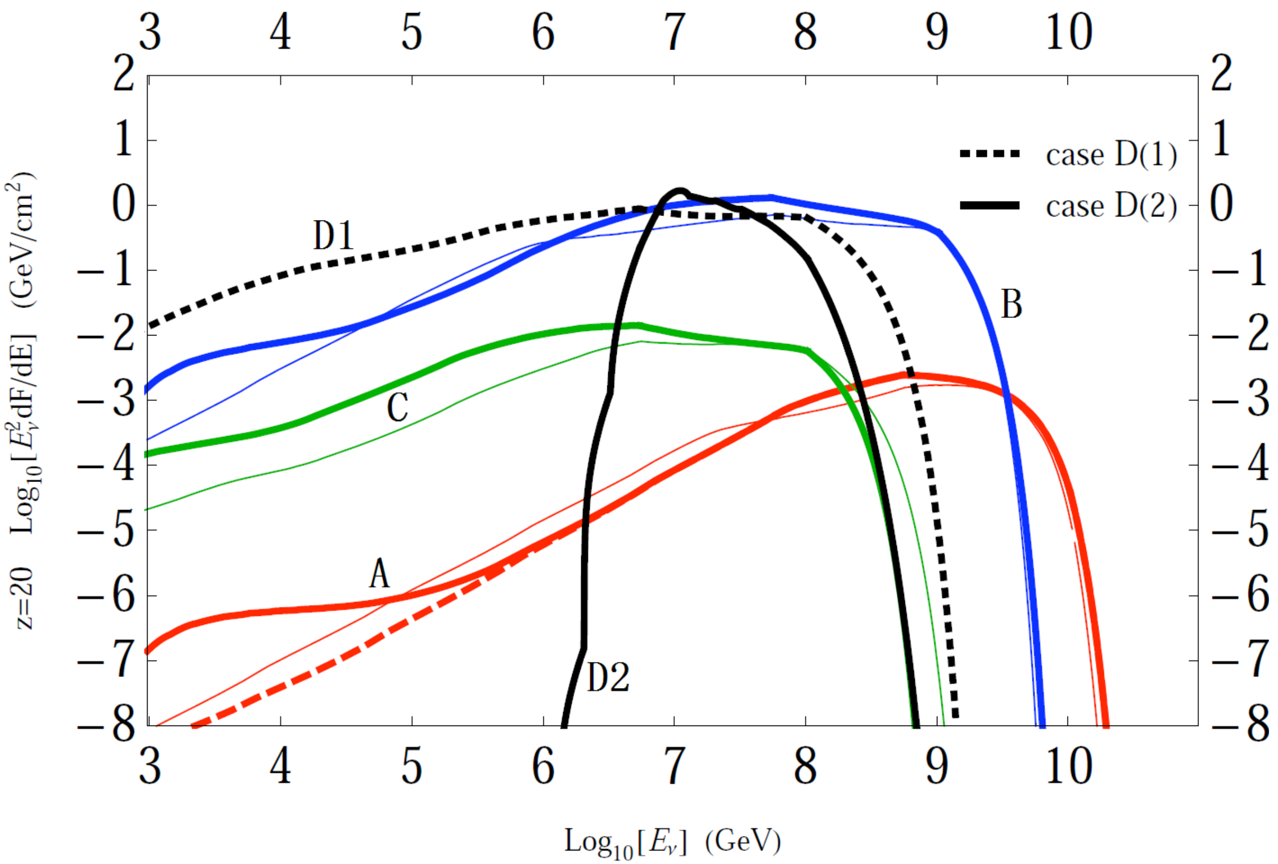
  (use observed MeV γ & same shocks as accelerate $e^\pm$)
- E_ν ~1 TeV : (precursor) more model dependent,

  (assume collapsar, sub-stellar jet, and R ~10^{11} cm)
- E_ν ~ 10^{17} eV : (afterglow) need assume reverse shock prompt opt flash is ubiquitous (?)
- E_ν ~ 5 GeV: (decoupling) p,n likely, but detection needs Deep Core or similar
- E_ν ~5-100 TeV : (pop III) speculative; very massive star

Population III GRB UHE-ν ?

(here, assumed an external shock model!)

(MHD jet, no baryons, no IS: pick up baryons at ext. shock)



Gao, Toma, Mészáros, 2011, PRD 83:103004

Pop. III: earliest "stellar" objects to form after the Big Bang

Pop. III v. massive stars →v. massive black holes

- ← Nu-fluence from one burst over ~1 day
- ← $M_h \lesssim 300 M_\odot$ $E_j \lesssim 10^{55.3}$ erg, $z=20$, $\theta_j=10^{-2}$, B,D: $n_{ext}=(10^2, 10^4)$ cm^{-3}

case	$M_h/M_\odot$	E_j/erg	θ_{-2}	$\epsilon_{e,-1}$	n/cm^3
A_{300}	300	$10^{55.3}$	10	1	1
B_{300}	300	$10^{55.3}$	1	2	10^2
B_{100}	100	$10^{54.8}$	1	2	10^2
B_{30}	30	$10^{54.3}$	1	2	10^2
C_{300}	300	$10^{55.3}$	10	2	10^4
D_{300}	300	$10^{55.3}$	1	2	10^4
D_{100}	100	$10^{54.8}$	1	2	10^4
D_{30}	30	$10^{54.3}$	1	2	10^4

UHE-ν muons from ***one*** Pop. III GRB

Model parameters↑

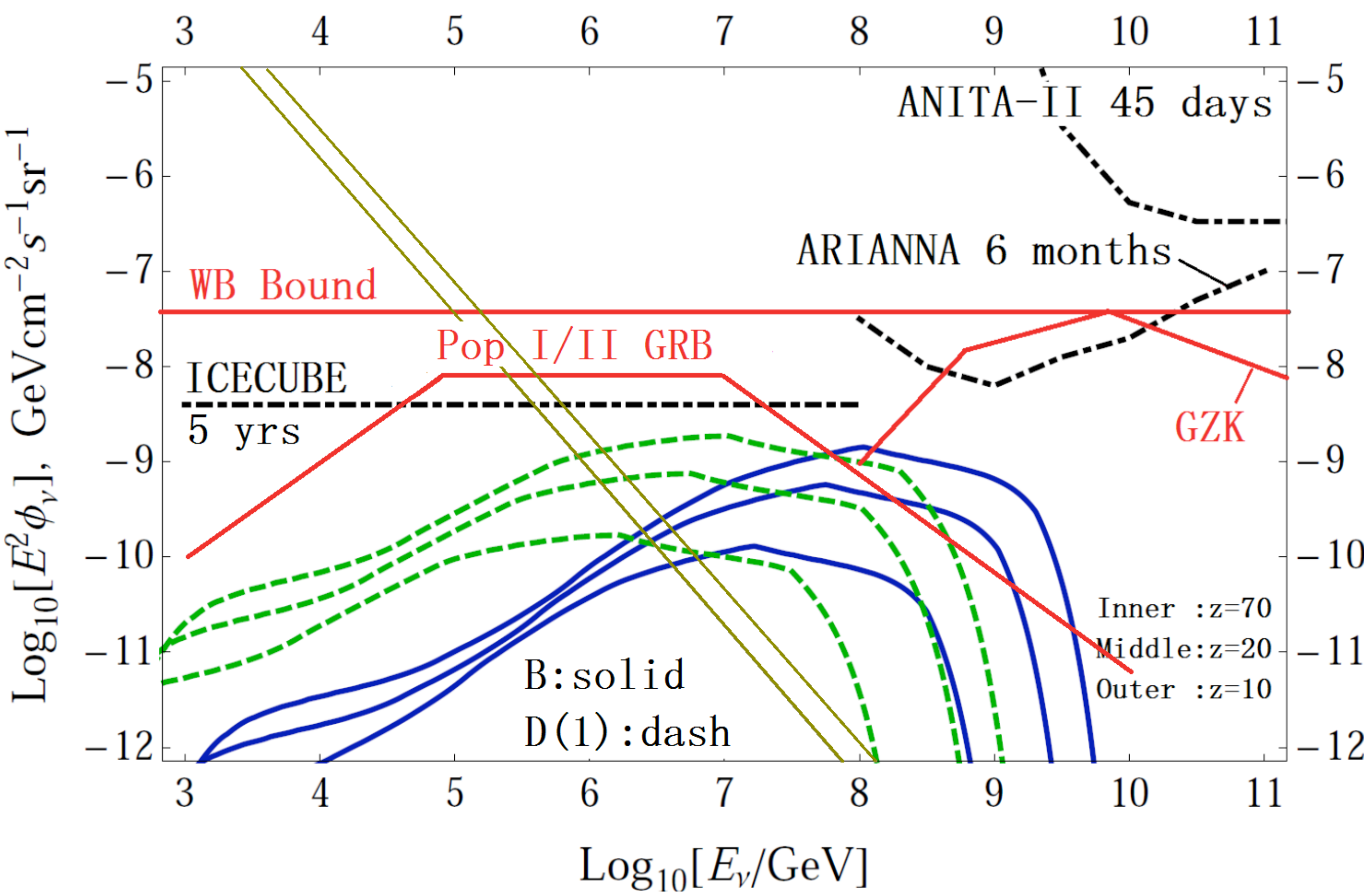
Gao, Toma, Mészáros, 2011, PRD 83:103004

M_h	E	B			$D(2)$			$D(1)$		
		10	20	70	10	20	70	10	20	70
300	$TeV - PeV$	3.0	2.1	1.4	0	0	0	10.3	5.6	2.1
	$PeV - EeV$	6.1	3.2	1.0	2.7	1.5	0.65	3.8	1.6	0.37
100	$TeV - PeV$	0.71	0.51	0.33	–	–	–	4.5	2.7	1.1
	$PeV - EeV$	1.6	0.83	0.28	0.64	–	–	2.1	0.90	0.18
30	$TeV - PeV$	0.16	0.11	–	–	–	–	1.8	1.0	0.40
	$PeV - EeV$	0.41	0.22	–	–	–	–	0.72	0.30	0.06

← μ-events / burst: Models B,D with M_h= 30,100,300 $M_\odot$, at avg. z= 10, 20, 70

Pop. III diffuse nu-flux

vs. instrumental sensitivity



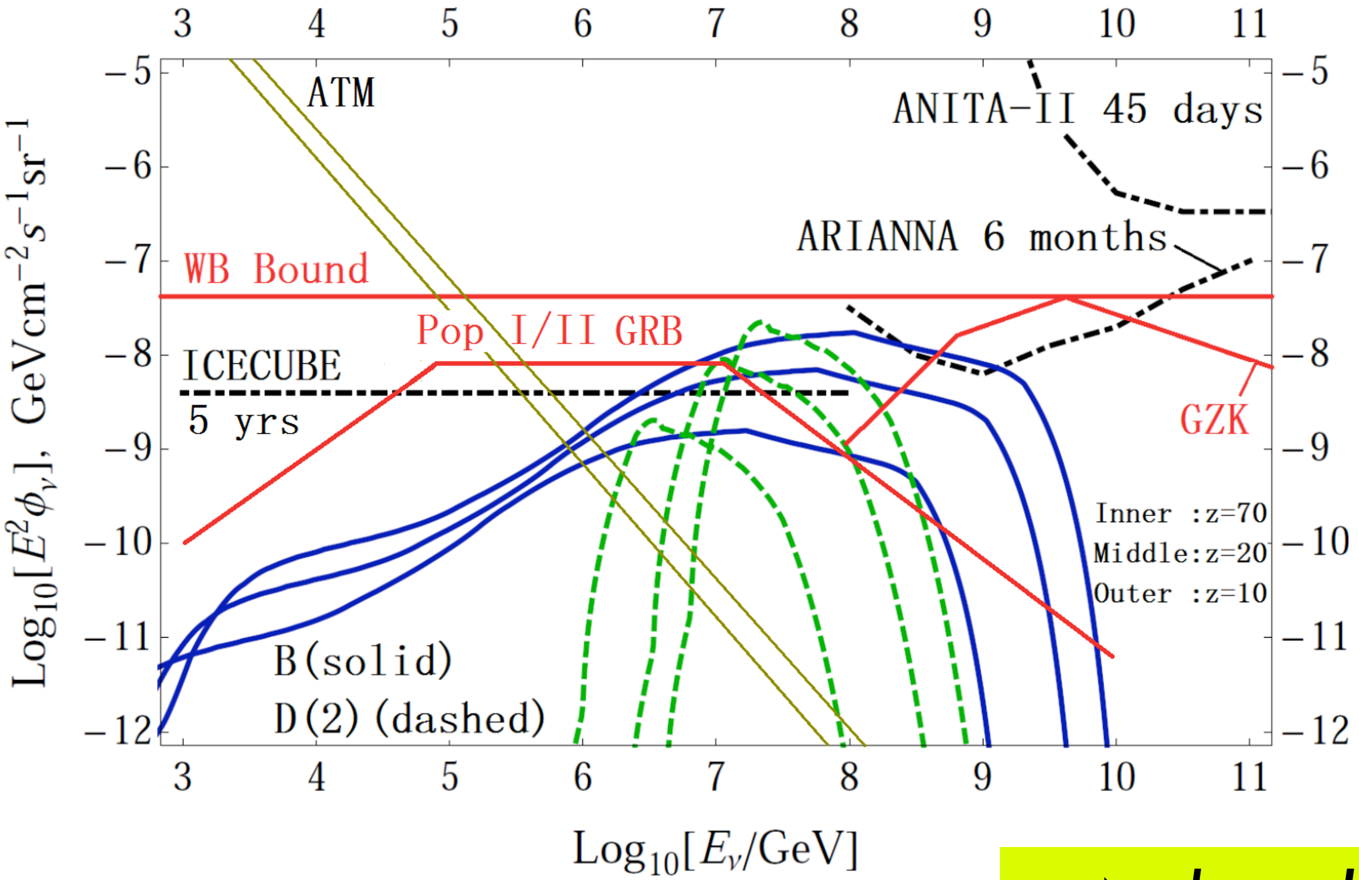
if M_h= ***30*** $M_\odot$

- Diff. nu flux, avg'd/yr (green, blue lines)
- $M_h=30\ M_\odot$, $z=20$, $n_b=1$/yr, $E_j=10^{54.5}$ erg, $\theta_j=10^{-2}$, B,D: $n_{ext}= (10^2,10^4)$ cm^{-3}

→below IceCube 5 year limit

Pop. III diffuse nu-flux

if M_h= ***300*** $M_\odot$



- Diff. nu flux, avg'd/yr (green, blue lines)
- M_h=300 $M_\odot$, z=20, n_b=1/yr, Ej=$10^{55.3}$ erg, θ_j=10^{-2} , B,D: n_{ext}= (10^2,10^4) cm^{-3}

→ *above IceCube 5 year limit*

Gao, Toma, Mészáros, 2011, PRD 83:103004

Outlook

- *The sources of the UHECR and UHENU are still unknown*
- *GRB remain good candidates, together with AGN, maybe HNe, MGR*
- *IC59 constraints on GRB int. shock nus severe: other regions?*
- *Will increasingly constrain such possibilities with GeV and TeV photon observations*
- *Will learn even more if & when astrophysical UHENUs are observed from any type of source*
- *Would be able to constrain particle acceleration / shock parameters, compactness of emission region (dimension, mag.field,.)*
- *UHE ν will allow test of proton content of jets, proton injection fraction, test shock acceleration physics, magn. field*
- *If UHE ν NOT detected in GRB, AGN → jets are Poynting dominated!*
- *Probe ν interactions at ~ TeV CM energies*
- *Constraints on stellar birth & death rates @ high-z, first structures?*