TeV-EeV Neutrinos from GRB

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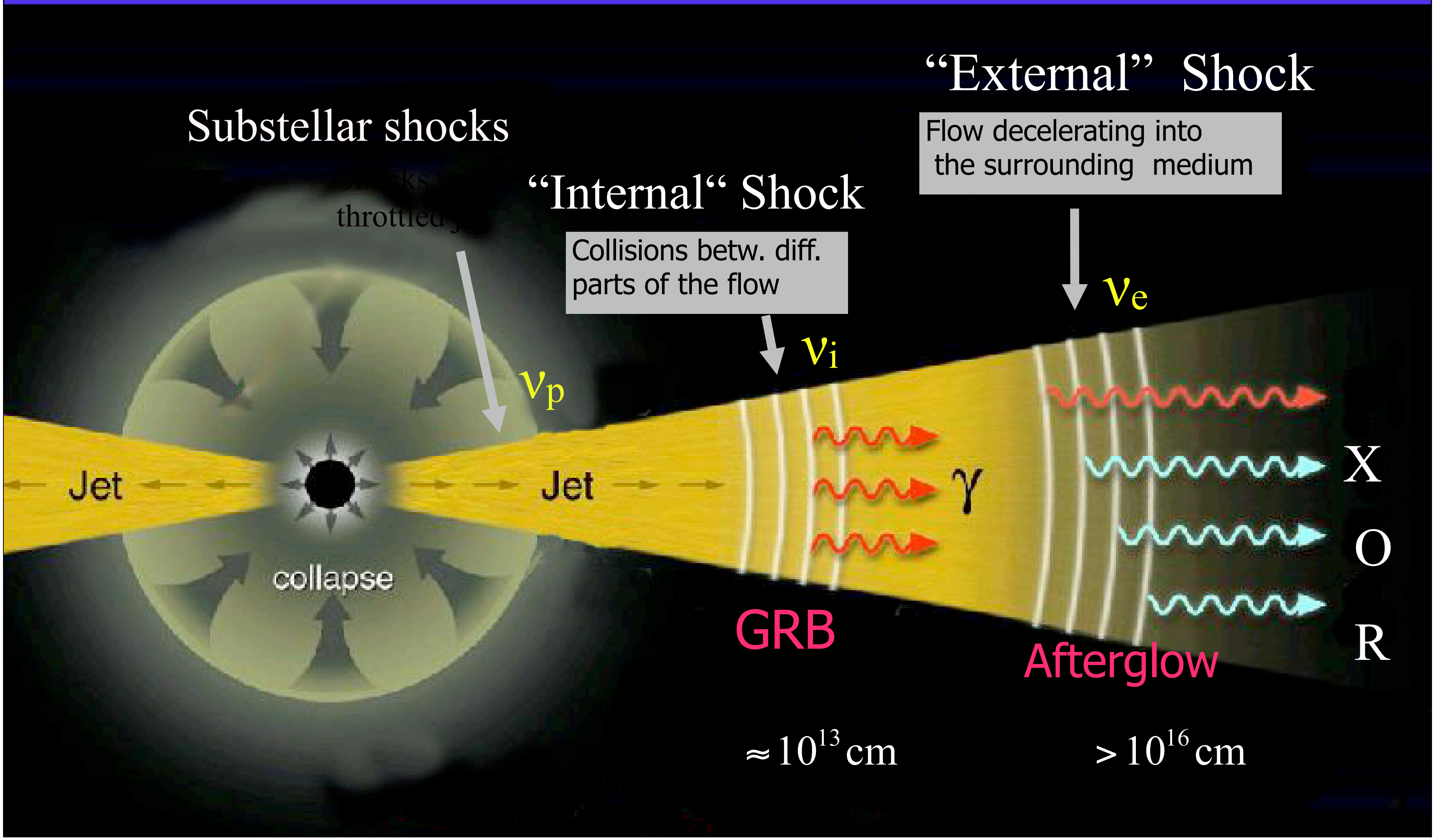
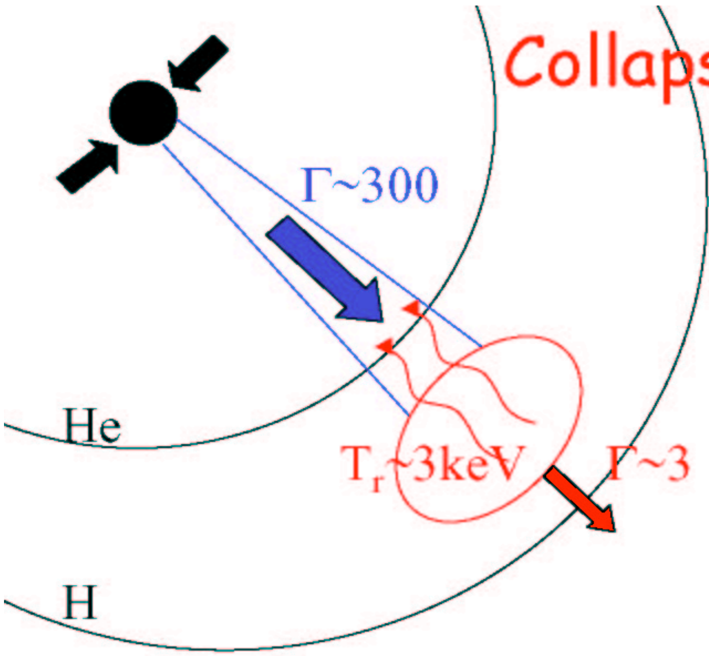
Neutrino production in baryonic GRB

3 types of neutrino energy & timescale, depending on shock location



While jet is inside progenitor:



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

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

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

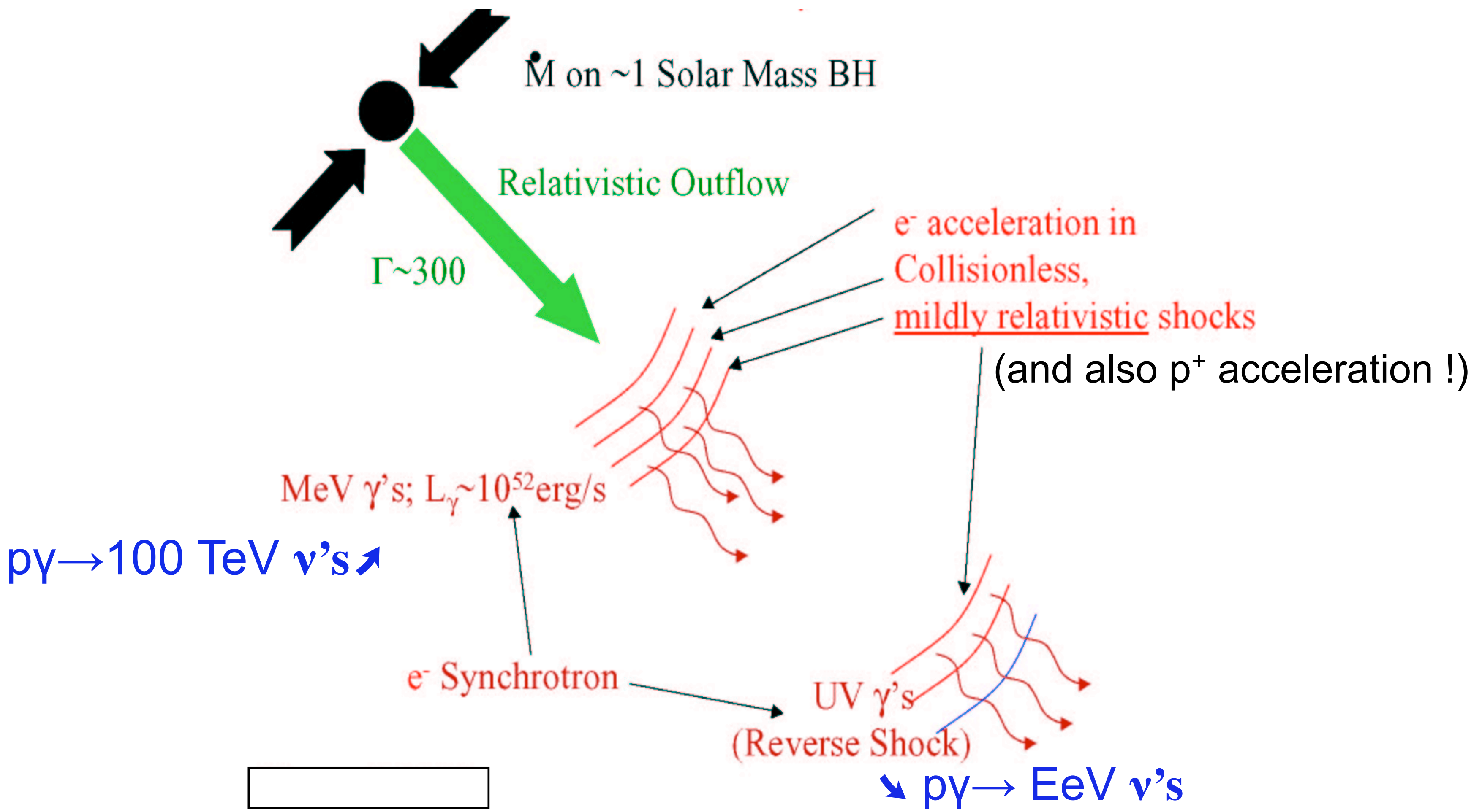
  $N_{\nu\to\mu} \approx 0.2\,/\,\mathrm{km}^2/\mathrm{Collapse}$ (10^3 GRBs/yr)

- Both "Chocked" and "successful" jets

Meszaros & Waxman 01

GRB: internal & external shocks

(outside progenitor star)



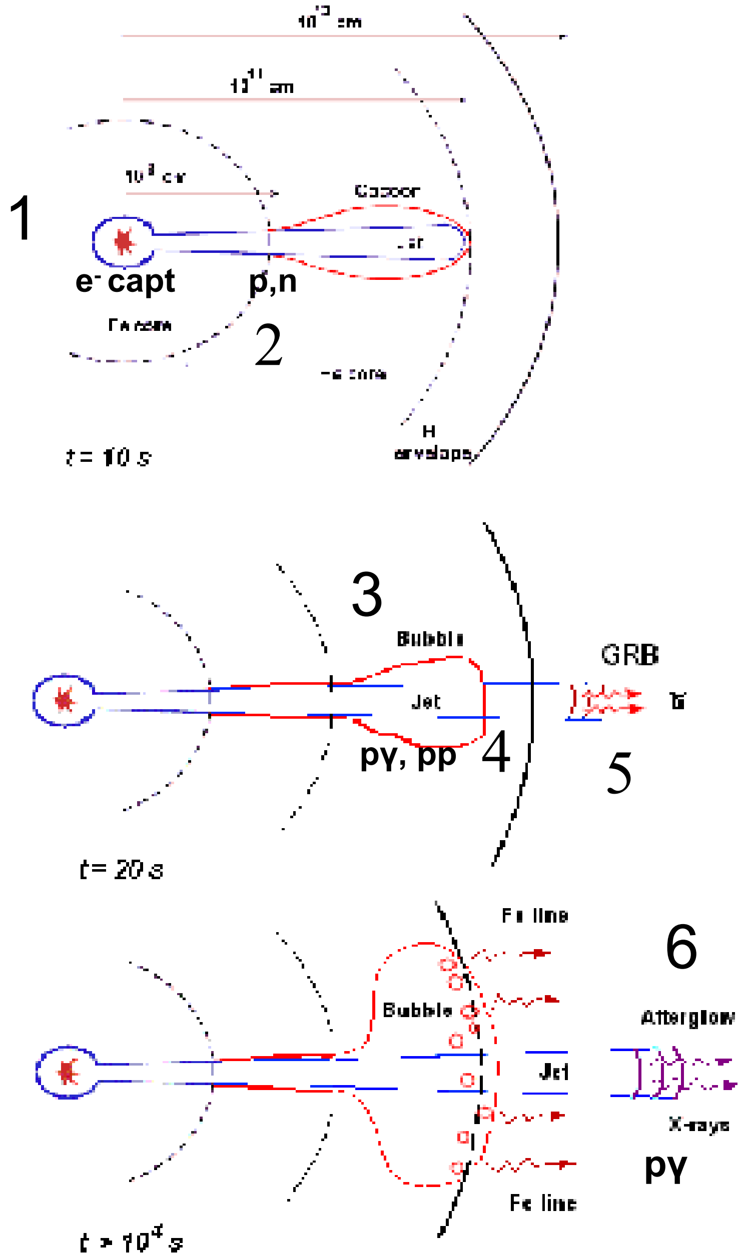
UHE neutrinos from GRB

$p\gamma$, pp → UHE ν , γ

- If protons present in (baryonic) jet → p^+ Fermi accelerated (as are e^-)
- $p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_{e}, \nu_{\mu}$ (Δ-res.: $E_p E_\gamma \sim 0.3$ GeV^2 in jet frame)
- → $E\nu_{,br} \sim 10^{14}$ eV for MeV γs (int. shock)
- → $E\nu_{,br} \sim 10^{18}$ eV for 100 eV γs (ext. rev. sh.) : ICECUBE
- → π^0 → 2γ → γγ cascade : GLAST, ACTs..
- Test hadronic content of jets (are they pure MHD/$e^\pm$, or baryonic …?)
- Also (if dense): $p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_{e}, \nu_{\mu}$
- Test acceleration physics (injection effic., ε_e, ε_B..)
- Test scattering length (magnetic inhomog. scale?..or non-Fermi?..)
- Test shock radius: γγ cascade cut-off:
- $E_\gamma \sim$ GeV (internal shock) ; $E_\gamma \sim$ TeV (ext shock/IGM)
- ⟶ photon cut-off: diagnostic for int. vs. ext-rev shock

UHE ν in GRB

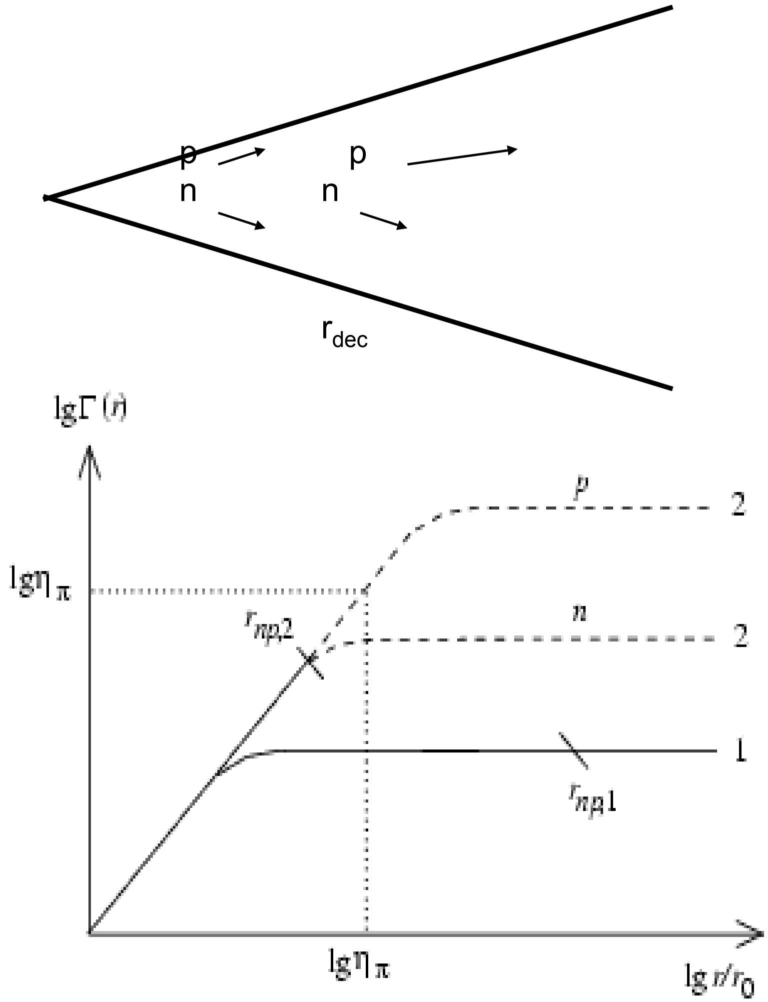
Various collapsar GRB ν-sites



- 1) at collapse, similarly to supernova core collapse, make GW + **thermal ν (MeV)**
- 2) If jet outflow is baryonic, have p,n
- → p,n relative drift, **pp/pn** collisions
- → inelastic nuclear collisions
- → **VHE ν (*GeV*)**
- 3 Int. shocks while jet is inside star, accel. protons → **pγ, pp/pn** collisions → **UHE ν (*TeV*)**
- 4) internal shocks below jet photosphere, accel. protons → **pγ, pp/pn** collisions → **UHE ν (*TeV*)**
- 5) Internal shocks outside star accel. protons
- → **pγ** collisions → **UHE ν (*100 TeV*)**
- 6) ← External rev. shock: → **pγ** → **EeV ν (10^{18} eV)**

"Hadronic" GRB Fireballs:

Thermal p,n decoupling $\rightarrow$ VHE ν,γ

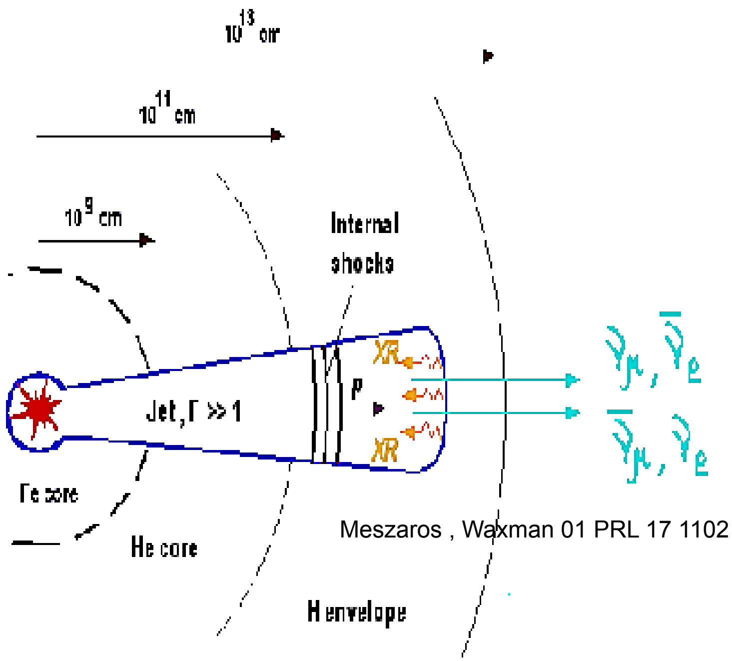


(Bahcall & Meszaros 2000 PRL 85:1362); Lemoine 2002; Beloborodov, 2002

- **p,n** in fireball move together while
- $t_{pn} > t_{exp}$ (rad. acts on p, while elastic scattering couples p,n)
- **p,n** decouple when $t_{pn} \gtrsim t_{exp}$, where
- this occurs for $\Gamma \gtrsim 400$
- (Derishev etal 99; Bahcall,Meszaros 00; Fuller etal 00)
- Inelastic pn :
  $\rightarrow \pi^{\pm} \rightarrow \mu^{\pm},\nu_\mu \rightarrow e^{\pm},\nu_e,\nu_\mu$
- **$\rightarrow \pi^0 \rightarrow 2\gamma$**
- **$E_{\nu\mu}$~5-10 GeV $\rightarrow$ ICECUBE?**
- det @ z~1, Rν~7/yr from all GRB,
- **but** only if larger PMT density
- **γ-rays:** $\pi^0 \rightarrow 2\gamma$, $\rightarrow$ **GLAST,**
- **E_γ ~10 GeV**, detect @ **$z \lesssim 0.1$**

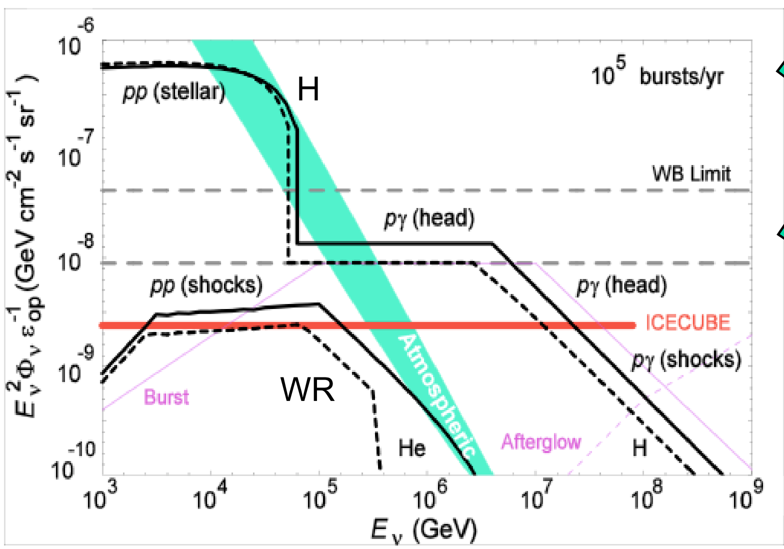
(2) Jet inside star:

GRB ν,γ Precursor



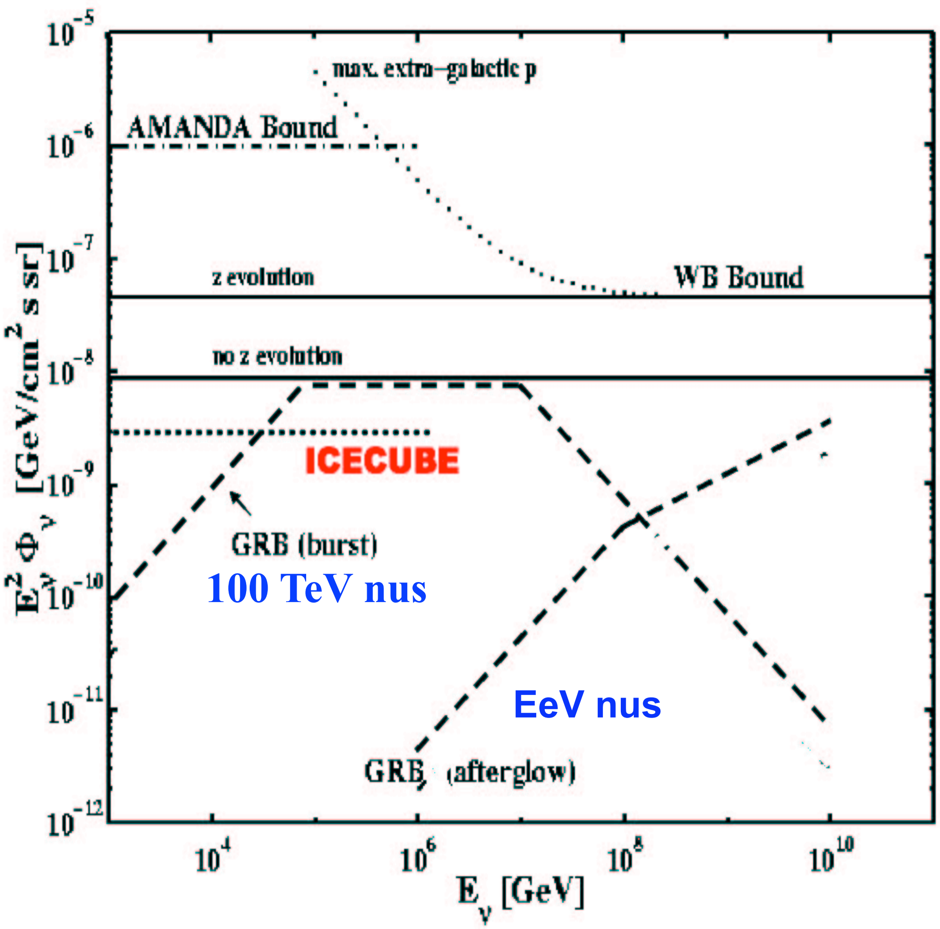
Meszaros , Waxman 01 PRL 17 1102

- Jet propagating through progenitor,
- *BEFORE* emerging from stellar envelope,
- can have int. shocks which accel. p^+ →
- pγ on unobserved X-rays , → $\pi^\pm$, ν
- pp, pn on stellar envelope → $\pi^\pm$, ν
- →~ few TeV neutrino **precursor**
- If progenitor has H-layer $R_\varnothing \sim 10^{12}$ cm (BSG) →
- Rate($\nu_{m\,,\,TeV}$) prec > Rate($\nu_{m\,,\,100\,TeV}$)int.shock
- (easier to detect in ICECUBE)
- but, if WR (He core), $R_\varnothing \sim 10^{11}$ cm →
- Rate($\nu_{m\,,\,TeV}$) prec < Rate($\nu_{m\,,\,100\,TeV}$) int.shock
- → test progen. size (e.g. @ high z : popIII?)
- If jet DOES NOT escape ⇒ "choked" jet,
- vs escape, γs don't → **"hidden ν source**
- If jet break-out: → photon flashes
- → Blue ν- spectrum: ~100 TeV
- p,γ→ν from shocks outside star



Razzaque, Mészáros, Waxman 03 PRD 68, 3OO1)

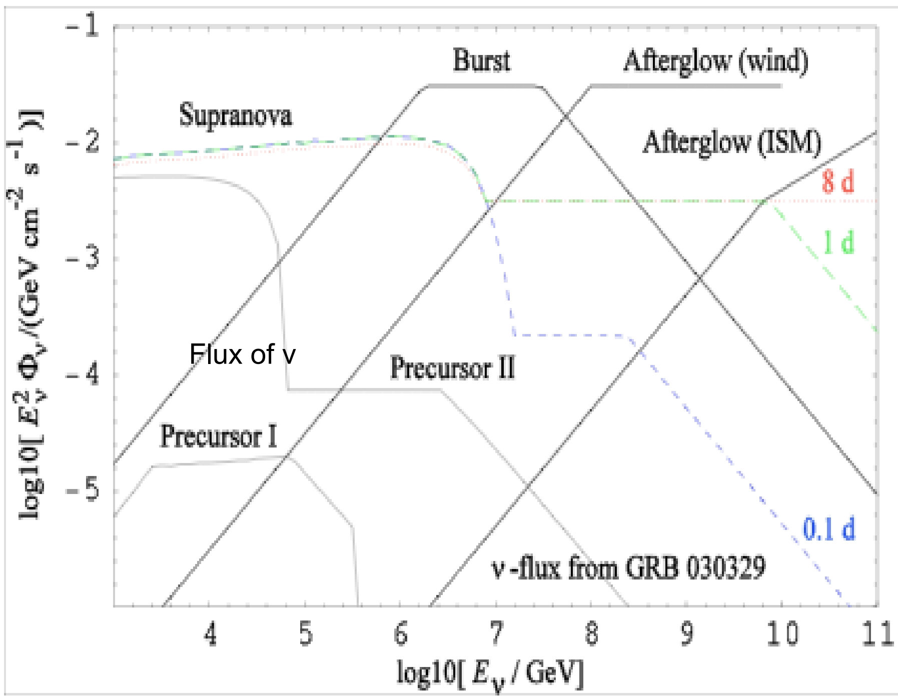
νs from pγ in internal & external shocks in GRB



- Shocks accelerate p^+ (as well as the e^- which produce γ_{MeV})
- Δ-res.: $E'_p \, E'\gamma \sim 0.3 GeV^2$ in comoving frame, in lab:
- $\rightarrow E_p \geq 3x10^6 \, \Gamma_2^2$ GeV
- $\rightarrow E\nu \geq 1.5x10^2 \, \Gamma_2^2$ TeV
- Internal shock p,γ_{MeV}
- $\rightarrow \sim$100 TeV νs
- External shock p,γ_{UV}
- $\rightarrow \sim$ 0.1-1 EeV νs
- Diffuse flux: detect in km^3

GRB 030329: ν precursor, burst, and afterglow, with ICECUBE

Burst of $L\gamma \sim 10^{51}$ erg/s, $E_{SN} \sim 10^{52.5}$ erg, q~68°, ***@ z~0.17***

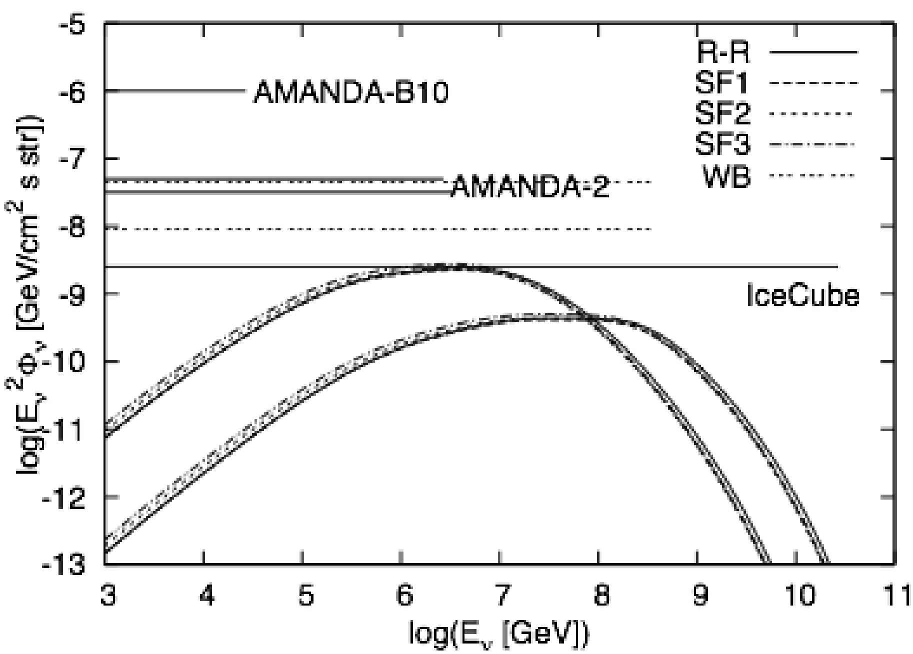


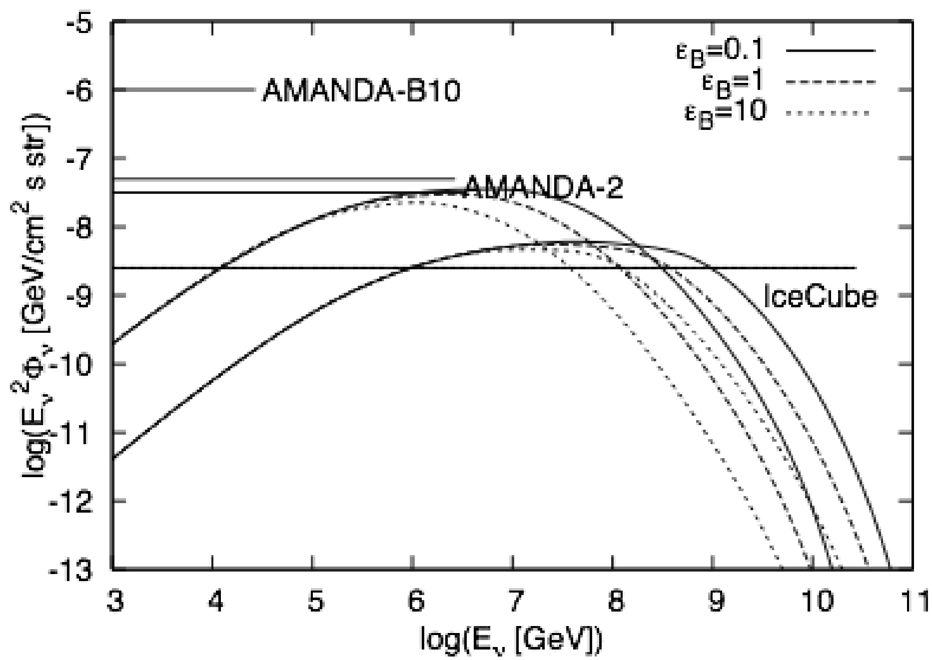
Flux Component	TeV-PeV μ-track	TeV-PeV e-cascade	PeV-EeV μ track	PeV-EeV e-cascade
Precursor I	$9 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	-	-
	$6 \cdot 10^{-3} \uparrow$	$2 \cdot 10^{-3} \uparrow$	-	-
	$0.01 \rightarrow$	$2 \cdot 10^{-3} \rightarrow$	-	-
Precursor II	4.1	1.1	$3 \cdot 10^{-3}$	$2 \cdot 10^{-4}$
	$2.9 \uparrow$	$0.9 \uparrow$	-	-
	$4.4 \rightarrow$	$1.2 \rightarrow$	$0.01 \rightarrow$	$8 \cdot 10^{-4} \rightarrow$
Burst	1.8	0.2	1.4	0.1
	$0.3 \uparrow$	$0.04 \uparrow$	-	-
	$2.9 \rightarrow$	$0.3 \rightarrow$	$7.6 \rightarrow$	$0.4 \rightarrow$
Afterglow (ISM)	$2 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-5}$
	$3 \cdot 10^{-5} \uparrow$	$4 \cdot 10^{-6} \uparrow$	-	-
	$2 \cdot 10^{-4} \rightarrow$	$2 \cdot 10^{-5} \rightarrow$	$0.01 \rightarrow$	$5 \cdot 10^{-4} \rightarrow$
Afterglow (wind)	0.03	$3 \cdot 10^{-3}$	0.05	$3 \cdot 10^{-3}$
	$5 \cdot 10^{-3} \uparrow$	$7 \cdot 10^{-4} \uparrow$	-	-
	$0.05 \rightarrow$	$5 \cdot 10^{-3} \rightarrow$	$1.4 \rightarrow$	$0.06 \rightarrow$
Supranova 0.1 d	12.4	2.4	0.5	0.03
	$6.1 \uparrow$	$1.6 \uparrow$	-	-
	$14.9 \rightarrow$	$2.7 \rightarrow$	$1.6 \rightarrow$	$0.1 \rightarrow$
Supranova 1 d	12.4	2.4	0.5	0.03
	$6.1 \uparrow$	$1.6 \uparrow$	-	-
	$14.9 \rightarrow$	$2.7 \rightarrow$	$1.9 \rightarrow$	$0.1 \rightarrow$
Supranova 8 d	10.9	2.2	0.4	0.03
	$5.4 \uparrow$	$1.4 \uparrow$	-	-
	$13.2 \rightarrow$	$2.4 \rightarrow$	$1.7 \rightarrow$	$0.1 \rightarrow$

Razzaque, Mészáros, Waxman 03 PRD 69, 23001

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)

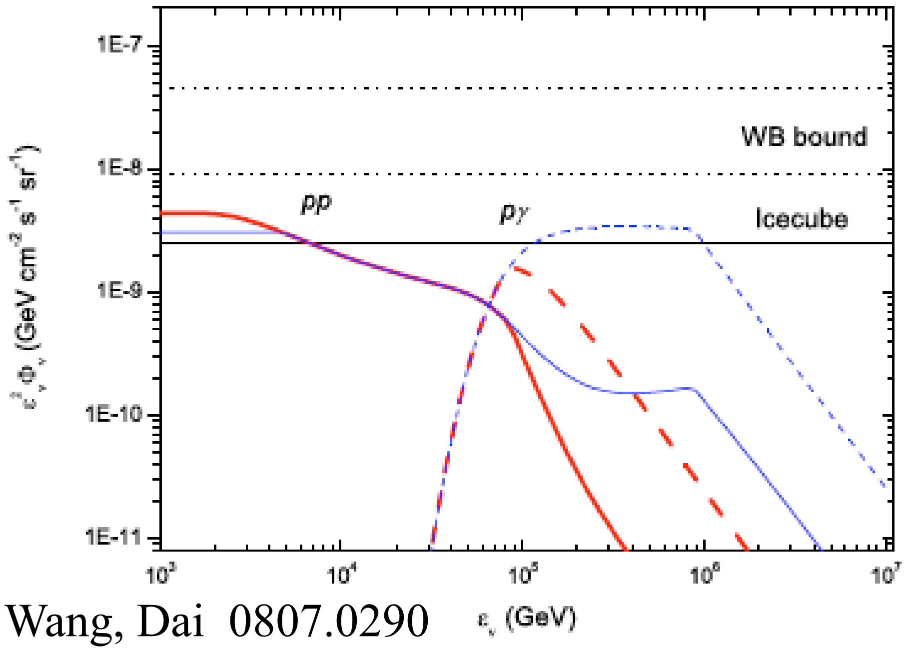




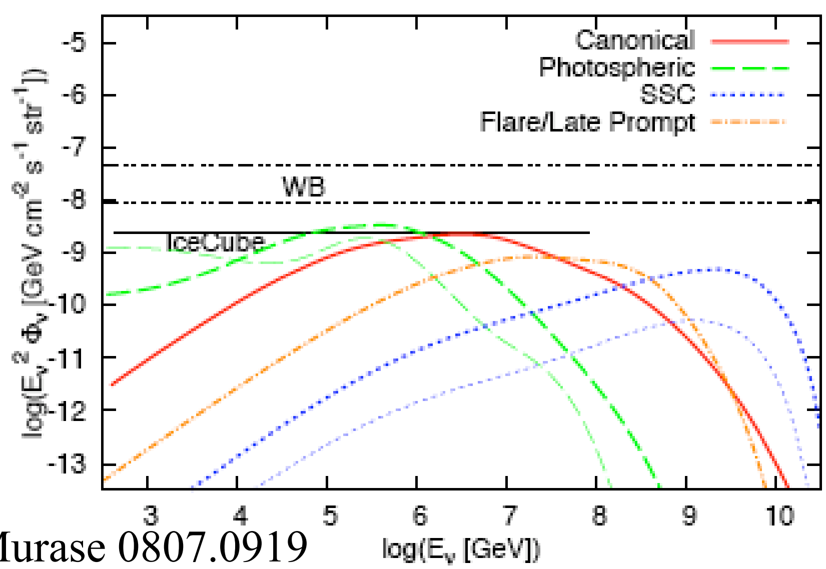
Asano 05, ApJ 623:967; Murase & Nagataki 06, PRD 73:3002

GRB "Photospheric" Neutrinos

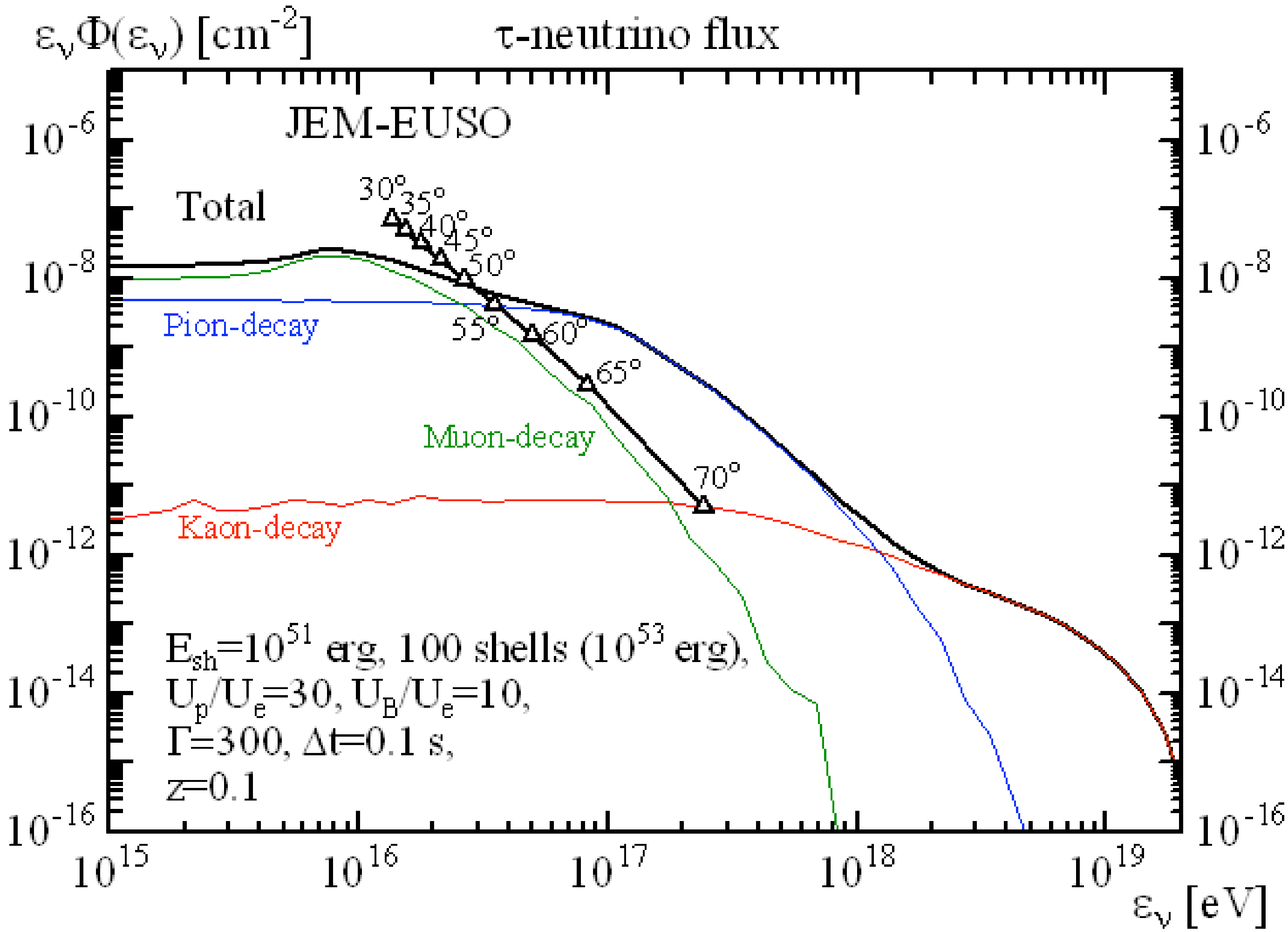
- GRB relativistic outflows have a Thomson scattering $\tau_T \sim 1$ "photosphere" , below which photons are quasi-thermal
- Shocks and dissipation can occur below photosphere.
- Acceleration of protons occurs, followed by pp and pγ interactions → neutrinos
- Gas and photon target density higher than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



Wang, Dai 0807.0290



Murase 0807.0919



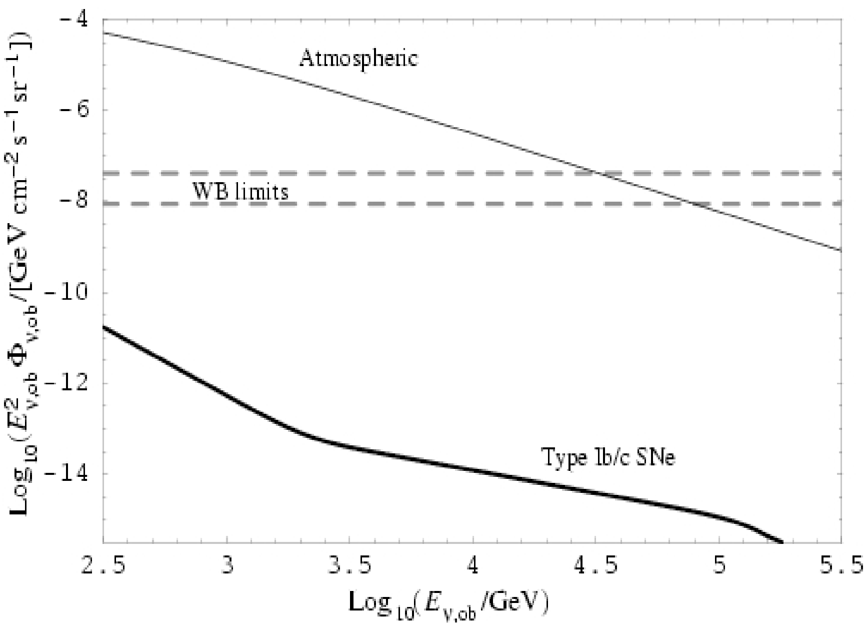
VHE ν's

Neutrino fluxes; Asano et al, 2008, in prep.

(JEM-EUSO sens.: M. Teshima, MPI)

- Crucial parameter for neutrino (and CR) flux is U_p/E_e .
- Note that ν's from pion decay are good targets too (not just muon decay)
- For typical values $U_p/E_e \sim 30$ needed to make GRB "interesting" UHECR sources, the neutrino flux might be detectable from ***individual*** GRB sources at ***z~0.1*** with JEM-EUSO (K. Asano et al, 2008, in prep.)

Core collapse SN : slow jets?



Spectrum and diffuse flux ↑

Razzaque, Mészáros, Waxman, 2004, PRL 93, 181101

Ando & Beacom, 2005, PRL 95, 1103

- Maybe all core coll. (or Ib/c) SN resemble (watered-down) GRB?
- Evidence for asymmetric expansion of c.c. (Ib/c) SNR: slow jets Γ~ few ?
- If so, accel protons while jet inside star, $p\gamma \rightarrow \pi, \mu \rightarrow \nu$ (TeV)
- **Diffuse flux: negligible,**
- *but*
- **individual SN** in nearby (2-3 Mpc) gals, e.g. M82, NGC253, **detectable** (if have slow jets),

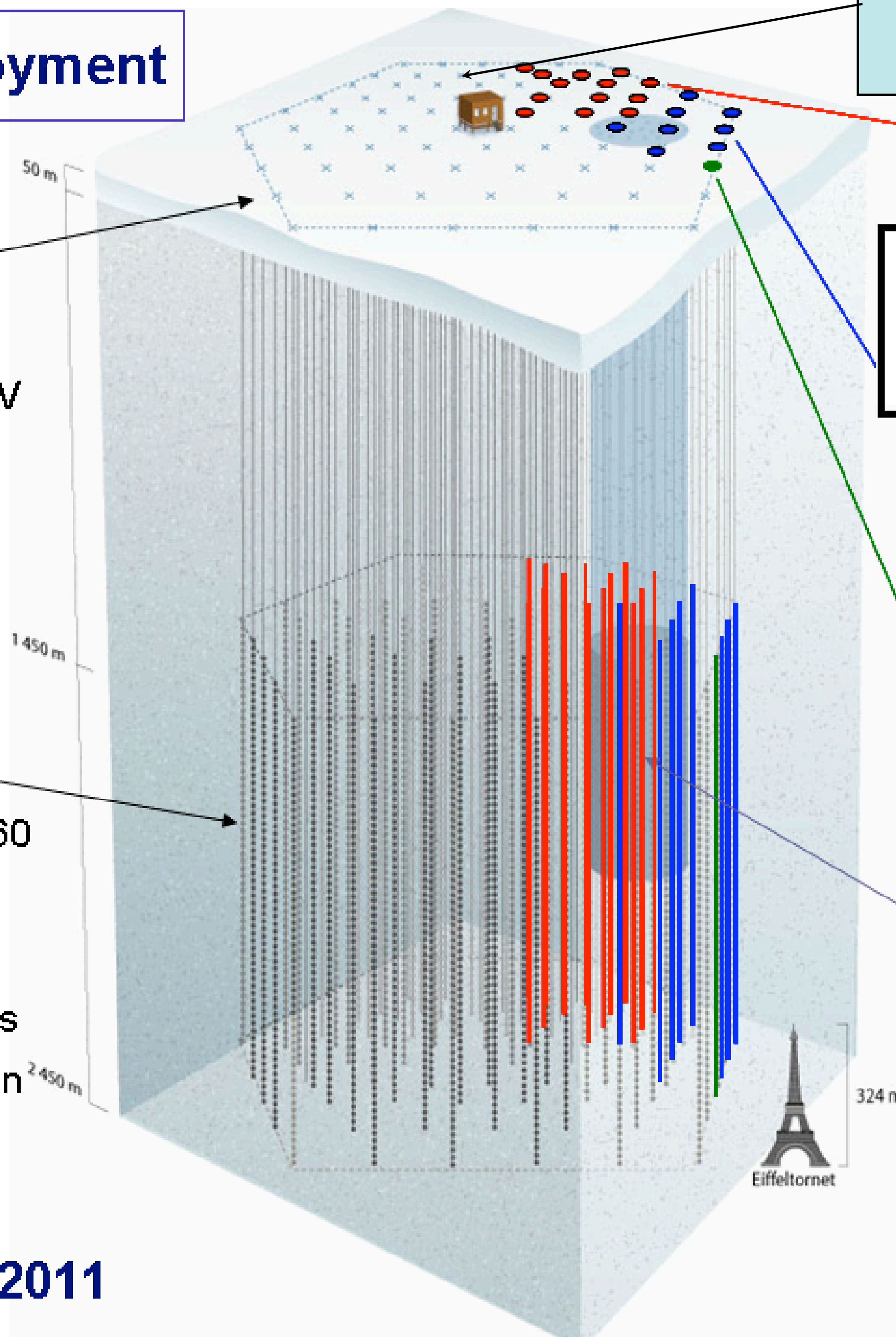
  at a rate ~ 1 SN/5 yr,
  fluence ~2 up-muons/SN

  (hypernova: 1/50 yr, 20 up-μ), negligible background, in km^3 detectors - **ICECUBE**

Model-dependence of predictions & detectability of GRB ν

- E_ν~100 TeV (simult.) are least model dependent
- (use observed MeV γ and same shocks as accelerate $e^\pm$)
- E_ν ~1 TeV : (precursor) more model dependent,
- (assume collapsar, sub-stellar jet, and $R_ø$t 10^{11} cm)
- E_ν ~ 10^{17} eV : (afterglow) need assume reverse shock prompt opt flash is ubiquitous (?)
- $E\nu$ ~ 5 GeV: (decoupling) p,n likely, but detection needs special instrumentation (e.g. Deep Core)
- $E\nu$~5-100 TeV : (pop III) speculative; very massive star envelope ejection and rotation rate? Constraints useful
- $E\nu$~0.3-1 TeV : (cc SN) ***if*** semi-rel. jets (fraction?)
- $E\nu$~ 1 TeV : (photosph. ν) ***if*** sub-photospheric dissip. (?)

IceCube Deployment



2007-2008: 18 strings,
Total: ***40 strings***

2006-2007:

13 strings deployed

22 strings
1320 digital modules
52 surface detectors

2005-2006: 8 strings

2004-2005 : 1 string

First data in 2005
first upgoing muon:
July 18, 2005

AMANDA

19 strings

677 modules

IceTop

Air shower detector

Threshold ~ 300 TeV

InIce

planned 80 strings of 60

optical modules each

17 m between modules

125 m string separation

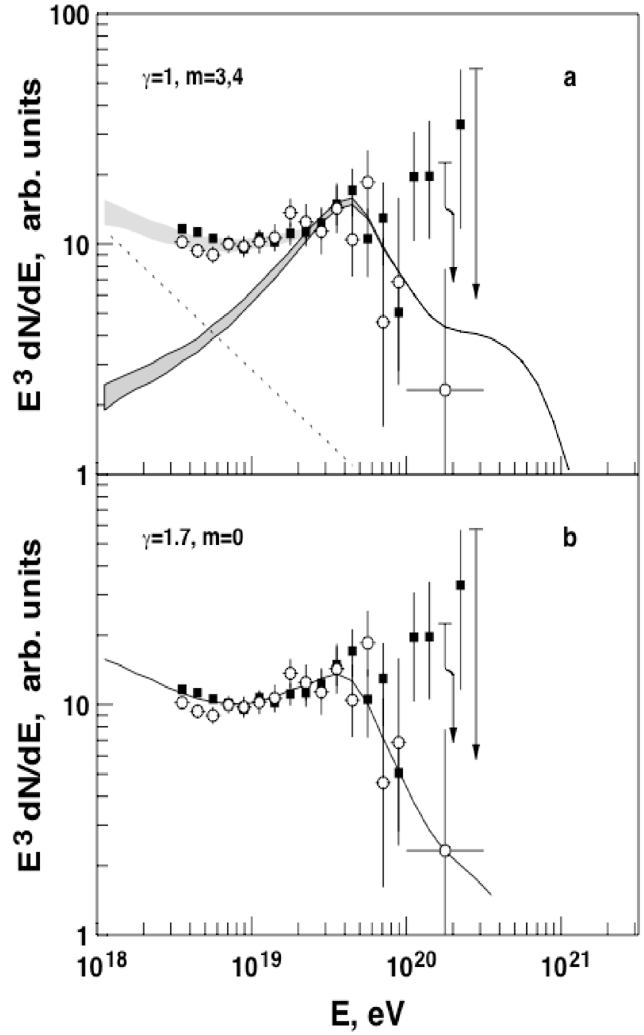
Completion by 2011

What about $E_\nu \gtrsim 10^{19}$ eV ?

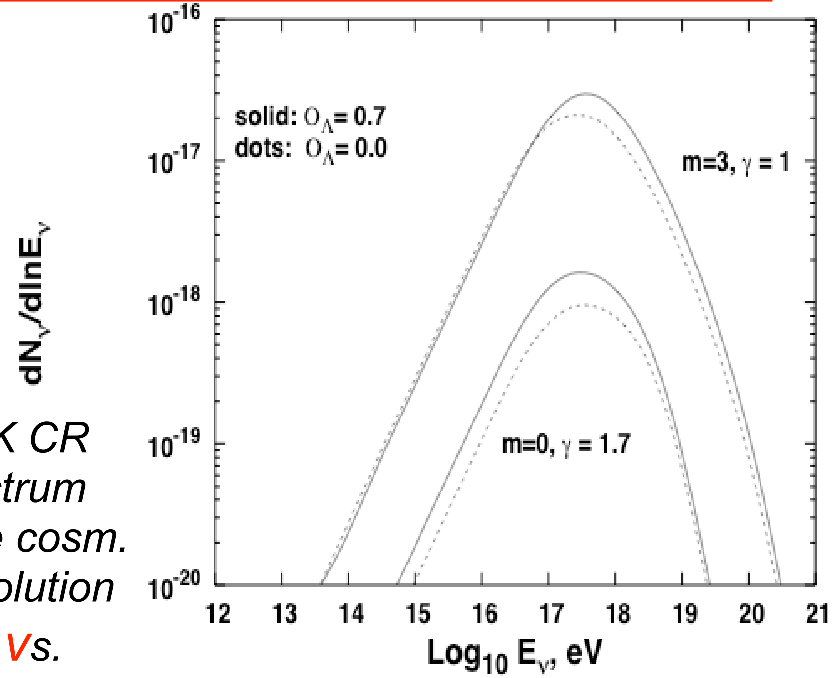
from GZK CRs *to* GZK νs

2 ≠CR models

↓ **same GZK** CR fit

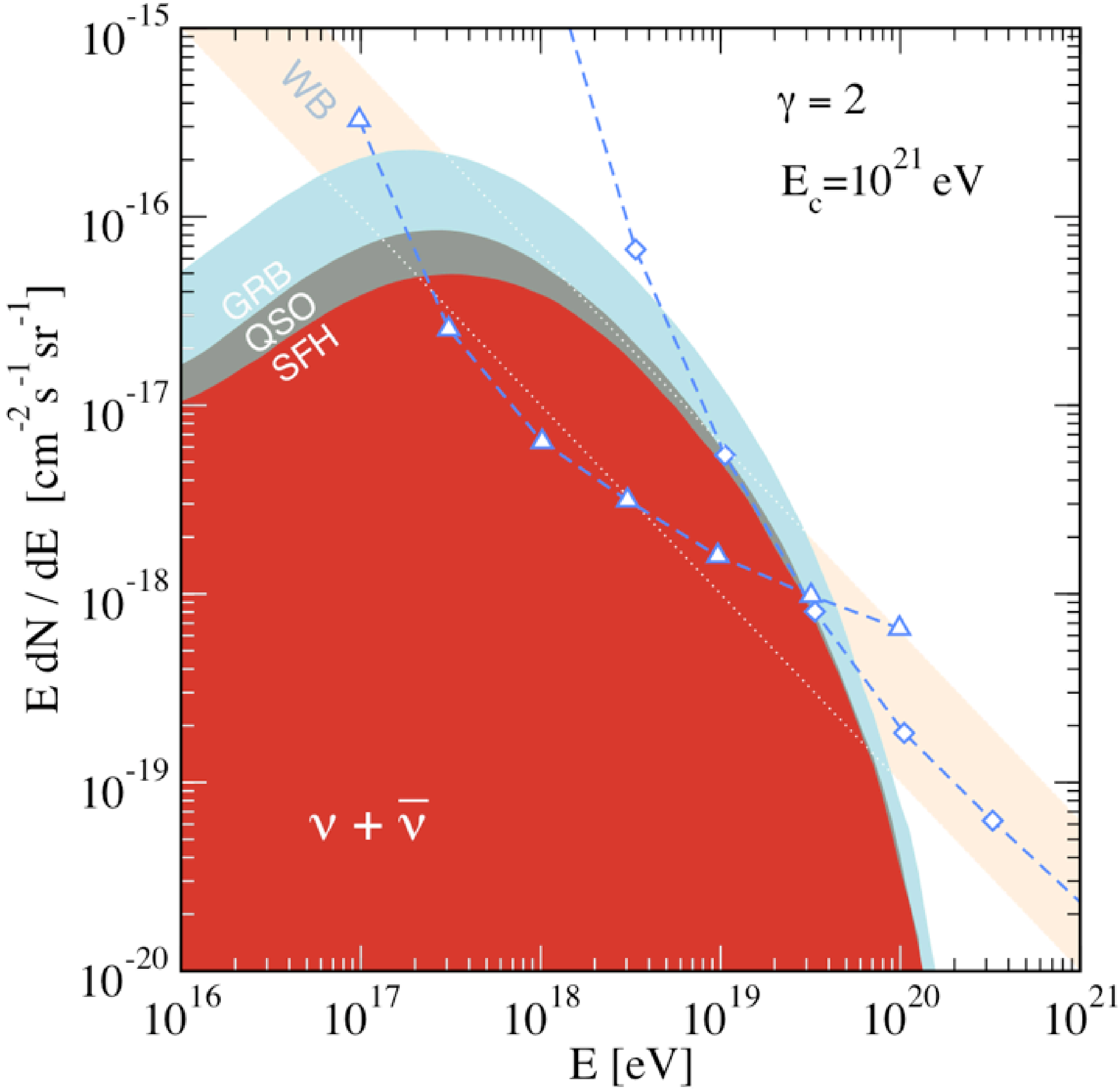


But … lead to ≠ *GZK* ν *flux* ↓



Can infer GZK CR injection spectrum and/or source cosm. luminosity evolution via their GZK νs.

Seckel & Stanev astroph/050244



GRB GZK

cosmogenic neutrinos

Yuksel & Kistler 07
PRD 75:083004

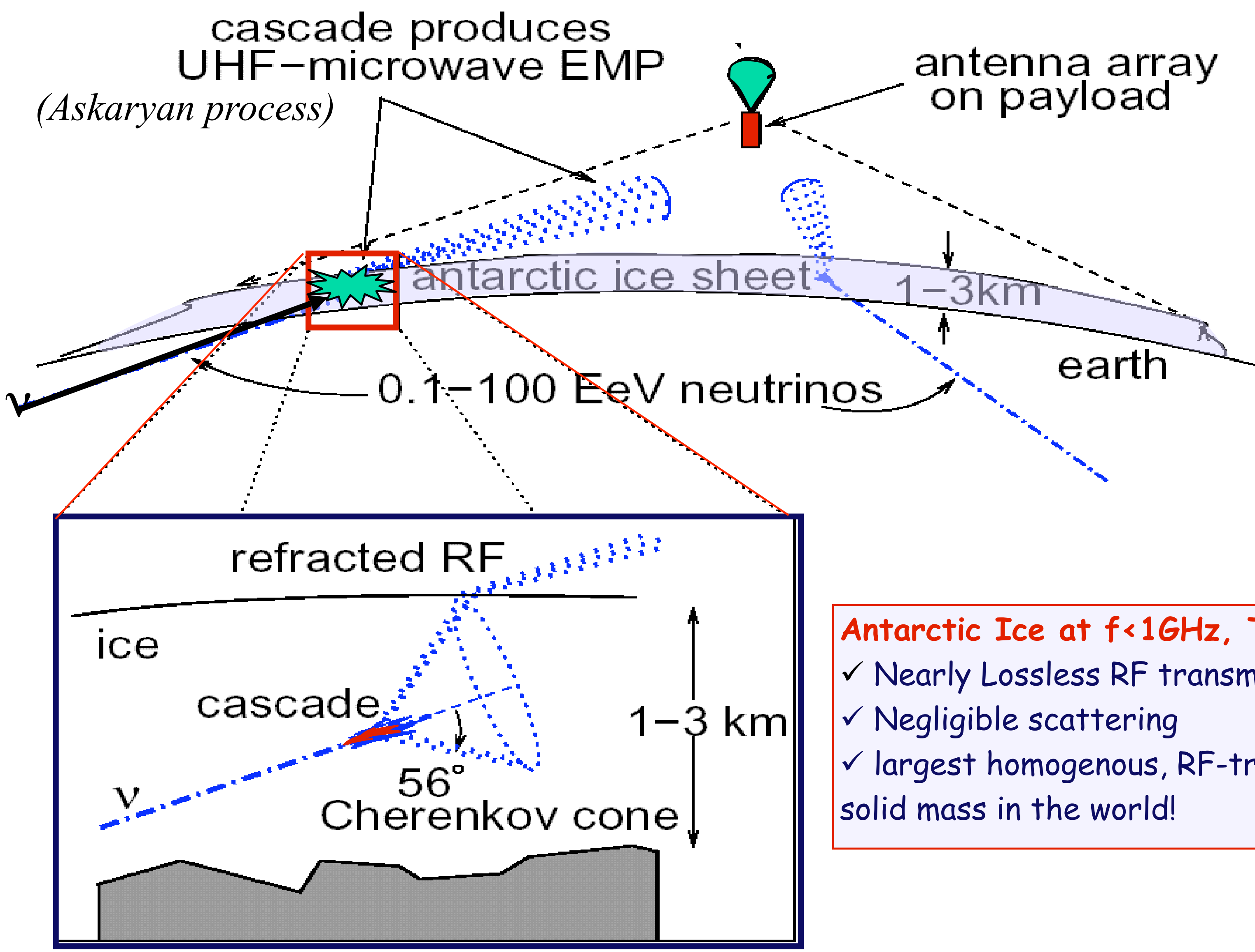
If GRB make the GZK UHECR, then:

ν flux dep. on GRB rate vs. z (from z>> R_{GZK})

Potential of Cosmogenic νs for CR Composition

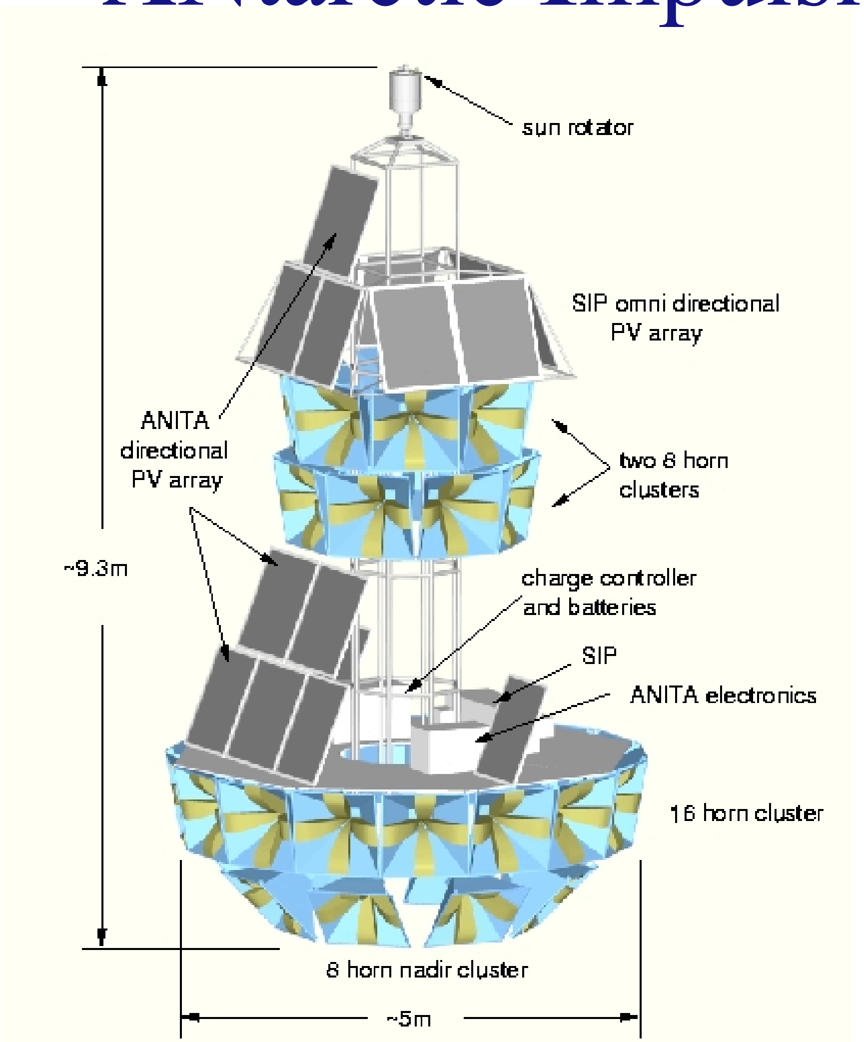
- If CRs have large fraction of heavies, depending on source distance, photodissociation opt. depth could be <1 → only some of them break up into p,n
- Implies smaller fraction contributes to π^+ and cosmogenic ν production (Anchordoqui et al 06)
- Cosmogenic ν flux vs. CR flux may help resolve discrepancy between Auger X_{max} data and apparent correlation with AGN suggesting protons

Cosmogenic ν : ANITA



Antarctic Ice at f<1GHz, T<-30C
- ✓ Nearly Lossless RF transmission
- ✓ Negligible scattering
- ✓ largest homogenous, RF-transmissive solid mass in the world!

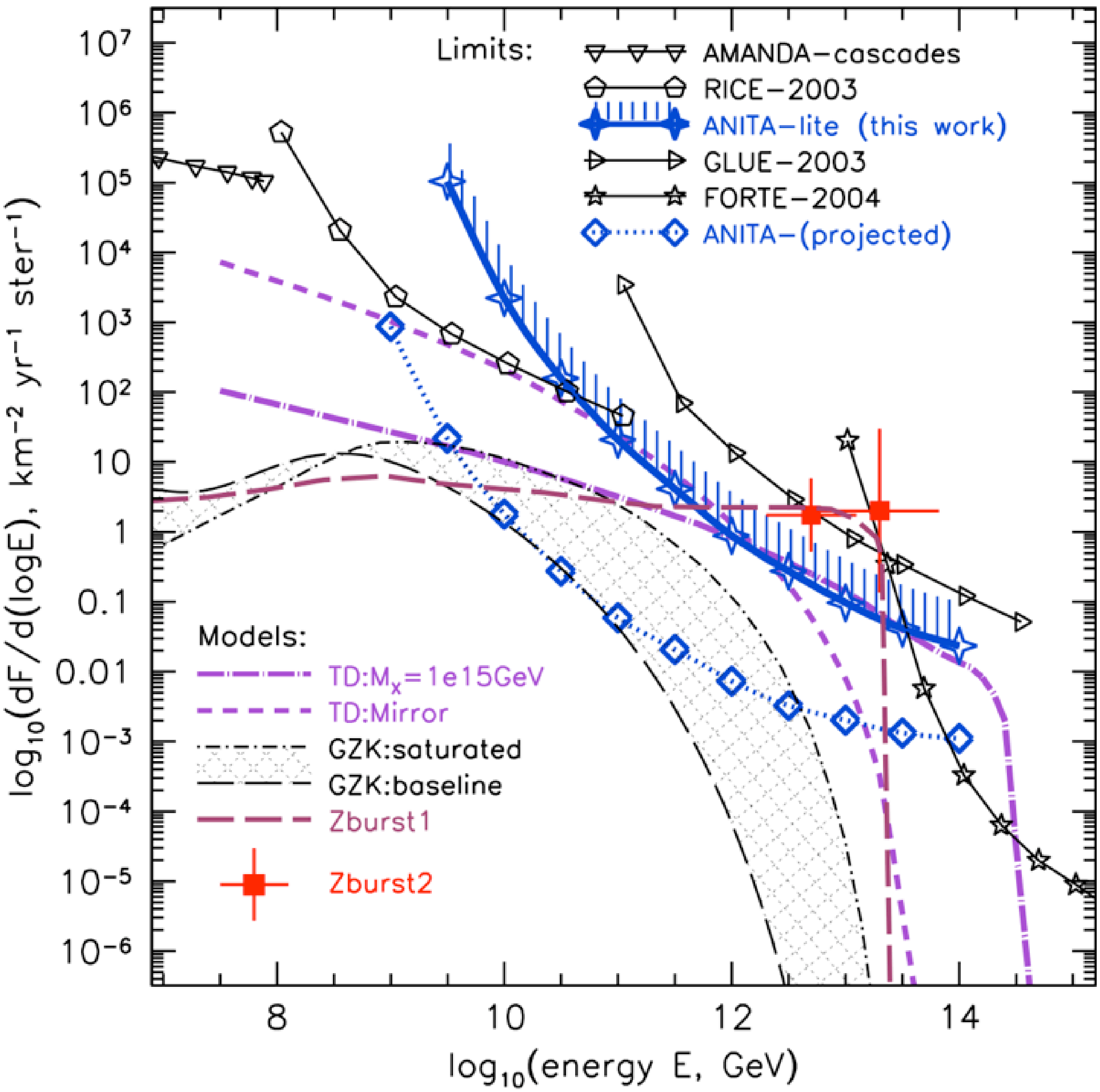
ANtarctic Impulsive Transient Antenna



600 km radius,
1.1 million km^2

- Launched & flown 30 days in early 07

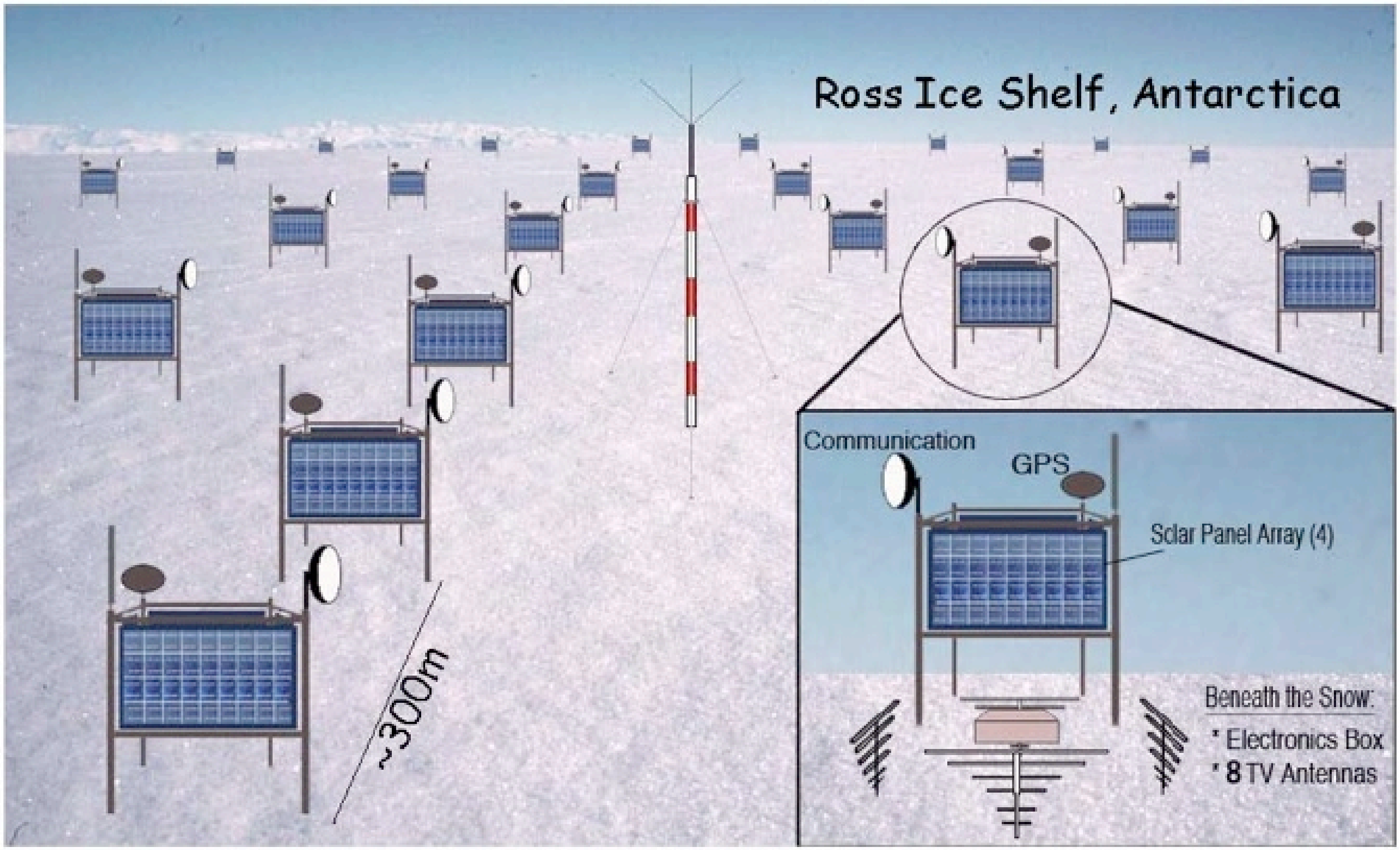
ANITA GZK limits



Barwick et al, PRL 96:171101

ARIANNA Concept

100 x 100 station array, ~1/2 Teraton

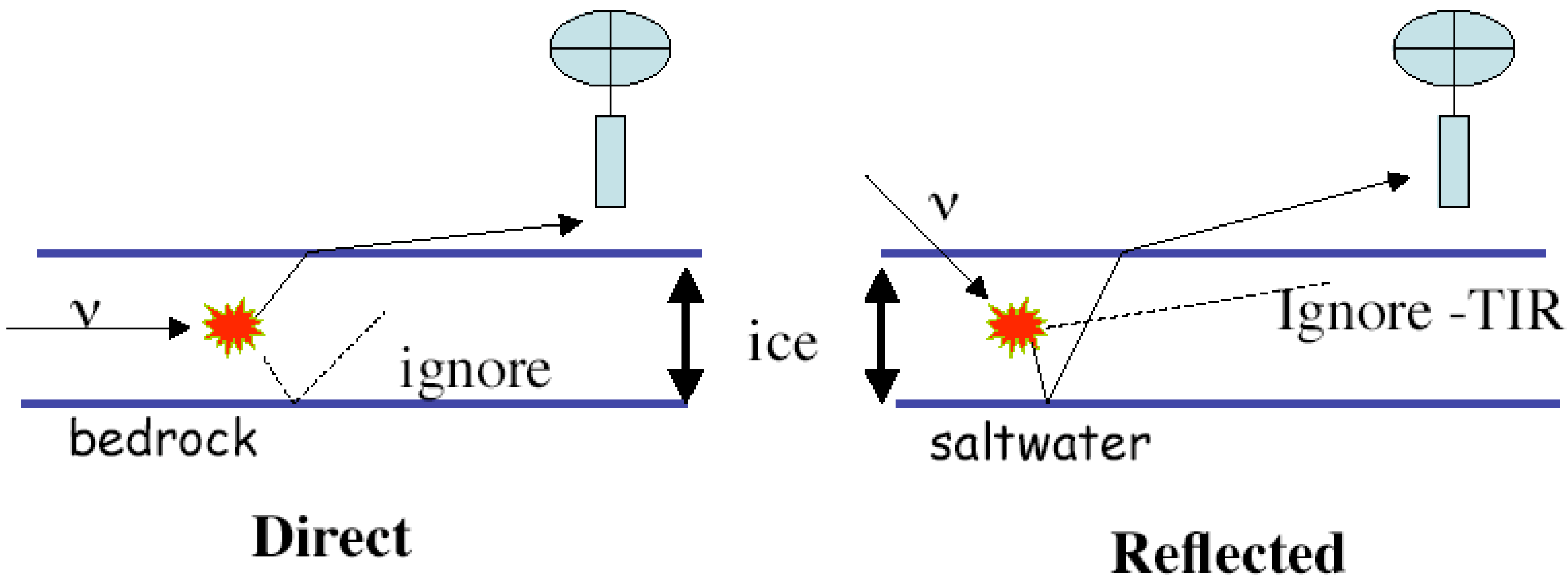


100x100 stations under the snow,
sep. 300 m, pointed downwards ➚

Barwick 07

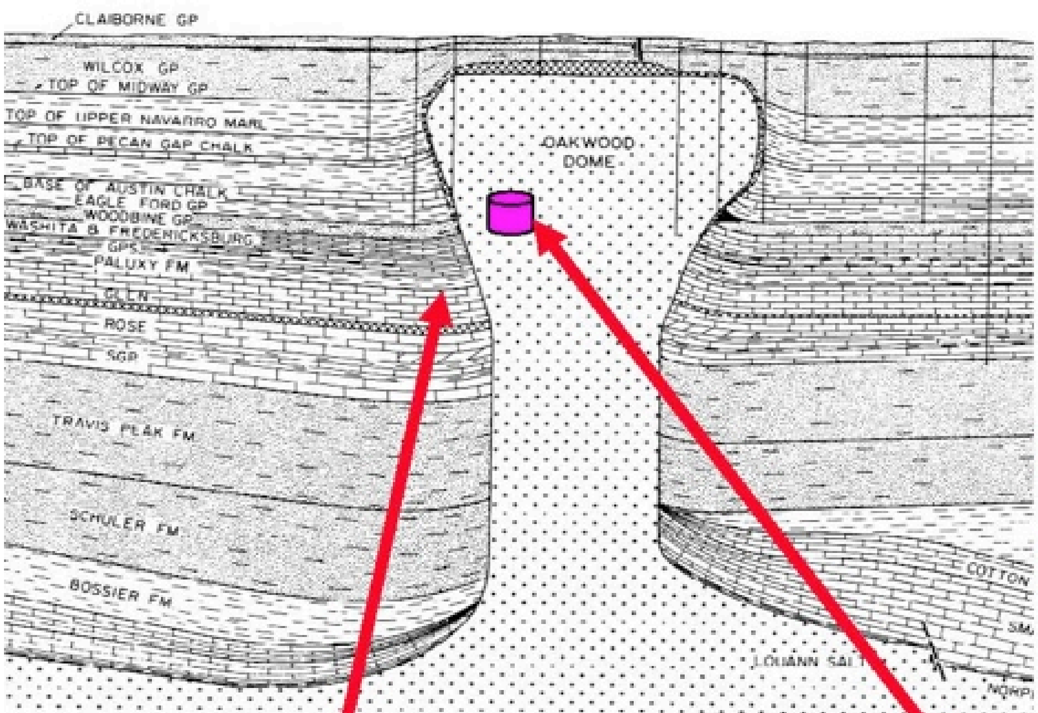
Arianna concept

Reflected and Direct Events



Threshold: 3×10^{17} eV , 2π sky coverage - Expect 40 (down) GZK ν/yr, Δθ~1 deg, point sensitivity $E^2 dN/dE \sim 3 \times 10^{-9}$ GeV/cm^2/s after 1 year

SALSA:
A possible salt detector



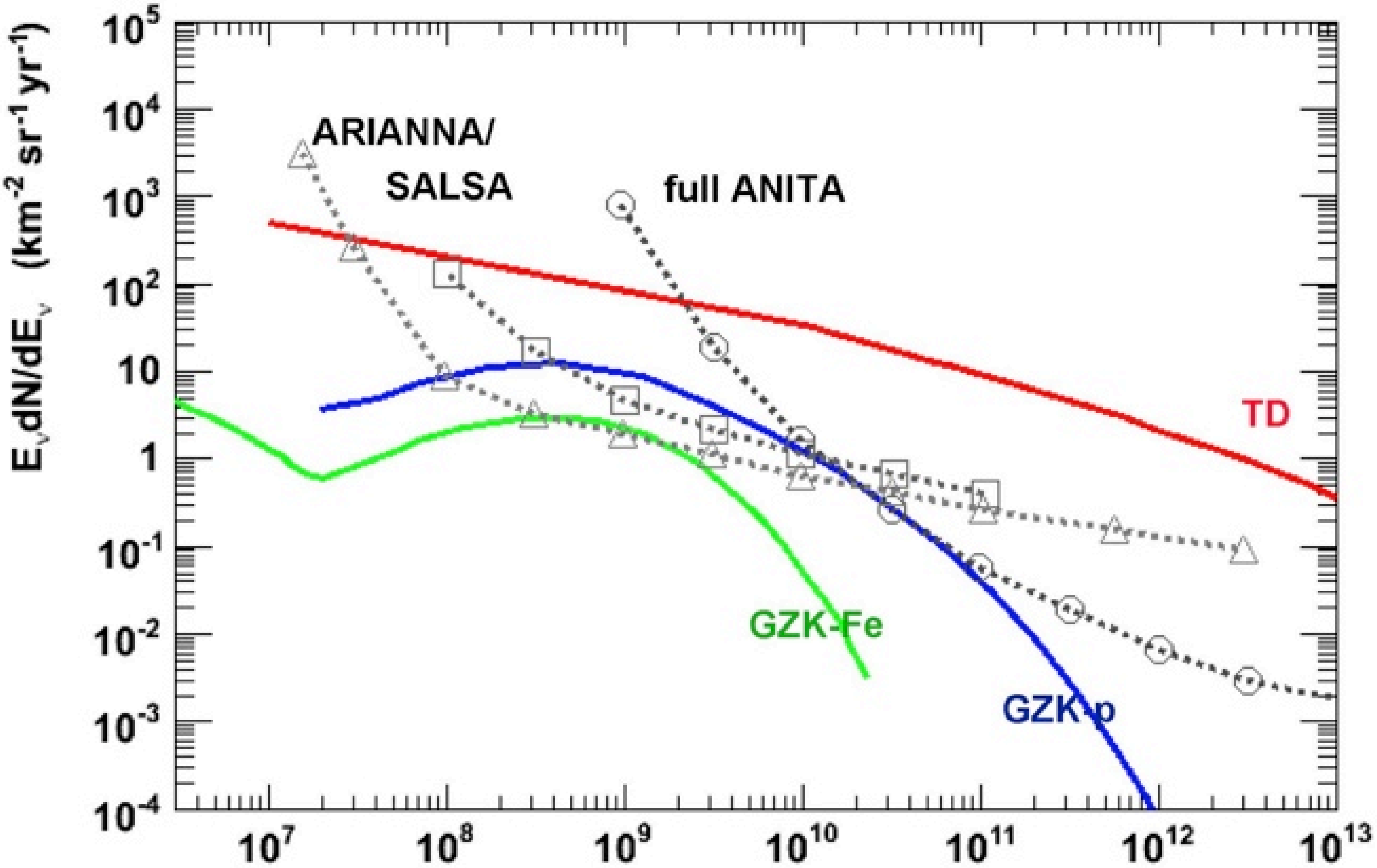
diapir action pushes out water

~1km^3 w.e.

- ~25km^3 in upper 3km of dome (75 km^3 water-equiv.)
  - ↗ >2× denser than ice
  - ↗ easier to deploy than S.Pole
- Calorimetric; large V,$\Delta\Omega$; Cherenkov polarization usable for tracking
- Good candidates in Texas and Louisiana, maybe Utah
- Dutch investigating sites as well

Saltzberg 07

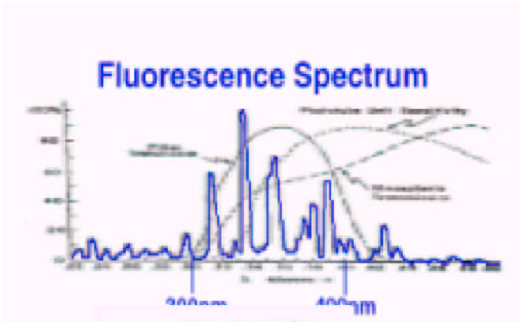
Reaching GZK sensitivity & Lowering the Theshold

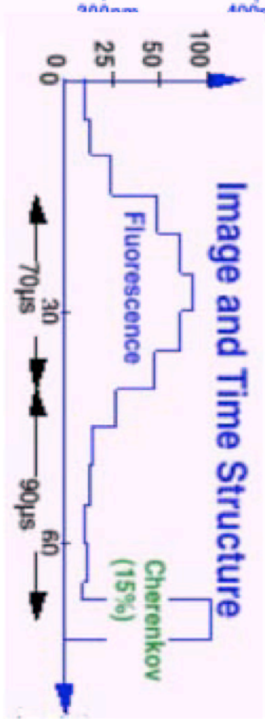


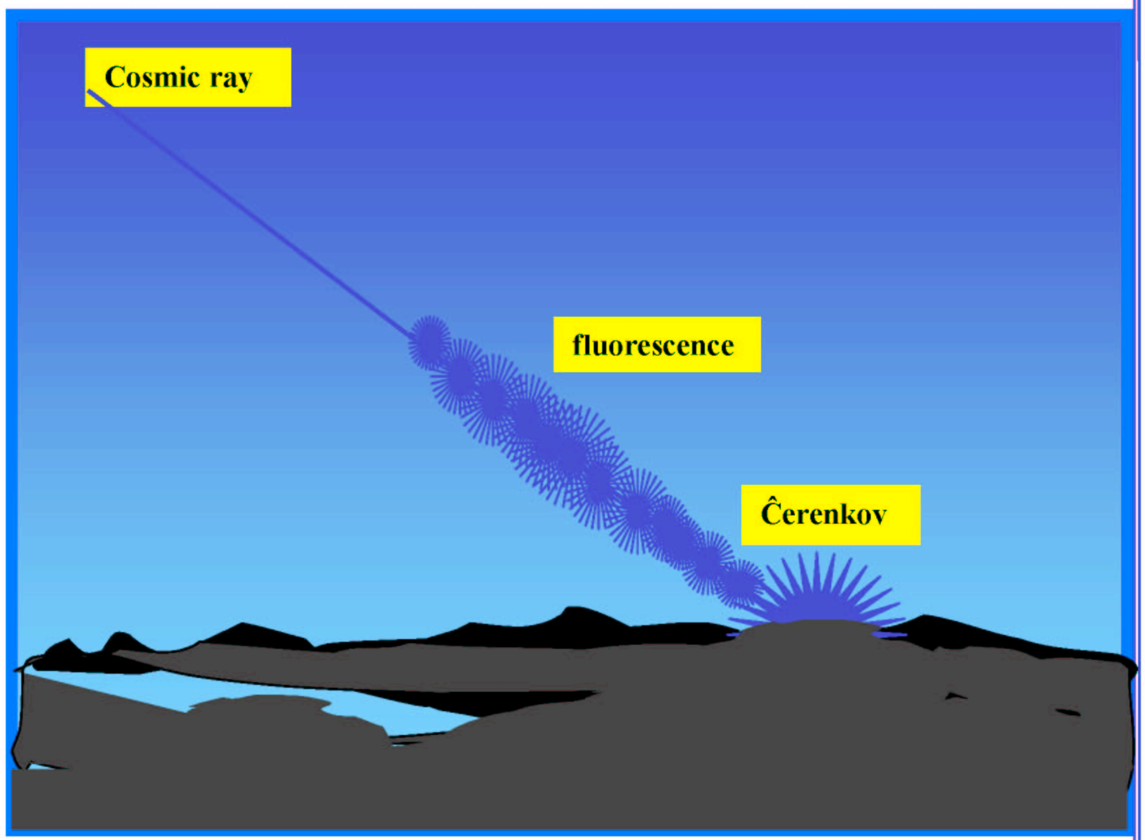
limits are for energy bin with E_{hi}/E_{lo}=e

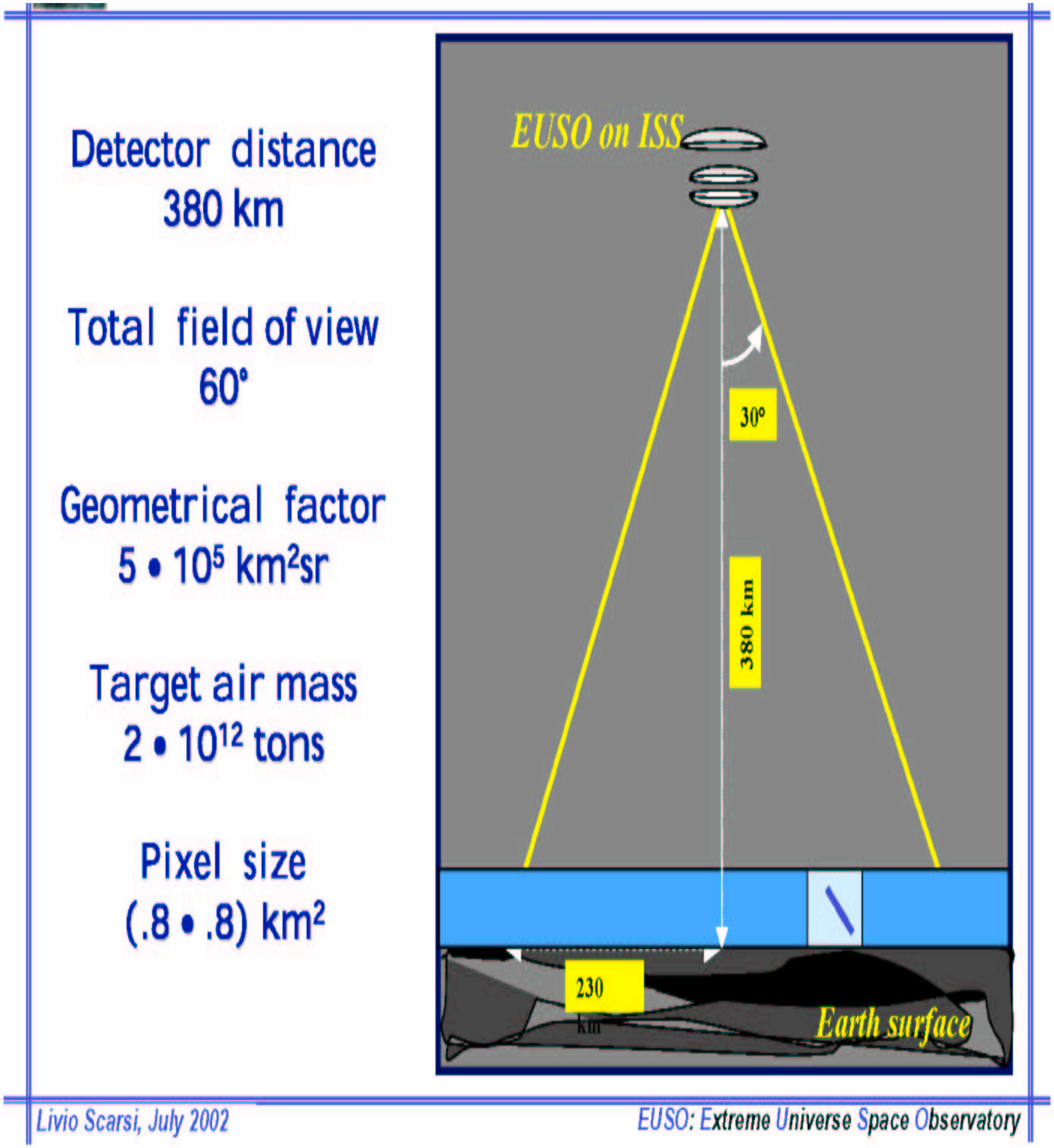
Events! even if UHECR are Iron

EUSO Approach









JEM EUSO

- ISS project, orig. ESA/NASA/RSA/JAXA; precursor for **OWL** (free-flyer)
- $5.10^{19} – 10^{21}$ eV EECRs, EENUs
- Monocular 2.5m Fresnel lens, measure EAS via atmos. fluor. emiss
- Thresh: 3.10^{19} eV; Effic. @ 10^{20} eV : 300-1000 event/yr
- Orig. launch: 2012, but shuttle?
- **Current plan: JEM/JAXA, 2013 unmanned vehicle**

Other Implications of GRB **UHE ν**

- **Special relativity**: simultaneity of arrival of **ν**,γ
- tested to $\Delta t \lesssim 1$ s (10^{-3} s in short bursts)
- **Time delay** due to $\boldsymbol{\nu}_i$ mass:
- $\Delta t\ (\nu_i\ ) \sim 10^{-12} (D/100\mathrm{Mpc})(E_{\nu_i}/100\mathrm{TeV})^{-2}(m_{\nu_i}\ /\mathrm{eV})^2$ s
- (whereas for SN 1987a Dt $(n_i\ ) \sim 10^{-8}$ s)
- **Vacuum oscillations**: at source expect $N\boldsymbol{\nu}_\mu \sim 2N\boldsymbol{\nu}_e$
- at observer get ≠ ratios , and upgoing **τ** appear.
- → sensitive to
- $\Delta m^2 \sim 10^{-16}\ (E_\nu/100\mathrm{TeV})(100\mathrm{Mpc}/D)\ \mathrm{eV}^2$
-

Conclusions

- UHE ν will allow test of proton content of jets, test shock accel.physics, magn. field
- If UHE ν NOT detected, $\rightarrow$ jets are MHD!
- Probe ν interactions at $\gtrsim$ TeV CM energies
- Test SR, oscillations, ν masses, vacuum disp.
- Constraints on stellar evolution and death, star formation rates at redshifts of first structures
- Could be probes of “pop III” first gen. Objects
- May test SN-GRB connection & transition
- Cosmogenic ν : probe CR origins, sources
- New physics: need to know the boundaries of SM astrophysical UHENU mechanisms