High energy neutrinos and gravitational waves from Gamma-Ray Bursts

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Introduction

GRBs: flashes of MeV gamma rays that last 1-100 s

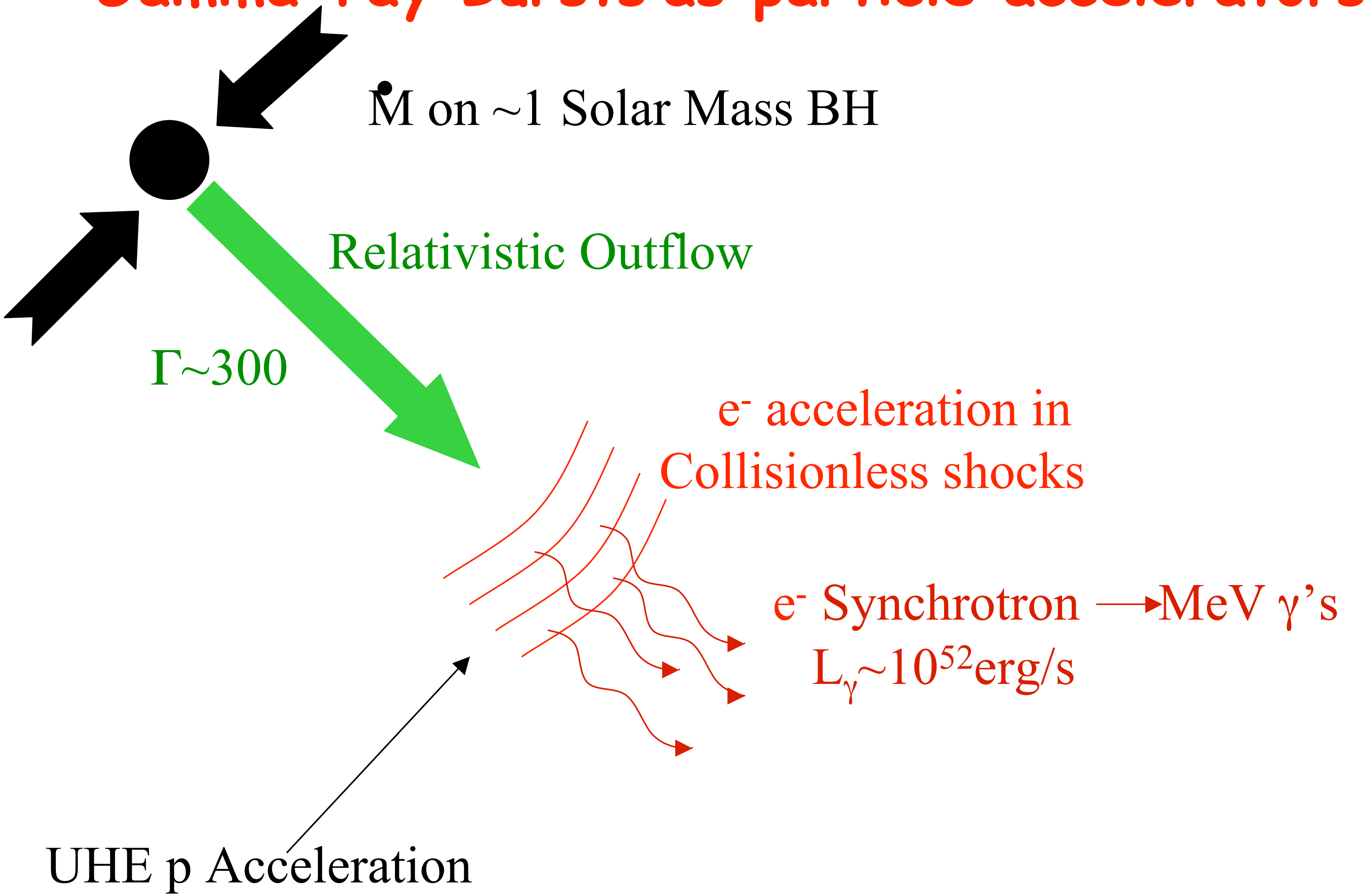
- Main properties of GRBs and their afterglow
- The fireball model: internal and external shock
- Possible progenitor models

High Energy ν from GRBs

- Neutrinos from internal shocks, coincident with GRBs
- Neutrinos from the external shock, delayed.
- Neutrinos from different progenitors models

Gravitational waves from short GRBs

Gamma-ray Bursts as particle accelerators



$\dot{M}$ on ~1 Solar Mass BH

Relativistic Outflow

$\Gamma \sim 300$

e^- acceleration in
Collisionless shocks

e^- Synchrotron → MeV γ's
$L_\gamma \sim 10^{52}$erg/s

UHE p Acceleration

[Meszaros, ARA&A 02;
Waxman, Lecture Notes in Physics 598 (2003).]
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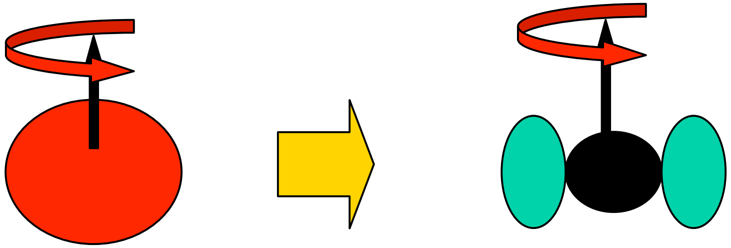
Leading models for Progenitors of long GRBs

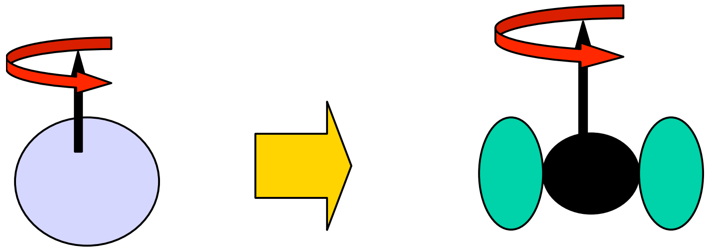
[Mezaros 2001]

- Core collapse of a massive star: *Collapsar*



[Woosley 1993, Paczynski 1998]

- Formation of a BH from a NS left by a SN: *Supranova*



[Vietri &Stella 1998, Inoue, Guetta & Pacini 2001]

+ Pulsar Wind Bubble full of photons

[Guetta&Granot, Granot&Guetta PRL 2003]

Ultimate en. Source of the FB: gravitational en. release associated with temporary mass accretion onto a black-hole !!

HE ν from GRBs

In the FB dissipation region: protons accelerated to ~ 10^{20}eV

photo-meson interaction of HE p with the FB photons

Internal shocks ν: ~ 100 TeV, coincident with GRBs

[Waxman & Bahcall ‘97,’99,Guetta Spada & Waxman 2001]

External shock ν: ~ Early afterglow ν ~ 1000 PeV,delayed

In the collapsar: Emission of ~ TeV ν from *p,γ* interactions occurring inside collapsar while the jet is burrowing its way out of the star [Meszaros & Waxman 2001,Schneider Guetta & Ferrara 2002]

In the Supranova: Emission of ~ 10^{15}-10^{17}eV ν from the interaction of GRB p, with the PWB photons

[Guetta & Granot PRL 2003]

Why neutrino is a “nice” particle

- Is neutral → trajectory not affected by magnetic fields (information on cosmic rays that are affected).
- Is stable → can reach us from cosmic distances (not like neutrons)
- Only weak interactions → can give us informations on regions opaque to photons.

- Escape from deep within the sources Study the physics responsible for powering

- Study basic ν properties
    - Flavor change("oscillations")
    - ν masses
    - Interaction with Gravity

☹ •But: Weak interaction Big detectors 10's of kilo-tons

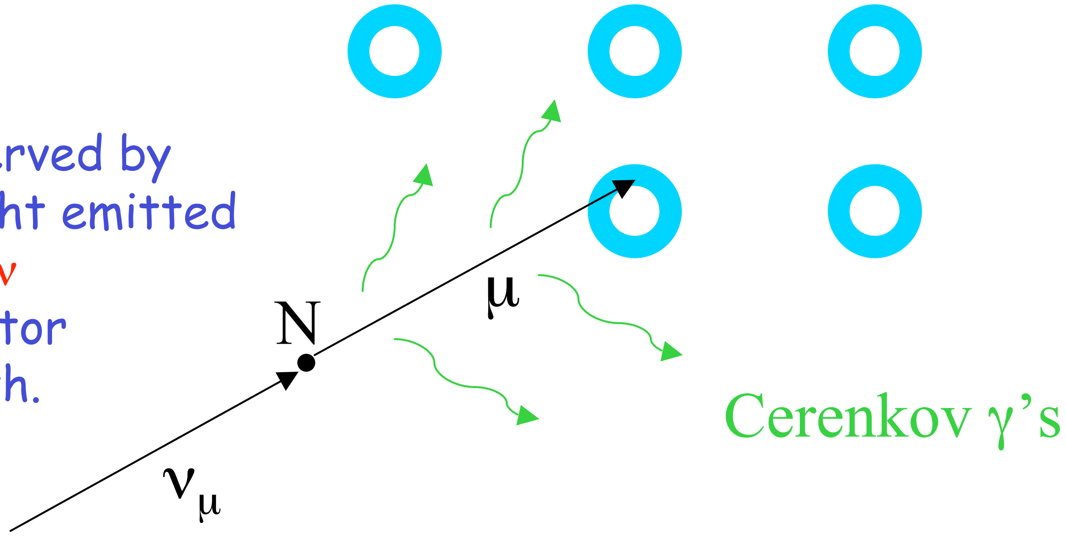
Basic process: $\nu_\mu + N \rightarrow \mu + X$

The signals are upward μ

Detection

○ γ detector

High energy ν may be observed by detecting the Cerenkov light emitted by HE muons produced by ν interactions below a detector on the surface of the Earth.



$\lambda_\mu > 1$ km for $\varepsilon_\mu > 0.3$ TeV

⇓

1km^3 feasible for transparent medium

The detectors of high energy ν

Important quantity is the **muon-neutrino detection probability:**

$P_{\nu\mu} \sim R_{\mu}/\lambda_{\mu\nu}$ *Probability that a ν produce a μ in a detector*

HE muon range to the neutrino mean free path

$$P_{\nu\mu} \sim 10^{-4}\left(\frac{E_{\nu}}{100TeV}\right)^{\alpha} \quad \begin{cases} \alpha=1 & E\nu < 100 \text{ TeV} \\ \alpha=1/2 & E\nu > 100 \text{ TeV} \end{cases}$$

$N=(\Phi_{\nu}/\varepsilon_{\nu})P_{\nu\mu}AT$

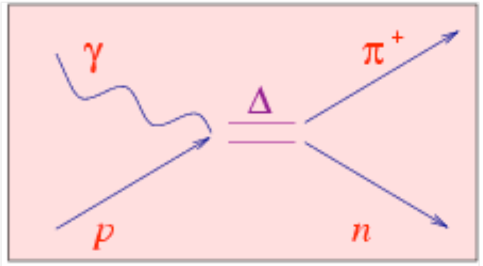
- Detectable ν flux at km^3 detectors:

Amanda, Antares, Nestor, IceCube, Nemo

The main mechanism: photomeson interaction

$$\gamma + p \rightarrow n + \pi^+ \; ; \quad \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$(\varepsilon_p / \Gamma)(\varepsilon_\gamma / \Gamma) \geq 0.3\,\mathrm{GeV}^2$$



In each collision $\varepsilon_\nu \approx 0.05\,\varepsilon_p$

Fireball

Int. Shocks $\varepsilon_\gamma \sim \mathrm{MeV}, \Gamma \sim 200$: $\varepsilon_p \geq 10^{16}\,\mathrm{eV}$ ⇒ $\varepsilon_\nu \geq 10^{14}\,\mathrm{eV}$

Ext. shock $\varepsilon_\gamma \sim \mathrm{keV}, \Gamma \sim 200$: $\varepsilon_p \geq 10^{19}\,\mathrm{eV}$ ⇒ $\varepsilon_\nu \geq 10^{17}\,\mathrm{eV}$

proton en. lost to pion production: $f_\pi \sim \Delta t / t_\pi \sim L / (\varepsilon_\gamma \Gamma^4 t_v) \sim$ typ.

0.2 I.S.
0.01 E.S.

Δt is the comoving shell expansion time and

t_π the proton photo-pionenergy loss time

Burst to burst fluctuations look at each burst detected by BATSE [Guetta, Hooper, Halzen et al. 2003]

For a typical burst at $z\sim1$, $E \sim 10^{53}$erg

Internal shocks ν: "effective" $f_\pi \sim 20\%$ [Guetta Spada Waxman 2001]

⇨ ν Fluence $\varepsilon^2_\nu \Phi_\nu \sim 10^{-3}(f_\pi/0.2)(\varepsilon_\nu/10^{14}\,\mathrm{eV})^\alpha$ GeV/cm^2

$$\begin{cases} \alpha=0 & E_\nu > E_\nu^b \\ \alpha=1 & E_\nu < E_\nu^b \end{cases}$$

Detection probability ~ 0.01 per burst in km-cube neutrino telescope ⇨ **Ten events per yr correlated in time and direction with GRBs!**

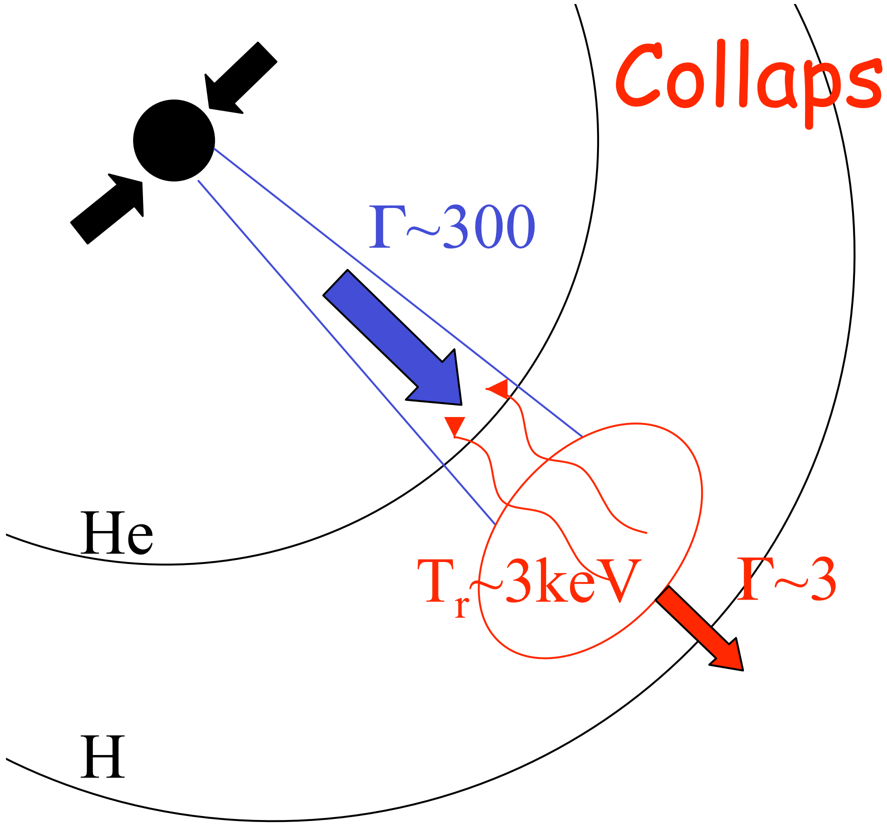
External shock ν: "effective" $f_\pi \sim 0.01$ [Waxman & Bahcall 2000]

⇨ ν Fluence $\varepsilon^2_\nu \Phi_\nu \sim 10^{-4.5}(f_\pi/0.01)(\varepsilon_\nu/10^{17}\,\mathrm{eV})^\alpha$ GeV/cm^2

$$\begin{cases} \alpha=½ & E_\nu > E_\nu^b \\ \alpha=1 & E_\nu < E_\nu^b \end{cases}$$

0.06 events per yr in a km-cube detector delayed ~10s after the GRB

Collapsar GRB ν's



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

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

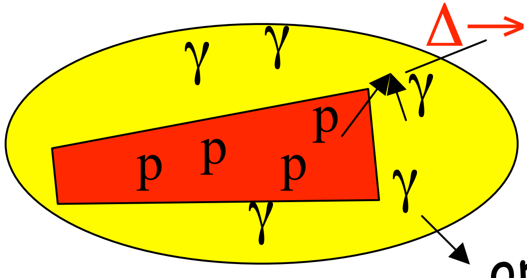
[Meszaros & Waxman 01; Granot & Guetta 03; Schneider, Guetta & Ferrara 2002]

- $\varepsilon_\nu \geq 10^{12.5}\ \mathrm{eV}$
  $N_{\nu\to\mu} \approx 0.2\,/\,\mathrm{km}^2/\mathrm{Collapse}$ $(10^3$ GRBs/yr)

- Both “Chocked” and “successful” jets

Supranova

Massive star collapses in a NS of $\sim 3M_o$ which loses its rotational energy before collapsing to a BH triggering a GRB. During this time, t_{sd}, an ambient rich of photons is formed.



optical

$\Delta \rightarrow \pi^+ + n$

$\mu^+ + \nu_\mu \rightarrow e^+ + \nu_\mu + \nu_\mu + \nu_e$

$\boxed{\varepsilon_\nu \sim 10^{17}\,\mathrm{eV}}$

Flux coincident with GRB and the rates depend on t_{sd} for t_{sd} ~0.07 yr, ~7 events per year BUT 1 event in 10 year for t_{sd} ~0.4 yr coincident with GRB.

[Guetta & Granot PRL 2003]

Implications

- $J_\mu \sim 10/\ \mathrm{km}^2\ \mathrm{yr}$, $\varepsilon_\nu \sim 100$ TeV from internal shocks
- $J_\mu \sim 5/\ \mathrm{km}^2\ \mathrm{yr}$, $\varepsilon_\nu \sim 100$ PeV from ext. shock + wind
- $J_\mu \sim 100/\ \mathrm{km}^2\ \mathrm{yr}$, $\varepsilon_\nu \sim 1$ TeV jet+envelope in collapsars
- $J_\mu \sim 7/\ \mathrm{km}^2\ \mathrm{yr}$, $\varepsilon_\nu \sim 100$ PeV from supranova.

Help to resolve open questions in astrophysics:

- **Baryonic component of the Jet:** **Composition of the jet is an open issue** e^+e^- or pe^- plasma? Still not clear

- **GRBs progenitors**

Test sources of Ultra-high energy Cosmic rays

- The highest energy particles observed:

  10^{20} eV

  (most likely) Extra-Galactic

  (most likely) Protons

Are GRBs the most powerful accelerators?

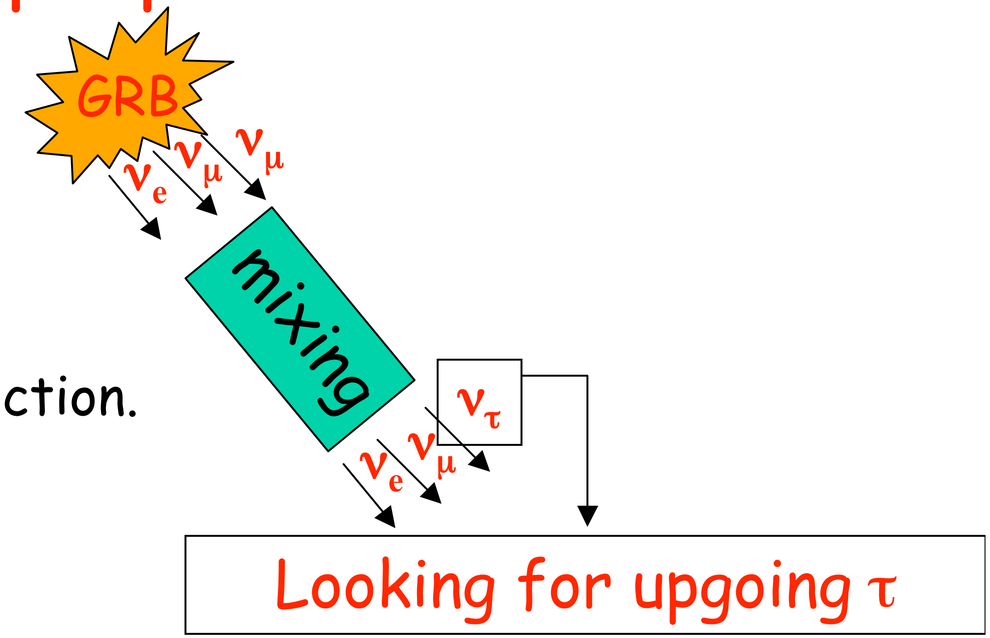
•Detection of HE ν is a test of the acceleration mechanism and UHECR origin.

Neutrino properties

Test of ν oscillation

$\nu_\mu \leftrightarrow \nu_\tau$: τ appearance

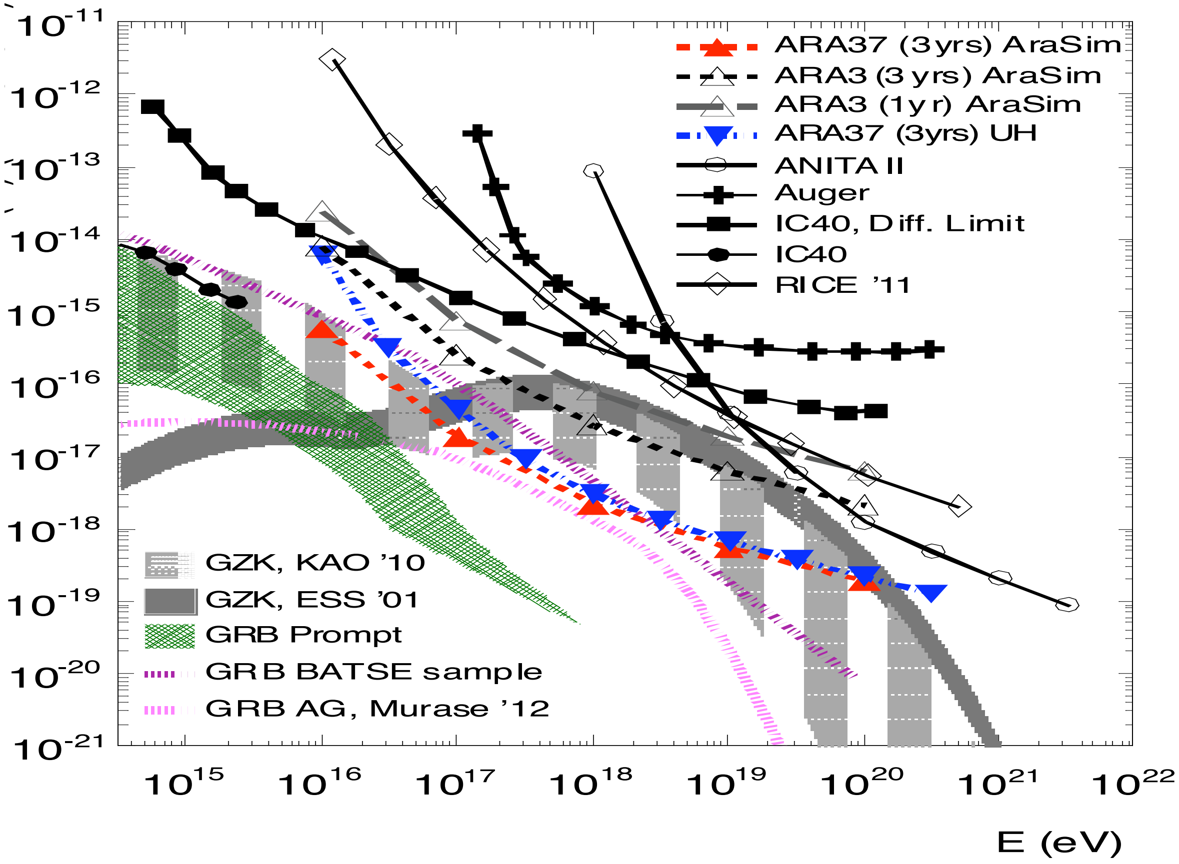
High energy neutrinos allow τ production.



Test the weak equivalence principle: ν and γ should suffer the same time delay in gravitational potential

Astrophysics $\xleftrightarrow{\nu}$ Particle physics

Summarizing picture

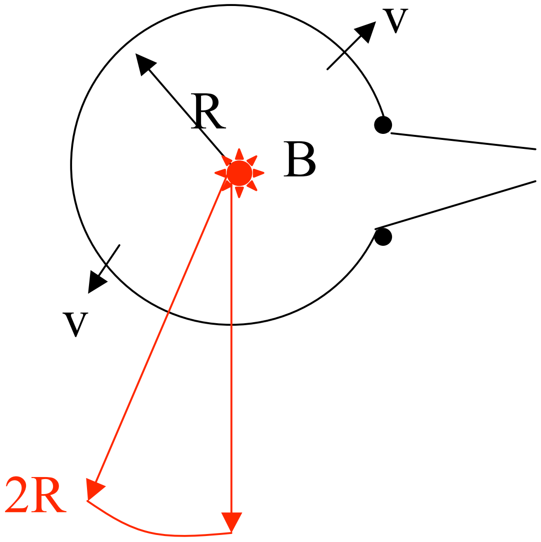


Published constraints on neutrino fluxes (solid with markers) and projected sensitivities (broken lines), compared to models for GZK and GRB neutrinos .

Results from IceCube: **No signal!!!**

- Fireball model challanged by Icecube?
- No! Maybe f_π is smaller (Hummer et al. 2012) **If effects of particle physics are taken into account**
- GeV emission from Fermi may be due to pion cascade, the ν flux related to GeV flux. Constrain on hadronic emission models

GRB as Accelerator



l =R/Γ

(δt_{RF}=R/Γc)

$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/\mathrm{v}} = \beta BR \quad \Rightarrow \quad \varepsilon_p < \beta eBR/\Gamma$$

⇓

$$L > 4\pi R^2\,\Gamma^2\,\frac{B^2}{8\pi}\mathrm{v} > \frac{1}{2\beta}\left(\frac{\varepsilon_p}{e}\right)^2 c\ \Gamma^2$$

⇓

$$\boxed{L > 2\frac{\Gamma^2}{\beta}\varepsilon_{p,20}^2 \times 10^{45}\ \mathrm{erg/s}}$$

[Hillas, ARA&A (1984); Waxman astro-ph/0310079]

Collapsar

Choked *GRB*

Successful *GRB*

In both cases the jet produces a burst of Tev ν while propagating in the stellar envelope *(Meszaros & Waxman 2001)*

- The TeV fluence from an individual collapse with E �10^{53}erg at z �1 implies 0.1 events per collapse/burst in a km-cube detector

•If precursor of GRB, the signal is well above the atmospheric one, 100 events expected per yr in a km-cube detector

•AMANDA may provide limits on the rate of the dark collapses *(Schneider, Guetta & Ferrara 2002)*