Ultra-high energy neutrinos from the atmosphere and the cosmos

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Overview

- Atmospheric neutrinos:
  - New calculation of the prompt neutrino flux

- Neutrinos from astrophysical sources:
  - Introduction to GRBs and other sources
  - Neutrinos from charm production ⇒ prompt flux

- Based on work with M.H. Reno and I. Sarcevic

[arXiv:0806.0418 and arXiv:0808.2807, in PRD]

Cosmic neutrinos

- Neutrino background (1.9 K → 10^{-4} eV)
- Solar neutrinos (MeV)
- Supernova neutrinos (MeV)
- **Atmospheric neutrinos** (up to 10^{8}—10^{9} GeV)
- **Galactic / extragalactic neutrinos** (GeV to EeV)

  (GZK, AGNs, GRBs, SNe with jets, other astrophysical sources etc...)

- New physics (e.g. dark matter annihilation)

Neutrinos as probes

- Escape from extreme environments
- Not deflected by magnetic fields, so point back to source
- Probe particle production in astrophysical sources
- Much higher energies than available in colliders
- Experiments: IceCube, Antares, KM3NeT, etc...

Atmospheric and extragalactic

- I will talk about two processes that generate high energy neutrinos:
  - Atmospheric interactions of cosmic rays
  - Astrophysical sources (SNe, GRBs, etc.)
- Common theme:
  - Hadronic or photo-hadronic collisions produce hadrons, some of which decay to neutrinos
- Example: $pp \rightarrow \pi^+ + X$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow \bar{\nu}_\mu \nu_e e^+$$

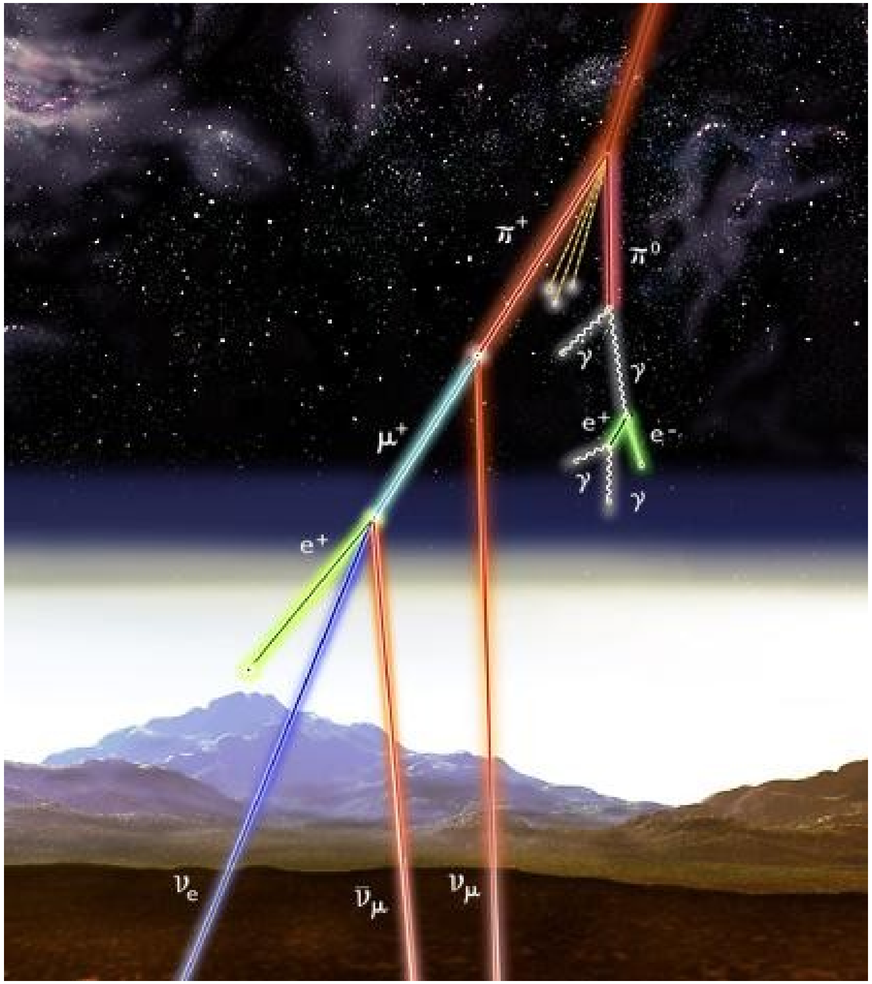
Atmospheric neutrinos

Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei

- CMS energy is large
  ⇒ secondary hadrons:
  pions, kaons, D-mesons …

- Secondary particles interact and decay
  ⇒ cascade of particles



Credit: INFN-Notizie No.1 June 1999

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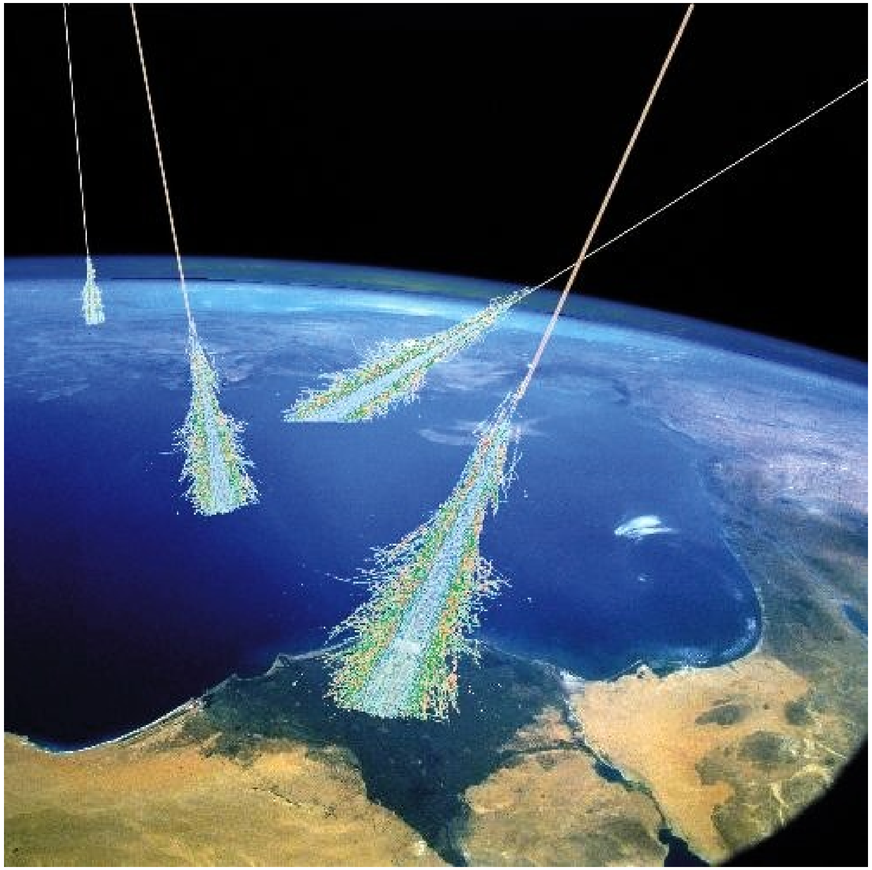


Credit: Astropic of the day, 060814

Why are we interested?

- Atmospheric neutrinos are a background to extragalactic neutrinos

- They are a test beam for neutrino experiments

- Can learn about cascades and the underlying production mechanism

- Higher energy pp collisions than in LHC:
  can maybe even learn something about QCD

Conventional neutrino flux

- Pions and kaons are produced in more or less every inelastic collision

- π^+ always decays to neutrinos ($\pi^+ \rightarrow \mu^+\nu_\mu$ is 99.98 %)

- *But π, K are long-lived* ($c\tau$ ~ 8 meters for π^+)
  ⇒ lose energy through hadronic collisions before decaying
  ⇒ neutrino energies are degraded

- This is called the *conventional neutrino flux*

Prompt neutrino flux

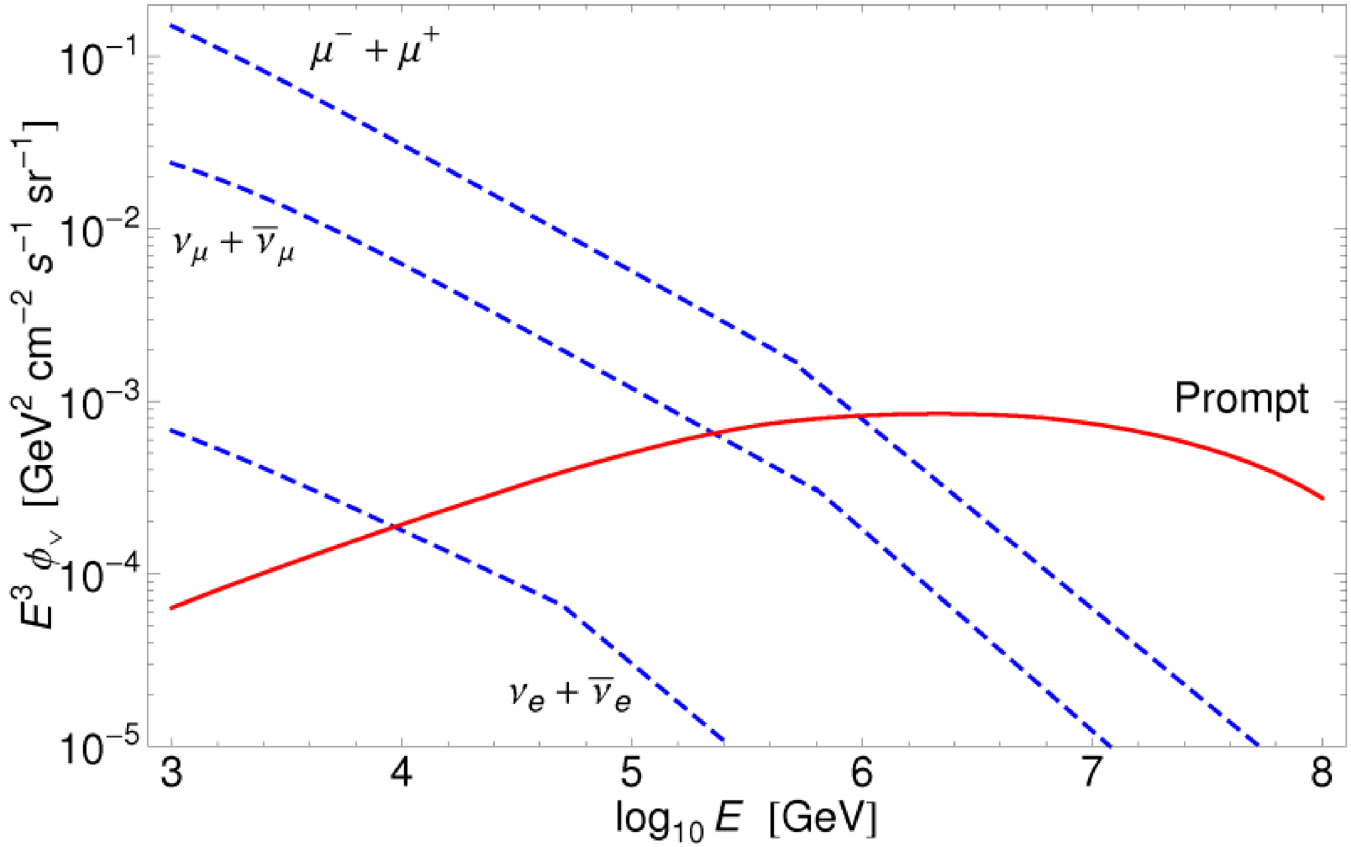
- Hadrons containing heavy quarks *(charm or bottom)* are extremely short-lived:
  ⇒ decay before losing much energy
  ⇒ neutrino energy spectrum is harder

- However, production cross-section is much smaller

- But it turns out that there is a cross-over energy above which prompt neutrinos dominate over the conventional flux

- This is called the *prompt neutrino flux*

Prompt vs conventional fluxes



Prompt flux: RE, M.H. Reno, I. Sarcevic, arXiv:0806.0418

Conventional: Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. **52,** 153 (2002)

All three lepton flavors are approximately equal for prompt flux

Prompt flux calculation

- Prompt fluxes have been calculated years ago using various phenomenological models of the charm production mechanism

- Thunman, Ingelman, Gondolo [Astropart. Phys. **5**, 309 (1996)] did the first “real” QCD calculation

- Used LO perturbative QCD (in PYTHIA) and Monte Carlo-simulated the cascade

- Extended to NLO QCD by Pasquali, Reno, Sarcevic

Problem with QCD

- Charm cross section in QCD:

$$\frac{d\sigma_{\rm LO}}{dx_F} = \int \frac{dM^2_{c\bar{c}}}{(x_1+x_2)s}\sigma_{gg\to c\bar{c}}(\hat{s})G(x_1,\mu^2)G(x_2,\mu^2)$$

where

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M^2_{c\bar{c}}}{s}} \pm x_F\right)$$

- CMS energy is large

- Thus at large energy, $x_1 \sim x_F$ and $x_2 \ll 1$

Problem with QCD

- In this case, fixed order QCD (LO or NLO) does not work well — there are large logarithms that must be resummed:

$$[\alpha_s \log(1/x)]^n$$

- Parton distribution functions poorly known at small x

- If logs are resummed ***(BFKL equation)*** one finds power growth of gluon distribution as $x \to 0$

- It grows so large that ultimately unitarity would be violated (T-matrix > 1)

Parton saturation

- Unitarity is saved through a phenomenon known as ***saturation***:
  - The number of gluons in the nucleon becomes so large that gluons start interacting
  - Leads to a reduction in the growth
  - Non-linear parton evolution equations

- This is sometimes called the ***color glass condensate***

- The simplest evolution equation is the Balitsky–Kovchegov equation: BFKL with non-linear term

Charm production

- We calculate the differential charm production cross section $d\sigma/dx_F$

- To include the effects of parton saturation, calculation is done in *dipole picture*, using an approximate solution of the Balitsky—Kovchegov equation

- This suppresses the cross section at larger energy relative to NLO QCD

Cascade equations

- To find the neutrino flux we must then solve the cascade equations given the incoming proton flux:

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY)$$

$$\frac{d\phi_M}{dX} = S(NA \to MY) - \frac{\phi_M}{\rho d_M(E)} - \frac{\phi_M}{\lambda_M} + S(MA \to MY)$$

$$\frac{d\phi_\ell}{dX} = \sum_M S(M \to \ell Y)$$

- X is the slant depth: “amount of atmosphere”

ρd_M is the decay length, with ρ the density of air

λ_M is the interaction length for hadronic energy loss

The atmosphere

- The distance traveled in the atmosphere is measured by the slant depth:

$$X(\ell,\theta) = \int_{\ell}^{\infty} d\ell' \rho(h(\ell',\theta)),$$

where $\rho(h) = \rho_0 \exp(-h/h_0)$

and $h_0 = 6.4 \text{ km}$

$$\rho_0 = 2.03 \times 10^{-3} \text{ g/cm}^3$$

- The total vertical depth $X \simeq 1300 \text{ g/cm}^3$ and horizontal $X \simeq 36{,}000 \text{ g/cm}^3$
- The atmosphere consists of “air nuclei” with *A*=14.5

The incoming proton flux

- We assume the incoming flux is protons, with a flux with a knee given by

$$\phi_N(E) = \begin{cases} 1.7\,E^{-2.7} & \text{for } E < 5\cdot 10^6 \text{ GeV} \\ 174\,E^{-3} & \text{for } E > 5\cdot 10^6 \text{ GeV} \end{cases}$$

- To good approximation it is isotropic at high energy

Particle production

The regeneration function is defined by

$$S(k \to j) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k)}{\lambda_k(E_k)} \frac{dn(k \to j; E_k, E_j)}{dE_j}.$$

where dn/dE = (1/σ) dσ/dE.

Describes energy distribution of produced particles

Z-moments

- We solve the cascade equations by introducing Z-moments:

$$Z_{kh} = \int_E^\infty dE' \frac{\phi_k(E', X, \theta)}{\phi_k(E, X, \theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

- Then

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\rho d_M} - \frac{\phi_M}{\lambda_M} + Z_{MM}\frac{\phi_M}{\lambda_M} + Z_{NM}\frac{\phi_N}{\lambda_N}$$

- Solve equations separately in low- and high-energy regimes where attenuation is dominated by decay and energy loss, respectively, and interpolate

Lepton fluxes

- This gives

$$\phi_\ell^{\text{low}} = Z_{M\ell,\gamma+1} \frac{Z_{NM}}{1 - Z_{NN}} \phi_N(E)$$

$$\phi_\ell^{\text{high}} = Z_{M\ell,\gamma+2} \frac{Z_{NM}}{1 - Z_{NN}} \frac{\ln(\Lambda_M / \Lambda_N)}{1 - \Lambda_N / \Lambda_M} \frac{\epsilon_M}{E} \phi_N(E),$$

where ε_M separates low and high energy regions:

$$\epsilon_M(\theta) = \frac{m_M c^2 h_0}{c\tau_M} f(\theta)$$

For small angles (near vertical): $f(\theta) = 1/\cos\theta$

- We include charmed hadrons $M = D^\pm, D^0, \bar{D}^0, D_s^\pm, \Lambda_c^\pm$

Attenuation lengths

- Interaction (cooling) length for particle N is given by

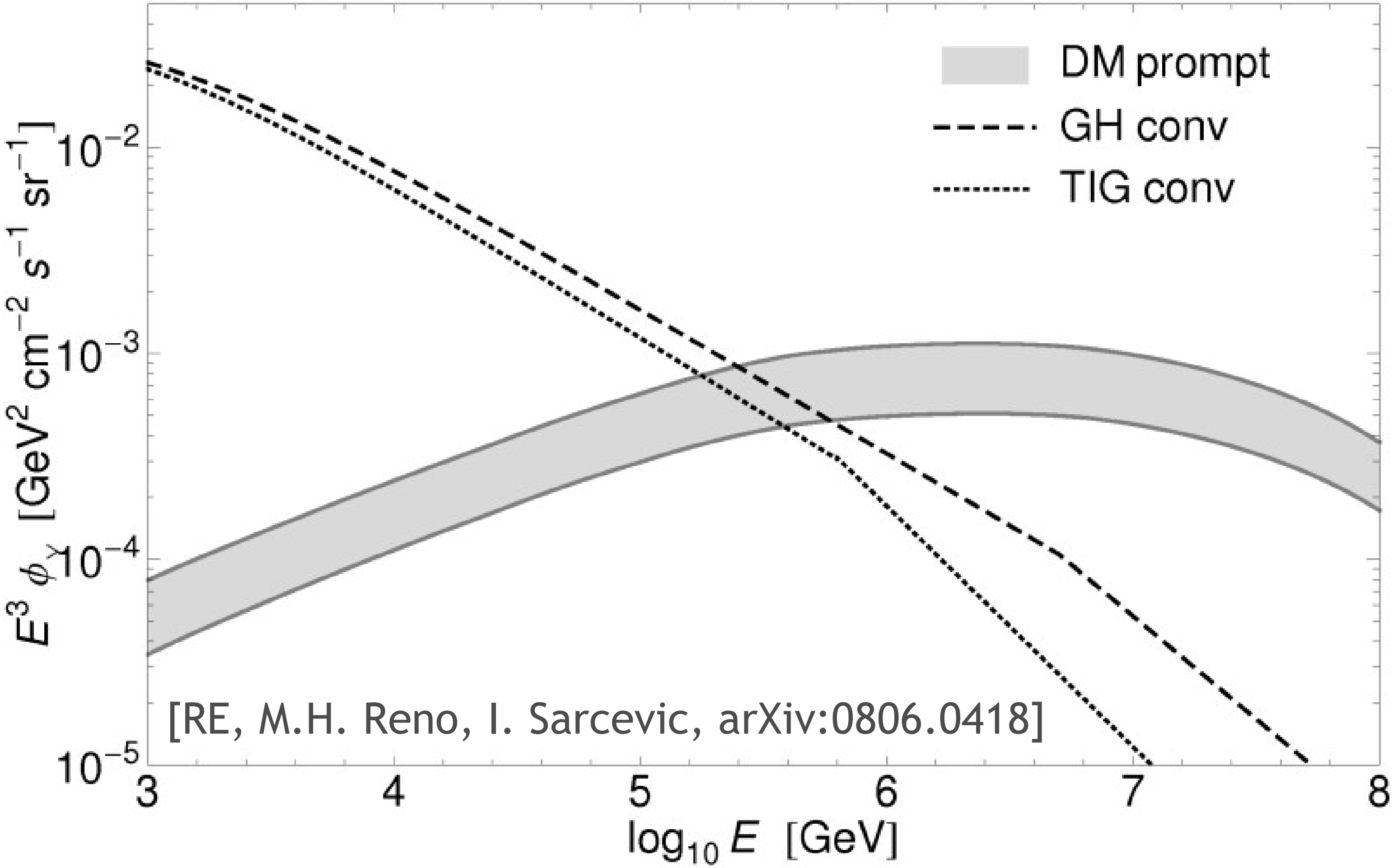
$$\lambda_N(E) = \frac{\rho(h)}{\sigma_{NA}(E)\, n_A(h)}$$

- Attenuation length is defined as

$$\Lambda_N(E) = \frac{\lambda_N(E)}{1 - Z_{NN}(E)}$$

where (1-Z_{NN}) takes the energy loss in each interaction into account

Best result for ν_μ

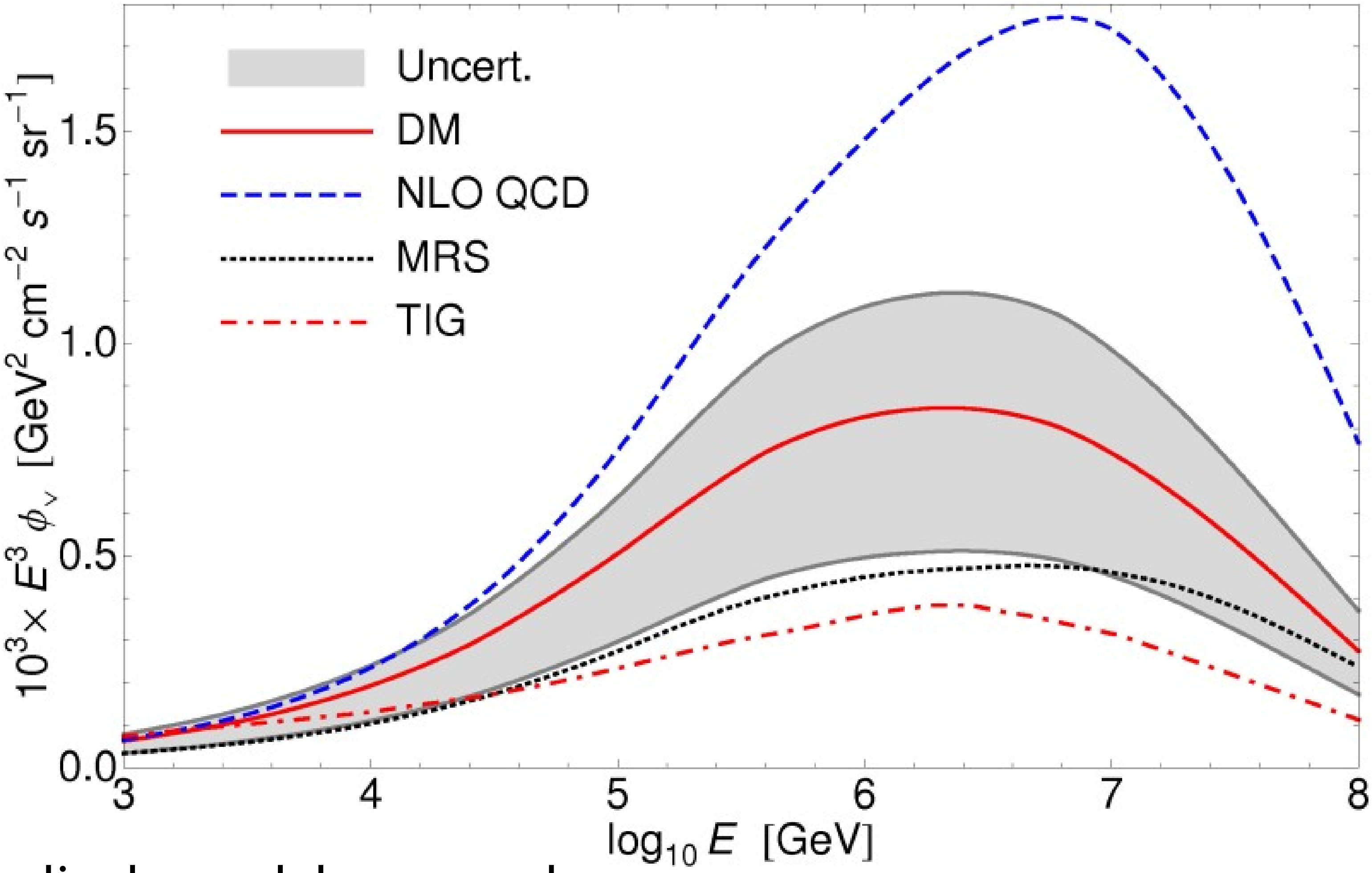


[RE, M.H. Reno, I. Sarcevic, arXiv:0806.0418]

Uncertainty: gluon distribution, charm mass, factorization scale, parameters in saturation calculation

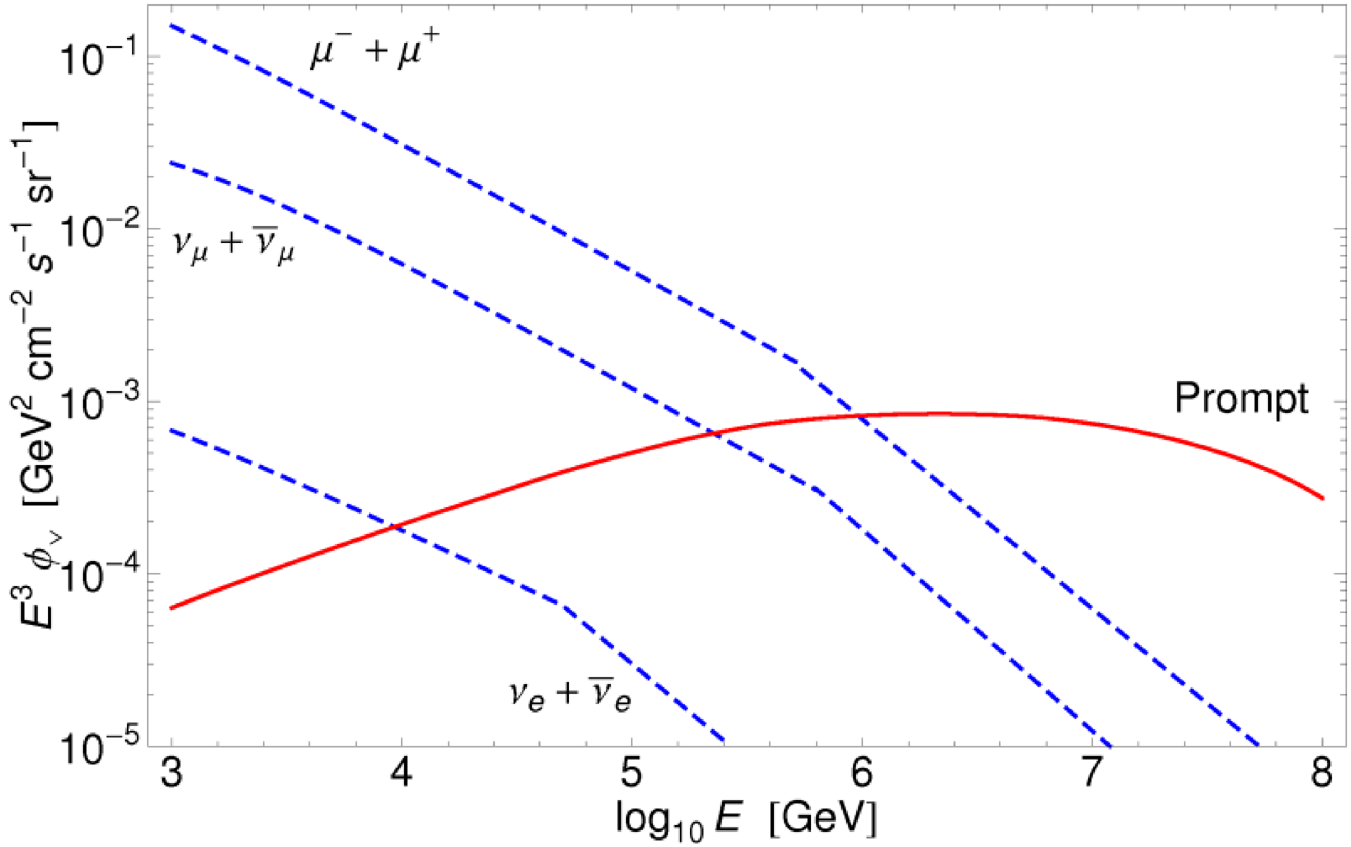
Prompt flux crosses over at 10^5—$10^{5.5}$ GeV

Comparison: earlier calculations



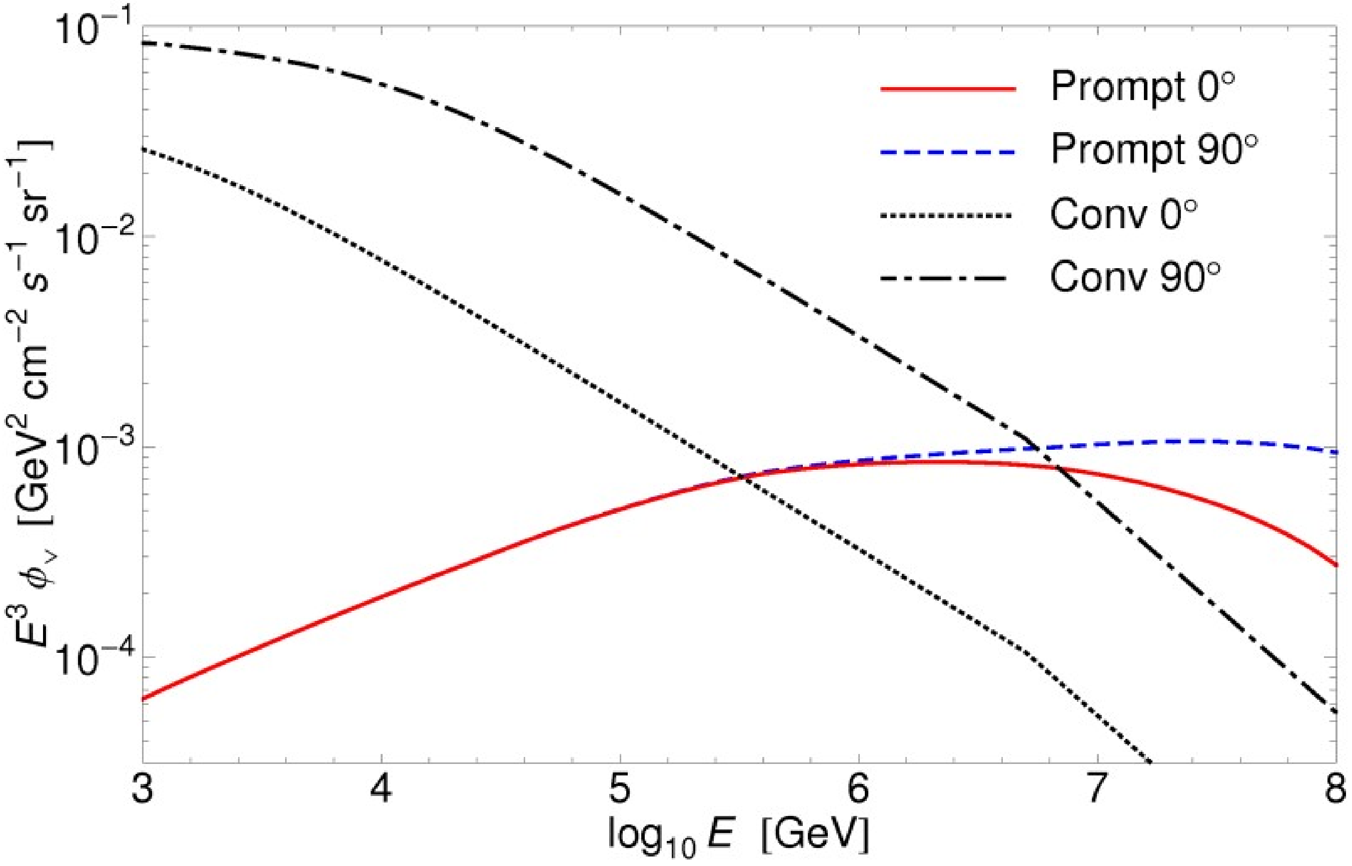
DM: dipole model — our calc.
NLO QCD: Pasquali, Reno, Sarcevic
MRS: Martin, Ryskin, Stasto *(included simpler saturation pheno.)*
TIG: Thunman, Ingelman, Gondolo

Prompt vs conventional fluxes



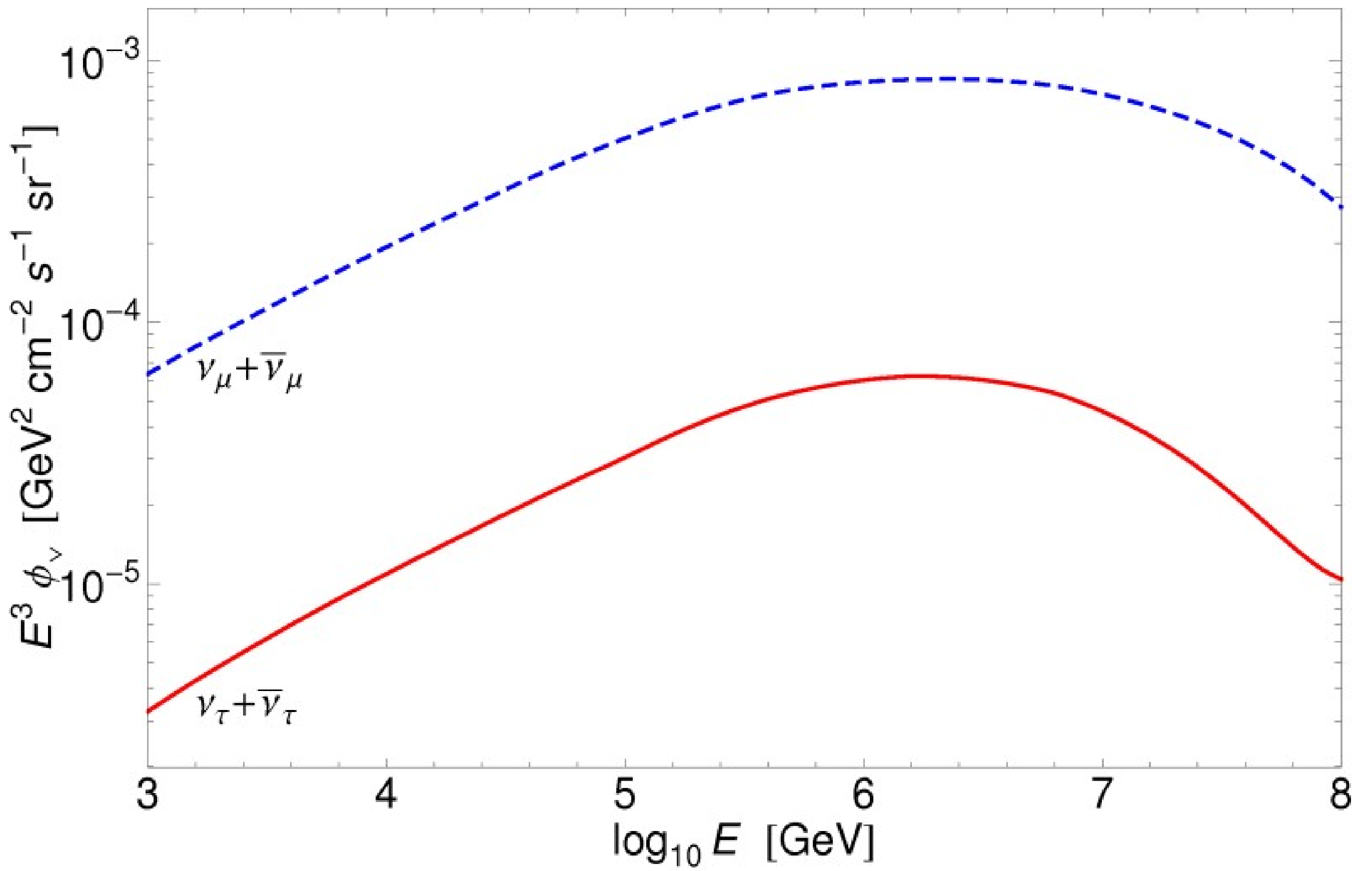
- Conventional flux different for different flavors — ν_e would be good for studying prompt flux

Zenith angle dependence



To see the prompt flux we want to look in the **vertical direction**

Tau neutrinos



Only D_s decays give tau neutrinos

Gamma ray bursts and astrophysical sources

Charm in astrophysical sources

- We saw that for atmospheric neutrinos, charm dominates at high energies because D-mesons decay before they lose energy through hadronic interactions

- Obvious question: what about charm in astrophysical sources? Not usually taken into account.

- We'll see that then electromagnetic energy loss is more important, but the overall result is similar

Gamma ray bursts

- Gamma Ray Bursts (GRBs) are the most violent phenomena observed in the universe

- Energy output in 10 sec:

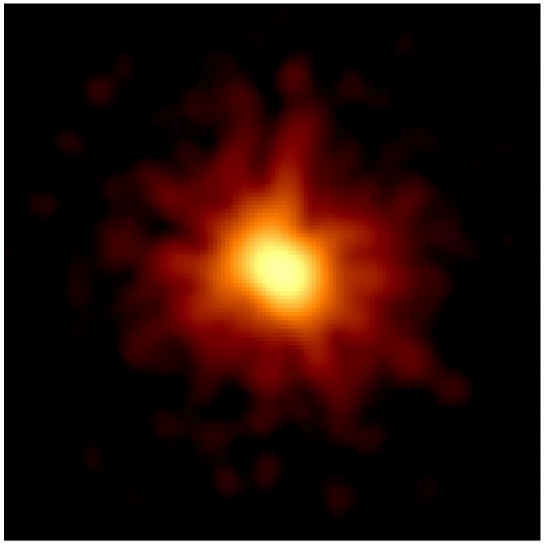
  ~ 10^{53}—10^{54} ergs isotropic energy equivalent
  ~ 10^{51}—10^{52} ergs if emission is *jetted* (θ ~ 5°)

- Supernovae emit a similar amount of energy during several months

- About one GRB per day is observed

Biggest burst: GRB 080319B

- GRB 080319B ($z = 0.94$) was the most distant object ever observed that could have been seen with the naked eye



- Above picture is in X-ray
- More than a million times brighter than SN 2005ap
- Unclear why so bright: maybe jet was head on

Gamma ray bursts

- Cosmological distances — observed up to z = 6—7

  z=7 means the universe was less than a billion years old!

- There are two classes of GRBs:
  - *Long:* (t > 2 s) occur in star-forming regions
  - *Short:* (t < 2 s) occur anywhere

- Long-duration bursts can be used as probe of star formation rates

- Not good standard candles for cosmology

What are GRBs ?

Probably short and long GRBs are of different origin;

both involve formation of a black hole

- Short bursts are believed to be binary mergers: NS-NS or NS-BH
- Long bursts are believed to be core-collapse SNe (e.g. Wolf-Rayet stars, type Ic)

There is observational evidence for the latter:
SNe seen at GRB sites

(e.g. GRB 980425 and SN 1998bw)

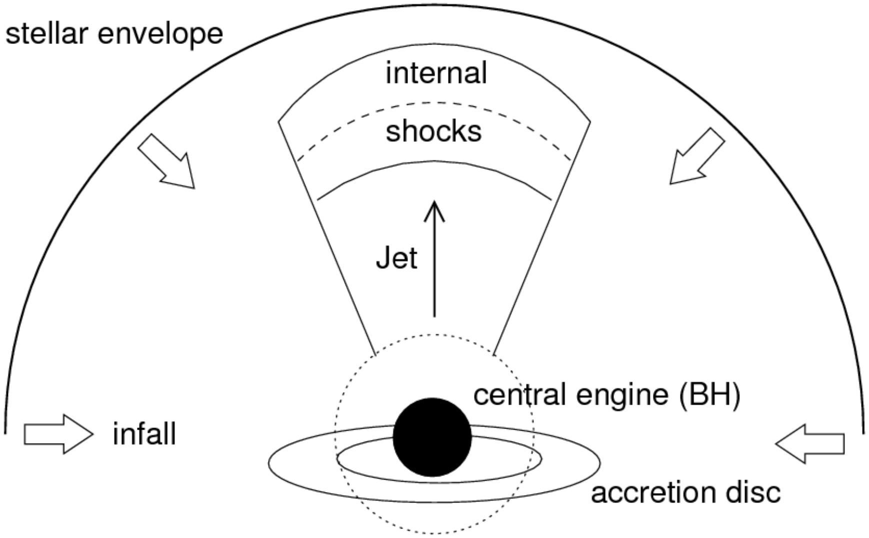
What are GRBs ?

Standard interpretation:

- GRBs are related to births of black holes
- The central engine releases a huge amount of energy in a small region
- This creates a very dense fireball
- Fireball expands due to trapped radiation pressure
- Relativistic outflow in two opposite jets

- The burst of gamma rays comes from dissipation in the outflow due to shocks
  – synchrotron emission and inverse Compton

Schematic picture



Relativistic jet inside a collapsing star — may or may not punch through the envelope

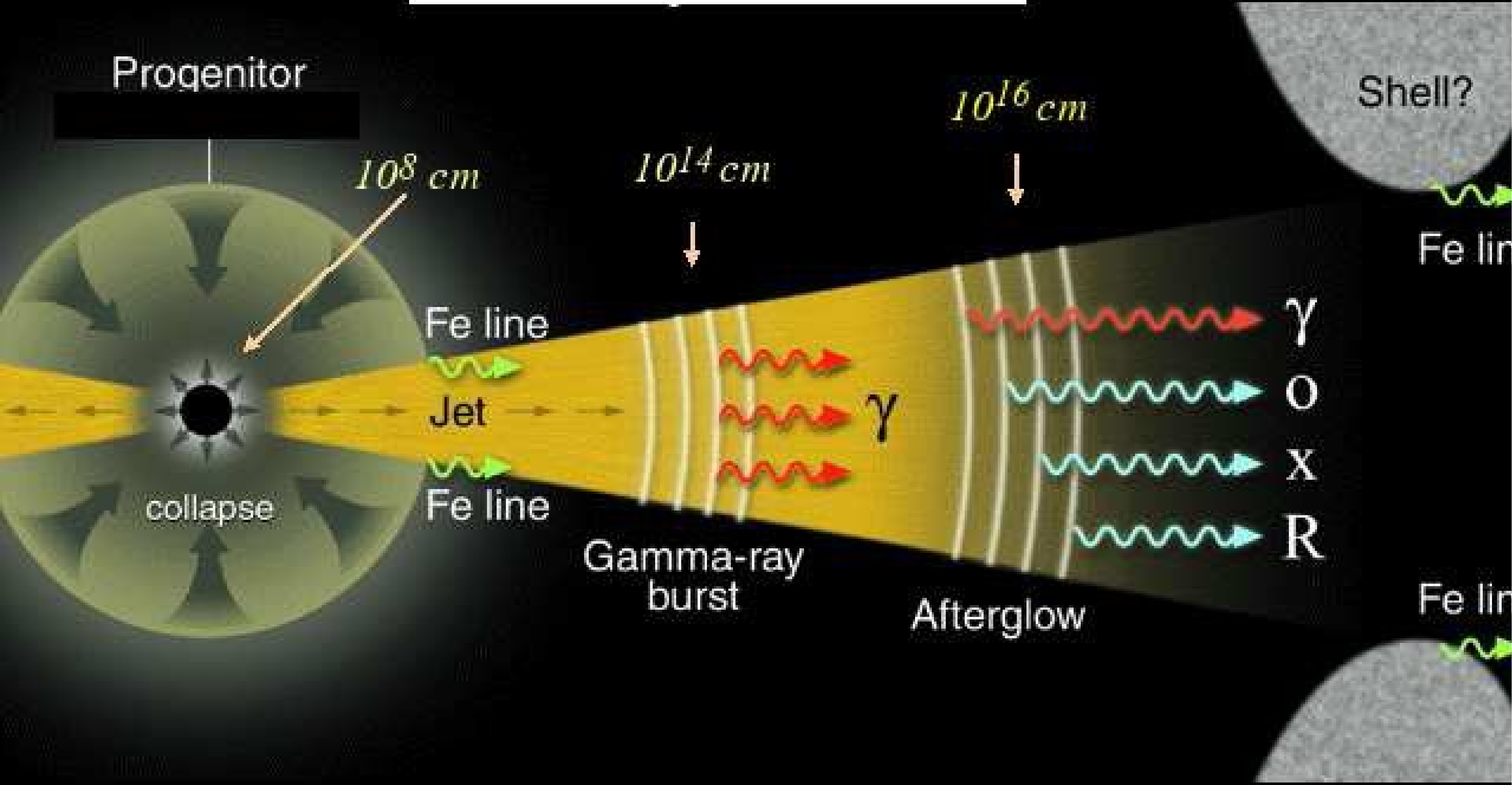
Protons and electrons are shock accelerated in jet

There are many similar types of astrophysical sources with jets:

- Active Galactic Nuclei *(jets from supermassive black hole)*
- Supernovae with jets *(slower jets, halted in star)*
- Microquasars

[Fig from Razzaque et al, astro-ph/0509729]

Anatomy of a GRB



See Piran 1999; Mészáros 2002 (ARAA) for reviews

Type Ic supernovae and GRBs

GRBs connected to core-collapse supernovae ?

Animation shows a Wolf-Rayet star of mass $M \sim 10\, M_\odot$ exploding due to a GRB

- Core collapses to black hole ⇒ fireball & jet
- Jet protrudes and blows up the star ⇒ SN Type Ic

Animation from http://imagine.gsfc.nasa.gov/docs/science/know_l1/grbs.html

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Acceleration and emission

- There are internal shocks in the jet
- Electrons and protons are shock accelerated to very high energy through the *Fermi mechanism*
- Electrons cool down through synchrotron emission in magnetic field
- If optically thin environment: gamma rays escape and make up the burst
- If optically thick: photons can thermalize
- Bulk Lorentz factor of jet must be $\gtrsim 100$ to obtain optical thin system

Neutrinos from astrophysical sources

Cosmic beam dump

- Shock accelerated protons may collide with protons and photons in the jet and the star

- Mesons produced in collisions decay to γ and ν

- Waxman & Bahcall (1997) considered high energy neutrino flux from pions produced in GRBs — many authors have considered π and K in various sources
  (Ando-Beacom, Mészáros-Razzaque-Waxman, Koers-Wijers, many others)

- Pions, kaons are cooled before decay
  — charmed mesons will persist to higher energies

Astrophysical sources

We consider two kinds of sources as examples:

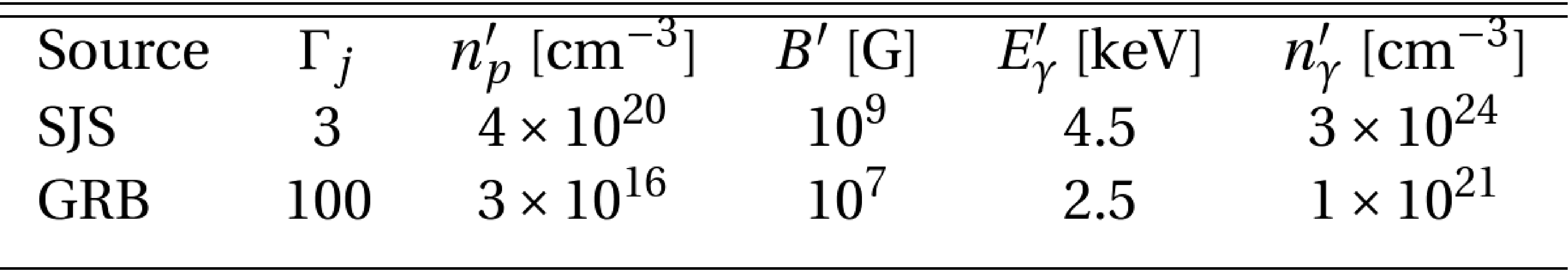
- GRB:
  - Non-thermal photons and highly relativistic jet

- “Slow-jet supernova” (SJS):
  - Supernova with mildly relativistic jet that doesn't punch through
  - Thermal photons
  - SNe with jets may be common and may help with blowing up the star

(Razzaque, Meszaros, Waxman; Ando and Beacom)

Parameters

Calculation or obs, with L_j=3×10^{50} erg/s :



Source	Γ_j	n'_p [cm^{-3}]	B' [G]	E'_γ [keV]	n'_γ [cm^{-3}]
SJS	3	4×10^{20}	10^9	4.5	3×10^{24}
GRB	100	3×10^{16}	10^7	2.5	1×10^{21}

We calculate the neutrino fluxes for these two toy-model sources

To do this, we need to take proton and meson cooling into account

Cooling

- Time scales for cooling of protons and mesons are

$$t'_{\mathrm{cool}} = \frac{E'}{|dE'/dt'|}$$

  with

$$\left|dE'/dt'\right| \simeq n'\sigma v \Delta E$$

- For photons, we use $\left|dE'/dt'\right| \simeq \langle n'\sigma v \rangle \Delta E$,

  averaged over the photon distribution

Hadronic cooling

- *pp* and *pγ* interactions as well as synchrotron and inverse Compton cool the accelerated protons
- Roughly,the cooling time scales are

$$t'_{p\gamma} = \frac{E'_p}{c\sigma_{p\gamma} n'_\gamma \Delta E'_p} \qquad t'_{pp} = \frac{E'_p}{c\sigma_{pp} n'_p \Delta E'_p}$$

- For photons,

$$\langle n'\sigma v\rangle = \frac{c}{8\beta'_p E'^2_p} \int dE'_\gamma \frac{\hat{n}_\gamma(E'_\gamma)}{E'^2_\gamma} \int ds(s - m_p^2)\sigma_{p\gamma}(s)$$

Electromagnetic cooling & decay

- Synchrotron and Inverse Compton scattering are the two EM (radiative) cooling mechanisms:

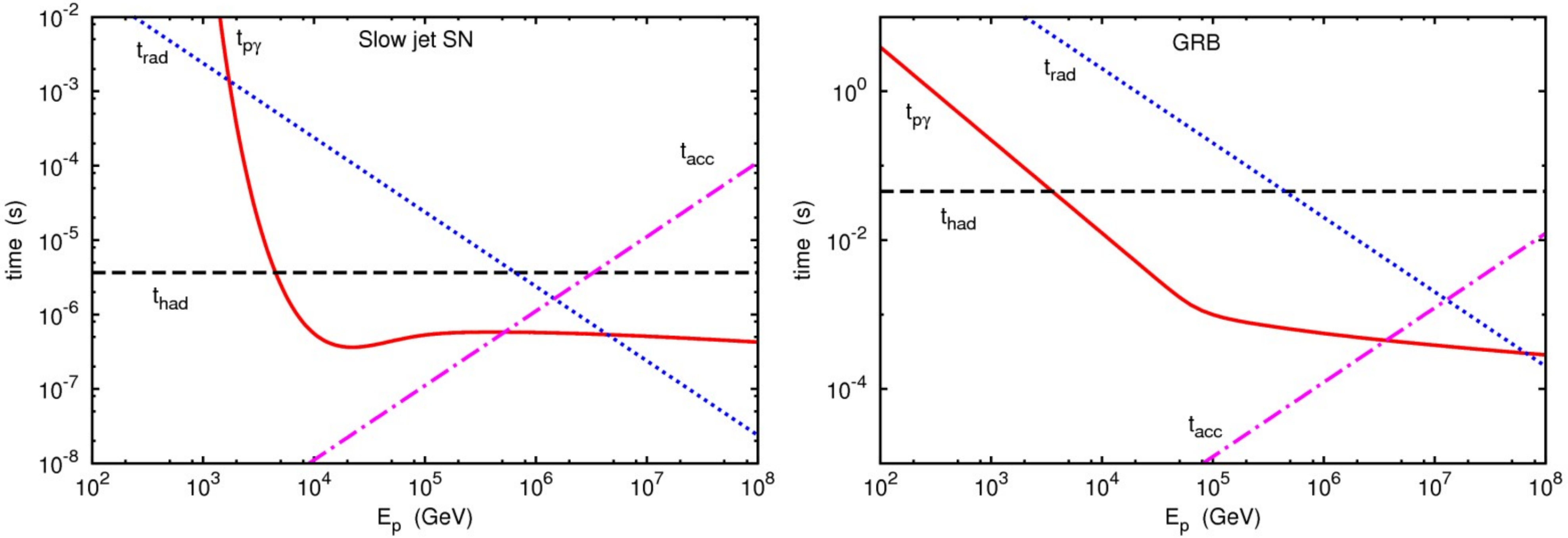
$$t'_{\mathrm{syn},p} = \frac{6\pi m_p^4 c^3}{\sigma_T m_e^2 E'_p B'^2} \qquad t'_{IC,p} = \frac{3 m_p^4 c^3}{4\sigma_T m_e^2 E'_p U'_\gamma}$$

$$(t'_{\mathrm{rad},p})^{-1} = (t'_{\mathrm{syn},p})^{-1} + (t'_{IC,p})^{-1}$$

- Meson cooling times obtained by using meson mass
- Decay time scale is just $t'_{\mathrm{dec},M} = (E'_M / m_M c^2)\tau_M$

- Note that non-rel Thompson cross section is used for IC: this is OK because IC is irrelevant for higher energies when cooling time becomes very large

Time scales for protons



[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807]

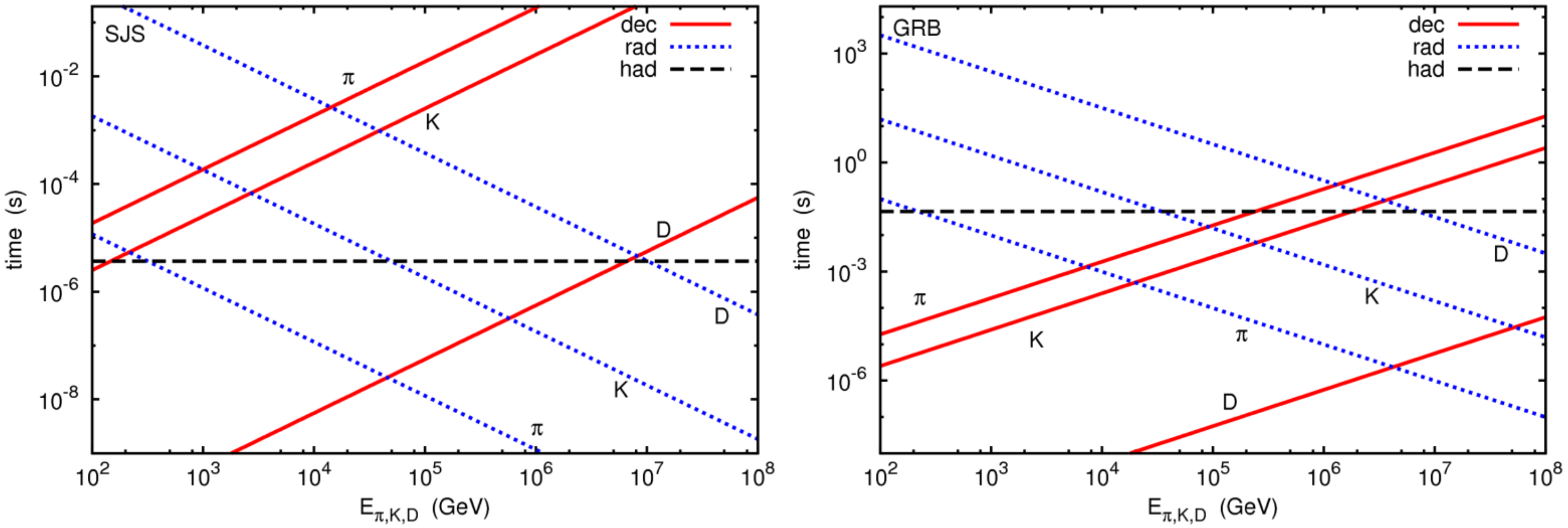
Maximum proton energy roughly estimated from when cooling times meet acceleration time

Above E_{max} there will be a rather quick drop-off in proton flux

Neutrino production

- $p\gamma$: charged pion decays from $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$ and $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu\nu_\mu$
- pp: pions, kaons, D-mesons
- Proton spectrum is $\propto (E'_p)^{-2}$
- If no cooling, meson spectrum follows proton spectrum

Time scales for mesons



When cooling time gets shorter than decay time the meson flux becomes suppressed

- D-mesons decay before cooling until E_D~10^7 GeV (SJS) or E_D~10^9 GeV (SJS)
- Pions, kaons are cooled much earlier

Computation of neutrino flux

- We generalize the method of Z-moments to apply to sources

- Start with cascade equations for all species of particle *j*, schematically

$$\frac{d\phi_j}{dx} = -\frac{\phi_j}{\ell_j^{\rm tot}} + S^{\rm tot}(jp \to jY)$$

- Use actual lengths *x* and *l* instead and assume constant density

Z-moments

- We calculate the Z-moments for charm production in the same way as for atmospheric charm

- For *pp* → *π* we use the parametrization (Costa et al)

$$\frac{dn_\pi}{dx_E} = 0.12\frac{(1-x_E)^{2.6}}{x_E^2}$$

and for *pγ* → *π* we fit this form to HERA data. For kaons we rescale pions by 0.1.

The flux

The neutrino flux is proportional to the proton flux:

$$\phi_\nu(E') = Z_{M\nu} \frac{L_M^{\mathrm{eff}}}{L_M^{\mathrm{dec}}} \frac{Z_{NM}\ell_N^\gamma + Z_{NM}^\gamma \ell_N^{\mathrm{had}}}{\ell_N^{\mathrm{had}} + \ell_N^\gamma} \phi_N(E')$$

This is the flux in the frame comoving with the jet.

We are interested in the flux in the Earth frame.

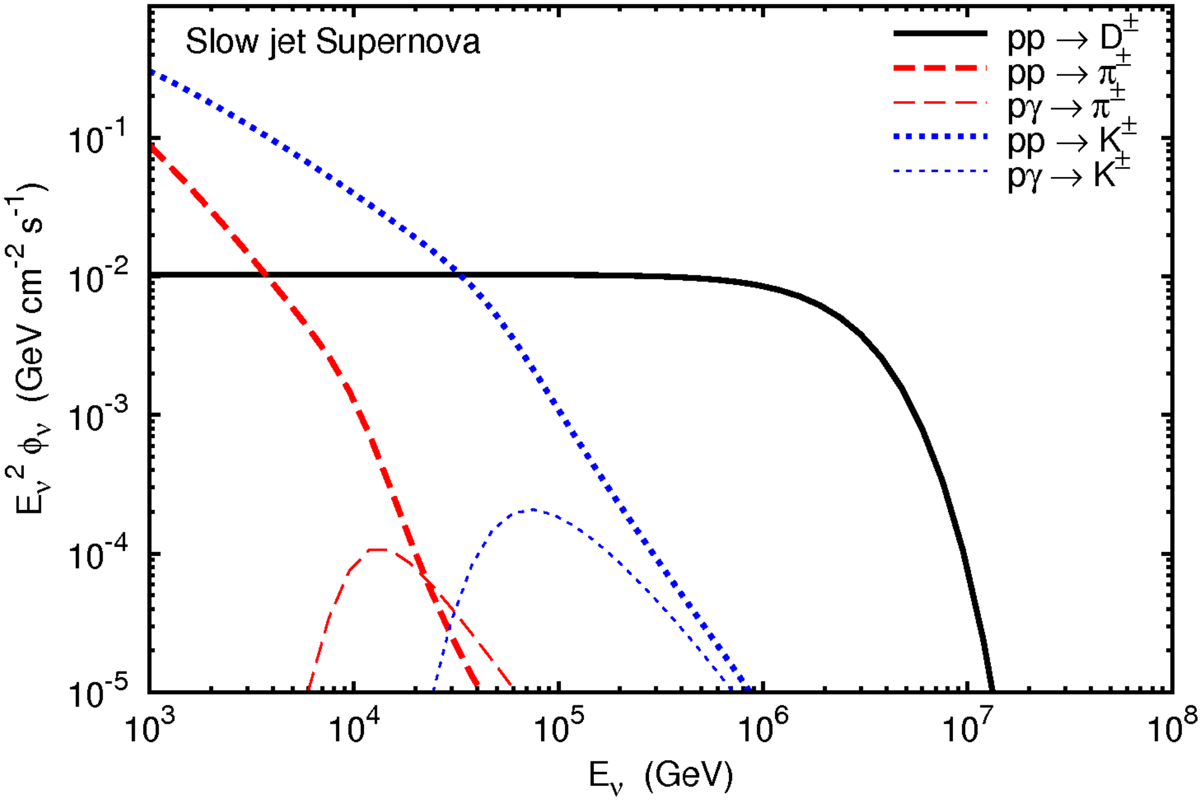
Normalization

The normalization of the flux from a single source depends on the overall luminosity, jet opening angle, jet Lorentz factor, and the distance:

$$\begin{aligned}\phi_\nu(E) &= Z_{M\nu}\frac{L_M^{\mathrm{eff}}}{L_M^{\mathrm{dec}}(\ell_N^{\mathrm{had}}+\ell_N^{\gamma})} \\ &\times (Z_{NM}\ell_N^{\gamma}+Z_{NM}^{\gamma}\ell_N^{\mathrm{had}}) \\ &\times \frac{L_j\Gamma_j^2}{2\pi\theta_j^2 d_L^2\ln(E'_{\mathrm{max}}/E'_{\mathrm{min}})}E^{-2}\end{aligned}$$

We choose d_L = 20 Mpc = 6×10^{25} cm (Virgo cluster)

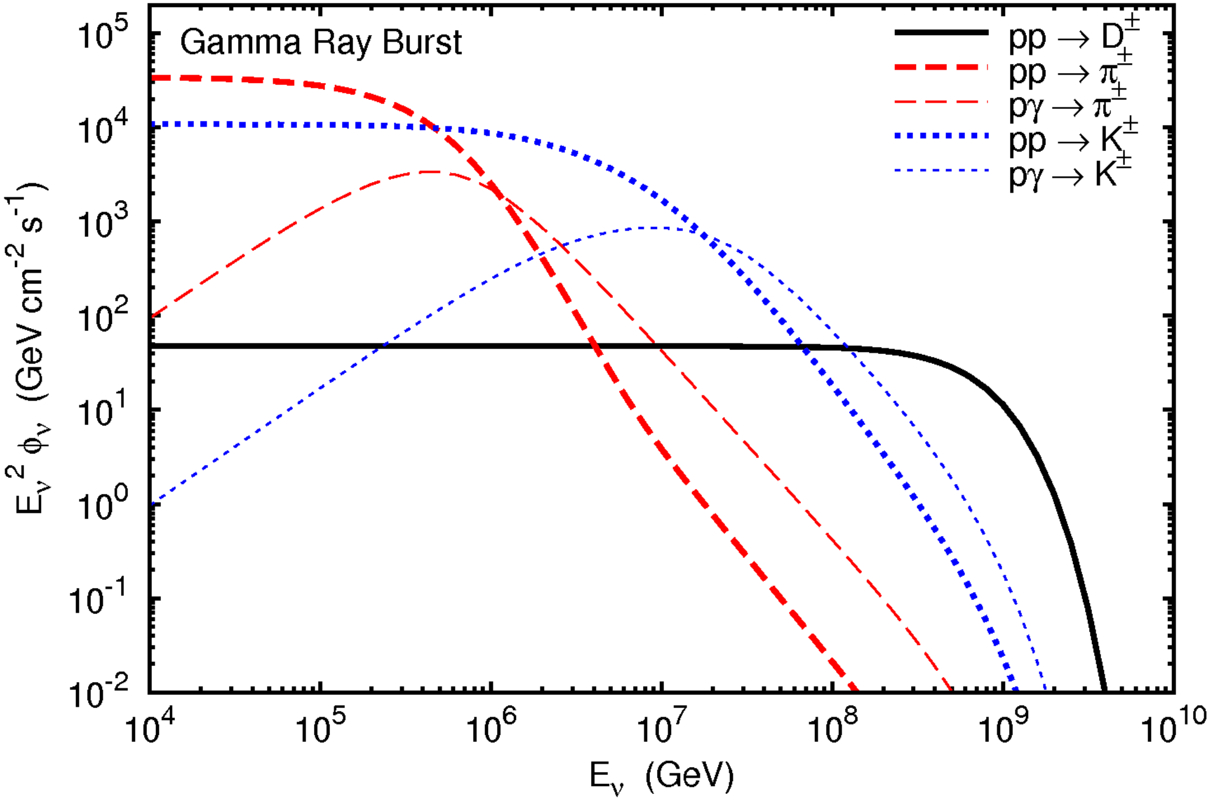
Neutrino flux from slow-jet SNe



[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807]

- No cooling of D-mesons
- Fall-off is due to maximum proton energy
  (we use parameterization of Protheroe & Stanev, astro-ph/9808129)

Neutrino flux from GRB



- Again no cooling of D-mesons
- For this particular choice of parameters, charm has a smaller range where it dominates
- Some scenarios have much higher max proton energy

To be done

- We have done a toy-model calculation to show feasibility
- Look at detection prospects:
  Both diffuse flux and single source
  —IceCube are already looking for single GRBs
  (See also Gandhi, Samanta & Watanabe, in preparation)
- GRB parameters can vary widely
- More careful look at proton acceleration, cooling, source environment etc

Flavor ratios

- Pions lead to a 1:2:0 neutrino flavor ratio
- This is modified by oscillations to ~ 1:1:1
- D-mesons give an equal amount of ν_e and ν_μ
- Flavor ratios may be different at very high energy where charm dominates

Conclusions

- Atmospheric neutrinos are more or less guaranteed
- Astrophysical sources driven by jets are potential sources of high energy neutrinos
- Neutrinos can provide information on the nature of the source
- At low energies, primarily pions.
  At intermediate energies, kaons dominate.
  At very high energies, D-mesons may give the dominant contribution.

Backups follow

Protons and electrons

- The (comoving) density of protons and electrons in the jet is given by

$$n'_e = n'_p = \frac{L_j}{2\pi\theta_j^2 r_j^2 \Gamma_j^2 m_p c^3}$$

where L_j is the total jet power, Γ_j is the Lorentz factor and

$$r_j = 2\Gamma_j^2 c t_v$$

is the radius where the shock occurs

Photons and magnetic field

- The photon energy and number densities are

$$U'_\gamma = \frac{\epsilon_e L_j}{2\pi\theta_j^2 r_j^2 \Gamma_j^2 c} \qquad n'_\gamma = 2\zeta(3)\left(15^3/\pi^{14}\right)^{1/4}\left(\frac{U'_\gamma}{\hbar c}\right)^{3/4}$$

for thermal photons and $U'_\gamma = n'_\gamma E'_\gamma$ for non-thermal

- The magnetic field is

$$B' = \left[\frac{4\epsilon_B L_j}{\theta_j^2 r_j^2 \Gamma_j^2 c}\right]^{1/2}$$

Z-moments for sources

- Z-moments are again defined as

$$Z_{kj} = \int_E^\infty dE' \frac{\phi_k(E')}{\phi_k(E)} \frac{\lambda_k^{\rm had}(E)}{\lambda_k^{\rm had}(E)} \frac{dn(k \to j; E', E)}{dE}$$

- Assume Feynman scaling, energy-independent cooling length, and power-law flux $\phi_N \sim E^{-\alpha}$:

$$Z_{NM} = \int_0^1 dx_E \, x_E^{\alpha-1} \frac{dn_{N\to M}}{dx_E}$$

where $x_E \equiv E_M / E_N$