Muon Acceleration in Cosmic Ray Sources

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Introduction to particle acceleration in cosmic sources
Muon Acceleration
Neutrino Flux Enhancement
Some Comments on Source Models
    Plasma Wakefield Acceleration
    Magnetars
    GRBs
Conclusions

Refs.: Ap. J. 779, 106 (2013) & Astron & Astrophy. 569, A58 (2014)

Motivation: transient sources

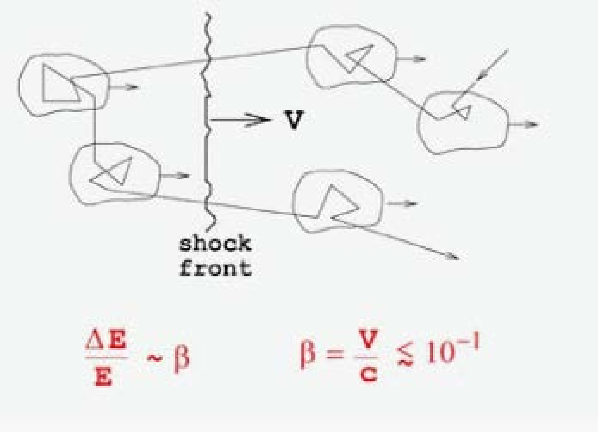
- Many of the most interesting astrophysical phenomena are transient and/or variable
  - Gamma-ray bursts
    - Supermassive star collapse
    - Colliding black holes
  - Supernovae
  - Active galactic nuclei are exhibit variability at diverse energies
- Short time scales require high accelerating gradients
- Gradient g > Emax/ct = 10^{20} eV/cτ
  - τ=100 s (GRB...) -> g > 3.3 GeV/m [laser-plasma in lab]
  - τ=1 day (AGN..) -> g > 4 MeV/m [SLAC/4]
  - If the source is a relativistic jet moving toward Earth, time dilation reduces the gradients by Γ^2 (Γ= source boost)

Cosmic acceleration mechanisms

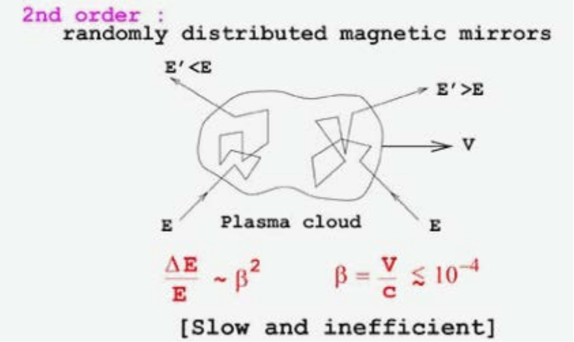
- Acceleration likely occurs in an energetic, turbulent plasma containing ionized gases and magnetic fields
- Astrophysical plasma may contain shock fronts, collisions between clouds of plasma moving at different speeds.
- In Fermi acceleration, when a charged particle encounters a shock front moving toward it, it may rebound gaining energy.
  - Multiple encounters needed to reach high energies
- Alternative models
  - Astrophysical plasma wakefield accelerators allow for very high gradients in multiple types of sources
  - In some magnetar models, acceleration is via a strong electric field

Fermi shock acceleration

- Type 1 acceleration involves encounters between single particles and moving shock fronts.
  - Energy gain $\zeta \sim 4/3\ \Delta\beta$, where $\Delta\beta$ is the velocity difference between the upstream and downstream media



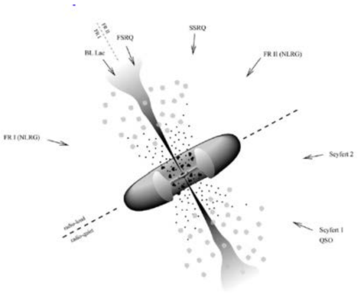
- Type 2 acceleration involves encounters between single particles and randomly oriented plasma blobs
  - $\zeta \sim 4/3\ \beta^2$– slower than type 1

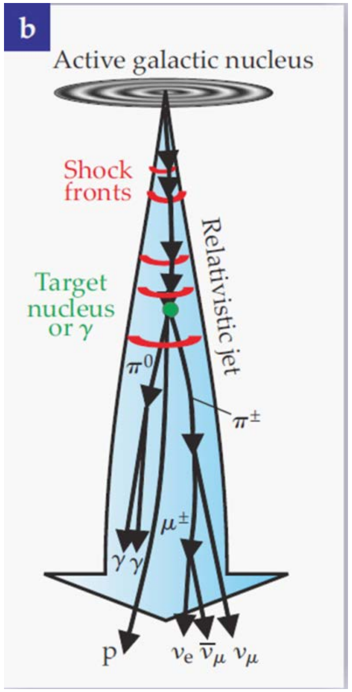


- $\zeta < 2$ requires many encounters to reach high energies
- After each encounter, there is a probability P_{esc} of escape or another encounter
  - Leads to a power law spectrum, dN/dE~ $E^{-\sim 2}$

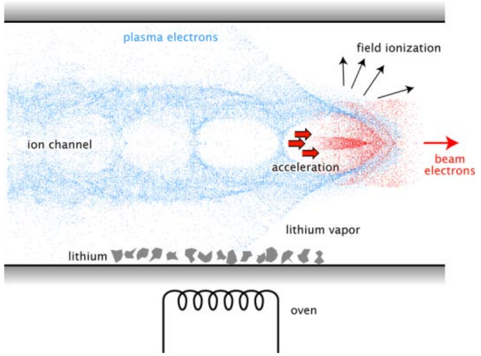
More detailed modelling

- Detailed models exist for most types of source
- Two different classes of geometries
  - Spherical sources
    - Supernova remnants…
    - Magnetic fields provide confinement, leading to repeated particle-shock front encounters
  - Relativistic particle jets
    - Emitted from axes of active galactic nuclei, GRBs,
    - Linear accelerators with many shock fronts
- Many sources are transient – GRBs, magnetars
  - Even supernova remnants have short (~1,000 y) lifetimes
- Most models predict a spectrum dN/dE~E-$^{\sim 2}$
  - Spectrum softens to $E^{-2.7-3.0}$ en-route to Earth





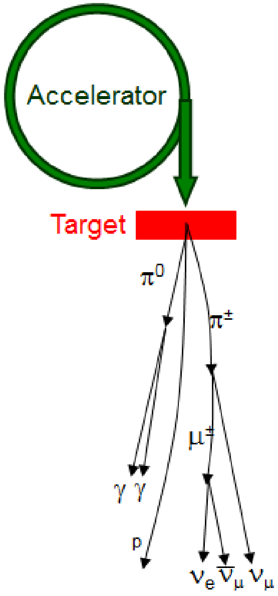
Other acceleration mechanisms

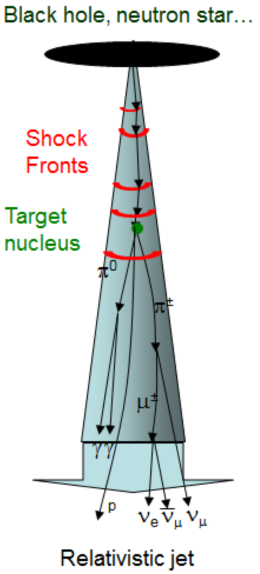


- In plasma wakefield acceleration, periodic variations in charge density (i.e. plasma waves) lead to very high accelerating gradients
  - Similar to more conventional accelerators
  - Astrophysical gradients of 10^{14}-10^{16} eV/cm quoted in papers
- In some magnetar models (Arons, 2003), particle acceleration is from particles ‘surf-riding’ the expanding electromagnetic fields
  - Magnetars are fresh neutron stars with ultra-high (Peta-Gauss) surface magnetic fields.
  - $dN/dE \sim E^{-1}$

ν and γ production in hadronic accelerators

- γ and ν are produced from π & K ion decay when accelerated nucleon interact with beam-gas or photons
  - Most interactions in accelerator; in-flight interactions also occur.
  - These interactions may not be in the same region as the acceleration
- The ratio of $\pi^0 \rightarrow \gamma$ to $\pi^{\pm} \rightarrow \mu^{\pm}\nu_\mu \rightarrow e\nu_\mu\nu_e$ is fixed by the hadron physics
  - Leads to a 2:1 $\nu_\mu:\nu_e$ ratio
    - Oscillation leads to 1:1:1 $\nu_\mu:\nu_e:\nu_\tau$ at Earth
      - Experiments have little at-source flavor sensitivity
  - Exception – heavy quarks produce mostly ν, few γ
- ν energy spectrum is similar to that of CR nuclei





ν flux estimates

- Relate to photon flux measured at GeV energies, from Fermi & Cherenkov telescopes
  - Extrapolation in energy
  - Photons may be absorbed
  - Photons may come from electromagnetic interactions
- Relate to cosmic-ray nucleon flux
  - ν flux depends on beam-gas/photon density in source
  - Maximum E_ν is ~ 5% of maximum CR nucleon energy
- Maximum total E_ν:E_{CR} ratio is ~ 1:1
  - The Waxman-Bahcall bound
  - If ratio were higher, sources would be ‘choked,’ without visible cosmic-ray emission
- The observed IceCube flux is close to this bound

Muon acceleration and energy loss

- 2/3 of the neutrinos come from μ decay
- If the muons gain or lose energy during their lifetime, the ν flux will be enhanced/reduced
- Energy loss can occur via bremsstrahlung, pair production, photonuclear interactions, or synchrotron radiation
  - Synch. Rad is usually most important
- A similar phenomena occurs for pions/kaons, except that the lifetimes are 100 times shorter

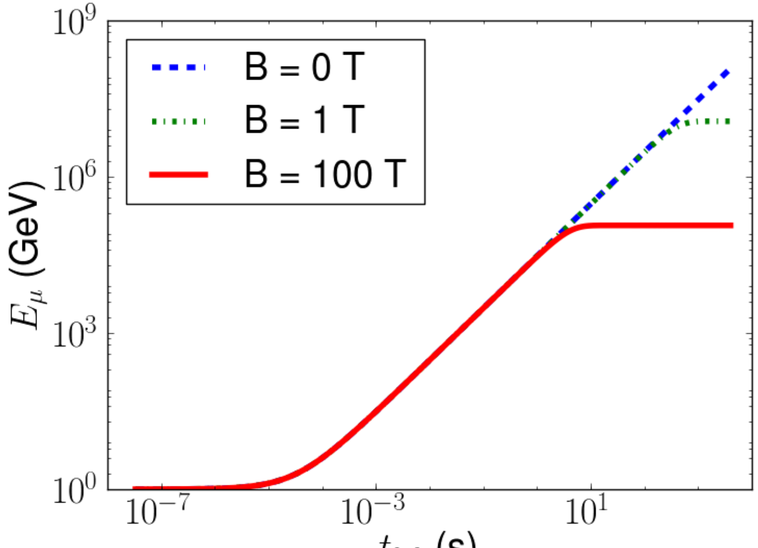
Kashti & Waxman (2005)

μ acceleration

- For small accelerating gradients g (in keV/cm), energy gain/loss for an individual muon that lives lifetime t is
  - As long as $\Delta E_\mu < E_\mu$, **$\Delta E_\mu = g\gamma ct/m_\mu$**
  - Lorentz boost lengthens time acceleration occurs
- If the gradients are larger, then
  - **$E_{final} = E_{init} \exp(gct/m_\mu)$**
    - For $g > m\mu/ct \sim g_0 = 1.6$ keV/cm, acceleration is large
- Similar considerations apply to π
  - Since $\tau_\pi \sim 0.01\ \tau_\mu$, π acceleration is much less important
  - Included in our calculations

μ Acceleration with energy loss

- If g> $m_\mu/c\tau_\mu$ muons gain significant energy before they decay.
- They also lose energy
  - μ-matter interactions
    - Much smaller than for p-matter energy loss
  - μ-photon interactions
    - Usually smaller than p-photon energy loss
  - Synchrotron radiation
    - $\Delta E/\Delta t \sim \gamma^2 B^2$
    - The only energy loss mechanism that is larger for μ than protons. So, we focus on it, as the limiting case
- Maximum energy E_c when $dE_{gain}/dx = dE_{loss}/dx$



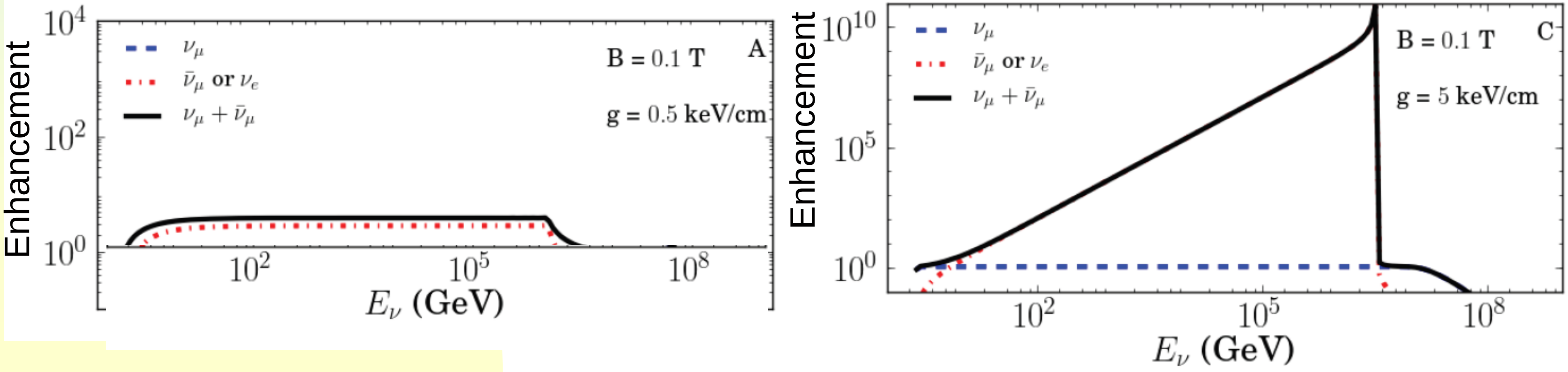
Calculating the ν spectrum

- Start with a proton spectrum with a given index
  - Generate π with the same index
    - Pion gets ~ 20% of proton energy
  - Propagate π, including acceleration and energy loss
    - Decay times are distributed exponentially
  - Assume ν_μ from π decay takes ¼ of energy
  - Propagate μ, including acceleration and energy loss
  - Divide μ energy equally among e, ν_μ, ν_e
  - The longest lived π make the biggest contribution to the spectrum

Resulting ν flux

- ν flux is greatly enhanced, up to E_c, where energy loss by synchrotron radiation balances the energy gain
  - At high gradients g >> g_0, ν spectrum hardens significantly, to roughly $N \sim E^{-g0/g}$, not very dependent on the initial spectrum
  - Maximum energy determined by accelerator length, or when $E_{gain} = E_{loss}$

Enhancements for an E^{-2} spectrum at 0.5 keV/cm & 5 keV/cm gradients

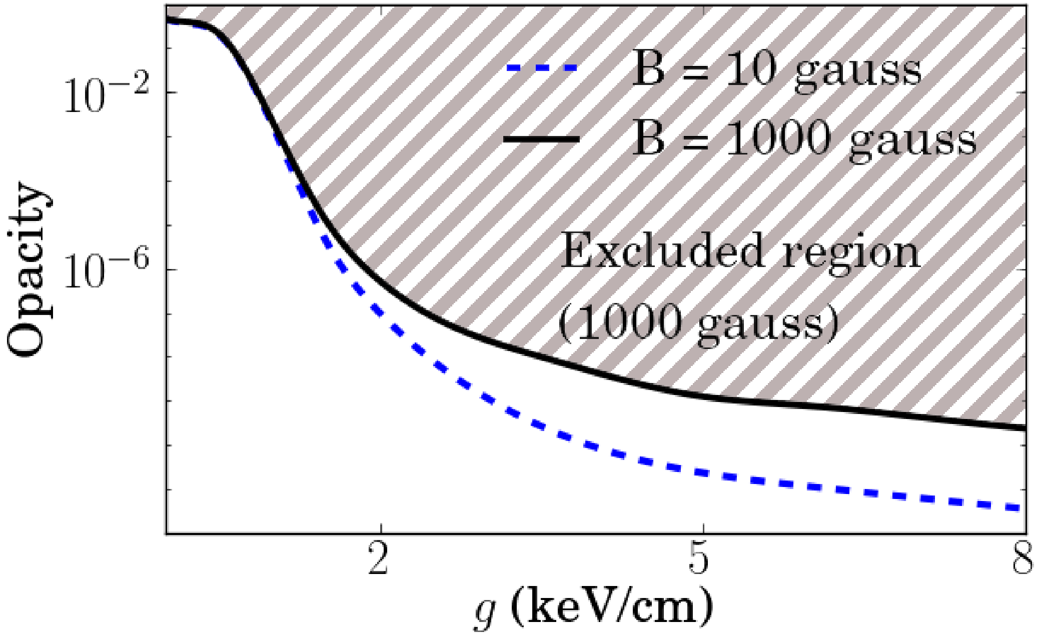


Limits on g and opacity

- Waxman & Bahcall used the measured 10^{19-20} eV cosmic-ray flux and assumed the maximum opacity $O=1$ to set a limit on the neutrino flux.
  - Reverse to set limits on opacity $O < \phi_{\mathrm{observed}}/\phi_{\mathrm{WB}}$
- IceCube prefers a spectrum softer than $dN/dEn \sim E^{-2}$, but not decisively so. We will consider E^{-2} here.
    - These calculations used the IC40 limit on diffuse ν_μ
    - The IceCube 3-year contained event flux is close to the IC40 limit, so we can just replace ‘limit’ with measurement
- The data can be used to set 2-dimensional limits on opacity (or density) and accelerating gradient
  - Muon acceleration alters the spectrum.
  - Calculate the number of events needed to be seen as an excess using new spectrum, based on the published below-the-horizon effective area vs. E_ν

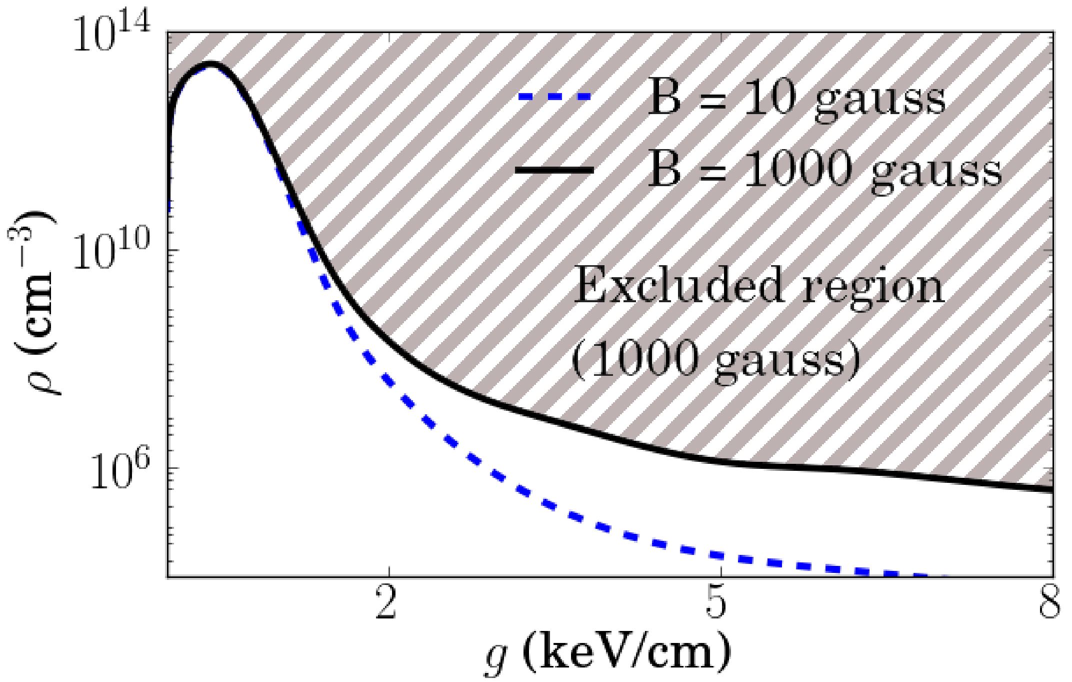
O $_{max}$ max vs. g

- 1-d limit, O ~ 0.4 holds up to about 500 eV/cm
- At higher gradients, maximum opacity drops rapidly
  - Magnetic field enters via changing E_c
- For g > ~ 8 keV/cm opacity < 10^{-7}
  - A rather tight constraint



Matter density (ρ) constraints

- Probability of interaction is O = $\sigma\rho L$
  - $L = 10^{20}$ eV/g
  - For $g > 5$ keV/cm, density $\rho < 10^6/\text{cm}^3$ Problematic for some accelerator models

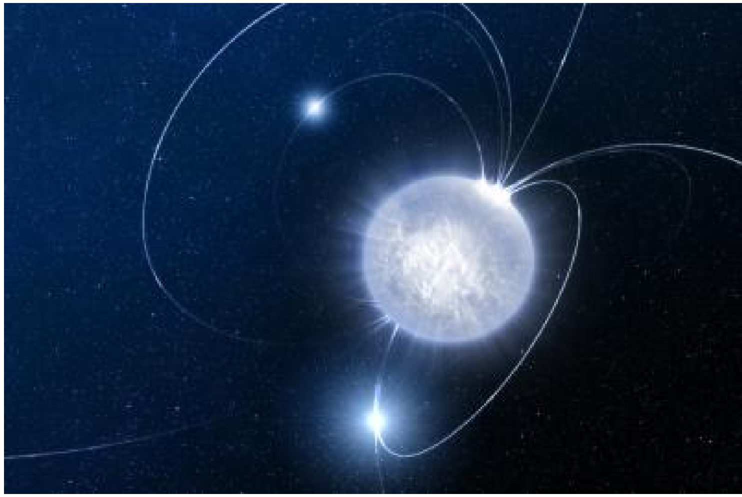


Plasma Wakefield Acceleration

- Allows very high accelerating gradients
  - 1 GeV in 10 cm observed in laboratory
    - (10 GeV in 1 meter this fall?)
- Proposed for diverse astrophysical sources
  - E. g 10^{13} keV/cm in GRBs
  - AGNs?
- PWA uses an excited plasma for acceleration
  - In cosmos, ‘magnetowaves’ excite plasma
  - Computer simulations show that this requires density ~ $10^{10}/cm^3$
  - This density is ruled out by the neutrino flux
    - Can a PWA operate at significantly lower densities?

P. Chen et al., 2002, F. Y. Chang et al. 2008, 2009…

Magnetars



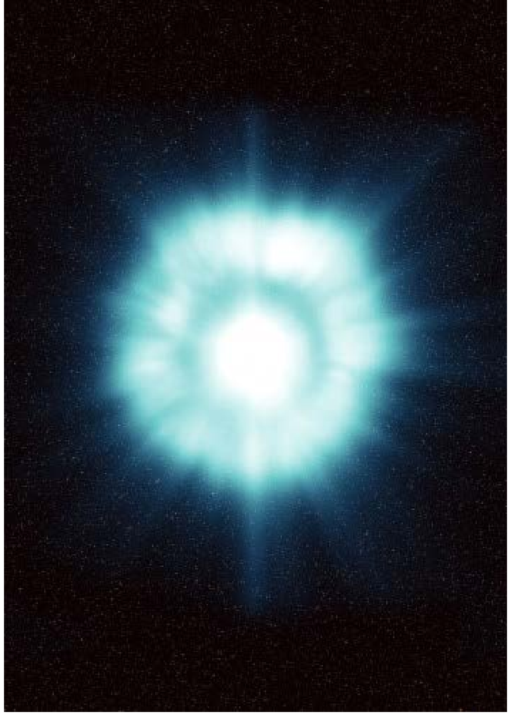
- Newborn neutron stars with Peta-Gauss fields
- Very high electric fields can develop in (nearly) magnetic field free regions
  - Region size (~30,000 km) requires high accelerating gradients, > $3*10^7$ keV/cm
  - These regions are also short-lived
- IC40 ν flux limits require that the matter density in these regions be very low, < $2*10^6/cm^3$
  - Is this realistic in the immediate neighborhood of a post-collapse environment?

J. Arons, 2003

Caveats

- Assumes that ν-producing interactions occur at the acceleration site, rather than after the acceleration.
  - The matter is in the accelerator.
- Assumes (~) that acceleration occurs linearly.
  - Stochastic acceleration OK as long as there are multiple stochastic encounters/particle.
  - Varying gradients during acceleration may change the magnitude of the enhancement.
- We focus on energy loss due to synchrotron radiation.
- If muon acceleration is large enough, it will drain the accelerator.
  - Don’t take the exact magnitudes of the enormous enhancements too seriously.
    - They do show that something big is going on, though.

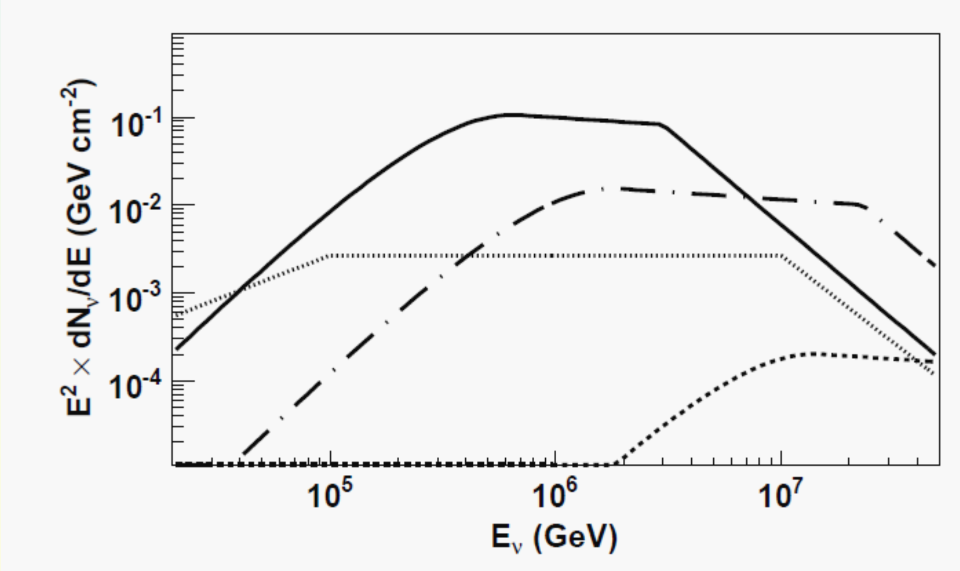
GRBs



- Short bursts (<2 s or > 2s) imply short acceleration times
- Here take an average t = 10 s burst length
  - g > $3*10^4$ keV/cm for 10^{20} eV
- Assume that the accelerator (fireball) is moving toward us at boost Γ
  - Accelerator length increases by Γ
  - Maximum energy decreases by Γ
  - g decreases by Γ^2
  - For Γ = 100, g = 3 keV/cm > 1.6 keV/cm
    - μ acceleration enhances the neutrino flux greatly

Simplified GRB ν energy spectrum

- Broken power law with 2 energy breaks
  - Central region corresponds to proton spectrum (E^{-2})
  - Lower energy region is below pion production threshold in jet frame
  - Above the higher energy break, secondary particles (π,K) lose energy before decaying

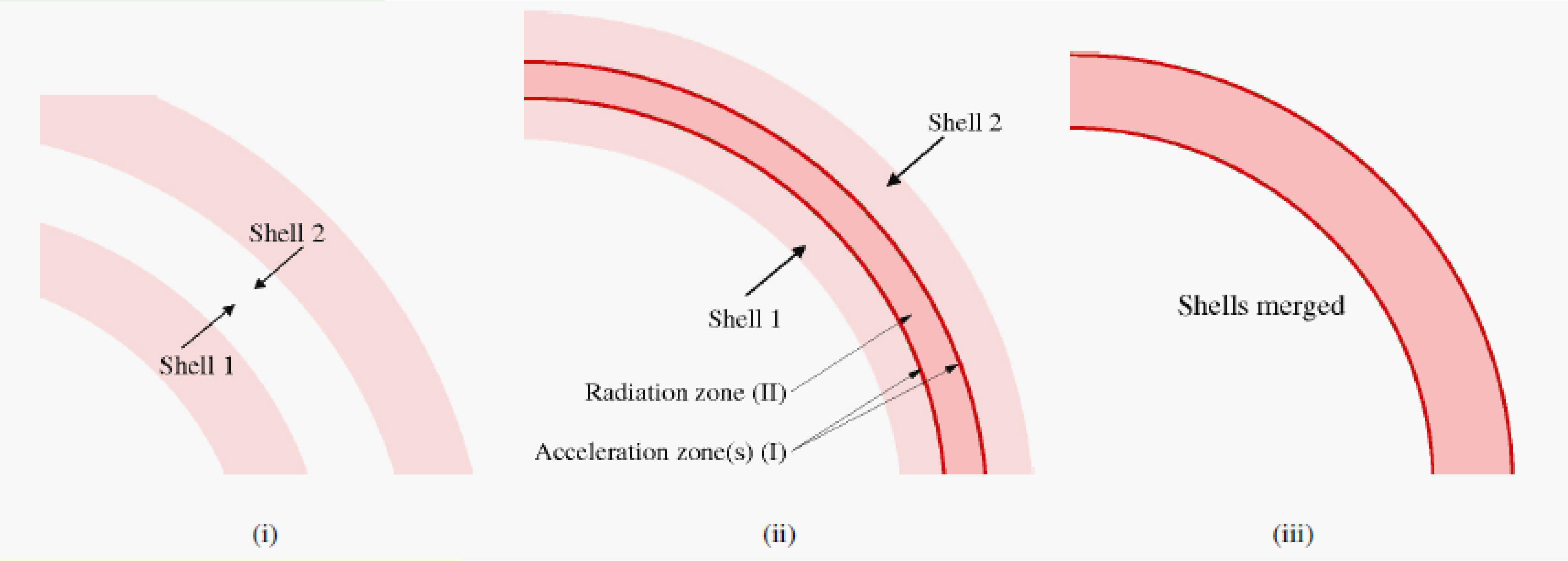


$$F(E) = \begin{cases} F_0 \left(\frac{E}{E_0}\right)^{\alpha} \exp\left(-\frac{E}{E_c}\right) & E \leqslant E_b \\ F_1 \left(\frac{E}{E_0}\right)^{\beta} & E \geqslant E_b \end{cases},$$

Waxman & Bahcall, 1997, Hummer Baerwald & Winter, 2012

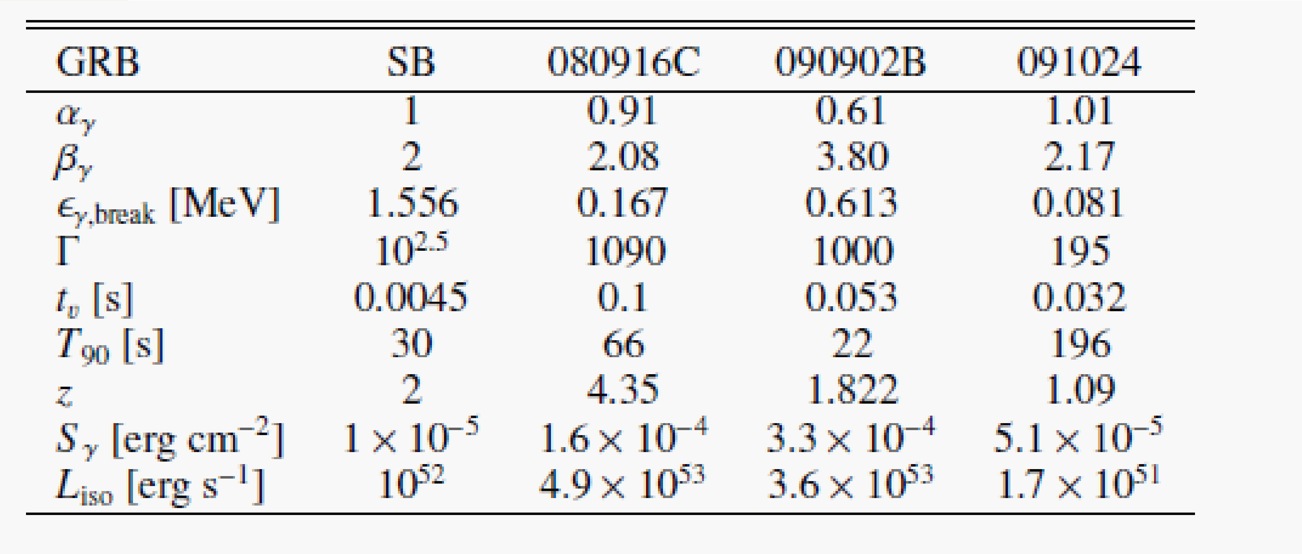
GRB modelling

- μ acceleration has been considered in a more detailed GRB model
- Acceleration occurs at the collision of expanding two shells
  - Acceleration at shock front boundaries, radiation in downstream plasma



GRB modelling

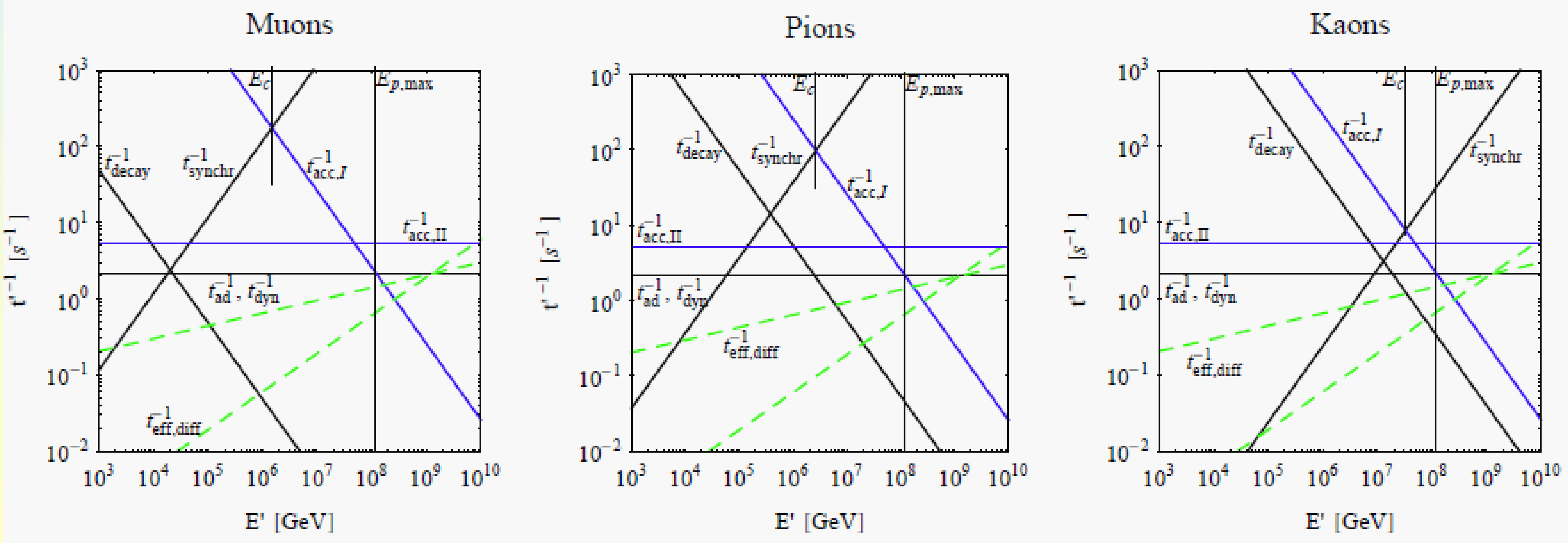
- Individual GRBs are modelled, using measured characteristics
  - Luminosity, fluence, duration, redshift, & observed spectrum
  - From these, internal parameters are inferred, and used in a detailed model of transport and acceleration
- Four representative GRBs are used as examples
  - ‘SB’ = ‘standard burst’



GRB	SB	080916C	090902B	091024
α_γ	1	0.91	0.61	1.01
β_γ	2	2.08	3.80	2.17
$\epsilon_{\gamma,\mathrm{break}}$ [MeV]	1.556	0.167	0.613	0.081
Γ	$10^{2.5}$	1090	1000	195
t_v [s]	0.0045	0.1	0.053	0.032
T_{90} [s]	30	66	22	196
z	2	4.35	1.822	1.09
S_γ [erg cm^{-2}]	1×10^{-5}	1.6×10^{-4}	3.3×10^{-4}	5.1×10^{-5}
L_{iso} [erg s^{-1}]	10^{52}	4.9×10^{53}	3.6×10^{53}	1.7×10^{51}

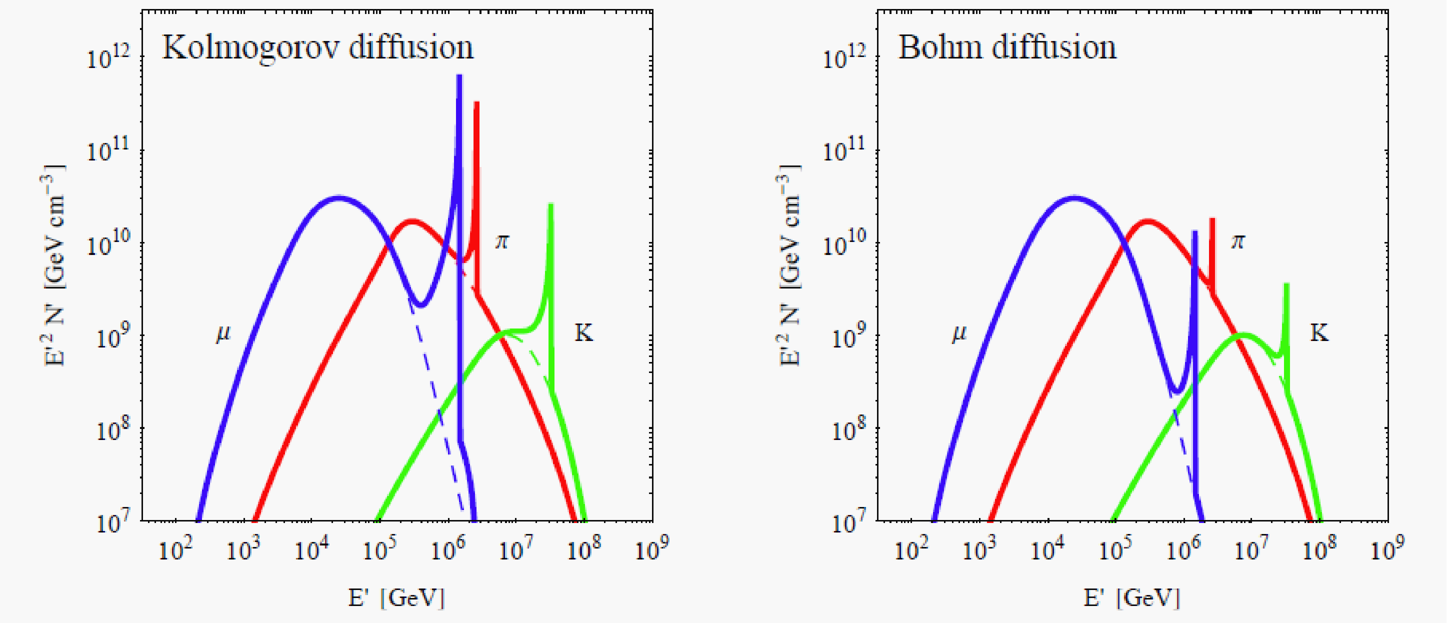
Time scales

- The effect of muon, pion and kaon acceleration depends on the relative time scales for acceleration vs. interaction and/or decay
  - Species are treated via in coupled differential equations
    - Different diffusion, energy loss, etc.



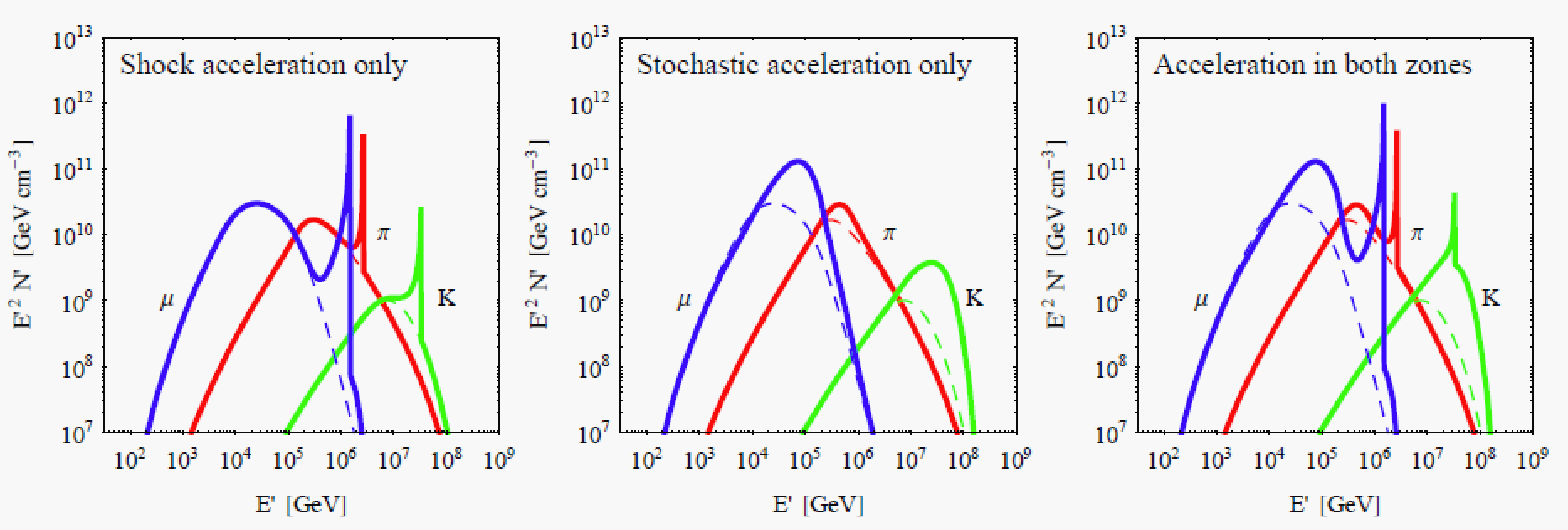
Diffusion models

- Alters P_{escape} – probability of reacceleration
- Kolmogorov and Bohm diffusion have different energy dependencies
- Calculation done for steady state sources
  - Large concentration abundance at critical energies, where energy gain = energy loss



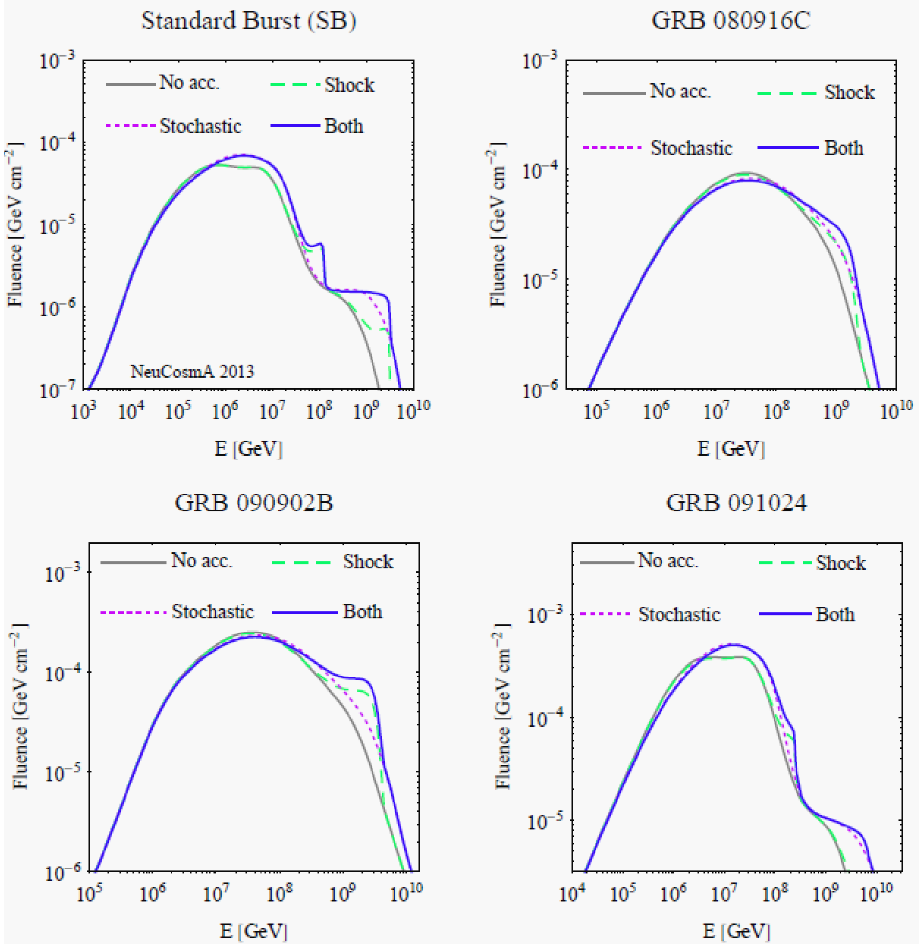
μ,π,K flux

- Steady state densities



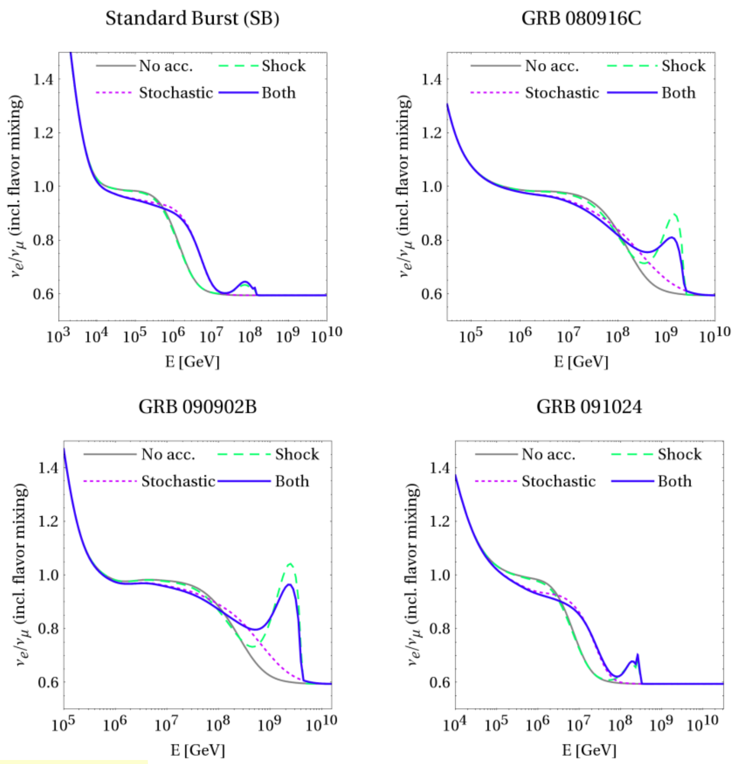
ν flux

- ν flux enhancement varies with model
- Enhancement by factors of 2-10 for E> 10^{16} eV
- Enhancements largest in GRBs with jets with high Lorentz boosts and low magnetic fields (to minimize synch.rad.)



ν flavor ratios

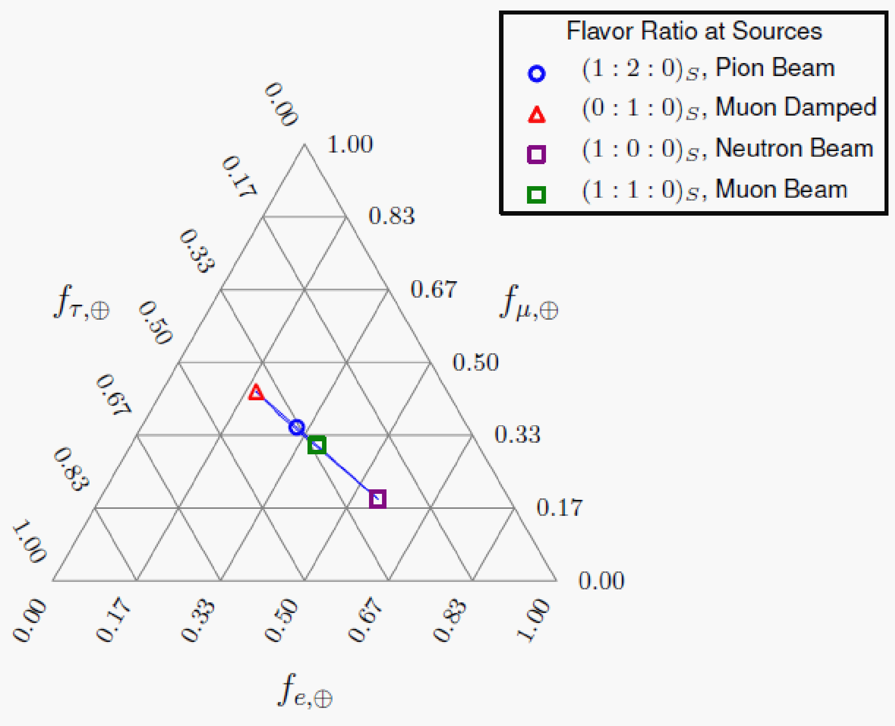
- μ acceleration or energy loss alters the flavor ratio from the usual (for π/K decay) $\nu_e:\nu_\mu:\nu_\tau=1:2:0$
- Can get distinctive flavor ratio variation with energy

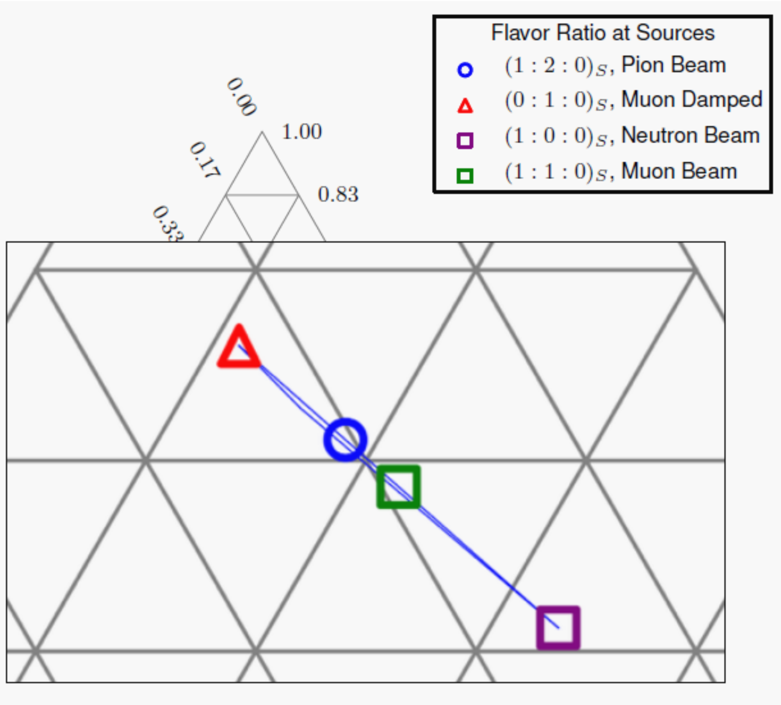


Plot from W. Winter, 2014

Flavor ratios on Earth

- Flavor ‘triangle’ collapses to almost a line
  - Slight triangle width since $\theta_{23} \sim \pi/4$, $\theta_{13} >\sim 0$
- Anything outside this triangle is beyond the standard model
- Small observable differences for very different at-source compositions





Plots from Gary Binder, 2014

Conclusions

- The inclusion of π/μ acceleration greatly increases the predicted ν flux in models with high accelerating gradients.
  - This ‘breaks’ the standard relationship between γ and ν fluxes.
- One can use the IceCube data limit to set 2-dimensional limits on opacity (or density) and accelerating gradient.
  - For compact short-duration sources, these limits are quite constraining.
  - These limits rule out published models invoking plasma wave acceleration.
- A detailed calculation has been done for GRBs; the ν flux is enhanced by a factor of 2-10 at energies above 10^{16} eV.