Aspen 2016

Astrophysical Neutrino Probes

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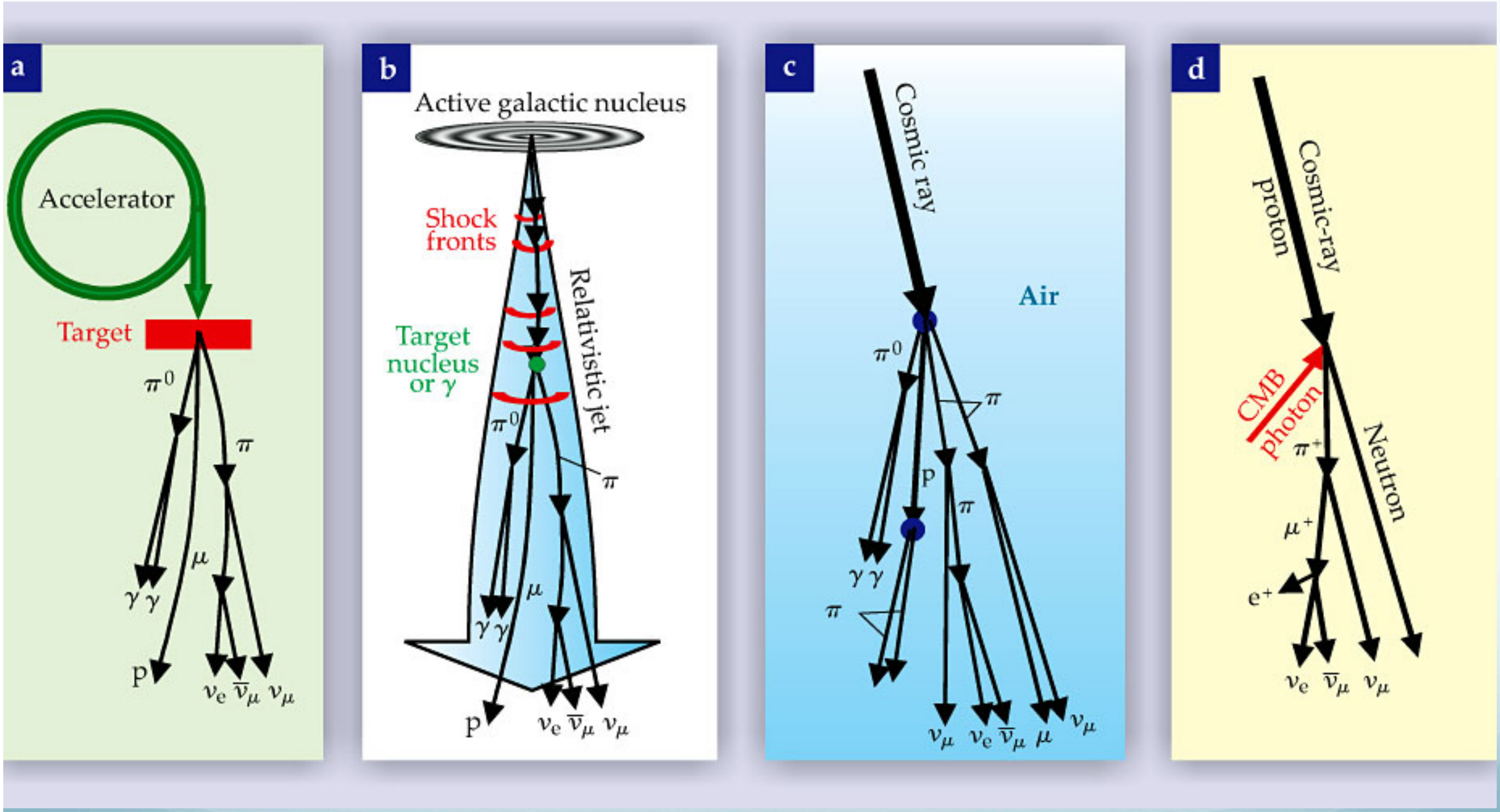
Origin of High Energy Neutrinos: Cosmic Accelerators

- Particles (electrons, protons, etc) are accelerated to high energies via Fermi shock acceleration
- High energy protons collide with ambient protons and photons
- Hadronic production of pions, kaons and D-mesons which decay into neutrinos

Cosmic Accelerators

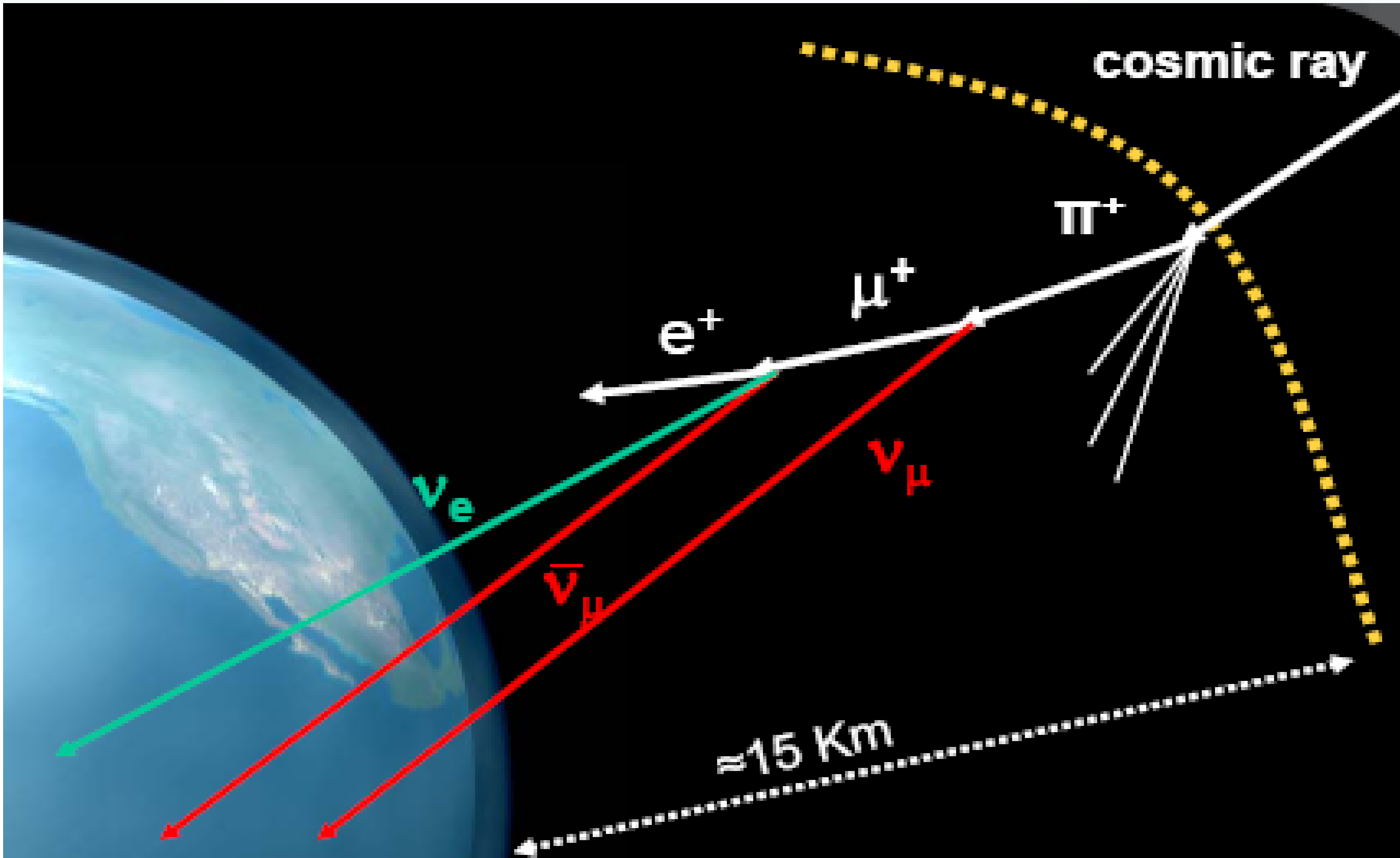


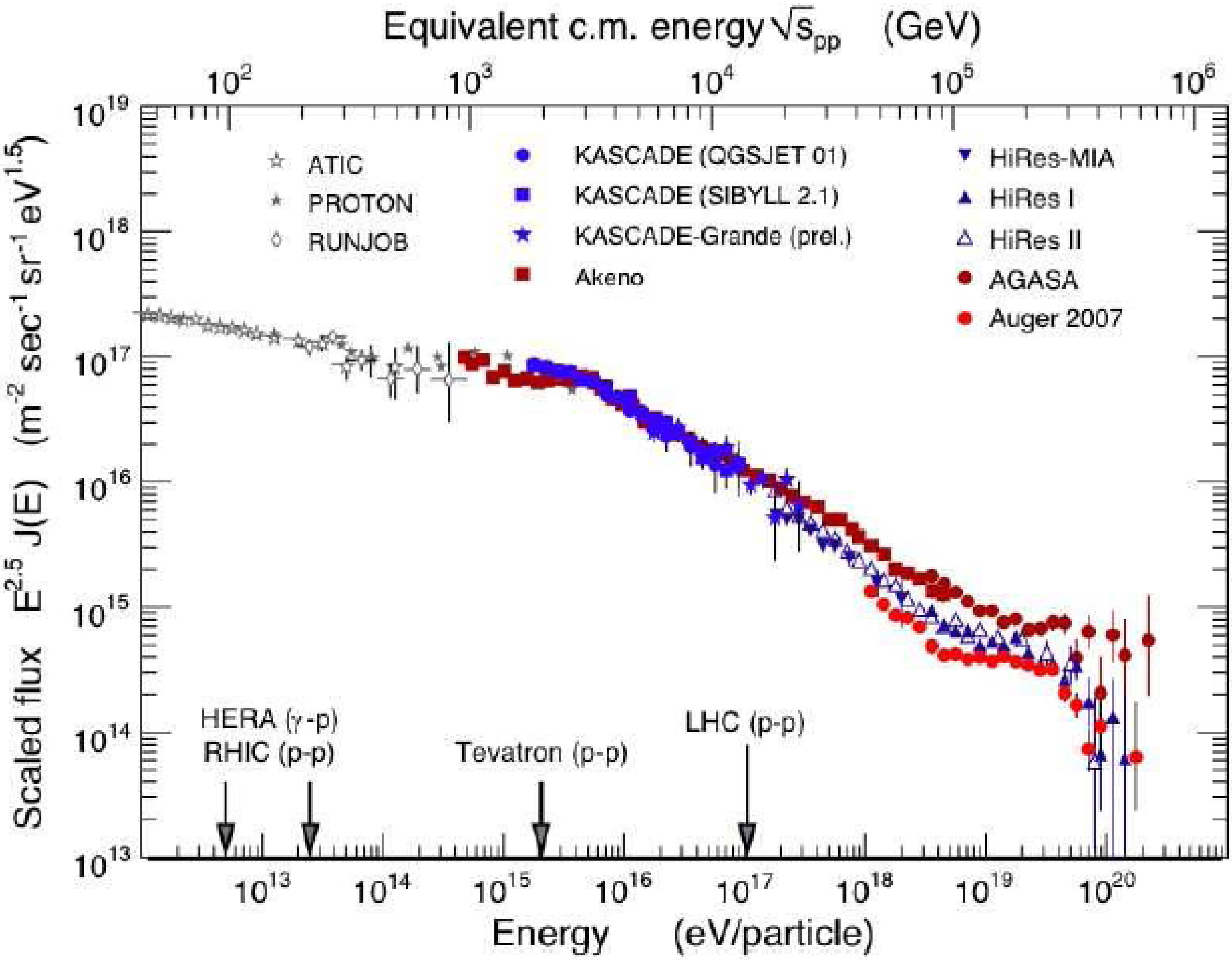
Physics Today 2009

Observed High Energy Particles from the Sky

- Cosmic Rays (energy up to 10^{21} eV)
- Gamma - rays (energy up to 10^{13} eV)
- Atmospheric Neutrinos (energy up to 10^{9} eV)
- Astrophysical Neutrinos (30GeV – 2 PeV)

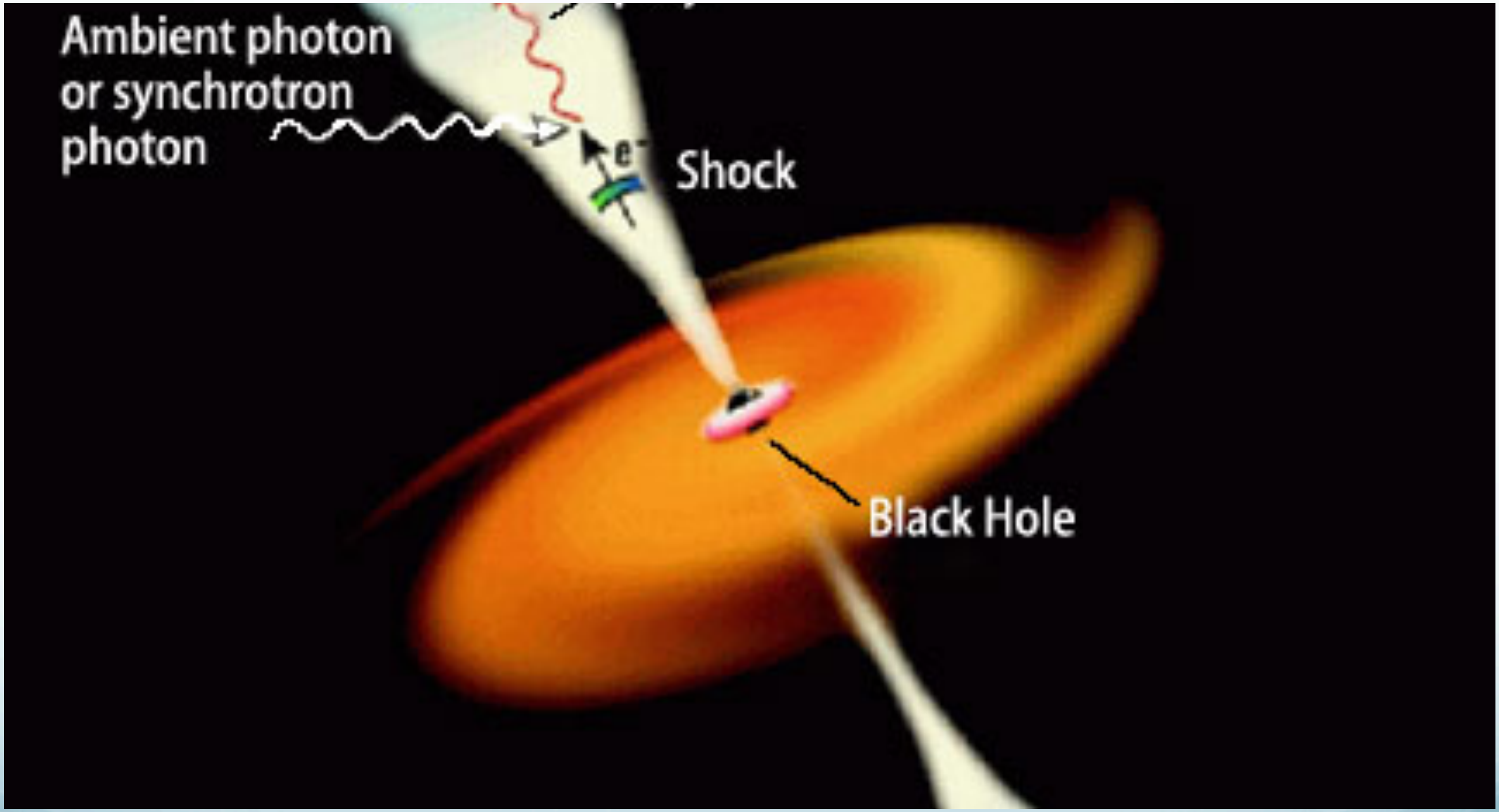
Cosmic Rays





Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

Active Galaxy



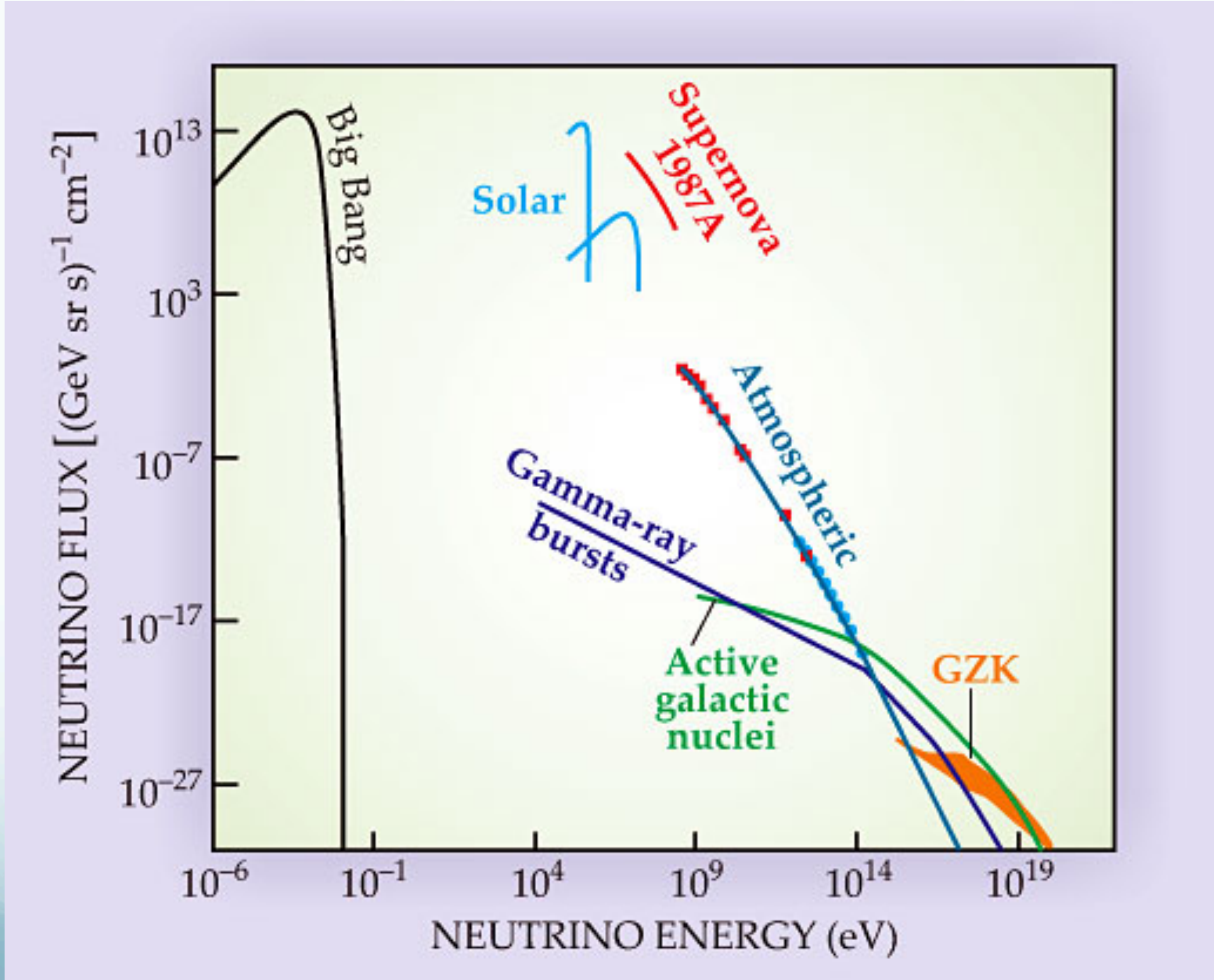
High Energy Gamma Rays

- Active Galactic Nuclei (AGNs) are prodigious particle accelerators and the most powerful radiation sources known in the Universe, with luminosities ranging from $10^{42} - 10^{48}$ erg/s.
- Over 50 AGNs observed by EGRET in MeV energy range, and about 15 AGNs in TeV range.

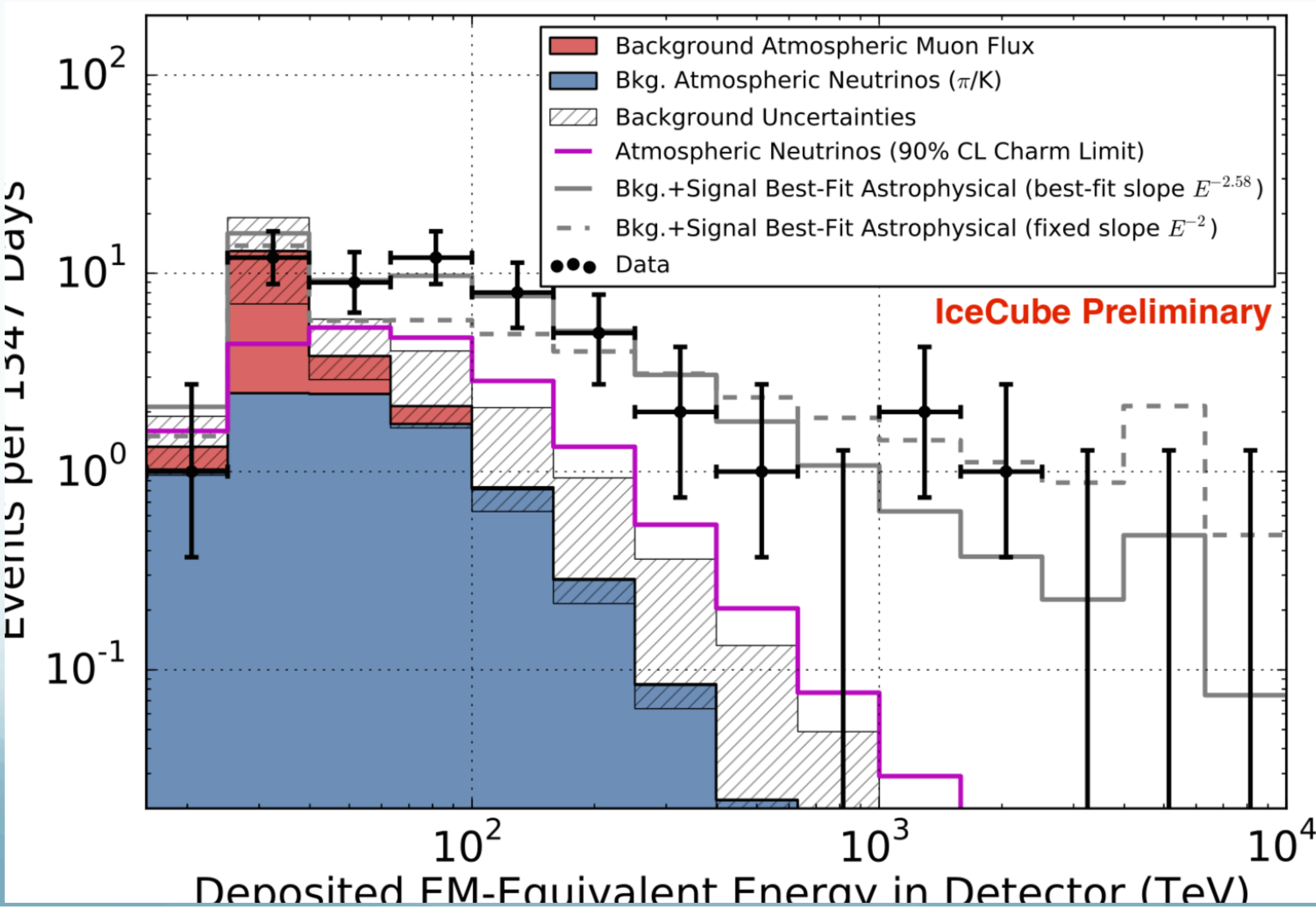
Cosmic Neutrinos

- Solar Neutrinos (MeV energies)
- SN 1987A (MeV energies)
- Atmospheric Neutrinos (GeV to TeV energies)
- Astrophysical (extragalactic) Neutrinos (AGN, GRB, cosmogenic, etc; GeV to EeV energies)
- Neutrinos from Dark Matter Decay or Dark Matter Annihilation

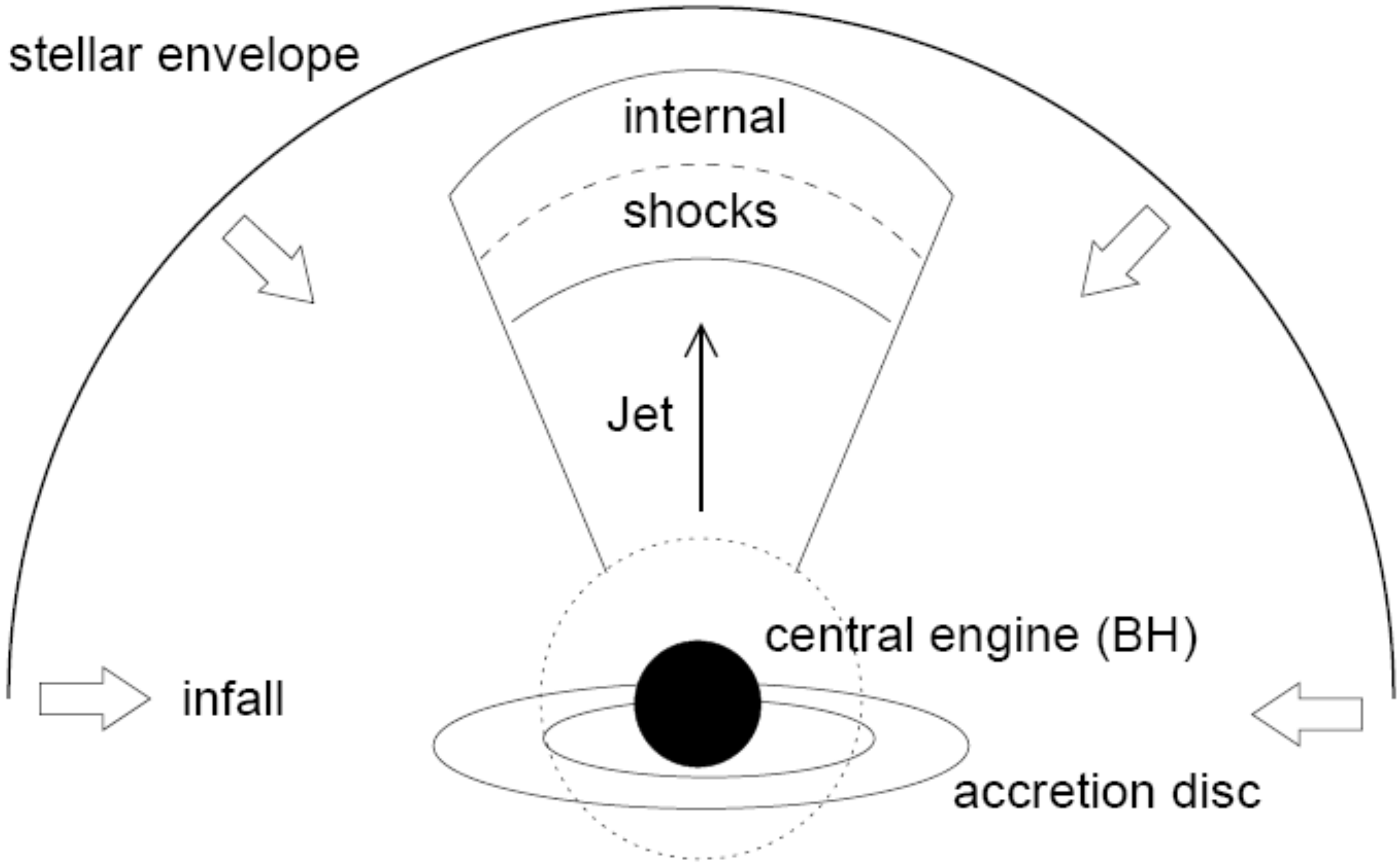
Neutrino fluxes



First Observation of HE Cosmic Neutrinos



Example of Cosmic Accelerator



Schematic picture of a relativistic jet buried inside the envelope of a collapsing star – Slow-jet Supernovae (SJJ)

Razzaque, Meszaros and Waxman (2004)

Mechanism for particle production

- Electrons and protons are accelerated to very high energy in internal shocks via Fermi shock acceleration. Electrons cool down rapidly via synchrotron radiation in the presence of the magnetic field
- In an optically thin envirement, these relativistic electrons emit synchrotron photons which are observed as gamma-rays on Earth

Proton Acceleration and Cooling Processes

- The shock acceleration time for a proton

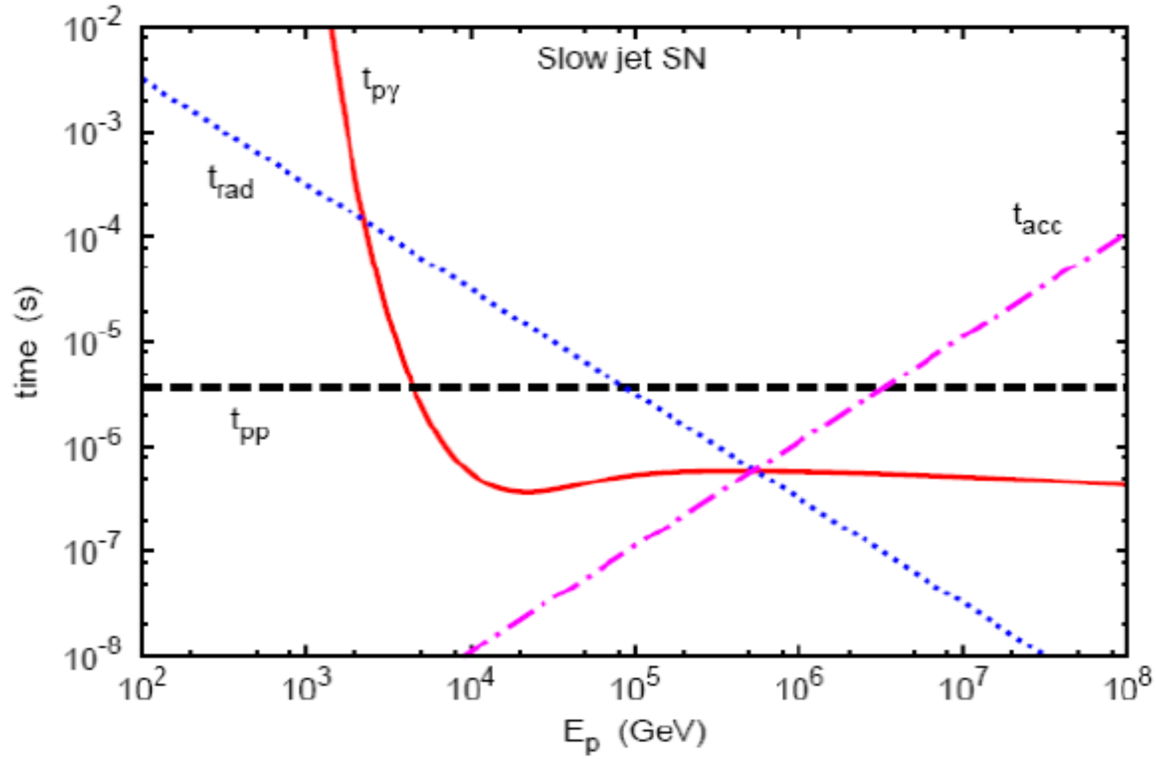
$$t'_{\rm acc} \simeq \frac{E'_p}{qcB'} \qquad t'_{\rm acc} \approx 10^{-12}\left(\frac{E'_p}{\rm GeV}\right)\ {\rm s} \quad \text{for} \quad B = 10^9 G$$

- The maximum proton energy is limited by requiring this time not to exceed the dynamic time scale for any proton cooling process time scale (hadronic cooling, electromagnetic cooling, synchrotron and inverse Compton, Bethe-Heitler).

- Proton Hadronic Cooling Channels: Photomeson and proton-proton interactions serve as a cooling mechanism for the shock accelerated protons.

Proton Hadronic Cooling Channels

- Photomeson $(p\gamma)$ and proton-proton (pp) interactions produce high energy neutrinos. They also serve as a cooling mechanism for the shock accelerated protons.



Enberg, Reno and Sarcevic, Phys. Rev. D79, 053006 (2009)

Neutrino Production and Flux on Earth

- Shock accelerated protons in the jet can produce non-thermal neutrinos by photomeson $(p\gamma)$ interactions with thermal synchrotron photons and/or by proton-proton (pp) interactions with cold protons present in the shock region.

- In the case of $p\gamma$ interactions neutrinos are produced from charged pion (π^+) decay as

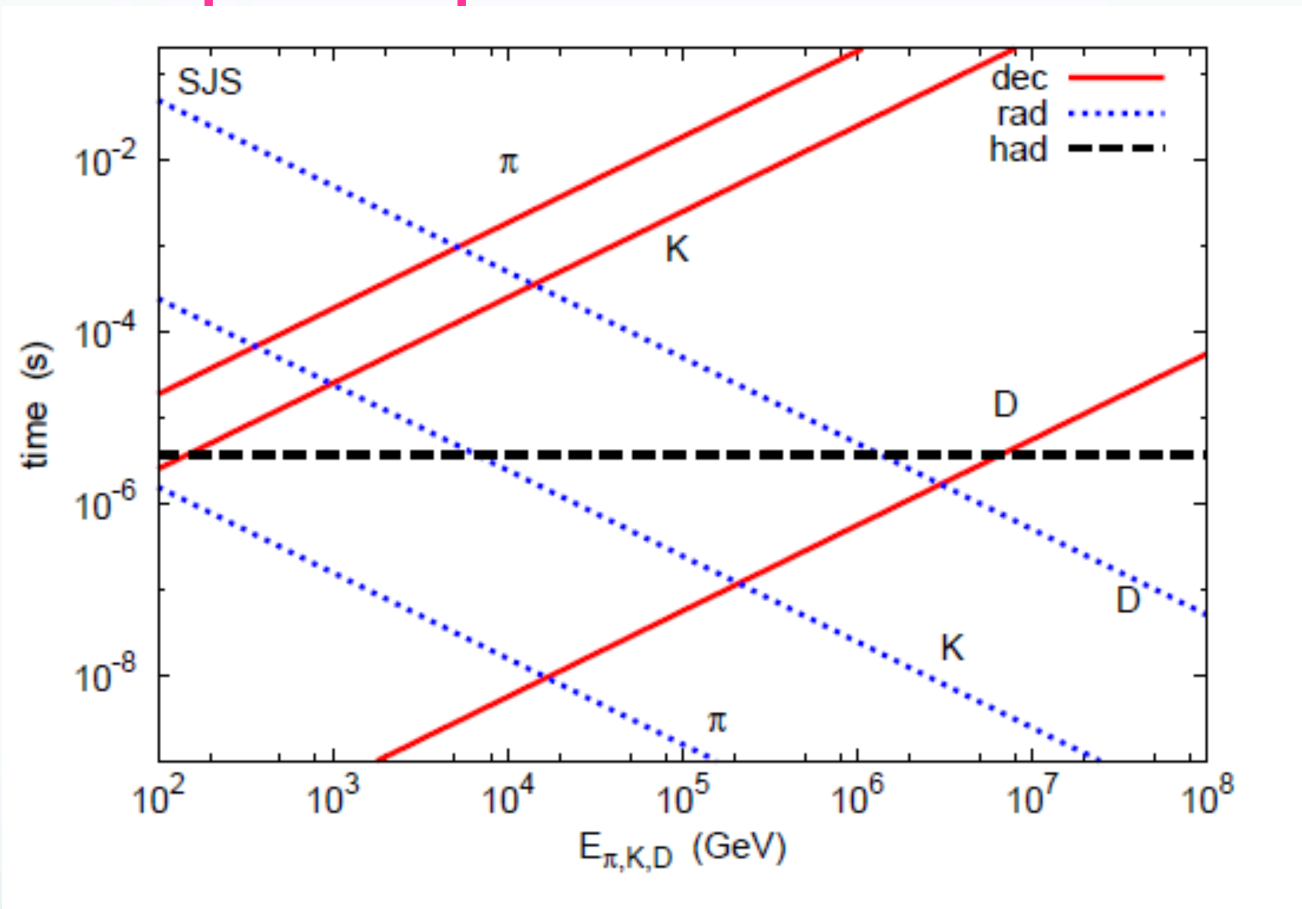
$$p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\overline{\nu}_\mu\nu_\mu$$

- The pp interactions also produce charged pions , kaons , D mesons . The energy of the shock accelerated protons in the jet is expected to be distributed as $\sim 1/E^2$ following the standard shock acceleration models. Charged mesons, produced by pp and $p\gamma$ interactions, are expected to follow the proton spectrum with $\sim$ 20% of the proton energy for each pion or kaon .

Meson Cooling Channels

- High-energy pions, kaons, D-mesons and muons produced by $p\gamma$ and pp interactions do not all decay to neutrinos as electromagnetic (synchrotron radiation and IC scattering) and hadronic (πp and Kp interactions) cooling mechanisms reduce their energy.
- Muons are severely suppressed by eloctromagnetic energy losses and do not contribute much to high-energy neutrino production.
- Suppression factors for neutrinos from pion and kaon decay are important. .
- The hadronic energy losses for mesons is similar to the proton energy losses.

Meson cooling times for the slow-jet core collapse supernovae



Enberg,Reno and Sarcevic, Phys. Rev. D79 (2009)

Neutrino Fluxes at Earth

Enberg, Reno and Sarcevic, Phys. Rev. D79 (2009)

- Astrophysical neutrino flux is obtained by solving the evolution equations for nucleon, meson and neutrino fluxes which are given by

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S^{had}(Np \to NY) - \frac{\phi_N}{\lambda_{rad}} + S^{EM}(Np \to NY)$$

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\lambda^{dec}} - \frac{\phi_M}{\lambda^{had}} - \frac{\phi_M}{\lambda^{rad}} S^{had}(Np \to MY) + S^{had}(Mp \to MY)$$

$$\frac{d\phi_l}{dX} = \sum_M S(M \to \nu)$$

where $\lambda^{had}{}_{N,M}$ is the interaction length $(\lambda_N = 1/(n_p \sigma_{pp}))$, $\lambda^{dec} = \gamma c \tau_M$ is the decay length in the comoving frame and $\lambda^{rad} = ct_{rad}$ is the radiative interaction length .

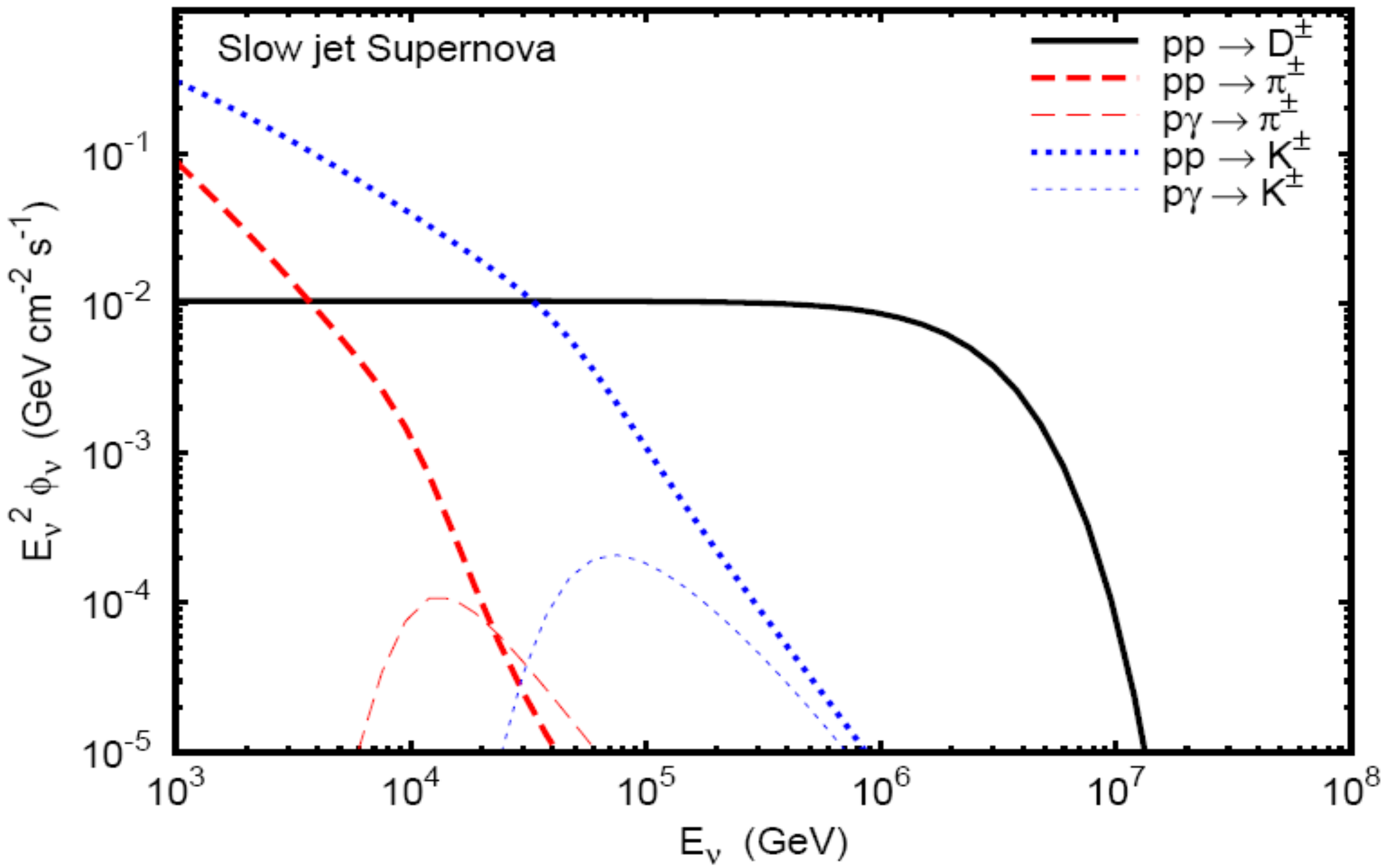
Proton flux has energy cut-off (because of the cooling) and is given by

$$f_N(E') = \left[1 + \left(\frac{E'}{E'_{\max}}\right)\right] e^{-E'/E'_{\max}}$$

In general Z-moments are energy-dependent and they also have energy cut-off coming from the proton flux cutt-off (but at lower energies)

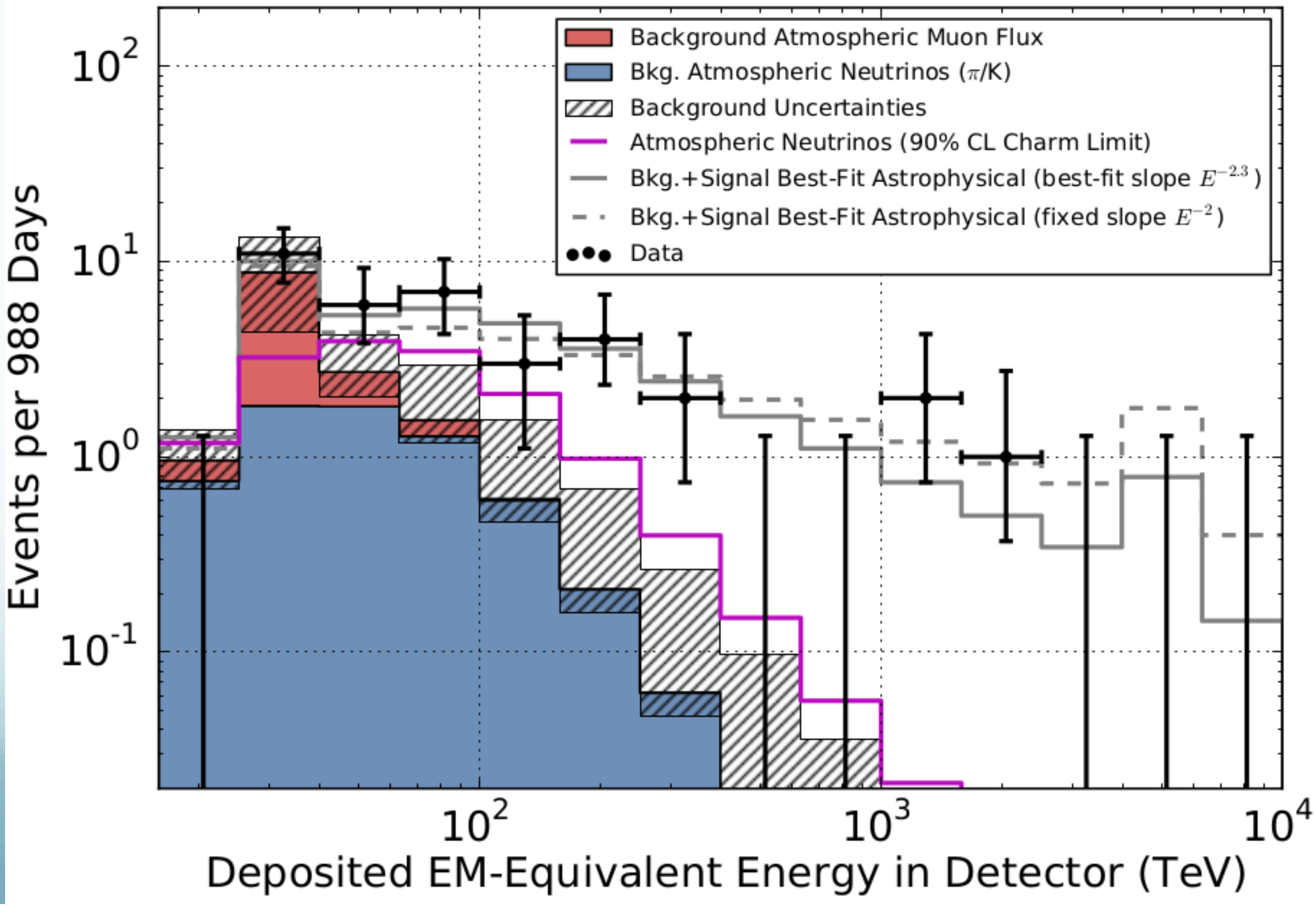
$$Z_{NM} = \int_0^1 \frac{\lambda_N(E)}{\lambda_N(E/x_E)} \frac{\phi_N(E/x_E)}{\phi_N(E)} \frac{\mathrm{d}n_{N\to M}}{\mathrm{d}x_E} \frac{\mathrm{d}x_E}{x_E}$$

Neutrino Flux From Slow-Jet Core Collapse Supernova (obtained with energy-independent Z-moments)



Enberg, Reno and Sarcevic, Phys. Rev. D79, 053006 (2009)

Could IceCube Excess in PeV Neutrino Flux be Due to Charm from Slow-jet Supernovae?



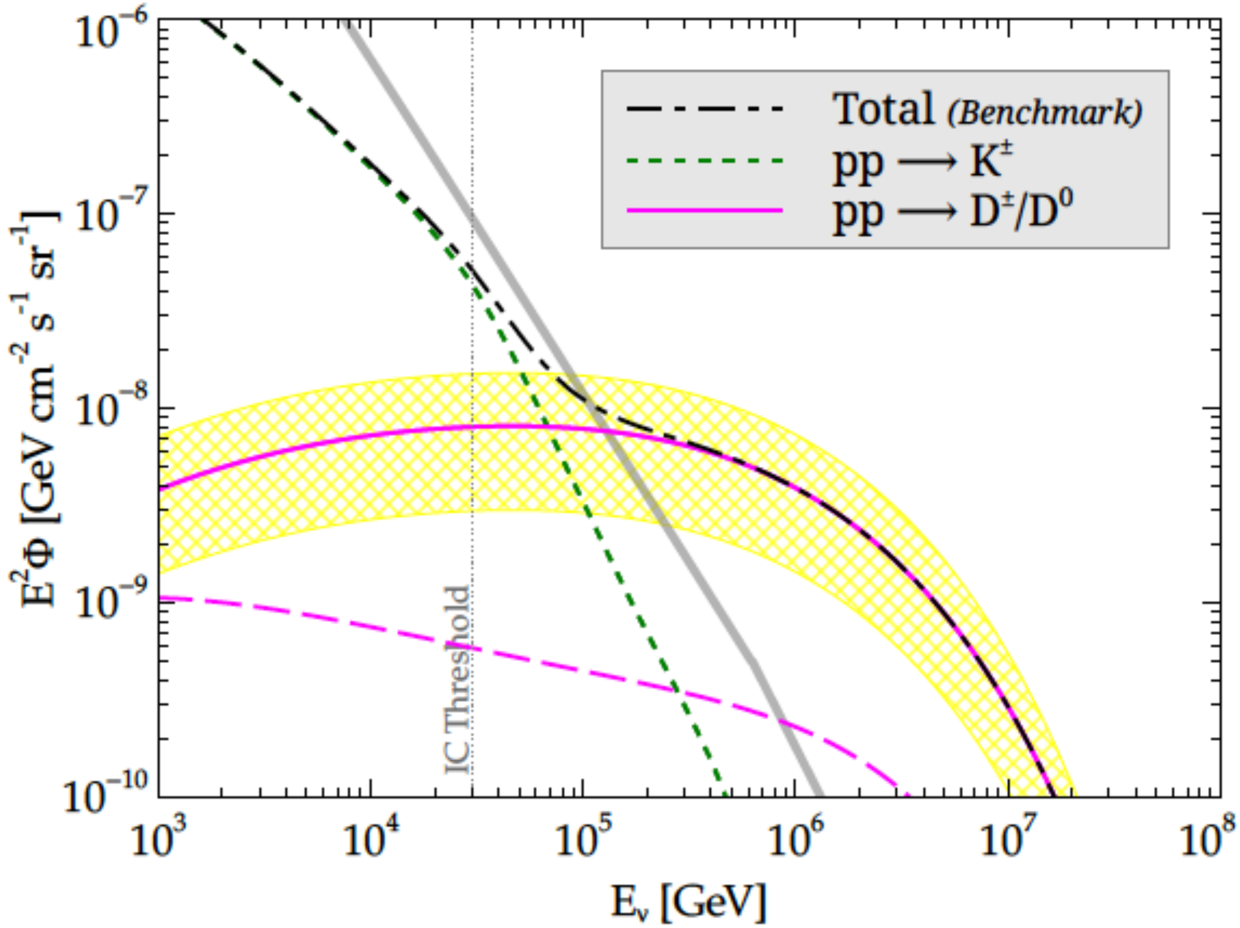


Figure 2: The (unoscillated) diffuse $\nu_\mu + \bar{\nu}_\mu (= \nu_e + \bar{\nu}_e)$ flux obtained with the jet luminosity $L_j = 10^{50}$ erg s^{-1}, $\Gamma_j = 5$, $E'_{\max} = 10.2$ PeV and $\xi_{sn} = 1$. The upper solid line and lower long-dashed line show the range of QCD uncertainties from the scale choices in evaluating the charm production cross section. The yellow hatched region shows the variation of the QCD upper limit flux (using $[\mu_R, \mu_F] = [1.71 m_c, 4.65 m_c]$) from uncertainties in the SN formation rate. The short-dashed lines show the kaon contributions to the diffuse neutrino flux from SJS. For comparison, the gray curve shows the vertical flux of conventional atmospheric $\nu_\mu + \bar{\nu}_\mu$ (see, *e.g.*, [46]).

A. Bhattacharya, R. Enberg, M.H. Reno and I. Sarcevic, JCAP 06 (2015) 034

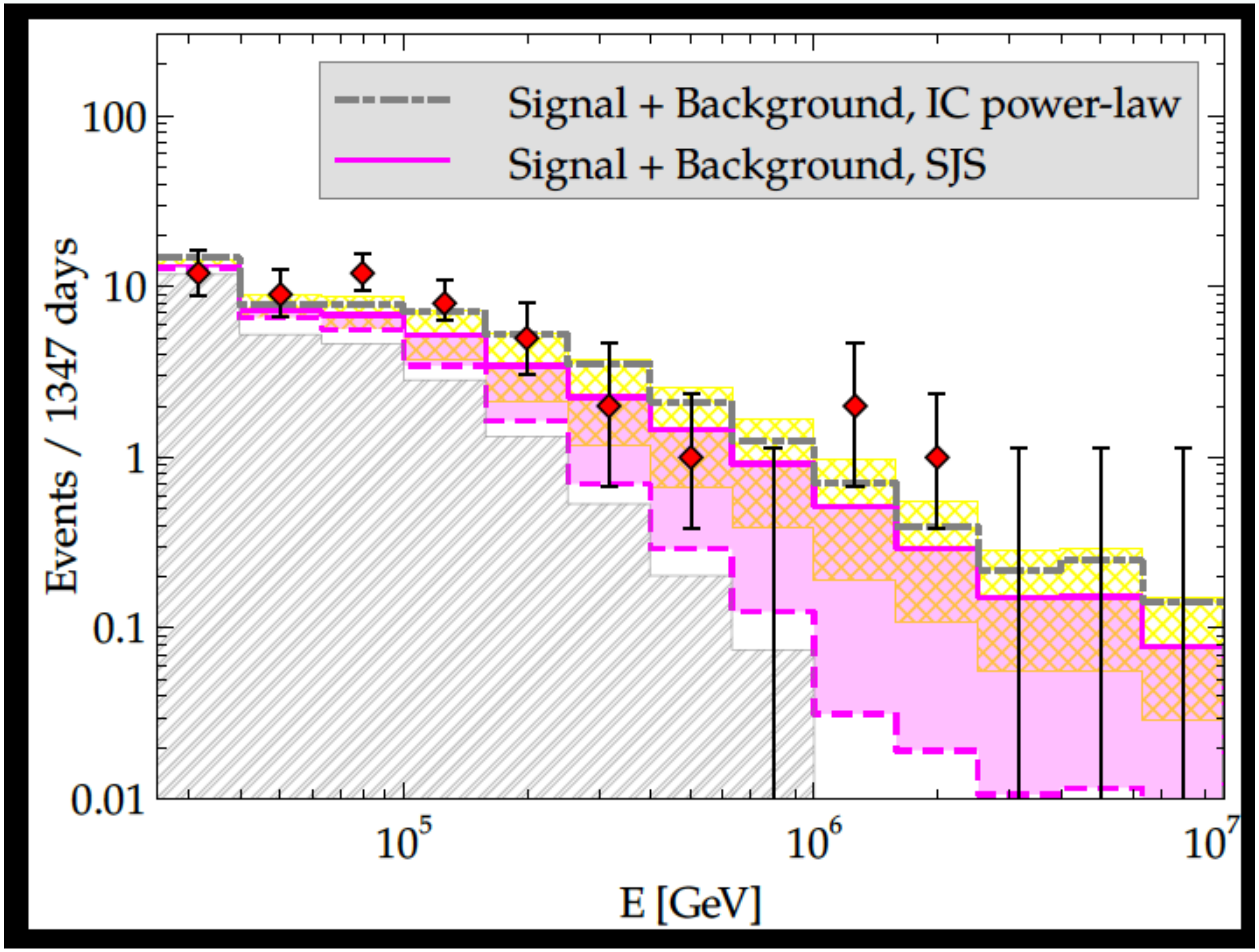


Figure 3: Predicted 988-day total (shower + track) event rates at IC from slow-jet sources for $L_j = 10^{50}$ erg s^{-1}, $\Gamma_j = 5$, $E'_{max} = 10.2$ PeV and $\xi_{sn} = 1$. The solid shaded histogram reflects the QCD scale uncertainties in the charm pair production cross section calculation, with the solid (dashed) histogram showing the upper (lower) range of the SJS diffuse plus atmospheric background number of events. The variation in event-rates relative to the solid histogram from uncertainties in the SN formation rate is shown as a yellow hatched area. Observed event-rates from [3] along with 1σ statistical error bars are shown (red diamonds), as is the total atmospheric neutrino + muon background estimated in the same reference (grey shaded region).

A. Bhattacharya, R. Enberg, M.H. Reno and I. Sarcevic, JCAP 06 (2015) 034

Additional Neutrino Flux from Heavy Dark Matter Decay

A. Bhattacharya, M.H. Reno and I. Sarcevic, JHEP 1406 (2014) 110

A. Bhattacharya, Arman Esmaili, Sergio Palmarez-Ruiz and I. Sarcevic, in preparation

Galactic:

$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s,$$

Extragalactic:

$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} [(1+z)E_\nu]\, \mathrm{d}z$$

Decay modes:

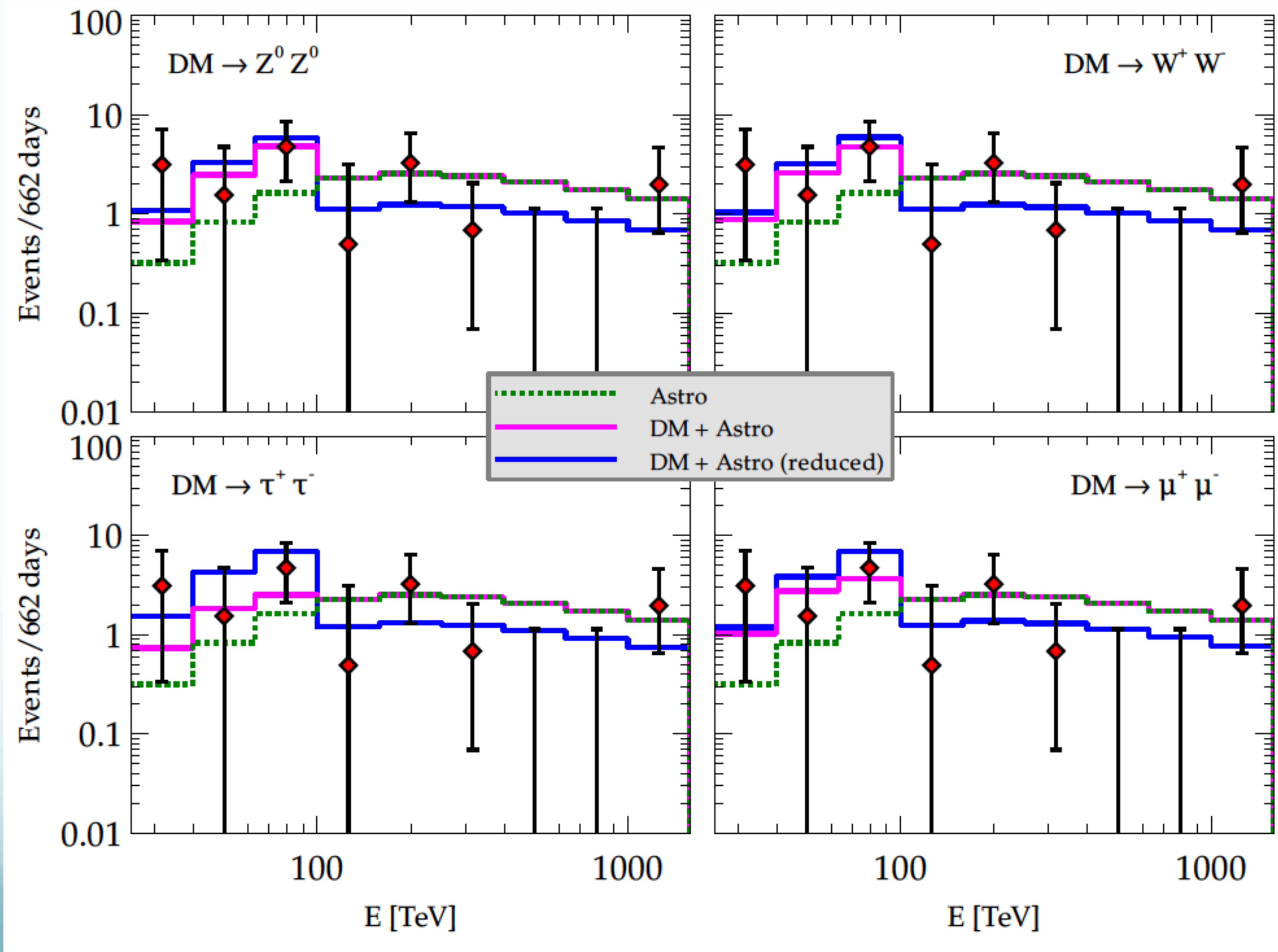
$DM \to \tau^+\tau^-$

$DM \to \mu^+\mu^-$

$DM \to Z^0 Z^0$

$DM \to W^+W^-$

A. Bhattacharya, M.H. Reno and I. Sarcevic, JHEP 1406 (2014) 110

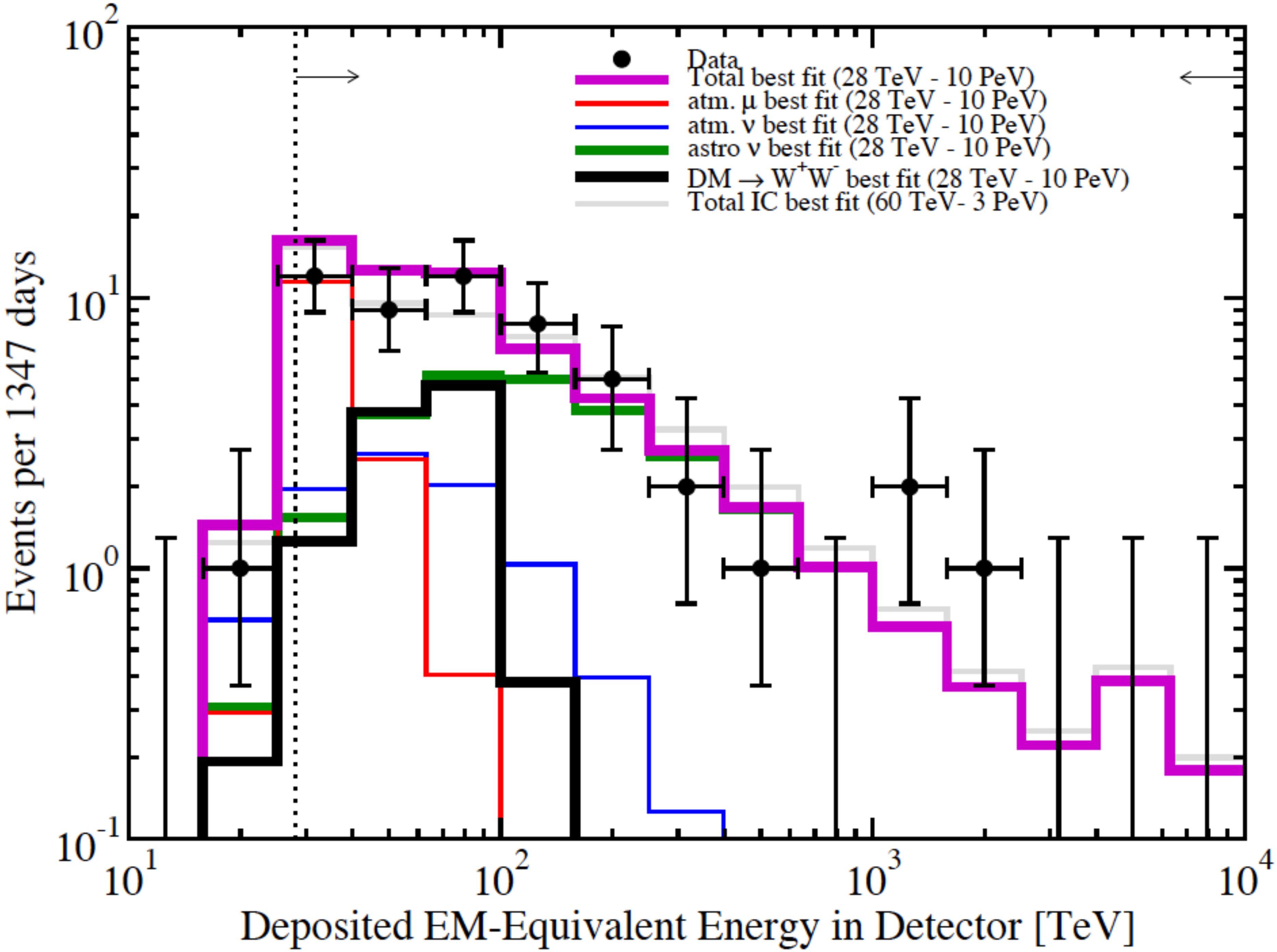


Decay mode	$m_{\rm DM}^{\rm b.f.}$ (TeV)	$\tau_{\rm DM}^{\rm b.f.}/10^{27}$s	χ^2	p-value
DM $\rightarrow Z^0 Z^0$	196.69	1.77	8.861	0.268
DM $\rightarrow W^+ W^-$	195.83	1.50	8.864	0.268
DM $\rightarrow \tau^+ \tau^-$	148.49	7.21	9.554	0.390
DM $\rightarrow \mu^+ \mu^-$	166.01	5.20	8.976	0.282

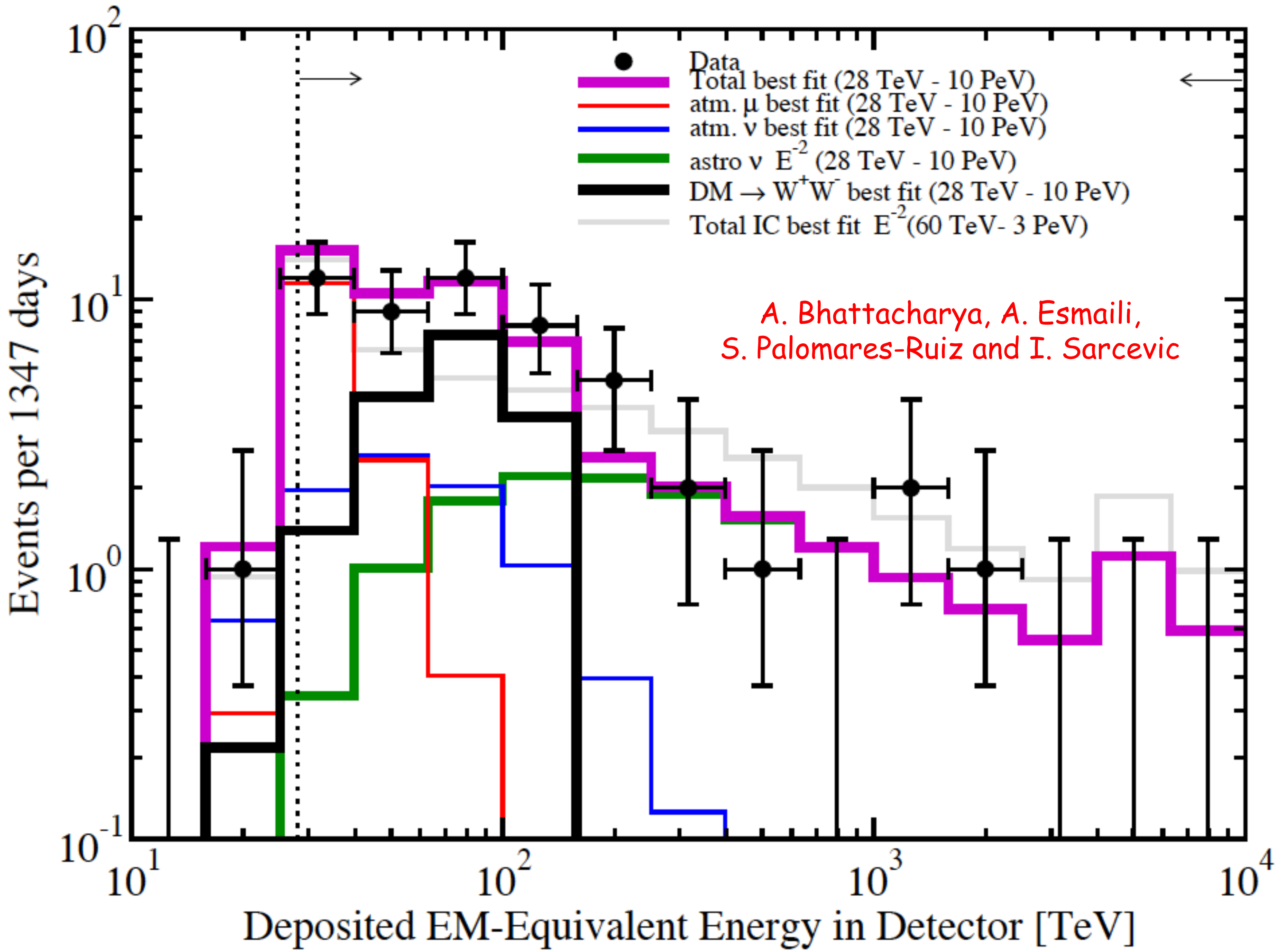
Table 1: The best fit parameters for each of the DM decay modes and a comparison with the IC best-fit power law spectrum. The rightmost column represents the p-values for the F-test to determine if, in comparison to the IC best-fit, the improvement to the fit obtained in the DM + Astro model is significant. A lower p-value indicates a more significant improvement. The astrophysical flux normalization is fixed at the IC best-fit

Decay mode	$m_{\rm DM}^{\rm b.f.}$ (TeV)	$\tau_{\rm DM}^{\rm b.f.}/10^{27}$s	$\frac{E^2\Phi^{b.f.}_{\rm Astro}}{(10^{-9}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}})}$	χ^2	p-value
DM $\rightarrow Z^0 Z^0$	191.82	1.27	5.86	4.209	0.061
DM $\rightarrow W^+ W^-$	199.32	1.18	5.82	4.209	0.061
DM $\rightarrow \tau^+ \tau^-$	176.61	3.11	6.29	4.188	0.060
DM $\rightarrow \mu^+ \mu^-$	197.97	5.01	6.14	4.445	0.072

Table 2: The best fit parameters for each of the DM decay modes and a comparison with the IC best-fit power law spectrum. In addition to the DM mass and lifetime, the normalization for the astrophysical flux is varied as a free parameter. As in table 1, the p-values indicate the significance of improvement to the fit with the DM + Astro model over the IC best-fit. The low values of the p-value indicate that the fit to the data in the DM + Astro model with a reduced astrophysical flux improves upon the IC best-fit significantly.



Data
Total best fit (28 TeV - 10 PeV)
atm. μ best fit (28 TeV - 10 PeV)
atm. ν best fit (28 TeV - 10 PeV)
astro ν best fit (28 TeV - 10 PeV)
DM → W+W- best fit (28 TeV - 10 PeV)
Total IC best fit (60 TeV- 3 PeV)
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]



Data
Total best fit (28 TeV - 10 PeV)
atm. μ best fit (28 TeV - 10 PeV)
atm. ν best fit (28 TeV - 10 PeV)
astro ν E^-2 (28 TeV - 10 PeV)
DM → W+W- best fit (28 TeV - 10 PeV)
Total IC best fit E^-2(60 TeV- 3 PeV)
A. Bhattacharya, A. Esmaili,
S. Palomares-Ruiz and I. Sarcevic
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]
10^-1
10^0
10^1
10^2
10^1
10^2
10^3
10^4

Best fit parameters for energy 28Gev-10PeV:

DM mass = 240 TeV, lifetime =3 x 10^27 s

power-index = 2.55

(varying all the parameters)

10 DM events plus 26 astro events

Best fit IC:

power index = 2.58

Best fit parameters for energy between 28TeV-10PeV when power-index is fixed to 2

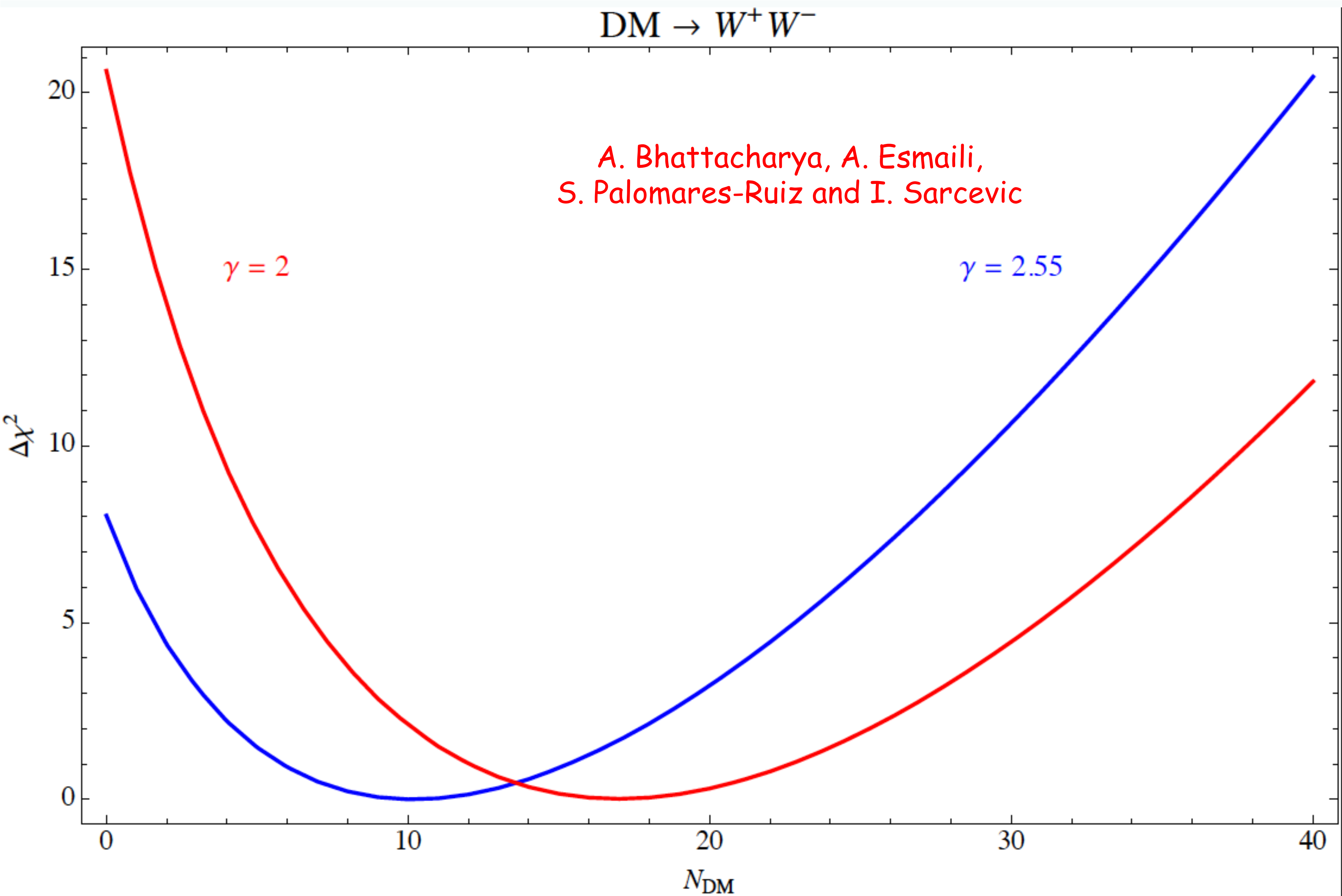
DM mass = 319 TeV, lifetime =2.6 x 10^27 s (varying all the parameters except power-index)

17 DM events plus 16 astro events

Summary

- Astrophysical neutrinos are valuable probes of new physics (solar neutrinos, atmospheric neutrinos have provided us with the very first indication that neutrinos have mass).
- Ultrahigh energy cosmic neutrinos (from AGNs, GRB, SJS, etc.) probe physics at energies beyond the LHC
- Dark matter which decays into neutrinos gives unique signatures in observed neutrino spectrum (bump in IceCube data?)
- Understanding of astrophysical neutrino flux produced in pp collisions at energies close or above the LHC is very important – charm contribution dominant at high energies.

Back-up Slides



DM → W+W−
A. Bhattacharya, A. Esmaili,
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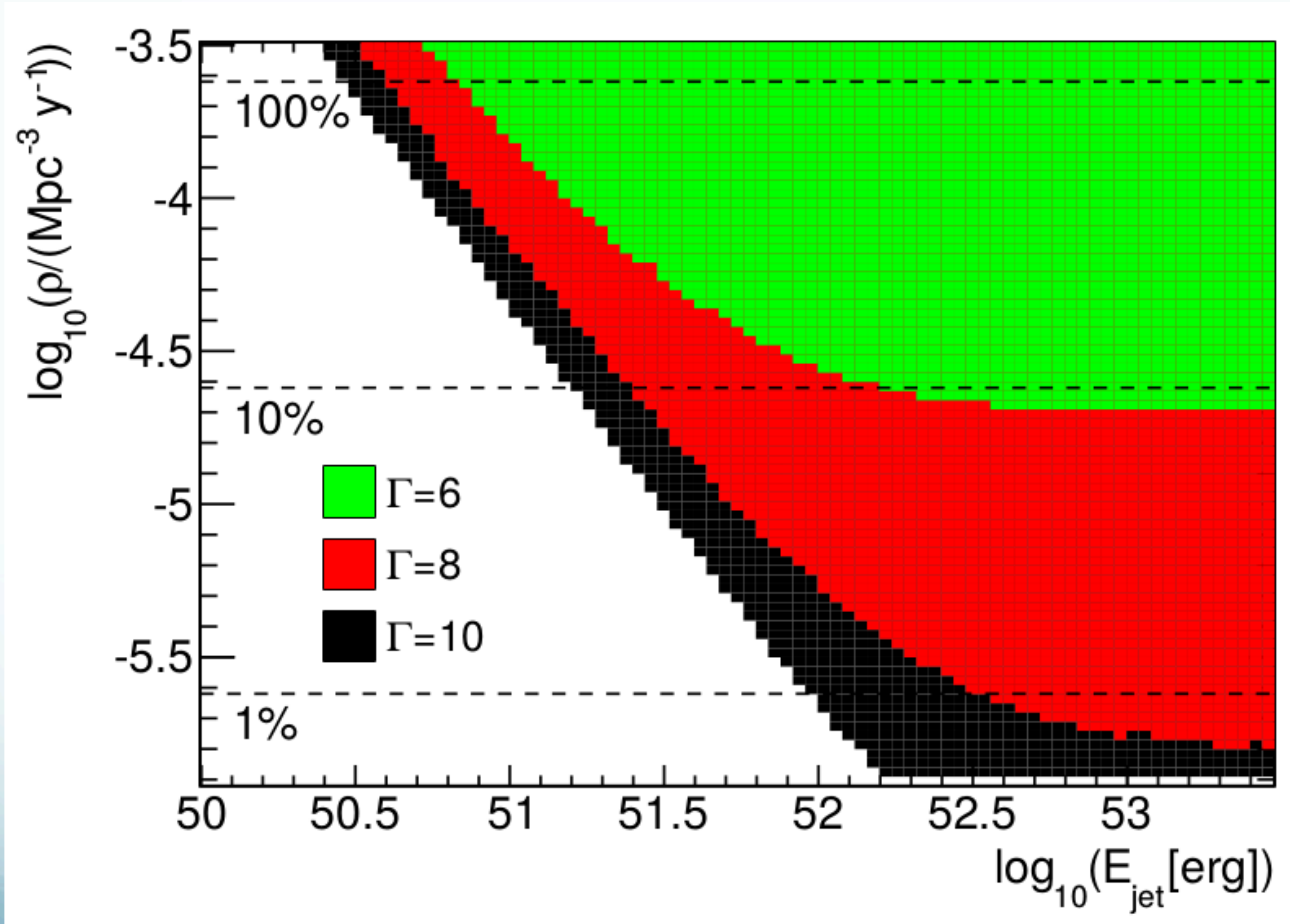
γ = 2
γ = 2.55
Δχ2
NDM
0
5
10
15
20
0
10
20
30
40

- We consider difuse flux from SJS with astrophysical parameters allowed by IceCube



IceCube Exclusion Region

Diffuse Neutrino Flux from Slow-Jet Supernovae Sources

$$\Phi(E_\nu) = \frac{\xi_{\rm sn}}{2\Gamma_j^2} \int_0^\infty \frac{\dot{n}_{\rm sn}(z) d_L^2 c t_j}{(1+z)^2} \phi_\nu \left[E_\nu(1+z)\right] \left|\frac{{\rm d}t}{{\rm d}z}\right| {\rm d}z$$

where

$$\frac{{\rm d}z}{{\rm d}t} = H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_{\rm M}(1+z)^3}.$$

S(k→ j) is the regeneration function for k=p, $\pi^{\mp}$, $K^{\mp}$, $D^{\mp}$, D^0,

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

$dn(k\to j;E_k,E_j)/dE_j$ is the meson ($\pi^{\mp}$, $K^{\mp}$, $D^{\mp}$, D^0) production or decay distribution :

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kp \to jY, E_k, E_j)}{dE_j}$$

$$\frac{dn(k \to j; E_k, E_j)}{dE_k} = \frac{1}{\Gamma_k} \frac{d\Gamma(kj \to jY, E_j)}{dE_j}$$

We define the Z-moments :

$$Z_{kj} = \int_E^{\infty} dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_k^{had}(E)}{\lambda_k^{had}(E')} \frac{dn(kp \to jY; E', E)}{dE}.$$

- For proton flux the propagation over distance X in the co-moving jet frame is given by

$$\left(\frac{d\phi_N}{dX}\right)_{cool} = -\frac{\phi_N}{\lambda_N^{had}} + Z_{NN}^{had} \frac{\phi_N}{\lambda_N^{had}} - \frac{\phi_N}{\lambda_N^{EM}} + Z_{NN}^{EM} \frac{\phi_N}{\lambda_N^{EM}}$$

- Meson flux is determined by solving the evolution equation:

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\lambda^{dec}} - \frac{\phi_M}{\lambda^{had}} - \frac{\phi_M}{\lambda^{rad}} + Z_{MM} \frac{\phi_M}{\lambda^{had}} + Z_{NM} \frac{\phi_N}{\lambda_N}$$