Ultra-high energy neutrinos from charm production:
Atmospheric and astrophysical origins

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Will consider three related ideas

- Cosmic rays of enormous energies are generated in ***astrophysical sources***
  → Acceleration driven by some "central engine"
  → This also generates neutrinos

- Cosmic rays collide with Earth's ***atmosphere***
  → This gives showers and neutrinos

- Cosmic rays collide with the ***Sun***
  → Neutrinos

Based on a series of papers:

Atmospheric neutrinos:

- RE, Mary Hall Reno, Ina Sarcevic, arXiv:0806.0418 [hep-ph] **(ERS)**
- Atri Bhattacharya, RE, Mary Hall Reno, Ina Sarcevic, Anna Stasto, arXiv:1502.01076 [hep-ph] **(BERSS)**
- Atri Bhattacharya, RE, Yu Seon Jeong, C.S. Kim, Mary Hall Reno, Ina Sarcevic, Anna Stasto, arXiv:1607.00193 [hep-ph] **(BEJKRSS)**

Astrophysical sources:

- RE, Mary Hall Reno, Ina Sarcevic, arXiv:0808.2807 [astro-ph]
- Atri Bhattacharya, RE, Mary Hall Reno, Ina Sarcevic, arXiv:1407.2985 [astro-ph.HE]

Neutrinos from the cosmic rays interacting in the Sun:

- Joakim Edsjö, Jessica Elevant, Rikard Enberg, Calle Niblaeus, in preparation

Many previous works

Atmospheric neutrinos, e.g.

- M. Thunman, G. Ingelman, P. Gondolo, hep-ph/9505417 **(TIG)**
- L. Pasquali, M.H. Reno, I. Sarcevic, hep-ph/9806428 **(PRS)**
- A.D. Martin, M.G. Ryskin, A. Stasto, hep-ph/0302140 **(MRS)**

Astrophysical sources:

- *Huge field, thousands of papers…*

Neutrinos from the cosmic rays interacting in the Sun, e.g.

- M. Thunman, G. Ingelman, hep-ph/9604288

Main message

QCD is crucial for some astrophysical processes:

- Atmospheric neutrinos
- Neutrino-nucleon cross-section @ high energy
- Interactions in astrophysical sources

For example:

- What happens at **small Bjorken-x**? (Need very small x)
- Forward region (Hard to measure at colliders)
- Fragmentation of quarks → hadrons
- Nuclear effects in pA hard interactions

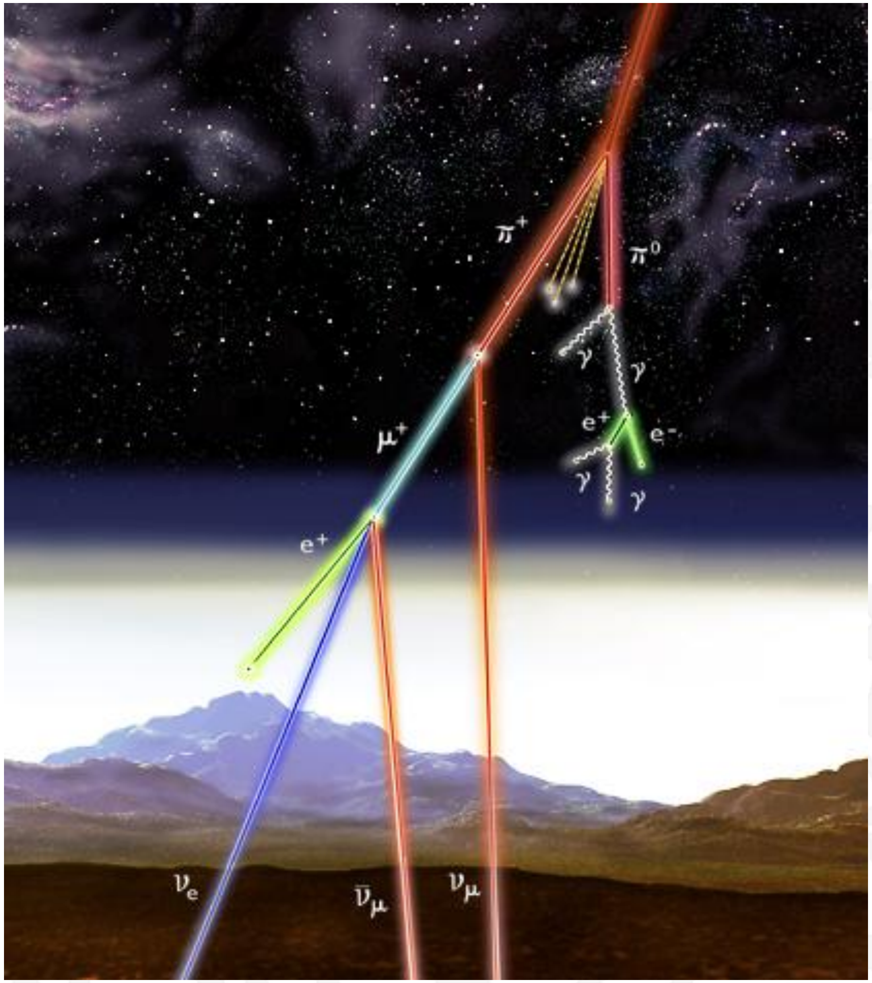
Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei

- Very large CMS energy → Hadron production: pions, kaons, D-mesons …

- Interaction & decay
  ⇒ cascade of particles

- Semileptonic decays
  ⇒ neutrino flux



INFN-Notizie No.1 June 1999

Atmospheric neutrinos

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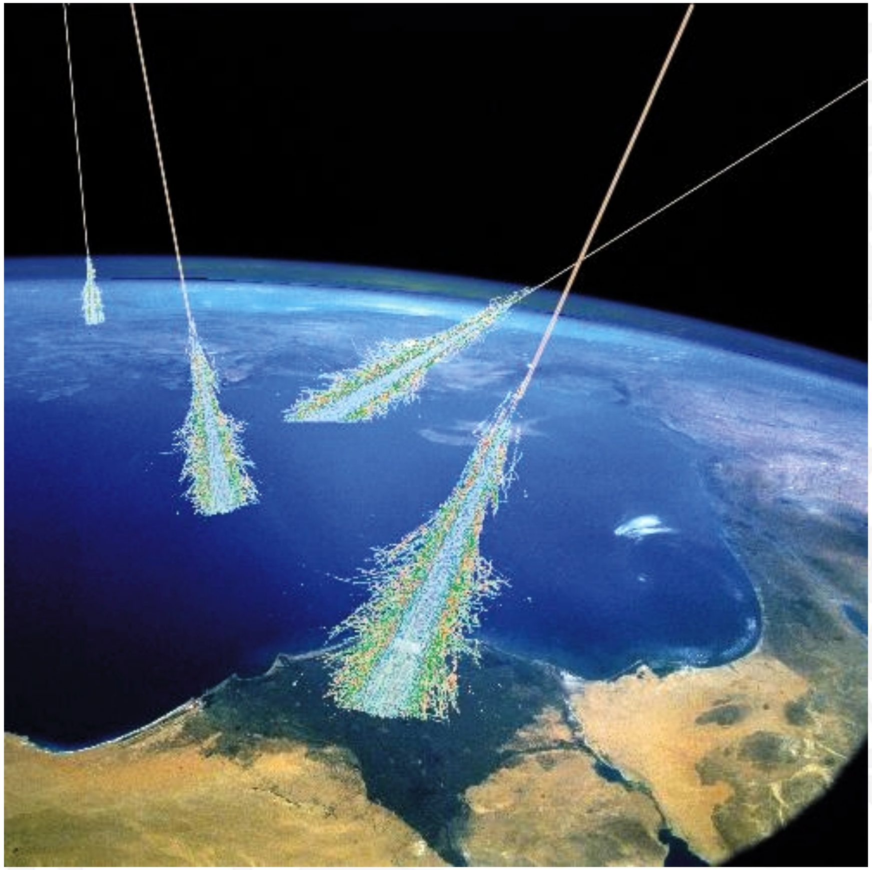


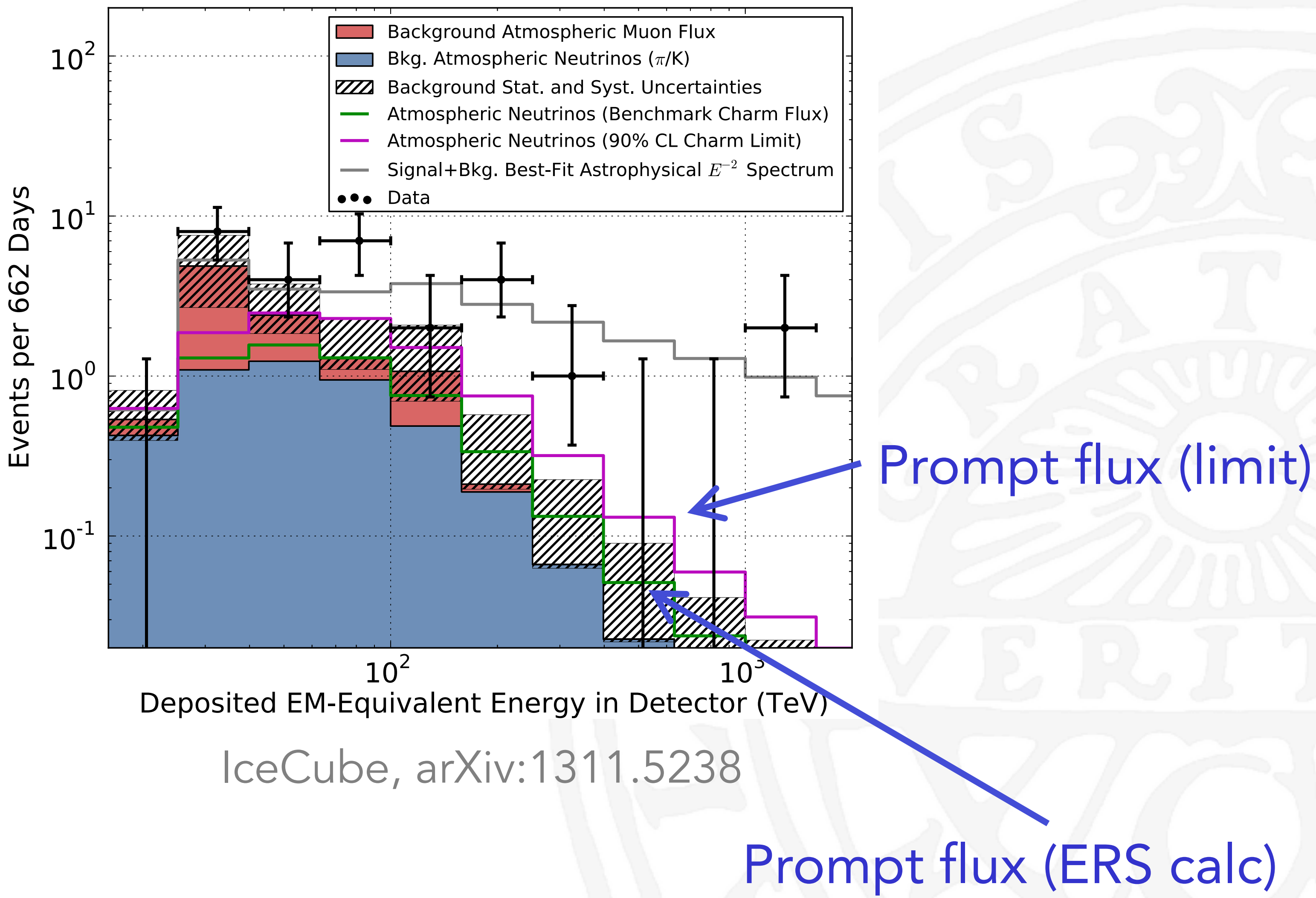
Credit: Astropic of the day, 060814

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

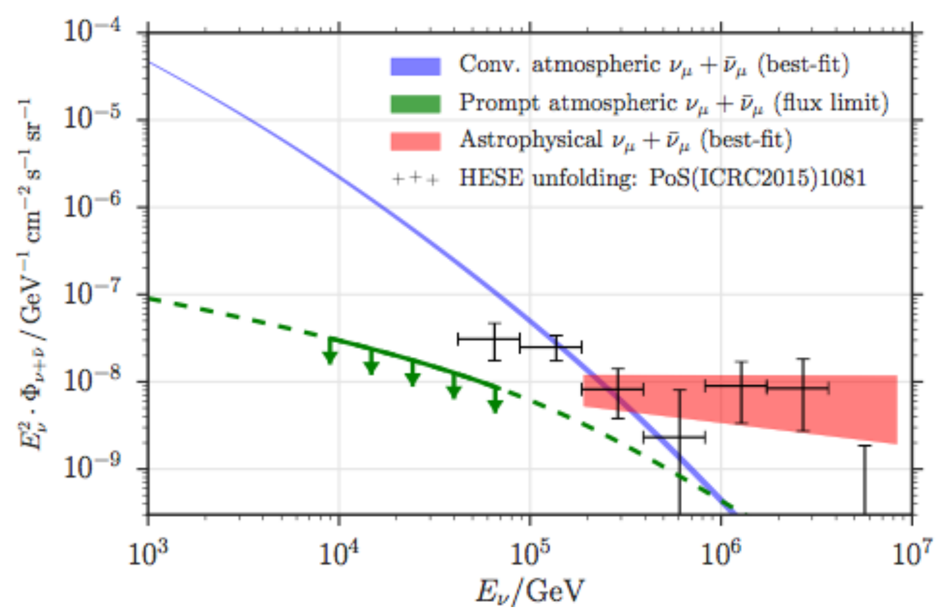
IceCube events

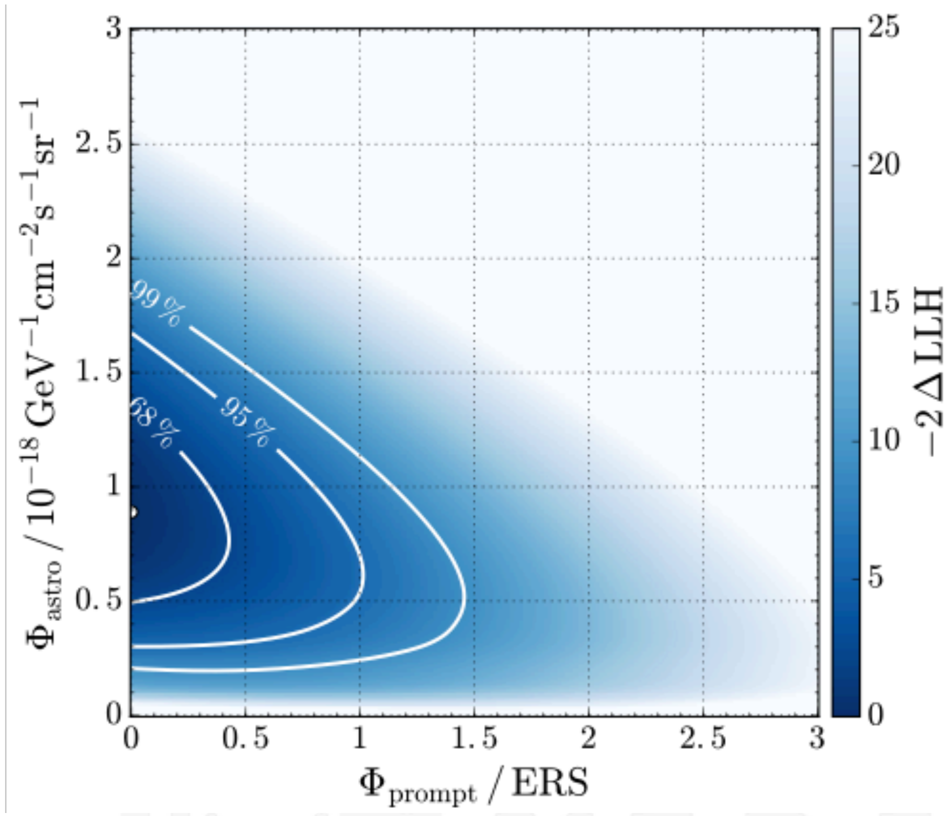
The significance is sensitive to the prompt flux prediction



IceCube, arXiv:1311.5238

IceCube are using ERS





The shape of the ERS flux is used with overall normalization a free parameter

M.G. Aartsen et al., arXiv:1607.08006

Conventional neutrino flux

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

- π^+ always decay 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 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:
  $\Rightarrow$ decay before losing much energy
  $\Rightarrow$ neutrino energy spectrum is harder

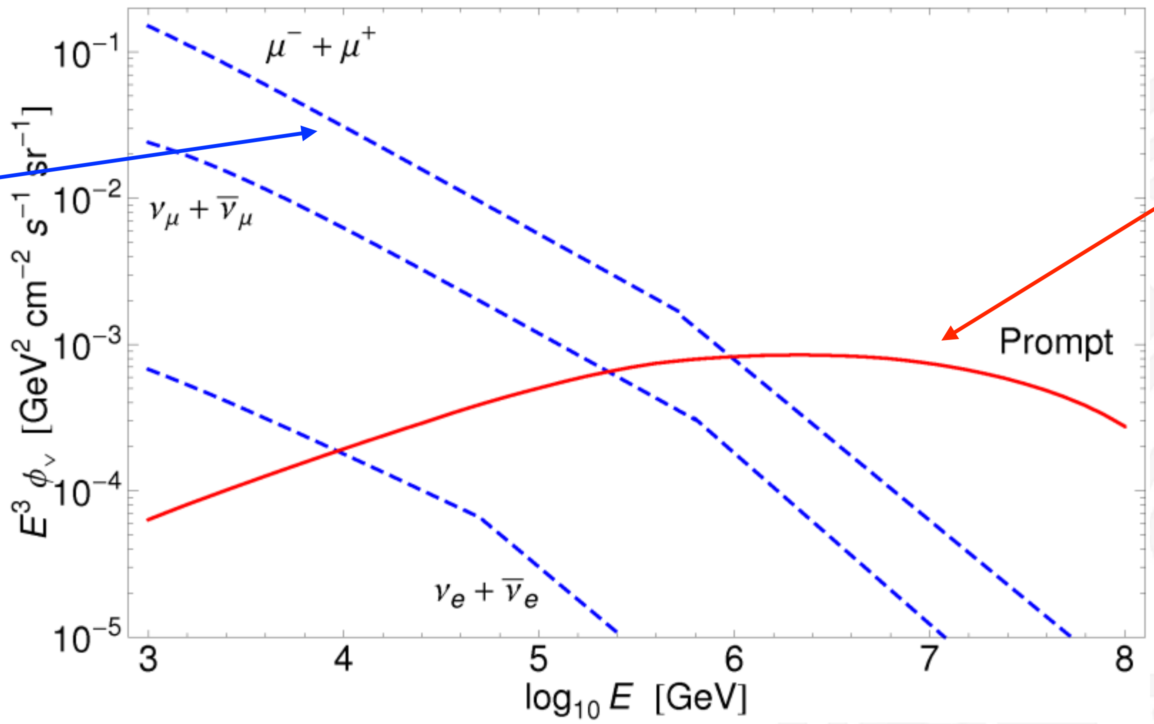
- However, production cross-section is much smaller

- 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 of atmospheric neutrinos

Pions & kaons: long-lived ⇒ lose energy before decay



Charmed mesons: short-lived ⇒ don't lose energy ⇒ harder spectrum

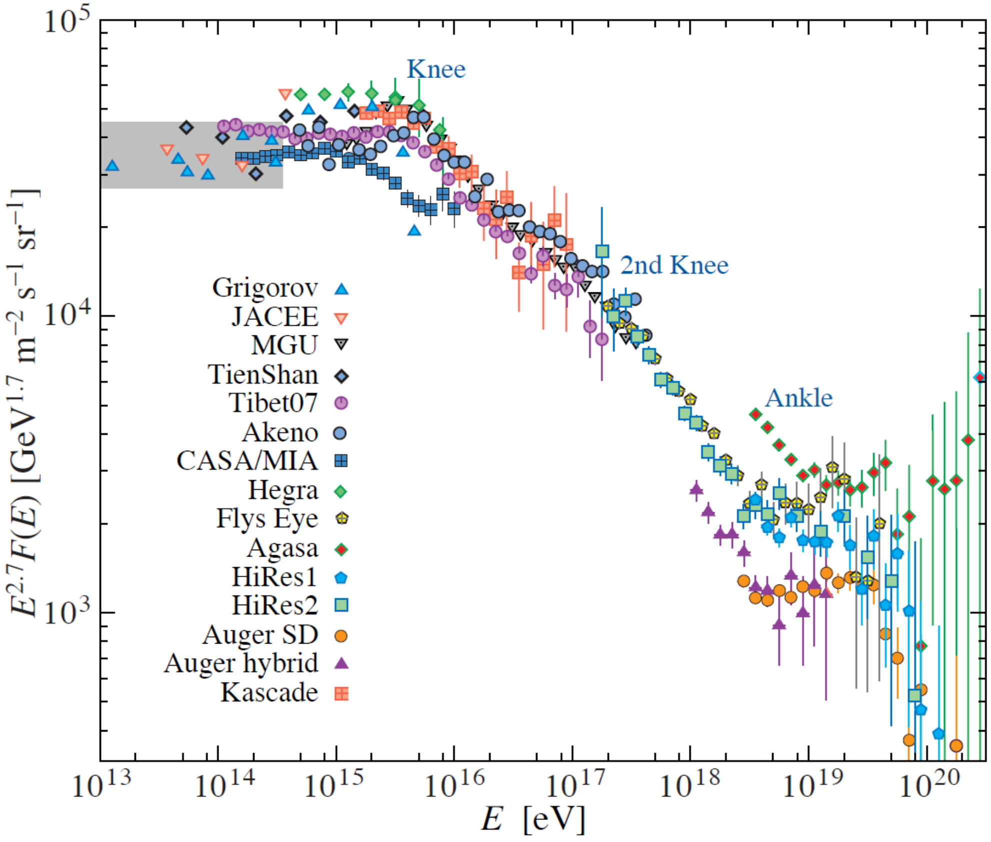
Prompt flux: Enberg, Reno, Sarcevic, arXiv:0806.0418 (ERS)
Conventional: Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. **52,** 153 (2002)

The calculation has many ingredients

- *Incident cosmic ray flux*
- Atmospheric density
- ***Cross section for heavy quarks in pp/pA collisions at extremely high energy (pQCD)***
- Rescattering of nucleons, hadrons (hadronic xsecs) (scattering lengths)
- Decay spectra of charmed mesons & baryons (decay lengths)
- Cascade equations and their solution (Semi-analytic: spectrum-weighted Z-moments)

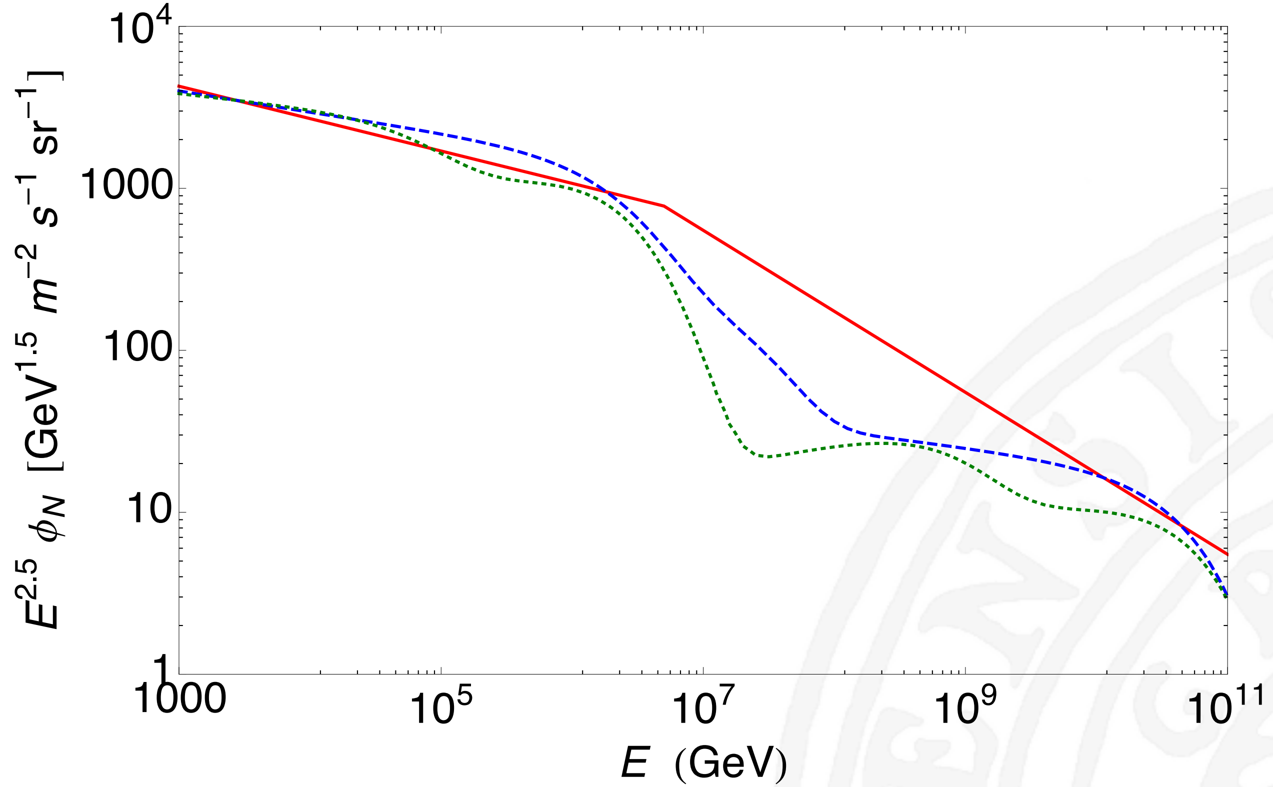
Cosmic rays (CR)

Plot from Particle Data Group



- Knees and ankles → seems natural to associate different sources with different energy ranges of the CR flux
- Highest energies: Extragalactic origin?
  → GRBs, AGNs, or more exotic
- Lower energies: Galactic origin?
  →SNRs etc

Incident cosmic ray flux: nucleons



Solid red = Broken power law (old standard)

Dashed blue = Gaisser all proton (H3p)

Dotted green = Gaisser, Stanev, Tilav (GST4)

Calculating the neutrino flux

- To find the neutrino flux we must solve a set of cascade equations given the incoming cosmic ray 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"
  $\rho\, d_M$ 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 $h_0 = 6.4\ \mathrm{km}$

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

Total vertical depth $X \simeq 1300\ \mathrm{g/cm^3}$

horizontal $X \simeq 36{,}000\ \mathrm{g/cm^3}$

The atmosphere consists of "air nuclei" with A=14.5

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

Particle production

Particle physics inputs: energy distributions

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

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

along with interaction lengths, or cooling lengths

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

→ Need the charm production cross section $d\sigma/dx_F$

Problem with QCD in this process

Charm cross section in LO QCD:

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

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

CMS energy is large: $s = 2E_p m_p$ so $x_1 \sim x_F \quad x_2 \ll 1$

x_F=1:	$E=10^5 \rightarrow x \sim 4\cdot 10^{-5}$	**x_F=0:**	$E=10^5 \rightarrow x \sim 6\cdot 10^{-3}$
	$E=10^6 \rightarrow x \sim 4\cdot 10^{-6}$		$E=10^6 \rightarrow x \sim 2\cdot 10^{-3}$
	$E=10^7 \rightarrow x \sim 4\cdot 10^{-7}$		$E=10^7 \rightarrow x \sim 6\cdot 10^{-4}$

Very small x is needed for forward processes (large x_F)!

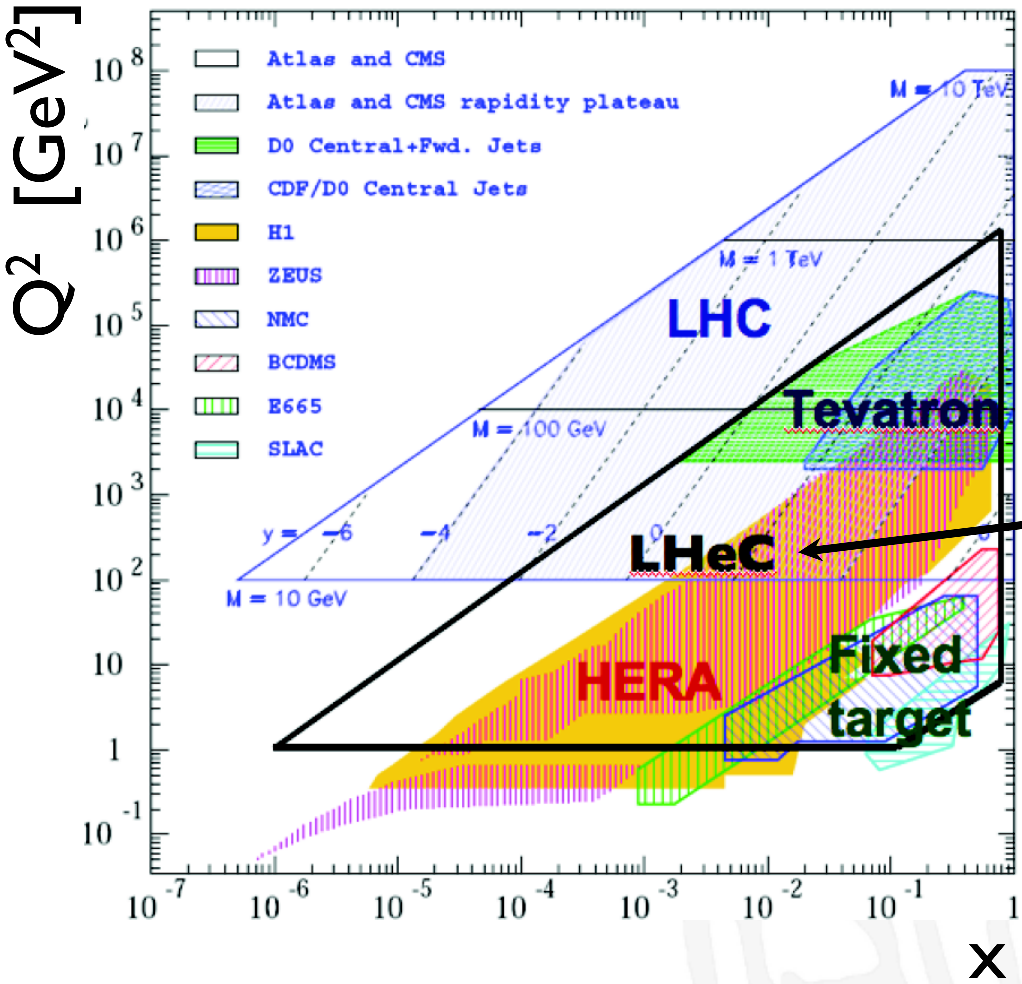
Problem with QCD at small x

- Parton distribution functions poorly known at small x
- At small x, must resum large logs: $\alpha_s \log(1/x)$
- If logs are resummed *(BFKL)*:
  power growth ~ $x^{-\lambda}$ of gluon distribution as $x \to 0$
- Unitarity would be violated (T-matrix > 1)

How small x do we know?

- We haven't measured anything at such small x
- E.g. the MSTW pdf has $x_{min}=10^{-6}$
- But that is an extrapolation!
- HERA pdf fits: $Q^2 > 3.5\ GeV^2$ and $x > 10^{-4}$!

Kinematic plane



Note LHeC!

HERA: x_{min} ~ 10^{-4} used for PDF fits (Q^2 ~ 3.5 GeV^2)

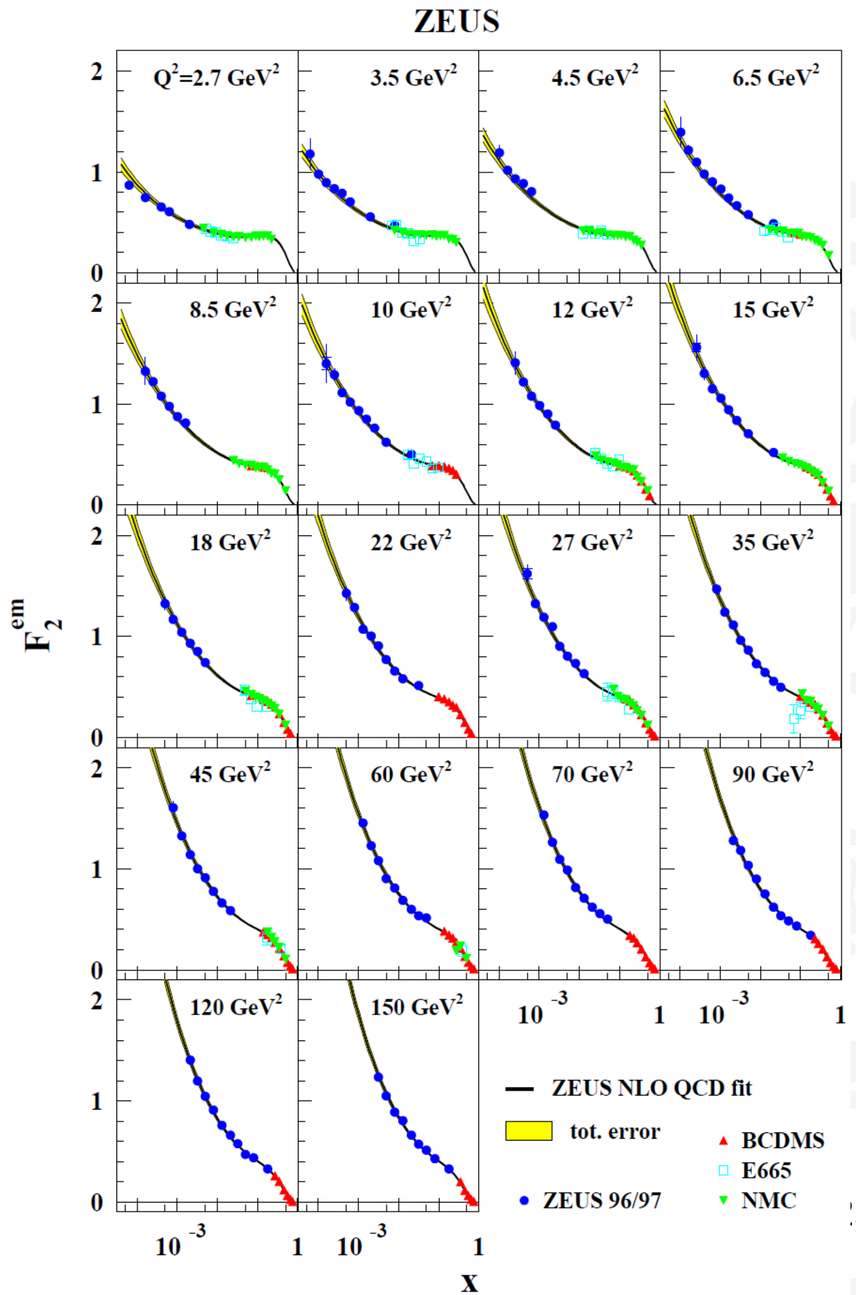
Small x

F2 measured at HERA (ZEUS) as a function of Bjorken-x.

Note the steep power-law rise

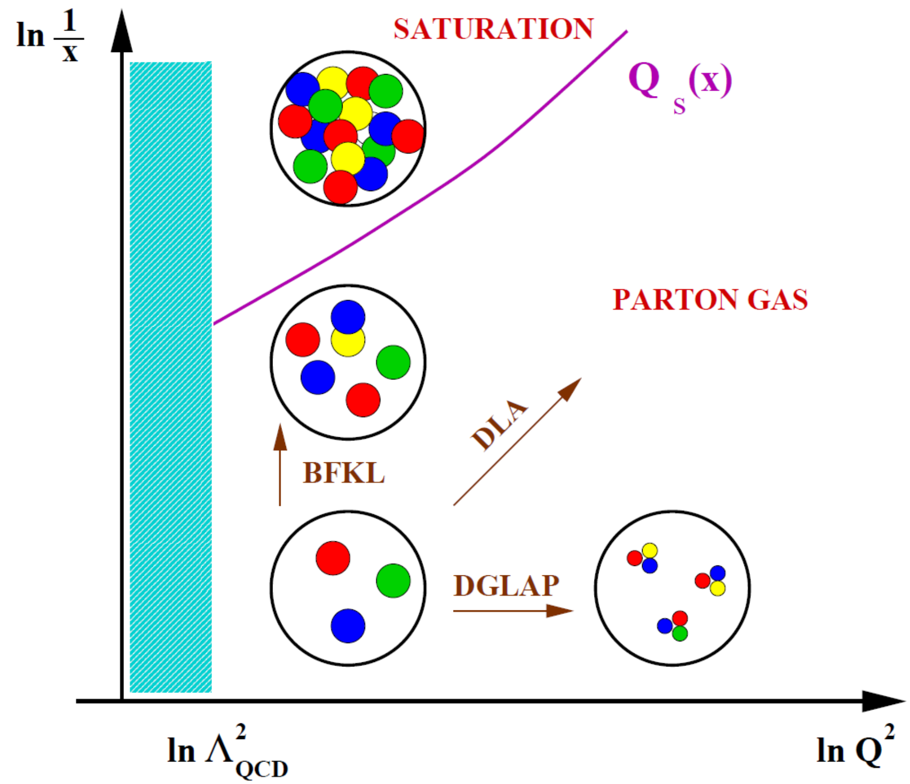
Can this rise continue?

Theoretical answer: no



Parton saturation

- *Saturation* to the rescue:
  - Number of gluons in the nucleon becomes so large that gluons recombine
  - Reduction in the growth



- This is sometimes called the *color glass condensate*
- Non-linear QCD evolution: Balitsky-Kovchegov equation

Redoing QCD calculations

- ***Standard NLO QCD with newest PDFs***
  - BERSS updated with RHIC/LHCb input,
    uses Nason, Dawson, Ellis and Mangano, Nason, Ridolfi
- ***Dipole picture with saturation***
  - Approximate solution of Balitsky-Kovchegov equation
  - Update of ERS calc with new HERA fits + other dipoles
- ***kT factorization with and without saturation***
  - Resums large logs, $\alpha_s \log(1/x)$ with BFKL
  - Off-shell gluons, unintegrated PDFs (+ subleading…)
  - Kutak, Kwiecinski, Martin, Sapeta, Stasto (permutations)

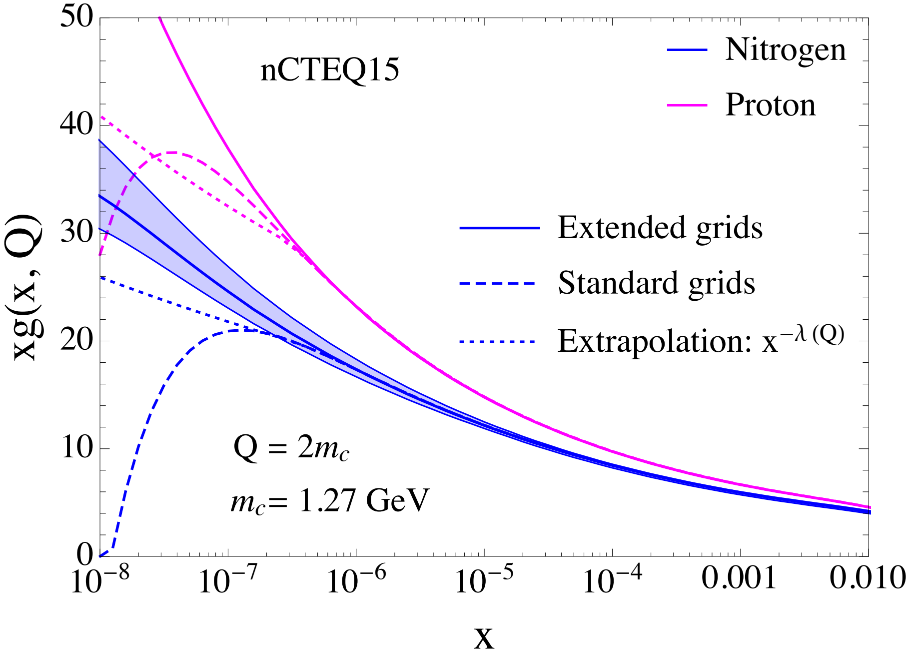
Include scale variations, PDF errors, charm mass, etc
→ Plausible upper and lower limits on xsec

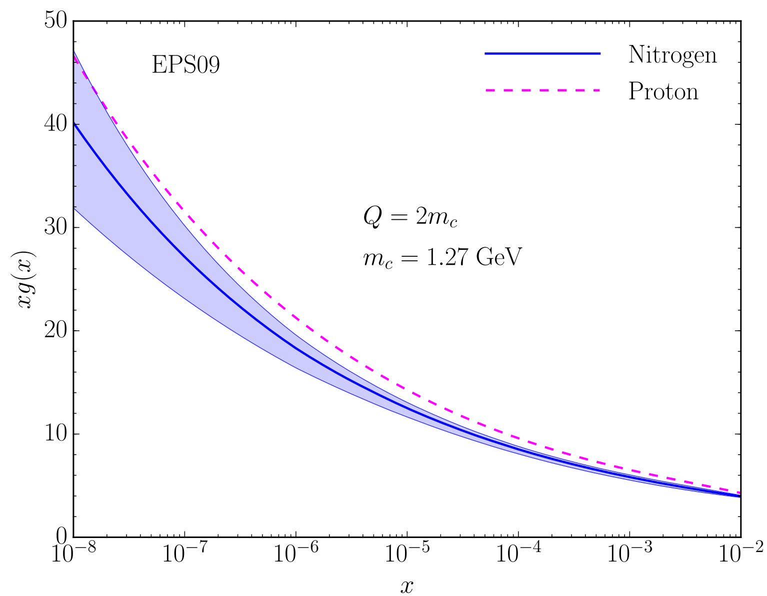
Also include nuclear shadowing

Partons are not in a free nucleon, but in a nucleus!

To estimate shadowing, we use PDFs:

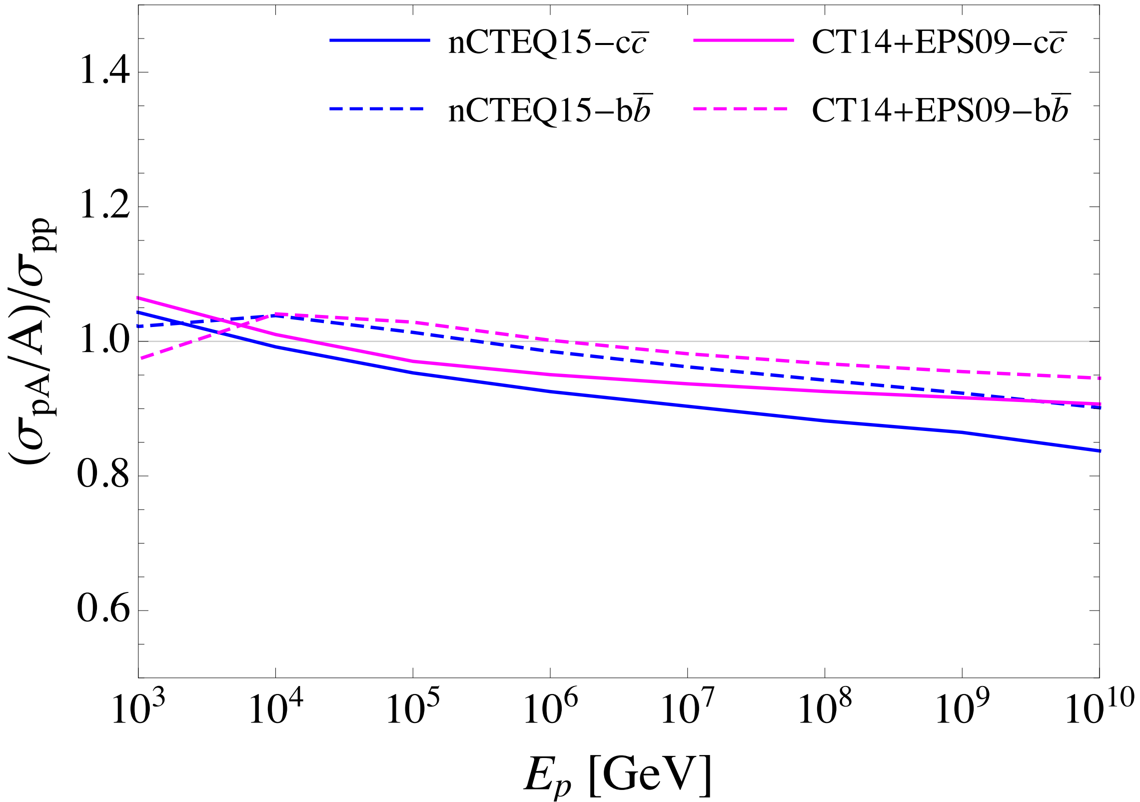
- Eskola, Paukkunen, Salgado (EPS) for ^{16}O
- nCTEQ15 for ^{14}N
- CT14 for free protons



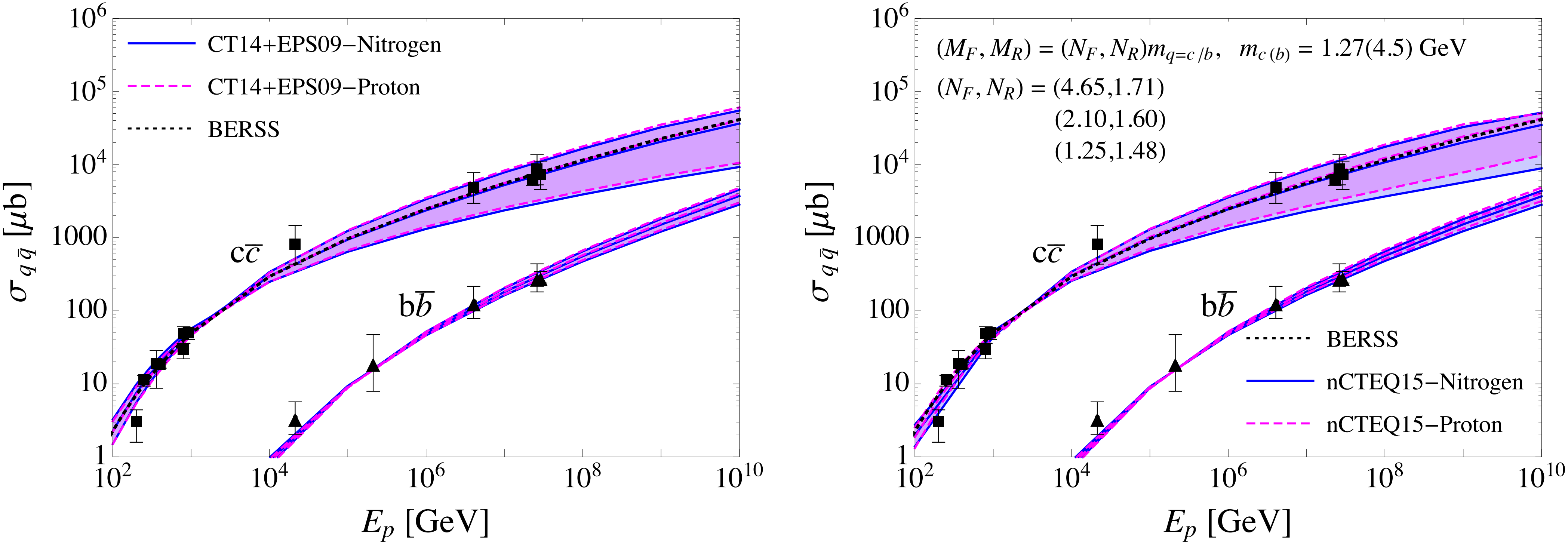


Nuclear effects

- Executive summary: nuclear shadowing reduces the flux by 10–30% at the highest energies
- Effect is larger on the flux than on the total σ(cc) due to asymmetric $x_{1,2}$



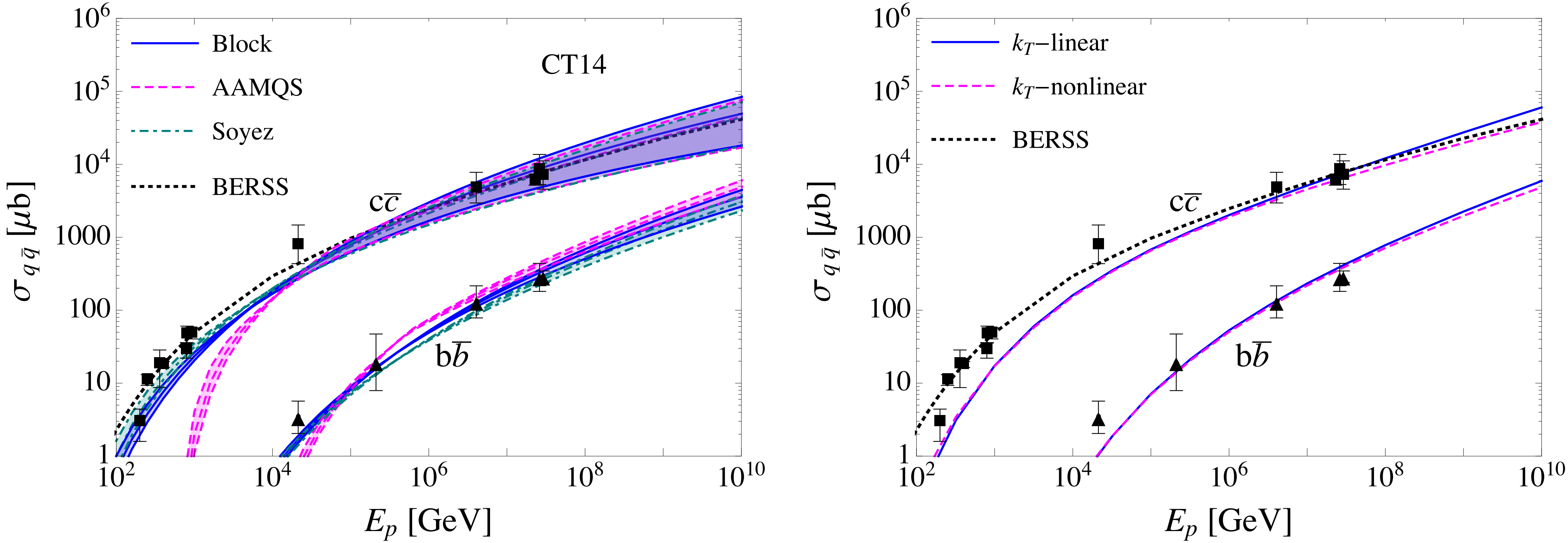
Total cc and bb cross sections



Data from RHIC, LHC and lower energies
Total cross sections well described by NLO QCD, nuclear shadowing small

Error bands=scale variations and PDF uncertainties

Dipole picture and kT factorization



These calculations are not valid for lower energies (larger x) but more or less agree with NLO QCD for larger energies (relevant here)

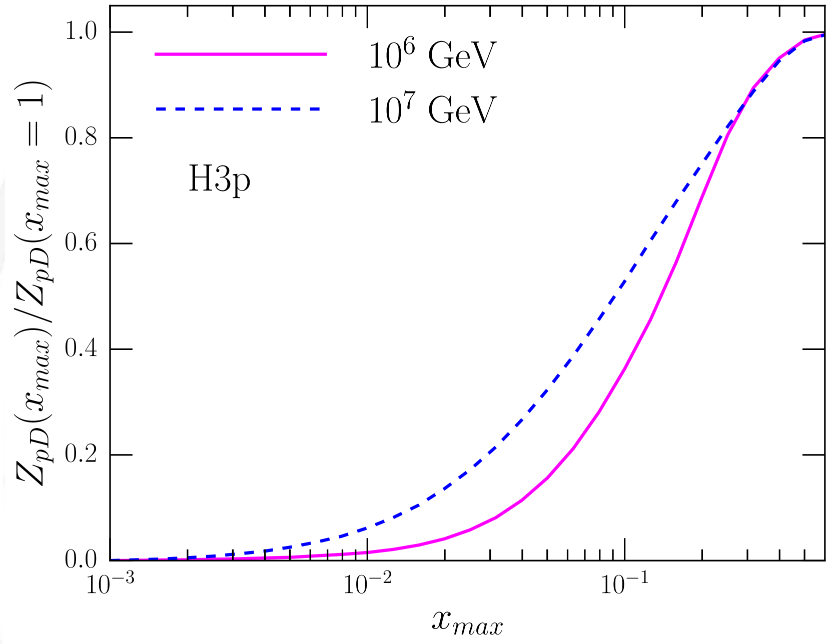
Differential cross sections (LHCb)

LHCb measured D-meson production at 7 and 13 TeV

Kinematical range: pT < 8 GeV, 0 < y < 4.5

The flux is mostly sensitive to ***large y and small pT***.

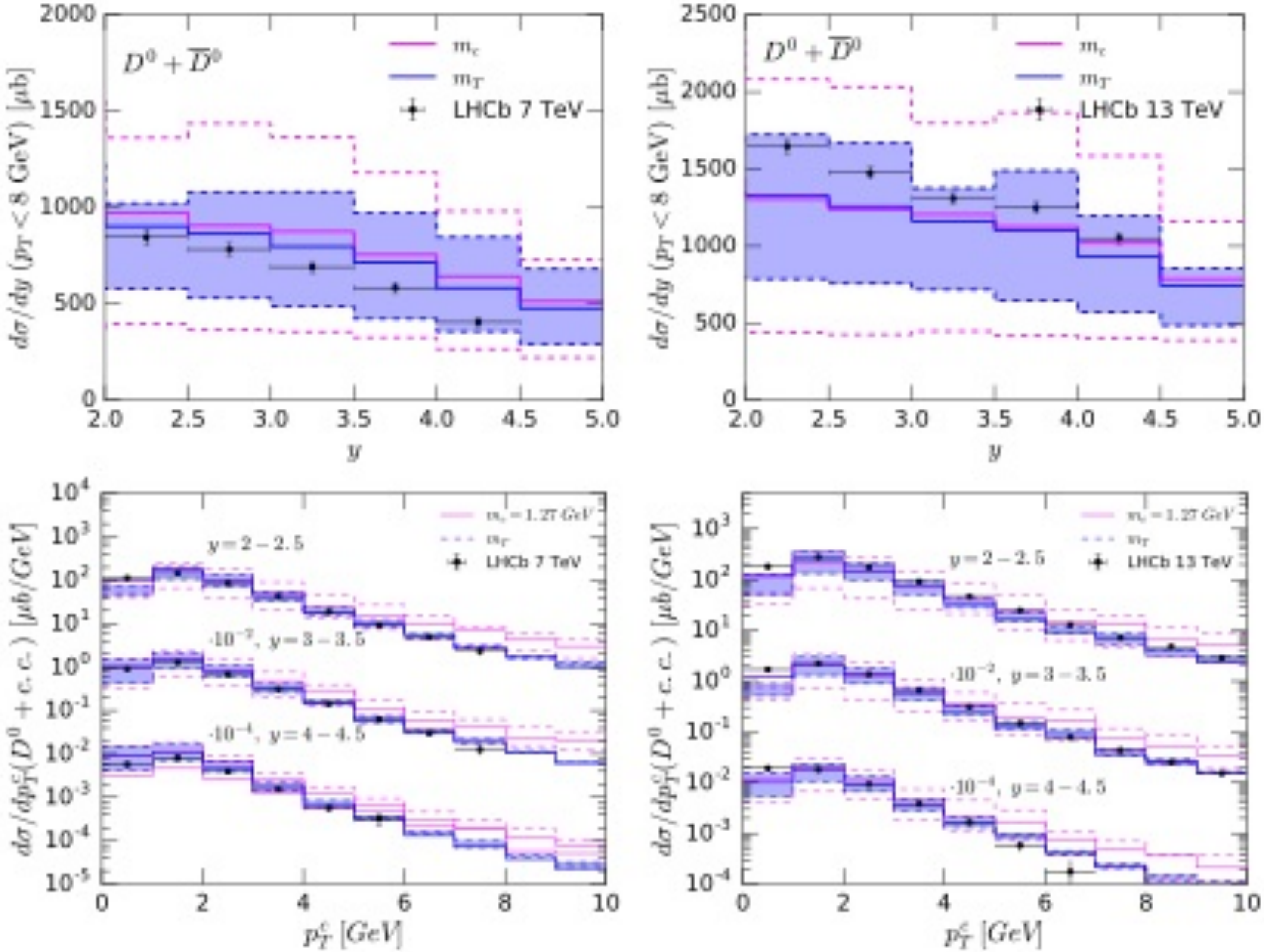
Cumulative fraction of Z-moment as function of xF:



Estimate: 90% of Z_{pD} given by

y > 4.9 for $E_p=10^6$ TeV
y > 5.7 for $E_p=10^7$ TeV

Comparison of NLO QCD



Data from LHCb: arXiv:1302.2864 and arXiv:1510.01707

Prompt ν_μ ($=\nu_e=\mu$) fluxes

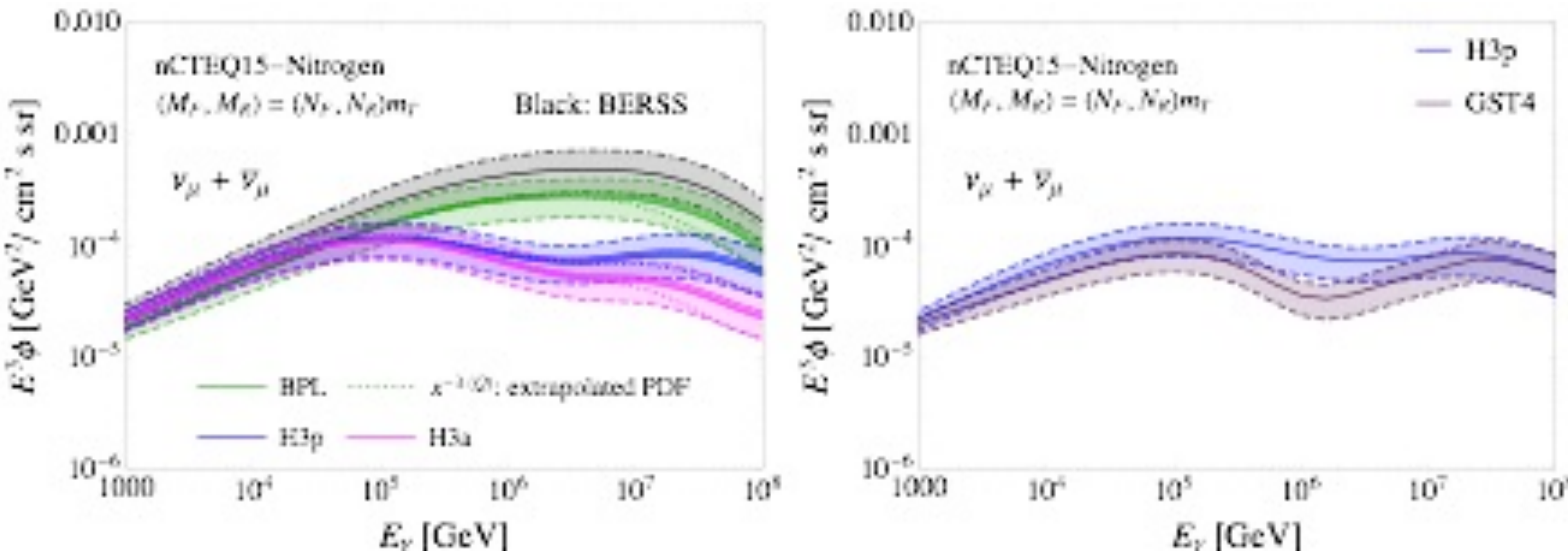
We have calculated prompt neutrino fluxes using all these variations in QCD, nuclear effects, cosmic ray fluxes.

Also compare to other calculations:

- ERS, 0806.0418
- BERSS, 1502.01076
- Garzelli, Moch, Sigl, 1506.08025
- Gauld, Rojo, Rottoli, Sarkar, Talbert, 1511.06346

→ estimate of theoretical uncertainties

NLO QCD

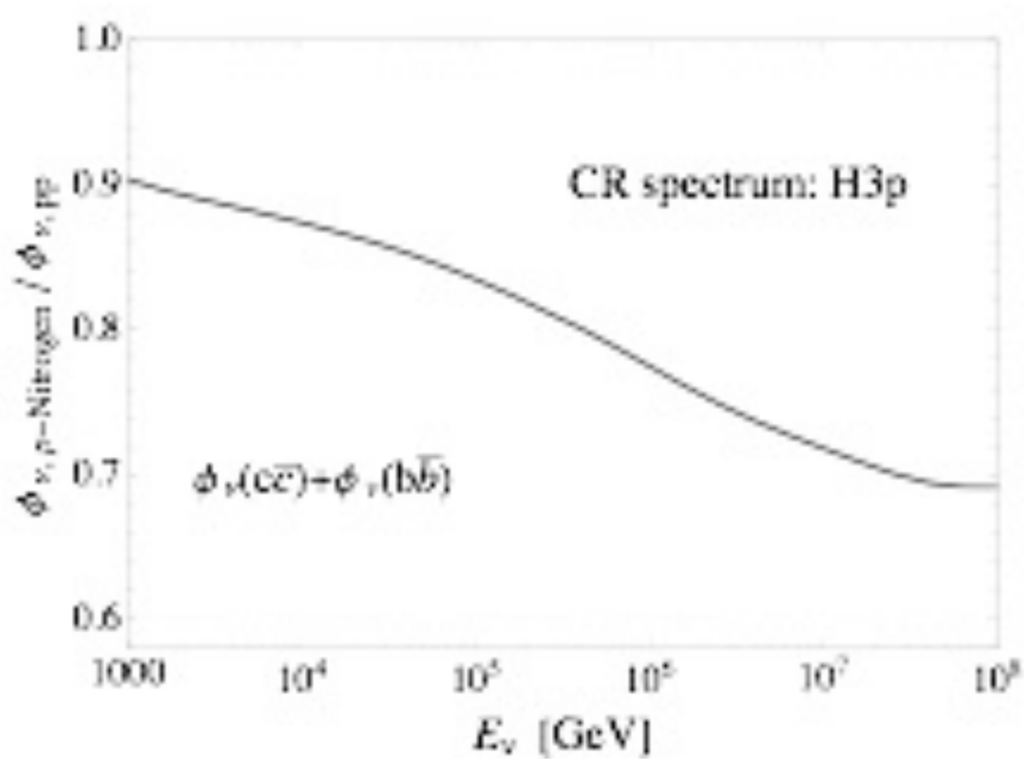


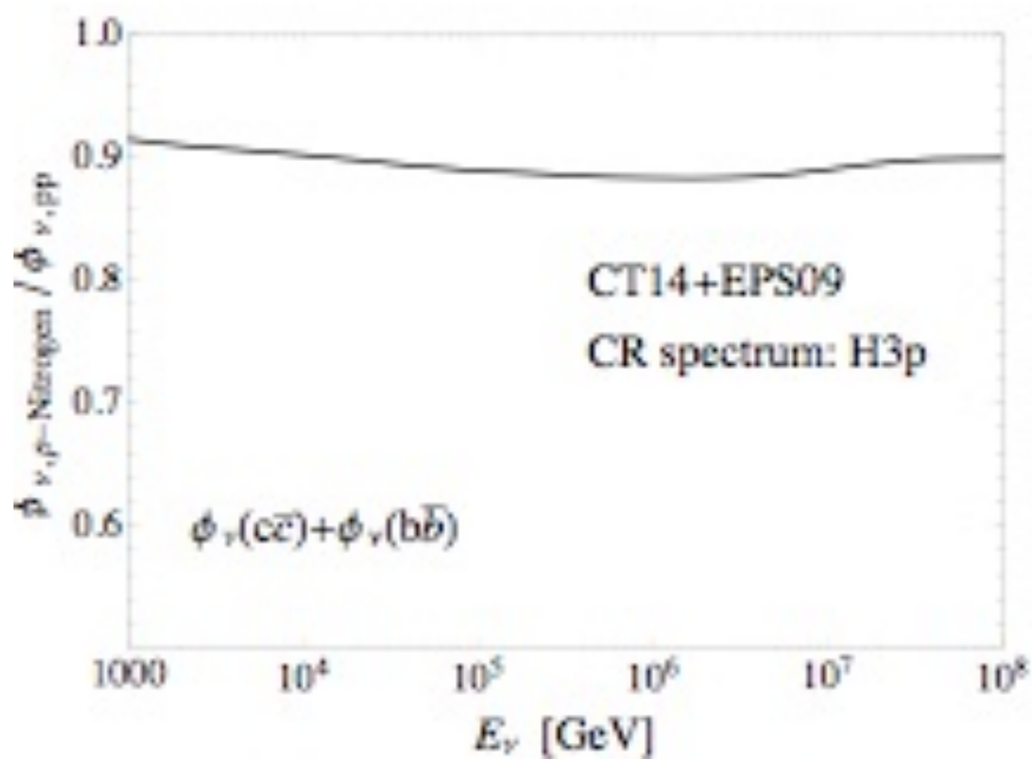
Compare with our BERSS NLO QCD and different cosmic ray fluxes

Difference to BERSS: bb now included, modified fragmentation fractions, nuclear effects (here: nCTEQ15)

Overall: 30%, 40%, 45% lower than BERSS at 10^3, 10^6, 10^8 GeV

Influence of nuclear shadowing





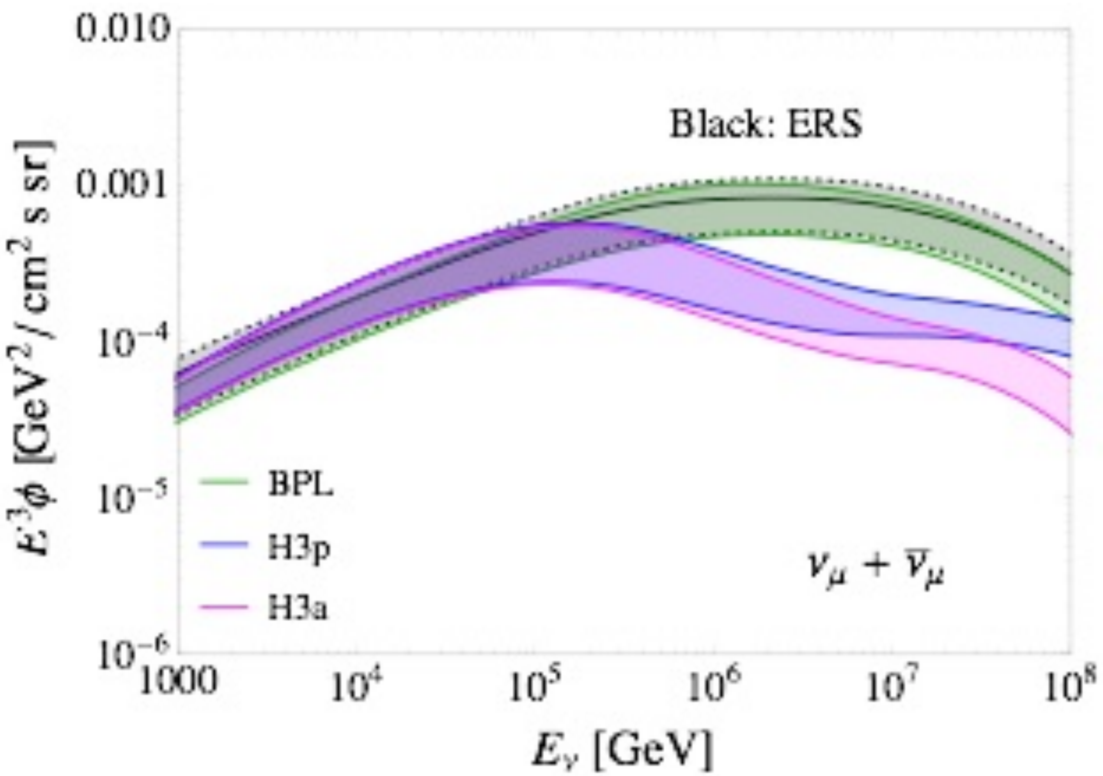
Ratio of NLO QCD flux with and without nuclear effects

→ 20–30% suppression from 10^5 to 10^8 GeV for nCTEQ

(only 4–13% for total cross section)

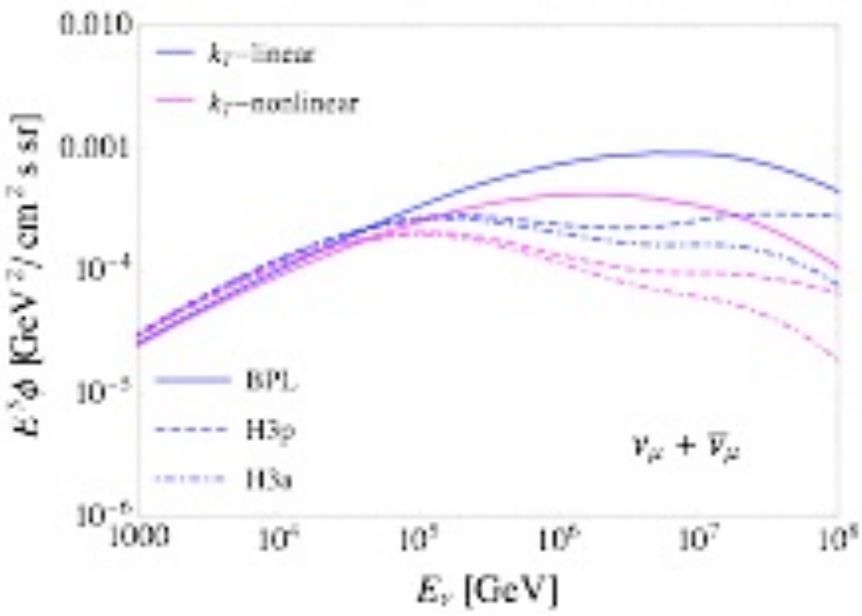
→ But much less for EPS (frozen at $x=10^{-6}$)

Dipole models

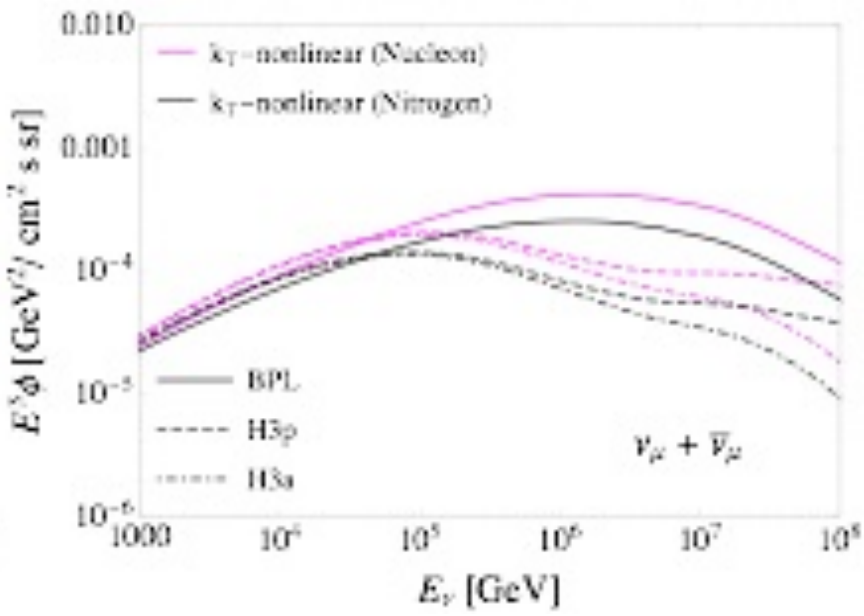


All three models for the dipole cross section are similar

kT factorization

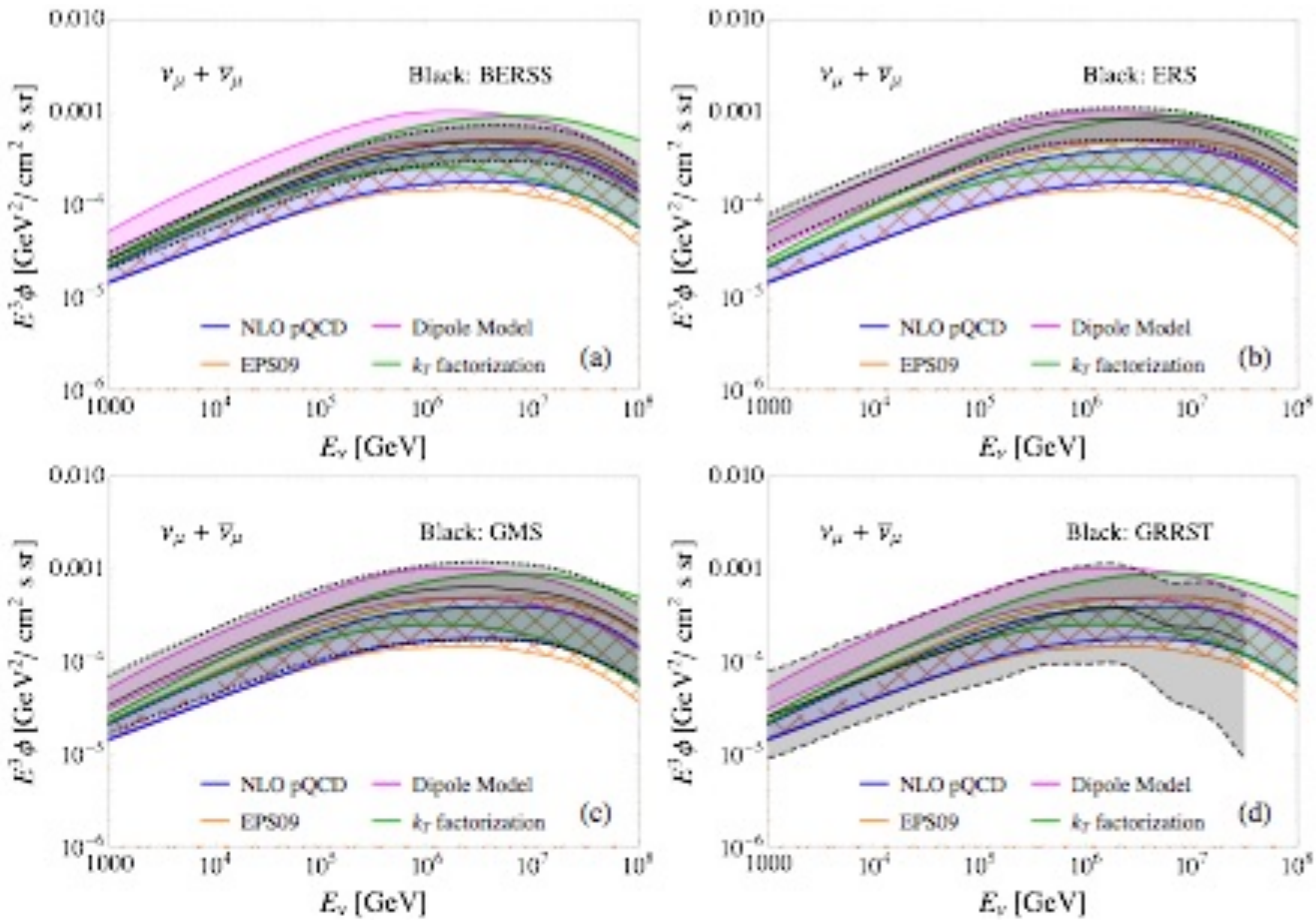


With and without saturation

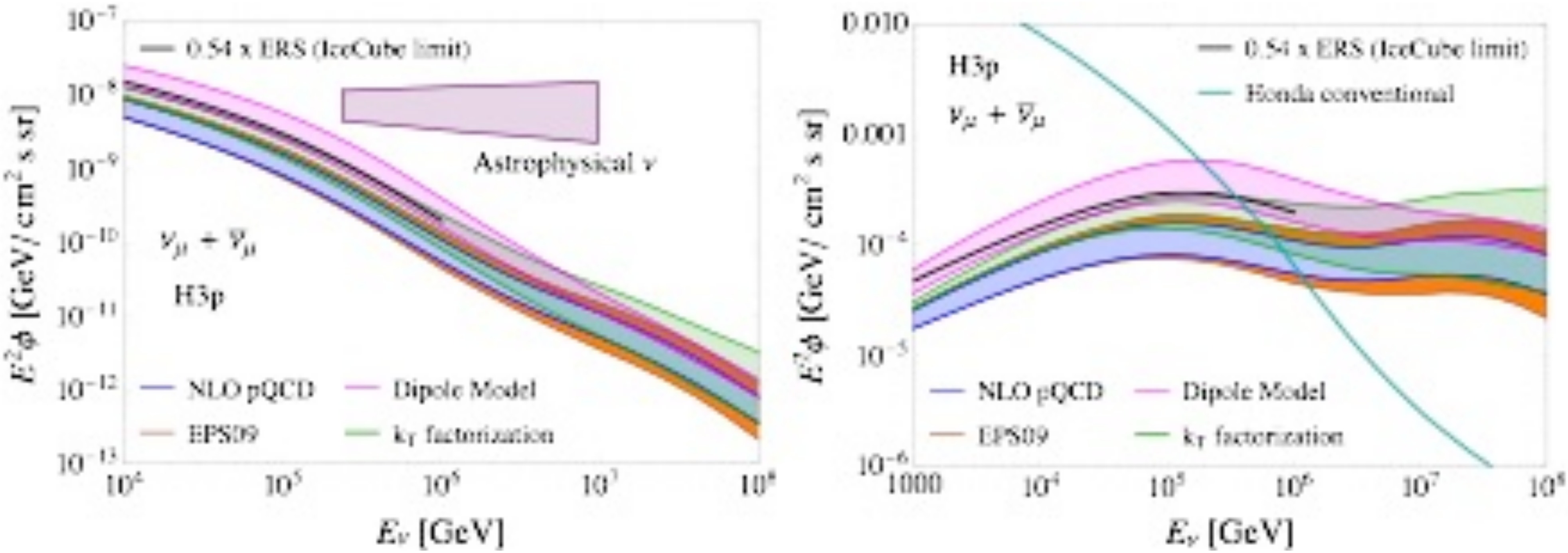


With and without nuclear effects

And now everything, using broken power law



And what does IceCube say?



The most recent IceCube limit (3 yrs) on the prompt flux sets a limit at 90% CL of

0.54 x (*a flux with the same shape as ERS and H3p*)

L. Rädel & S. Schoenen (IceCube), PoS ICRC2015, 1079

Intrinsic charm

- "Normal" charm parton distribution is generated from gluon splittings
- There may be an "intrinsic" non-perturbative charm component in the nucleon
  [Brodsky, Hoyer, Peterson, Sakai, 1980]
- Would contribute charmed mesons at large xF
  [See e.g. Thunman et al or Bugaev et al.]

But there is hardly room in the data for that!

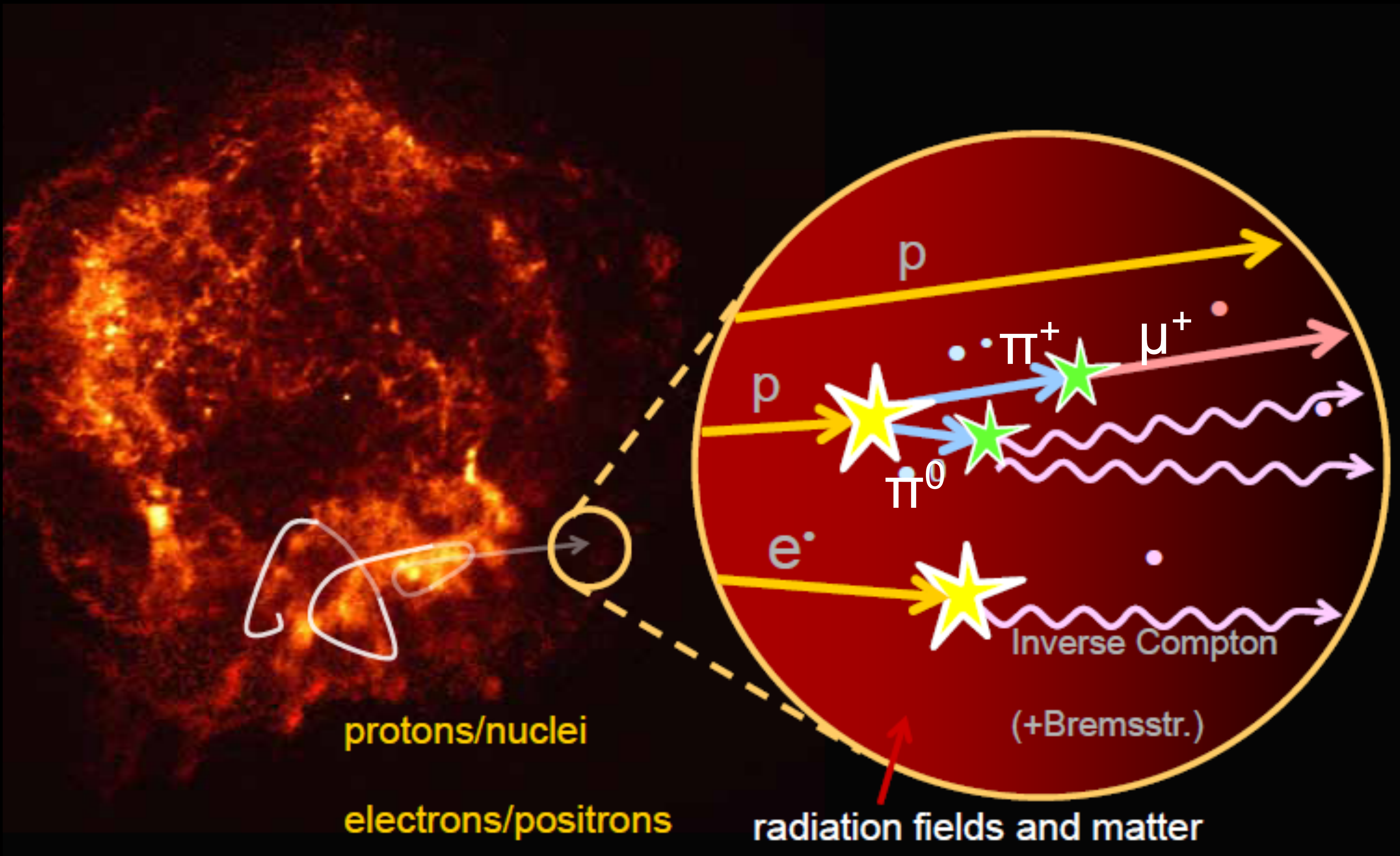
“Astrophysical sources”

Name for various cosmic objects or events which **accelerate** charged particles to high energies and **emit** high-energy photons, hadrons and/or neutrinos

Examples:

- Supernova remnants
- Gamma ray bursts (GRB)
- Active galactic nuclei (AGN)
    - E.g. quasars, blazars, Seyfert galaxies,…
- Supernovae with jets

Cosmic accelerators



Interesting objects: what we think

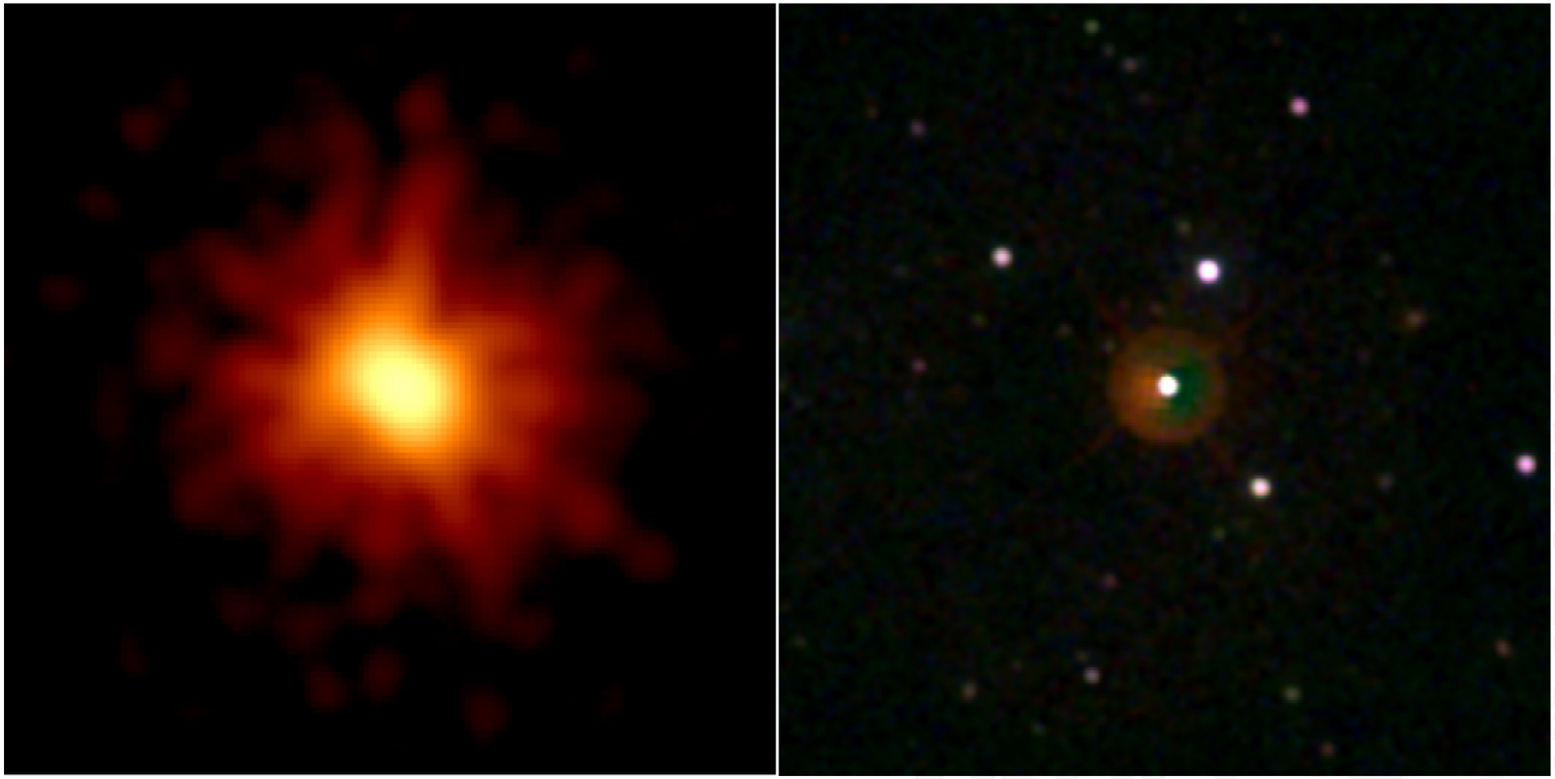
- ***Supernovae (SNe):***
  - Supernova remnants (SNRs) emit cosmic rays
  - Some gamma ray bursts (GRBs) are Sne
  - Produce some cosmic rays themselves
- ***Black holes:***
  - Are created in GRBs
  - Are the engines behind active galactic nuclei (AGNs)
- ***Gamma ray bursts:***
  - Produce cosmic rays of all types (transient source)
- ***Active galactic nuclei:***
  - Produce cosmic rays of all types (steady source)

Highest energies: GRBs and AGNs

- ***Gamma Ray Bursts*** are ***enormously*** violent explosions that last for only a few seconds or minutes
  - Transient sources, a few a.u. in size
  - Emit gamma rays, photons at other energies, and probably charged particles and neutrinos
  - Total energy output comparable to SN but emitted in much shorter time

- ***Active Galactic Nuclei*** mean that the ***whole galactic center*** takes part in accelerating particles
  - Constant sources, many lightyears in size

Example: GRB 080319B



NASA. Left: X-ray. Right: optical/UV

Was visible to the naked eye for 30 seconds and millions of times brighter than brightest SN

Brightest GRB ever seen, $z = 0.937$ → 7.5 billion years ago!!

(Before our solar system existed.)

GRBs and jets

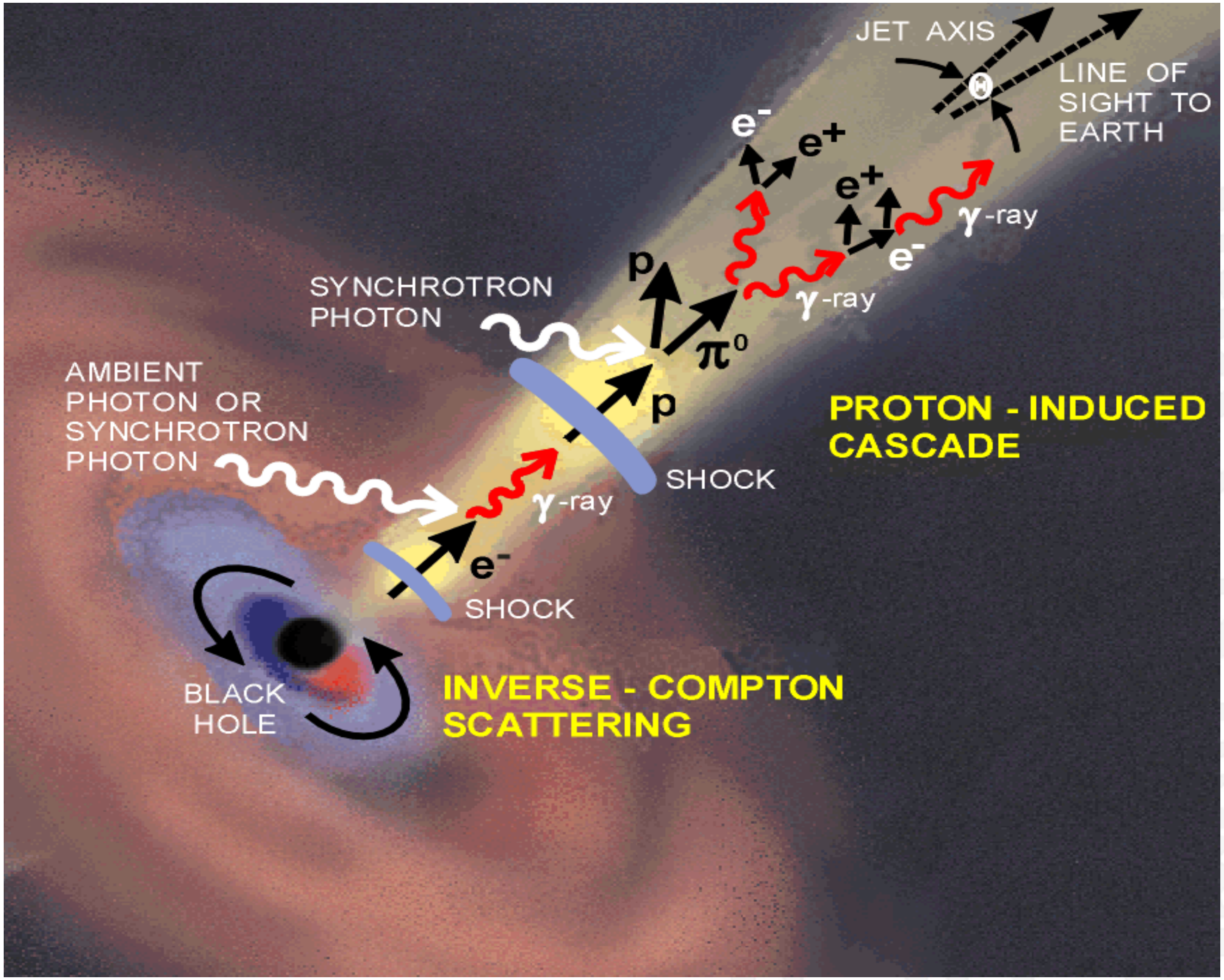
- In fact most GRBs are very far away ("cosmological distances") and thus need to be **extremely energetic**

  (observed up to redshift z = 6–7, where z = 7 means the universe was less than a billion years old!)

- GRBs are believed to be catastrophic events leading to the birth of a **stellar mass black hole**

- Black hole drives relativistic outflow in jets

Astrophysical jet



The jet is relativistic → time dilation and beaming

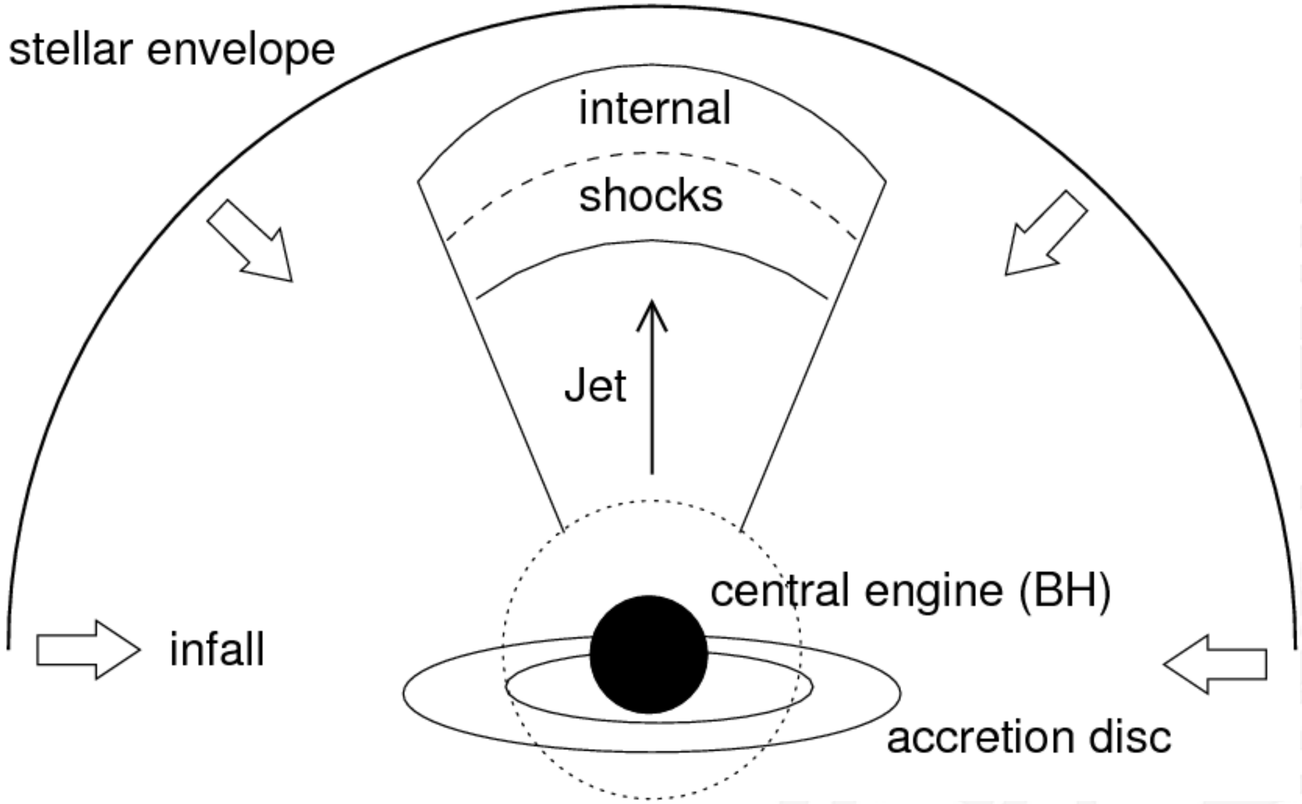
To sum up:

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

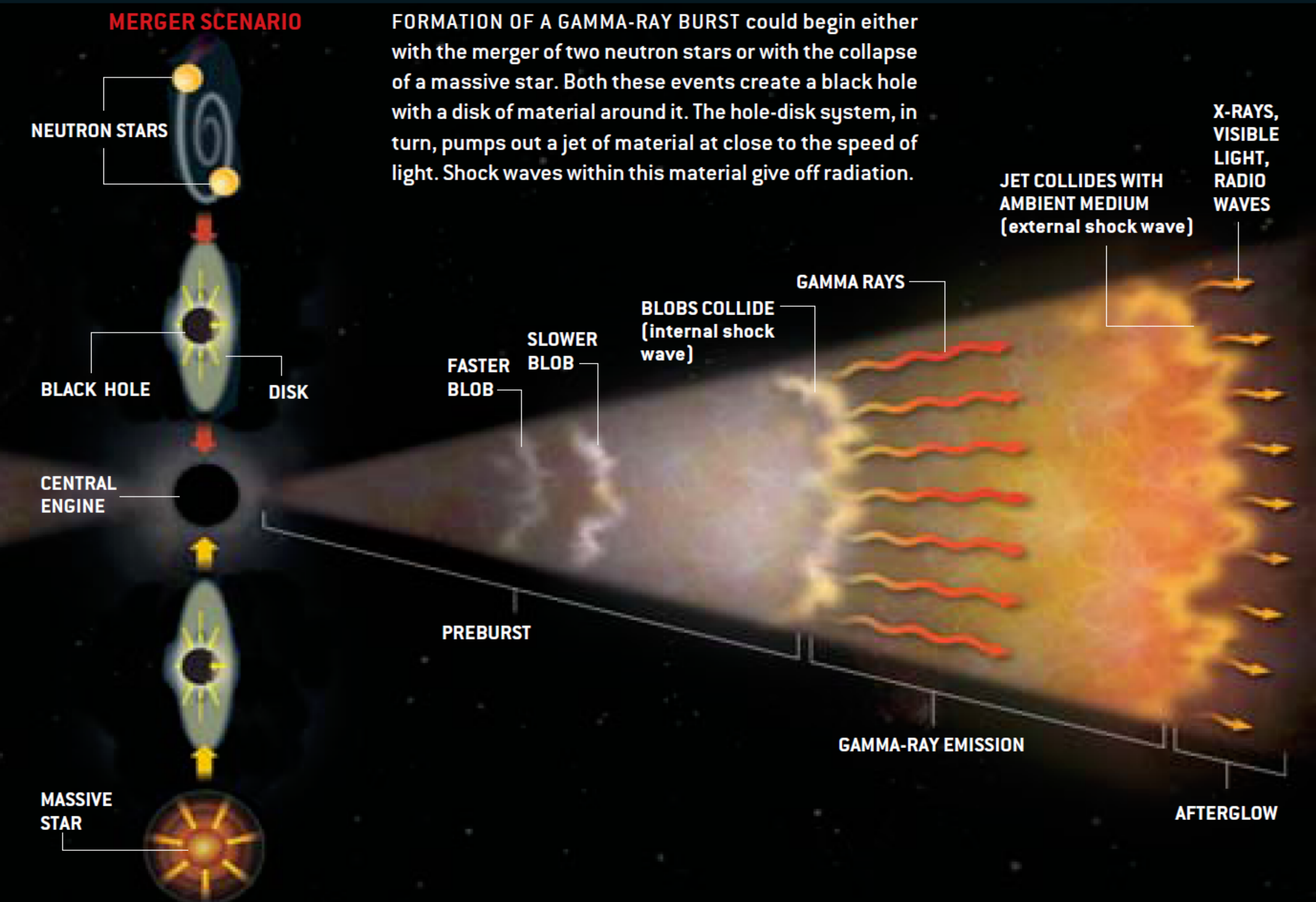
Schematic picture



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

Protons and electrons are shock accelerated in jet

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



Gehrels et al., Scientific American, Dec. 2002

Slow-jet Supernovae (SJS)

- **GRBs**: jets with bulk gamma factors of 100s-1000s
- The jets punches through the envelope and the gamma emission is seen as a gamma ray burst
- ***If the jet is slower***, it may be stalled and the gammas are absorbed and thermalized instead
  → this would look like a supernova
  but could still generate neutrinos
- Razzaque, Meszaros and Waxman called this "**Slow-Jet Supernovae**" (SJS)

Cosmic beam dumps

- Charged particles are shock accelerated in the jet: may collide with protons and photons in the jet and the surrounding 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

Photon, neutrino emission

- **Neutrinos**: Emitted in decay of charged pions $\pi^{\pm}$, which are copiously produced in hadron collisions:

$$pp \rightarrow \pi^{+} + X \quad \text{or} \quad p\gamma \rightarrow n\pi^{+}$$

followed by

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

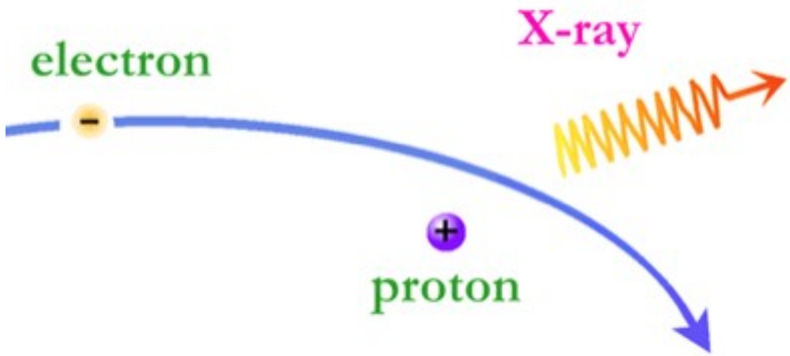
- **Photons**: "Hard" (i.e. high energy) photons from e.g.

$$p\gamma \rightarrow p\pi^{0}$$
$$\pi^{0} \rightarrow \gamma\gamma$$

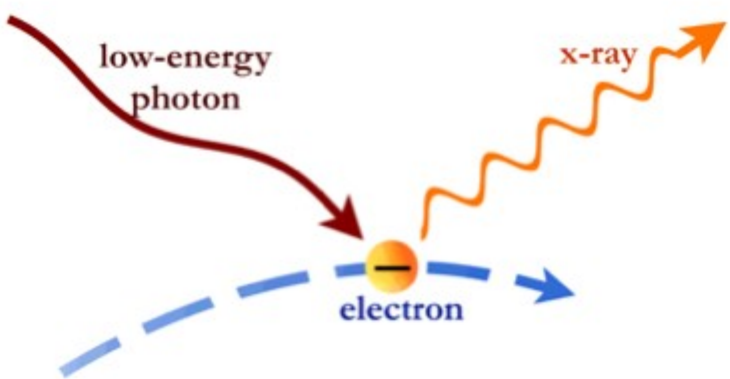
(ν, γ also from other decays)

Photon mechanisms

Bremsstrahlung:
An accelerated charge emits photons:

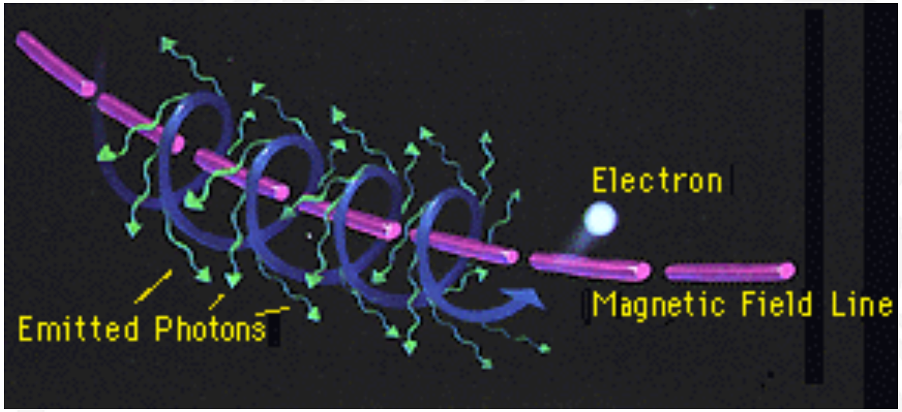


Inverse Compton scattering:



In magnetic field:
Cyclotron & Synchrotron
(v/c << 1) (v/c ≈ 1)

Relativistic: beaming and time dilation



Images from NASA: Imagine the universe

Astrophysical sources

We consider two kinds of sources as examples:

GRB:

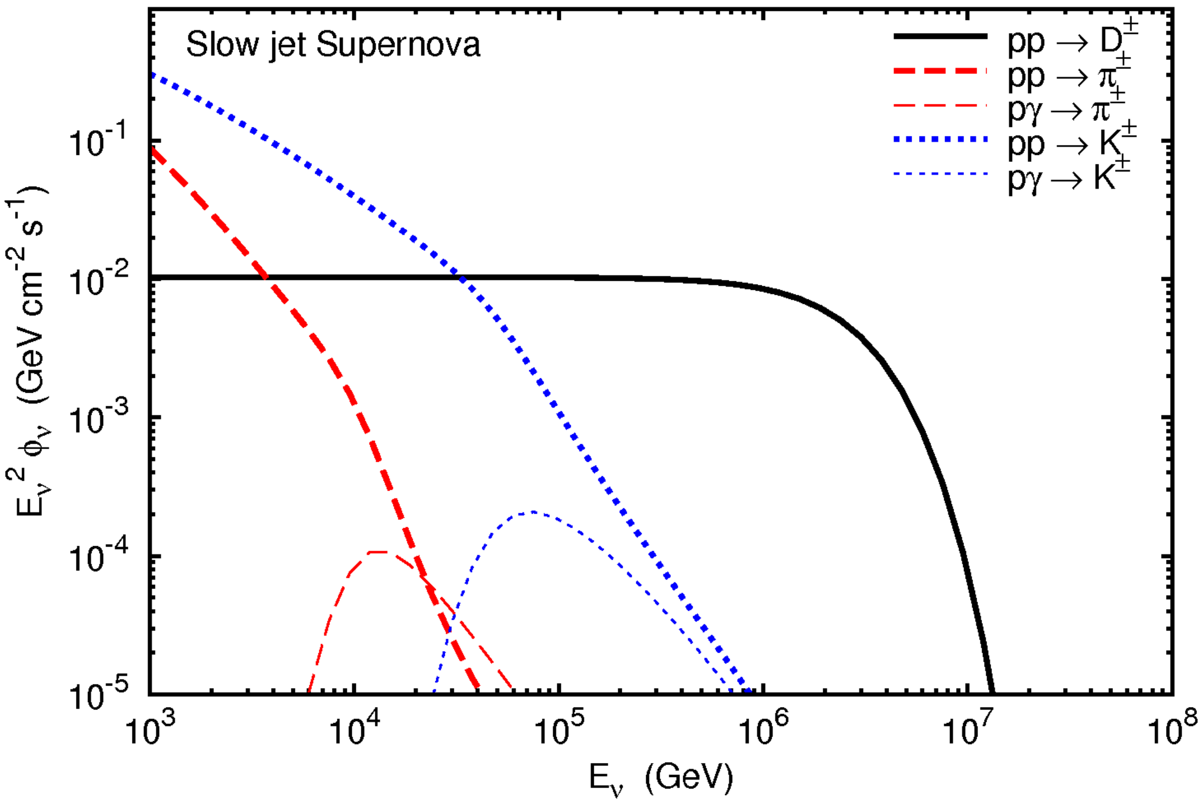
- Non-thermal photons and highly relativistic jet

"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)

Neutrino flux from slow-jet SNe



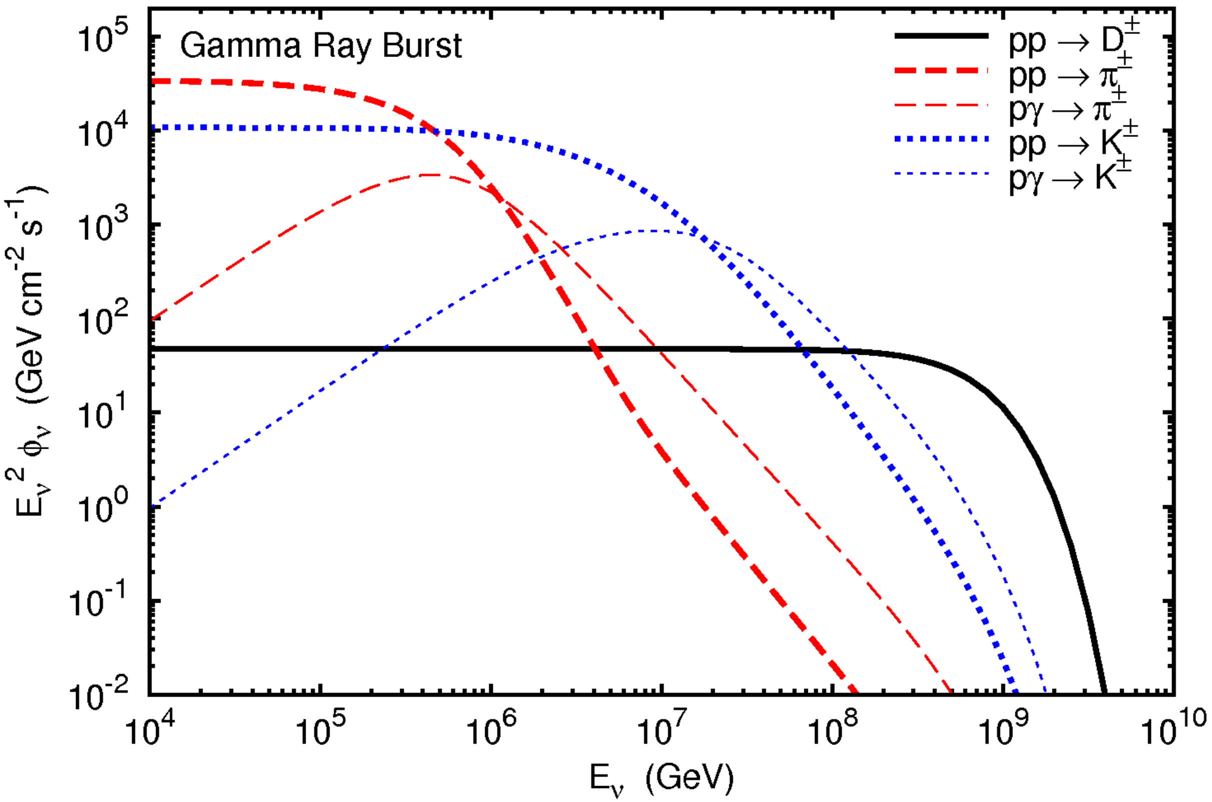
[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807]

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

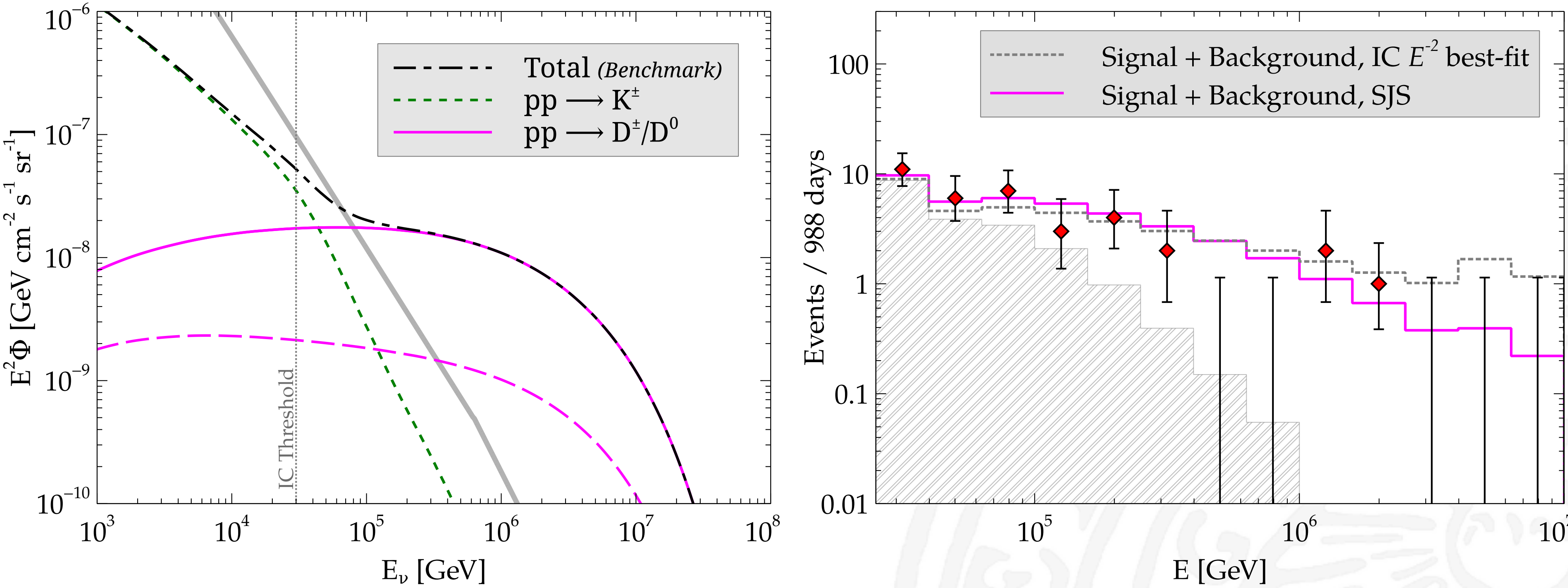


Again no cooling of D-mesons

For this particular choice of parameters, charm has a smaller range where it dominates

Some scenarios have much higher max proton energy

IceCube events from Slow-jet SN



We proposed charm production in SJS as the source of IceCube's events:

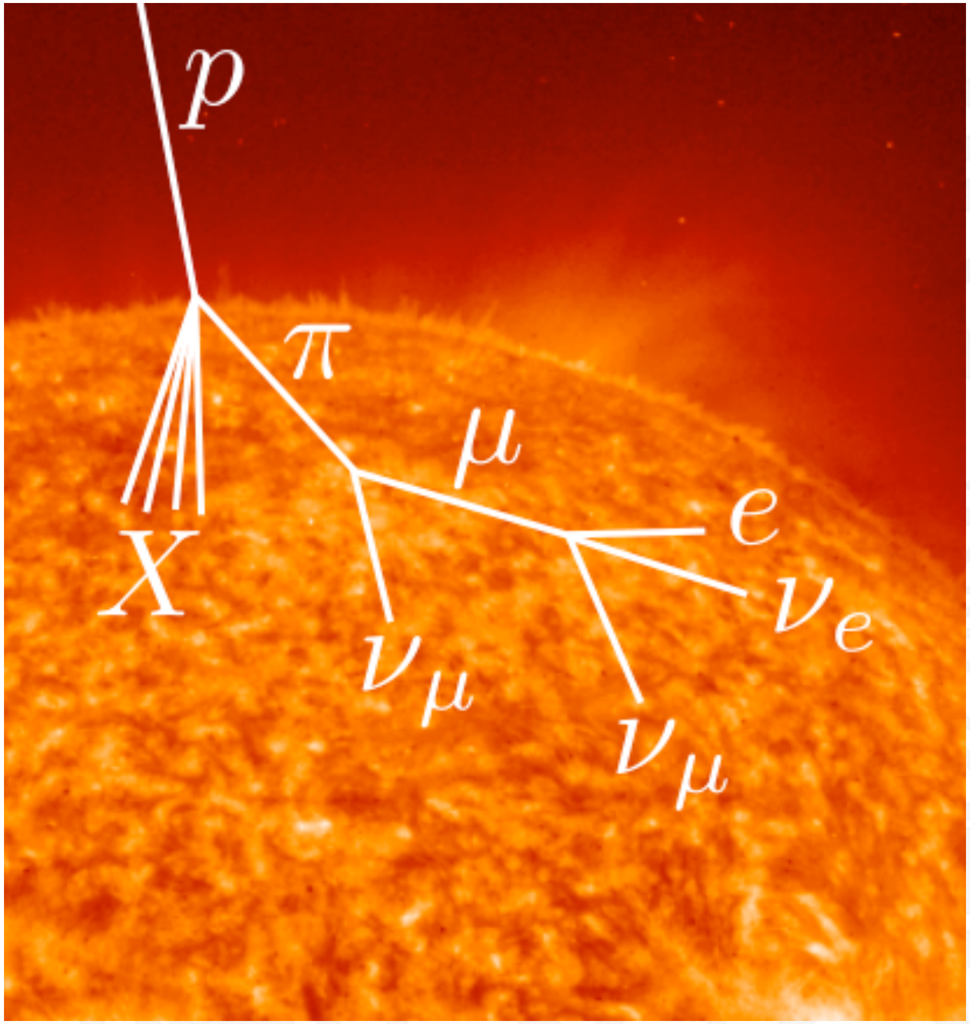
A. Bhattacharya, RE, M.H. Reno, I. Sarcevic, arXiv:1407.2985 [astro-ph.HE]

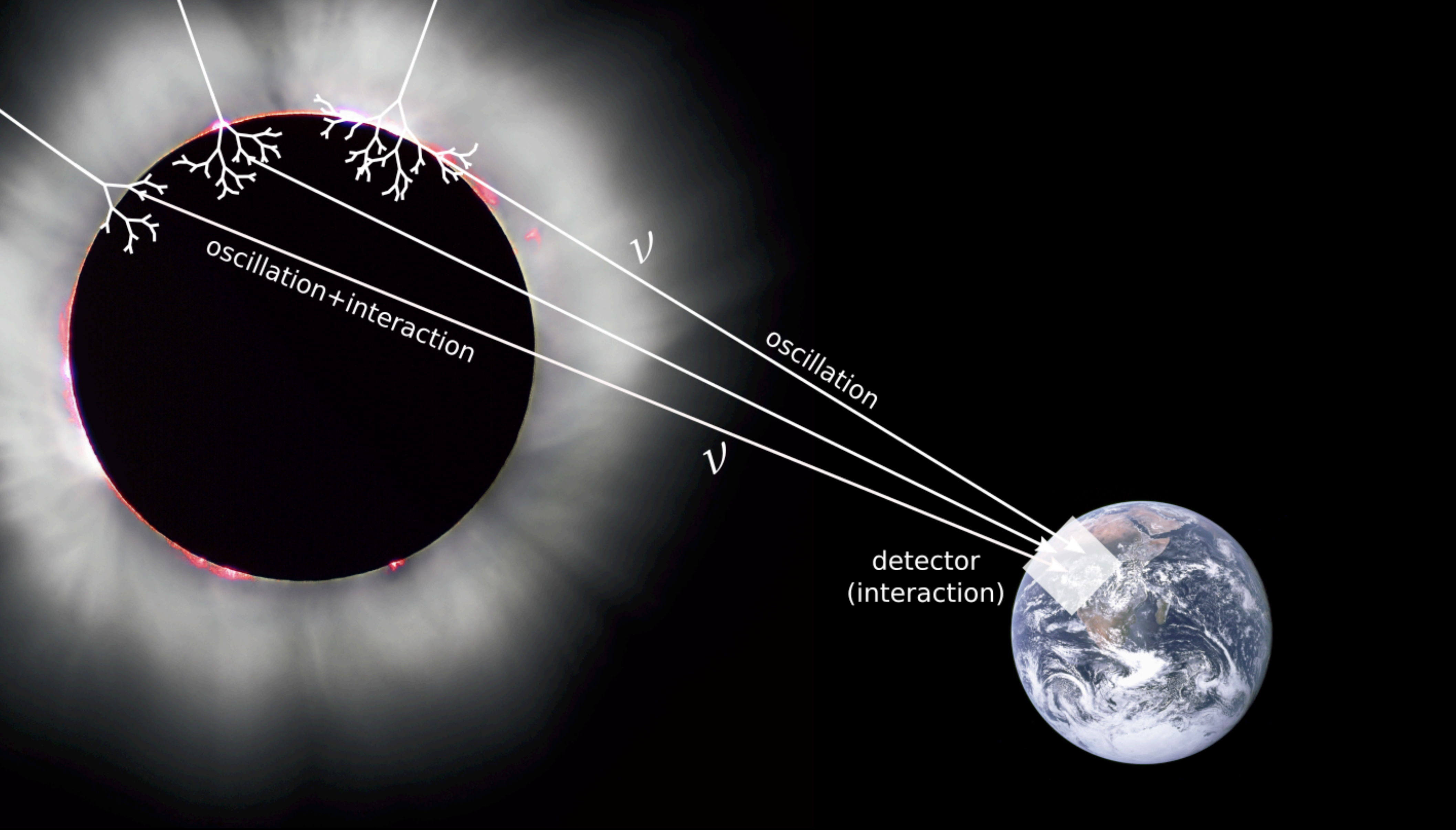
Neutrinos from the Sun

Standard search:
: Neutrinos from the center of the Sun from dark matter annihilation

Standard calculation 20 yrs old:
: M. Thunman, G. Ingelman, hep-ph/9604288

J. Edsjö, J. Elevant, RE, C. Niblaeus (in prep)





We use MCeq to compute (conventional) neutrino fluxes and WimpSim to compute propagation inside the Sun

Conclusions

- There are a lot of known and unknown unknowns in astroparticle neutrino physics
  - How large is the astrophysical flux?
  - Where does it come from?
  - What are the backgrounds?
- At least for the prompt neutrinos, we think we know what we don't know – more accelerator and cosmic ray data needed!
- There are lots of explanations for the IceCube events, we have one, but there are many others