Nuclear physics meets sources of UHECR

HAP Workshop | Non-Thermal Universe

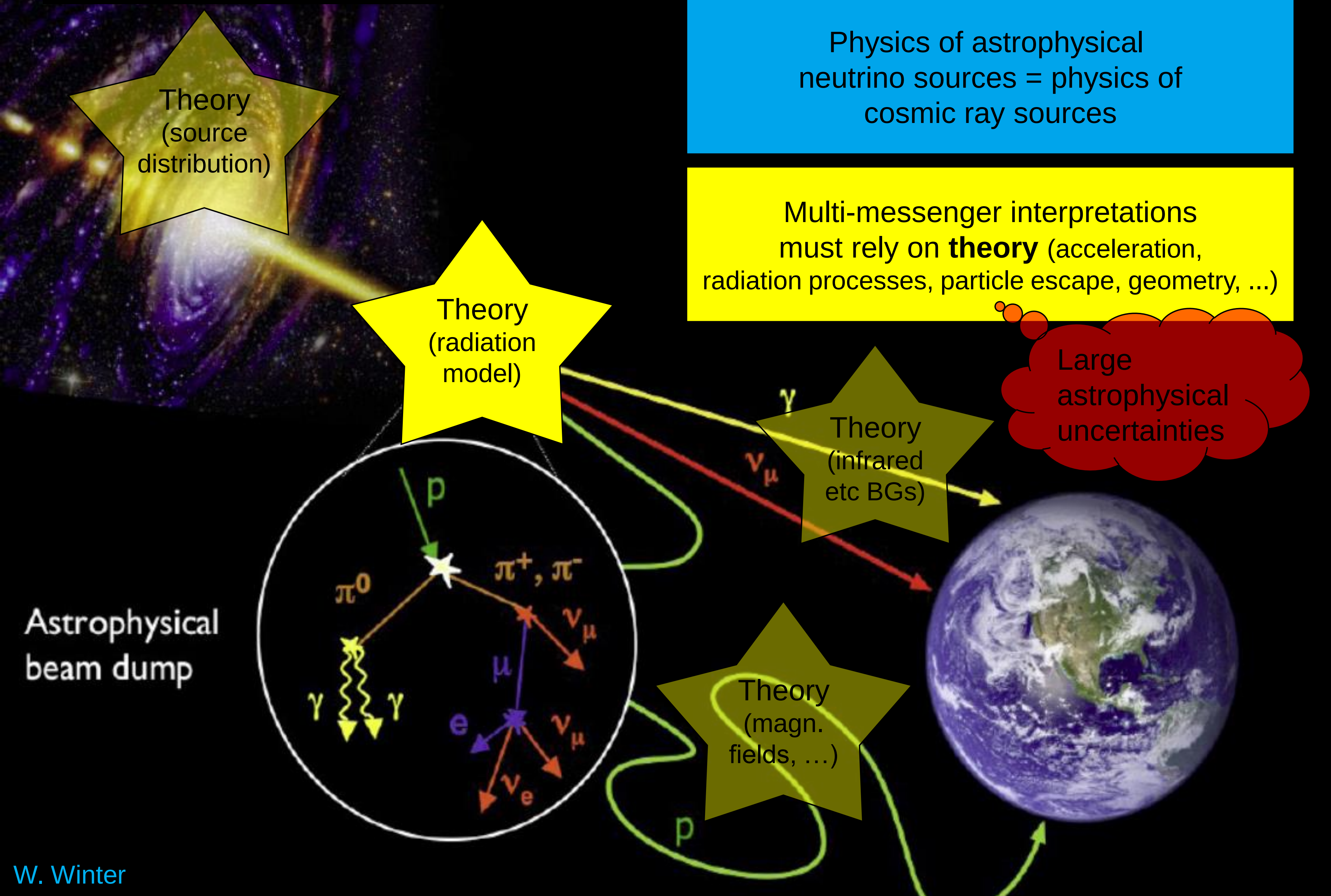
Anatoli Fedynitch

DESY Zeuthen

The universe in multiple messengers ... a challenge for theory

Physics of astrophysical neutrino sources = physics of cosmic ray sources

Multi-messenger interpretations must rely on **theory** (acceleration, radiation processes, particle escape, geometry, ...)

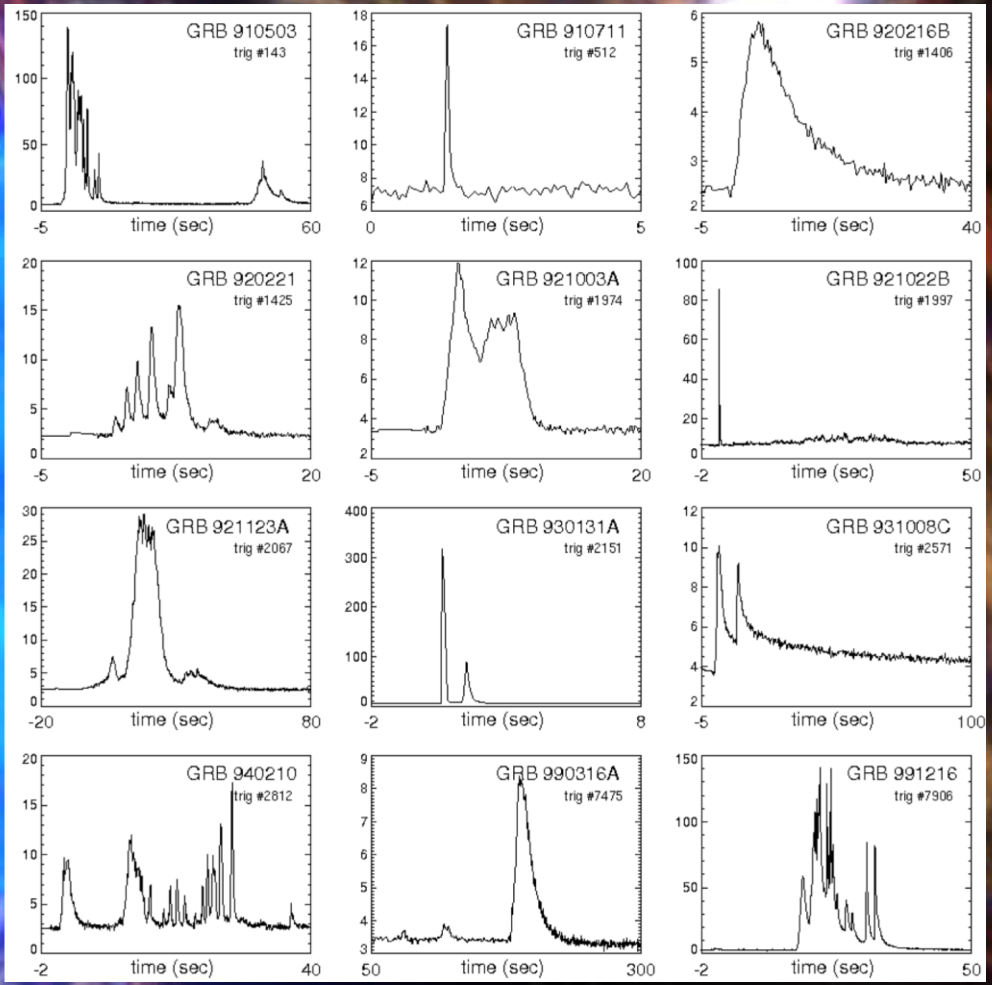


W. Winter

Candidate for UHECR source: Gamma-ray bursts (GRBs)

- Most energetic electromagnetic (gamma-ray) outburst class
- Several populations, such as
  - Long-duration bursts (~10 – 100s), from collapses of massive stars?
  - Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers?
- Observed light curves come in large variety

Daniel Perley



Source: NASA

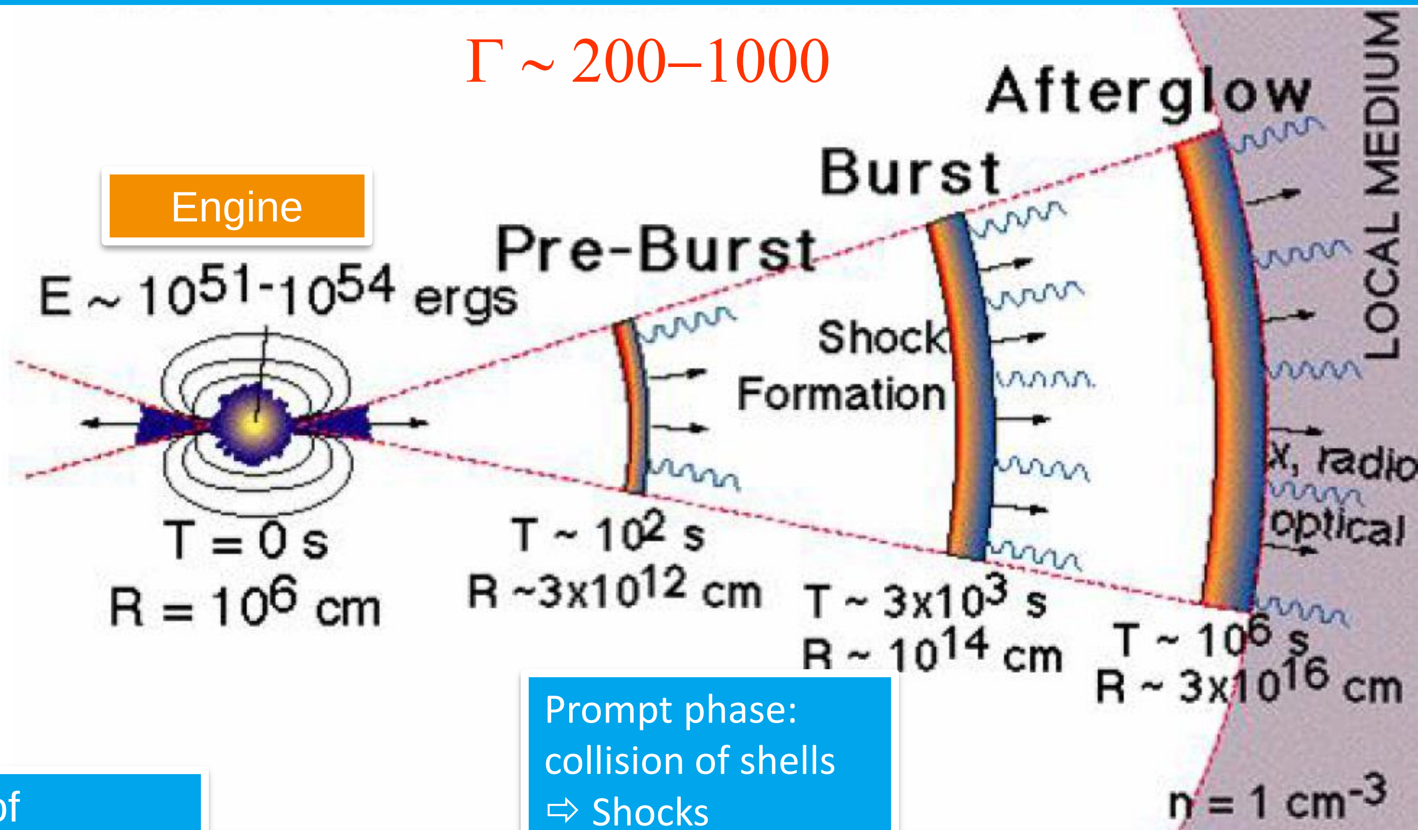
GRB - Internal shock model

(Source: SWIFT)

$\Gamma \sim 200\text{–}1000$

“Isotropic equivalent energy“

Engine



Prompt phase: collision of shells
⇨ Shocks
⇨ Particle acc.

Maximum energy of escaping UHECR depends on competition between acceleration and cooling

$$N'_\gamma(\varepsilon') \propto \begin{cases} \left(\frac{\varepsilon'}{\varepsilon'_{\gamma,\mathrm{break}}}\right)^{-\alpha_\gamma} & \varepsilon'_{\gamma,\mathrm{min}} \leq \varepsilon' < \varepsilon'_{\gamma,\mathrm{break}} \\ \left(\frac{\varepsilon'}{\varepsilon'_{\gamma,\mathrm{break}}}\right)^{-\beta_\gamma} & \varepsilon'_{\gamma,\mathrm{break}} \leq \varepsilon' < \varepsilon'_{\gamma,\mathrm{max}} \\ 0 & \text{else} \end{cases}$$

Modelling of radiation zone

Boltzmann Equations for each particle species (and energy bin)

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\mathrm{esc}}} + \tilde{Q}_{ji}(E)$$

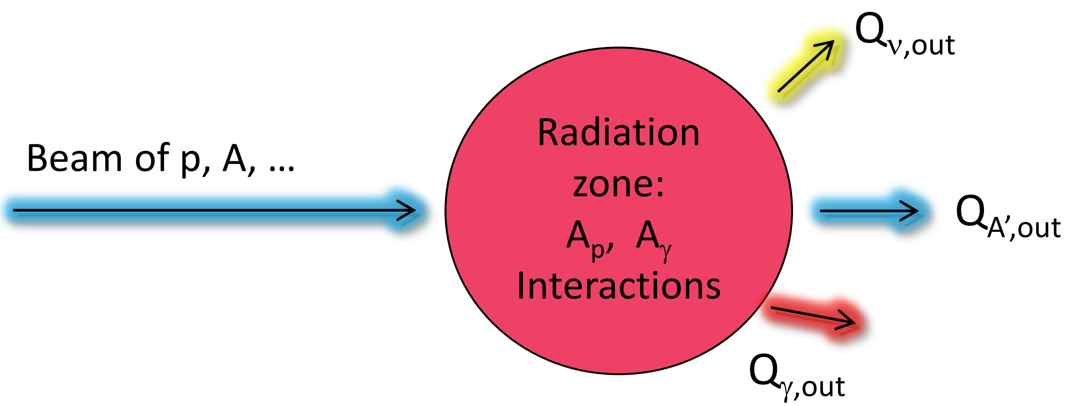
Evolution of density for particle species i

Energy loss:
- synchrotron
- adiabatic
- …

Escape:
- dynamical timescale
- interactions
- decays
- …

$$\tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E)$$

Injection from:
- acceleration zone
- interactions or decays



How does nuclear physics enter?

- How often does a nucleus/particle in a source interact?

$$\Gamma_j(E_j) = \int d\varepsilon \int_{-1}^{+1} \frac{d\cos\theta_{j\gamma}}{2} (1 - \cos\theta_{j\gamma}) \cdot n_\gamma(\varepsilon, \cos\theta_{j\gamma})\, \sigma_j^{\mathrm{abs}}(\epsilon_r)$$

Photon energy in nucleus rest frame

$$\epsilon_r = \frac{E_j\, \varepsilon}{m_j}(1 - \cos\theta_{j\gamma})$$

- Depends on target photon field n_γ
- n_γ isotropic in shock rest frame
- σ_j^{abs} from nuclear models or parametrizations
- j = p, n, α, … ^{12}C, …^{56}Fe

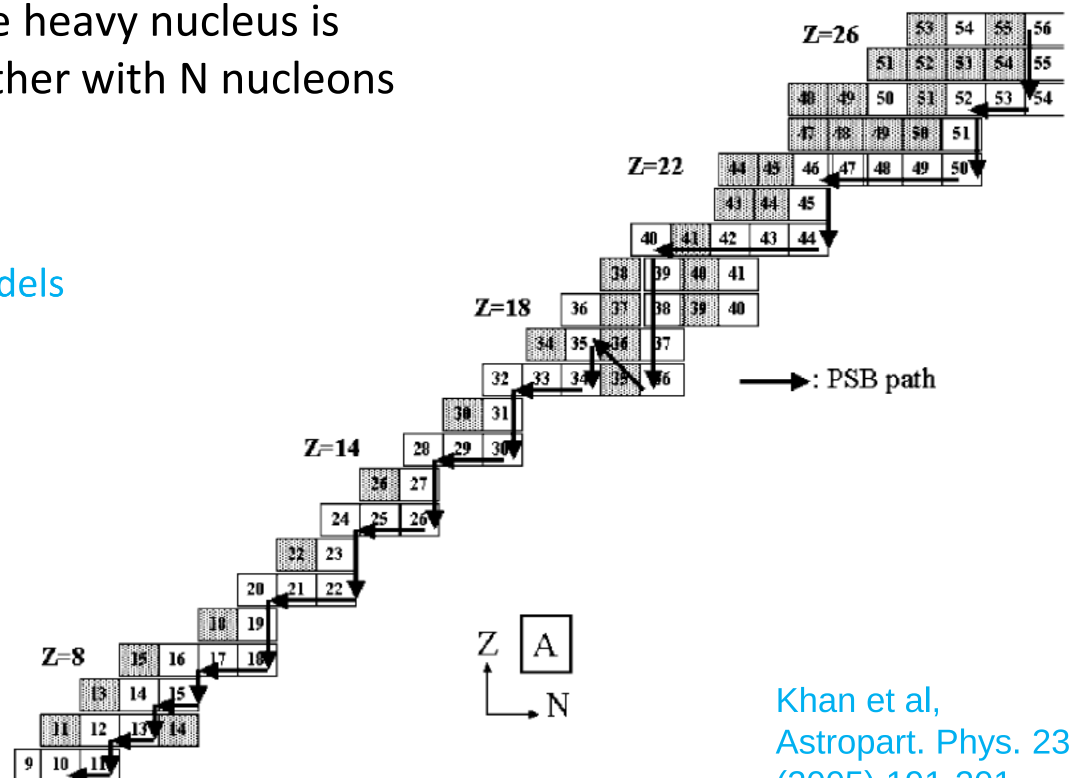
high energy nucleus
+
"low" energy photon
=
photo-nuclear physics in MeV – GeV range

Typical astrophysical "photo-disintegration" models

- Basic (propagation) calculations were based on PSB Puget et al Astrophys.J. 205 (1976) 638-654
- Only one stable isotope per isobar (same A)
- In each photodisintegration, one heavy nucleus is produced in the final state together with N nucleons
- No competitive channels

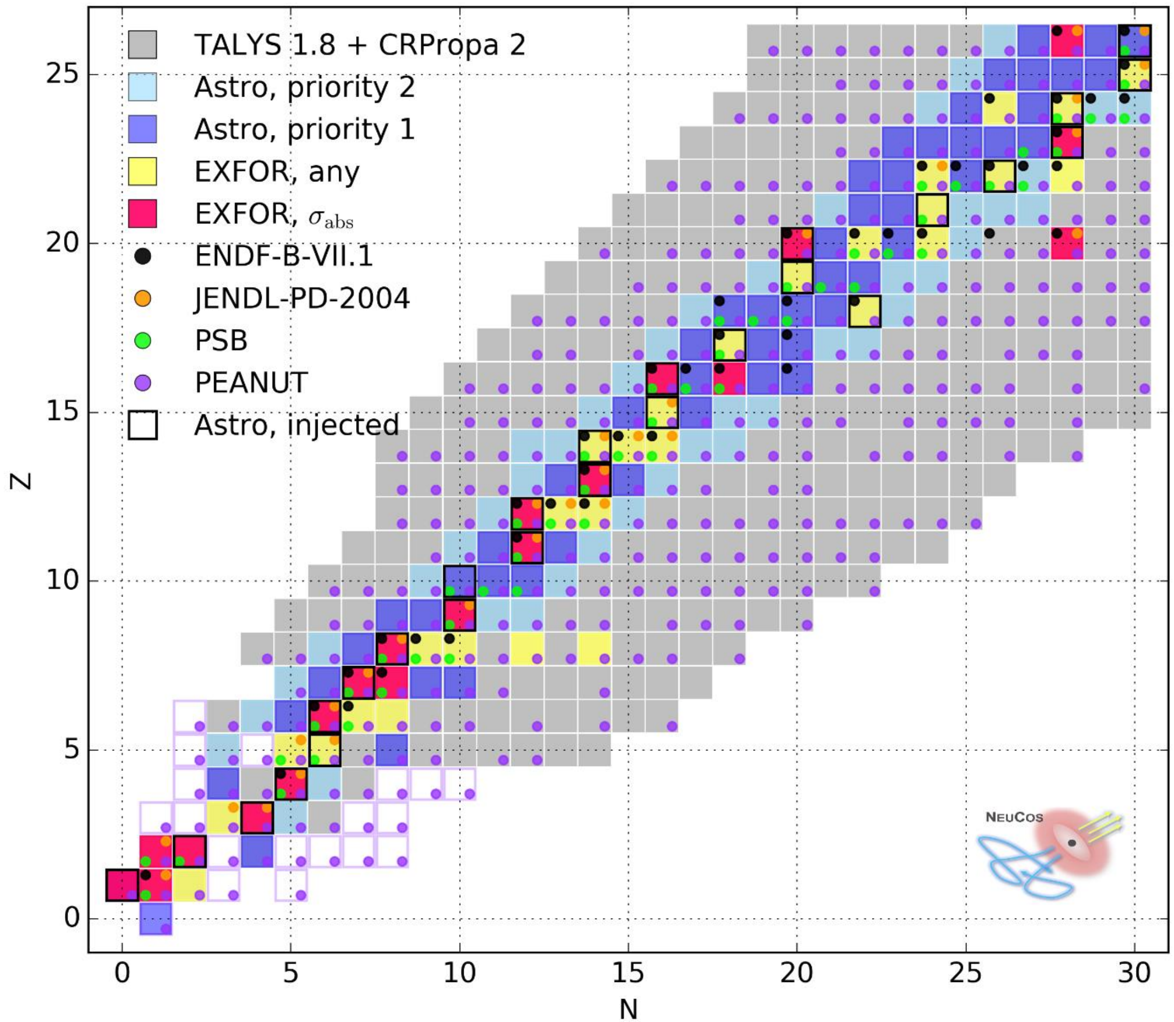
Or more sophisticated interaction models

- CRPropa 2/3
- based on TALYS for A >= 12
- Data and GEANT 4 for A < 12
- Competitive channels + some optimization



Khan et al, Astropart. Phys. 23 (2005) 191-201

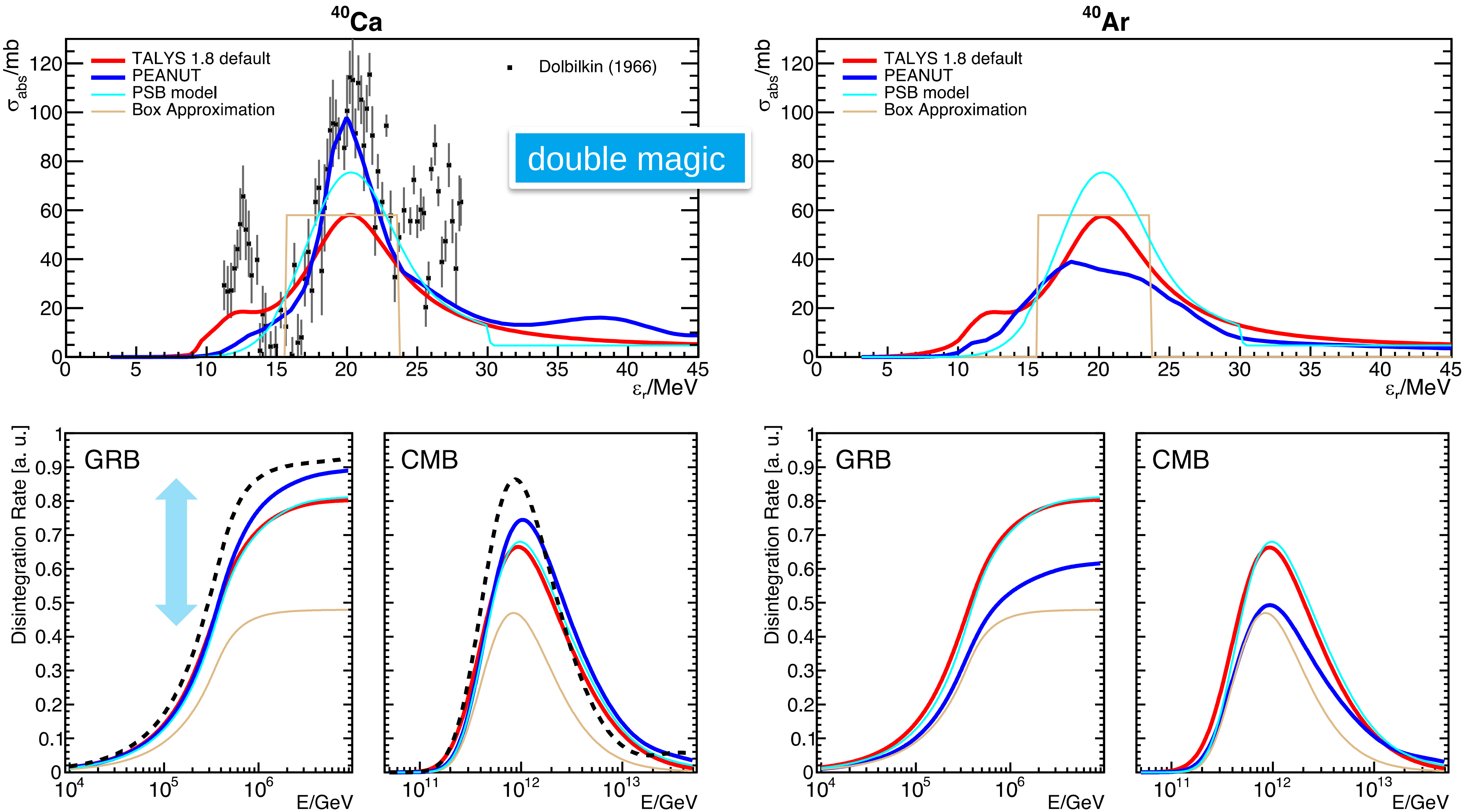
Known nuclear absorption cross sections up to mid-heavy isotopes



- EXFOR database contains 14 absorption cross sections < Fe
- 47 measurements where at least one inclusive cross section available
- Nuclear model dependent σ_{abs} possible
- Located mostly on main diagonal (stable elements)
- All other isotopes need model prediction!

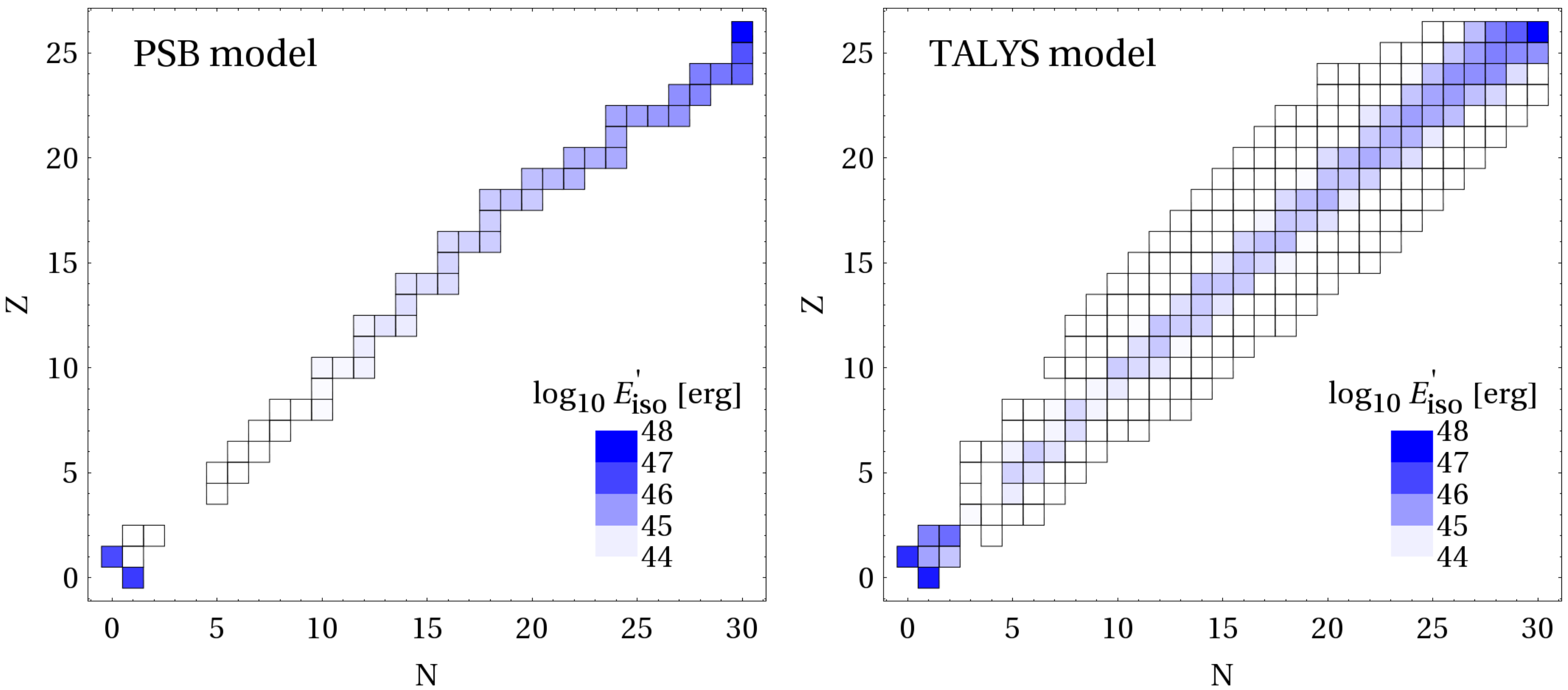
D. Boncioli, A. Fedynitch and W. Winter
arXiv:1607.07989

Example 1: Calcium-40



Up to factor two differences in disintegration rates!

Elemental compostion in disintegration chain of GRB

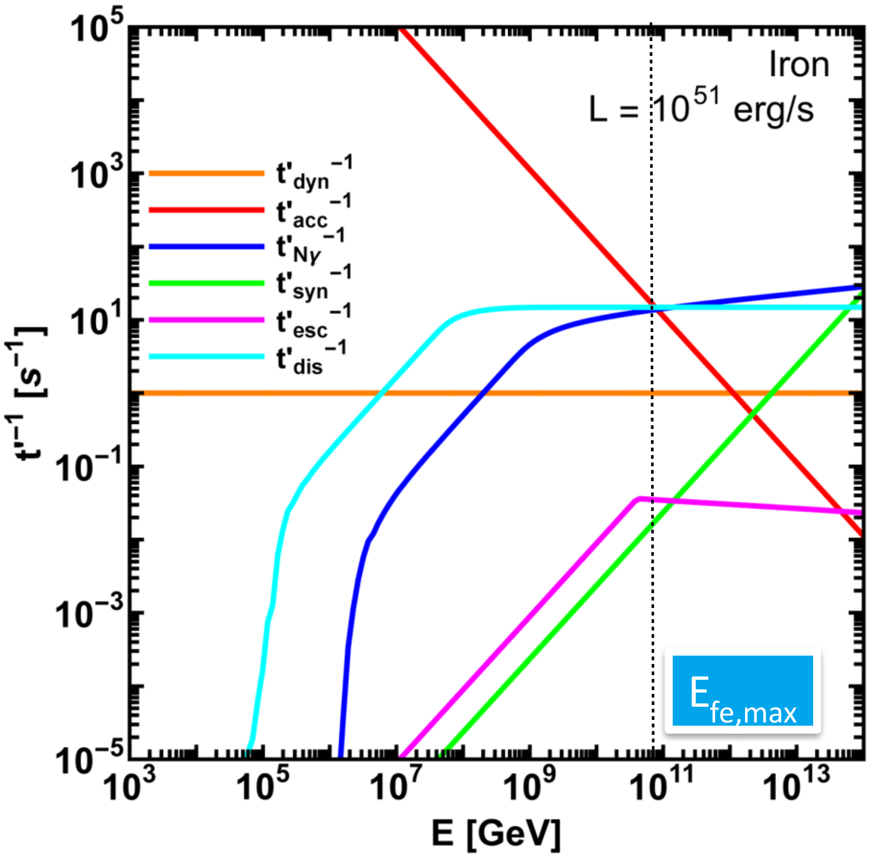


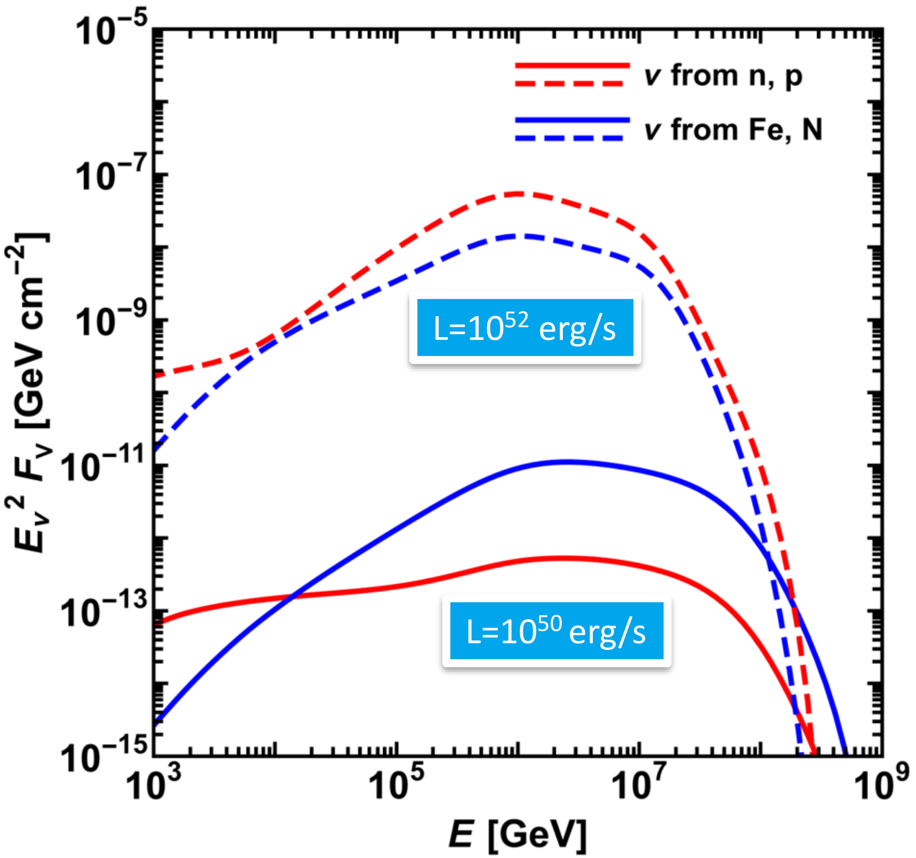
- Obtained by injecting only iron in a GRB
- PSB disintegration chain goes not down to light elements; multi-nucleon emission and break-up weakly described

Connection between neutrinos and composition at the source

Competing process in a GRB model

Daniel Biehl, DESY Z.

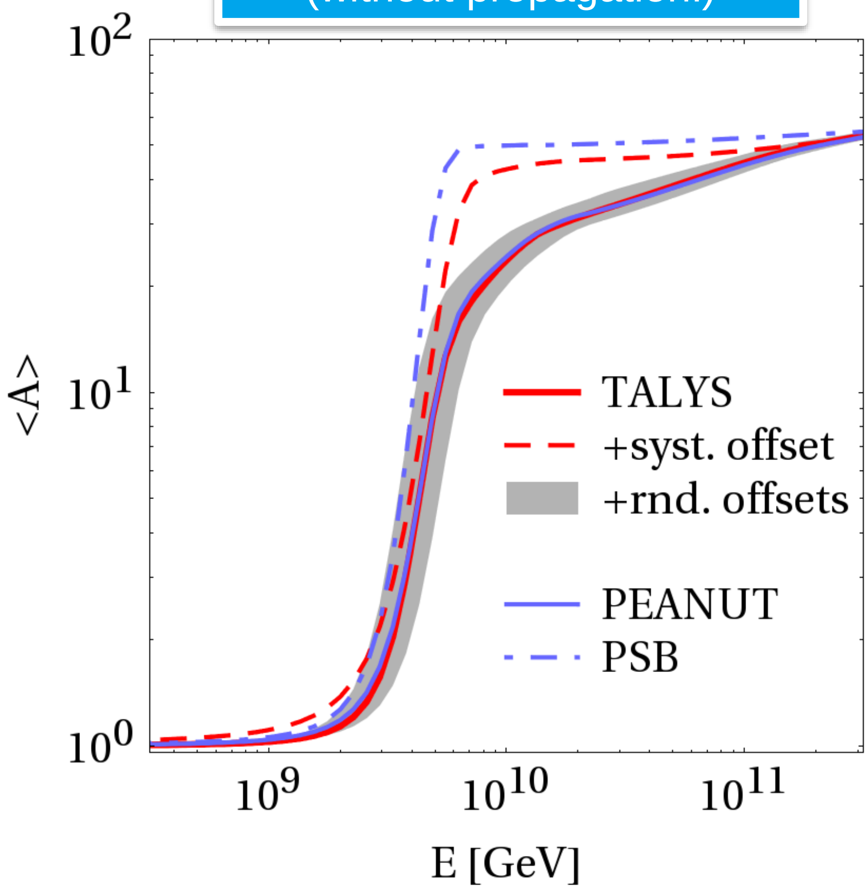




Can sources of UHECR nuclei be an important source for neutrinos at the same time?

Conclusions

Composition after source (without propagation!)

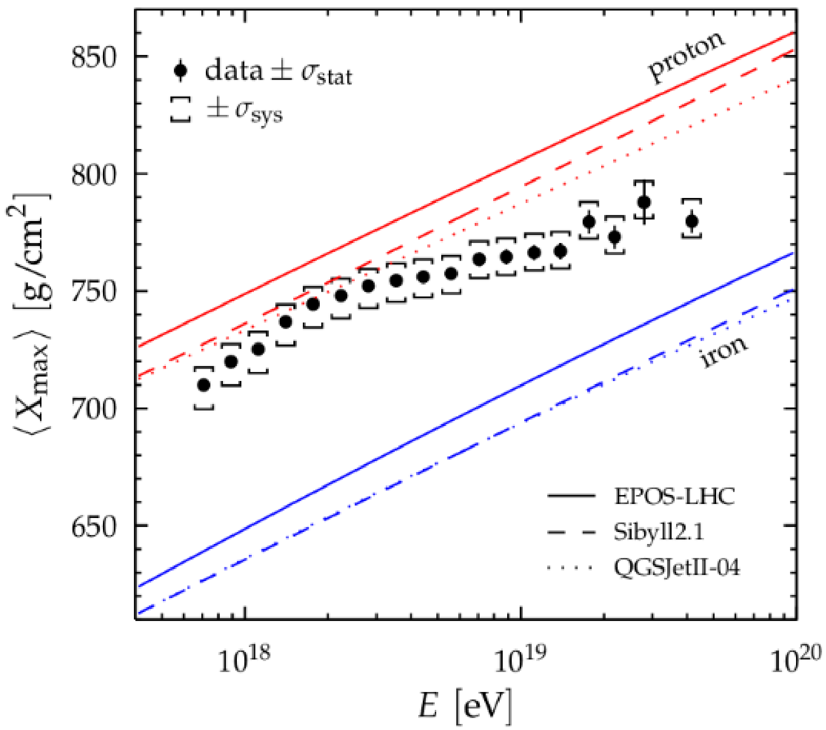


- Simplified nuclear models produce over-simplified results
- More realistic models predict a softer transition from light to heavier composition
- Predictive power for unstable elements is serious source of uncertainty
- Need for (exp.) verification of photo-nuclear σ_{abs} for unstable elements

Backup

Acceleration of heavy nuclei and their role for neutrinos

Auger Collaboration, ICRC 2015

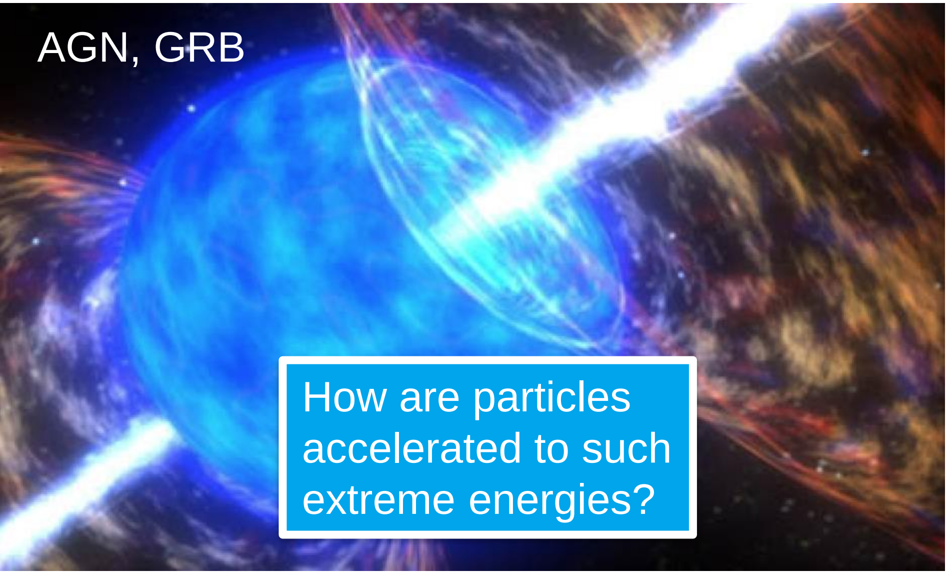


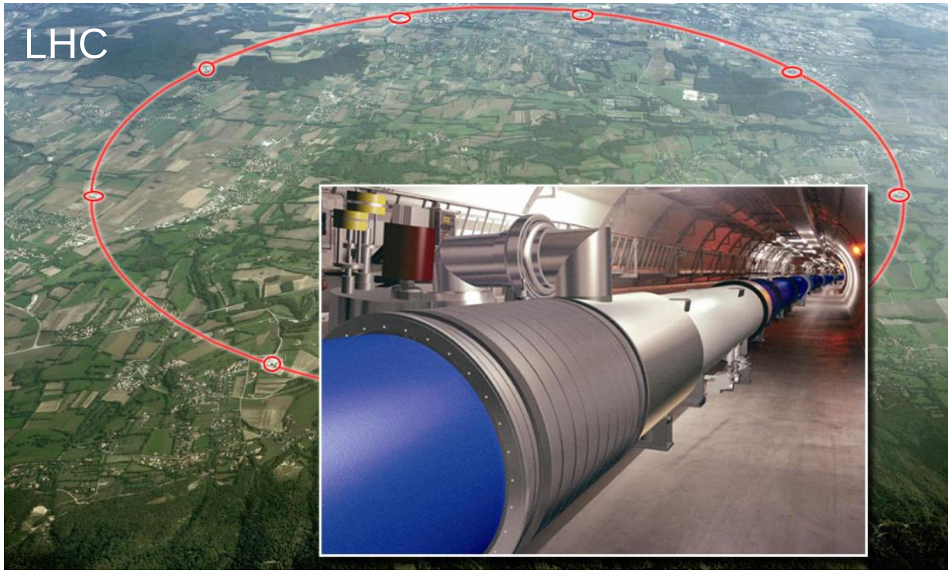
- Thanks to Auger we know that at highest energies are not just protons
- Efficiency of acceleration and abundance of heavy nuclei is one question

Our questions:

- What are the conditions for escape of nuclei from the various source classes?
- How does the presence of nuclei affect the expected flux of neutrinos and their flavors?

Cosmic vs. terrestrial particle accelerators





Lorentz force = centrifugal force → $E_{max} \sim q\,B\,R$

E_{max} ~ **300,000,000 TeV**

B ~ 1 mT – 1 T

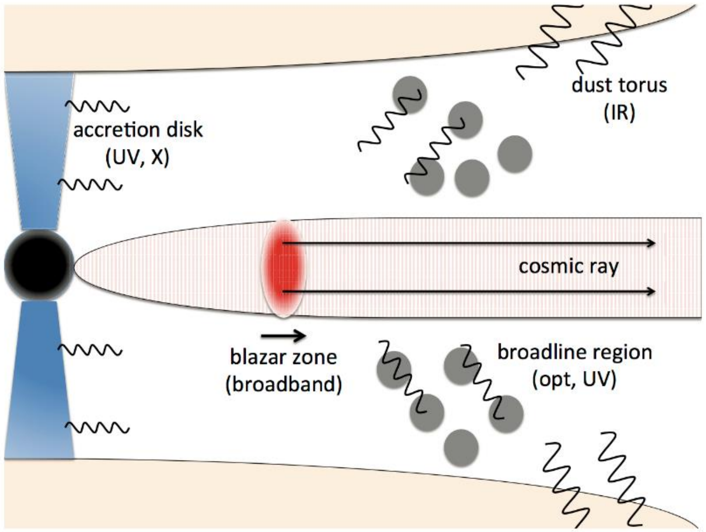
R ~ 100,000 – 10,000,000,000 km

E_{max} ~ 13 TeV

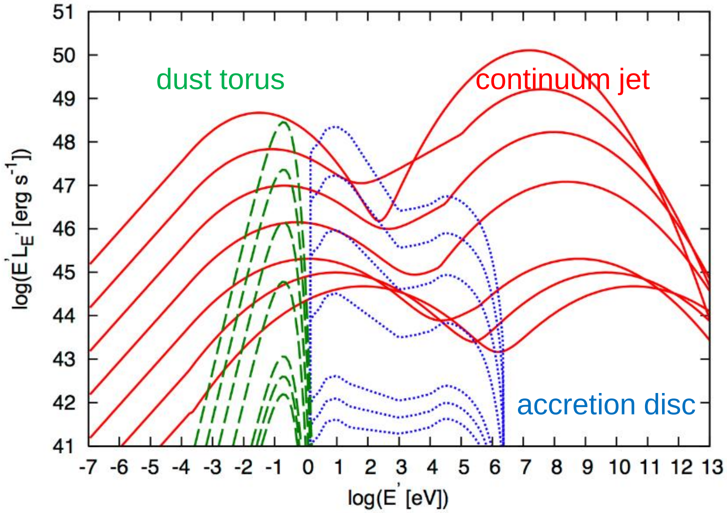
B > 8 T

R ~ 4.3 km

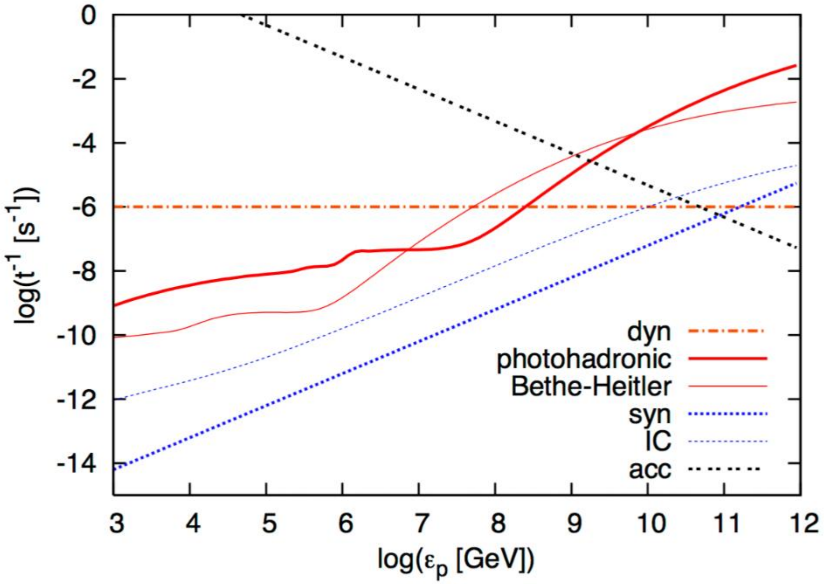
Source candidates: Active Galactic Nuclei



Target photon density



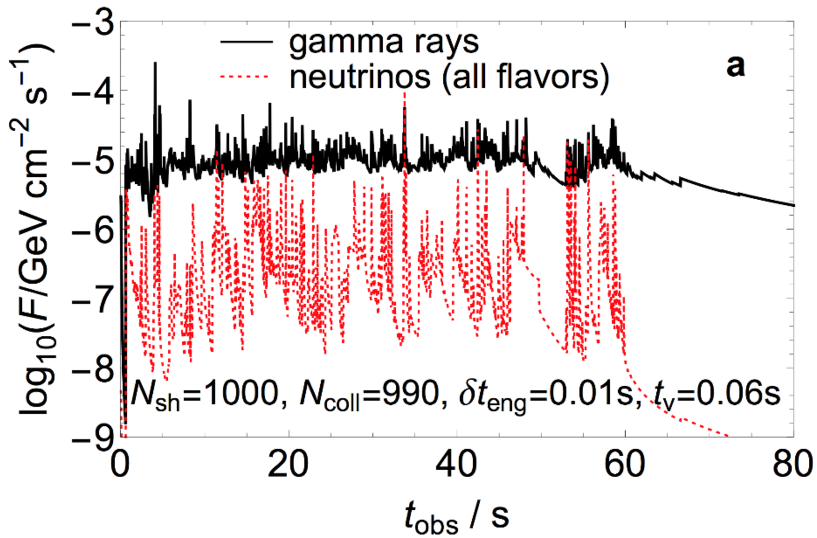
K. Murase et al. Phys.Rev.D 90 (2014) 023007

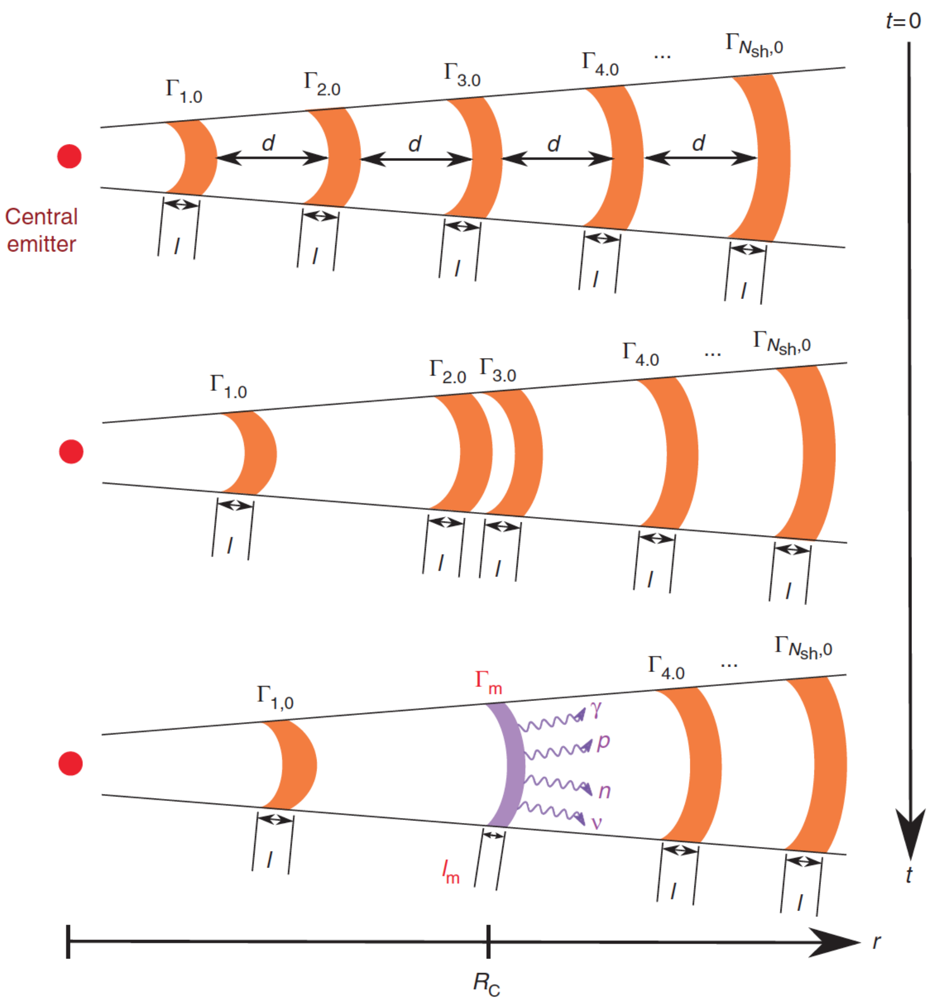


- Longer dynamical time scales than GRB
- Other processes can limit maximum energy

How can such a model explain the observed light curves?

- Distribute shells with varying Γ
- The light curves can be predicted as a function of the engine parameters
- Efficient energy dissipation (conversion from kinetic to radiated E) requires broad Γ distribution
- Consequence: Collision radii are widely distributed!

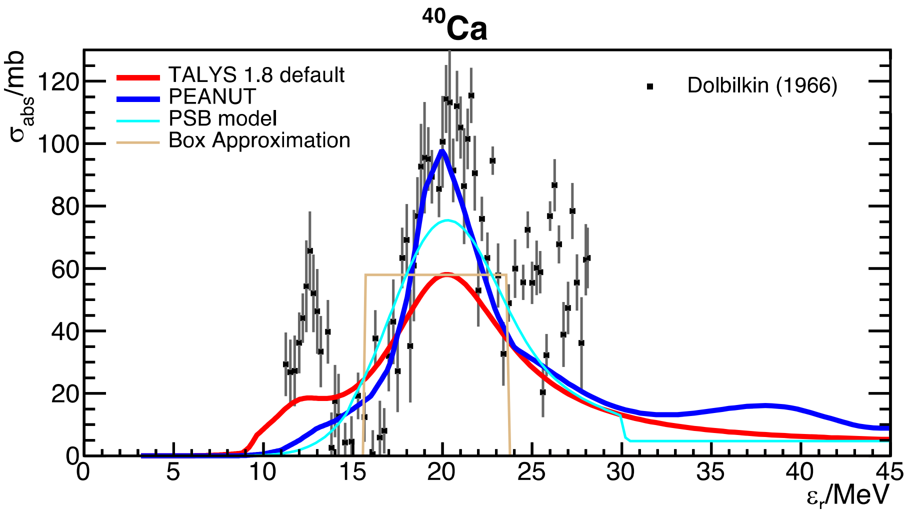


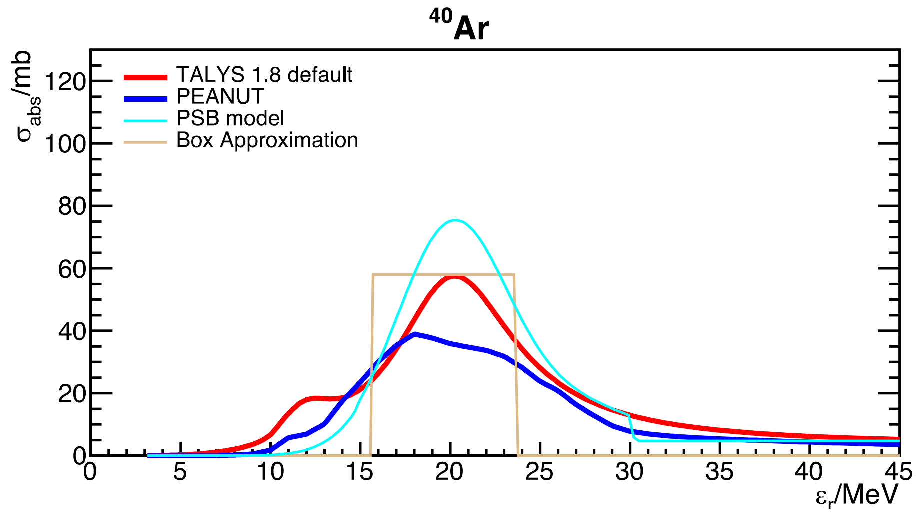


From: Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)

W. Winter

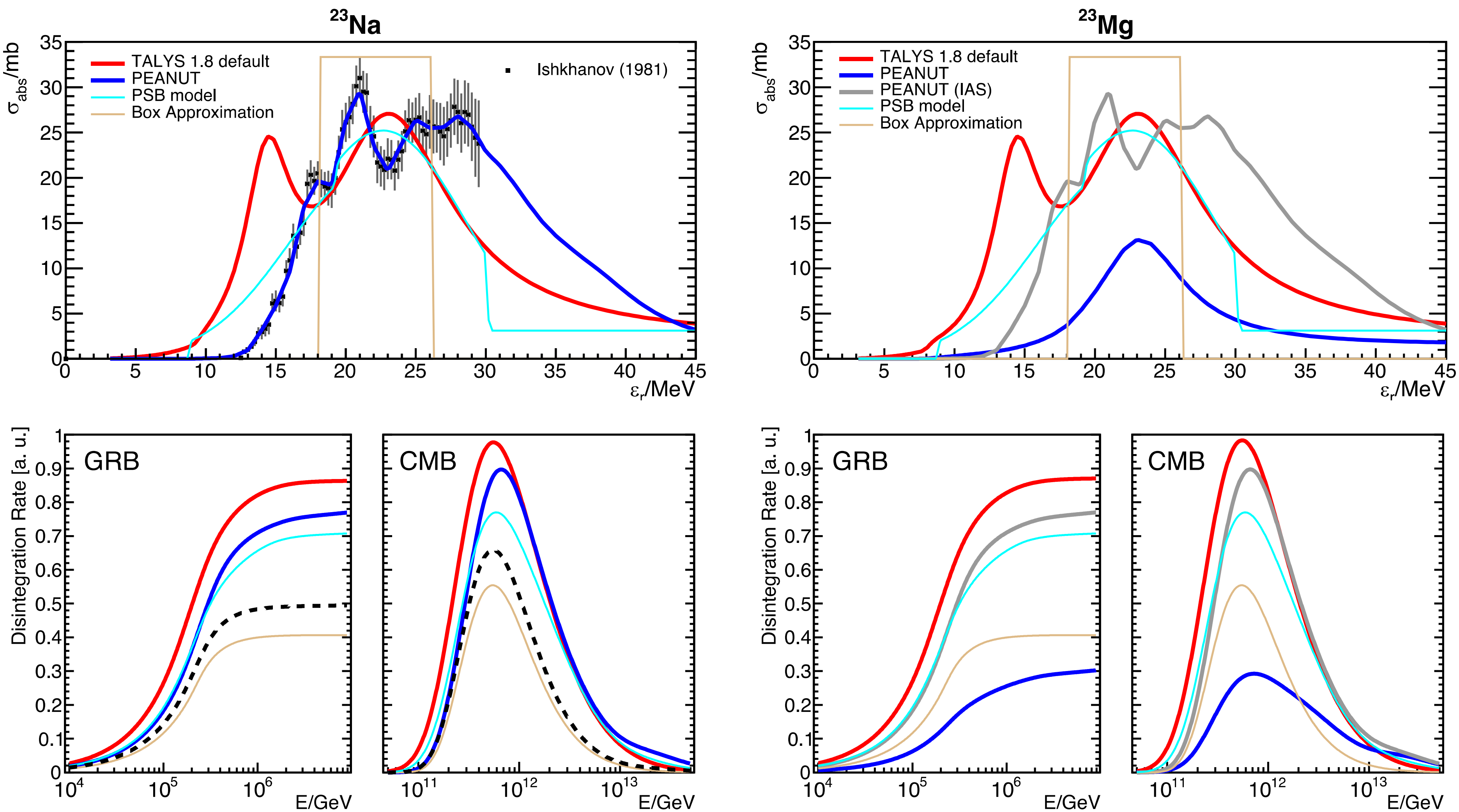
Example 1: Calcium-40





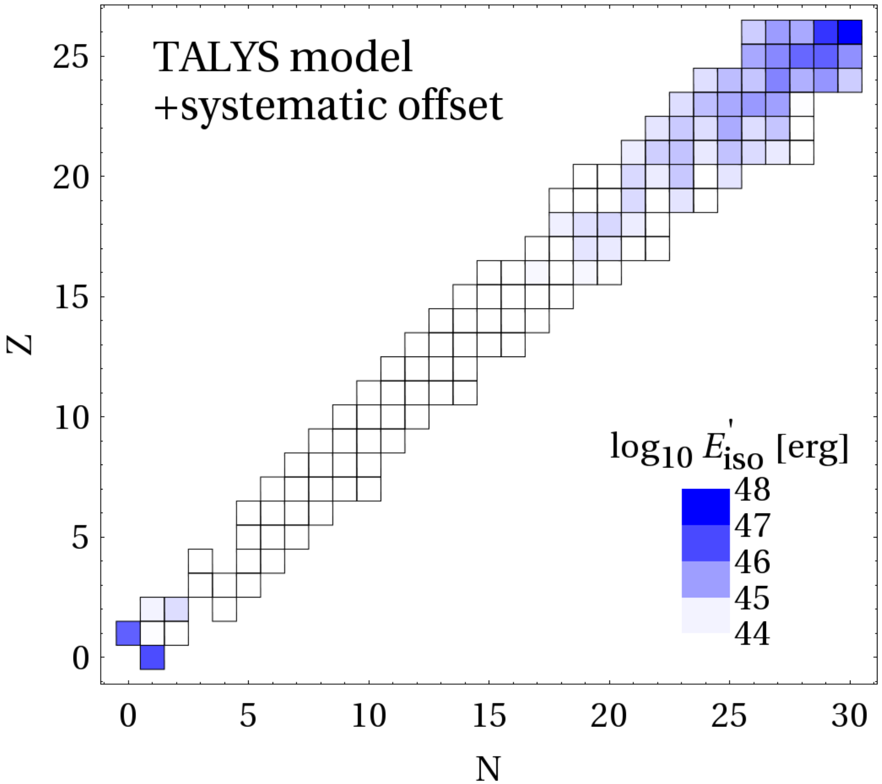
- ^{40}Ca is double magic, ^{40}Ar not. No reason for cross sections to be equal!
- PEANUT reproduces data where available
- Cross sections in TALYS weakly depend on nuclear mass, and very weakly on element
- Astrophysical box model (e.g. in Murase and Beacom, Phys Rev. D81 2010) has insufficient description

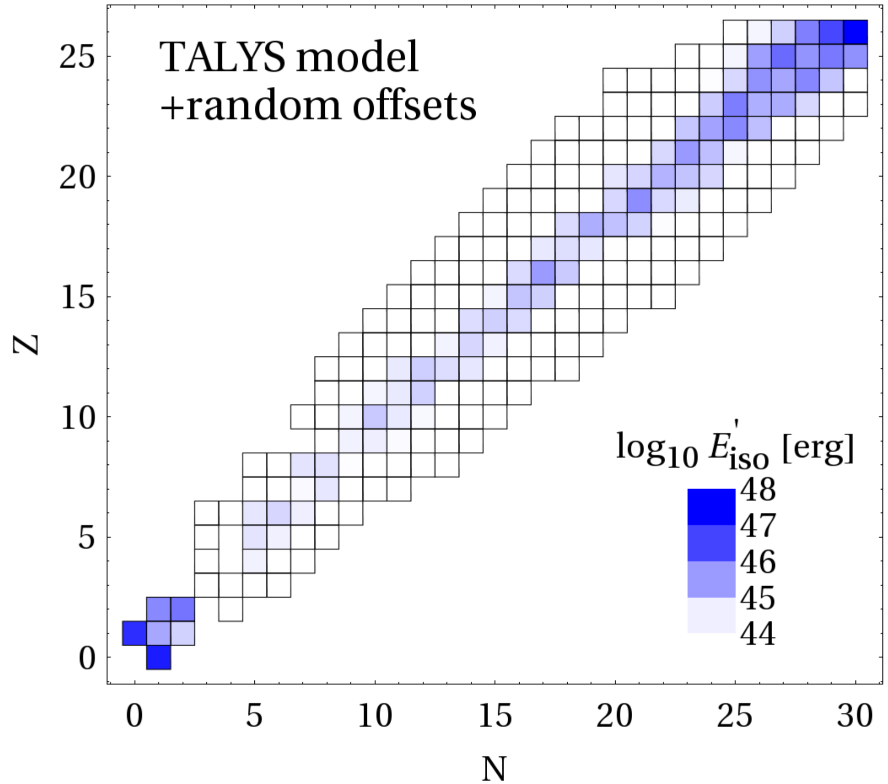
Example 2: Sodium-23



^{23}Mg is Isobar Analog State (IAS) of ^{23}Na: meaningful to assume similar cross sections

Treatment of uncertinaties





- Random offsets: unmeasured cross sections are varied by factor 0…2 randomly, those with some certainty between 0.5…1.5
- Systematic offset = “don’t trust unmeasured cross sections”

A simple toy model for the source

If neutrons can escape:
Source of cosmic rays

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutrinos produced in
ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

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

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

Delta resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Cosmic messengers

$$\pi^0 \longrightarrow \gamma + \gamma$$

High energetic gamma-rays;
typically cascade down to lower E
Additional constraints!

(Same process during propagation of cosmic
rays in CMB: "cosmogenic neutrinos")

How do cosmic rays escape from the source?

Three extreme cases:

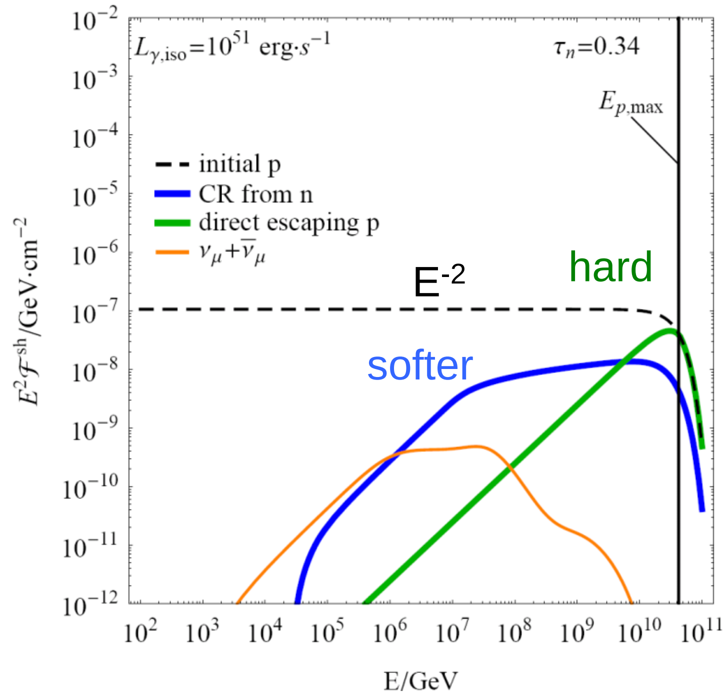
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

- **Neutron model**
  Neutrinos and cosmic rays (from neutrons) produced together
  (depends on pion prod. efficiency, blue curve, softer)
  (pure neutron model excluded in IceCube, Nature 484 (2012) 351)

- **Direct escape** (aka "high pass filter", "leakage")
  Cosmic rays can efficiently escape if Larmor radius reaches size of shell width
  (conservative scenario, green curve, hard)
  (from:Baerwald, Bustamante, Winter, ApJ 768 (2013) 186; same argument used for nuclei in Globus et al, 2014)

- **"All escape"**: magnetic fields decay quickly enough that charged cosmic rays can escape (most aggressive scenario, dashed curve, ~ E^{-2})

- Diffusion, …



(without prop. effects)

In the presence of strong B: Secondary cooling

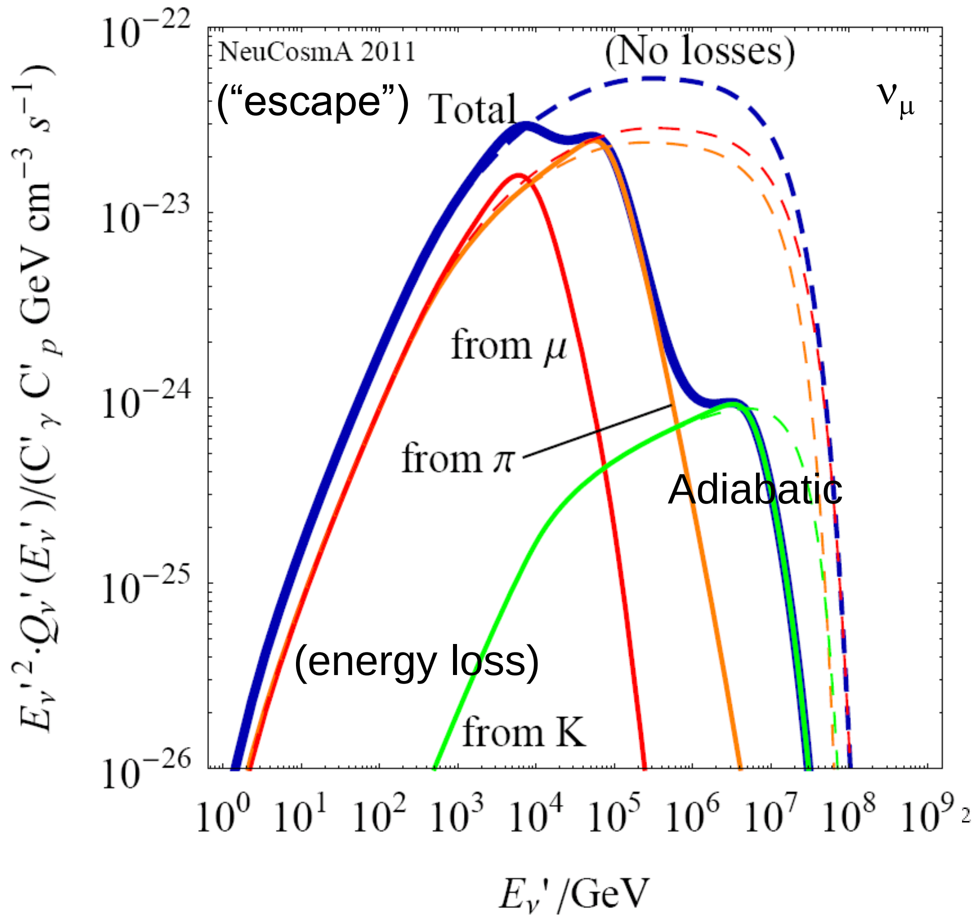
Example: GRB

- Secondary spectra (m, p, K) loss-steepend above critical energy

$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

  - E‘$_c$ depends on particle physics only (m, t_0), and **B‘**
  - Leads to characteristic flavor composition and shape

Decay/cooling: charged μ, π, K



Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508;
also: Kashti, Waxman, 2005; Lipari et al, 2007; ...