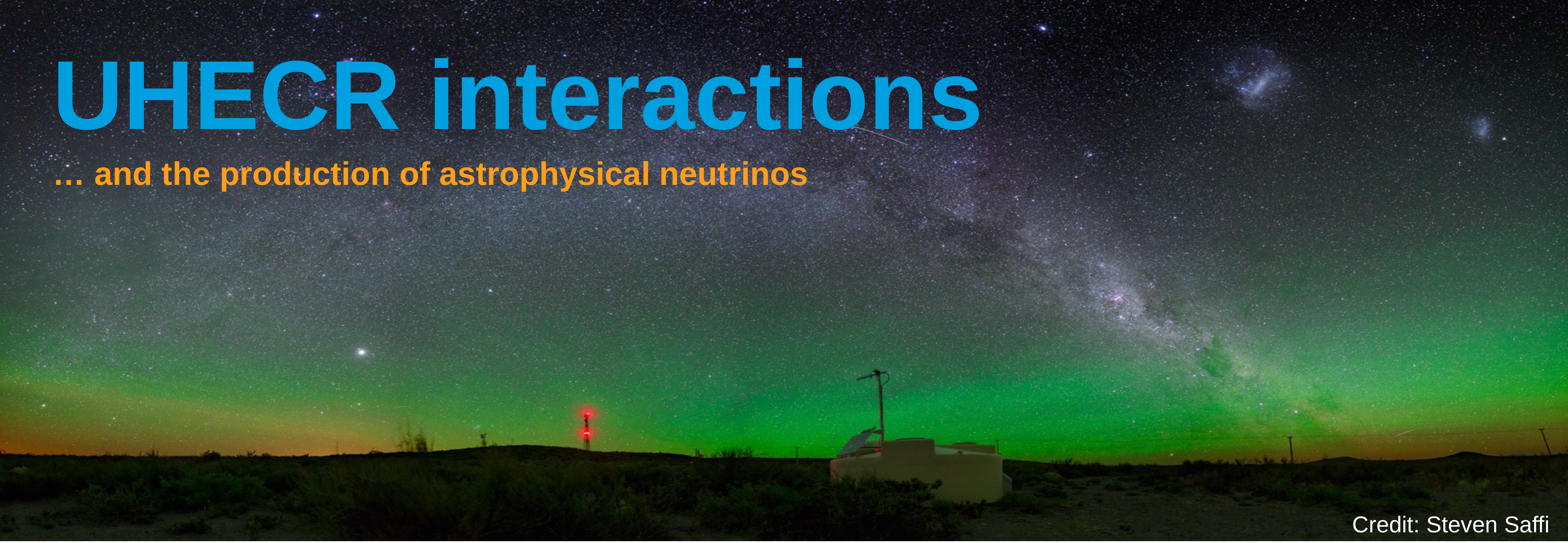
UHECR interactions

… and the production of astrophysical neutrinos



Credit: Steven Saffi

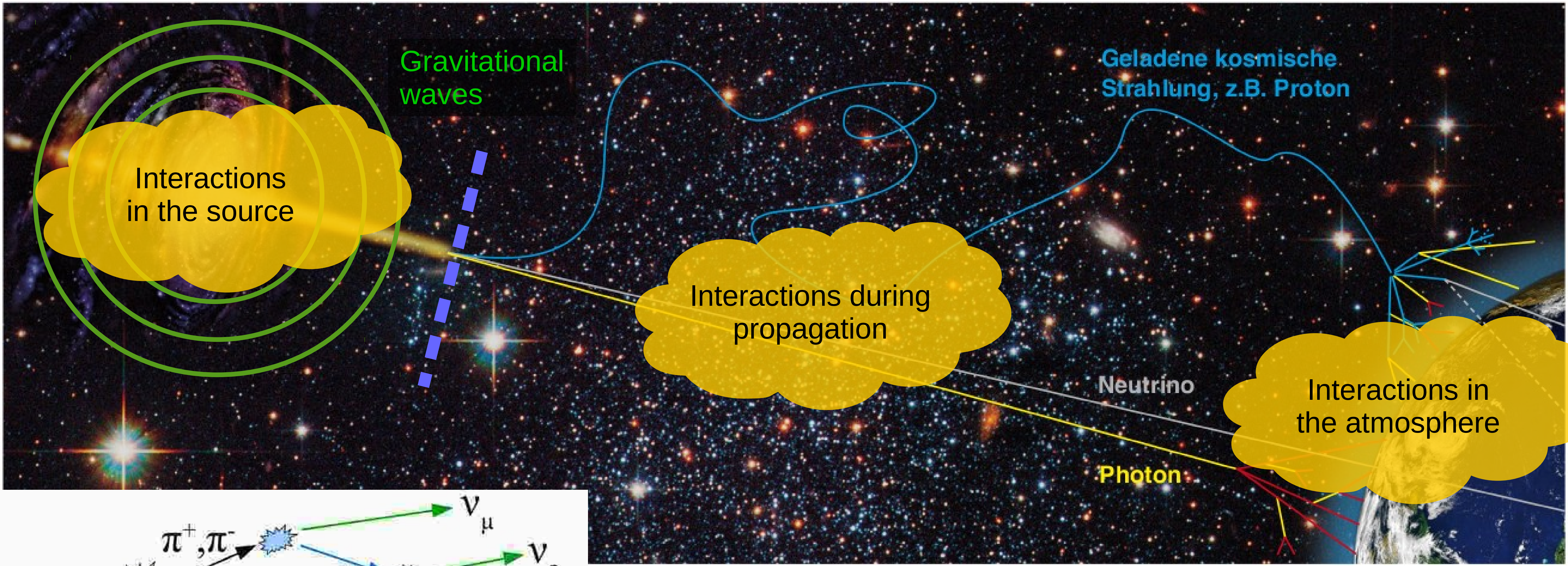
Daniel Biehl
DESY Zeuthen, Germany

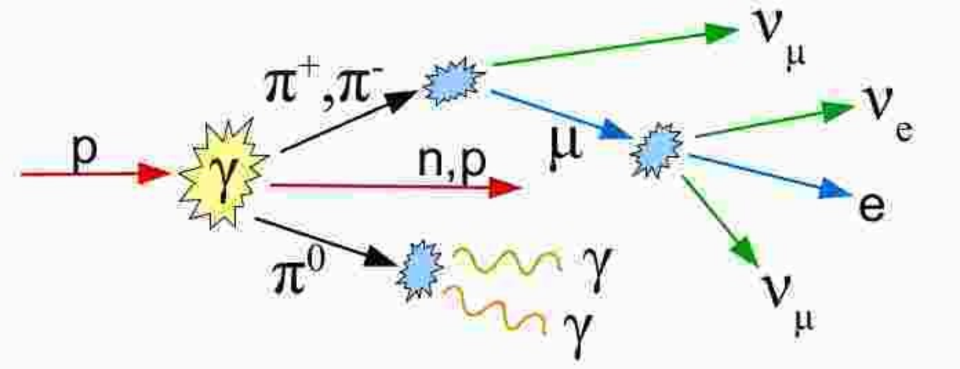
20th ISVHECRI, Nagoya University
May 21, 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Interactions of UHECRs in the multi-messenger context

The connection between neutrinos and ultra-high energy cosmic rays

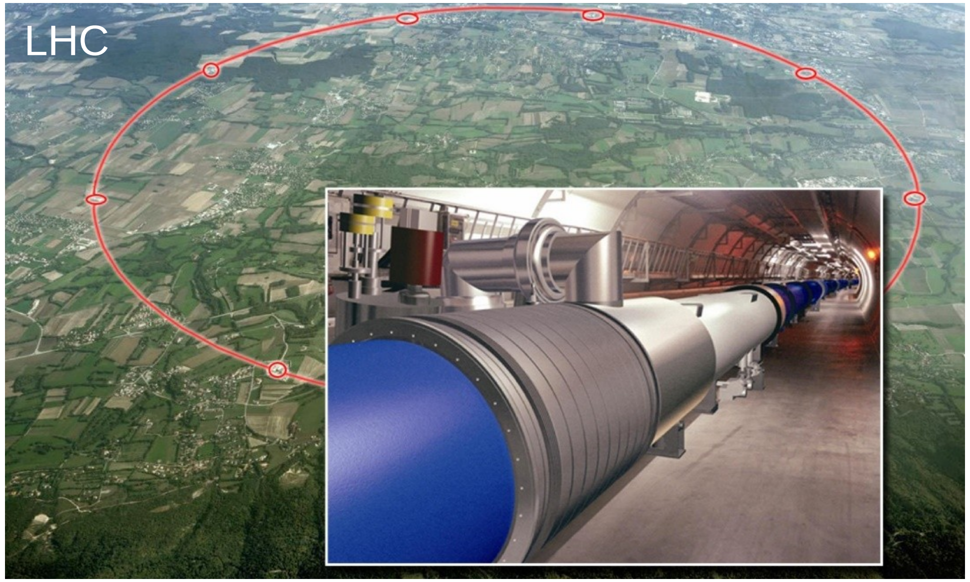




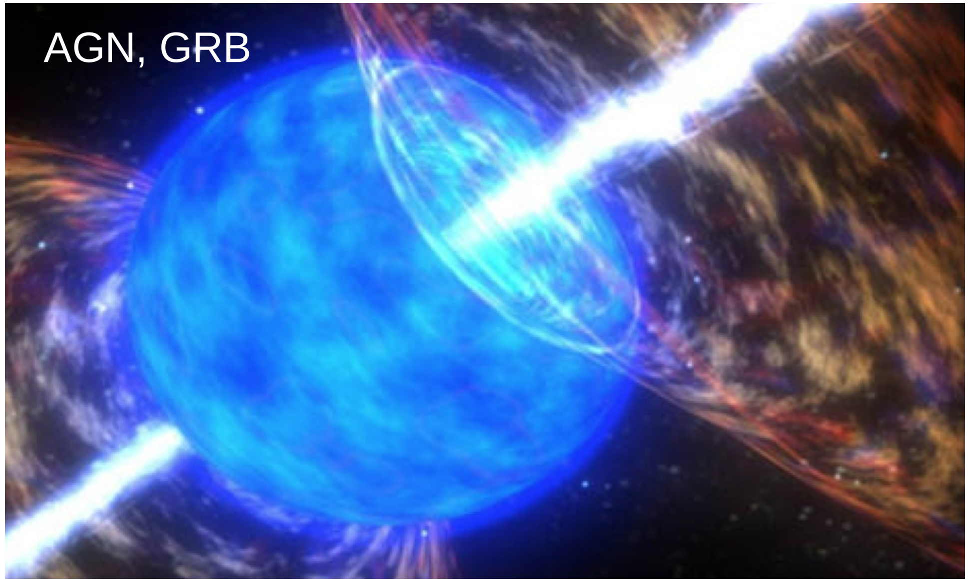
Multi-messenger interpretations rely on our understanding of the involved interactions!

Maximum reachable energy

Why size matters



$E_{max} \sim q\ B\ R$



Terrestrial particle accelerators

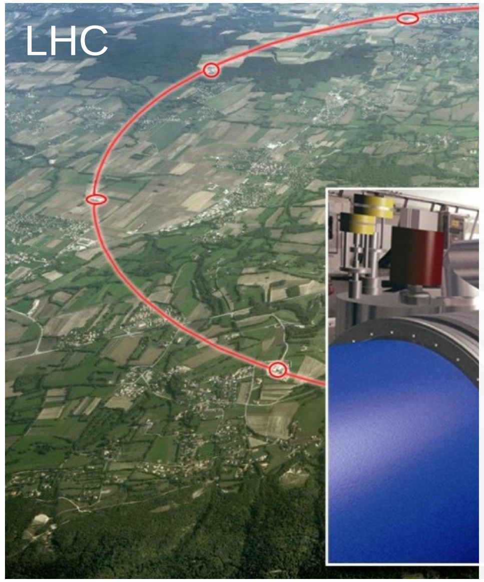
- B > 8 T
- R ~ 4.3 km
- E_{max} ~ 13 TeV

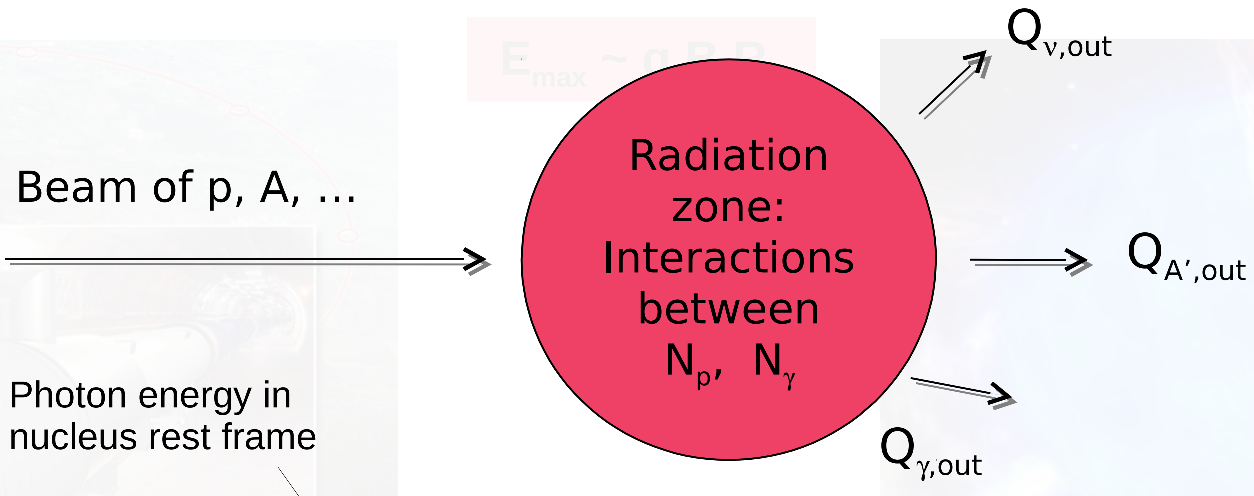
Cosmic particle accelerators

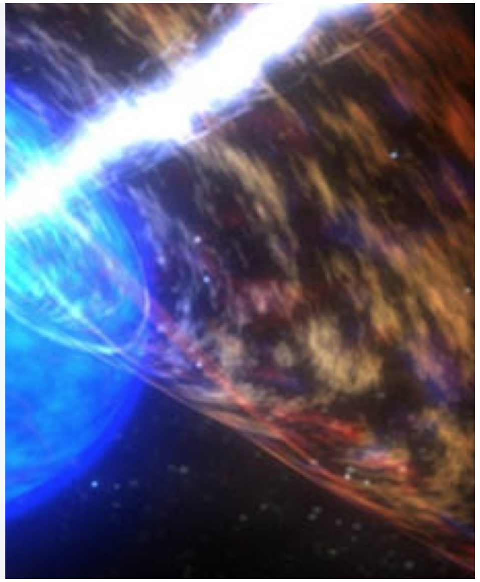
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km
- E_{max} ~ **300,000,000 TeV**

Maximum reachable energy

Why size matters







Photon energy in nucleus rest frame

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

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

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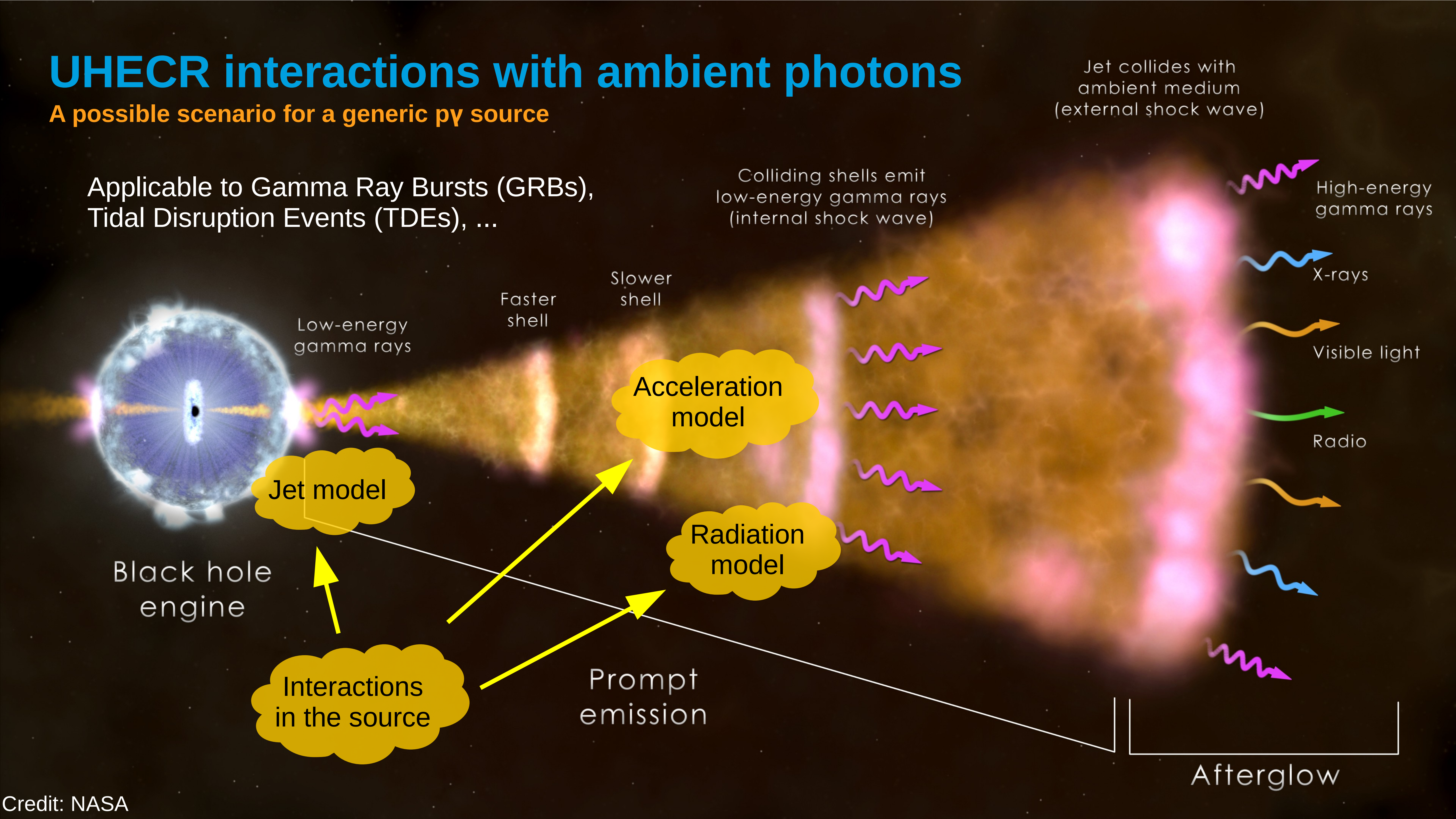
UHECR interactions with ambient photons

A possible scenario for a generic pγ source

Applicable to Gamma Ray Bursts (GRBs), Tidal Disruption Events (TDEs), ...



Credit: NASA

Relevant energy scales for UHECR interactions with photons

High-energy nucleus + 'low energy' photon = photo-nuclear physics in the MeV – GeV range

Photo-hadronic (Aγ) interactions

Photon energy in nucleus rest frame

- **QED scale**: e.g. pair-production

$$A + \gamma \rightarrow A + e^+ + e^- \qquad \varepsilon_r > 1 \text{ MeV}$$

- **Nuclear scale**: nuclear **photo-disintegration**, e.g.

$$A + \gamma \rightarrow (A-1) + n \qquad \varepsilon_r > 8 \text{ MeV}$$

- **Mesonic scale**: baryonic resonances, **photo-meson production** (produces neutrinos), e.g.

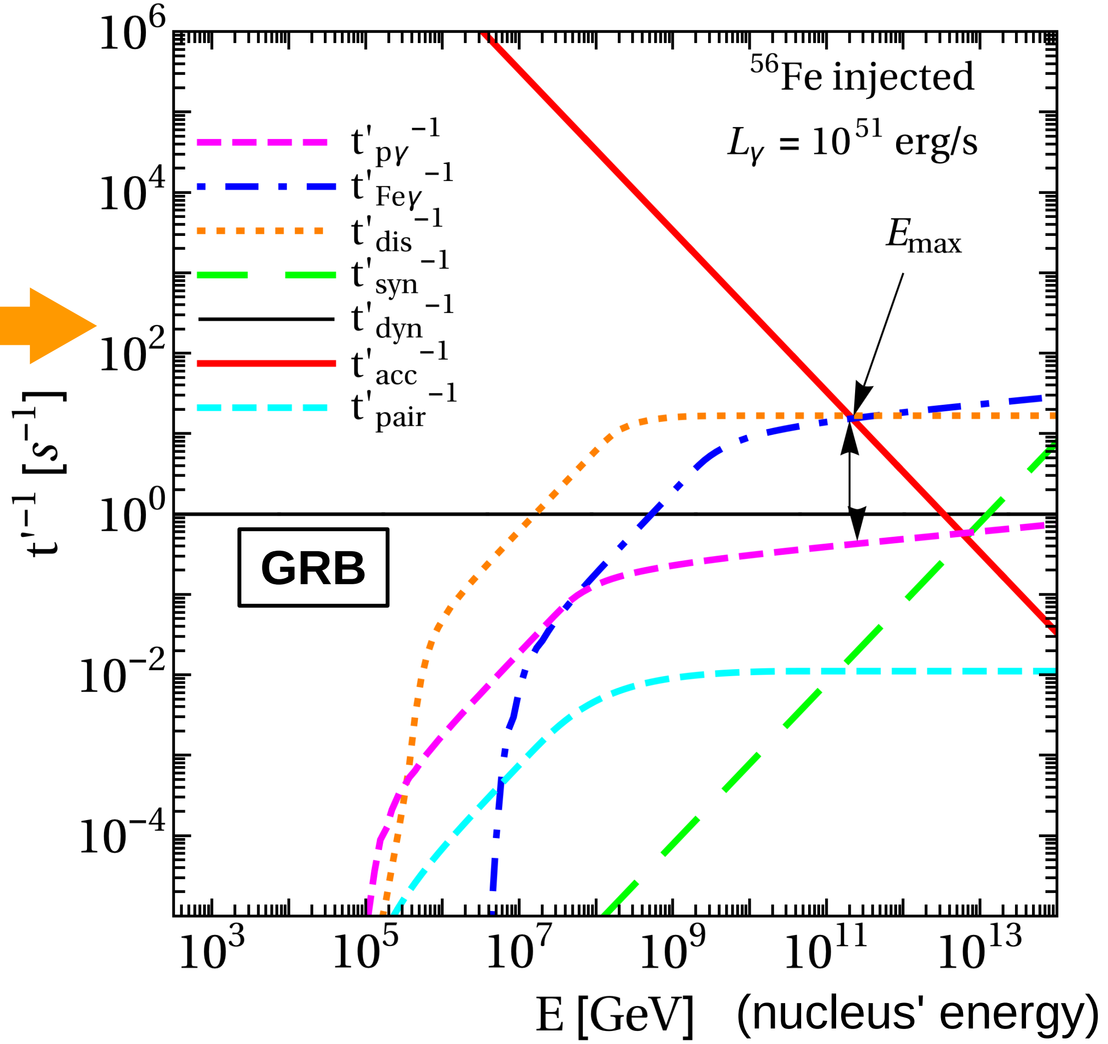
$$A + \gamma \rightarrow \tilde{A} + \pi^+ \qquad \varepsilon_r > 140 \text{ MeV}$$

- **Hadronic scale**: hadronic structure becomes relevant for the interaction

$$\varepsilon_r > 1 \text{ GeV}$$

Other processes

- Beta-decays, pp-interactions, spontaneous nucleon emission, spallation, de-excitation, ...



[**DB**, D. Boncioli, A. Fedynitch, W. Winter – A&A (2018)]

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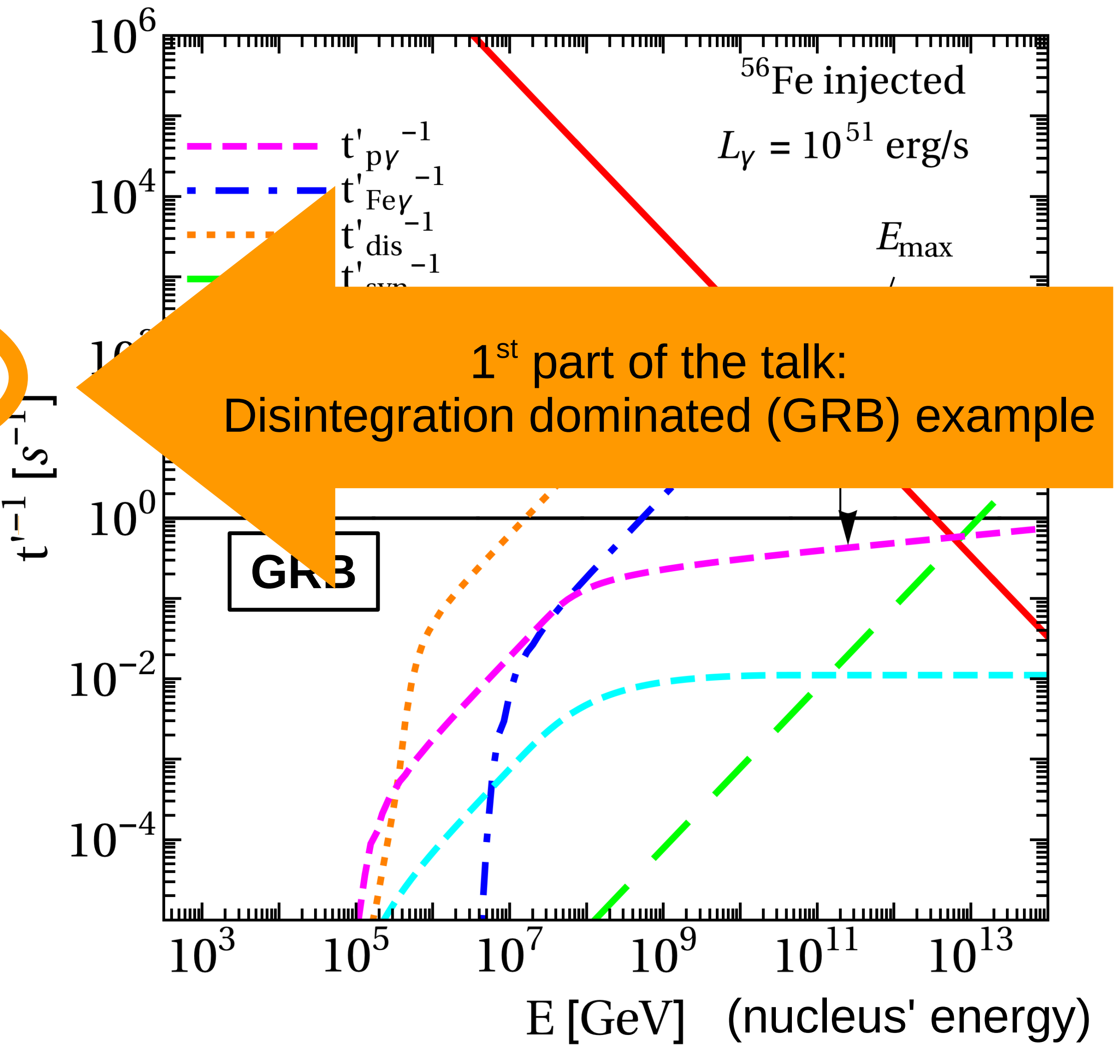


1st part of the talk:
Disintegration dominated (GRB) example

[**DB**, D. Boncioli, A. Fedynitch, W. Winter – A&A (2018)]

Development of the nuclear cascade

A qualitative and quantitative representation of interactions

Triggering the nuclear cascade

- Example: pure iron injected in a GRB shell, different luminosities
- Development of the nuclear cascade scales with the photon density

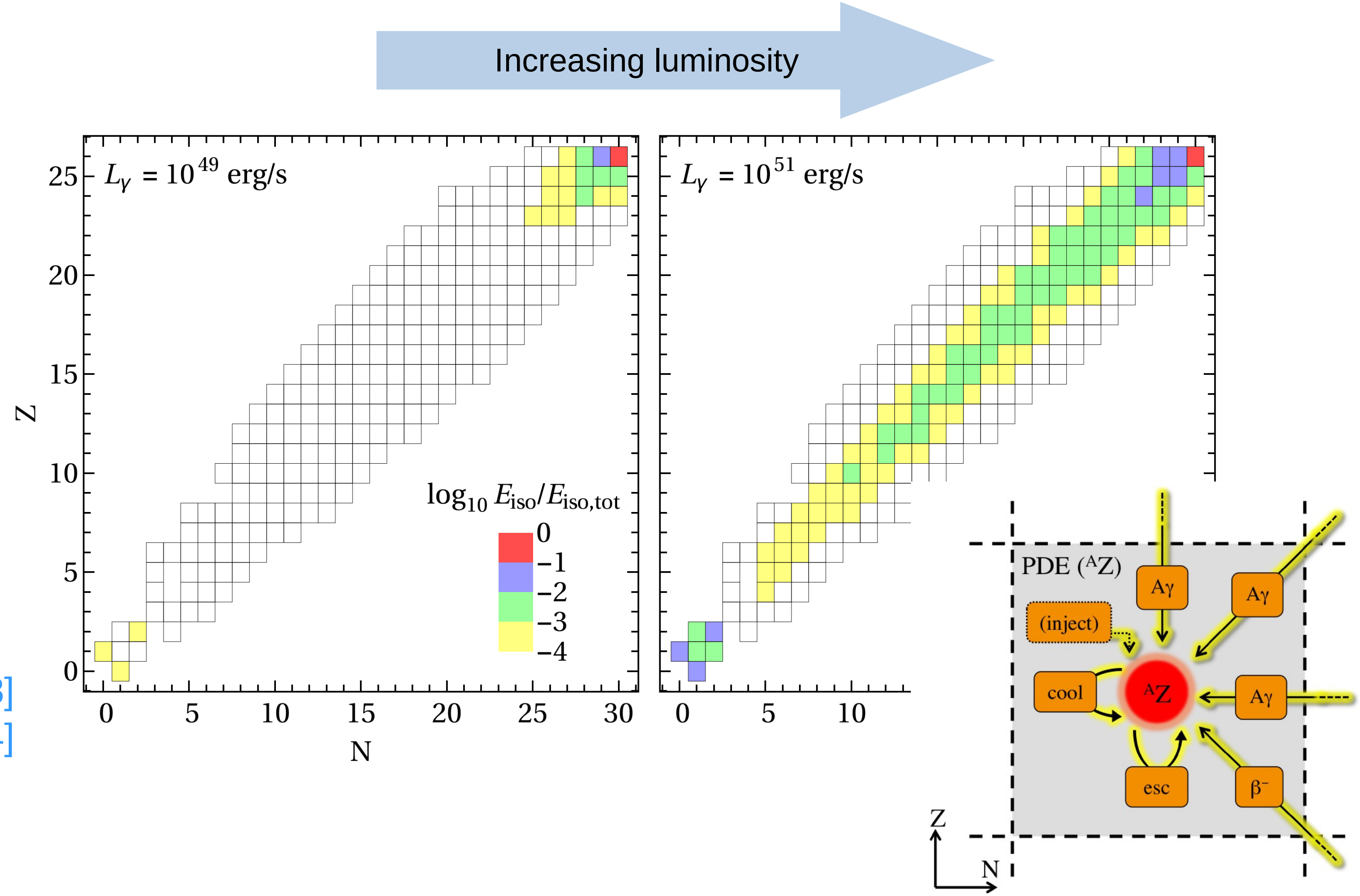
$$u'_\gamma \sim \frac{L_\gamma}{\Gamma^2 R^2}$$

- Internal shock scenario: $R \simeq 2\,\Gamma^2 \, \frac{c\, t_v}{1+z}$

$$\Rightarrow \quad f_{p\gamma} \propto L_\gamma / (\Gamma^4 t_v \epsilon_{\gamma,\mathrm{br}})$$

[Waxman, Bahcall, 1998]
[Guetta et al., 2004]

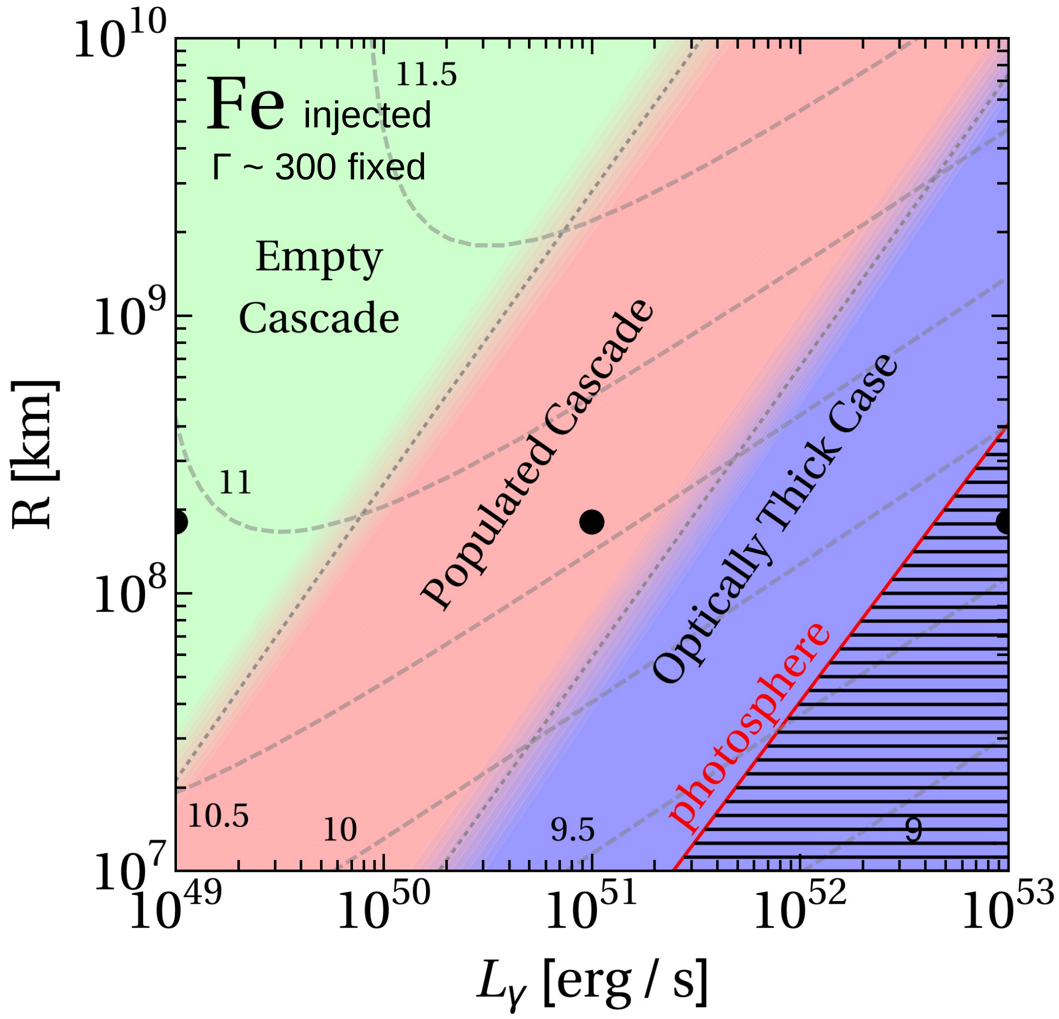
- **Production radius R and luminosity L are the main control parameters for the nuclear cascade and neutrino production**



[DB, D. Boncioli, A. Fedynitch, W. Winter – A&A (2018)]

The nuclear cascade in the parameter space

Classification of interactions regions



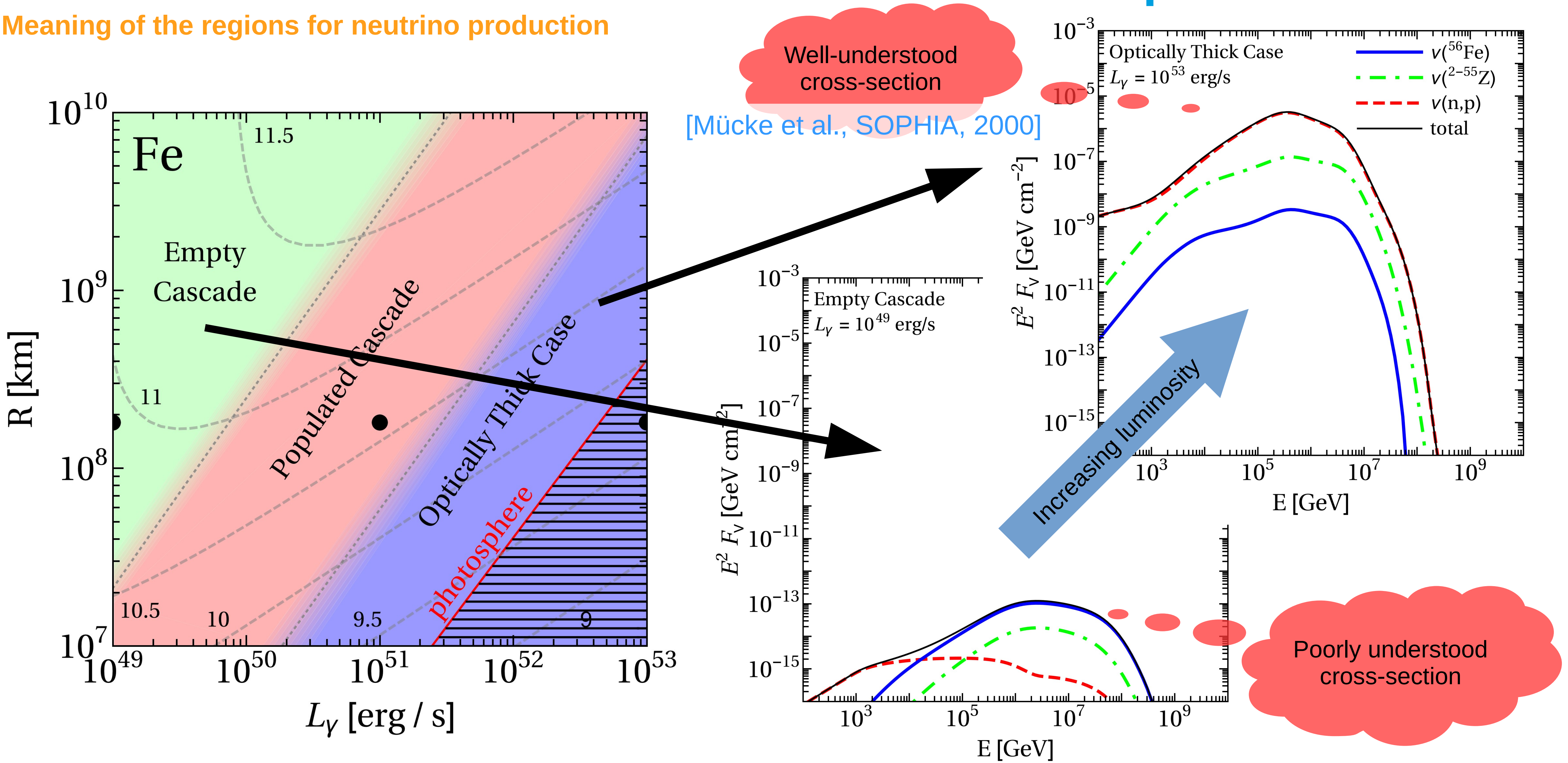
Parameter space regions for interactions

- **Empty cascade**:
  - Optically thin to photo-hadronic interactions of all species
  - Low neutrino production, nuclear cascade does not develop
- **Populated cascade**:
  - Optically thick to nuclei heavier than protons
  - Intermediate neutrino production, broad cascade develops
- **Optically thick case**:
  - Optically thick to all particles
  - High neutrino production, narrow cascade along the main diagonal

[**DB**, D. Boncioli, A. Fedynitch, W. Winter – A&A (2018)]

UHECR interactions as a measure for neutrino production

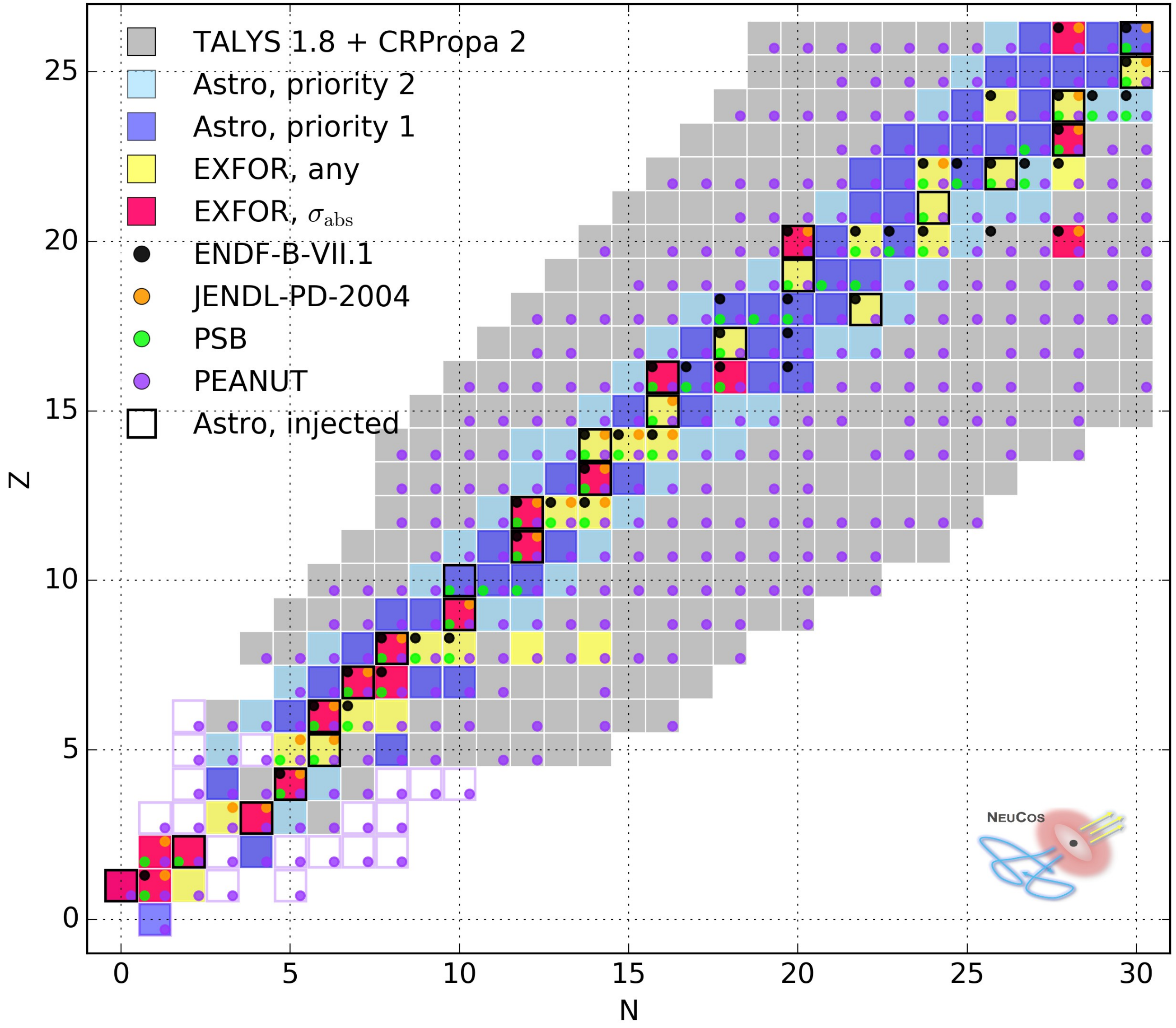
Meaning of the regions for neutrino production



[**DB**, D. Boncioli, A. Fedynitch, W. Winter – A&A (2018)]

Current situation on experimental data and theoretical models

Importance of future measurements and improved models



EXFOR data base cross-sections

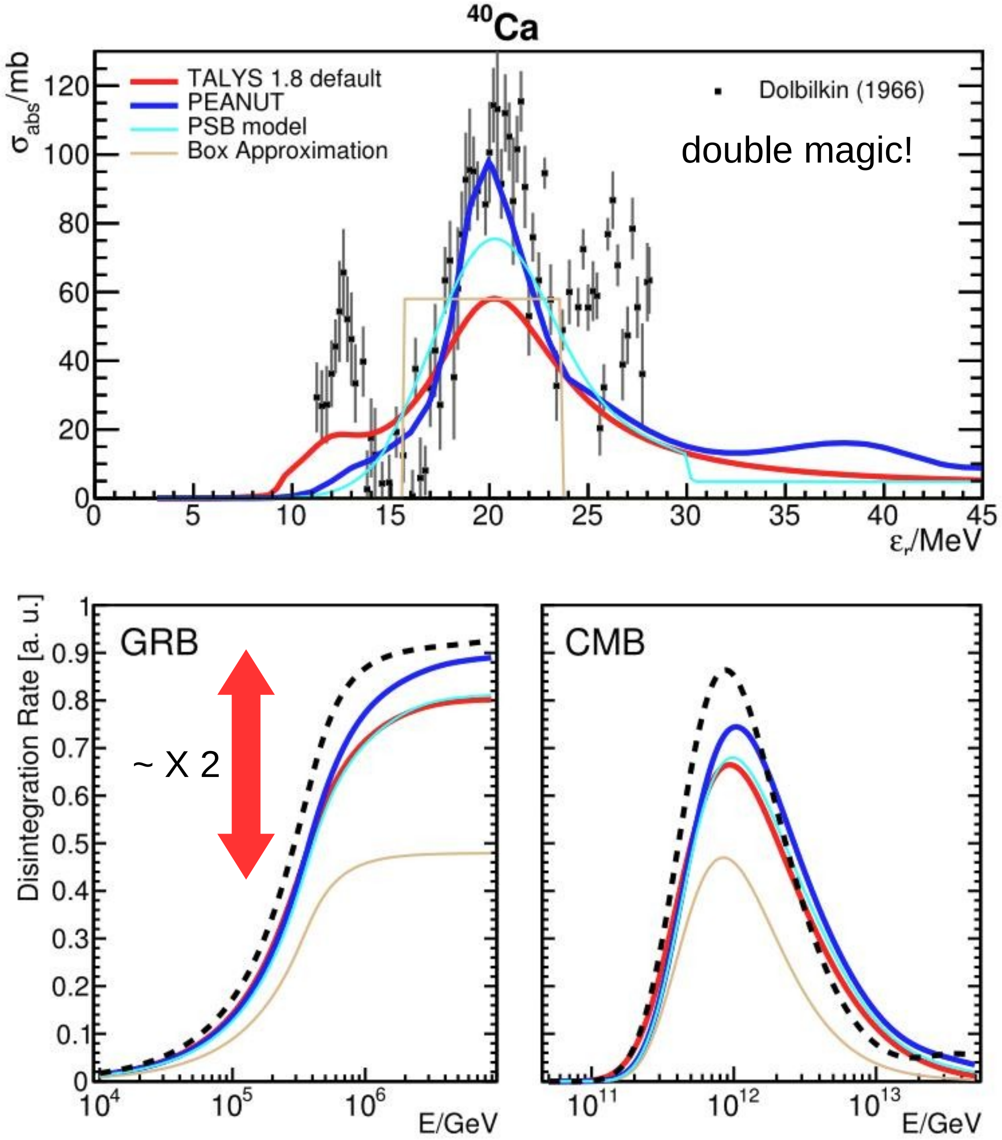
[https://www-nds.iaea.org/exfor/exfor.html]

- Cross-sections only measured for very few isotopes (red)
- Located mostly on main diagonal (stable elements)
- All other isotopes need models prediction → not always well in reproducing the data
- **Need future measurements and improved models**

[D. Boncioli, A. Fedynitch, W. Winter – Sci. Rep. (2017)]

Impact of nuclear cross-section data and models

Large uncertainties originating from nuclear physics



Comparison between different models

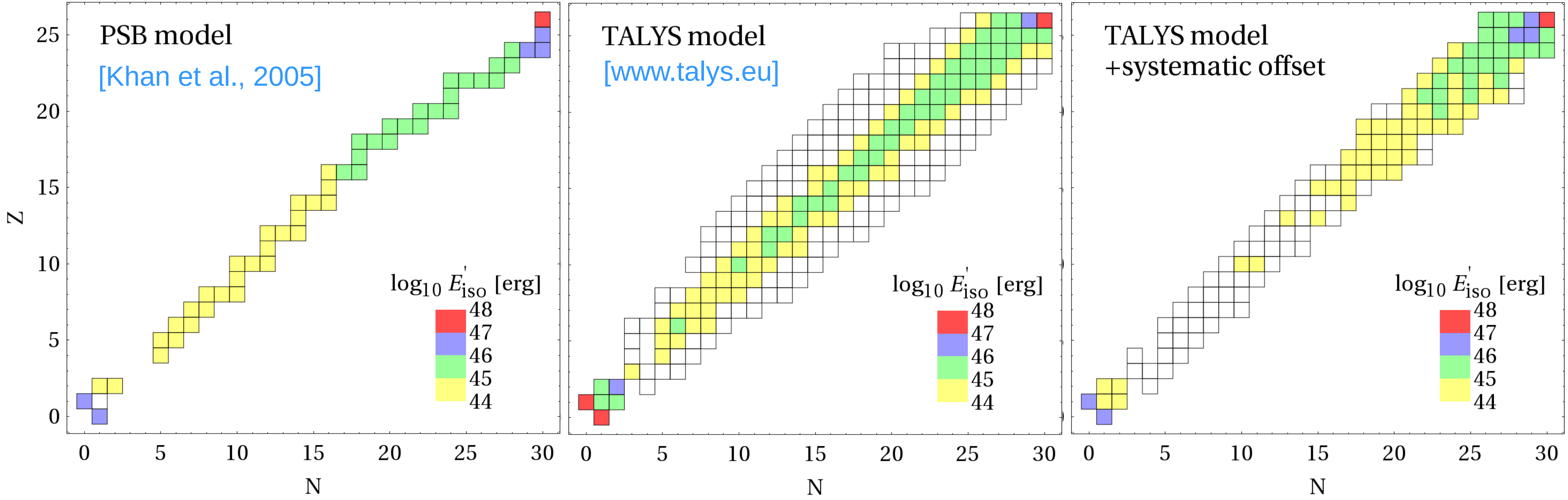
- TALYS (CRpropa 2+ - style) predictions not / weakly depending on nuclear mass and element, e.g. ^{40}Ca is double magic, ^{40}Ar (no data) is not, so no reason for cross sections to be equal [A. J. Koning et al., 2007] [K.-H. Kampert et al., 2005]
- PEANUT (a module of FLUKA) predictions are different in the same isobar, if data available at least the central GDR peak is reproduced [A. Ferrari et al., 2005]
- Box approximation, e.g. used in [Murase, Beacom 2010] underestimates data and models, insufficient description
- **Up to factor two differences in disintegration rates**

[D. Boncioli, A. Fedynitch, W. Winter – Sci. Rep. (2017)]
see also e.g. [Soriano et al., 1805.00409]

Impact of different models on the nuclear cascade

Disintegration strongly depending on interaction models

[D. Boncioli, A. Fedynitch, W. Winter – Sci. Rep. (2017)]



- PSB disintegration chain weakly describes multi-nucleon emission, only small fragments can be ejected
- TALYS provides much more channels, ejection of p, n, d, t, He-3, He-4
- Systematic offset = 'do not trust unmeasured cross-sections' → **cascade will not be populated** → **ejection composition!**

see also e.g. [Alves Batista et al., JCAP 2015]
[Pierre Auger collaboration, JCAP 2017]

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Other processes

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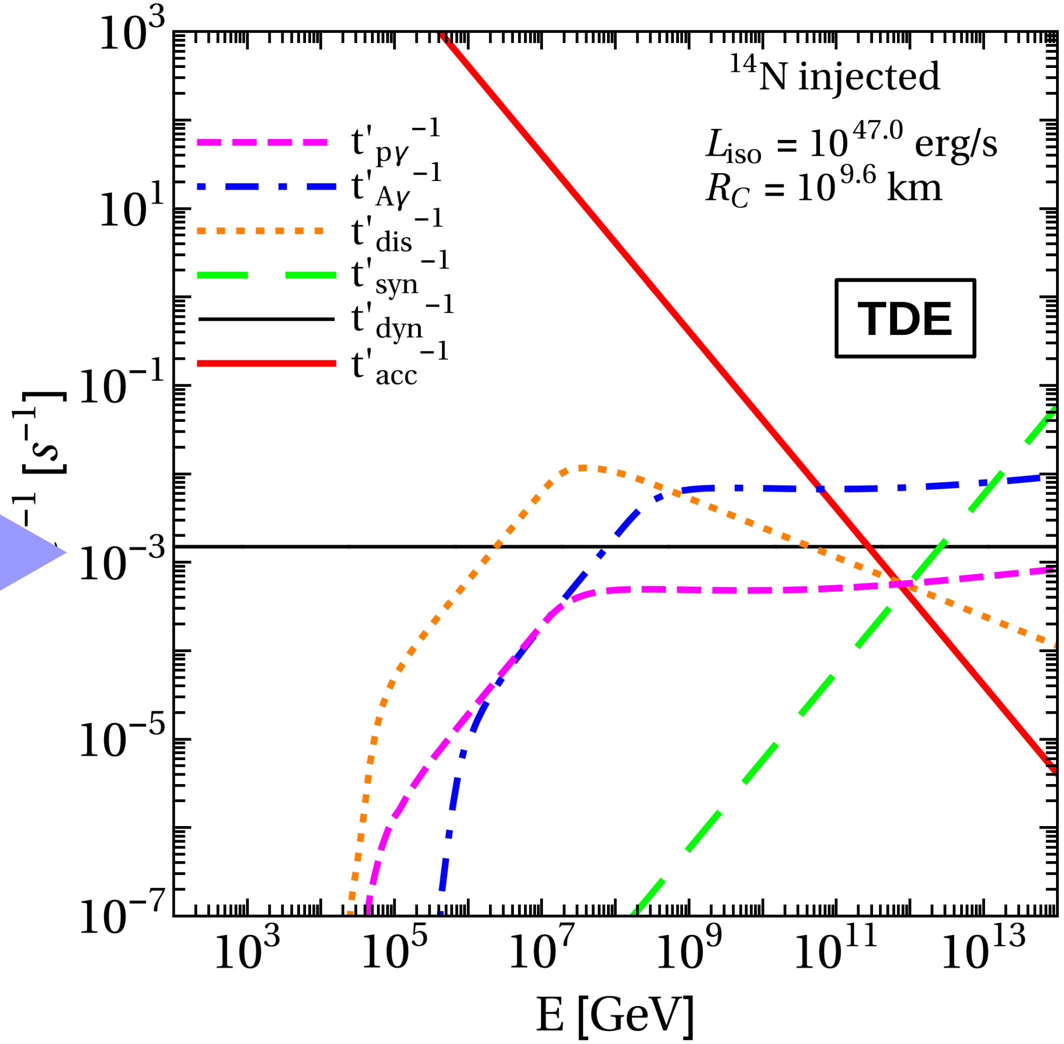
TDEs as origin of UHECRs **AND** PeV neutrinos



[**DB**, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

Photo-meson production dominated objects

A few examples

Photon energy in nucleus rest frame

Photo-hadronic (Aγ) interactions

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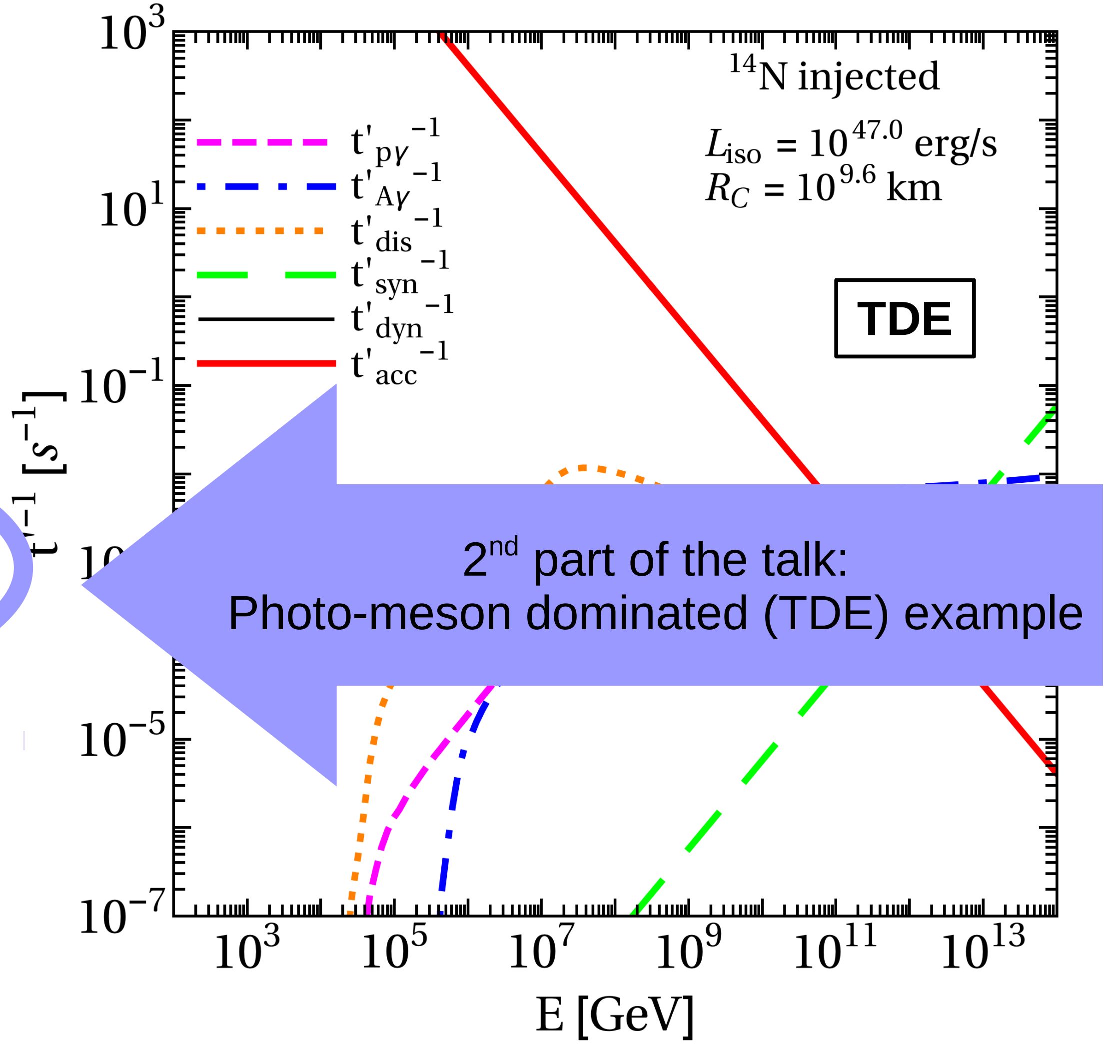


2nd part of the talk:
Photo-meson dominated (TDE) example

[**DB**, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

Cross-section models for photo-meson production

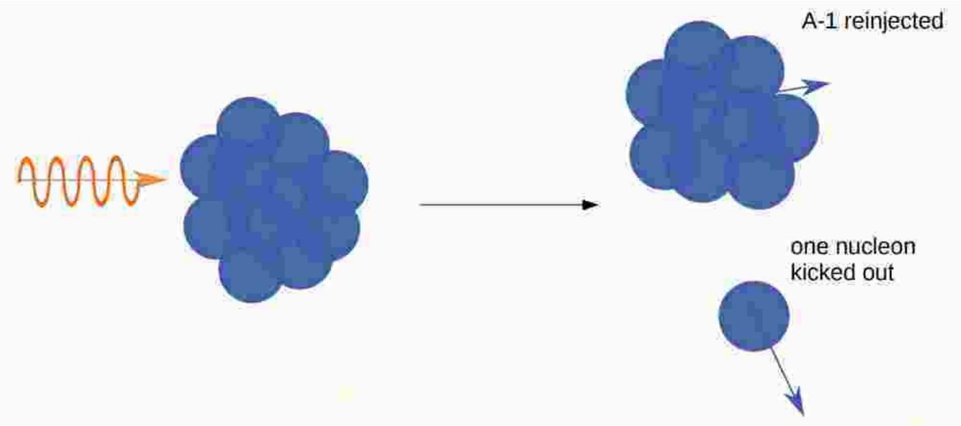
Comparison of different approaches

Superposition model vs. universal curve

- Current state-of-the-art photo-meson models: superposition model with individual nucleon interaction

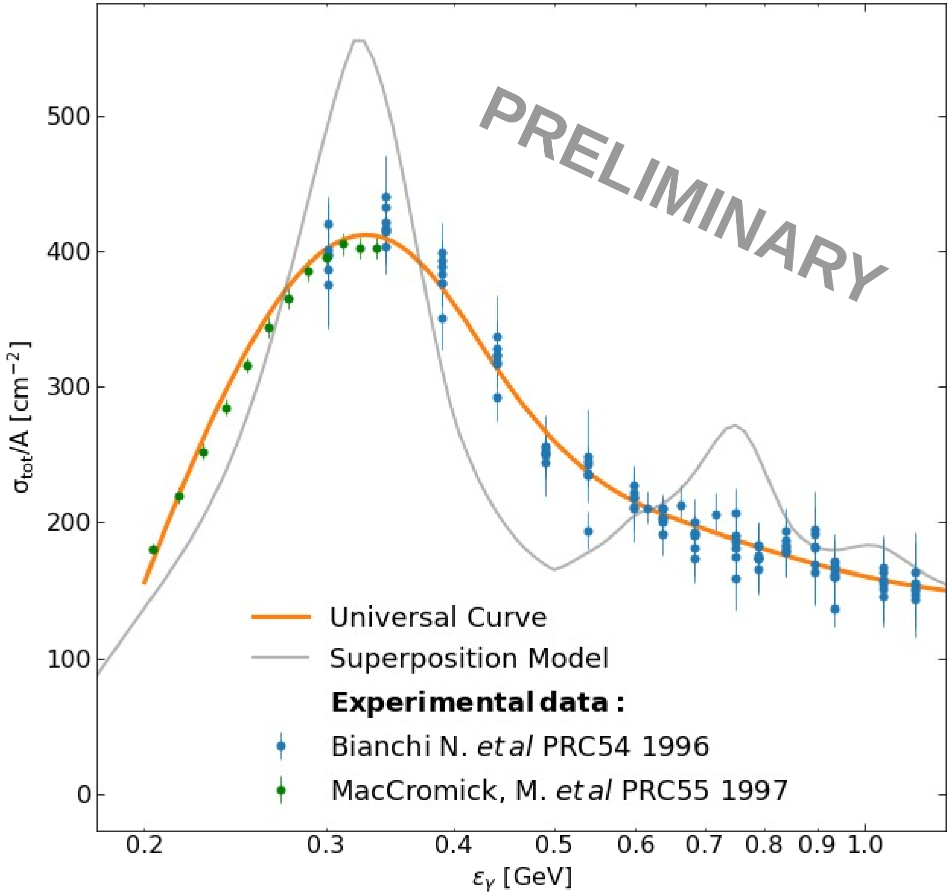
$$\sigma_A^{tot}(E) = \frac{Z}{A}\sigma_p(E) + \frac{N}{A}\sigma_n(E)$$

- Remaining nucleus (A-1) reinjected with no mediating de-excitations or decays



- CRpropa uses scaling ~ $A^{2/3}$ for the whole energy range

Instead: universal behaviour for nuclei observed, spline interpolation of data to obtain universal curve



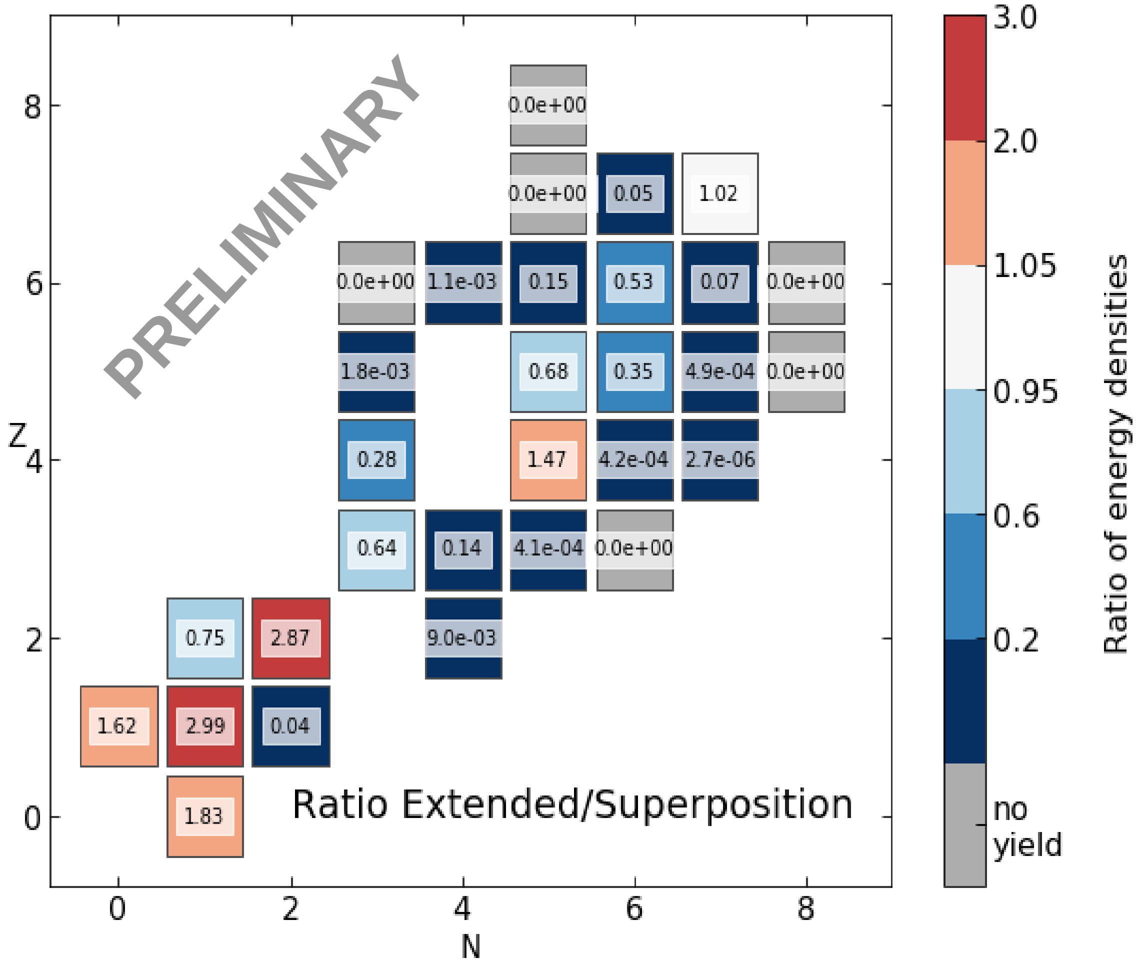
[L. Morejon et al., in preparation]

Impact of photo-meson models on nuclear cascade

Comparison between extended and superposition model

Disintegration chain and ejected composition

- Example: pure nitrogen injected in TDE (zoom in on the low-mass tail of the nuclear cascade shown before)
- Extended model allows for ejection of multi-nucleon fragments
  - More energy for specific channels along the main diagonal
  - Less energy off the main diagonal, some isotopes basically not populated anymore
- **Direct impact on neutrino production!**



[L. Morejon et al., in preparation]

Glashow resonance: pγ vs. pp interactions

More realistic models making the difference

Triggering the resonance and flavor composition

- Resonant interaction of an astrophysical electron antineutrino with electron

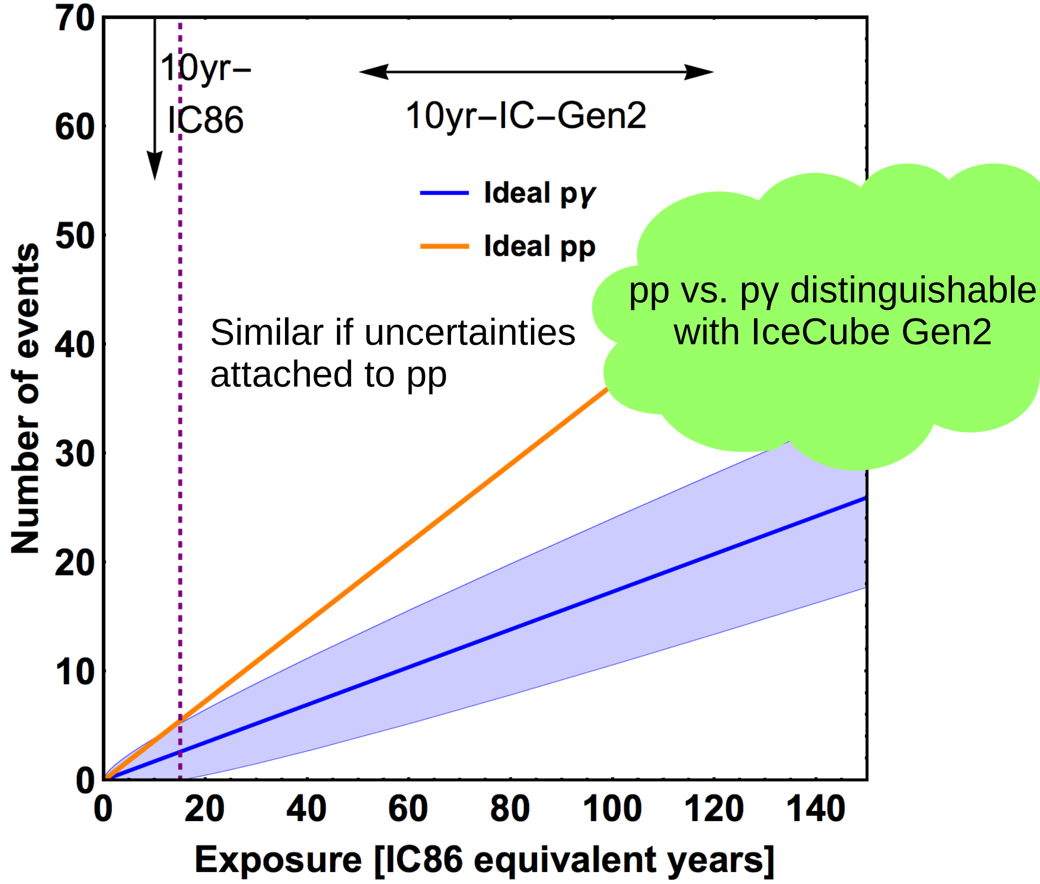
$$\bar{\nu}_e + e^- \to W^- \to \text{hadrons at } 6.3 \text{ PeV}$$

- Origin of the incoming neutrino

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

$$\mathrm{p} + \mathrm{p} \to \begin{cases} \pi^+ + \text{anything} & 1/3 \text{ of all cases} \\ \pi^- + \text{anything} & 1/3 \text{ of all cases} \\ \pi^0 + \text{anything} & 1/3 \text{ of all cases} \end{cases}$$

$$\pi^+ \to \mu^+ + \nu_\mu \,, \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



[**DB**, A. Fedynitch, A. Palladino, T. Weiler, W. Winter – JCAP (2017)]

Glashow resonance: pγ vs. pp interactions

More realistic models making the difference

More realistic description: pp source

- Pion charge ratio not exactly equal to one, reasonable estimate from hadronic interaction models: average of EPOS-LHC, QGSJet-II-04 and SIBYLL 2.3

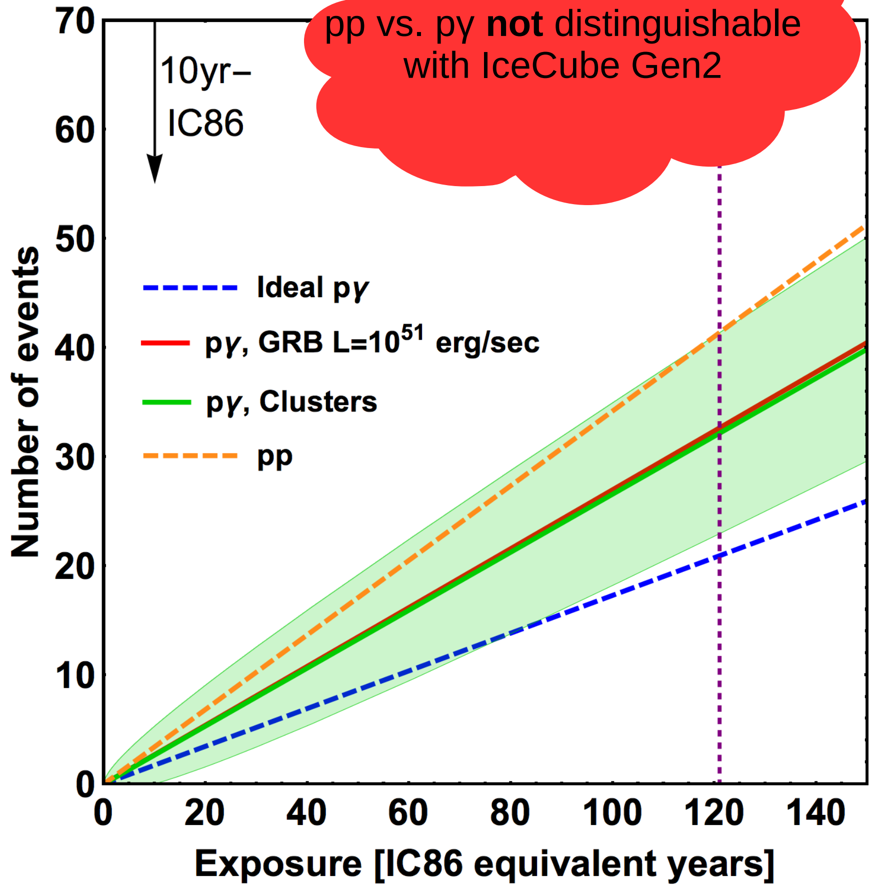
α	N_{π^+}/N_{π^-}
2.0	1.25 ± 0.20
2.3	1.34 ± 0.15
2.6	1.43 ± 0.24

Gets even worse with softer injection spectrum

More realistic description: pγ source

- Multi-pion processes and neutrons from the disintegration of nuclei (if present) lead to contamination by π^-

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



pp vs. pγ **not** distinguishable with IceCube Gen2

[**DB**, A. Fedynitch, A. Palladino, T. Weiler, W. Winter – JCAP (2017)]

… but pγ vs. Aγ might work!

Summary and conclusions

Neutrinos from UHECR interactions

- Efficient neutrino production requires high radiation densities, where on the other hand UHECRs efficiently disintegrate
  - Nuclear cascade as a measure of UHECR interactions and neutrino production, needs to be triggered for a combined treatment
  - Challenges the hypothesis of a common origin of neutrinos and cosmic rays at the highest energies

- Future measurements and improved theoretical models are essential for a better description of neutrinos from UHECR interactions, as the current data is sparse and the models do not always reproduce it well leading to large uncertainties

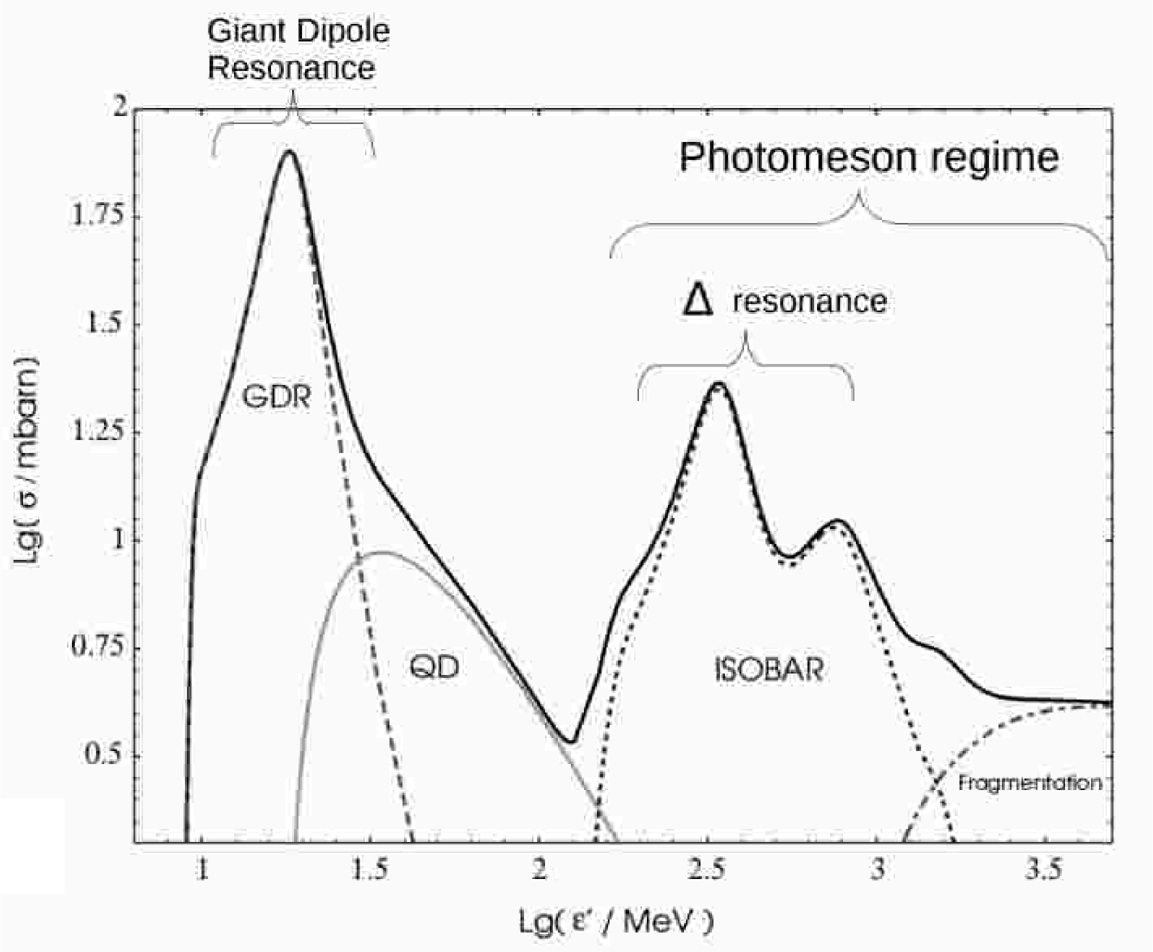
- Development of the nuclear cascade and neutrino production strongly depend on the model assumptions, different disintegration chains lead to different ejected compositions and neutrino yields

- Strong implications can be obtained when interactions producing neutrinos are well-understood, as in the case of the Glashow resonance, which with increasing exposure will help constrain the sources

BACKUP

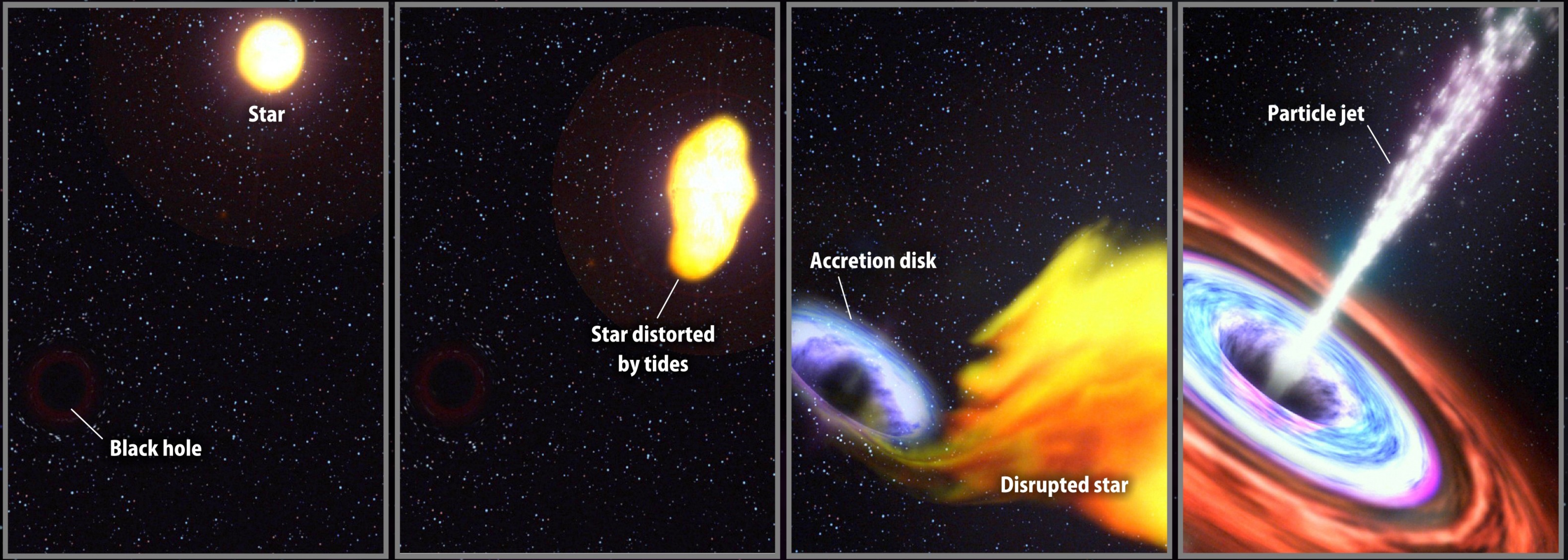
Cross section of different energy scales

And individual contributions to it



[Rachen J. P. 1996 PhD Thesis]

Swift J1644+57: Onset of a relativistic jet



1. A sun-like star on an eccentric orbit plunges toward the supermassive black hole in the heart of a distant galaxy.

2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.

3. The part of the star facing the black hole streams toward it and forms an accretion disk. The remainder of the star just expands into space.

4. Near the black hole, magnetic fields power a narrow jet of particles moving near the speed of light. Viewed head-on, the jet is a brilliant X-ray and radio source.

Credit: NASA/Goddard Space Flight Center/Swift

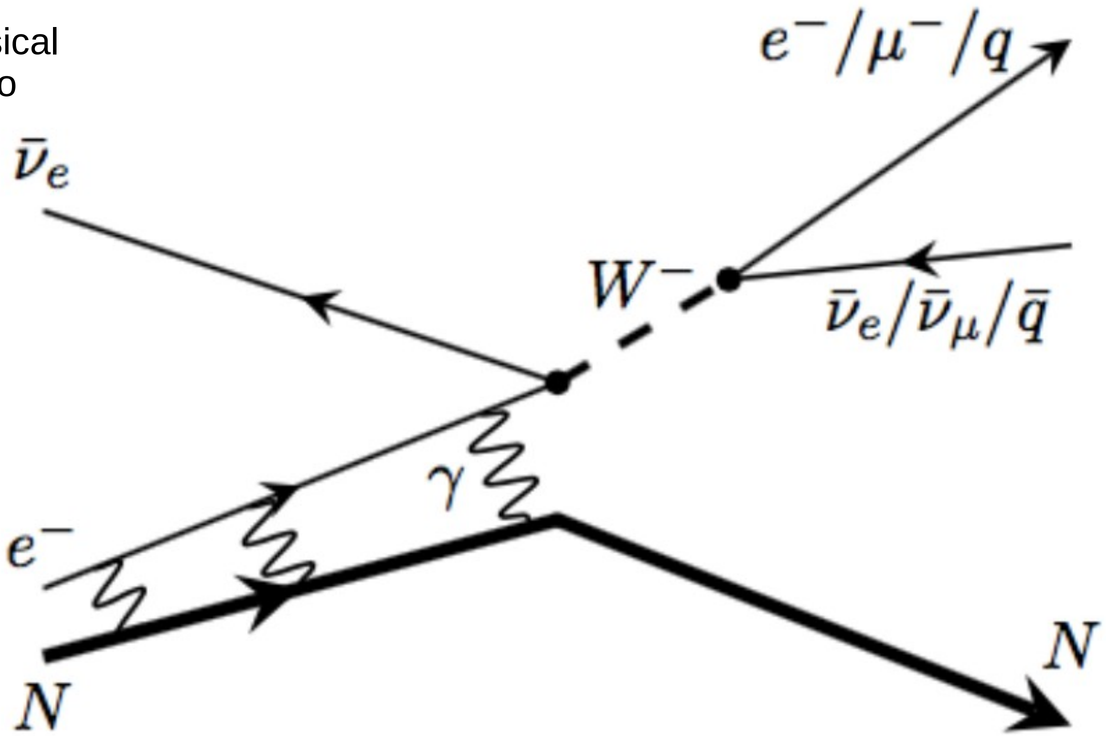
Glashow resonance: pγ vs. pp interactions

More realistic models making the difference

Leptonic channel not distinguishable from non-resonant events since energy is carried away by neutrino

Incoming astrophysical electron antineutrino with E ~ 6.3 PeV

Electron from ambient atom in the detector



Description of models

NBuclear data libraries

What is TALYS?

www.talys.eu

TALYS is software for the simulation of nuclear reactions. Many state-of-the-art nuclear models are included to cover all main reaction mechanisms encountered in light particle-induced nuclear reactions. **TALYS** provides a complete description of all reaction channels and observables, and is user-friendly.

ENDF-B-VII.1 [18] is an evaluated nuclear data library based on calculations using the GNASH code system. Its photo-nuclear part contains absorption cross-sections a sometimes inclusive emission spectra of neutrons and protons, but no residual cross-sections. Comparisons with data reveal a very good agreement with the measurements.

JENDL/PD-2004 [19] is another evaluated library, based on Lorentz fits at GDR energies and quasi-deuteron emission above. Elements without $\sigma_{\rm abs}$ measurements are evaluated through branching ratios from pre-quilibrium and evaporation models, together with photo-neutron data. The description of $\sigma_{\rm abs}$ is good for all measured elements.