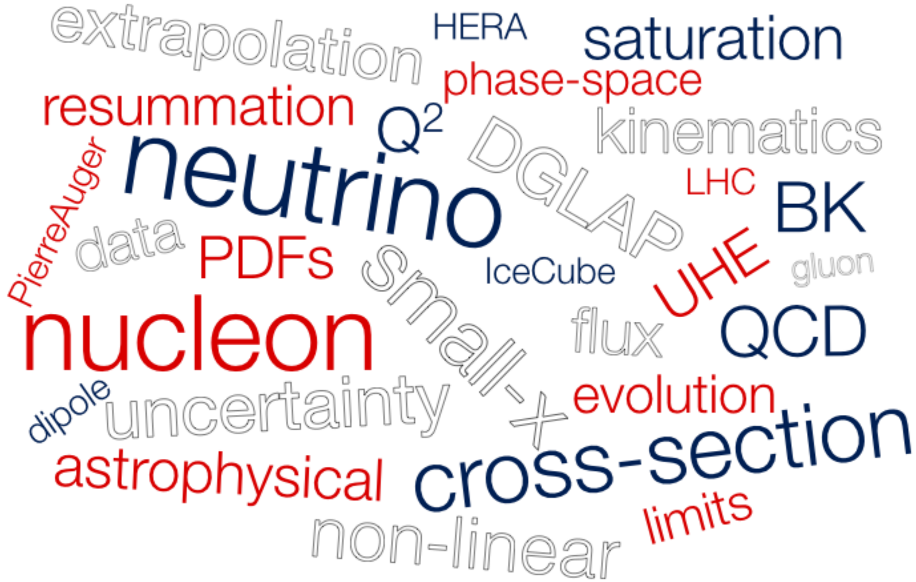
The Neutrino-Nucleon cross section at UHE and its astrophysical implications



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based on Phys. Rev. D 92 (2015) 014027

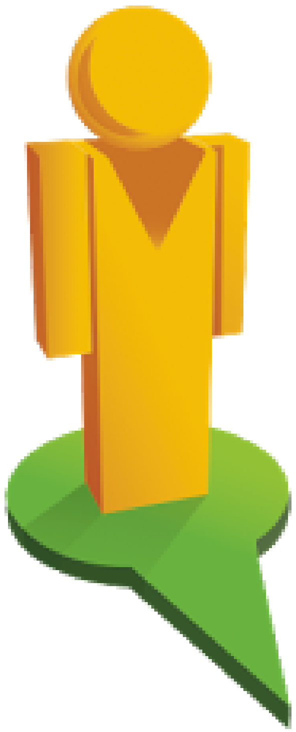
ugr Universidad de Granada

Outline

1. Motivation
    - ▷ Neutrinos @ IceCube
2. Ingredients
    - ▷ $\frac{\mathrm{d}^2\sigma_{\nu N}^{\mathrm{CC}}}{\mathrm{d}x\mathrm{d}y}, \frac{\mathrm{d}^2\sigma_{\nu N}^{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}y}$
    - ▷ DGLAP approach
    - ▷ *À* la BK
3. Results
    - ▷ $\sigma_{\nu N}$
    - ▷ Limits on astrophysical neutrino fluxes
4. Conclusions

Manual of use/disclaimer

- There is NO physics BSM in this talk.
- Emphasis in qualitative aspects. *Equations* and *diagrams* only schematic.
- Do not lose sight of this guy,



Region probed in
UHE neutrino interactions

1. Motivation

νN cross section

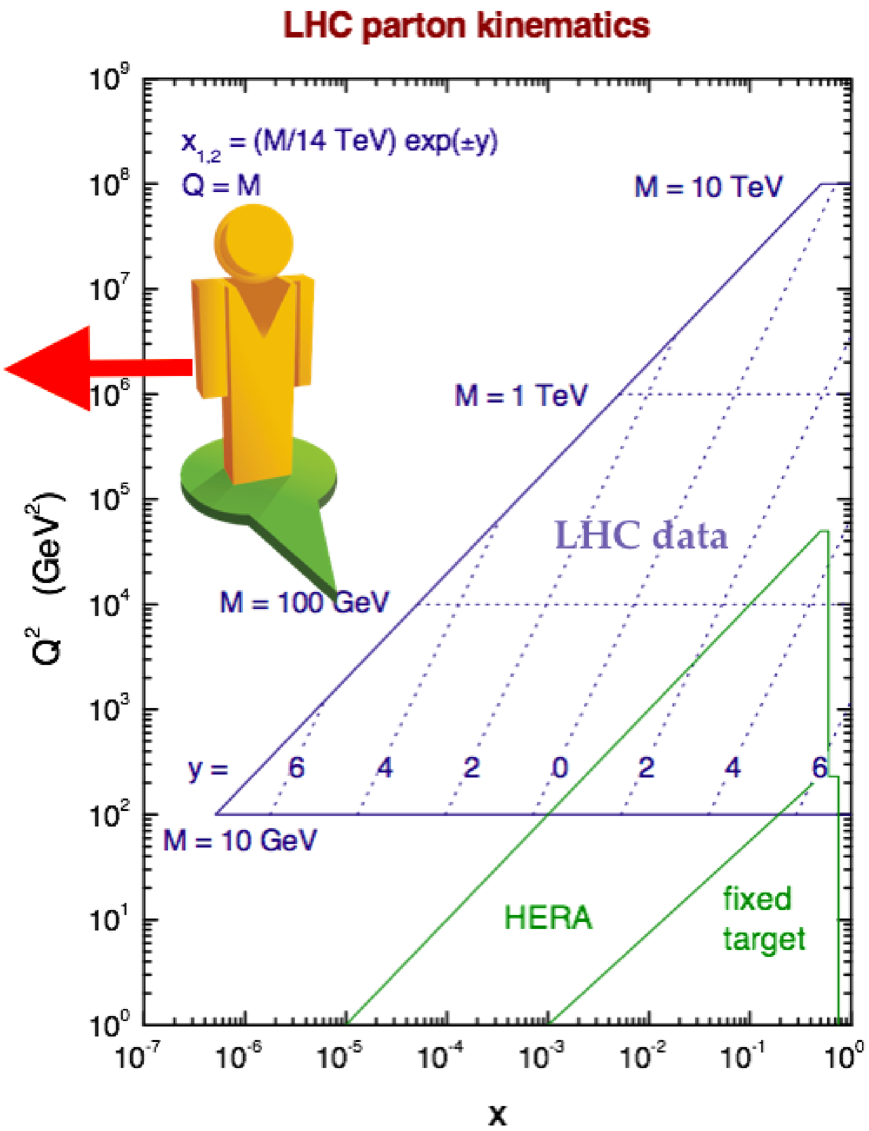
- General structure of factorization theorems,

$$\sigma_{\nu N} \sim \underbrace{\begin{pmatrix} \text{Probability of} \\ \text{finding a quark/gluon} \\ \text{in nucleon} \end{pmatrix}}_{\text{Low energy QCD}} \otimes \underbrace{\sigma^{q/g-\nu}}_{\text{Perturbative}}$$

$\left(\ldots \right)$: Parton Distribution Function,

Unintegrated Gluon Distribution

νN kinematic regime



$\Rightarrow$ Test of QCD at high energies

$\Rightarrow$ No available data in νN phase space region

$\Rightarrow$

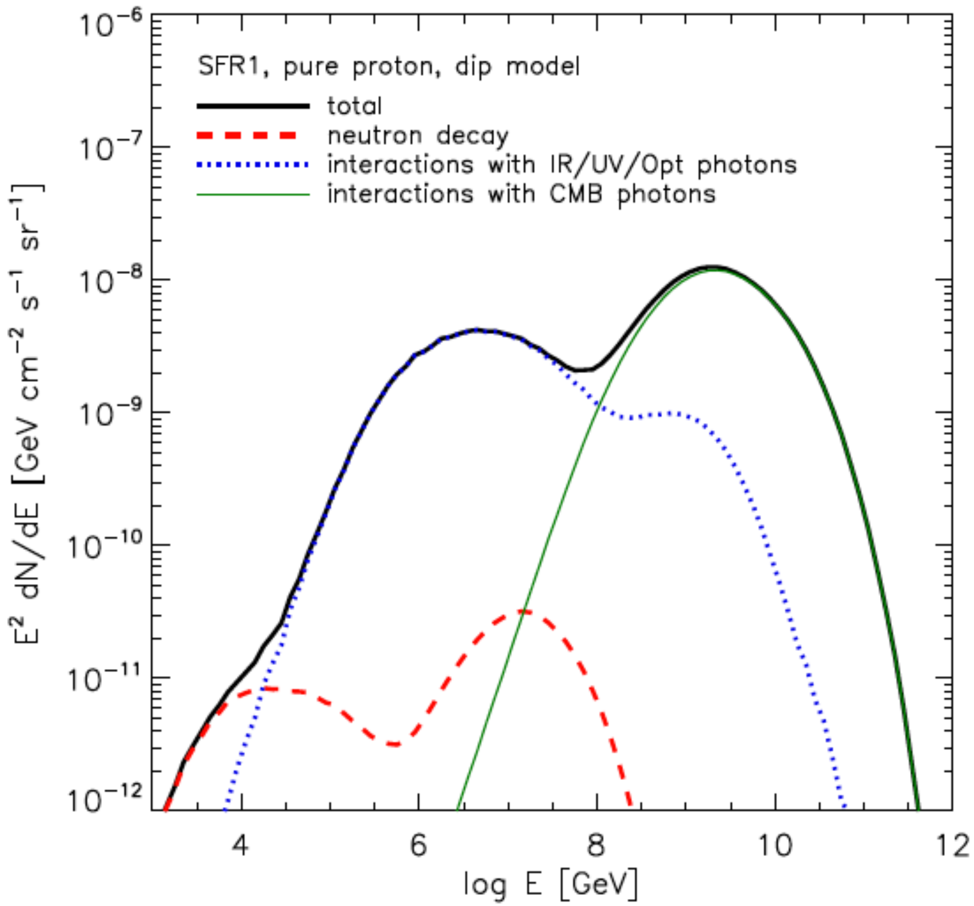
$$Q^2 \sim M_i^2 \sim 10^4 \text{ GeV}^2$$
$$\&$$
$$10^{-11} \lesssim x \lesssim 10^{-5}$$

Where do they come from?

[Berezinsky and Zatsepin '69] [Kotera,Allard and Olinto '10]

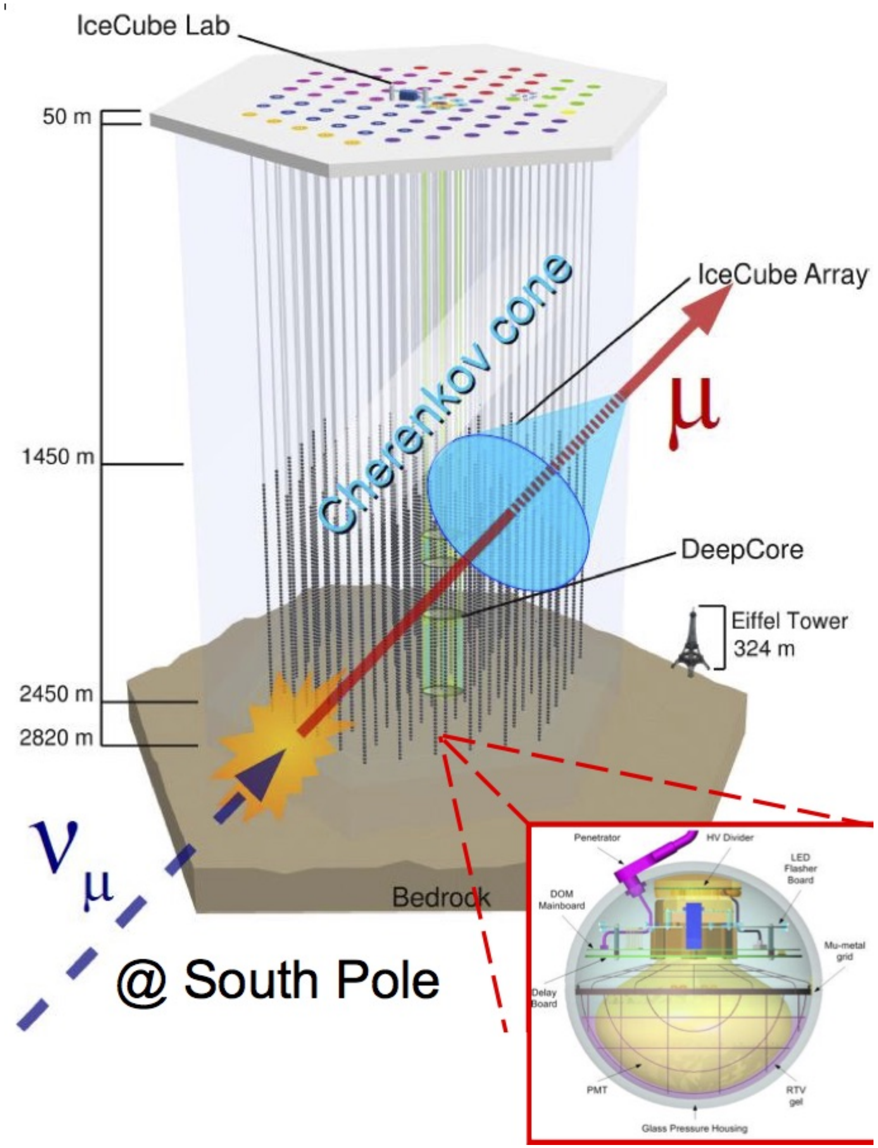
- Sources of UHE neutrino: GZK

$$p\gamma \to \pi N$$
$$\pi^+ \to \mu^+ \nu_\mu$$



- Up to $E_\nu \sim 10^{14}$ GeV. Information about UHECRs: nature, sources, spectrum...

Who is looking for these neutrinos? **IceCube** (and many more...)



⇒ $1km^3$ of Antartic glacier ice

⇒ Neutrino telescope

⇒ Cosmic ray physics

⇒ Observes Cherenkov light

Neutrinos @ IceCube

20. arXiv:1412.8361 [pdf, ps, other]
Star-forming galaxies as the origin of the IceCube PeV neutrinos
Xiao-Chuan Chang, Ruo-Yu Liu, Xiang-Yu Wang
Comments: 8 pages, 6 figures
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**

32. arXiv:1411.7491 [pdf, other]
PeV-EeV neutrinos from GRB blastwave in
Soebur Razzaque, Lili Yang
Comments: 8 pages, 5 figures, minor changes. Accepted for p
Journal-ref: Physical Review D 91, 043003 (2015)
Subjects: **High Energy Astrophysical Phenomena (astro-ph.**

6. arXiv:1502.02649 [pdf, other]
Spectral analysis of the high-energy IceCube neutrinos
Sergio Palomares-Ruiz (Valencia U., IFIC), Aaron C. Vincent (Durham U., IPPP), Olga Mena (Valencia U., IFIC)
Comments: 31 pages, 12 figures. v2: some typos corrected and comments added. New Fig.10 and slightly corrected Fig.5
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenolog

5. arXiv:1502.02923 [pdf, other]
Which is the flavor of cosmic neutrinos seen by IceCube?
A. Palladino, G. Pagliaroli, F.L. Villante, F. Vissani
Comments: 4 pages, 1 figure
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**

33. arXiv:1411.6457 [pdf, other]
Neutron β-decay as the origin of IceCube's PeV (anti)neutrinos
Luis A. Anchordoqui
Comments: To be published in PRD
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; High Energy Physics - Phenomenology (hep-ph)

48. arXiv:1411.0498 [pdf, other]
Problems with Ultrahigh-energy Neutrino Interactions
Dieter Schildknecht
Comments: 15 pages, 9 figures, Presented at the International School of Subnuclear Physics, 52nd Course, Erice, Sicily, 24 June - 3 July 2014
Subjects: **High Energy Physics - Phenomenology (hep-ph)**

59. arXiv:1410.3208 [pdf, other]
A new physics interpretation of the IceCube data
José Ignacio Illana, Manuel Masip, Davide Meloni
Comments: 13 pages, version to appear in Astroparticle Physics
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Astrophysical Phenomena (astro-ph.H

11. arXiv:1501.07798 [pdf, other]
Exploring the Universe with Very High Energy Neutrinos
A. Kappes, for the IceCube Collaboration
Comments: 10 pages, 15 figures, to appear in the proceedings of ICHEP 2014
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**

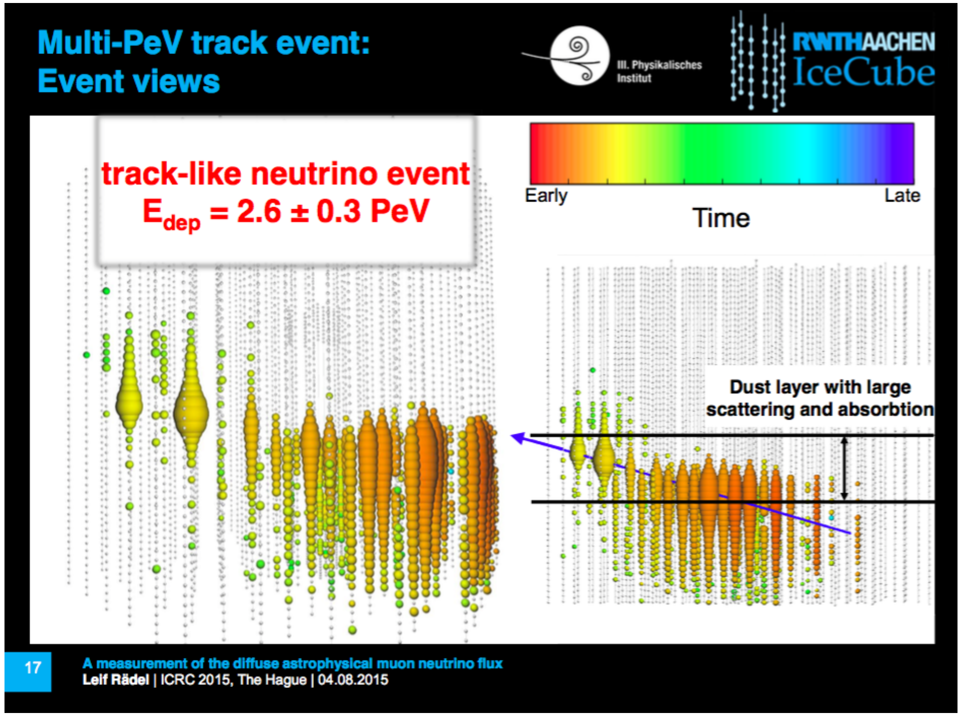
79. arXiv:1408.3664 [pdf, ps, other]
Some possible sources of IceCube TeV-PeV neutrino events
Sarira Sahu, Luis Salvador Miranda
Comments: 11 pages, 1 figure, references added

64. arXiv:1409.5896 [pdf, ps, other]
New IceCube data and color octet neutrino interpretation of the PeV energy events
A.N. Akay (TOBB ETU), O. Cakir (Ankara U.), Y.O. Gunaydin (K.S.U), U. Kaya (TOBB ETU), M. Sahin (Usak U.), S. Sultansoy (TOBB ETU & National Academy of Sciences, Institute of Physics)
Comments: 10 pages, 4 figures
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)

Neutrinos @ IceCube

[IceCube'15]

- So far the fattest neutrino at IceCube has $E_\nu = 2.6\ \text{PeV} = 2.6 \cdot 10^6\ \text{GeV}$



$$\frac{dN}{dE} \sim \phi_\nu \cdot \sigma_{\nu N}$$

– $\frac{dN}{dE}$: what they measure.

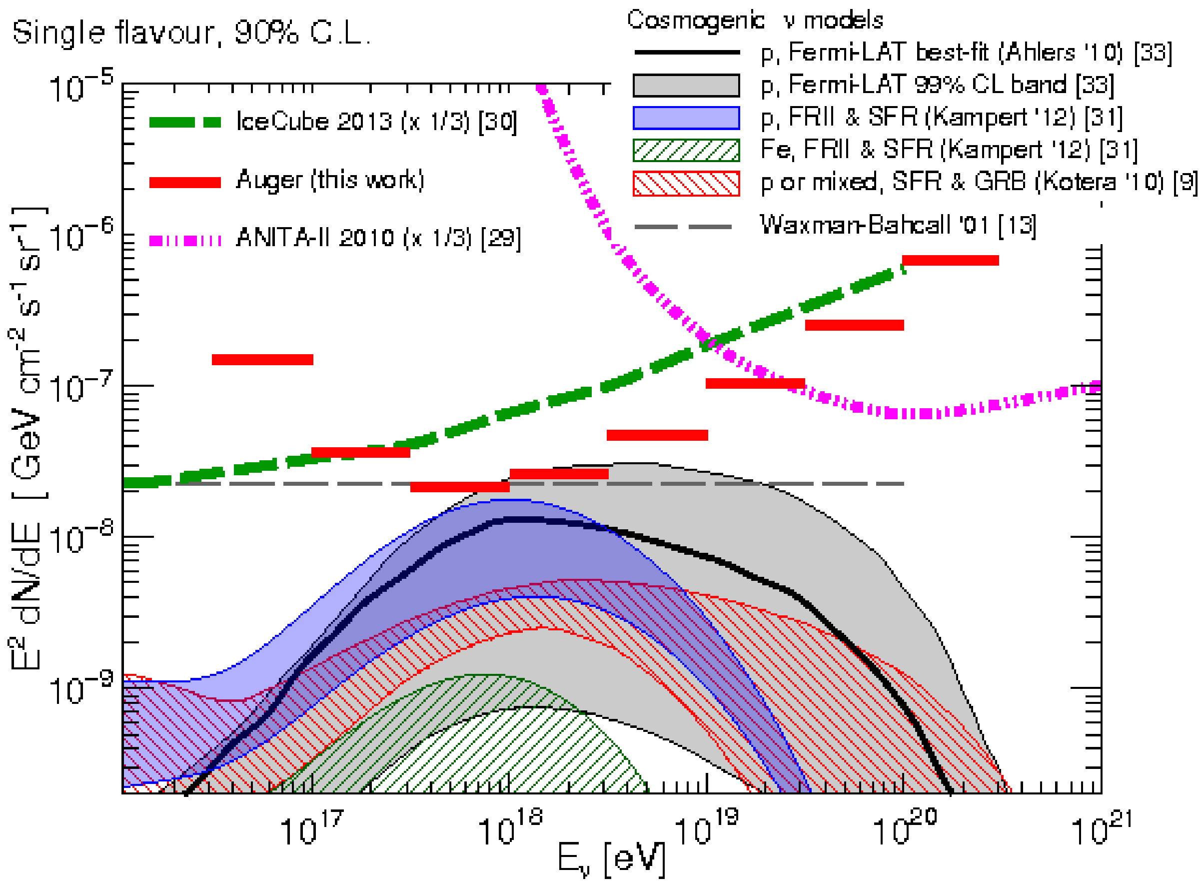
– ϕ_ν: what they want to know.

– $\sigma_{\nu N}$: our contribution.

Road map

[The Pierre Auger collaboration '15]

- Study of the different approaches to QCD dynamics at high energies.
- New dynamical effects in the QCD evolution ⇒ Is $\sigma_{\nu N}$ sensitive?
- Recalculate the actual limits of the UHE neutrino flux for various experiments.



2. Ingredients

$$\frac{d^2\sigma_{\nu N}^{CC}}{dx dy}, \frac{d^2\sigma_{\nu N}^{NC}}{dx dy}$$

- The cross section can be computed as:

$$\frac{d^2\sigma_{\nu N}^{CC,NC}}{dx dy} = \frac{G_F^2 s}{\pi}\left(\frac{M_i^2}{M_i^2+Q^2}\right)^2 \left[xy^2 F_1^{CC,NC}(x,Q^2) + (1-y)\, F_2^{CC,NC}(x,Q^2) + y\left(1-\frac{y}{2}\right) xF_3^{CC,NC}(x,Q^2)\right]$$

where,

$-F_{1,2,3}^{CC,NC}(x,Q^2)$: structure functions.

– Integral dominated by:

$Q^2 \sim M_i^2 \sim 10^4$ GeV^2

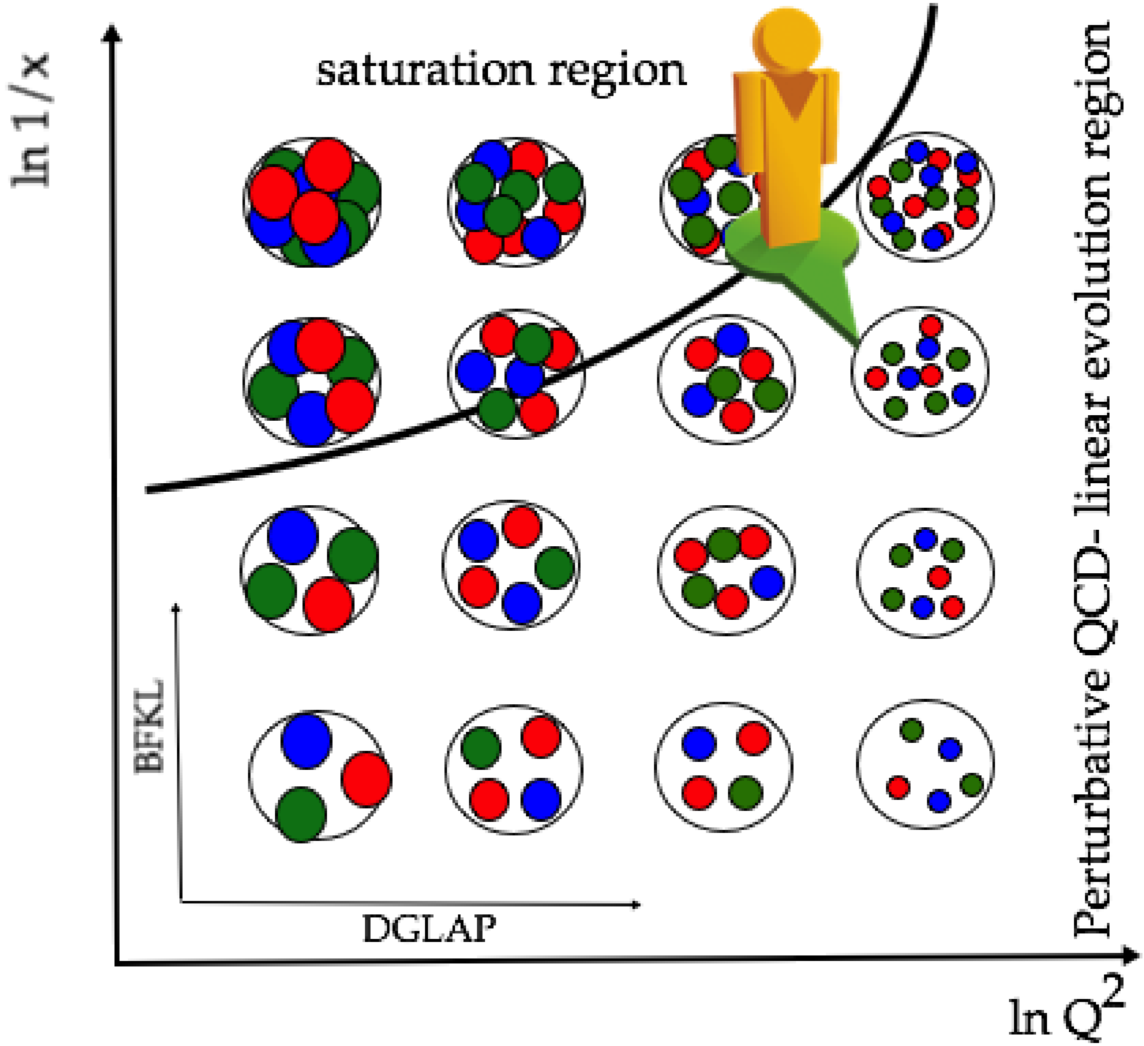
&

$x_{min} \sim M_i^2/2M_N E_\nu < 10^{-5}$ for $E_\nu > 10^8$ GeV

No experimental data

$\Rightarrow$ Expressions for the structure functions?

Map of high energy QCD

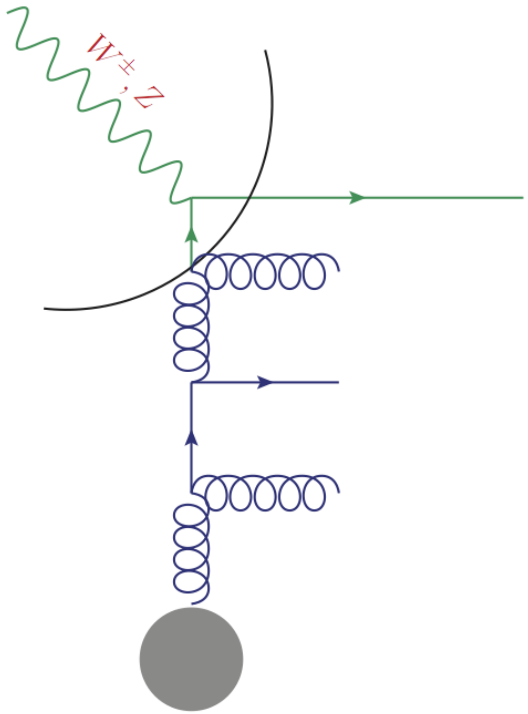


- For νN interaction, both $\ln Q^2$ and $\ln 1/x$ are relevant.

DGLAP approach ($\alpha_s \ln(Q^2/Q_0^2) \sim 1$)

[Dokshitzer'77, Gribov&Lipatov'72, Altarelli&Parisi'77]

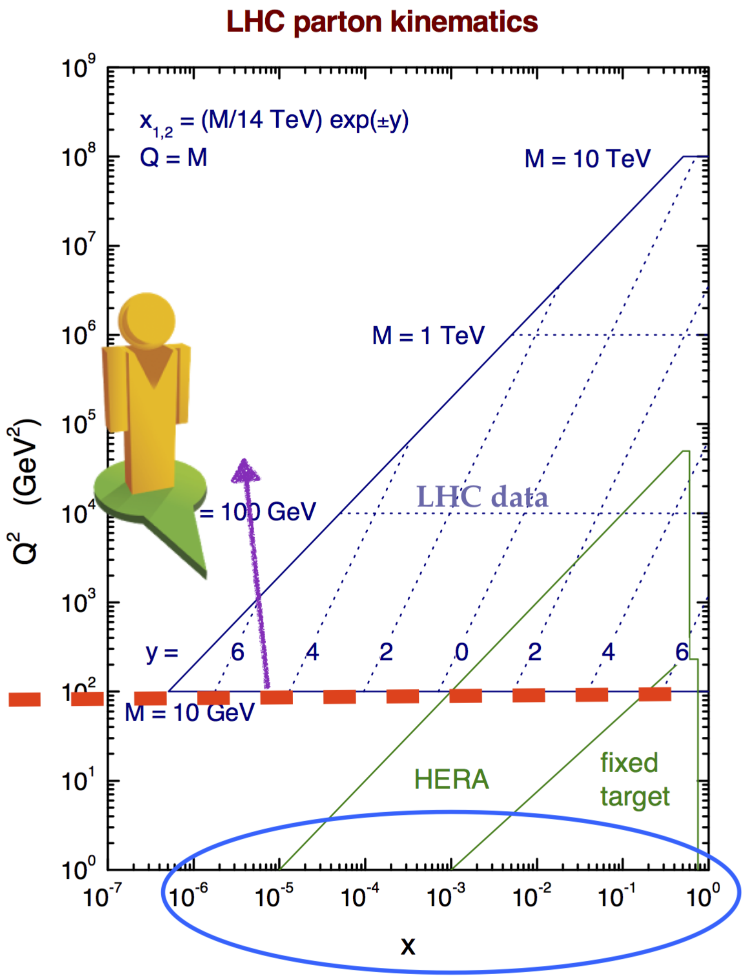
- We can compute $\sigma_{\nu N}$ as,



$$\sigma_{\nu N} = \mathrm{PDF}(x, Q^2) \otimes \sigma^{\nu q}$$

+

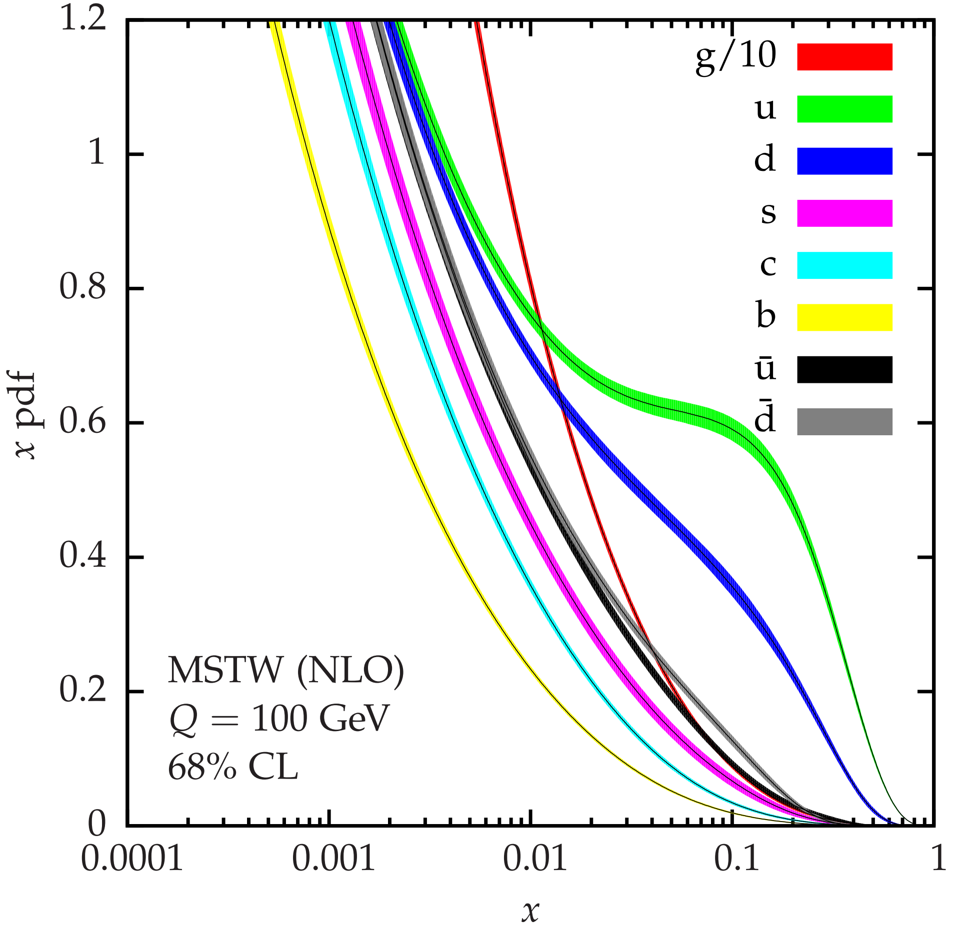
$$\frac{\partial \mathrm{PDF}(x, Q^2)}{\partial \ln Q^2} \propto \mathcal{P} \otimes \mathrm{PDF}(x, Q^2)$$

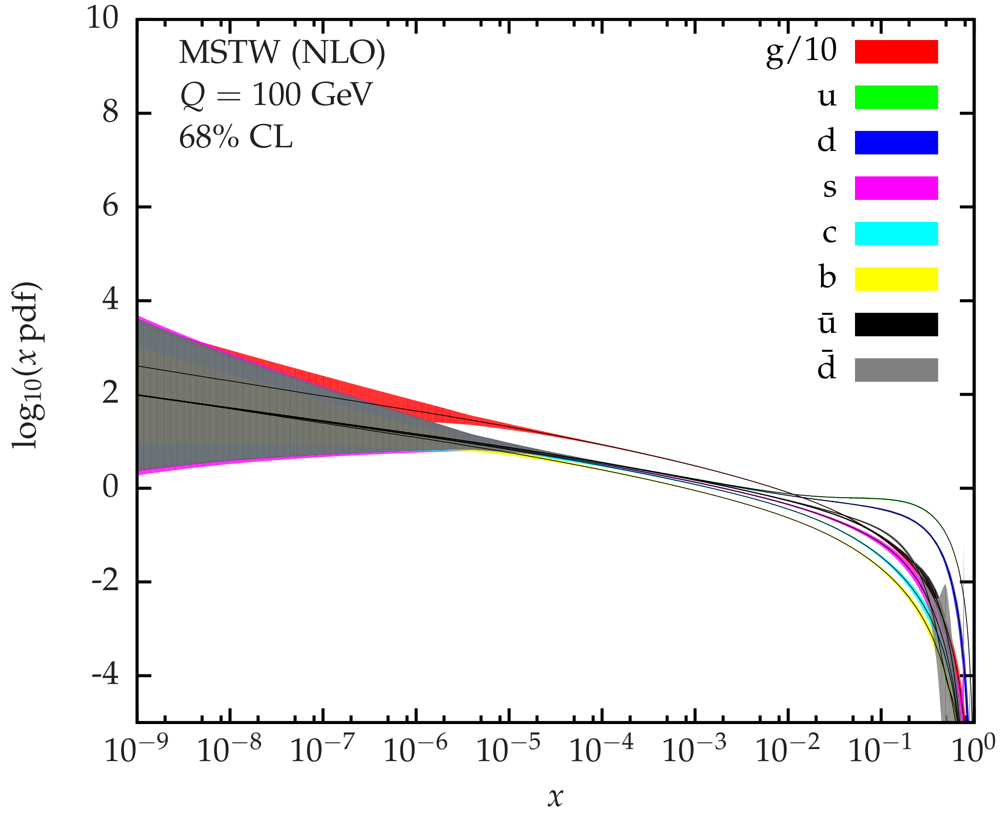


$x \lesssim 10^{-6}$ PDFs are essentially unconstrained!!

DGLAP approach | PDFs

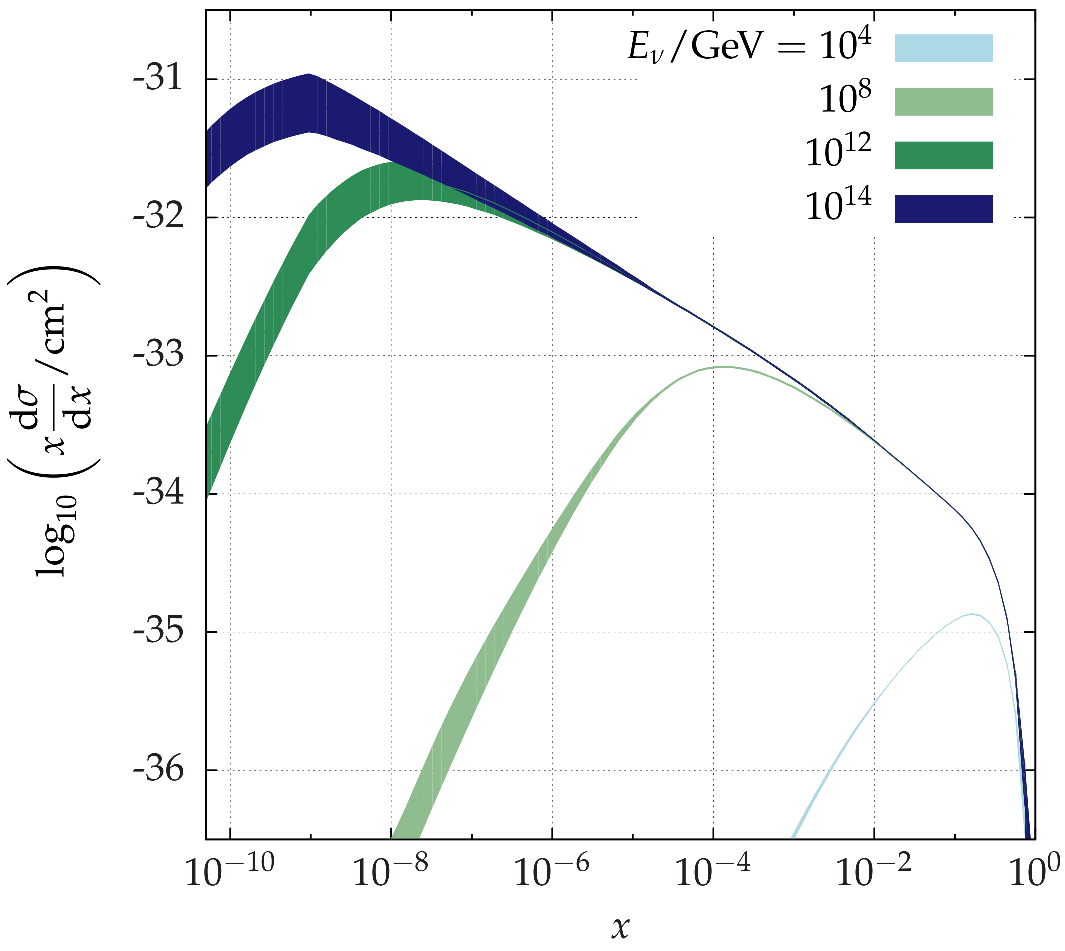
[MSTW collaboration]





DGLAP approach $\sigma_{\nu N}$

- This uncertainty is fully propagated to the neutrino x-sections

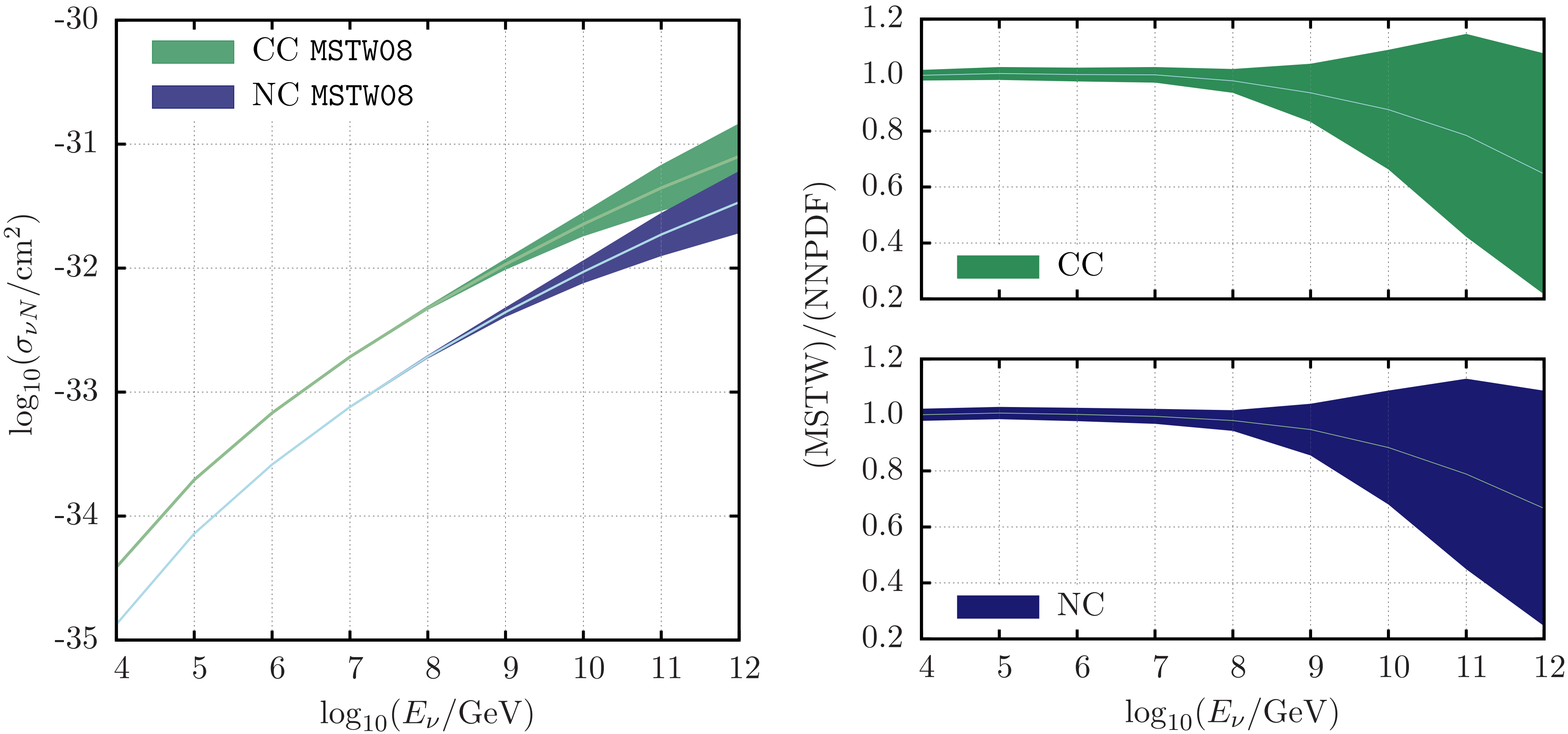


- Note: 20% error at the highest E_ν.

NLO DGLAP+NNPDF3.0

DGLAP approach | MSTW08 **vs** NNPDF3.0

[Gandhi'98, Cooper-Sarkar'08, Chen'14 et Al.]



- Note: 30% error at the highest E_ν.

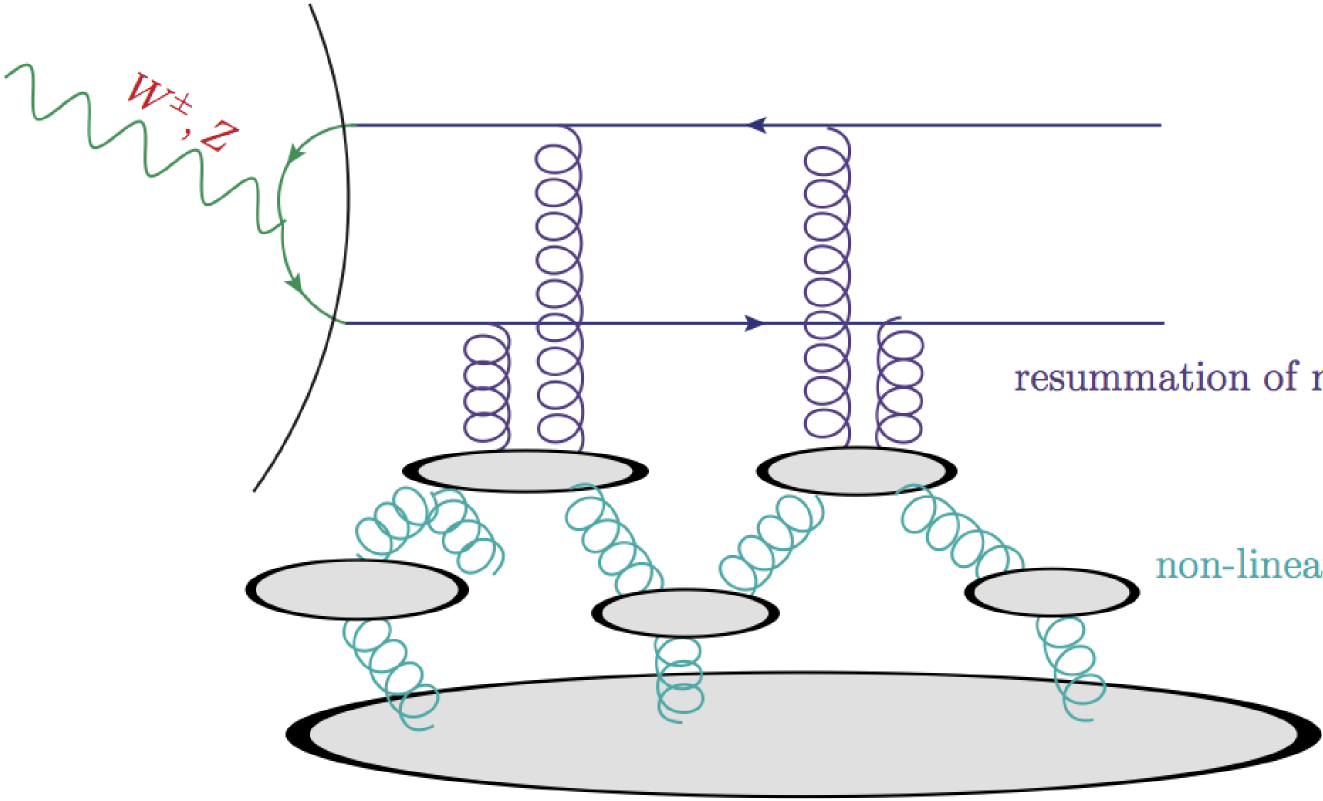
NLO DGLAP+MSTW08/NNPDF3.0

- They become incompatible within the error band at $E_\nu = 10^{12}$ GeV.

À la BK ($\alpha_s \ln(x_0/x) \sim 1$)

[Balitsky'96, Kovchegov'99]

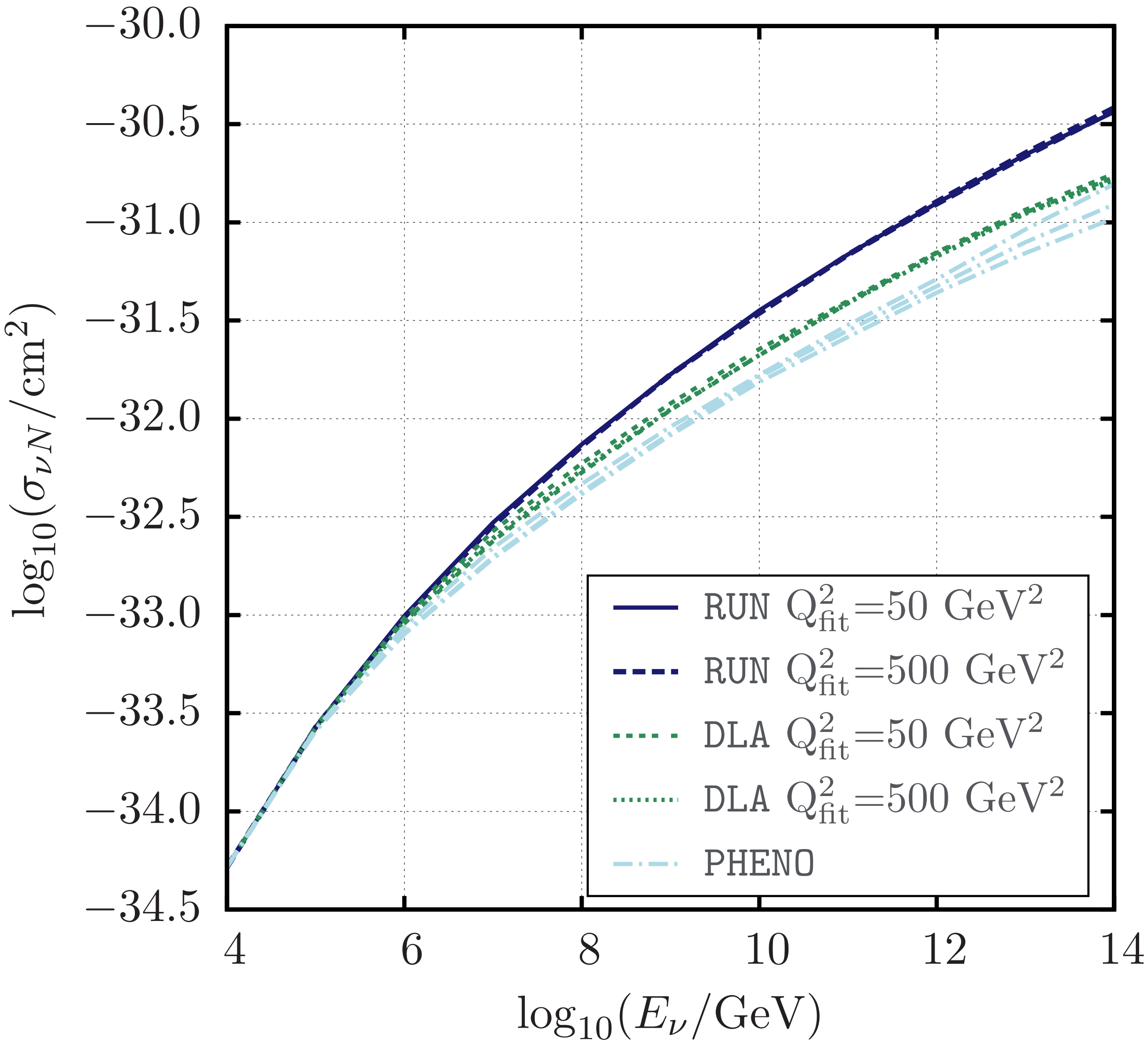
- We can compute $\sigma_{\nu N}$,



$$\sigma_{\nu N} \sim |\psi_{\mathrm{T,L}}^{W^{\pm},Z^0}(z,Q^2,r)|^2 \otimes \mathcal{N}(x,r)$$ +

$$\frac{\partial \mathcal{N}(x,r)}{\partial \ln(x_0/x)} \propto \mathcal{K} \otimes [\mathcal{N}(x,r_1) + \ldots - \mathcal{N}(x,r_1)\mathcal{N}(x,r_2)]$$

Parametrizations of $\mathcal{N}$ | Theoretical fits to HERA data



⇒ RUN: [AAMQS], [Gonçalves'13]

⇒ DLA: [see talks by Albacete,Iancu]

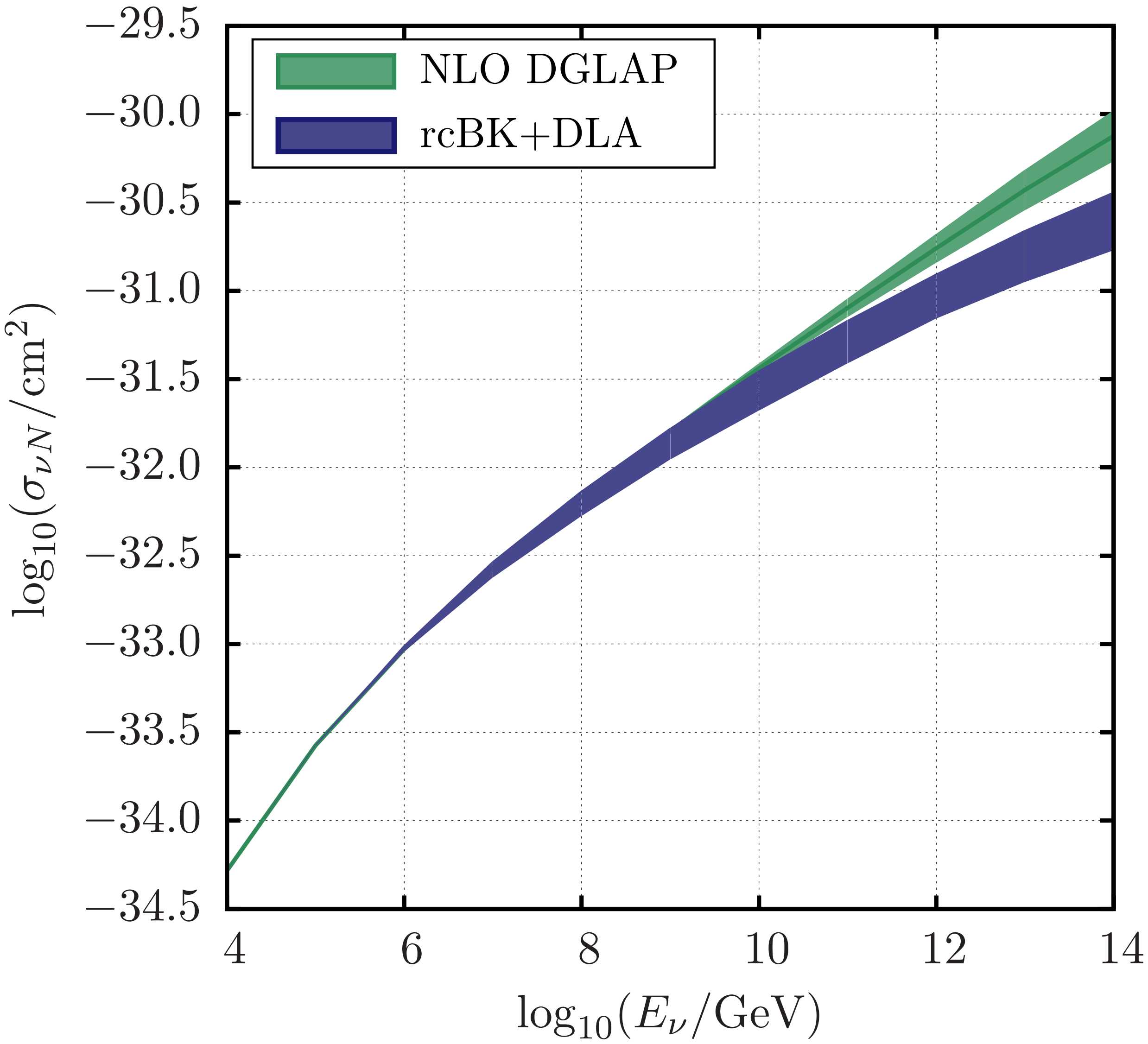
⇒ PHENO: [GBW,IIM and Soyez]

- Uncertainty in $\sigma_{\nu N}$ is due to the evolution kernel NOT to the initial conditions.

4. Results

4.1 The neutrino-nucleon cross section at UHE

NLO DGLAP+`NNPDF3.0` vs rcBK+DLA



- Differences for $E_\nu > 10^8$ GeV, as large as a factor 4.5 at $E_\nu = 10^{14}$ GeV.

4.2 . . . and its astrophysical implications

Limits on astrophysical ν fluxes — The P. Auger

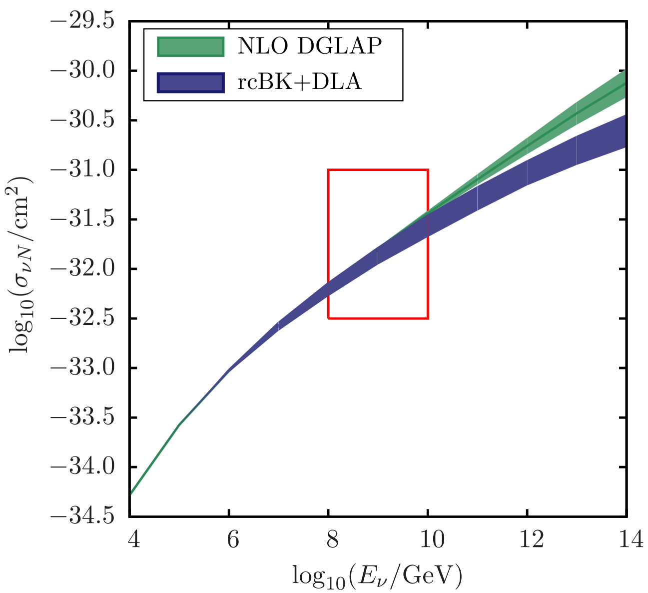
[P.Auger collab. '15]

- The event rate is neutrino flavor and interaction dependent

$$N_{\rm evt} = \sum_{i=1,2,3}\sum_{\nu_i,\bar{\nu}_i}\int \mathrm{d}E_\nu \frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu}\omega_{\nu_i}(E_\nu)\int_0^1 \mathrm{d}y\,\mathcal{E}(yE_\nu)\frac{\mathrm{d}\sigma_{\nu_i N}}{\mathrm{d}y}$$

Assuming the same flux of all flavors they set a limit at 90% C.L,

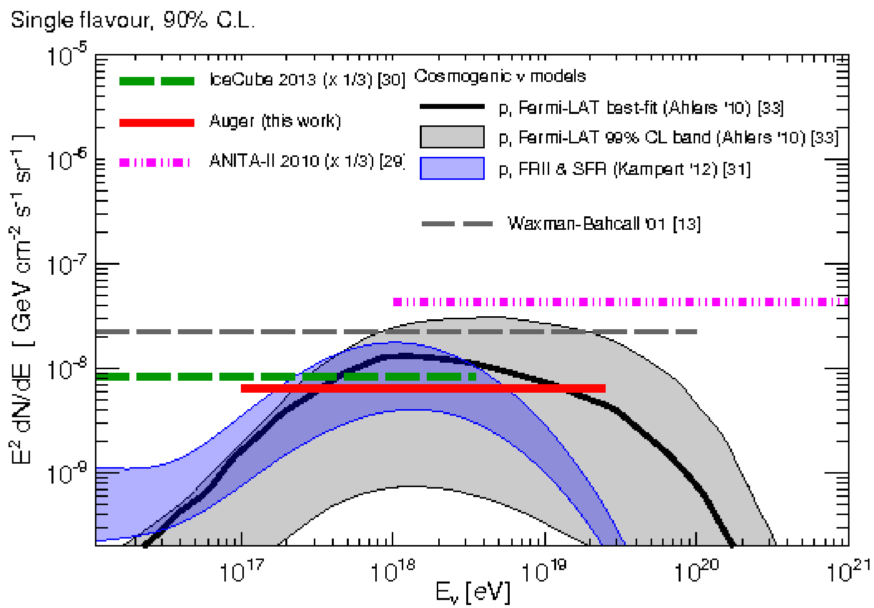
$$\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu} = k\,E_\nu^{-2} \Rightarrow k_{90} < \frac{N_{\rm up}}{\int \mathrm{d}E_\nu\, E_\nu^{-2}\mathcal{E}_{\rm tot}(E_\nu)} = 6.4\times 10^{-9}\ \mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}}$$



With rcBK+DLA $\sigma_{\nu N}$:

$$k_{90} \sim 1.5 \times k_{90}$$

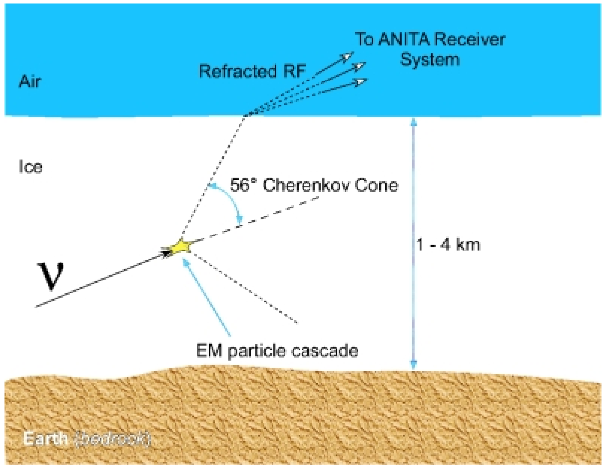
at $E_\nu = 10^9$ GeV.



Limits on astrophysical ν fluxes | ANITA-II

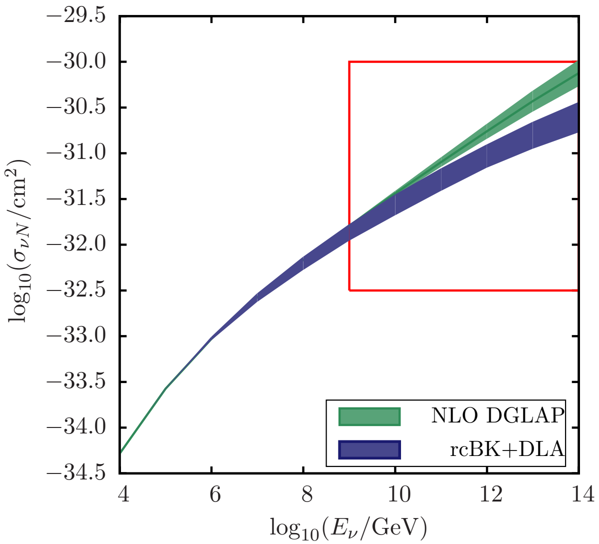
[The ANITA collab. '10]

- Higher energies are accesible with neutrino radio-detection experiments based on the Askaryan effect:



$\Rightarrow$ Production of a coherent radio emission in the UHE particle interaction.

$\Rightarrow$ Radio transparent medium needed: ice, sand, lunar regolith...

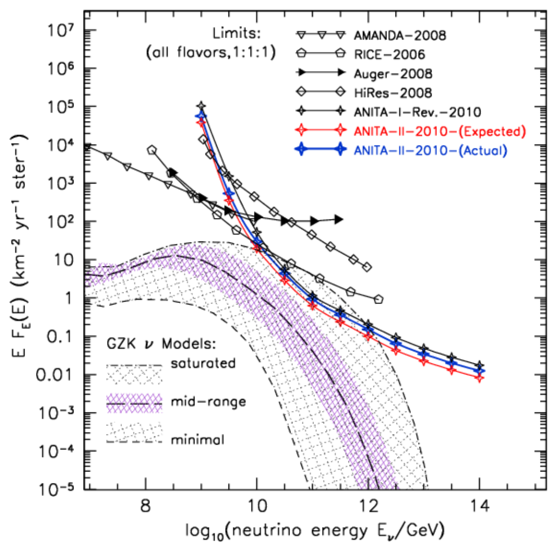


With rcBK+DLA $\sigma_{\nu N}$:

$$k_{90} \sim 1.4 \times k_{90}$$

at $E_\nu = 10^{11}$ GeV.

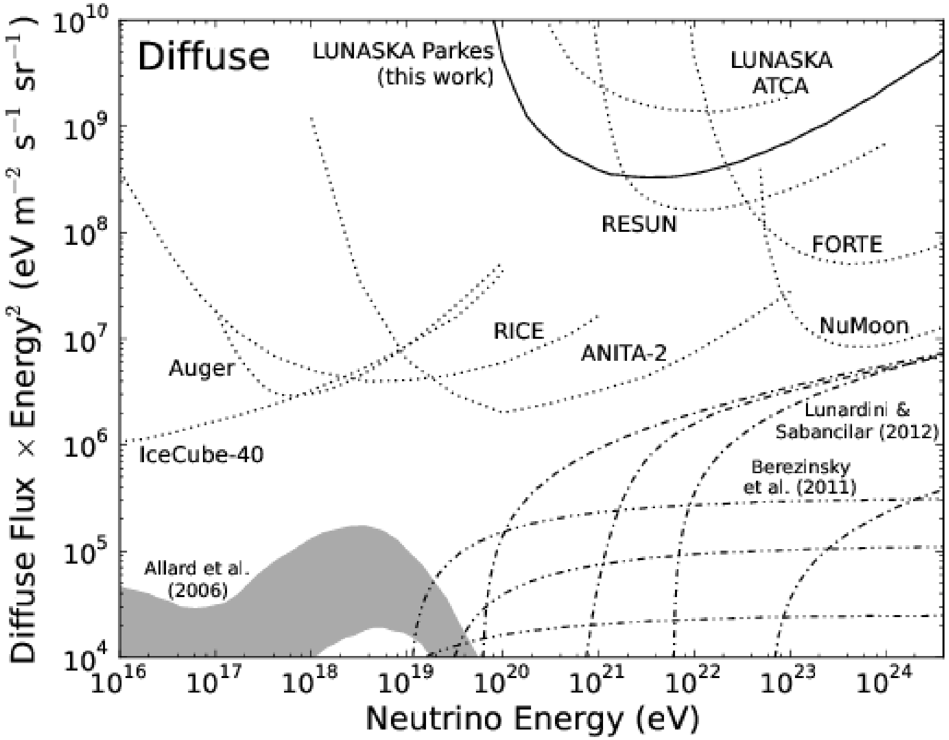
(Scales with $\sigma_{\nu N}^{0.45}$).



Limits on astrophysical ν fluxes | LUNASKA

[Bray et Al. '15]

- Several experiments detecting radio pulses in the Moon:
  - *Only* sensitive to $E_\nu > 10^{12}$ GeV ($d_{\text{moon}} \sim 3.8 \times 10^8$ m).
  - Future prospects (2018): the Square Kilometre Array (SKA).



The flux limits can be up to 2.5-4.5 larger in $10^{12} < E_\nu < 10^{14}$ GeV

Take home message

- Goal: Obtain $\sigma_{\nu N}^{CC,NC}$ in the ultrahigh energy regime.
- Why?: Essential to characterize cosmogenic neutrino flux.
- Problem: The kinematical region is uncharted territory.
- Theoretical tools:
  - NLO DGLAP with different sets of PDFs.
  - Running coupling+DLA BK small-x evolution with HERA tested UGDs.
- Conclusions:
  - $\sigma_{\nu N}^{\rm DGLAP} = 4.5\ \sigma_{\nu N}^{\rm BK}$ at $E_\nu = 10^{14}$ GeV.
  - Current upper limits for the UHE neutrino flux could be modified accordingly.


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
DANKSCHEEN
BÏYAN
SHUKRIA
TINGKI
YAQHANYELAY
TASHAKKUR ATU
SUKSAMA
EKHMET
GRAZIE
MEHRBANI
MAAKE
KOMAPSUMNIDA
PALDIES
BOLZÏN
MERCI
JUSPAXAR
GOZAIMASHITA
EFCHARISTO
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MAITEKA
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