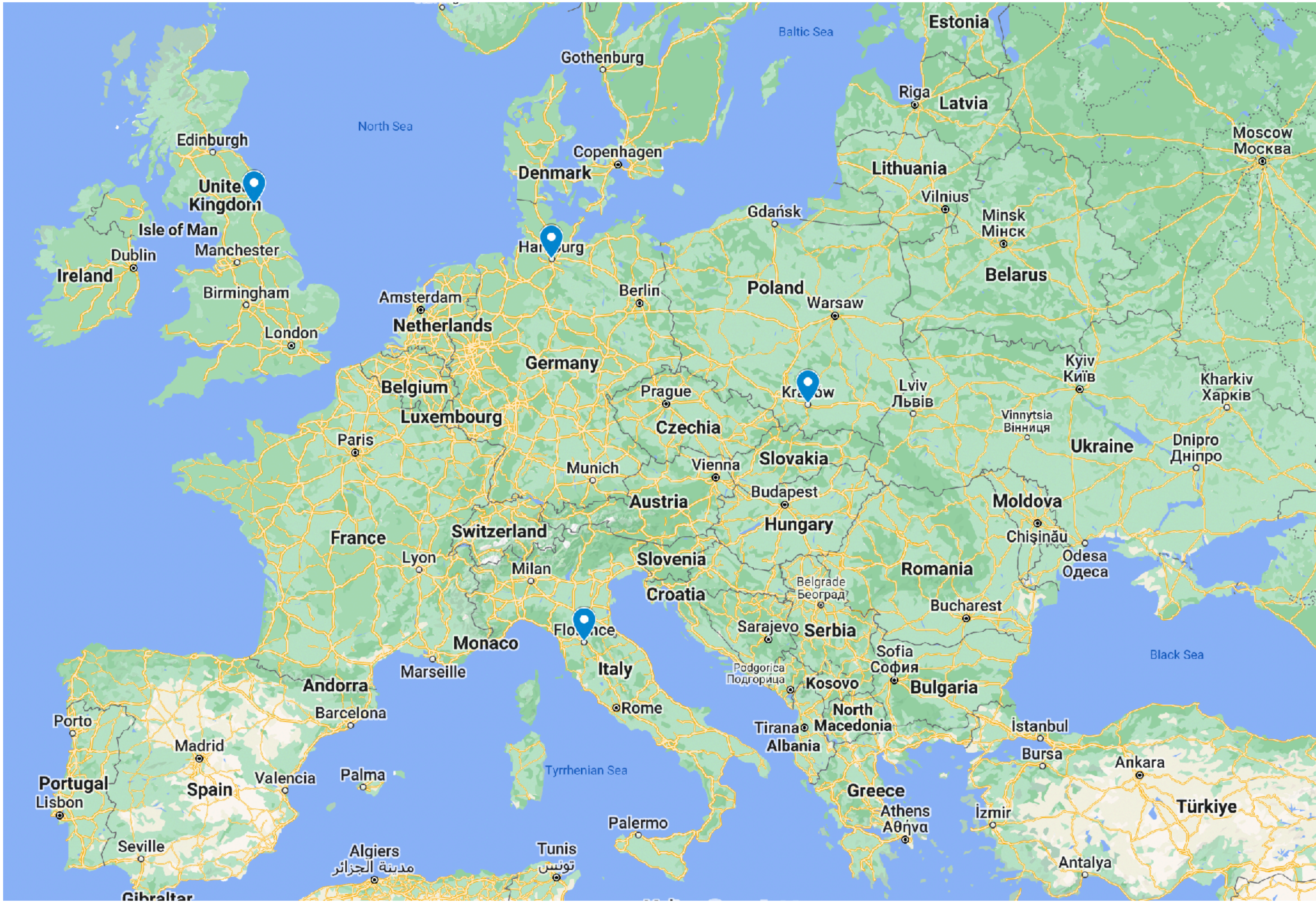
From strong protons to weak neutrinos

Anna Staśto
Penn State University

My journey:...from Old World...



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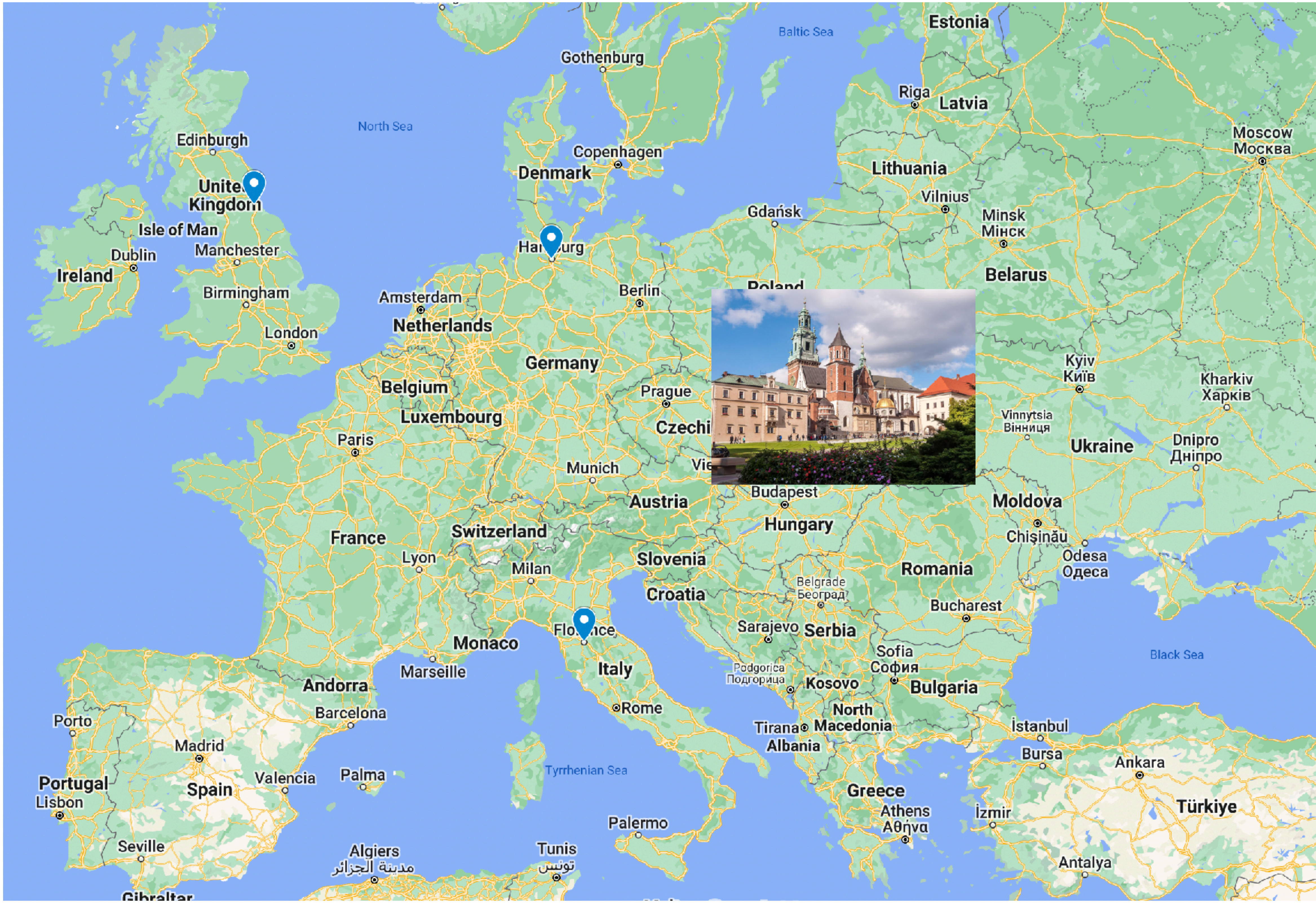

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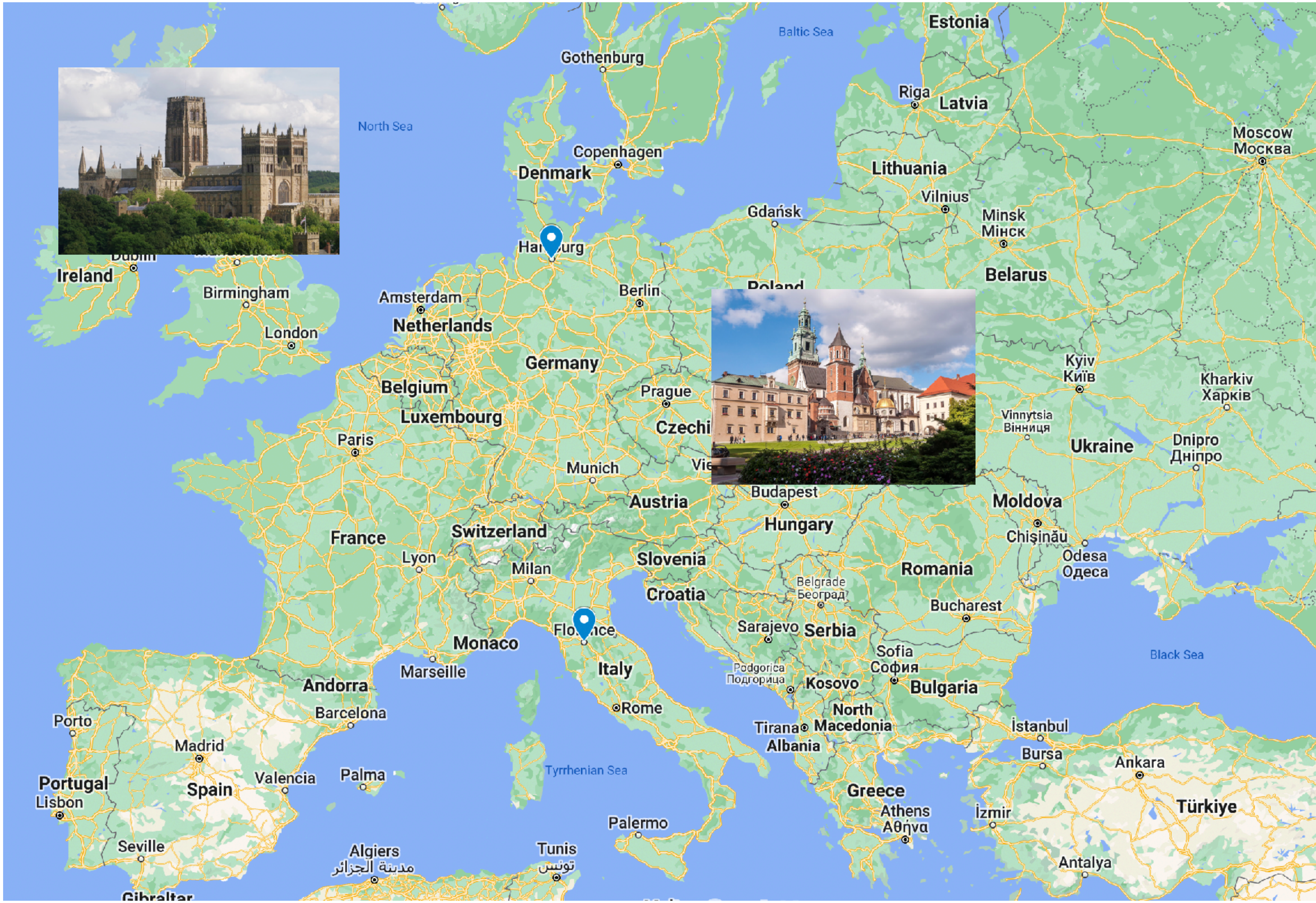
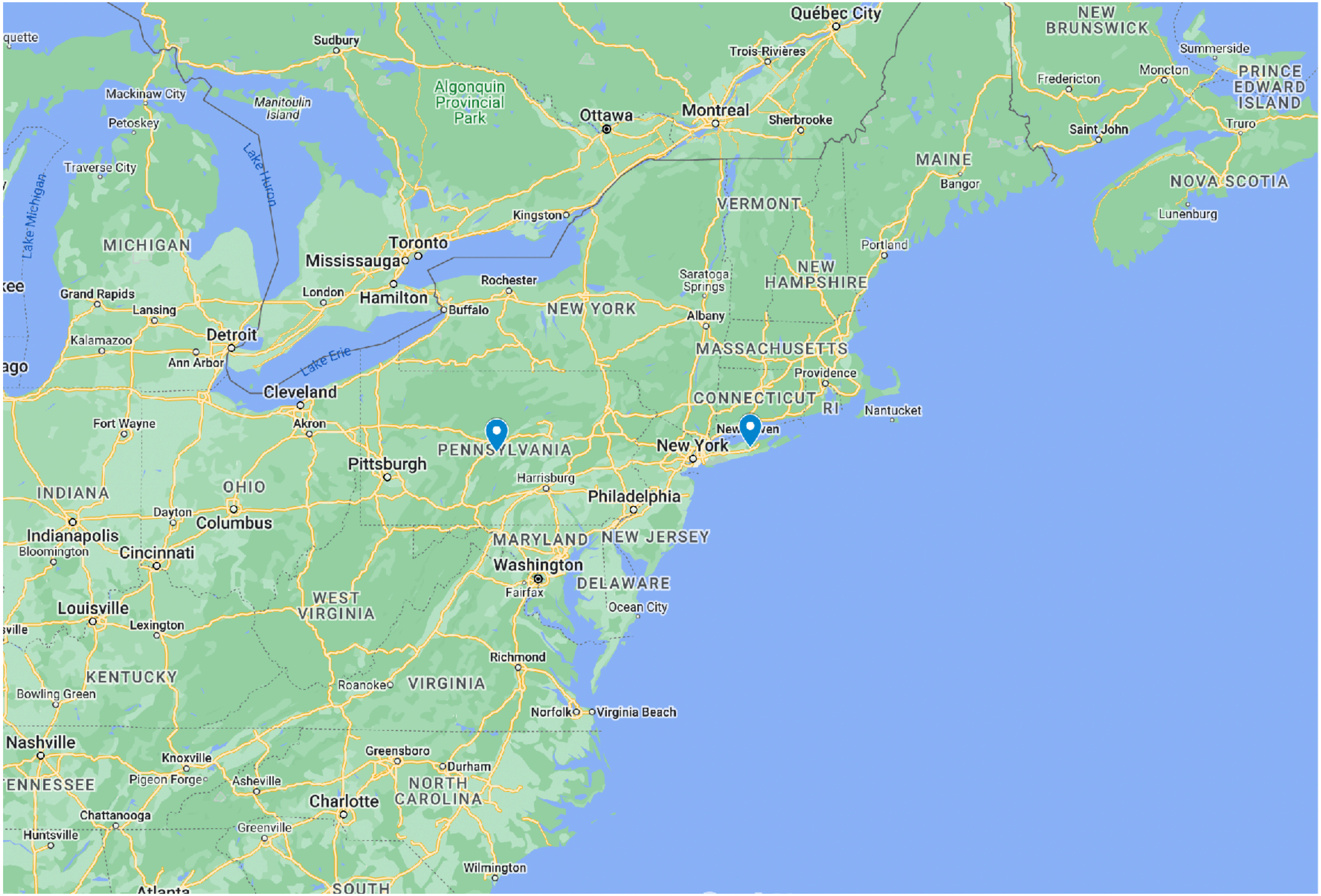


My journey:…from Old World…

My journey:…from Old World…

...to New World...



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Greensboro
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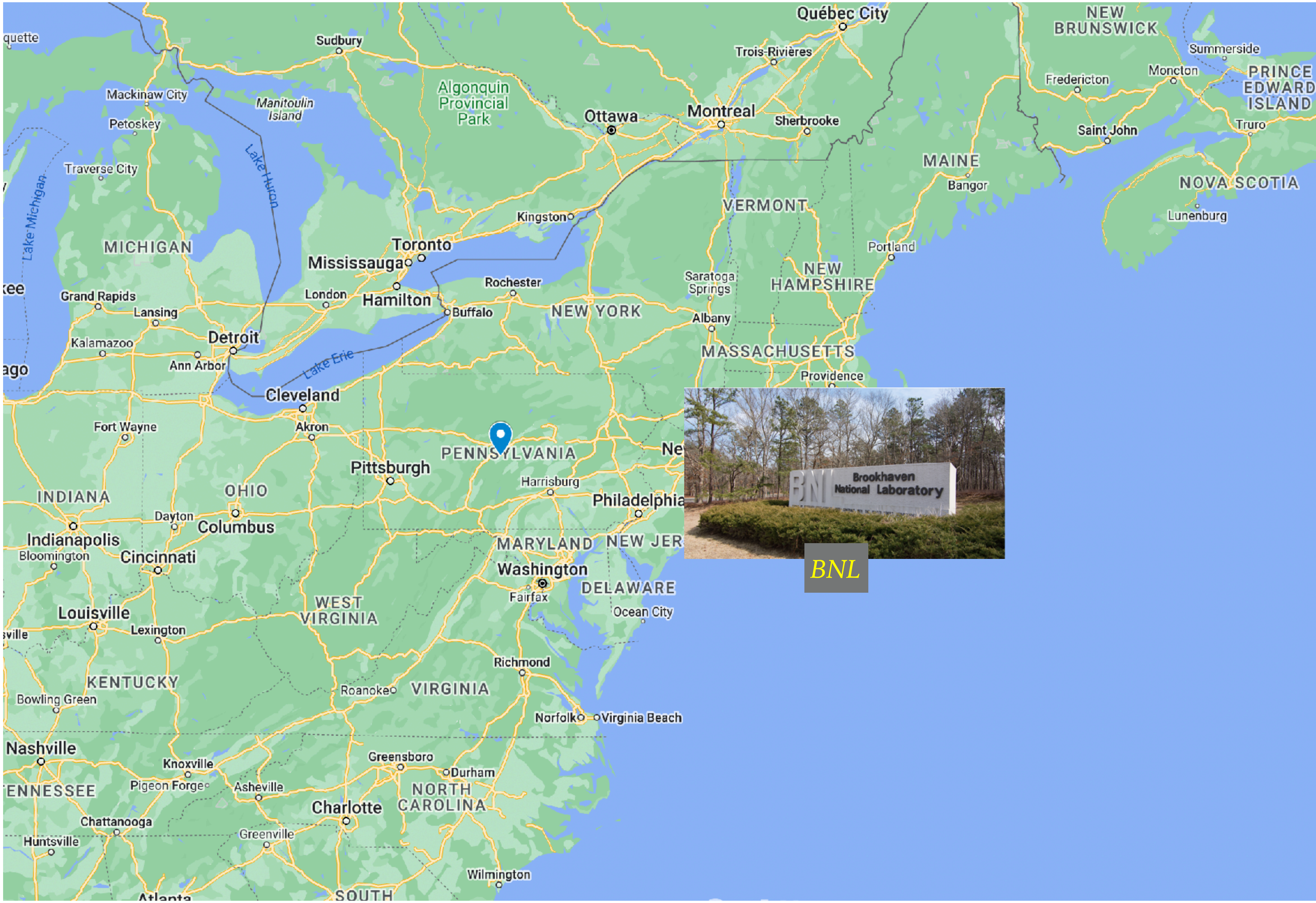
SOUTH

. . .to New World. . .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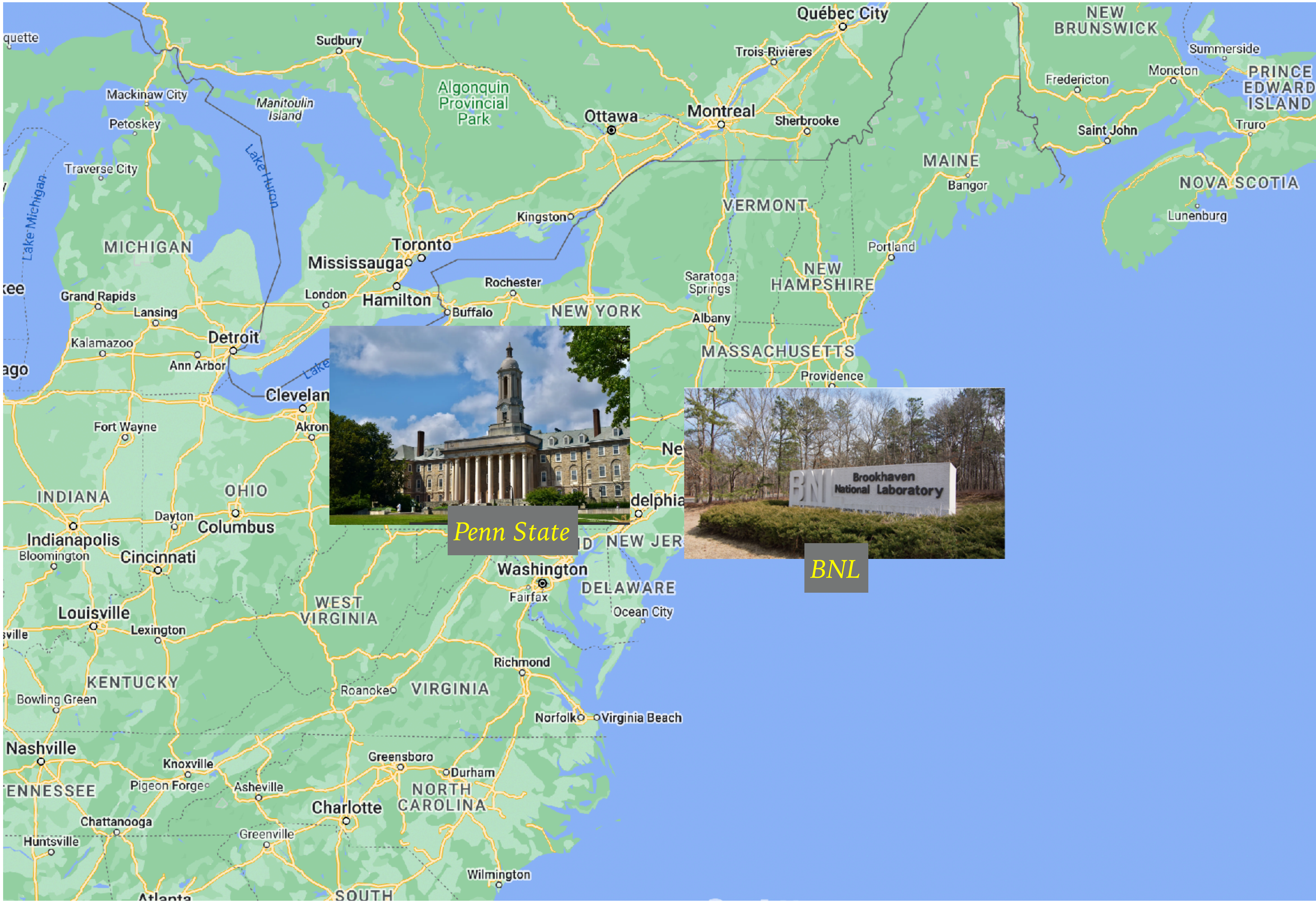
...to New World...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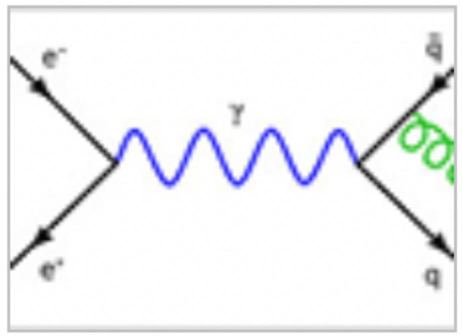
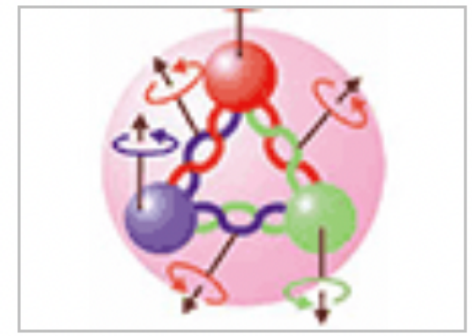
RBRC research

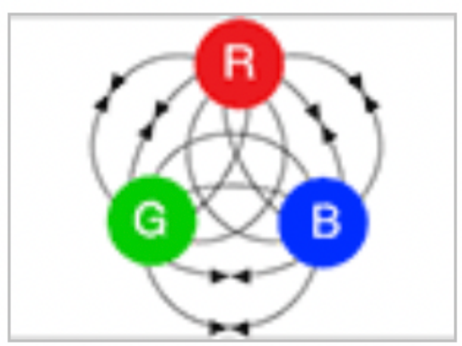
Lattice QCD



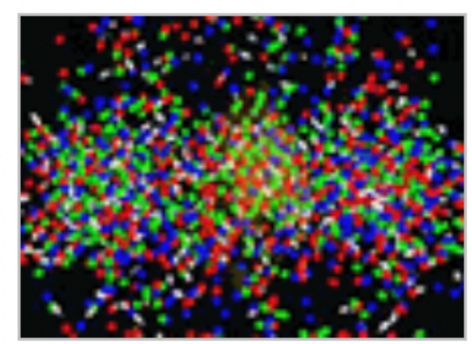
Spin Physics



Quantum Chromodynamics



Physics of QGP



RBRC research

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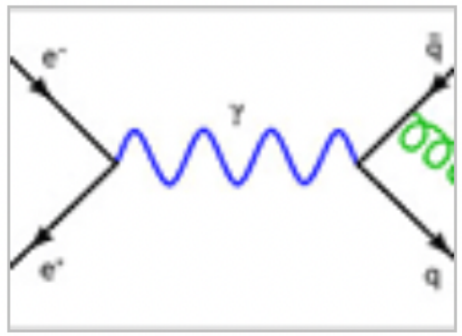

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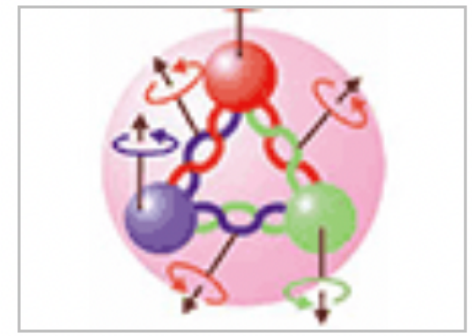

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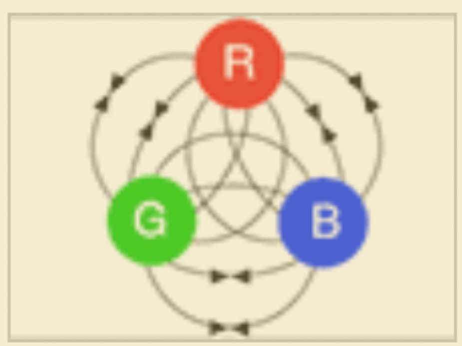

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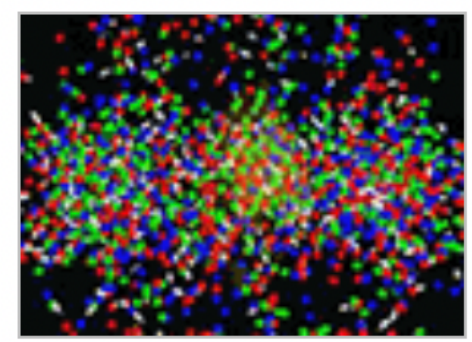


My research:
proton structure, QCD at high energy and density, scattering amplitudes, ultrahigh energy neutrinos

Proton structure

What is the structure of the proton ?

First observation of proton structure: SLAC experiment (1969)

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

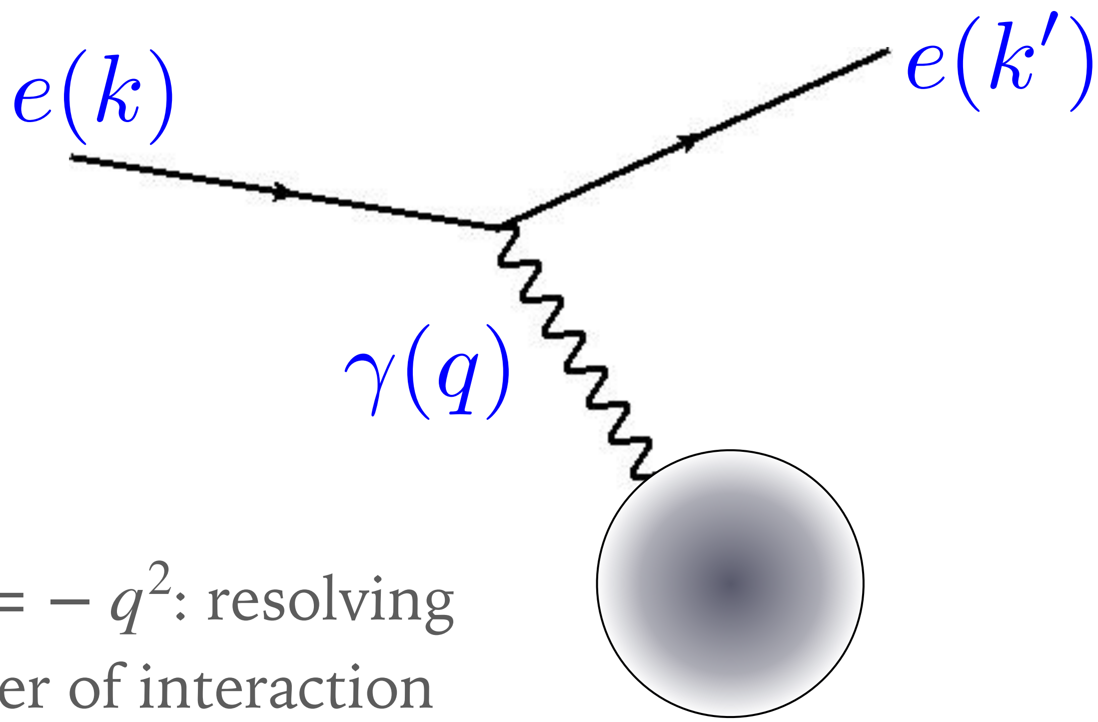
OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305

(Received 22 August 1969)



$Q^2 = -q^2$: resolving power of interaction

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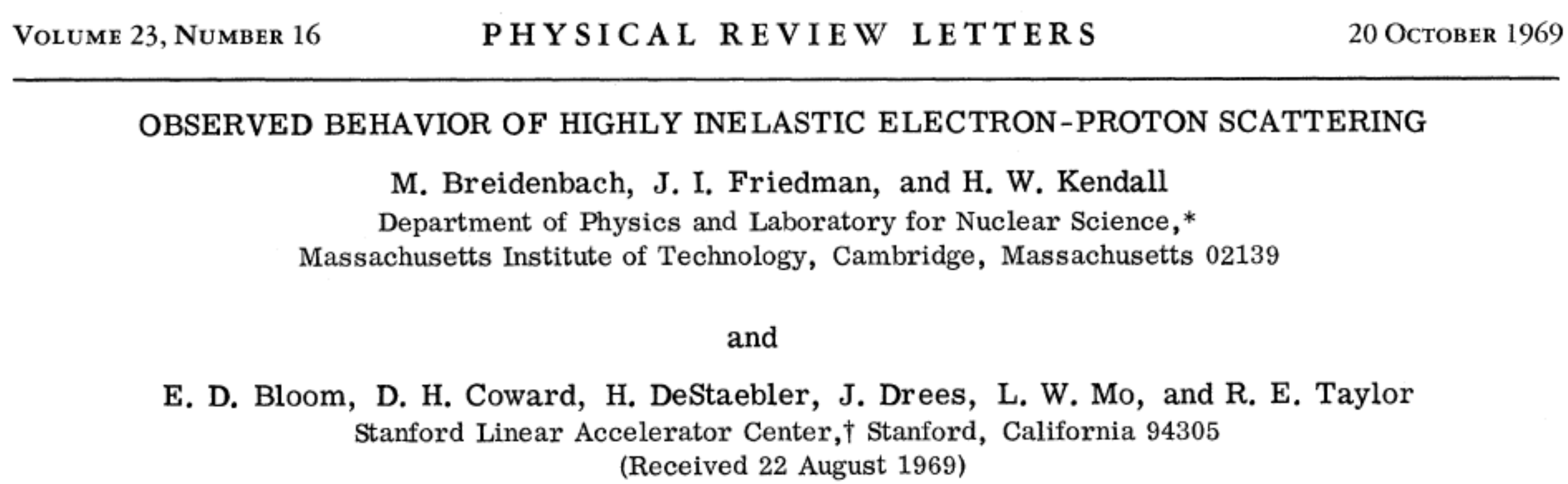

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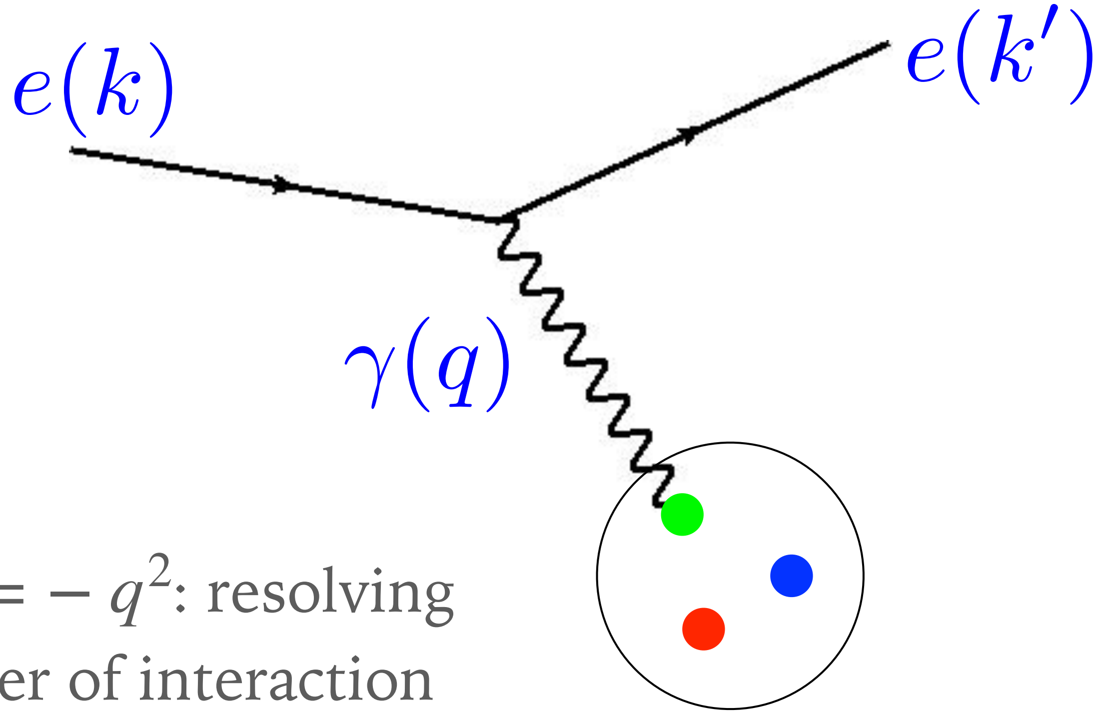

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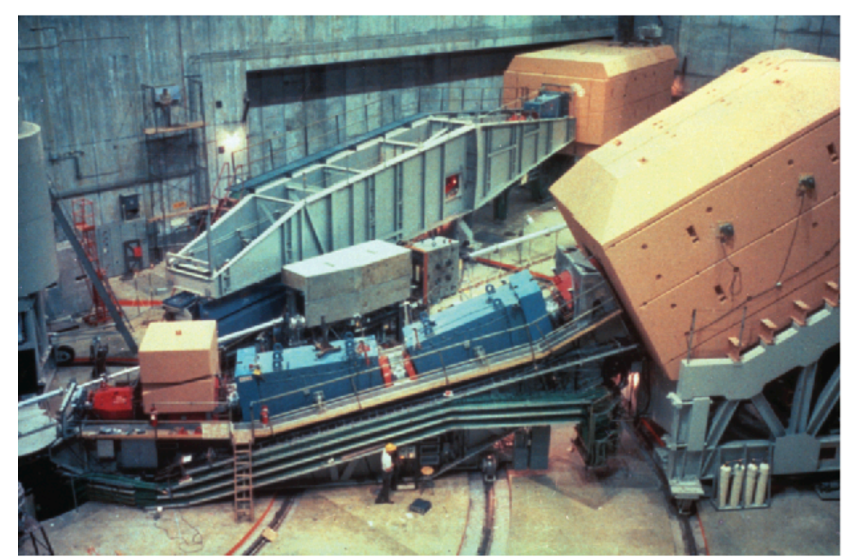
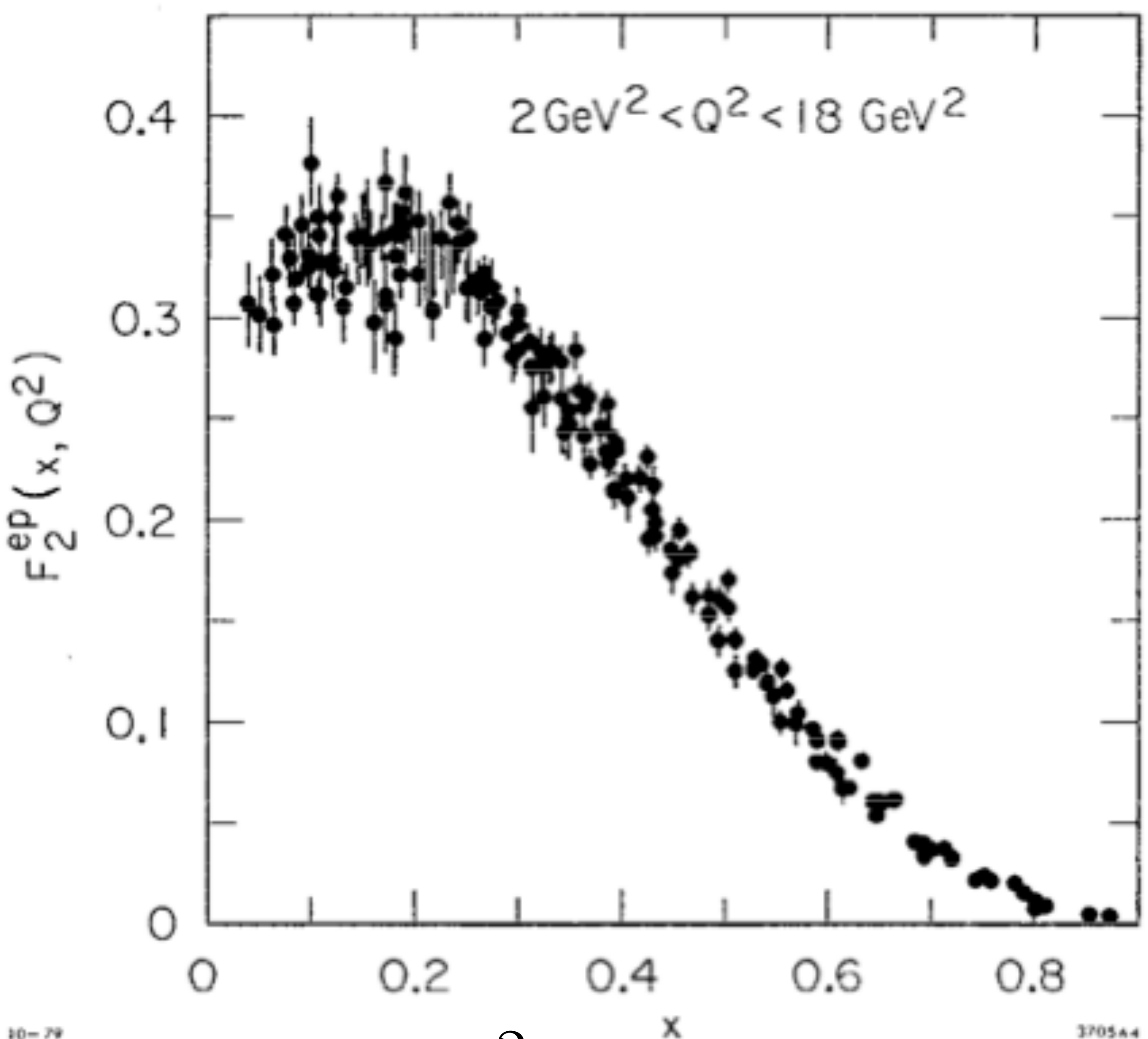


Revealing proton structure

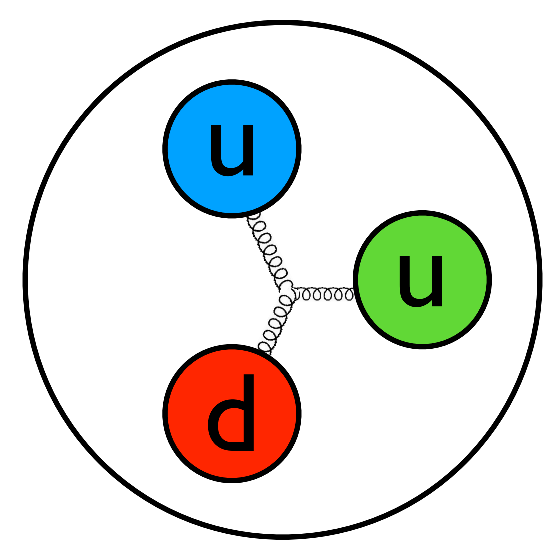
proton structure function



$$x \sim \frac{Q^2}{s}$$

Measured cross section

Momentum distribution of partons inside the proton



Exploring proton structure at high energy

DESY - Hamburg
HERA Collider
1992-2007

The only electron(positron)-proton collider ever built ...so far...looking forward to EIC !

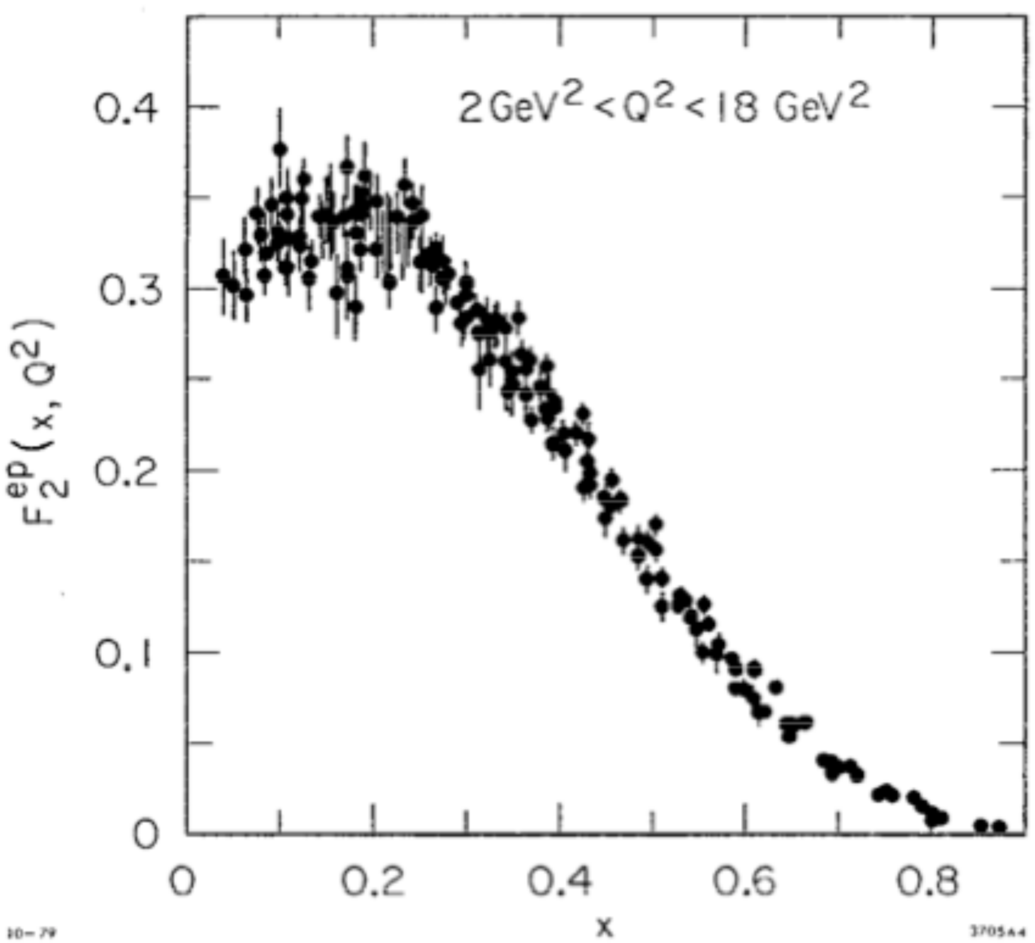
Center of mass energy:

$$E_{\rm cm} = 320 \text{ GeV}$$

equivalent to 50 TeV electron beam on a fixed proton target...about 2500 times more than at SLAC

Measurements of proton structure function

low energy



Measurements of proton structure function

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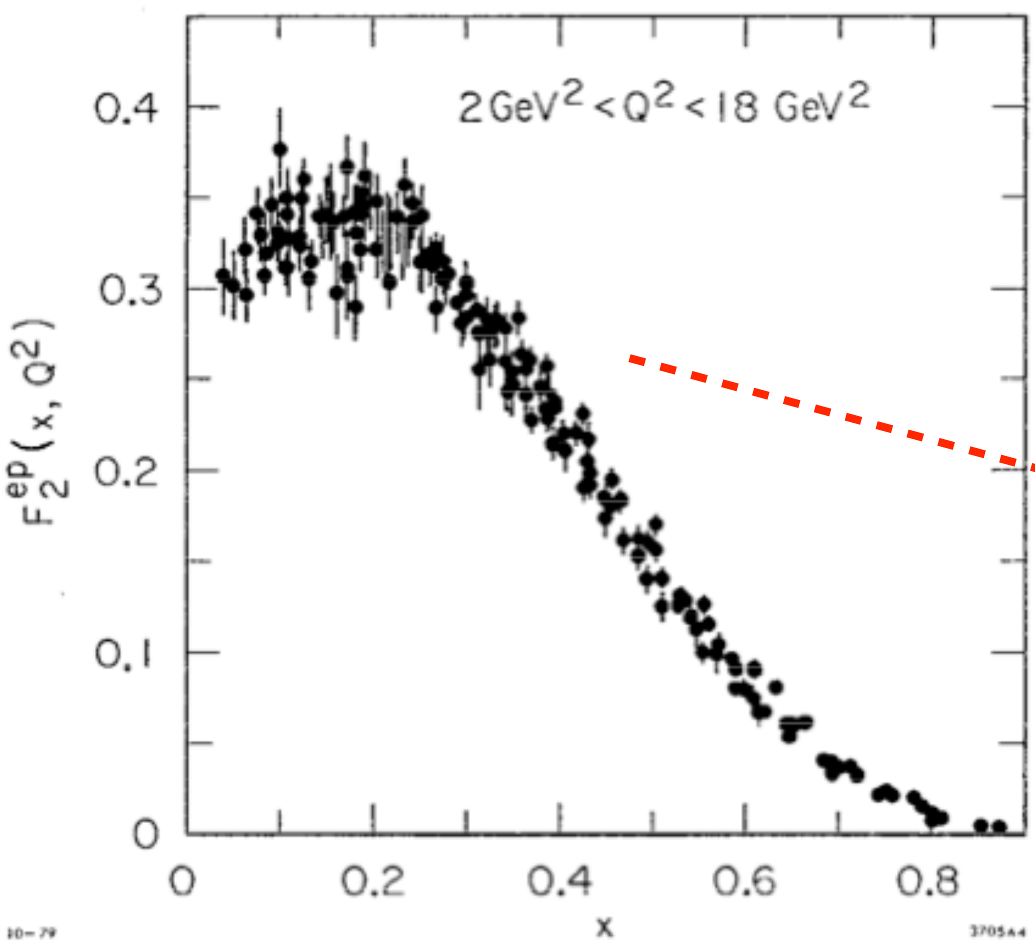
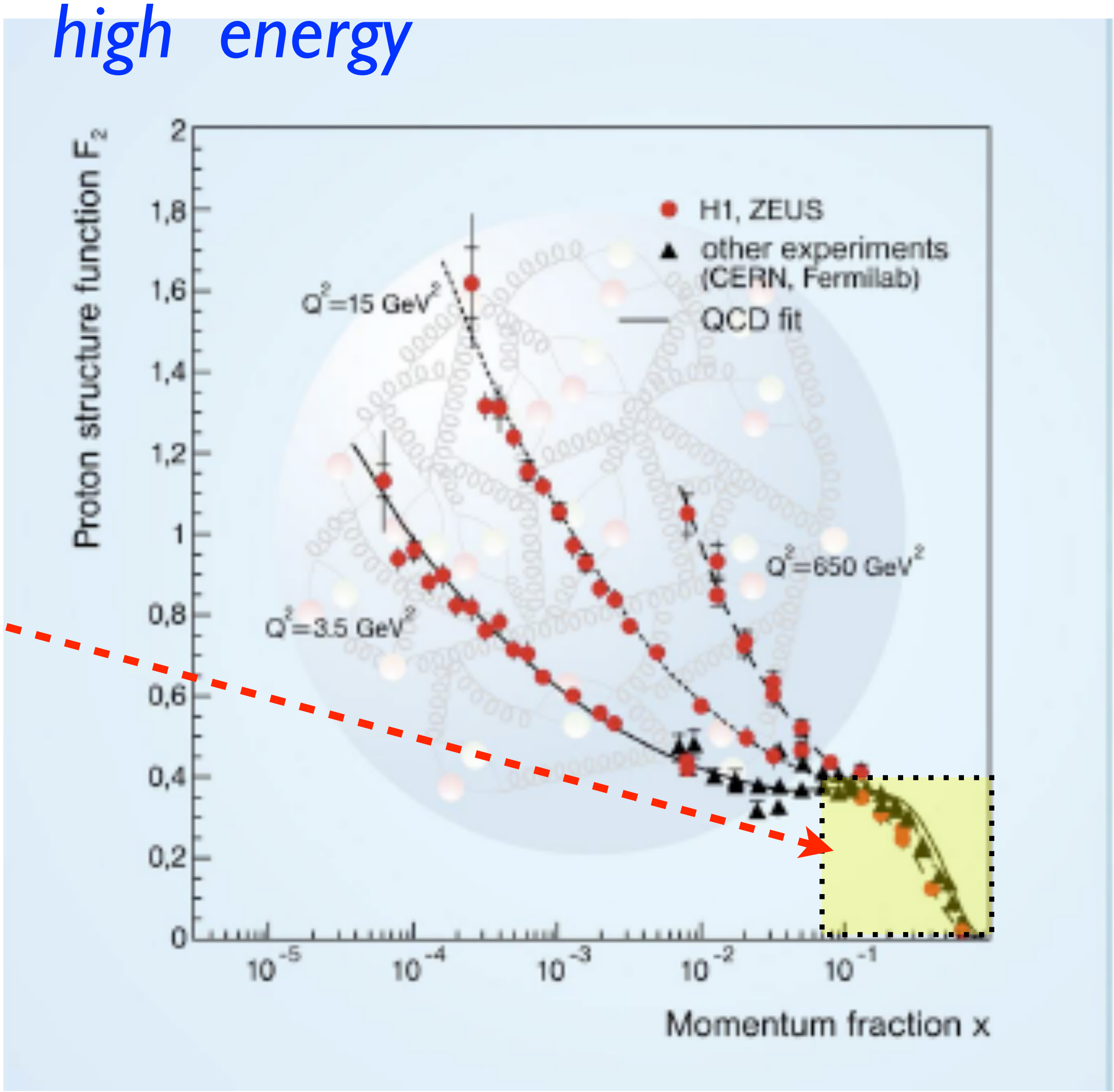
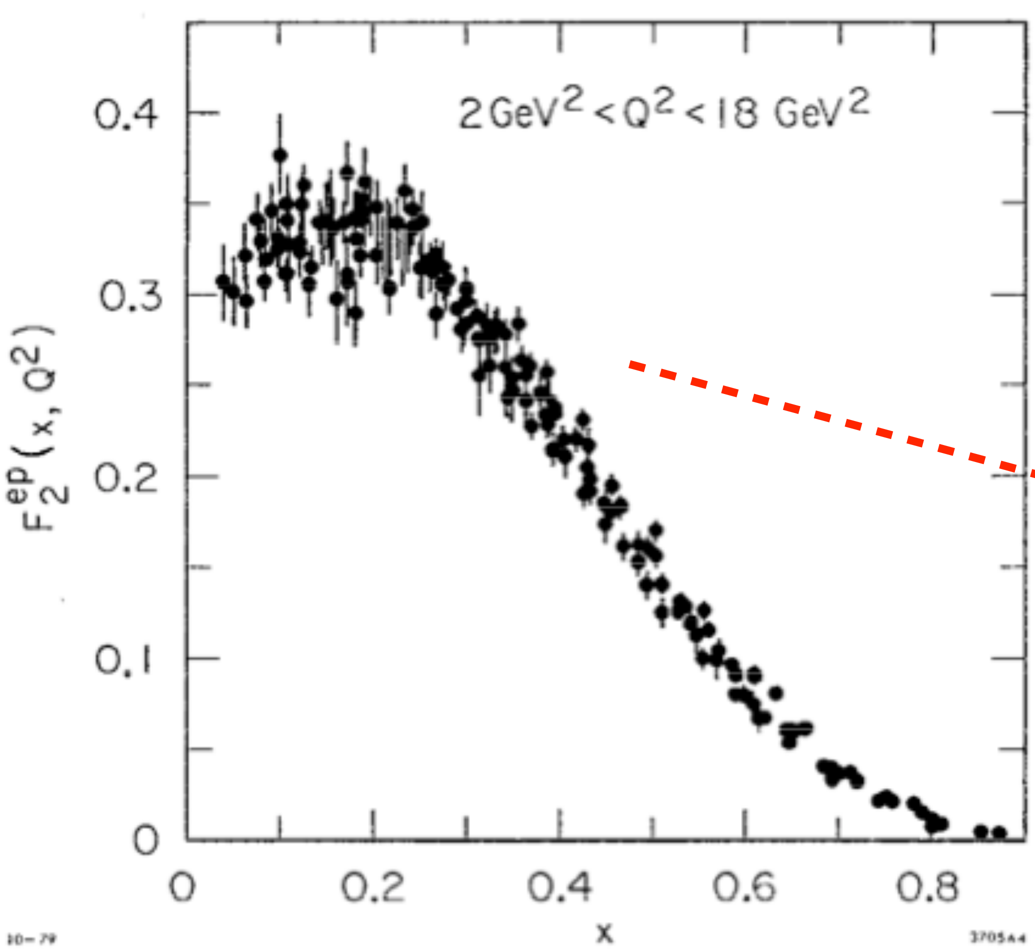


high energy

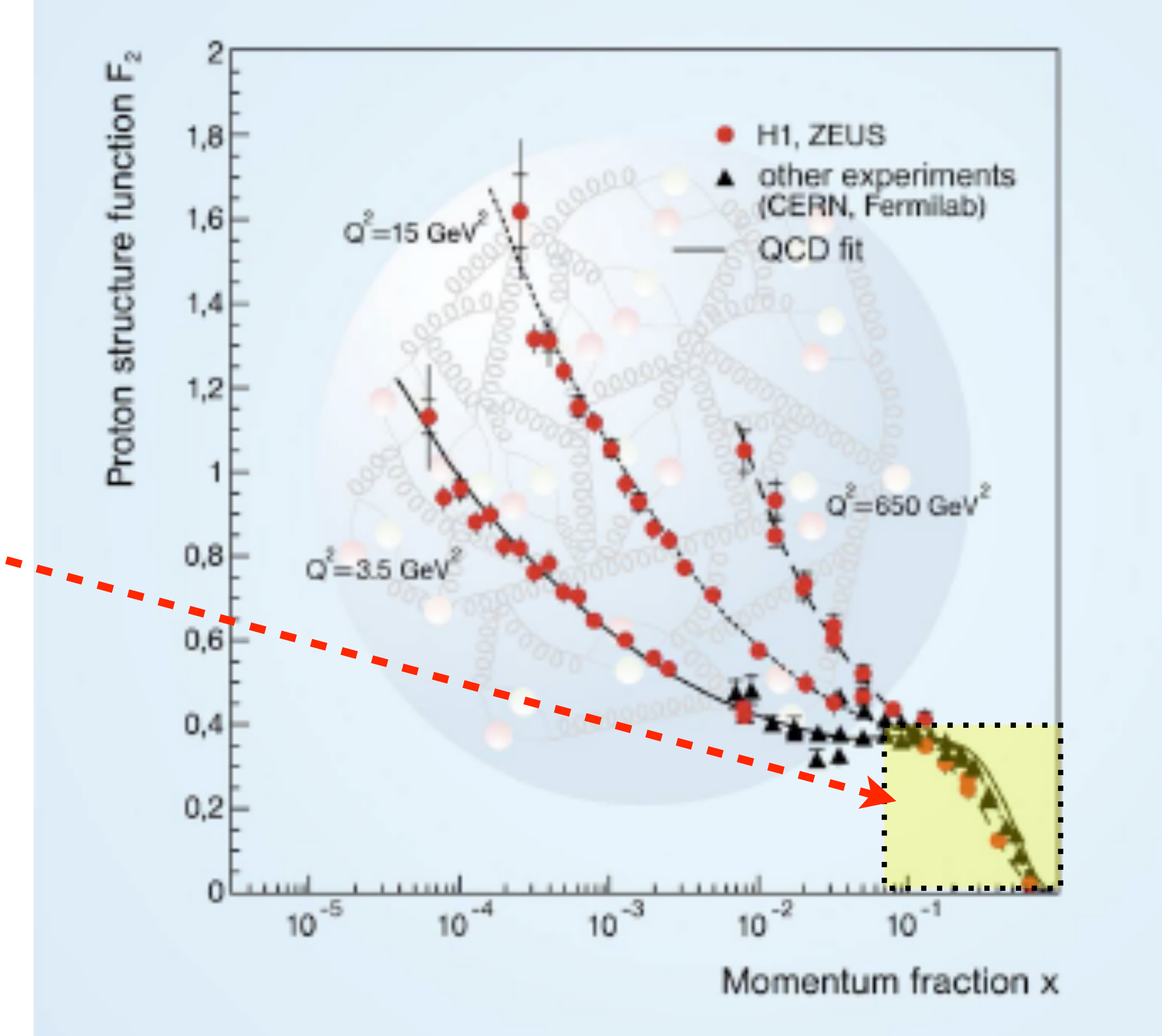


Measurements of proton structure function

low energy



high energy



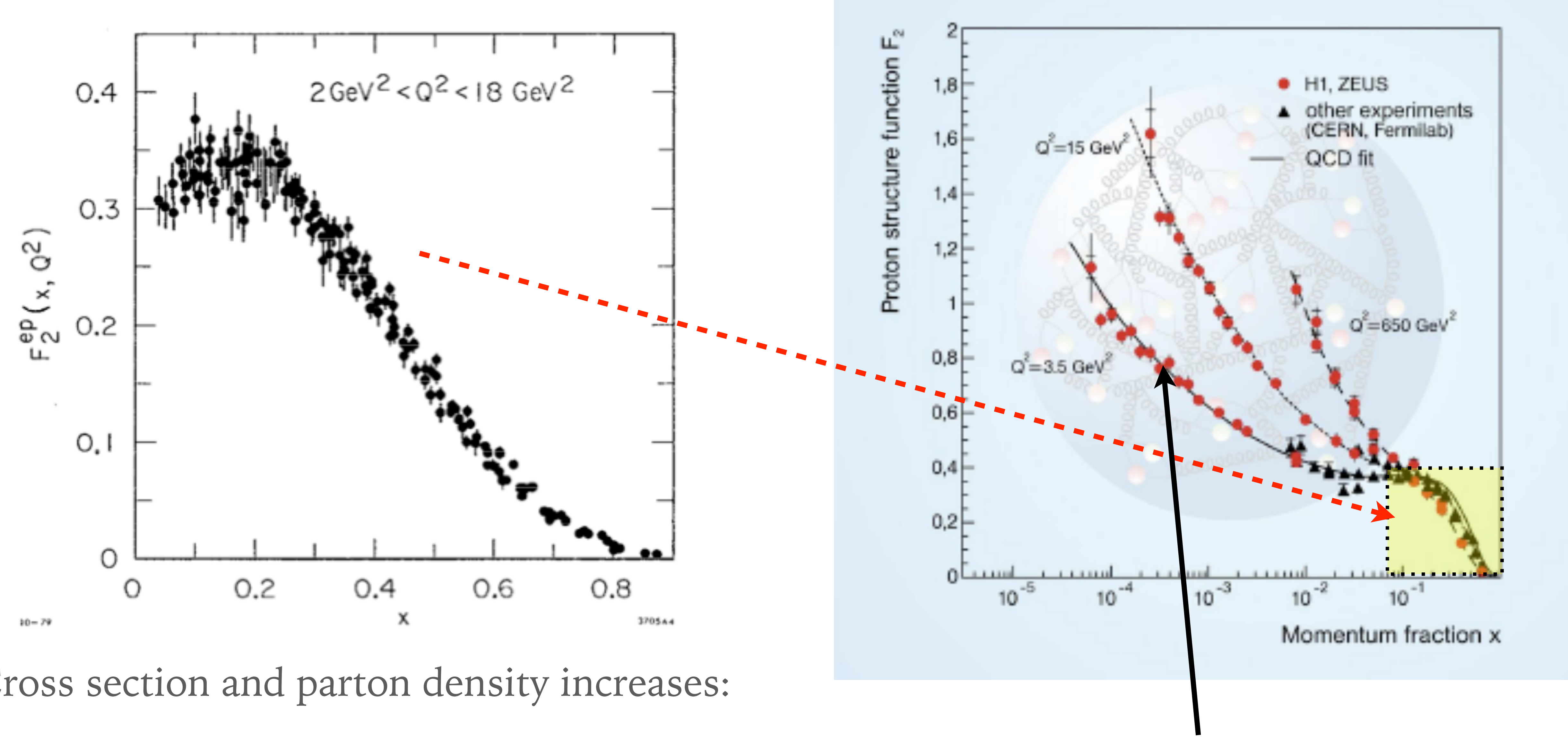
Cross section and parton density increases:

- with decreasing x
- with increasing scale Q

(small $x \leftrightarrow$ high energy s)

Measurements of proton structure function

low energy *high energy*



Cross section and parton density increases:

- with decreasing x
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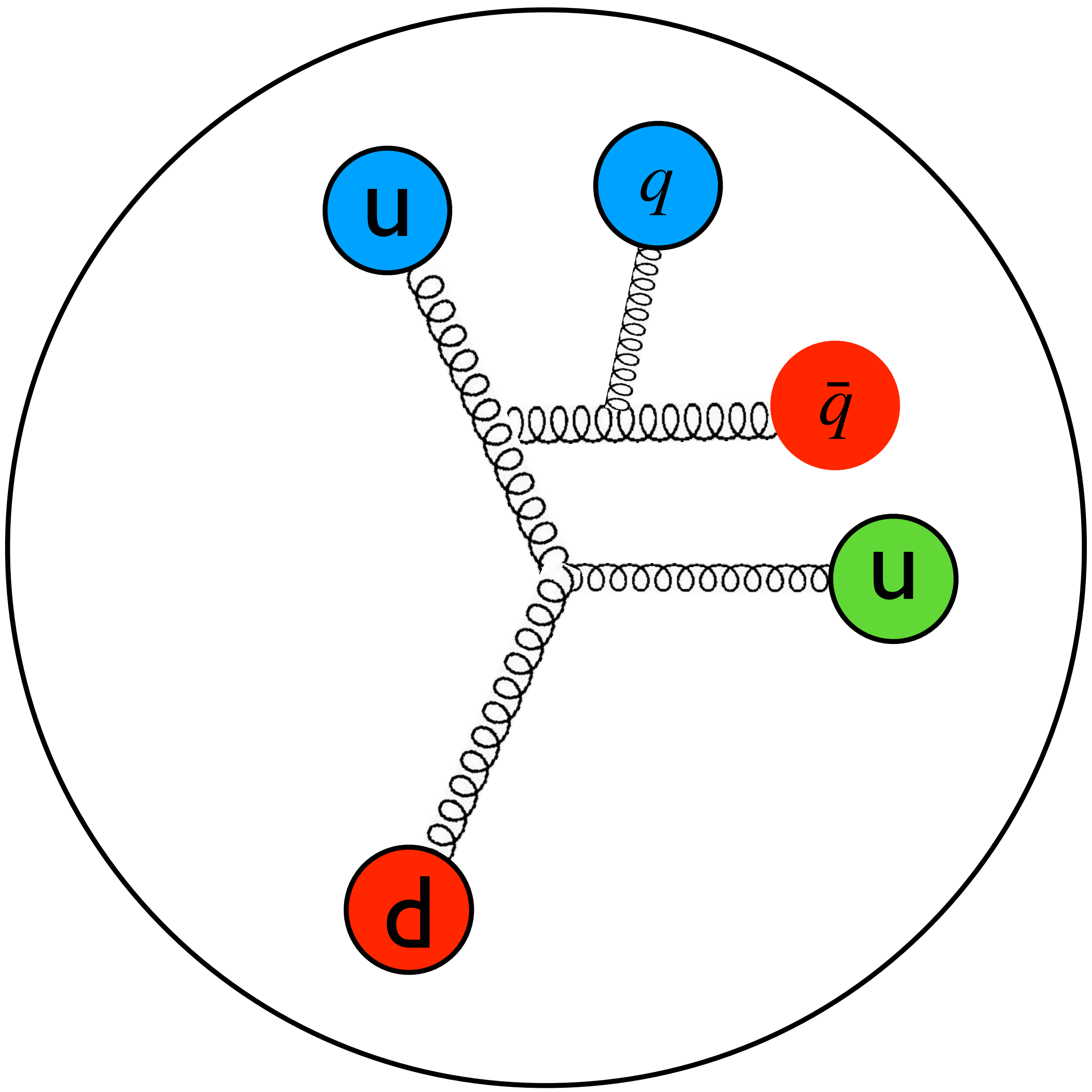
(small $x \leftrightarrow$ high energy s)

Where does this rise come from?

Answer: **gluon radiation in QCD**

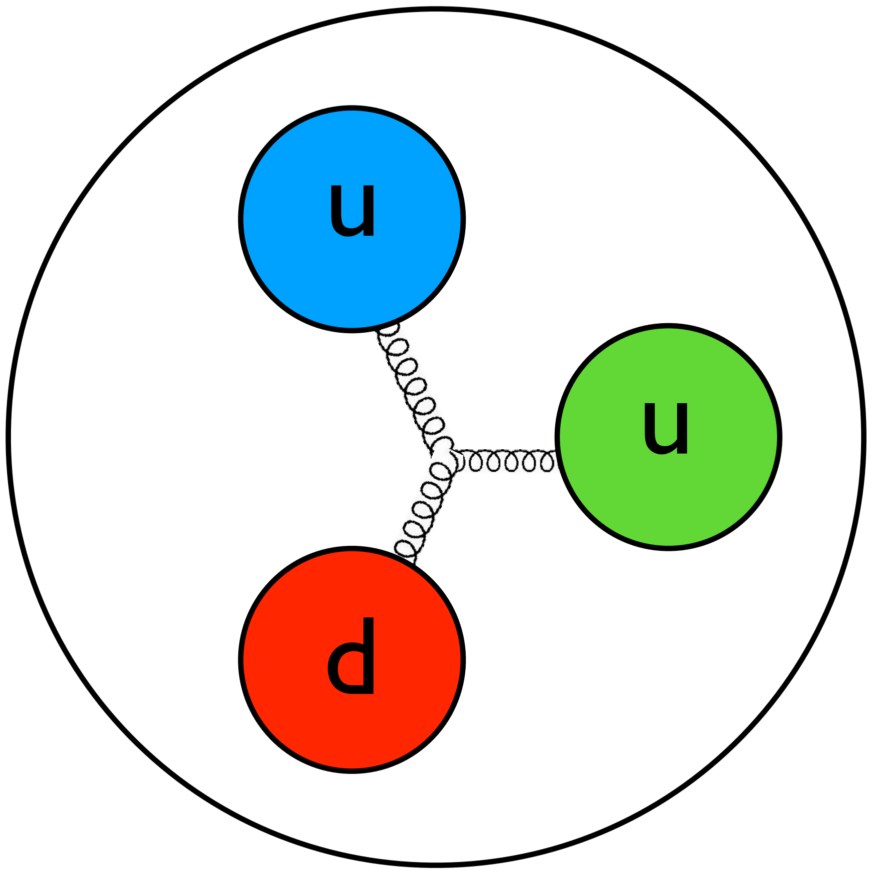
High energy: more gluons and sea quarks

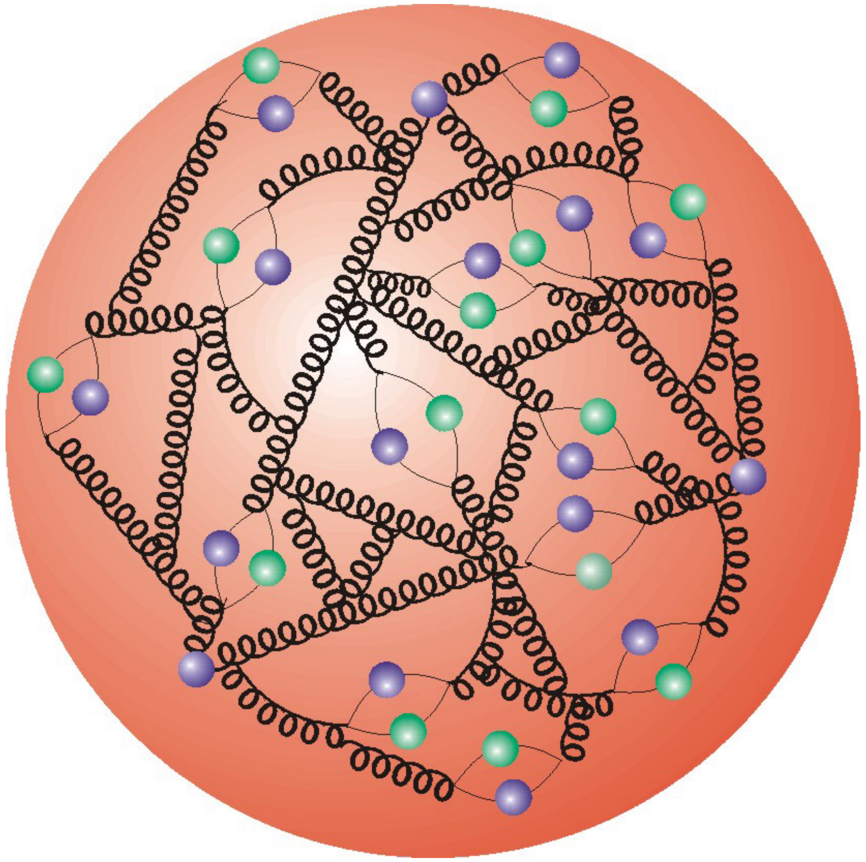


More and more gluon radiation at high energy
More ‘sea ’ quarks resolved

Ocean beach at Smith Point

Proton structure from low to high energy…





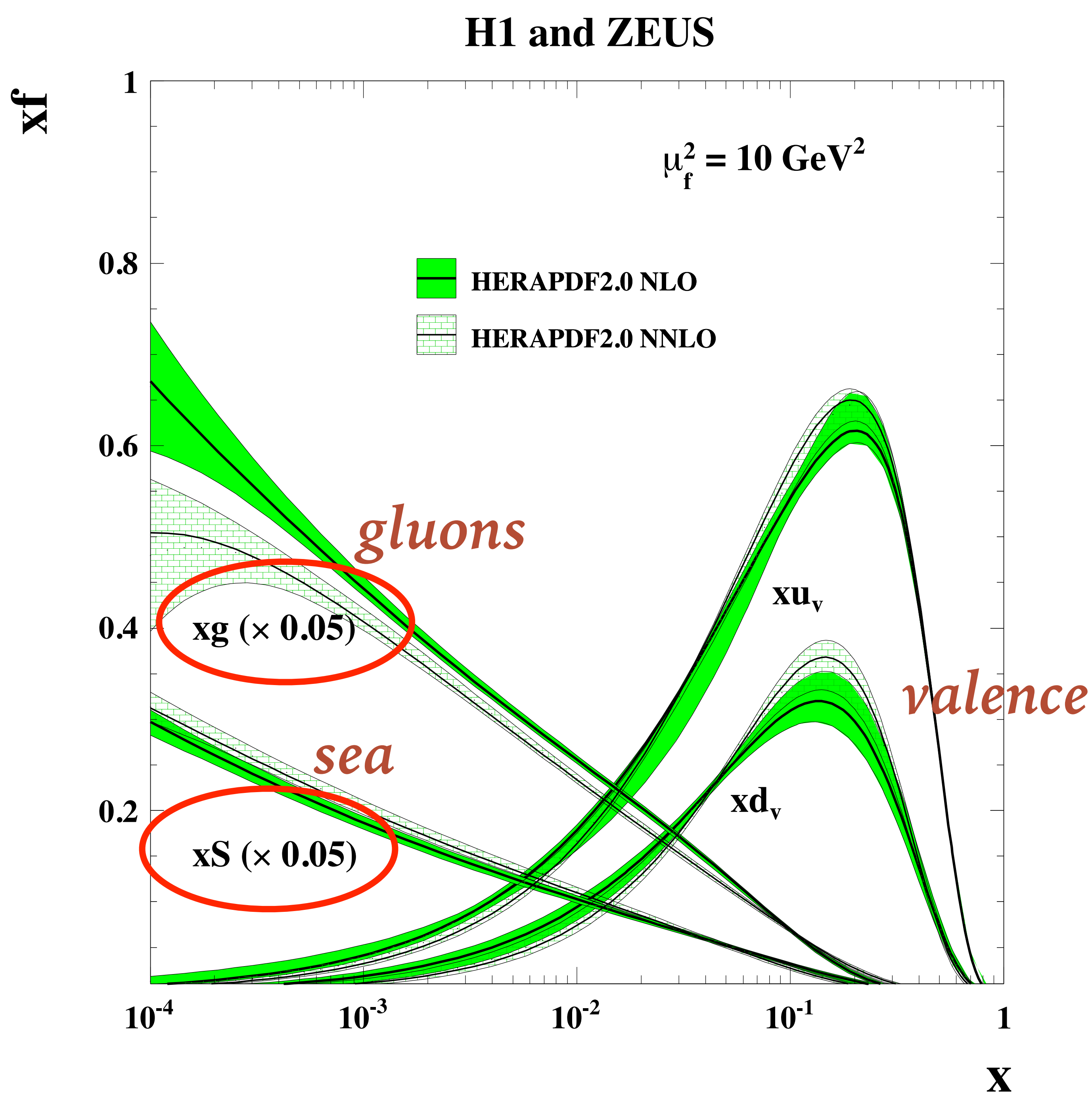
Proton has very rich structure:

At high collision energies structure

dominated by **gluons** with very low fractional momenta x

What happens at very large gluon density ?

very large density of gluons



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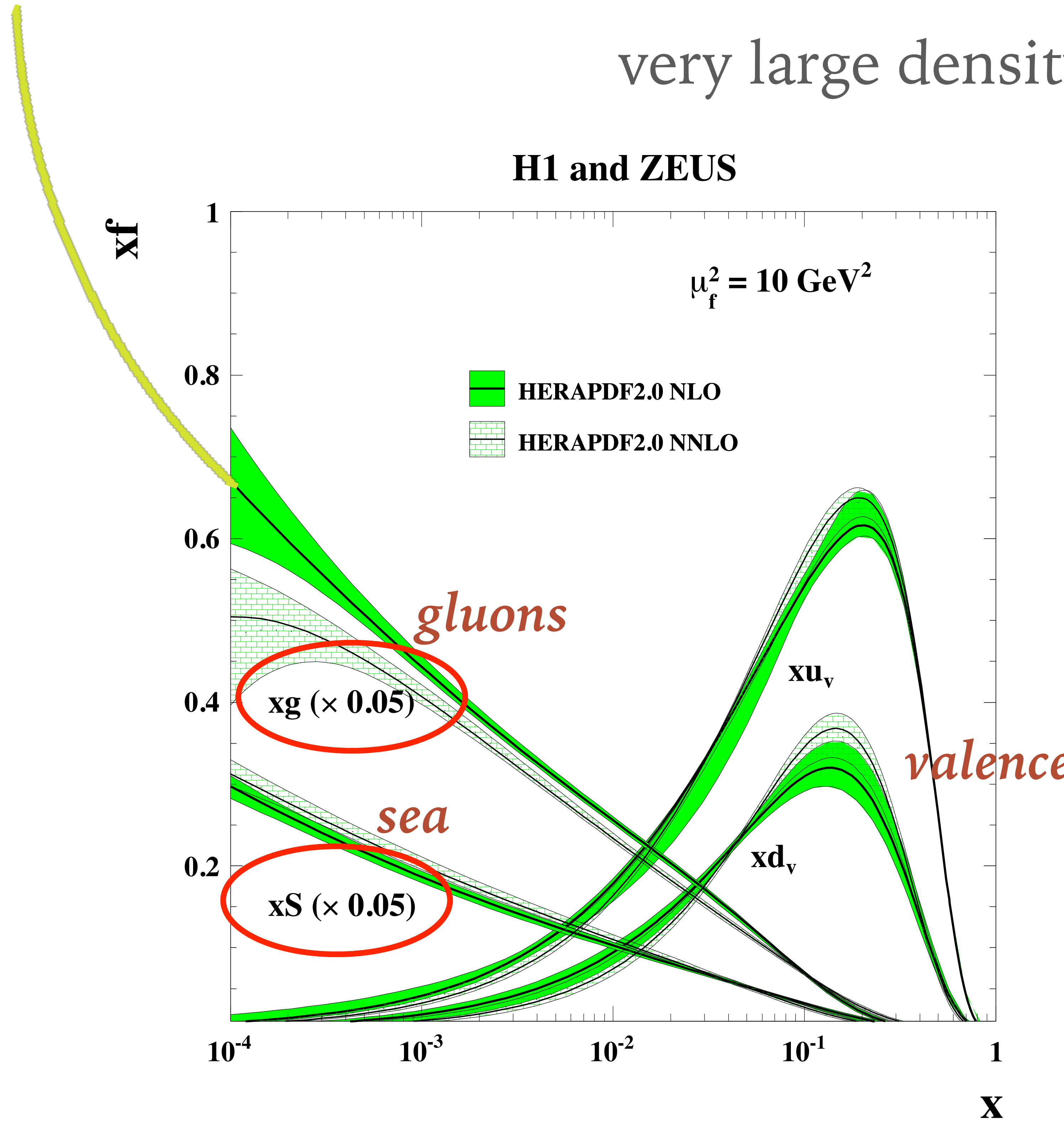

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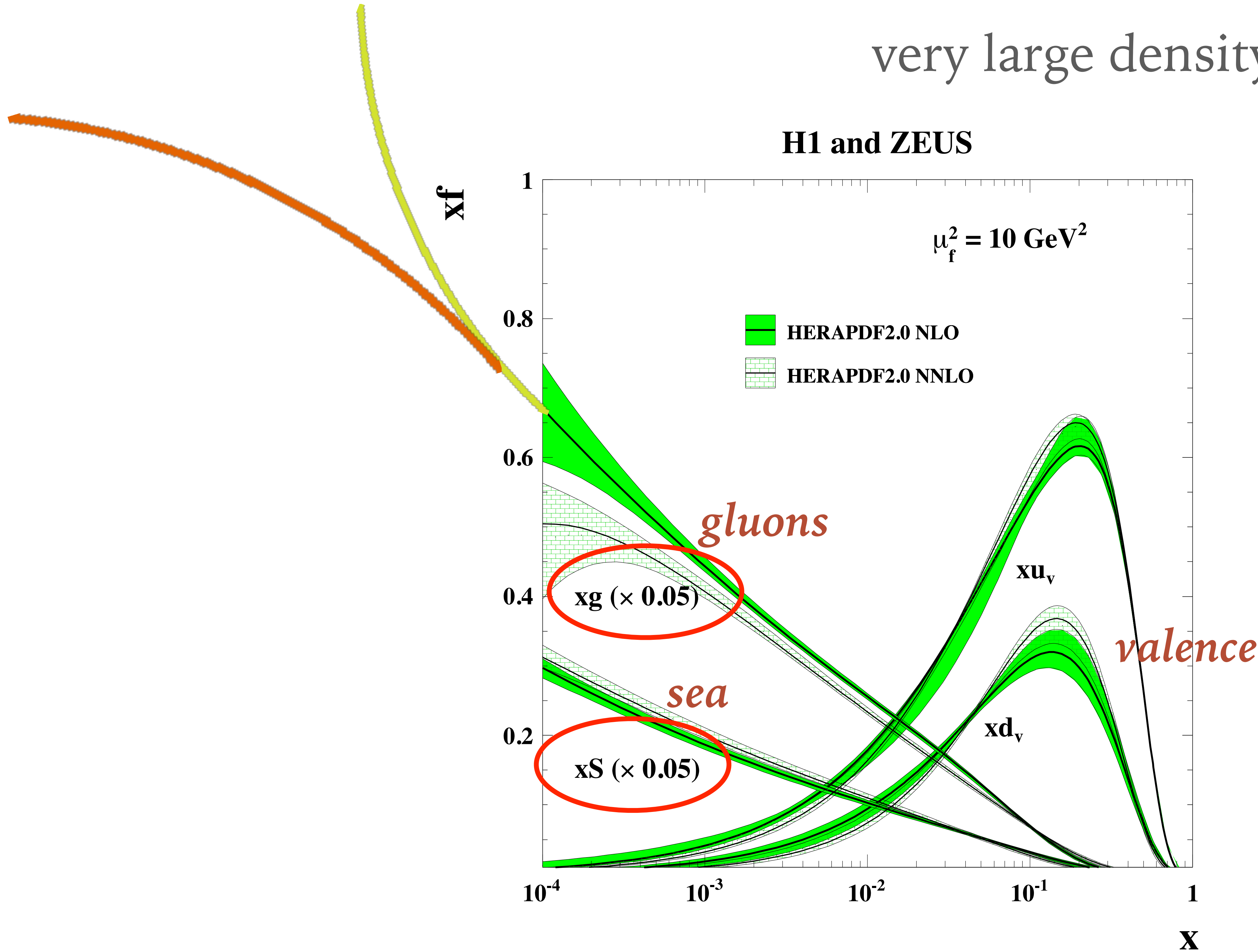

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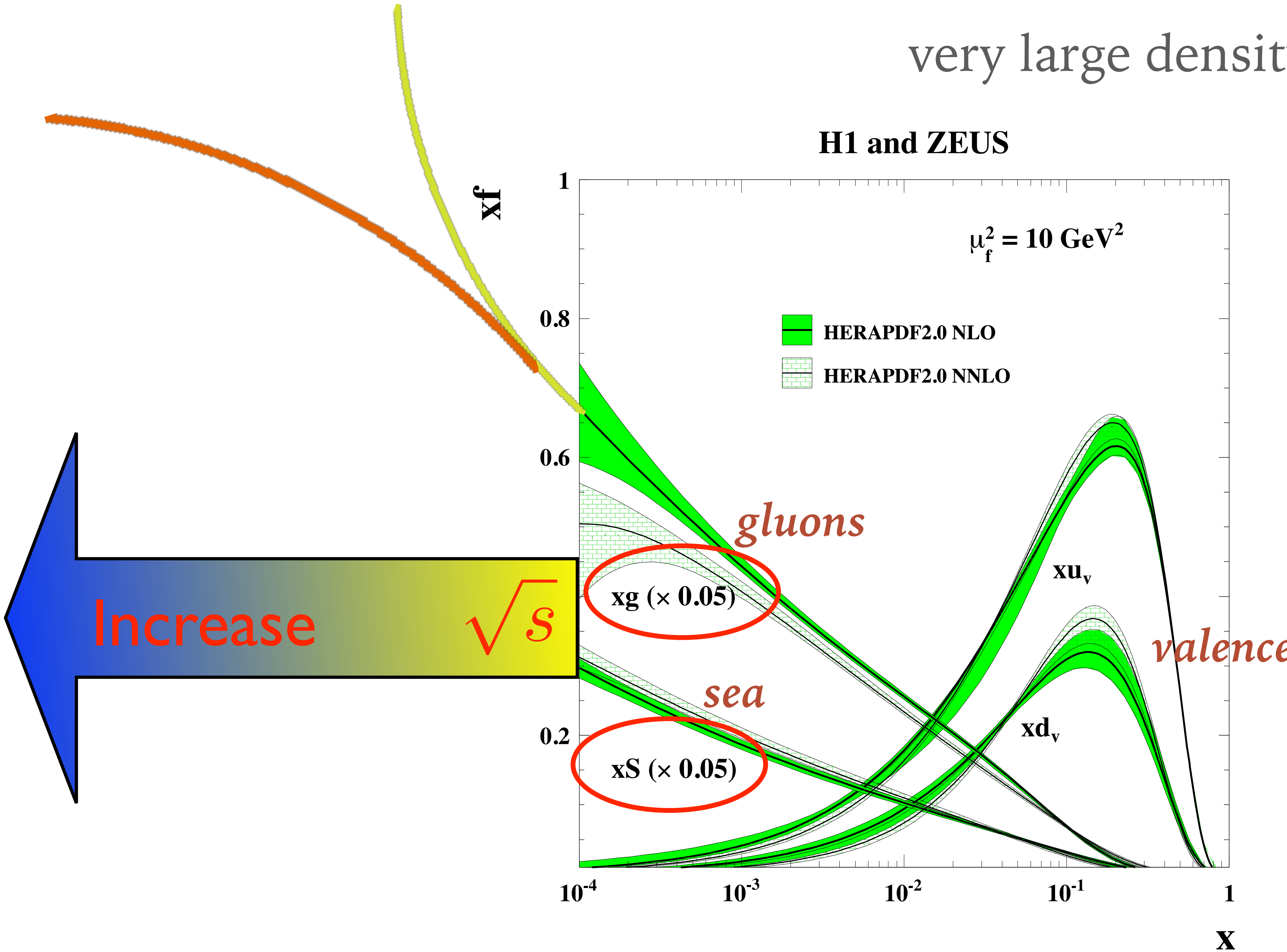
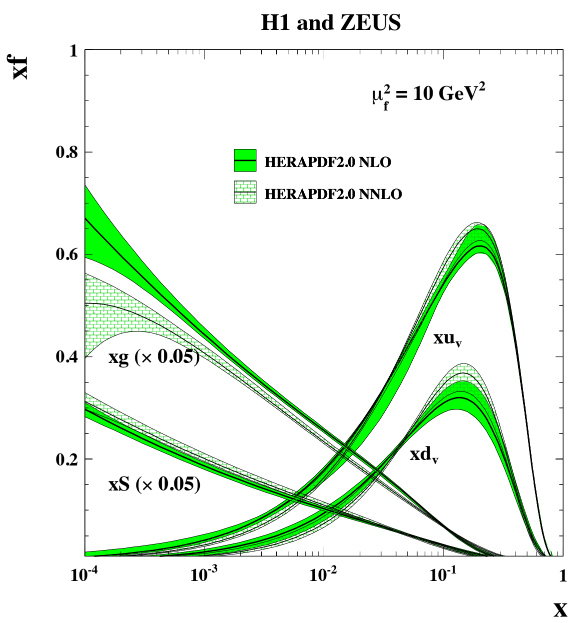
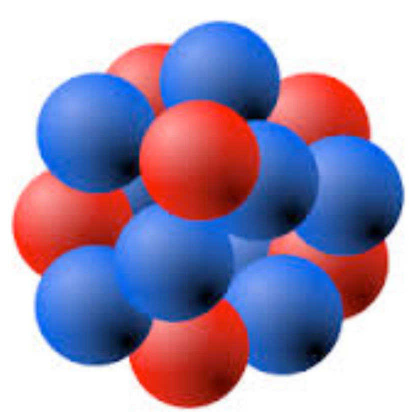


Color Glass Condensate

Proton target: small x



Nuclear target: large mass number A



McLerran, Venugopalan

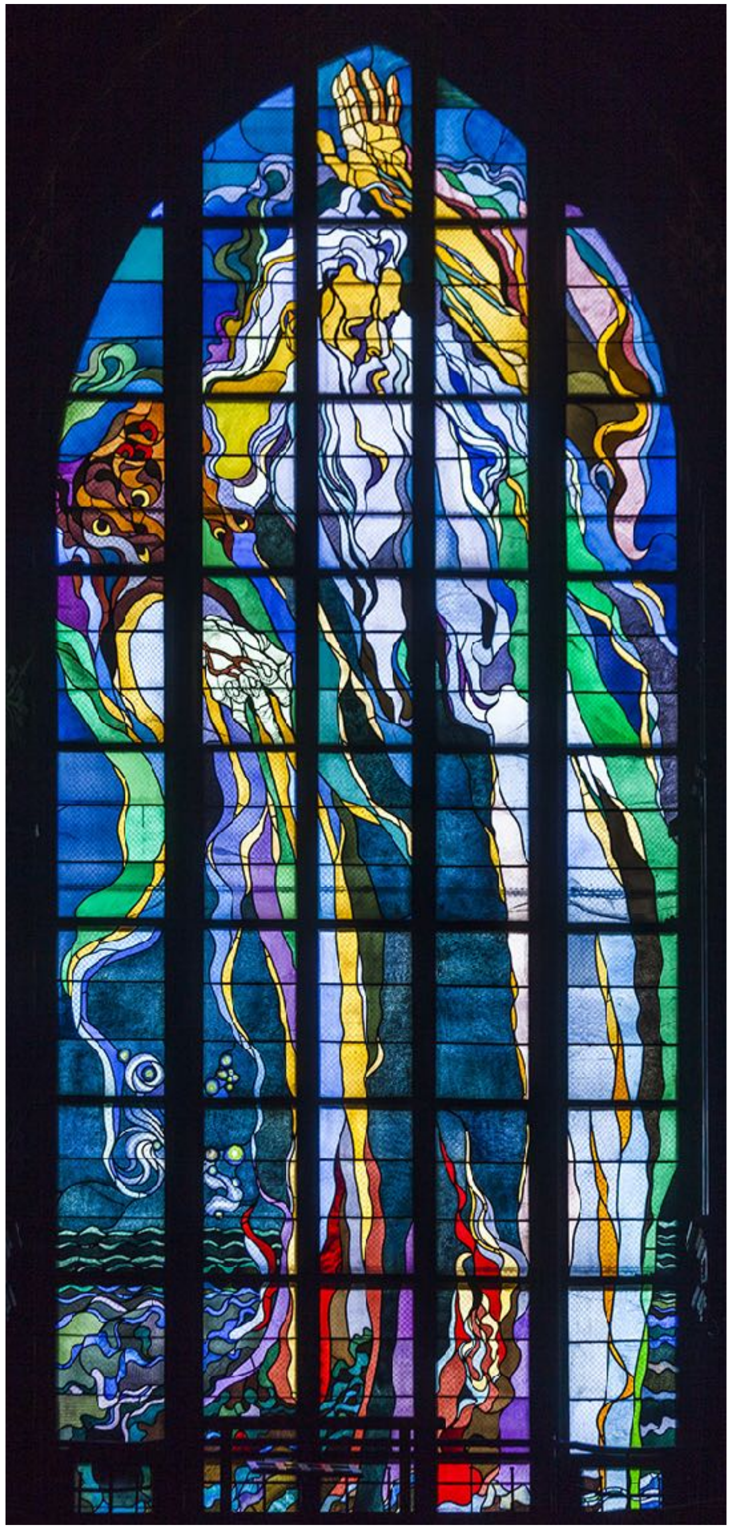
Color Glass Condensate: **effective theory at high energy and high density**

Color Glass Condensate

My rough idea

about Color Glass Condensate

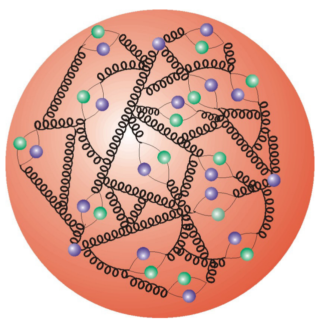
before coming to BNL…



'God the Father', stained glass by S.Wyspiański; Church of St. Francis of Assisi, Cracow

Interaction size increase with energy

CGC predicts **increase** in size of gluon density with increasing energy



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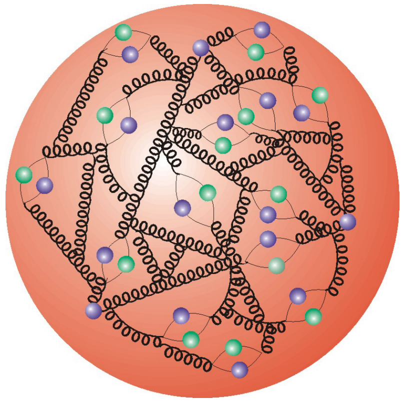

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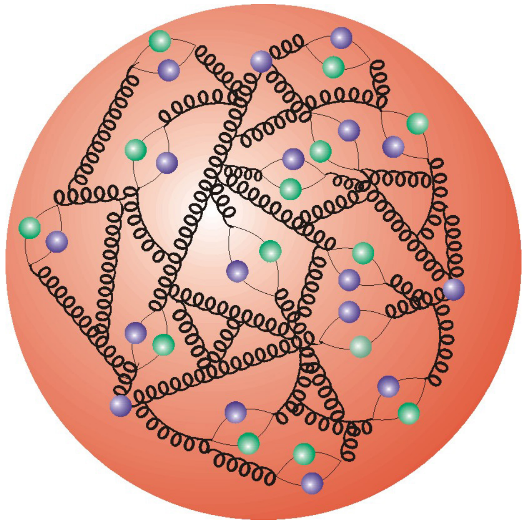

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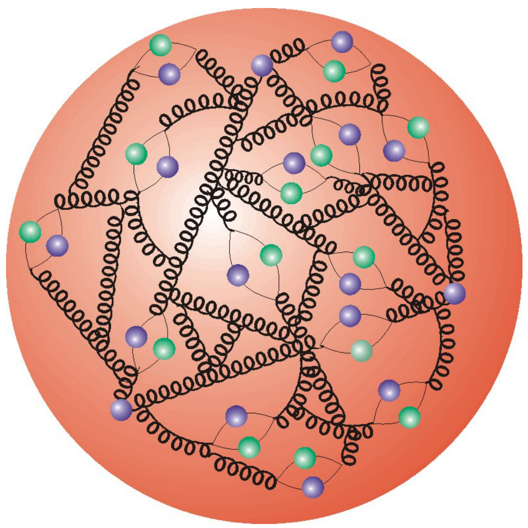

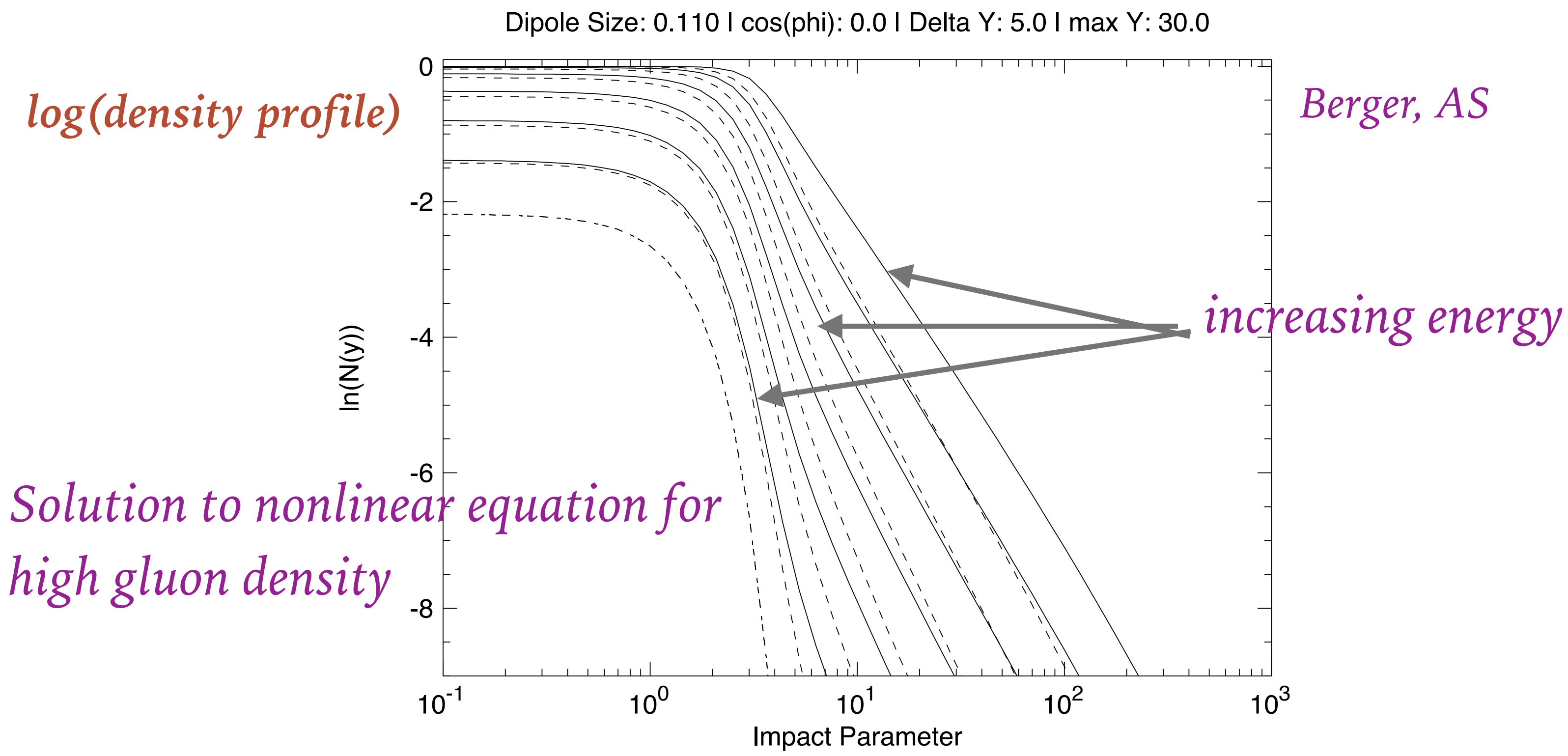

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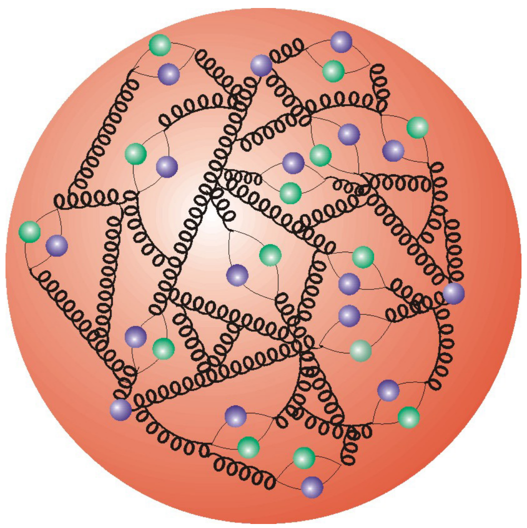

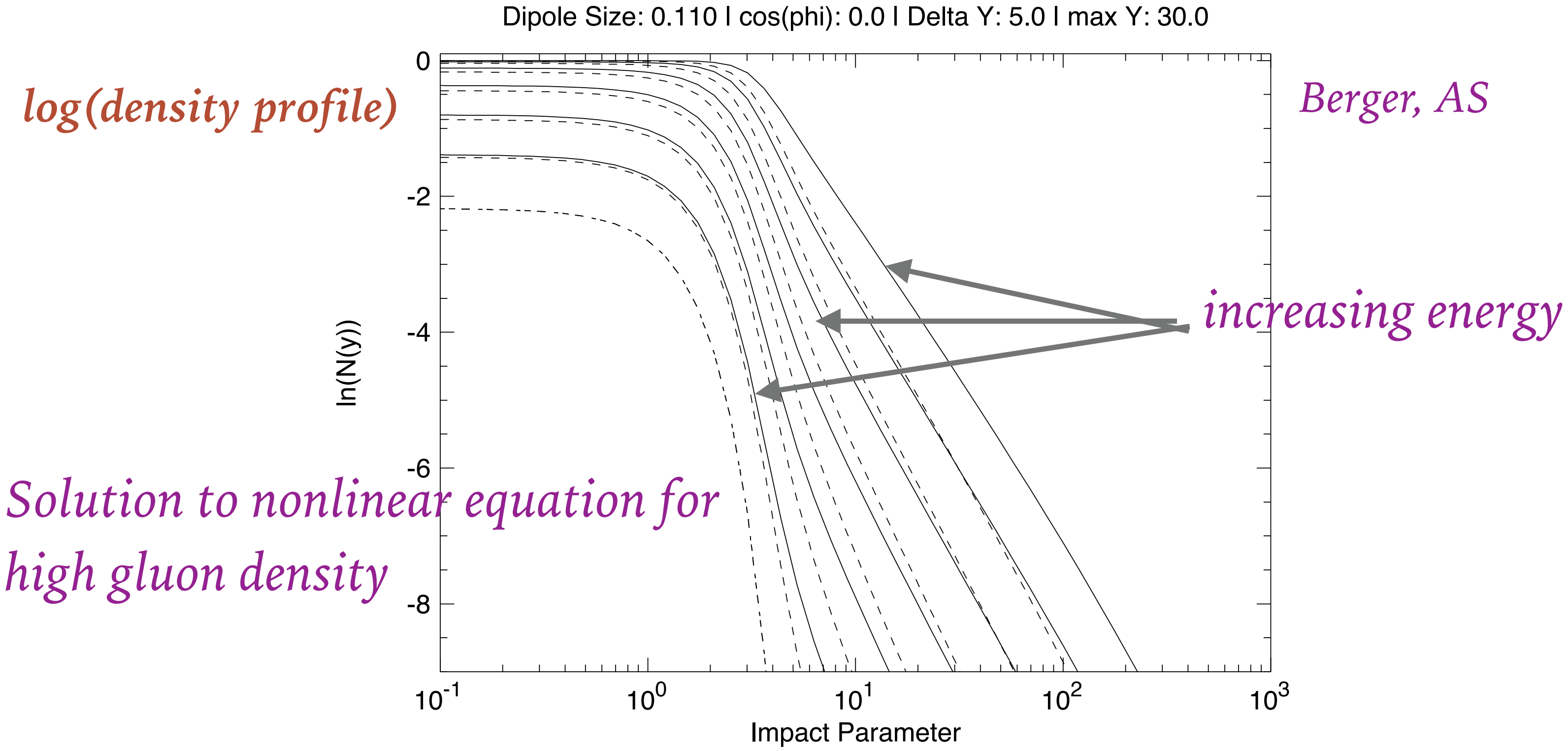

Predicts very strong change of size: requires additional **non-perturbative** effects

Interaction size increase with energy

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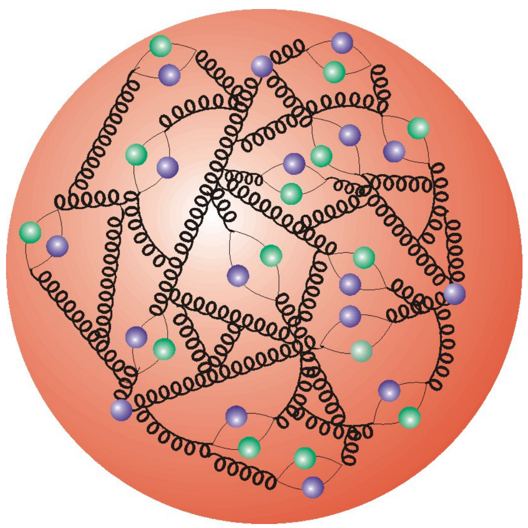
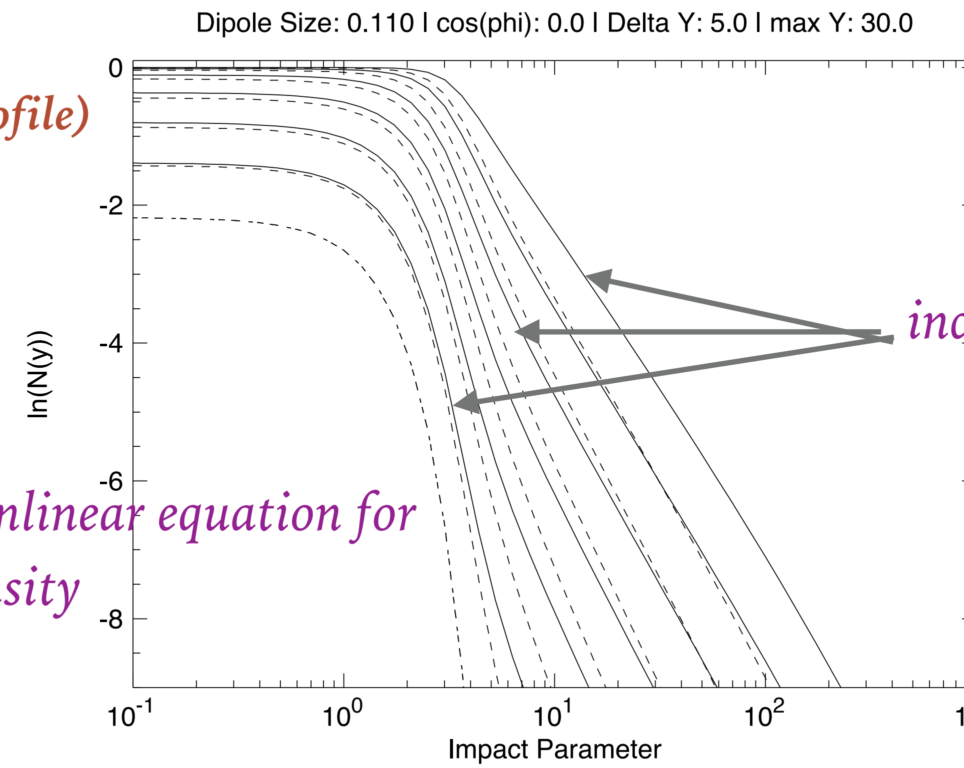


log(density profile)



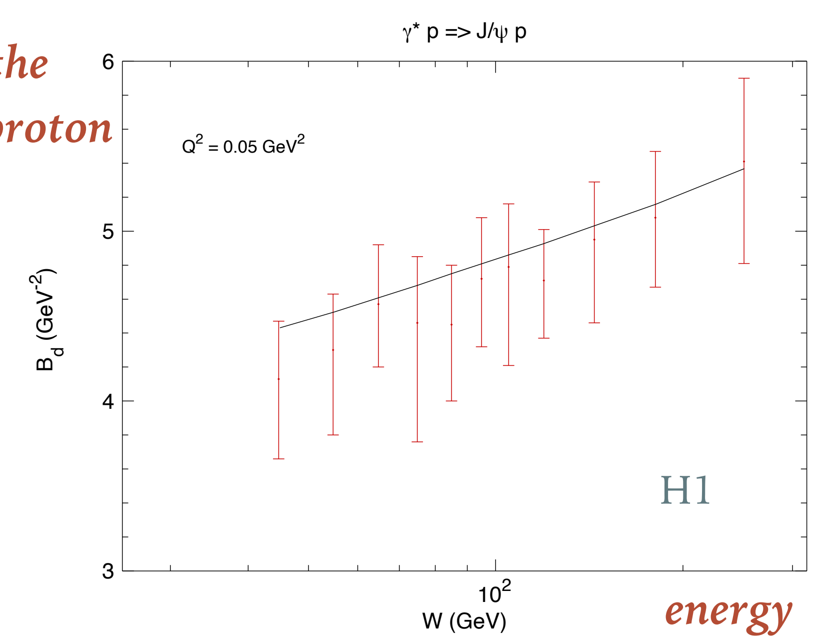
Berger, AS

increasing energy

Solution to nonlinear equation for high gluon density

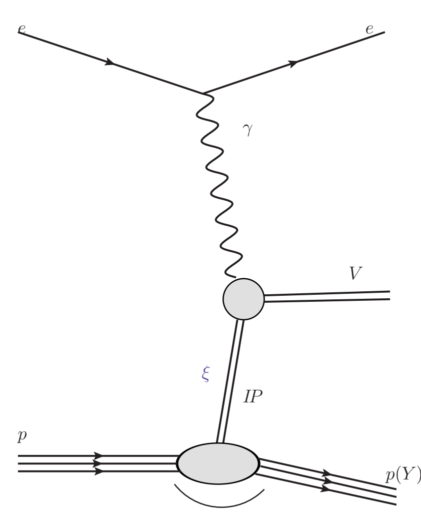
Predicts very strong change of size: requires additional **non-perturbative** effects

spatial extent of the gluon density in proton



energy

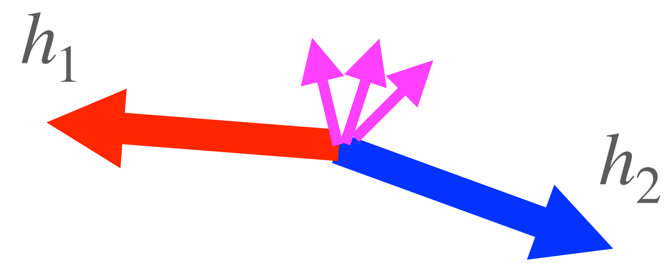
After including nonperturbative parameter can describe the data on **vector meson** production



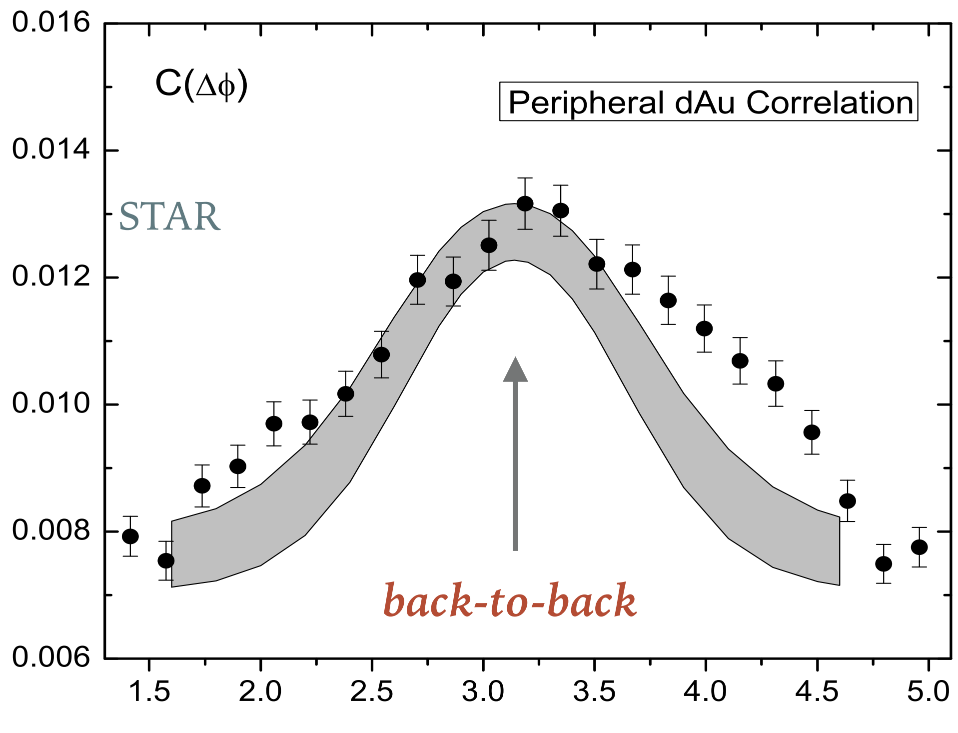
Angular (de)correlations: low vs high gluon density

The angular correlations are a measure of the gluon density: two hadrons

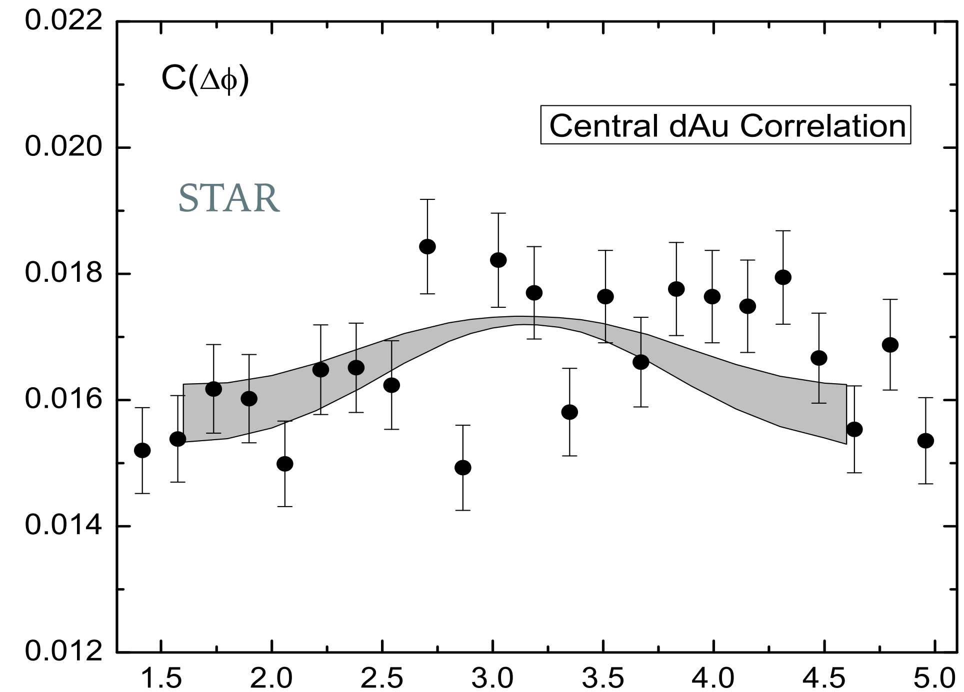
$$p + A \to h_1 + h_2 + X$$



correlation function



angle between hadrons



Xiao, Yuan, AS

low density ↔ large correlation

large density ↔ low correlation

Angular (de)correlations: low vs high density

Crude analogy: pool game

Images by DALL-E AI

Low number of balls: easier to plan the trajectory, high correlation

High number of balls: trajectory can be heavily modified since balls can rescatter many times

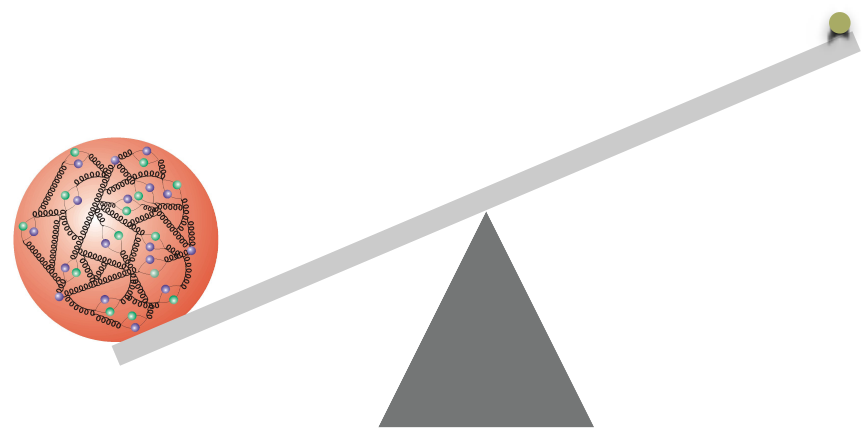
Impact on ultrahigh energy neutrino physics

proton

heavy:

$m_p = 0.938\,\mathrm{GeV/c^2}$

complex structure with strongly interacting quarks and gluons



neutrino

very light:

$m_\nu < 0.8\,\mathrm{eV/c^2}$ (KATRIN exp.)

no structure (?)

weakly interacting

Impact on ultrahigh energy neutrino physics

proton

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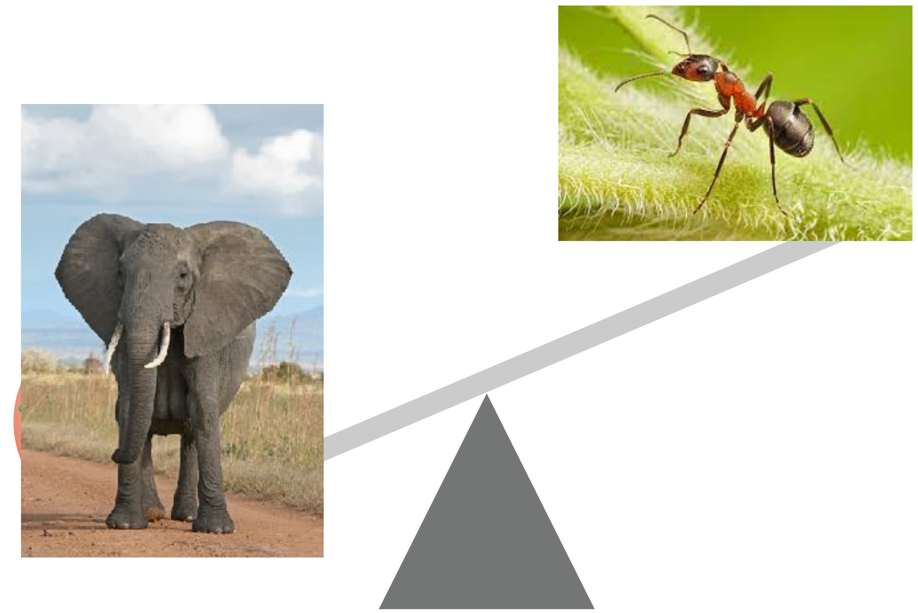

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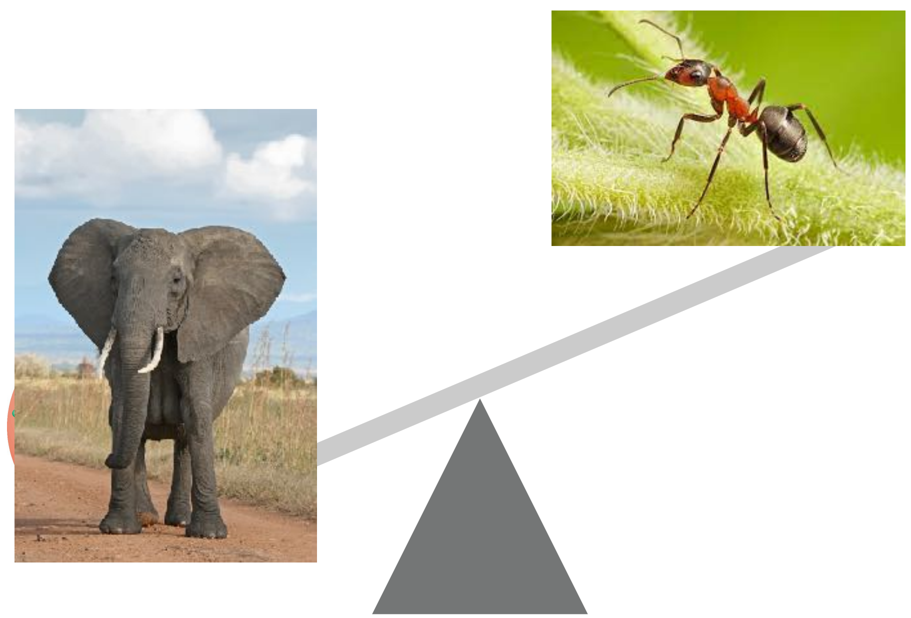

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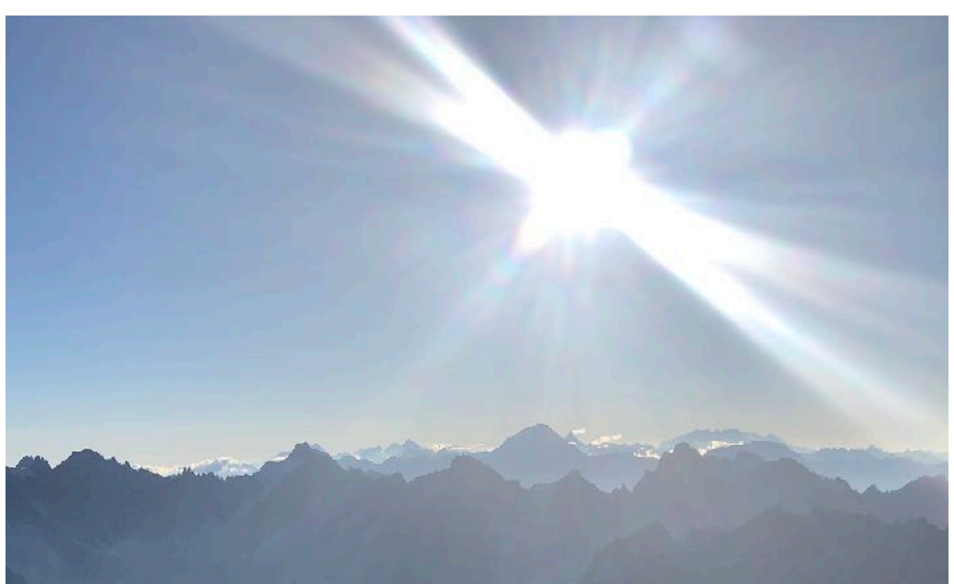
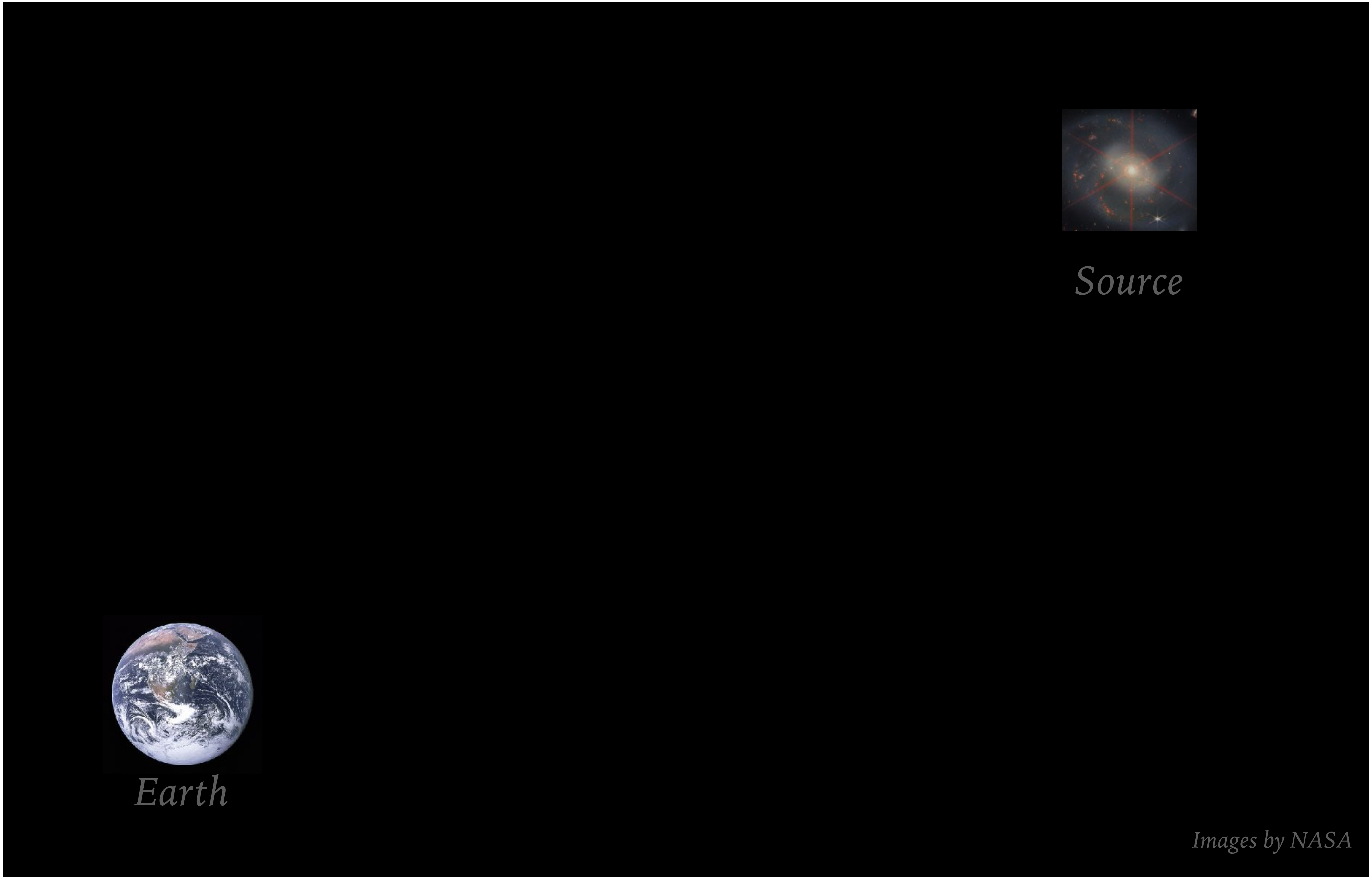


On Earth 65 billion neutrinos passing through cm^2 each second, mostly from the Sun

Ultrahigh energy neutrinos in astrophysics



Ultrahigh energy neutrinos in astrophysics

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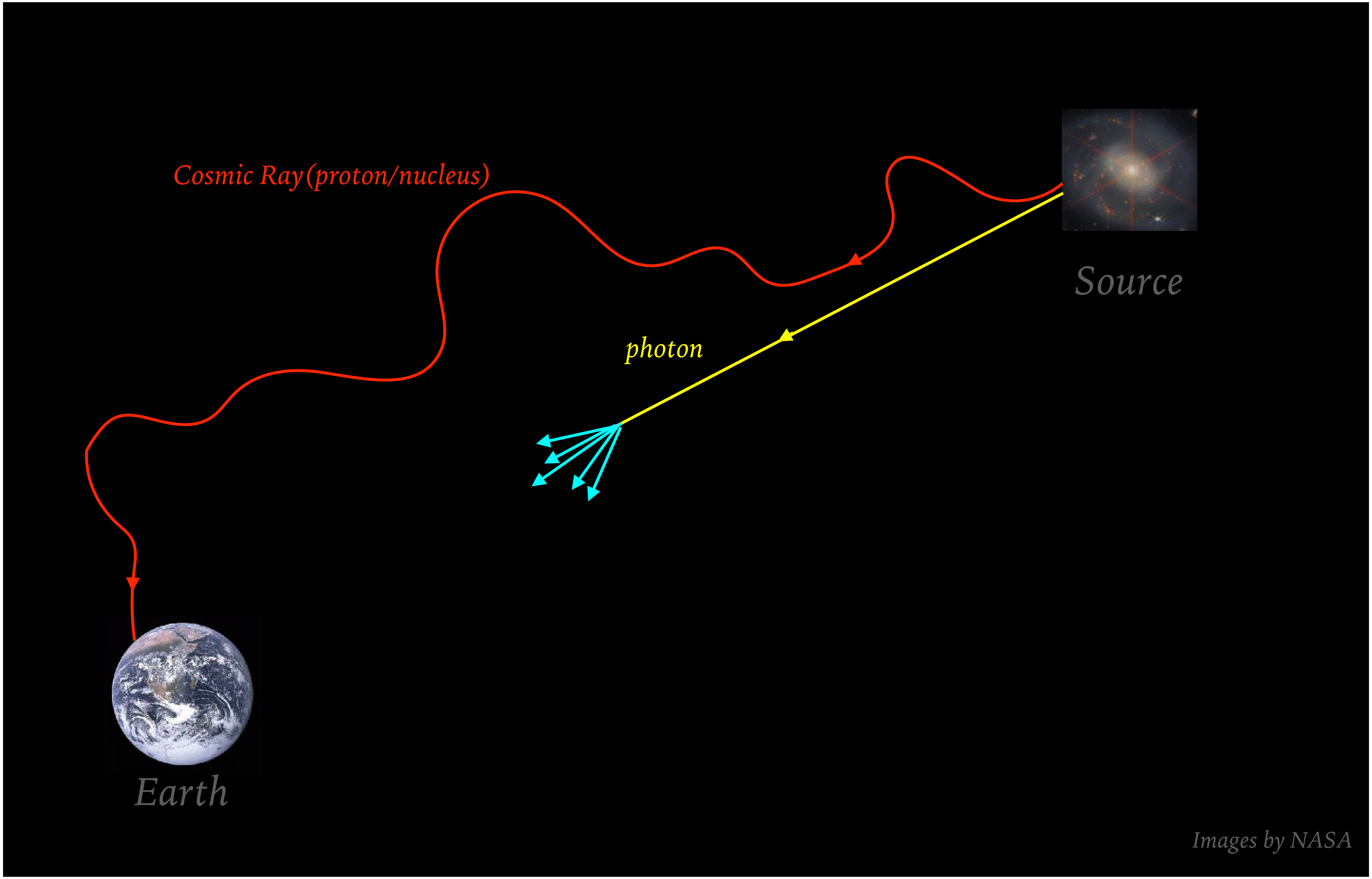
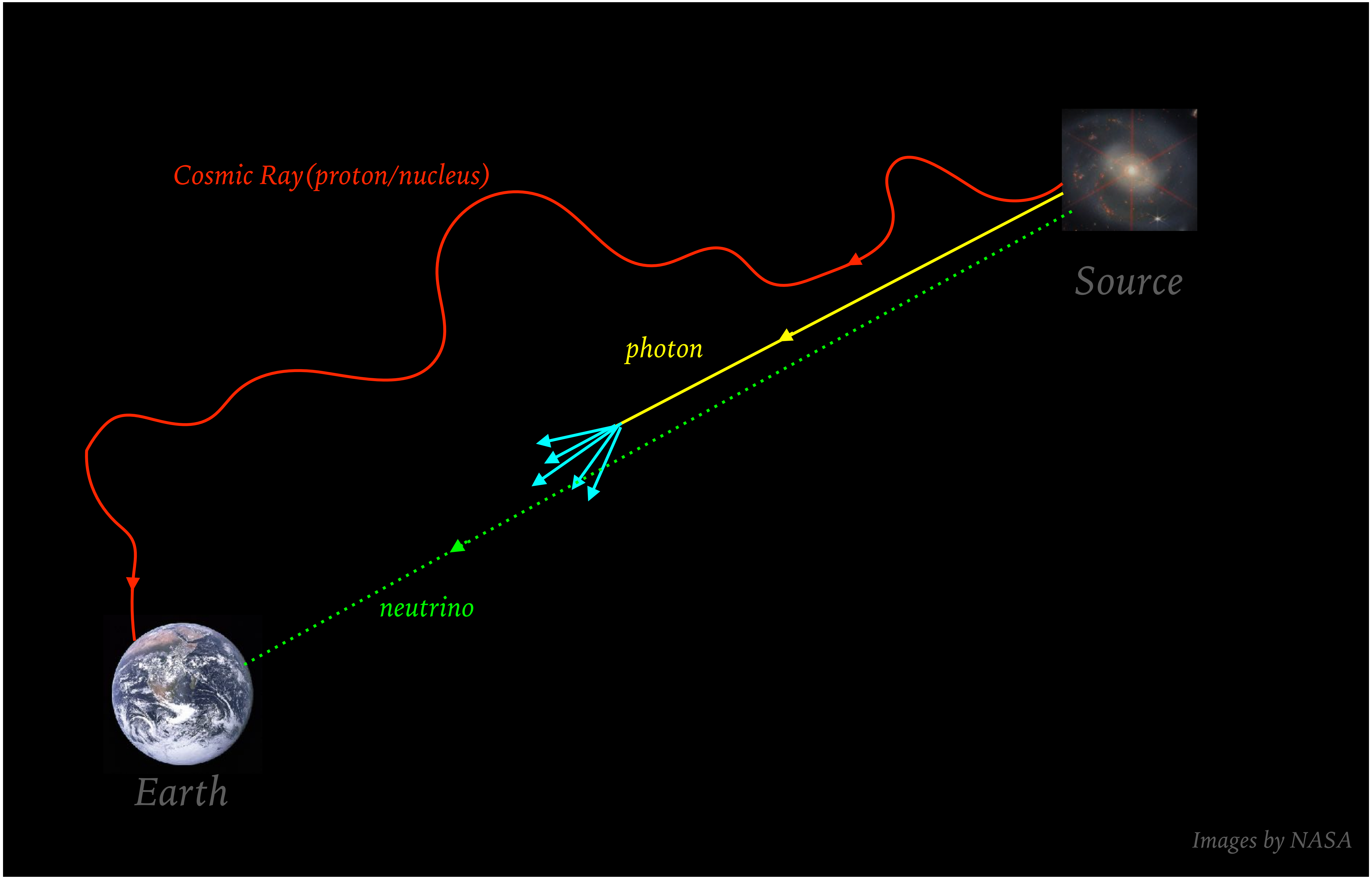
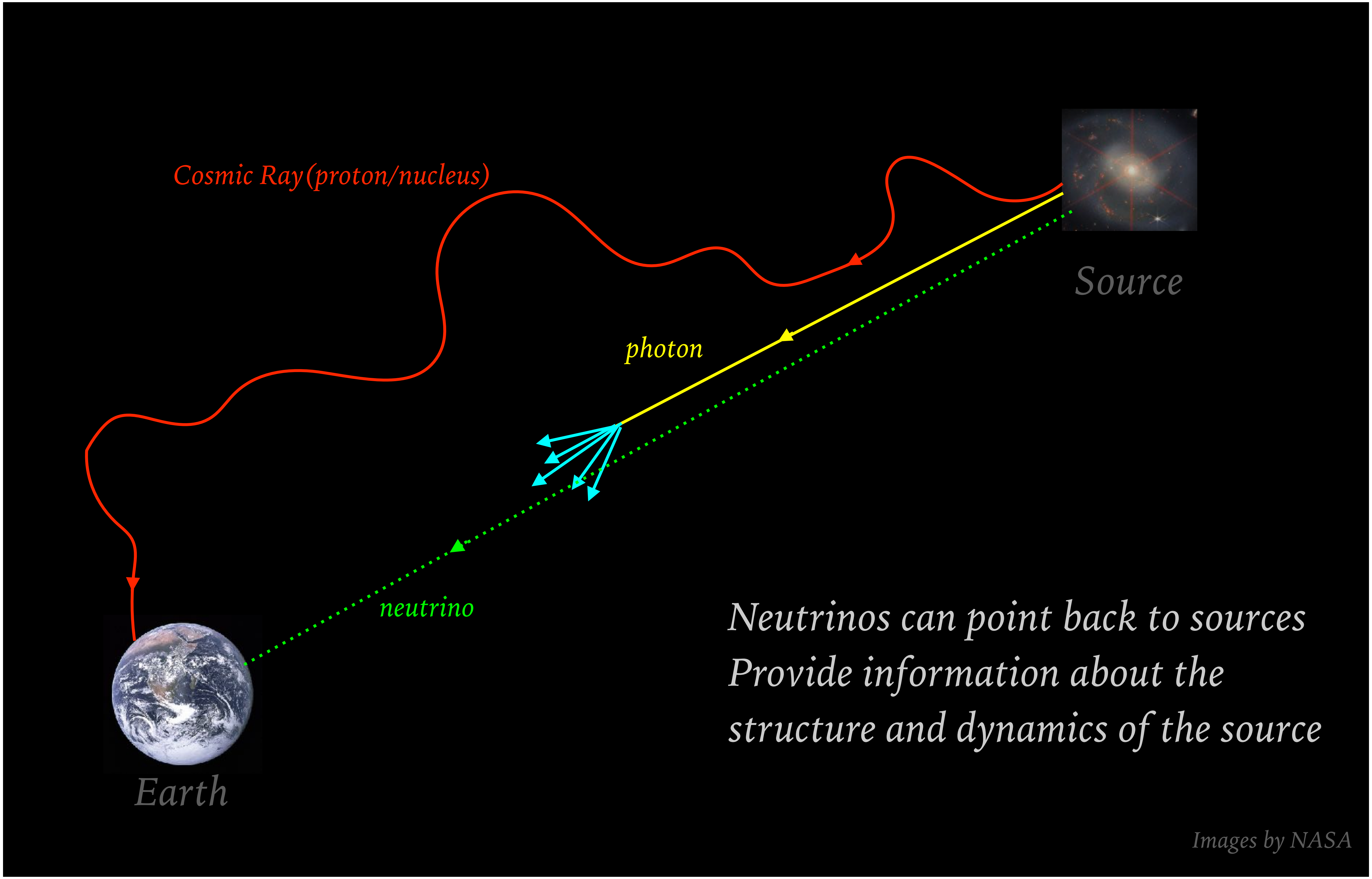


Ultrahigh energy neutrinos in astrophysics



Ultrahigh energy neutrinos in astrophysics

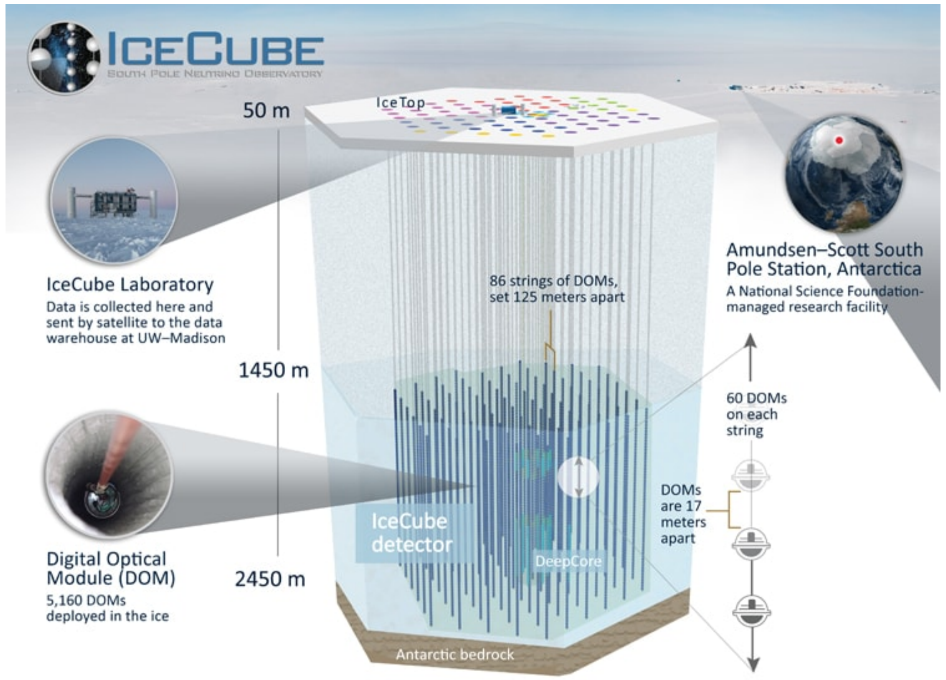


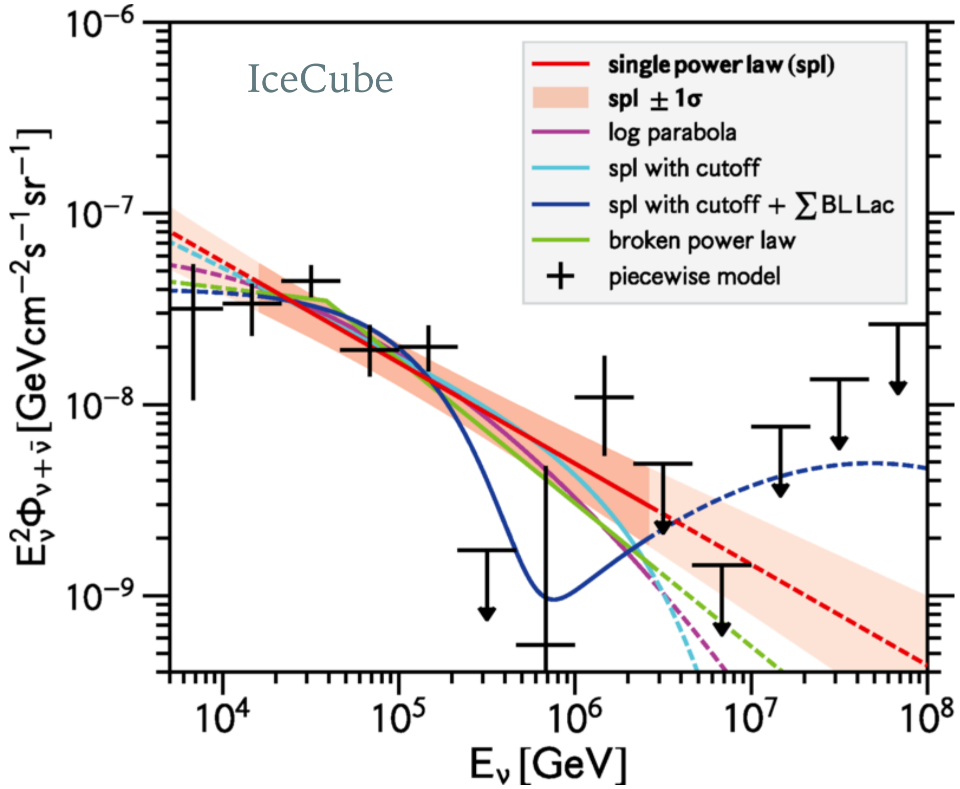
Proton structure and ultrahigh energy neutrinos

Ultrahigh energy neutrinos: $E_\nu > 1$ TeV

IceCube experiment on the South Pole

Flux of neutrinos





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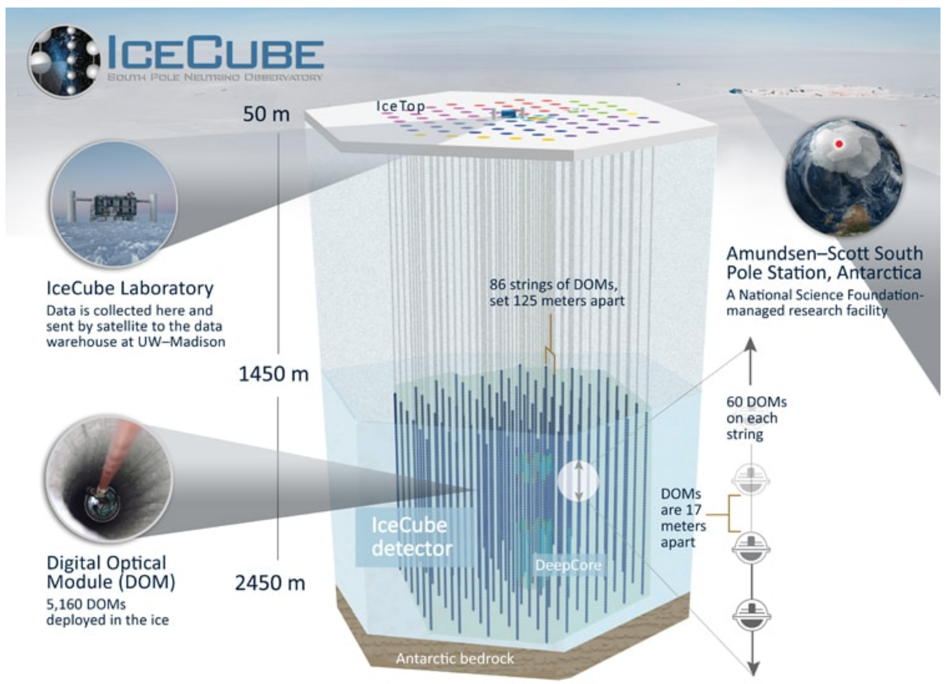
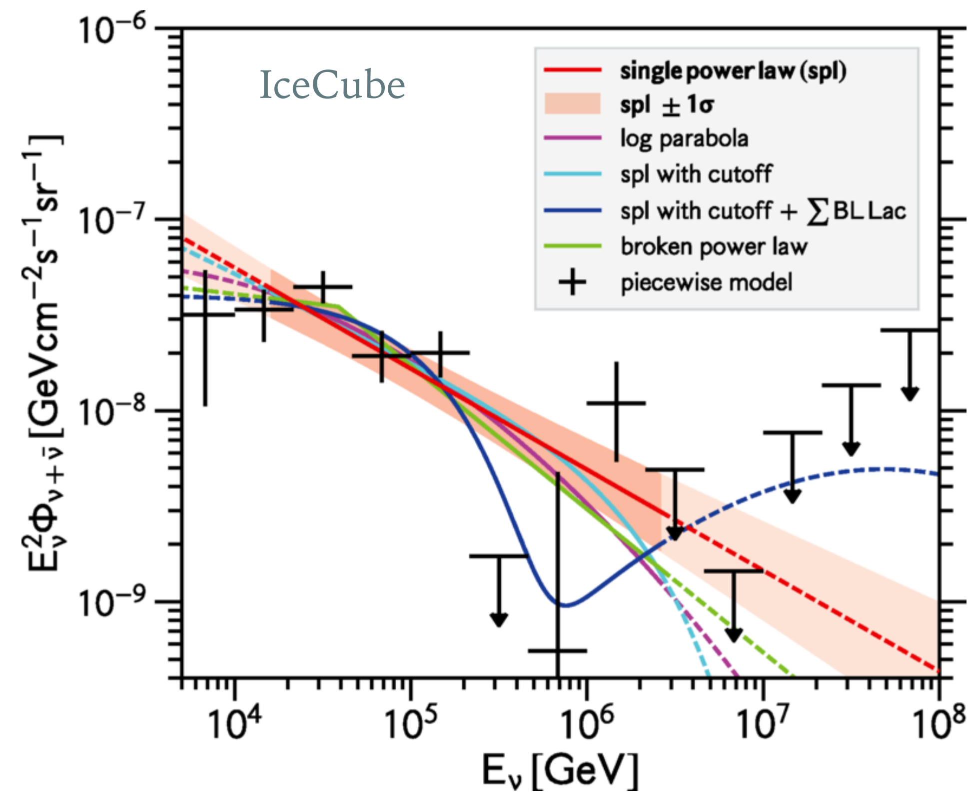
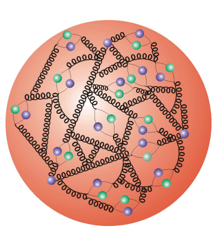


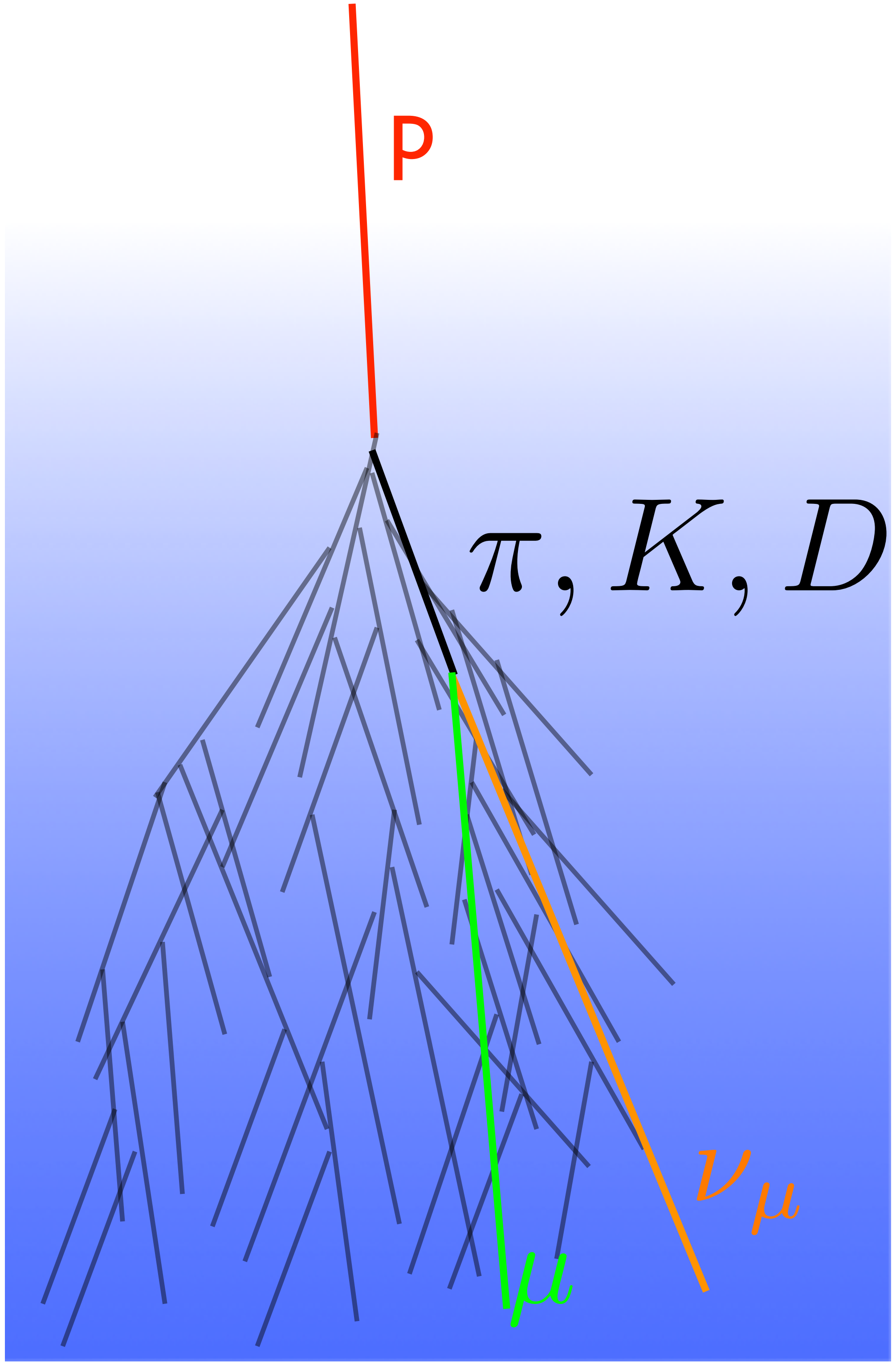




Proton structure at high energy essential for understanding :

- How high energy neutrinos are **produced** ?
- How high energy neutrinos **interact** ?

Neutrino flux from charmed hadrons



<u>Example</u>

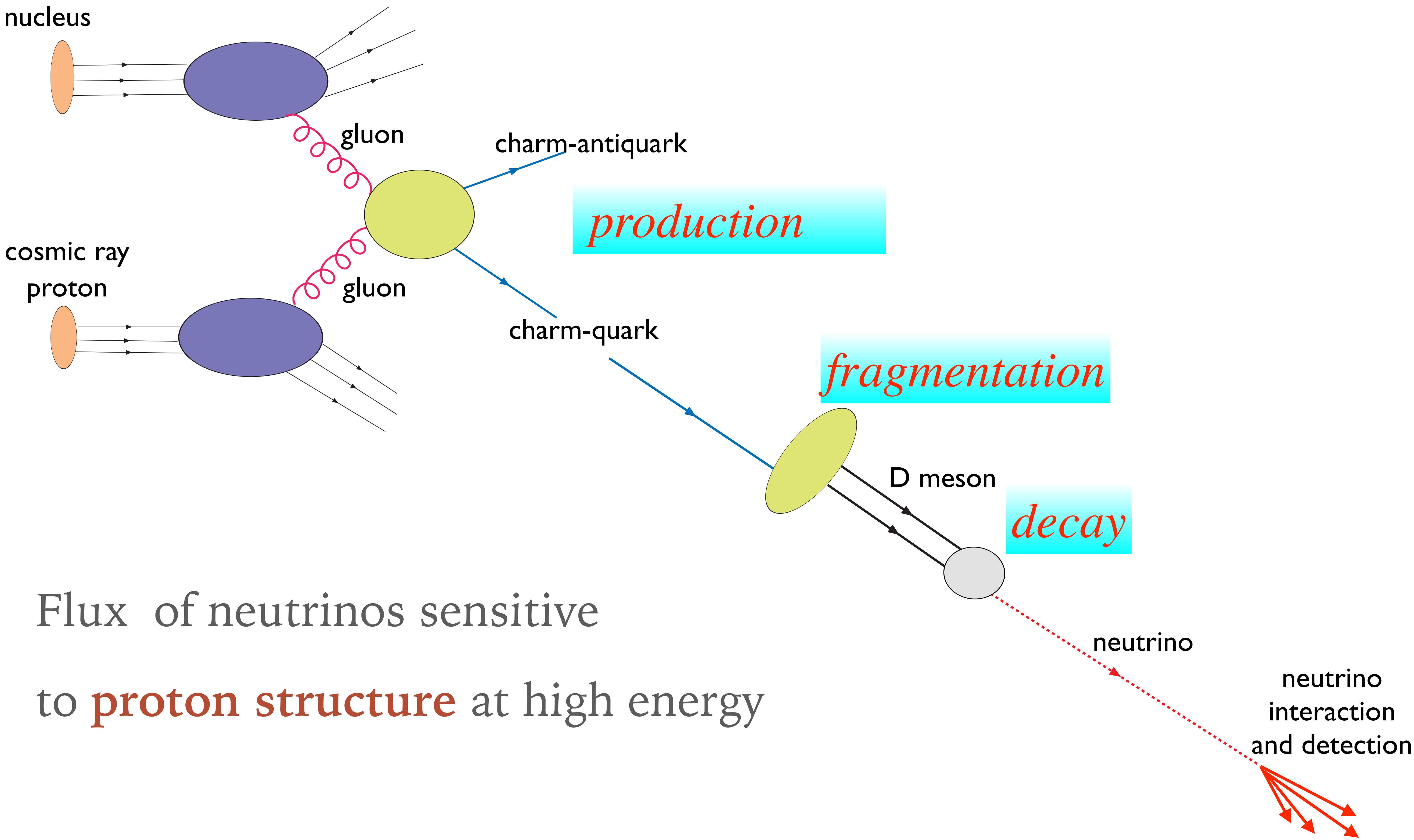
Atmospheric neutrinos at high energy:

Cosmic ray proton collides with **nucleus in air**

Produced **mesons** decay : energetic neutrinos

π, K	decays from light mesons: lower energy flux
D	decays from charmed mesons: higher energy flux

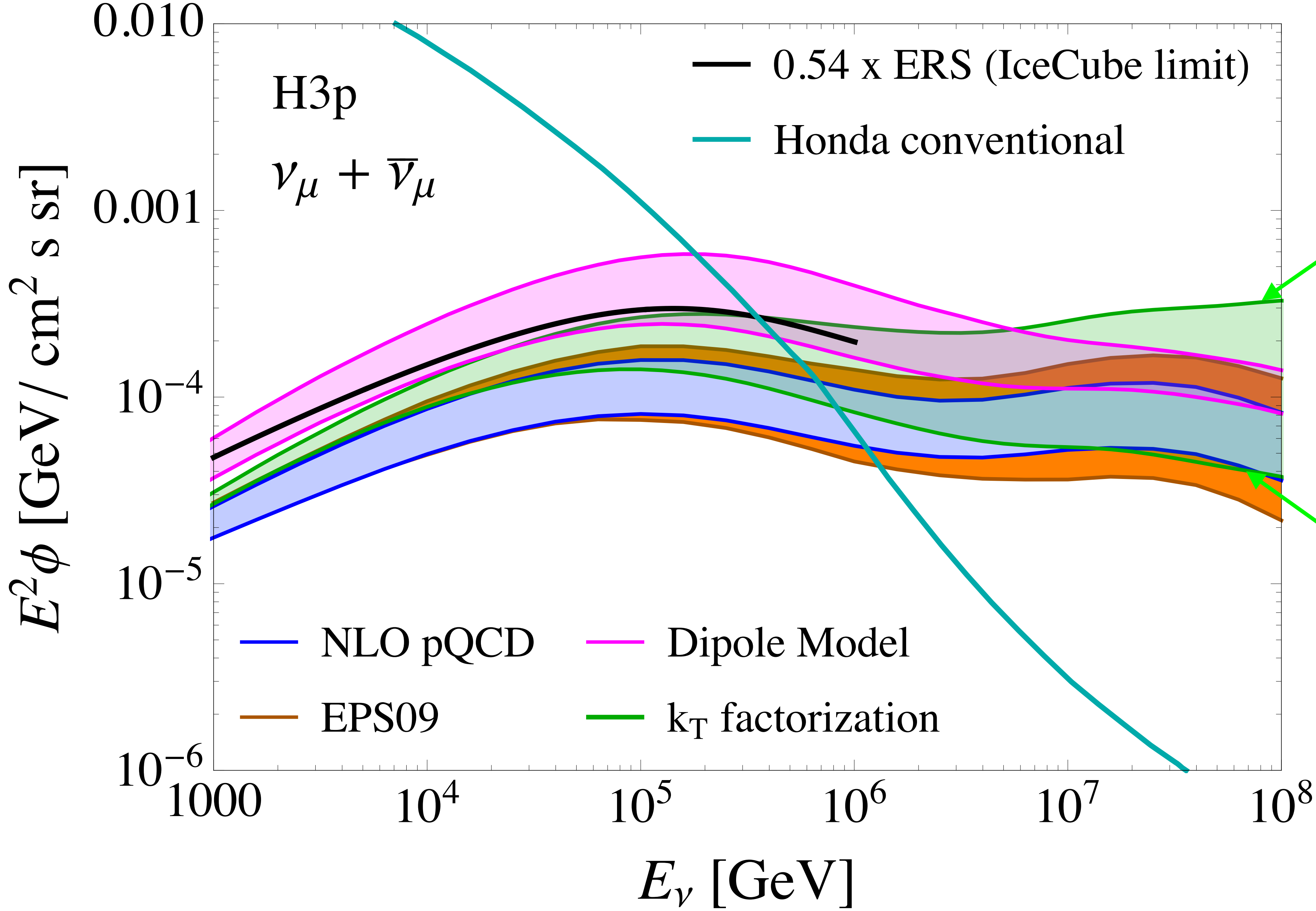
Production of high - energy neutrinos



Flux of neutrinos sensitive

to **proton structure** at high energy

Flux of high energy neutrinos in the atmosphere



high gluon density

lower (**saturated**) gluon density

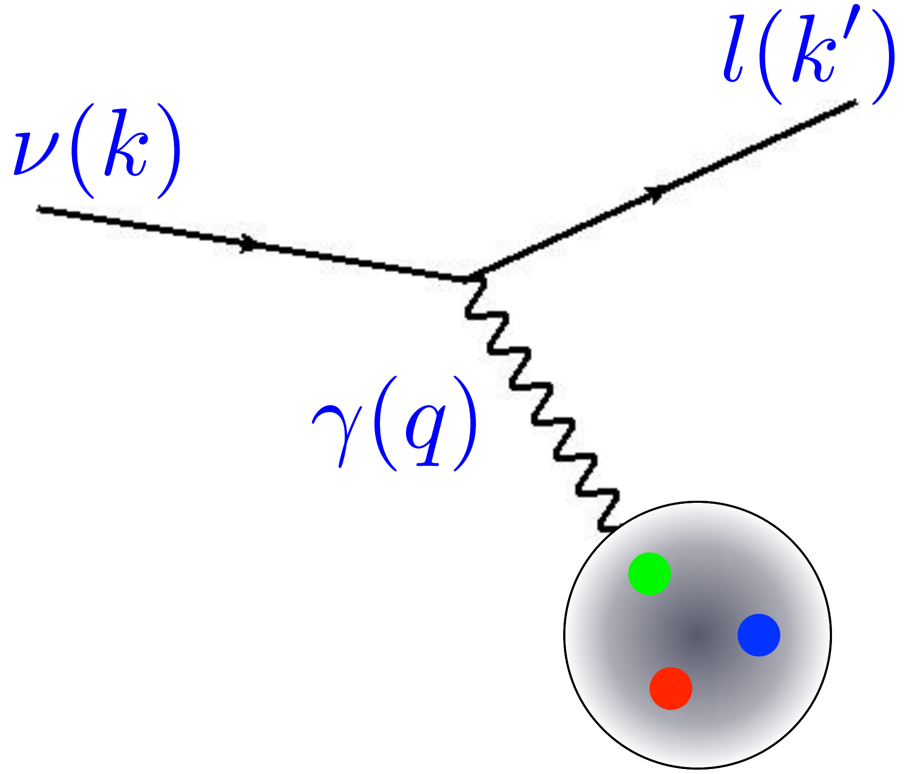
Seong Jeong, Bhattacharya, Enberg, Kim, Reno, Sarcevic, AS;
Bhattacharya, Enberg, Reno, Sarcevic, AS

Similarly: production at the source through pp interactions

Proton structure and neutrino interactions

Proton structure also impacts the neutrino interactions →cross section

Dominant interactions of neutrinos with matter at high energy is with the nuclei



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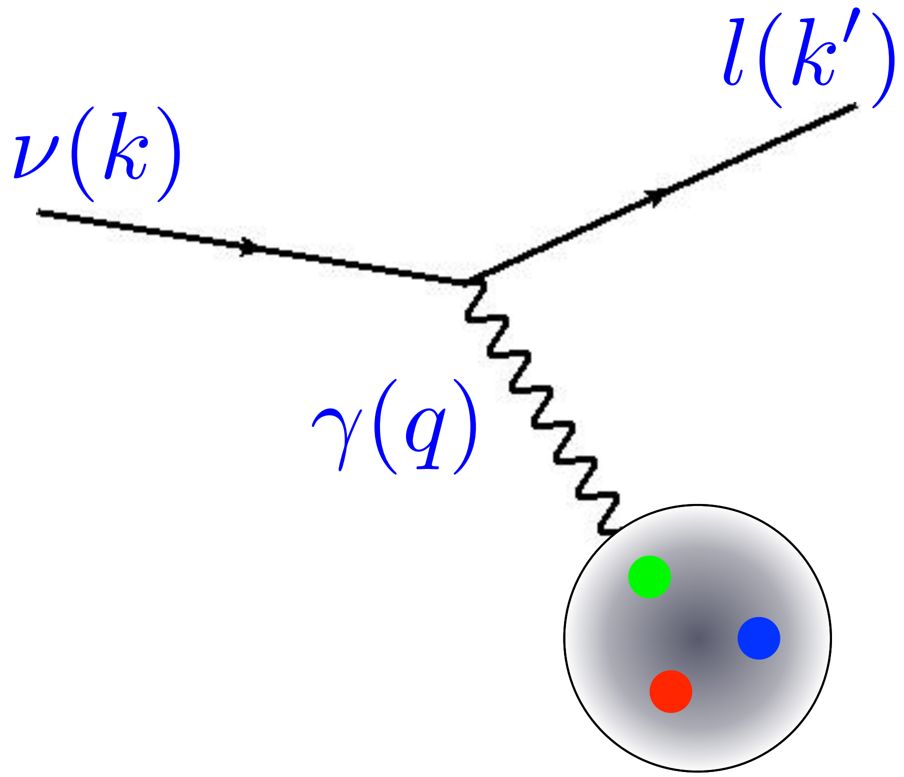
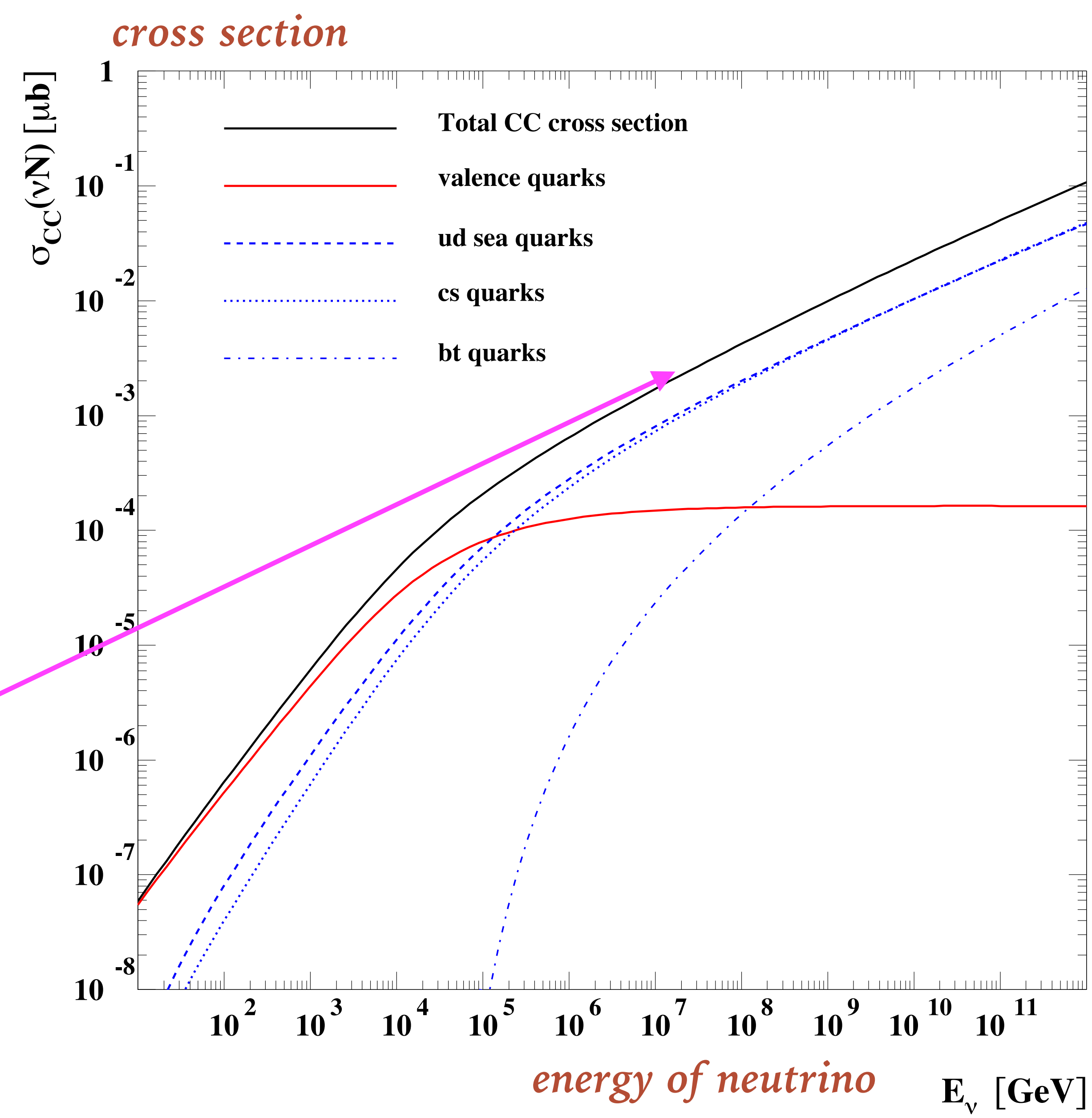
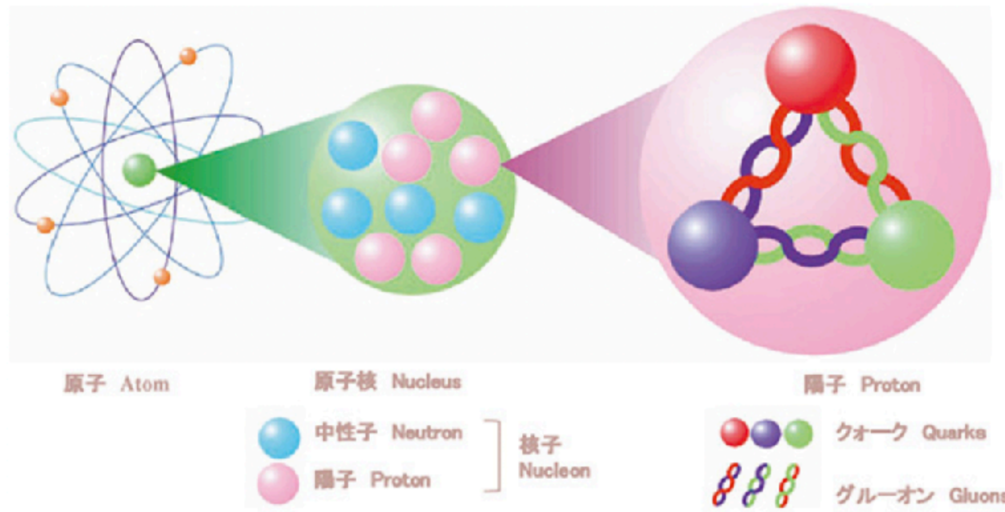


At high energy cross section driven
by the small *x* nucleon structure function



Final word…

RBRC research broad impacts on other fields and developments of future facilities



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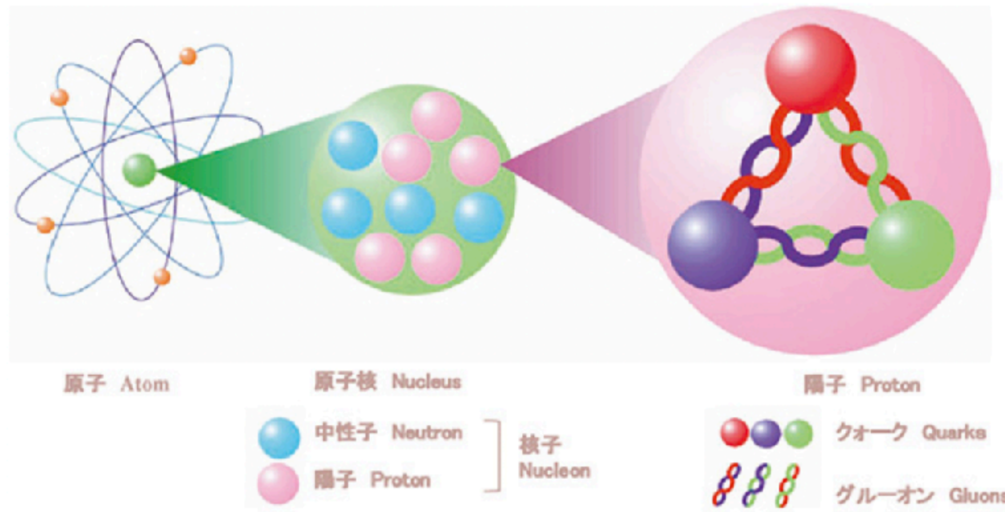

Astroparticle physics/ Astrophysics

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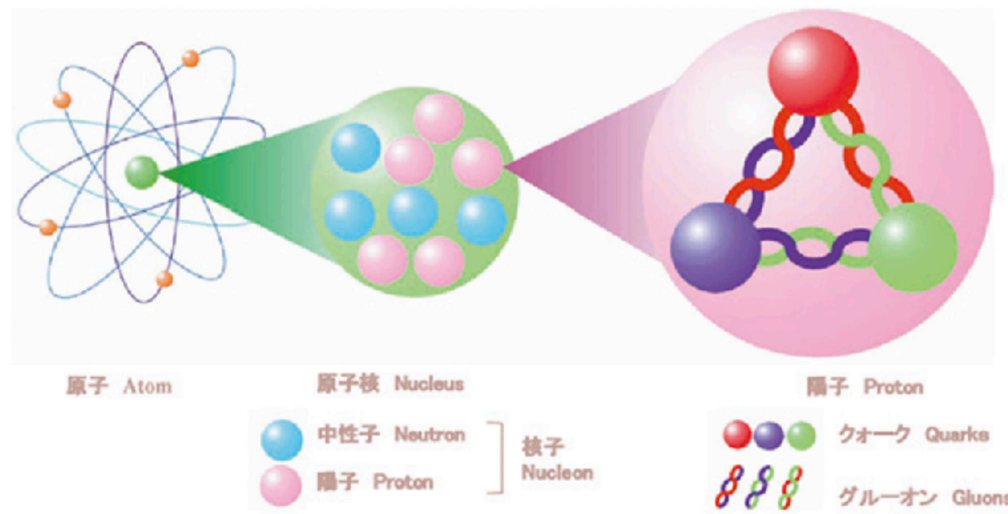

Astroparticle physics/
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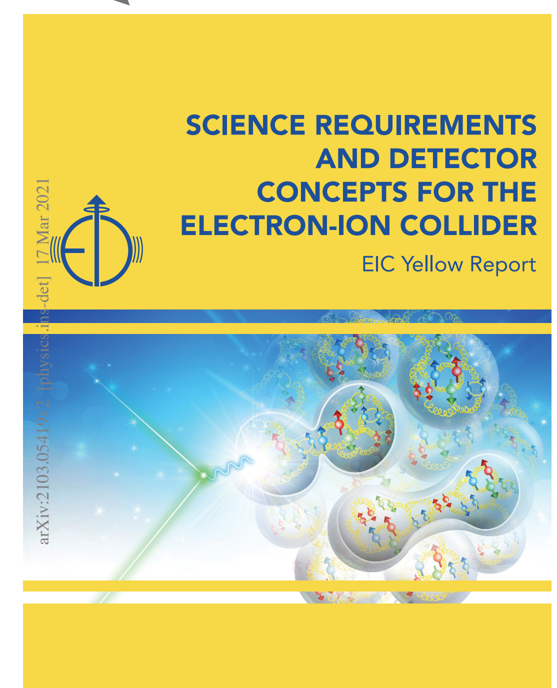

Electron Ion Collider

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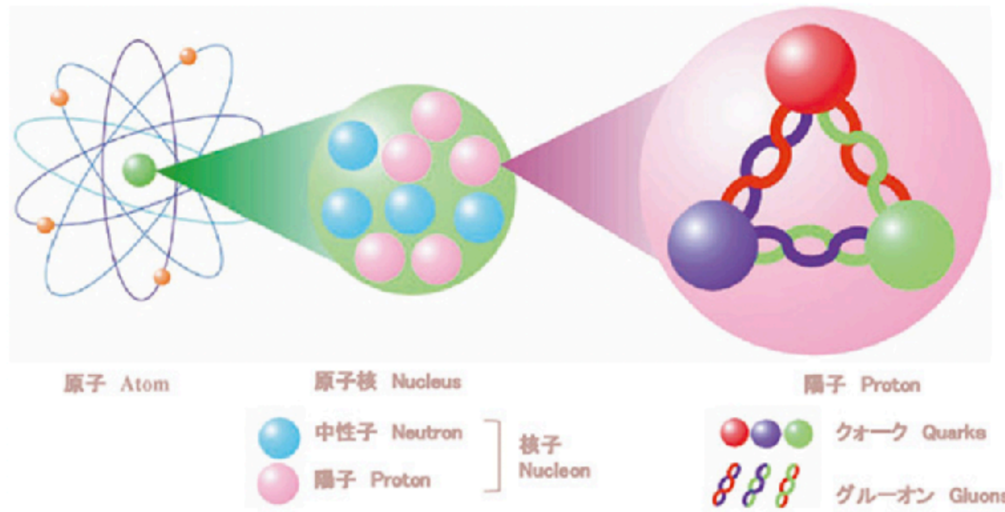

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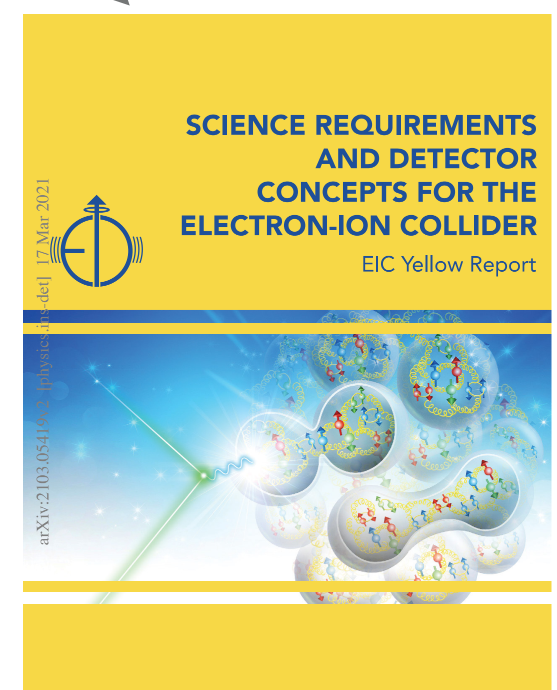

Electron Ion Collider

Thank you RBRC !