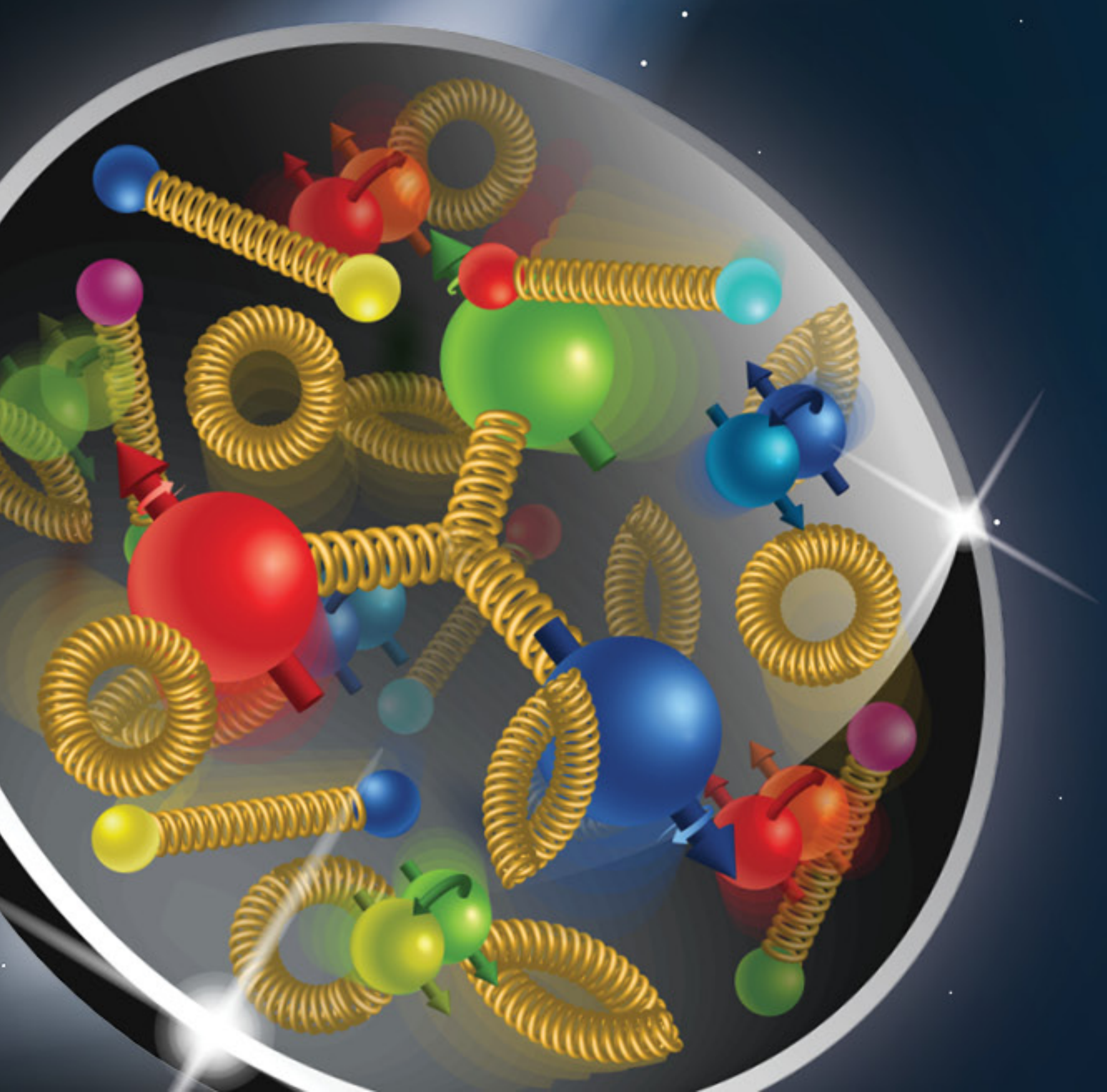
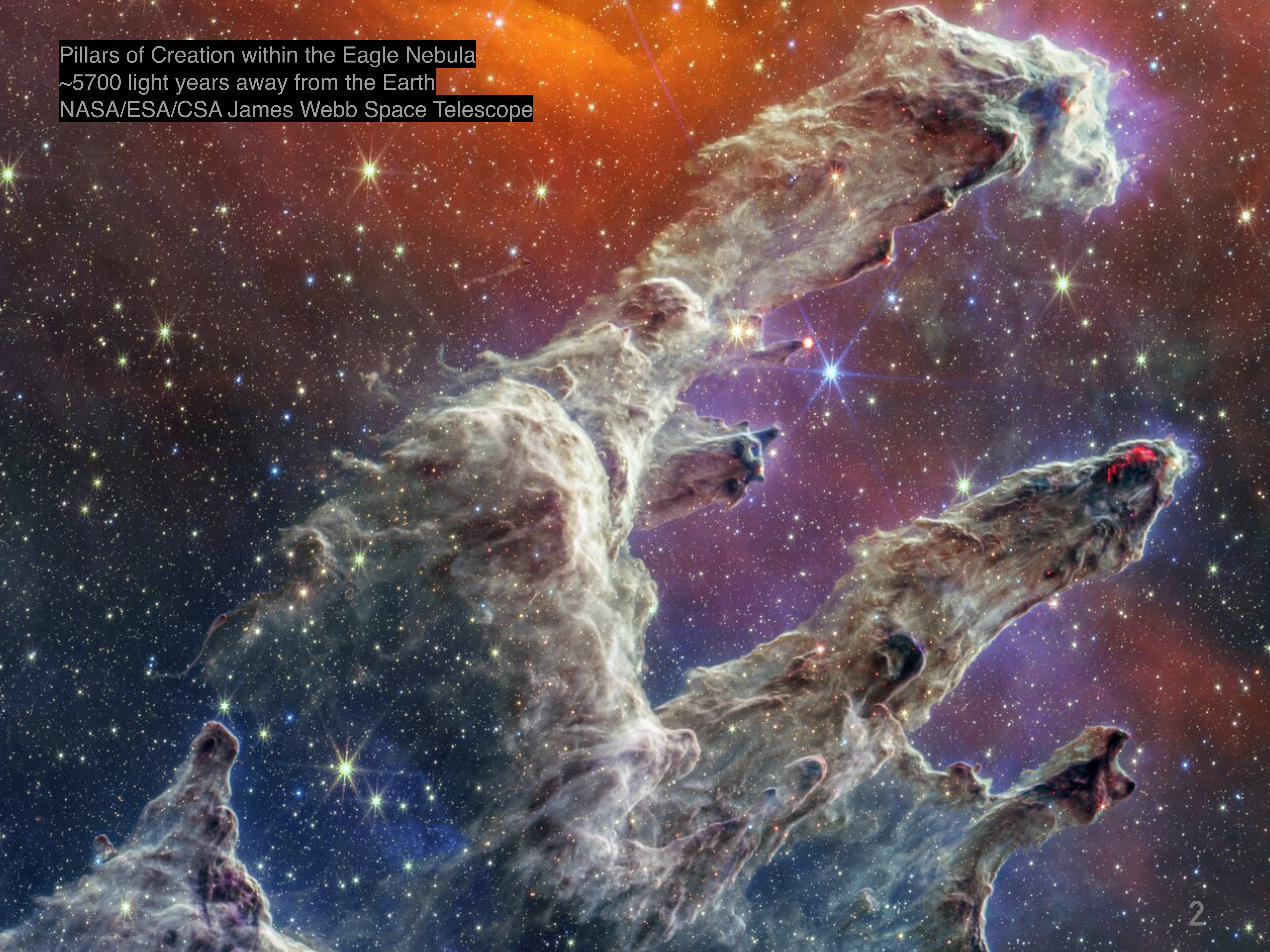
The Electron-Ion Collider

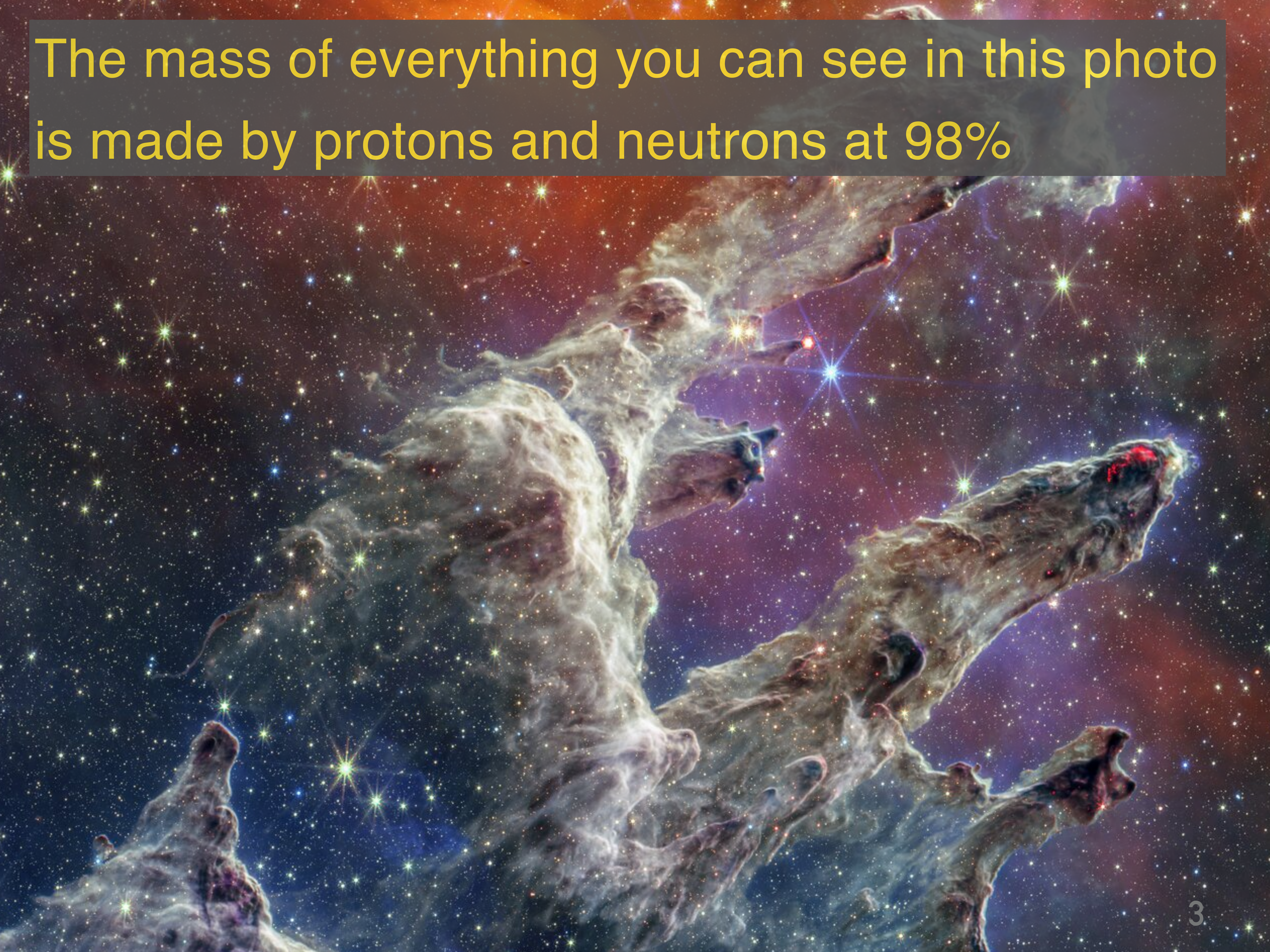


Alexei Prokudin



Pillars of Creation within the Eagle Nebula
~5700 light years away from the Earth
NASA/ESA/CSA James Webb Space Telescope

The mass of everything you can see in this photo is made by protons and neutrons at 98%



Department of Energy

2020

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

"The EIC promises to keep America in the forefront of nuclear physics research and particle accelerator technology, critical components of overall U.S. leadership in science," said **U.S. Secretary of Energy Dan Brouillette**. "This facility will deepen our understanding of nature and is expected to be the source of insights ultimately leading to new technology and innovation."

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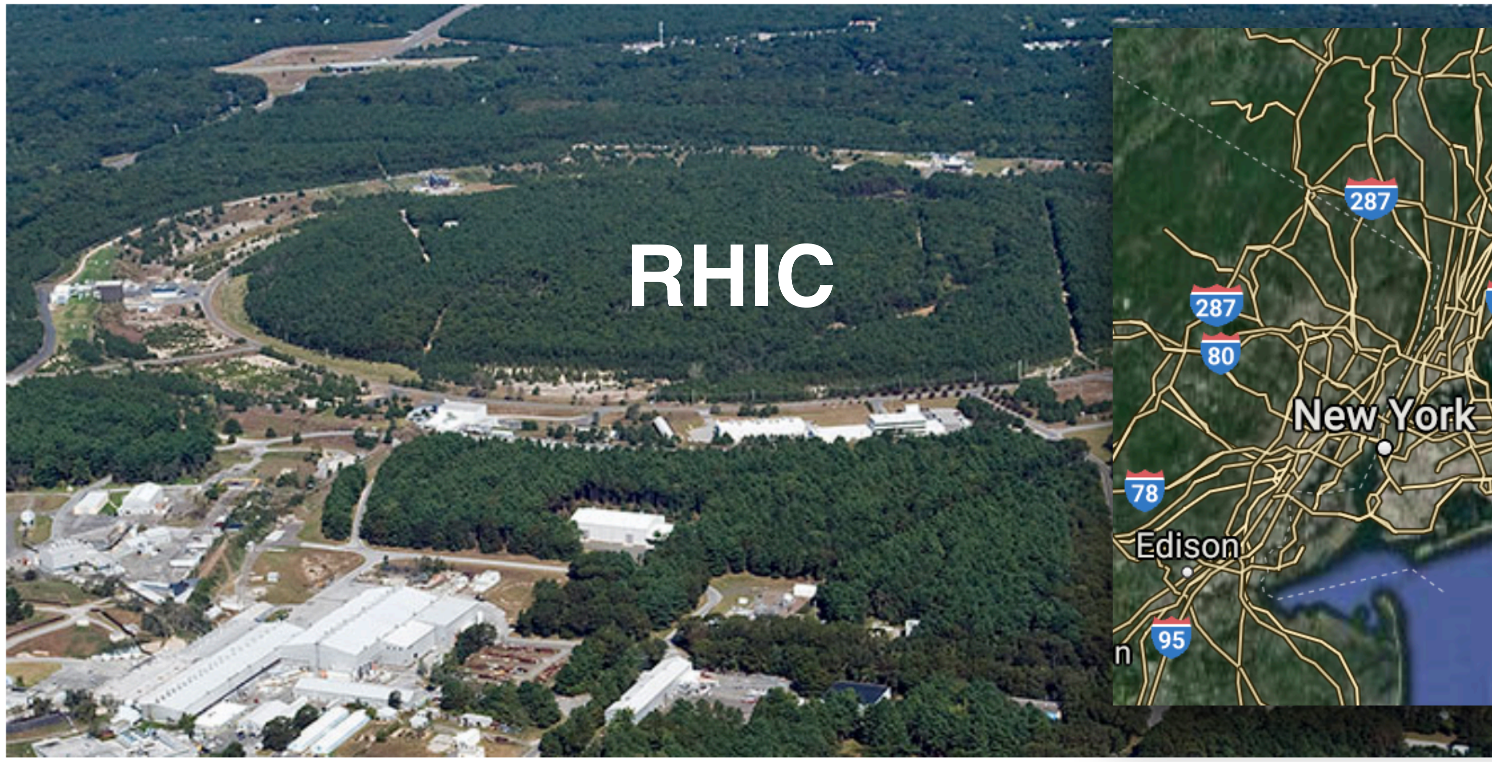

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will provide crucial infrastructure for the new Electron Ion Collider.

+ ENLARGE

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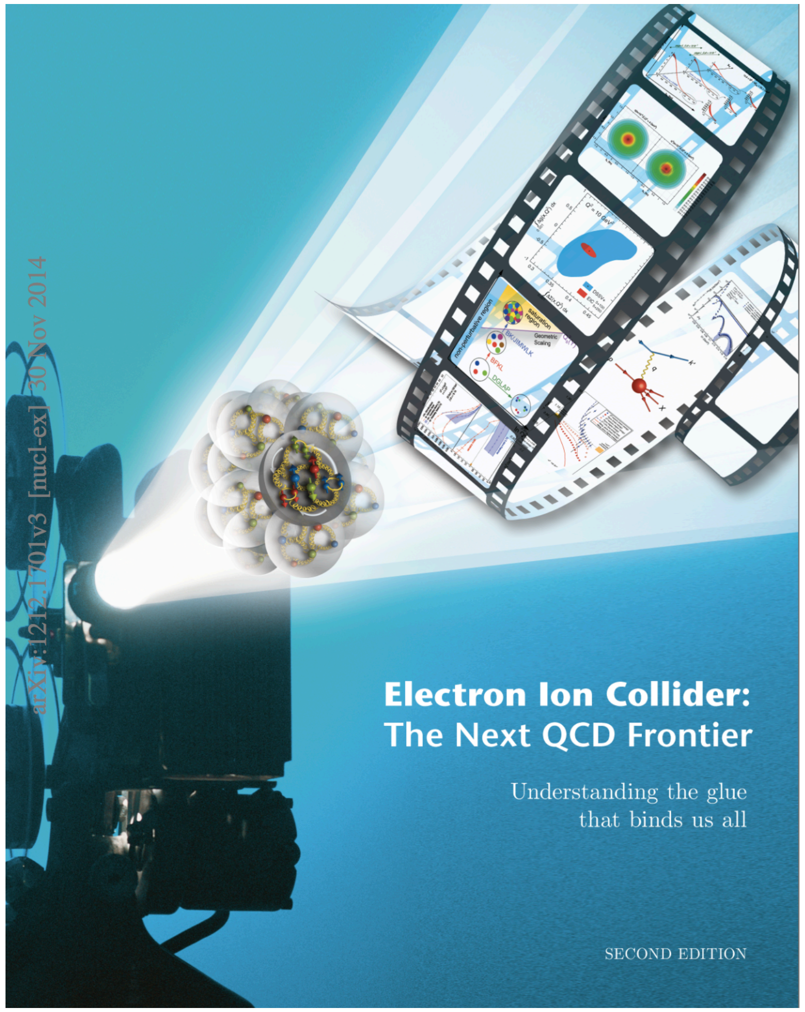
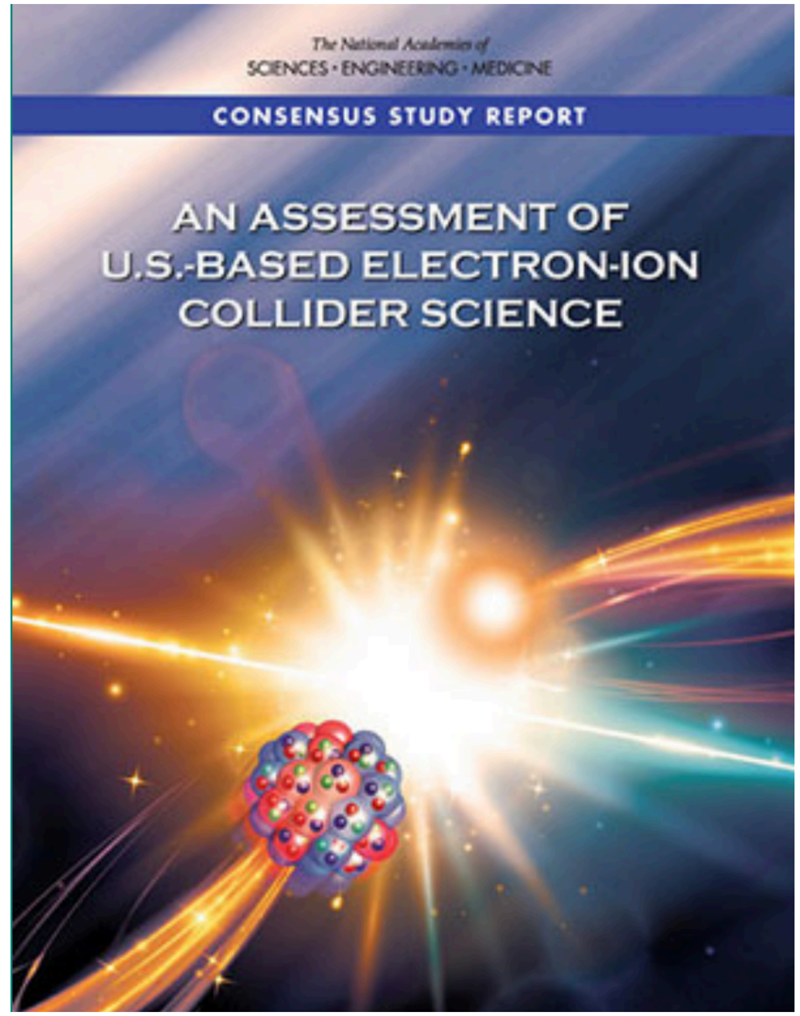
https://www.bnl.gov/eic/science.php

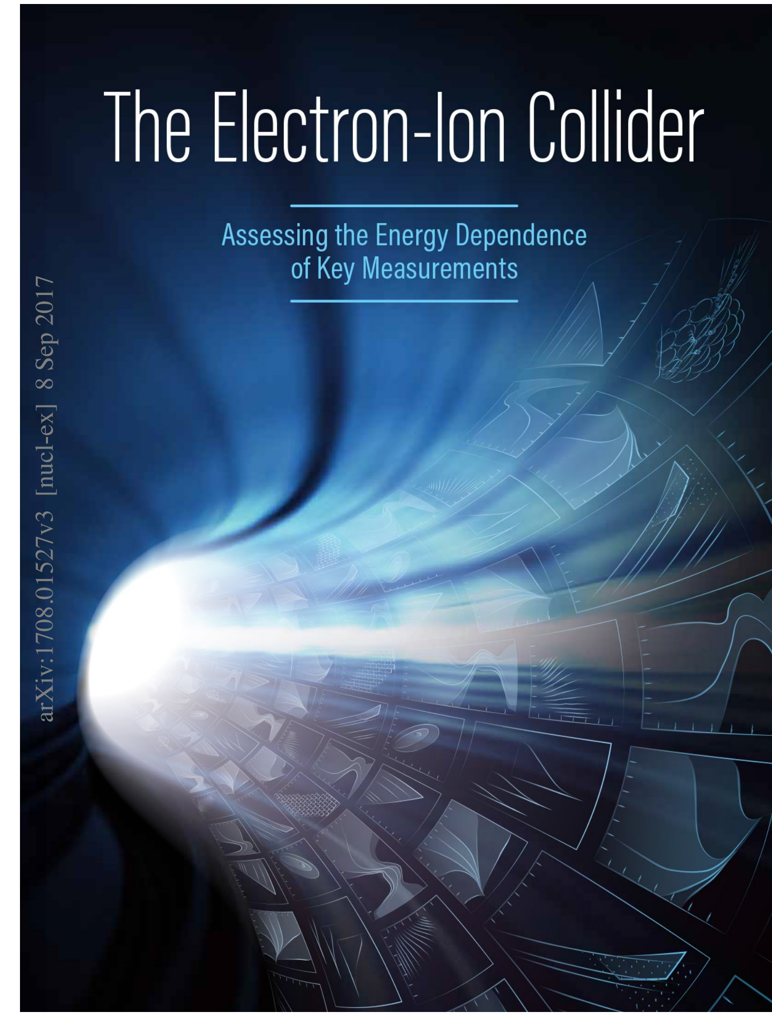
THE ELECTRON-ION COLLIDER: RELEVANT DOCUMENTS



White Paper (2012)
Accardi et al, arXiv:1212:1701



NSAC Study (2018)

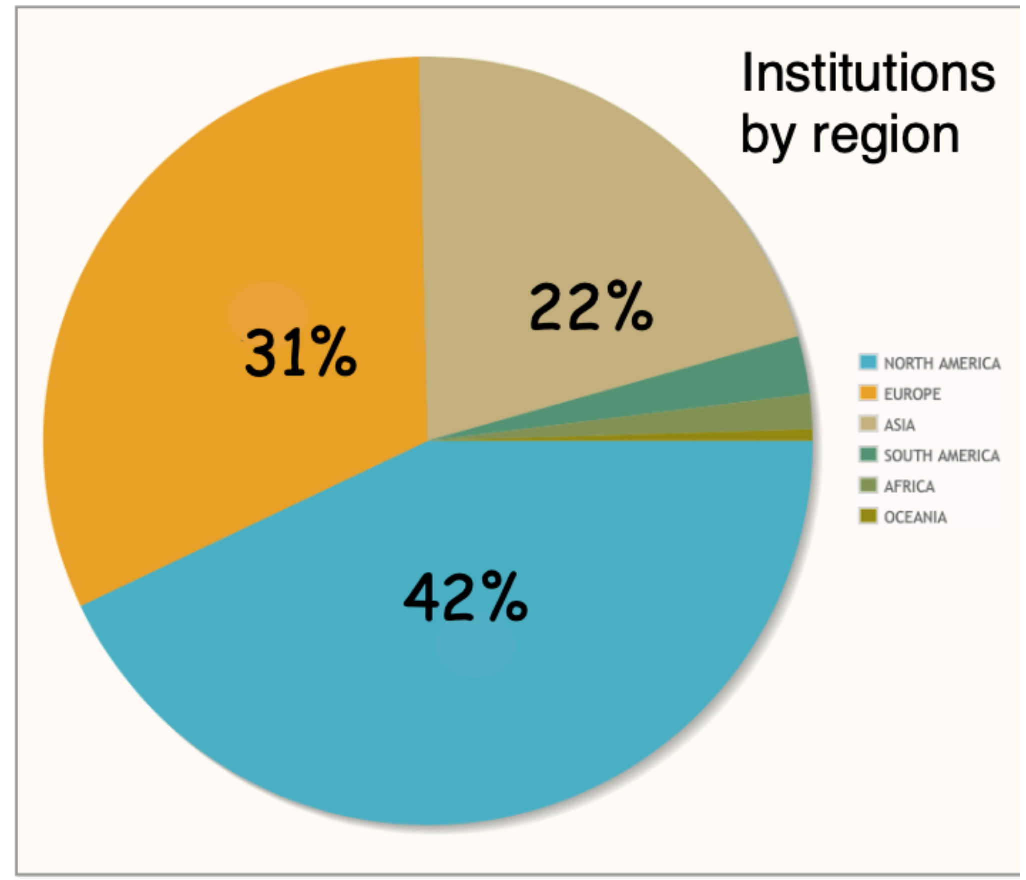


BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

Yellow Paper (2016)
Accardi et al, Eur. Phys. J. A (2016) 52: 268

ELECTRON ION COLLIDER USER GROUP

- EICUG.ORG, growing community, 1200+ members, 31 countries, 250 institutions



- EIC detector R&D program ~1M$/year
- EIC Accelerator R&D program ~7M$/year
- 2021: YELLOW REPORT on detector design

PHYSICS PROGRAM PILLARS

THE ELECTRON-ION COLLIDER'S PILLARS: SCIENTIFIC QUESTIONS

White Paper (2012)
Accardi et al, arXiv:1212:1701

- How are the *sea quarks and gluons*, and their spins, distributed in space and momentum inside the nucleon?

- Where does the *saturation of gluon densities* set in?

- How does the *nuclear* environment affect the distribution of *quarks and gluons* and their interactions in nuclei?

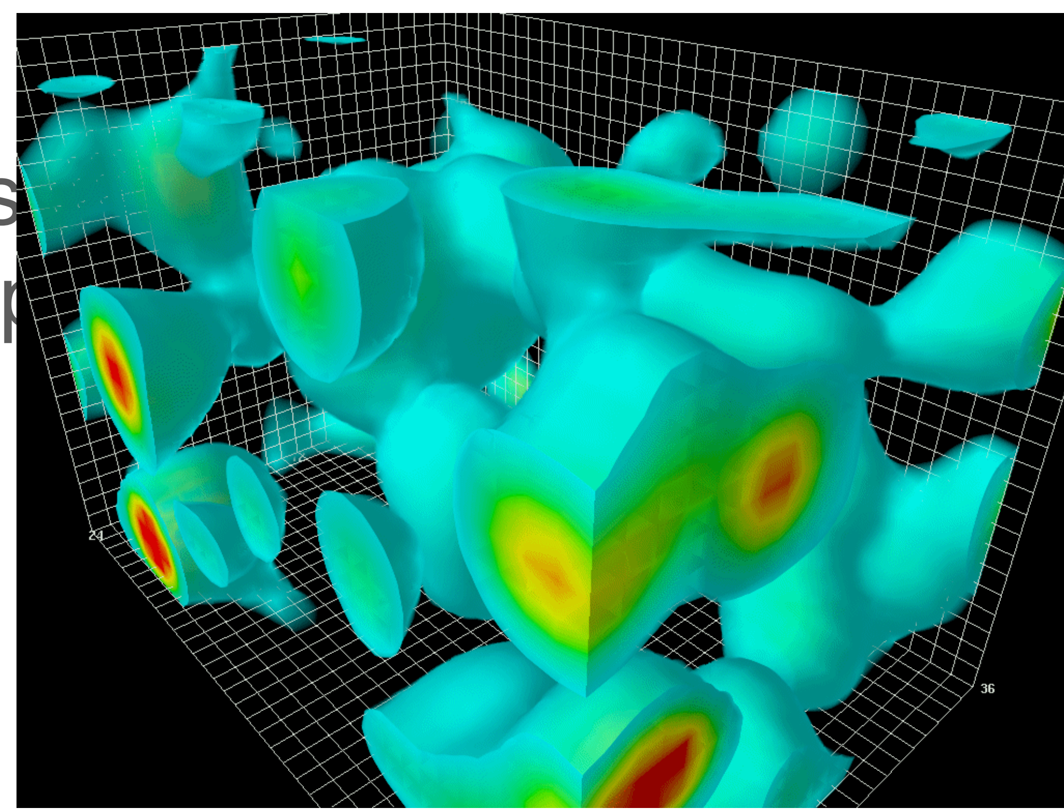
THEORETICAL FOUNDATIONS

White Paper (2012)
Accardi et al, arXiv:1212:1701

- EIC is a QCD lab to explore the structure and dynamics of the visible world

$$\mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j \left(iD_\mu \gamma^\mu - m_j \right) \psi_j - \frac{1}{4} \mathrm{Tr}\, G^{\mu\nu} G_{\mu\nu}$$

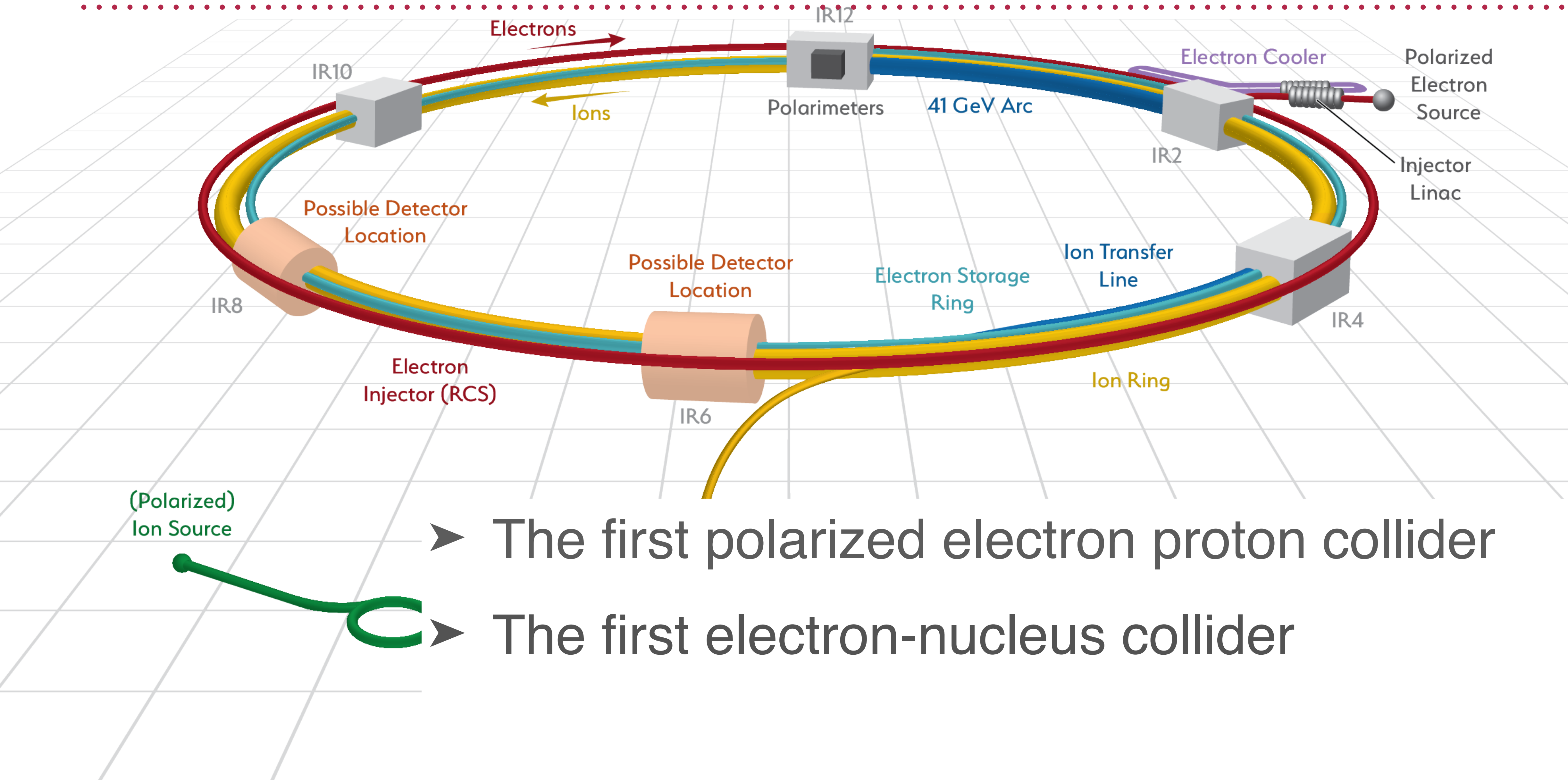
- Interactions arise from fundamental symmetries, properties such as mass and the spin are emergent through complex structure of QCD
- Major goal: unders … ties of QCD by exploring tomograp … matter



"Visualizations of the QCD Vacuum." lattice QCD calculation by by Derek Leinweber

FACILITY TO ADRESS THE QUESTIONS

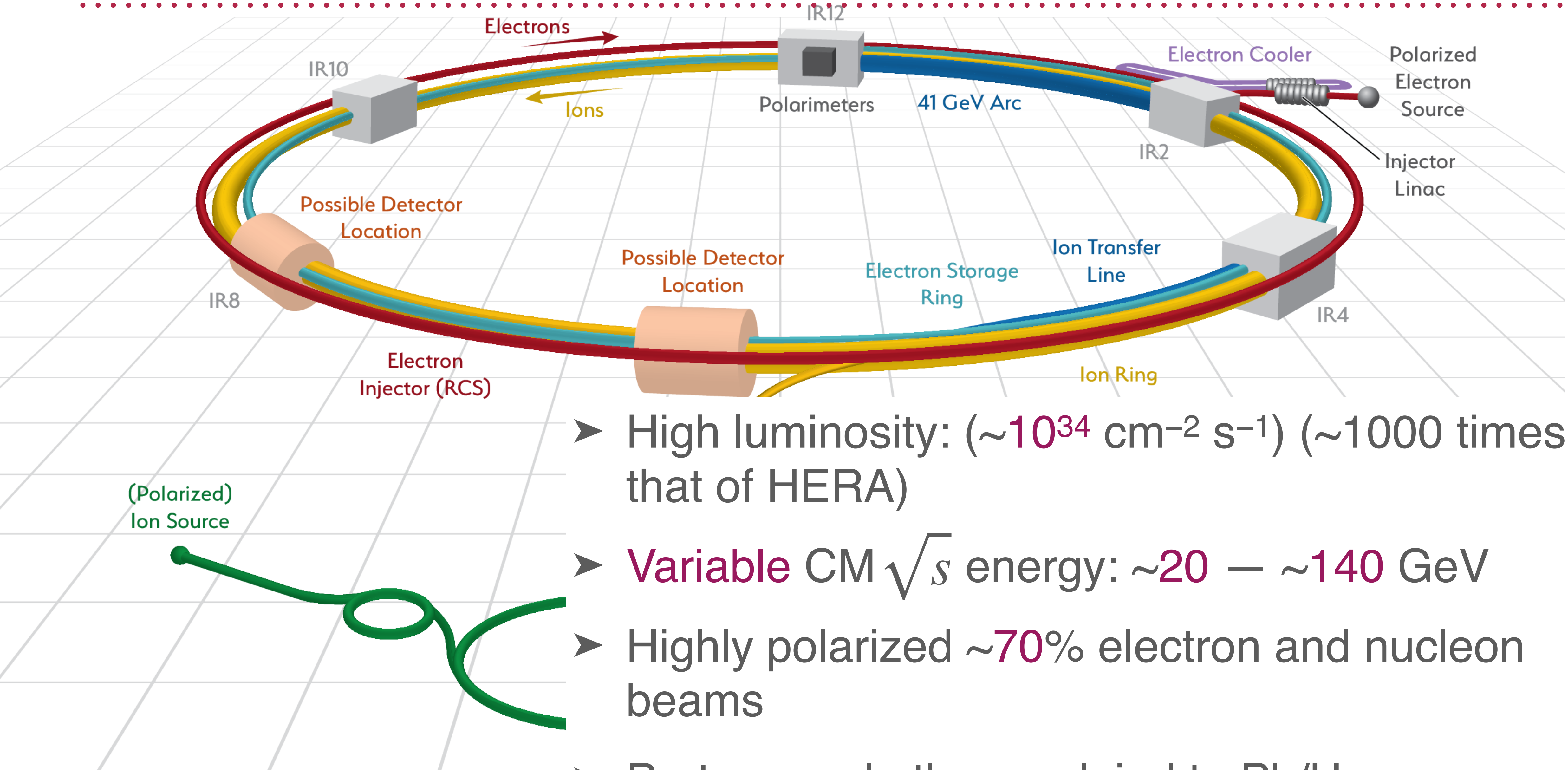
THE ELECTRON-ION COLLIDER @ BNL ~2030



- The first polarized electron proton collider
- The first electron-nucleus collider

White Paper (2012)
Accardi et al, arXiv:1212:1701

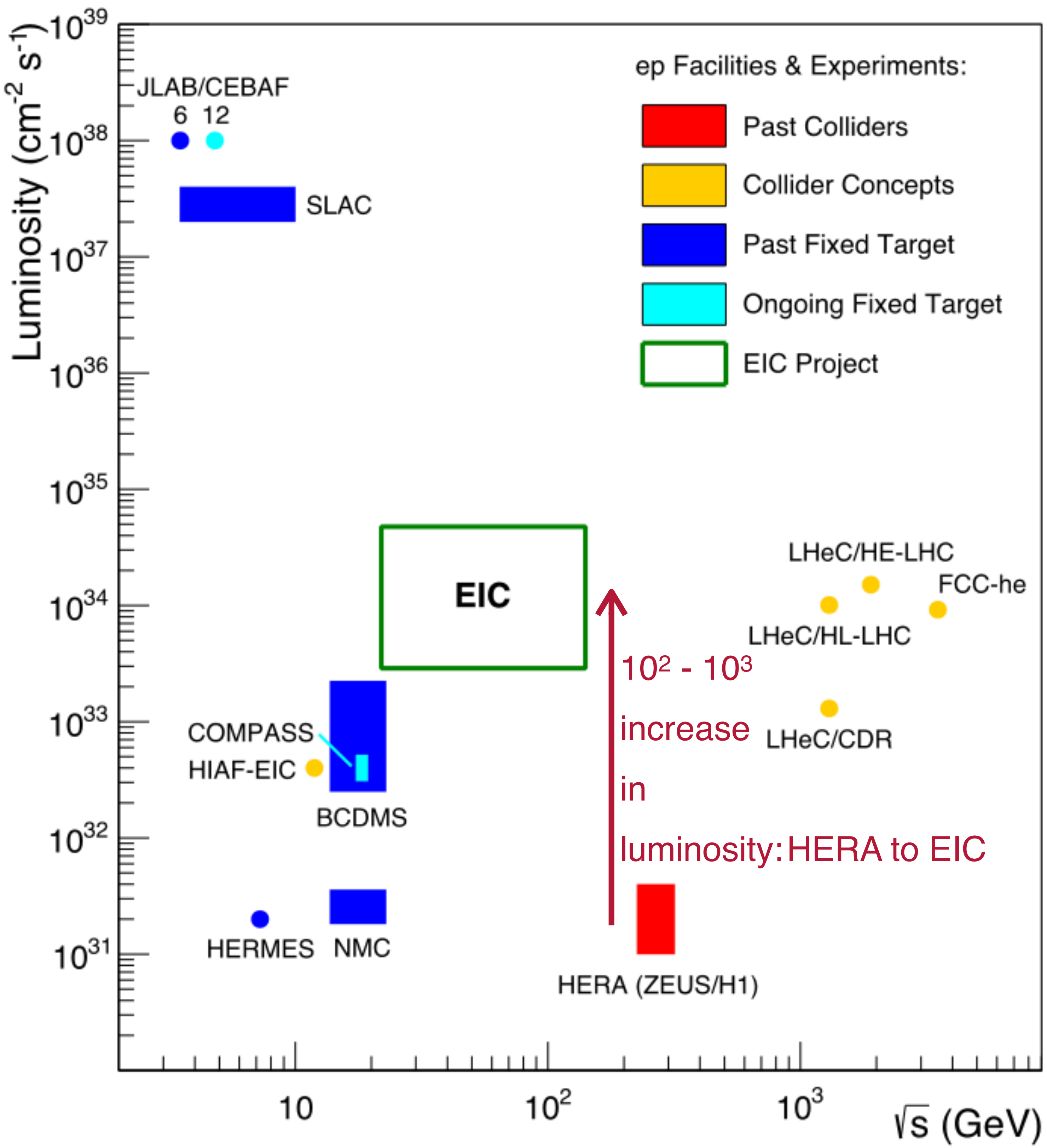
THE ELECTRON-ION COLLIDER @ BNL ~ 2030



White Paper (2012)
Accardi et al, arXiv:1212:1701

- High luminosity: (~10^{34} cm^{-2} s^{-1}) (~1000 times that of HERA)
- Variable CM $\sqrt{s}$ energy: ~20 — ~140 GeV
- Highly polarized ~70% electron and nucleon beams
- Protons and other nuclei, d to Pb/U
- Possibility of more than one interaction region (none of the major facilities operates with one detector only - important for discovery potential)

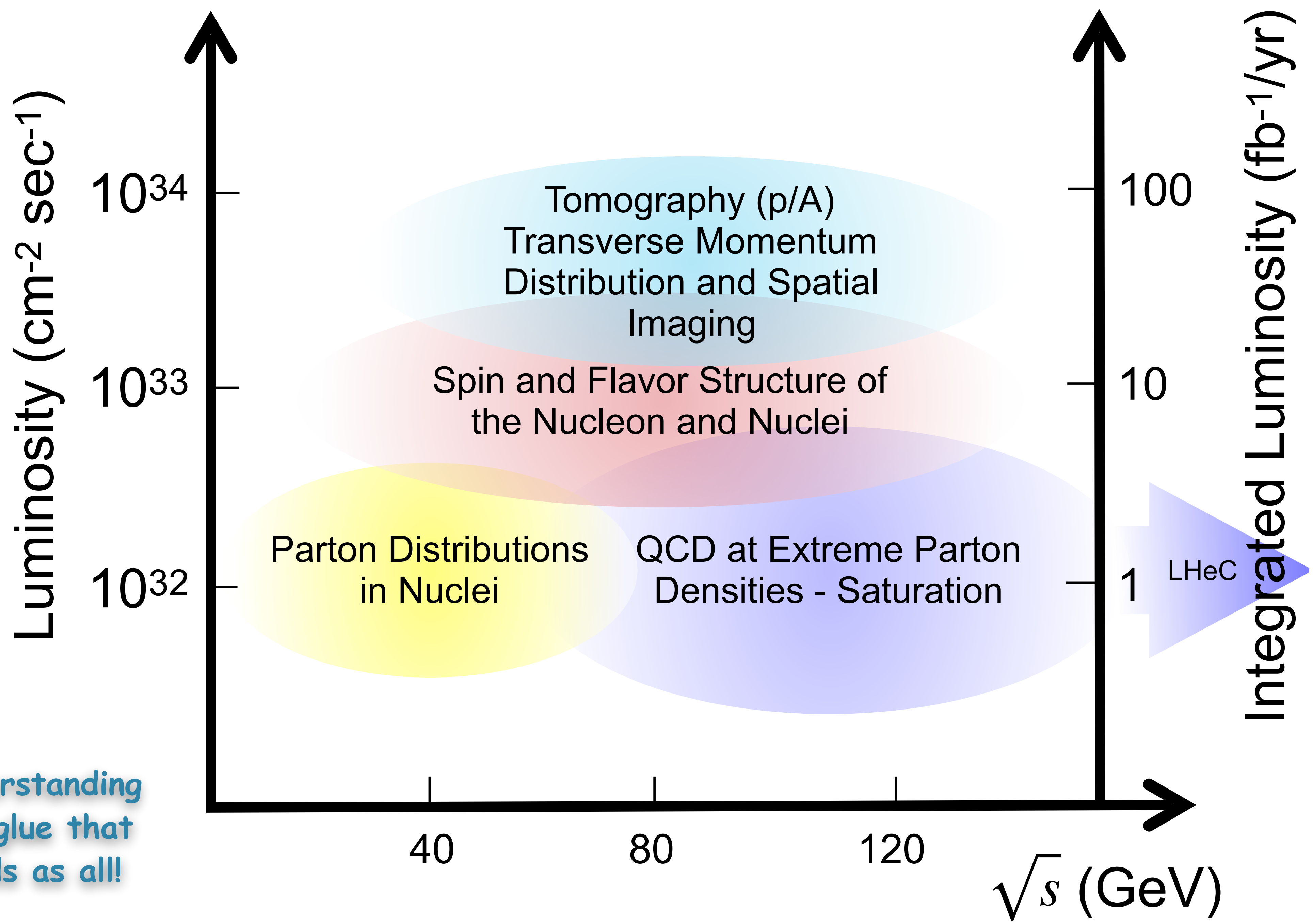
THE ELECTRON-ION COLLIDER @ BNL



- EIC and other e P facilities
- Luminosity vs energy

THE ELECTRON-ION COLLIDER @ BNL

➤ Luminosity vs energy



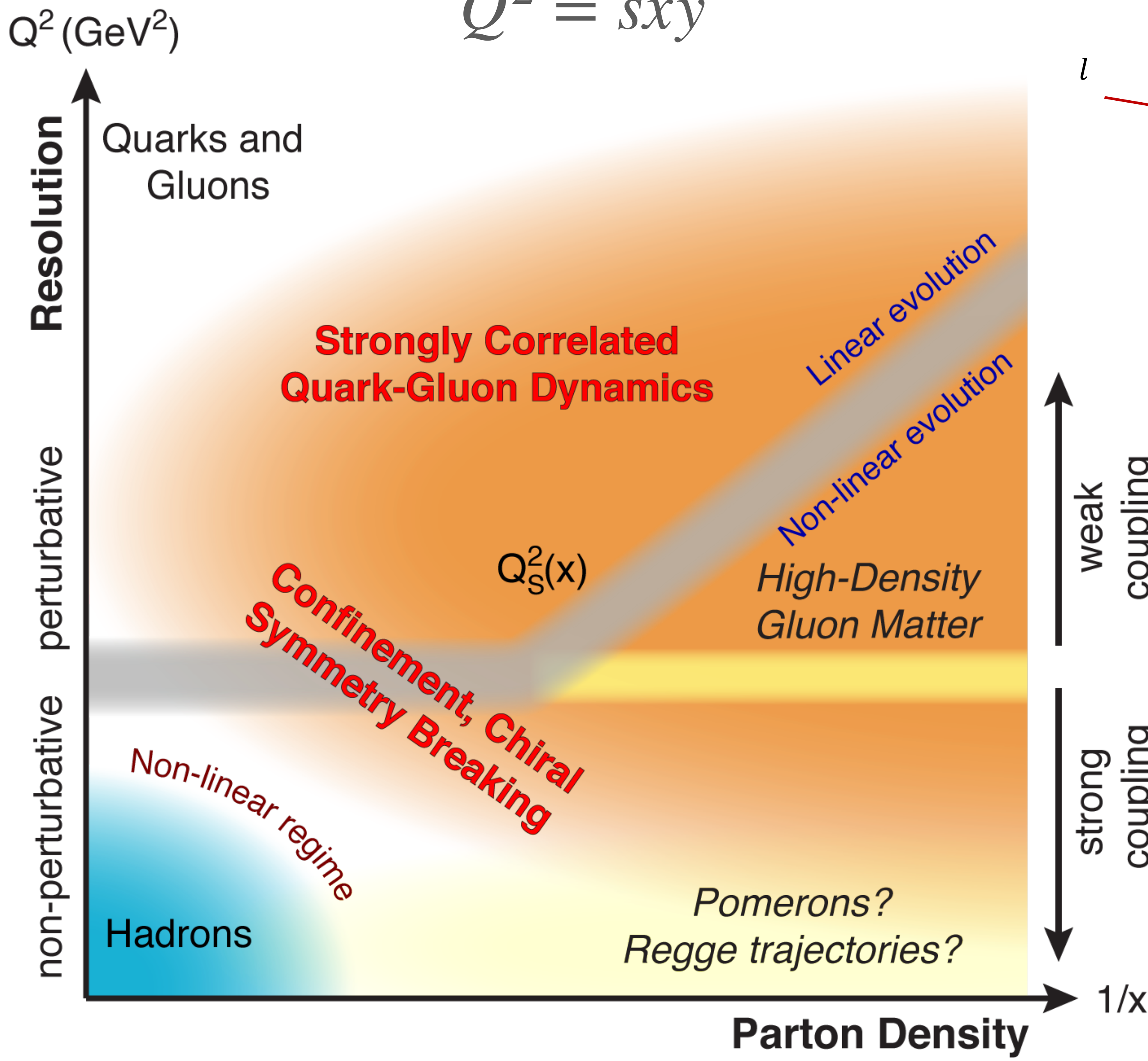
nderstanding
he glue that
binds as all!

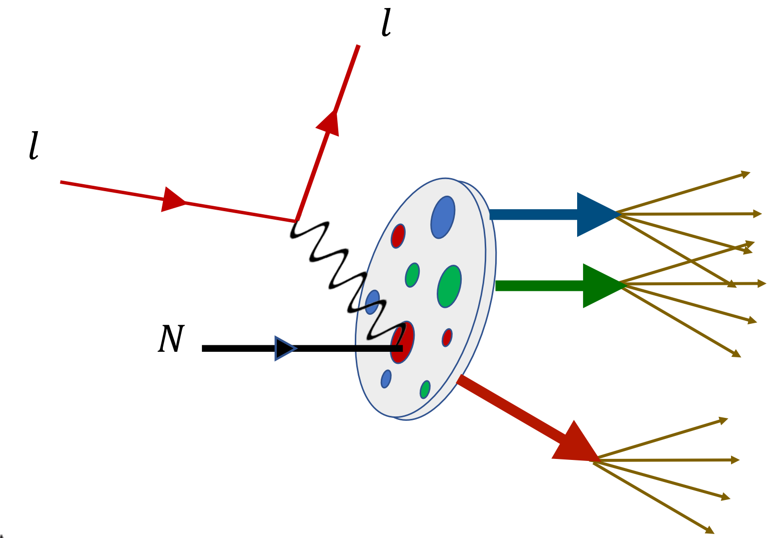
KINEMATICS

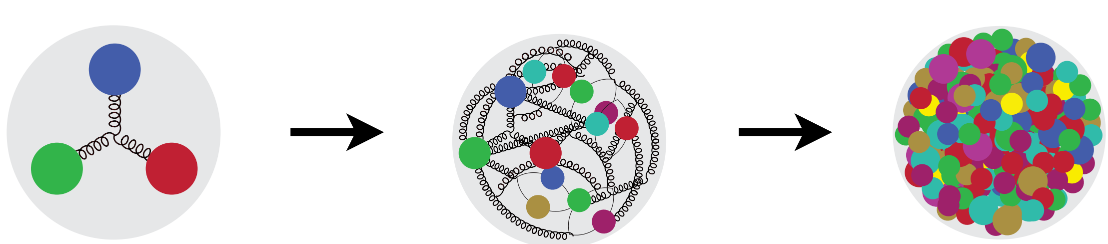
THE ELECTRON-ION COLLIDER: KINEMATICS

BNL Report (2017)
Aschenauer at el,
arXiv:1708.01527

$$Q^2 = sxy$$

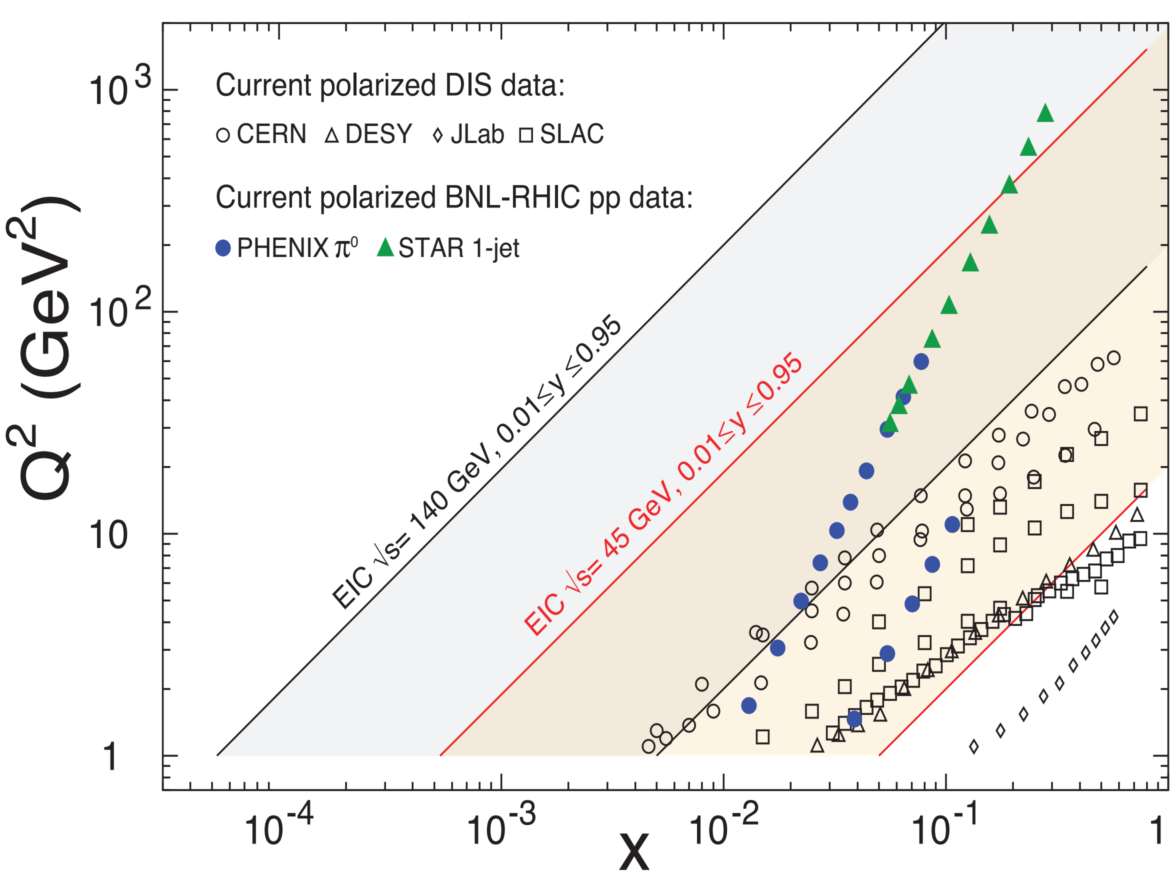


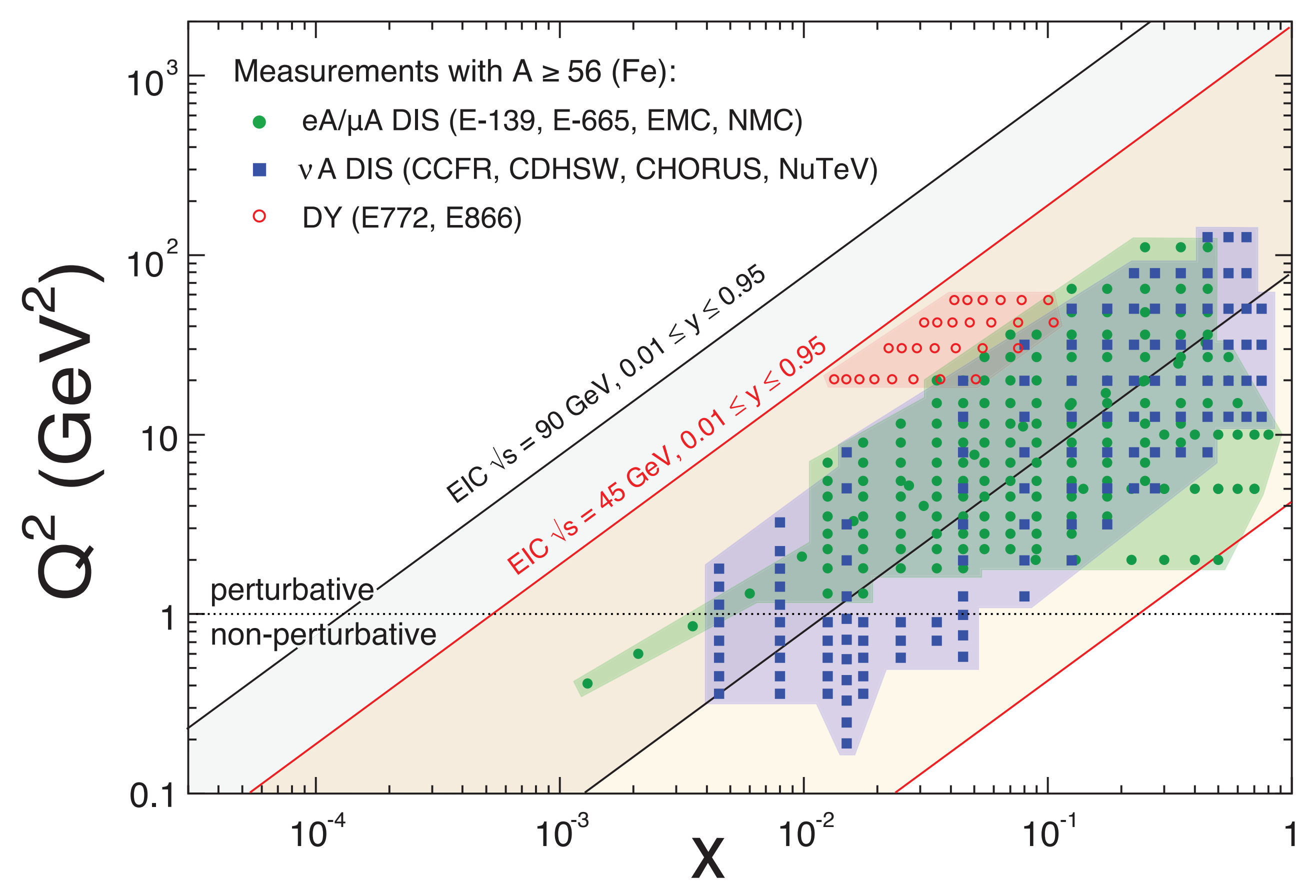




THE ELECTRON-ION COLLIDER: KINEMATICS

$$Q^2 = sxy$$



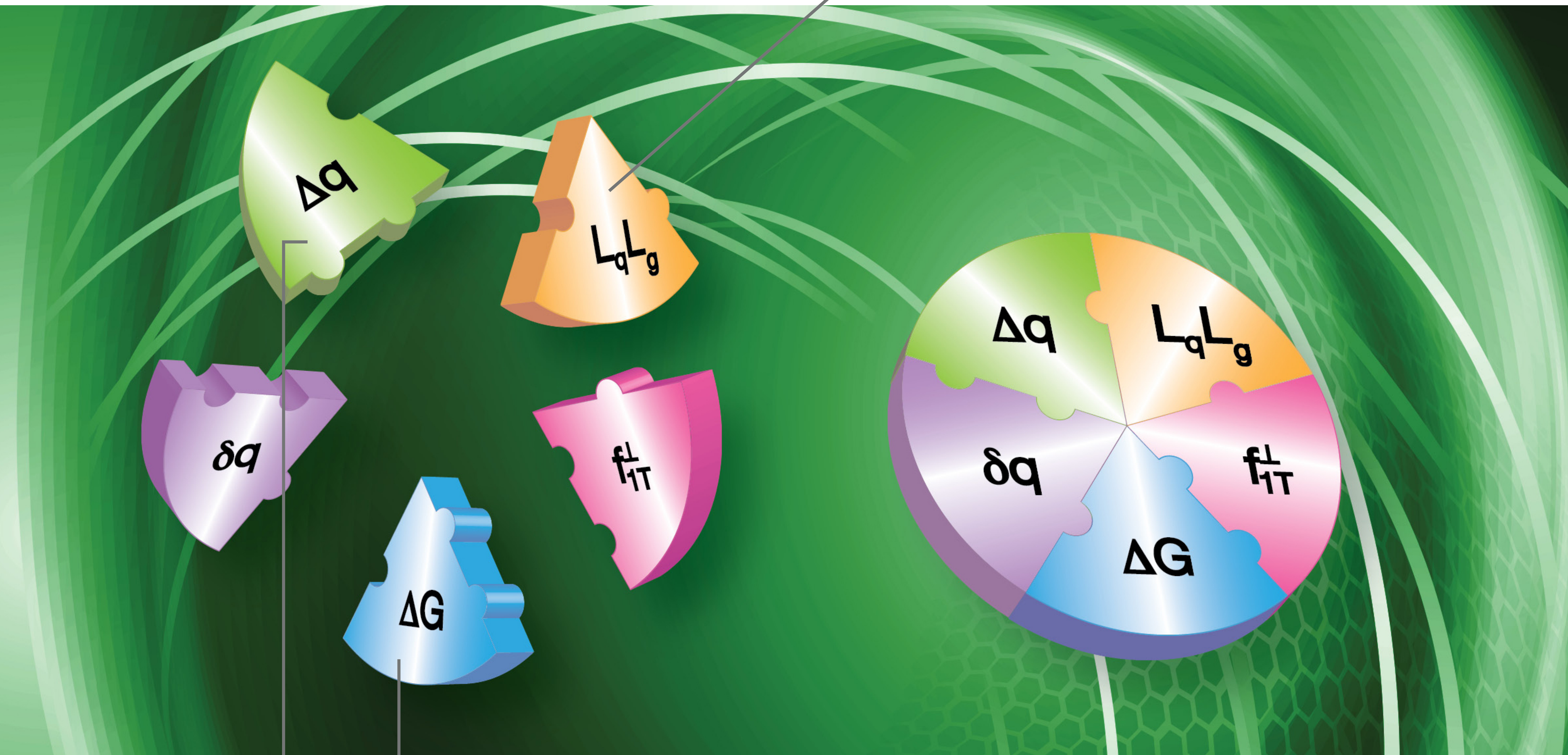


BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

WHAT ABOUT SPIN?

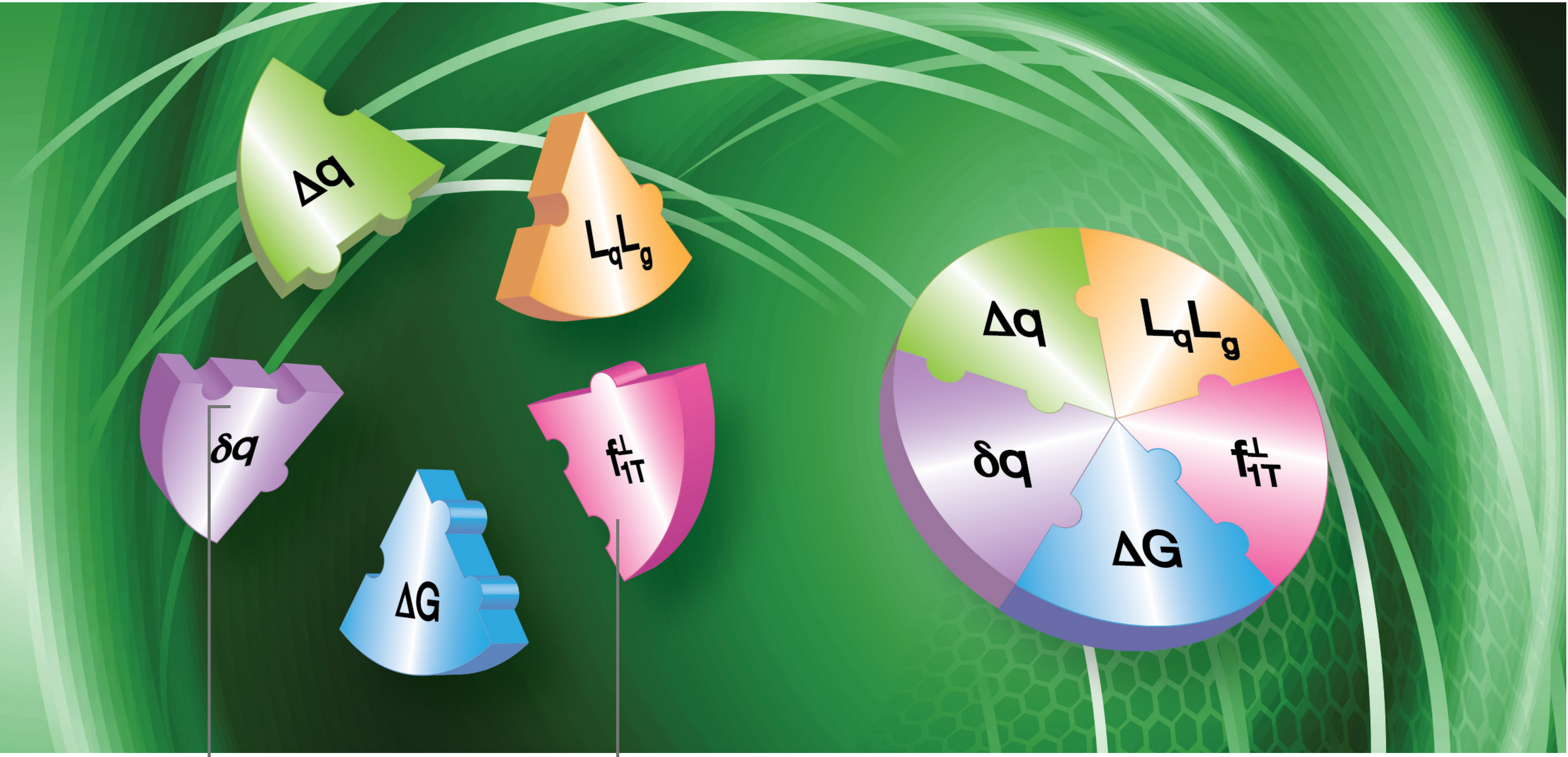
MANY THINGS TO STUDY

contribution of orbital angular momentum



quark and gluon contributions to the spin

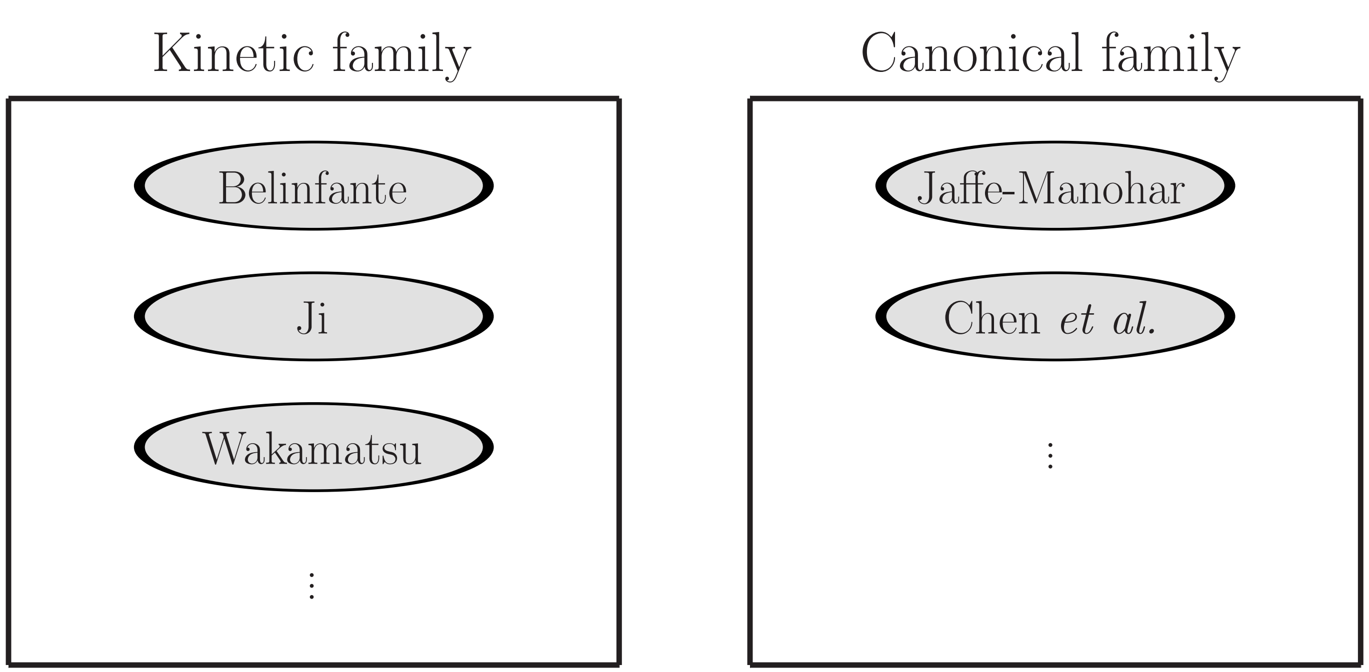
MANY THINGS TO STUDY



Transversity and Sivers functions

SPIN DECOMPOSITION

- The nucleon is a composite system. The spin is carried by its constituents: quarks, anti-quarks and gluons and the angular momentum generated by their motion.
- The nucleon at rest has spin 1/2, however its decomposition in terms of spin and orbital contributions associated with quarks and gluons is not unique.
- There are two types of decompositions of the proton spin operator: kinetic (also known as mechanical) and canonical. These two types differ by how the OAM operator is split into the quark and gluon contributions. They share the same quark spin operator.



R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)
S. Bashinsky and R. L. Jaffe, Nucl. Phys. B 536 (1998)
X. Ji, Phys. Rev. Lett. 78 (1997)
X. -S. Chen, X. -F. Lu, W. -M. Sun, F. Wang and T. Goldman, Phys. Rev. Lett. 100 (2008)
M. Wakamatsu, Phys. Rev. D 83 (2011)
Y. Hatta, Phys. Rev. D 84 (2011)
E. Leader and C. Lorce, Phys.Rept. 541, 163 (2014)
C. Lorcé and B. Pasquini, JHEP 09 (2013)
C. Lorcé and B. Pasquini, Phys. Rev. D 84, (2011)
C. Lorcé, B. Pasquini, X. Xiong and F. Yuan, Phys. Rev. D 85, (2012)
L. Adhikari and M. Burkard, Phys.Rev.D 94 (2016)

- Kinetic family is related to Generalized Parton Distributions, while canonical in light cone gauge is related to collinear helicity distribution functions

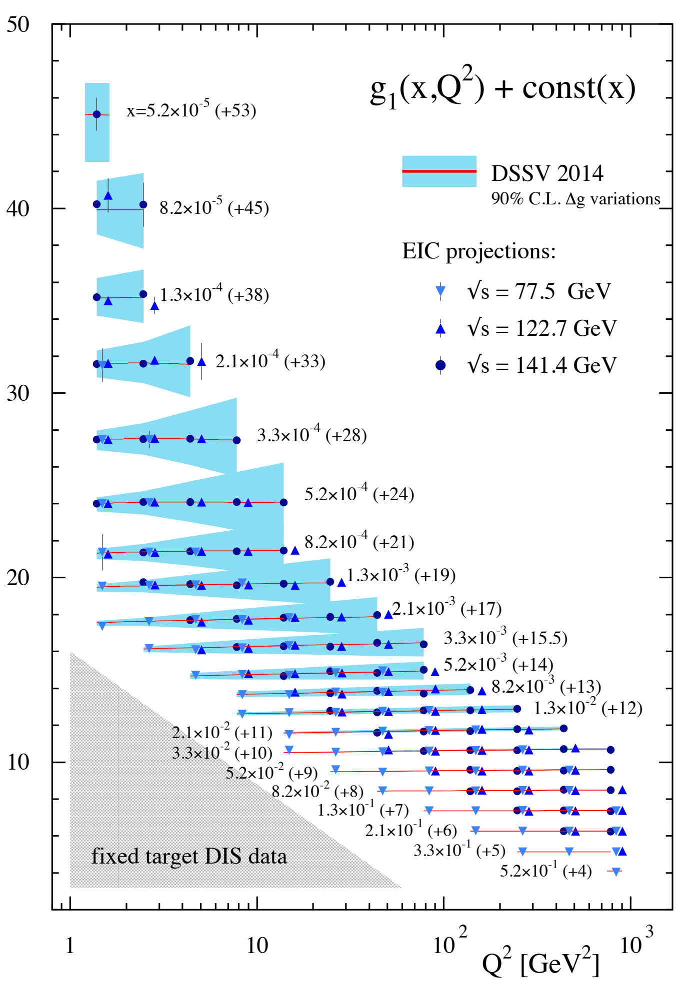
LONGITUDINAL SPIN

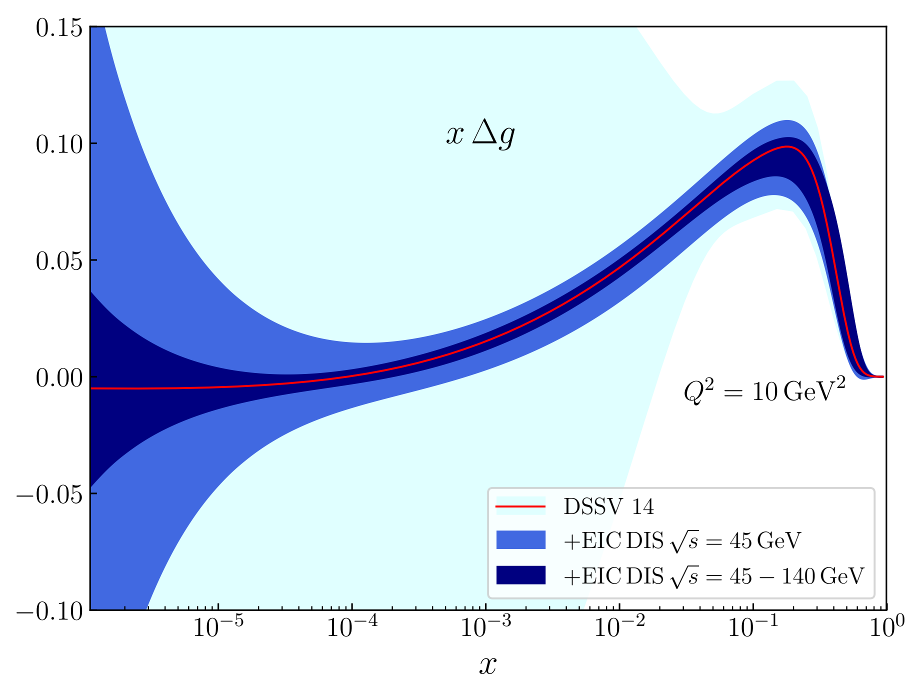
- Global QCD analyses are performed to extract helicity pdfs:

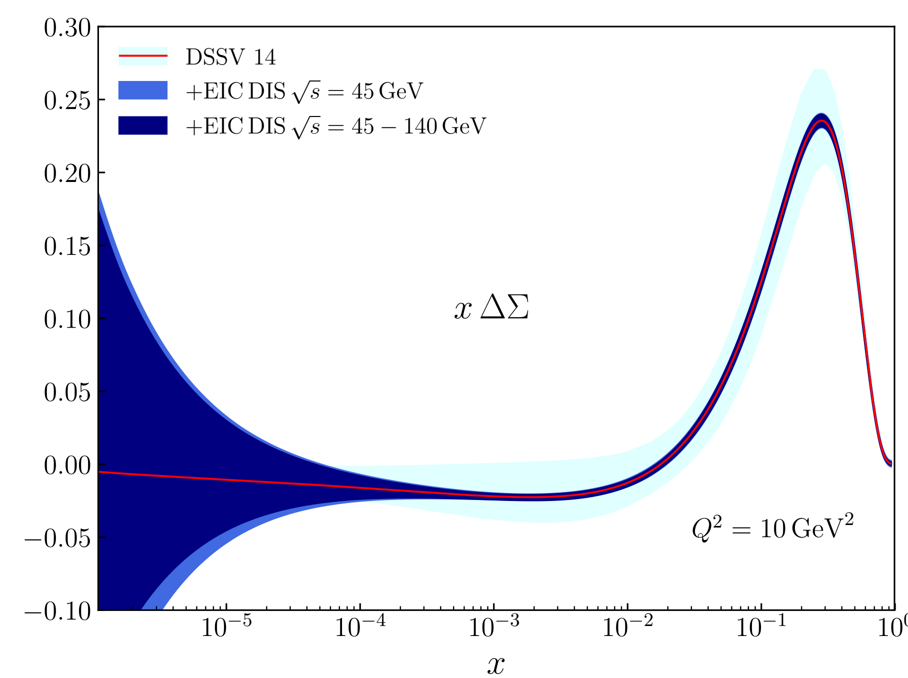
  DSSV: D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. Lett. 113 (2014)
  NNPDFpol: E. R. Nocera, R. D. Ball, S. Forte, G. Ridolfi, J. Rojo, Nucl. Phys. B 887 (2014)
  JAM: J. J. Ethier, N. Sato, W. Melnitchouk, Phys. Rev. Lett. 119 (13) (2017)

- At present around $25\ \%$ of the spin is attributed to quarks and anti-quarks.
- The evidence for non-zero gluon contribution, around $30\ \%$, is mainly due to RHIC spin program E. R. Nocera, Impact of Recent RHIC Data on Helicity-Dependent Parton Distribution Functions (2017). arXiv:1702.05077.

The impact of the EIC on determination of the quark and gluon contributions



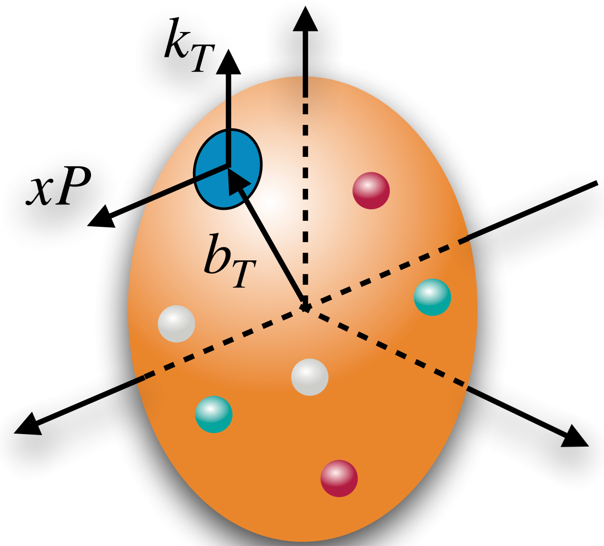




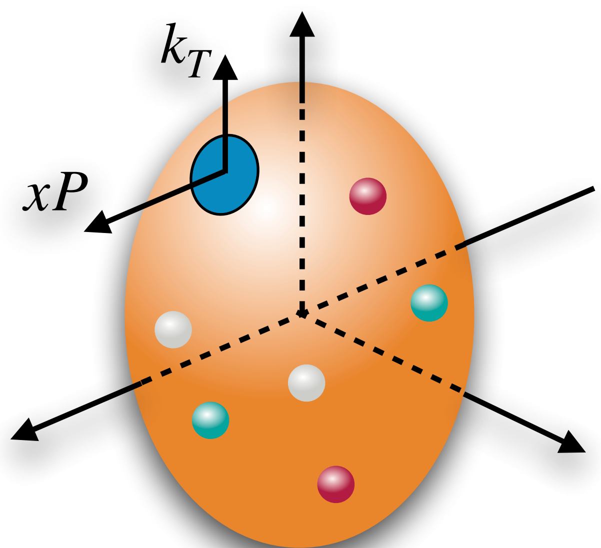
Yellow Report (2021) arXiv:2103.05419

Aschenauer , Sassot, Stratmann, Phys.Rev.D 92 (2015)

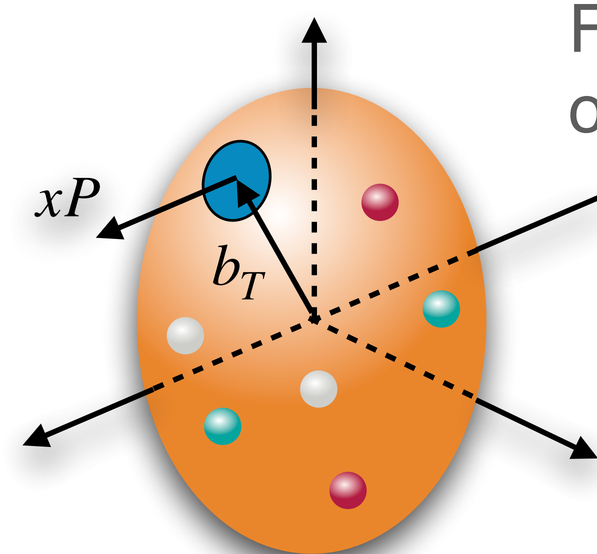
Wigner distributions
(Fourier transform of
GTMDs = Generalized
Transverse Momentum
Distributions)



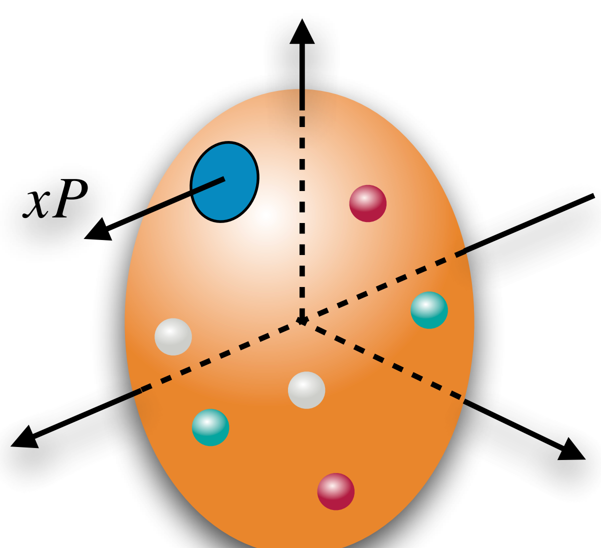
TMDs



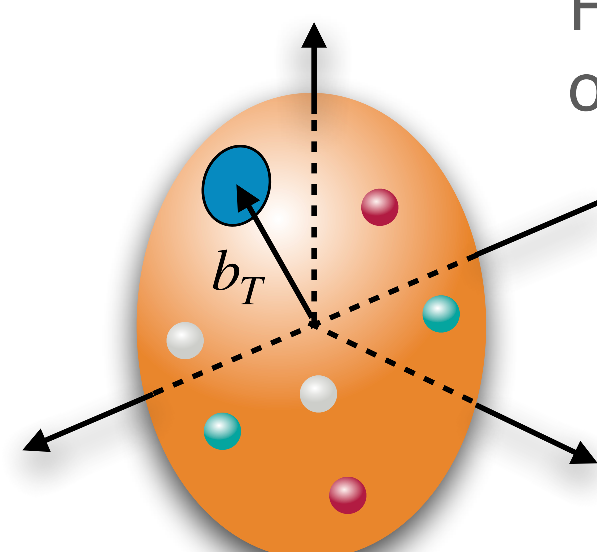
Fourier transform
of GPDs



PDFs

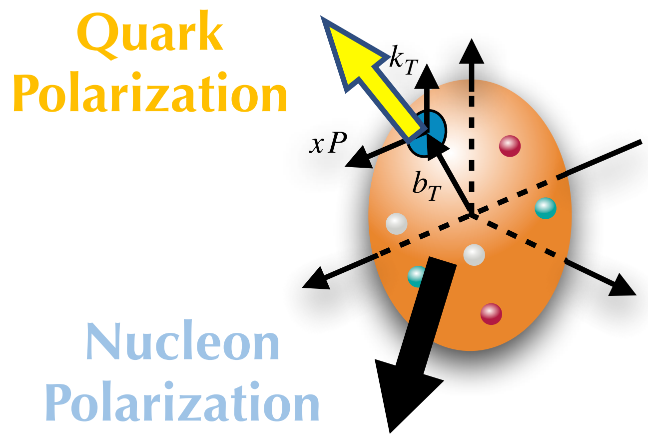


Fourier transform
of Form Factors



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Our understanding of the nucleon evolves: SPIN



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons

TMDs

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	$f_1(x,k_T^2)$ Unpolarized		$h_1^\perp(x,k_T^2)$ - Boer-Mulders
L		$g_1(x,k_T^2)$ - Helicity	$h_{1L}^\perp(x,k_T^2)$ - Kozinian-Mulders,“worm” gear
T	$f_{1T}^\perp(x,k_T^2)$ - Sivers	$g_{1T}(x,k_T^2)$ - Kozinian-Mulders, “worm” gear	$h_1(x,k_T^2)$ - Transversity $h_{1T}^\perp(x,k_T^2)$ - Pretzelosity

GPDs

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	
T	E		$H_T,\ \tilde{H}_T$

Many TMDs and GPDs cannot exist without OAM.

Examples: TMD Sivers function $f_{1T}^\perp$ and GPD *E*

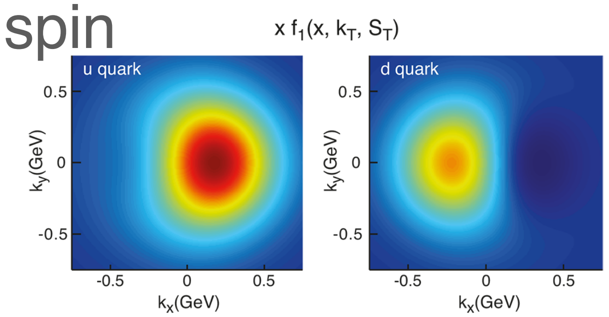
POLARIZED TMD FUNCTIONS

Sivers function $f_{1T}^{\perp}$

- Describes unpolarized quarks inside of transversely polarized nucleon

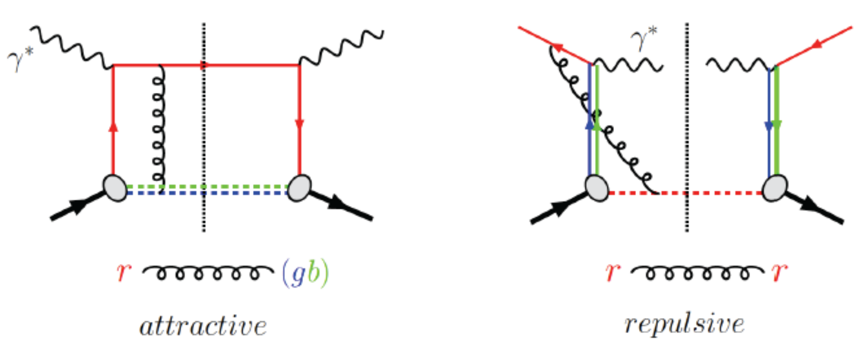
$$\rho_{1;q\leftarrow h^{\uparrow}}(x,\boldsymbol{k}_T,\boldsymbol{S}_T,\mu) = f_{1;q\leftarrow h}(x,k_T;\mu,\mu^2) - \frac{k_{Tx}}{M} f^{\perp}_{1T;q\leftarrow h}(x,k_T;\mu,\mu^2)$$

- Encodes the correlation of orbital motion with the spin



- Sign change of Sivers function is fundamental consequence of QCD

Brodsky, Hwang, Schmidt (2002), Collins (2002)



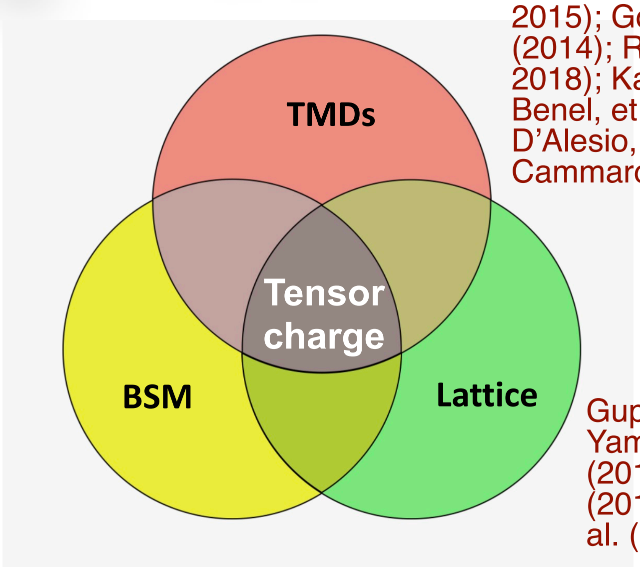
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

Transversity h_1

- The only source of information on tensor charge of the nucleon
- Couples to Collins fragmentation function or di-hadron interference fragmentation functions in SIDIS

$$\delta q \equiv g_T^q = \int_0^1 dx\ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$

Anselmino, et al. (2013, 2015); Goldstein, et al. (2014); Radici, et al. (2013, 2018); Kang, et al. (2016); Benel, et al. (2019); D'Alesio, et al. (2020); Cammarota, et al. (2020)

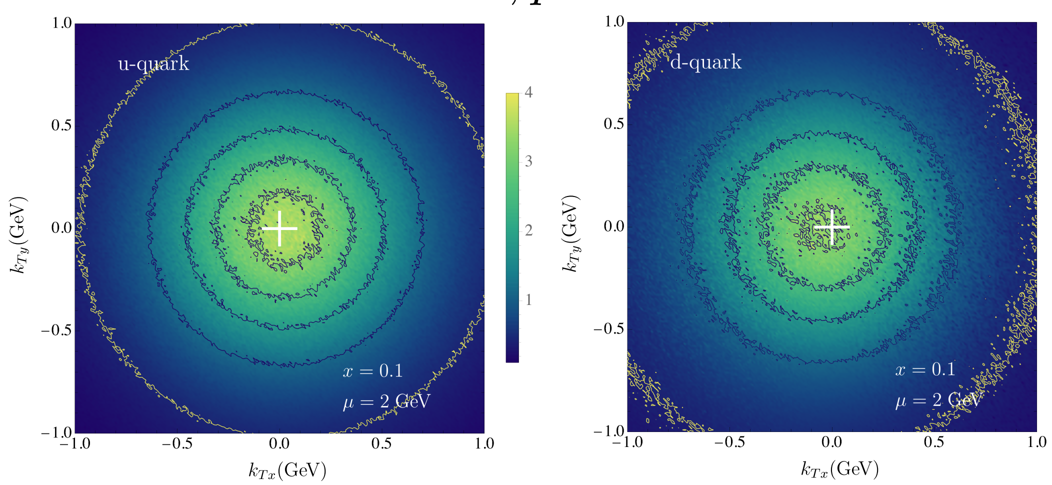


Courtoy, et al. (2015); Yamanaka, et al. (2017); Liu, et al. (2018); Gonzalez-Alonso, et al. (2019)

Gupta, et al. (2018); Yamanaka, et al. (2018); Hasan, et al. (2019); Alexandrou, et al. (2019)

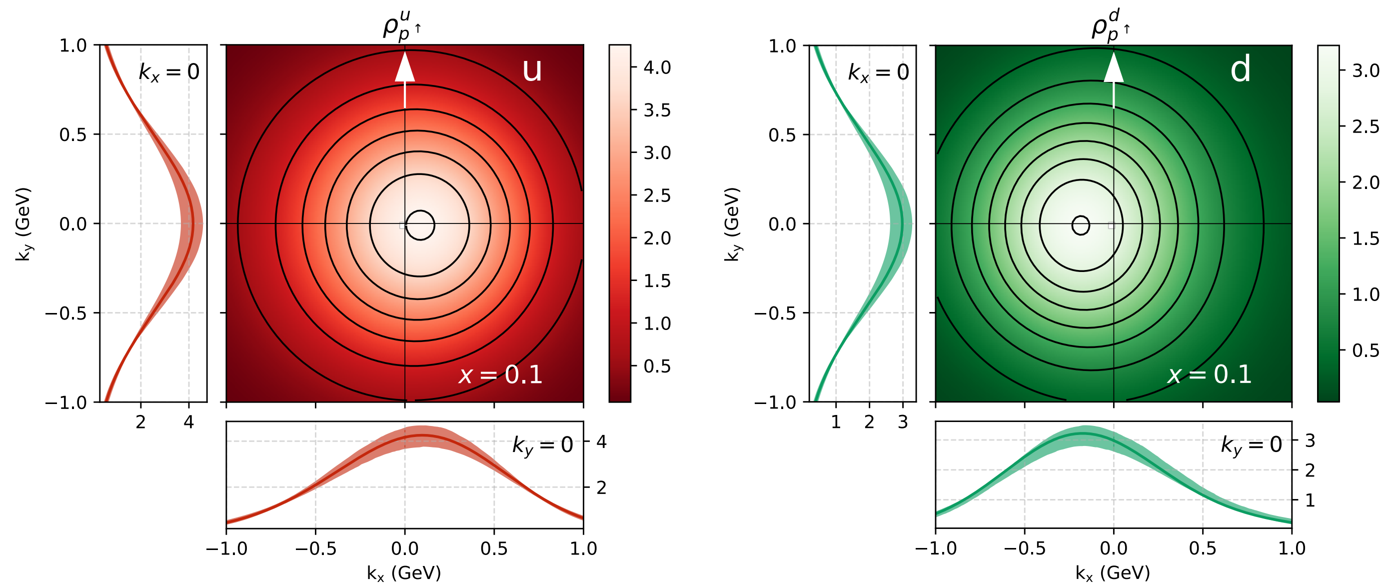
NUCLEON TOMOGRAPHY – THE FINAL GOAL OF THE EIC

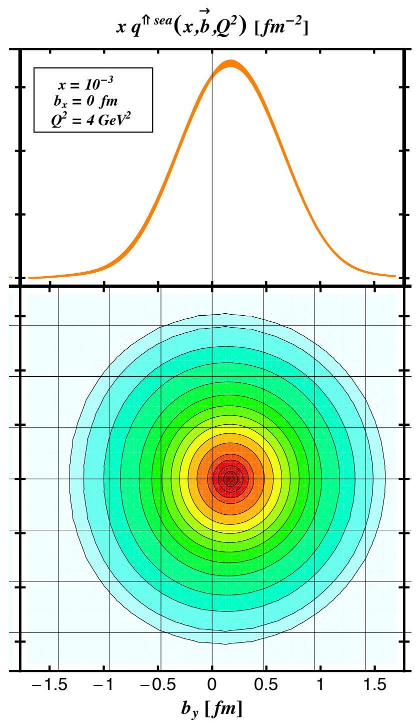
$$\rho_{1;q\leftarrow h^{\uparrow}}(x, \boldsymbol{k}_T, \boldsymbol{S}_T, \mu) = f_{1;q\leftarrow h}(x, k_T; \mu, \mu^2) - \frac{k_{Tx}}{M} f^{\perp}_{1T;q\leftarrow h}(x, k_T; \mu, \mu^2)$$



M. Bury, A. Prokudin, A. Vladimirov, Phys.Rev.Lett. 126 (2021)

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici (2020)





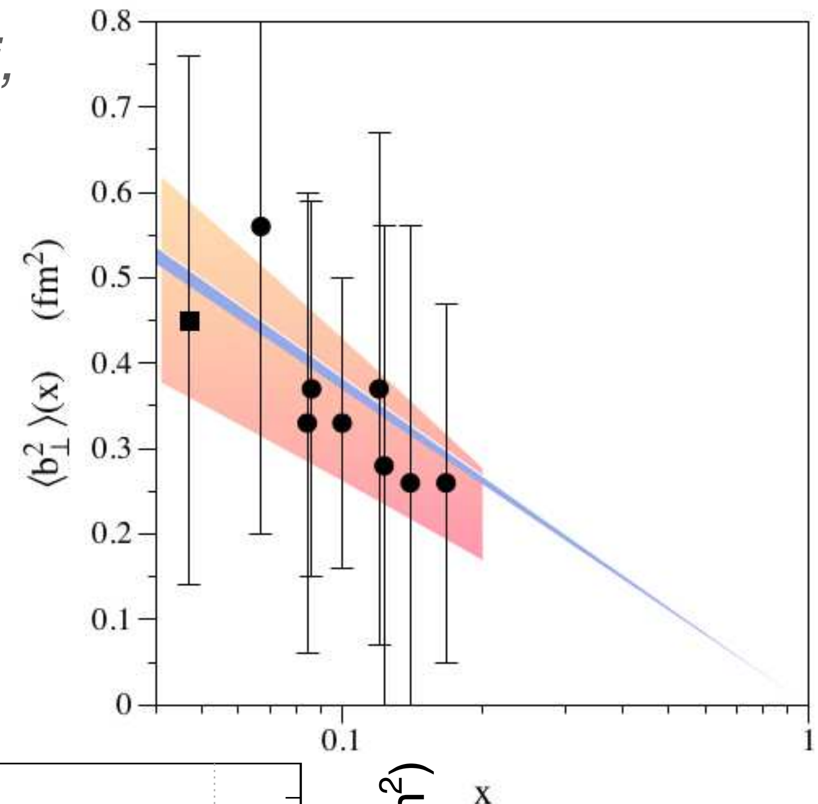
$$q^{\Uparrow}(x, \vec{b}, \mathcal{Q}^2) = q(x, \vec{b}, \mathcal{Q}^2) - \frac{1}{2M_p}\frac{\partial}{\partial b_y} E(x, \vec{b}, \mathcal{Q}^2)$$

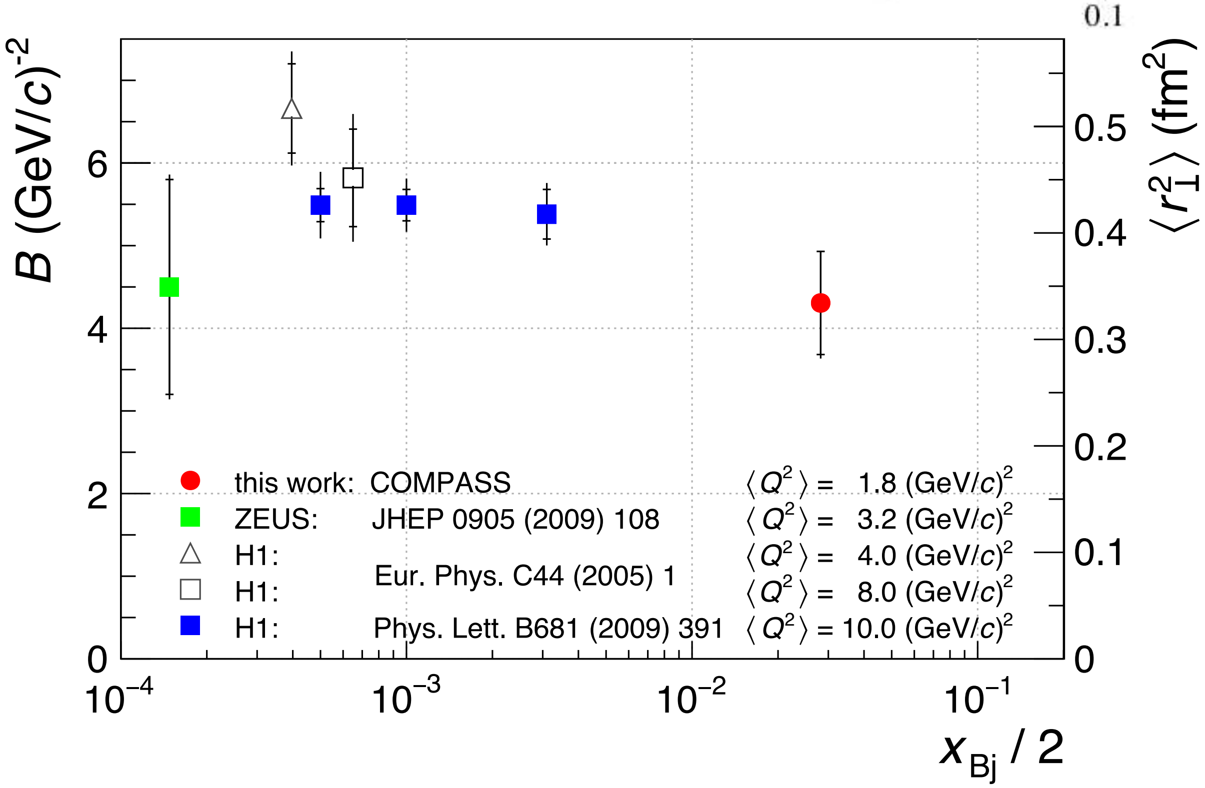
E. Aschenauer, S. Fazio, K. Kumericki, D. Mueller, JHEP 09 (2013) 093

- The shift in the transverse plane is generated by the Sivers function and GPD *E* that cannot exist without OAM
- The opposite signs of the shift is consistent with lattice QCD findings on the opposite signs of the OAM for u and d quarks

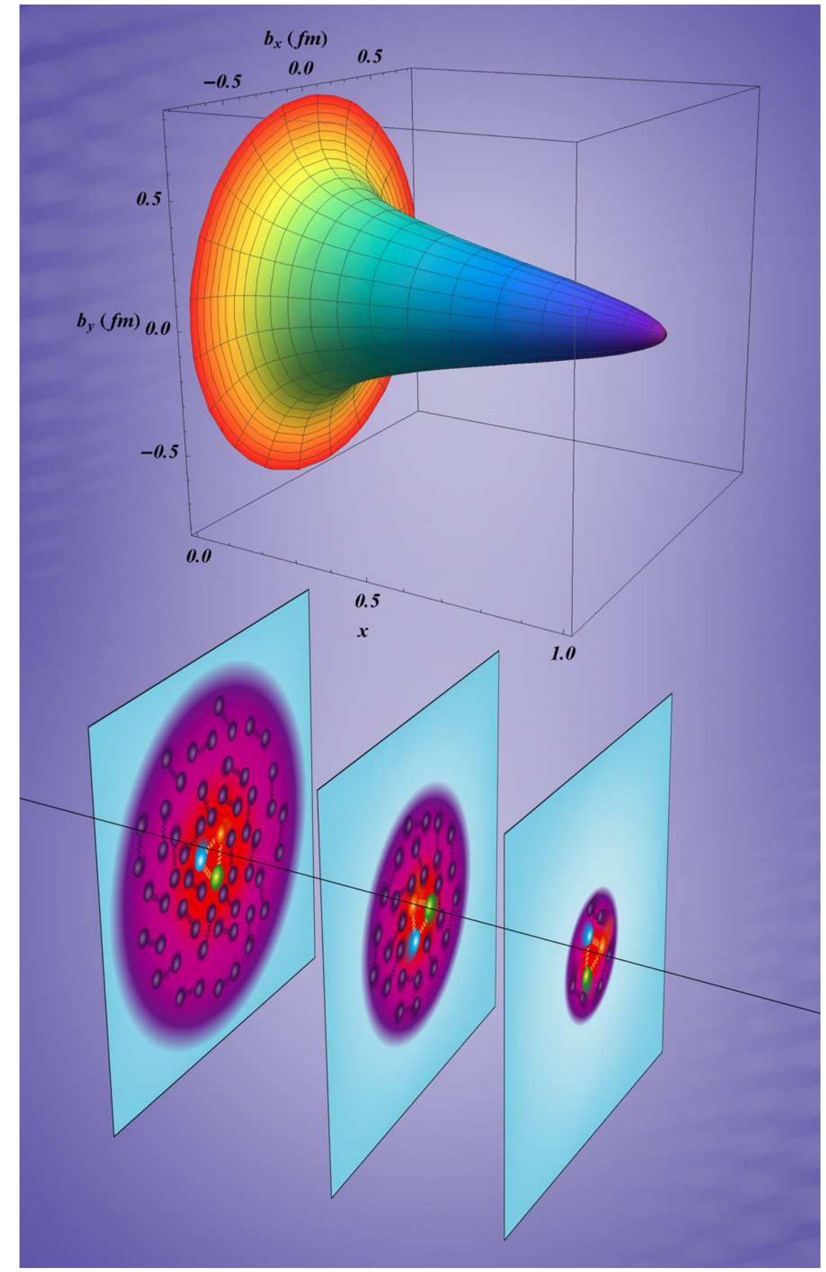
IMPACT PARAMETER DISTRIBUTIONS

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330





COMPASS coll., arXiv:1802.02739



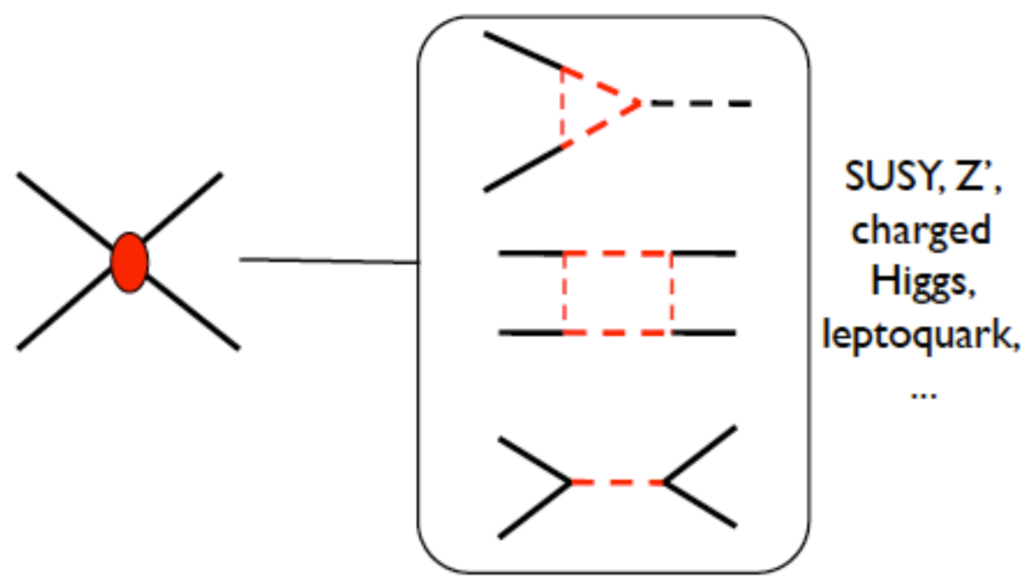
TRANSVERSE SPIN

Tensor charge

$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$

Knowledge of tensor charge is crucial, the only experimental source is transversity function $h_1(x)$

Tensor couplings, not present in the SM Lagrangian, could be the footprints of new physics at higher scales



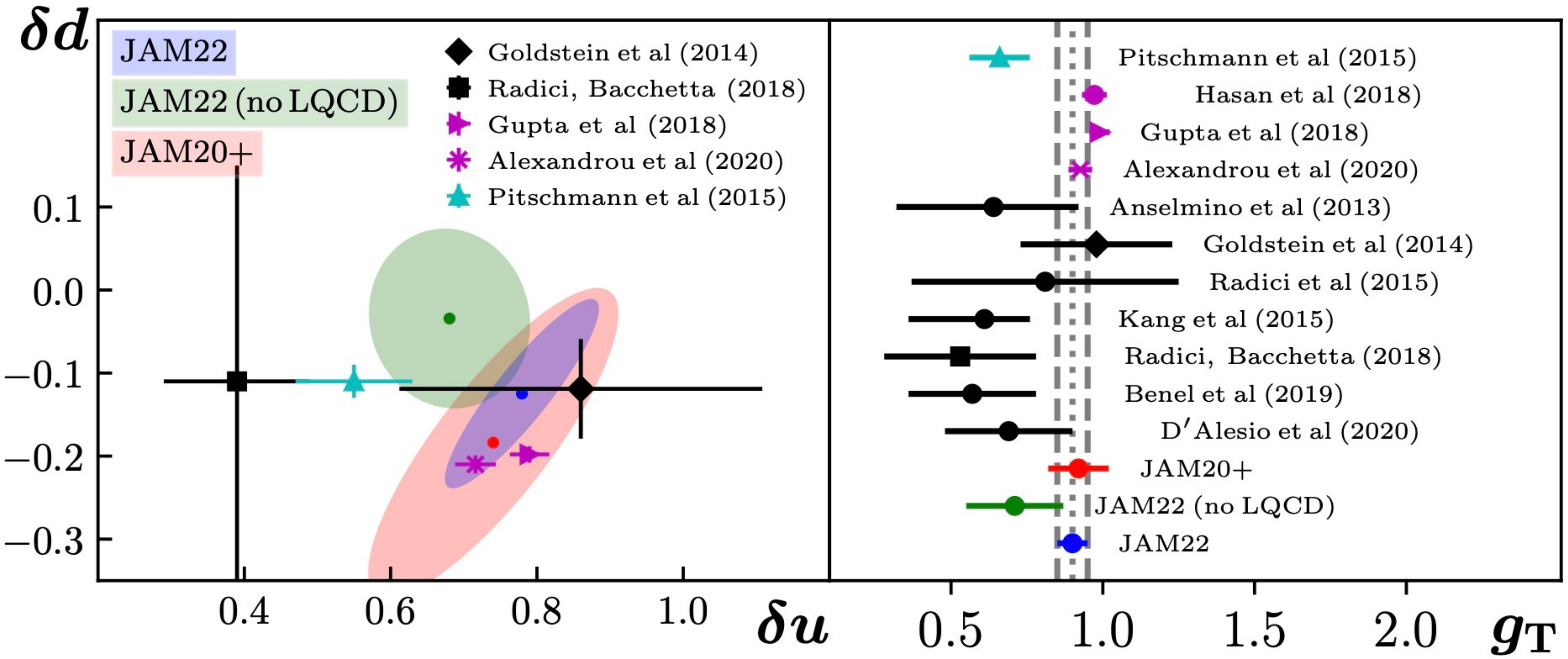
$$\varepsilon_T \, g_T \approx M_W^2 \, / \, M_{BSM}^2$$

Bhattacharya et al, PRD 85 (12)

Pattie et al., P.R. C88 (13)

UNIVERSAL GLOBAL ANALYSIS 2022

JAM22: Gamberg, Malda, Miller, Pitonyak, Prokudin, Sato, Phys.Rev.D 106 (2022) 3, 034014



- Tensor charge from up and down quarks and $g_T = \delta u - \delta d$ are well constrained and compatible with both lattice results and the Soffer bound

δu and δd Q^2=4 GeV^2

δu= 0.74 ± 0.11

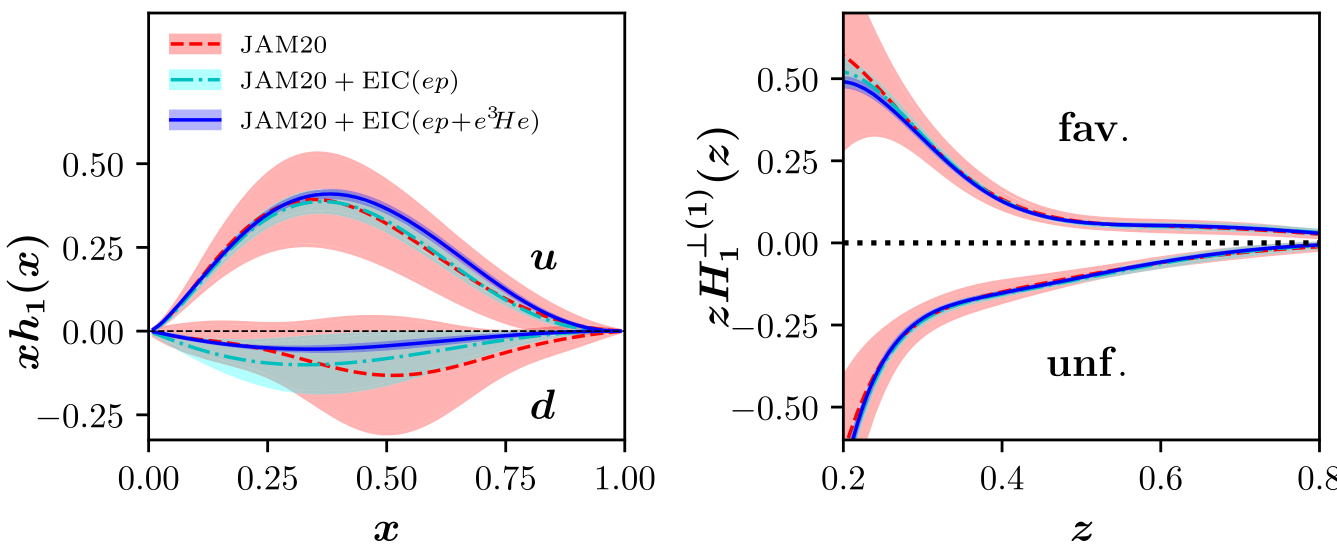
δd= -0.15 ± 0.12

g_T= 0.89 ± 0.06

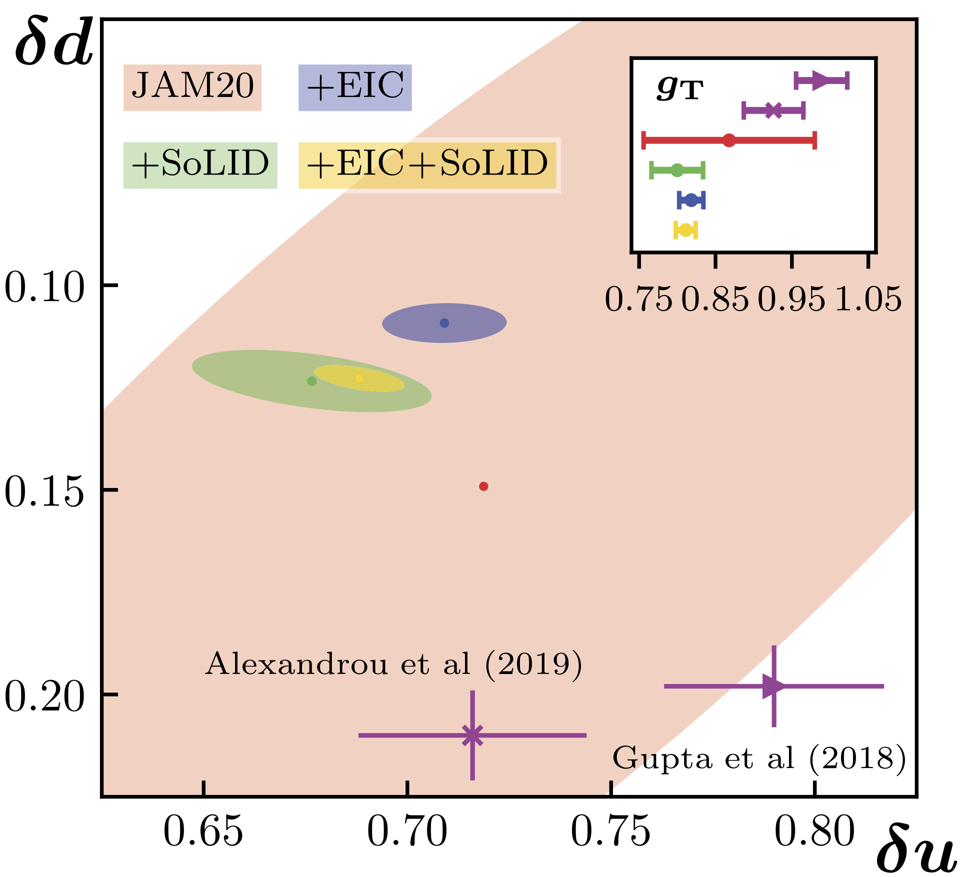
- The tension with diFF method, Radici, Bacchetta (2018) becomes more pronounced: is it due to the data, theory, methodology? Both methods should be scrutinized.

TENSOR CHARGE AT THE EIC AND JLAB

L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato Phys.Lett.B 816 (2021)



JAM20: Cammarota, Gamberg, Kang, Miller,
Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020)



- EIC data will allow to have g_T extraction at the precision at the level of lattice QCD calculations
- JLab 12 data will allow to have complementary information on tensor charge to test the consistency of the extraction and expand the kinematical region

Our journey of discovery is like the voyage of Christopher Columbus

Thank you

Columbus promised to find a new way to China and discovered a new continent!

We promise quite a lot of exciting studies, yet we may be about to discover a new world of QCD! Stay tuned!