THE EXHILARATION OF NUCLEAR SCIENCE TODAY

A ROLLER COASTER IN THE GOOD SENSE

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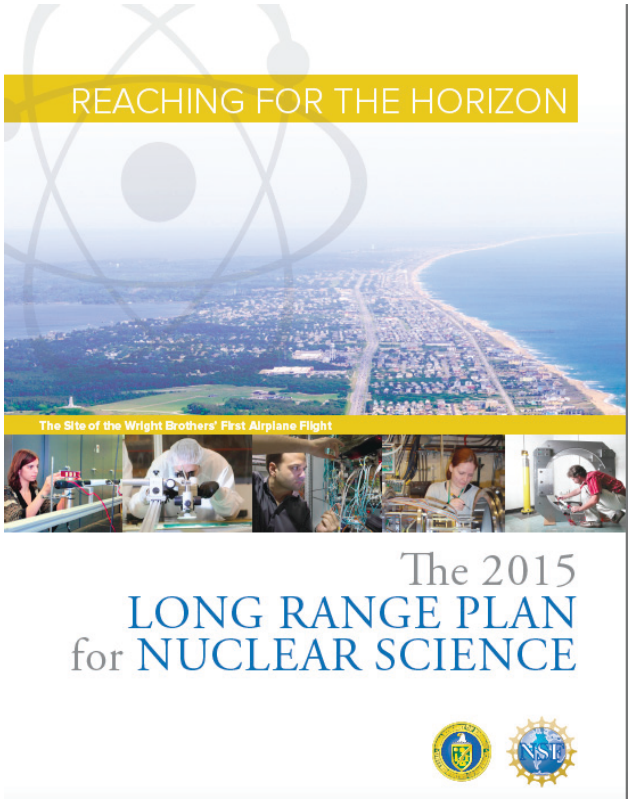
Argonne National Laboratory

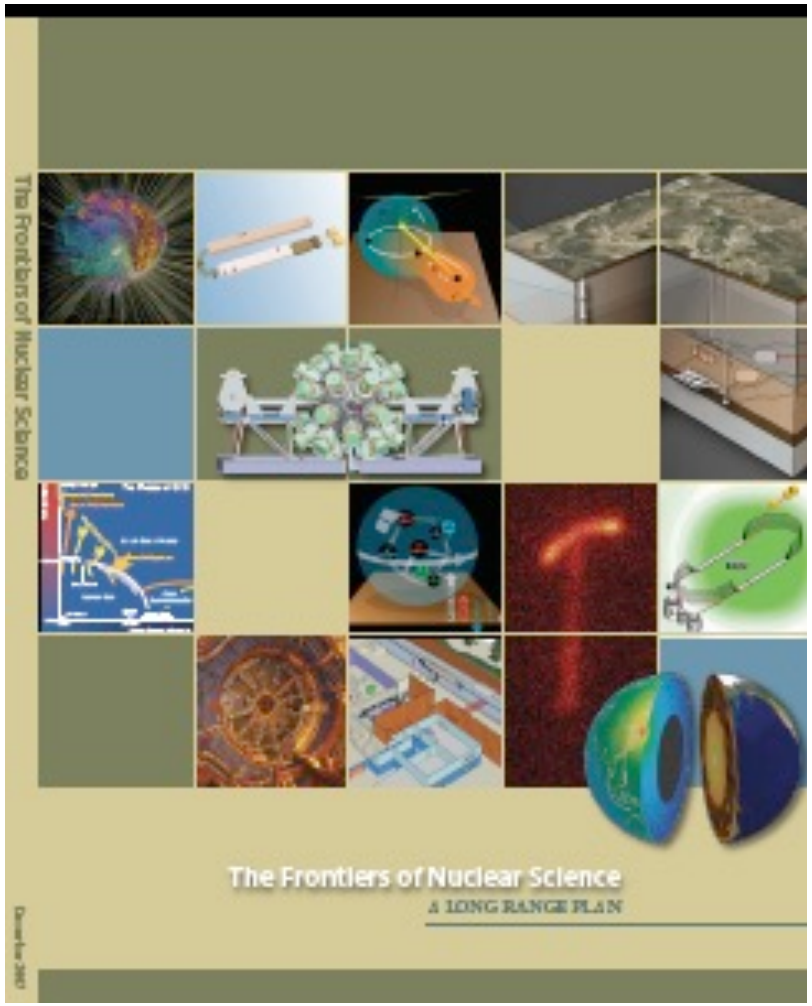
Inaugural Symposium of the Center for Frontiers
In Nuclear Science
November 28, 2018

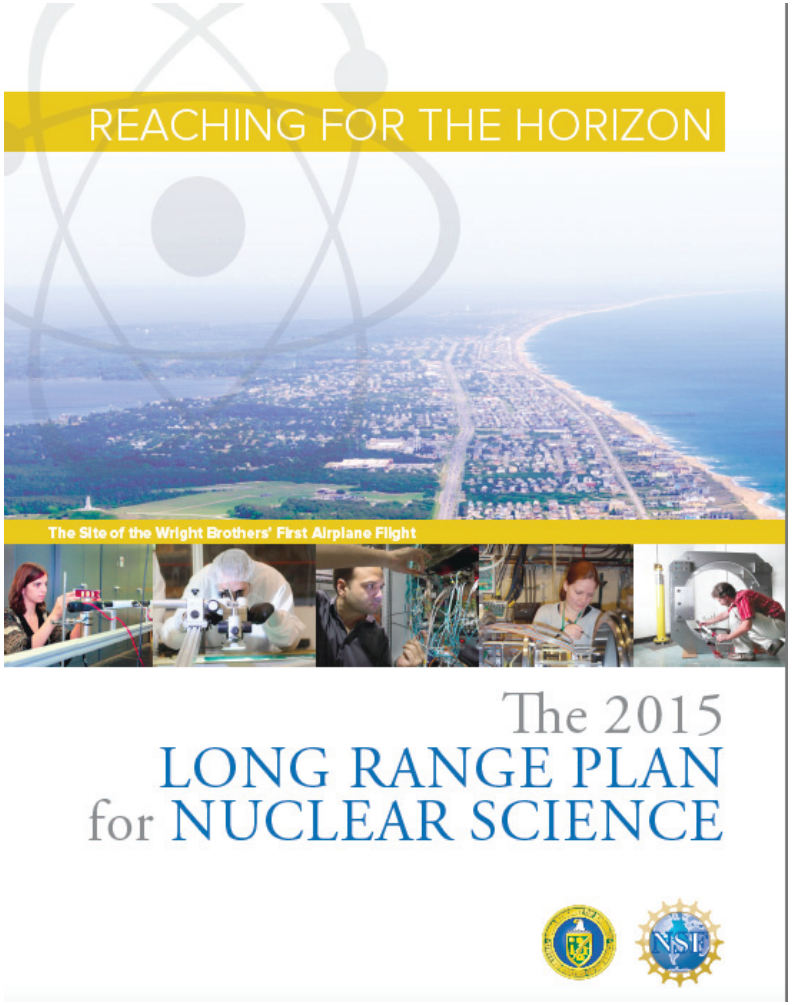
THE 2015 NSAC LONG RANGE PLAN IS OVER 3 YEARS OLD!



- Recommendations
  - Follow the 2007 LRP
  - Lead a ton-scale neutrinoless double beta decay experiment
  - Build an Electron Ion Collider after FRIB construction is compete
  - Increase investment in small and mid scale projects and initiatives
- Initiatives
  - Theory and Theory Computing
  - R&D for the EIC and neutrinoless double beta decay
- Workforce, Education and Outreach

THE 2015 AND THE PREVIOUS LONG RANGE PLANS PROVIDED A SOLID FOUNDATION AND PREPARED US FOR RECENT PROGRESS

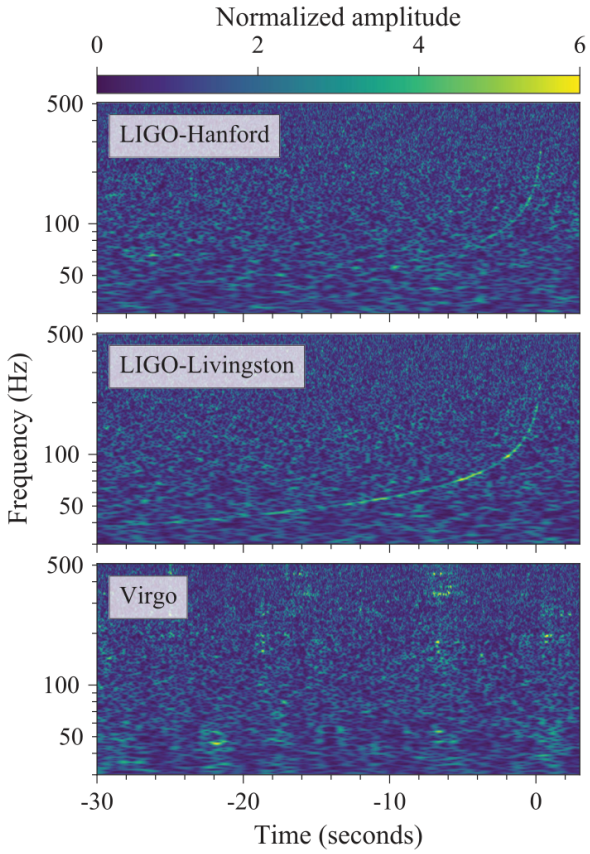




THE ULTIMATE IN MULTI-MESSENGER ASTRONOMY- GW170817 NEUTRON STAR MERGERS

Artist conception of the moment two neutron stars collide.

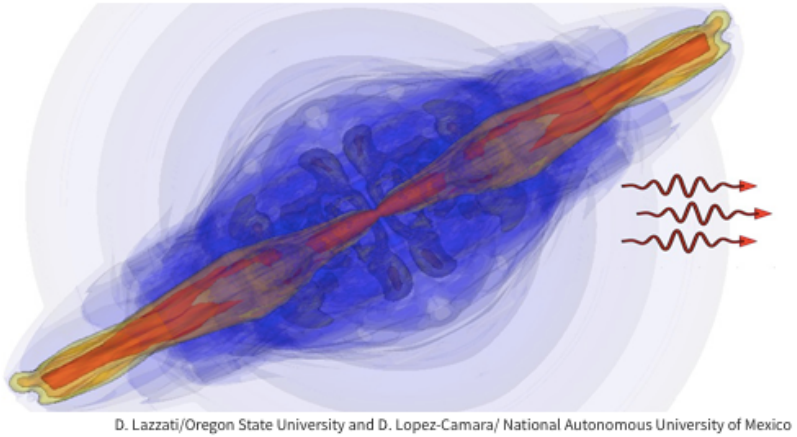
LIGO and VIRGO collaborations



- Confirmed neutron star mergers as a site of the r-process.
- Confirmed neutron star mergers as a source of short gamma-ray bursts.
- Confirmed gravitational waves travel at the speed of light.
- Provided constraints on radii of neutron stars.
- Provided insight into nuclear equation of state.

ONE SURPRIZE OF GW170817 WAS THE AFTERGLOW EMISSIONS INCREASED IN FLUX FOR A FEW MONTHS

Explanation: Structured Jets with Less Energetic Wings. As time passes larger sections of the outflow became visible.



D. Lazzati/Oregon State University and D. Lopez-Camara/ National Autonomous University of Mexico

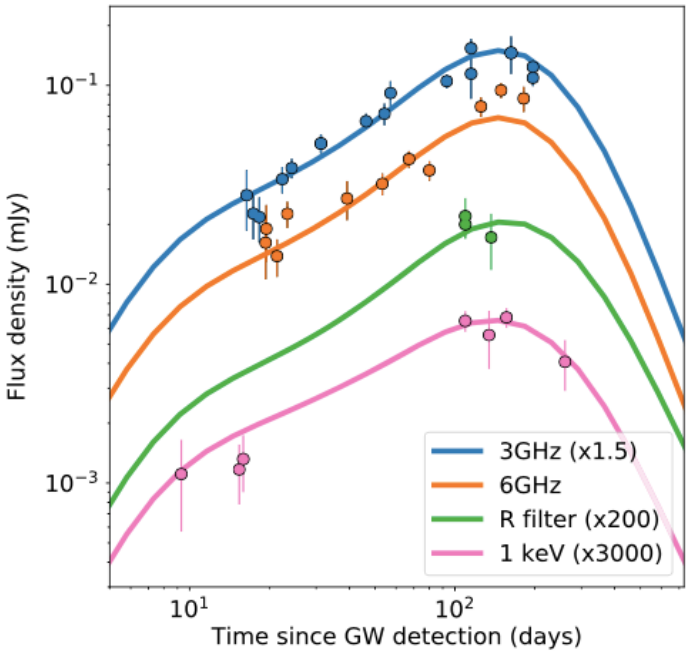


FIG. 2. The radio, optical, and x-ray light curves from a structured jet model are shown in blue (3 GHz), yellow (6 GHz), green (R band), and pink (x rays), respectively. For viewing purposes, all but the 6 GHz curves have been multiplied by a constant (as specified in the legend). Radio and x-ray measurements with uncertainties are shown with filled symbols.

Lazzati et al. PRL 120, 241103 (18)

NEW INSIGHT INTO HEAVY ELEMENT FORMATION MAY COME FROM LIGHT CURVES OF KILONOVA

Zhu et a. ApJL 863 2 (2010)

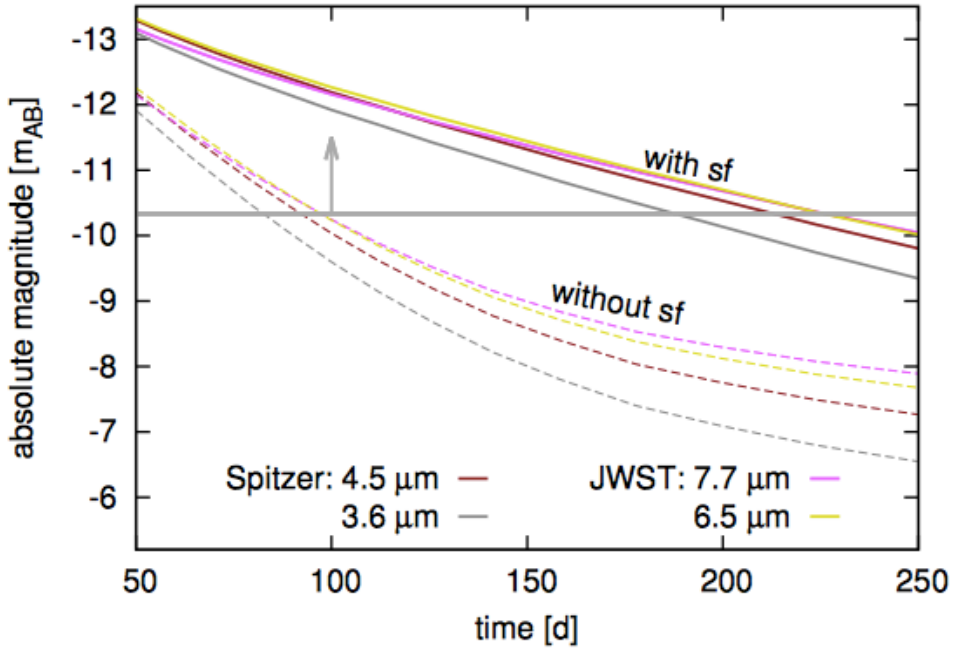


Figure 5. Theoretical predictions for mid-IR light curves with (solid) and without (dashed) spontaneous fission and ^{254}Cf contribution. The gray horizontal line indicates JWST sensitivity threshold for mergers at 200 Mpc, assuming 10 ks exposure (https://jwst-docs.stsci.edu/display/JTI/MIRI+Sensitivity).

While supernova light curves are dominated by ^{56}Ni decay chain, light curves of neutron star mergers may be powered by r-process radioactivity.

^{254}Ca ($t_{1/2}$=60.5 days) and its fission daughters are likely to dominate nuclear heating at ~15 to 250 day times scales.

Argonne NATIONAL LABORATORY

2018 NATIONAL ACADEMY STUDY OF ELECTRON-ION COLLIDER SCIENCE

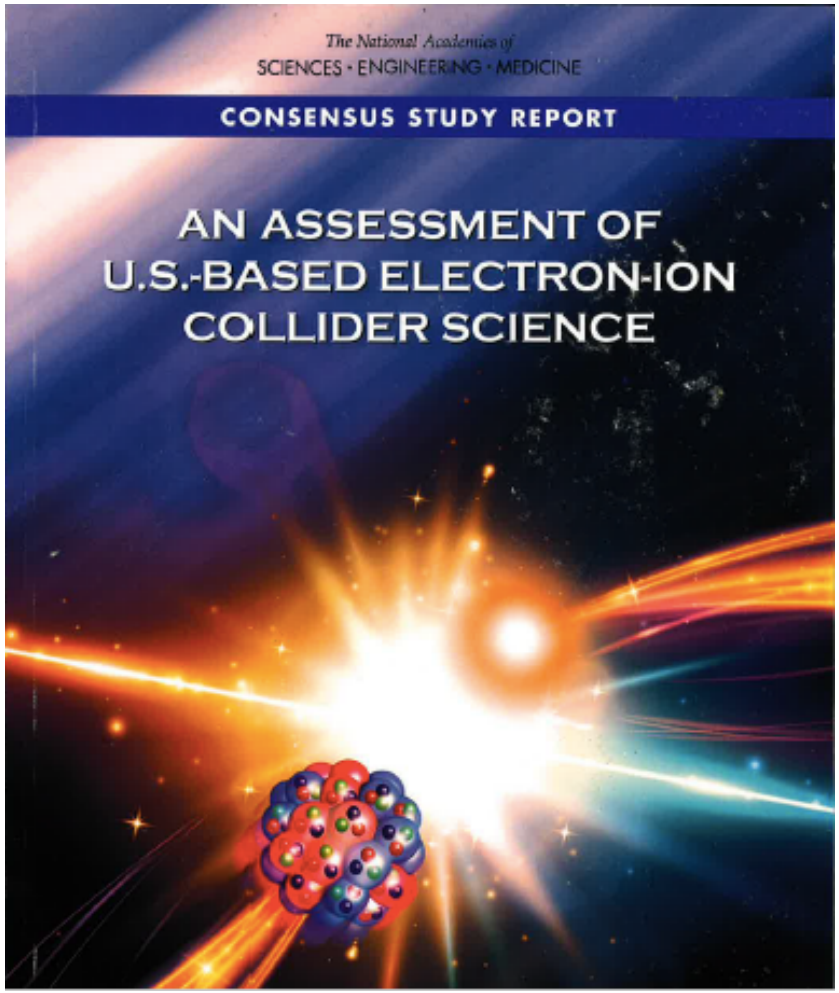
Findings

An EIC can uniquely address three profound questions about nucleons … and how they are assembled to form the nuclei of atoms

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons

These questions can be answered by an EIC…

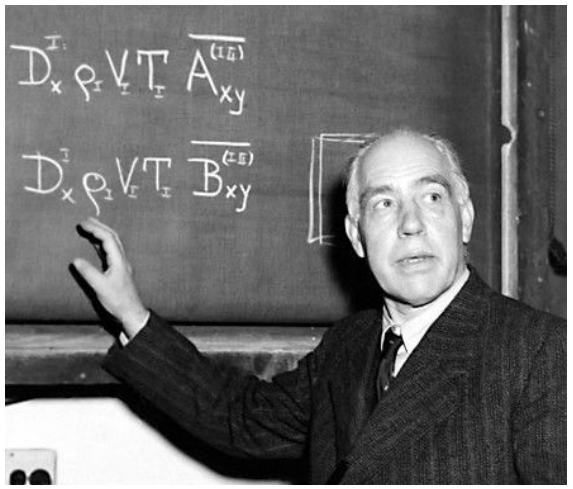
An EIC would maintain U.S. leadership in accelerator science and technology of colliders and help to maintain scientific leadership more broadly



THE FUTURE

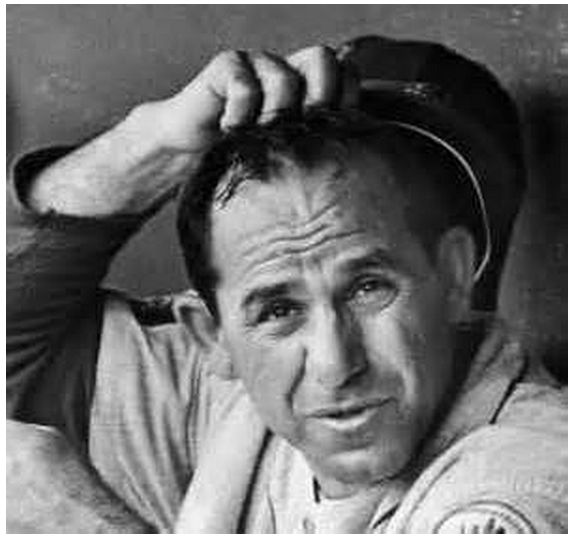
"Prediction is very difficult, especially if it's about the future."

Neils Bohr



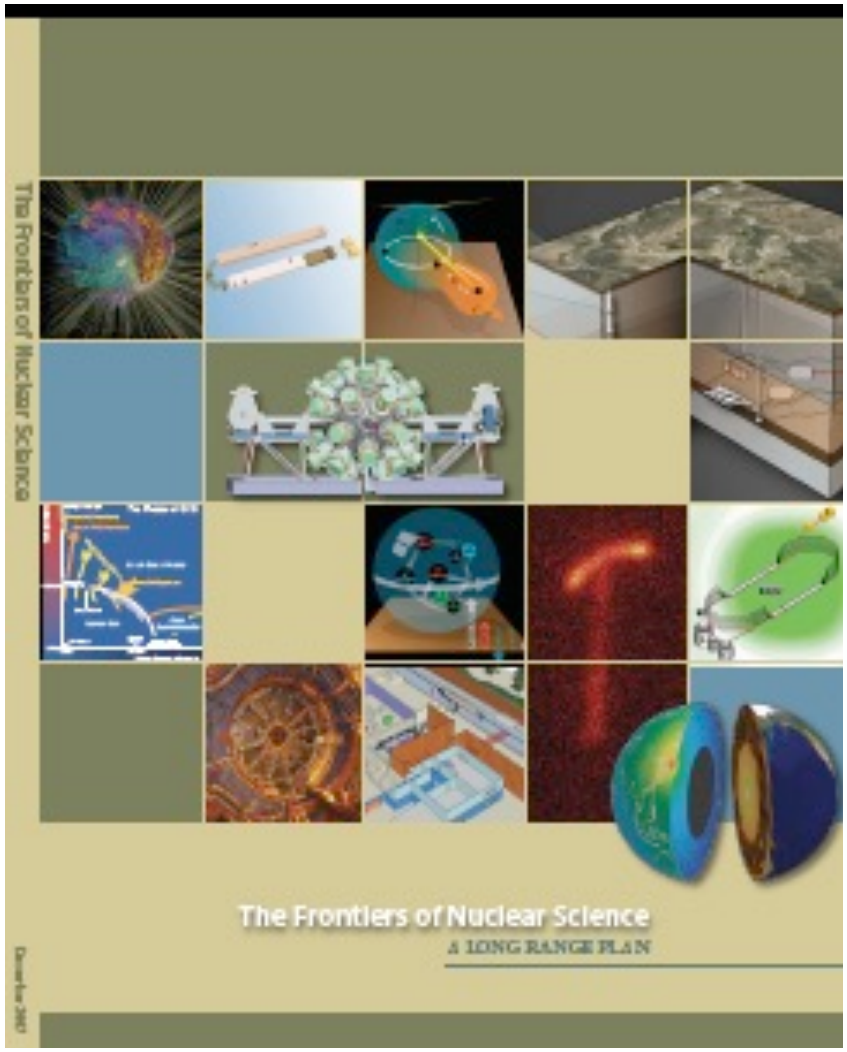
"It's tough to make predictions, especially about the future."

Yogi Berra



CAVEATS

- Let me start with where we were 10 years ago.
- Then what we might expect in a decade.



RECOMMENDATIONS OF THE 2007 LONG RANGE PLAN

- Complete JLAB 12 GeV - complete, taking first data
- Build FRIB - well underway
- Targeted program in fundamental symmetries
  - underway

  "Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative"

- Upgrade RHIC - completed at 1/7 the anticipated cost

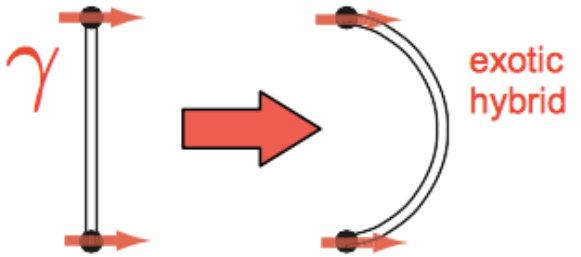
- Resources for R&D for EIC – small steps forward

- Initiatives in theory, gamma-ray tracking and Accelerator R&D
  - major progress, theory topical collaborations, GRETINA

THINGS ALMOST ALWAYS MOVE MORE SLOWLY THAN WE HOPE – HADRONIC PHYSICS

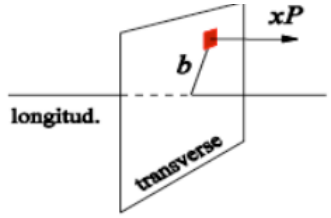
- We expected to have several years of GLUEX data in hand!

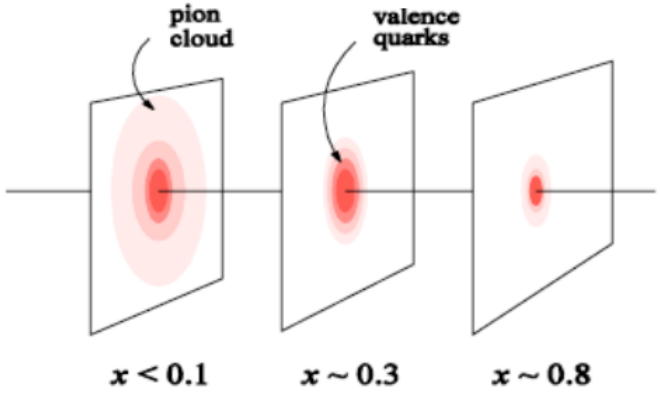
  But we have seen interesting states in the heavy quark sector X,Y, Z. GLUEX is now taking great data.



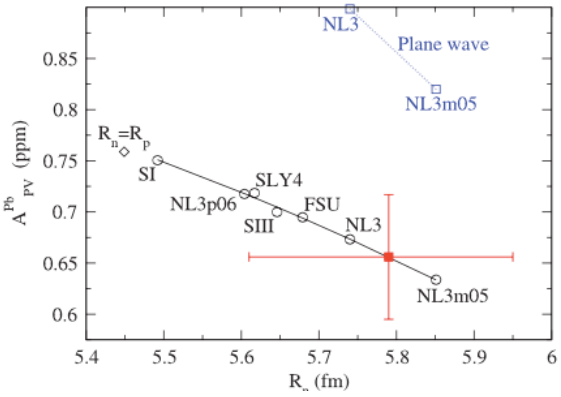
- We expected to have valence generalized parton distributions well measured.

Fourier transform of t-dependence





- We expected that the neutron radius of Pb and ^{48}Ca would be well measured.



PRL 108, 112502

This will all happen soon!

Tritium – ^{3}He comparison being analyzed

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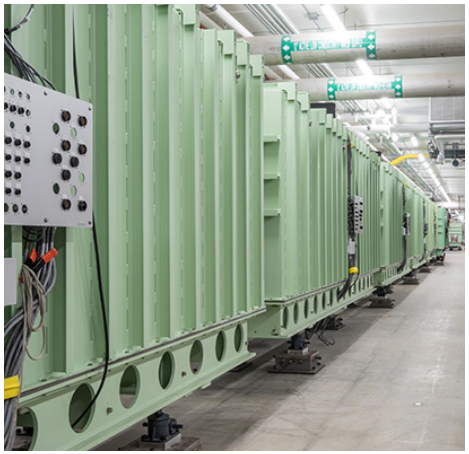
THINGS ALWAYS MOVE MORE SLOWLY THAN WE HOPE – NUCLEAR STRUCTURE AND ASTROPHYSICS

- FRIB on course for 2021 completion.
- FAIR on course for 2025 completion.

All cyromodules under construction.
At least three are cooled down



On the other hand we have unexpected insights

- **Link between SR correlations and EMC effect**
- **Part of proton spin carried by glue**
- **Gravitational waves**
- **Fluctuations in initial state preserved in RHI collisions**

CLOSE RELATION BETWEEN THE EMC EFFECT AND SHORT RANGE CORRELATIONS

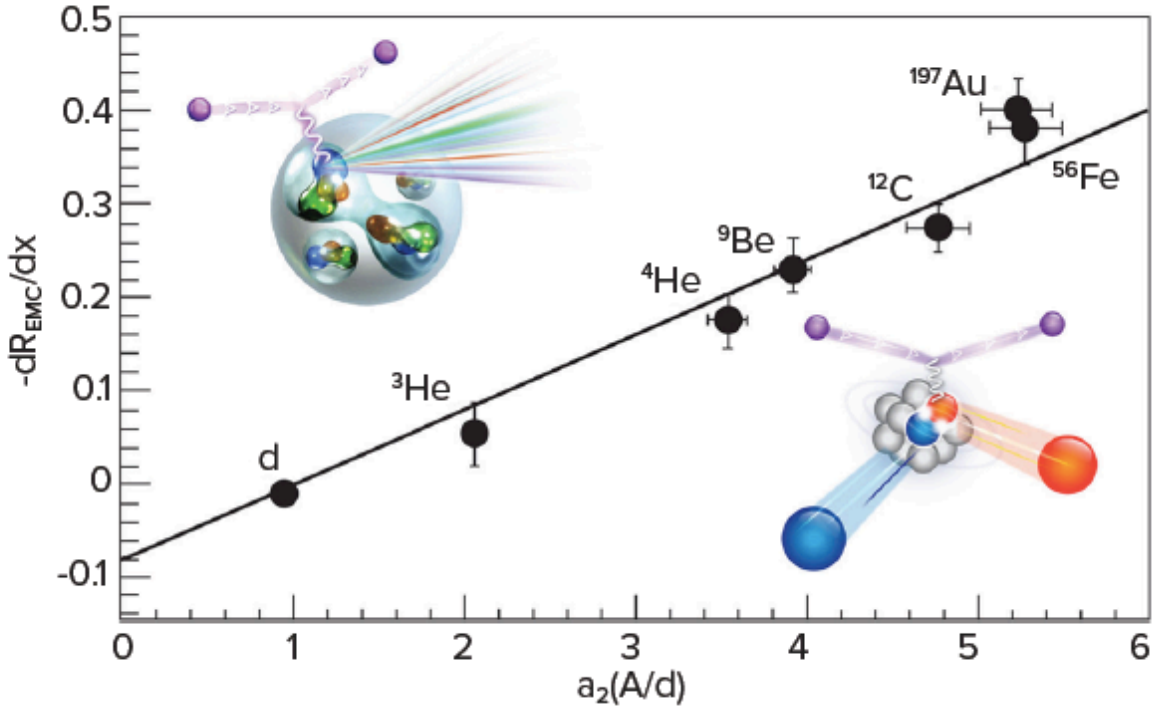
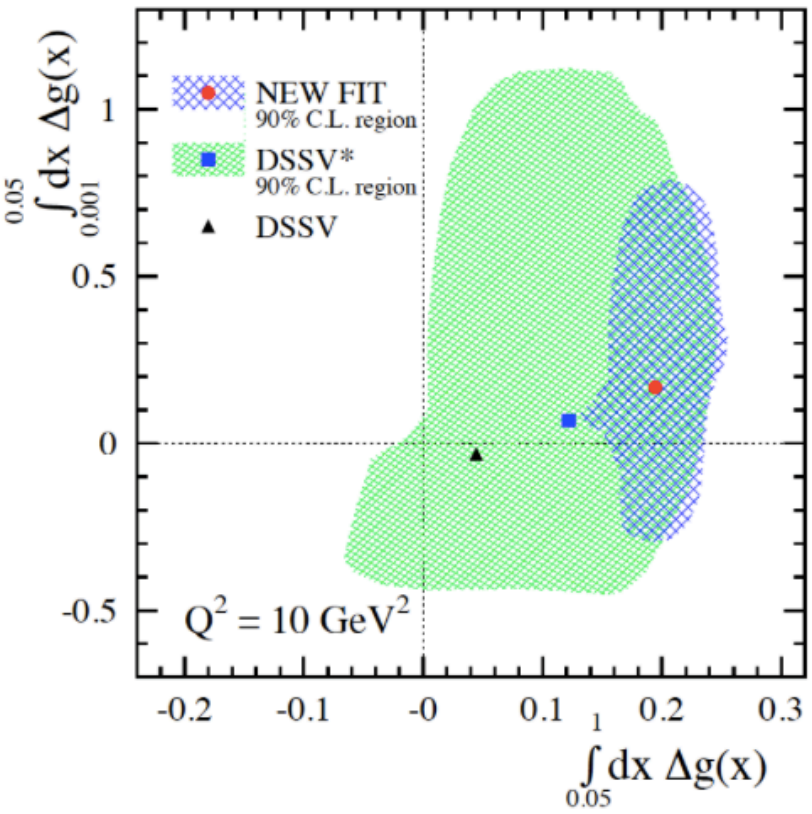
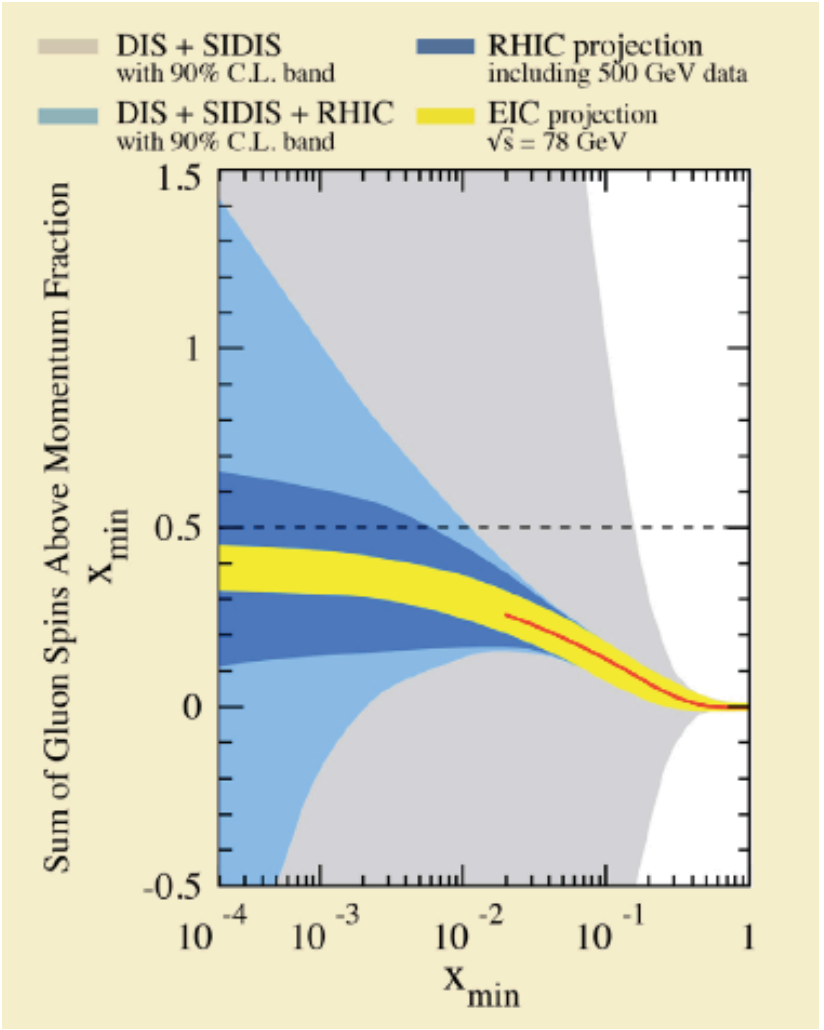


Figure 2.8: *This plot illustrates, for a sample of eight nuclei, the apparent linear relationship between a parameter that characterizes the number of two-nucleon correlated pairs, $a_2(A/d)$, and the strength (i.e., the slope) of the EMC effect. A clear correlation is evidenced by the straight line that all eight nuclei fall on.*

GLUE DOES CARRY SPIN!

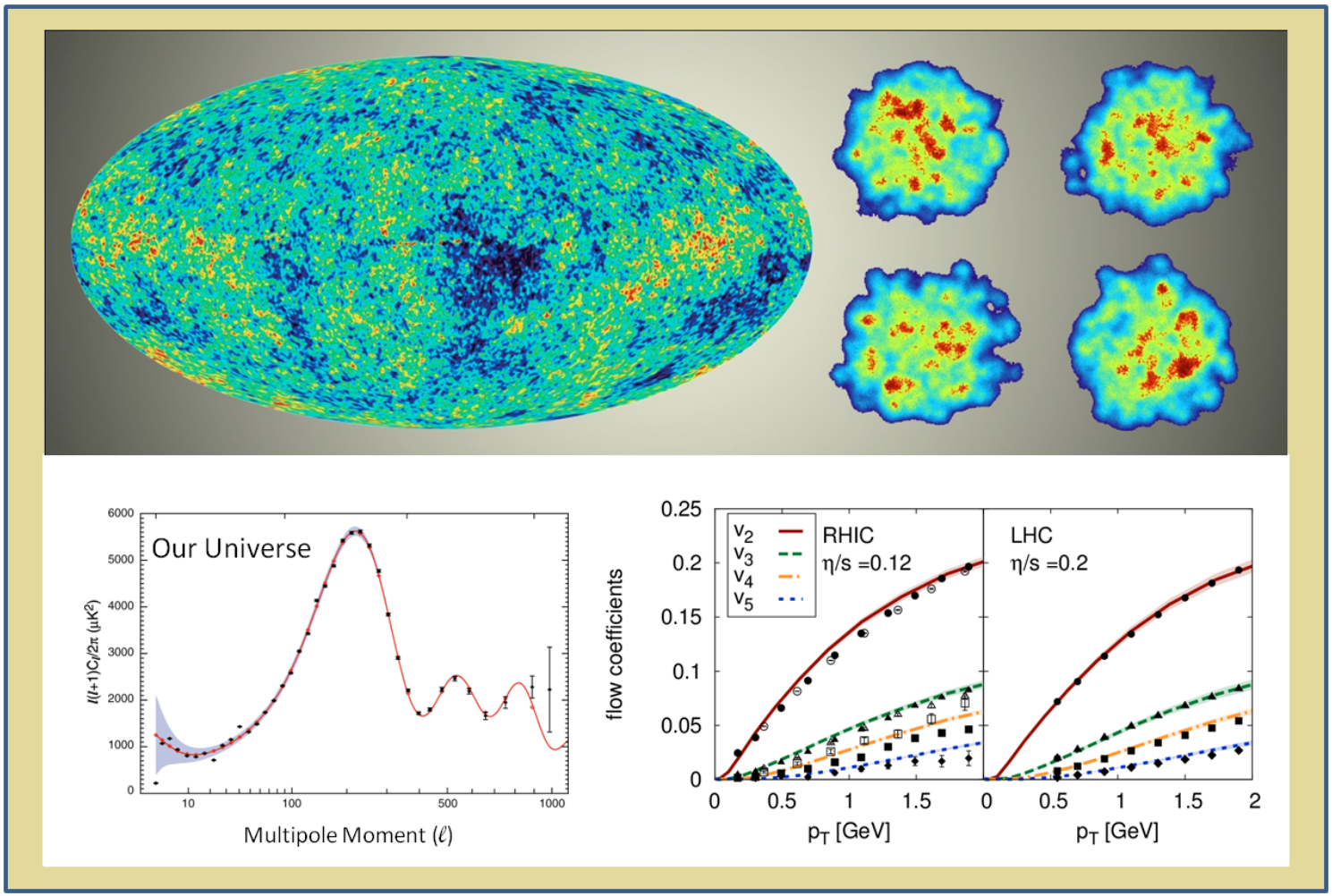


Lattice $S_G = 0.251(47)(16)$
PRL **118**, 102001



We need an EIC!

RHIC AND THE LHC: THE BIG BANG VS LOTS OF LITTLE BANGS



In both cases the measurements at later time reveal the fluctuations in the initial conditions which are remarkably preserved during the expansion.

NEUTRINOS

- We expected to understand whether the LSND indication of sterile neutrinos was real. This remains a cloudy issue.

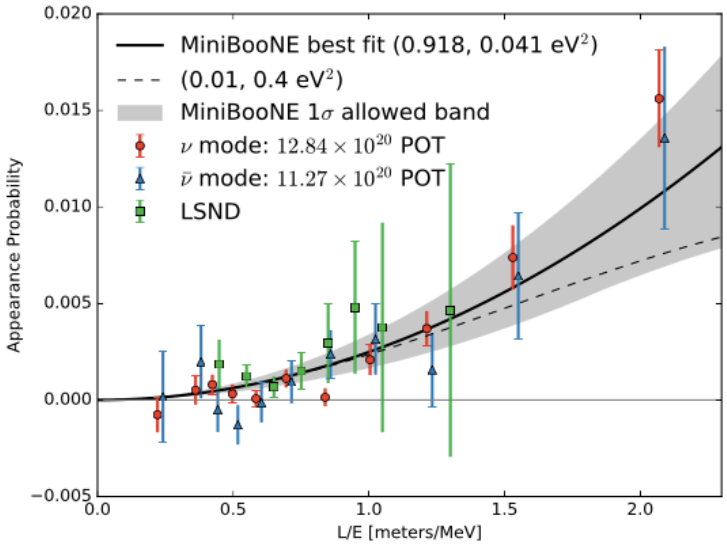


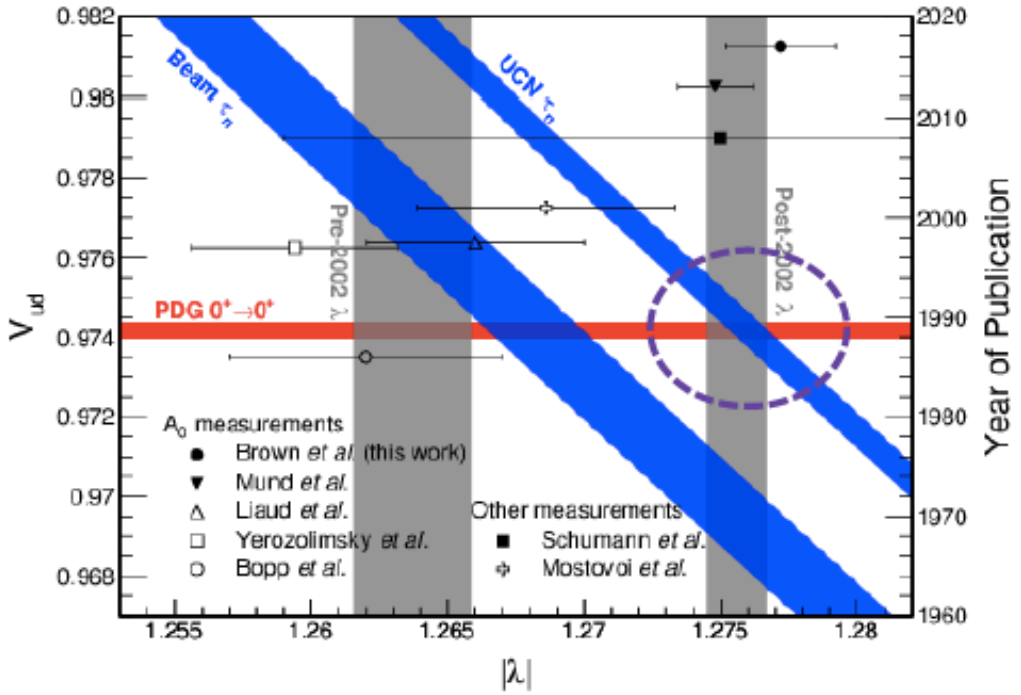
FIG. 5: A comparison between the L/E_ν^{QE} distributions for the MiniBooNE data excesses in neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) to the L/E distribution from LSND [1]. The error bars show statistical uncertainties only. The curves show fits to the MiniBooNE data, assuming two-neutrino oscillations, while the shaded area is the MiniBooNE 1σ allowed band. The best-fit curve uses the reconstructed neutrino energy, E_ν^{QE}, for the MiniBooNE data. The dashed curve shows the example 1σ fit point.

arXiv:1805.1202v2

- We found that Θ_{13} was large, making a measurement of CP violation in the neutrino sector feasible. Current hints from T2K and NOVA (1-2 σ) that CP is not conserved and the hierarchy is normal (T2K, NOVA and Cosmology). Lots of discussion of the influence of “priors” (i.e. arXiv:1703.0458)

Neutron beta decay updates developing consistent picture with SM … except "beam" n lifetime result

- New UCNtau lifetime (last year)
- New UCNA asymmetry: $A_0 = -0.12015(34)_{stat}(63)_{syst}$ (0.56%)



Outlier is in-flight n lifetime

Slide stolen from David Hertzog

THE BARYON ASYMMETRY OF THE UNIVERSE

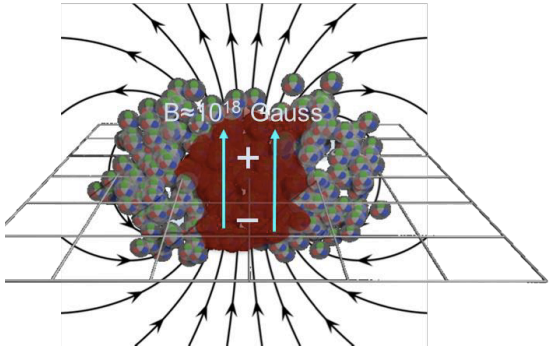
- Neutrinoless Double Beta Decay
  Heavy right handed neutrinos, the see-saw mechanism and leptogenesis

- Electric Dipole moments
  Neutrons and Nuclei provide insight into T violating interactions among quarks and gluons

- Chiral magnetic effects
  Do RHI collisions provide a signal for a new path to baryogenesis?

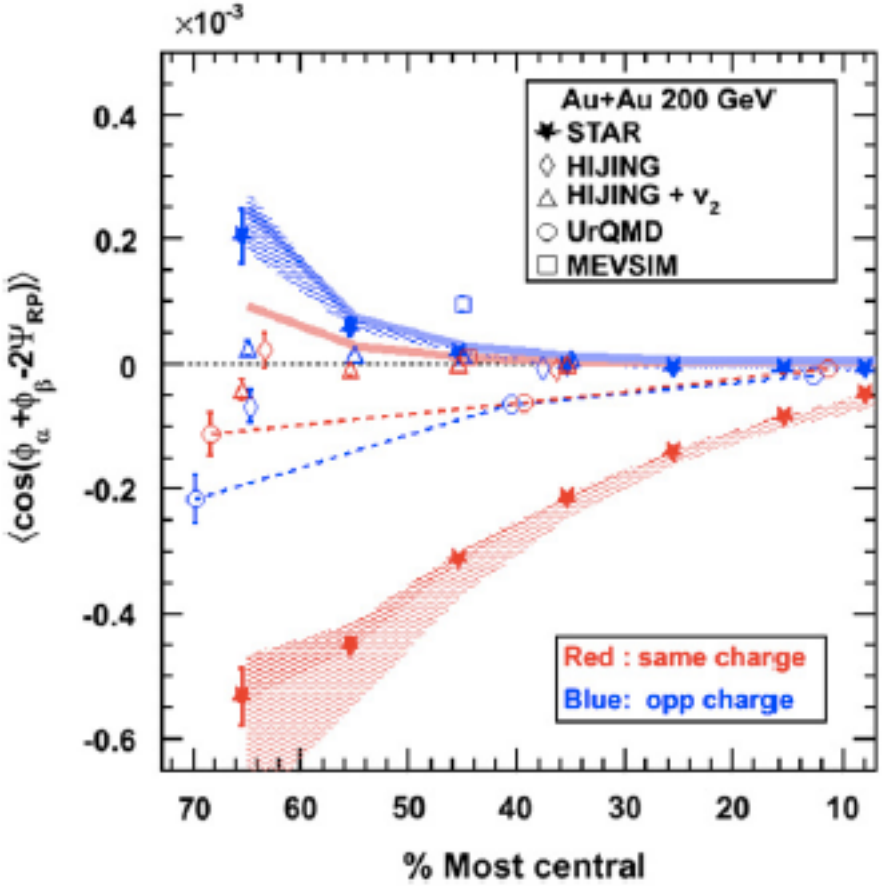
WILL THE COLOR MAGNETIC EFFECT IN RELATIVISTIC HEAVY ION COLLISIONS PROVIDE INSIGHT INTO THE BARYON ASYMMETRY OF THE UNIVERSE?

electric charge separation

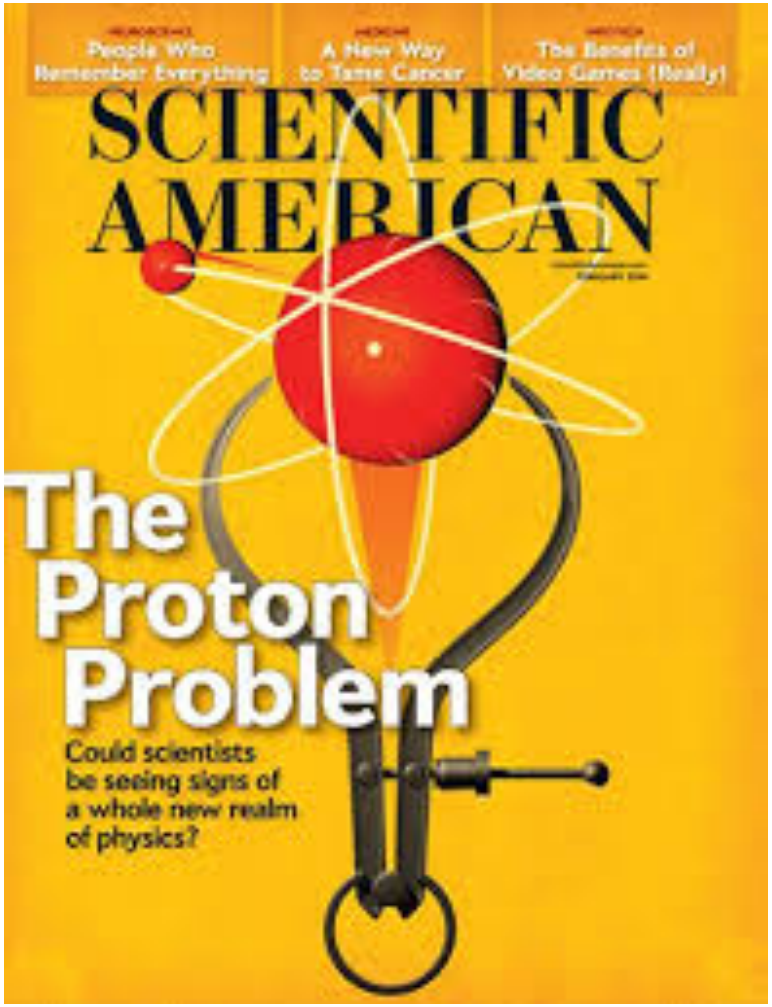


2018 ^{96}Zr+^{96}Zr vs ^{96}Ru+^{96}Ru. Can one measure the charge dependence?

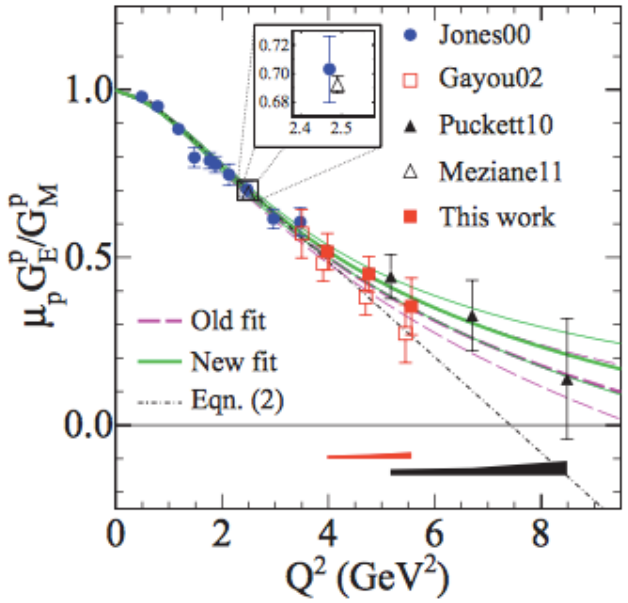
Chiral magnetic effect generates helical hypermagnetic fields which lead to baryon asymmetry.



WE DID NOT EXPECT A PROTON RADIUS PROBLEM



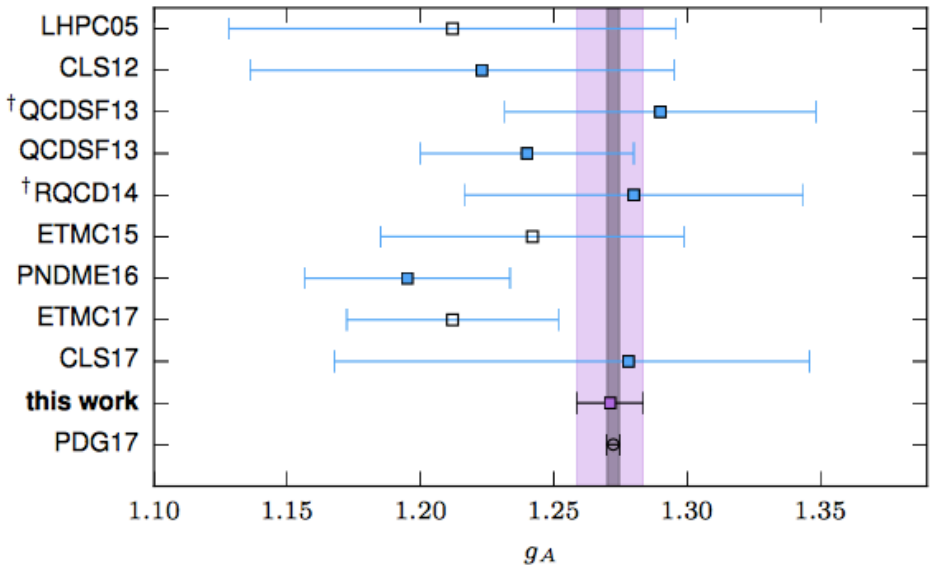
Perhaps this is reminiscence that no one expected a large difference between the electric and magnetic form factors of the proton two decades ago.



WE HAVE LEARNED OVER AND OVER YOU HAVE TO DO THE MANY BODY PHYSICS RIGHT!

- Nuclear Structure
  - Apparent quenching of G_A in beta decay
  - Short range correlations

- QCD
  - We are now doing lattice calculations with physical pion masses, and disconnected diagrams and getting benchmark parameters nearly right.
  - New approach to parton distributions



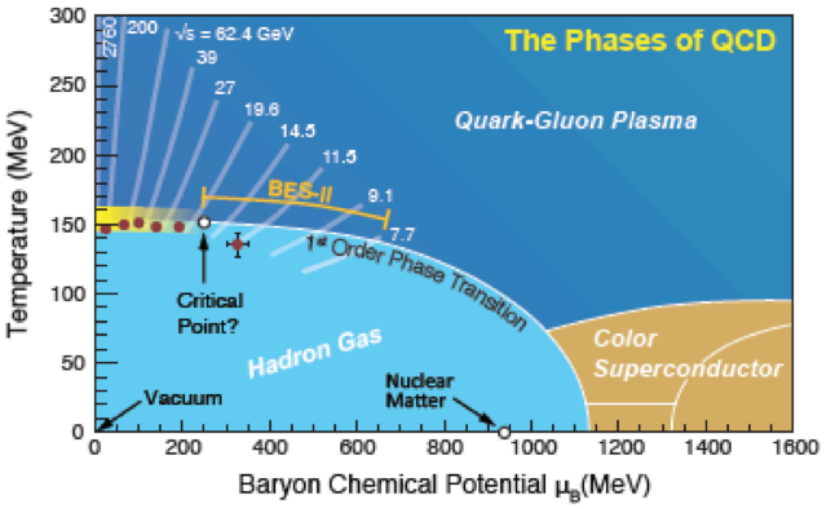
Chang et al. Nature 557, 91 (18)

This was hard for the lattice because it involves long range pion contributions.

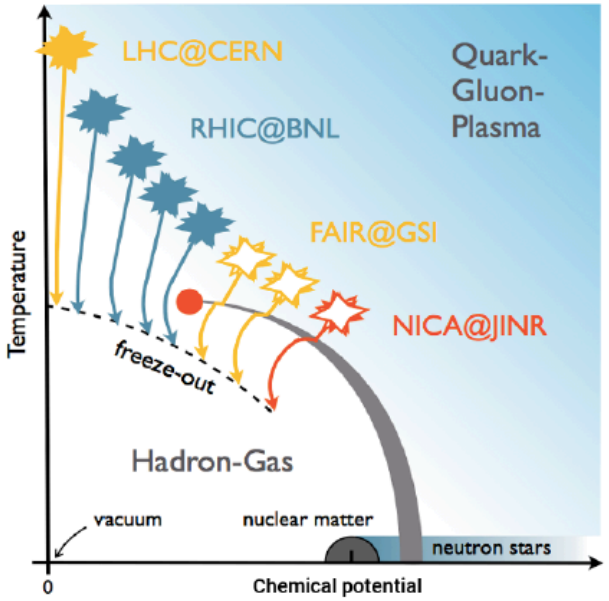
I SHOULD BE WEARING A BIG FURRY HAT WHILE DOING THIS.

PREDICTIONS FOR TWO YEARS FROM NOW- QCD CRITICAL POINT

We will have found the QCD critical point, or learned enough to know that nature has been unkind in allowing us to prepare systems to test it.



US version



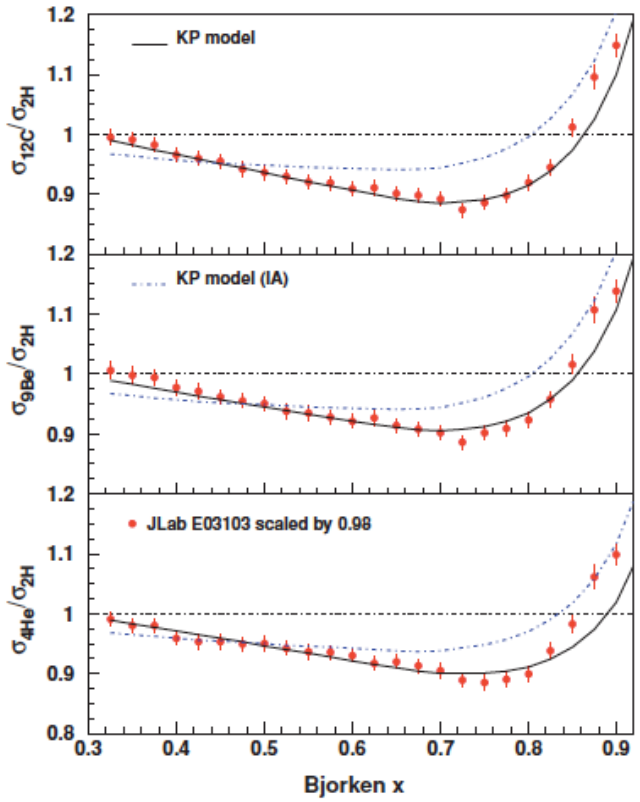
NUPECC version

IN MOST CASES, IT WILL BE JOINT PROGRESS BETWEEN THEORY AND EXPERIMENT THAT MOVES US FORWARD, NOT IN ONE SIDE ALONE

Does the structure of the proton and the forces between nucleons change in nuclear matter (beyond n-body force effects)?

This has been an active subject since the dawn of the EMC effect. The problem is we have just had “toy” models that fit systematics for one observable but gave us little insight into others.

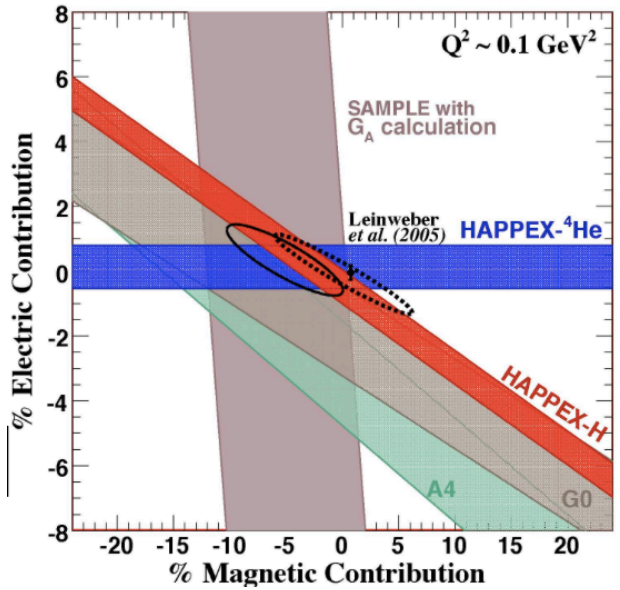
In ten years I expect lattice QCD calculations of nuclei to be able to properly ask this question and tell us what measurements will confirm it. I think we will have the measurements in hand.



I THINK WE ARE ABOUT TO ENTER A PARADIGM SHIFT IN QCD – REAL PREDICTIONS

So far, what quantitative prediction for experimental observables have been made by lattice QCD and confirmed by experiment?

I can think of one example, the **strange form factors of the proton**, where later dynamical simulations confirmed earlier quenched results.



Wide range of predictions for resonances that have not been yet found.

We are beginning to get calculations like spin carried by glue.

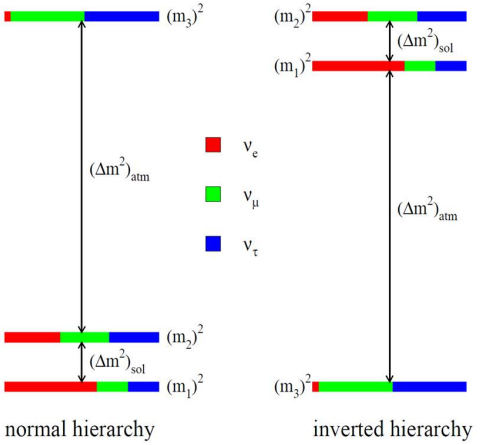
The key tests may be in the quark orbital angular momentum sector and sea quark observables.

The later require treating disconnected diagrams, and that is now happening.

PREDICTIONS FOR A DECADE FROM NOW- WE WILL KNOW WHERE THE HEAVY ELEMENTS ARE PRODUCED

- FRIB will measure enough neutron-rich masses and beta decays to limit the nuclear structure input. Modern measurements are showing weaknesses in the extrapolations
- LIGO will give us the rate of neutron star mergers and the light curves will tell us a lot
- The Core Collapse Supernova simulations will robustly detonate
- We may not completely understand fission recycling

PREDICTIONS FOR A DECADE FROM NOW- NEUTRINOS

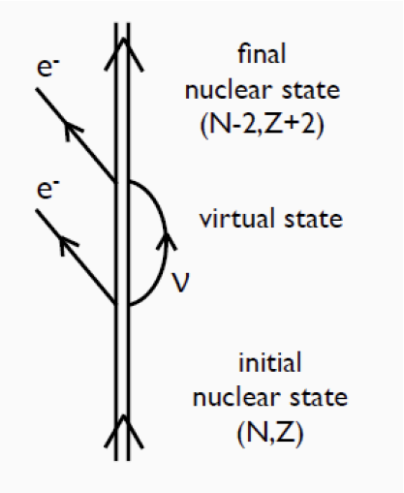


- We will know the neutrino hierarchy from direct oscillation measurements
- We are unlikely to be lucky enough to have a direct mass measurement
- I am willing to bet that the cosmological constraints are more sensitive to the physics assumptions than are usually presented.
- We will know if short baseline oscillations are real!

PREDICTIONS FOR A DECADE FROM NOW-

- We will understand nuclear structure well enough to predict neutrinoless double beta decay to the ~30% level
  - Realistic structure calculations
  - A theoretical understanding of whether G_A is quenched in neutrinoless double beta decay as it appears to be in two-neutrino DBD.
- Will we have seen neutrinoless double beta decay?

  That depends on nature.



GERDA, for example, is background free at the count/keV/ton/year. We probably need 2 more orders of magnitude reduction.

SINGLE ION BARIUM SENSITIVITY

PHYSICAL REVIEW LETTERS **120,** 132504 (2018)

Editors' Suggestion | Featured in Physics

Demonstration of Single-Barium-Ion Sensitivity for Neutrinoless Double-Beta Decay Using Single-Molecule Fluorescence Imaging

A. D. McDonald,[1,†] B. J. P. Jones,[1,‡] D. R. Nygren,[1,§] C. Adams,[2] V. Álvarez,[3] C. D. R. Azevedo,[4] J. M. Benlloch-Rodríguez,[3] F. I. G. M. Borges,[5] A. Botas,[3] S. Cárcel,[3] J. V. Carrión,[3] S. Cebrián,[6] C. A. N. Conde,[5] J. Díaz,[3] M. Diesburg,[7] J. Escada,[5] R. Esteve,[8] R. Felkai,[3] L. M. P. Fernandes,[9] P. Ferrario,[3] A. L. Ferreira,[4] E. D. C. Freitas,[9] A. Goldschmidt,[10] J. J. Gómez-Cadenas,[3,§] D. González-Díaz,[11] R. M. Gutiérrez,[12] R. Guenette,[2] K. Hafidi,[13] J. Hauptman,[14] C. A. O. Henriques,[9] A. I. Hernandez,[12] J. A. Hernando Morata,[11] V. Herrero,[8] S. Johnston,[15] L. Labarga,[16] A. Laing,[3] P. Lebrun,[7] I. Liubarsky,[3] N. López-March,[1,3] M. Losada,[12] J. Martín-Albo,[2] G. Martínez-Lema,[11] A. Martínez,[3] F. Monrabal,[1] C. M. B. Monteiro,[9] F. J. Mora,[8] L. M. Moutinho,[4] J. Muñoz Vidal,[3] M. Musti,[3] M. Nebot-Guinot,[3] P. Novella,[3] B. Palmeiro,[3] A. Para,[7] J. Pérez,[3] M. Querol,[8] J. Repond,[15] J. Renner,[3] S. Riordan,[15] L. Ripoll,[17] J. Rodríguez,[3] L. Rogers,[1] F. P. Santos,[5] J. M. F. dos Santos,[9] A. Simón,[3] C. Sofka,[3,‖] M. Sorel,[3] T. Stiegler,[18] J. F. Toledo,[8] J. Torrent,[3] Z. Tsamalaidze,[19] J. F. C. A. Veloso,[4] R. Webb,[18] J. T. White,[18,*] and N. Yahlali[3]

(NEXT Collaboration)

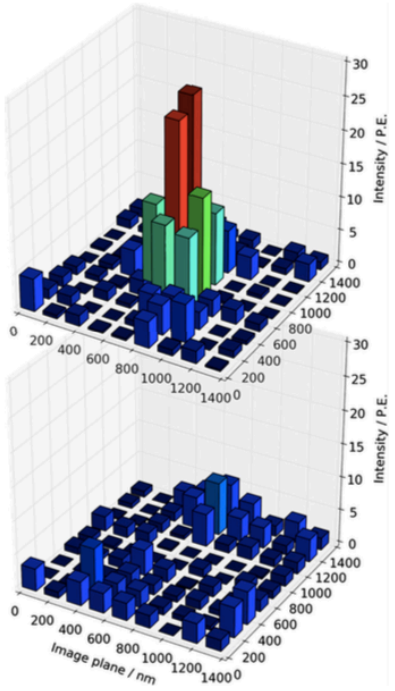


FIG. 1. A single Ba^{++} candidate. A fixed region of the CCD camera is shown with a 0.5 s exposure before (top) and after (bottom) the photobleaching transition.

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PREDICTIONS FOR A DECADE FROM NOW WE WILL NOT UNDERSTAND THE SATURATION OF THE GLUE OR HAVE MEASURED KEY ELEMENTS OF THE DYNAMICS OF THE GLUE

WE WILL BE BUILDING THE ELECTRON ION COLLIDER TO FIND OUT!

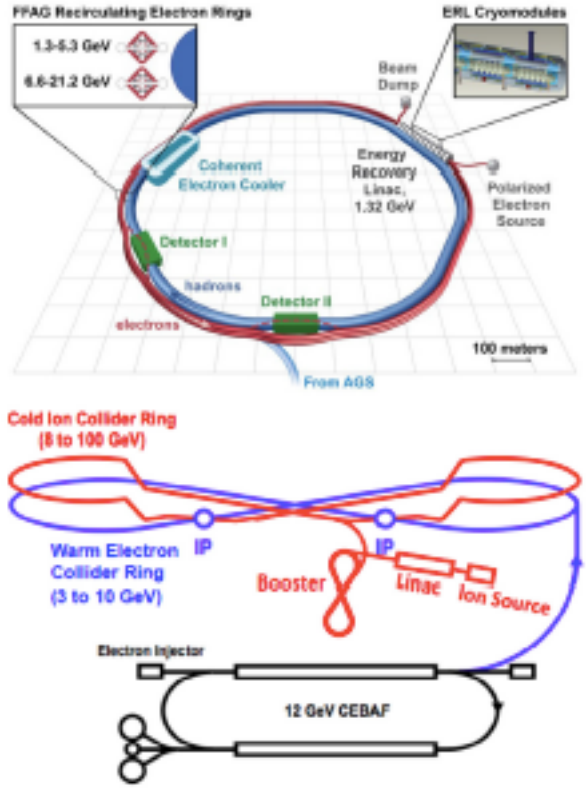


Figure 7.1: Top: The schematic of eRHIC at BNL, which would require construction of an electron beam facility (red) to collide with the RHIC blue beam at up to three interaction points. Bottom: The schematic layout of MEIC at JLab includes the 12-GEV CEBAF and would require construction of an ion linac, an ion collider ring (red), and an electron collider ring (blue) for collisions at two interaction points.

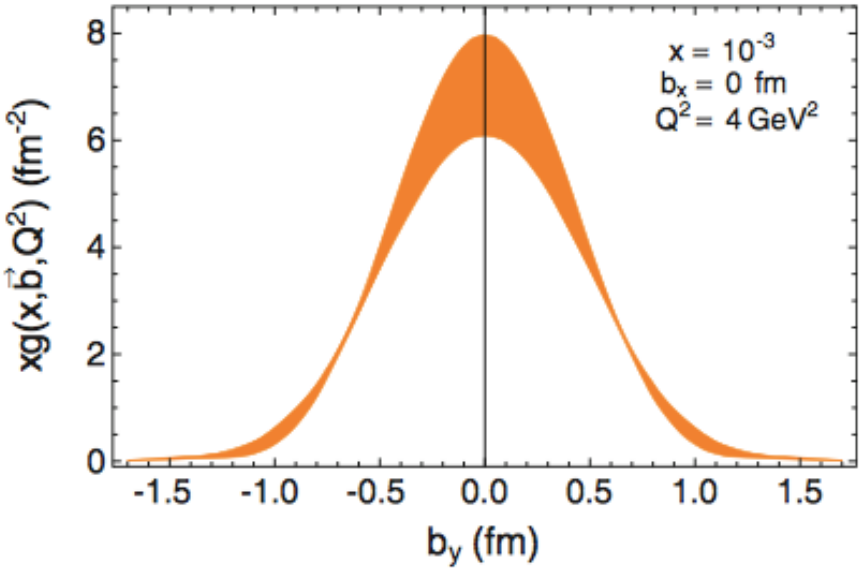


Fig. 29. The b_T space density for gluons obtained in the same fit as the densities in fig. 28.

EPJA **52**, 268 (2016)

WILD SPECULATIONS

PERHAPS

We will have detected neutrinoless double beta decay and know that a neutrino is its own antiparticle!

We will have found a new source of CP violation!

We will reach the island of long-lived superheavy nuclei.

We will find non-trivial topological configurations in relativistic heavy ion collisions (DCC, CME…)

We will find other low energy evidence for physics beyond the standard model.

We will learn how to apply quantum computing effectively to hadrons and nuclei.

PERHAPS DARK ENERGY WILL GO AWAY AS WE IMPROVE THE NUMERICAL CALCULATIONS OF GENERAL RELATIVITY

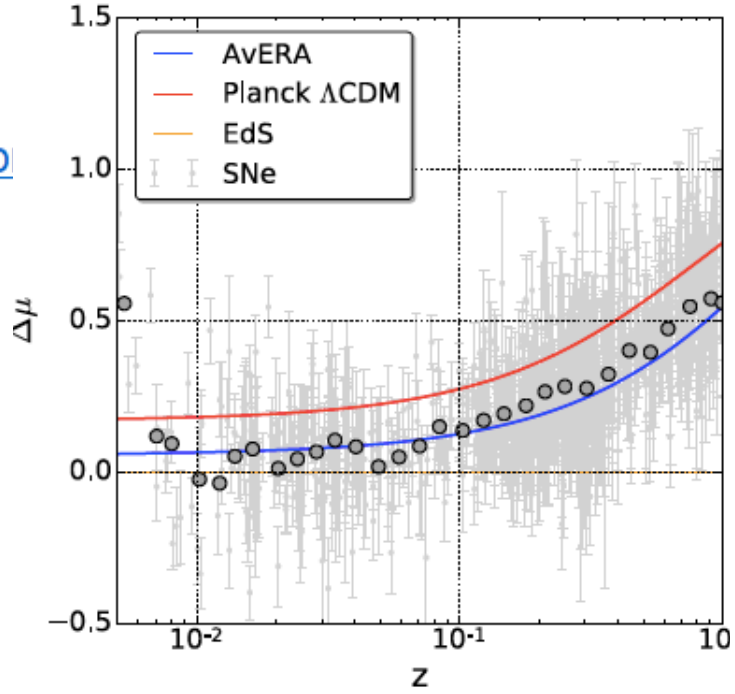
Concordance cosmology without dark energy

Gábor Rácz, László Dobos, Róbert Beck (Eotvos U.) , István Szapudi (Inst. Astron., Honolulu) , István Csabai (Eotvos U.)

Jul 29, 2016 - 5 pages

Mon.Not.Roy.Astron.Soc. (2017)
DOI: 10.1093/mnrasl/slx026
e-Print: arXiv:1607.08797 [astro-ph.CO] | PDF

This could explain difference in the measurement of the Hubble constant from SN and cosmology.



PRL 116, 251302 (2016) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2016

Effects of Nonlinear Inhomogeneity on the Cosmic Expansion with Numerical Relativity

Eloisa Bentivegna[1,2,*] and Marco Bruni[3]

SUMMARY

- Nuclear physics today is a roller coaster in the good sense. There is lots of progress and excitement
- It will be joint progress and theory and experiment that moves us forward, not on one side alone. The 2015 Long Range Plan and previous plans provide the foundations for this progress.
- Theory challenge in calculating the physics right
    - Nuclear structure
    - Hadron structure
        - Lattice is making great progress!
    - Astrophysical environments
    - Is quantum computing an answer?
- There is the potential for real breakthroughs in understanding.

GLOBAL COLLABORATION

All of this is in the context of more globalization of the research effort.

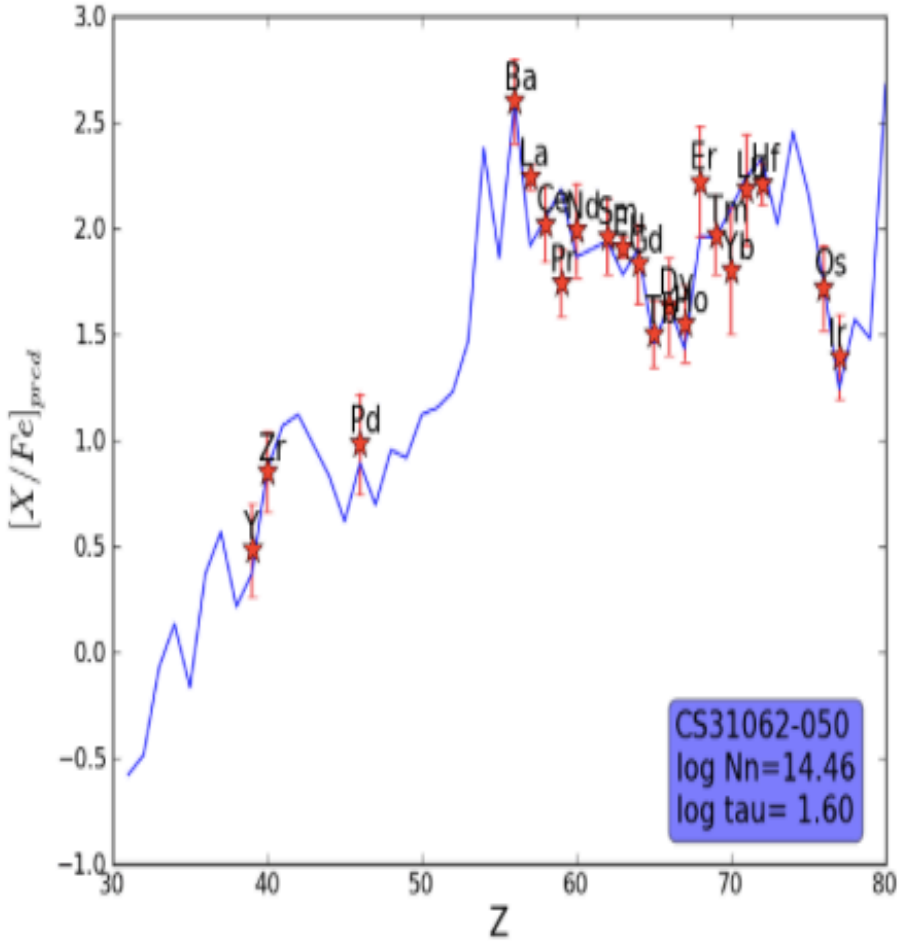
There will be an emphasis on

- Common Tools
- Common Structures
- Remote collaboration

but on diverse architectures and with diverse short range goals.

I-PROCESS

Intermediate density neutron capture process Dardelet et al.
Several possible sites
He-core and He-shell flashes
in low-metallicity low-mass stars,
super-AGB and post-AGB stars, as well as low-metallicity massive stars.



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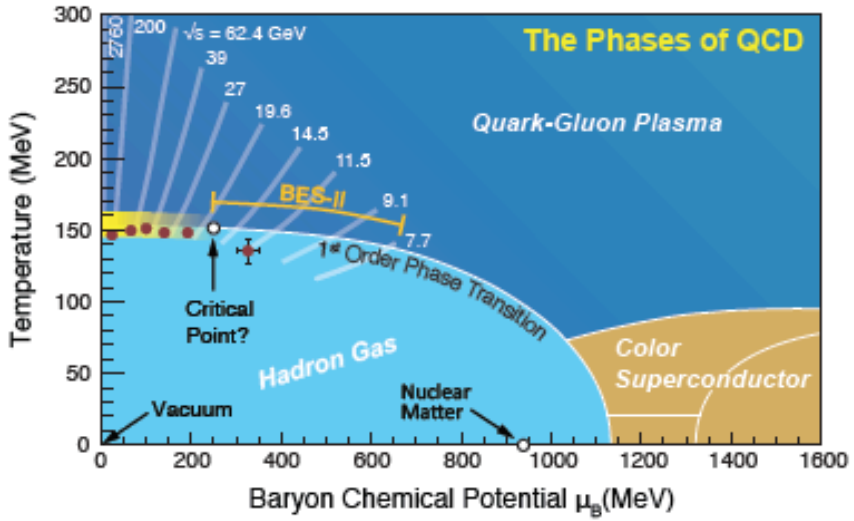
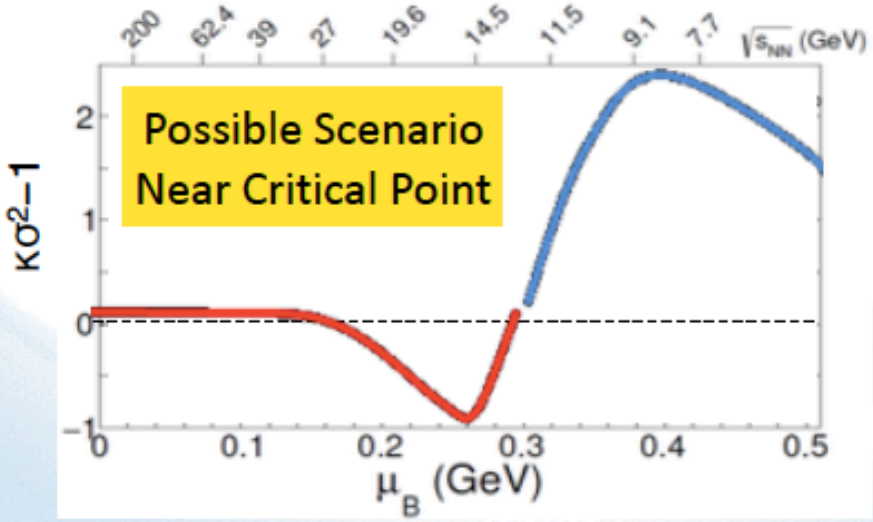
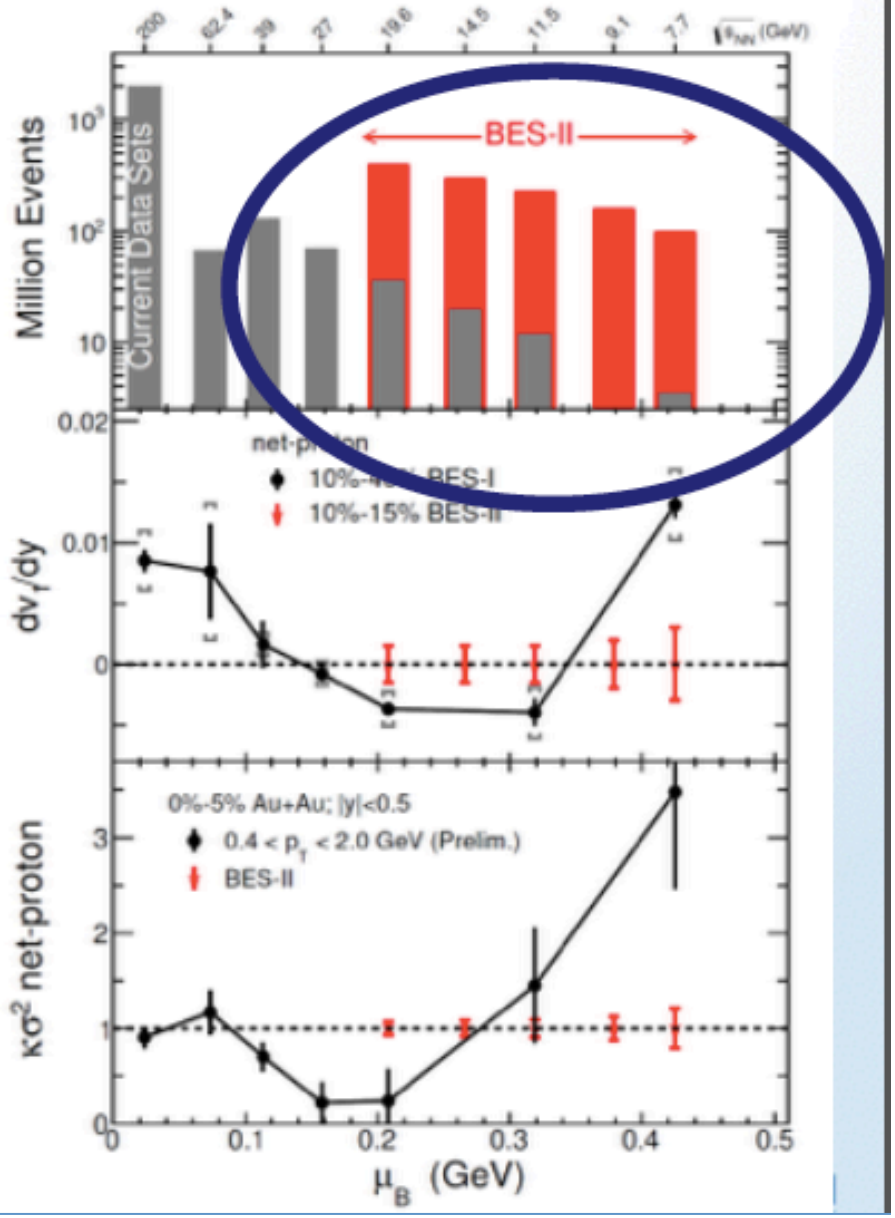
Toward critical fluctuations

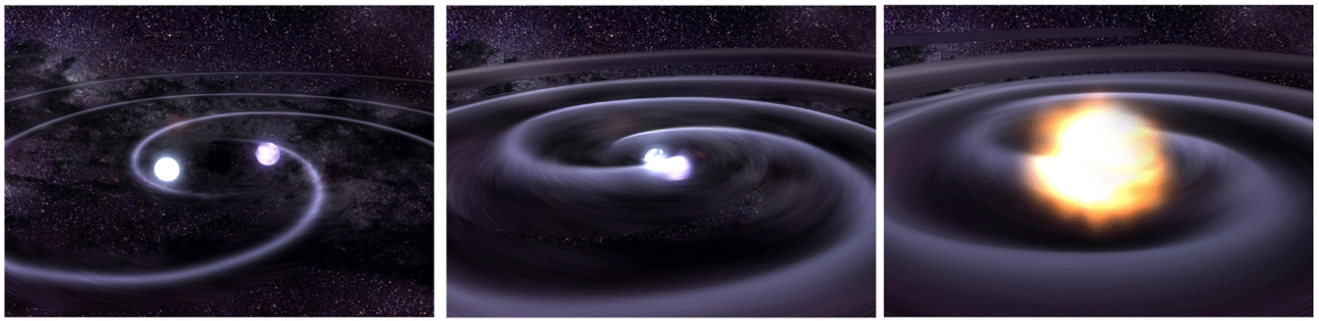


Model independent structure of net baryon number kurtosis





NUCLEAR PHYSICS IN GRAVITATIONAL WAVES



One of the best signals for the NSF's Advanced LIGO is the merger of two neutron stars

- This will immediately tell us the rate of neutron star mergers. Are there enough to create the heavy elements through the r-process?
- The waveform is sensitive to the nuclear equation of state for neutron stars