Asia Pacific Center for Theoretical Physics

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Physics of Nuclei with an Electron Ion Collider

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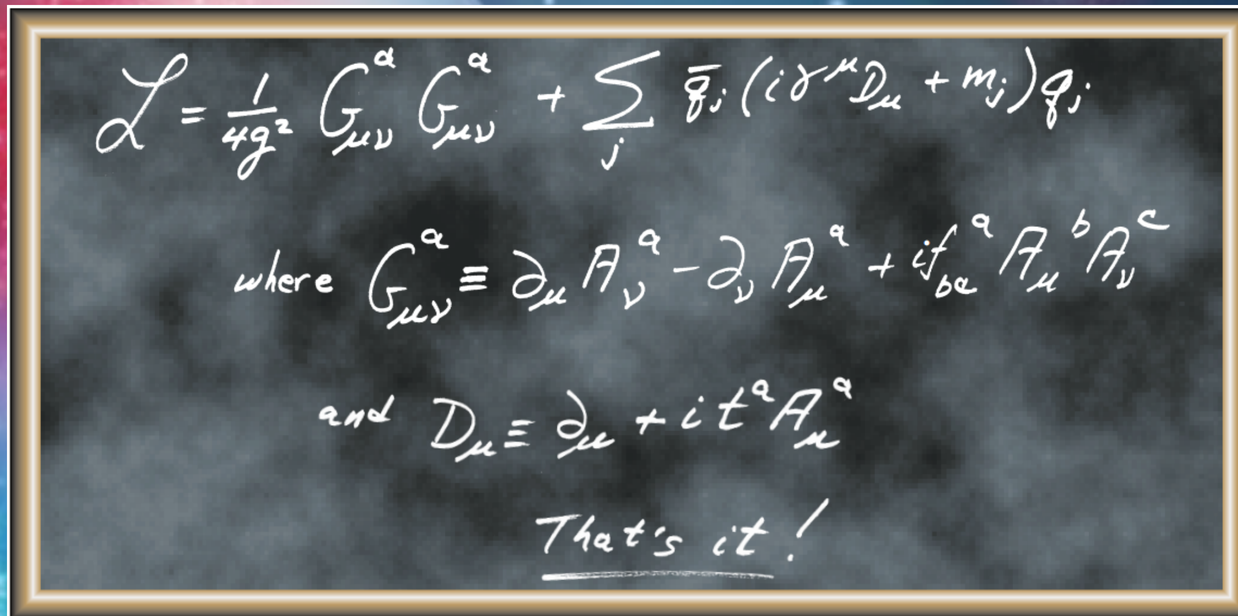
Mesons, Baryons, Nuclei, Nuclear Matter, Neutron Stars

- Many-Body systems. Unique combination:
  - Quantum Dynamics
  - Relativitistic
  - Strong coupling
- Described by an elegant microscopic theory:
  - Quantum Chromodynamics (QCD)

Quantum ChromoDynamics(QCD)

- Invariant under \`color’ SU(3) Gauge Transformations
- Gluon fields $G_{\mu\nu}$ are 3x3 color matrices
- Quark fields q_j are 3×1 color vectors



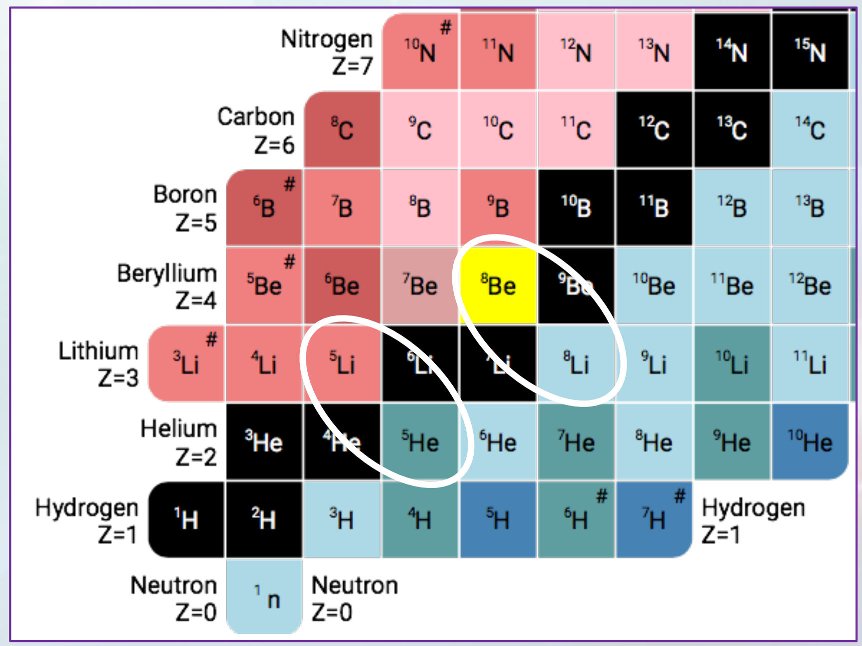
- Almost everything we observe about hadrons and nuclei is NOT in the QCD Lagrangian.
  ➔ Emergent phenomena!

Cosmic Puzzles
I. Mass

- Mass
  - Roughly 97% of the mass of the visible matter of the universe comes from the emergent dynamics of QCD.
  - The other 3% (quark masses)
    comes from the
    Higgs mechanism

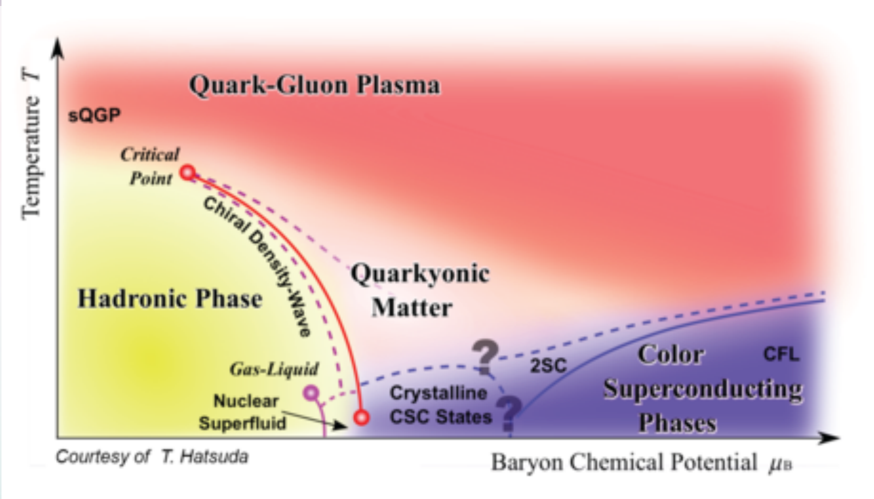
Cosmic Puzzles
II. Nuclear Binding

- Nuclear Binding is a color Van der Waals force
  - np system has bound state, nn system does not.
    ➔ Universe has atoms, chemistry, & stars, not just White-Dwarfs, Neutron-Stars and black-holes.
  - No bound 5-nucleon or 8-nucleon nuclei.
    ➔ Stars burn for billions of years, not just millions.



Cosmic Puzzles III. Structure and Dynamics of Neutron Stars

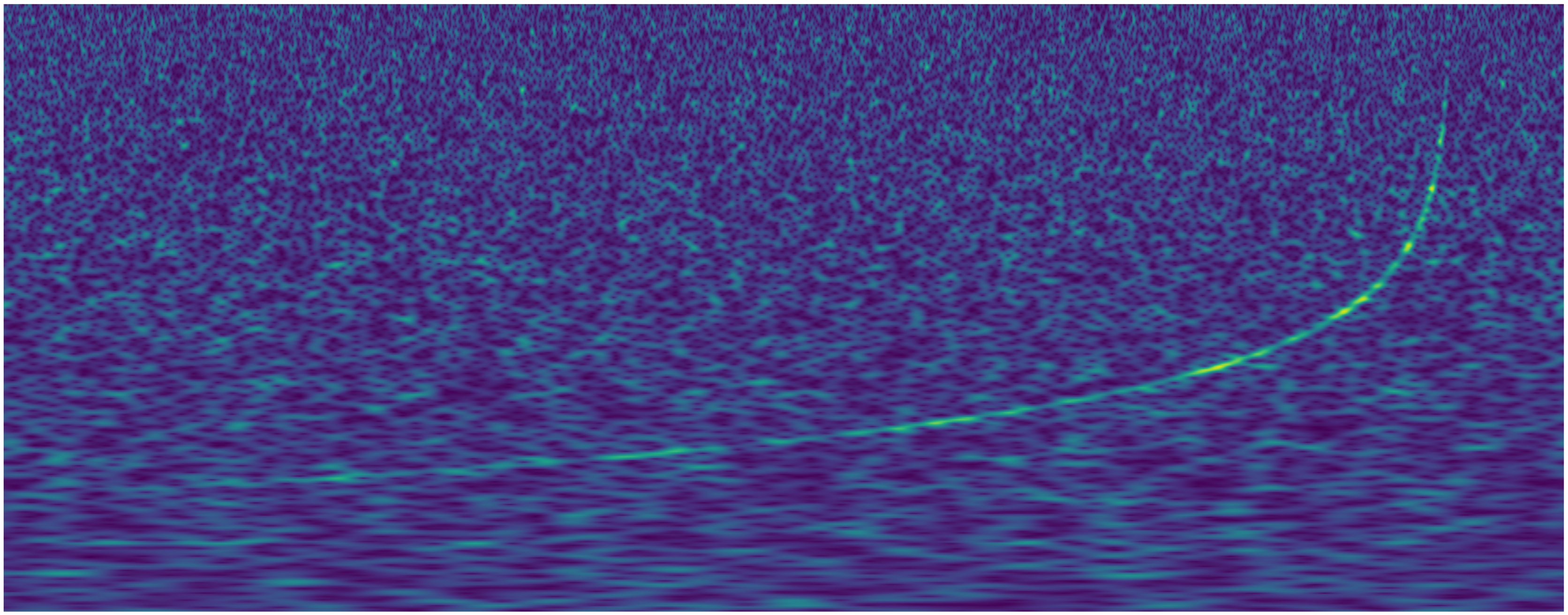
- Phases of QCD matter at high density / low T
  - Neutron star
  - Color Superconductivity



- Mass Limits of Neutron Stars
  - Measure the neutron radii of heavy nuclei to constrain the Nuclear Matter Equation of State (Pressure-density-temperature relation)
- Dynamics: Neutron Star Mergers

Neutron Star Merger:
The ultimate relativistic heavy ion collision

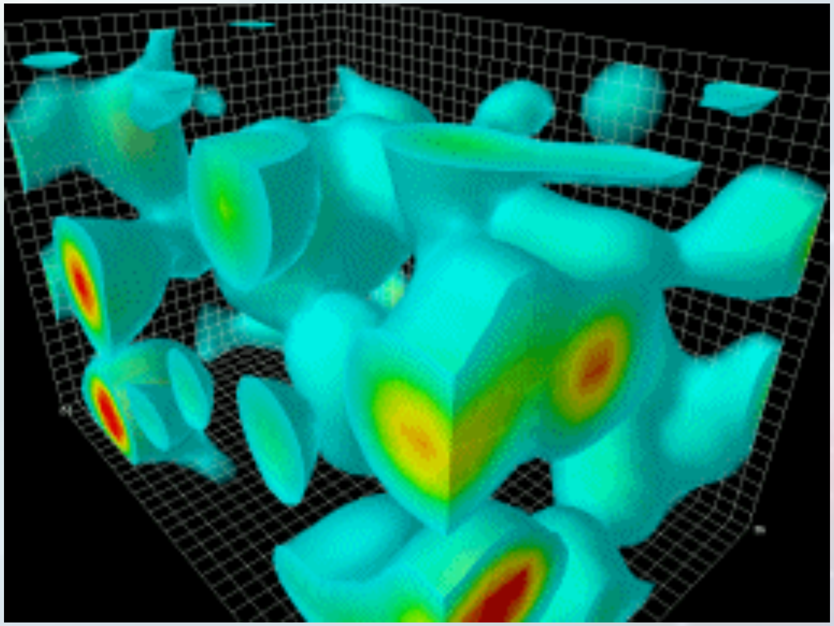
- LIGO Chirp and Fermi $\boldsymbol{\gamma}$-ray burst
  - https://youtu.be/-Yt5EmEgz2w



Cosmic Puzzles IV: The Vacuum

- Dynamic Quark and Gluon condensates
  - $\langle 0|\bar{q}(x)q(x)|0\rangle > 0$
  - $\langle 0|G(x)G(x)|0\rangle > 0$
  - Not static!
  - Nearly massless quarks moving through the lumpy gluon condensate acquire $q\bar{q}$-cloud and mass ~ 300 MeV.

D. Leinweber



Unique Features of the Electron Ion Collider

- High Center-of-Mass energy
  - *ep* Lower than HERA, but first ever *eA:* ^{2}H to ^{238}U
- High Luminosity: 100 x HERA
- Polarized Light nuclei: p, d, ^{3}He, ^{6,7}Li …
  - Longitudinally and transversely polarized, without the dilution of e.g. NH_3, ND_3, Butanol… targets
- Full reconstruction of nuclear final state
  - Effective zero target thickness *vis a vis* fixed target exp.
  - Far Forward acceptance 50x HERA
  - Spectator and evaporation neutrons are boosted:
    - Precision detection possible

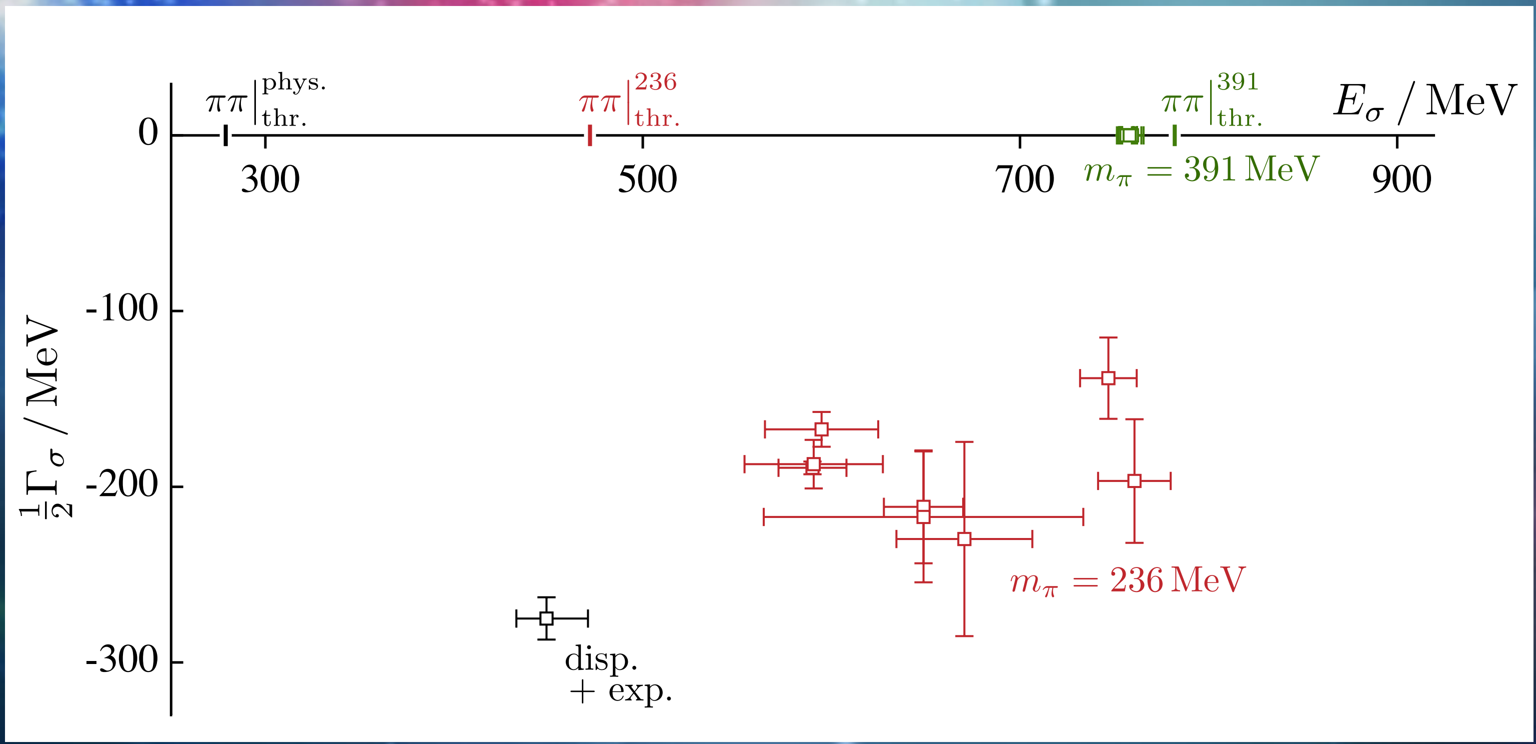
Theory Tools

- Lattice QCD
- Dyson-Schwinger Eq's
- Effective Field Theory
- Light Cone Quantization
- Density Functional Theory
- …

Scattering with Lattice QCD (2016)

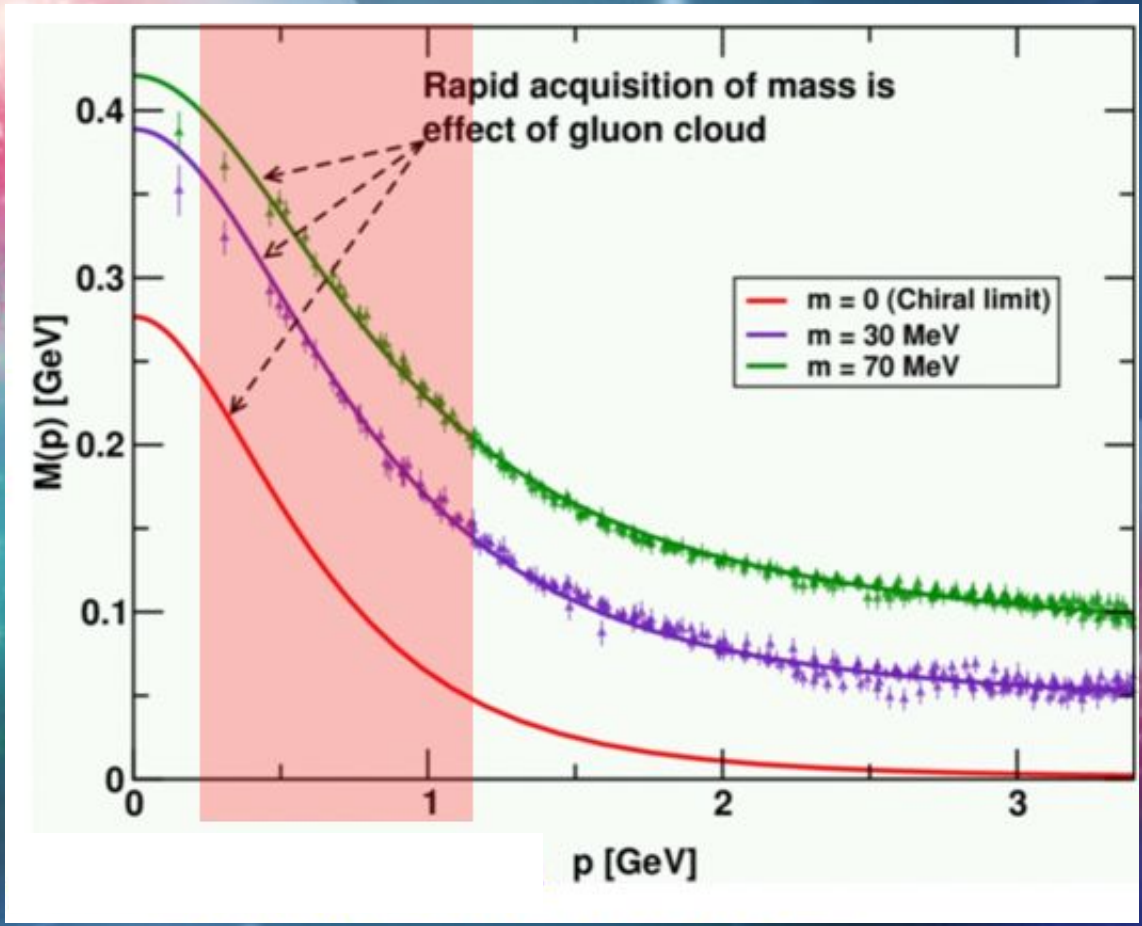
Isoscalar $\pi\pi$ scattering and the σ meson resonance from QCD

Raul A. Briceño,[1,2,*] Jozef J. Dudek,[1,2,†] Robert G. Edwards,[1,‡] and David J. Wilson[3,§]
(for the Hadron Spectrum Collaboration)



Dynamical Origin of Mass

- Dyson-Schwinger Eq'ns
  (C. Roberts)



Why a high energy EIC to investigate low energy nuclear binding?

I. Nuclear binding: delicate cancelation of high energy effects.
- QMC model: scalar (σ) and vector (ρ, ω) mean fields, Strengths ~ 500 MeV
- Nuclear Momentum Distributions have universal tails up to ≥ 1 GeV/c.