INSTITUTE for NUCLEAR THEORY

Nuclear Theory since 2007 and for the next decade: An overview

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  - ▶ amazing breadth of activity
  - ▶ strong cross talk with other fields: numerical relativity, quantum chemistry, condensed matter physics, string theory, particle theory, cosmology… the sign of vibrant science

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- Directions for the future
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- Nuclear theory in the context of the Long Range Plan

some selected highlights:

1. Viscosity and the QGP

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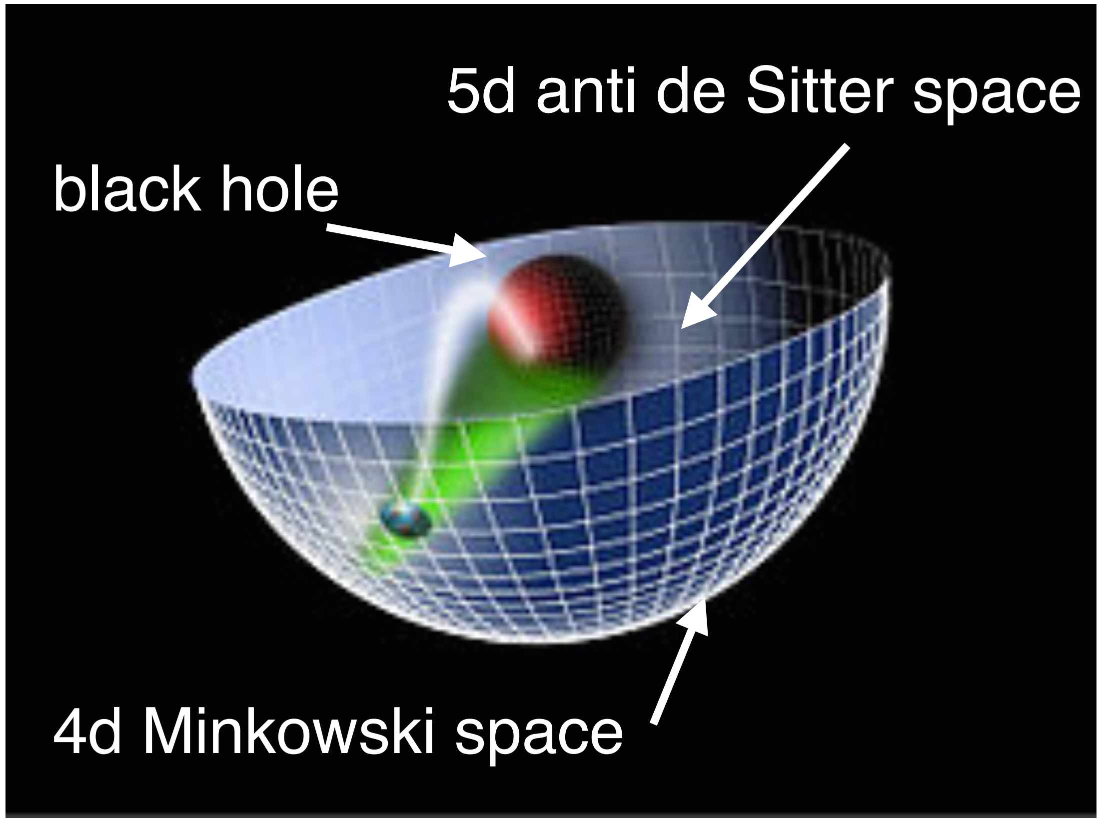

2004: Viscosity bound from AdS/CFT?
(Kovtun, Son, Starinets)

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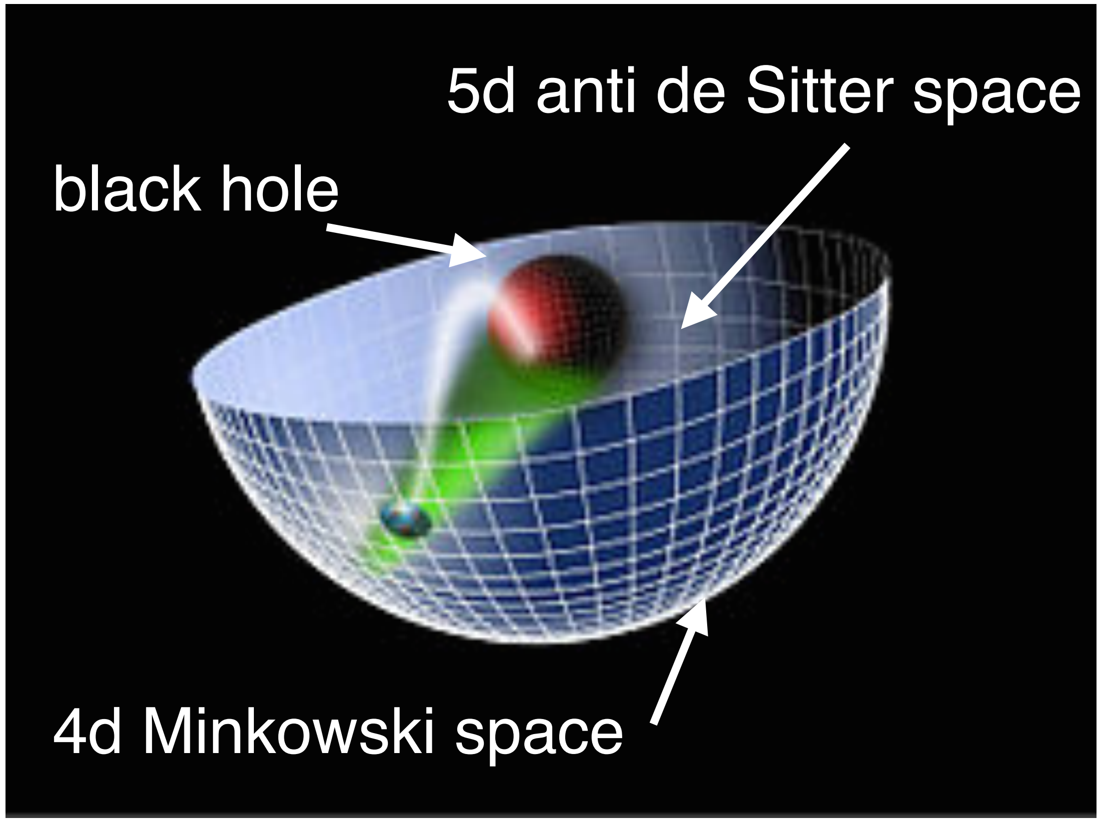
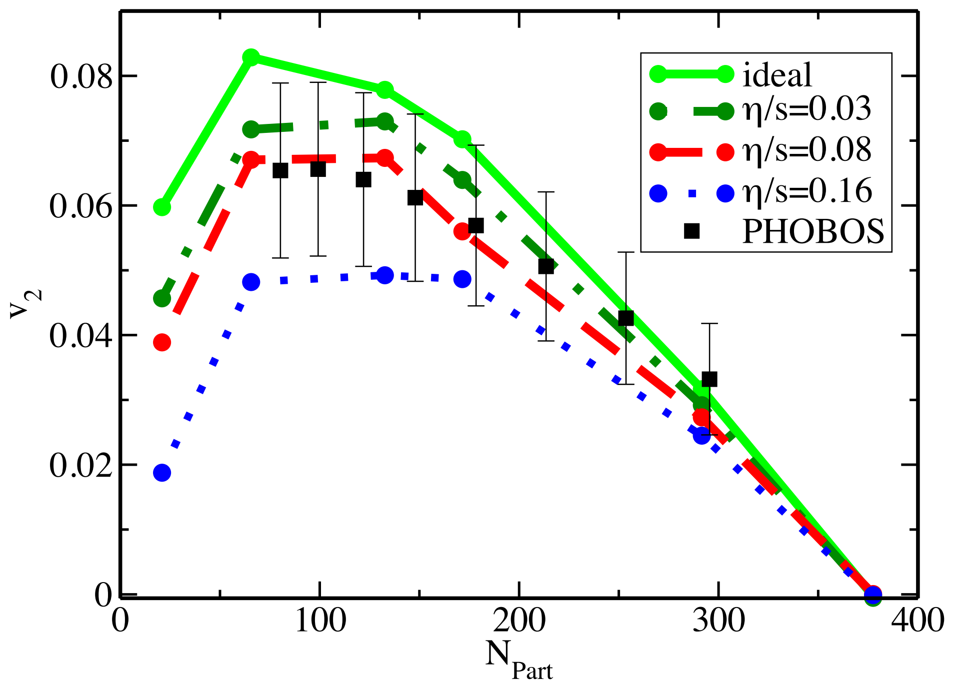
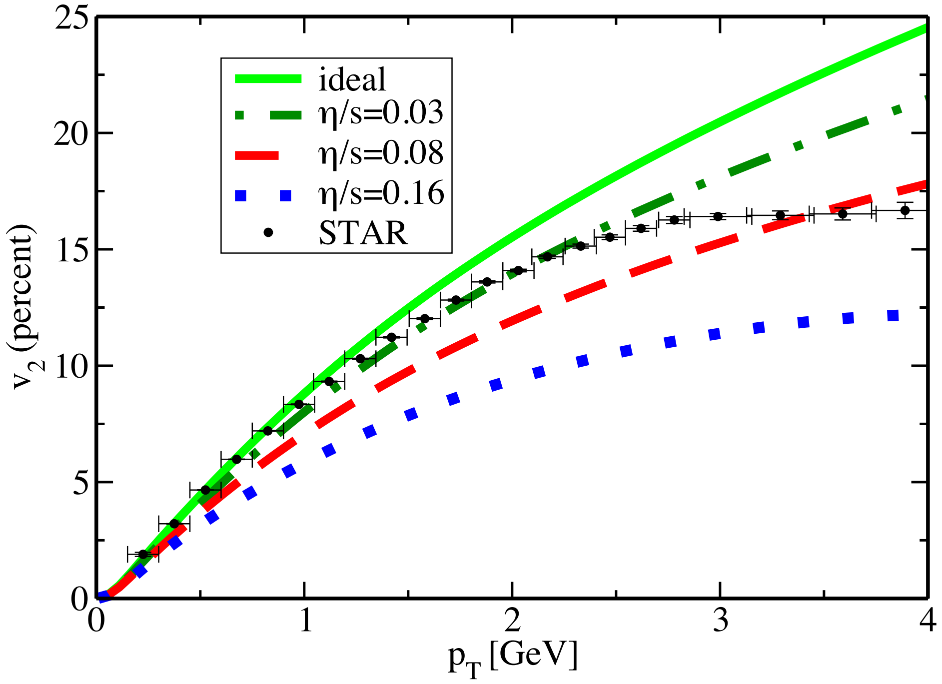
1. Viscosity and the QGP



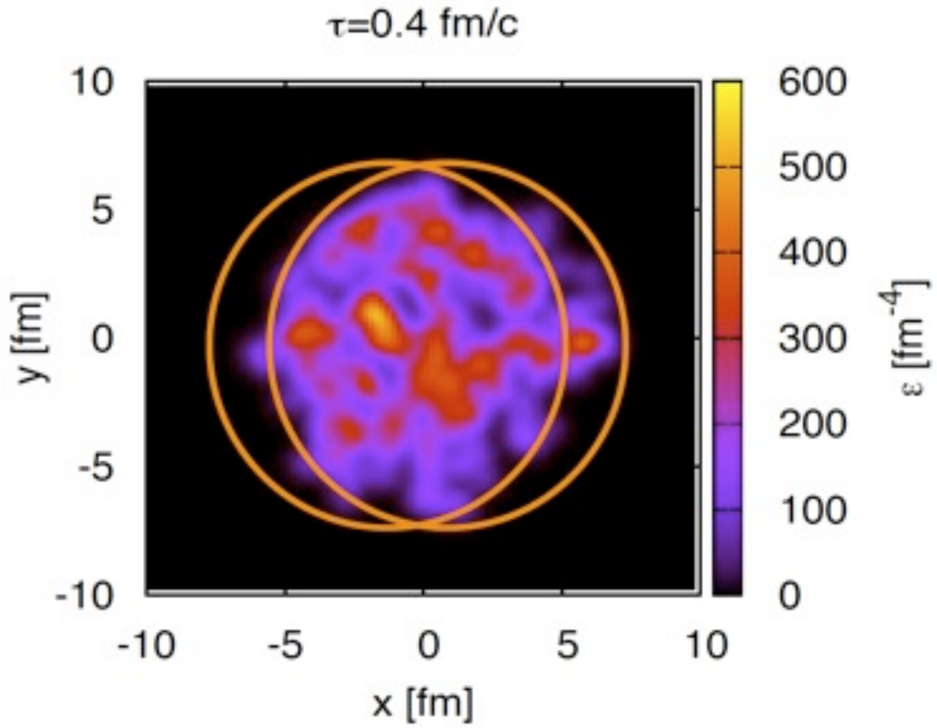
2004: Viscosity bound from AdS/CFT? (Kovtun, Son, Starinets)

2007: Numerical determination of QGP viscosity from relativistic hydro computation, fitting to v_2 (Romatschke[2])





Discovery of importance of higher harmonics arising from initial state fluctuations -- the cosmological analogy (2010)

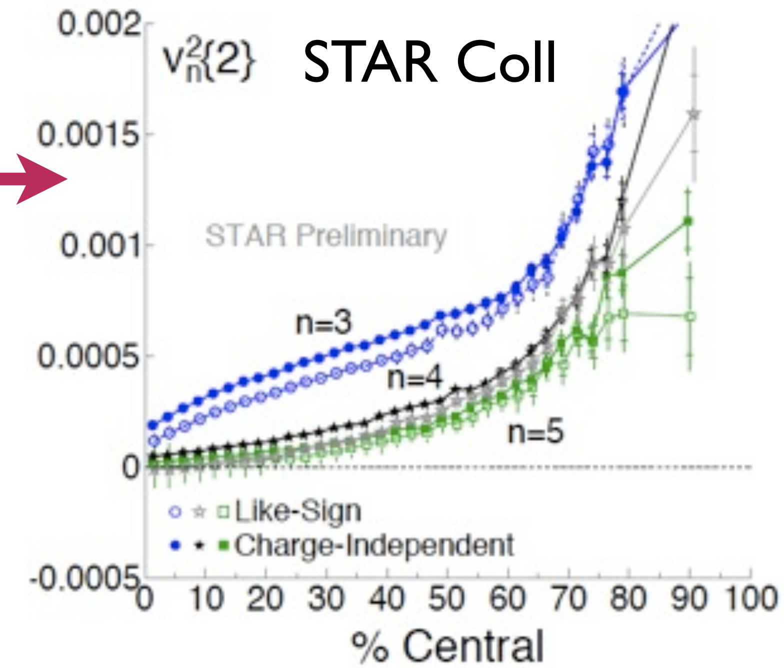


Hot spots provide correlated higher harmonics

Alver & Roland; Luzum; Teaney;...

Constraints on viscosity of hydro flow

STAR Coll



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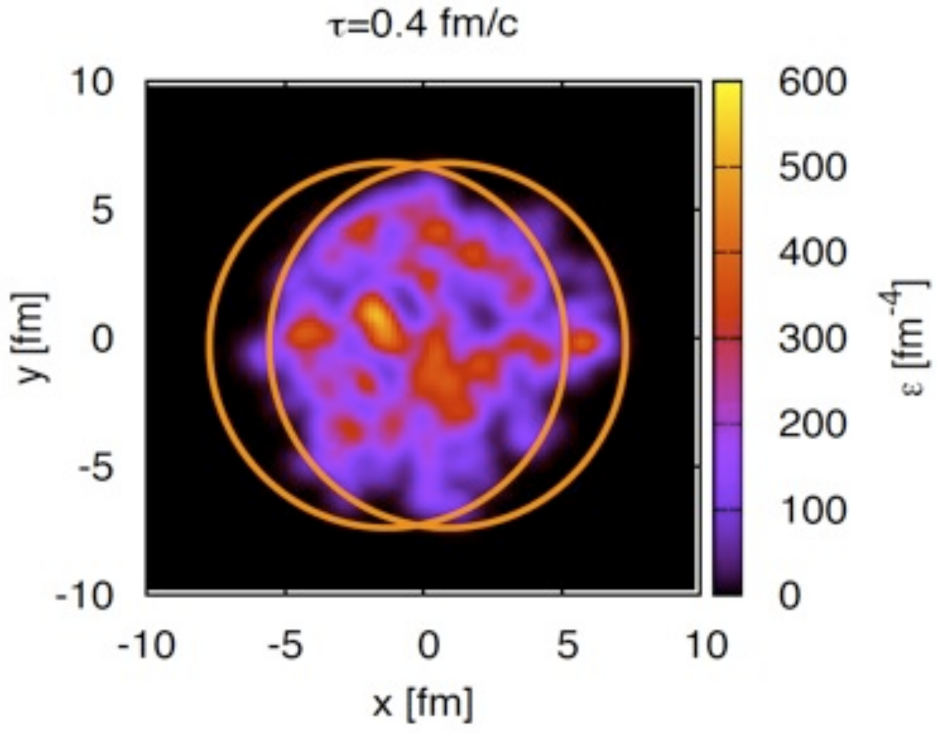

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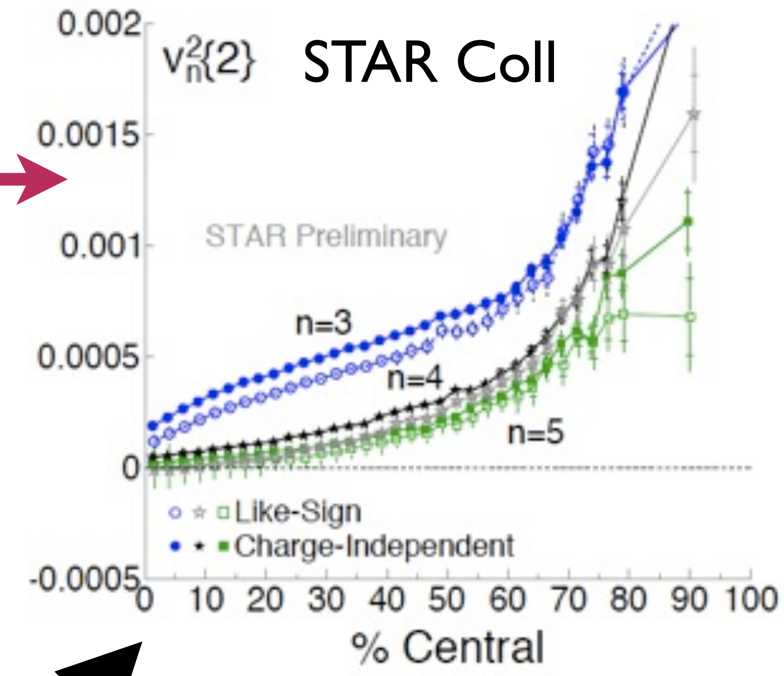
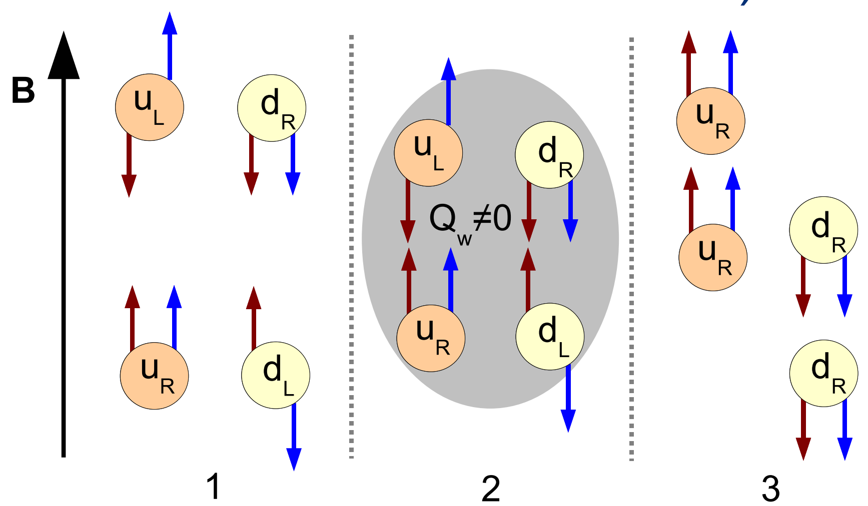


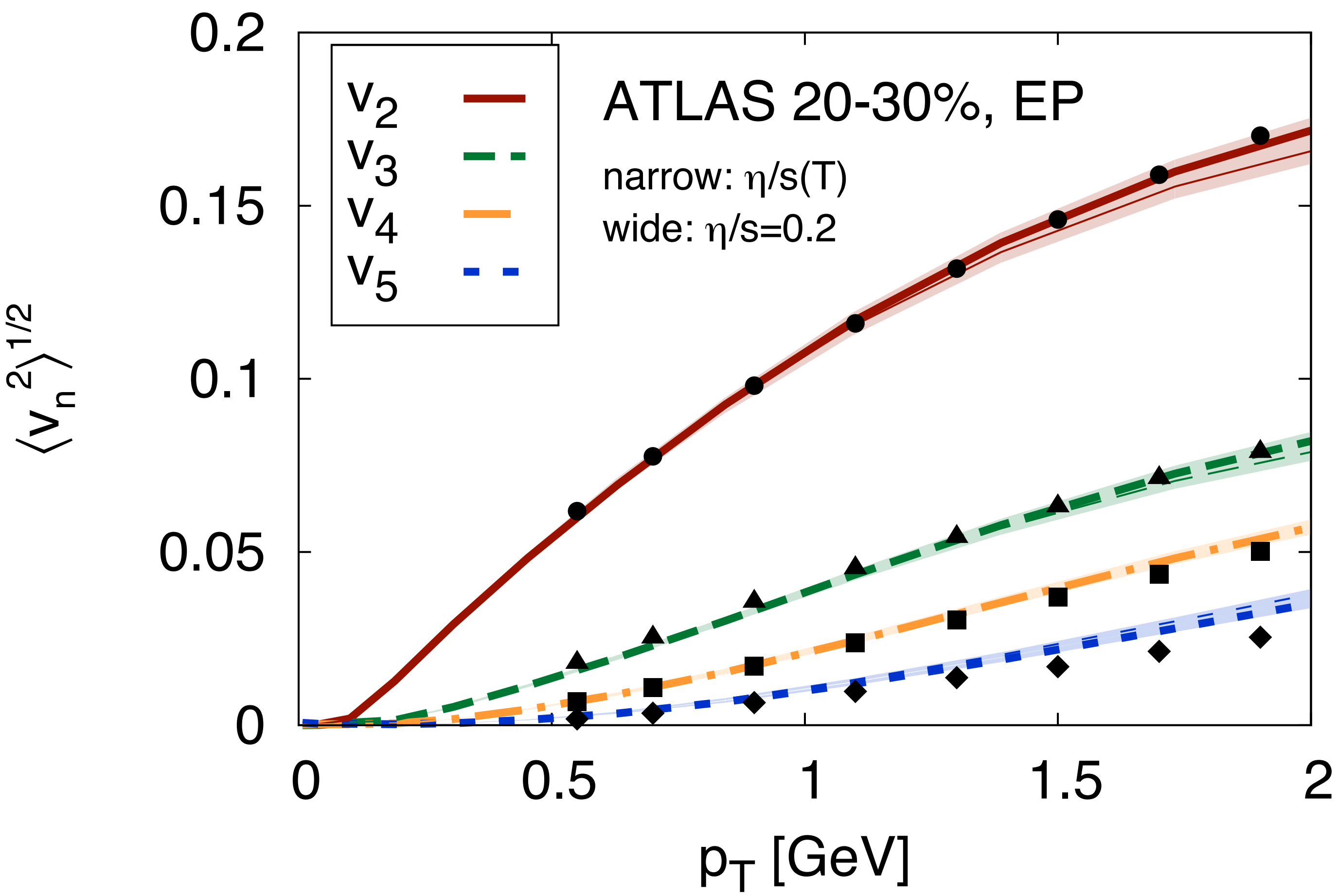
Perhaps charge separation is due to the topological "chiral magnetic effect" (Kharzheev et al., 2006 - 2010)

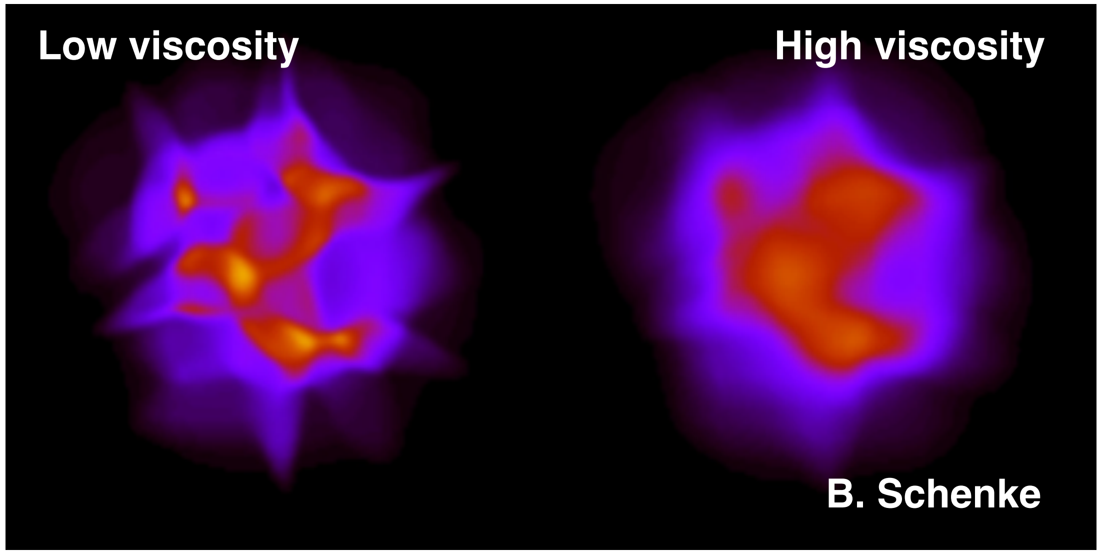


Derivation of initial quantum fluctuations:

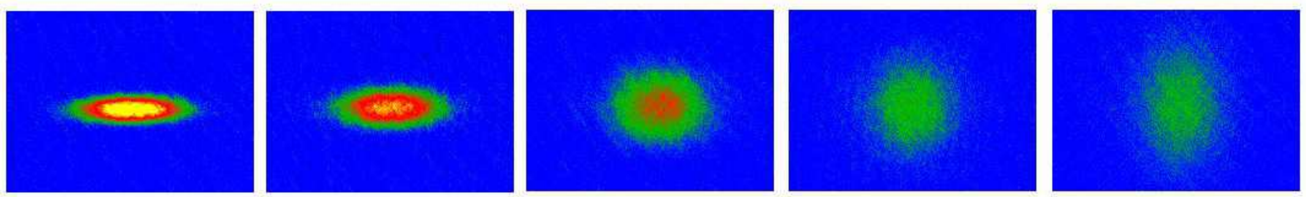
K. Dusling, F. Gelis and R. Venugopalan (2011)

K. Dusling, T. Epelbaum, F. Gelis and R. Venugopalan, (2012) 2013: Modeling of anisotropies, from initial fluctuations through hydrodynamical evolution, allowing determination of the temperature dependence of the viscosity (rising with T?!) - Gale, Jeon, Schenke, Tribedy, Venugopalan

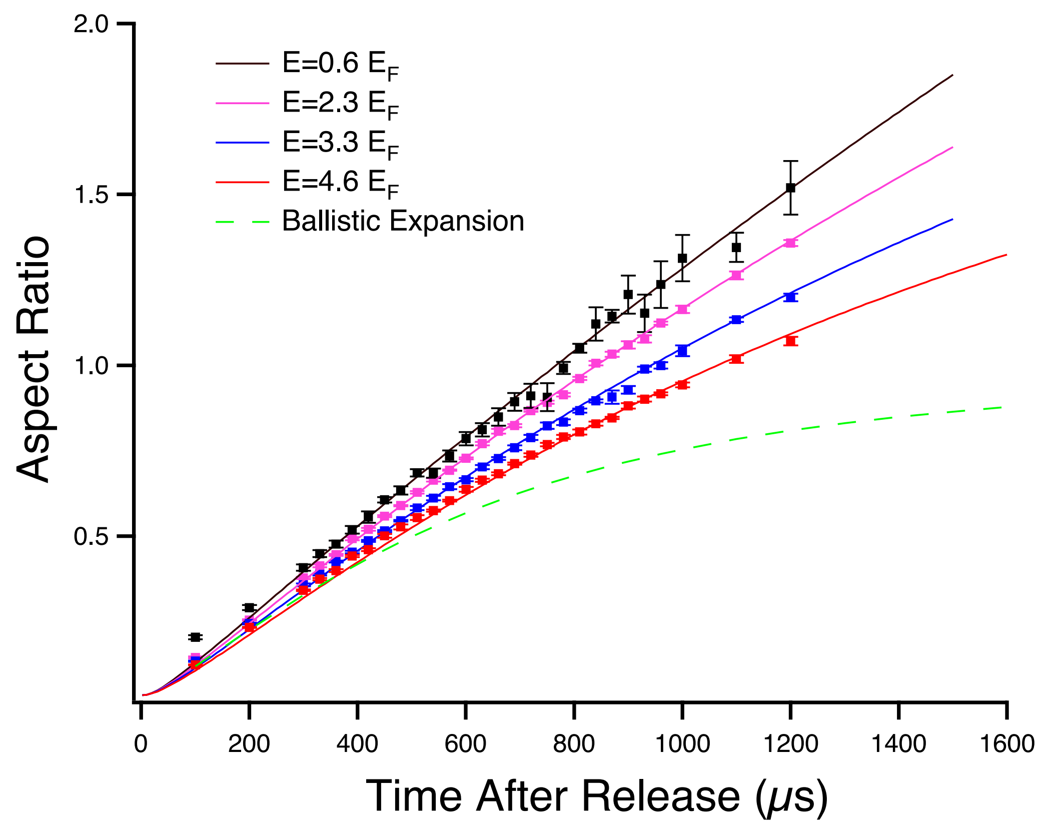




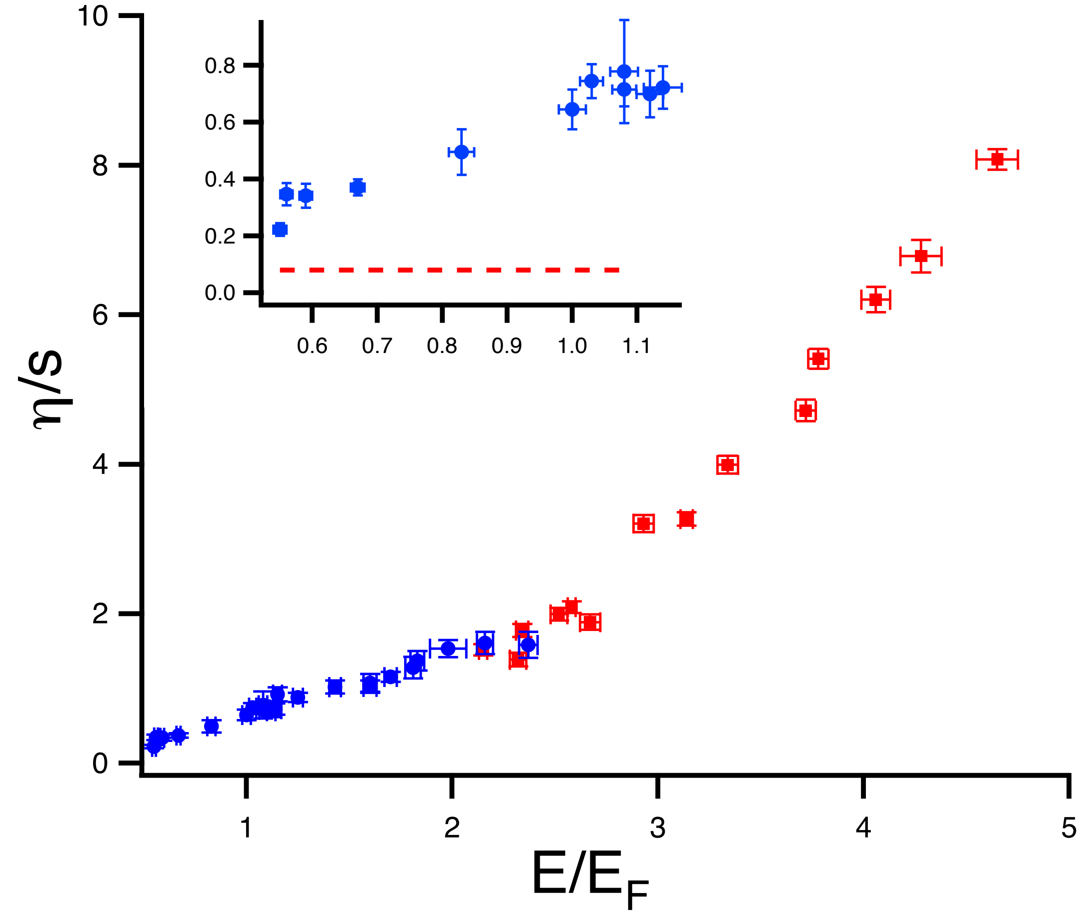
From heavy ion collisions to cold trapped fermionic atoms… the same physics spanning 25 orders of magnitude in scale



(A)



(B)



Extraction of η/s in cold trapped atoms from elliptic flow & breathing modes

Cao et al., 2010

Hard problems are being solved by importing tools from diverse fields of physics

One sees the same problems echoed at many different scales

High fallutin' theory and creative modeling work hand-in-hand toward creating a comprehensive theory

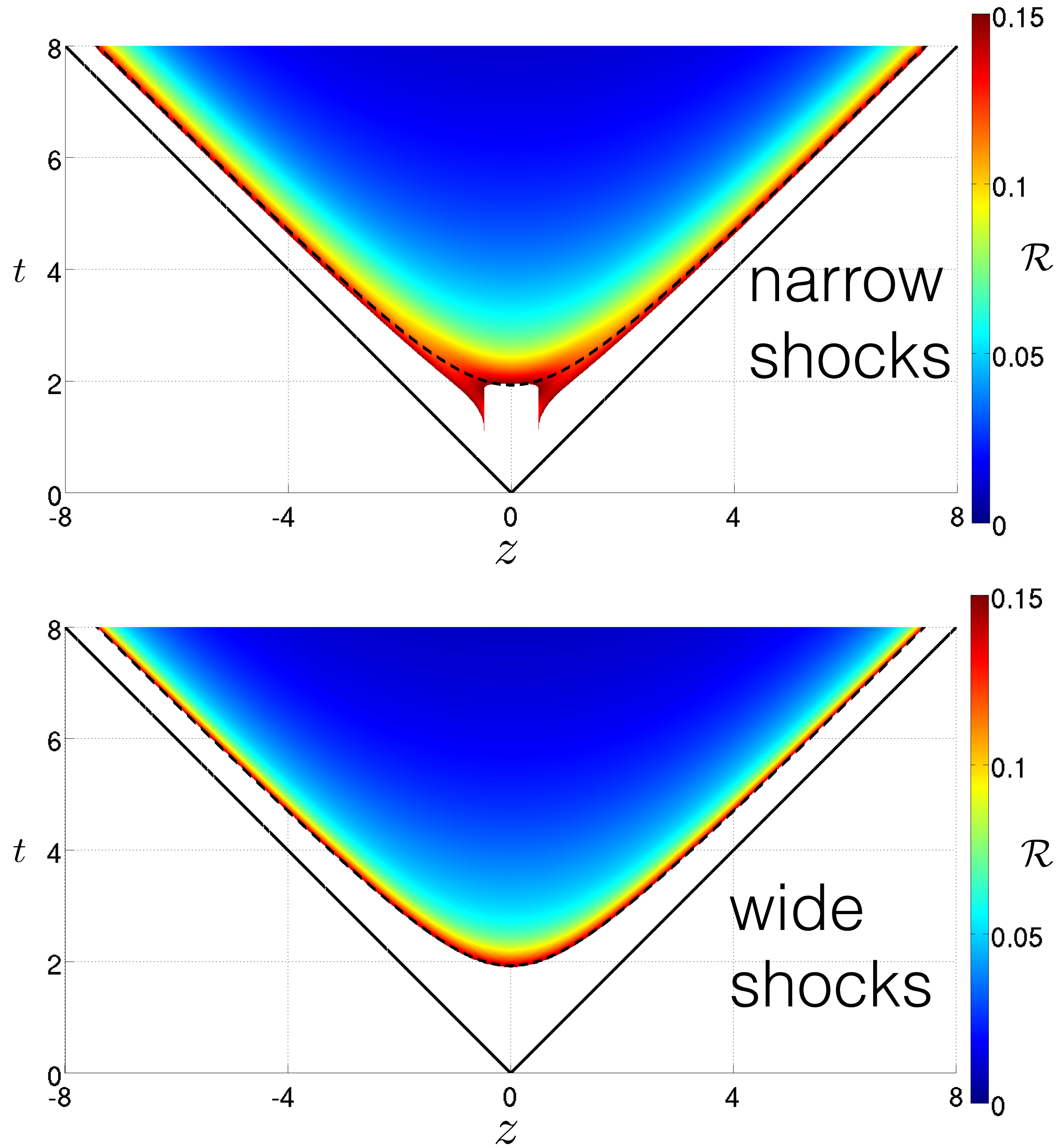
New theory ideas change experiments

2. “QGP” from AdS/CFT

Not QCD, but in some ways not too different

2. “QGP” from AdS/CFT

some highlights (Chesler & Yaffe 2013, JHEP 1407 (2014) 086):
solutions to Einstein eqs in 5d anti de Sitter space-time



Test of validity of
1st order viscous
hydrodynamics in the
collision of shock waves

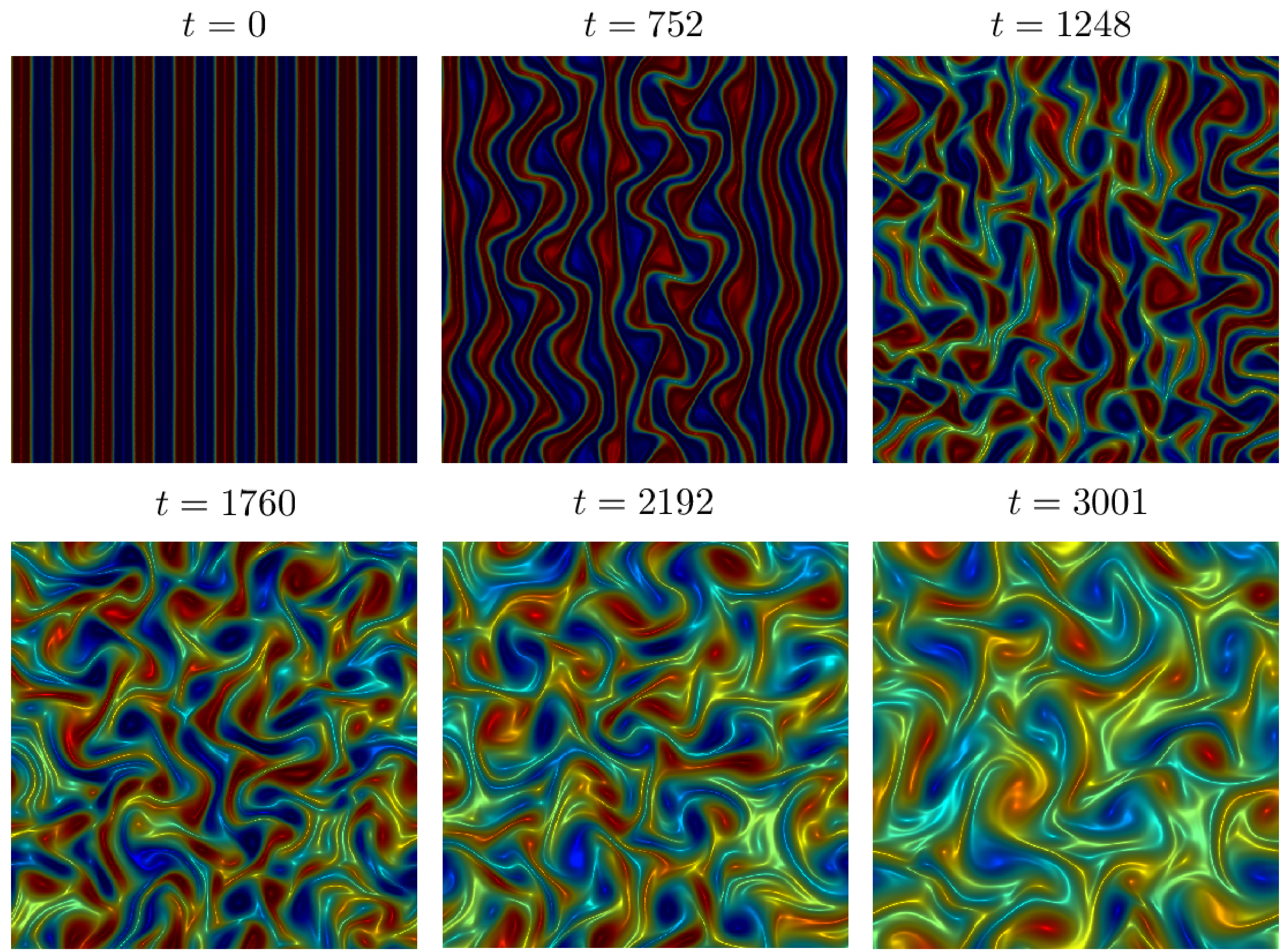
(R = relative deviation;
blue = good, red = bad)

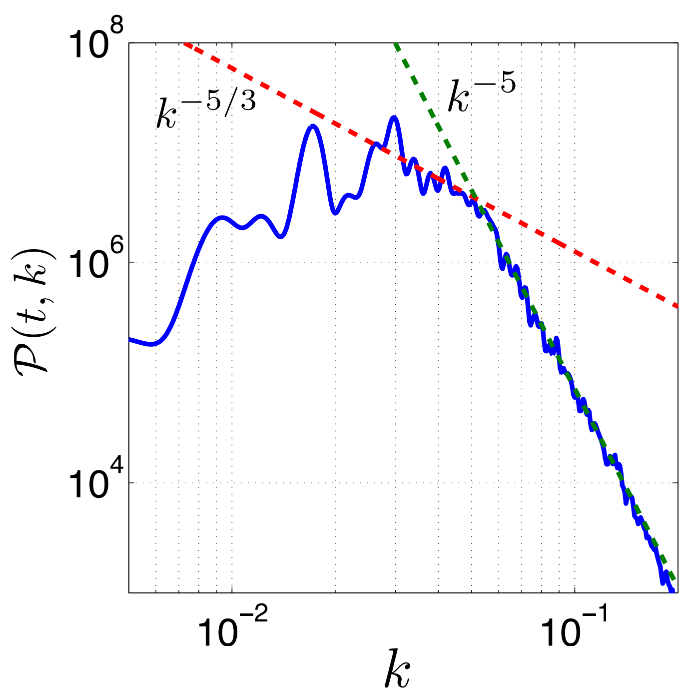
Not QCD, but in some ways
not too different

“QGP” from AdS/CFT

(Chesler & Yaffe 2013):

emergence of turbulent flow through cascade of plasma instabilities





Development of simple scaling behavior in power spectrum

When you wonder if you might be approximating the right problem wrong, it can help to solve the wrong problem right

Analytical and precise numerical results for complex systems are jewels to treasure

3. The ultimate heavy ion and the ultimate heavy ion collision:

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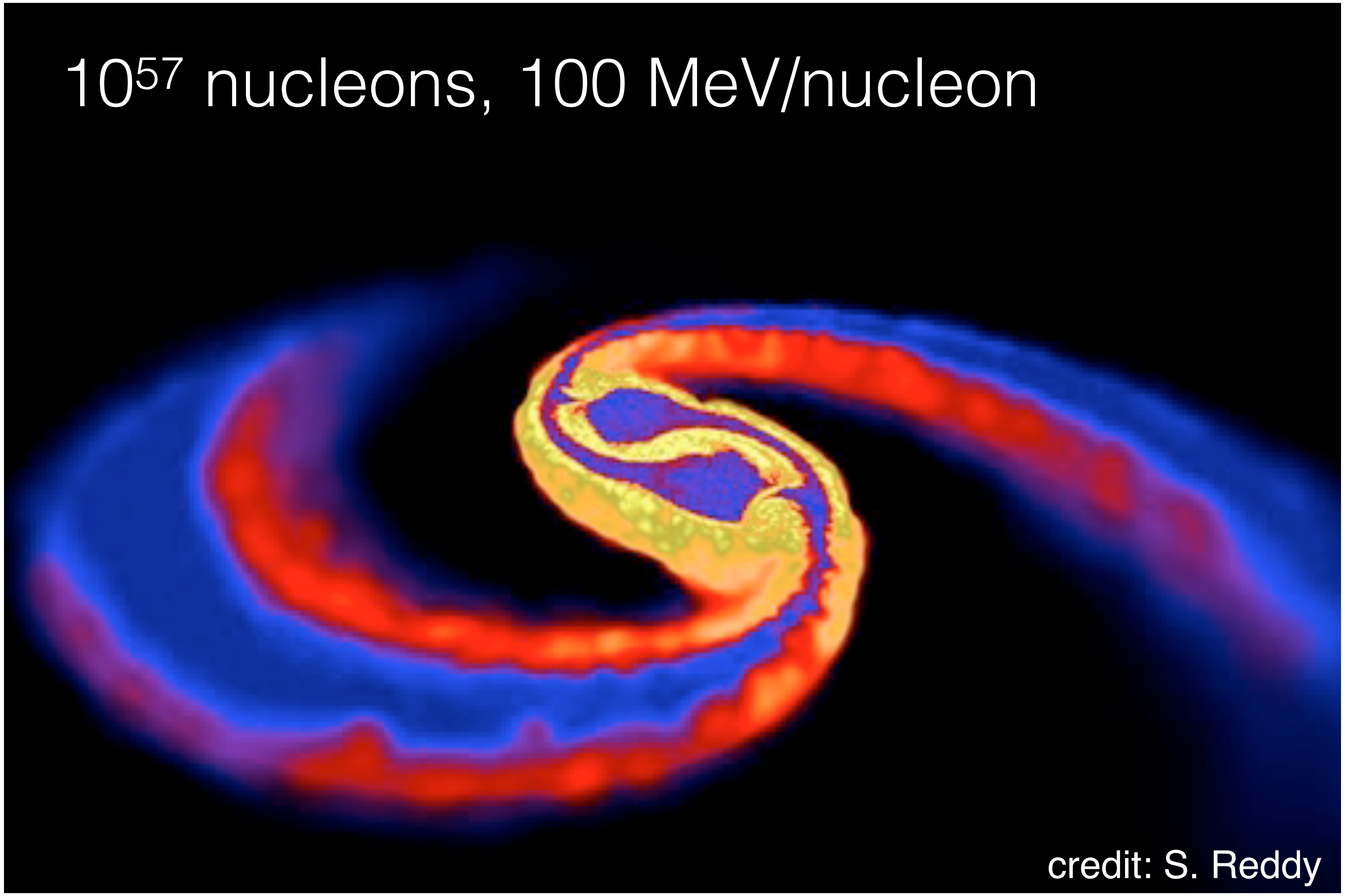
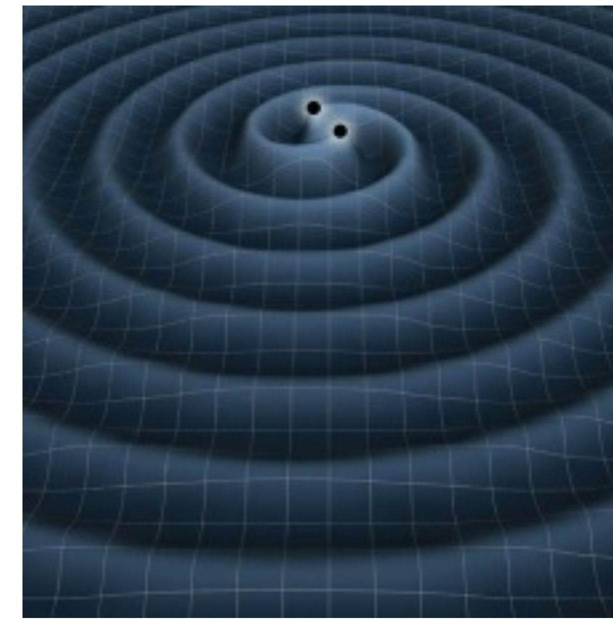


Binary neutron star mergers

Ligo will "see" n-star mergers ~300 Mpc away (!)…

1-100 mergers/year by 2016/17



200-300Mpc

Andromeda

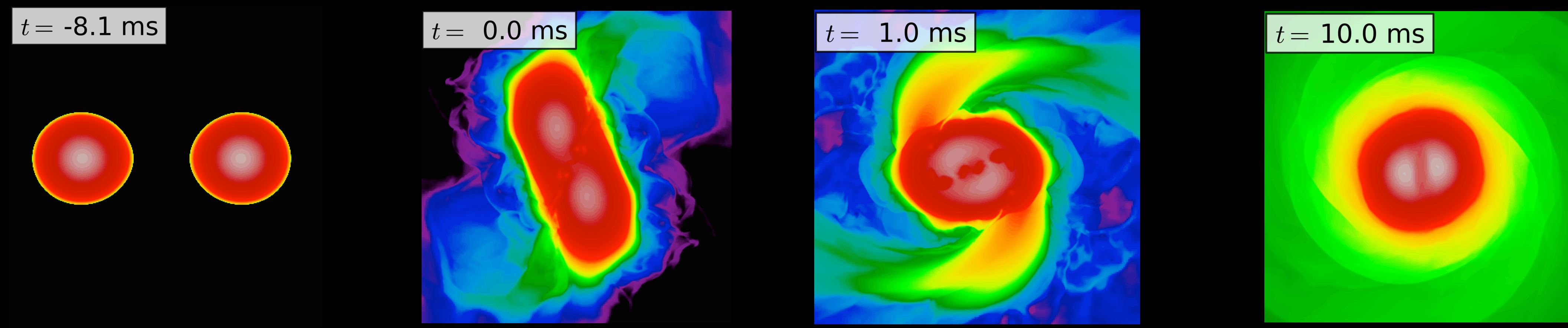
1Mpc

Ligo, Hanford WA

A new era begins:
gravity wave astronomy
…with implications for nuclear physics

Neutron Star Merger Dynamics

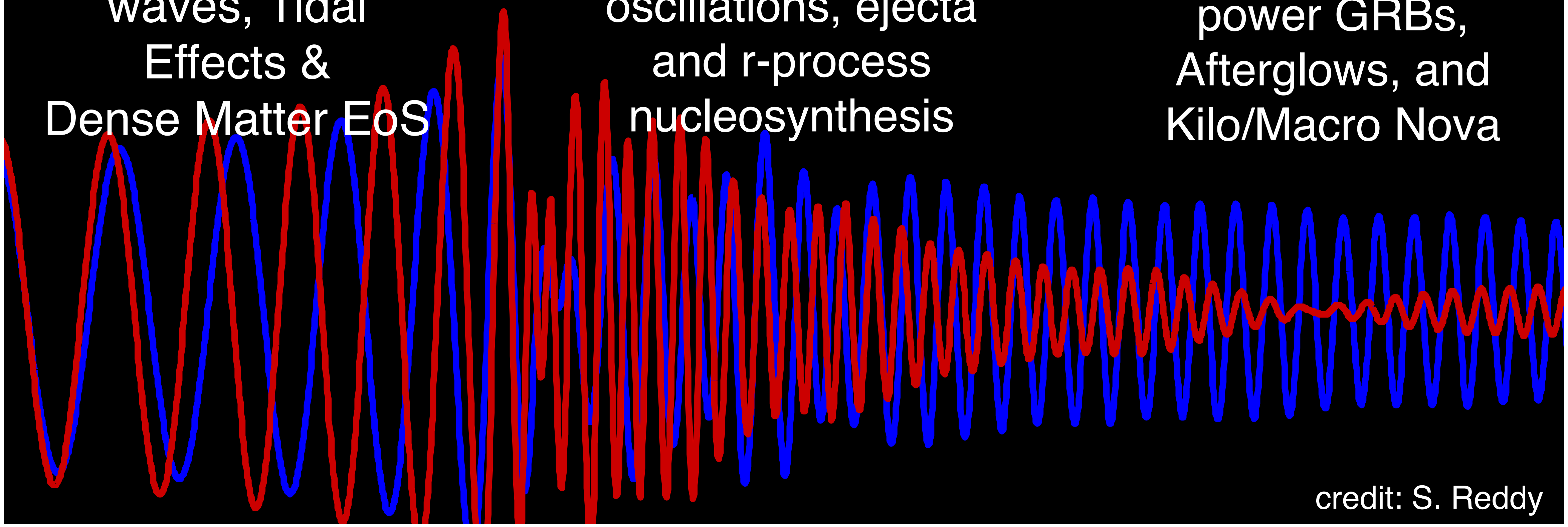
(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon



Inspiral:
Gravitational waves, Tidal Effects &
Dense Matter EoS

Merger:
Disruption, NS oscillations, ejecta and r-process nucleosynthesis

Post Merger:
Ambient conditions power GRBs, Afterglows, and Kilo/Macro Nova

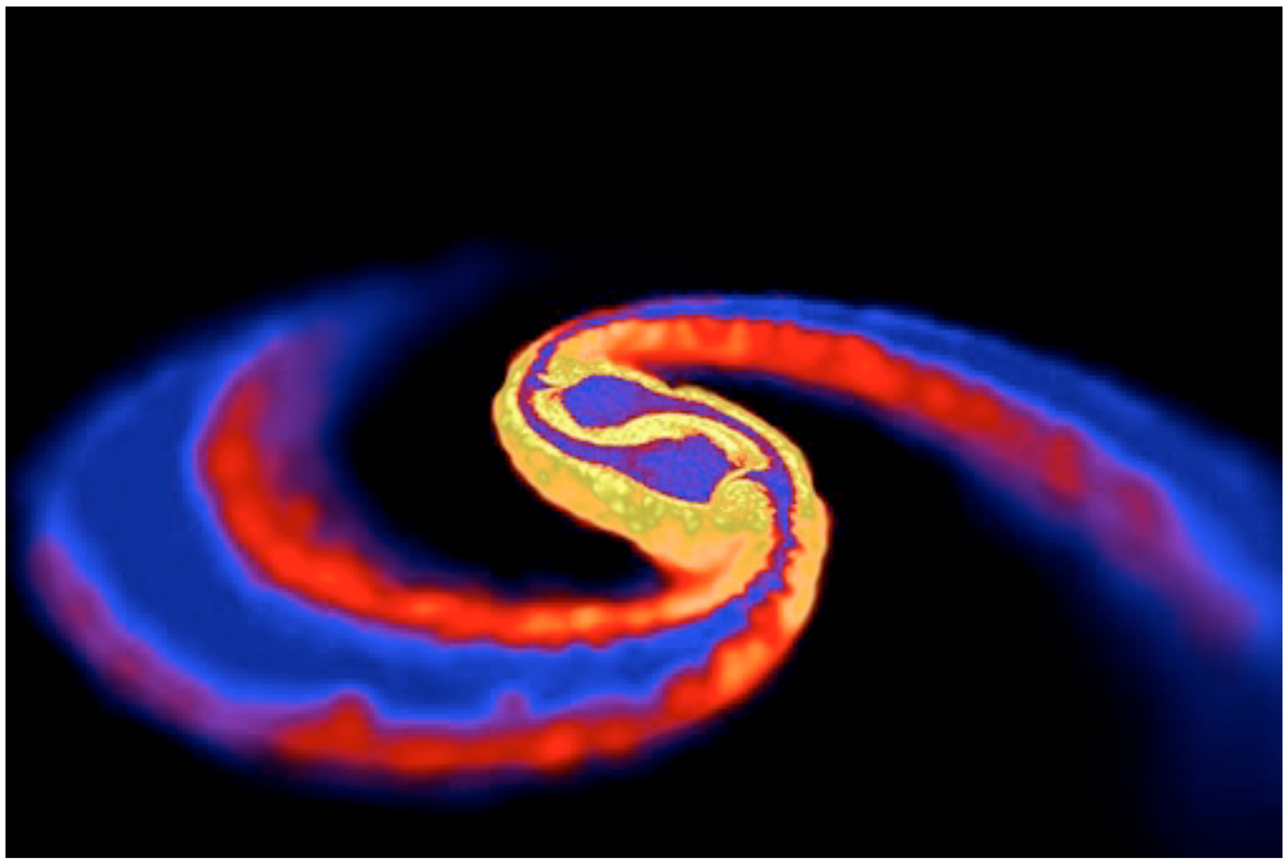


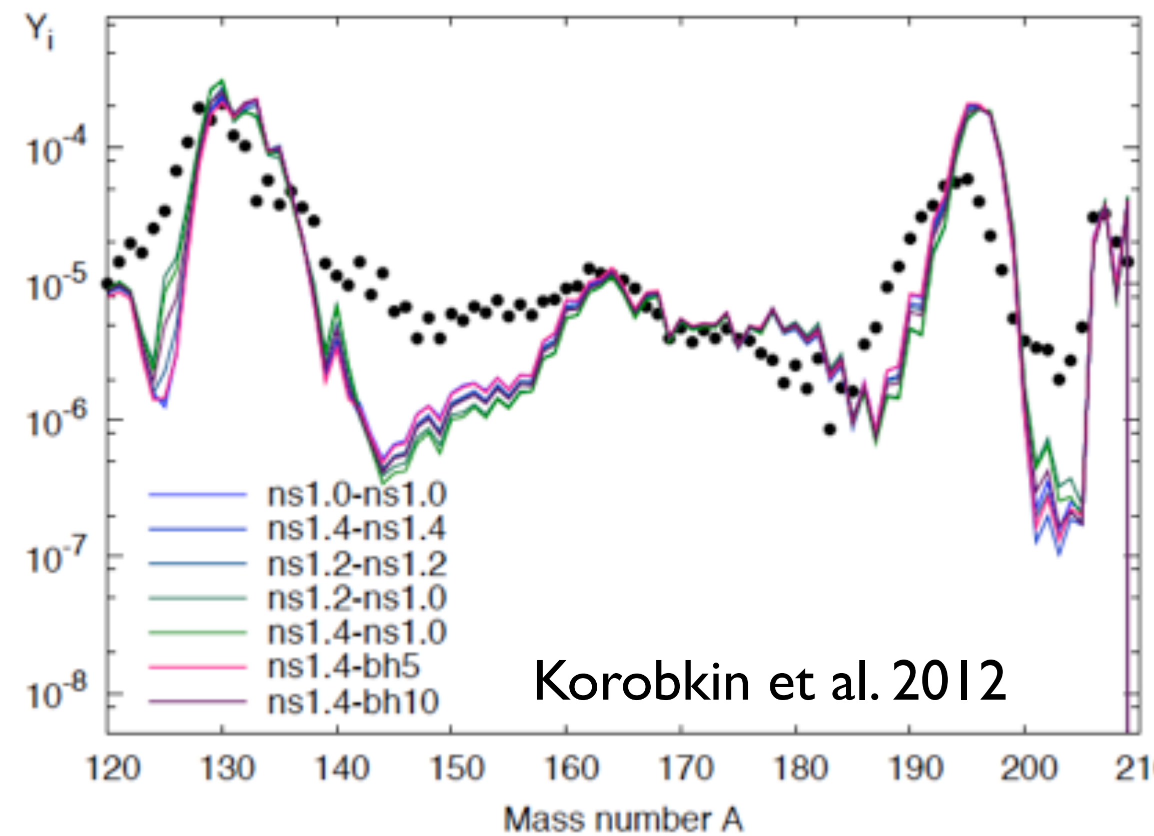
credit: S. Reddy

Stiff eq. of state

Soft eq. of state

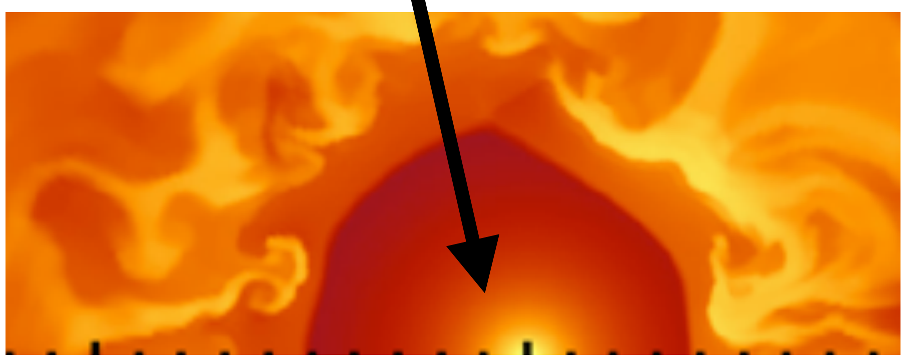
Are neutron star mergers the site of r-process nucleosynthesis?

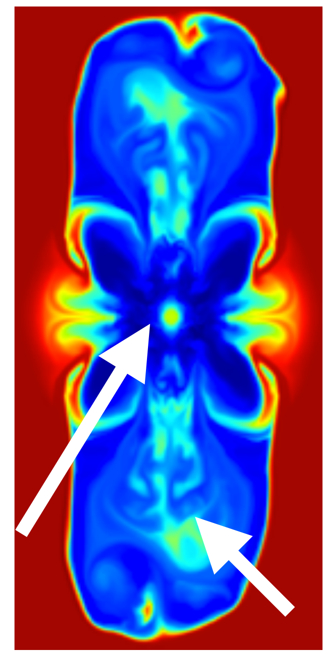




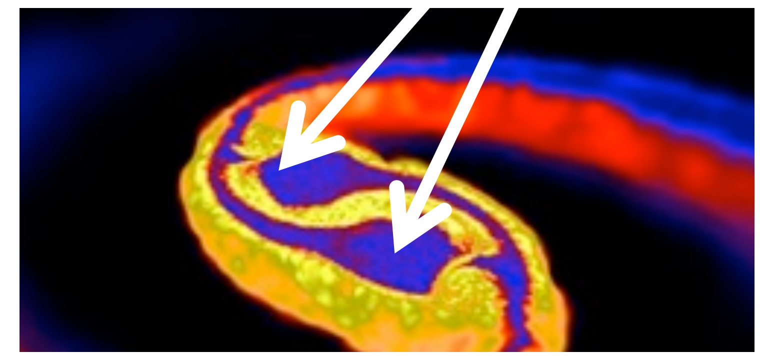
Nucleosynthesis & Neutrinos

proto-neutron stars





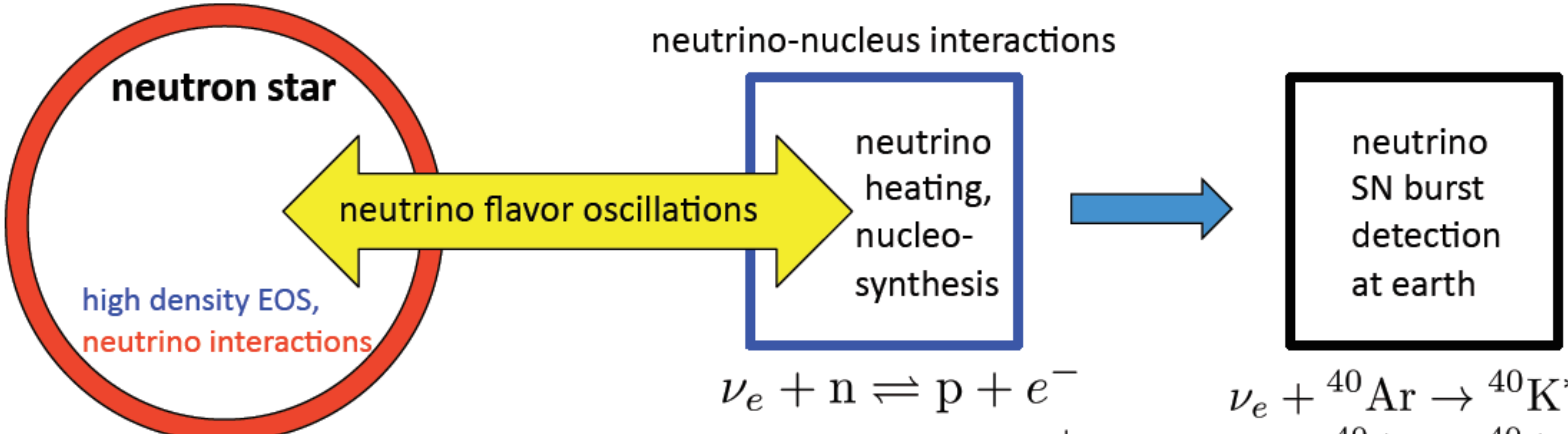
neutron stars



Disks

MHD jets

Neutrino oscillations play an important role (sets Y_e):



$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

Figure Credit: G. Fuller

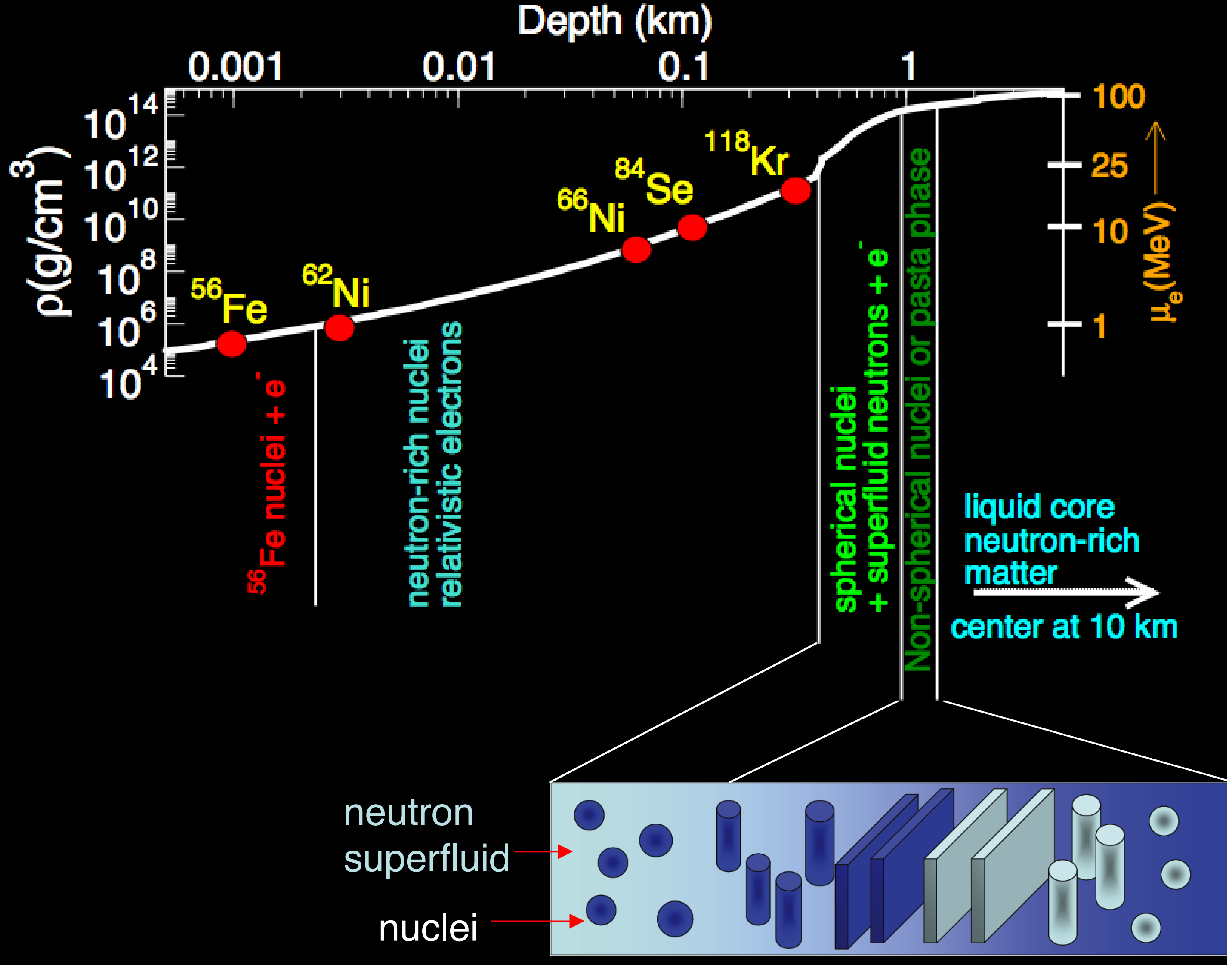
credit: S. Reddy

Dynamics & the Neutron Star Crust

Key to understanding a host of time dependent phenomena:
Glitches, Superbursts, Transient Cooling, Magnetic Field Decay, Giant Flares.

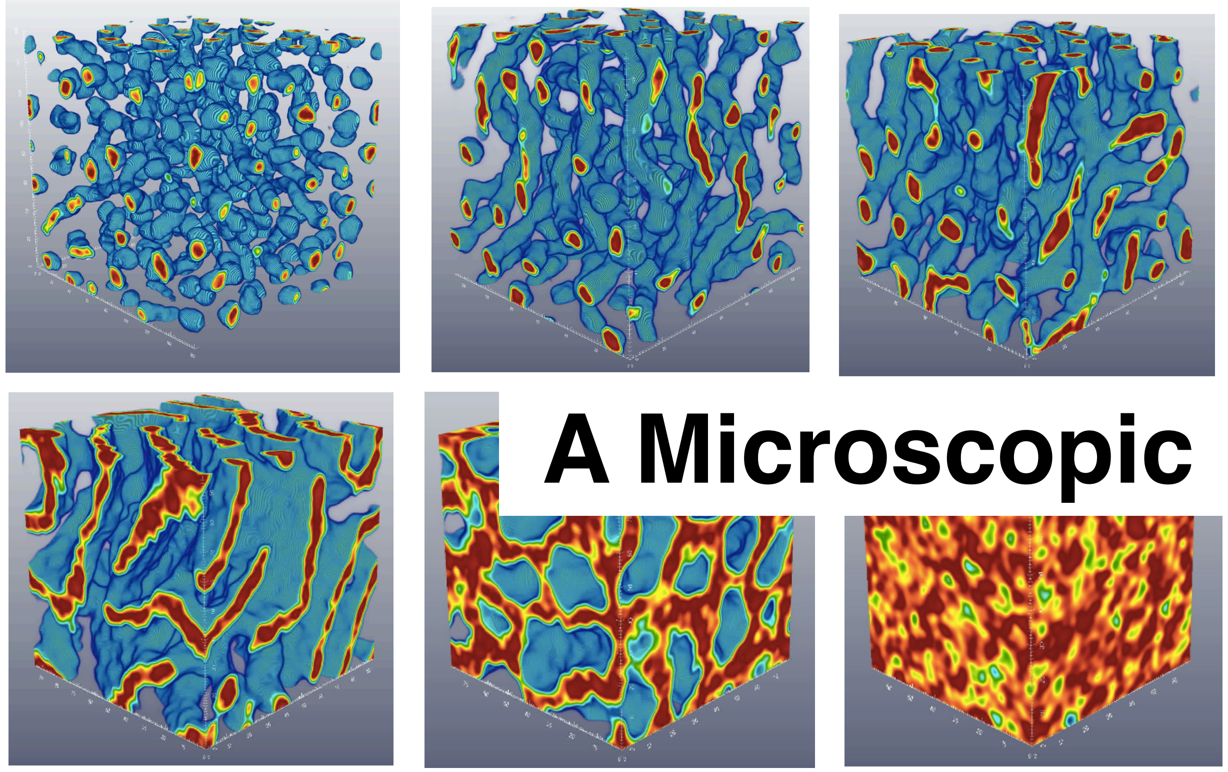
Recent theoretical work sheds light on:

- **Transport properties** (thermal and electrical conductivity, viscosity)
- **Nuclear and neutrino reactions**
- **Superfluid properties and vortex dynamics**



credit: S. Reddy

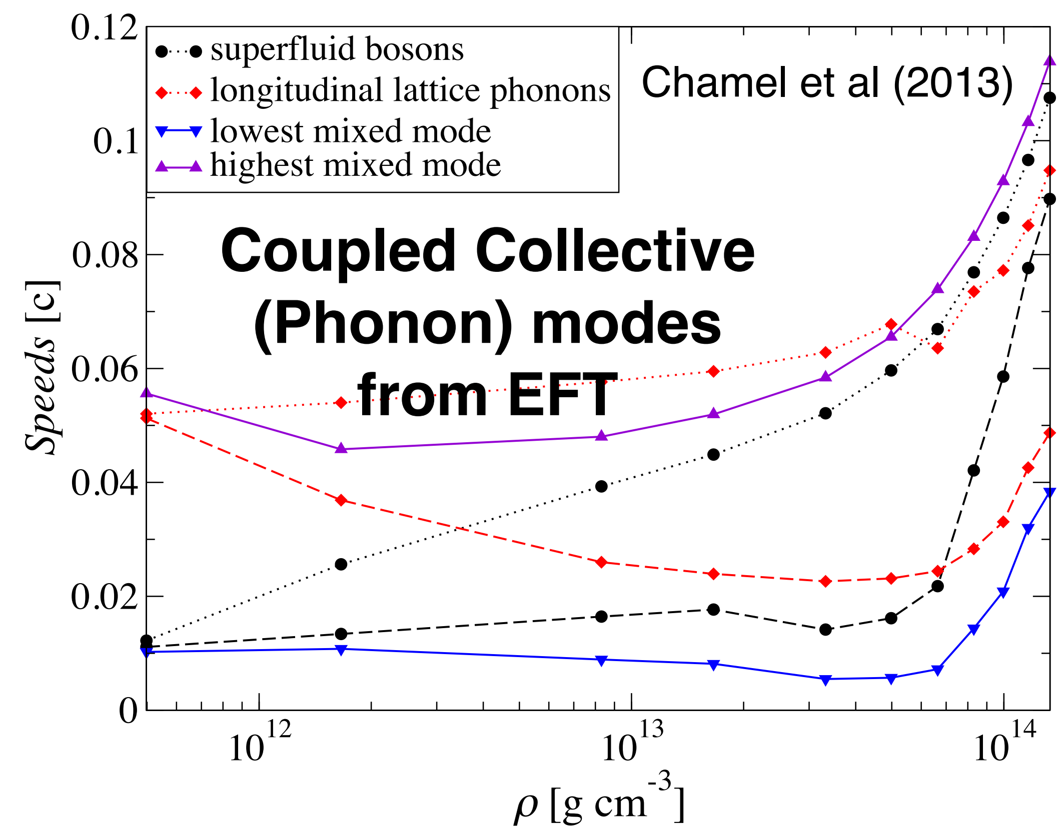
A Microscopic Basis for Crust Models



Molecular Dynamics of Pasta

Schneider, Horowitz, Berry (2013)

- **Large scale Hartree-Fock (HF) and Time-Dependent HF**
- **Molecular Dynamics at high temperatures.**
- **Vortex pinning and dynamics.**
- **Low energy effective field Theory.**



credit: S. Reddy

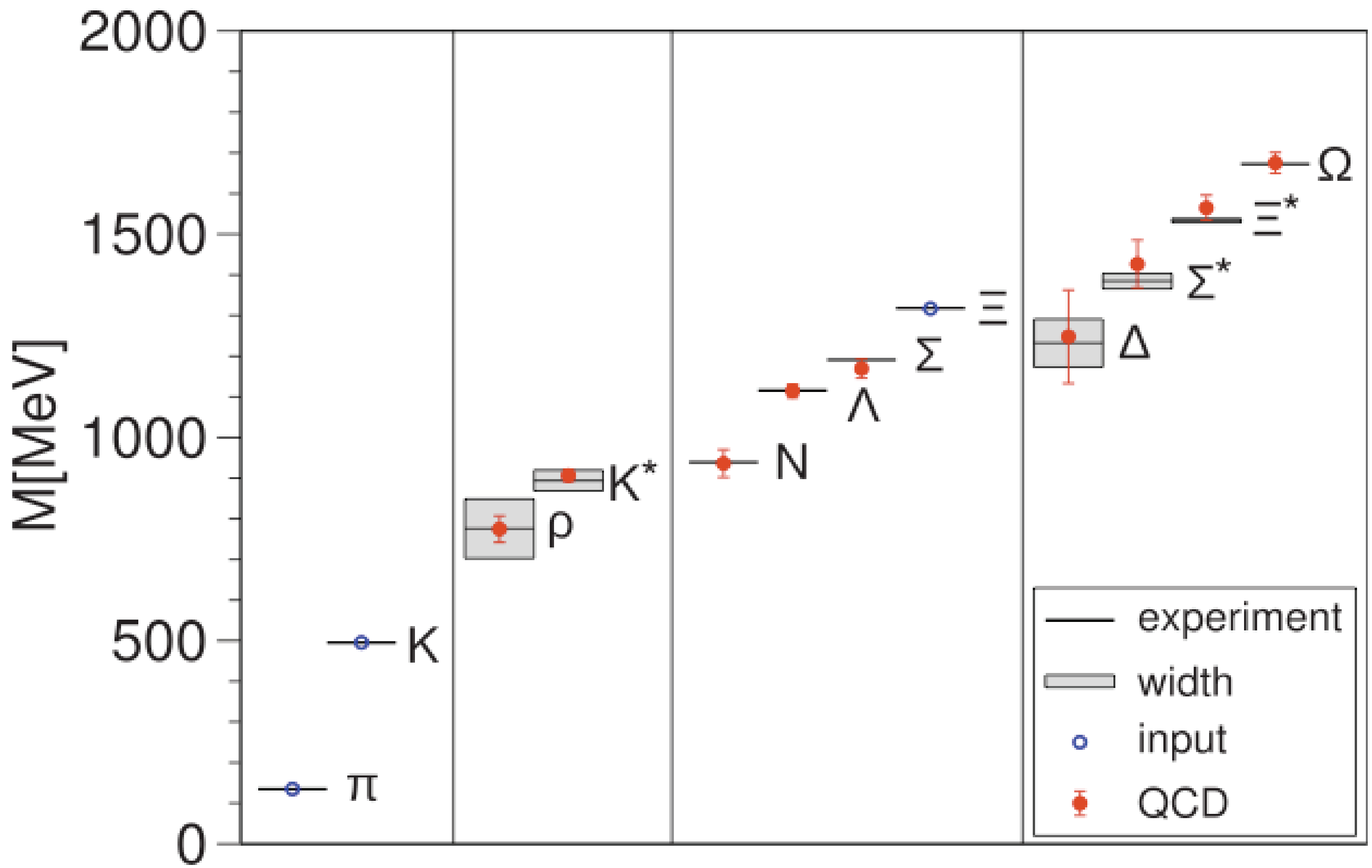
New frontiers for nuclear theory are constantly opening up.

There are no real boundaries between nuclear theory and branches of physics.

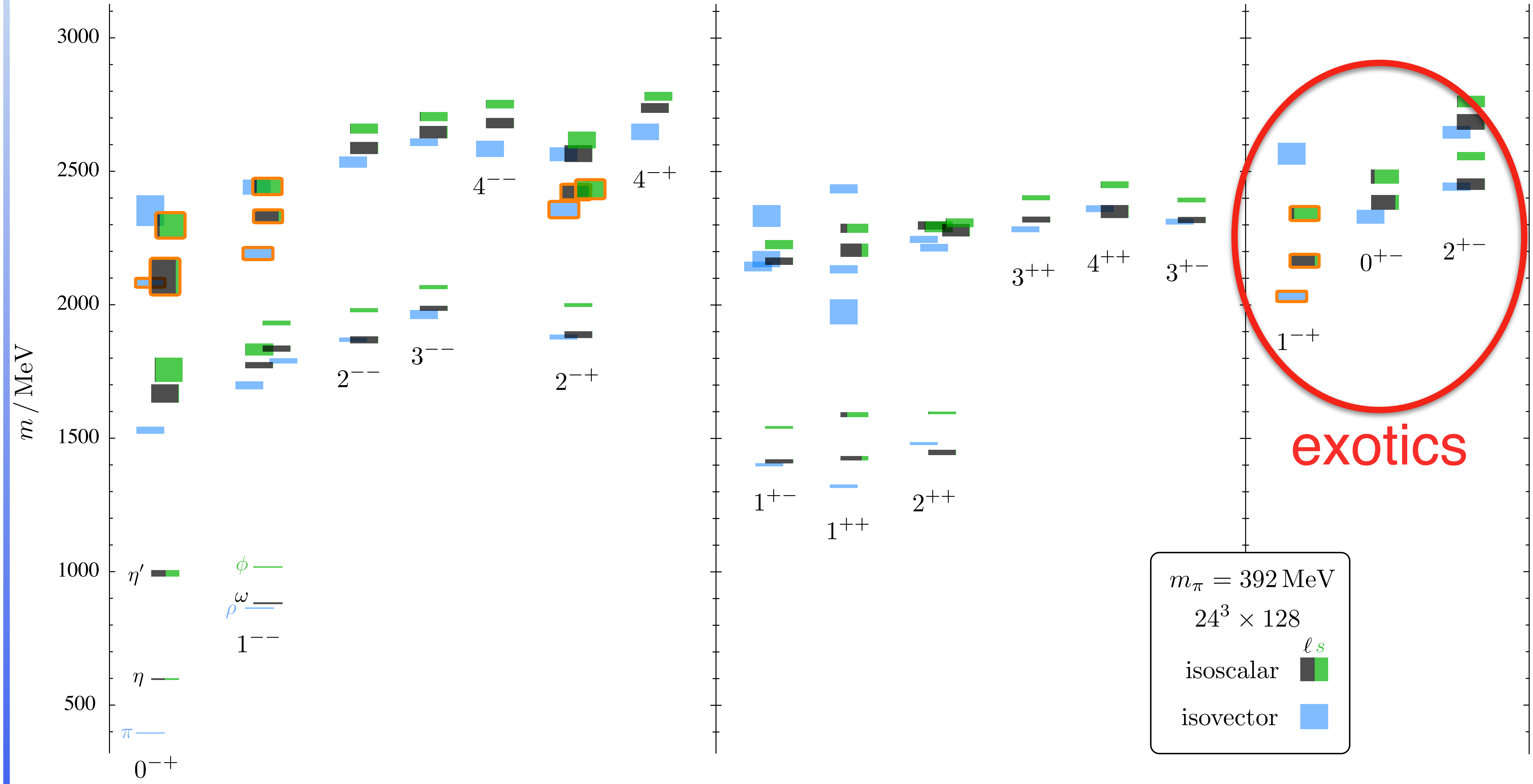
4. Advances in Lattice QCD

Precise determination of low-lying hadron spectrum with physical dynamical quarks

2008 (Dürr et al.):



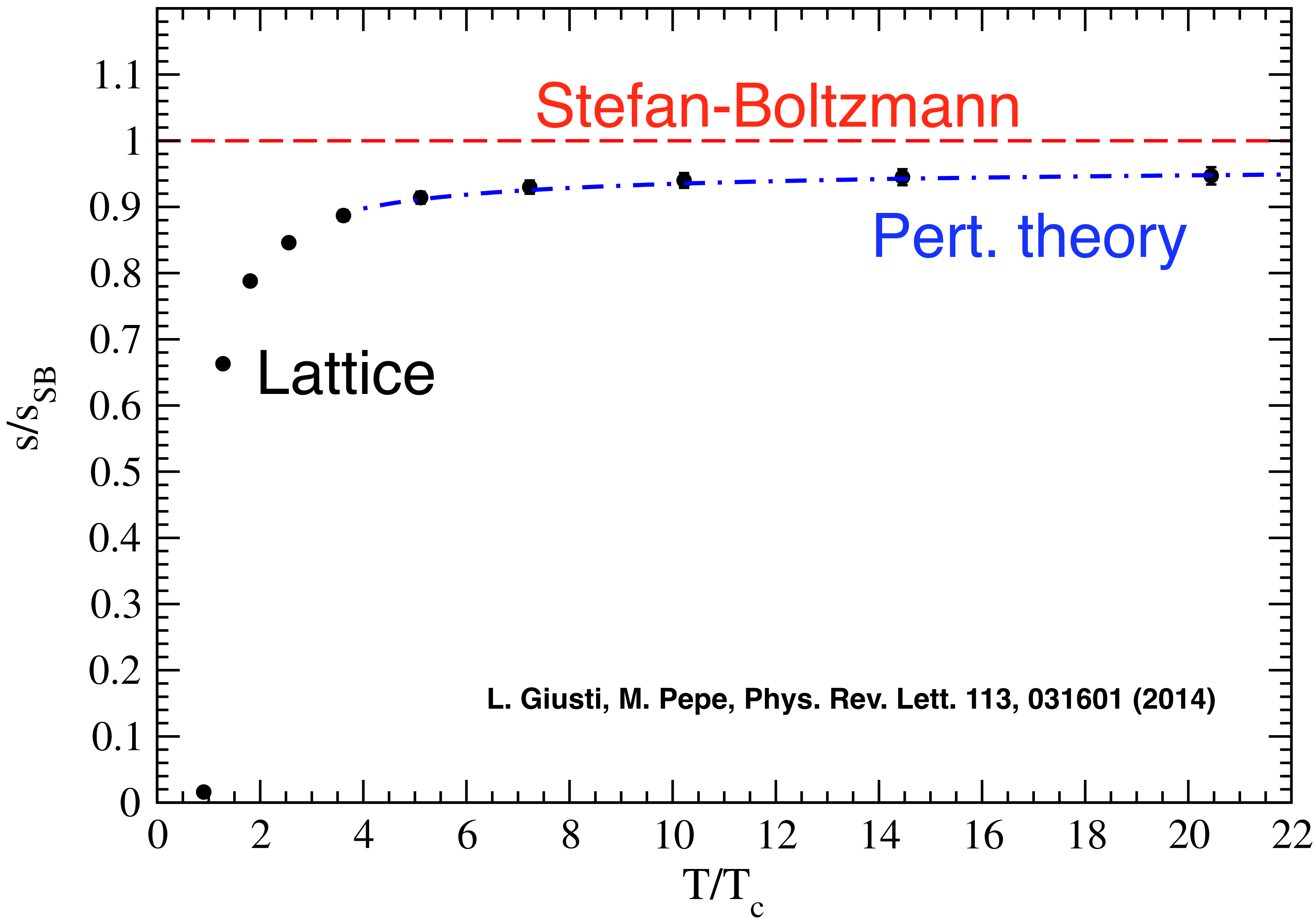
Meson resonances from LQCD



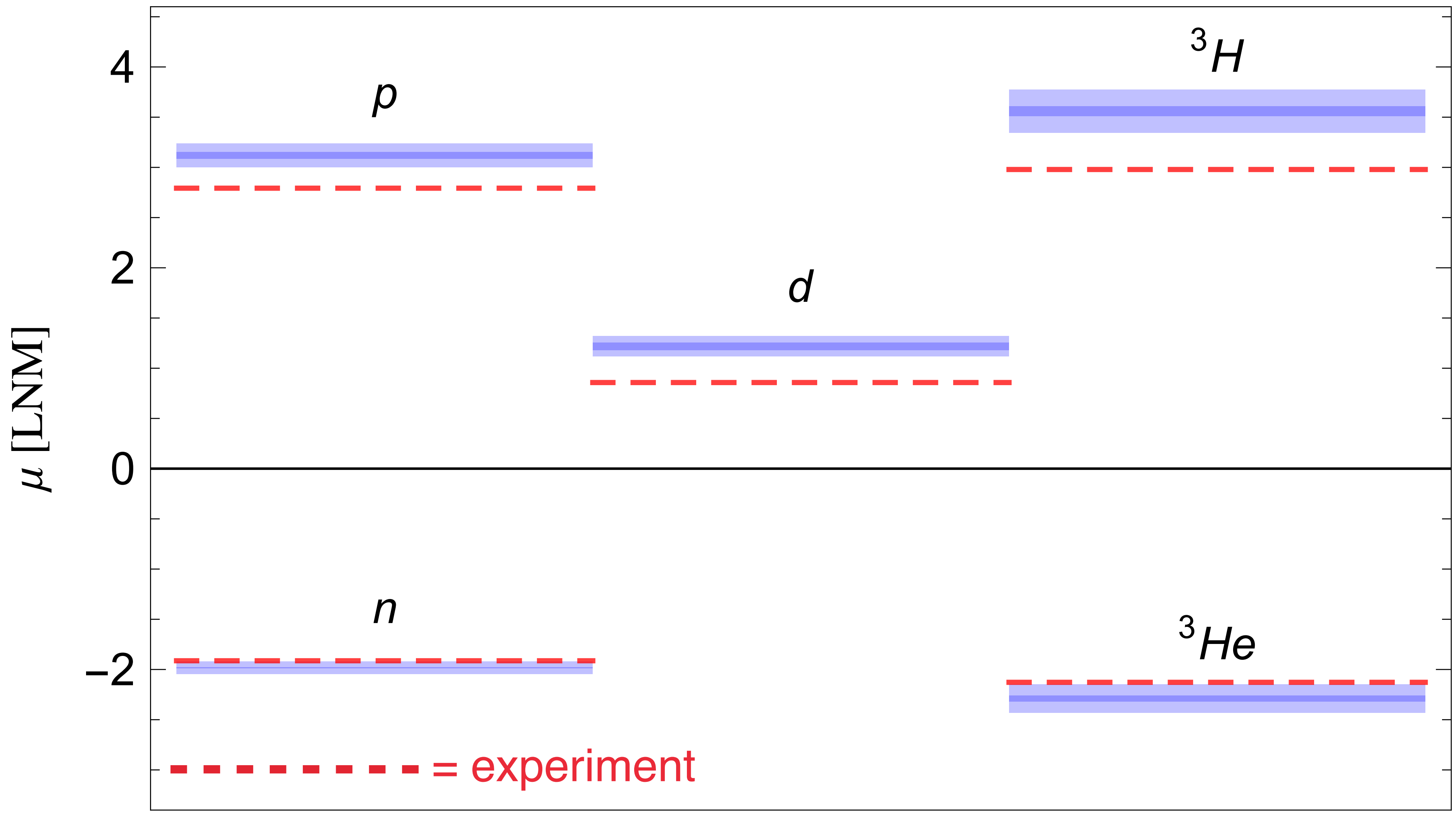
Dudek *et al*, Phys.Rev. D88 (2013) 094505

LQCD is constantly developing new ingenious algorithms for extracting physics directly from QCD with increasing precision

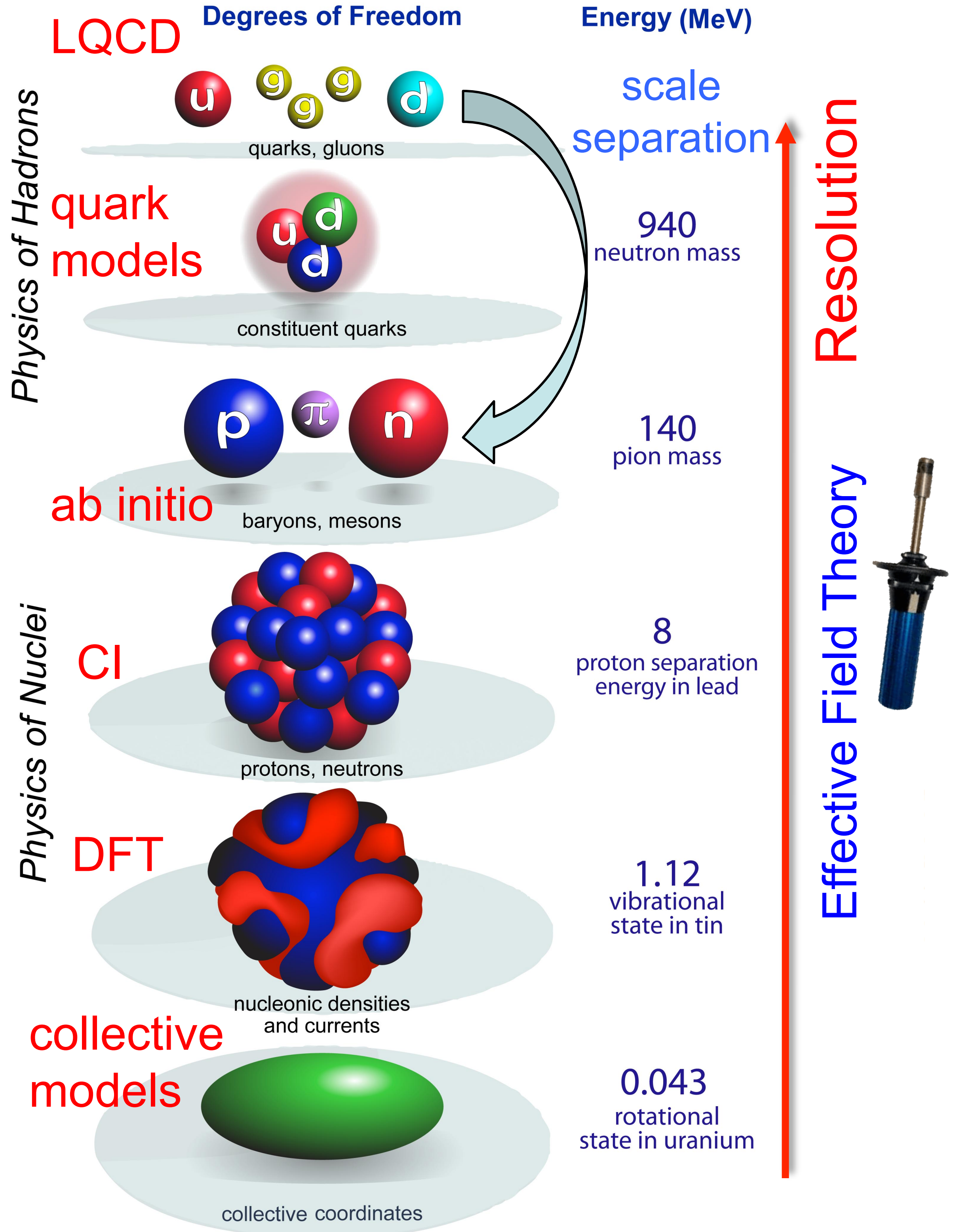
A new method for precision computation of the entropy density in hot pure glue



Magnetic moments computed from LQCD at m_π=806 MeV, in lattice nuclear magnetons

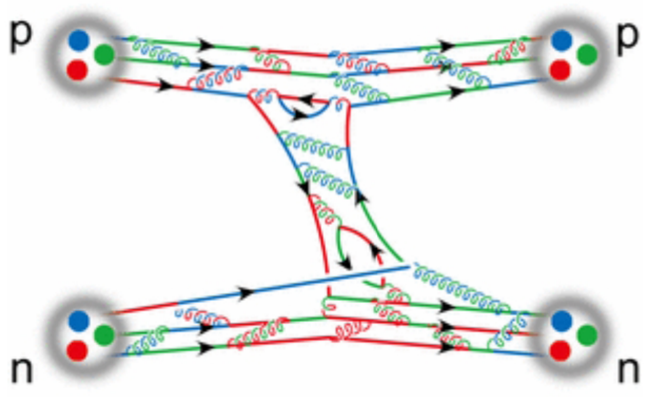


NPLQCD collaboration, arXiv:1409.3556



credit: W. Nazarewicz

The challenge and the prospect: physics of nuclei directly from QCD



LQCD as the 1st step in a sequence of descriptions of nuclei at different length scales

QCD (and more generally, the standard model) is informing nuclear theory from every direction…even where “more is different”

Computational physics is as much part of nuclear physics now as is theory and experiment

Overall lessons from Physics (Recent) Past:

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- This isn't your grandmother's nuclear theory

Overall lessons from Physics (Recent) Past:

- This isn't your grandmother's nuclear theory
- Experimental programs evolve and are enriched as experimentalists and theorists work together

Looking to the future

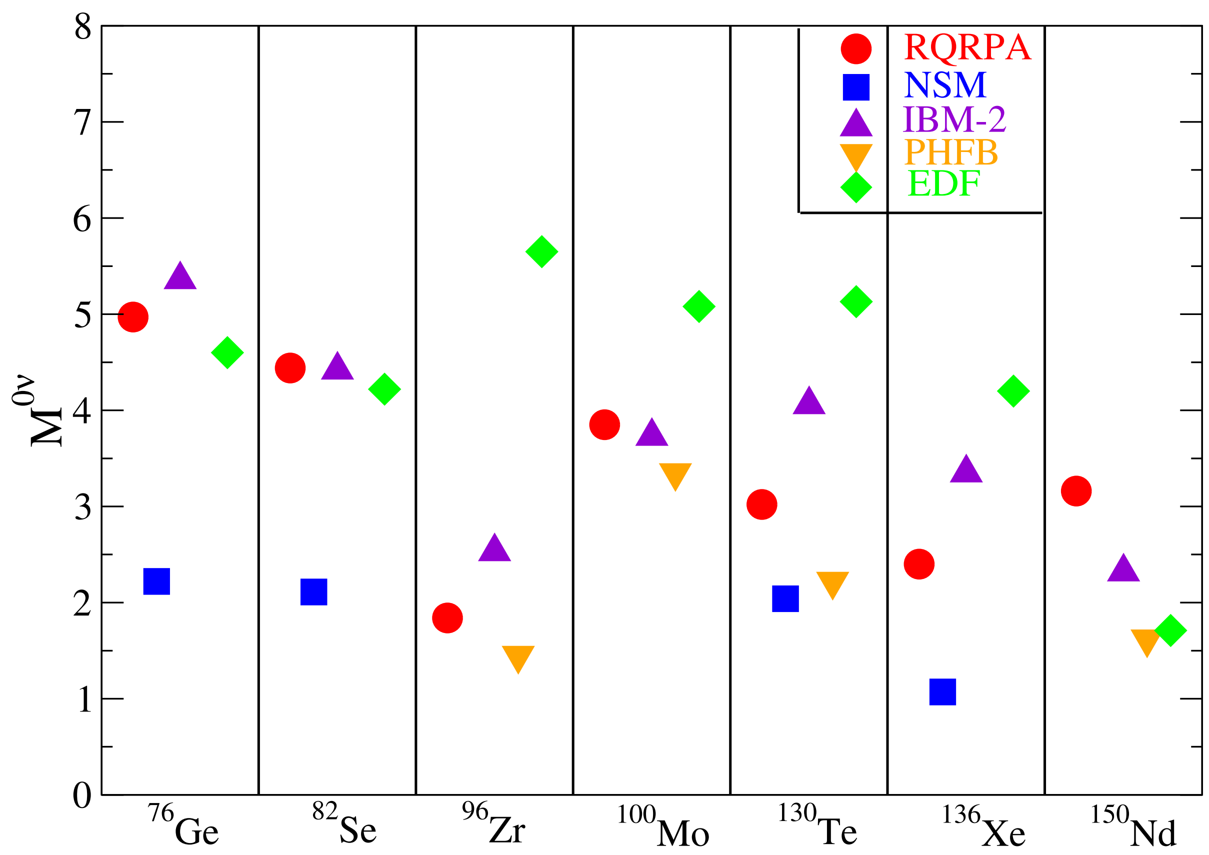
I. The fruitful collaboration between experiment and theory must continue to make the most of our investments…and will keep theorists *busy*

- Develop further the characterization of the QGP from combined RHIC and LHC results
- Predictions for and interpretation of GlueX data from JLab… can we see gluonic excitations in the hadron spectrum?
- Developing reaction theory to a level of sophistication where it can be used to predict and explain FRIB results.
- Computing hadronic corrections to the muon (g-2) to a precision comparable to the future experimental precision.
- Use observations of transient astrophysical phenomena to better understand the properties of extreme matter
- Compute nuclear matrix elements for precision symmetry tests and dark matter detection for physics beyond the SM…

One example

Fundamental symmetry tests and neutrino physics

- Superallowed Fermi $0^+ \rightarrow 0^+$ β-decays
- Neutrinoless double-beta decays
- Schiff moment for EDM
- Neutrino-nucleus scattering



Current $0\nu\beta\beta$ predictions

"There is generally significant variation among different calculations of the nuclear matrix elements for a given isotope. For consideration of future experiments and their projected sensitivity it would be very desirable to reduce the uncertainty in these nuclear matrix elements."
(Neutrinoless Double Beta Decay NSAC Report 2014)

II. **Keep an eye on the BIG questions (and have a tolerance for crazy no-good answers)**

~

Looking to the future

II. Keep an eye on the BIG questions (and have a tolerance for crazy no-good answers)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

SPIN AND UNITARY-SPIN INDEPENDENCE IN A PARAQUARK MODEL OF BARYONS AND MESONS

O. W. Greenberg*
Institute for Advanced Study, Princeton, New Jersey
(Received 27 October 1964)

Wigner's supermultiplet theory,[1] transplanted independently by Gürsey, Pais, and Radicati,[2] and by Sakita,[2] from nuclear-structure physics to particle-structure physics, has aroused a good deal of interest recently. In the nuclear supermultiplet theory, the approximate independence of both spin and unitary spin of those forces relevant to the masses of certain low-lying bound states (particles) makes it interesting to classify the states according to irreducible representations of SU(6). Three results

~

"This can be done if quarks are parafermions of order p=3. This suggestion is the main idea of this article."

II. Keep an eye on the BIG questions cont'd

- How can we map out the entire QCD phase diagram?
- How can we evade sign problems in computing the properties of many-body systems?
- Can we develop analytical tools to connect hadron structure at low energy to the parton description at high energy?
- How does glue arrange itself in hadrons?
- Is there a holographic dual of real QCD?
- Can one successfully complete a coherent and consistent framework to describe nuclei from QCD for few-body interactions, to *ab initio* methods for light and medium mass nuclei, to mean field and its generalizations for heavy nuclei?
- Can one develop the computational tools of mean field theory and its extensions capable of describing induced fission over its entire time evolution from excitation to scission?
- Where are heavy r-process elements created?
- How do massive stars evolve and explode?
- How will dark matter interact with ordinary matter? …

III. A future requires young scientists

Early Career Awards in Nuclear Theory 2010--2014

Principal Investigator	Institution	Year of award
Feng Yuan	LBNL	FY 2010
Denes Molnar	Purdue	FY 2010
Sofia Quaglioni	LLNL	FY 2011
Jozef Dudek	Old Dominion	FY 2011
James Kneller	North Carolina State	FY 2011
Ivan Vitev	LANL	FY 2012
Huaiyu Duan	U New Mexico	FY 2012
Daniel Kasen	UC Berkeley	FY 2012
Paul Romatschke	U Colorado	FY 2012
Gaute Hagen	ORNL	FY 2013
William Detmold	MIT	FY 2013
Carla Frohlich	North Carolina State	FY 2013
Matthias Schindler	U South Carolina	FY 2013
Bjoern Schenke	BNL	FY 2014
Andre Walker-Loud	William & Mary/JLab	FY 2014

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… and young scientists are attracted by both big ideas and job prospects

job prospects:

grad student support → post-doc positions → faculty/staff positions

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grad student support → post-doc positions → faculty/staff positions

- 👍 lab/university bridge positions
- 👍 topical collaborations

The INT experience:

- 57 former post-docs
- 35 now in tenured or tenure track university positions
- 6 have permanent lab staff positions
- 8 employed in industry

Exciting science enlarges job possibilities at universities

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grad student support → **post-doc positions** → **faculty/staff positions**

- 👍 topical collaborations
- 👍 SciDAC Collaborations

The vulnerable link

- 👍 lab/university bridge positions
- 👍 topical collaborations

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LRP needs for nuclear theory:

Personpower to be able to successfully develop with experimentalists the ongoing and upcoming **NP** experimental programs: GlueX, Qweak, Majorana, FRIB, RHIC, LHC, EIC…

Personpower to be able to successfully develop with experimentalists the ongoing and upcoming **other** experimental programs: (g-2), LHC, LIGO, LBNE, DM searches…

A viable and stable career path for young scientists

Support the needs for high performance computing…a critical partner to both theory and experiment

Encourage intellectual risk-taking as a critical element of a successful theory program

One way to quantify person-power needs:

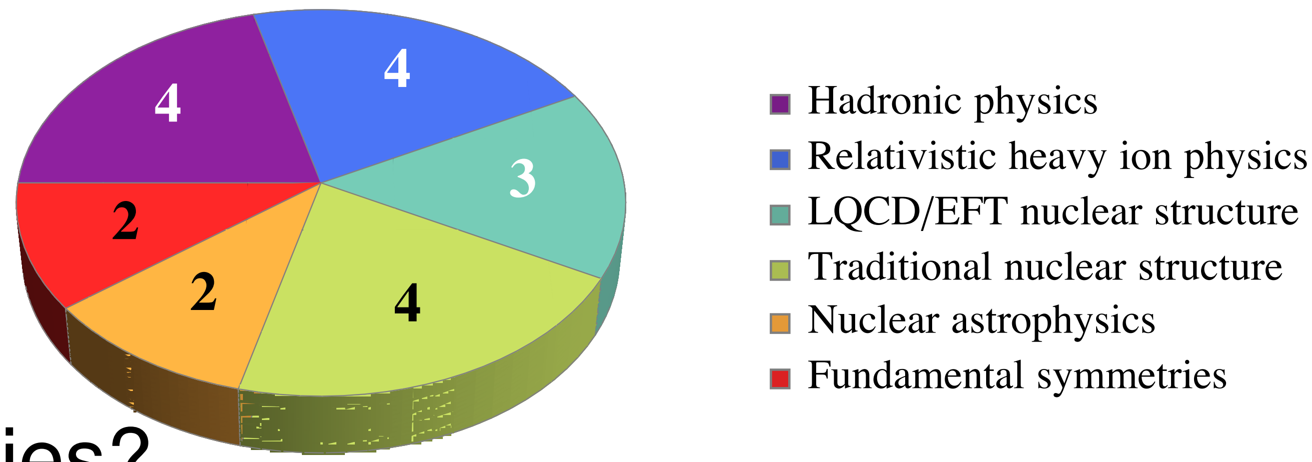
3 Topical Collaborations were funded in 2010:

- **JET**: Quantitative **J**et and **E**lectromagnetic **T**omography of Extreme Phases of Matter in HIC,
  lead PI: Xin-Nian Wang, LBNL
  5-year funding: $2,230k

- **NuN**: **Nu**cleosynthesis and **N**eutrinos in Hot and Dense Matter
  lead PI: Sanjay Reddy, INT, UW
  5-year funding: $2,270k

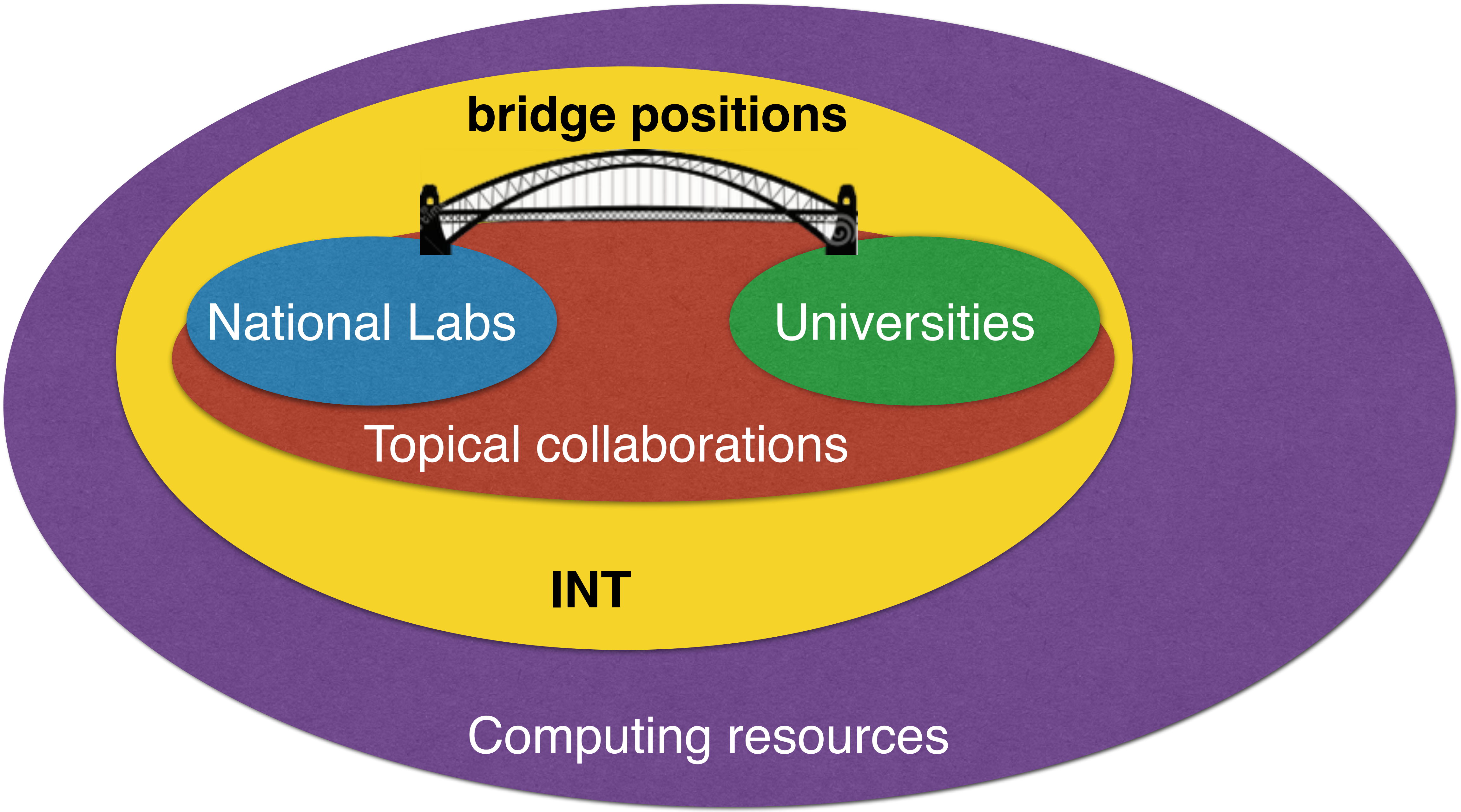
- **TORUS**: **T**heory **O**f **R**eactions for **U**nstable i**S**otopes,
  lead PI: Ian Thompson, LLNL
  5-year funding: $1,329k

…and **16** proposals were not:



What are the missed opportunities?
Are investments in the experimental programs being adequately exploited?

Nuclear theory support has a structure that works well overall

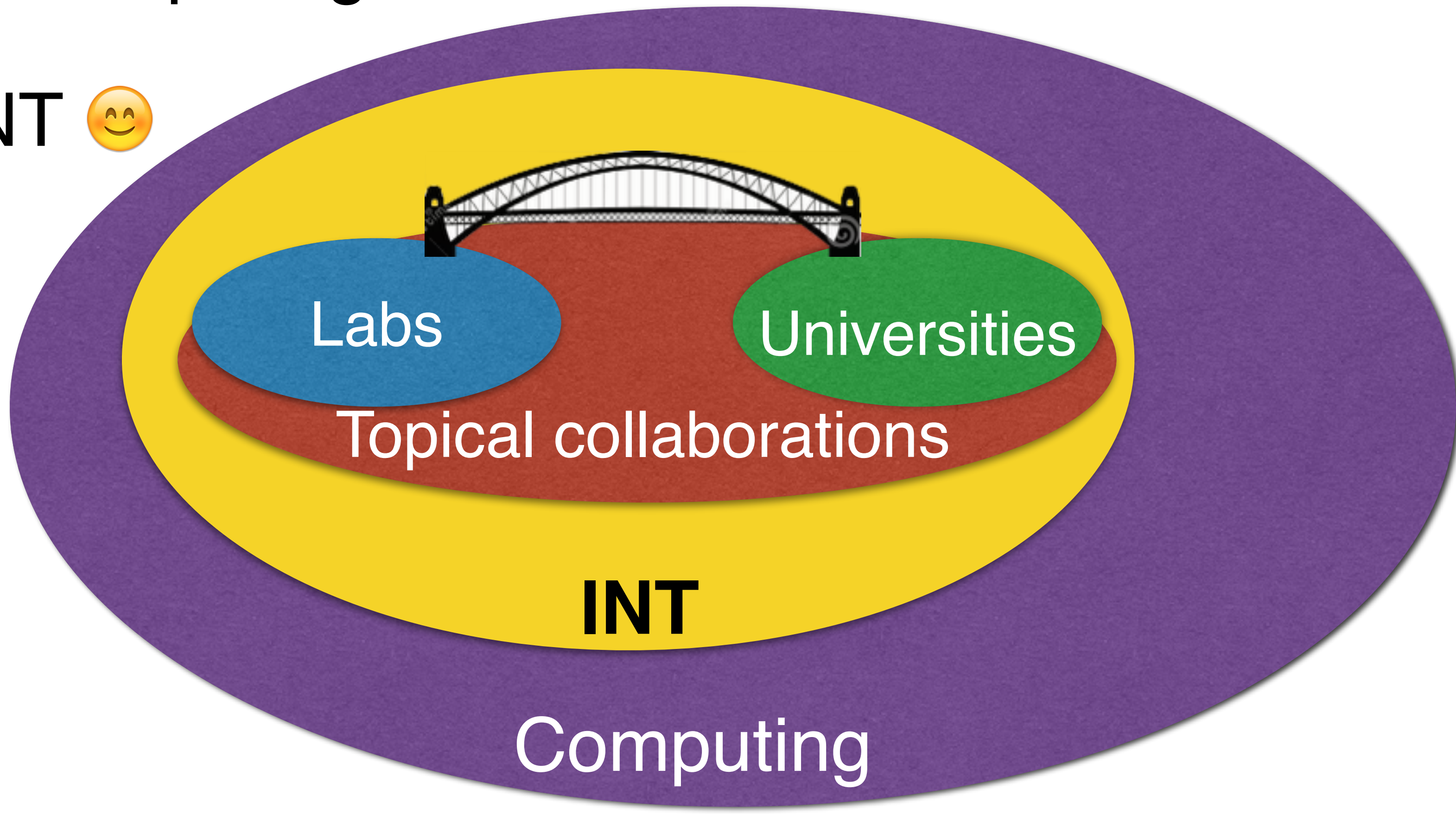


What is the best way to meet our needs without tearing down what works?

Meeting LRP needs for nuclear theory*:

**a consensus opinion of a committee of one*

- Encourage expanding bridge position programs bonding universities and national labs (e.g. with FRIB)
- "Regularize" the topical collaboration program (e.g., 1 new one funded per year), with an emphasis on student, post-doc, and bridged faculty/staff positions
- Support a high performance computing initiative
- Continued support for the INT 😊



…and emphasize throughout the LRP the collaborative effort between experimentalists and theorists to make the most of NP investments — and to discover more than what was originally envisioned