Quarks (and Glue) at Frontiers of Knowledge

Challenges, Opportunities

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and “applications”.

QCD has special features, that make its study especially attractive:

It is precisely defined

numerical ***realization***

It has enormous symmetry

beauty, uniqueness

It *embodies* many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ...)

The existence of interesting open questions is a sign of a field's vitality.

In this talk I'll be posing questions.

Some of them are about things we often take for granted (but shouldn't)!

Later speakers, of course, have a different job. They will be giving answers.

Emergent Phenomena

Quark Model Spectroscopy

Why does the quark model work so well?

Why do M and B body plans dominate?

Why don’t multibaryons make one big bag?

To address "*Why* X?", enable "*Not* X"!

Theoretically:

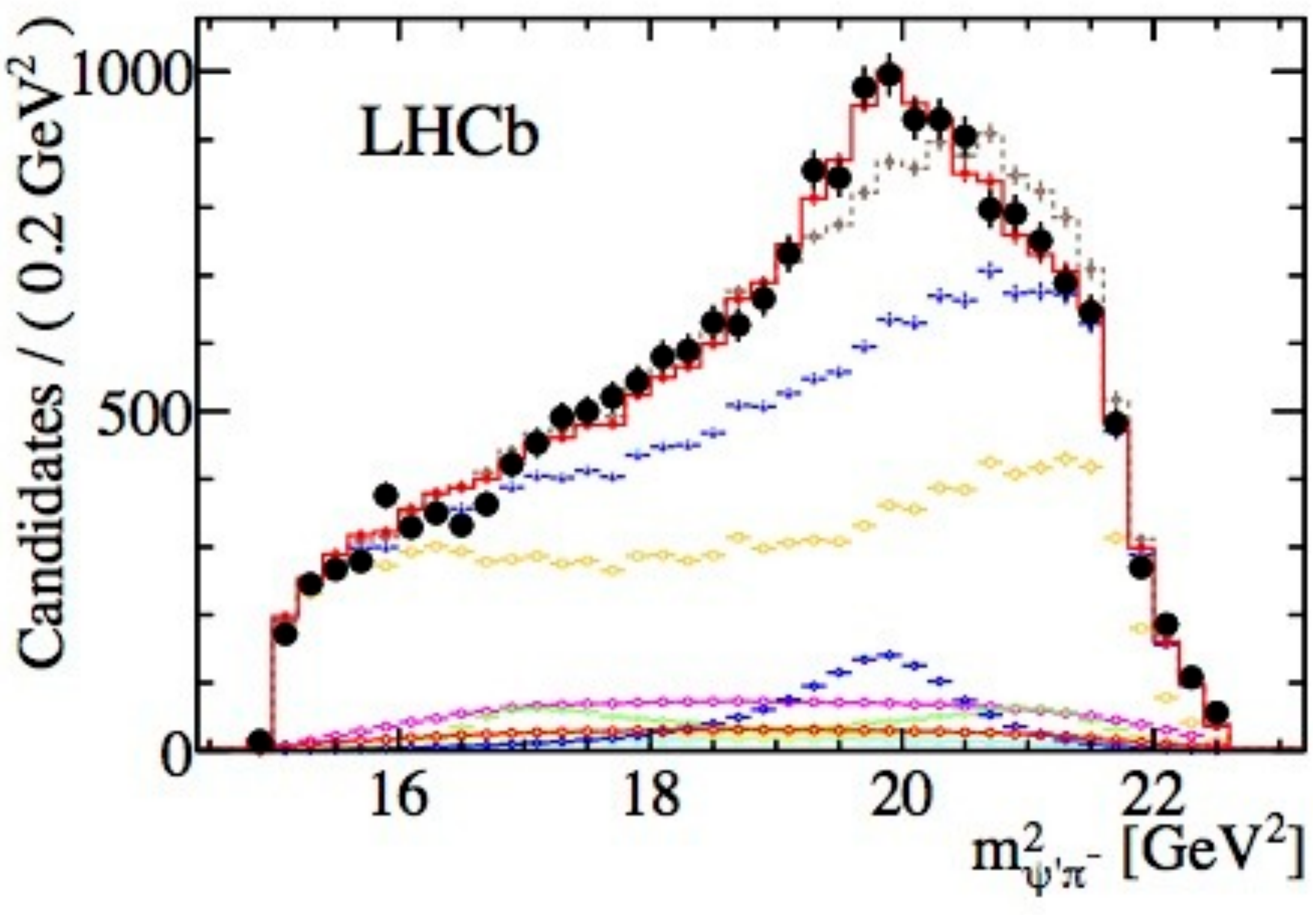
As we vary the quark masses, number of colors, light flavors, spin, or representations of quarks, does the quark model break down?

I'll answer that one: Yes.

But when and how, exactly? When and how do we proliferate non-M, non-B resonances? When and how does nuclear physics go funky?

Experimentally:

What lies outside the M and B body plans?



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Two Protons - Or More?

We have two very different pictures of protons, in the lab frame (quark model) and in the infinite momentum frame (parton model). Each is very successful.

How does one proton manage to become the other? Are there intermediate pictures?

Jets

Why do they exist?

What happens to jets in a world with heavier quarks?

Can we calculate their properties from first principles?

Is there a sensible, quantitative interpolation between totally inclusive (*n* particles) and exclusive (1 particle) production?

Bounded number of particles?

Bounded $(\text{mass})^2$?

Regge Behavior

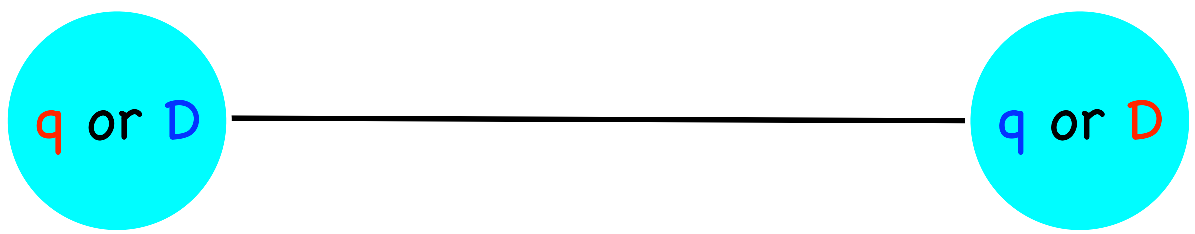
Regge phenomenology is strikingly successful, both in scattering and in spectroscopy, but its QCD foundations are weak.

For the spectroscopy, there is a nice qualitative *picture* involving stretched flux tubes, but the fits for practical L values work much better than that picture justifies.

Also striking is the near-identity of M and B, for $L \geq 1$ (and "good" diquarks).

Clear good/bad distinction	2	N(1680)	N(1720)	N(1990)	Δ (1950)	N(2000)	Δ (1905) Δ (2000)	N(1900)	Δ (1920)		Δ (1910)

$m_{good} \sim m_q$	2	ρ(1690)	ω(1670)			π(1670)	η(1645)	ρ(1700)	ω(1650)


q or D
q or D

This suggests tetraquark trajectories!

High Temperature

Why is the crossover so abrupt, and why does it happen at such low T?

> Is there a usable “underlying” phase transition?

Why is the quark-gluon gas description, which is surely correct asymptotically, so poor at accessible T?

Is the intermediate state of real QCD continuously connected to the "ideal liquid" suggested by large N supersymmetric versions of QCD?

If so, can we draw out any reasonably precise, quantitative consequences?

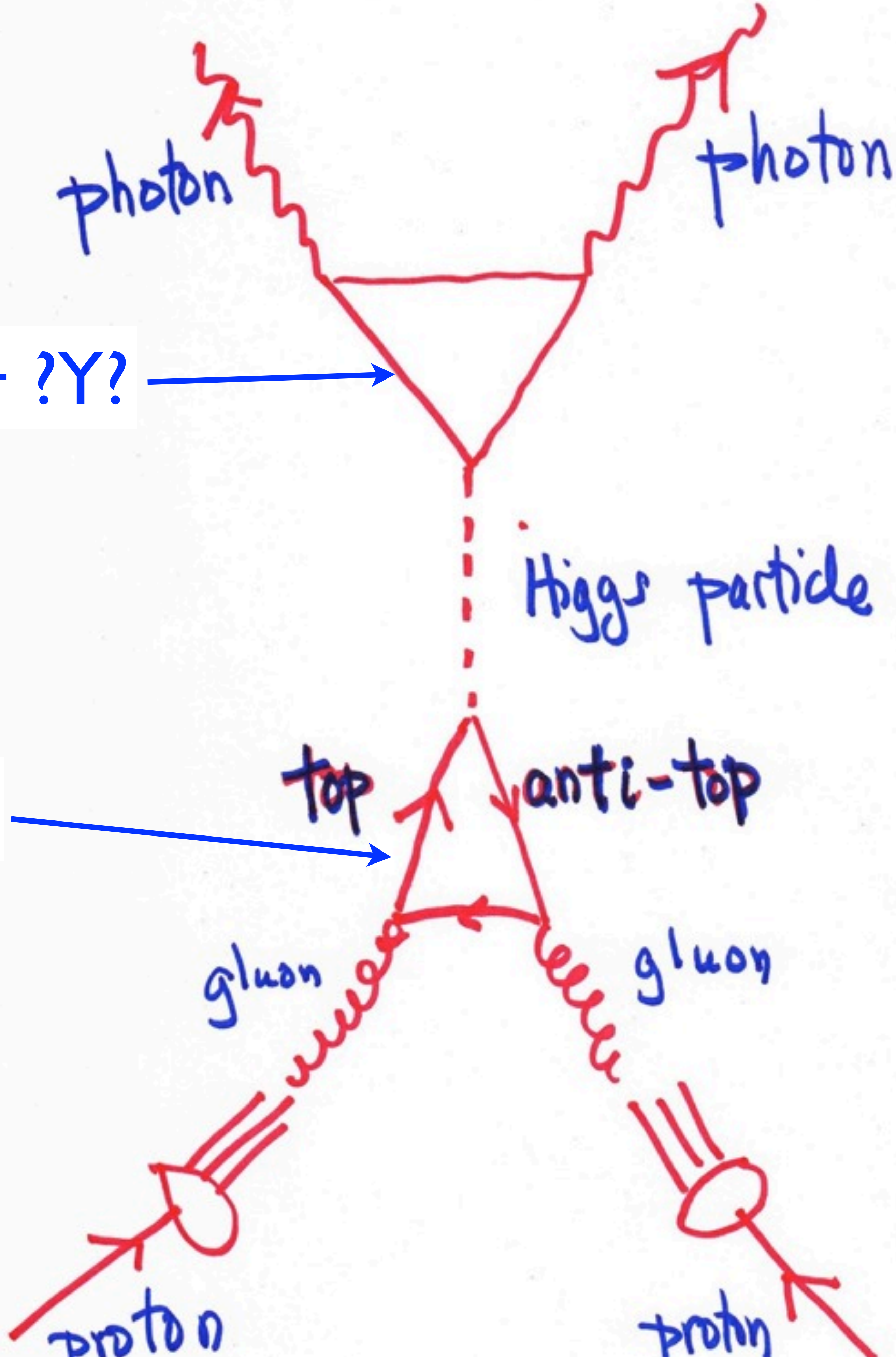
Applications

Perturbative QCD

Perturbative QCD has revolutionized experimental physics at the high energy frontier. Data is routinely, and successfully, analyzed in terms of quarks and gluons.

They are realized as partons inside protons, and as jets in the final states.

$t\bar{t} + W^+W^- + ?Y?$



$t\bar{t} + ?X?$

decay

production

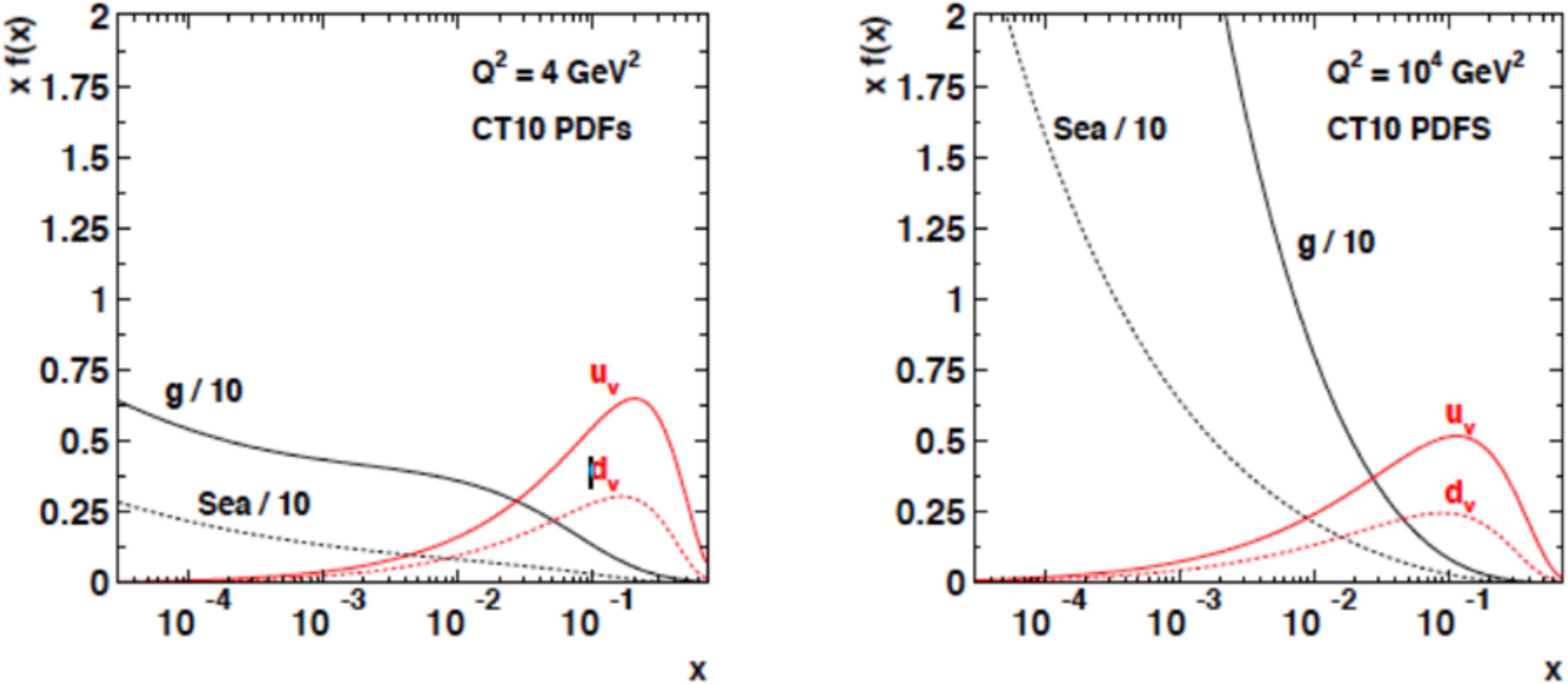


Figure 2: *Example PDFs at NLO at $Q^2 = 4$ GeV^2 and $Q^2 = 10^4$ GeV^2: the gluon density, the sea density $\sum \bar{q}$, and the valence densities $u_v = u - \bar{u}$ and $d_v = d - \bar{d}$.*

There's a lot more useful, honest work to be done here, for example bringing in more refined parton and jet ideas, as well as more complex processes and higher orders.

Nuclear Physics

Can we ground conventional nuclear physics in first-principles QCD?

Can we do improve it?

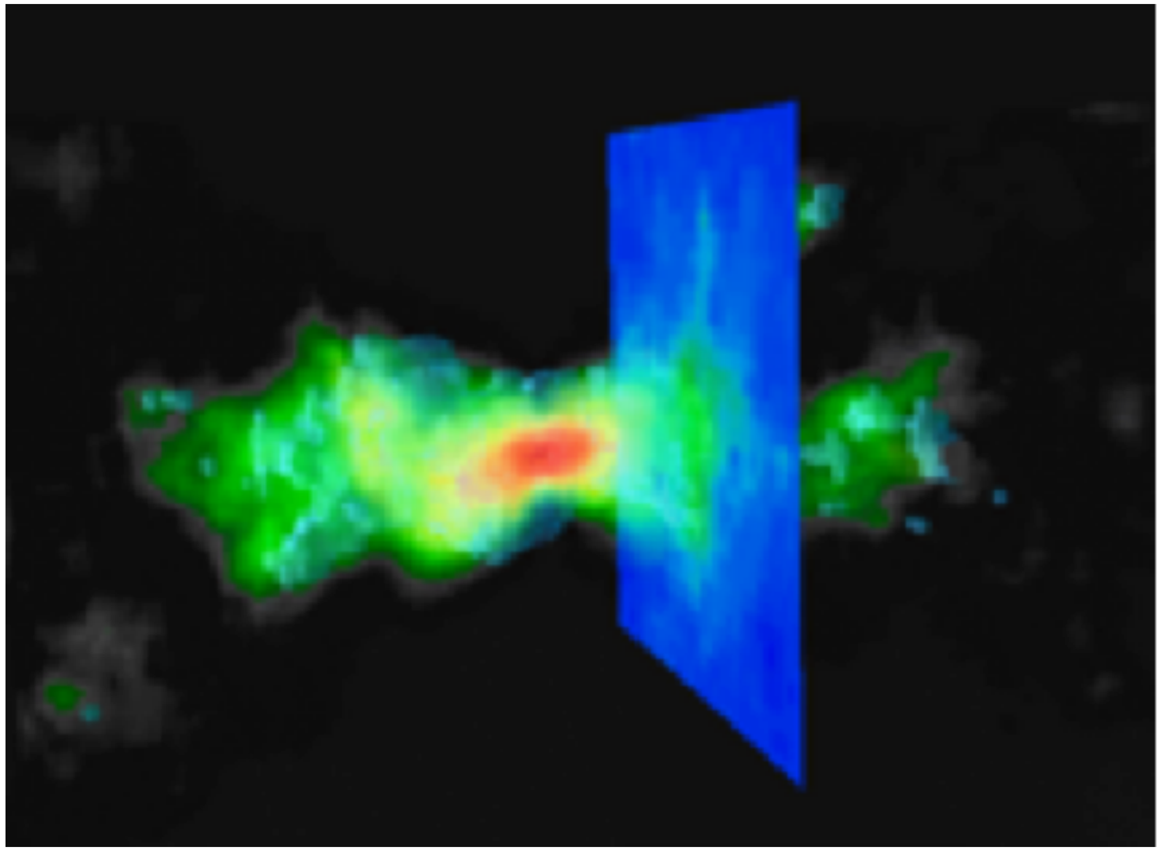
In contrast to the triumph of PQCD, the application of QCD to nuclear physics has, so far, been disappointing.

But that may be changing!

Nuclear Forces from Lattice Quantum Chromodynamics [1]

Martin J. Savage[a]

arXiv: 1309.4752



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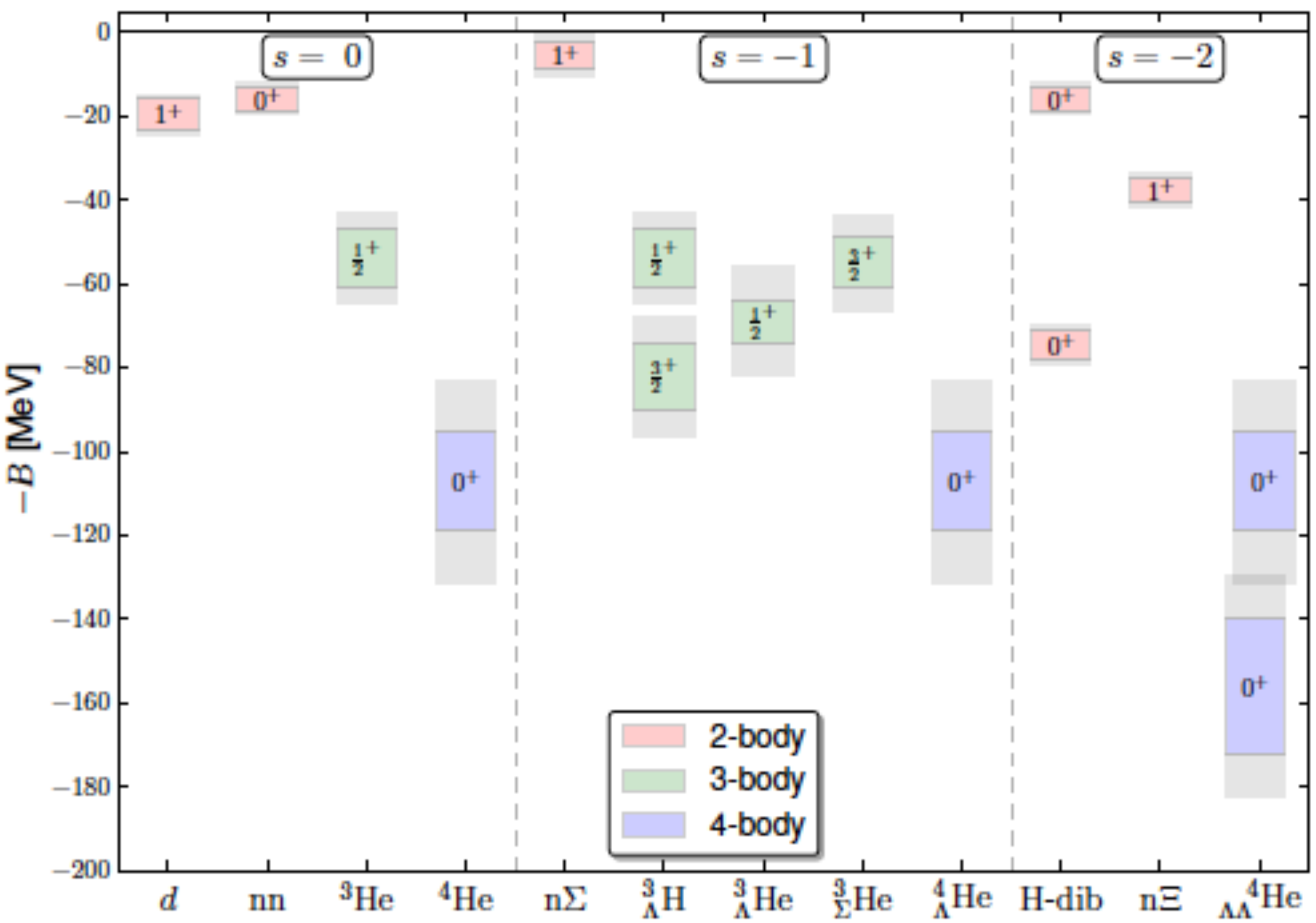


Figure 12: A compilation of the energy levels in light nuclei and hypernuclei in the limit of flavor SU(3) symmetry (with spin and parity J^π) calculated by NPLQCD [37] at a pion mass of $m_\pi \sim 800$ MeV.

Extreme Nuclear Physics

Nuclear physics is pushed into new regimes in the astrophysical contexts of neutron stars and supernova explosions.

Having validated methods in nuclear physics, we can address these issues convincingly.

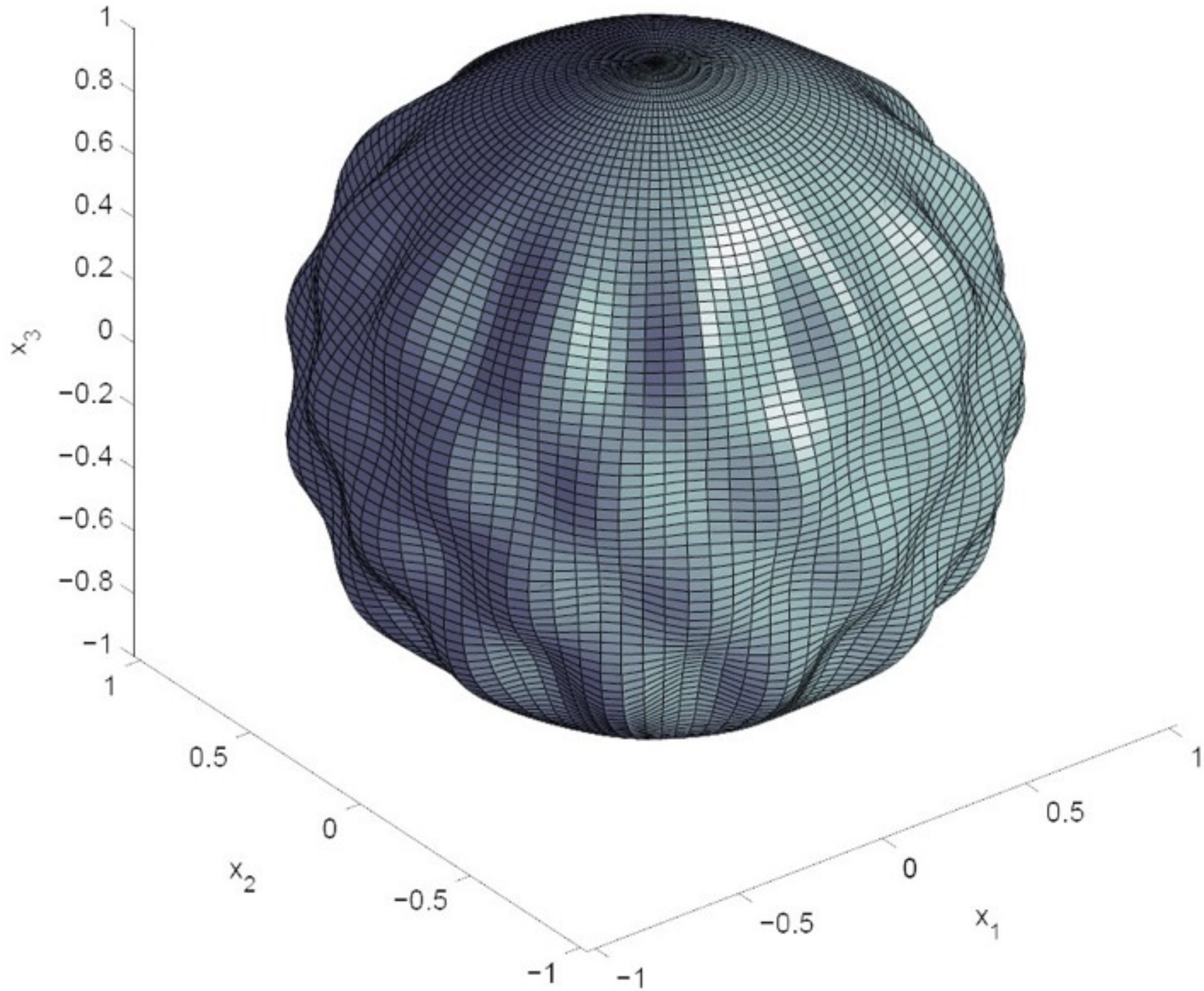
The subject is timely! Powerful automated inventory of neutron stars and supernovas, as well as new windows, are coming on line.

M versus R, cooling

“seismology”

gravity waves

(pulsar infall?)



R. Nilsson

How “Fine Tuned” is Matter?

An interesting question of natural philosophy, and perhaps of physics:

> To what extent is “intelligence-supporting matter” (in anything like the form we know it) is robust against parameter changes?

Here again, our “Why X?” / “Not X” philosophy is on point.

Nuclear Renaissance?

Atomic physics, once relegated to introductory chemistry, has had a remarkable renaissance in recent decades, thanks in large part to lasers and computers (plus brainpower).

Can we imagine something similar for nuclear physics?

Refined nuclear "chemistry" could be a powerful technology for

nuclear medicine

energy storage, e.g. enabling space travel

(and also, of course, weaponry)

Conclusion

The strong interactions still pose many important challenges and opportunities, post-QCD.

Our understanding has improved exponentially on some fronts (lattice QCD spectroscopy, PQCD and jets, finite T) ...

... but it lags in others (~ nuclear physics), that present inspiring prospects.

We desperately need better calculational techniques!

In sister fields, variational methods been most fruitful.