Nuclear Physics from Quantum Chromo-Dynamics (QCD)

A strange journey from nuclei to quarks and gluons...

then back again through extra dimensions and atomic traps

H. Bhabha, B. Peters, Paris 1953

H. Bhabha, B. Peters et al.
TIFR 1956

B. Peters, V. Sarabhai,
Ahmedabad, 1956

Outline for this talk:

I. *Some highlights in the history of the nuclear structure*

II. *From nuclei to quarks to QCD, and an unlikely celebrity*

III. *A map of QCD, and ingenious attempts to find our way back (but we wander off into extra dimensions instead)*

IV. *Life is simpler when you're very dense*

V. *Knowing that we don't know, and effective field theory...which leads us to an atomic trap*

VI. *Escape with the help of a computer to strange places*

VII. *Other universes*

I. *Some early highlights in the history of the nuclear structure*

1911: Rutherford discovers the atomic nucleus

1913: Moseley's study of X-ray spectra shows that the periodic table is ordered by the electric charge of the nucleus (atomic number, Z)

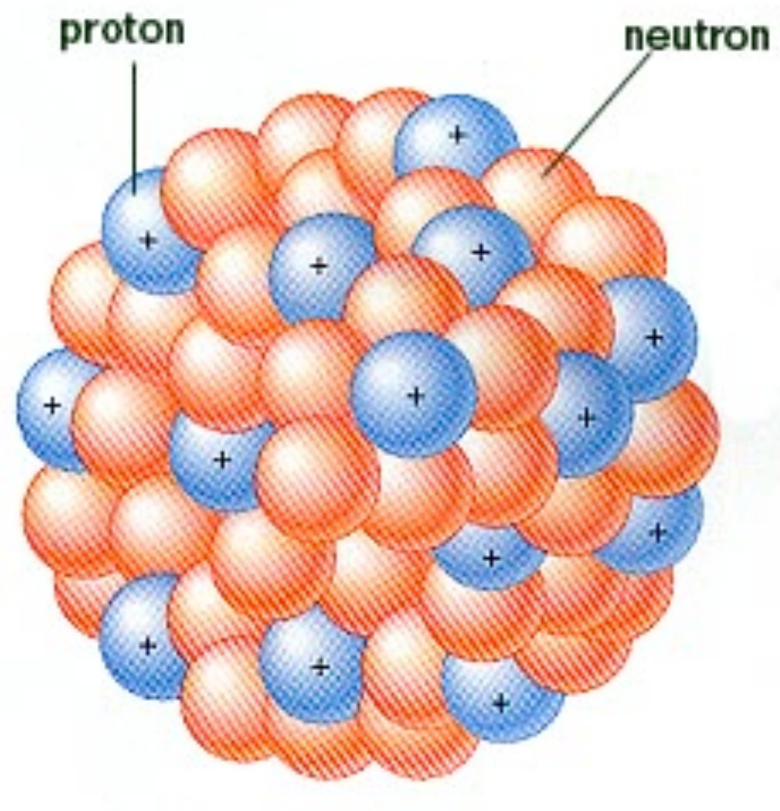
1919: Rutherford discovers the proton as a constituent of nuclei, accounting for Z but not A

1924: Anomalous magnetic moment of proton measured, not consistent with being a point particle

1932: Chadwick discovers the neutron...but free neutrons decay into proton + electron

1935: Yukawa proposes nucleus is held together by mesons (discovered 1947)

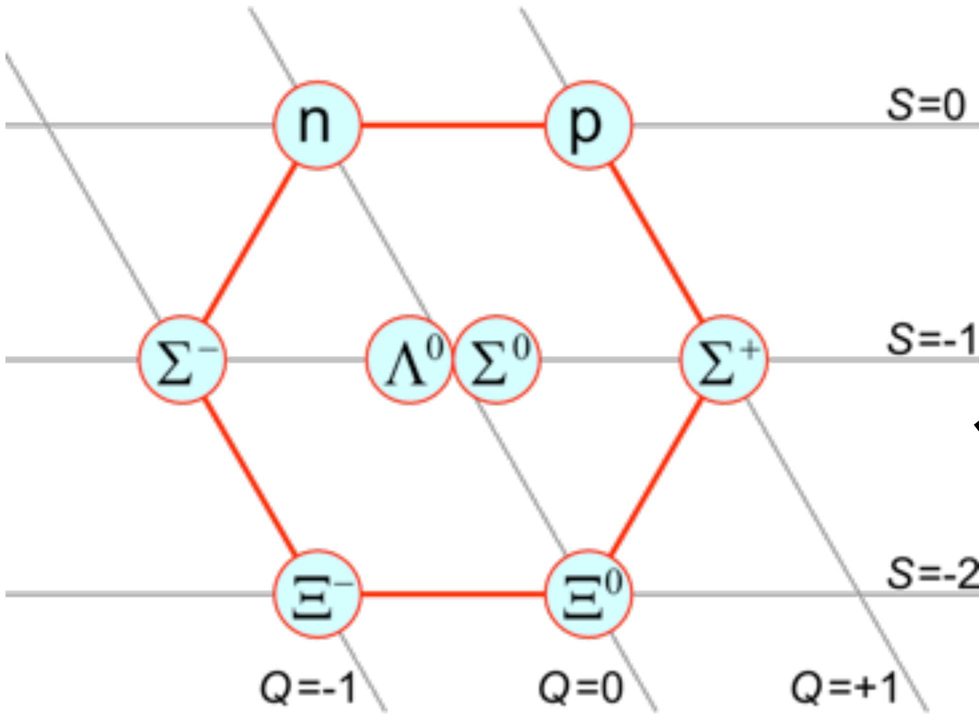
By 1950: heroic effort & a sophisticated theory of the nucleus

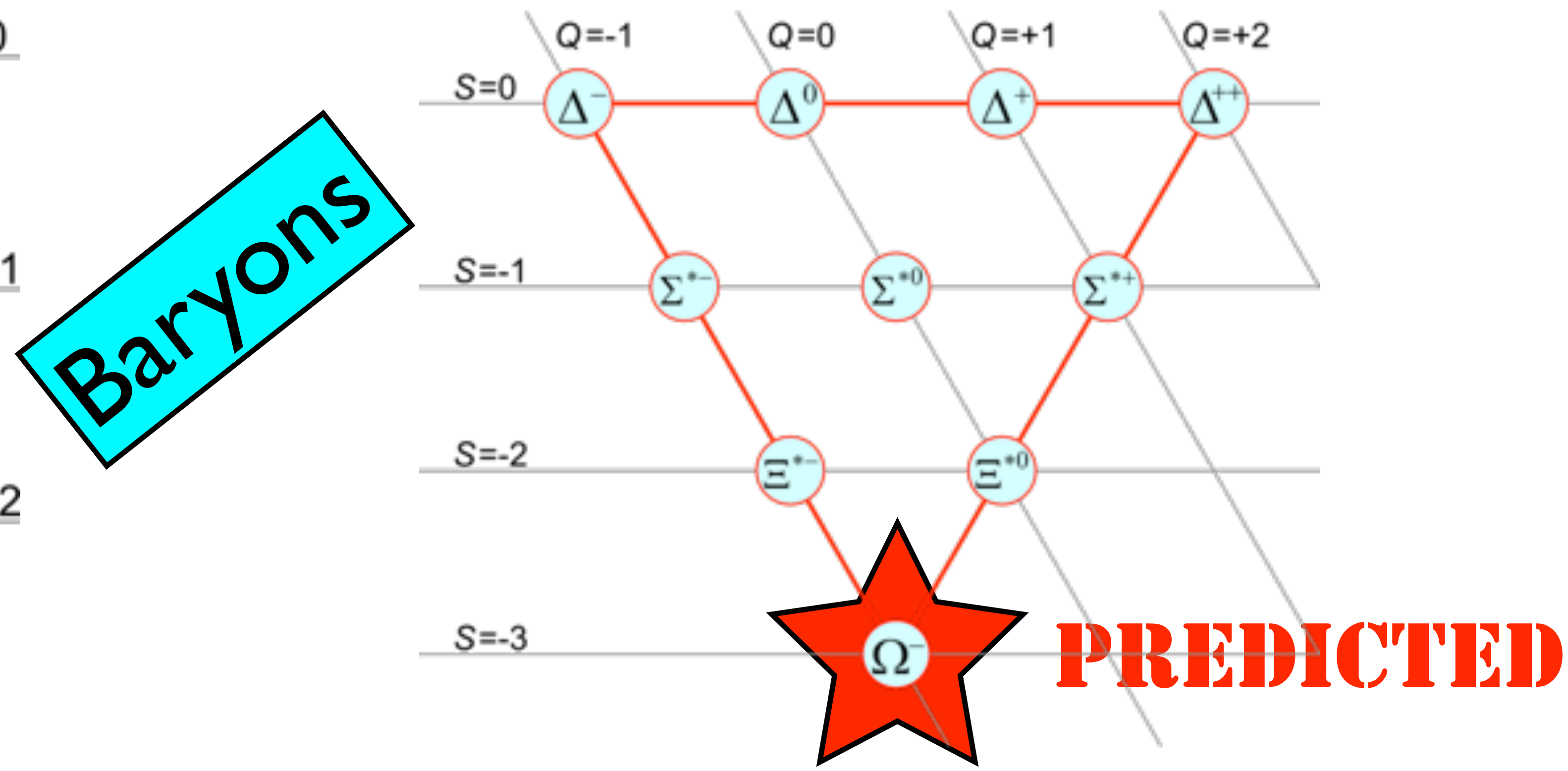


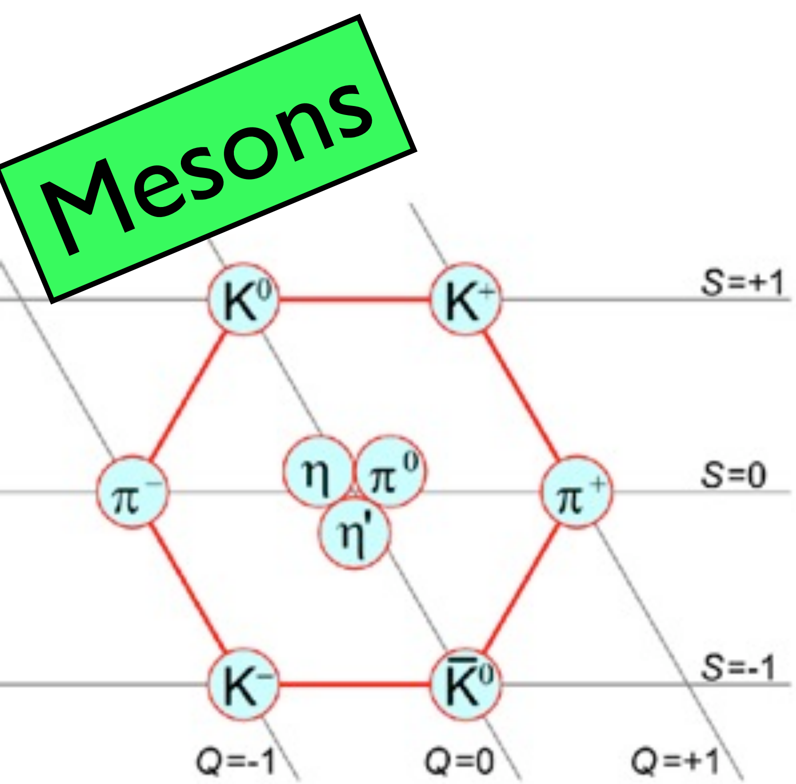
Nice picture, not satisfying

- Pions cannot explain nuclear forces by themselves
- Nucleons, mesons have size & excitations
- Strange particles discovered
- Strong force, weak force, electromagnetism, all look so unlike each other!

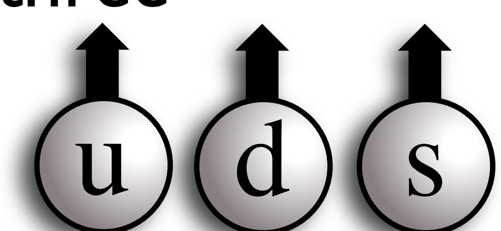
II. From nuclei to quarks to QCD, and an unlikely celebrity







Gell-Mann & Zweig note simple patterns: propose strongly interacting particles are composed of "quarks", which come in three "flavors": up, down, strange



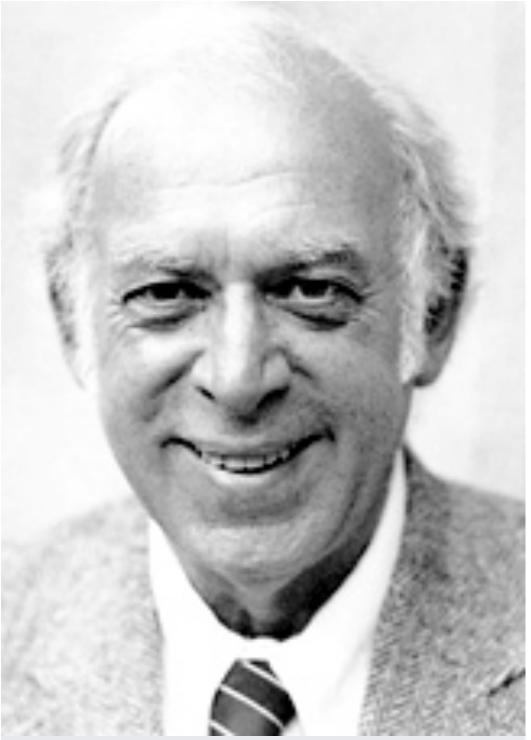
Baryons = 3 quarks

Mesons = quark + anti-quark

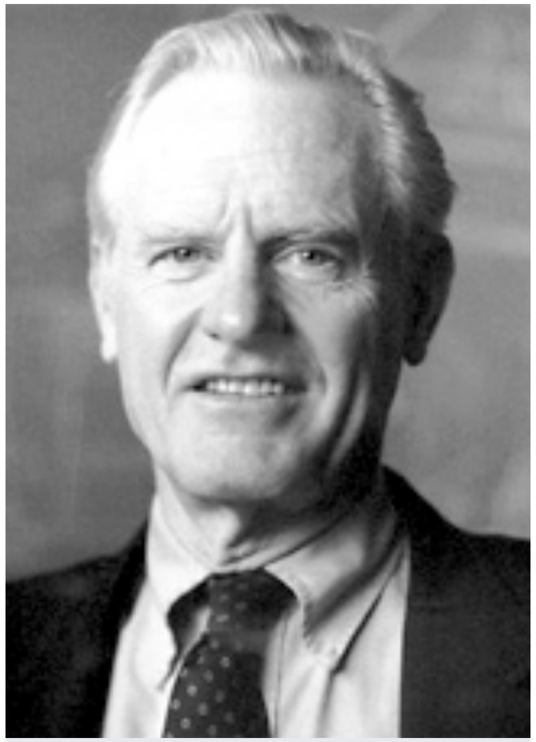
Quarks were "seen" in scattering electrons off nucleons in 1968

The Nobel Prize in Physics 1990

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"



Jerome I. Friedman



Henry W. Kendall

Photo: T. Nakashima

Richard E. Taylor

"In the future, everyone will be world-famous for 15 minutes."

Andy Warhol, 1968

Δ: the unlikely celebrity

Δ BARYONS
$(S = 0, I = 3/2)$

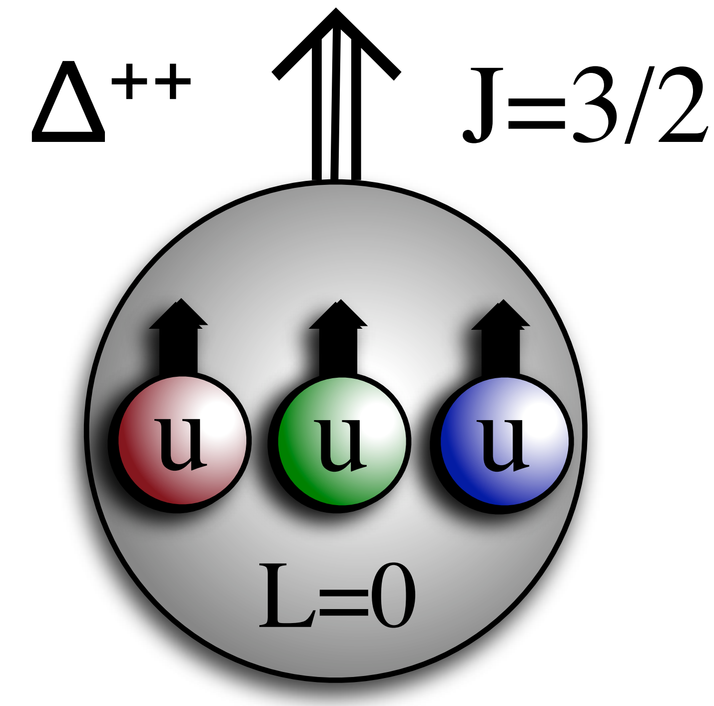
$\Delta^{++} = uuu, \quad \Delta^{+} = uud, \quad \Delta^{0} = udd, \quad \Delta^{-} = ddd$

$\Delta(1232)\ P_{33}$ $\qquad I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Breit-Wigner mass (mixed charges) = 1231 to 1233 (≈ 1232) MeV
Breit-Wigner full width (mixed charges) = 116 to 120 (≈ 118) MeV
$p_{\text{beam}} = 0.30$ GeV/c $\qquad 4\pi\bar{\lambda}^2 = 94.8$ mb
Re(pole position) = 1209 to 1211 (≈ 1210) MeV
−2Im(pole position) = 98 to 102 (≈ 100) MeV

Δ(1232) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	100 %	229
$N\gamma$	0.52–0.60 %	259
$N\gamma$, helicity=1/2	0.11–0.13 %	259
$N\gamma$, helicity=3/2	0.41–0.47 %	259

Δ^{++} Lifetime: 6×10^{-24} sec



Quark model:
three identical quarks in the same quantum state…
Violates Pauli principle!

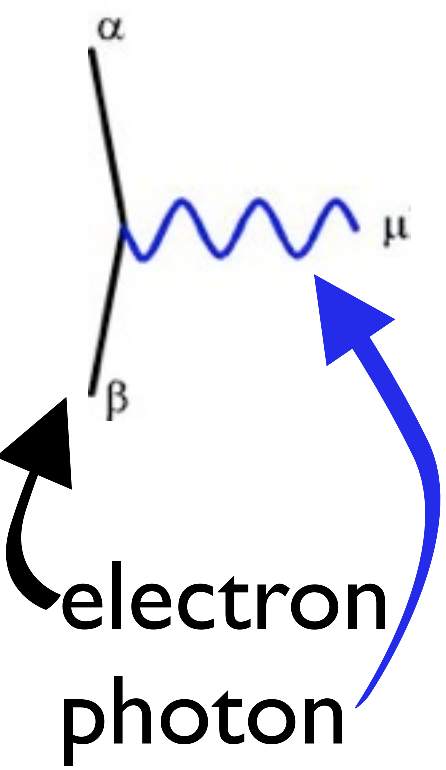
OK if quarks are not identical & carry a new quantum number:

color

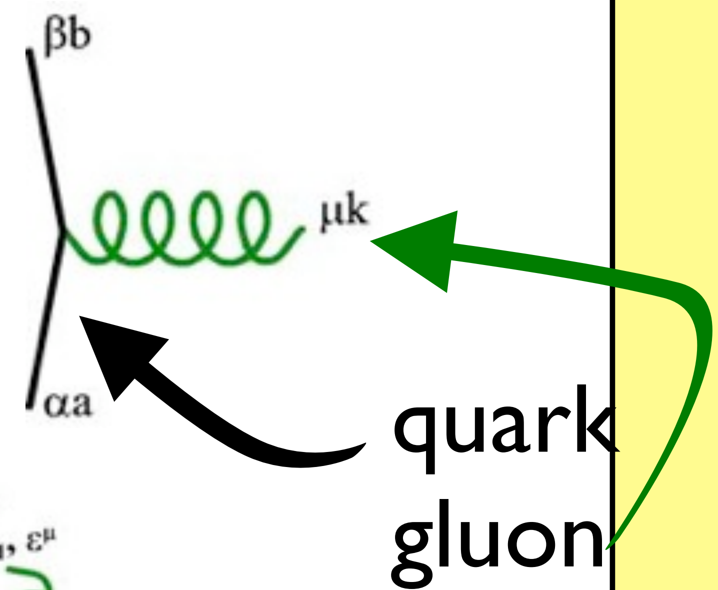
(1964)

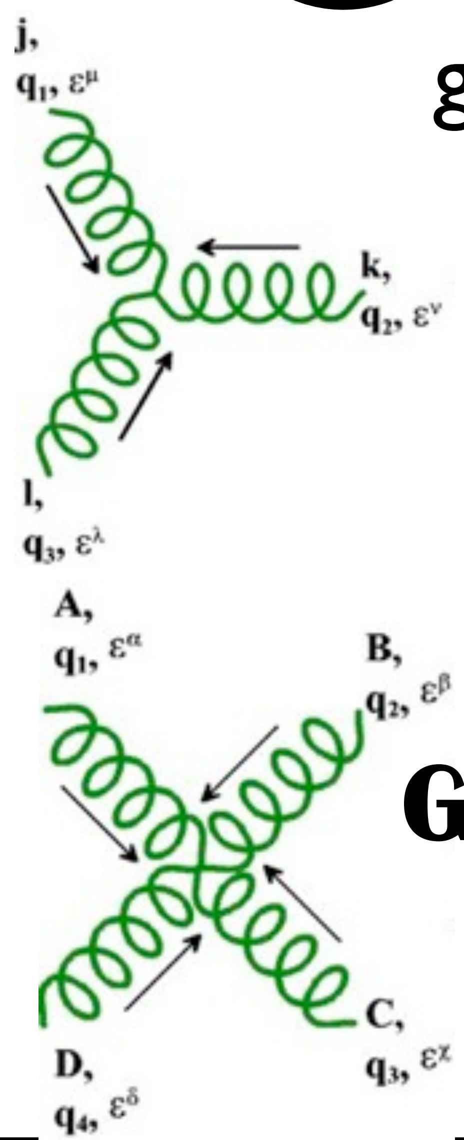
Color as charge: the birth of QCD (1973)

QED:



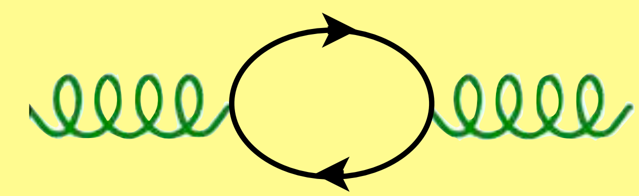
QCD:



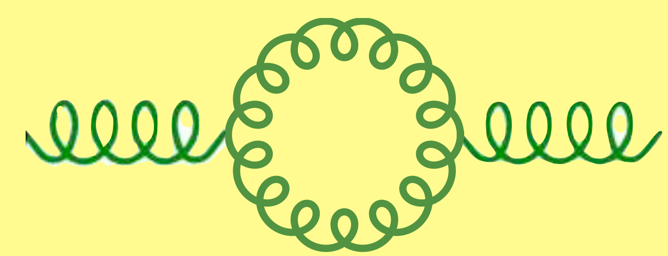


Gluons (8 of them) carry color!

Color screening in QCD:



Color **anti-screening** in QCD:



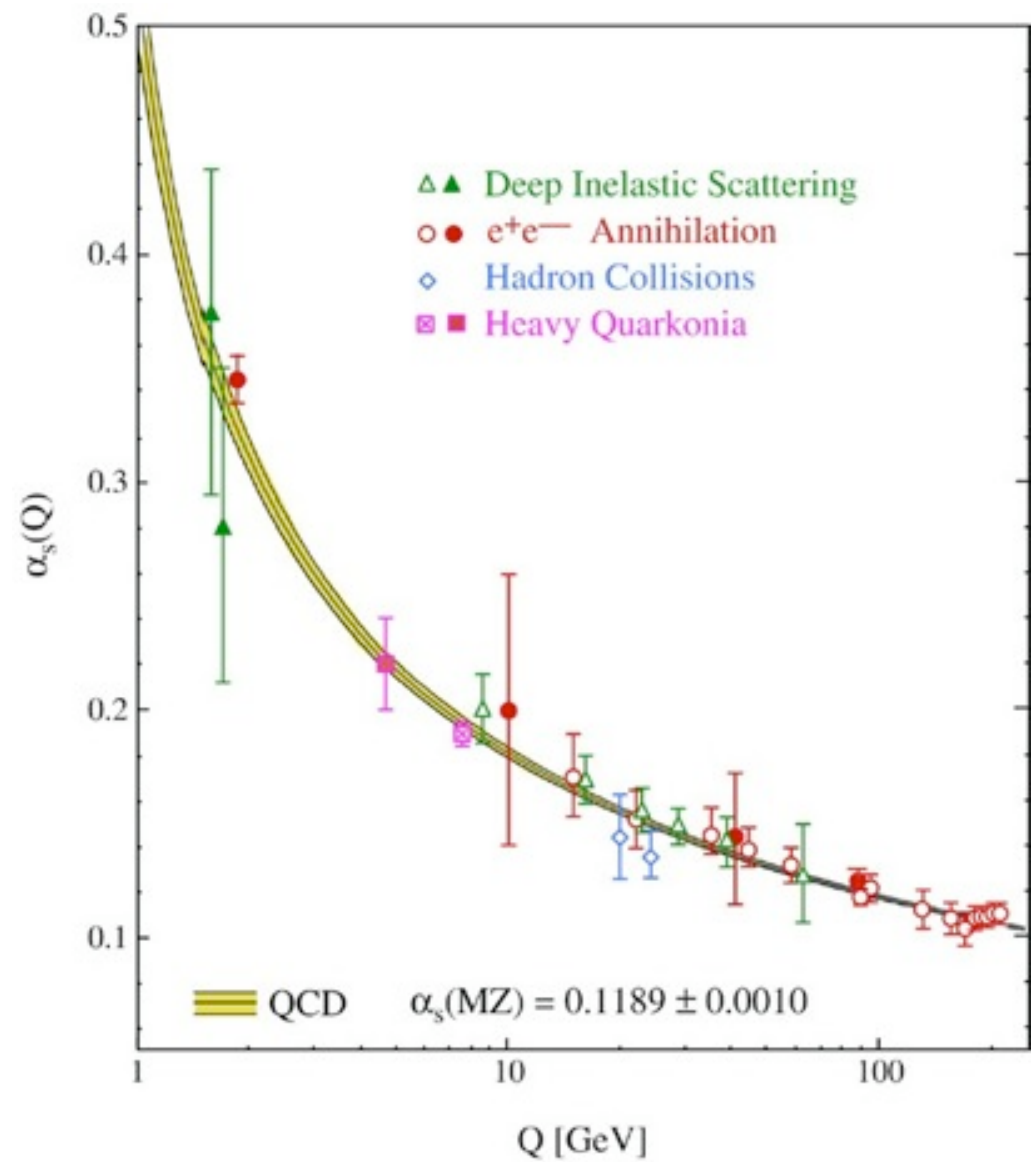
Gives rise to asymptotic freedom... very different than QED

Nobel Prize in Physics for 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross, H. David Politzer & Frank Wilczek

Asymptotic freedom (1973)



QCD:

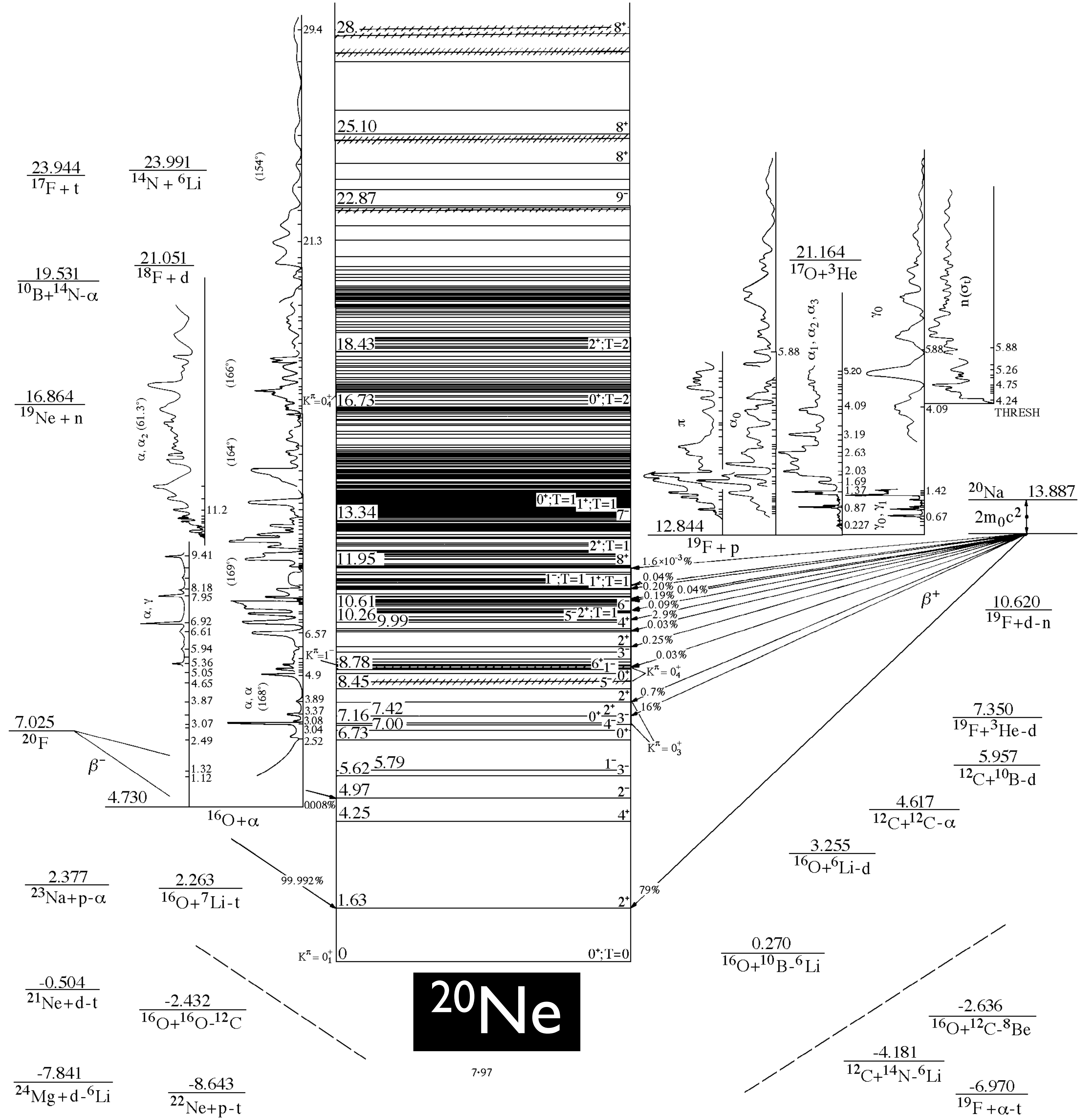
weak at short distance/high energy; ☛**Can test theory!**

strong at long distance/low energy ☛**Defines a strong scale O(200) MeV**

(long distance = 1 Fermi = 10^{-15} m) **Can explain nuclei?**

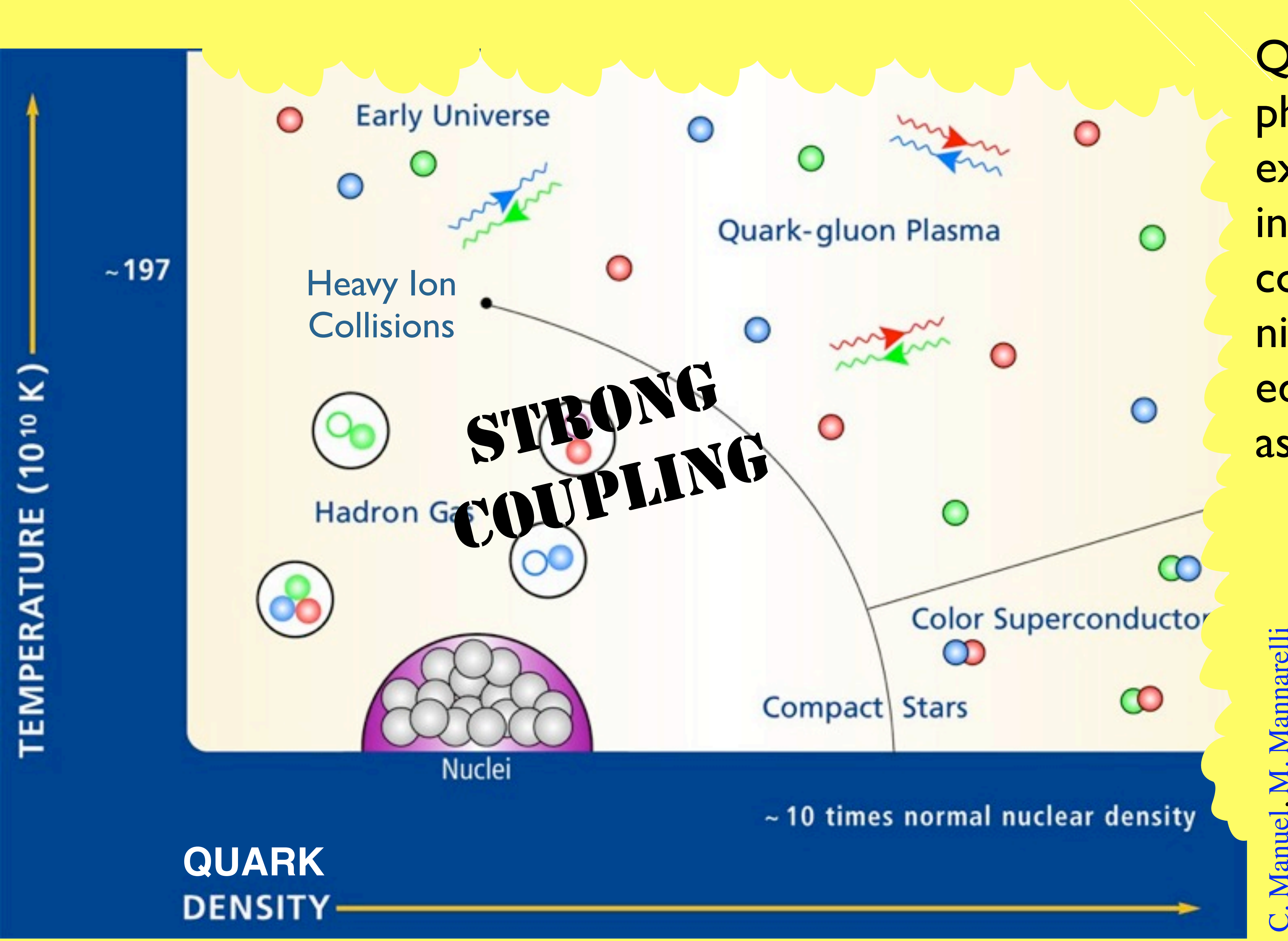
Can we now <u>solve</u> QCD and determine nuclear structure?!!

Nope.



Friday, February 12, 2010

III. A map of QCD, and ingenious attempts to find our way back (but we wander of into extra dimensions instead)

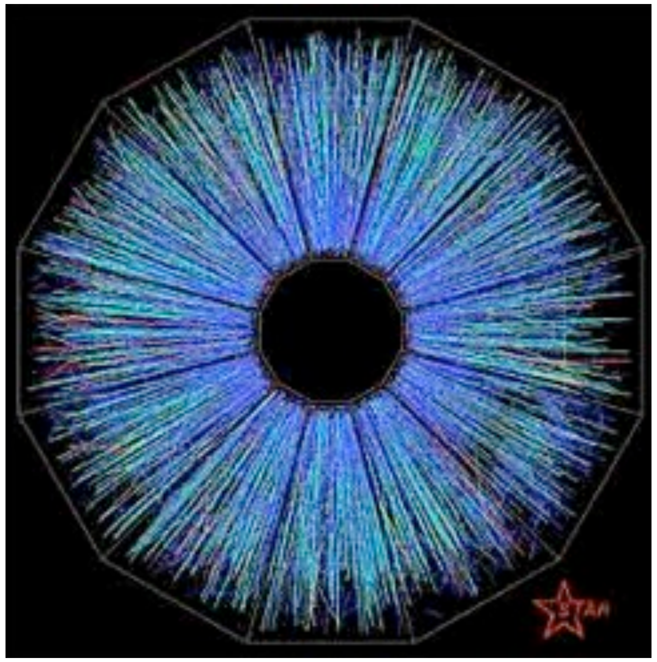


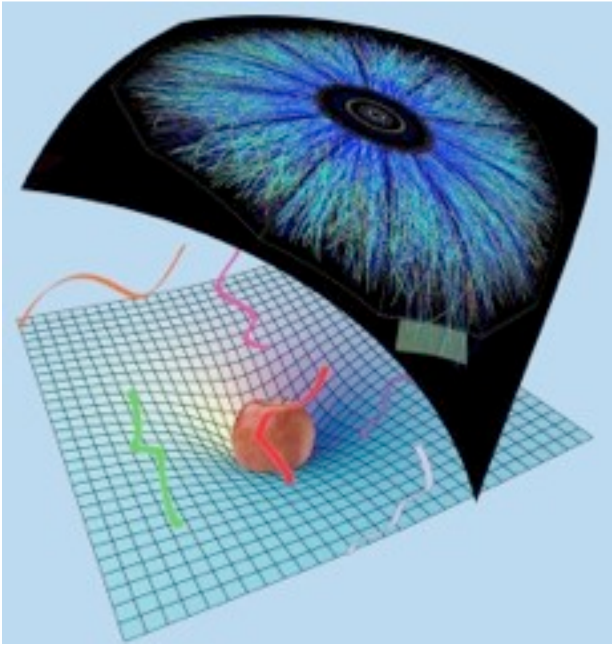
QCD phase diagram: extrapolation, inspired conjecture, computation, nibbling around the edges with asymptotic freedom

If you can't solve a hard problem exactly, solve a somewhat easier one.

- ★QCD has three types of colors...take the limit $N_c \rightarrow \infty$
- ★Change the charges of particles (no longer like quarks) so theory possesses more symmetry ("supersymmetry")
- ★From string theory: can calculate properties of this theory by solving classical differential equations in curved, 5-dimensional spacetime!?

Heavy ion collisions & the quark gluon plasma





From string theory: AdS/CFT correspondence

Strongly coupled field theory lives on 4 dim. surface of a curved 5 dim. space

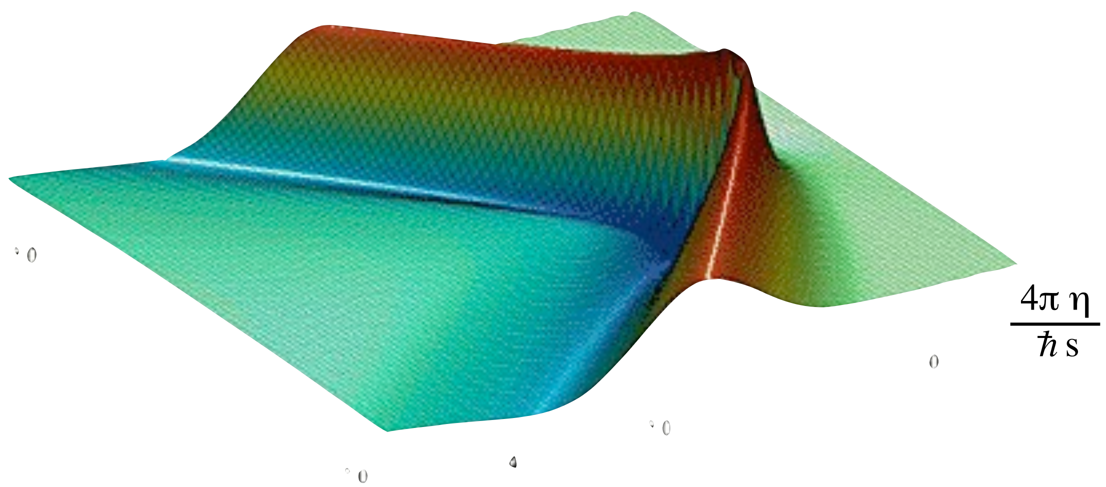
Properties of the boundary field theory may be computed by solving weakly coupled classical field theory in the interior. (!)

Insights for plasma physics from five dimensional gravity

Conjecture:

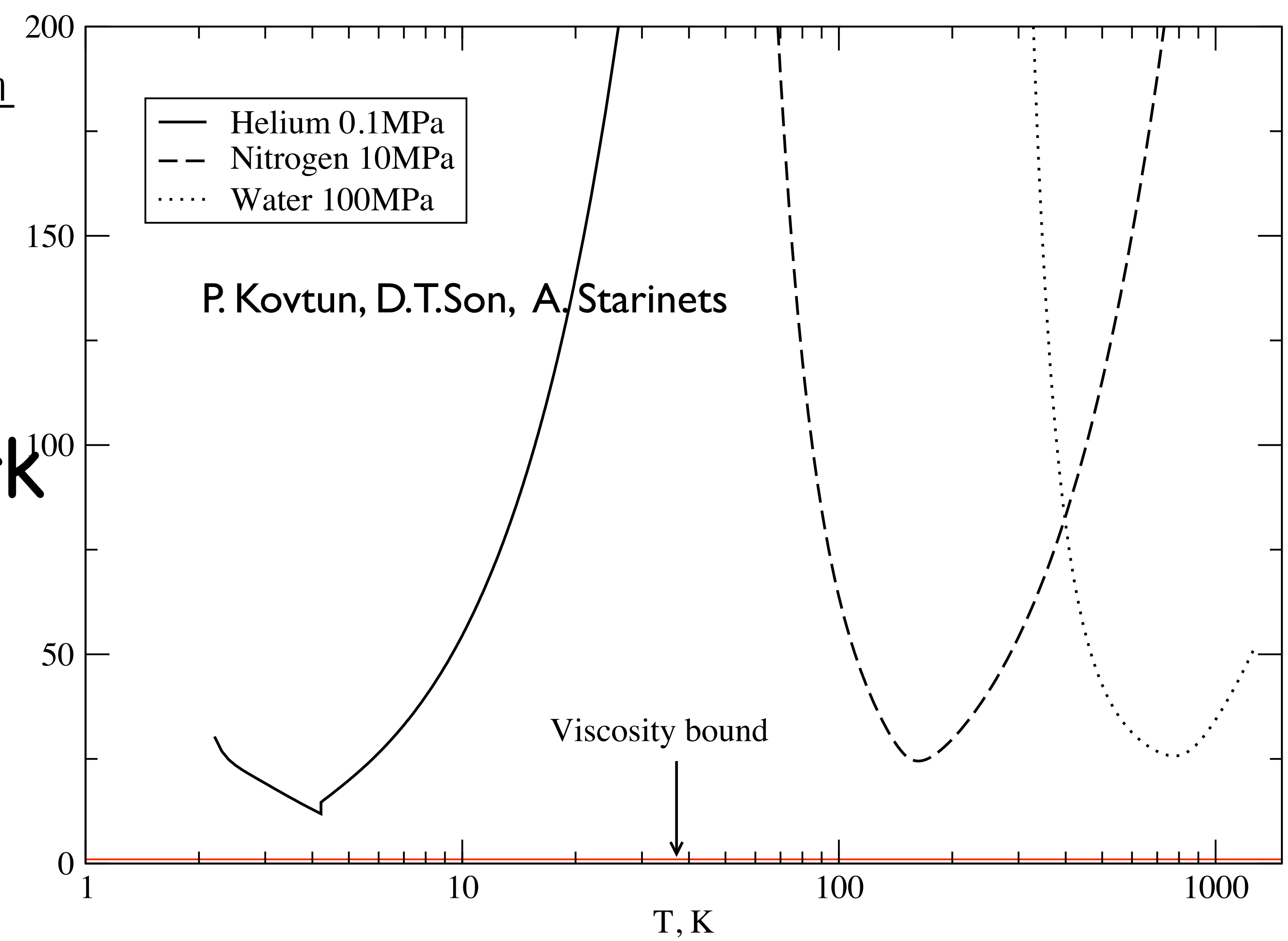
viscosity/entropy $\geq \frac{\hbar}{4\pi}$

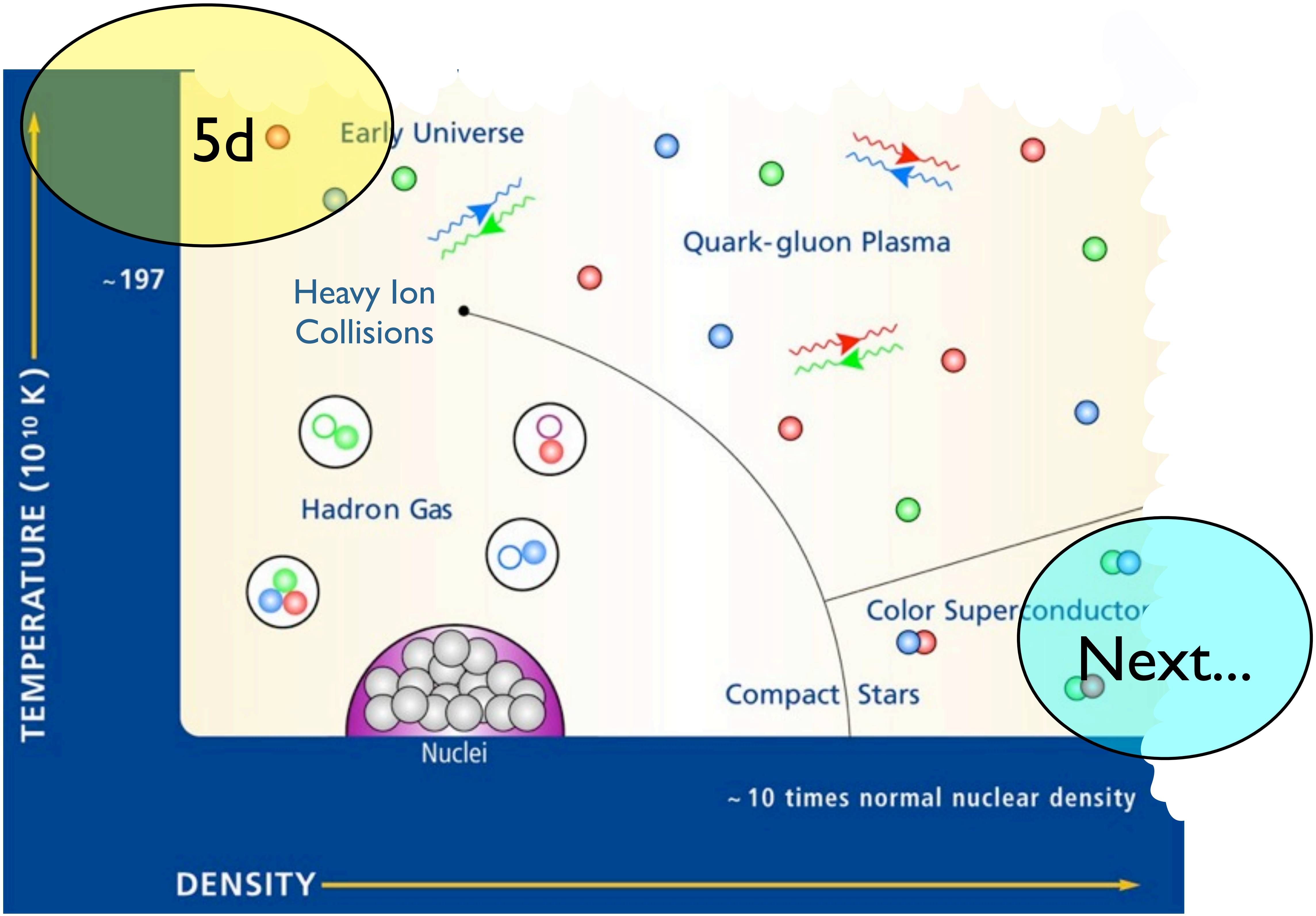
Is the quark gluon plasma at the bound?



L. Yaffe, P. Chesler

Shock wave as a heavy quark travels through the quark-gluon plasma

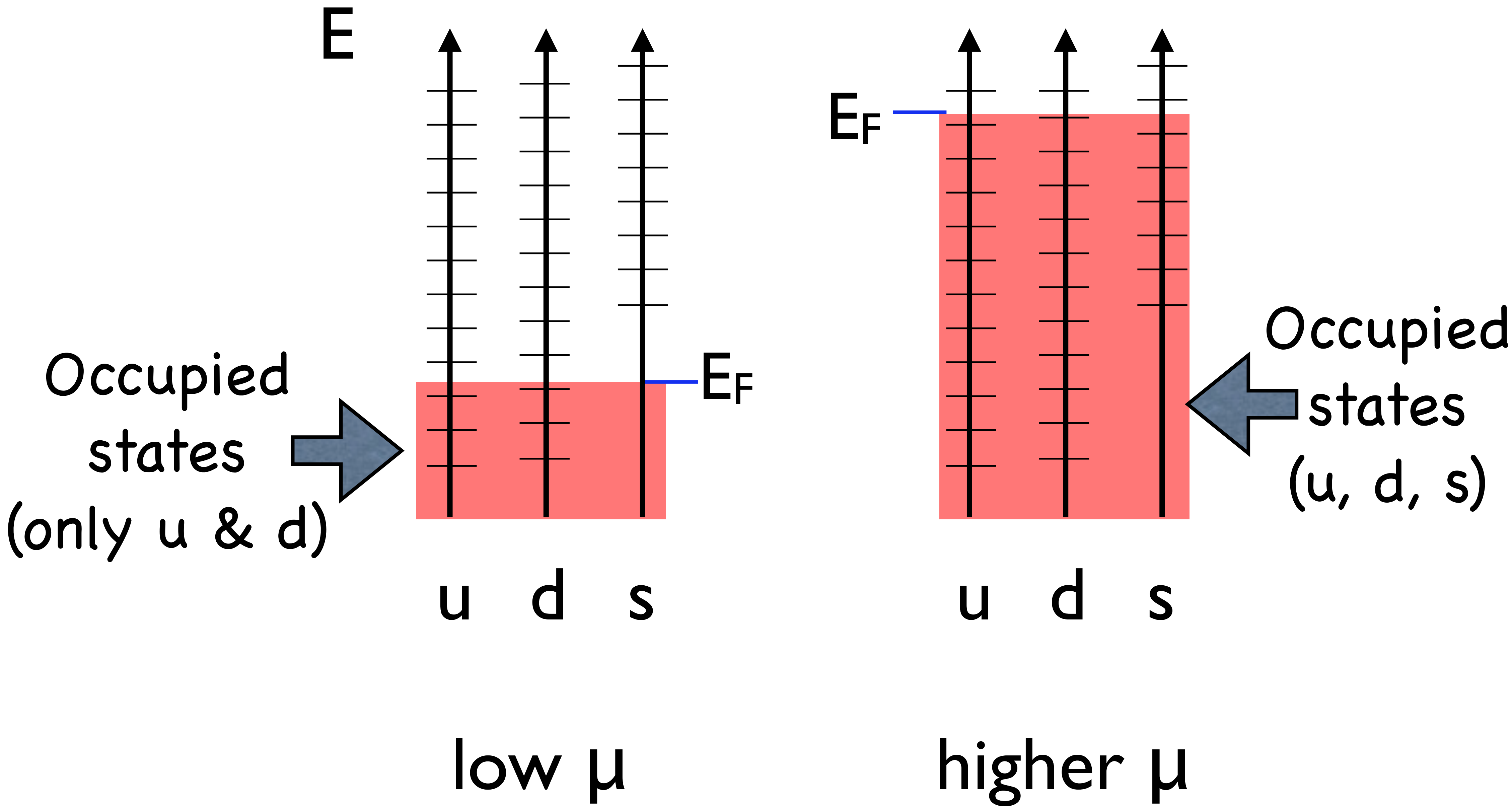



5d
Early Universe
Quark-gluon Plasma
~197
Heavy Ion Collisions
Hadron Gas
Color Superconductor
Next...
Compact Stars
Nuclei
~10 times normal nuclear density
TEMPERATURE (10^10 K)
DENSITY

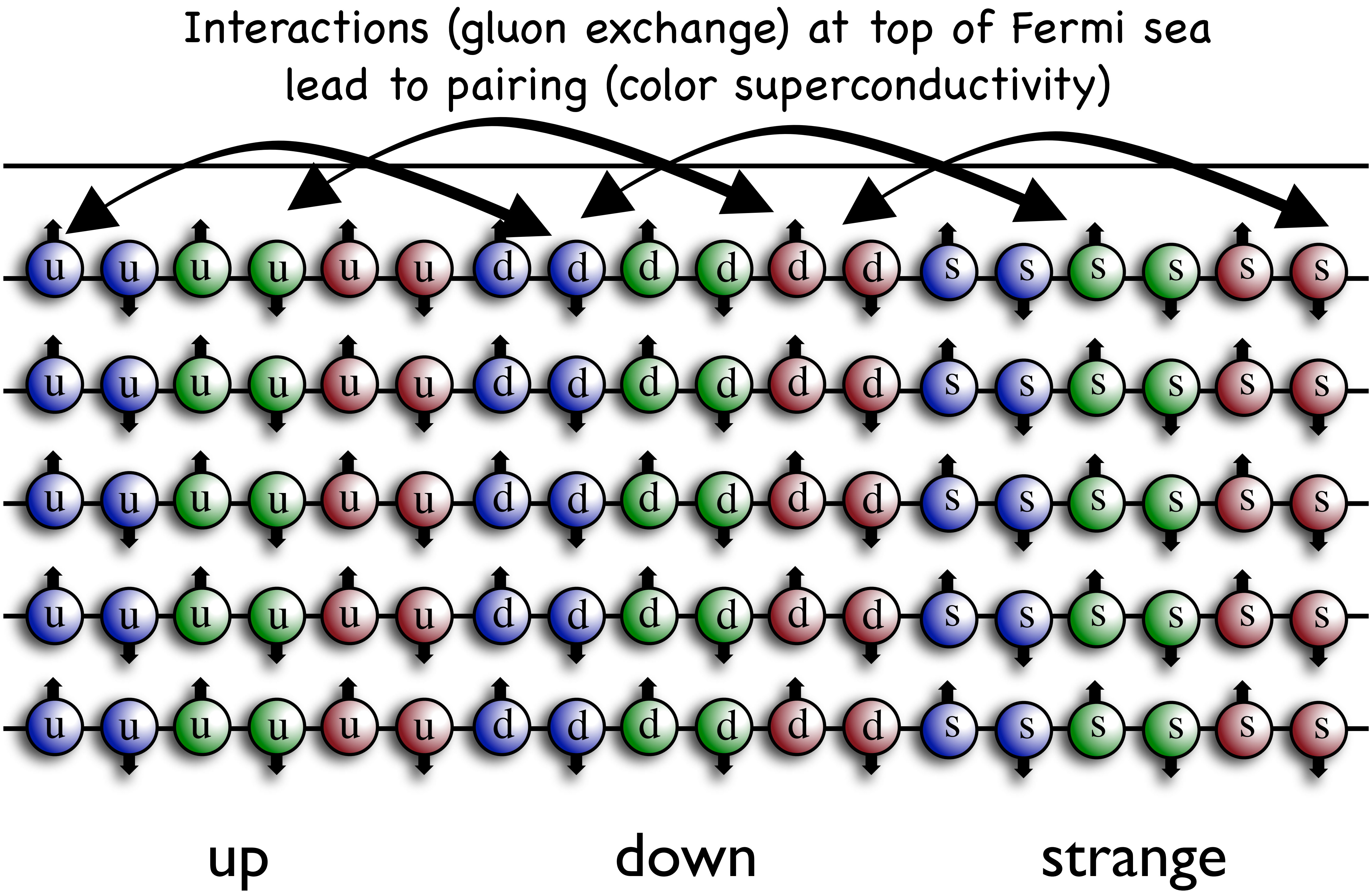
IV. Life is simpler when you're dense

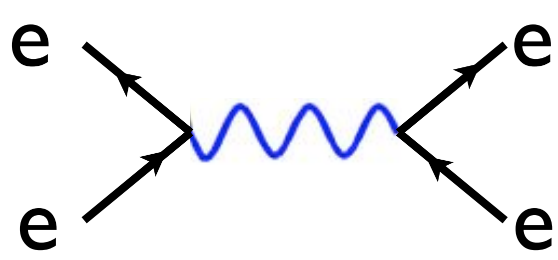
$$m_s \sim 20\, m_d \sim 40\, m_u$$

Expect to see stable strange quark matter at densities higher than nuclear density

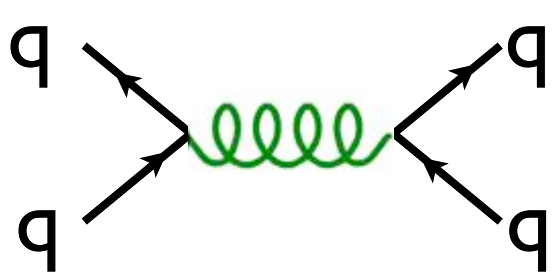


Very dense quark matter: like a Fermi gas of quarks?





Conventional superconductivity: phonon exchange attractive; electron pairs at Fermi surface Bose condense

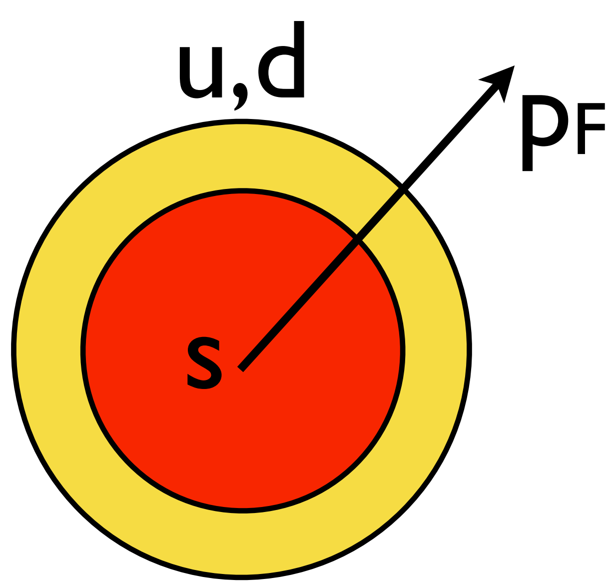


Color superconductivity: gluon exchange attractive; quark pairs at Fermi surface Bose condense

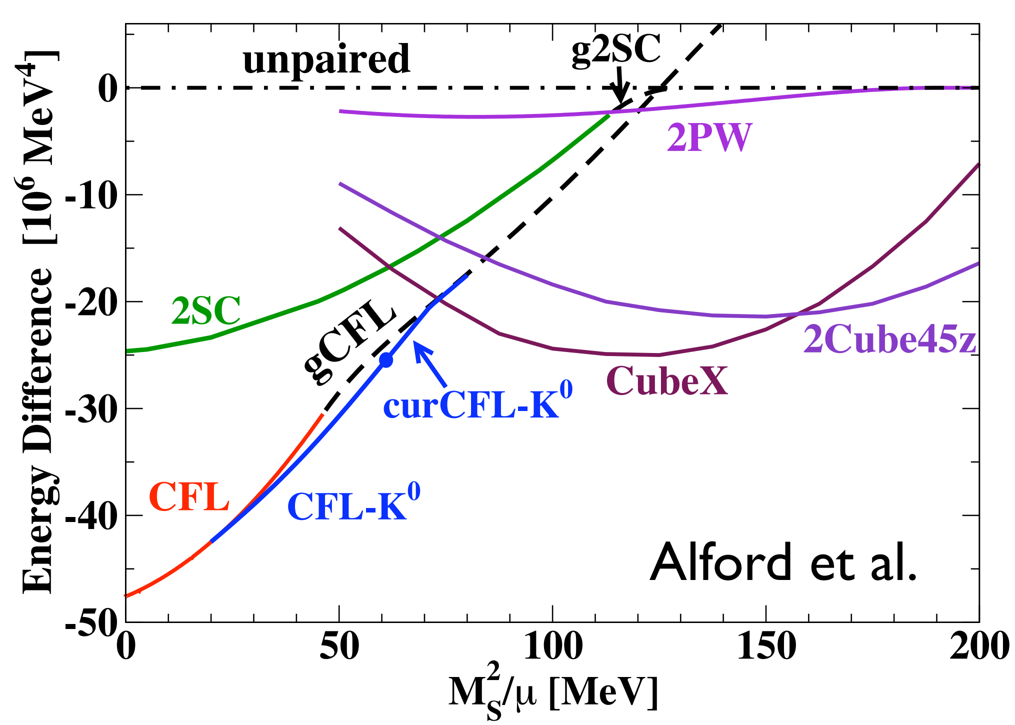
Reliable calculation at very high density: interaction weak due to asymptotic freedom

Very high density: get a very symmetric system ("Color-Flavor-Locked" - CFL - quark matter) with many very light excitations ("mesons")

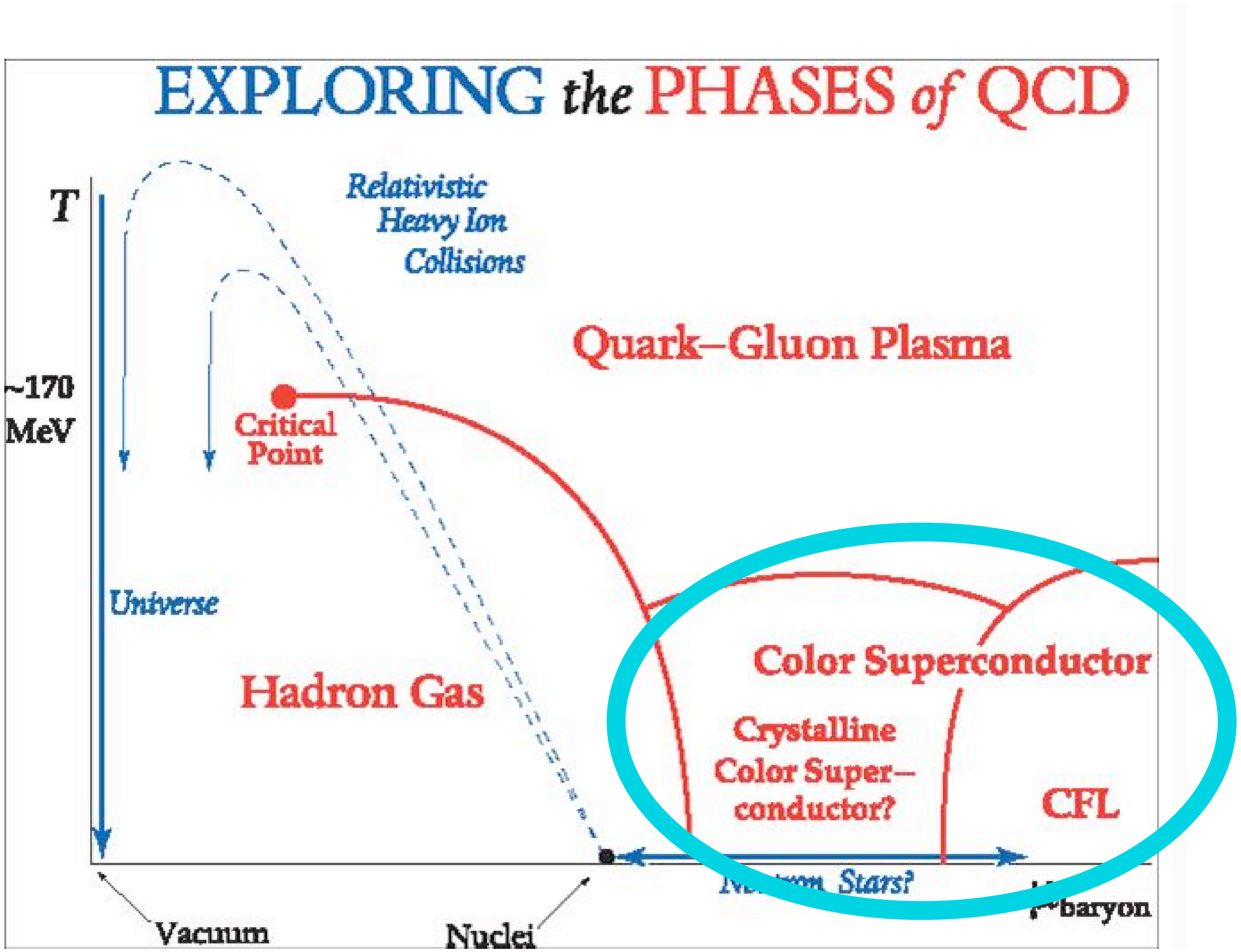
Lower densities μ~ (strange quark mass)²/**100 MeV**:
...get a very complex assortment of phases of quark matter, including crystals. Less reliable



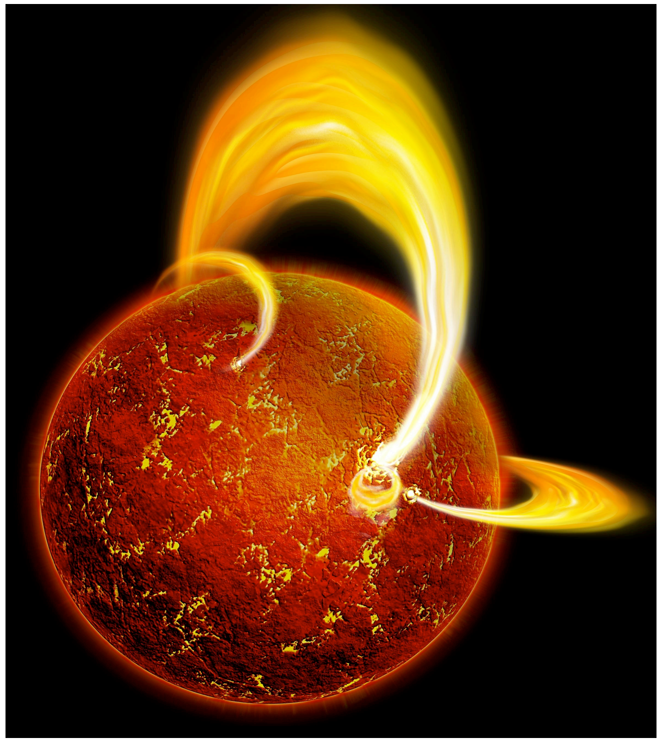
Fermi surface have mismatch due to s quark mass



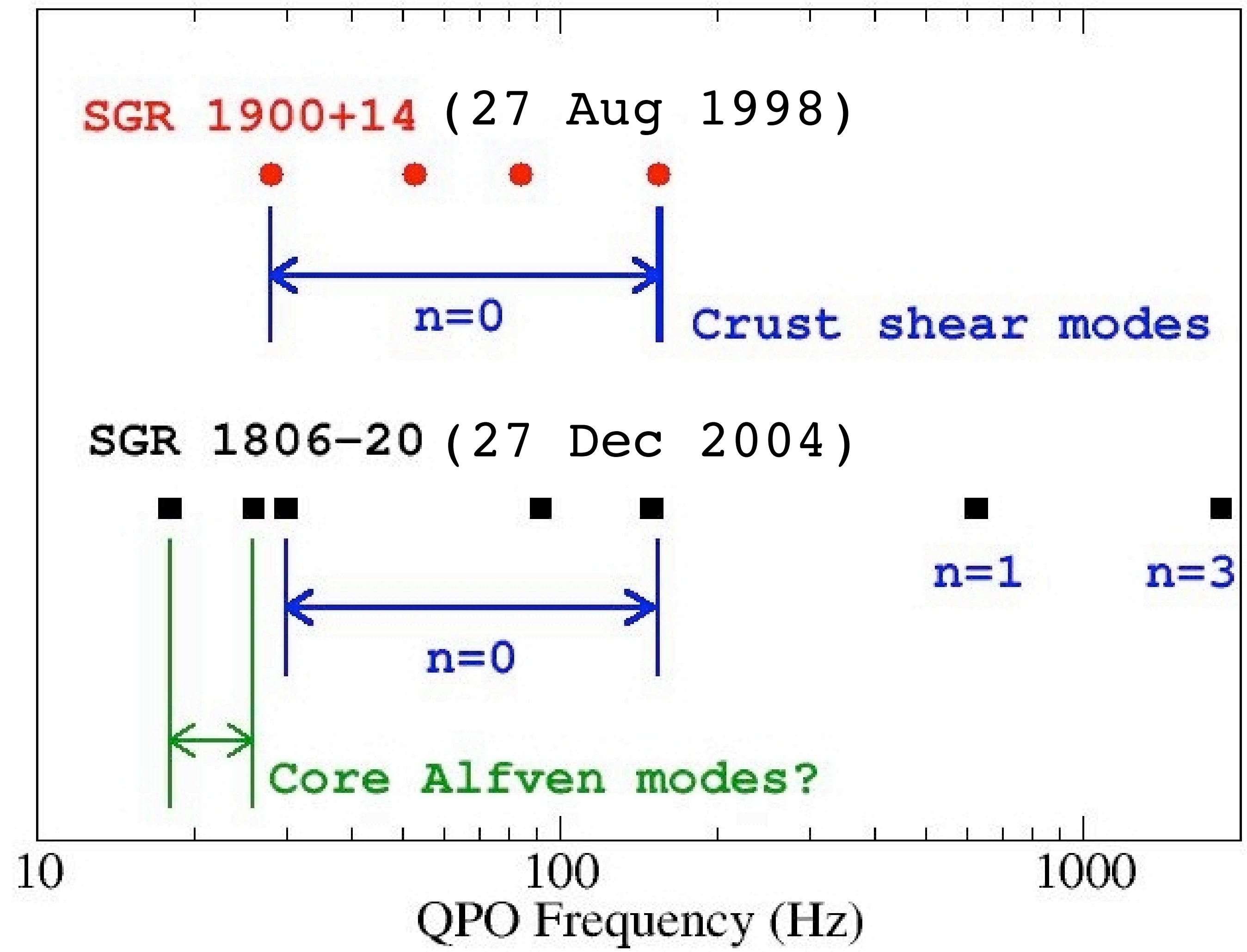
Could superconducting quark matter exist inside neutron stars?



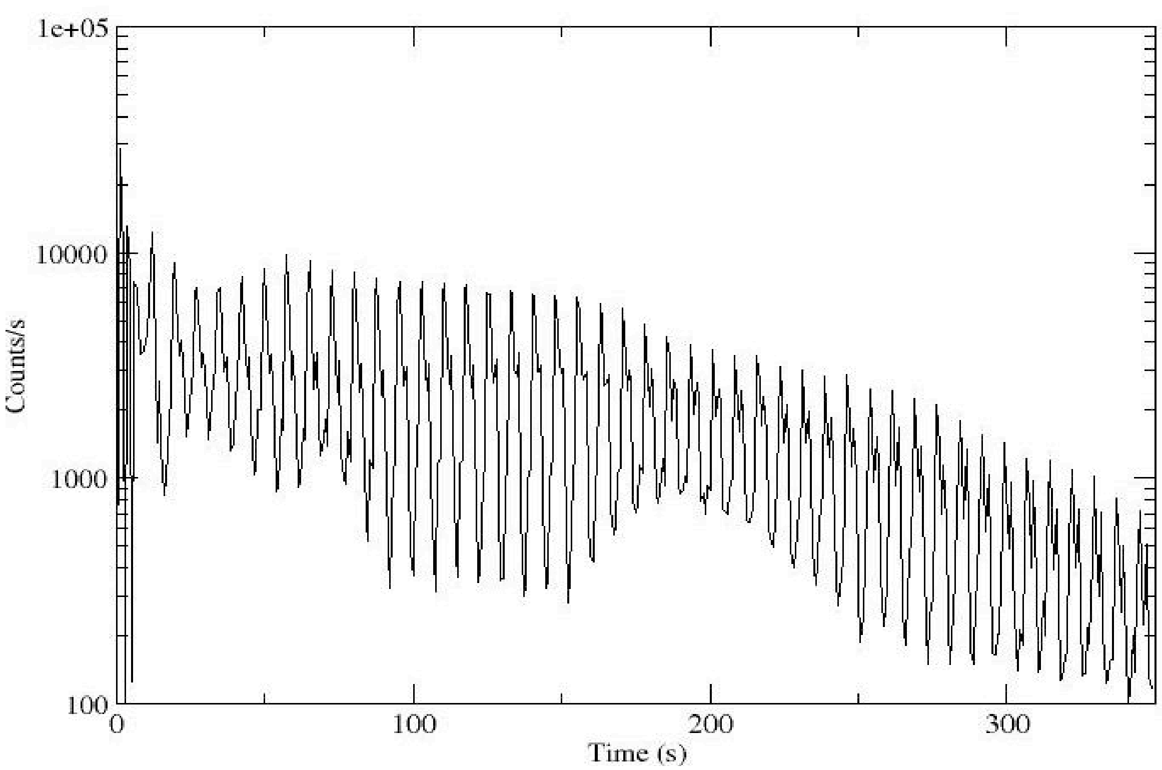
Growing data constraining neutron stars



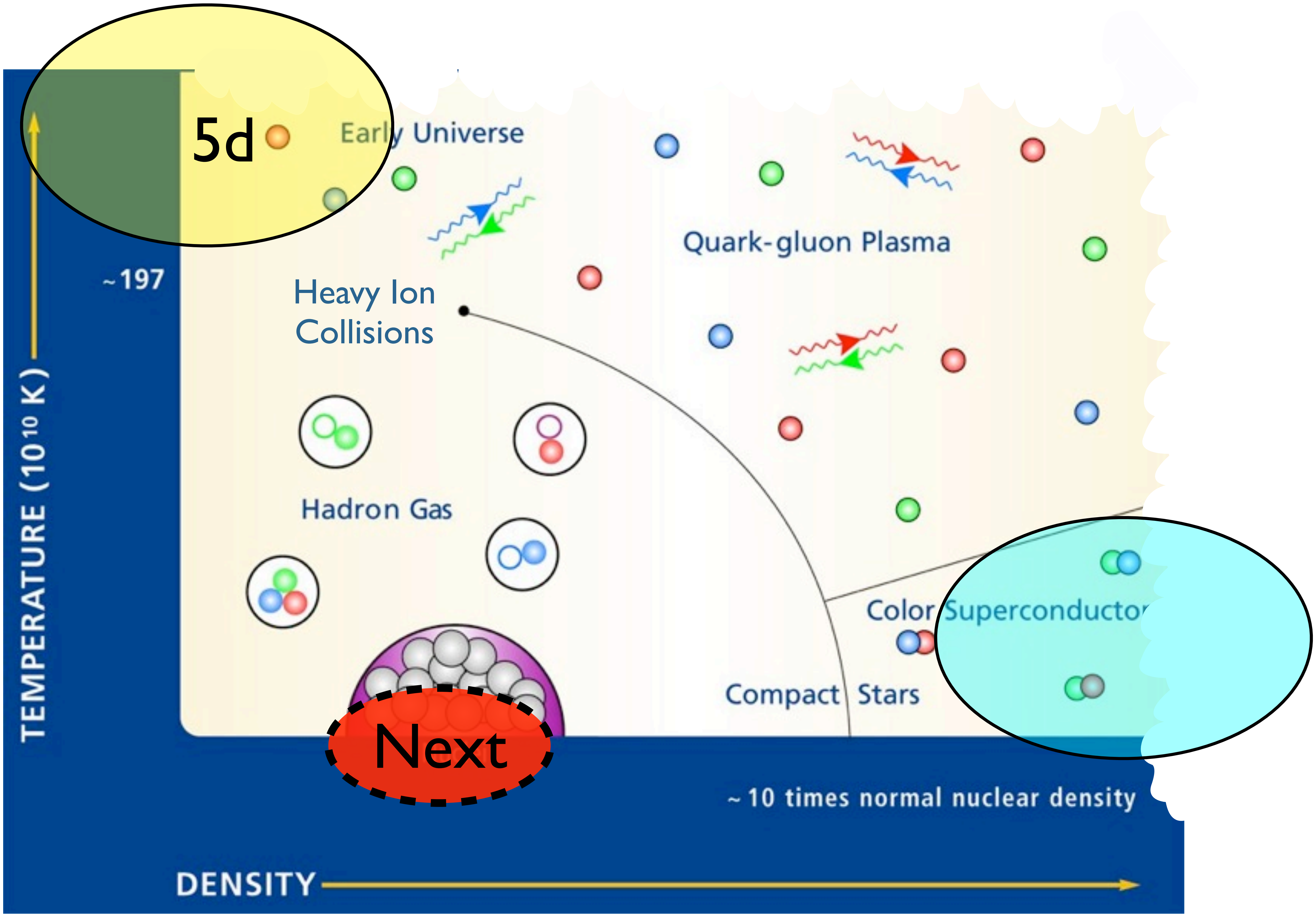
For example: flares from field instabilities can trigger star quakes; modes constrain crust properties



Anna Watts, 2007



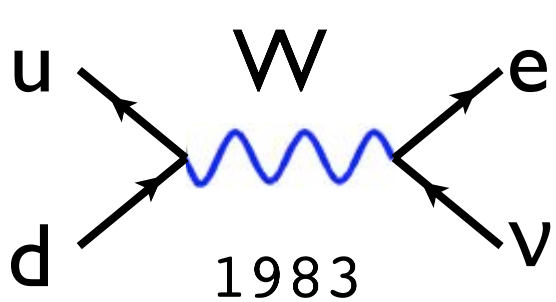
A number of other constraints

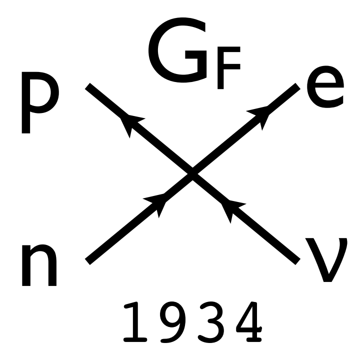

5d
Early Universe
Quark-gluon Plasma
~197
Heavy Ion Collisions
TEMPERATURE (10^10 K)
Hadron Gas
Color Superconductor
Compact Stars
Next
~10 times normal nuclear density
DENSITY

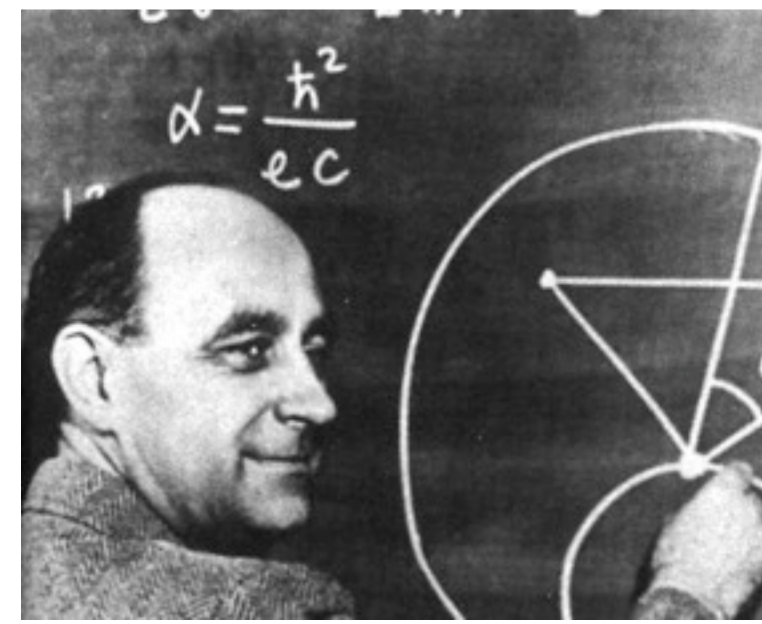
V. *Knowing that we don’t know & effective field theory... which leads us into an atomic trap*

Effective field theory:
Complicated short distance physics can be parametrized by a few coupling constants

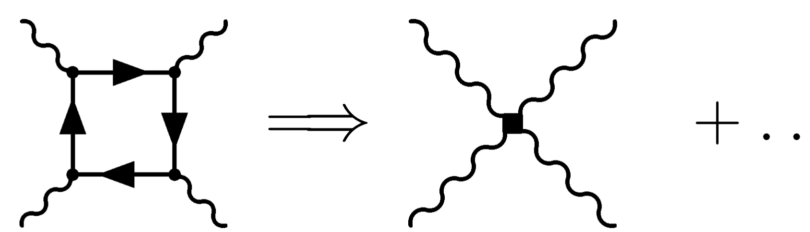
Eg: Fermi’s theory of weak interactions:







Eg: Euler-Heisenberg theory of light-by light scattering



Weinberg suggested using effective field theory to describe low energy interactions between nucleons

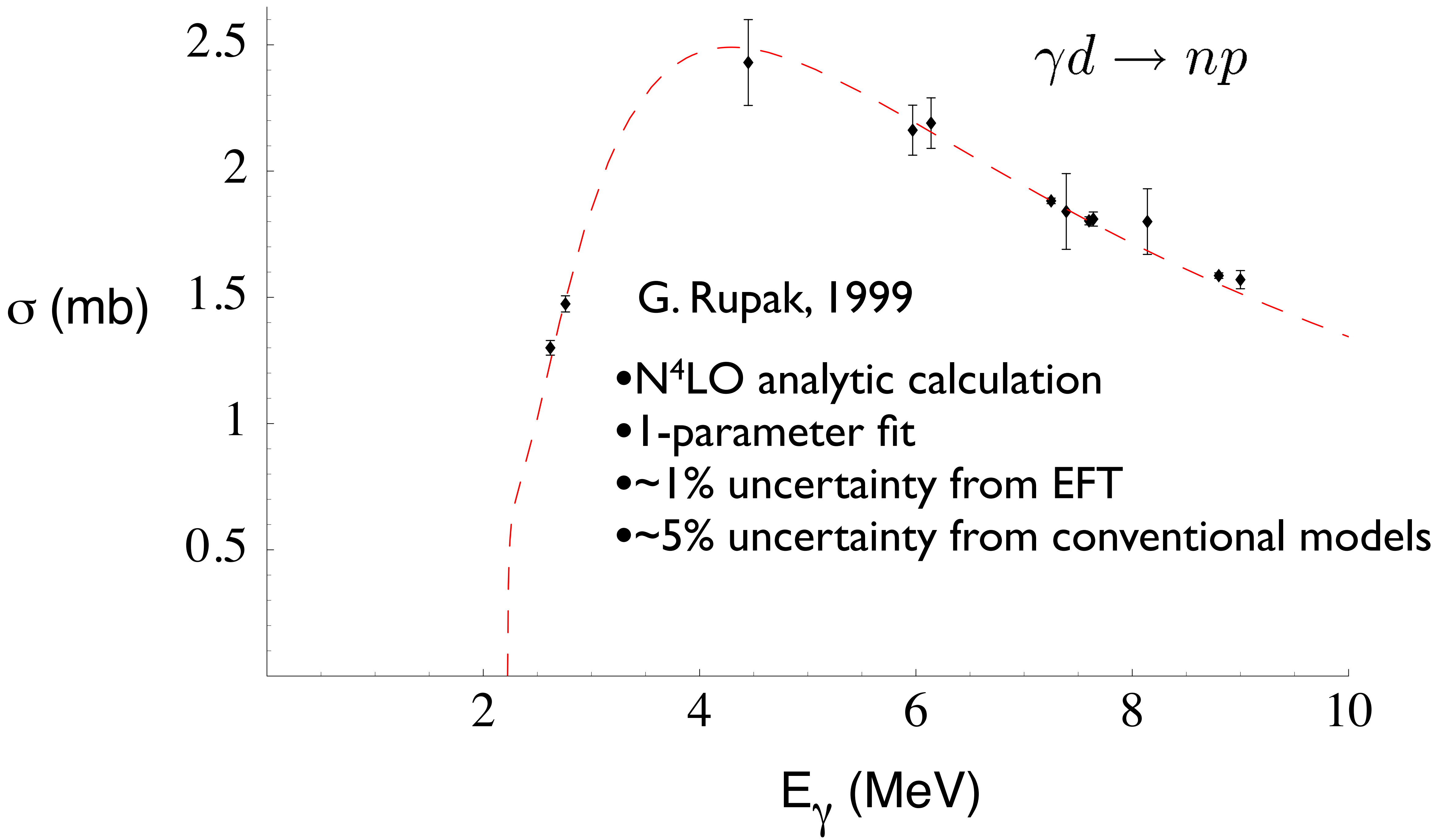
- *Construct most general low energy theory with the symmetries of QCD*

- *Systematic low energy expansion*

- *Not like Fermi theory: strong NN interaction characterized by a very shallow bound state (deuteron) and an almost bound 2-neutron state*

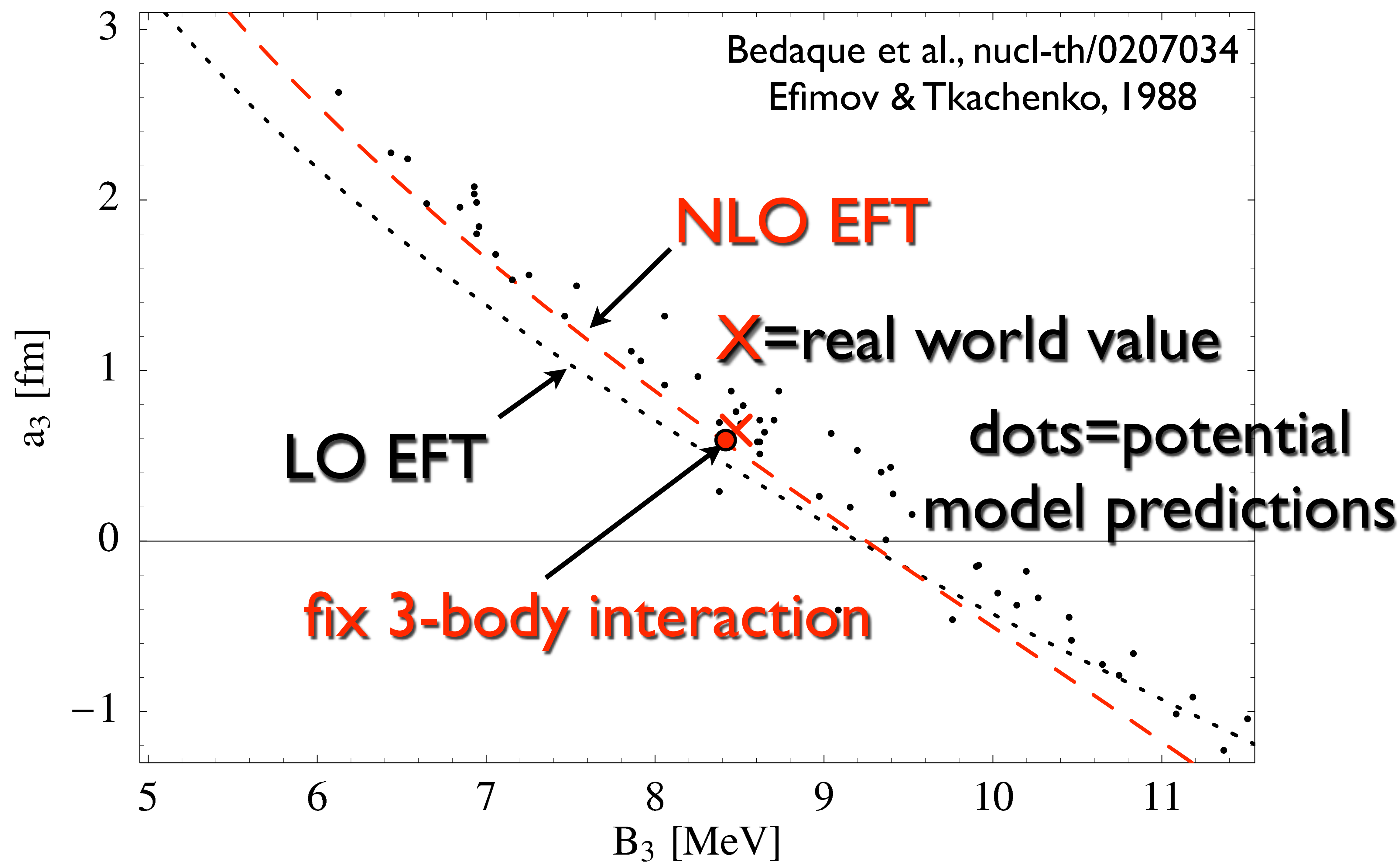
- *Only applies to few-body systems (2-3-4?)*

Example of an effective field theory calculation: critical process for nucleosynthesis during the Big Bang



3-body physics from effective field theory

Phillips line: ³H binding energy - Nd scattering length correlation

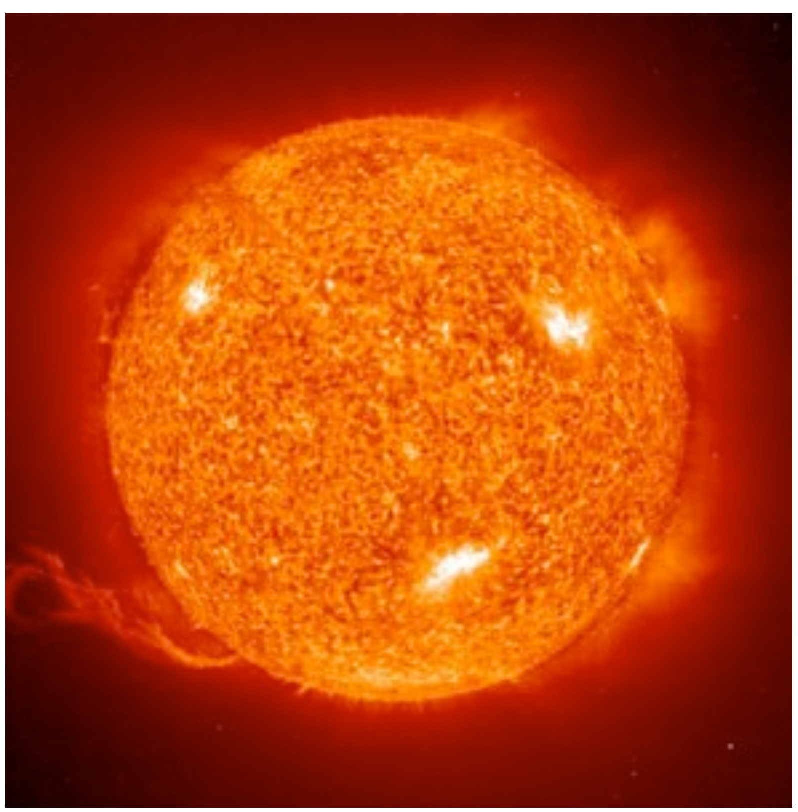


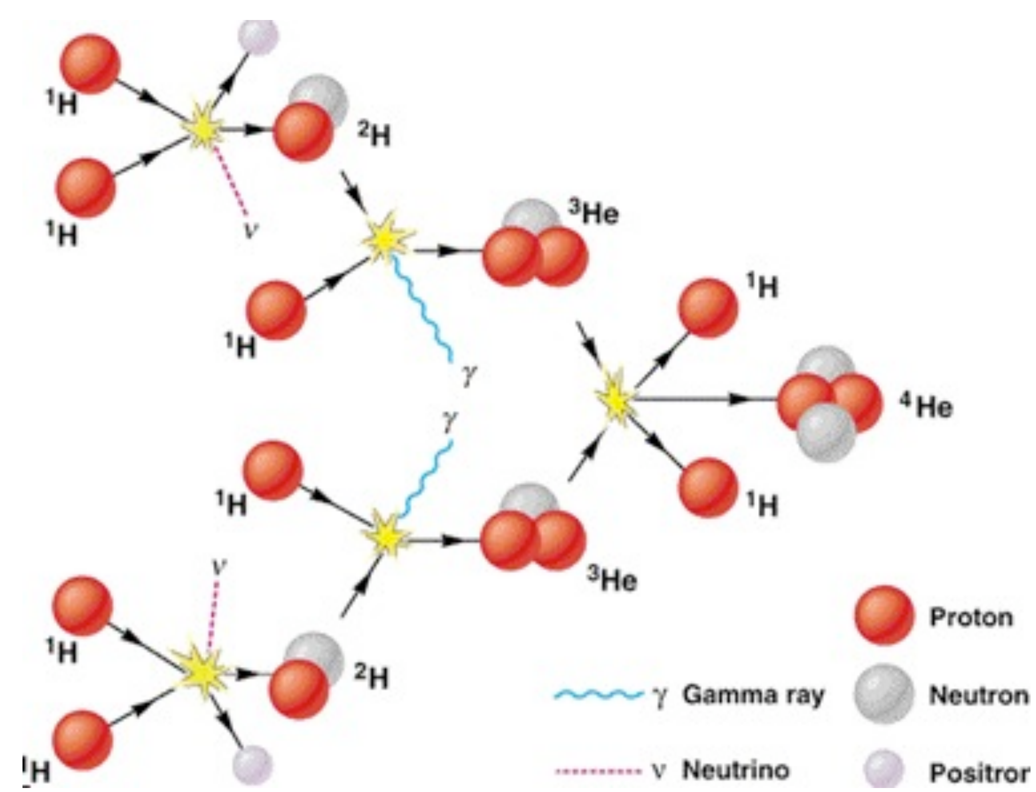
Phillips line: 3-body interaction

Other successful applications of effective field theory:

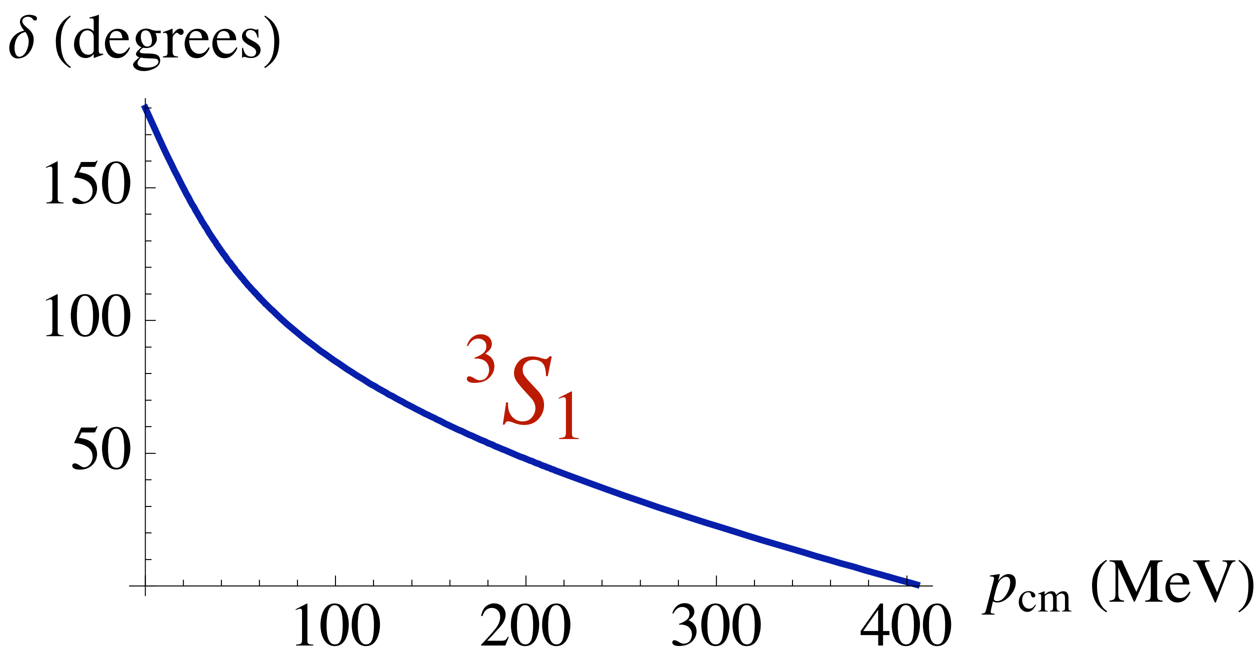
Neutrino-deuteron interactions (critical for SNO neutrino experiment)

p-p fusion (power plant of the sun) to <1% accuracy

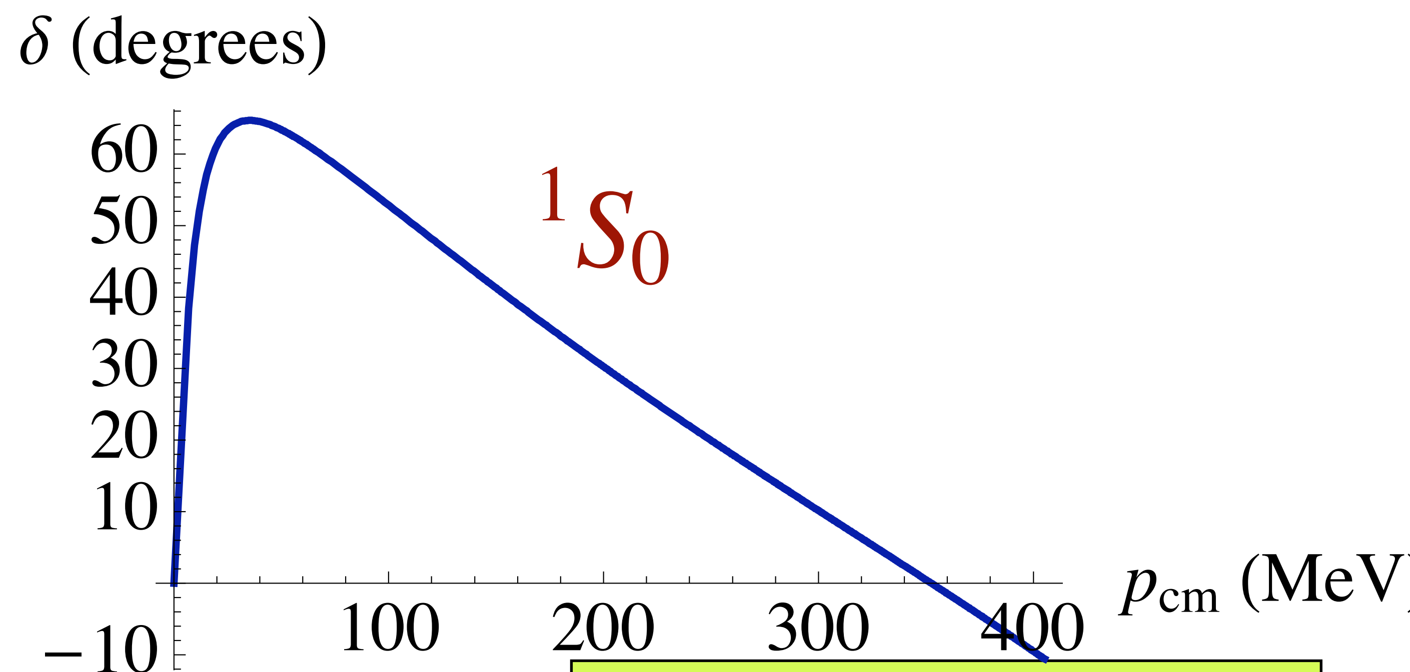




Nucleon-nucleon scattering



$$a_{^3S_1} = \frac{1}{45\ \text{MeV}}$$

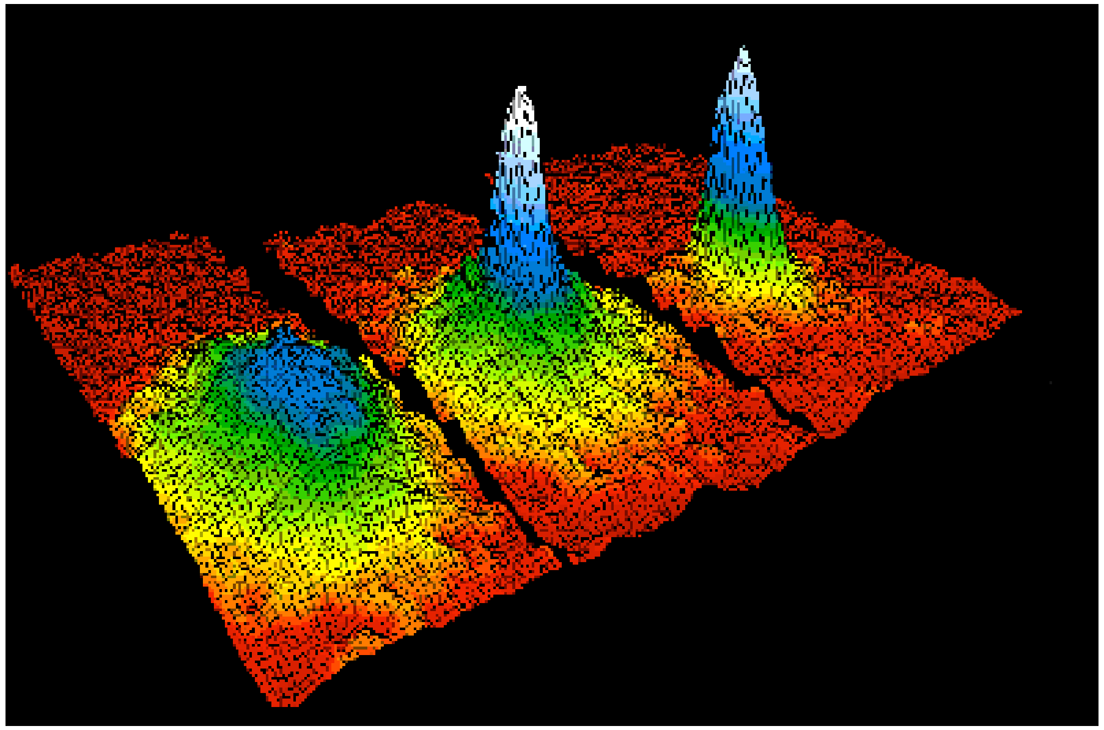


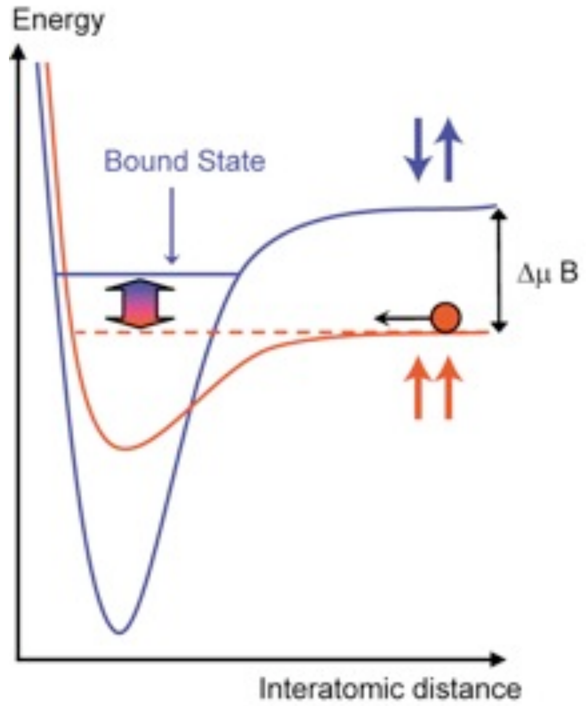
$$a_{^1S_0} = -\frac{1}{8\ \text{MeV}}$$

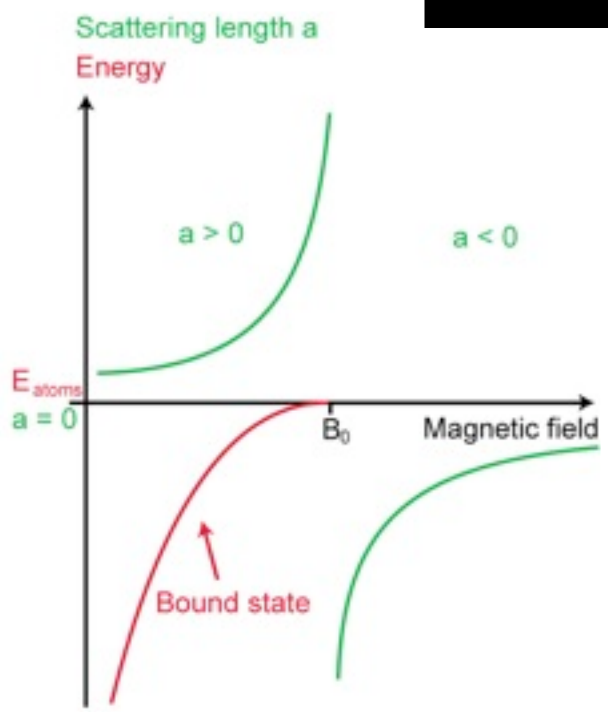
Not like νν scattering in Fermi theory!
Rapid change at low energy (large "scattering lengths")

Can experimentally explore such systems using trapped atoms

Strong connection between effective field theory for nucleon interactions, and for cold trapped atoms tuned to a Feshbach resonance:

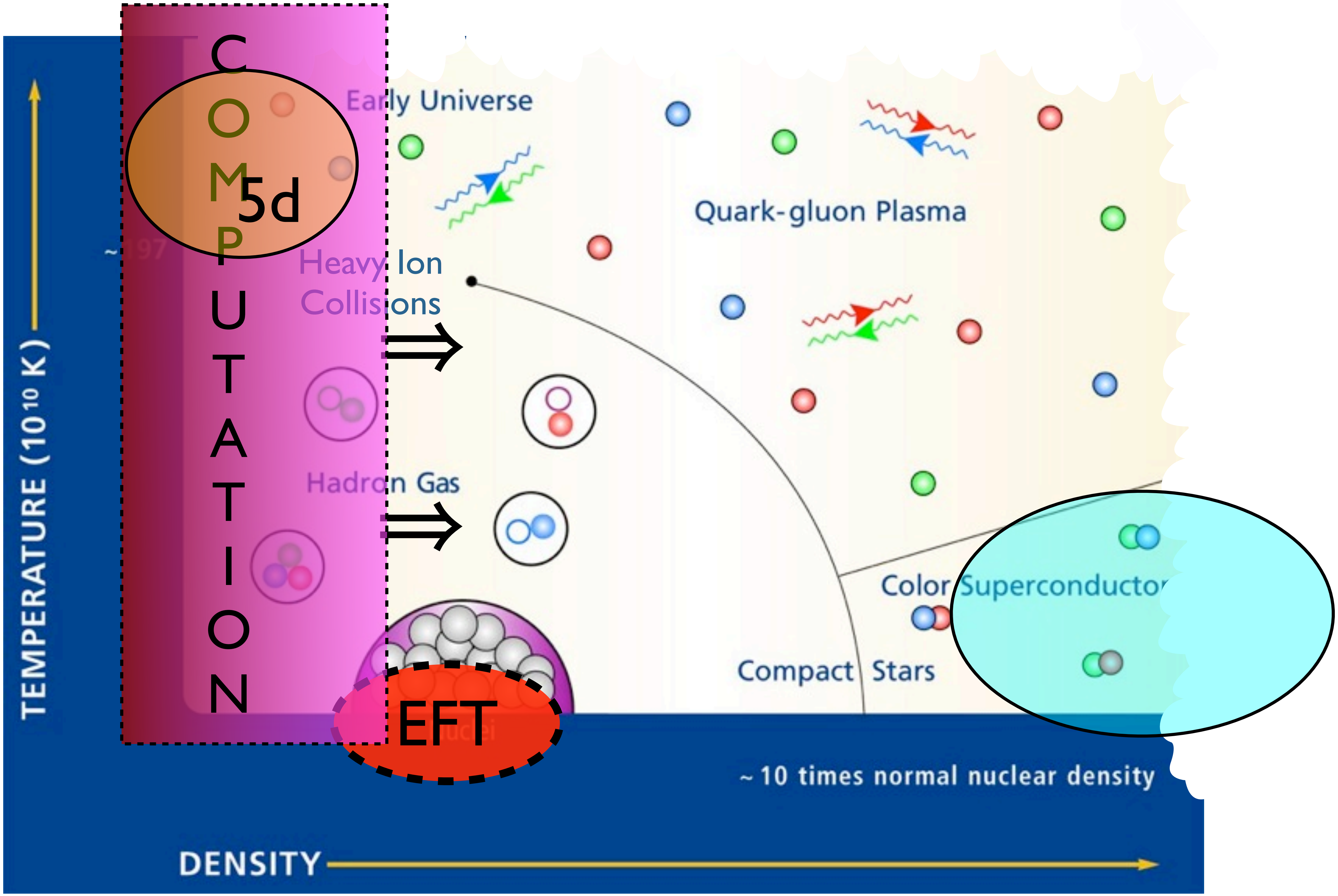






Trapped atom systems very interesting testing ground for nuclear many-body theory.

VI. *Escape with the help of a computer to strange places*



Consequences of QCD can be computed


Ken Wilson

Spacetime approximated by a finite size lattice on which quarks and gluons can hop around: "Lattice QCD" (1974)

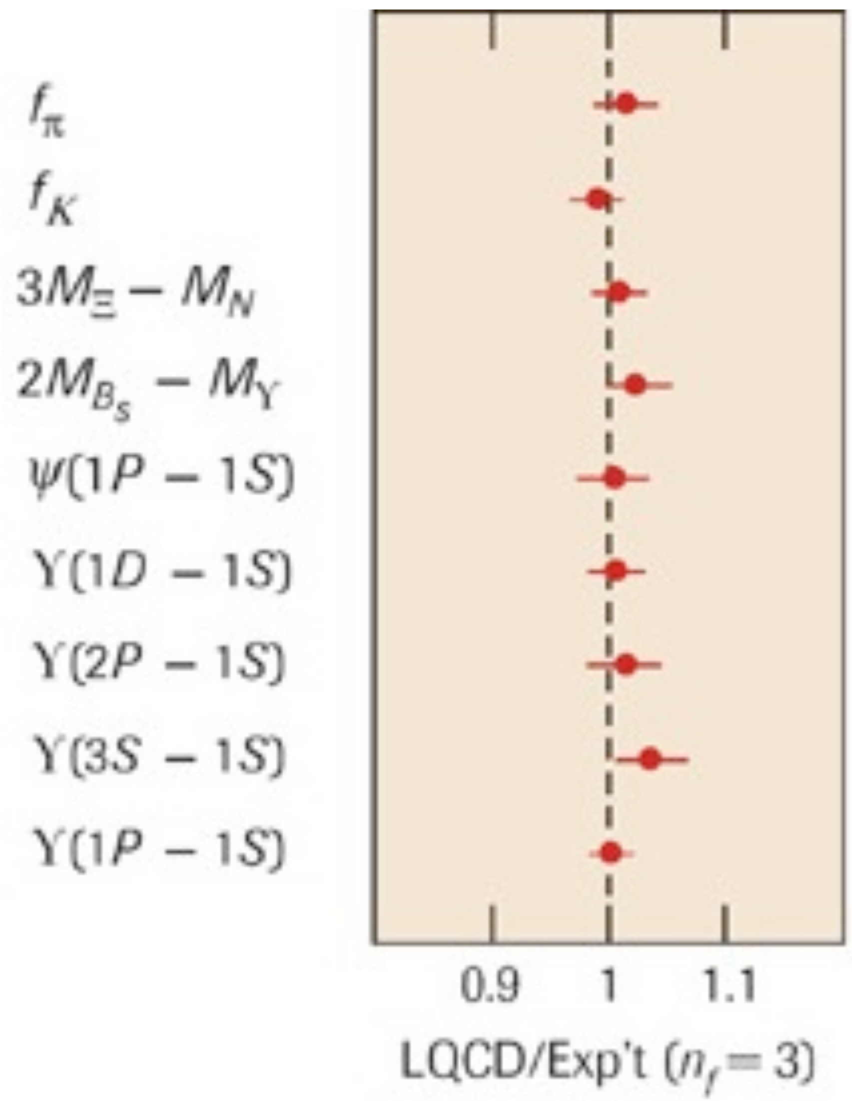
- Generate stochastic gluon fields with appropriate weight
- Average correlation functions
- Extract observable quantities

Computationally very expensive
Works well for

- low lying spectrum of strongly interacting states
- thermodynamic properties at zero chemical potential

Spectra:

Easier...

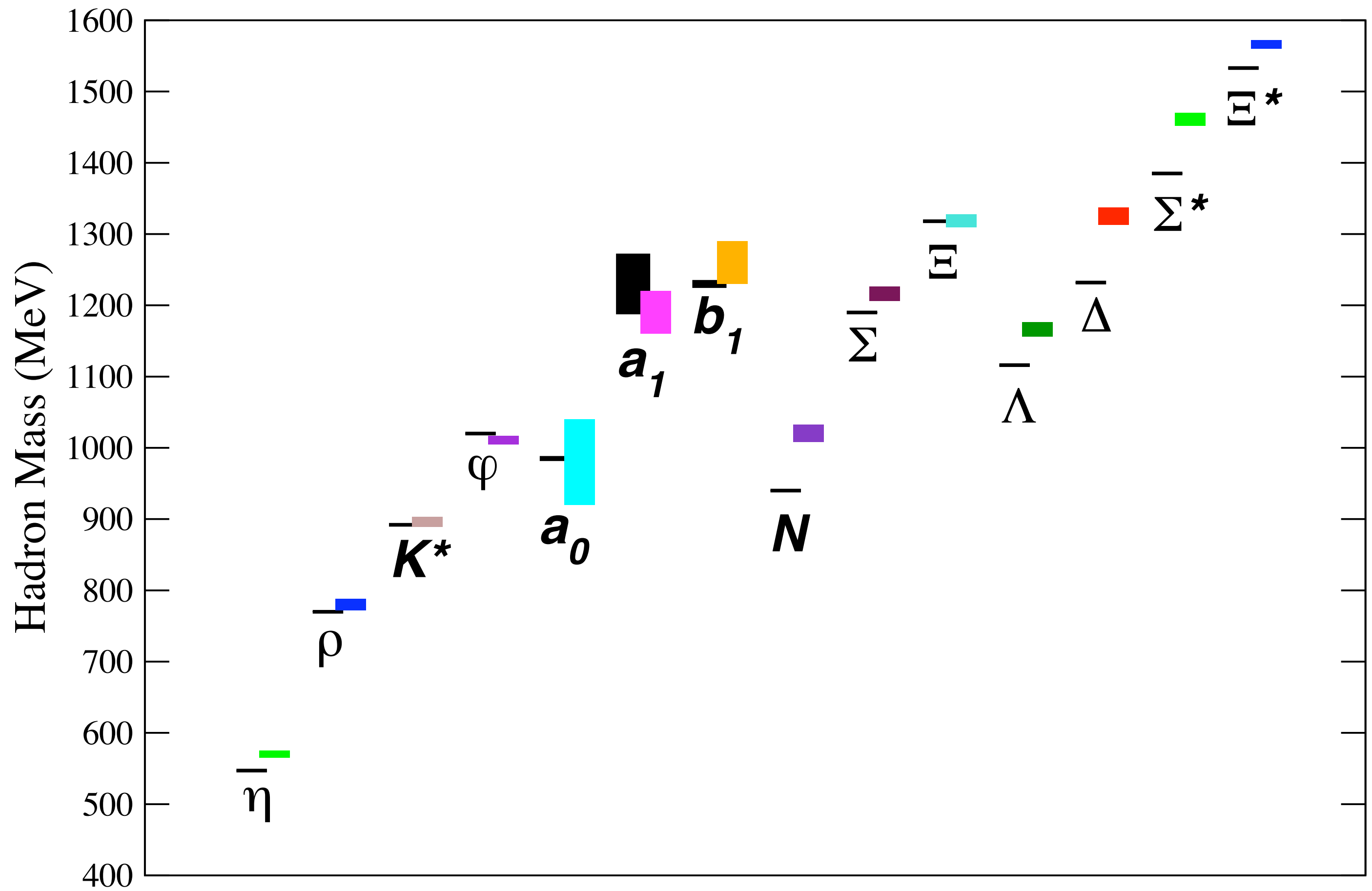


MILC collaboration

Spectra:

harder...

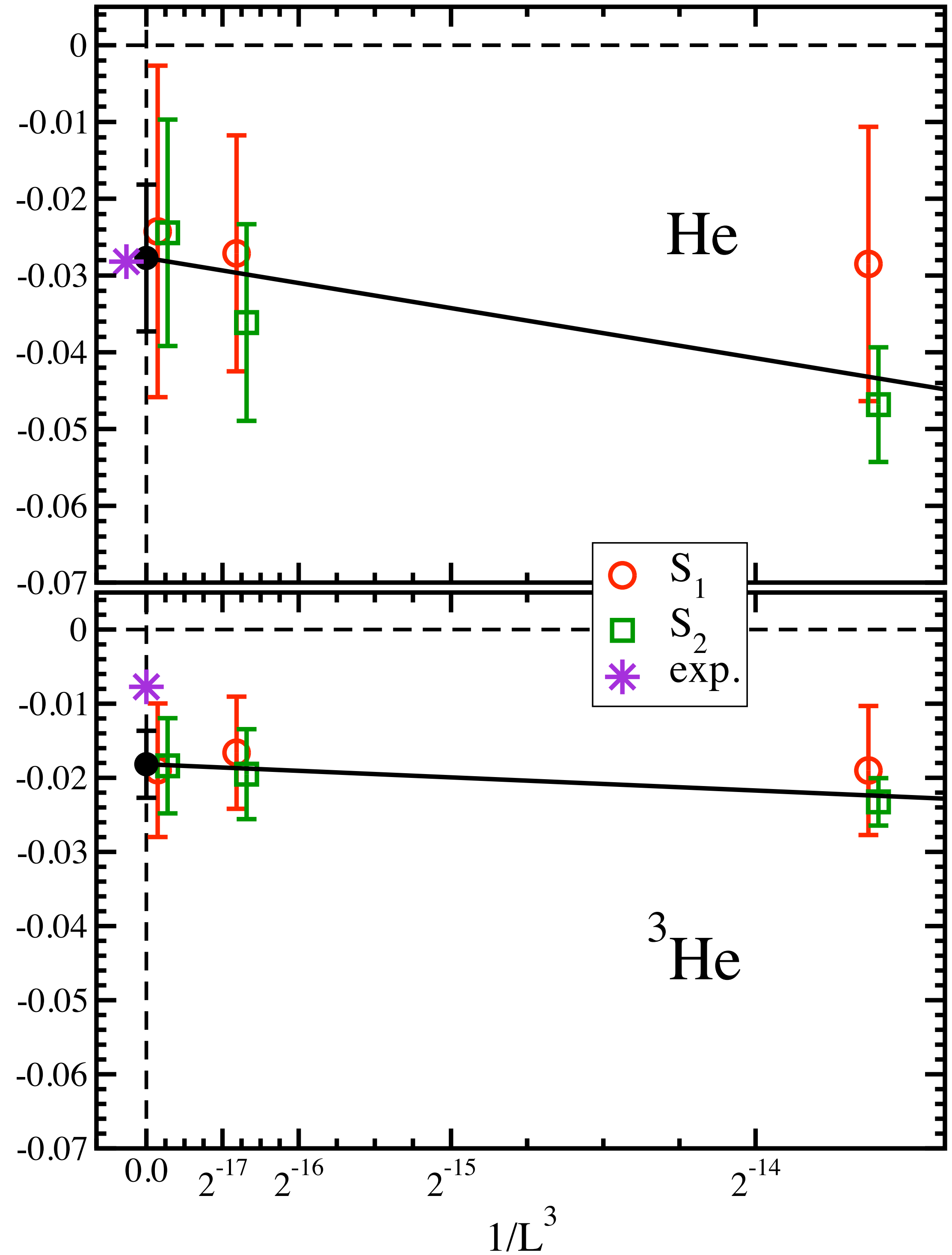
(black = experiment, color = lattice)



H.-W. Lin et al. (& N. Mathur, TIFR), 2008

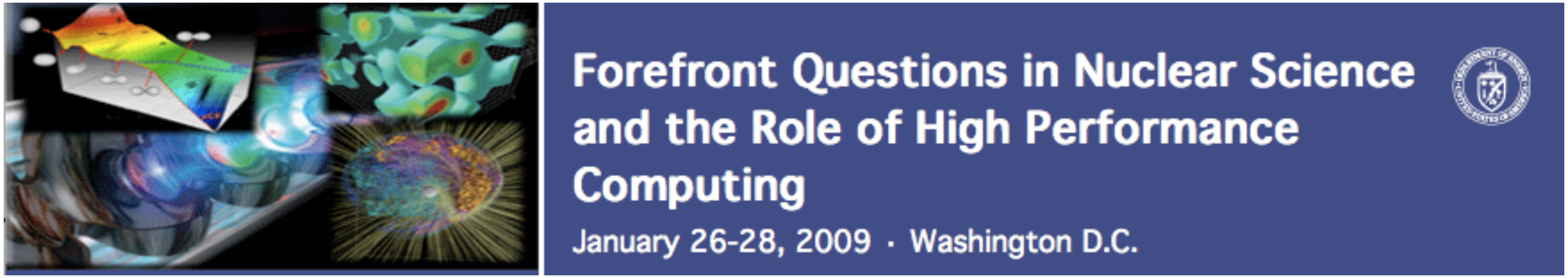
Spectra:

hardest...



T. Yamazaki,[1] Y. Kuramashi,[1,2] and A. Ukawa[1] 2009

very heavy quark masses, small coarse lattice.

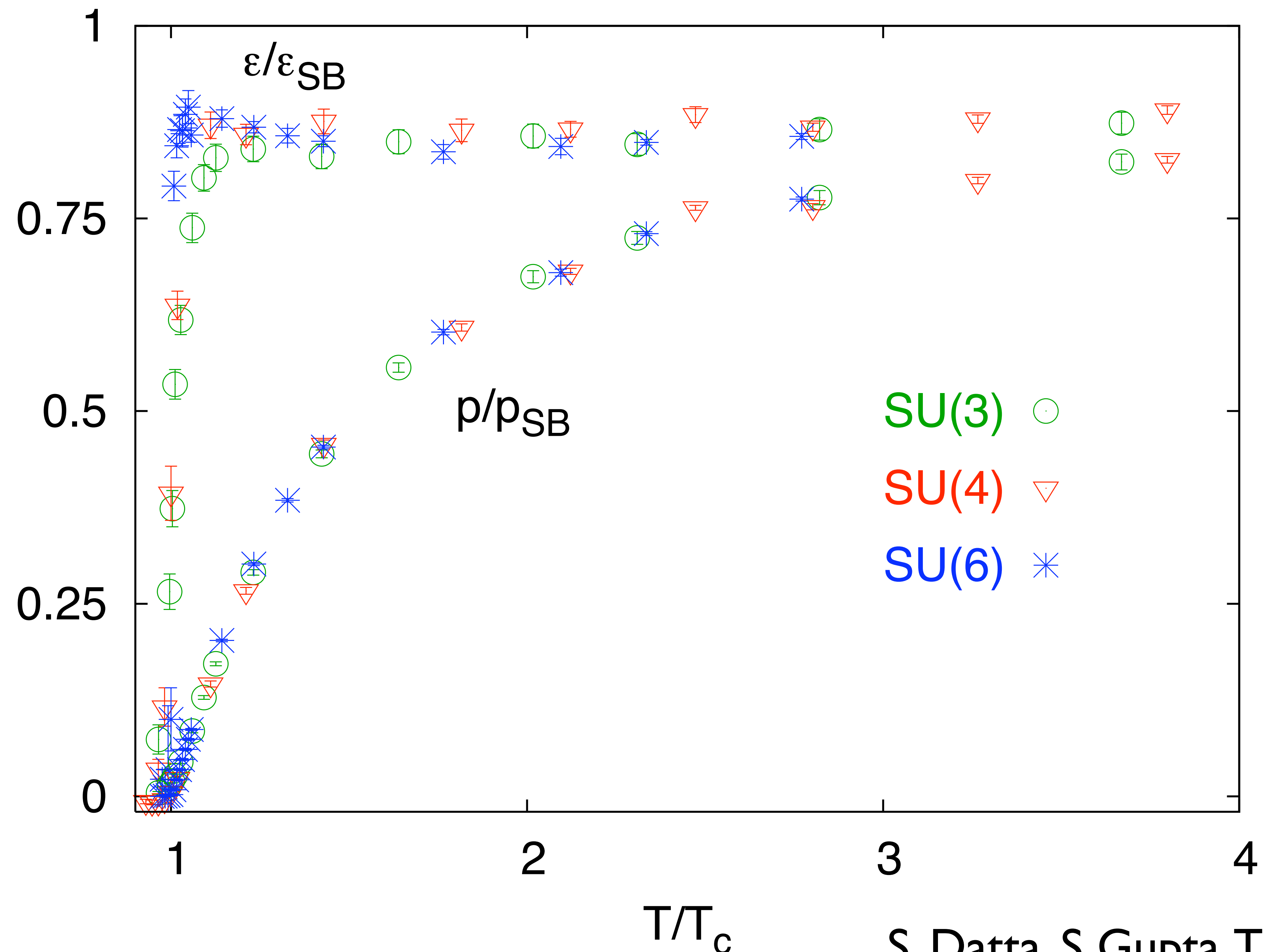


Compute properties of light nuclei from lattice QCD using ExaFlops computers?

(kilo, mega, giga, tera, peta, exa, zetta, yotta...)

Thermodynamics

Equation of state for hot QCD, μ=0



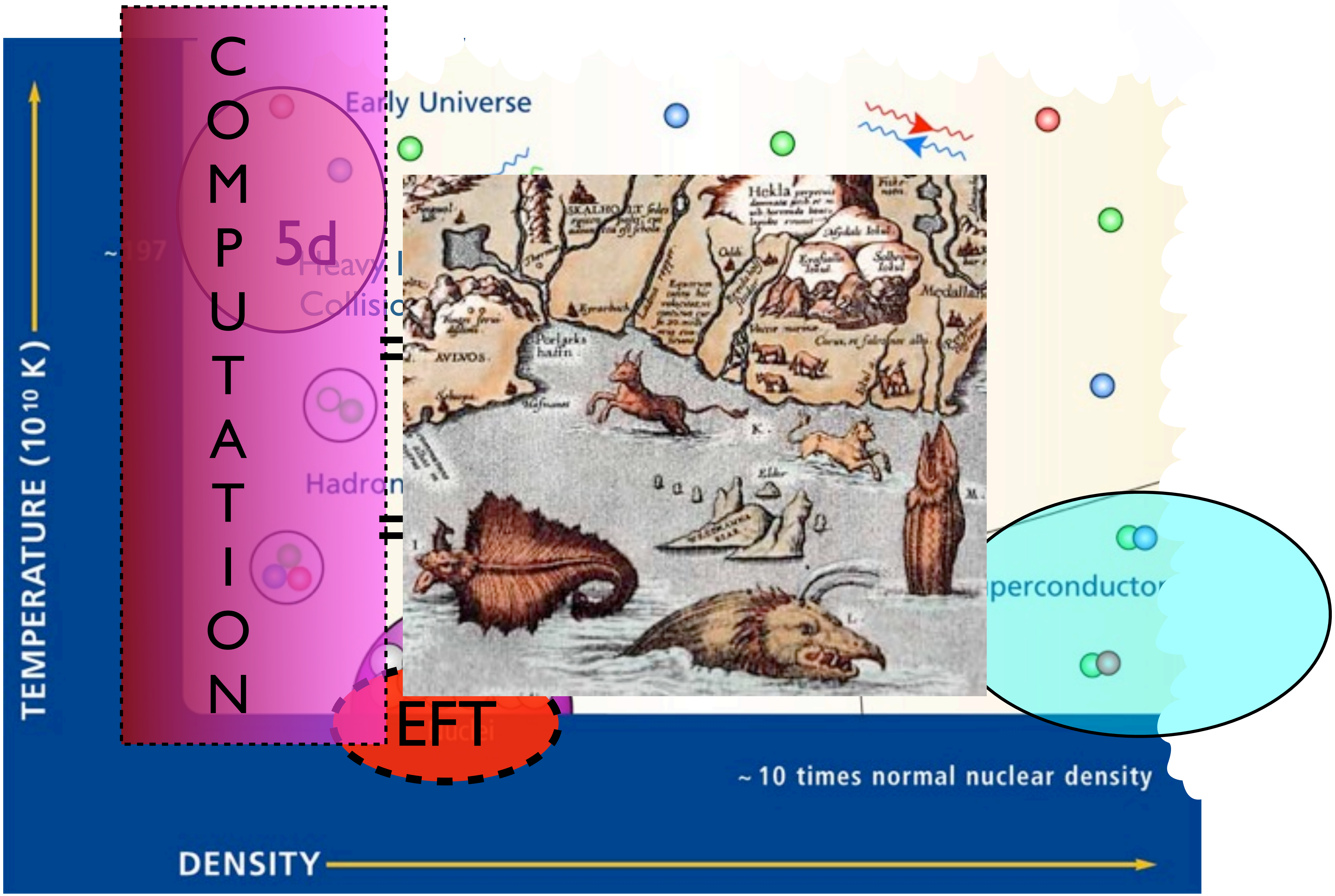
S. Datta, S Gupta, TIFR, 2009

Thermodynamics with $\mu \neq 0$?

A brute force attempt with lattice QCD appears to be an exponentially hard computational problem.

Much work is being done to make progress on this problem (eg: R Gavai, S. Gupta & students at TIFR)

There remains unknown territory to explore...



Best chance for nuclear structure from QCD:

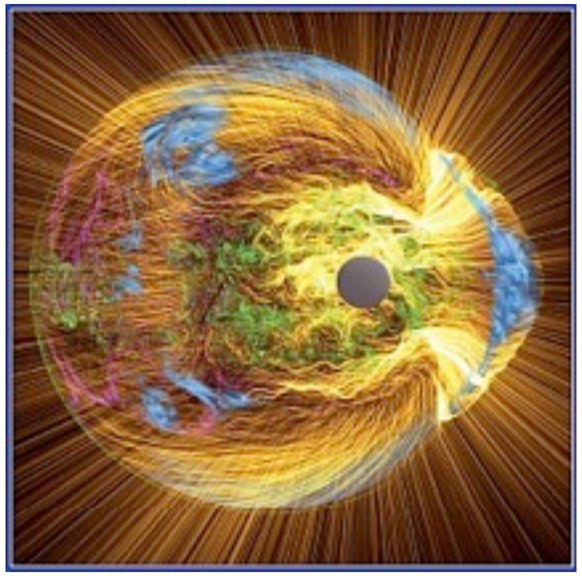
1. Map out A= 2,3,4,5? with PetaFlops-ExaFlops computing

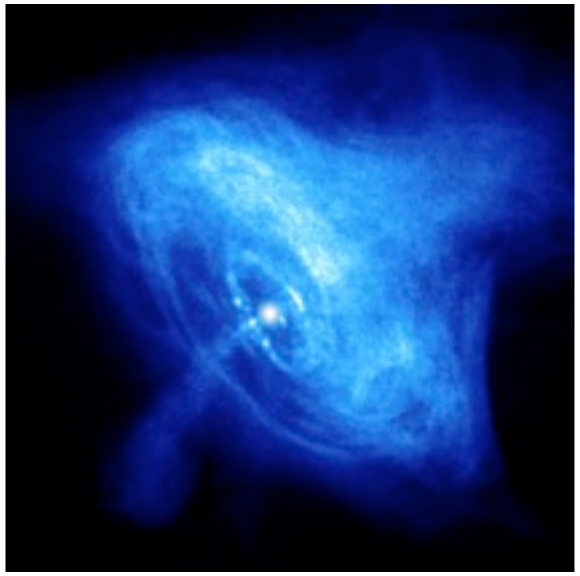
2. Match onto effective theory for nucleons

3. Develop numerical methods for solving the effective theory

4. Can also start seriously discussing the possibility of strange nuclear matter and kaon condensation in neutron stars

Kaon condensation, hyperon-nucleon interactions...interactions that cannot be measured experimentally now measured on lattice





VII. Other universes

Why do physical constants have the values they do?

Could they be different elsewhere in the universe?

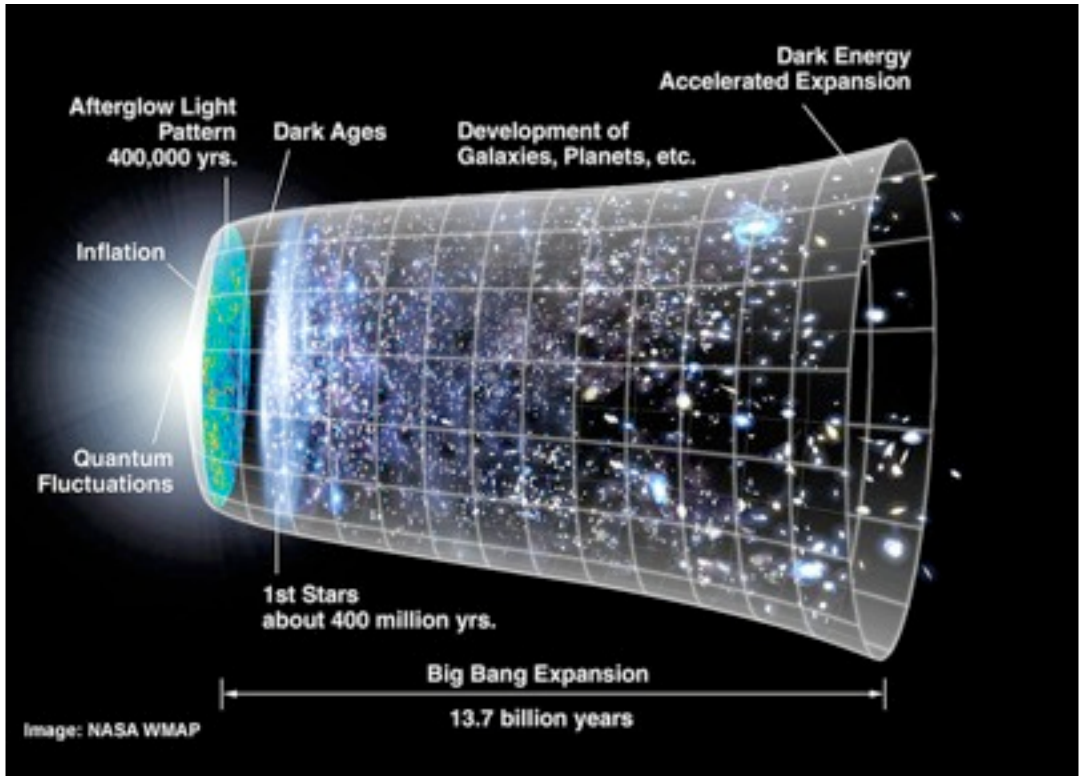
Why are there so many strange coincidences in nuclear physics necessary to make life possible?

- quark masses: We are lucky the neutron is slightly heavier than the proton (hydrogen would decay!)
- Existence of the Hoyle resonance, which is the gateway to making Carbon in stars...

Anthropic arguments have become fashionable: our world is as odd and unlikely as is necessary for our existence!

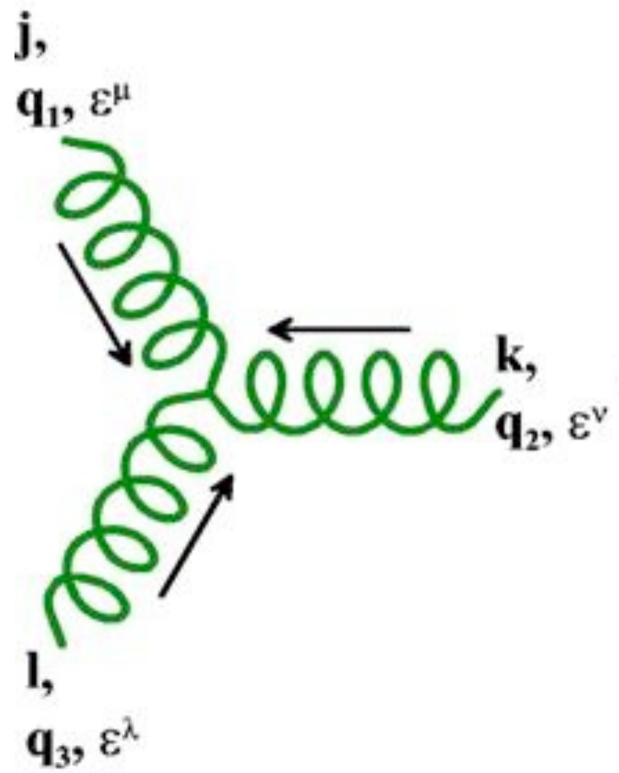
String theory: coupling "constants" can be fixed by local dynamics

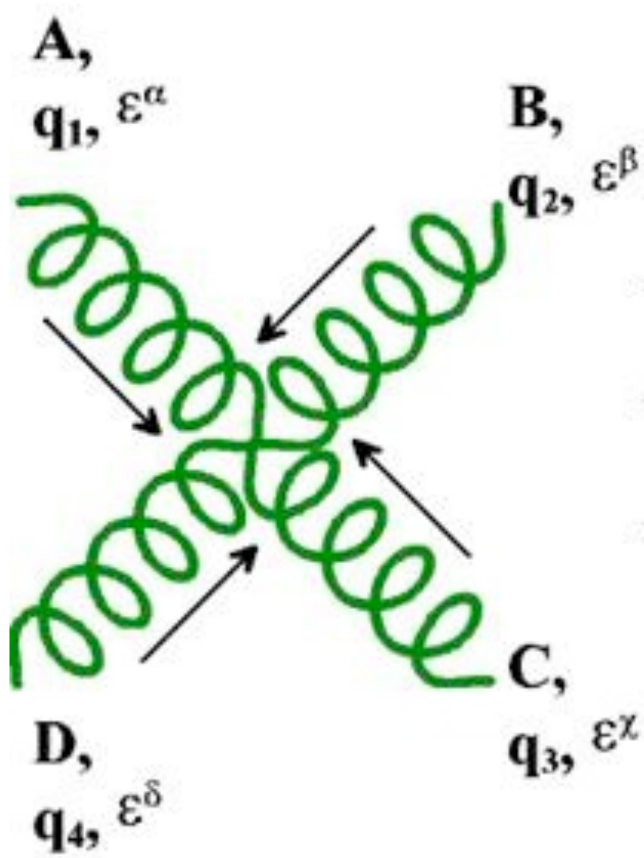
Cosmology theory: "inflation" in early universe allows large regions with all possible different physical constants



With lattice QCD/EFT we will be able to explore alternate possibilities and see how unlikely our existence might be!

About 50 years of studying strongly interacting particles led to these interactions...





...Probably decades more to fully understand their implications for nuclear physics and matter in general...

...with occasional challenges expected along the way.