QCD Theory:

Challenges, opportunities, & community needs

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Some of the exciting theoretical advances in recent years:

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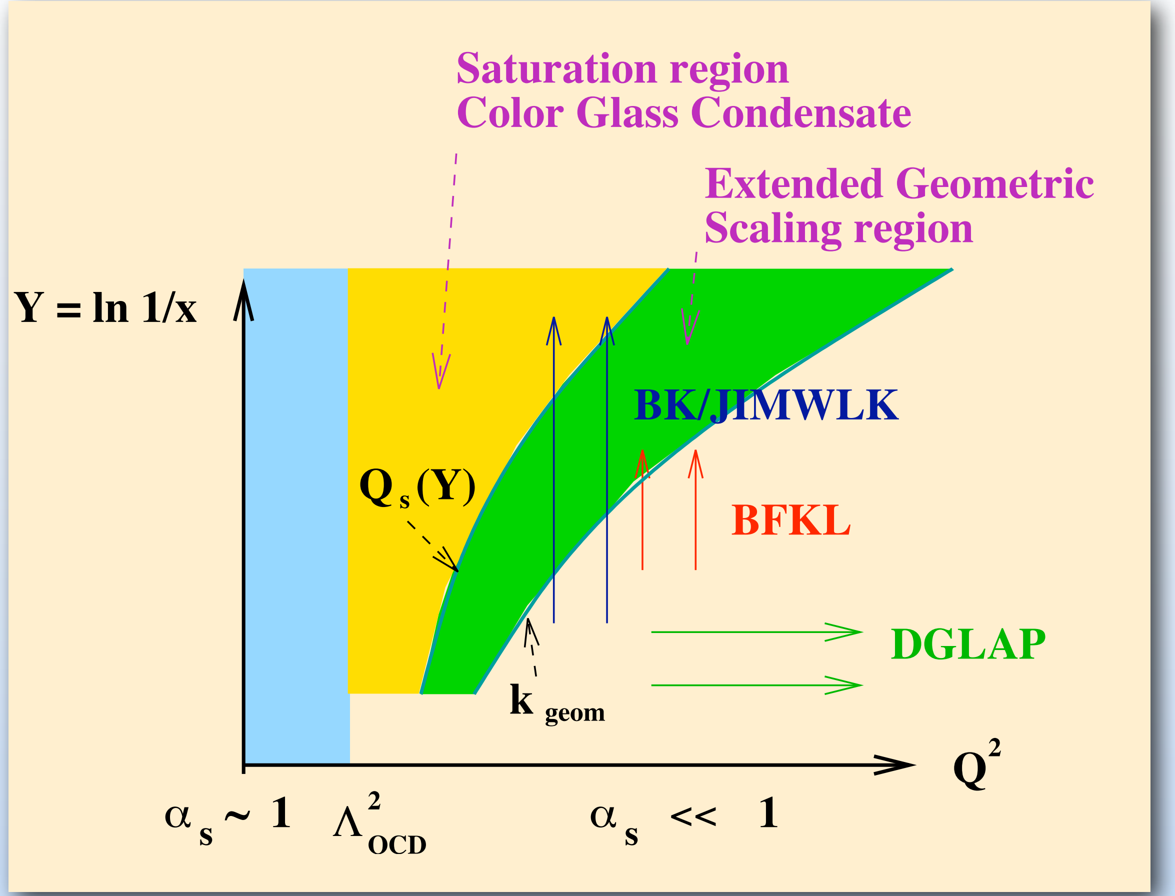
Challenges, opportunities, & community needs

Some of the exciting theoretical advances in recent years:

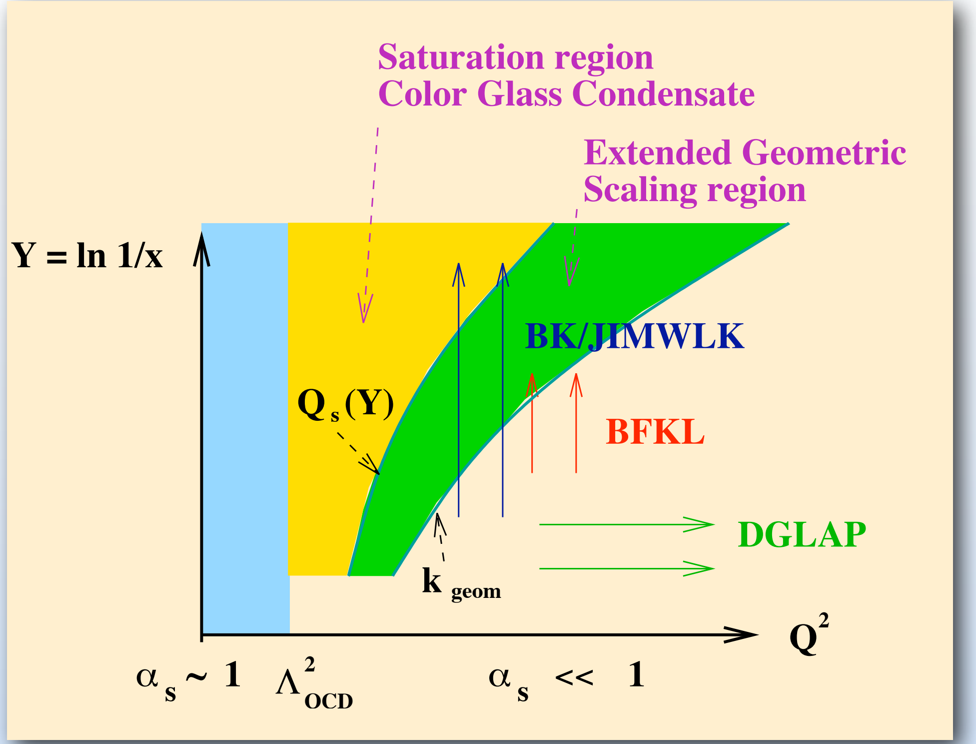
- Partons
- Hot and Dense QCD
- Effective Field Theory
- Ads/QCD
- Lattice QCD

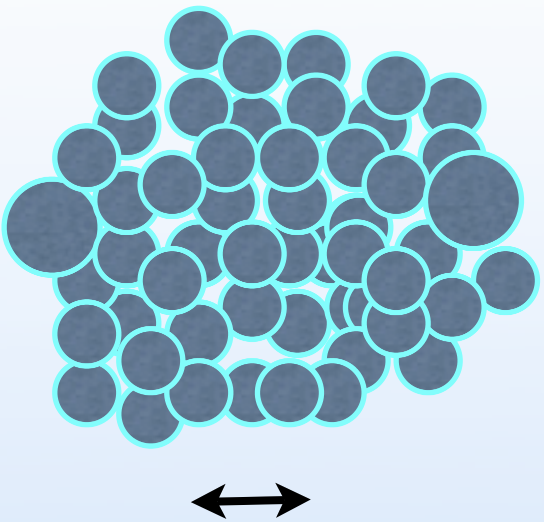


Violates
Froissard bound

BFKL: parton density increases with Y

$$N \sim e^{\#\alpha_s Y} \;, \quad \sigma \propto e^{\#\alpha_s Y} \propto s^{\#}$$



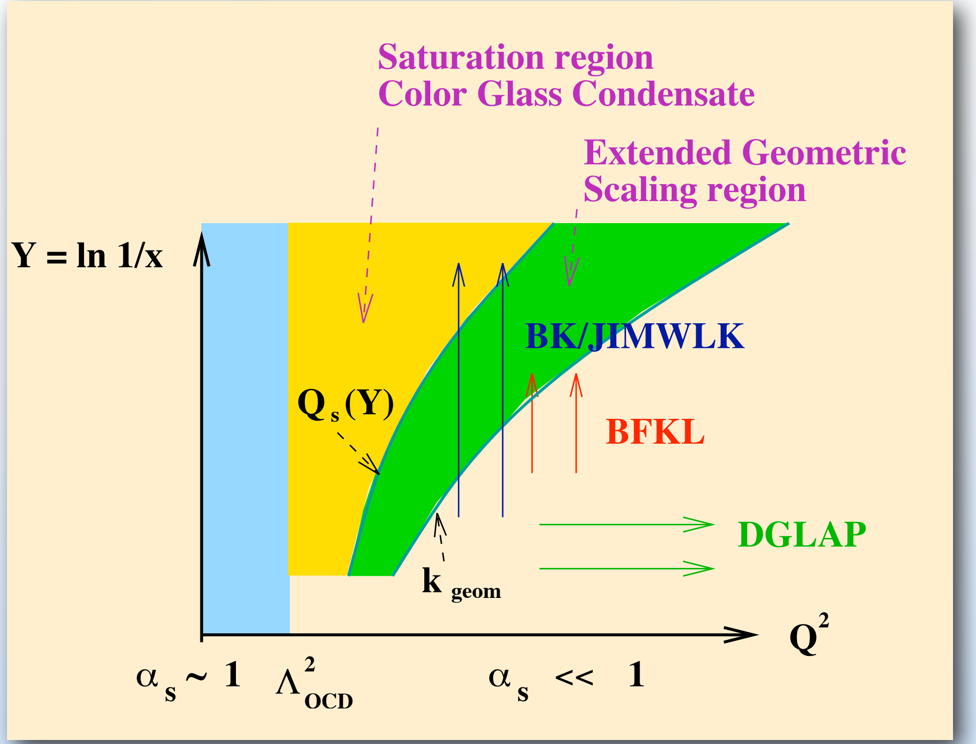


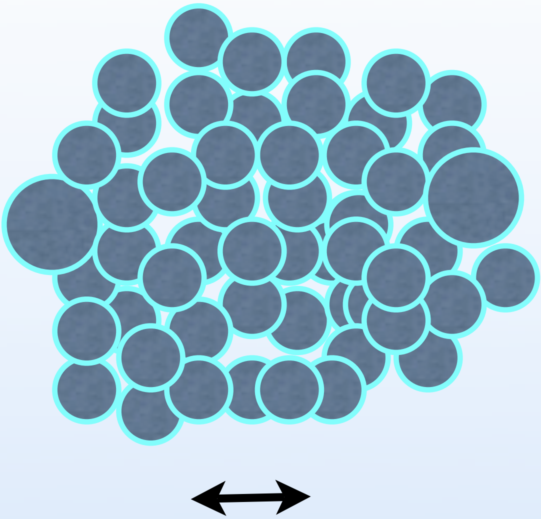
$$\sim 1/Q_s$$

BK/JIMWLK
equations
take into account
gluon fusion

Parton saturation:

$$Q_s^2 \sim \frac{\alpha_s \pi^2}{S_\perp N_c} xG(x, Q_s^2)$$



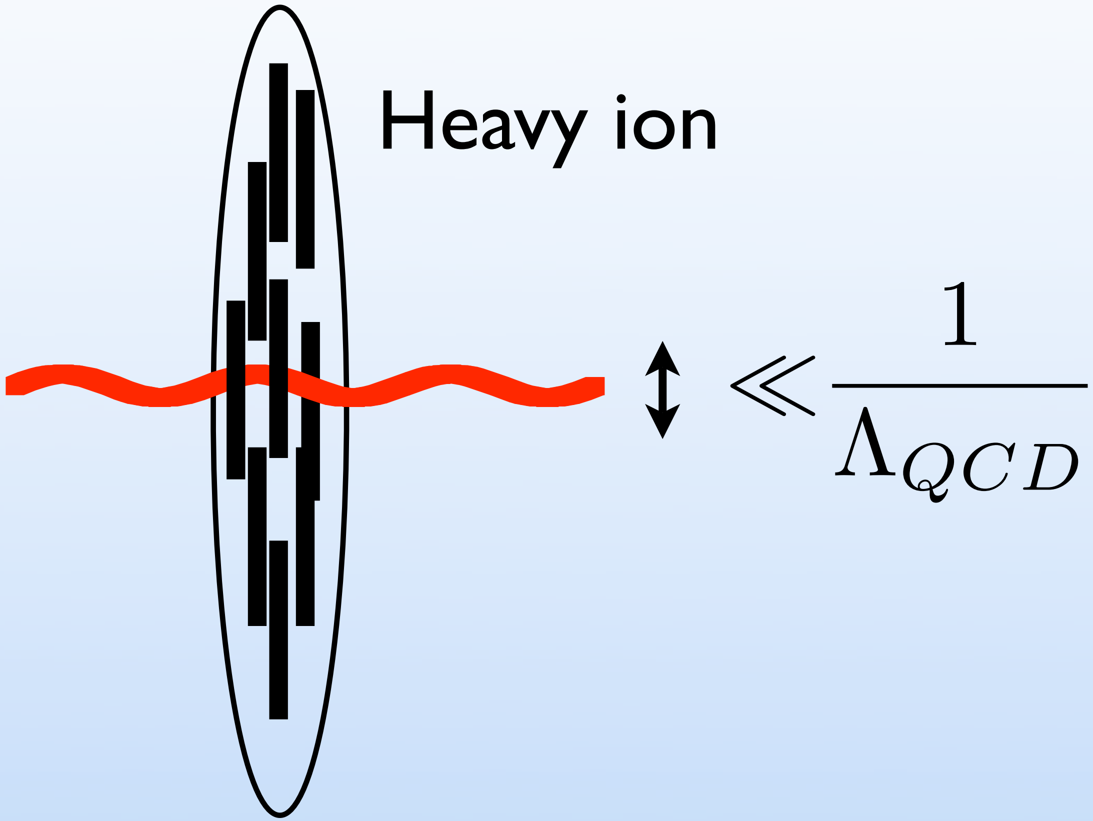


$$\sim 1/Q_s$$

In saturation region

$$\mathbf{A}_\mu \sim \frac{1}{g_s} \longrightarrow$$ Strong, semi-classical field

Color Glass Condensate (McLerran, Venugopalan)



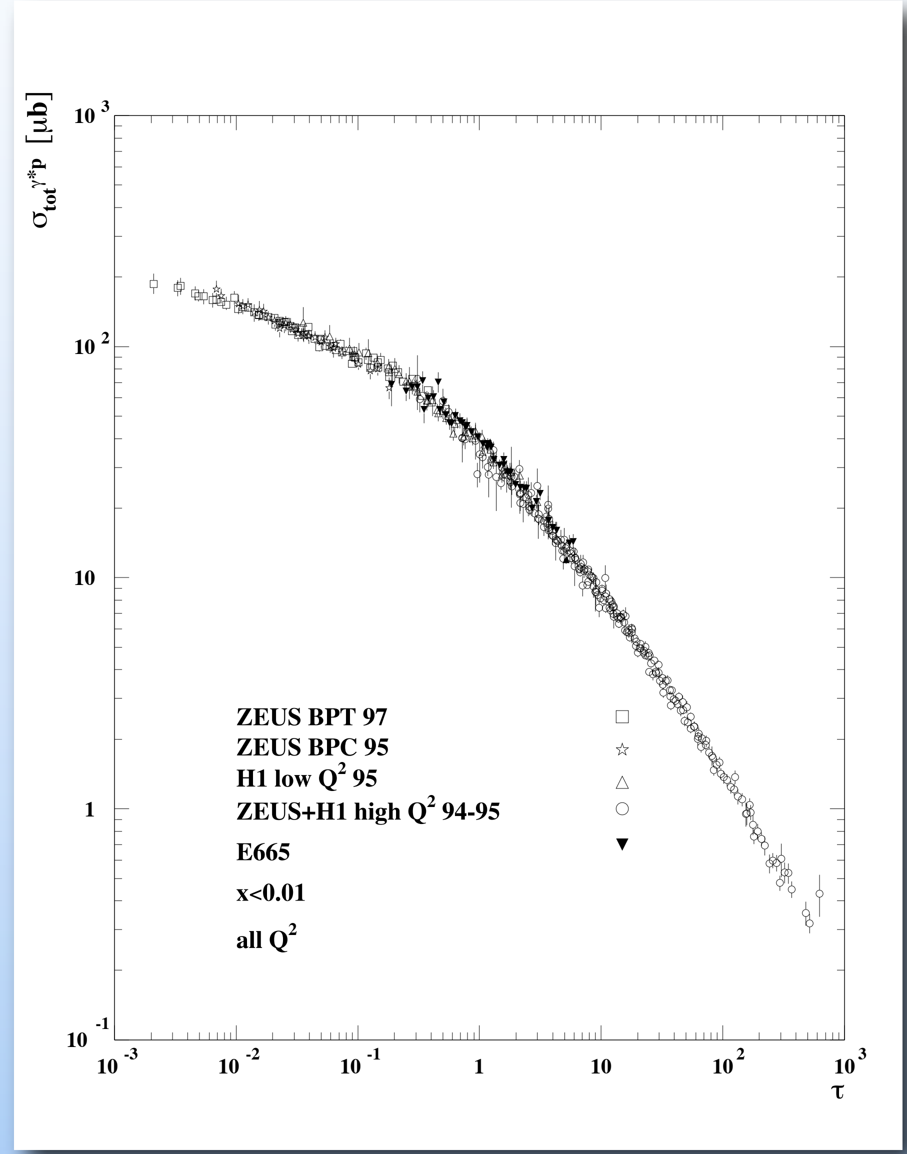
Saturated low-x partons =
classical field generated by
random color sources in plane

Geometric scaling

At transverse length scales $\frac{1}{Q_s} \ll x_\perp \ll \frac{1}{\Lambda_{QCD}}$

Scattering is only a function of $Q_s x_\perp$ or, Q/Q_s

HERA data: evidence for geometric scaling, saturation?

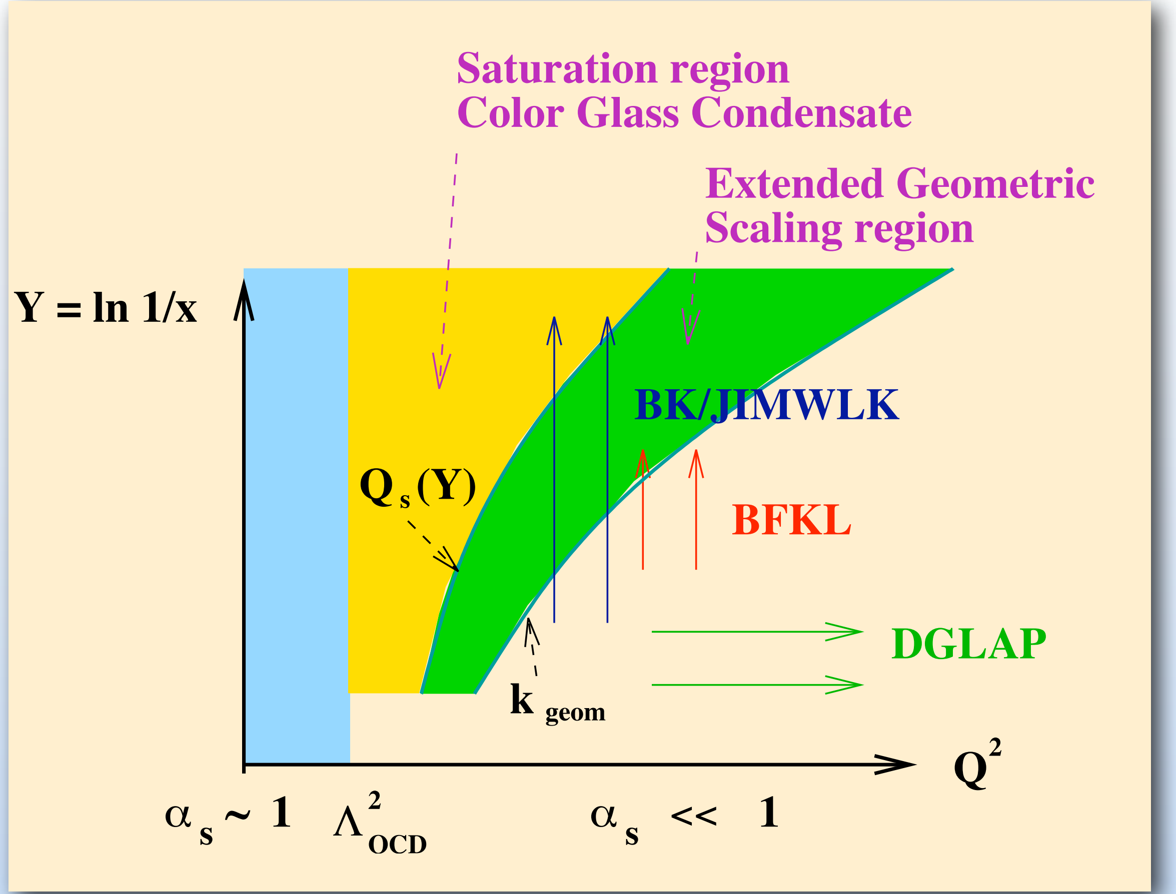


Q^2/Q_s^2

Extracted Q_s yields large α_s

Would like to see in eA scattering

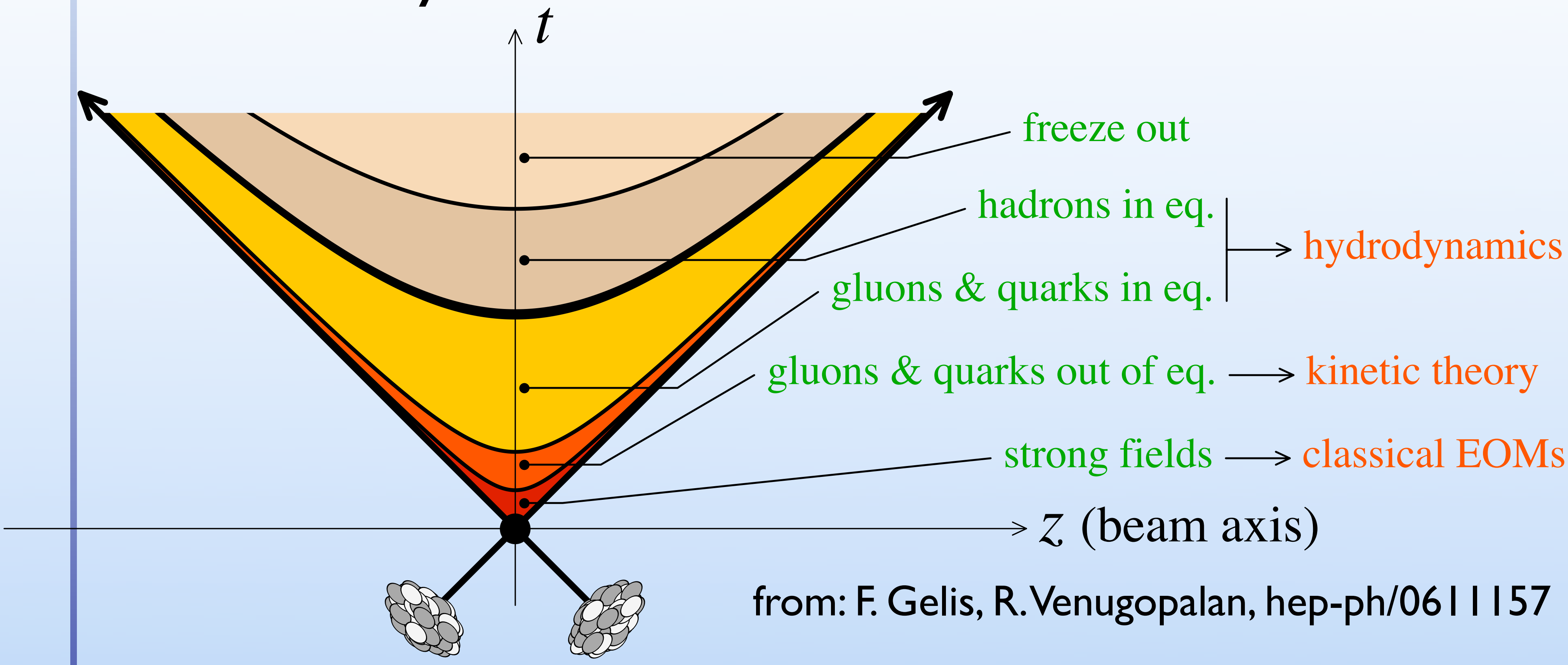
$$(Q_s \propto A^{1/3})$$



Outstanding issues:

- Theoretical connection between CGC & DGLAP?
- Detailed phenomenological tests?

On to heavy ion collisions



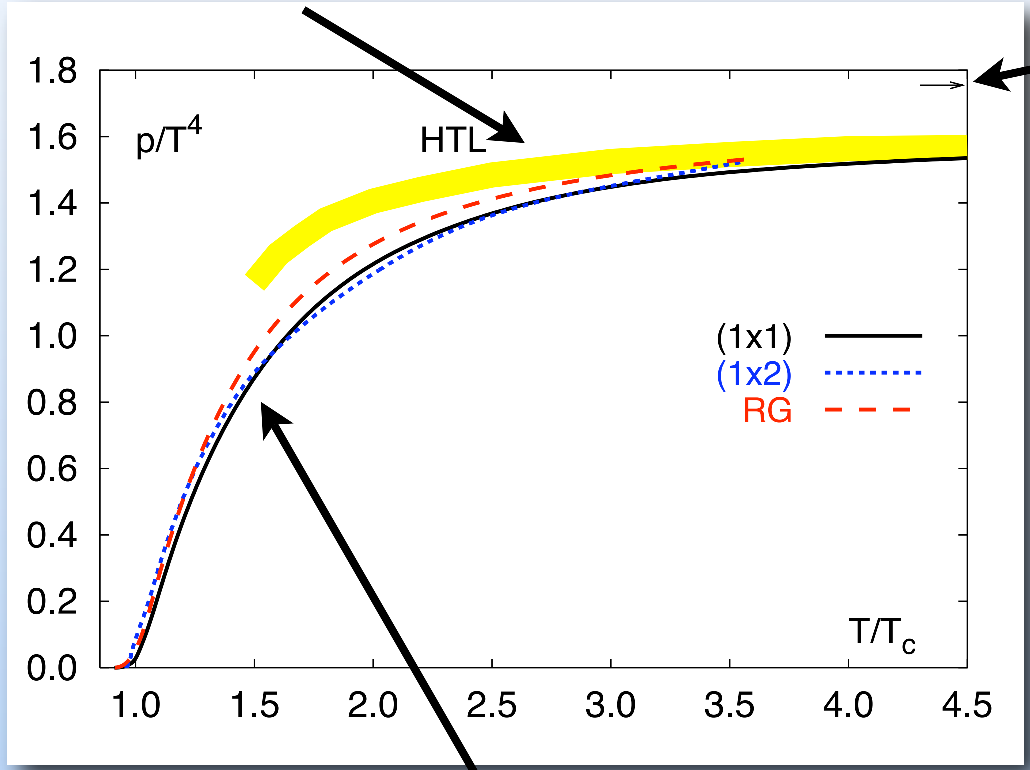
from: F. Gelis, R. Venugopalan, hep-ph/0611157

Working toward a comprehensive theory: a huge challenge with some progress made

Pressure of hot SU(3) gauge theory

Theory calculation

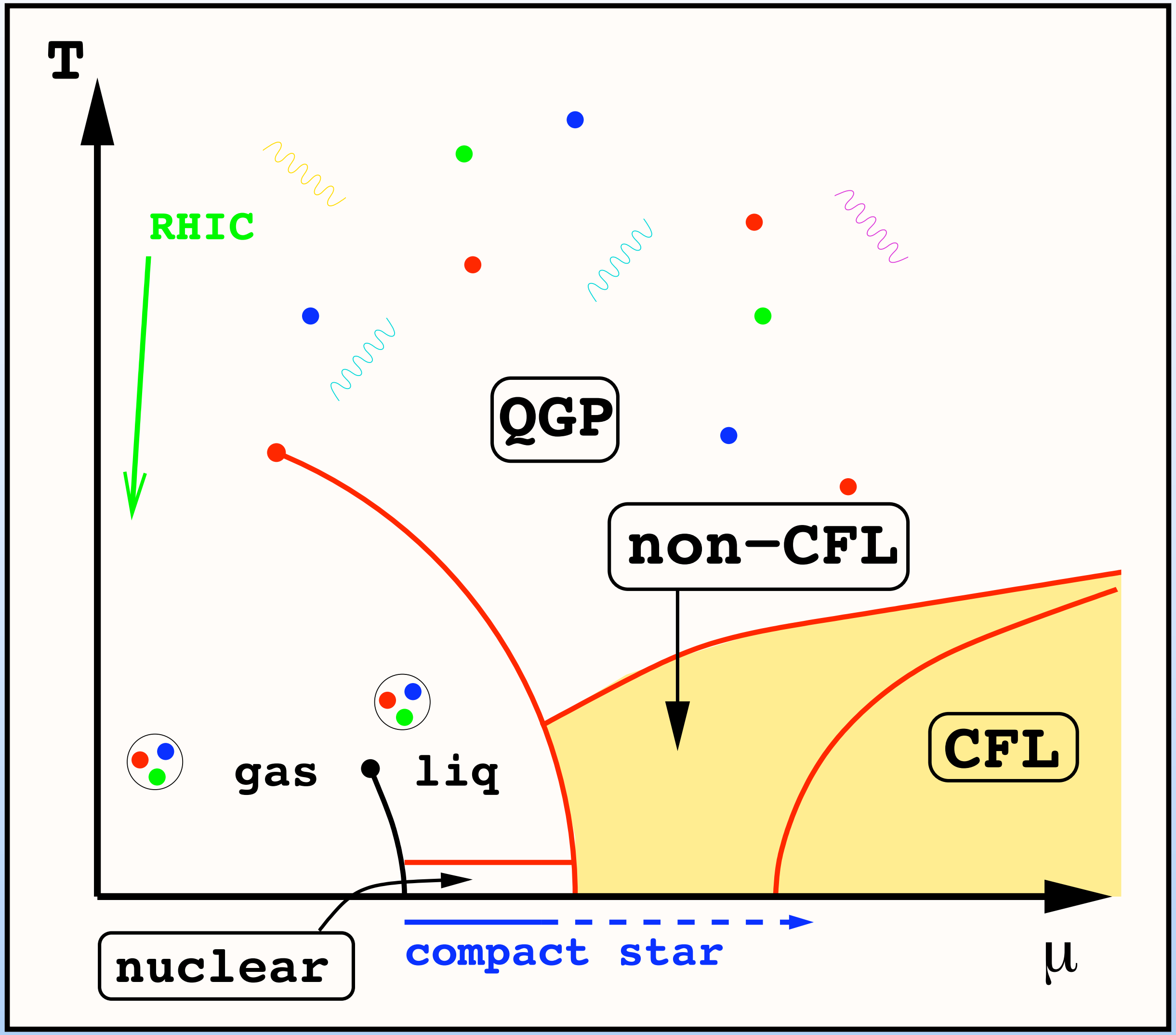
Ideal gas



from F. Karsch

Lattice results, various actions

The QCD phase diagram:



M. Alford, hep-ph/0610046

Effective Field theory: implementing the symmetries of QCD in phenomenological Lagrangians

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- Chiral perturbation theory

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Effective Field theory: implementing the symmetries of QCD in phenomenological Lagrangians

- Chiral perturbation theory
- SCET (Soft Collinear Effective Theory)
- Nuclear Effective Theory (Extending chiral Lagrangians to include multi-nucleon interactions)
- EFT for the lattice

Chiral perturbation theory

A remarkable new & rigorous result from an old theory:

The pole of the elusive σ- meson determined with great accuracy from dispersion relations & chiral perturbation theory:

$$M_\sigma - \frac{i}{2}\Gamma_\sigma = 441^{+16}_{-8} - i272^{+9}_{-12.5} \ \ \mathrm{MeV}$$

Caprini, Colangelo, Leutwyler (2006)

SCET: Soft Collinear Effective Theory

Bauer
Fleming
Luke
Pirjols
Stewart

- Allows one to separate perturbative from nonperturbative QCD in processes with energetic hadrons with nearly collinear constituents (e.g., B decays, hard scattering)
- all-orders factorization arguments, corrections to factorization
- RG resummation of large logs (eg, Sudakov factors)
- High precision extractions of V_{ub}, heavy-light form factors
- Event generation for LHC (SCET interpolates between PQCD for hard events and parton shower for soft events

Bauer
Schwarz

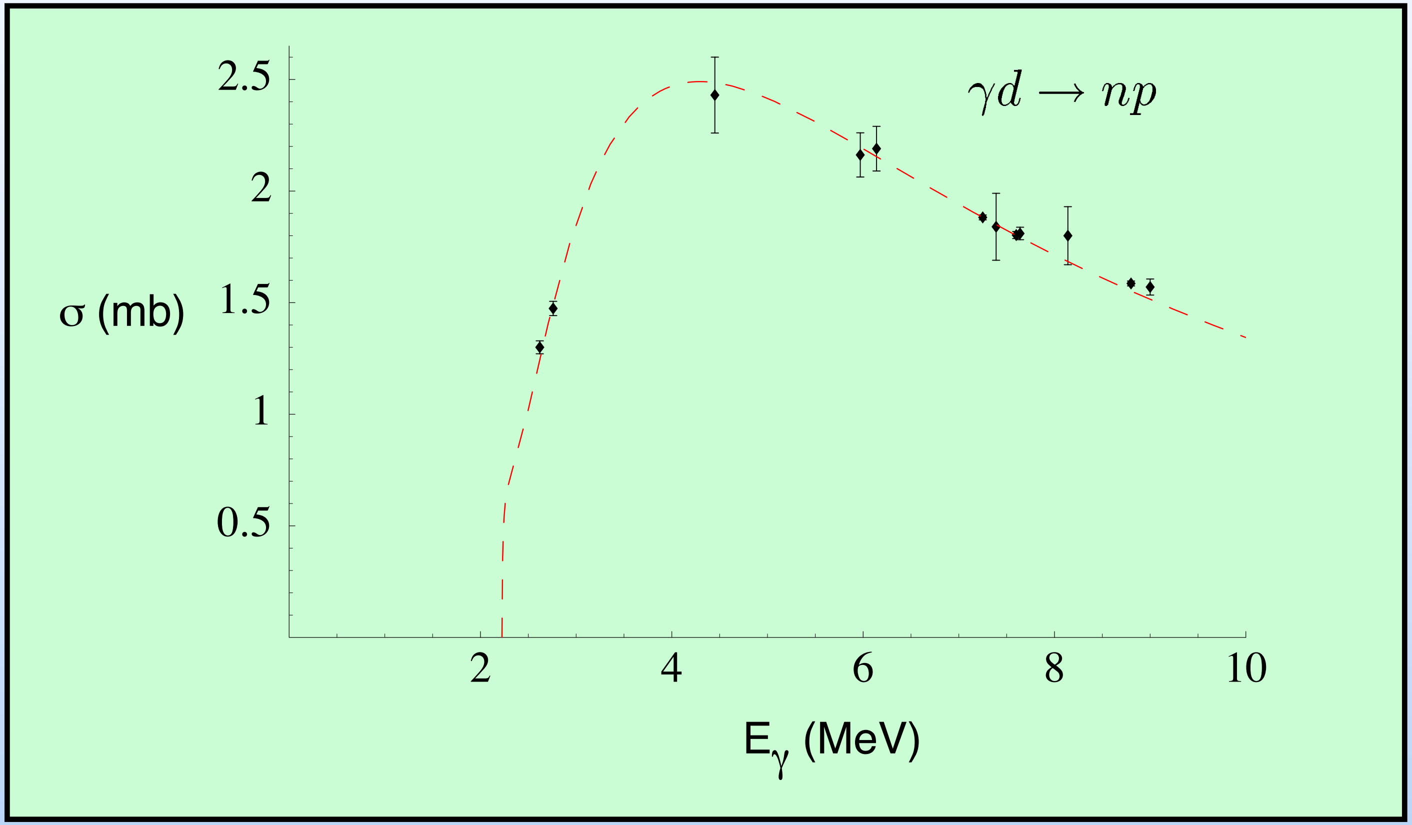
- Jets, event shapes, etc.

Nuclear effective theory

Extension of chiral perturbation theory to multi-nucleon (few-body) systems at low energy

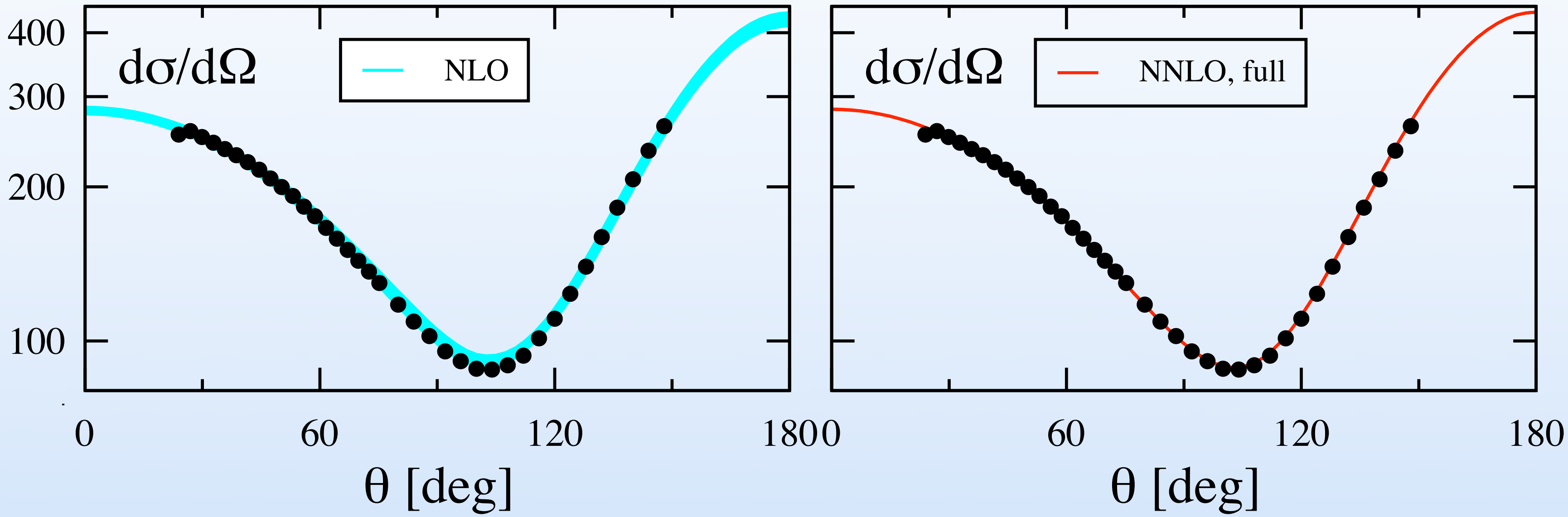
- Weinberg (1990), many subsequent authors
- High precision, model independent description of low energy few-body processes
- A key component for extracting few-nucleon physics from lattice QCD simulations

- Deuteron breakup @ N^{4}LO (1% accuracy, 2 free phenomenological constants)



G. Rupak, Nucl. Phys. A (2000)

- nd elastic scattering, 3 MeV



Epelbaum et al., Phys. Rev. C (2004)

- Triton binding energy:

$BE_{NNLO} = 8.54$ MeV $\quad BE_{EXP} = 8.48$ MeV

(3-body input = nd scattering length)

Platter, Phys. Rev. C (2006)

Ongoing EFT developments are critical for lattice QCD:

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- Extraction of S-matrix elements from Euclidean correlation functions
- Treatment of multi-baryon systems

AdS/CFT: a startling development from string theory

N=4 supersymmetric Yang-Mills theory in the limit of infinite colors is equivalent to a classical supergravity theory in 5-dimensional anti-deSitter space, and can be exactly solved.*

* Gluons, octet fermions, octet scalars (for N_c=3)

Can this theory be used to learn about the real world?

- Partons and BFKL
- Energy loss in a plasma
- Universal viscosity bound

Polchinski
Strassler
2001

Showed how glueball-glueball scattering exhibits hard scattering behavior (power law momentum scaling)

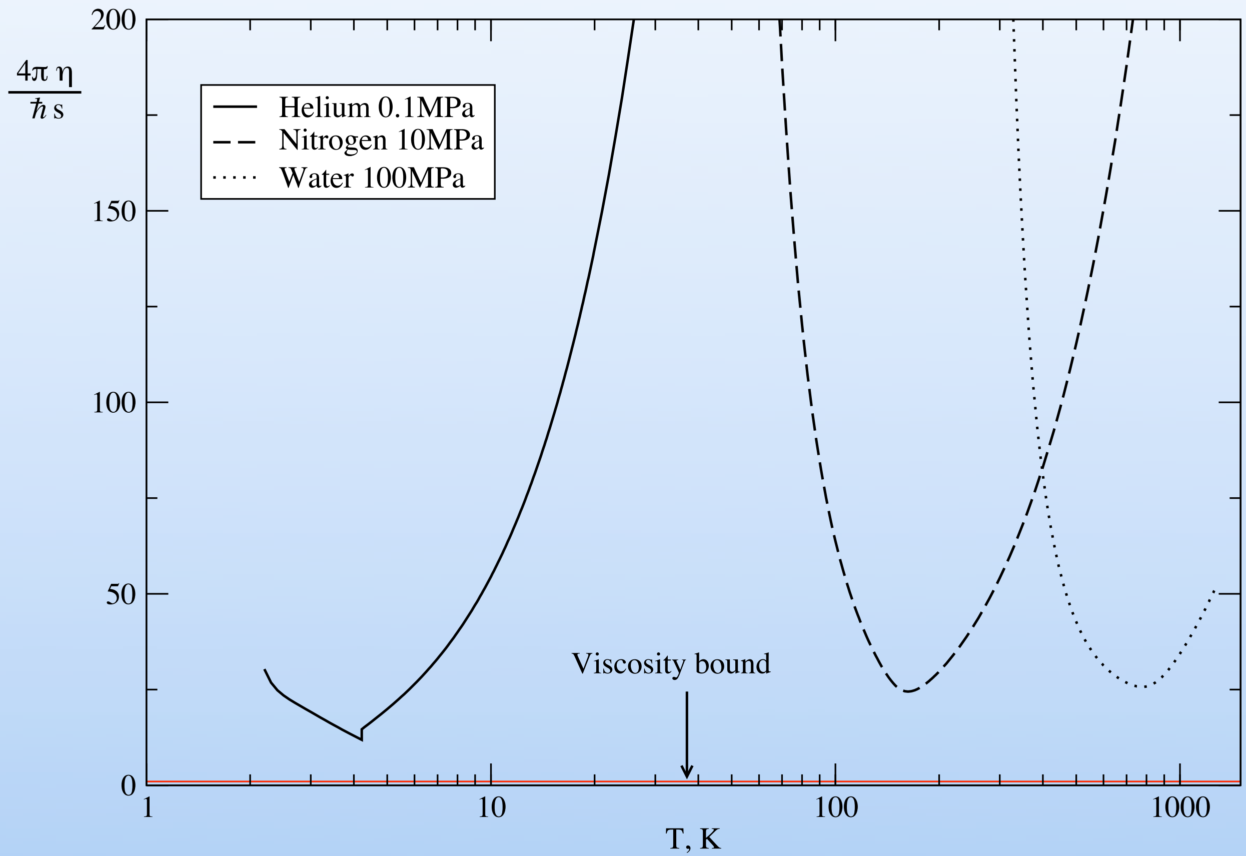
Brower
Polchinski
Strassler
Tan
2006

Derived interpolation between soft pomeron (glueball) exchange, and hard pomeron exchange (BFKL behavior)

Liu, Rajagopal, Wiedemann
Herzog et al.
2006

Jet quenching, energy loss of heavy quark in hot nonabelian plasma

Conjectured viscosity bound: $$\frac{\eta}{s} \geq \frac{1}{4\pi}$$



Kovtun, Son, Starinets (2004)

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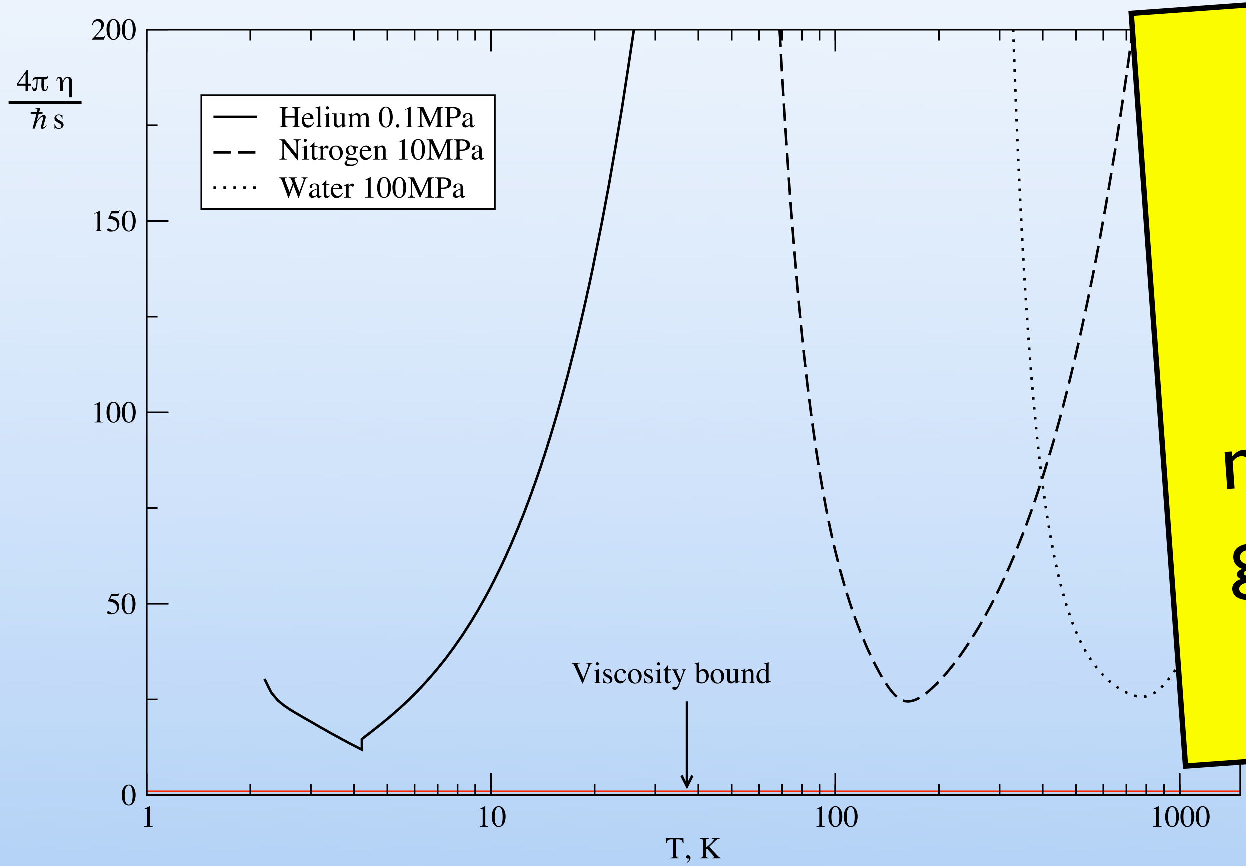

Does QGP go lower? The closer to saturation, the more likely a simple gravitational dual to QCD exists.

Kovtun, Son, Starinets (2004)

Improved technology + intense theoretical effort
= a new era in lattice QCD

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- High precision calculations of hadronic properties (1% for some quantities)

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  - resonance and glueball spectra

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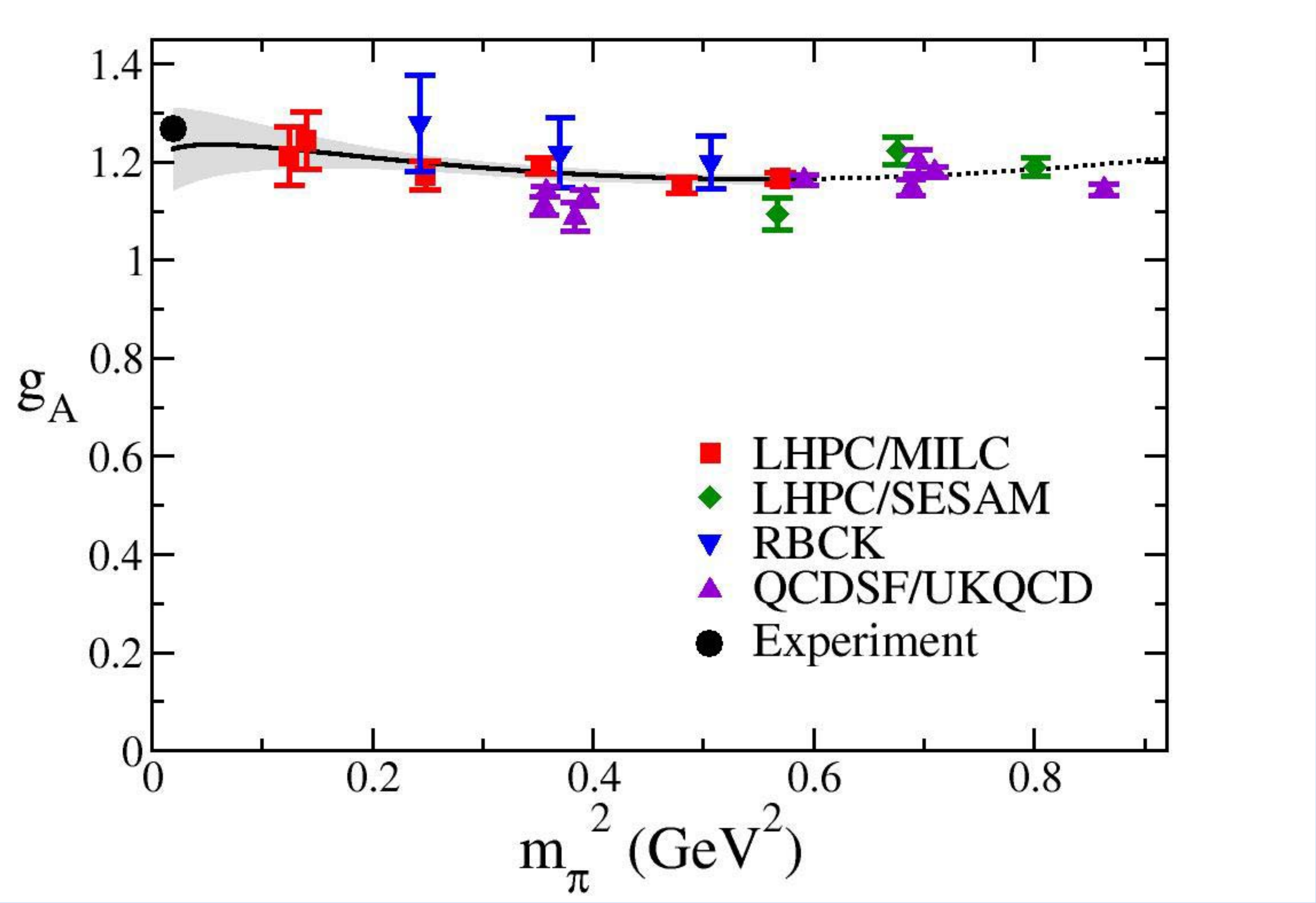
- Exploration of the QCD phase diagram
- Advancing frontier:
  - nucleon properties
  - structure functions
  - resonance and glueball spectra
  - two - baryon systems

1% precision from the lattice in the meson sector:

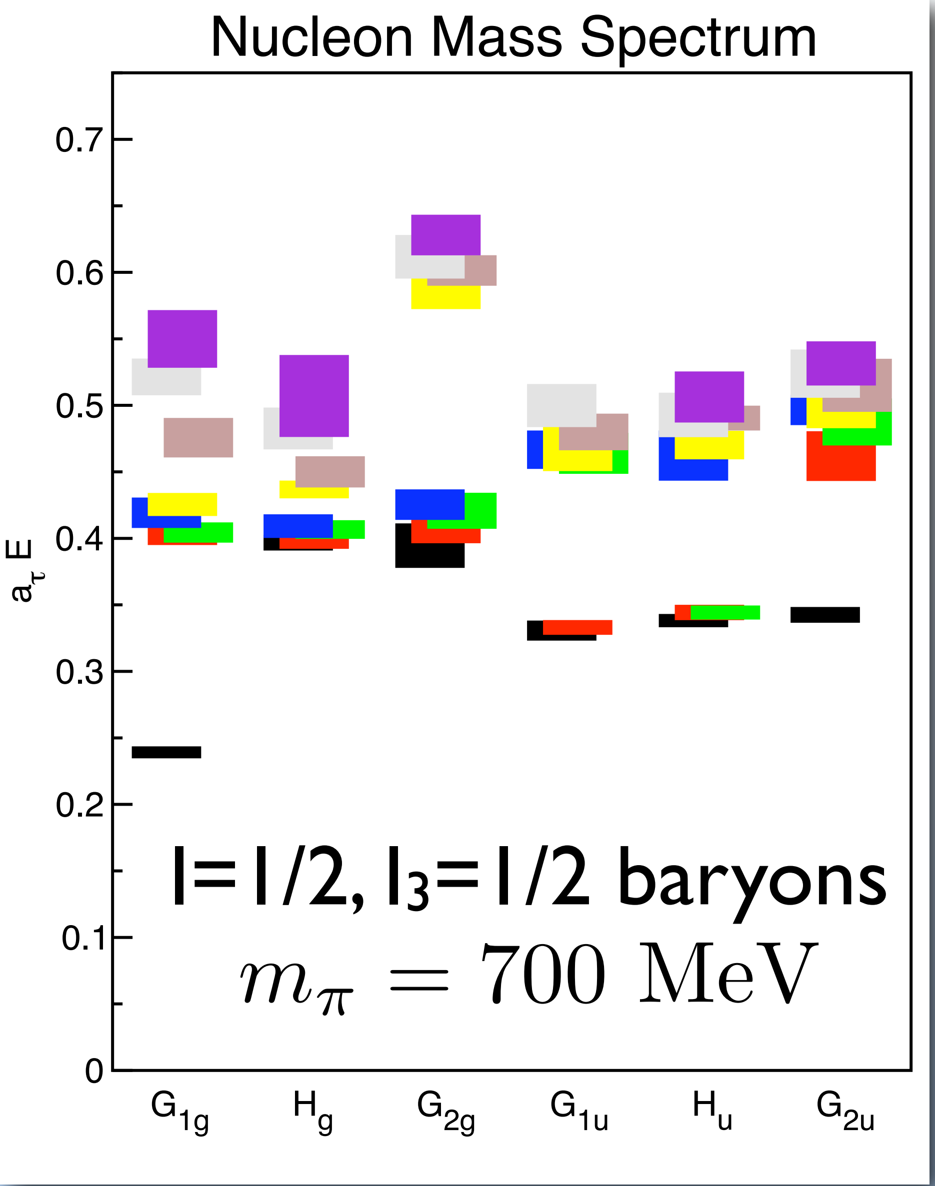
$$
\begin{aligned}
f_\pi/f_K &= 1.210(4)(13) && \text{MILC} \\
&= 1.223(12) && \text{Exp}
\end{aligned}
$$

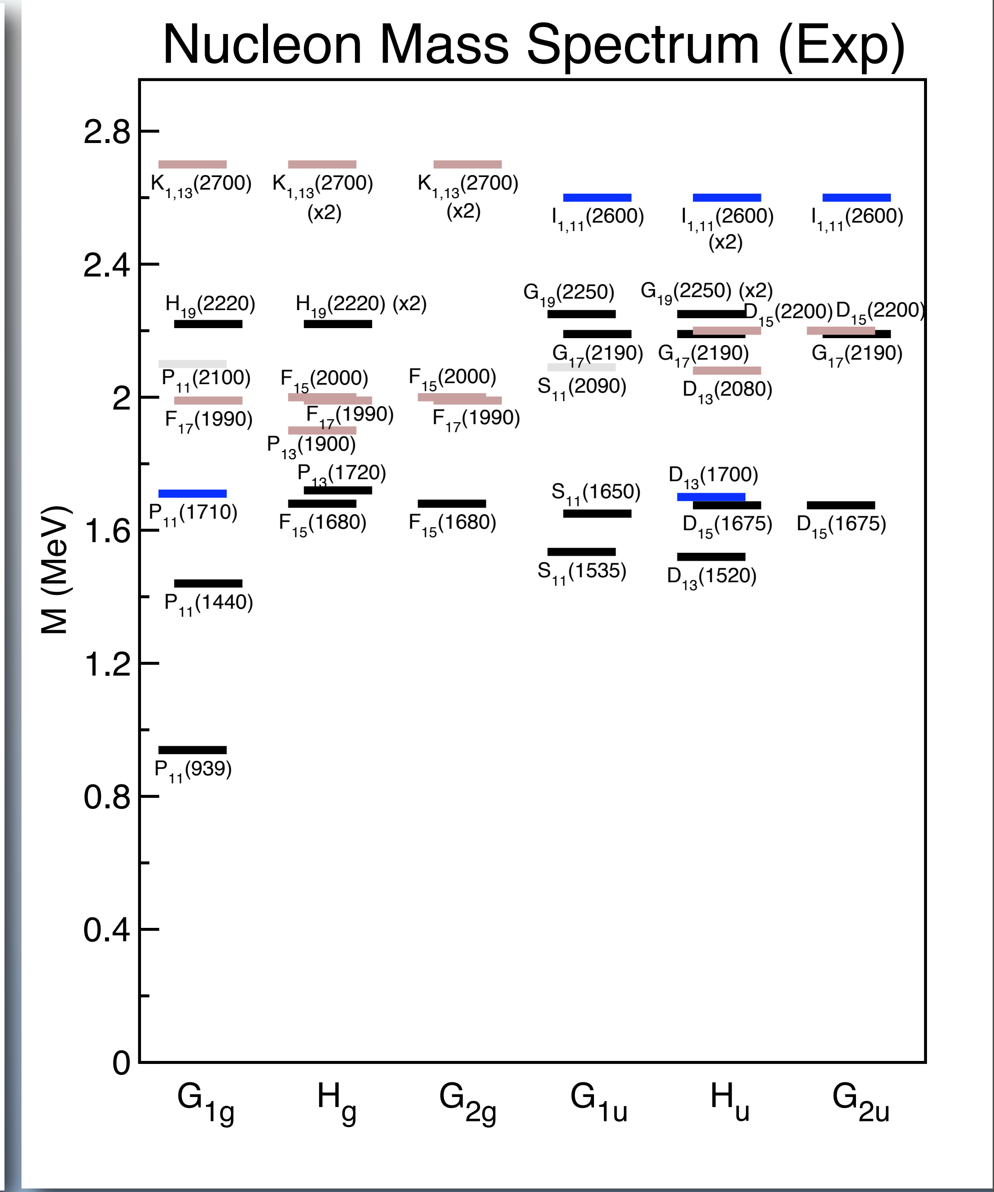
One nucleon properties: g_A



LHPC (Edwards *et al.*),
PRL 96 (2006) 052001

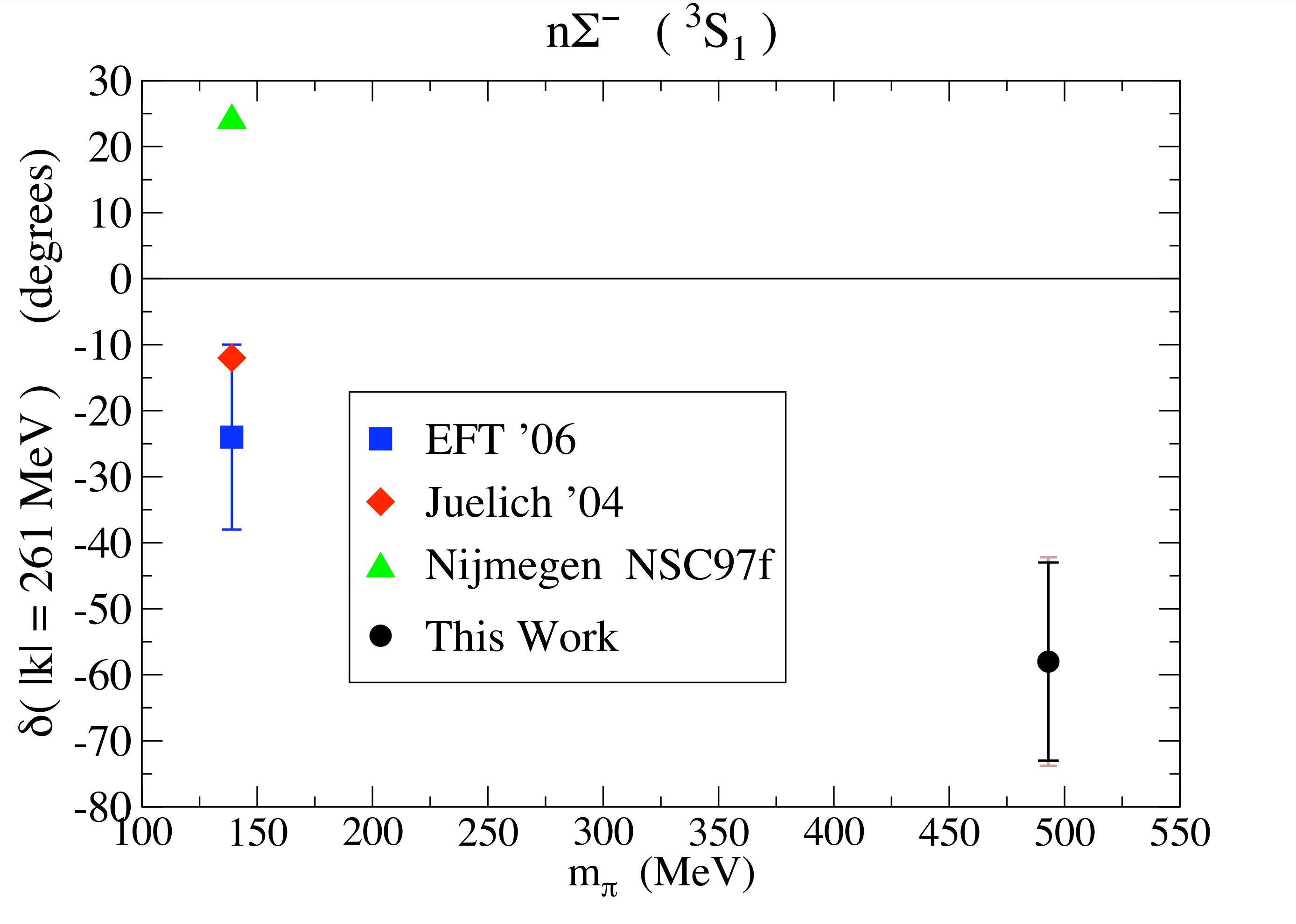
Partons ♦ Hot/dense QCD ♦ EFT ♦ AdS/QCD ♦ **Lattice**





LHPC collaboration, from Lichtl (2006)

Two baryon properties:



NPLQCD hep-lat/0612026

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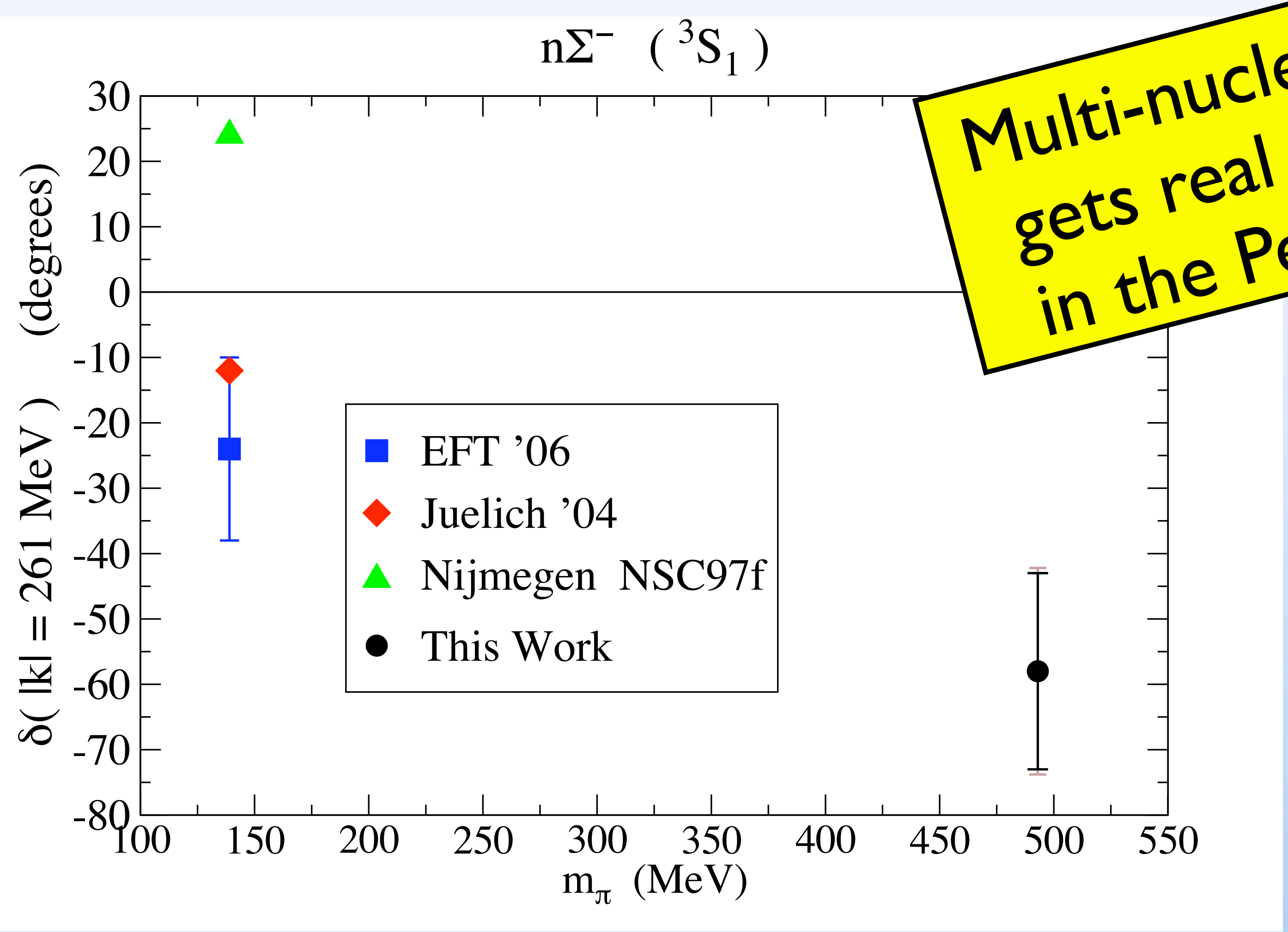
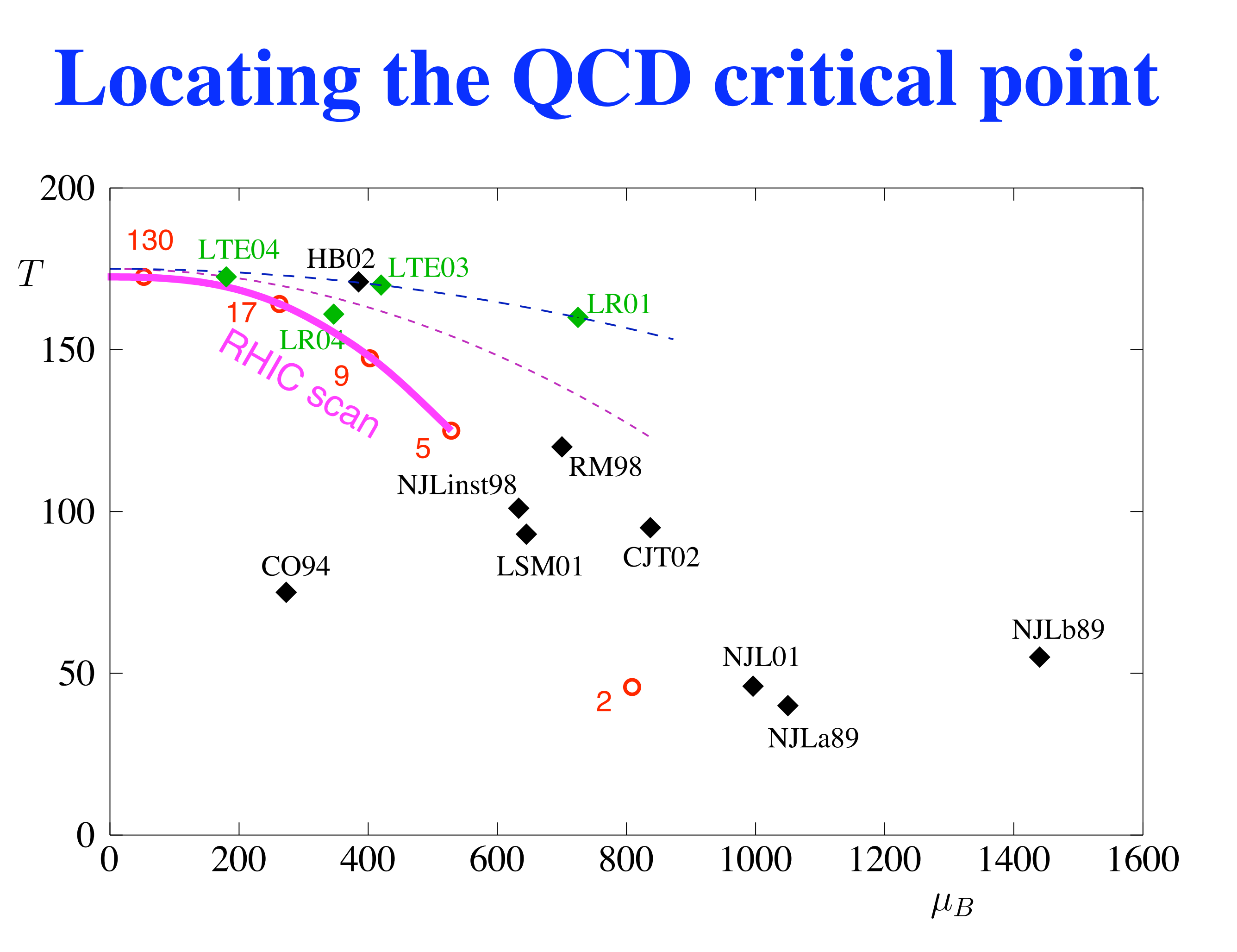


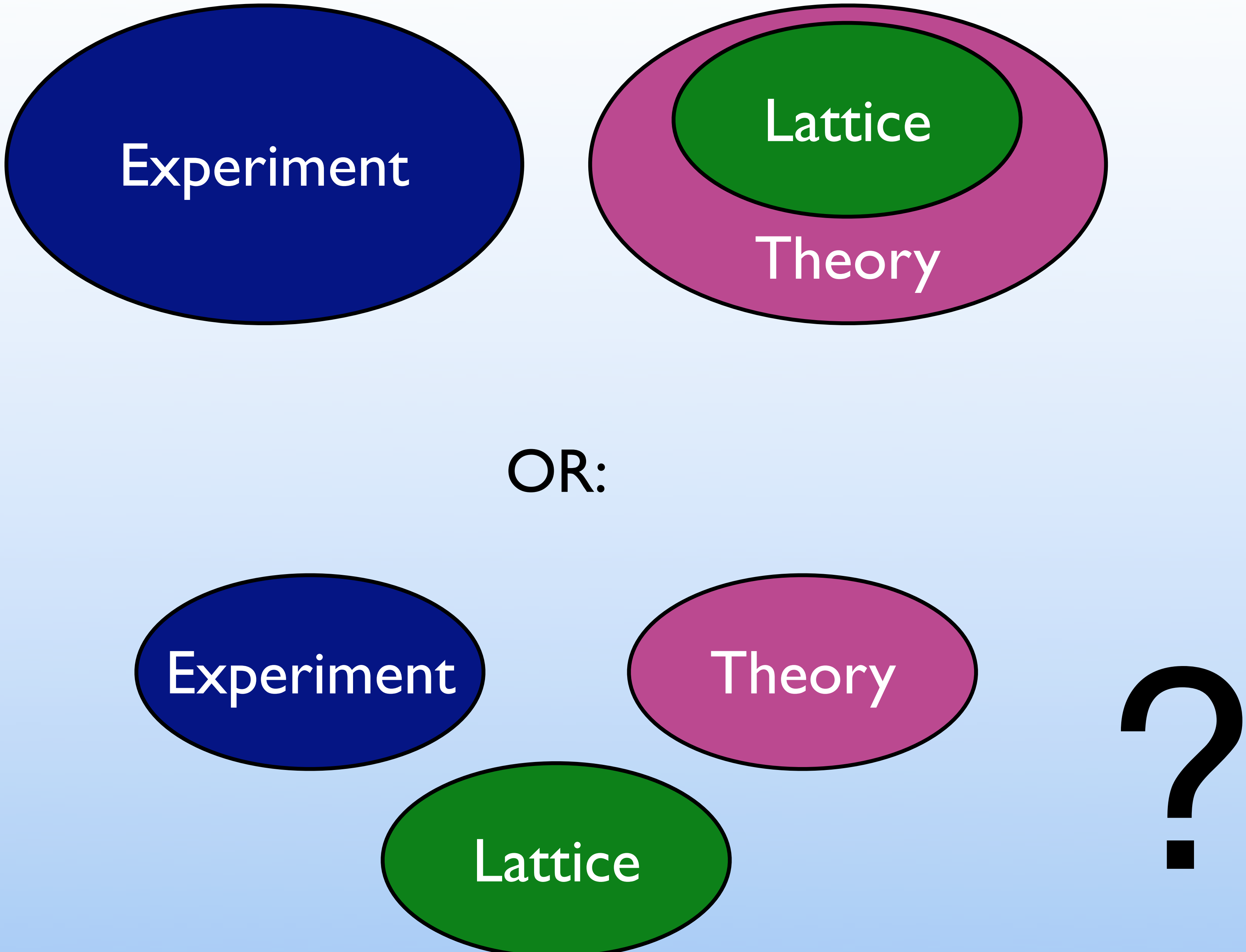
Multi-nucleon physics gets real interesting in the Petaflops era

NPLQCD hep-lat/0612026



From M. Stephanov, Lattice 2006

Scientific Computing



Scientific Computing

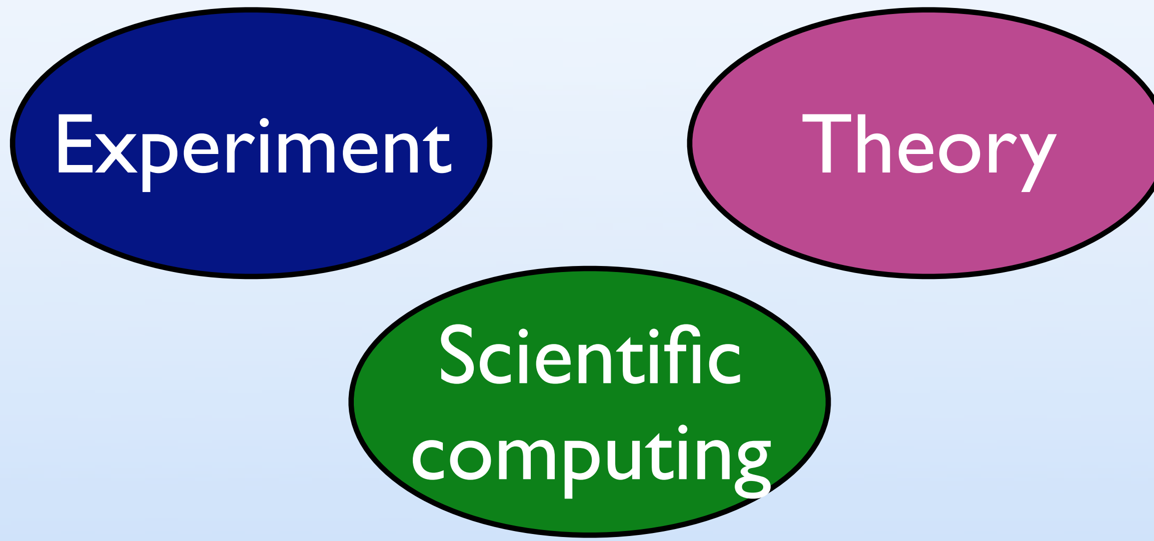
Lattice QCD is very theory intensive, but also shares many similarities with experimental physics

- **Multi-institution, long-term collaborations**
- **Infrastructure**
  - Dell cluster, 10 Tflops peak/2 Tflops sustained = $1M
  - Significant power & cooling requirements
- **Operating costs**
  - Above cluster: 0.5 MW power ~ $200K/yr
  - Technical staff: Scientific computing software developers

Scientific Computing

More generally, advanced scientific computing will play an ever-increasing role in all aspects of nuclear physics:

- Lattice QCD
- Hydro simulations for RHIC physics
- Nuclear astrophysics
- Nuclear structure



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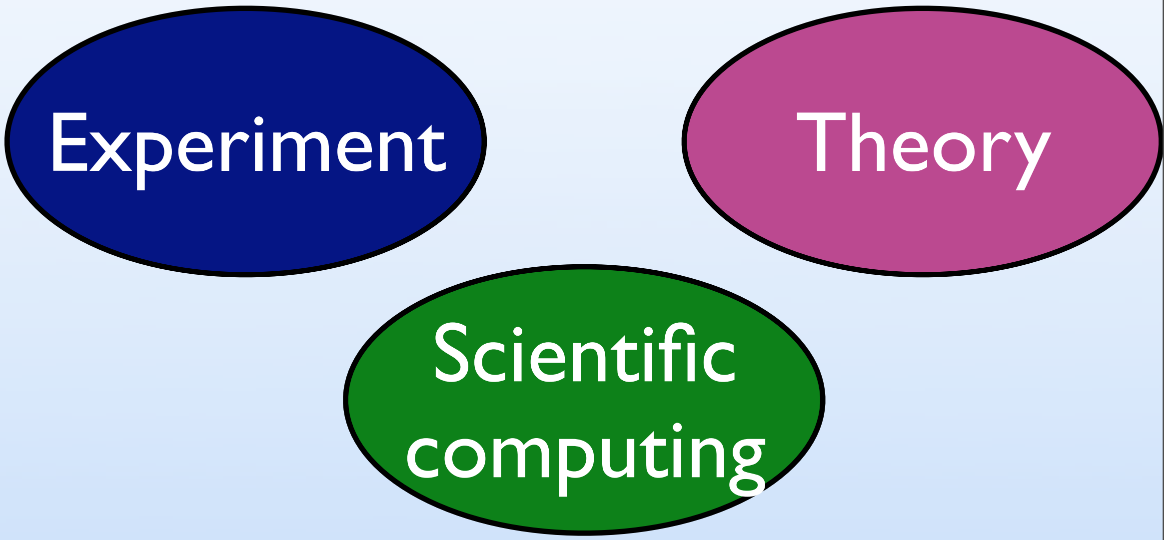

To keep up with scientific computing needs & opportunities will be a challenge.
Specifically addressed in LRP at the same level as experiment and theory?

End of theory survey

End of theory survey

Topics neglected:

- Generalized parton distributions
- Advances in understanding form factors
- Spin physics
- QGP properties, hydrodynamics...

End of theory survey

Topics neglected:

Generalized parton distributions

Advances in understanding form factors

Spin physics

QGP properties, hydrodynamics...

But hopefully clear: QCD is an extremely vital and active field

How do we move nuclear theory forward, and kick it up a notch?

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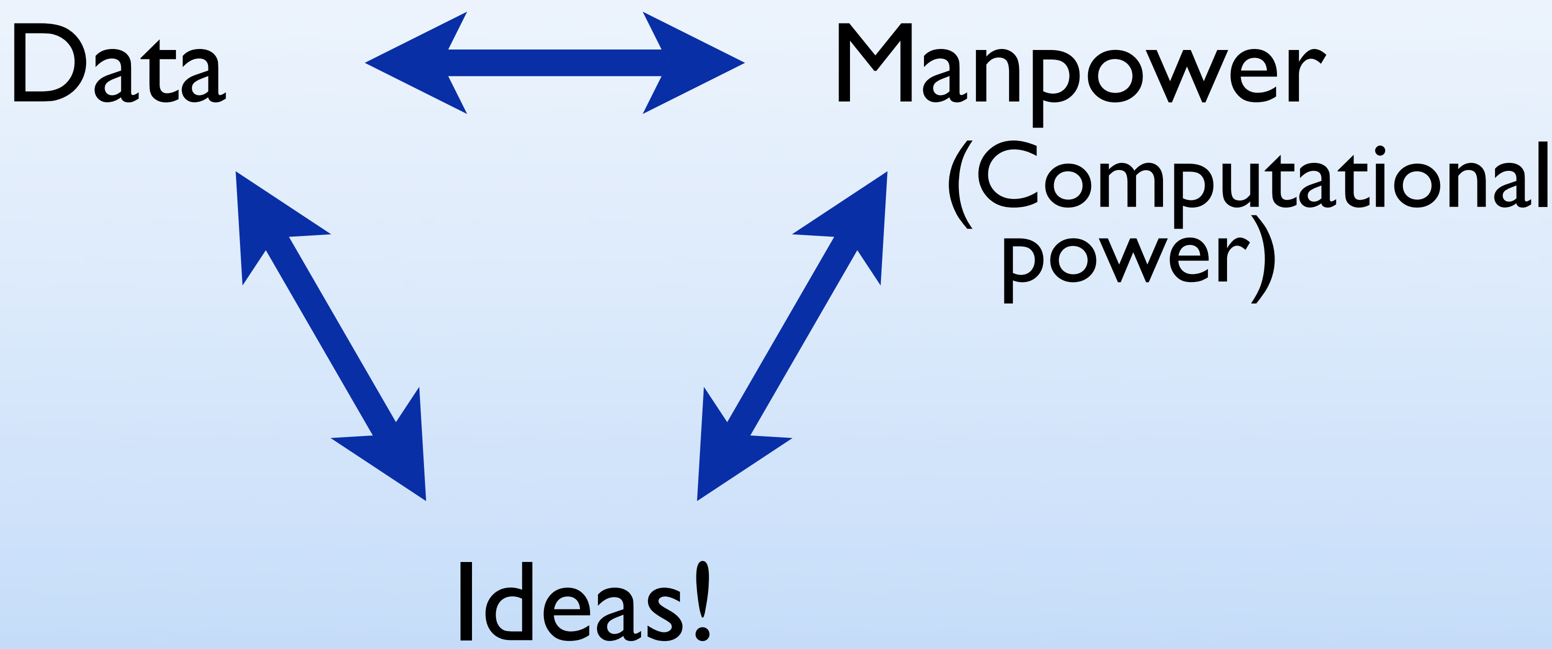

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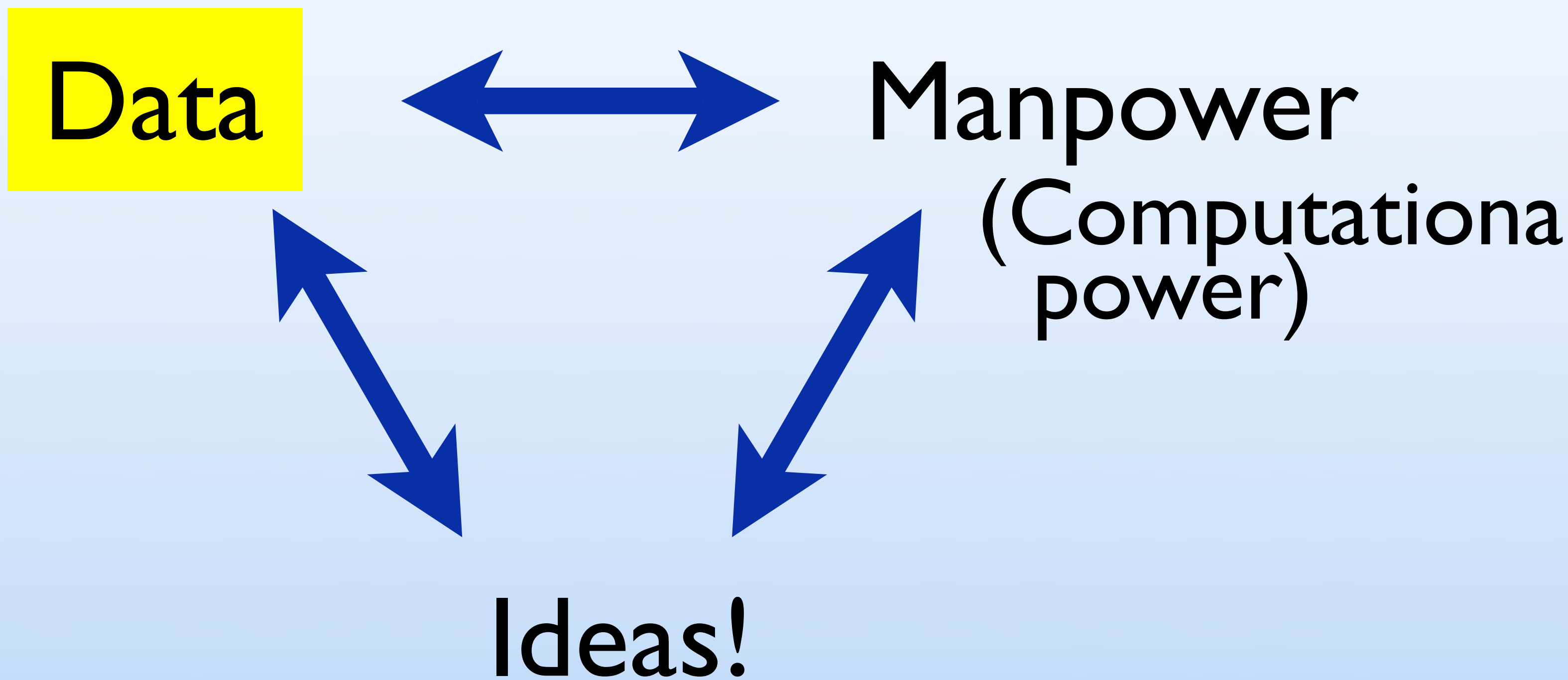

Data

A vigorous experimental program is vital for a healthy theory program

Data

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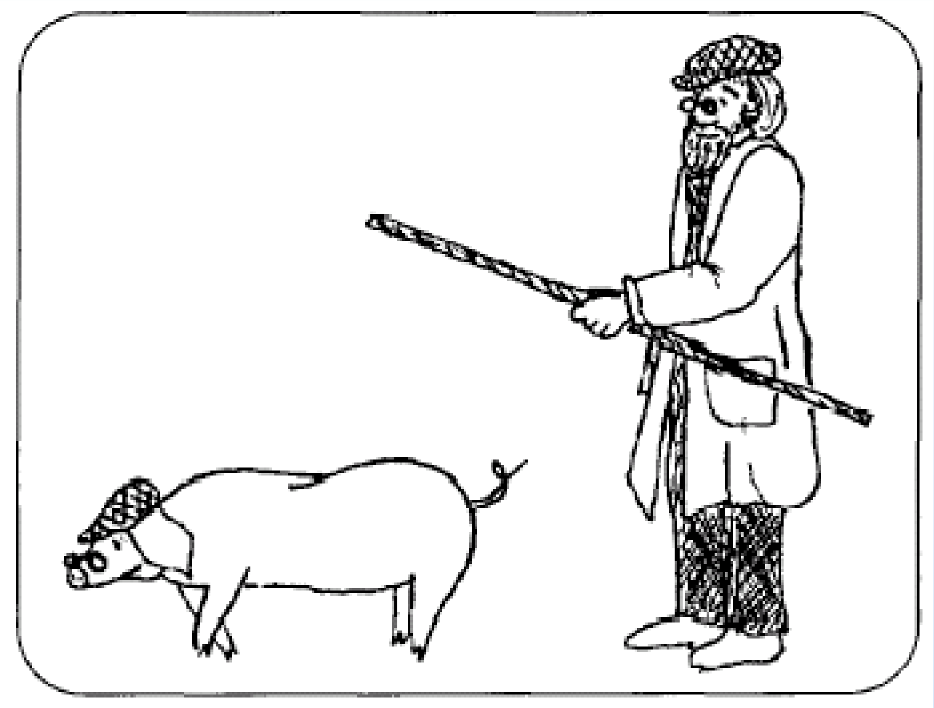
But how closely should theory initiatives be tied to particular experimental efforts?



Leon Lederman's view of the experimentalist and the theorist

...But there also has to be room for theorists to play around with ideas not directly applicable to experimental phenomenology

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1954:

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1954:

- First 4" prototype liquid hydrogen bubble chamber installed in Bevatron

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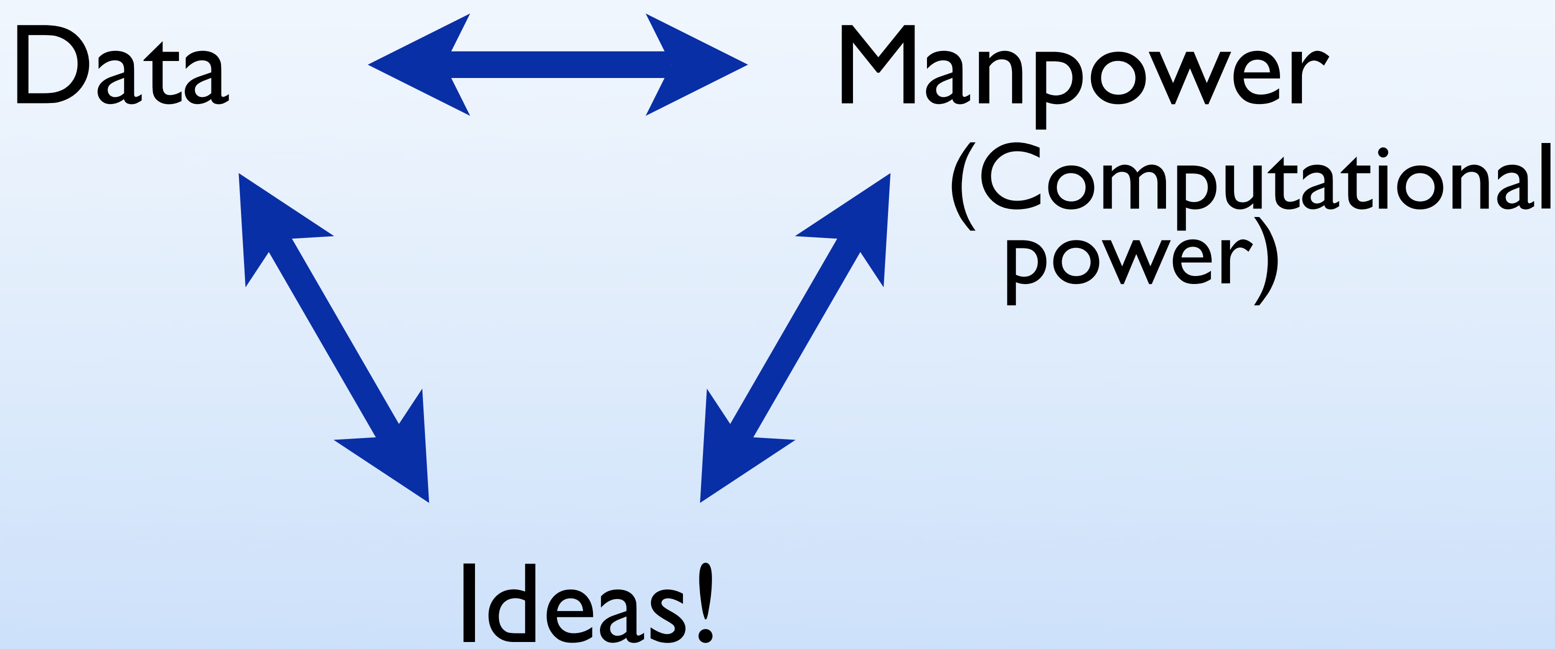
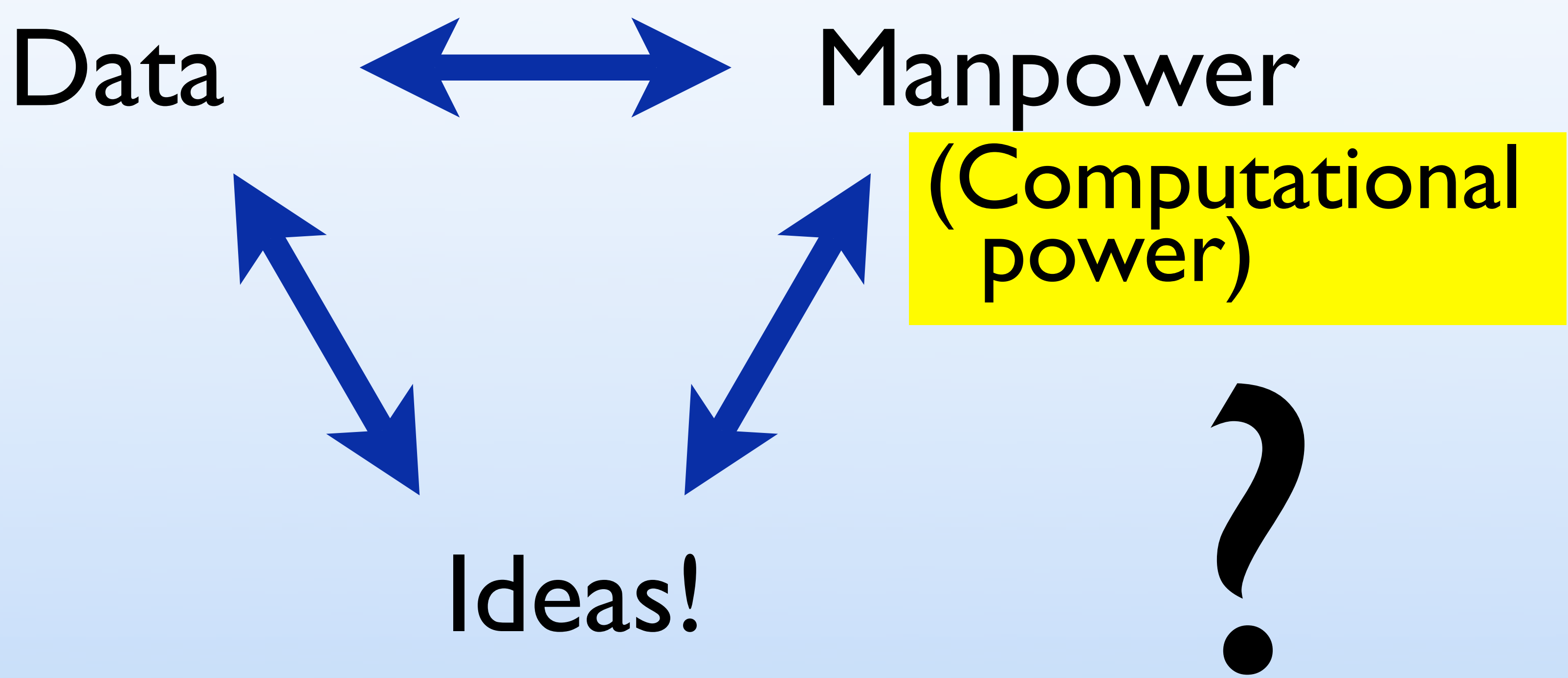
1954:

- First 4" prototype liquid hydrogen bubble chamber installed in Bevatron
- Yang & Mills invent nonabelian gauge theory


Data
Manpower
(Computational
power)
Ideas!


Data
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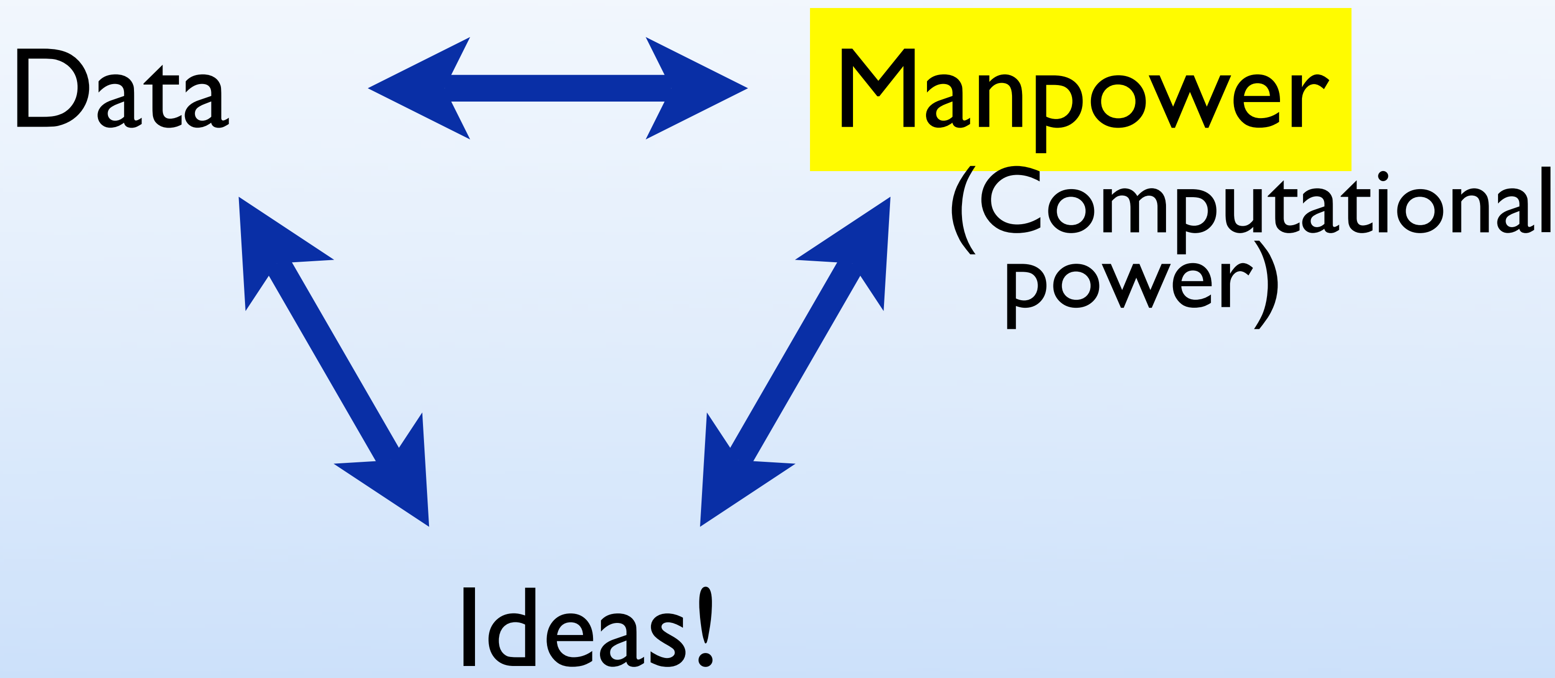
?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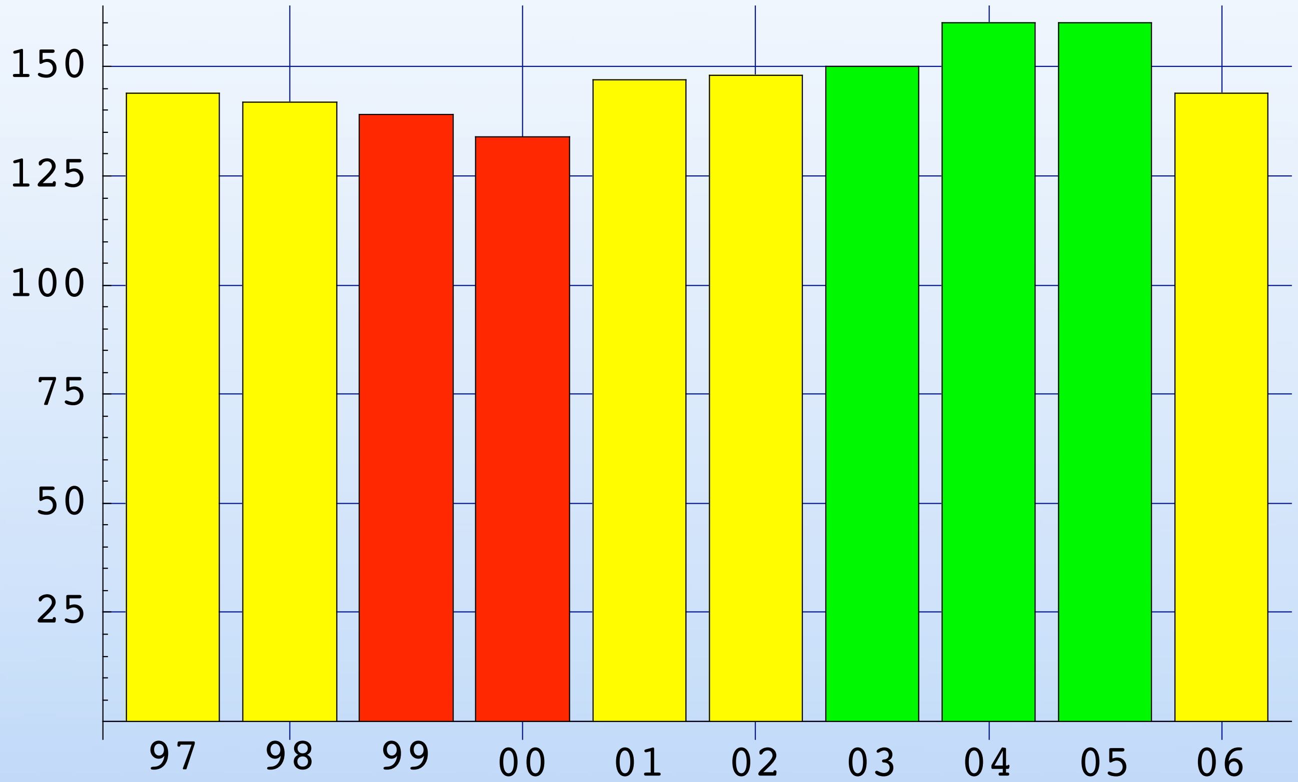
Ideas!

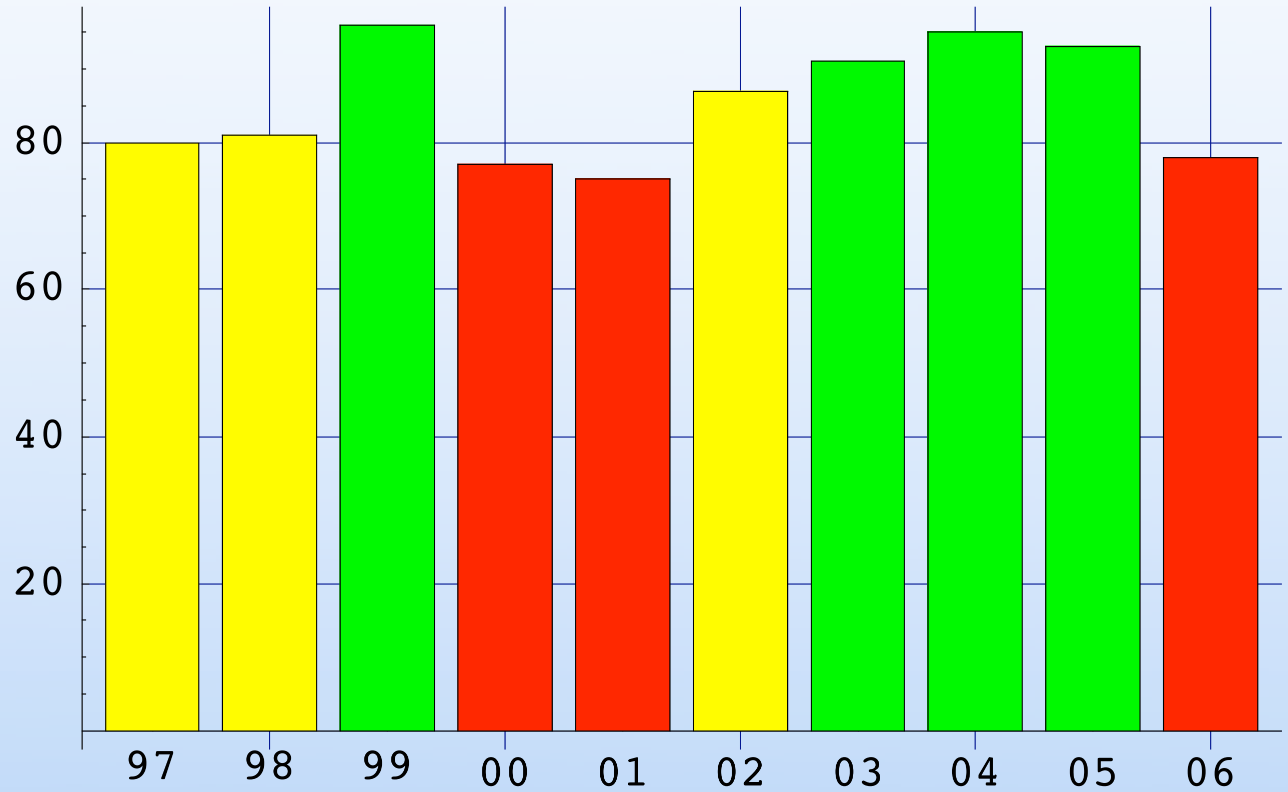
DOE supported permanent PhD staff (theory)



2005: 160

2006: 144 -10%

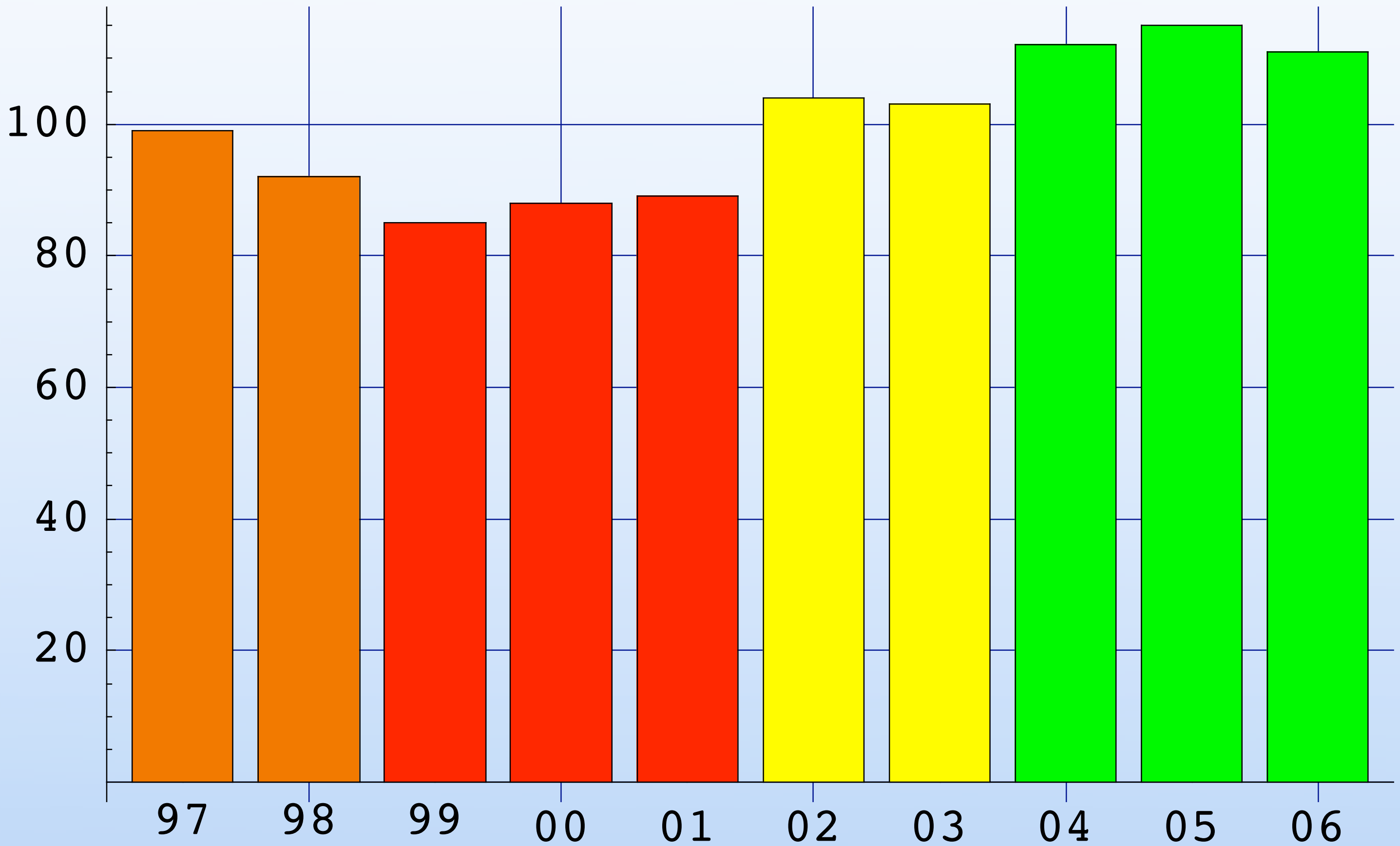
DOE supported non-permanent PhD staff (theory)



2005: 93

2006: 78 -16%

DOE supported graduate students (theory)



2005: 115

2006: 111 -3%

Manpower

2006, people supported by DOE:

- # of permanent theory PhDs: -10%
- # non-permanent theory PhDs: -16%
- # theory grad students: -3%

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- If 2006 is a trend rather than an aberration, nuclear theory is in trouble.

Manpower

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- # non-permanent theory PhDs: -16%
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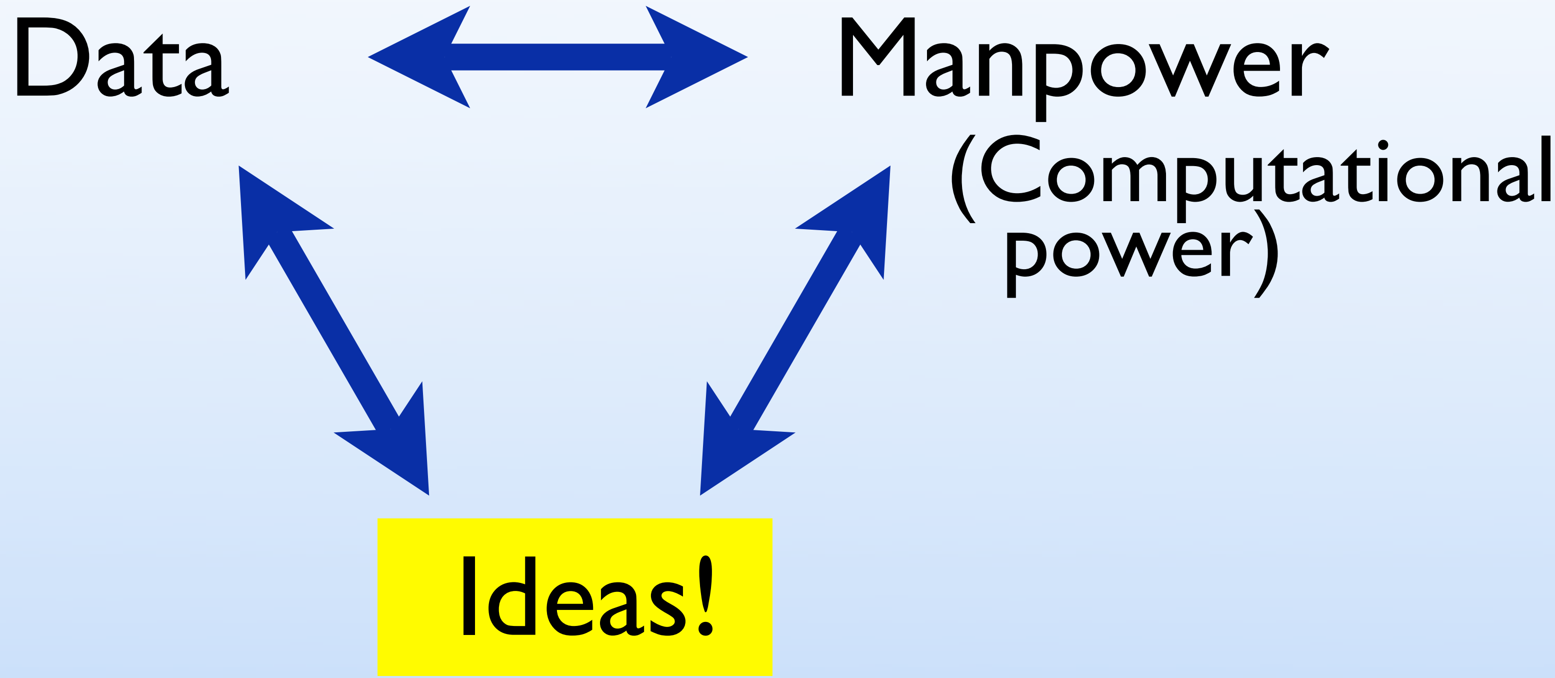
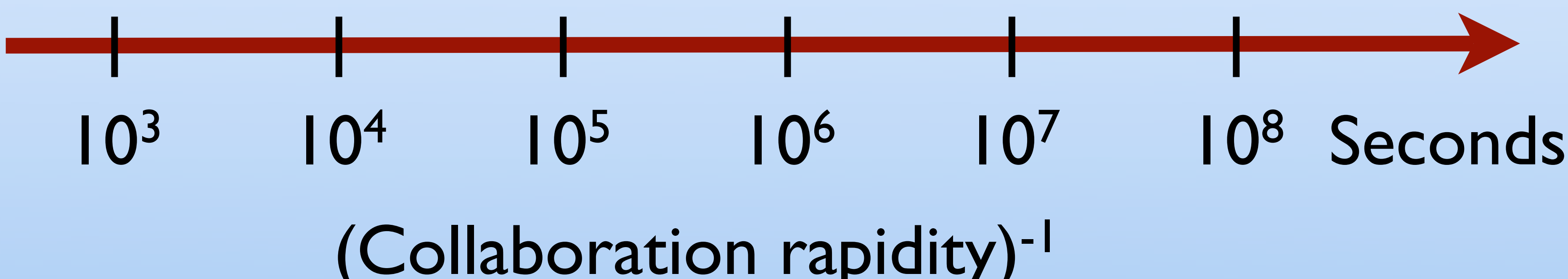
- If 2006 is a trend rather than an aberration, nuclear theory is in trouble.
- The reduction of post-doc positions is particularly alarming, and should be a focus for remediation



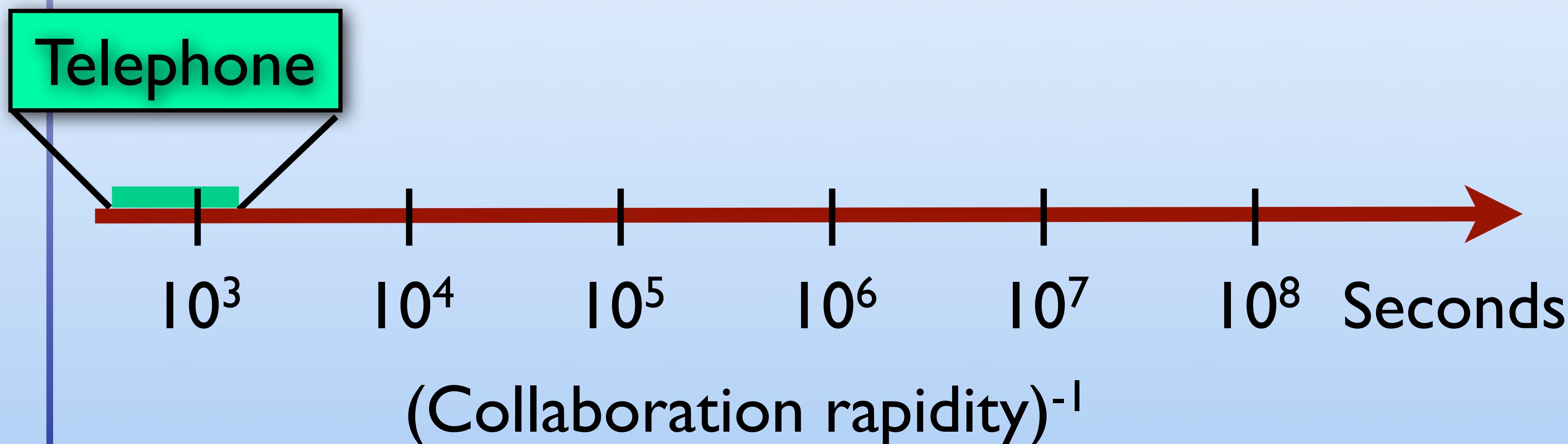
Competitive programs to assist the collaborations and individuals with great ideas

Collaborations

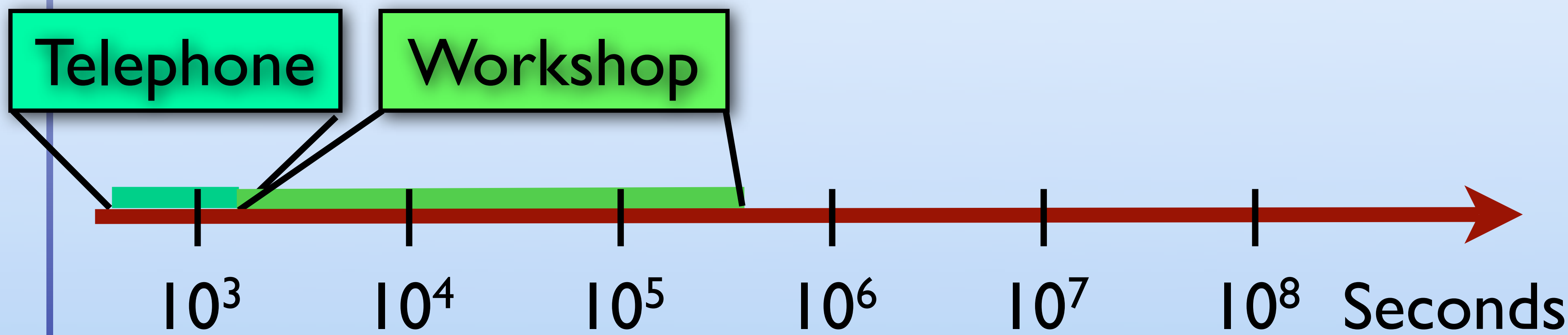
Collaborations



Collaborations

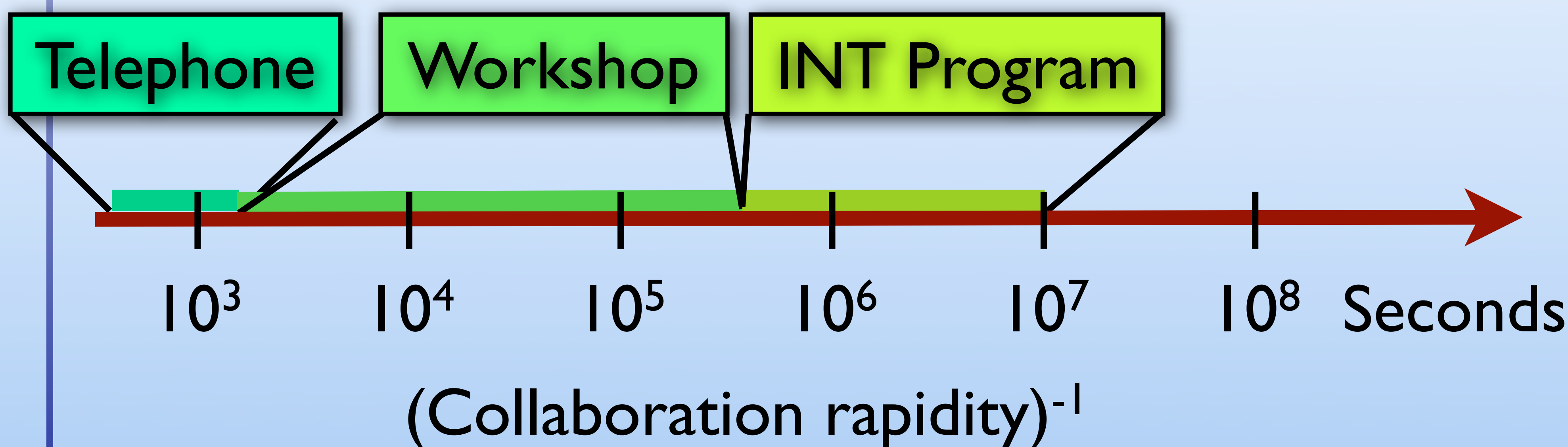


Collaborations

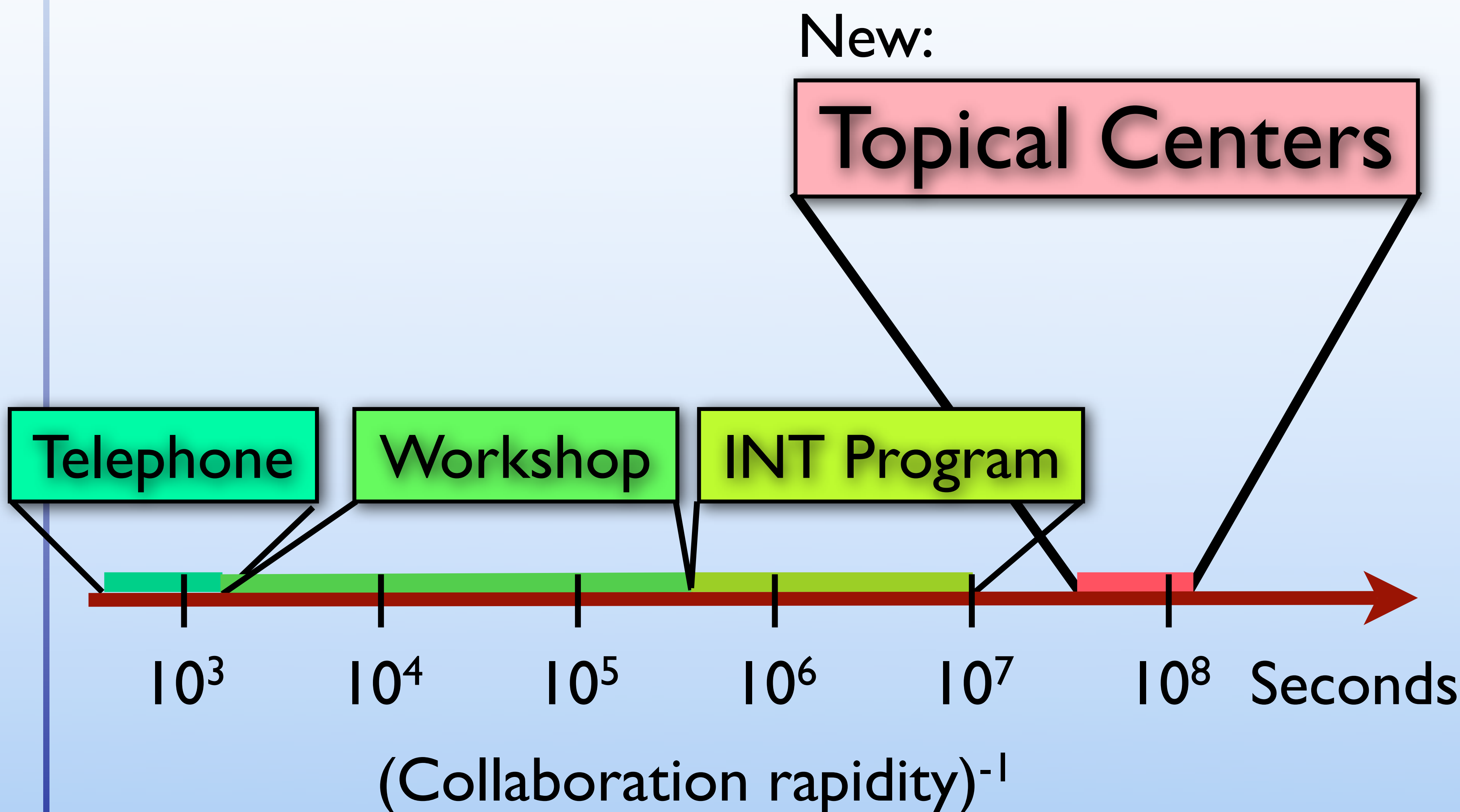


(Collaboration rapidity)$^{-1}$

Collaborations

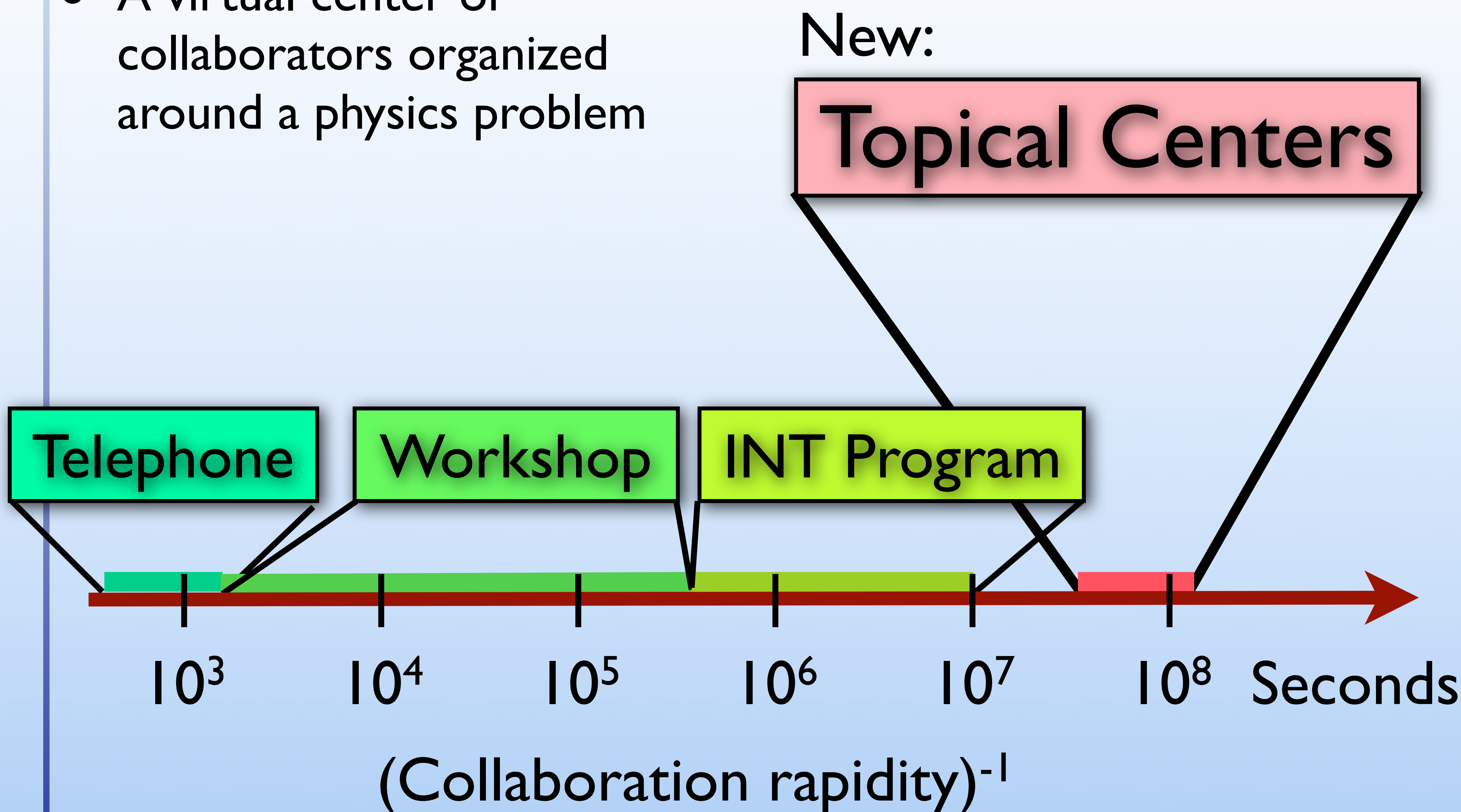


Collaborations



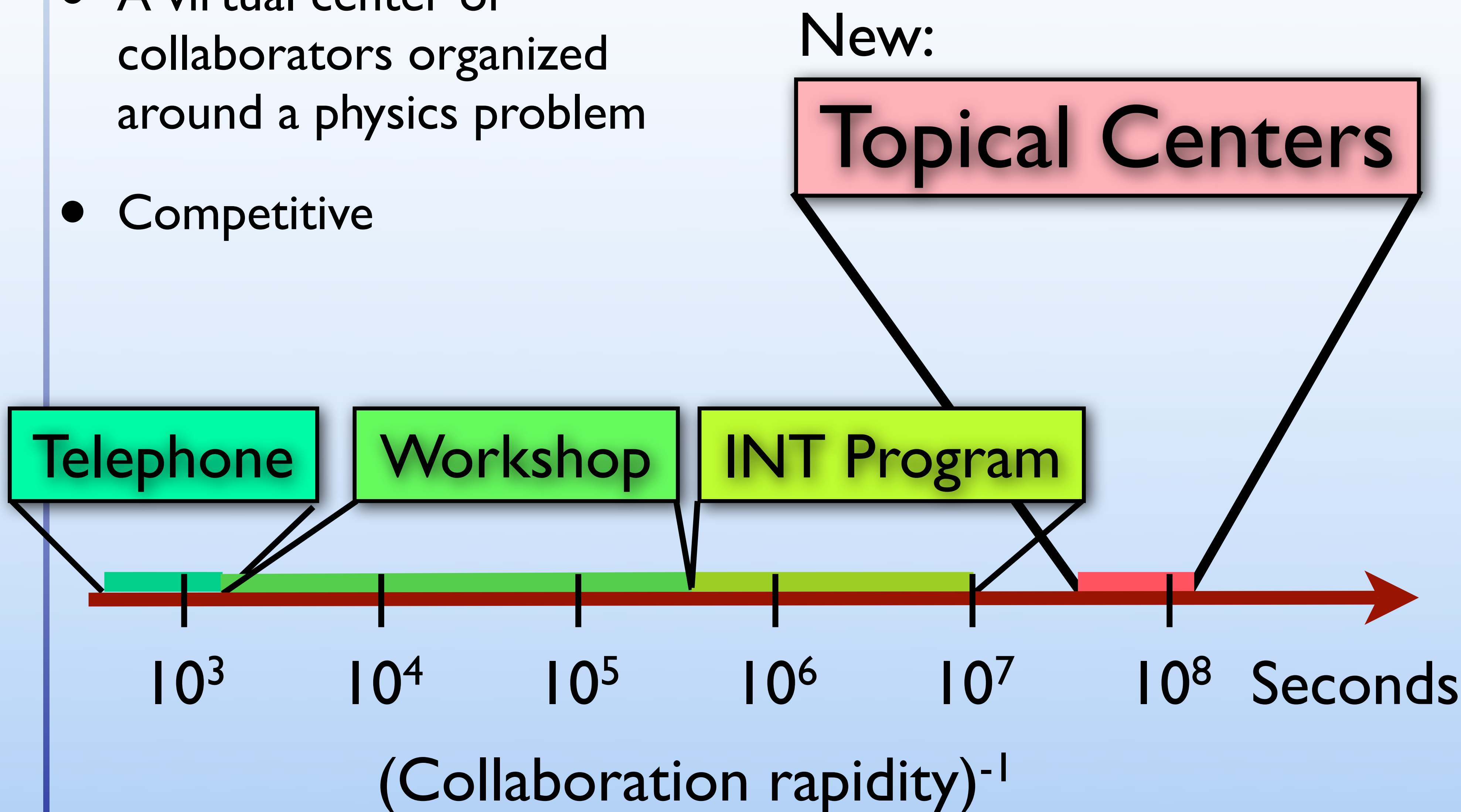
Collaborations

- A virtual center of collaborators organized around a physics problem



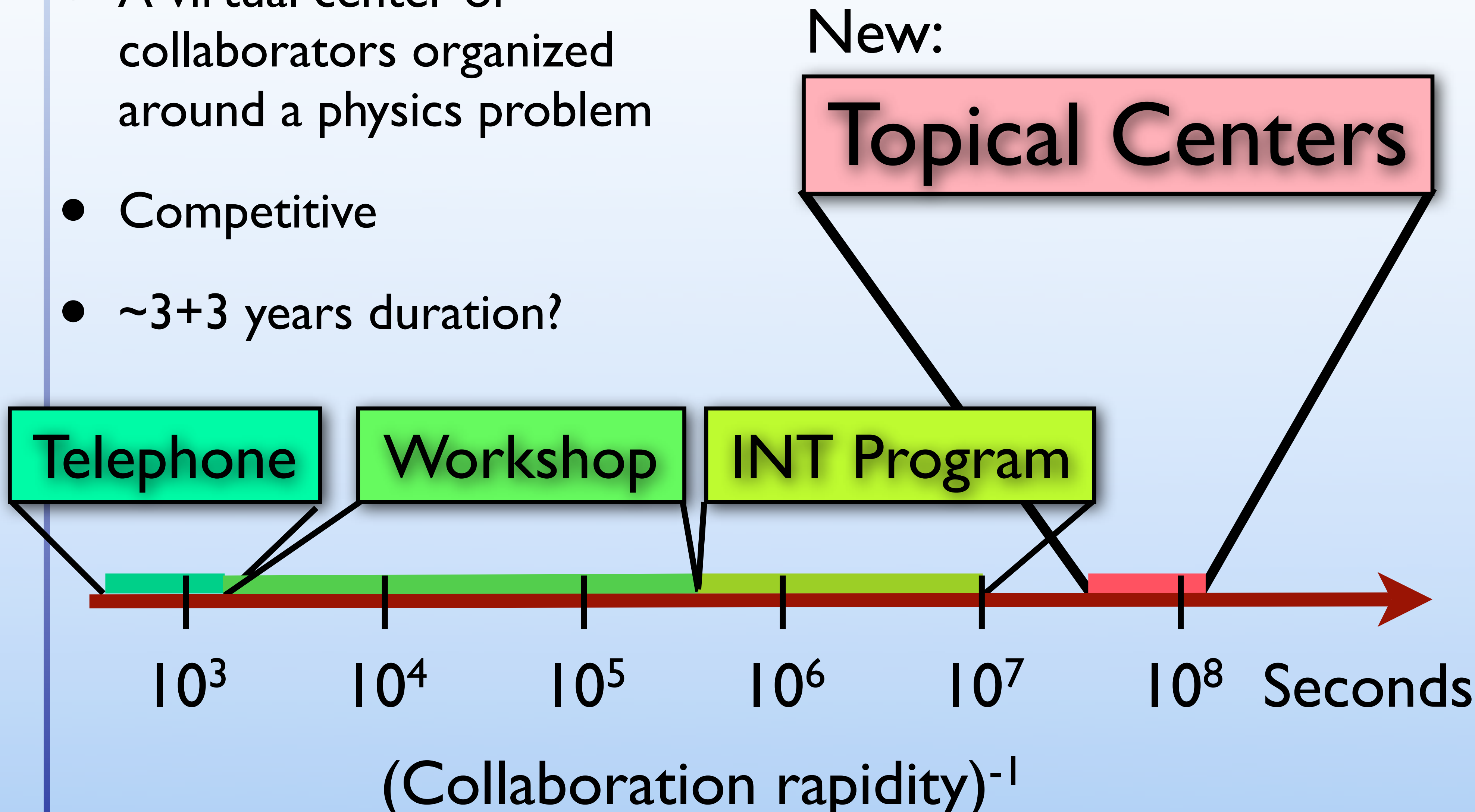
Collaborations

- A virtual center of collaborators organized around a physics problem
- Competitive



Collaborations

- A virtual center of collaborators organized around a physics problem
- Competitive
- ~3+3 years duration?



Individuals

Individuals

- Graduate students: Nuclear Theory Graduate Fellowships (as in 2003 Mueller report)

Individuals

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- Post-doc level: Post-doctoral prize fellowships (Mueller report)

Individuals

- Graduate students: Nuclear Theory Graduate Fellowships (as in 2003 Mueller report)
- Post-doc level: Post-doctoral prize fellowships (Mueller report)
- Assistant professor level: existing OJI program is great

Individuals

- Graduate students: Nuclear Theory Graduate Fellowships (as in 2003 Mueller report)
- Post-doc level: Post-doctoral prize fellowships (Mueller report)
- Assistant professor level: existing OJI program is great
- Tenured professor level: one-time ~$30K awards to allow senior researchers to buy out of teaching for proposed project (like a Guggenheim award)

Individuals

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- Assistant professor level: existing OJI program is great
- Tenured professor level: one-time ~$30K awards to allow senior researchers to buy out of teaching for proposed project (like a Guggenheim award)
- Analogous opportunities for those at National Labs

Competitive awards for the theorists with the ideas

Competitive awards for the theorists with the ideas

Graduate, Postdoctoral Prize Fellowships

Competitive awards for the theorists with the ideas

Graduate, Postdoctoral Prize Fellowships

OJI awards (Assist. Profs.)

Competitive awards for the theorists with the ideas

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Main Conclusions:

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- QCD theory is a vital field with innovation on many fronts & many opportunities
- Lattice QCD plays an increasingly important role in nuclear physics, and its combination of intensive theory + extensive infrastructure = neither "experiment" nor "theory"
- Manpower is a serious concern in light of the 2006 budget, especially the 16% cut in theory post-docs
- Fund virtual topical centers for theorists to spend several years attacking particular vital problems
- Competitive fellowships for the most productive theorists at all stages of career