Nuclear Physics: Nature on the Femtometer Scale

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(with help from O. Hashimoto, B. Jacak, T. Ludlam, W. Nazarewicz, and H. Tamura, and including the work of many, many scientists from many places)

COE International Symposium: Exploring New Science by Bridging the Particle-Matter Hierarchy, March 5-7, 2004

Families within families of matter

DNA

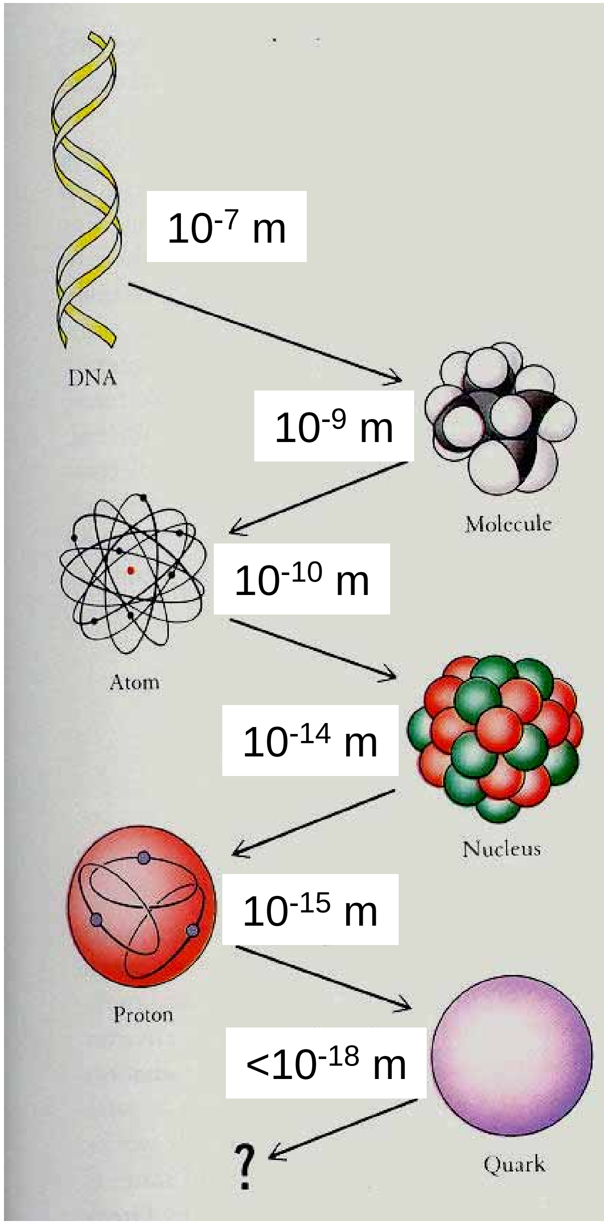
Molecule

Atom

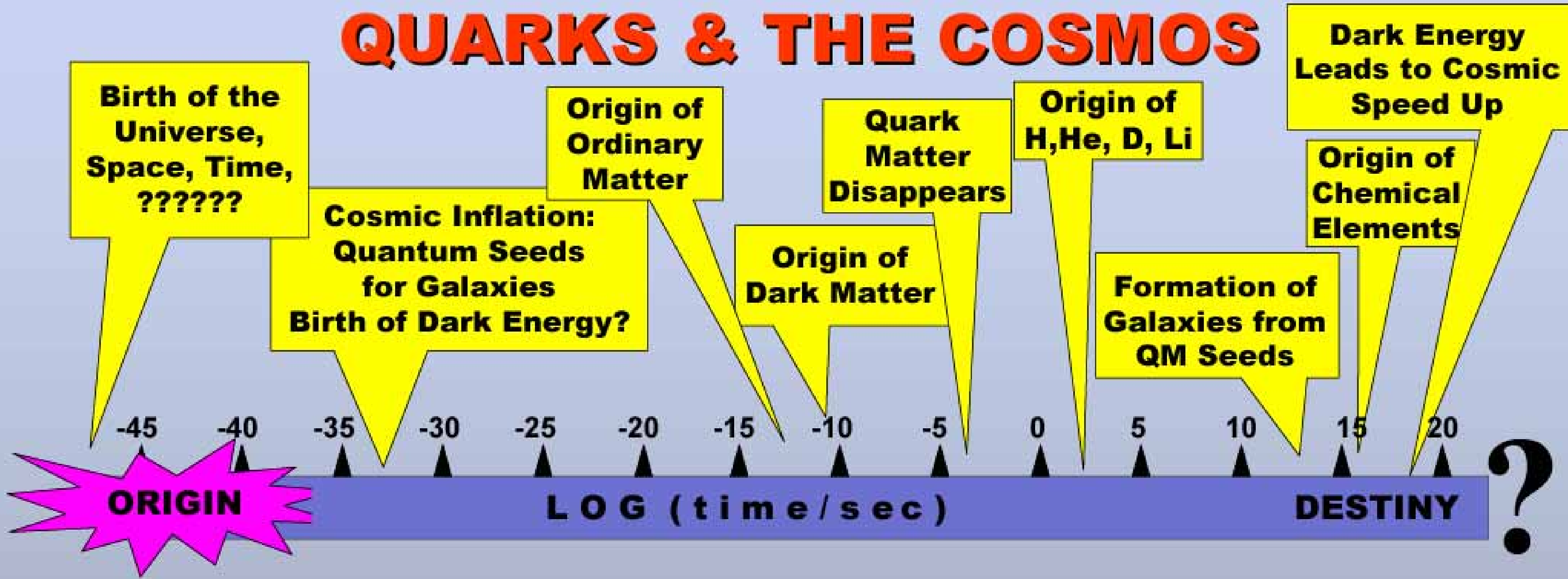
Nucleus

Proton

Quark



DEEP CONNECTIONS: QUARKS & THE COSMOS



GENESIS TIMELINE

Adapted from M.S. Turner and R. Orbach

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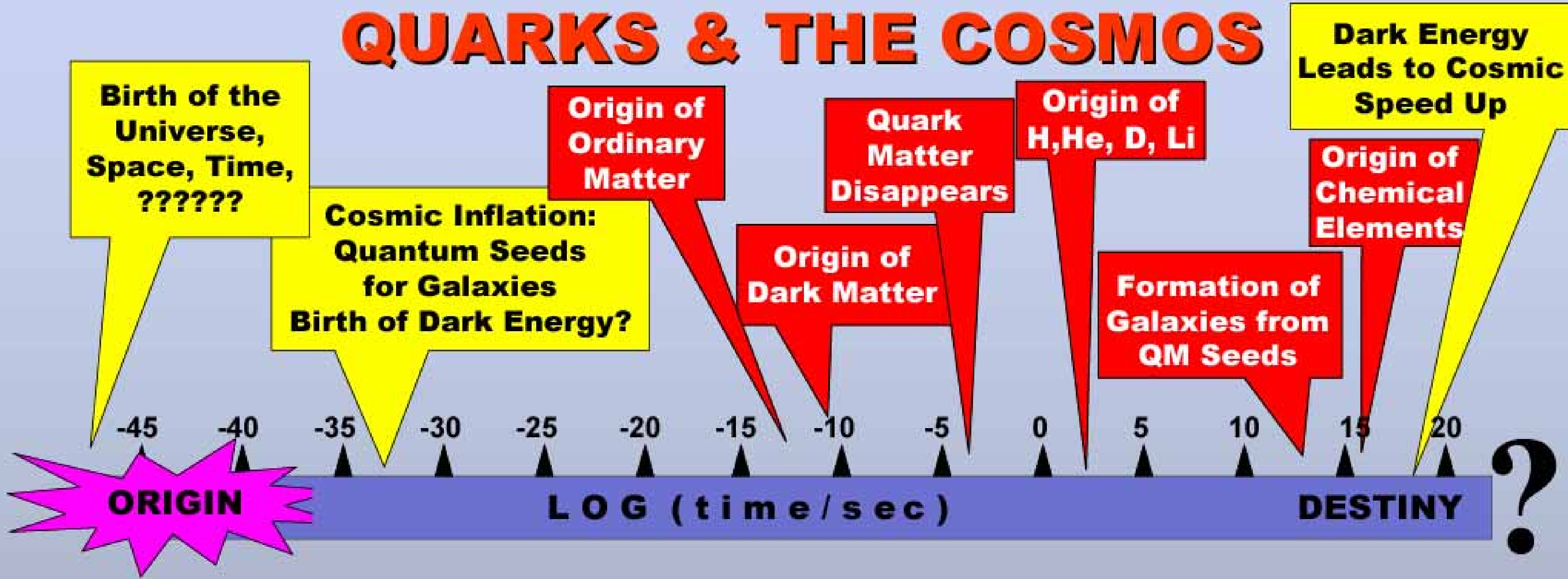

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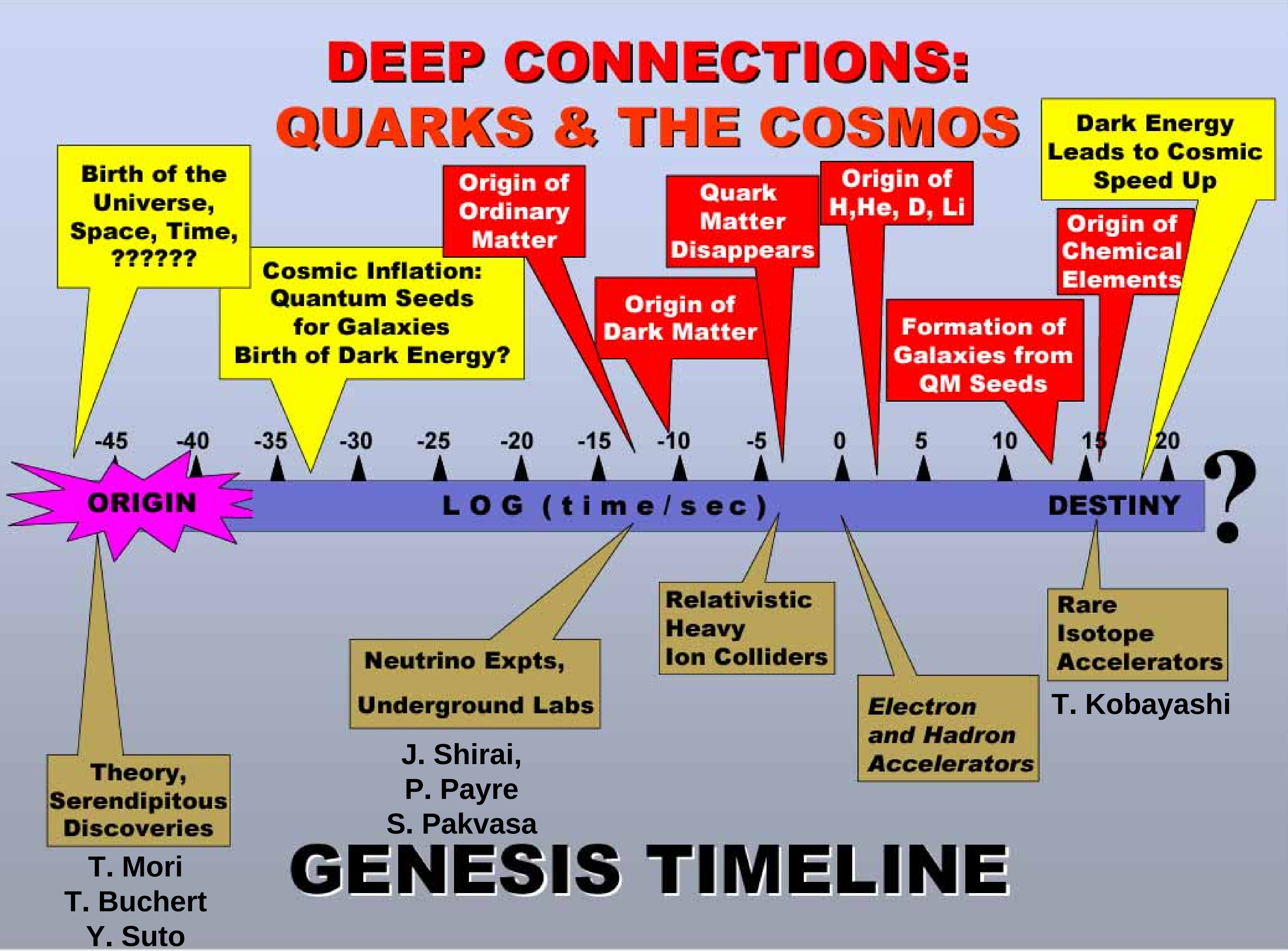
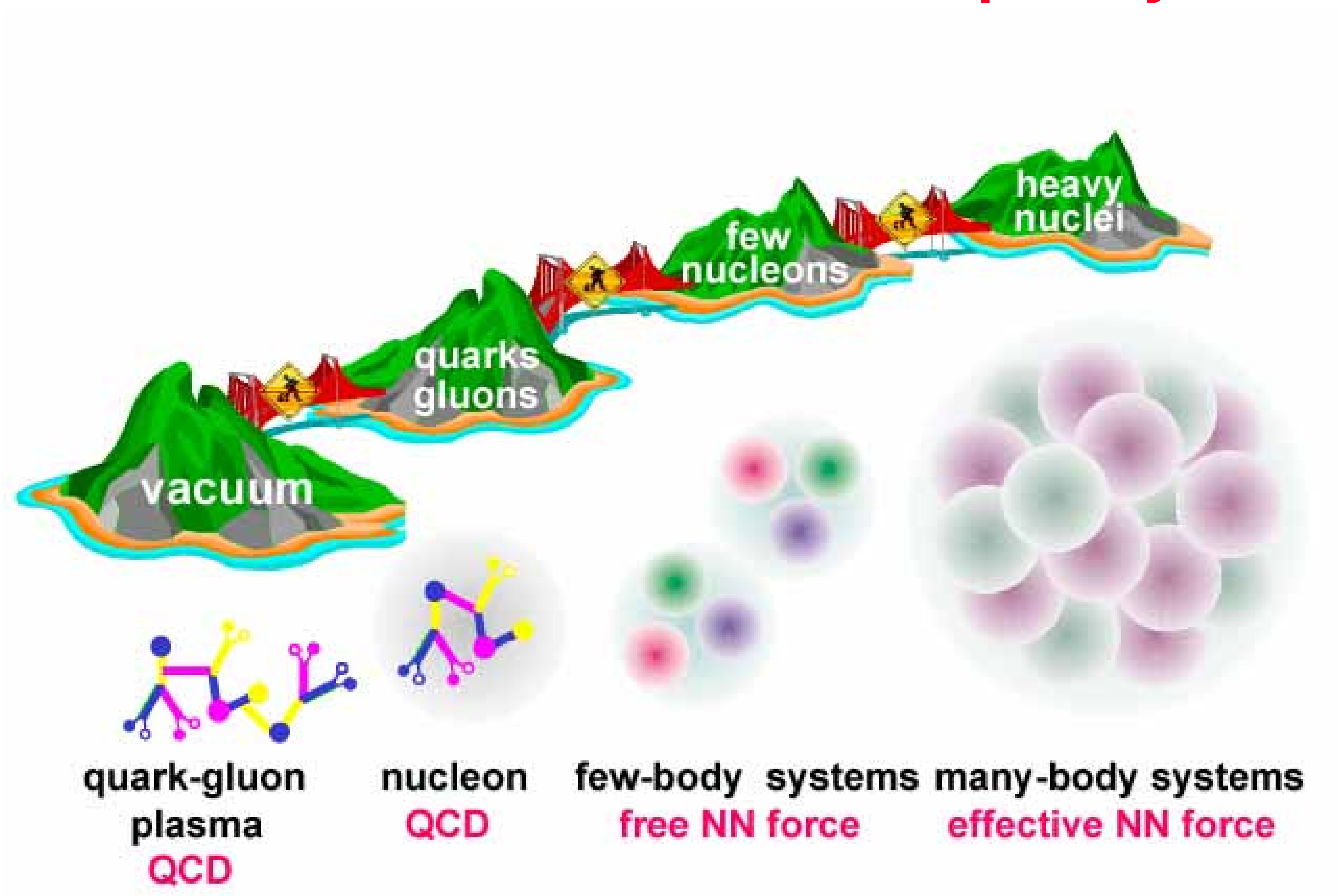
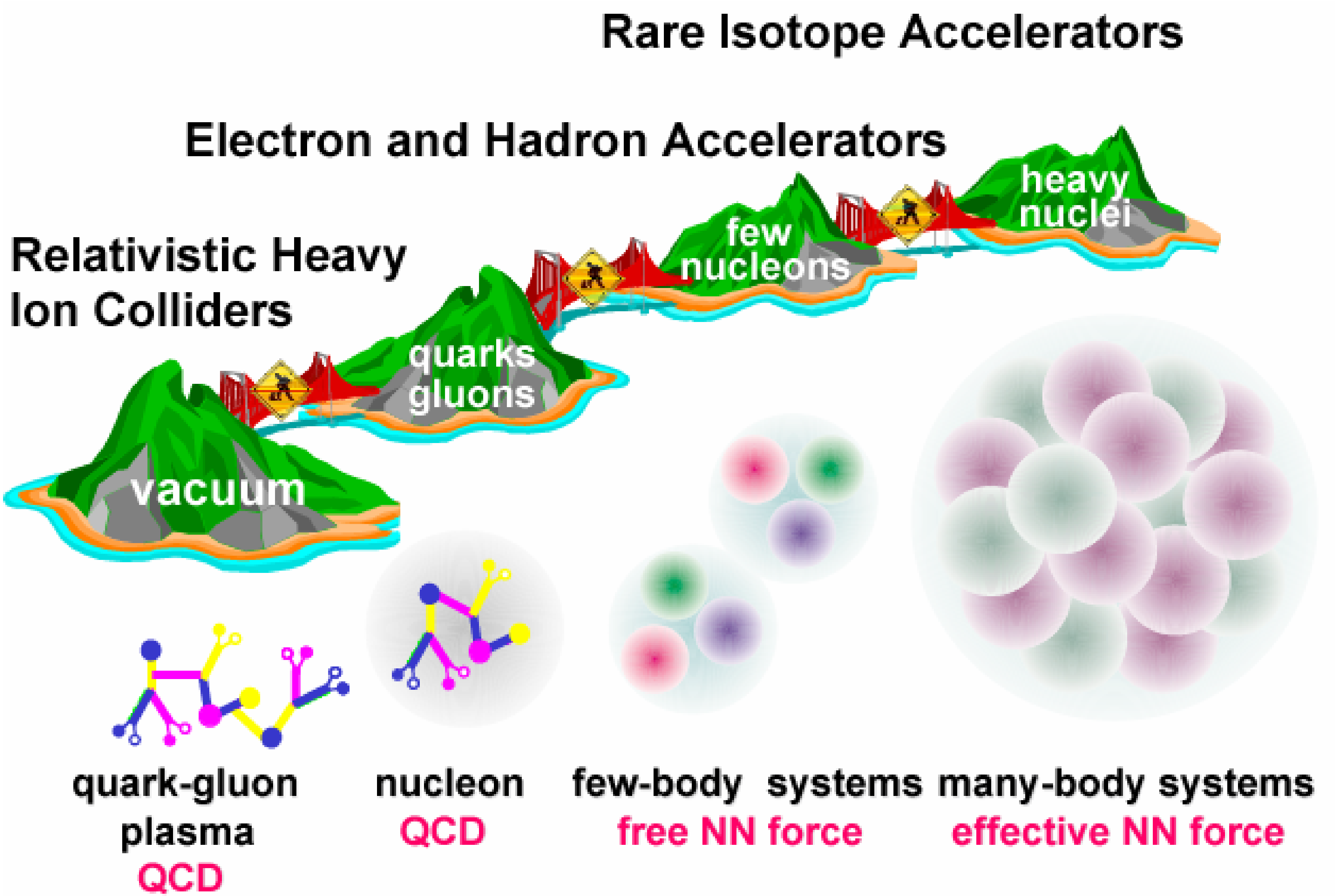
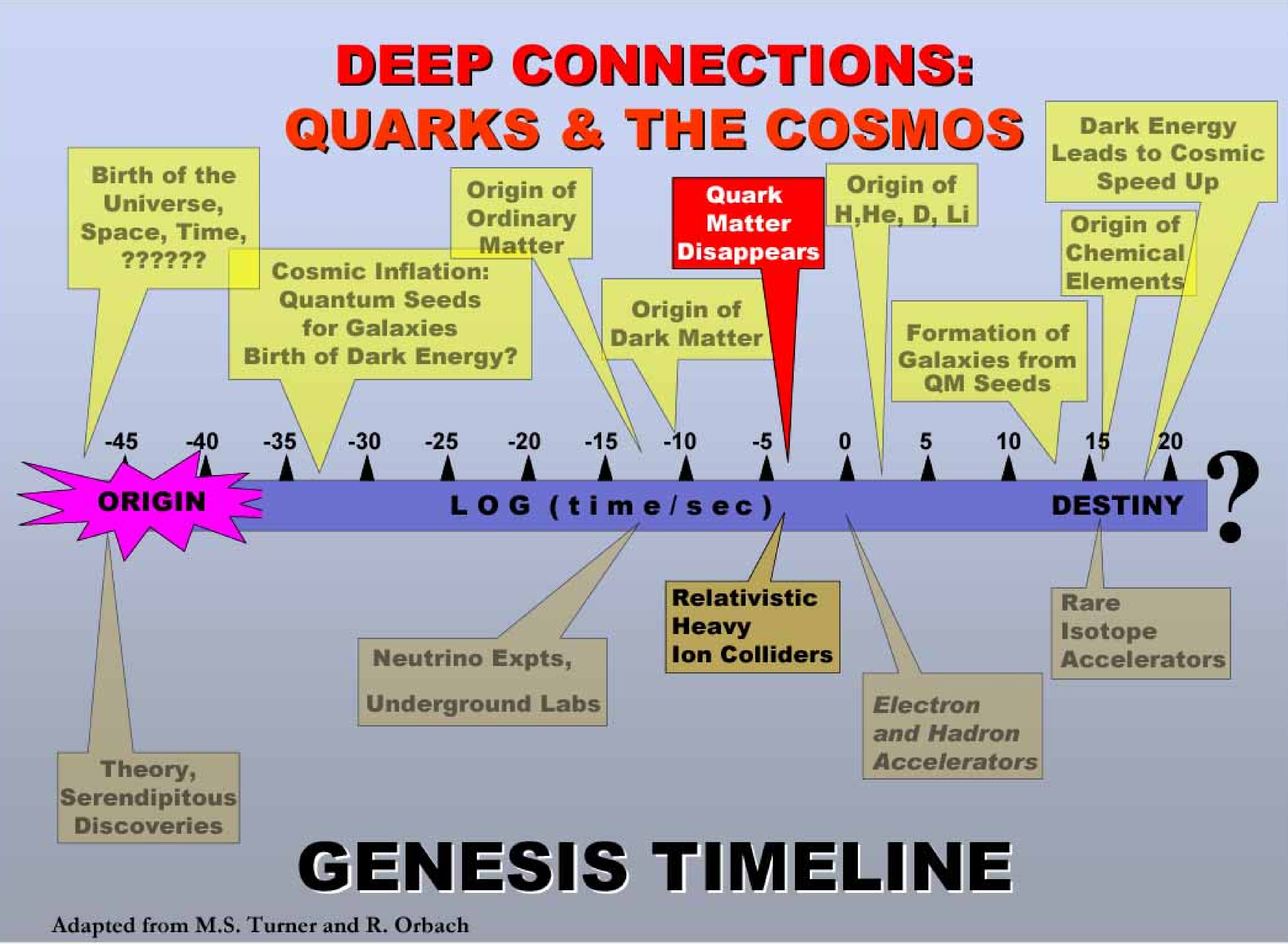

DEEP CONNECTIONS:
QUARKS & THE COSMOS
Birth of the Universe, Space, Time, ??????
Cosmic Inflation: Quantum Seeds for Galaxies Birth of Dark Energy?
Origin of Ordinary Matter
Origin of Dark Matter
Quark Matter Disappears
Origin of H,He, D, Li
Formation of Galaxies from QM Seeds
Origin of Chemical Elements
Dark Energy Leads to Cosmic Speed Up
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
ORIGIN
LOG (time/sec)
DESTINY
?
Theory, Serendipitous Discoveries
T. Mori
T. Buchert
Y. Suto
Neutrino Expts,
Underground Labs
J. Shirai,
P. Payre
S. Pakvasa
Relativistic Heavy Ion Colliders
Electron and Hadron Accelerators
Rare Isotope Accelerators
T. Kobayashi
GENESIS TIMELINE

Research Directions in Nuclear Physics: Distance Scales and Complexity



Research Directions in Nuclear Physics: The "Tools of the Trade"





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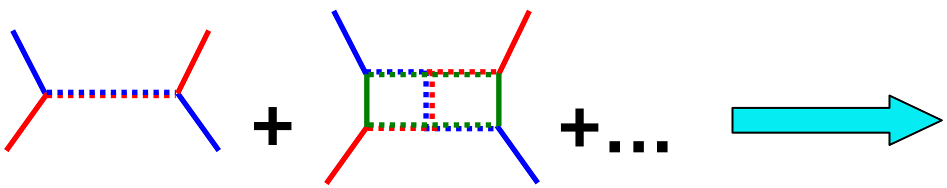
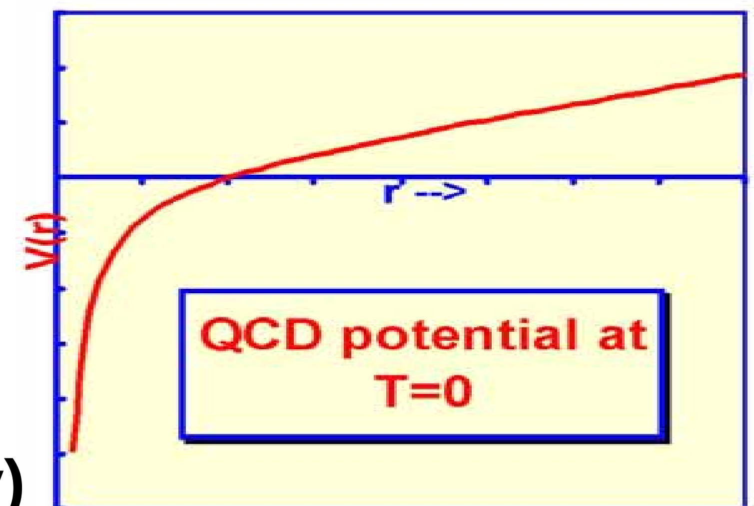
Study Quantum Chromo Dynamics Using Relativistic Heavy Ion Collisions

- Color charge of gluons ⇒ they interact among themselves
  - theory is non-abelian
  - curious properties at long distance, including confinement

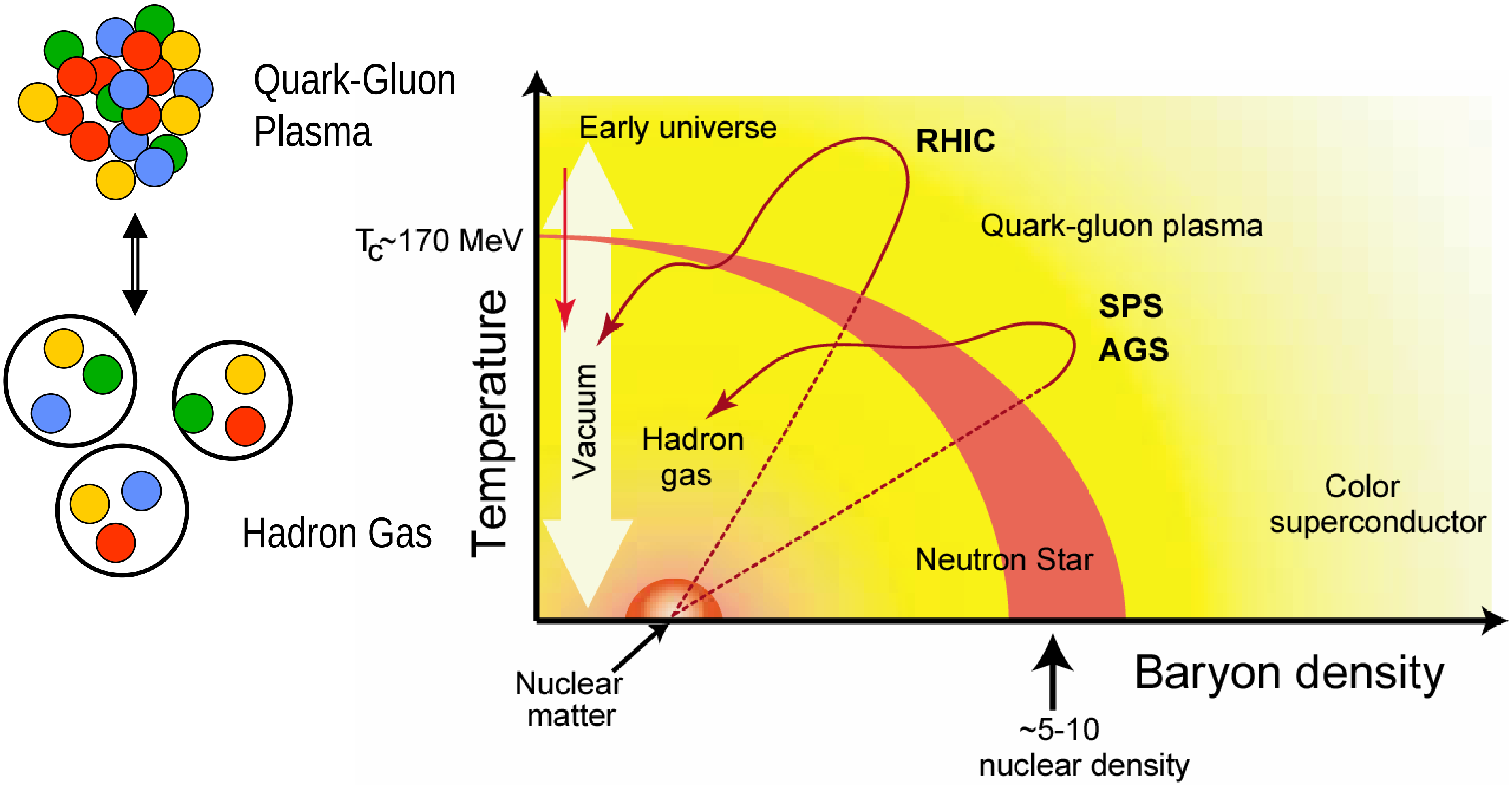




***short distance*:**
force is weak (probe w/ high Q^2, calculate with perturbation theory)
***large distance*: force is strong (probe w/ low Q^2, calculations must be non-perturbative)**

***High temperature*: force becomes screened by produced color-charges (gets weak)**

The Quark Gluon Plasma



The QCD phase transition:

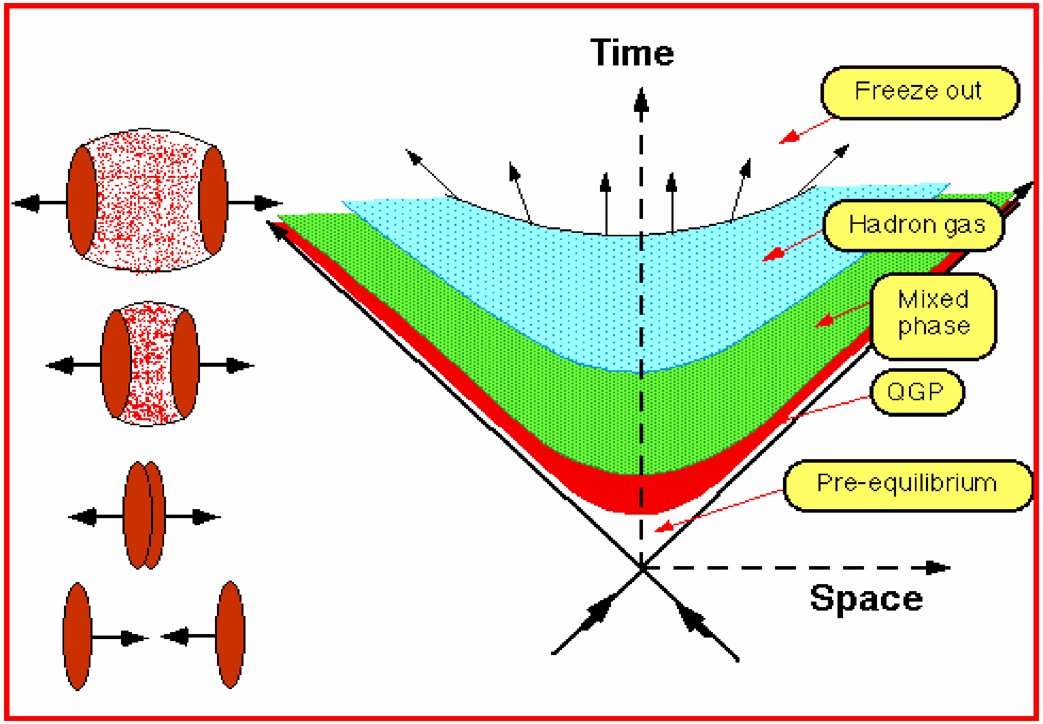
Critical temperature: 150 – 200 MeV ($\mu_B = 0$)

Critical density: ½ - 2 Baryons/fm^3 (T = 0)

Critical energy density: ~1 GeV/fm^3

A Mini-Bang:
Nuclear matter at extreme temperatures and density

Colliding nuclei at 100 + 100 GeV/nucleon



Freeze-out –
emission of hadrons

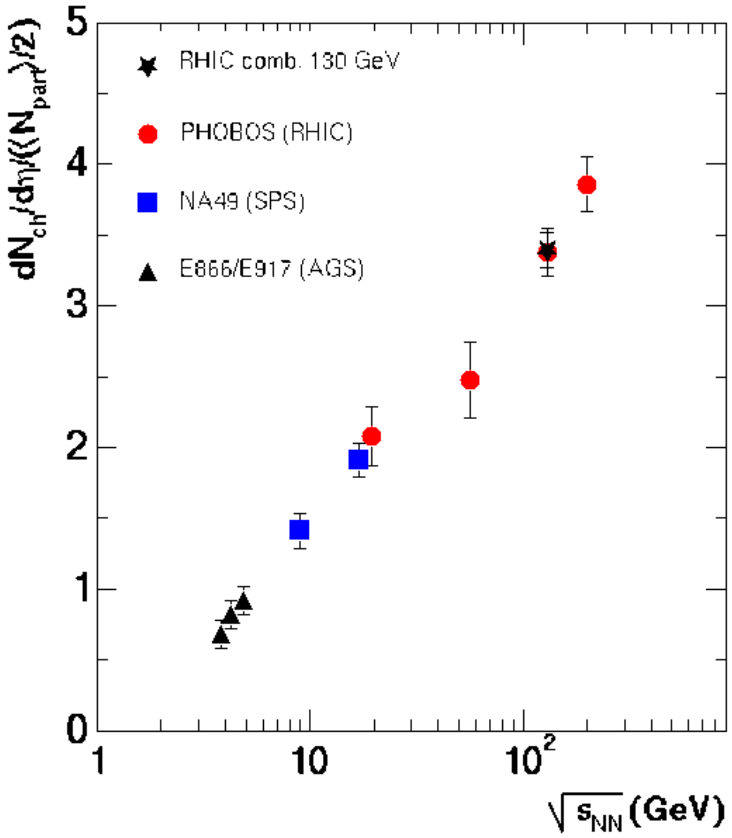
Hot and dense phase -
quark-gluon plasma and hadron gas

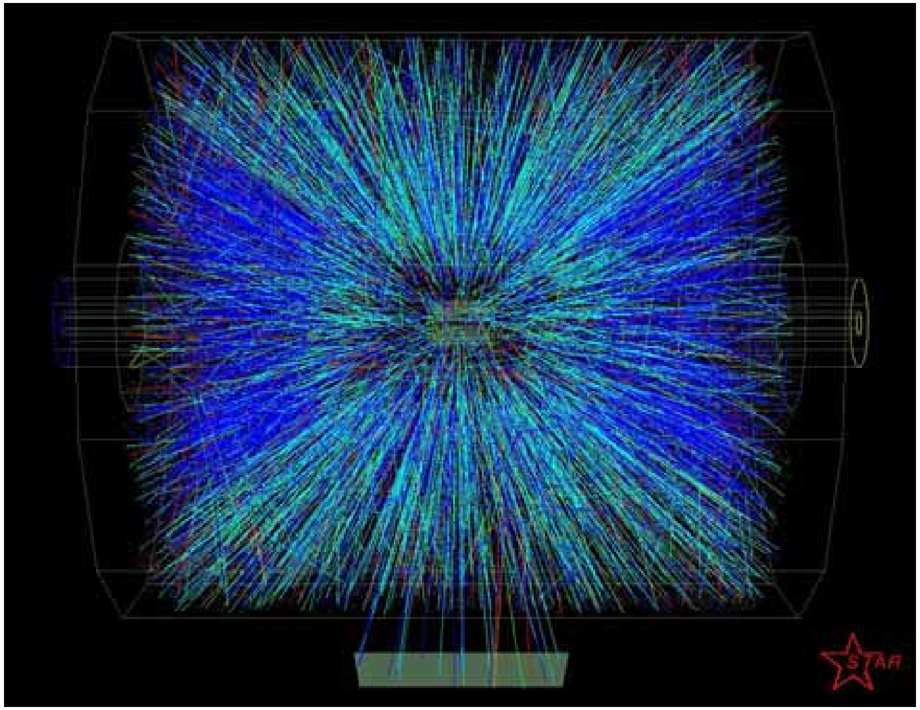
Formation phase -
parton scattering

Using heavy ions to excite the QCD vacuum on a large scale

Central Au-Au collision: A Mini-Bang?

Charged particle multiplicity density per interacting nucleon pair

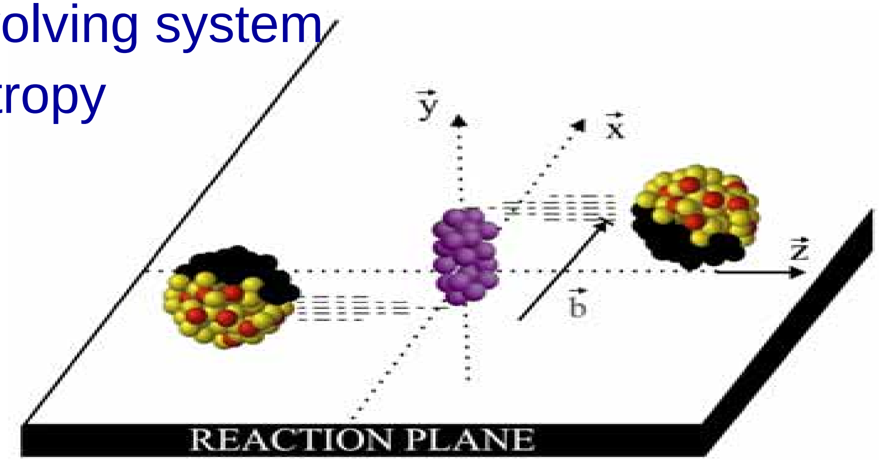




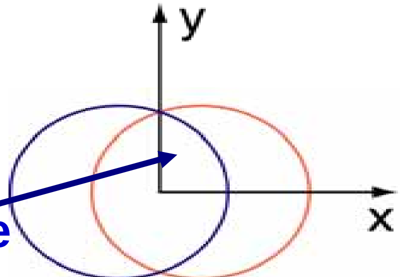
Initial energy density >10 GeV/fm^3 over a volume of ~1000 fm^3

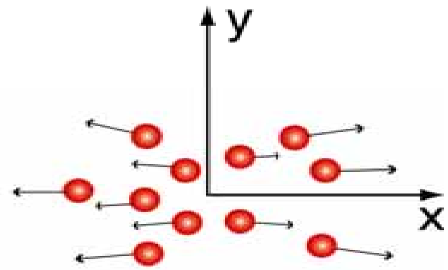
Pressure: a Barometer Called "Elliptic Flow"

Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system
spatial anisotropy $\rightarrow$ momentum anisotropy



v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



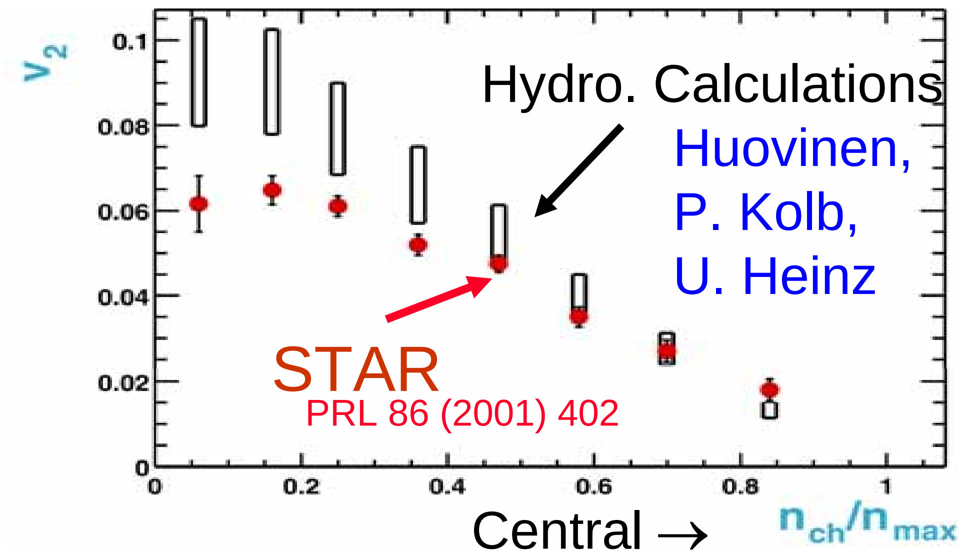


Almond shape overlap region in coordinate space

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \mathrm{atan}\frac{p_y}{p_x}$$

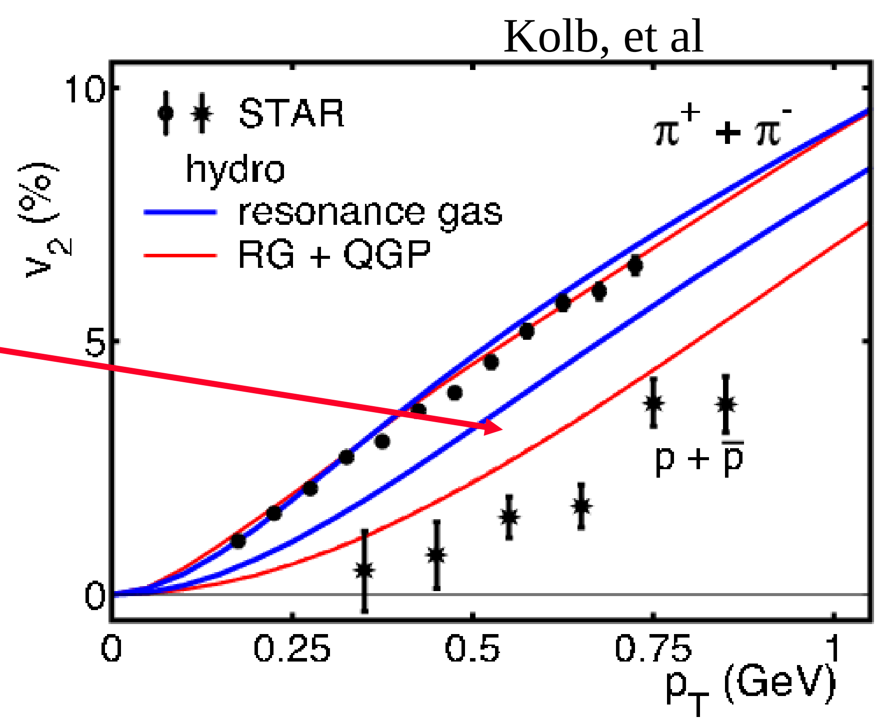
v_2 Predicted by Hydrodynamics



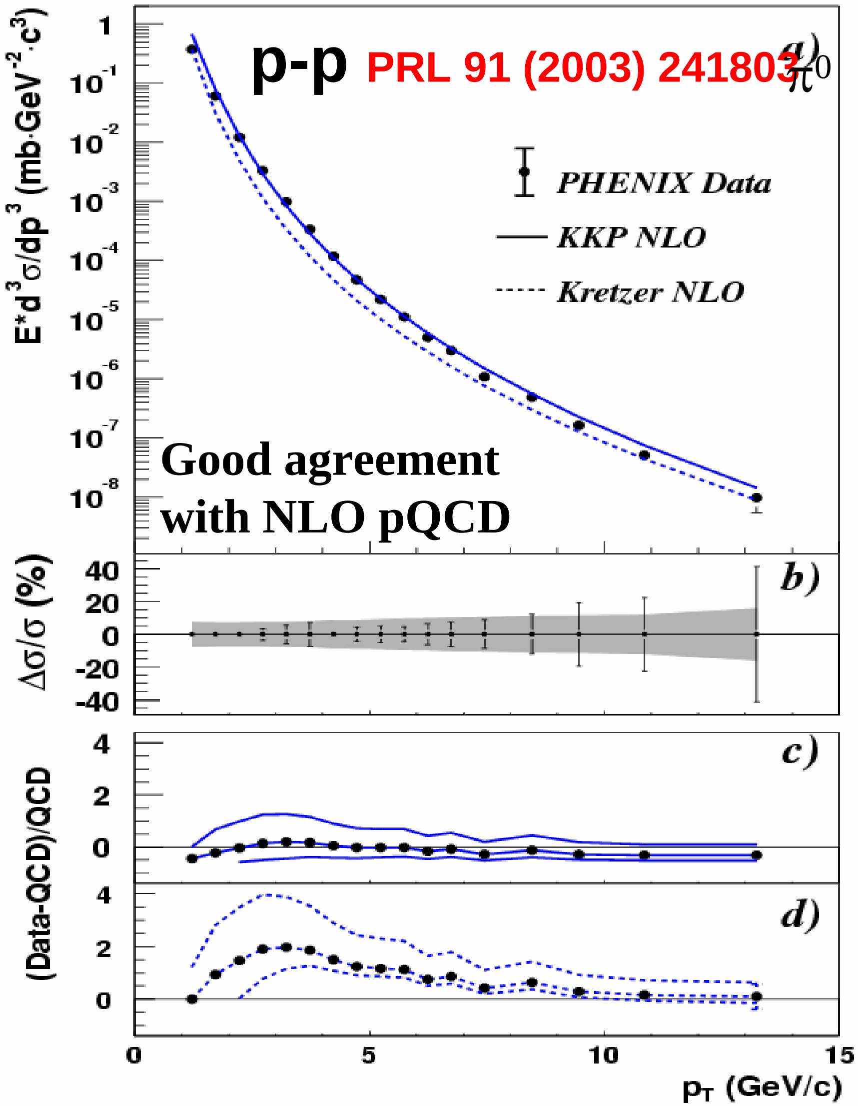
- see large pressure buildup
- anisotropy ⇒ the buildup happens fast
- v_2 reproduced by hydro ⇒ early equilibration !

Hydro can reproduce magnitude of elliptic flow for (p, p), BUT: ***must add QGP to hadronic Equation of State!!***

Similar conclusion reached by Ko, Kapusta, Bleicher, others…



Study Systems with Increasing Complexity to Understand: p+p, “p”+A, then A+A Collisions



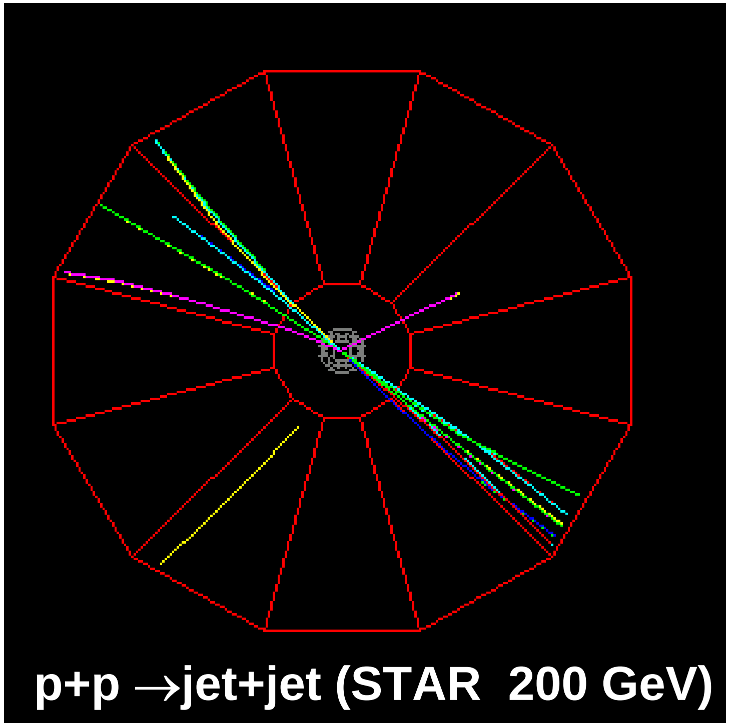
start with pQCD and “hard” pp collisions: it works!

Have a handle on initial NN interactions by scattering of q, g inside N

We also need:

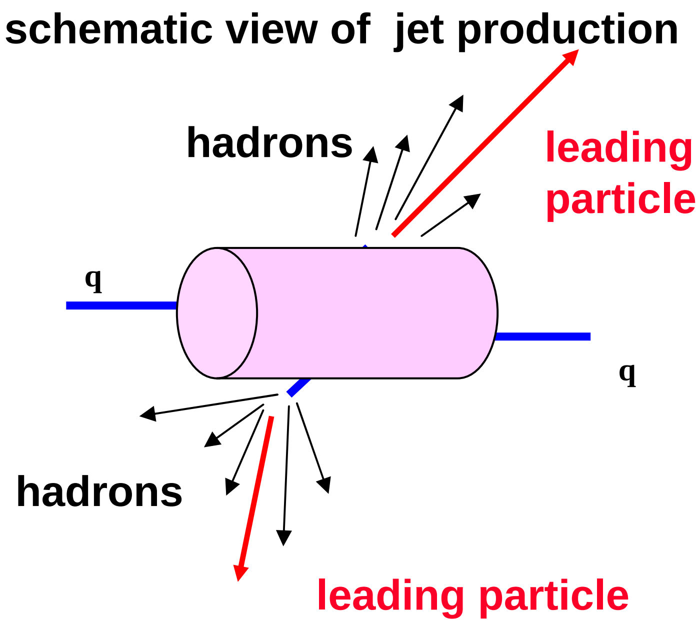
$f_{a/N}(x,Q^2)$ Parton distribution functions

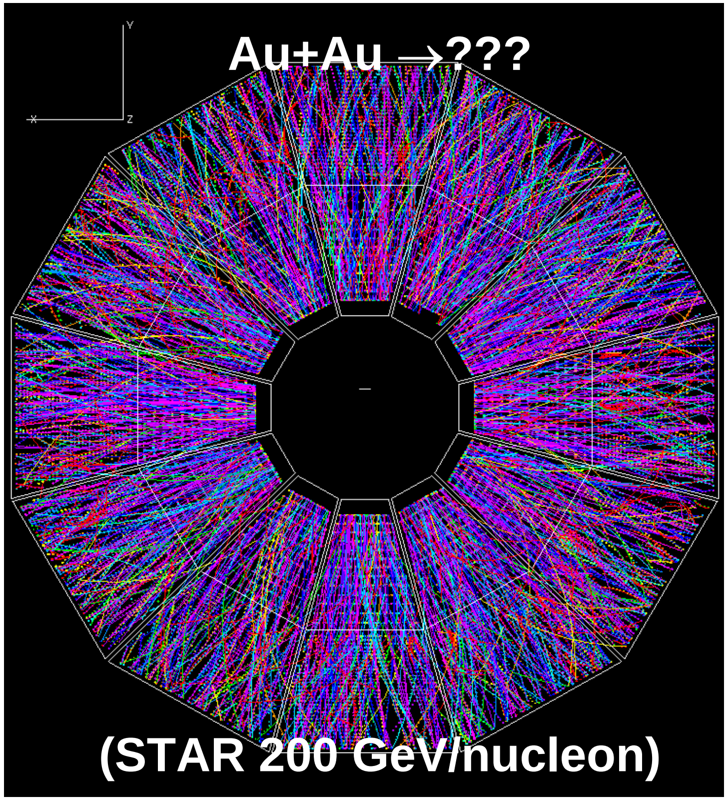
$D_{h/a}(z_C,Q^2)$ Fragmentation functions



Hard Scattering Leads to Jets Use Them to Probe the Medium

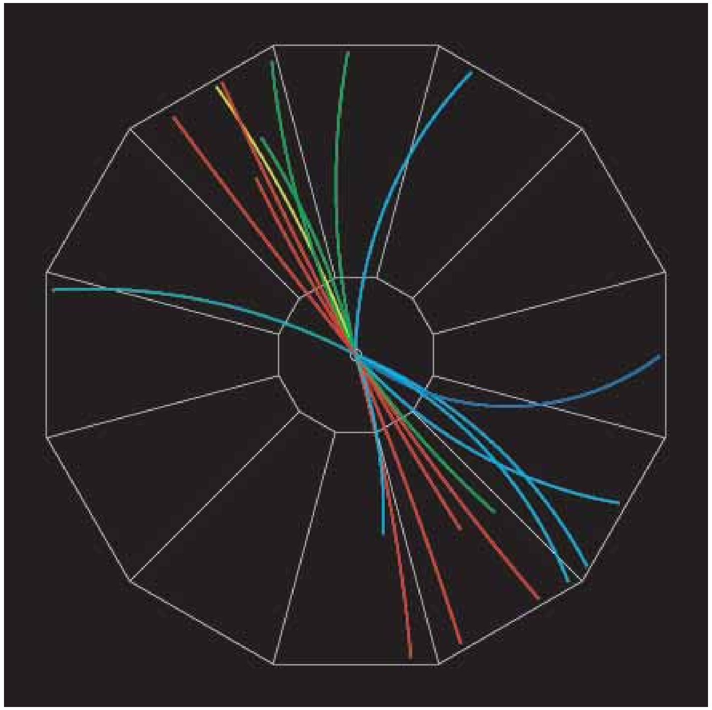
- Observed via fast leading particles and their angular correlations
- In the presence of a color-deconfined medium, the partons interact strongly (~GeV/fm), losing much of their energy via gluon Bremsstrahlung.





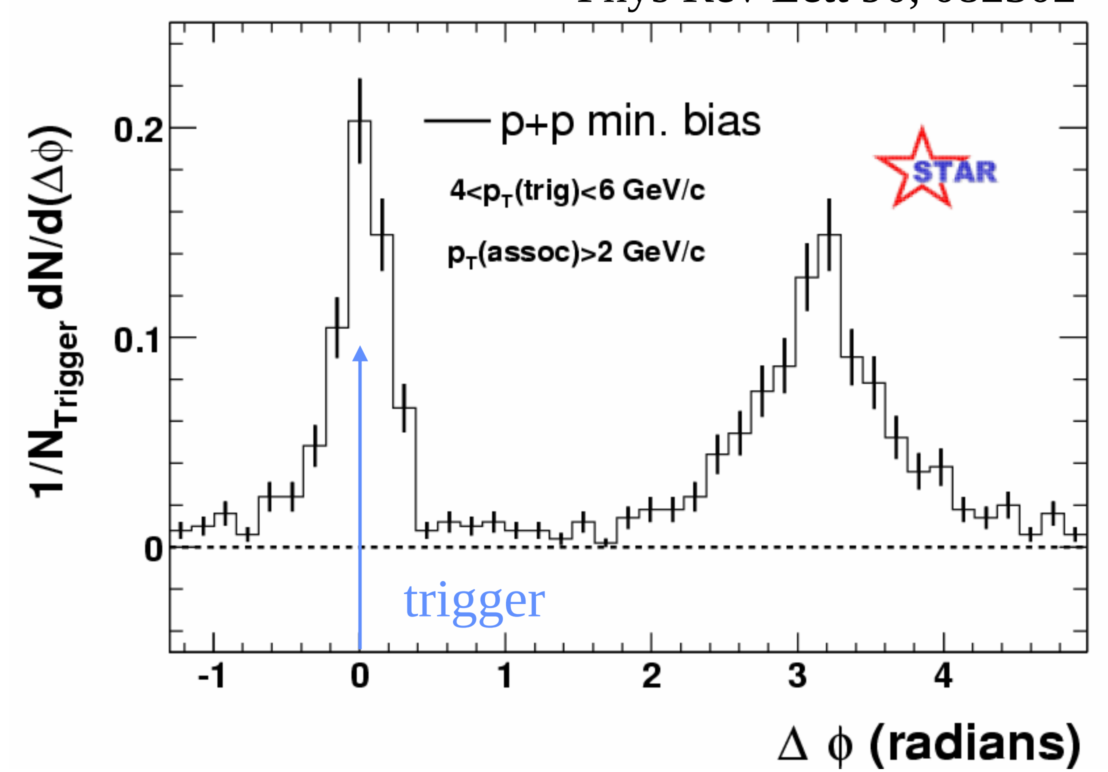
Jets and two-particle azimuthal distributions

p+p → dijet

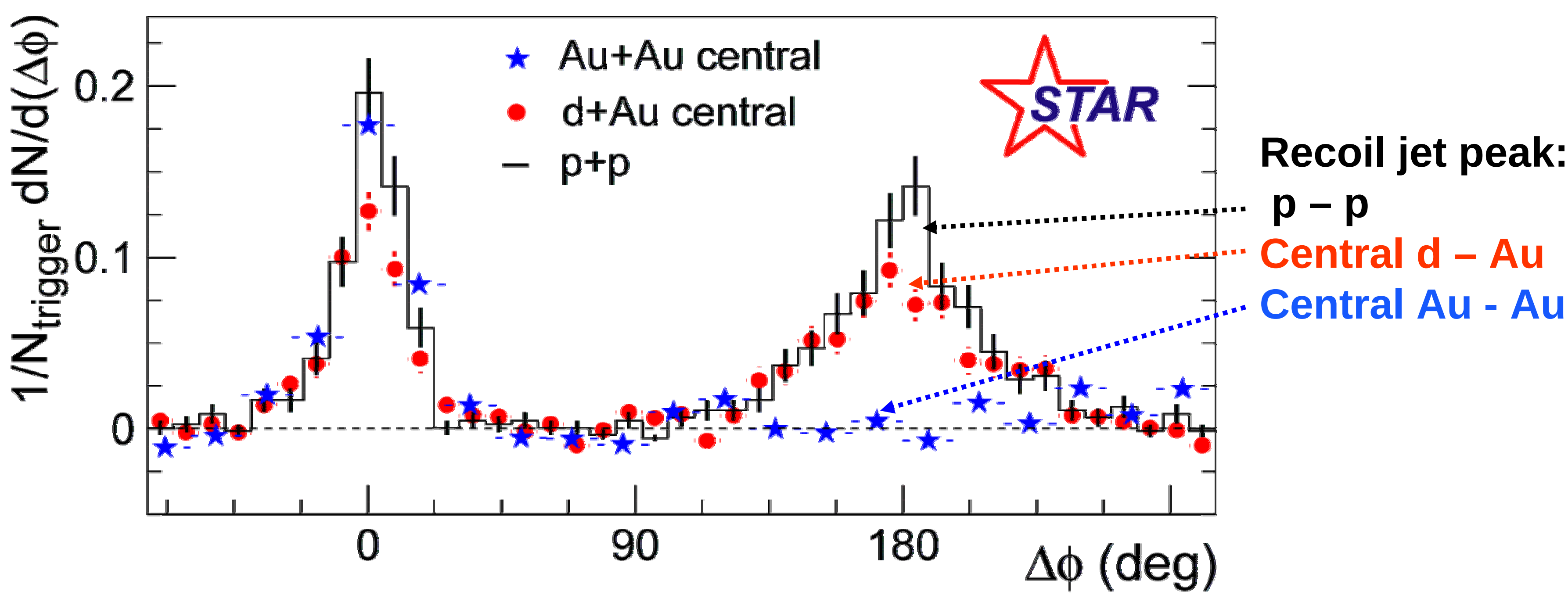


- trigger: highest p_T track, p_T>4 GeV/c
- $\Delta\phi$ distribution: 2 GeV/c<p_T<$p_T^{trigger}$
- normalize to number of triggers

Phys Rev Lett 90, 082302



"Opposite" Jet Suppressed
As We Go from p-p to d-Au to Au-Au



- **Need parton interaction cross sections 50X pQCD values to explain the quenching!**
- **The data indicate a hot, dense medium of final state particles characterized by *strong* collective interactions at very high energy densities.**

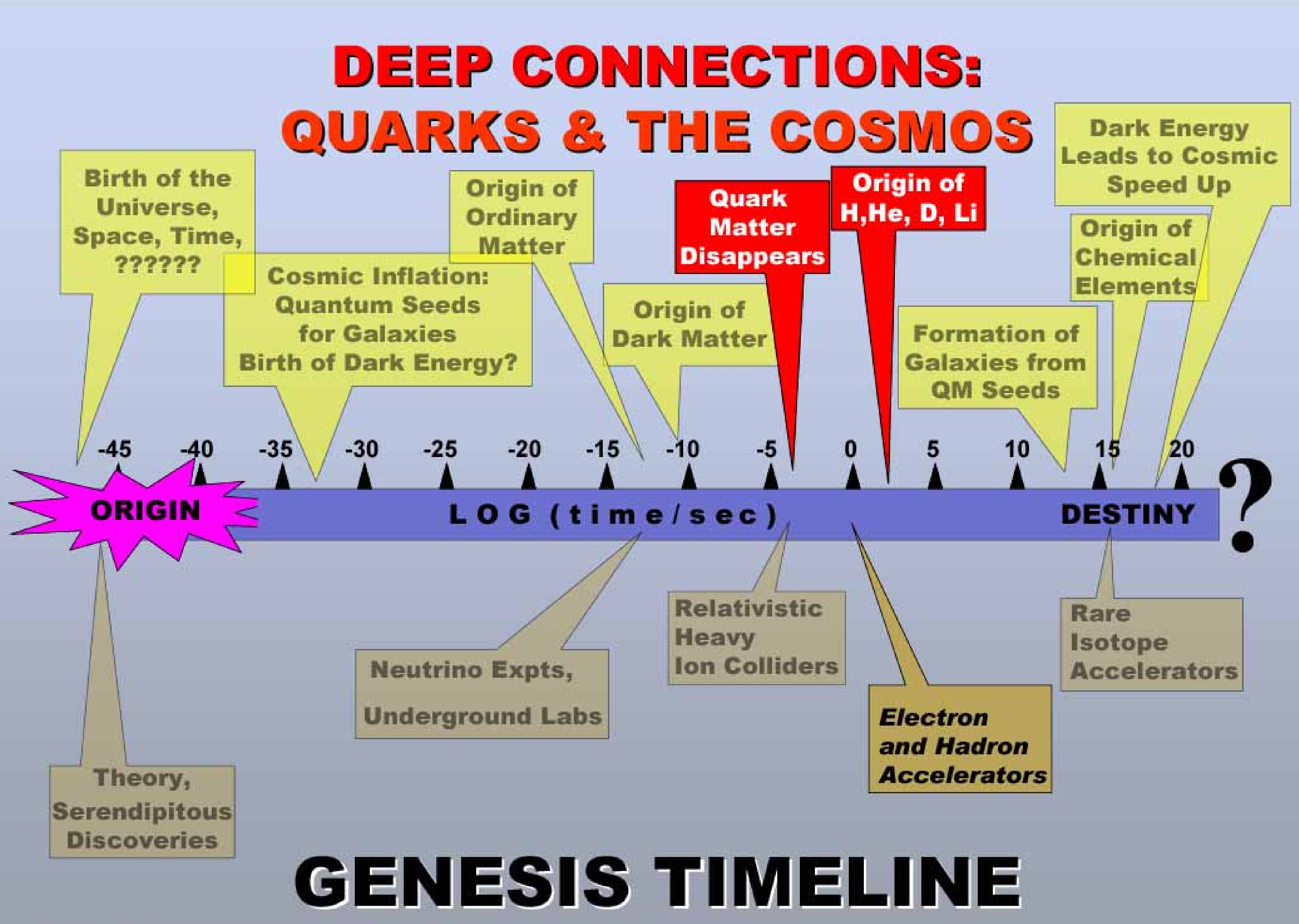
Medium properties

- Extract by constraining QCD-inspired models with measured jet suppression and v_2
- Find:

Energy loss <dE/dz> (GeV/fm)	7-10	0.5 in cold matter
Energy density (GeV/fm^3)	14-20	>5.5 from E_T data
dN(gluon)/dy	~1000	200-300 at SPS
T (MeV)	380-400	must measure!
Equilibration time τ_0 (fm/c)	0.6	Parton cascade agrees
Medium lifetime τ_{TOT} (fm/c)	6-7	

A Quark-Gluon Liquid???

(values from Vitev, et al; others consistent)



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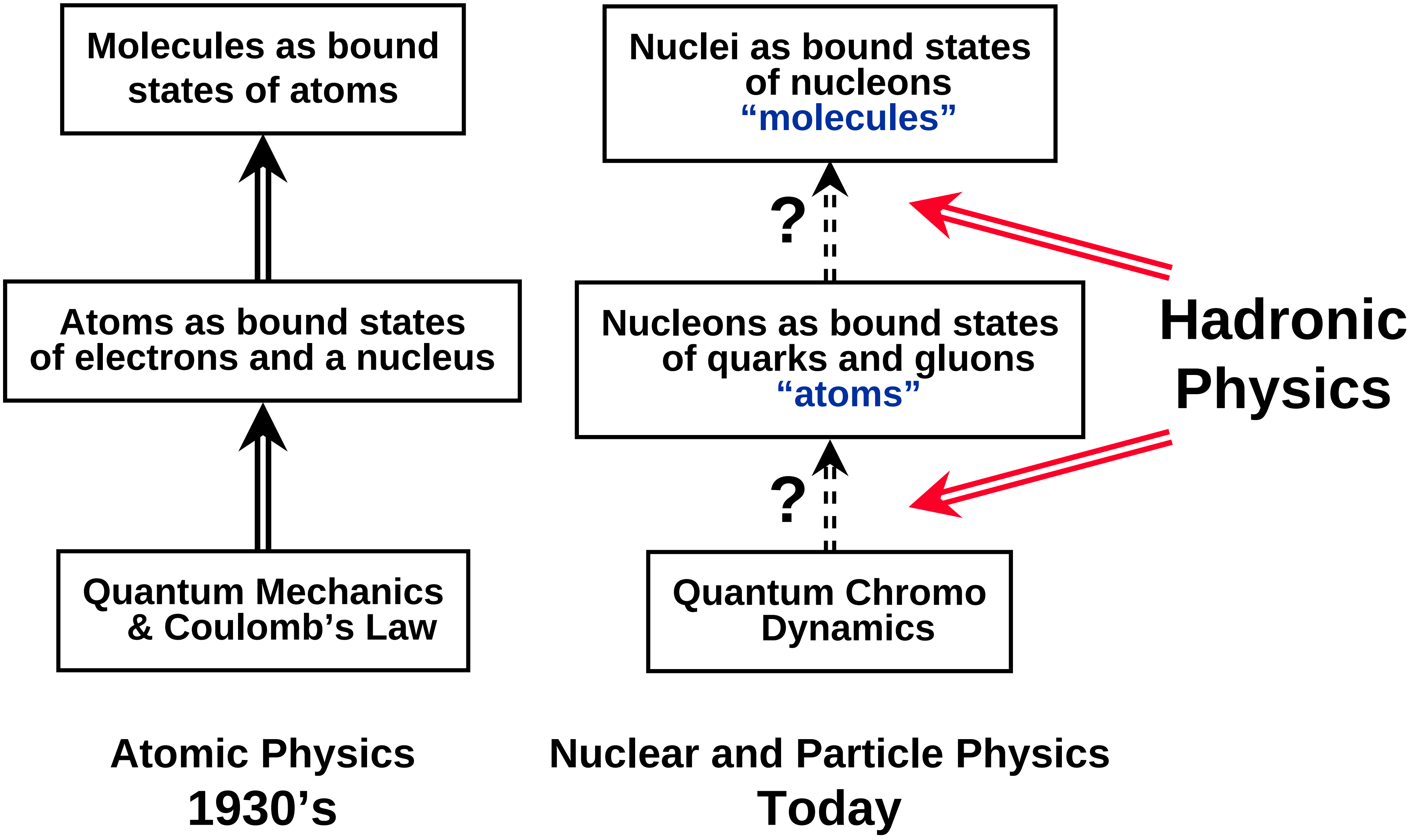
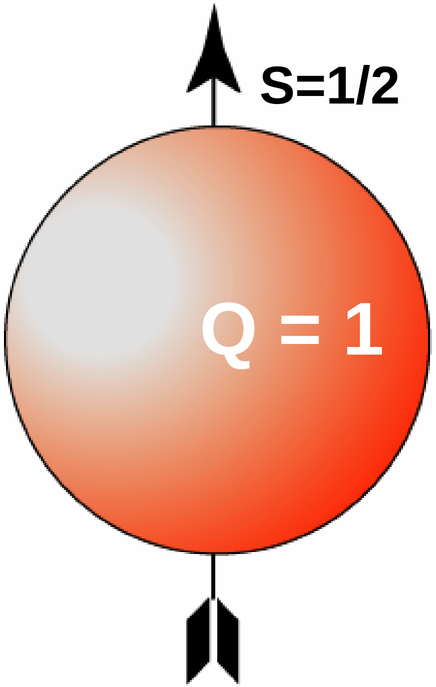
Atomic Physics versus Quark Physics

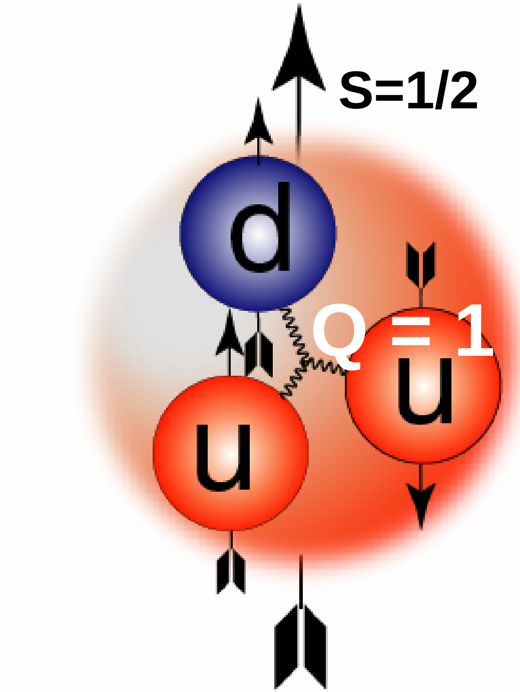


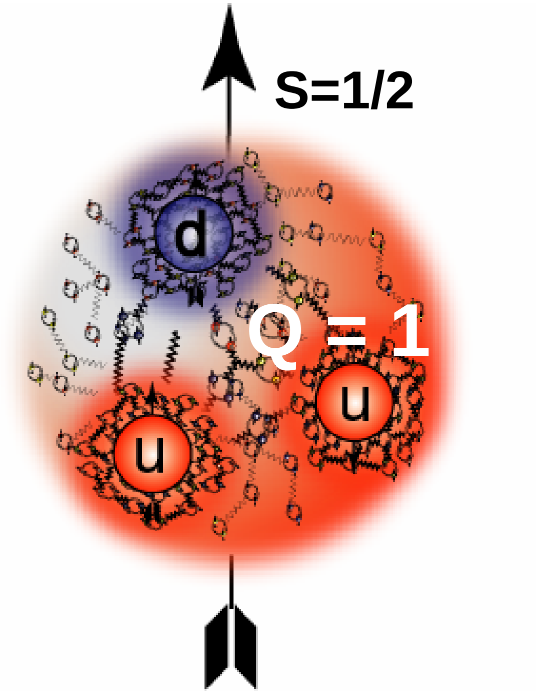
The Proton and Neutron are the "Hydrogen Atoms" of QCD

What we "see" changes with spatial resolution

>1 fm	0.1 — 1 fm	< 0.1 fm
Nucleons	**Constituent quarks and glue**	**"bare" quarks and glue**







Nucleon and Pion Form Factors

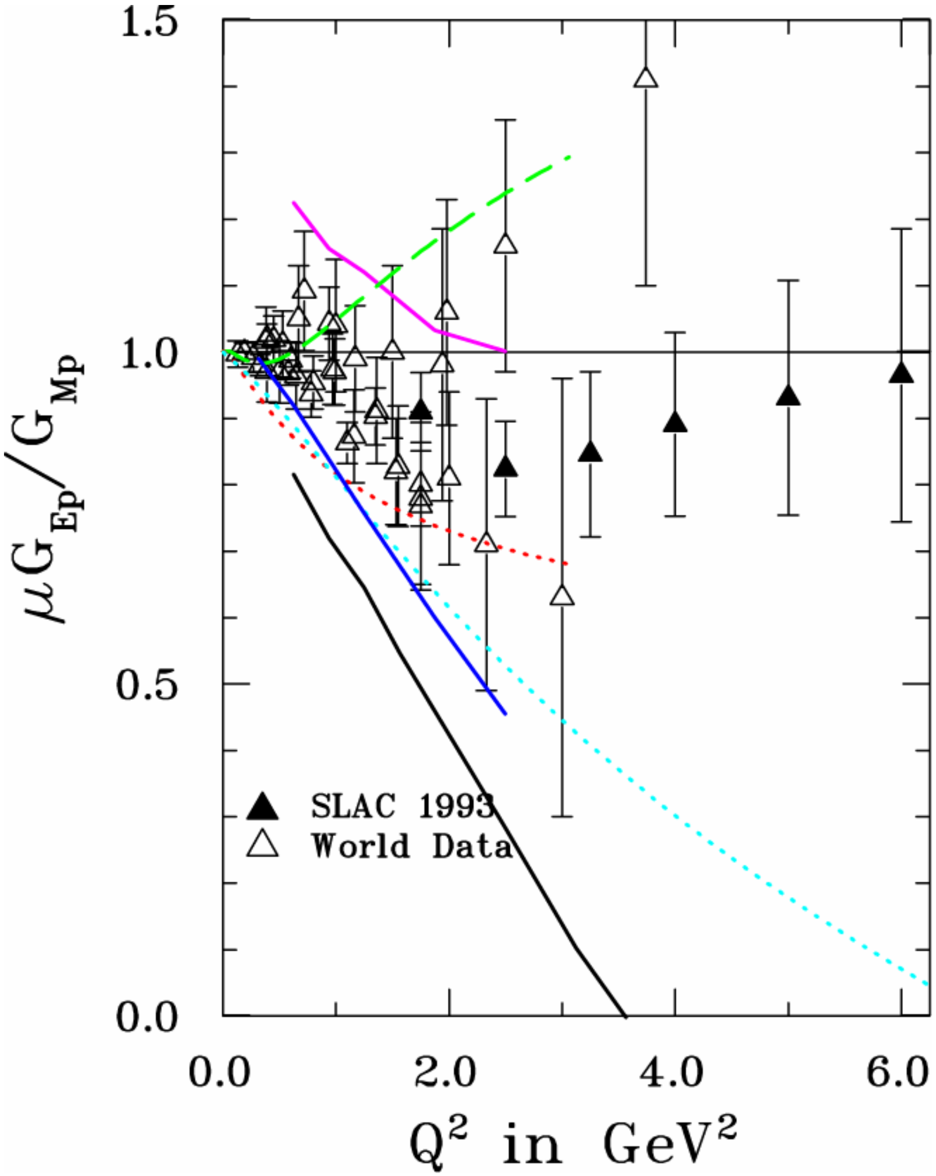
- Fundamental ingredients in "Classical" nuclear theory
- A testing ground for theories constructing nucleons from quarks and gluons.
  - spatial distribution of charge, magnetization
- Experimental insights into nucleon structure from the flavor decomposition of the nucleon form factors

PRECISION

$$\left.\begin{matrix} G_E^p & G_E^n & G_E^{p,Z} \\ G_M^p & G_M^n & G_M^{p,Z} \end{matrix}\right\} \Rightarrow \begin{matrix} G_E^u & G_E^d & G_E^s \\ G_M^u & G_M^d & G_M^s \end{matrix}$$

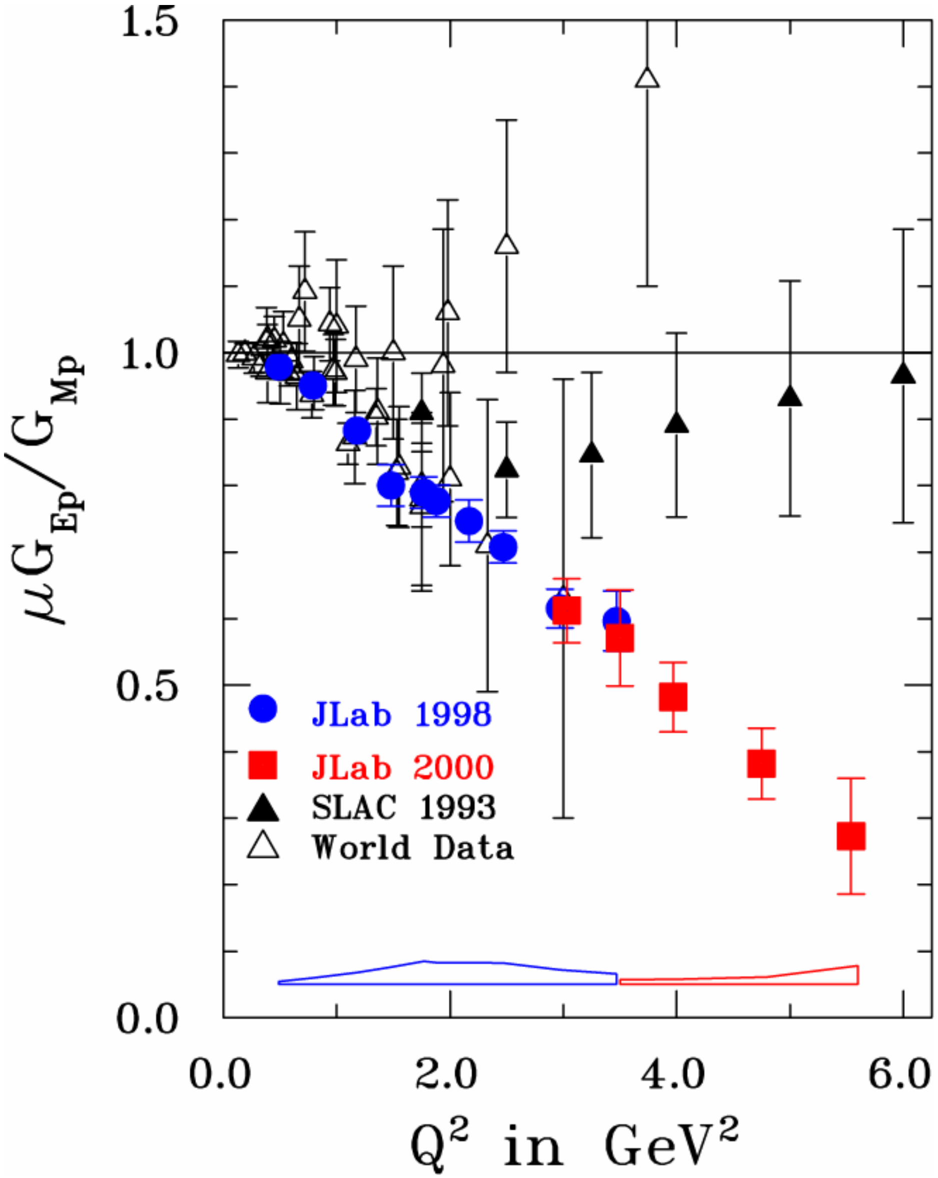
- Additional insights from the measurement of the form factors of nucleons embedded in the nuclear medium
  - implications for binding, equation of state, EMC…
  - precursor to QGP

The Proton's Electric Form Factor: Critical Data for Understanding Proton Structure



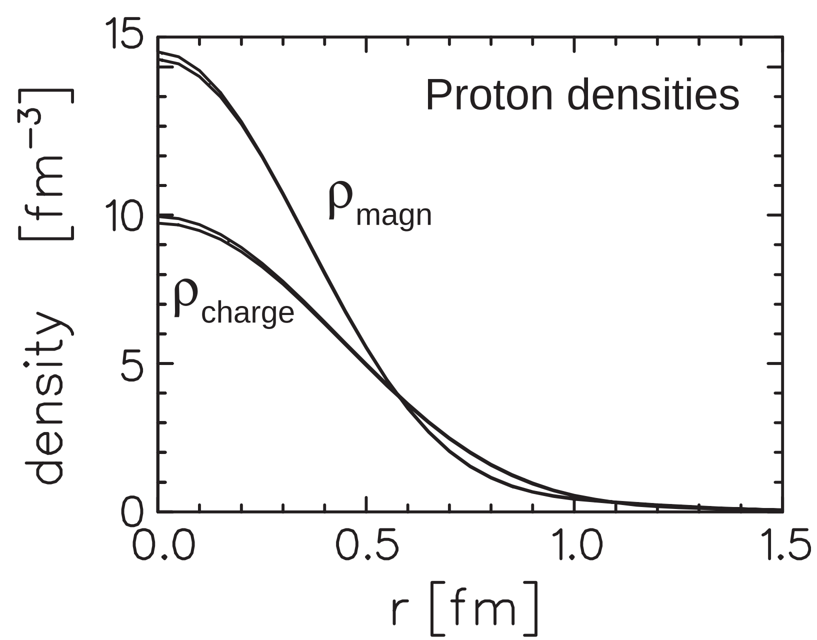
Previously-available data wasn't accurate enough to distinguish between theories of the proton

G_E^p/G_M^p as via ($\vec{e}$,e'$\vec{p}$): Critical New Data



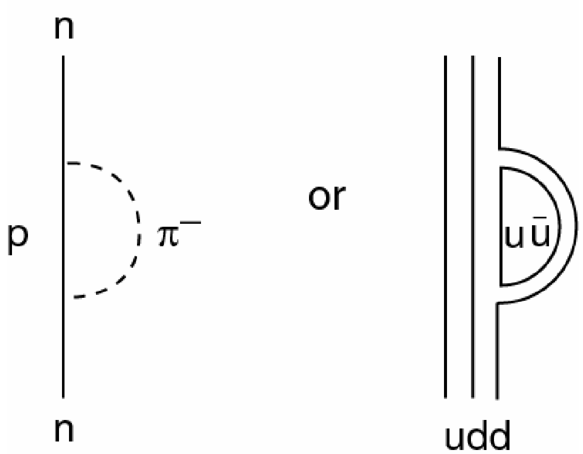
The combination of high intensity $\vec{e}$ beams and proton polarimetry has dramatically improved our knowledge of this fundamental system and revived theoretical interest in this important problem

⇒

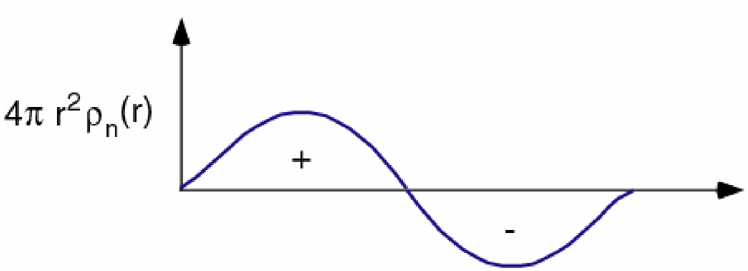


The Neutron's Charge Distribution Provides Further Insights into Hadron Structure

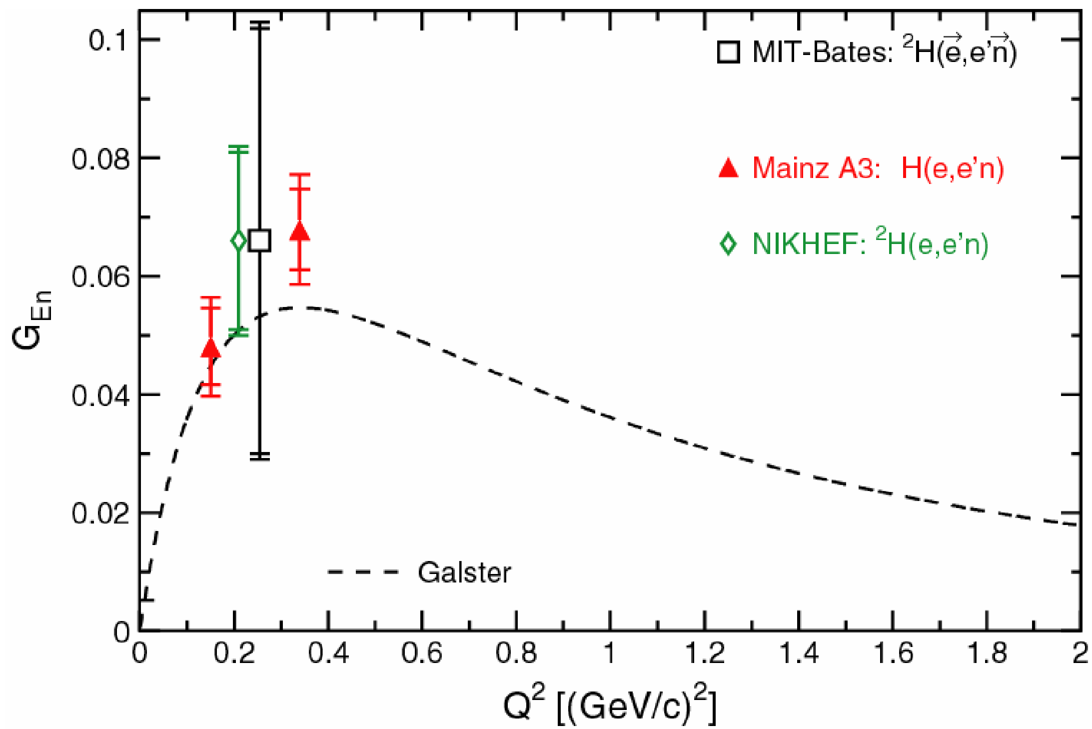
$Q_n = 0$ But $\rho_n(r) \neq 0$



n - Scattering => $G_E^n(q=0)$



Previously available data limited to modest Q^2, just barely sensitive to details beyond the RMS radius



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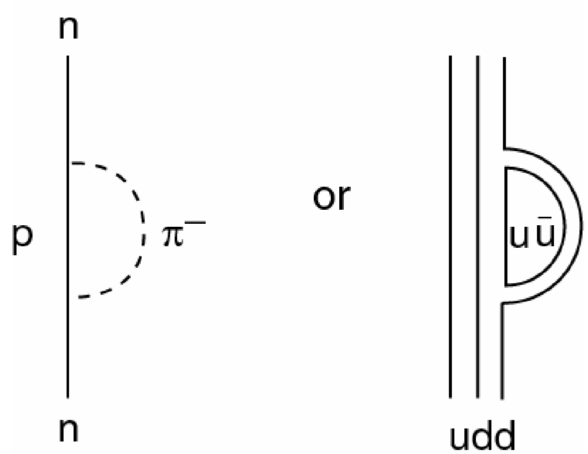

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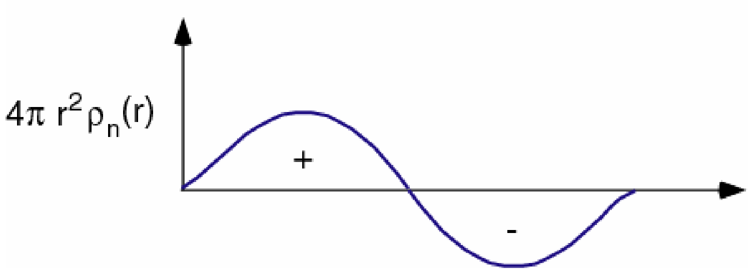
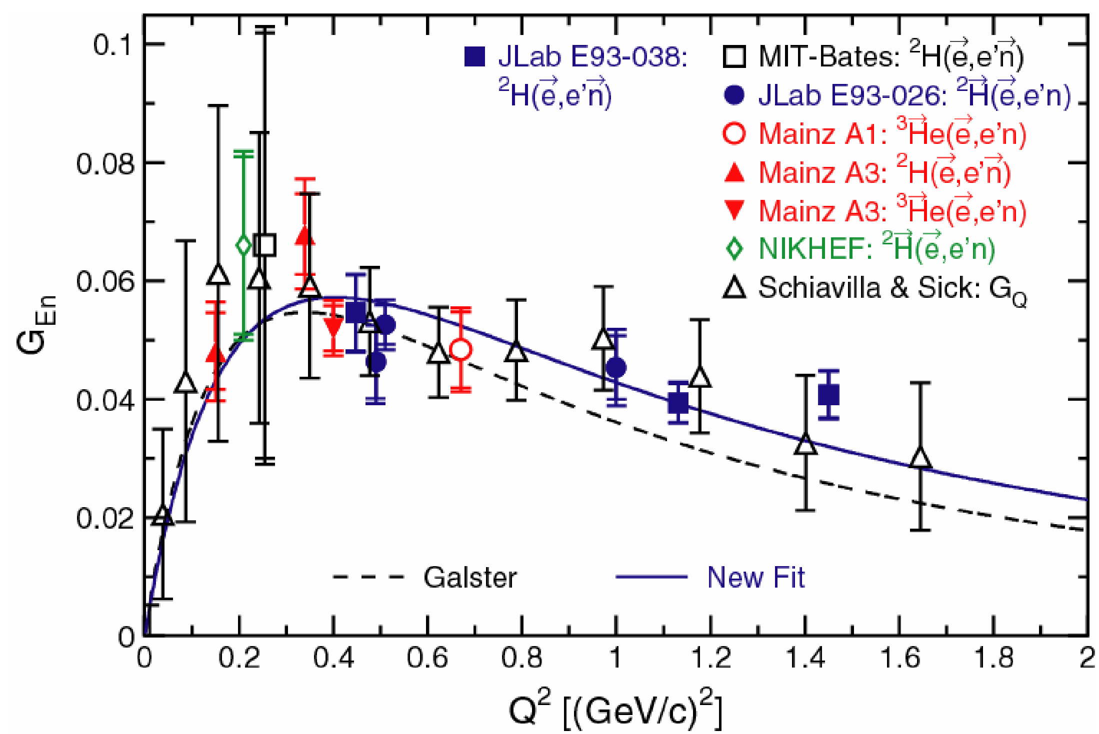
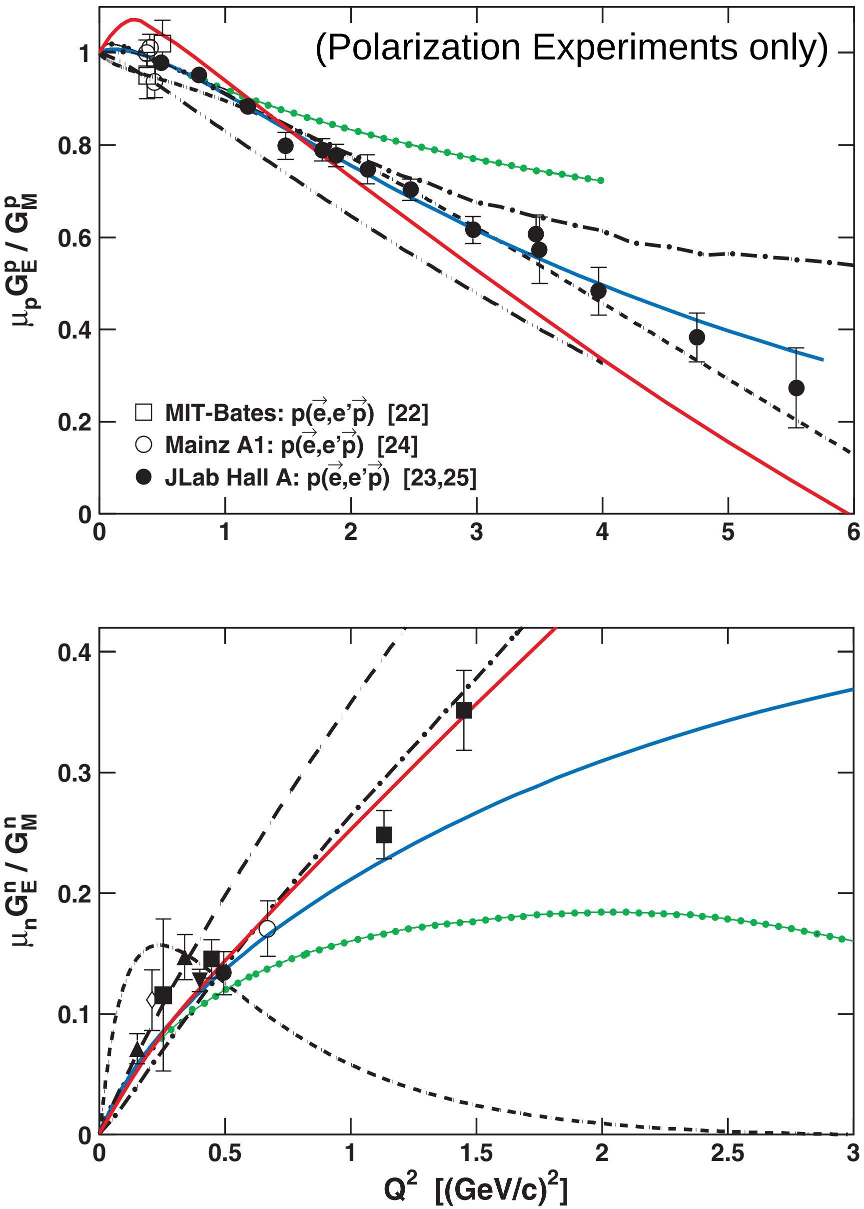


New data clearly determines the basic structure of the neutron's charge distribution



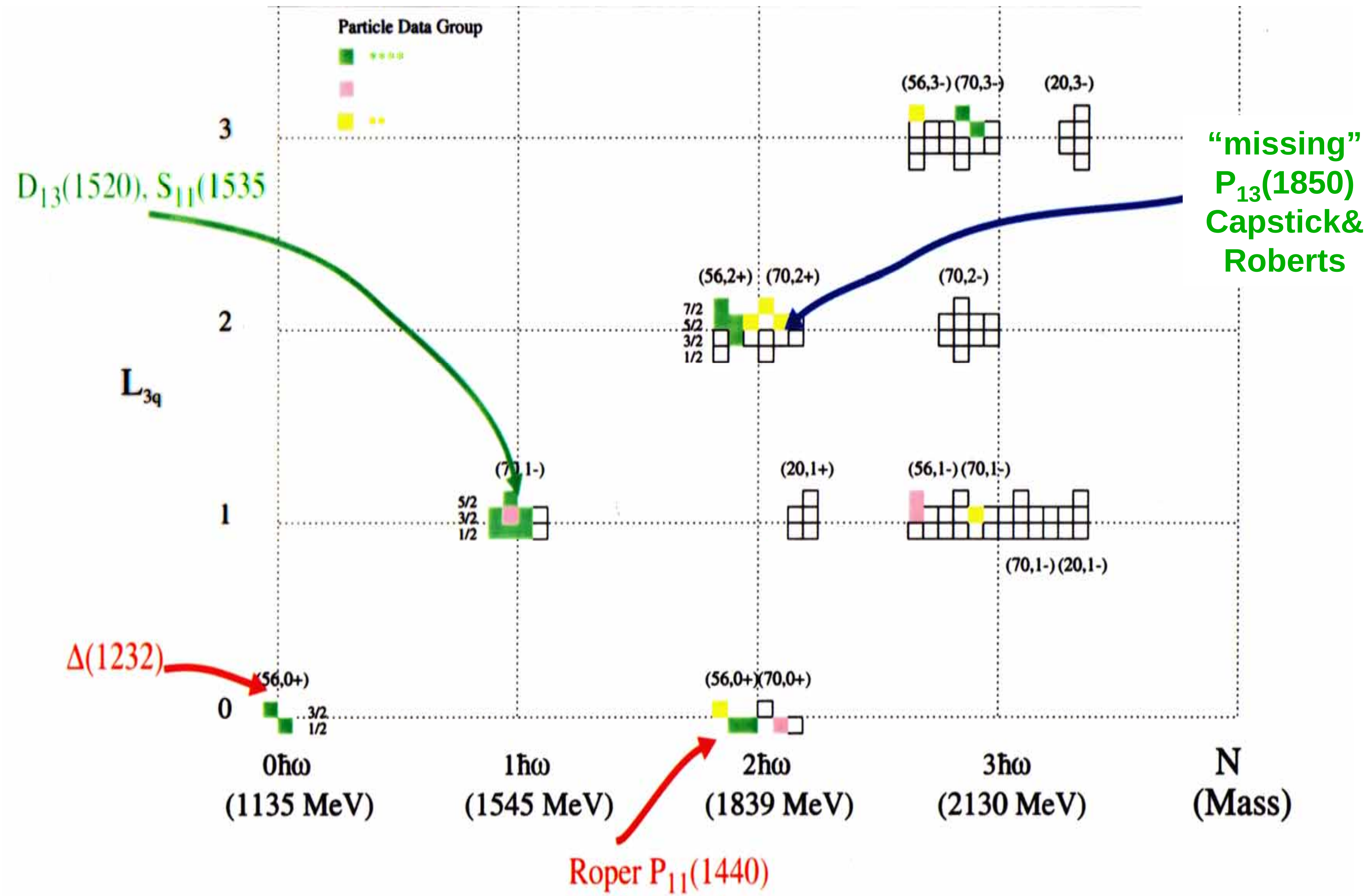
Unraveling Nucleon Structure Through a Consistent Analysis of both G_E^p and G_E^n



Explaining both G_E^p and G_E^n Consistently is Proving to be a Challenge

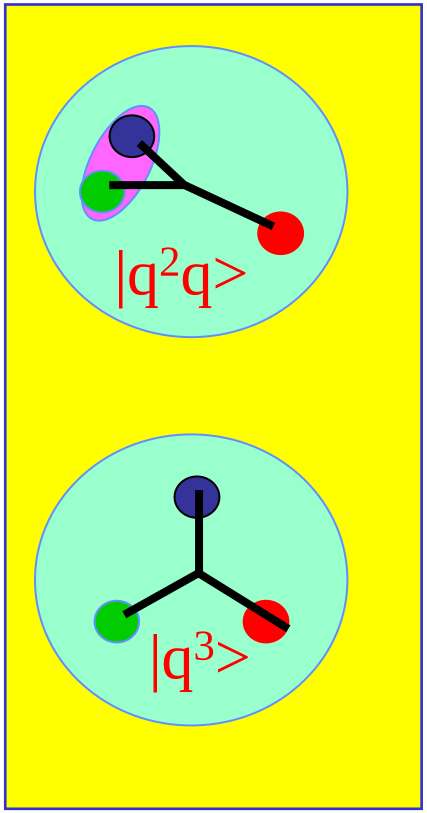
- Light-cone diquark
- 1-gluon exchange light front w/ constituent quark form factors
- Light-front (pointlike constituents)
- VMD and pQCD
- Chiral soliton
- Pointlike constituent quark and boson exchange

The Search for "Missing States" in the Quark Model Classification of N*



“Missing” Resonances?

Problem: Symmetric Constituent Quark Model predicts many more states than have been observed (in πN scattering)



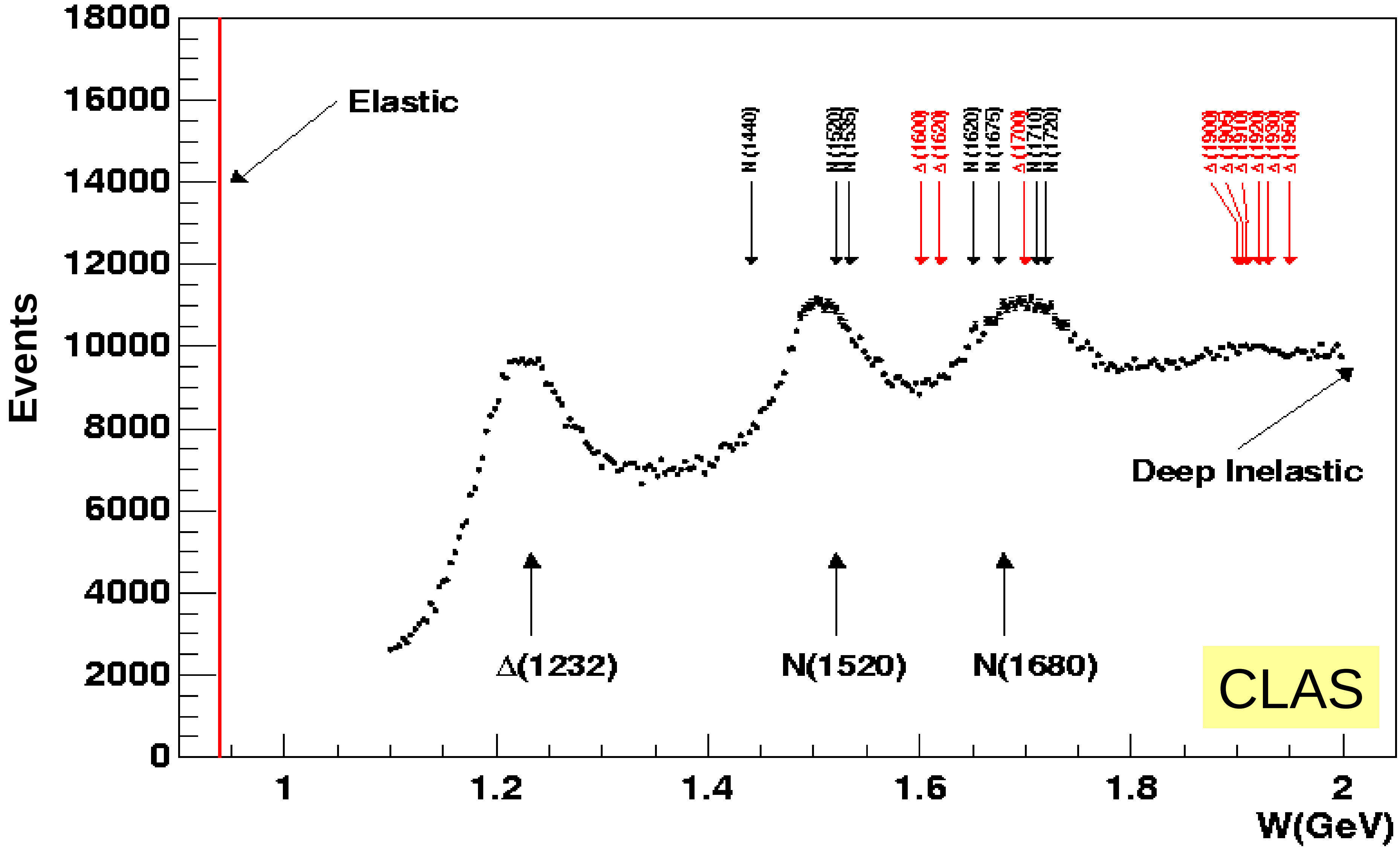
Two possible solutions:

1. Di-quark model
   - fewer degrees-of-freedom
   - open question: mechanism for q^2 formation?

2. Not all states have been found
   - Possible reason: decoupled from the πN-channel
   - Model calculations indicate that the missing states couple to $N\pi\pi$ ($\Delta\pi$, $N\rho$), $N\omega$, KY

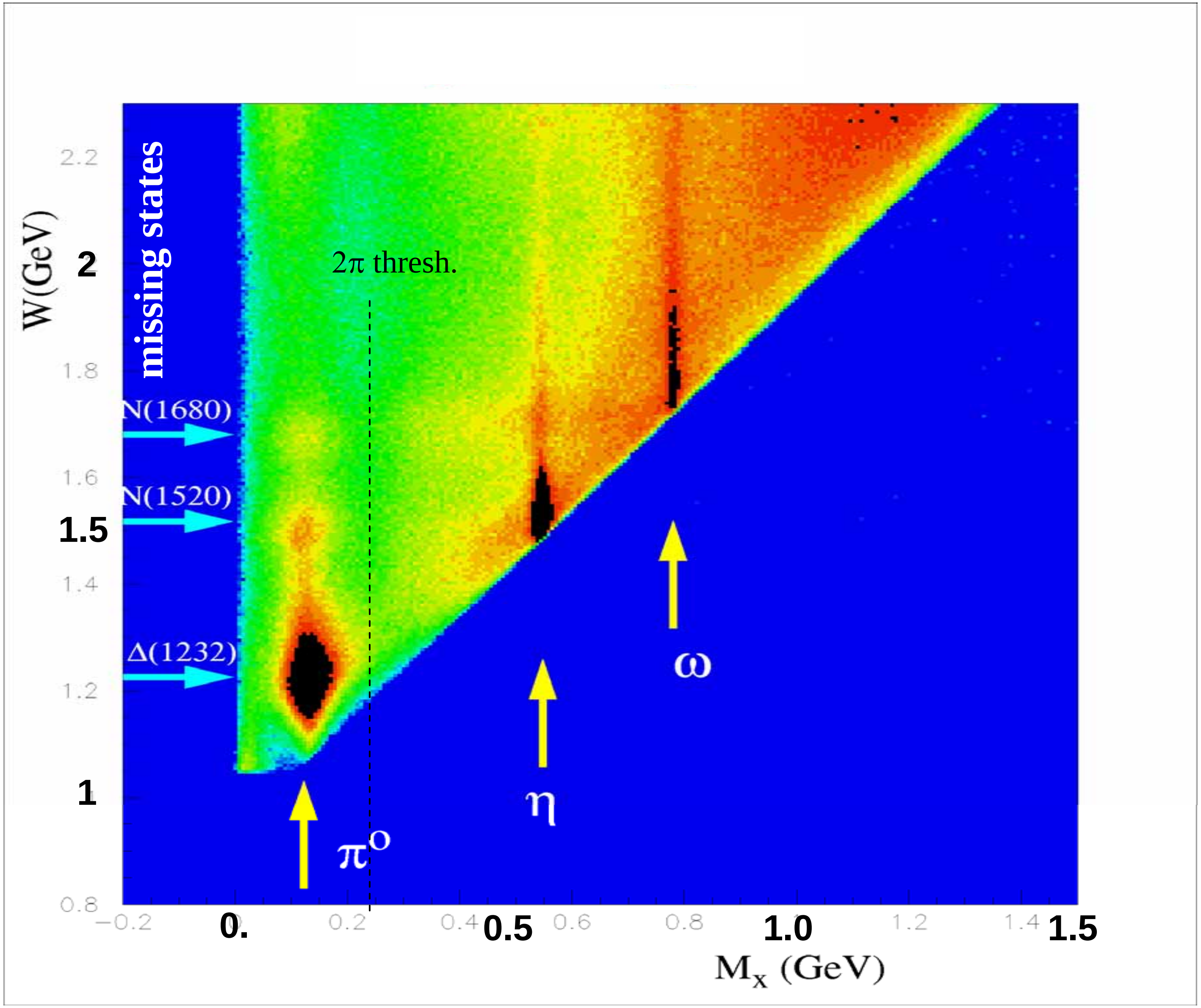
γ coupling is not suppressed, so electromagnetic excitation is an ideal probe to address this question

e p → e X at 4 GeV

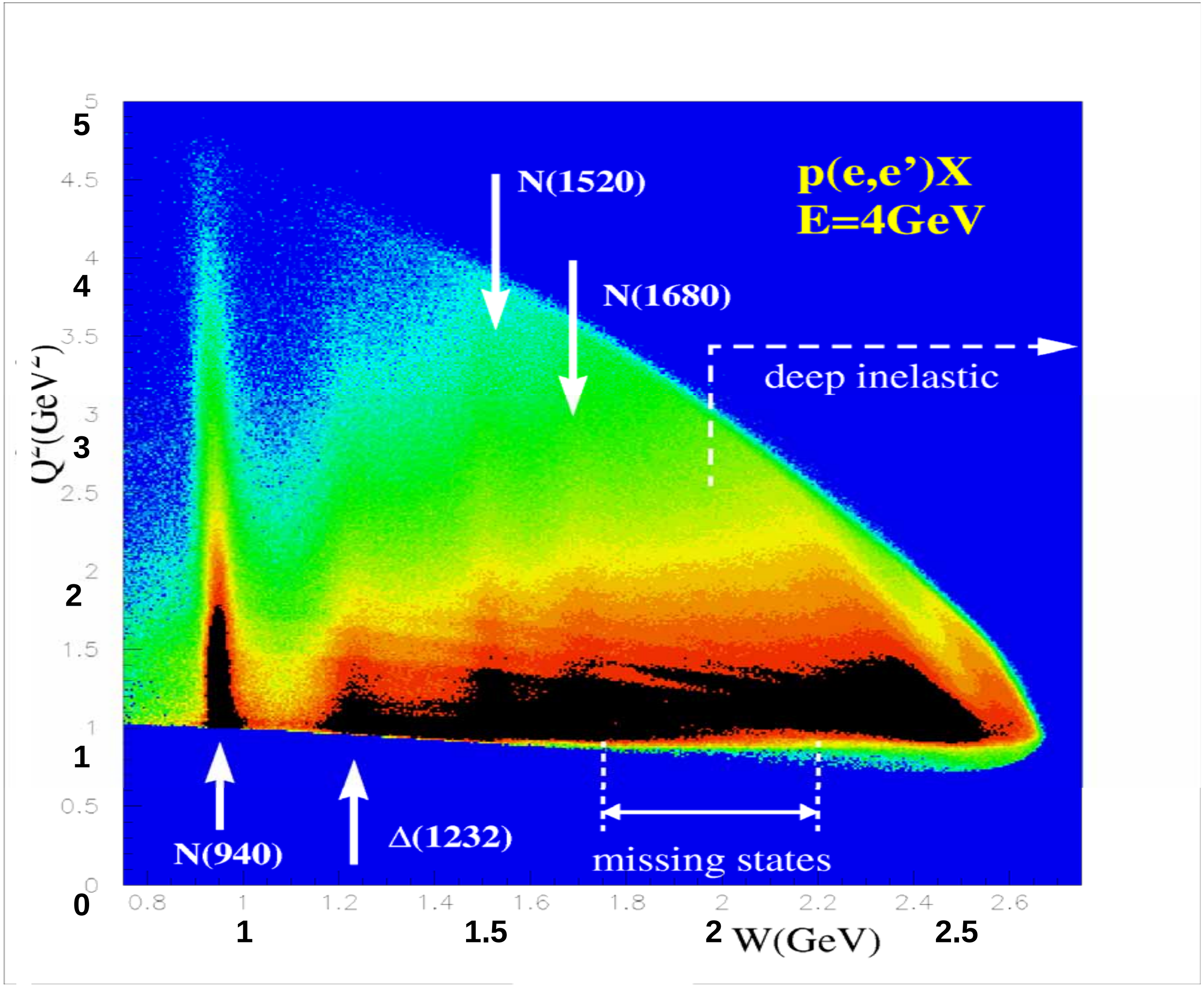


Events
W(GeV)
Elastic
Deep Inelastic
N(1440)
N(1520)
N(1535)
Δ(1600)
Δ(1620)
N(1620)
N(1675)
Δ(1700)
N(1710)
N(1720)
Δ(1232)
N(1520)
N(1680)
CLAS
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
1.2
1.4
1.6
1.8
2

CLAS: ep → epX, E = 4GeV



CLAS Coverage for e p → e' X E = 4 GeV



Resonances in $\gamma^* p \rightarrow p\pi^+\pi^-$

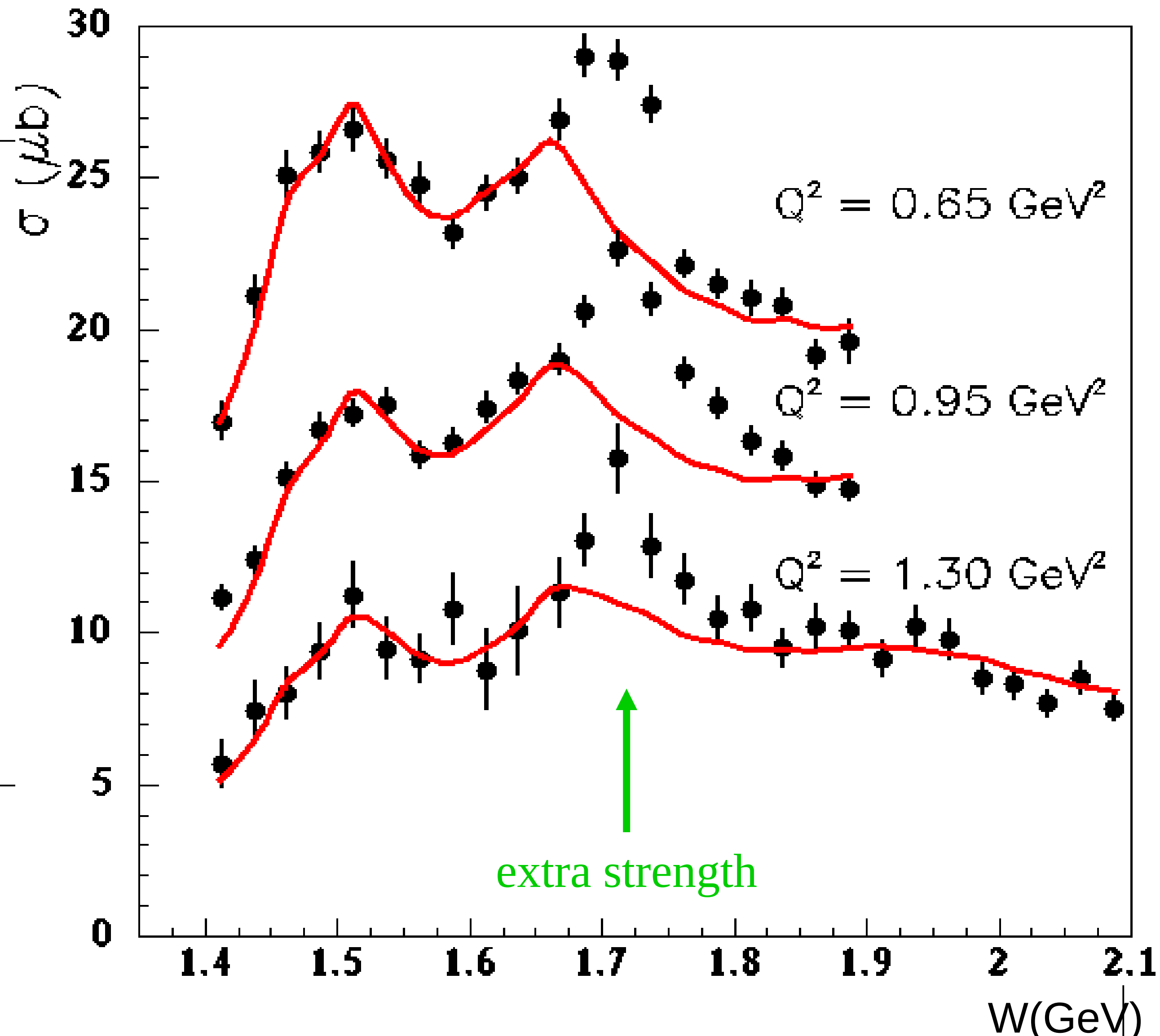
Analysis performed by Genova-Moscow collaboration

step #1:

use the best information presently available

$\Gamma_{N\pi\pi}$ from PDG

$\Gamma_{N\gamma}$ AO/SQTM



Attempts to fit observed extra strength

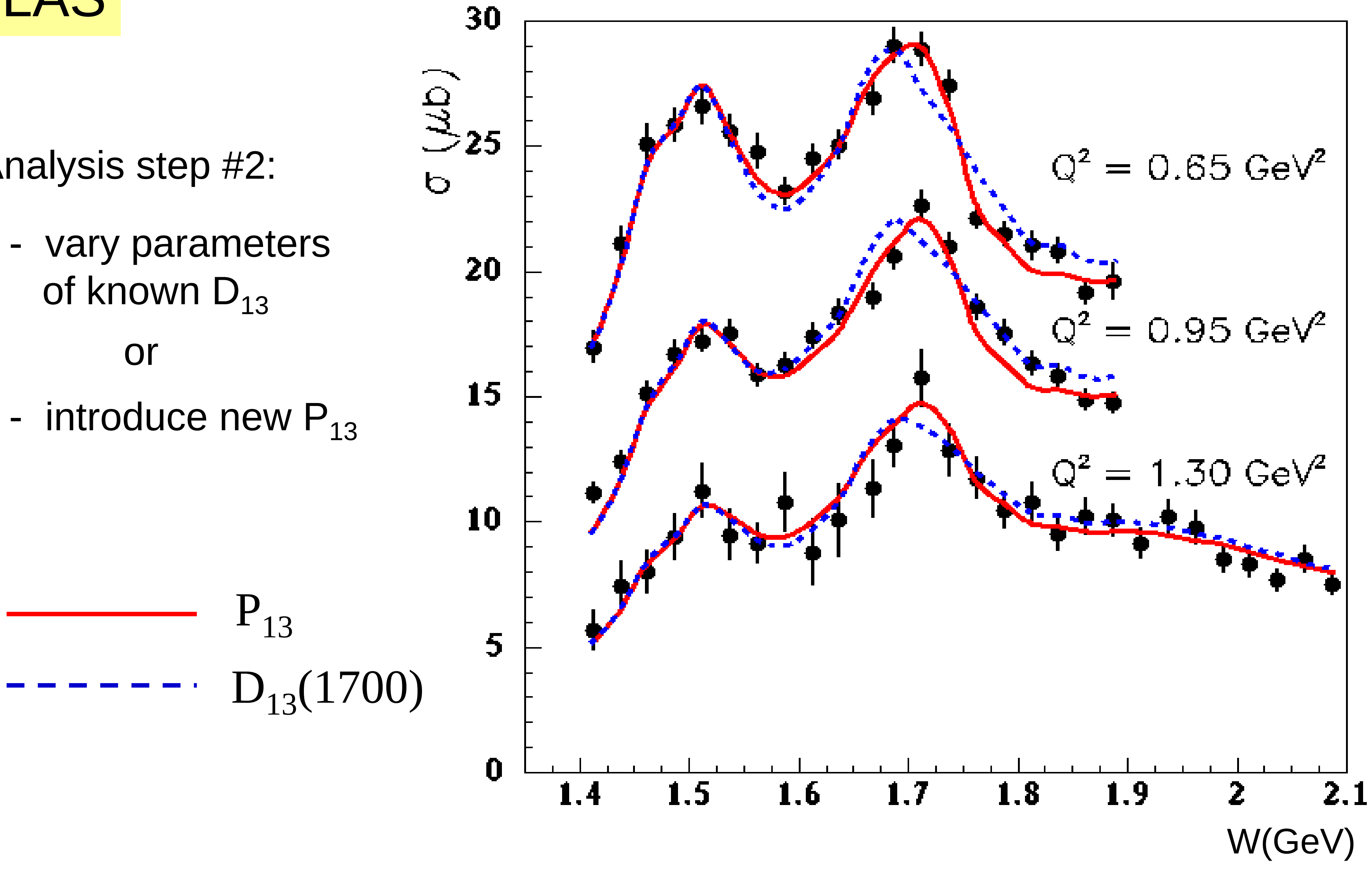
CLAS

Analysis step #2:

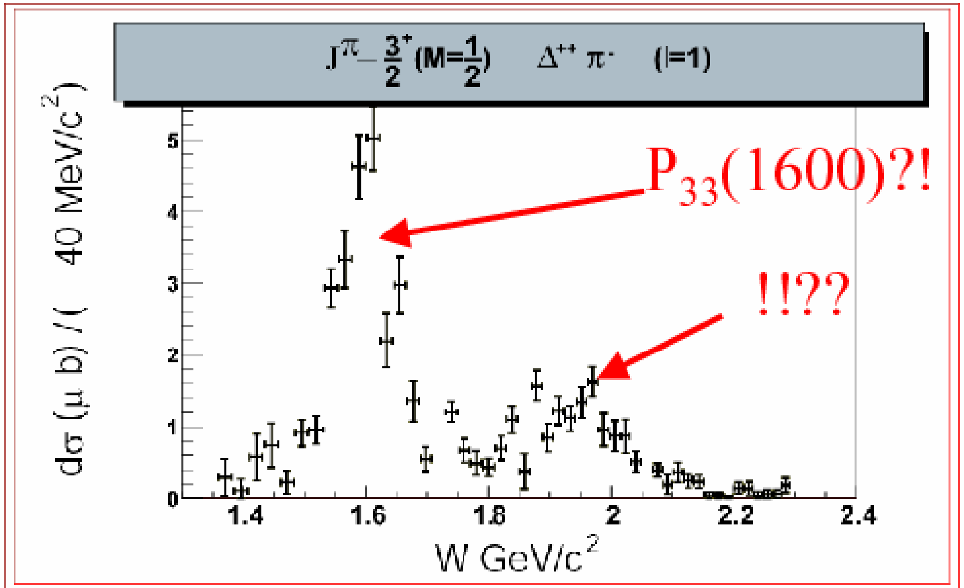
- vary parameters of known D_{13}

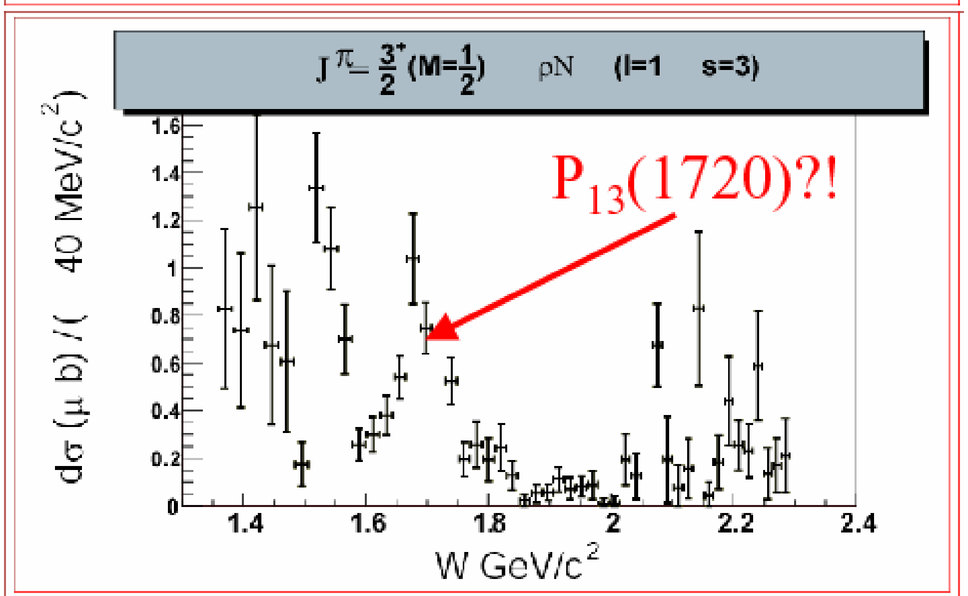
or

- introduce new P_{13}



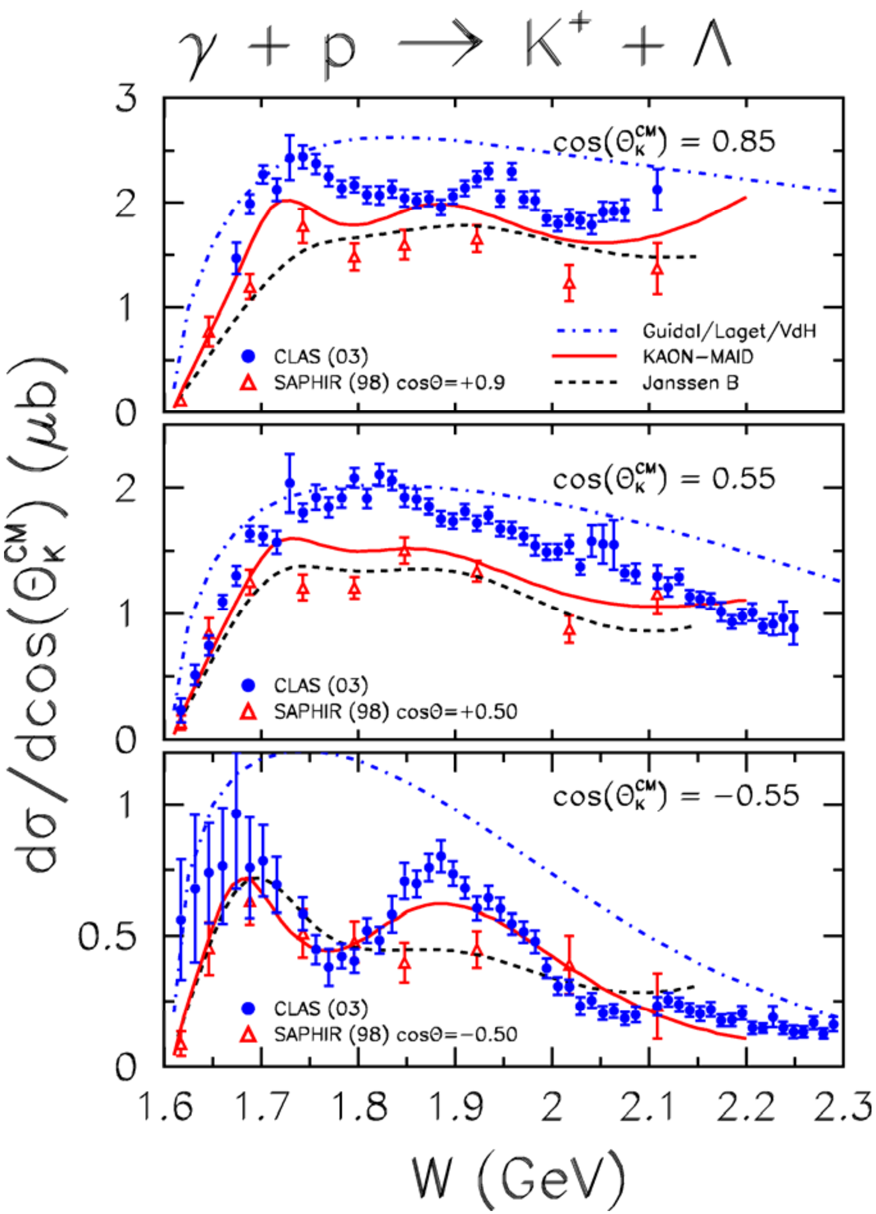
New Resonances are also Seen with Real Photons in $\gamma p \rightarrow p\pi^+\pi^-$





- Sample results from RPI-Jlab
- Preliminary (intriguing!) results
  - Peaks clearly seen
  - $P_{33}\Delta\pi$ decays presently poorly understood
  - $P_{13}\Delta\pi$, ρN decays of great interest
- No isospin separation

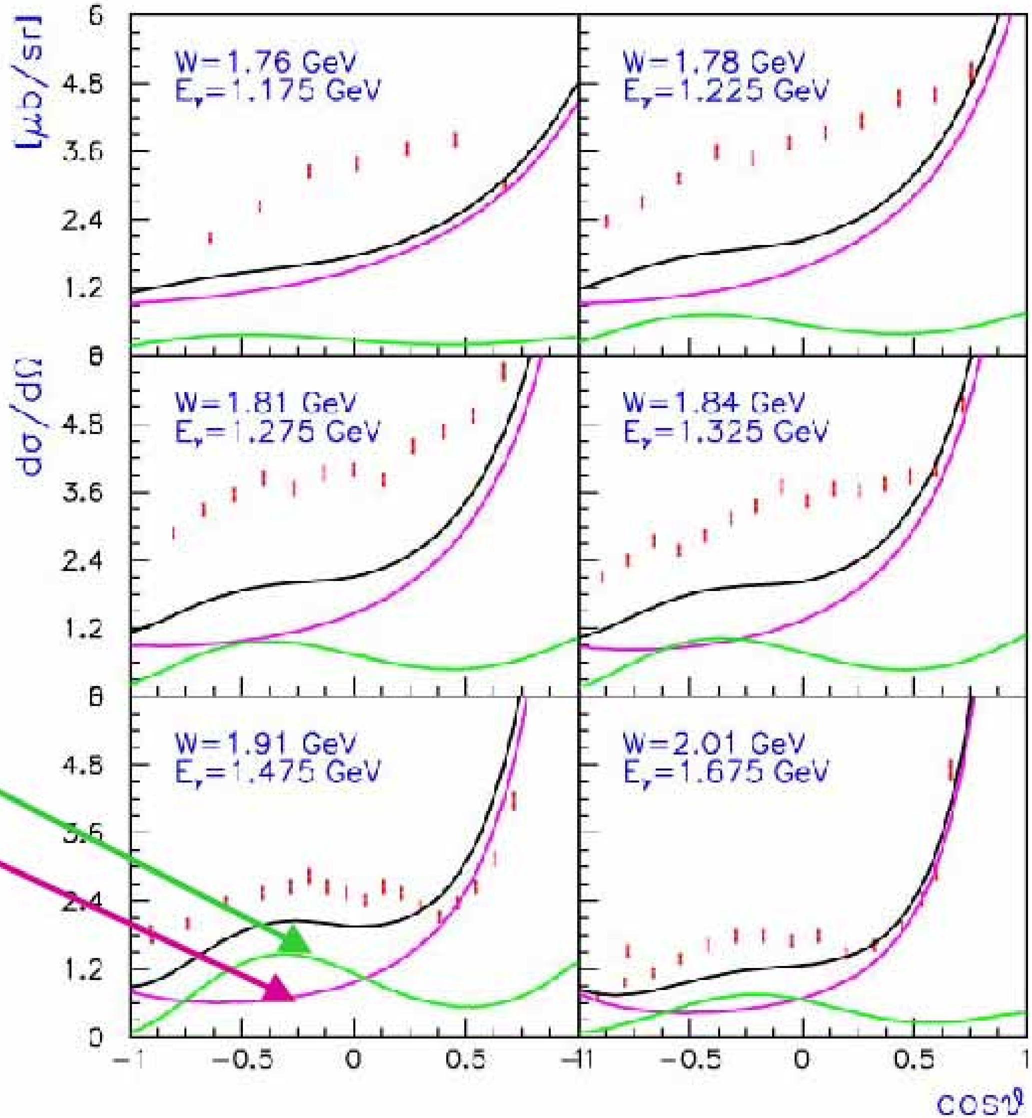
In Strangeness Production in the Resonance Region



- Small sample of data covering the full kinematic range in energy and angles for $K^+\Lambda$ and $K^+\Sigma$, including recoil polarization
- Data indicate significant resonance contributions, interfering with each other and with non-resonant amplitudes.
- Extraction of resonance Parameters requires a large effort in partial wave analysis and reaction theory.

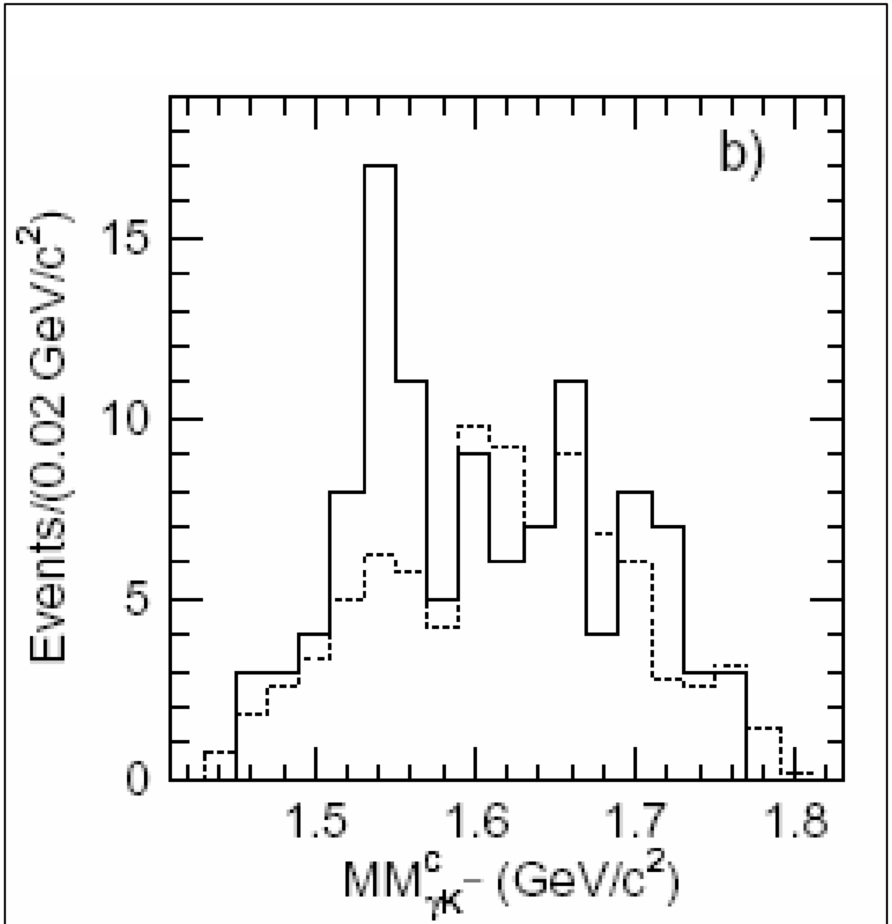
and in ω Production

- Old data only showed forward angle peaking (Regge)
- PDG lists no N*→ ωp decays
- Strong signal with e, γ beam
- Vector particle provides interesting observables with polarized beam/target
- Calculations from Y. Oh- 'good' representation of t-chan+res.
- Results preliminary- strong resonance contribution, but no single signature for a single state

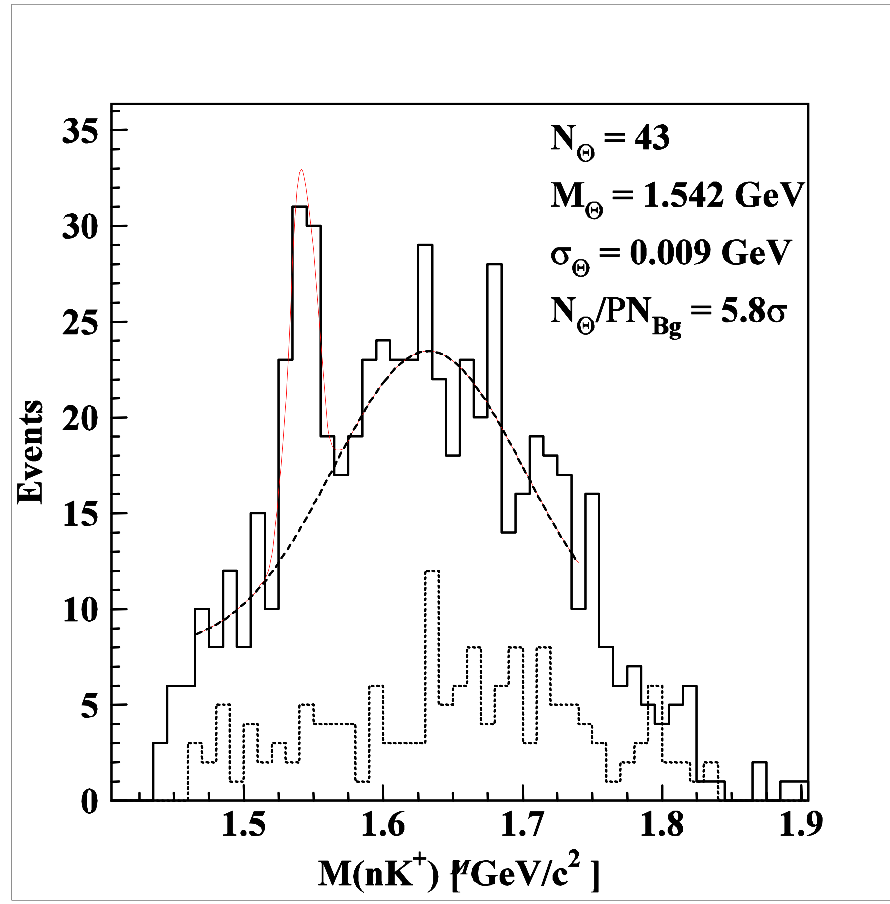


And there are NEW Mysteries: the "Pentaquark"

SPRING-8: $\gamma D \rightarrow K^{-}(K^{+}X)$ (p)

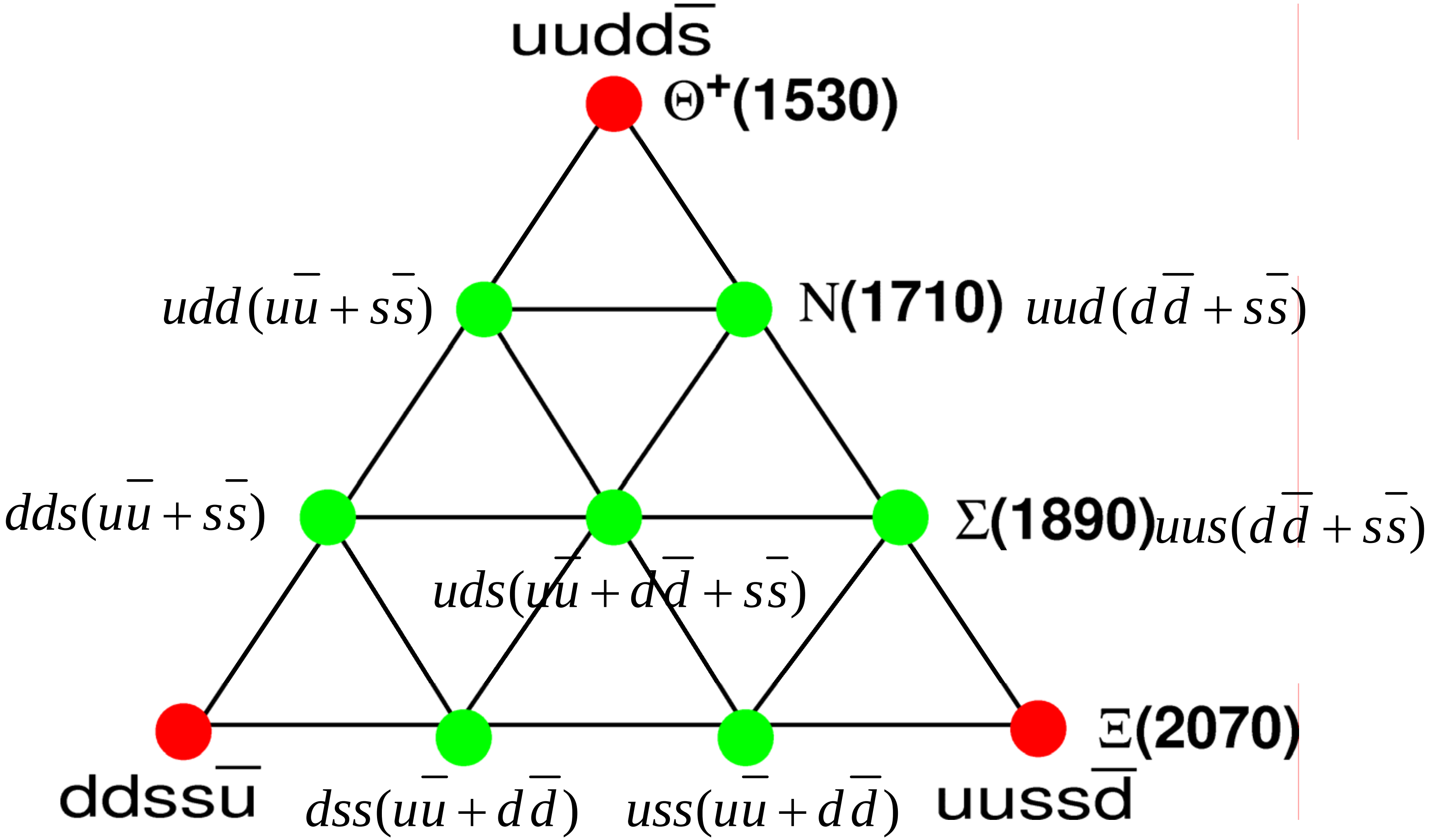


CLAS: $\gamma D \rightarrow K^{-}pK^{+}(n)$



Proposed by Diakonov *et al* in a Chiral Soliton Model

D. Diakonov, V. Petrov, M. Polyakov, Z.Phys.A359, 305 (1997)

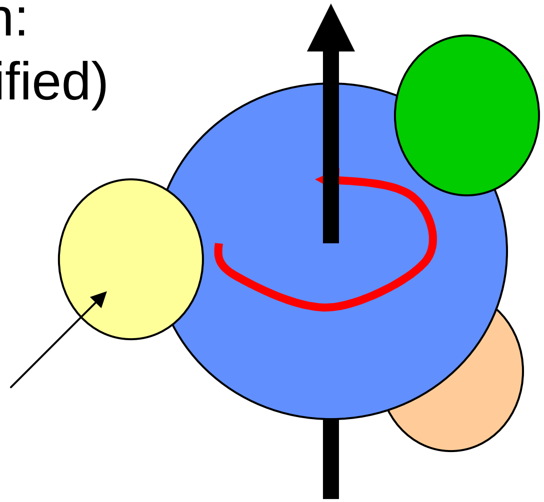


Pentaquarks – two model descriptions

Chiral soliton model: (Diakonov, Petrov, Polyakov)

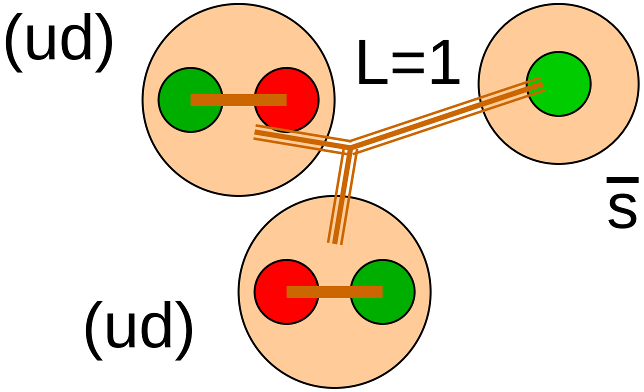
Pentaquark comes out naturally from these models as they represent rotational excitations of the soliton [rigid core (q^3) surrounded by meson fields ($\bar{q}q$)]

Soliton:
(simplified)



Meson
fields

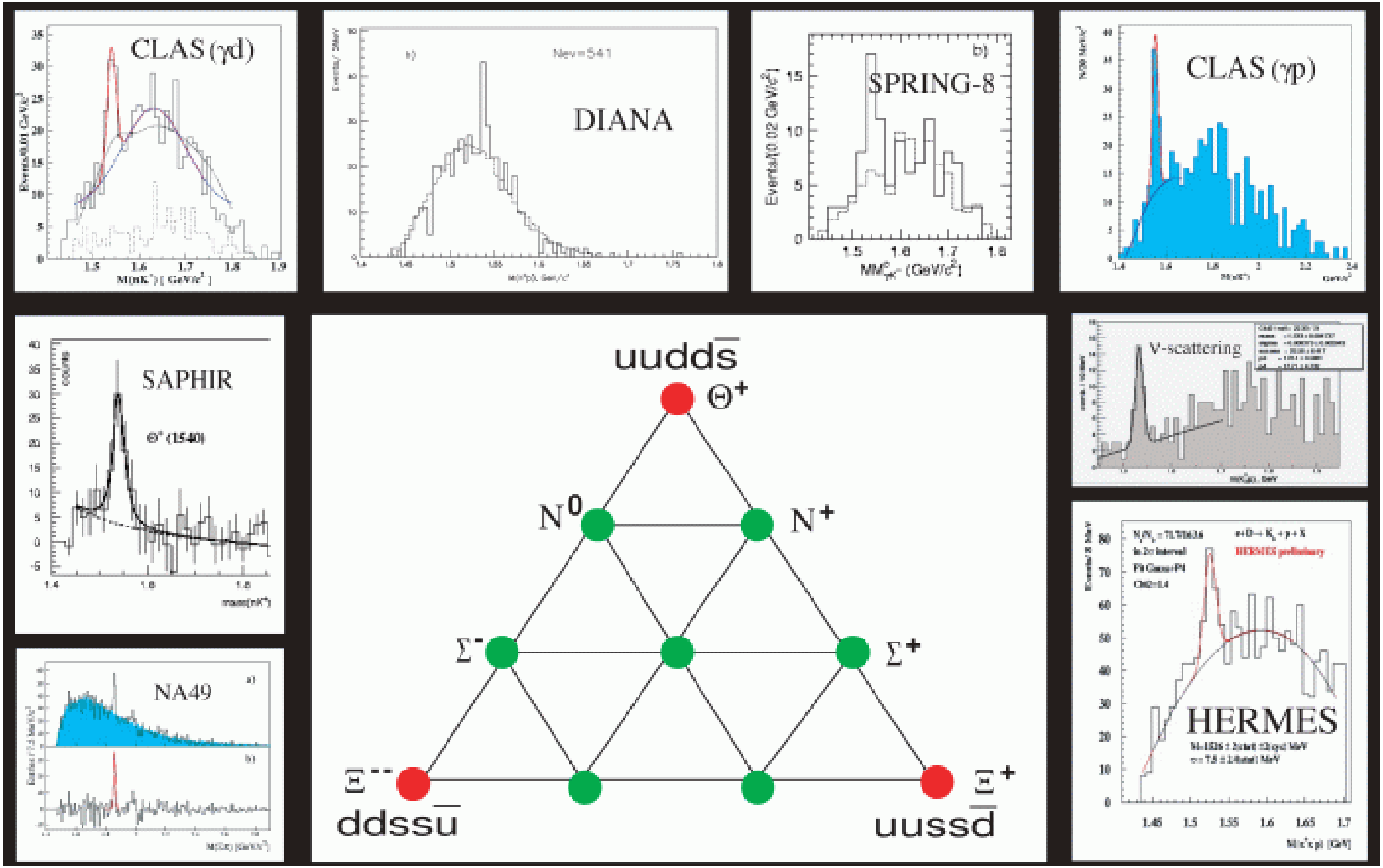
Quark description (Jaffe, Wilczek)



L=1, one unit of orbital angular momentum needed to get $J=½^+$ as in χSM

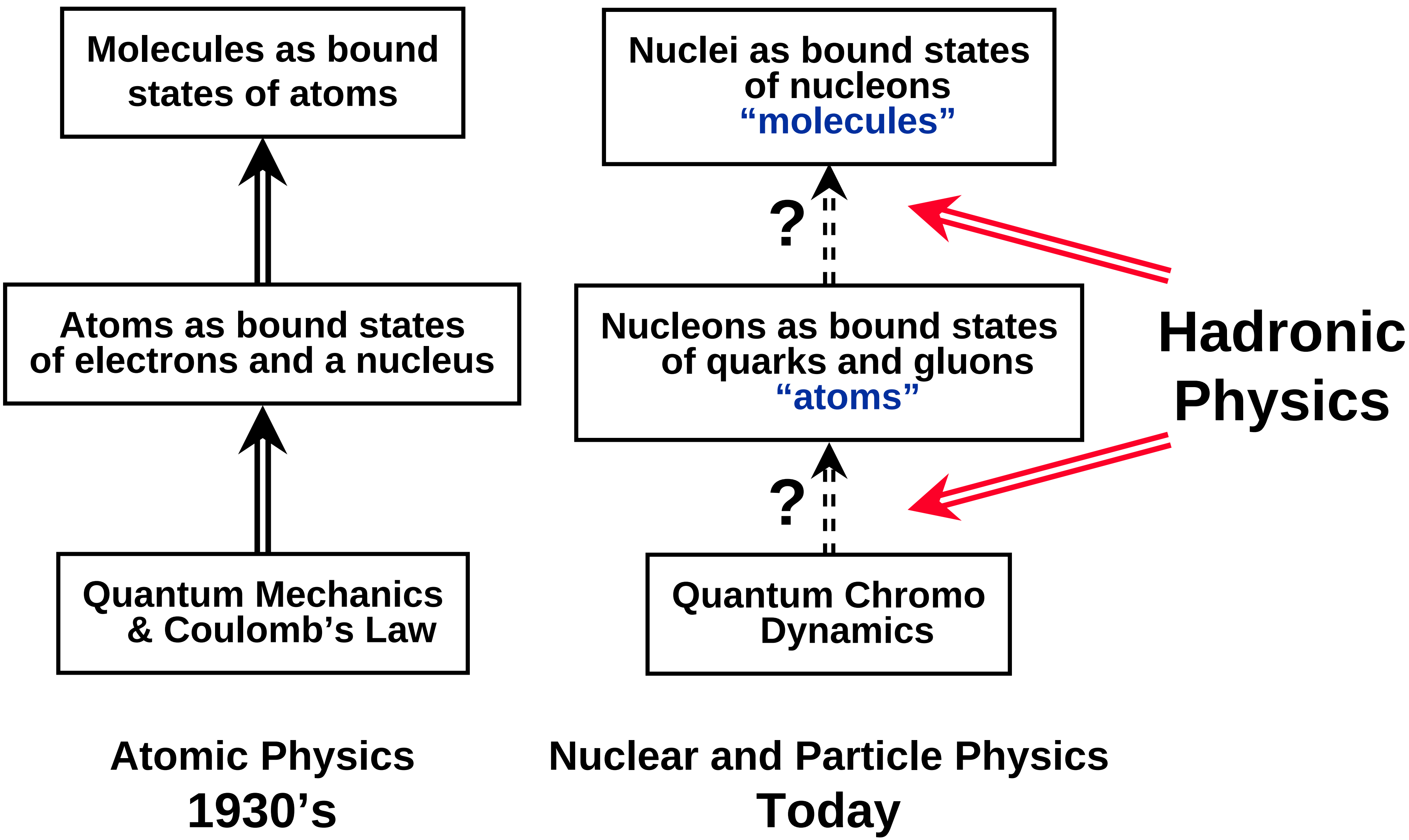
Lattice QCD $\Rightarrow J^\pi = 1/2^-$

Tantalizing Evidence from Many Laboratories



Planned Experiments Should Resolve the Issues Definitively

Atomic Physics versus Quark Physics



5. At What Distance and Energy Scale Does the Underlying Quark and Gluon Structure of Nuclear Matter Become Evident?

We begin with 'ab initio' ("exact") Calculations of the structure of few body nuclei, in which we assume:

- Nucleus has A nucleons interacting via force described by V_{NN}
- V_{NN} fit to N-N phase shifts
- Exchange currents and leading relativistic corrections in V_{NN} and nucleus

We test these calculations via electromagnetic interaction studies of few-body systems where precise, directly interpretable experiments can be compared with exact calculations

The goal is to determine the limits of the meson-nucleon description and to infer where a QCD-based description becomes substantially more straightforward

Push precision, λ to identify limits and answer the question

Deuteron:

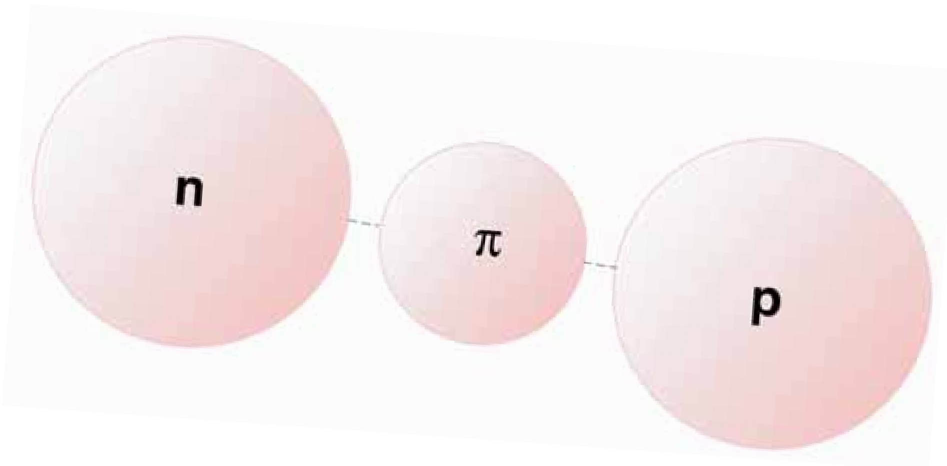
A, B, t_{20} form factors

photodisintegration (Halls C and A, and now CLAS)

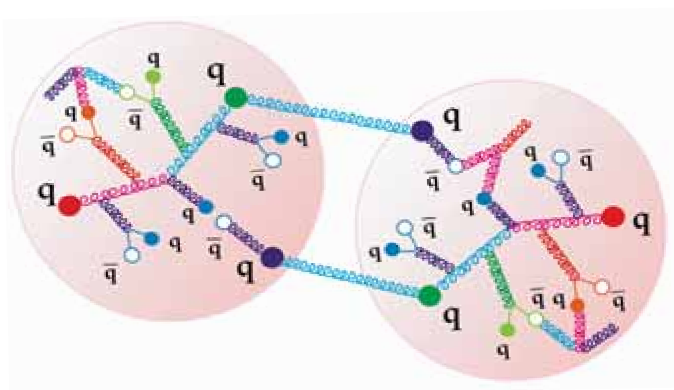
Induced polarization in photodisintegration

^3He form factors to high Q^2

Two Views of Deuteron Structure

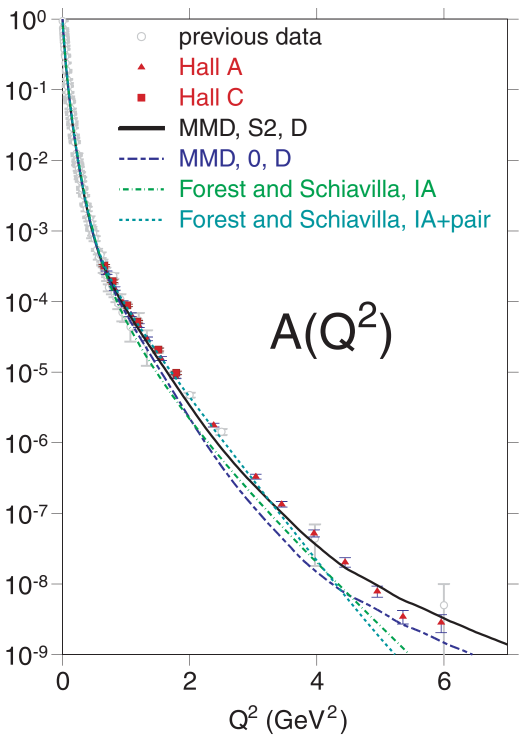


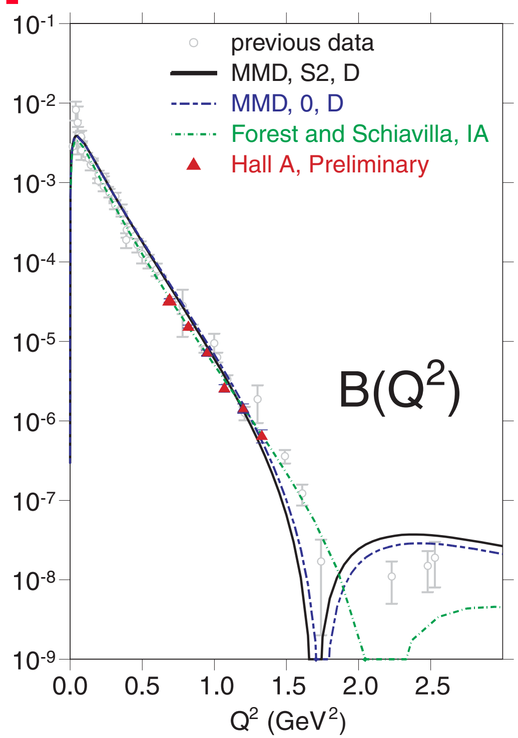
Two Nucleons interacting via the (pion-mediated) NN force



Two multi-quark systems interacting via the residue of the (gluon-mediated) QCD color force

JLab Data Reveals the Size and Shape of the Deuteron





For elastic e-d scattering:

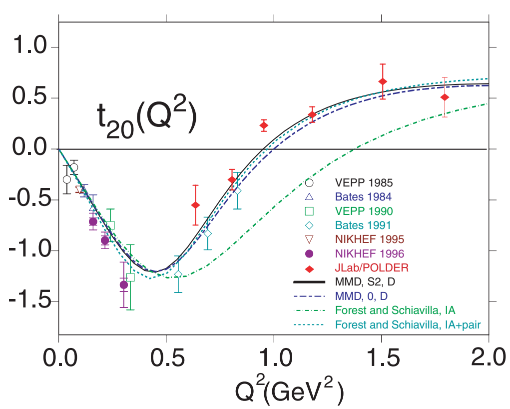
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \tfrac{\theta}{2}\right]$$

$$A(Q^2) = G_C^2 + \tfrac{8}{9}\tau^2 G_Q^2 + \tfrac{2}{3}\tau G$$

$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)G_M^2$$

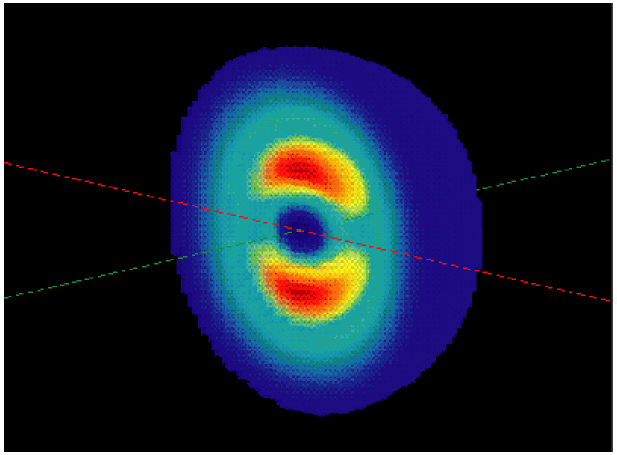
- 3rd observable needed to separate G_C and G_Q

→ *tensor polarization t_{20}*



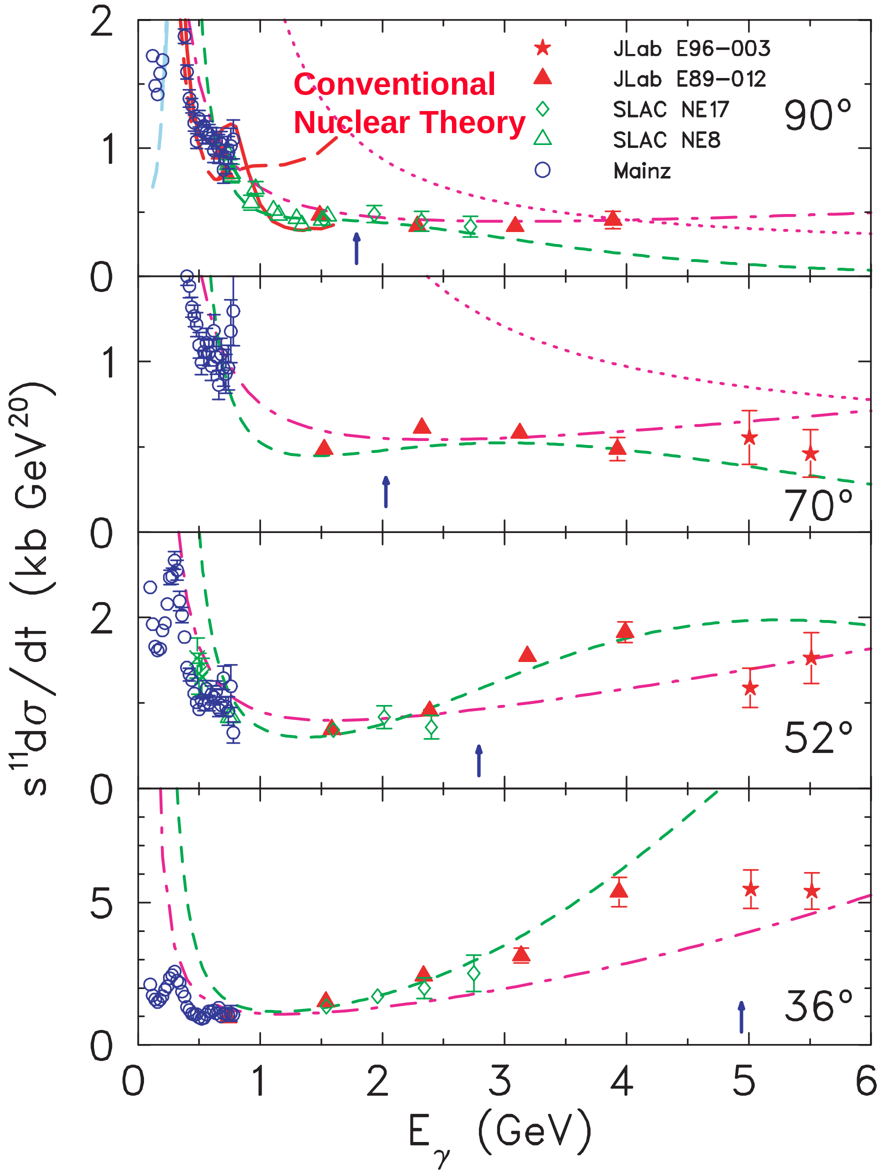
Combined Data ⟹

Deuteron's Intrinsic Shape



The nucleon-based description works to <0.5 fm

JLab d(γ,p) Data Identified the Transition to the Quark-Gluon Description

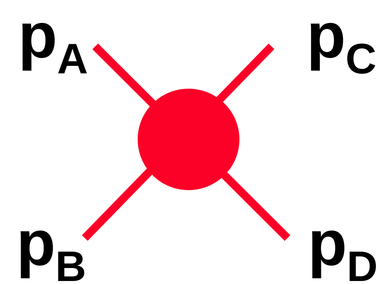


Deuteron Photodisintegration probes momenta well beyond those accessible in (e,e')
(at 90°, E_γ=1 GeV ⇔ Q^2= 4 GeV^2/c^2)

Conventional nuclear theory unable to reproduce the data above ~1 GeV

Scaling behavior ($d\sigma/dt \propto s^{-11}$) sets in at a consistent t = – 1.37 (GeV/c)^2 (see ↑)

⇒ seeing underlying quark-gluon description for scales below ~0.1 fm



$$d\sigma/dt \sim f(\theta_{cm})/s^{n-2}$$

Where $n = n_A + n_B + n_C + n_D$

$s = (p_A + p_B)^2$, $t = (p_A - p_C)^2$

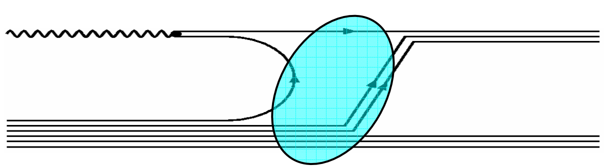
$\gamma d \rightarrow pn \quad \Leftrightarrow \quad n = 13$

Exploring the Transition Region: CLAS g2

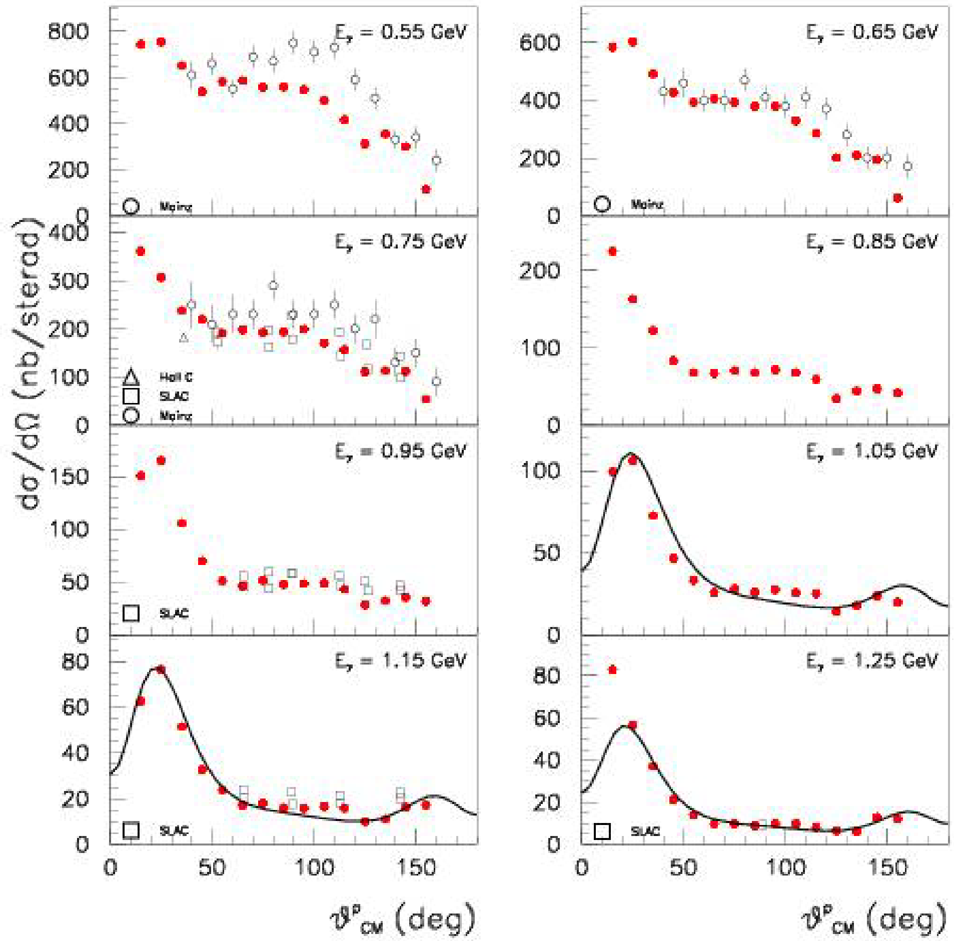
Quark Gluon String Model

- A microscopic theory for the Regge phenomenology.
- Non perturbative approach (V.Grishina et al Eur. Phys. Jour.A. 10 (2001), 355)

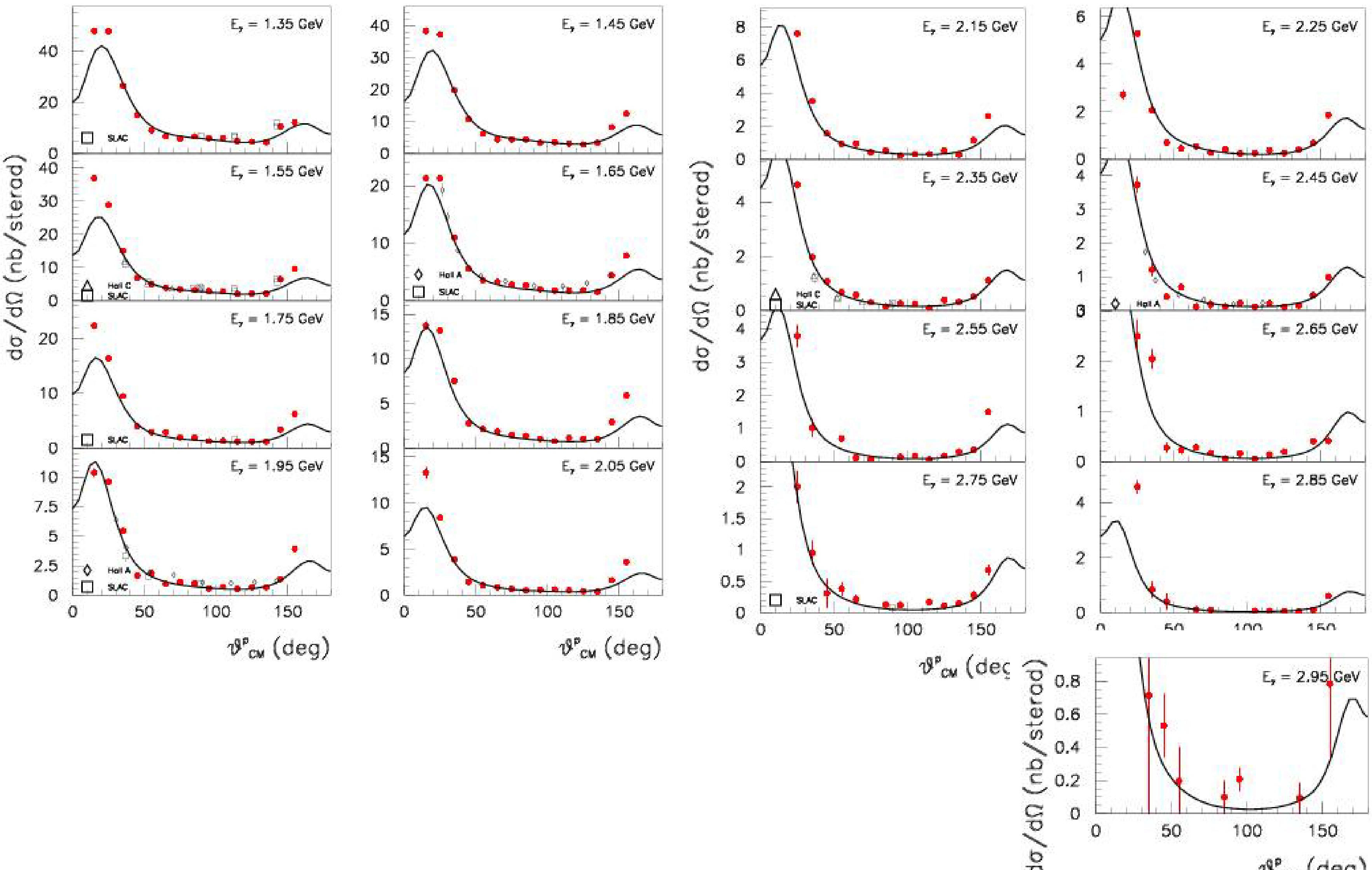
- Production in the intermediate states of a color string leading to factorization of amplitudes



- *t* channel : quark-gluon string (3 valence q + g's)

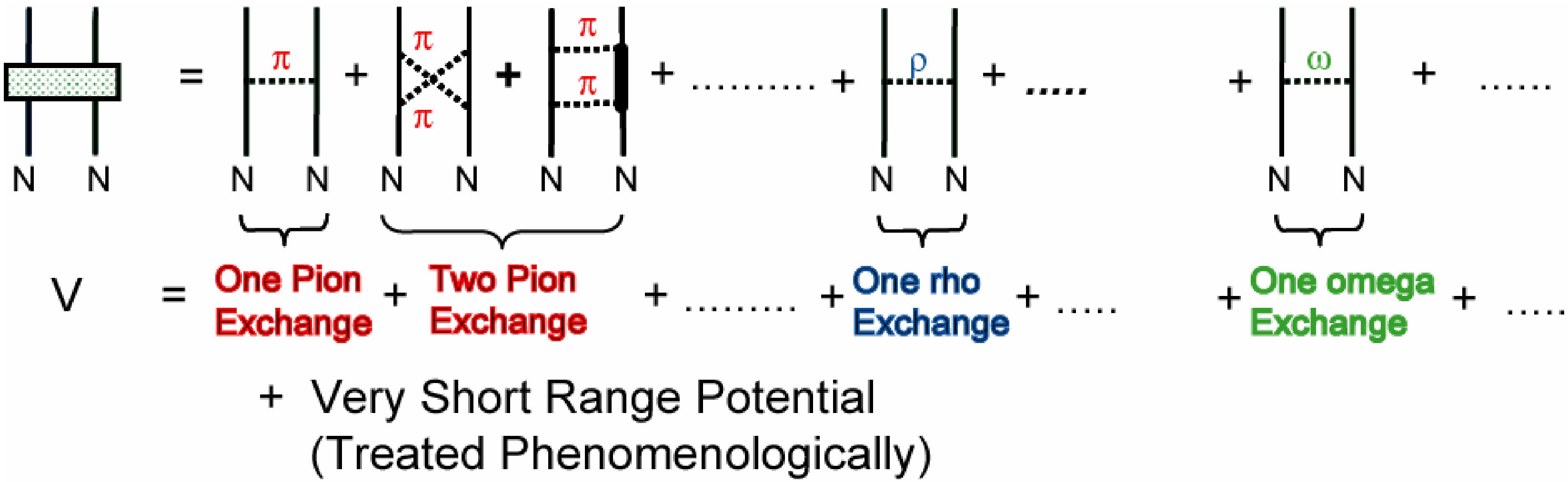


Exploring the Transition Region: CLAS g2 (cont.)

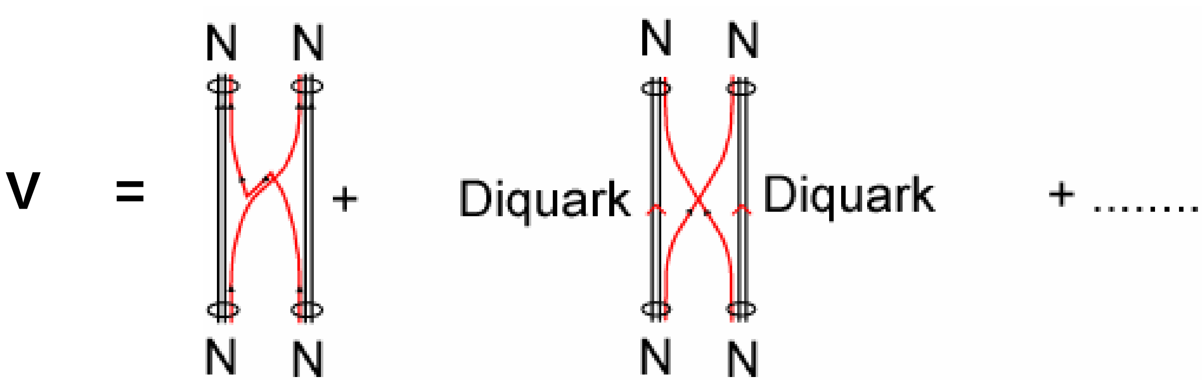


Understanding the *N-N* Force

In terms of mesons and nucleons:

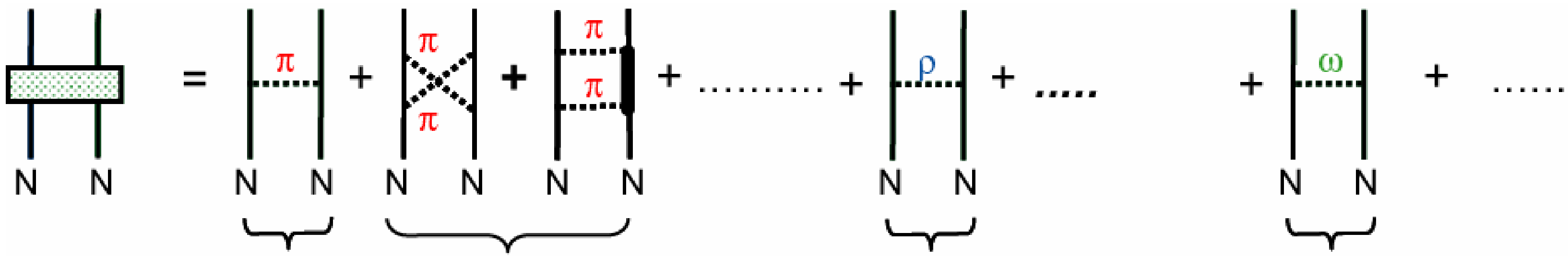


Or in terms of quarks and gluons:



Hypernuclei Provide Essential Clues

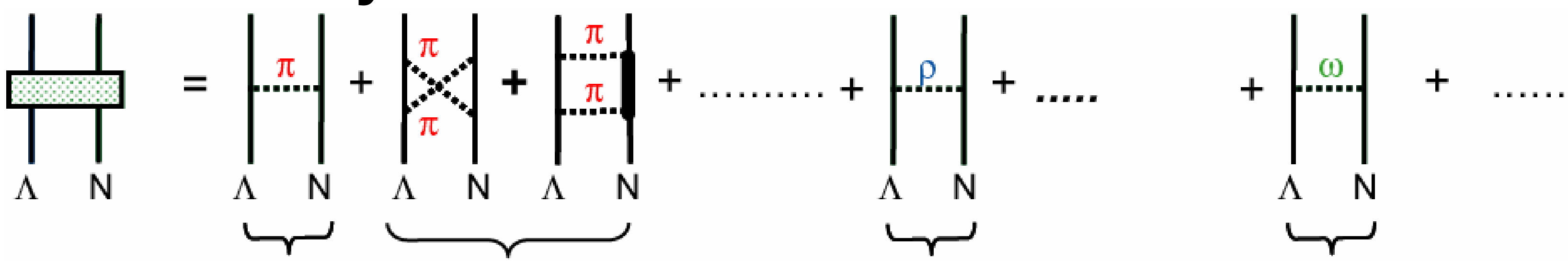
For the N-N System:



V = One Pion Exchange + Two Pion Exchange + ... + One rho Exchange + ... + One omega Exchange + ...

+ Very Short Range Potential
(Treated Phenomenologically)

For the Λ-N System:



V = One Pion Exchange + Two Pion Exchange + ... + One rho Exchange + ... + One omega Exchange + ...

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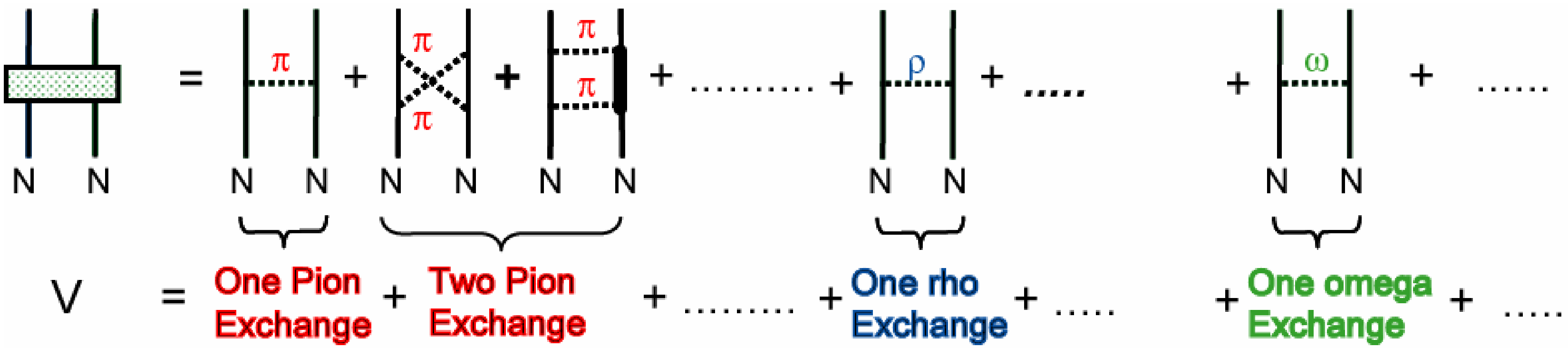
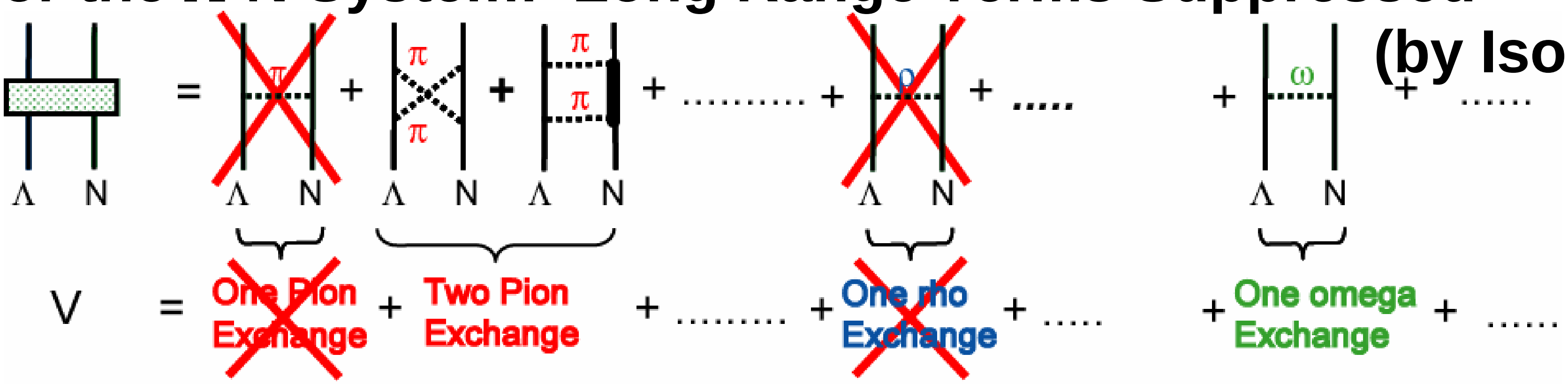
Hypernuclei Provide Essential Clues

For the N-N System:



\+ Very Short Range Potential
(Treated Phenomenologically)

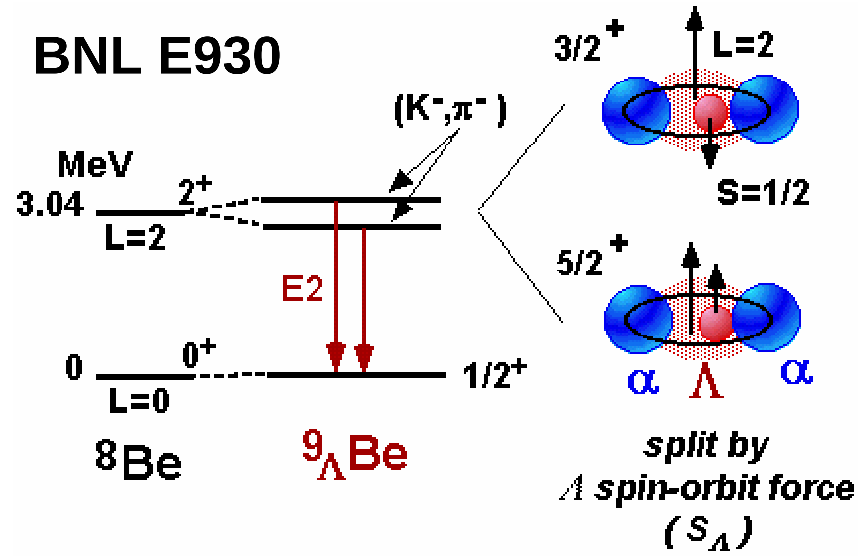
For the Λ-N System: Long Range Terms Suppressed (by Isospin)

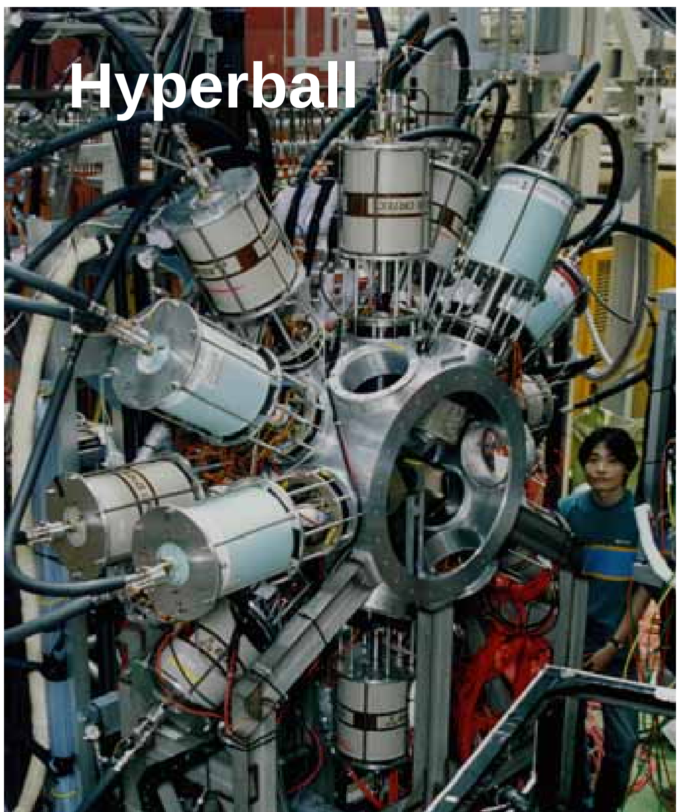


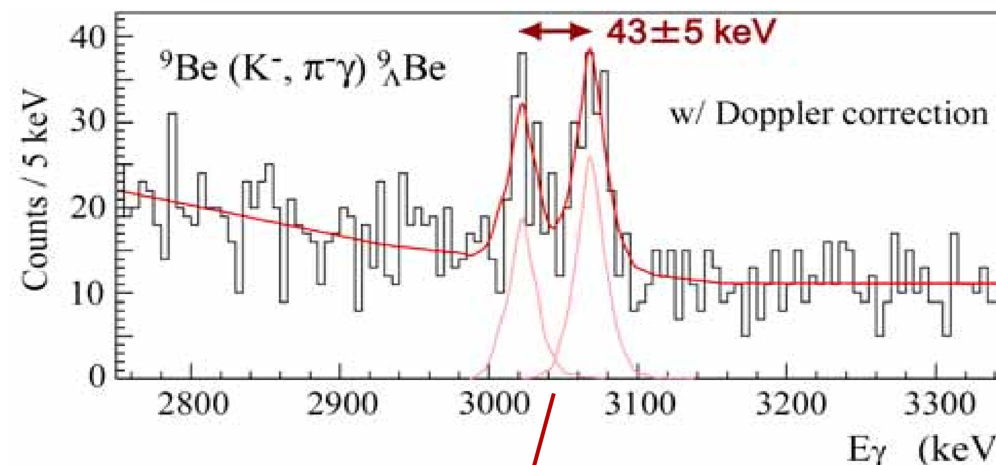
\+ Very Short Range Potential
(Treated Phenomenologically)

ΛN Spin-Orbit Force from γ Rays of Λ Hypernuclei

Akikawa et al., PRL 88 (2002) 082501

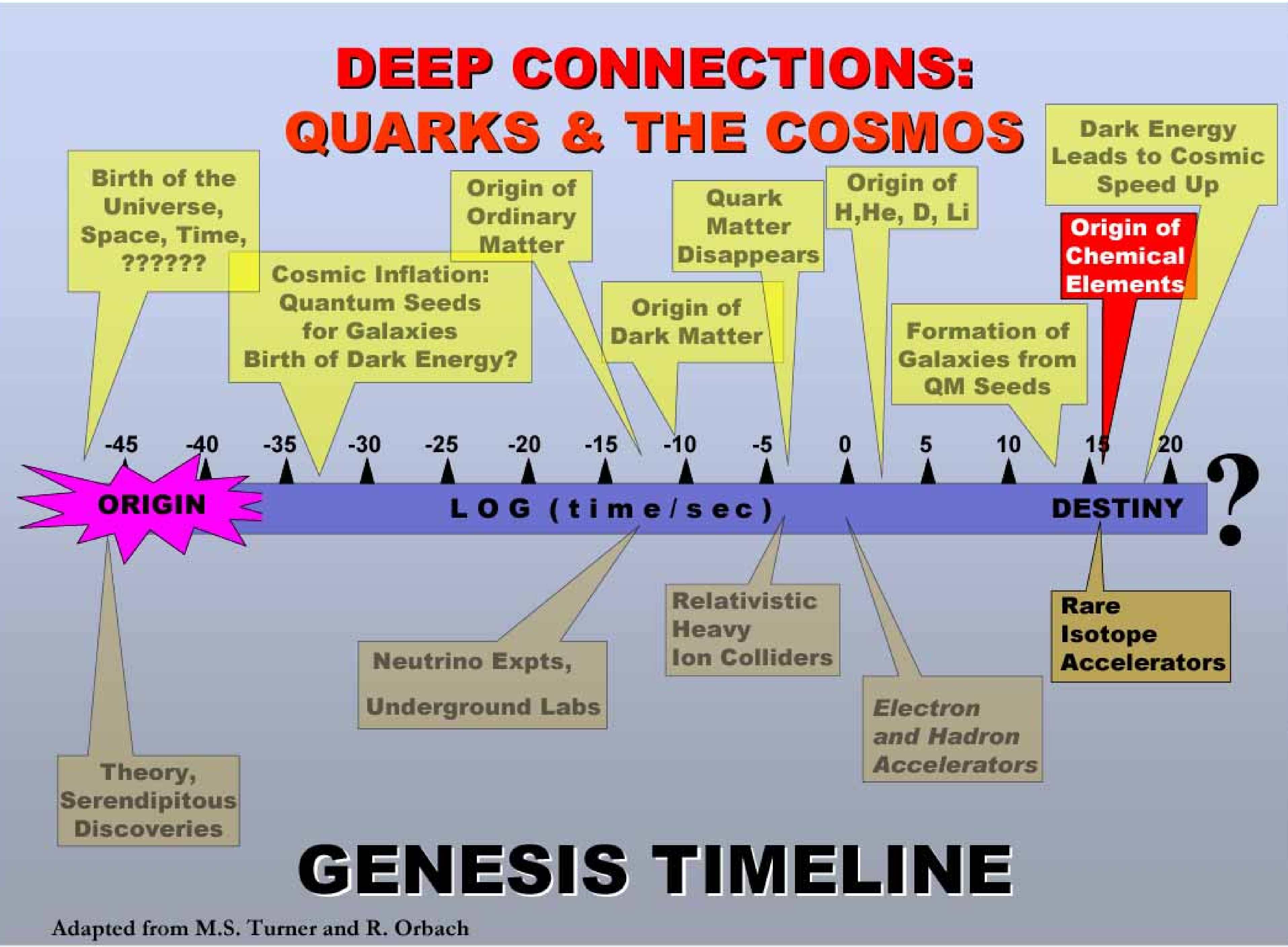




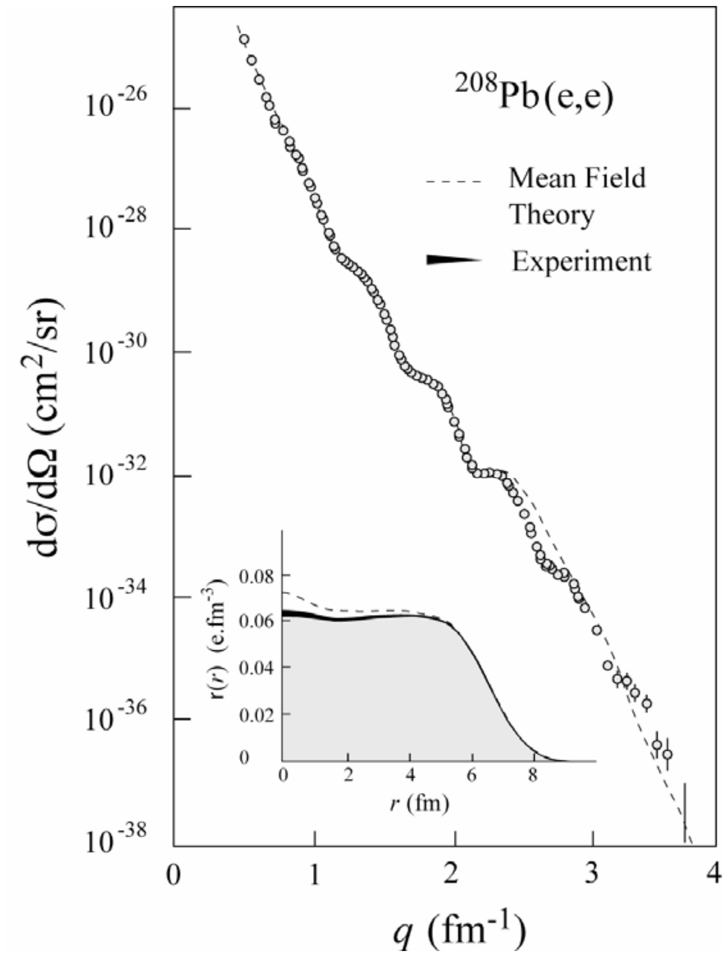


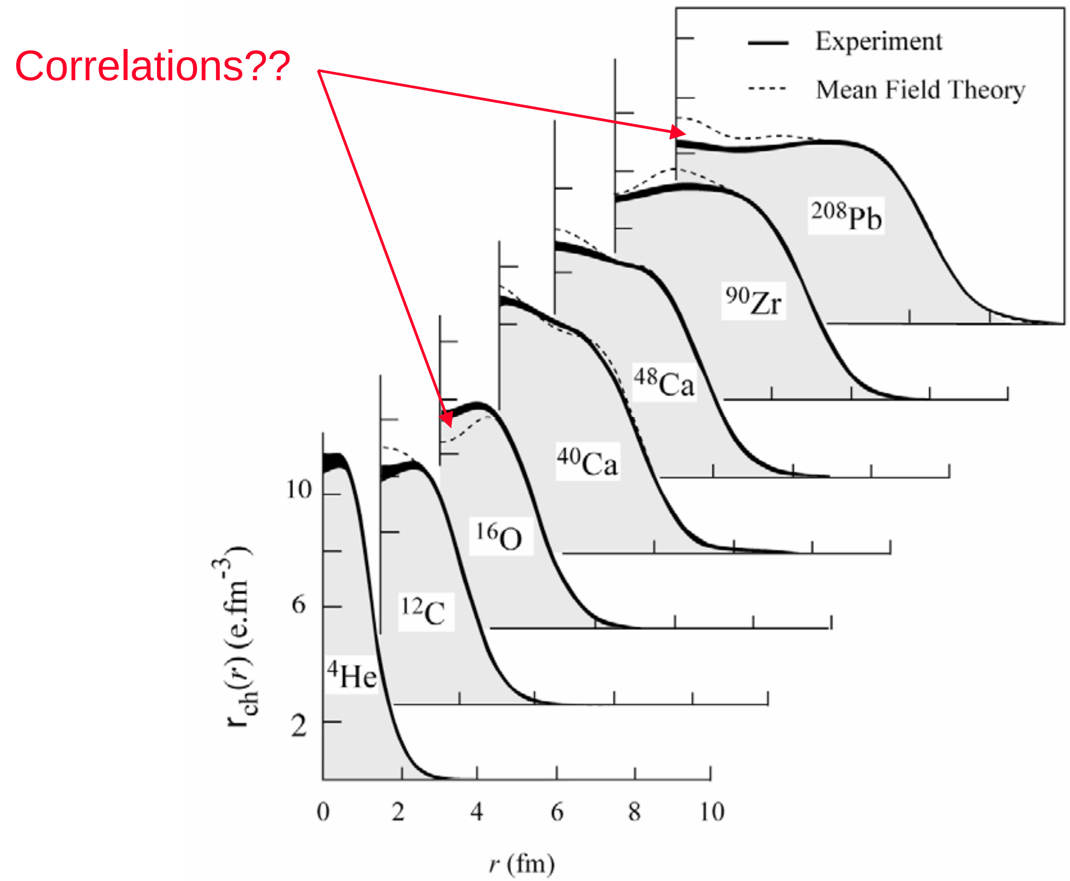
Spin-orbit forces		*exp.*	*meson*	*quark*
$[\, l_{\Lambda N}\, s_{\Lambda}\,]$	S_{Λ}	-0.01	-0.15	0.0
$[\, l_{\Lambda N}\, s_{N}\,]$	S_{N}	-0.45	-0.25	-0.4 (MeV)

Quark picture explains spin-orbit force well.


DEEP CONNECTIONS:
QUARKS & THE COSMOS
Birth of the Universe, Space, Time, ??????
Cosmic Inflation: Quantum Seeds for Galaxies Birth of Dark Energy?
Origin of Ordinary Matter
Origin of Dark Matter
Quark Matter Disappears
Origin of H,He, D, Li
Formation of Galaxies from QM Seeds
Origin of Chemical Elements
Dark Energy Leads to Cosmic Speed Up
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
ORIGIN
L O G (t i m e / s e c)
DESTINY
?
Theory, Serendipitous Discoveries
Neutrino Expts,
Underground Labs
Relativistic Heavy Ion Colliders
Electron and Hadron Accelerators
Rare Isotope Accelerators
GENESIS TIMELINE
Adapted from M.S. Turner and R. Orbach

(e,e) ⇒ Nuclear Charge Distributions



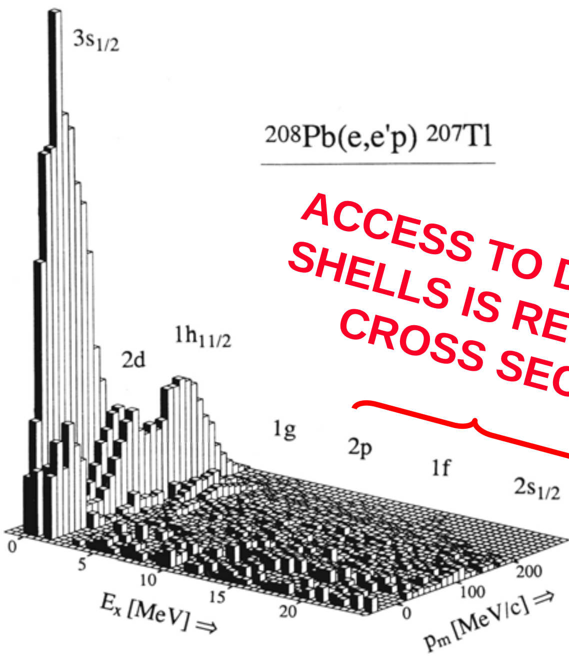


In ‘70s large data set was acquired on elastic electron scattering (mainly at Saclay) over large Q^2-range and for variety of nuclei

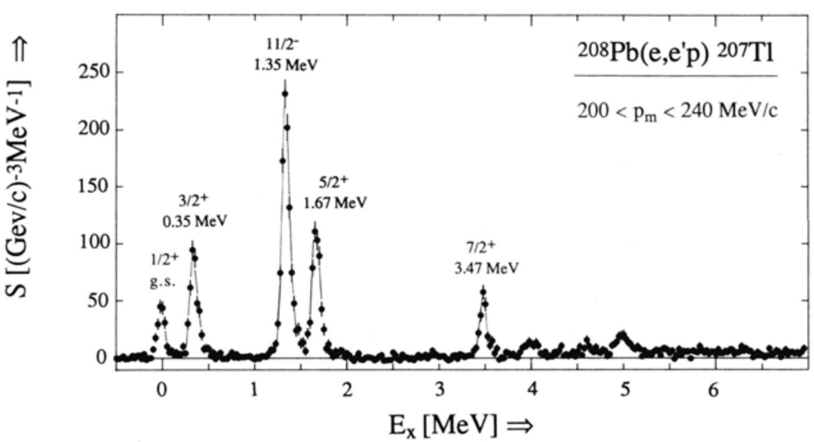
“Model-independent” analysis of these data provided accurate results on charge distribution for comparison with the best available theory: Mean-Field Density-Dependent Hartree-Fock

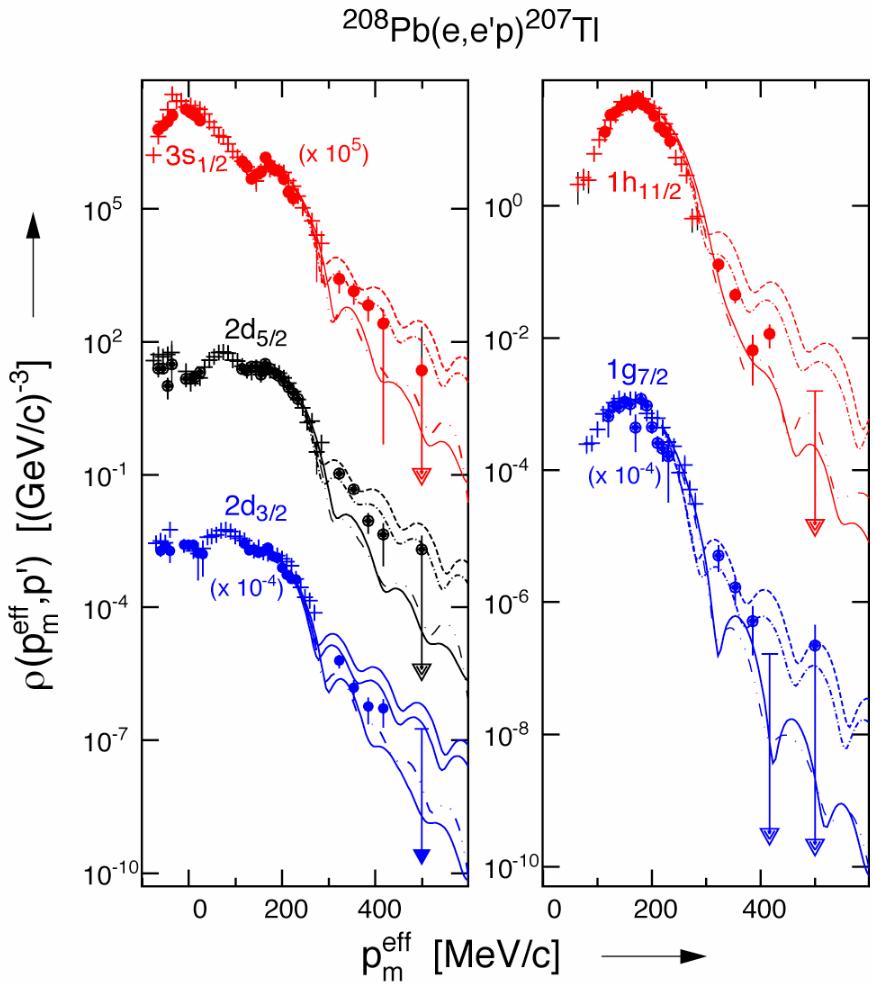
(e,e'p) ⇒ Nucleon Momentum Distributions, Shell-by-Shell

$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$



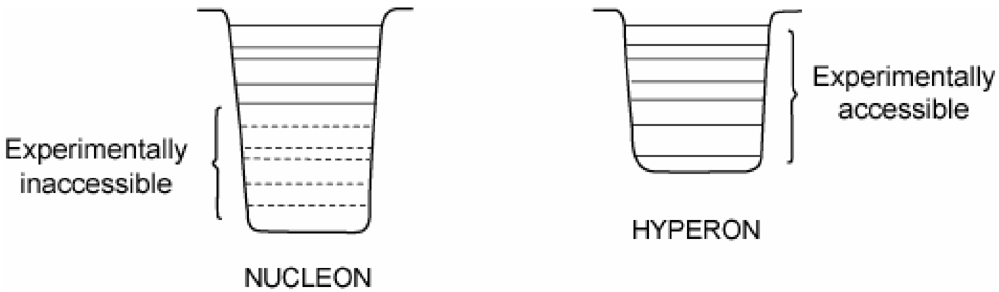
ACCESS TO DEEPLY LYING SHELLS IS RESTRICTED BY CROSS SECTION, FSI





“Impurities” Solve the Problem:

The distinguishability of the hyperon permits us to probe deeply-bound shells in nuclei



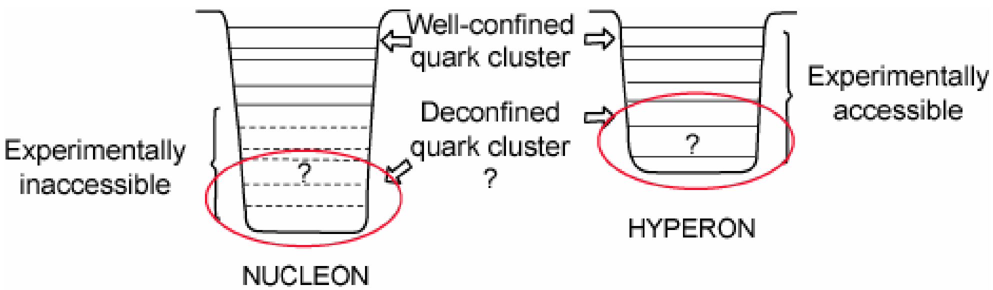
Possible single-particle orbitals for nucleons and for a hyperon. The nucleon orbitals are occupied up to the Fermi surface, while the hyperon orbitals are unoccupied.

T. Yamazaki

Access deeply bound nuclear states

“Impurities” Solve the Problem:

The distinguishability of the hyperon permits us to probe deeply-bound shells in nuclei



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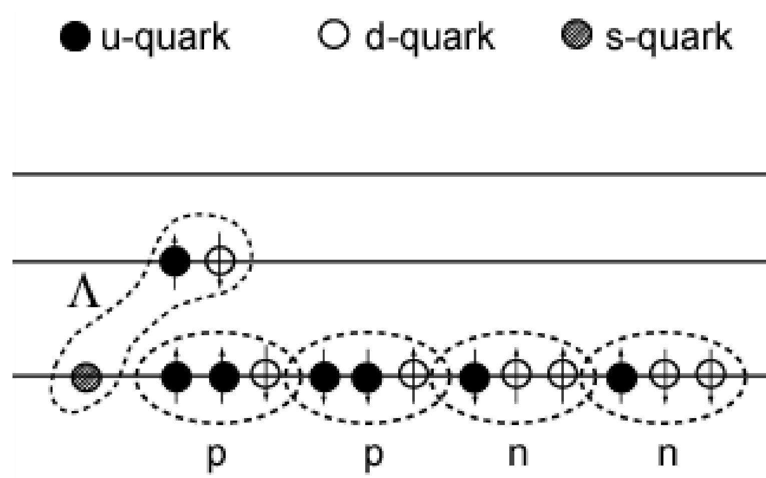
T. Yamazaki

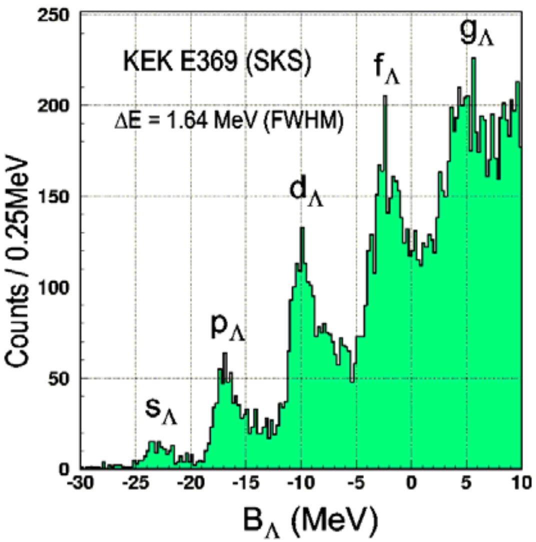


Access deeply bound nuclear states

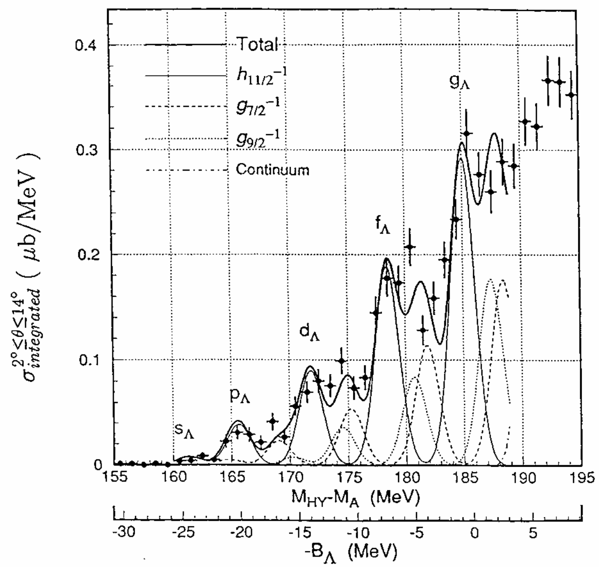
and provide the opportunity to probe the quark structure of nuclear systems in new and different ways.

Λ Single Particle Potential

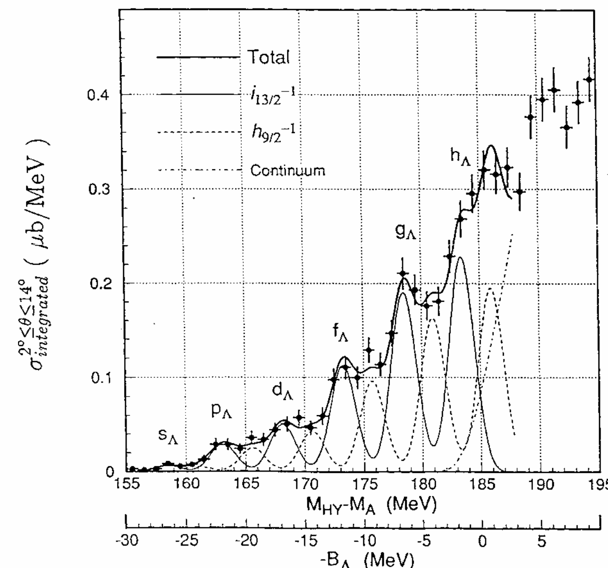
$^{89}Y(\pi^+,K^+)^{89}{}_{\Lambda}Y$



$^{139}La(\pi^+,K^+)^{139}{}_{\Lambda}La$



$^{208}Pb(\pi^+,K^+)^{208}{}_{\Lambda}Pb$



Hotchi et al., PRC 64 (2001) 044302

KEK E140a

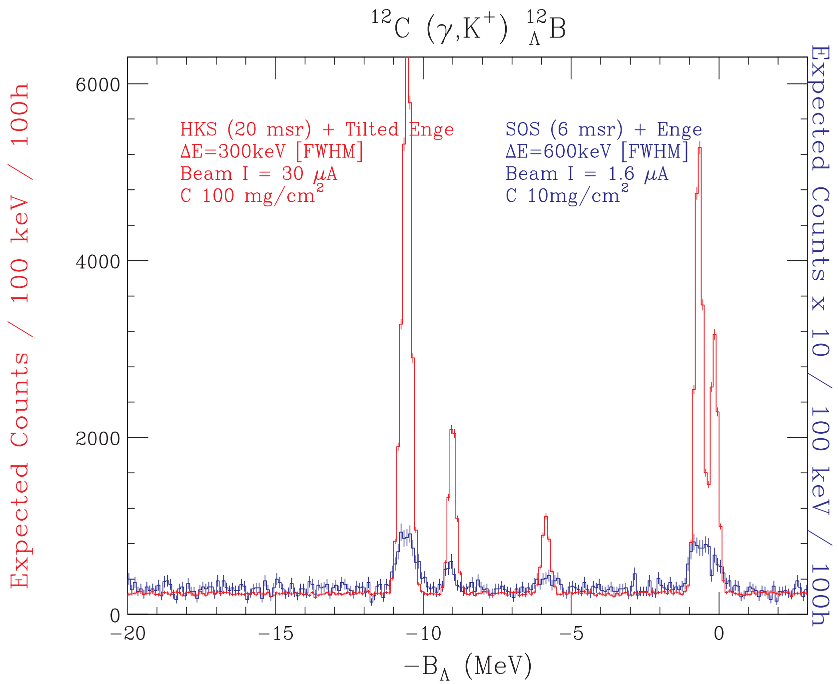
Hasegawa et. al., PRC 53 (1996)1210

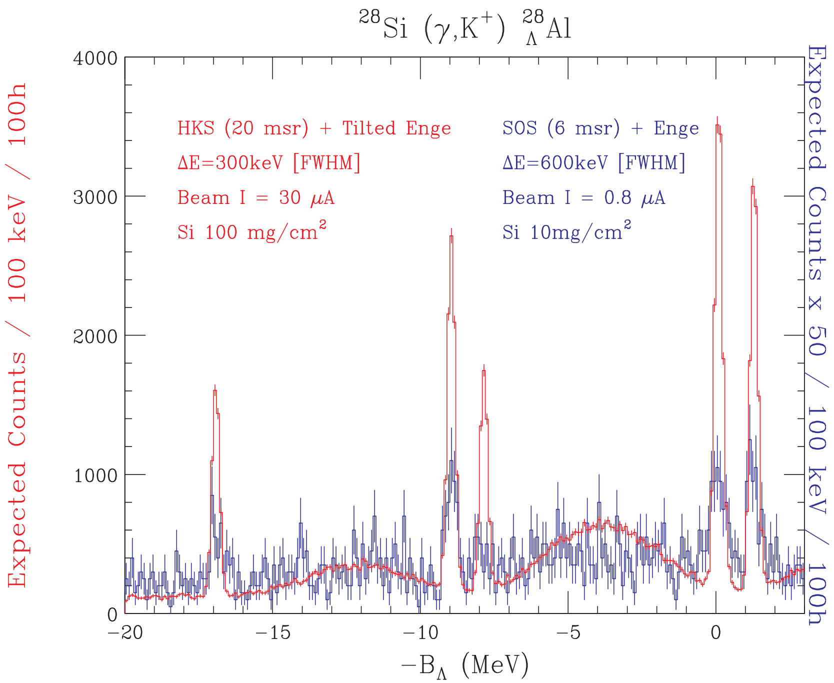
Textbook example of Single-particle orbits in a nucleus

Λ Single particle states
⇒ Λ-nuclear potential depth = - 30 MeV
⇒ $V_{\Lambda N} < V_{NN}$

Anticipated Hypernuclear Spectra

(New JLab Facility developed by O. Hashimoto et al)

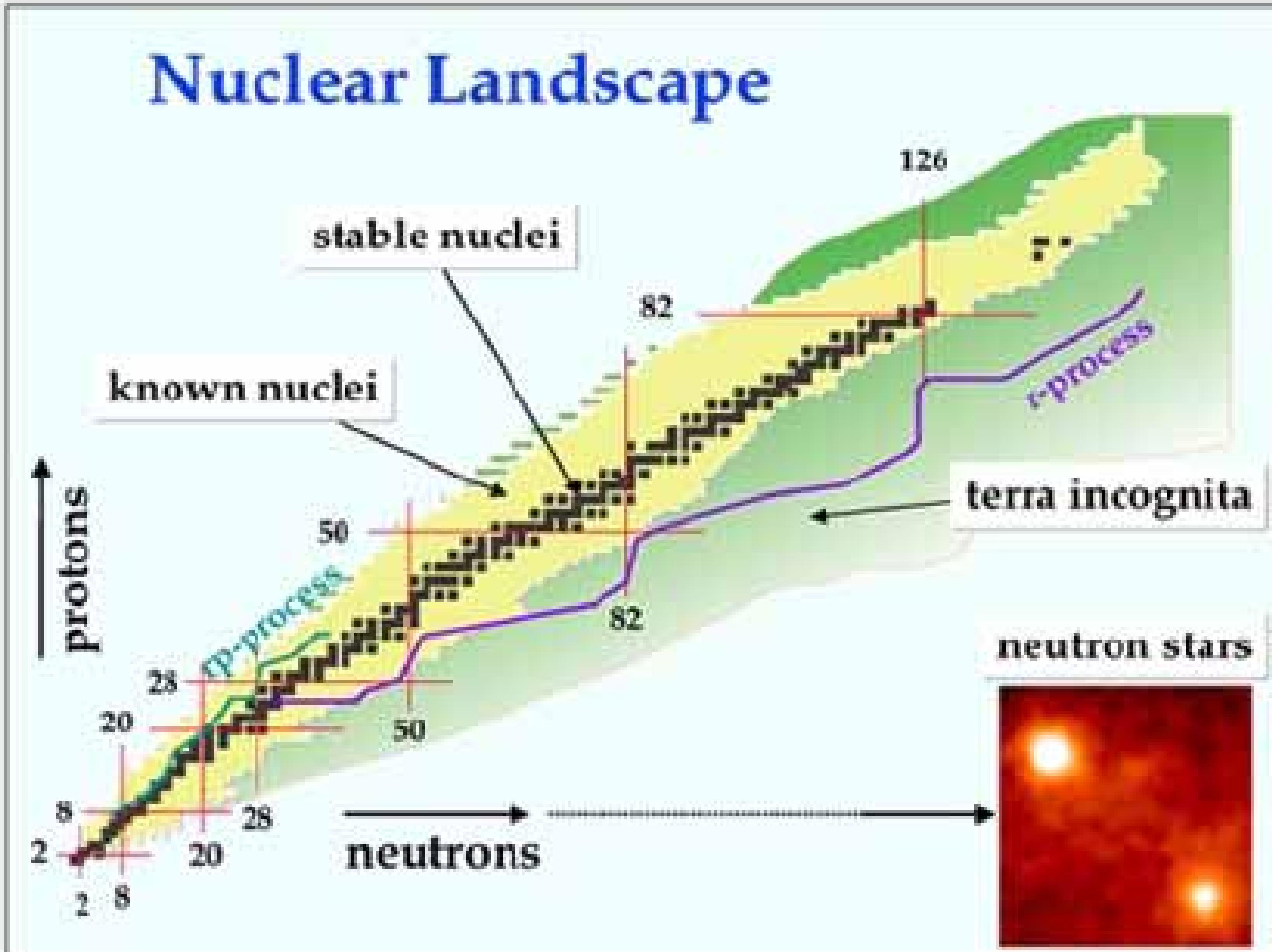




- Complements Hyperball for states that don't γ decay
- Complements π production with respect to spin, parity, and momentum transfer

With these new tools, the next generation of hypernuclear studies is now underway, with great promise for the future

New Facilities Providing Intense Beams of Rare (Radioactive) Isotopes will Greatly Expand our Understanding of Nuclei and Nucleosynthesis



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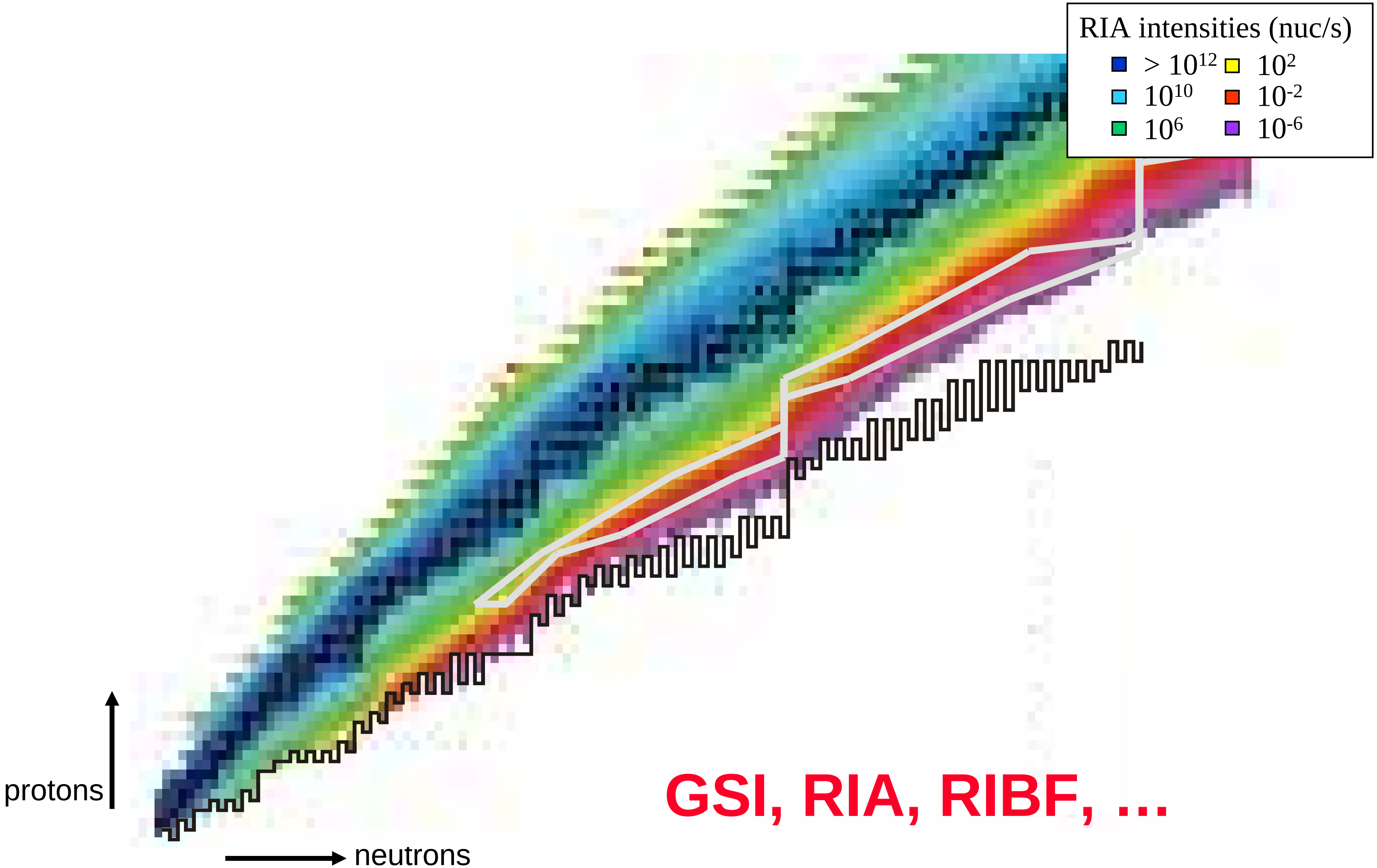
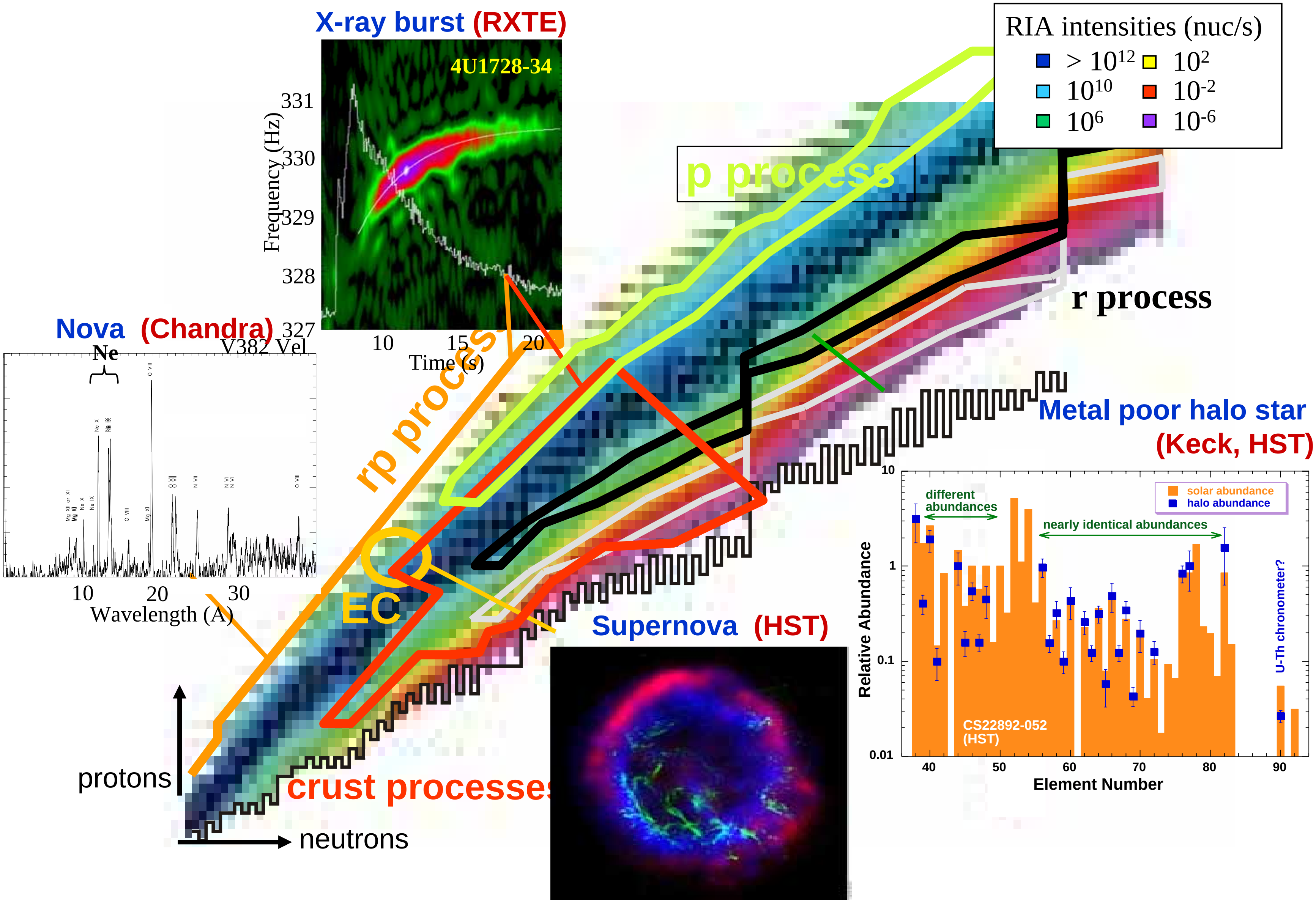
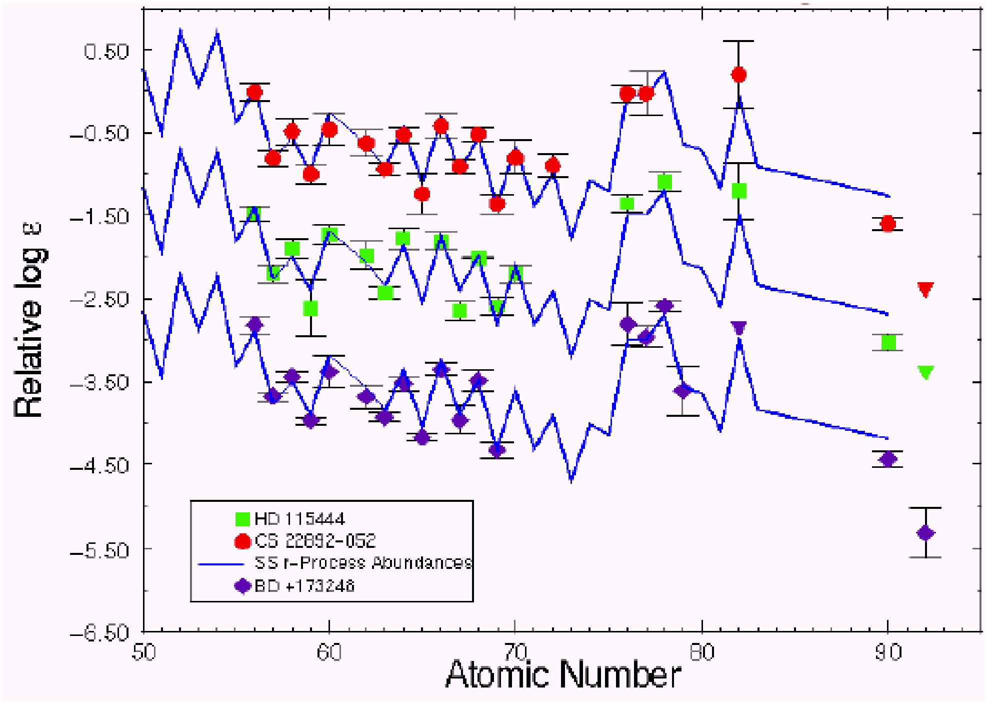


GSI, RIA, RIBF, …

For Example: How Were the Nuclei Created?
The Nuclear Microphysics of the Universe



r-process in the Early Universe



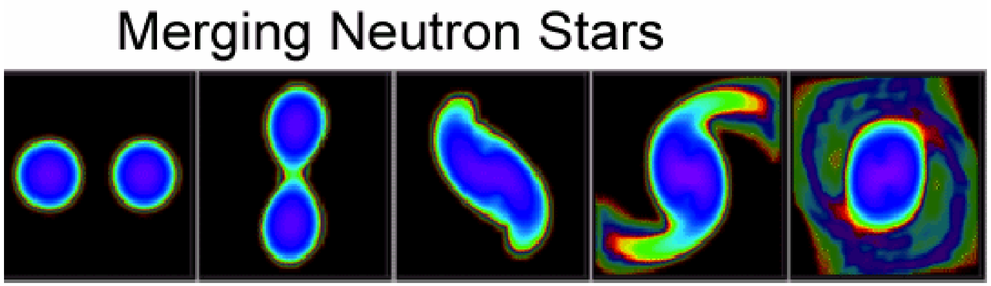
Three different stars born in early universe (measured by HST and Keck) match solar element distributions.

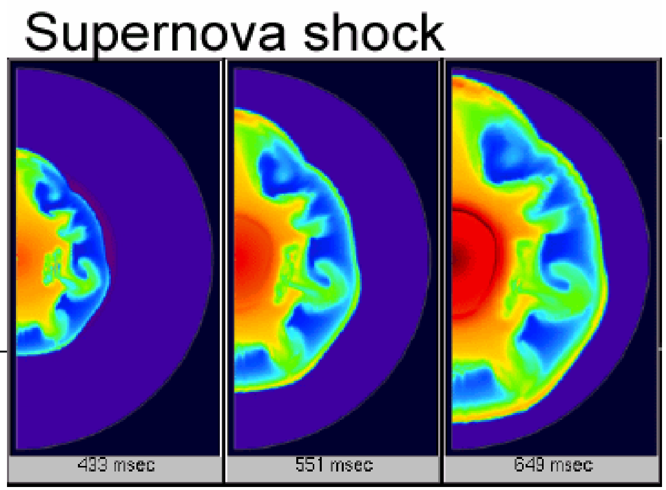
The identical pattern implies a unique source, fixed by nuclear structure and forces.

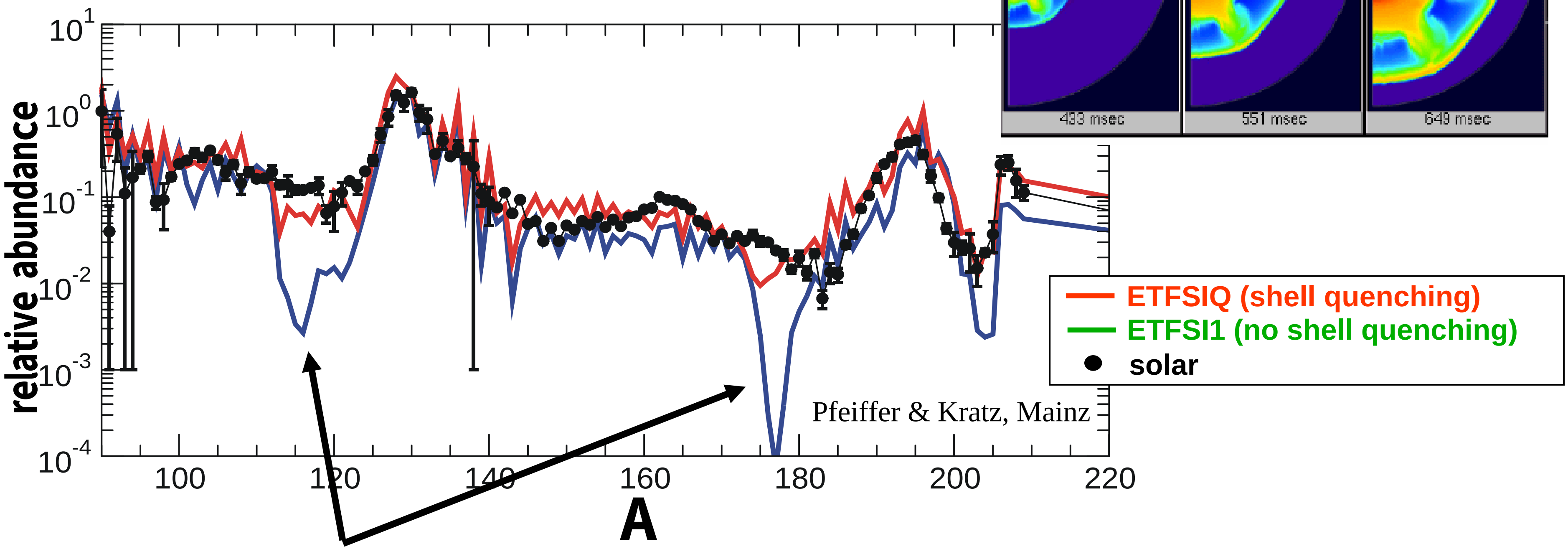
Rare Isotope Accelerator studies along r-process path will lead to its identification!

Rapid Neutron Capture Process (r-process)

How were the heavy elements from iron to uranium made? Two possibilities…



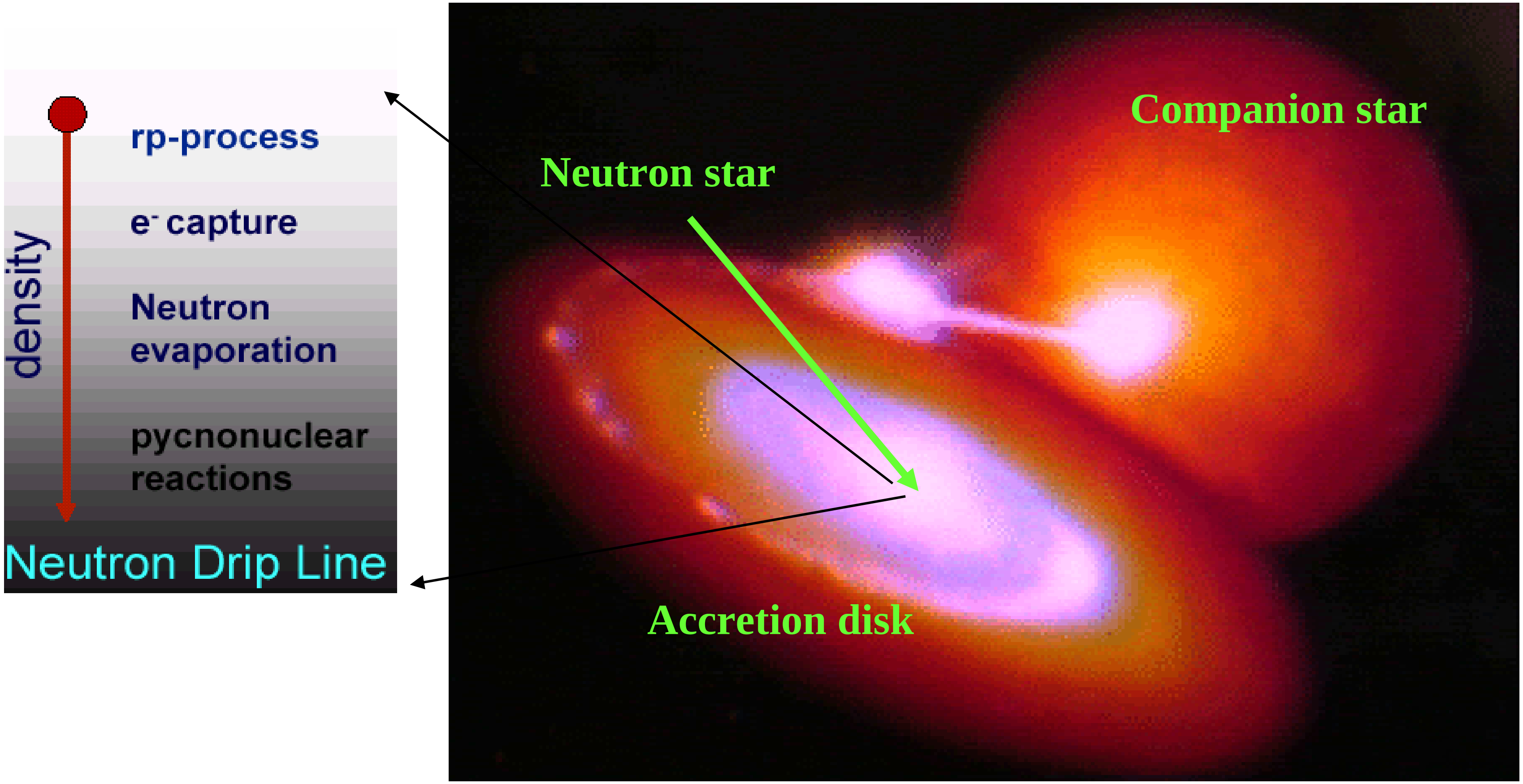




Question: Is this difference due to shell quenching for neutron-rich nuclei, or to a problem with the astrophysical model?

Rare Isotope Accelerators Provide a Laboratory for Neutron Star Science

X-ray bursts, super-bursts, and the fate of matter rp- process at extreme gravitational conditions



Summary

There Has Been Major Progress in Nuclear Physics, and There Are Fascinating Prospects for the Future:

- Deconfined Quark Matter in Relativistic Heavy Ion Collisions, with Surprises: (a liquid instead of a plasma?)
- Insights into the Physics of Hadrons and their Structure, with Fascinating Surprises, Are Emerging from Electron Facilities (we're still learning about the fundamental degrees of freedom!)
- Exciting Prospects in Traditional Nuclear Physics Research Provided by Evolving New Capabilities:
  - Strangeness "impurities"
  - Intense beams of rare ion species to extend our understanding of nuclear matter and the formation of the elements
- The Large Investments in New Facilities and Our Evolving Understanding of QCD as the Theoretical Underpinning for Strongly Interacting Matter Have Provided the Foundations for this Progress