Lattice QCD for Nuclear Physics (and maybe Nuclear Astro Physics)

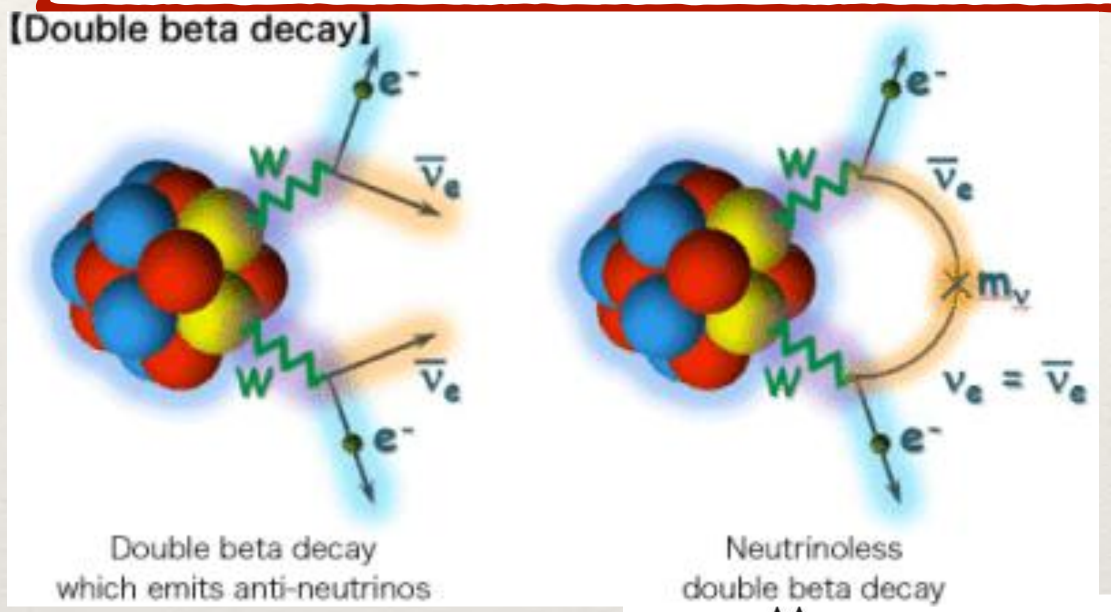
N3AS Seminar
26th July, 2022

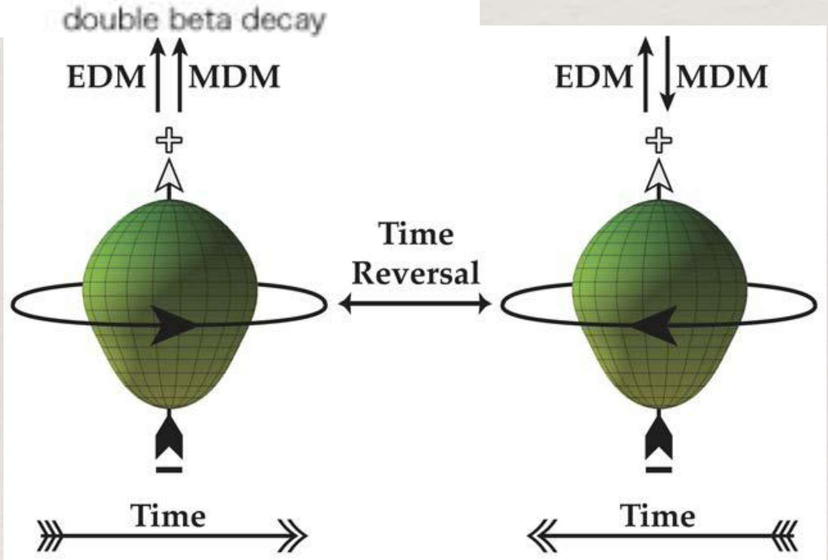
André Walker-Loud

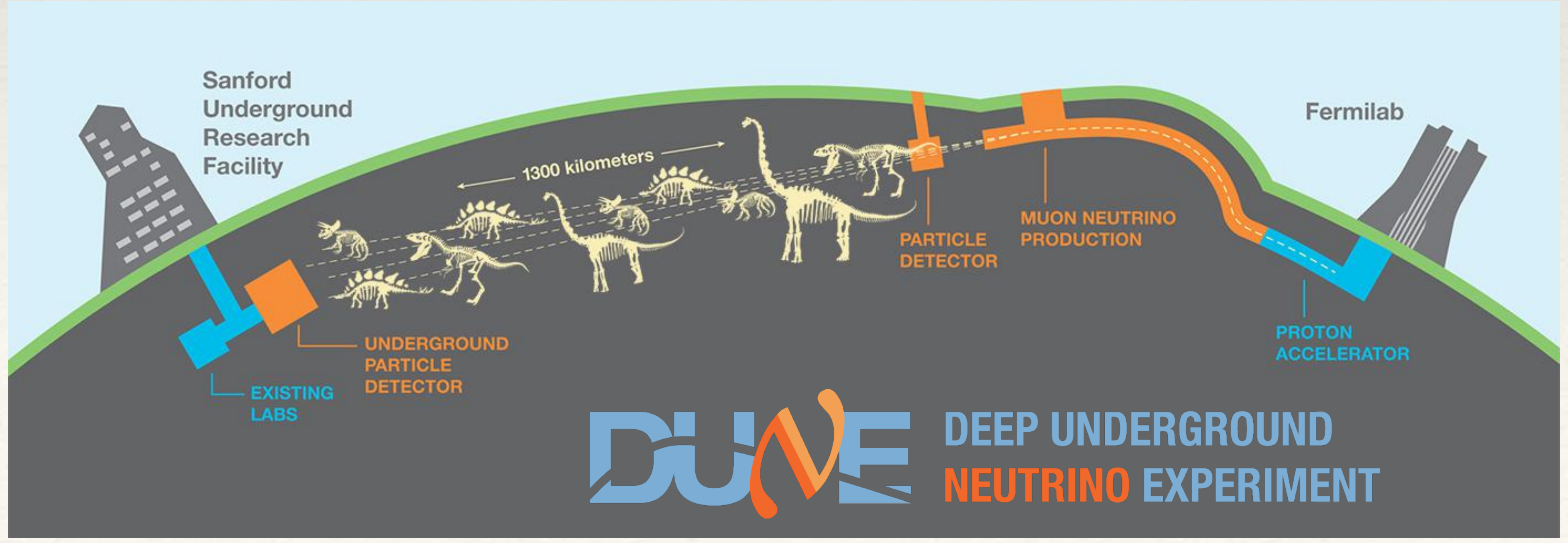
BERKELEY LAB

Science Questions

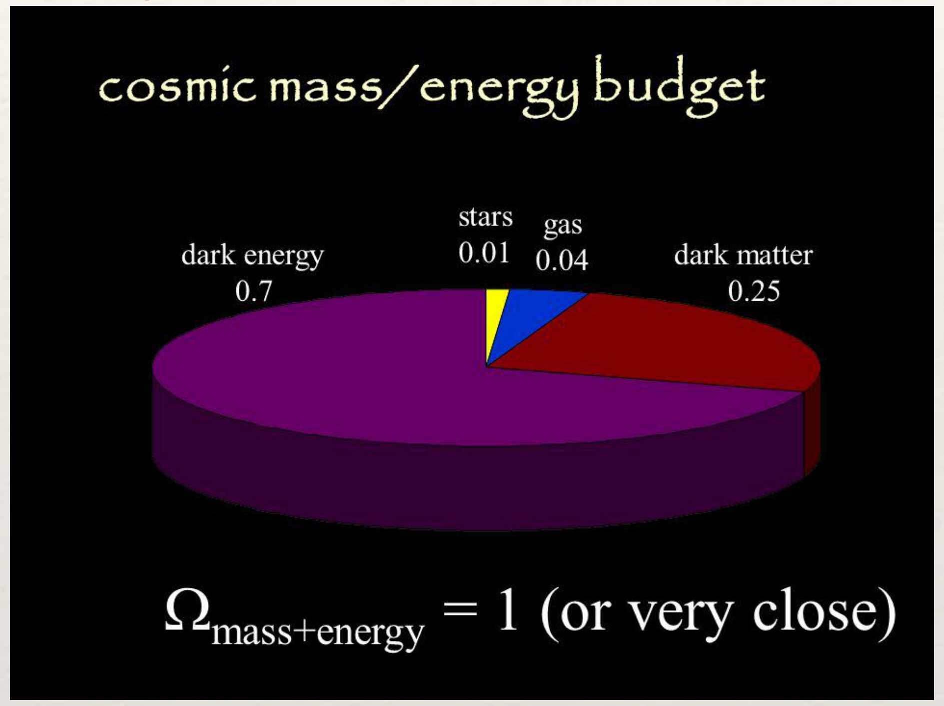
Why is the universe composed of matter? (and not anti-matter)

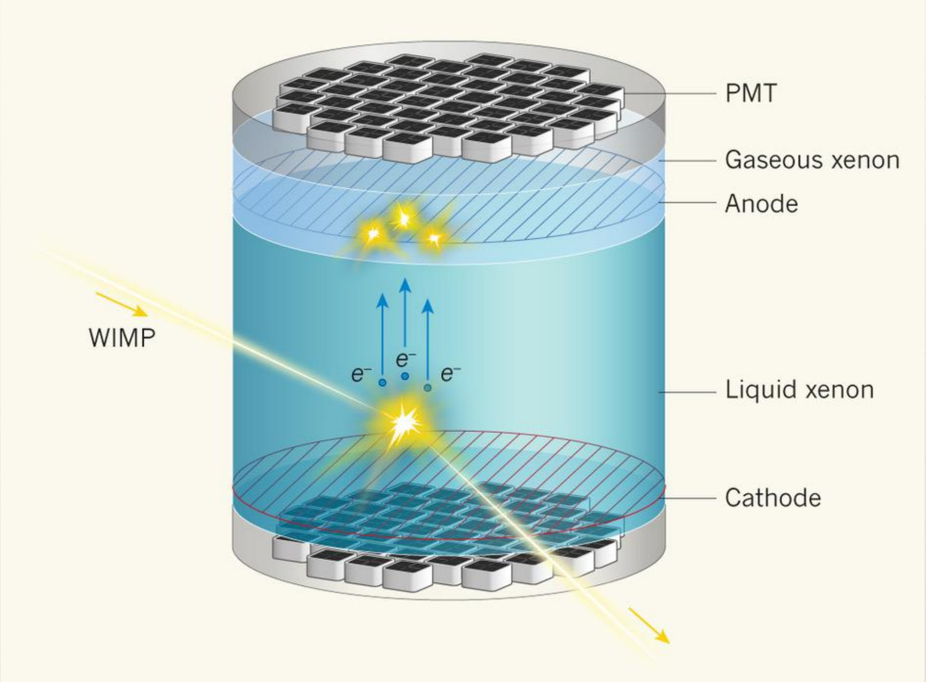




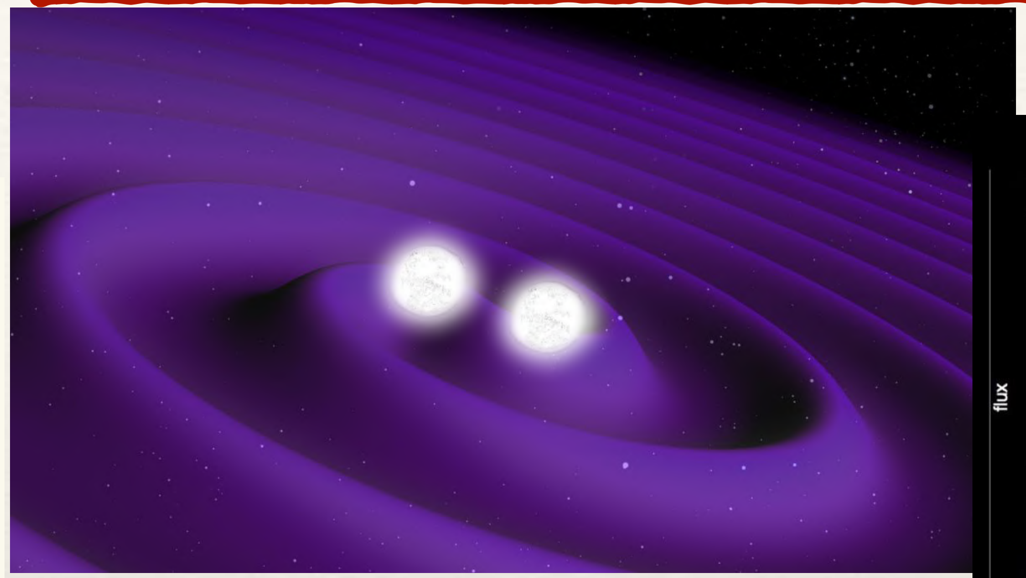


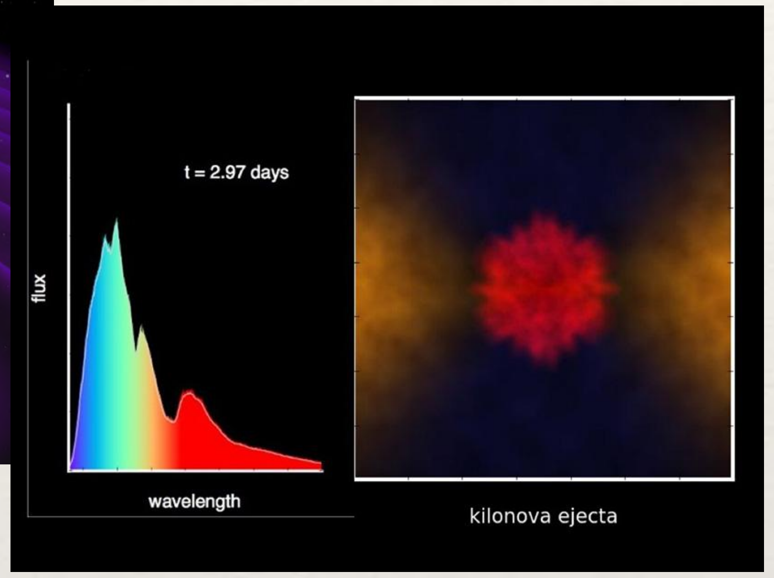
Does dark matter interact with matter? (beyond gravitationally)



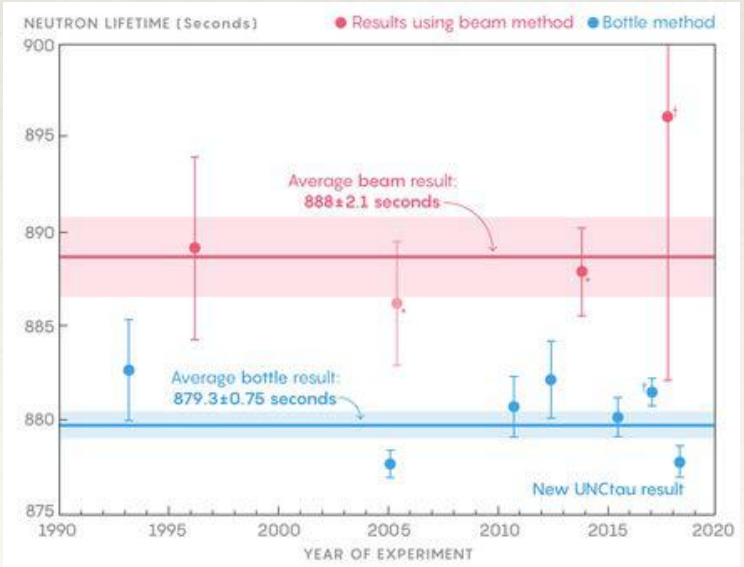


What are the properties of dense nuclear matter?

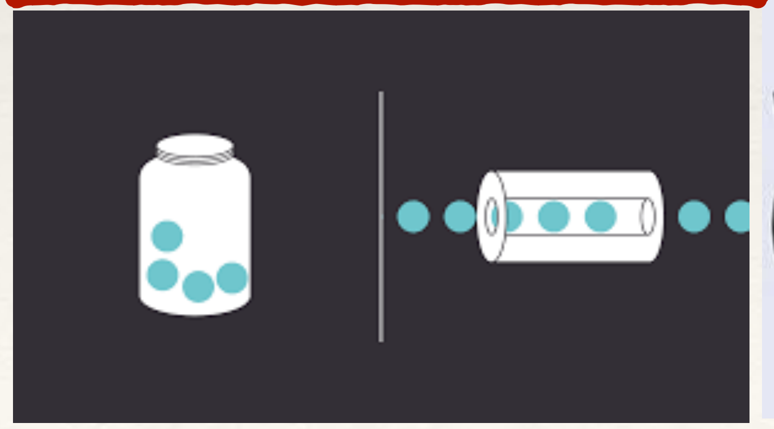




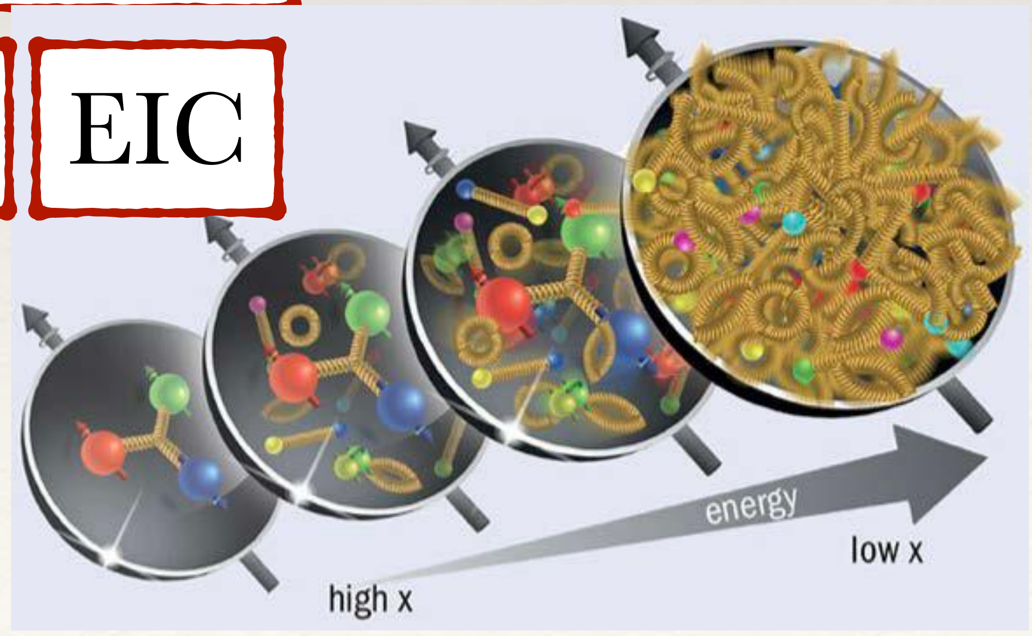
What are the properties of the proton?



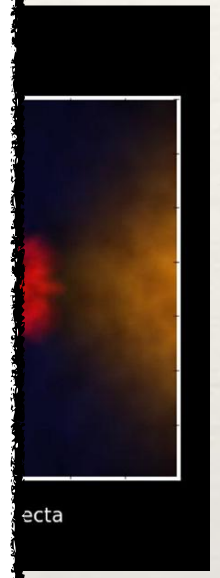
neutron lifetime



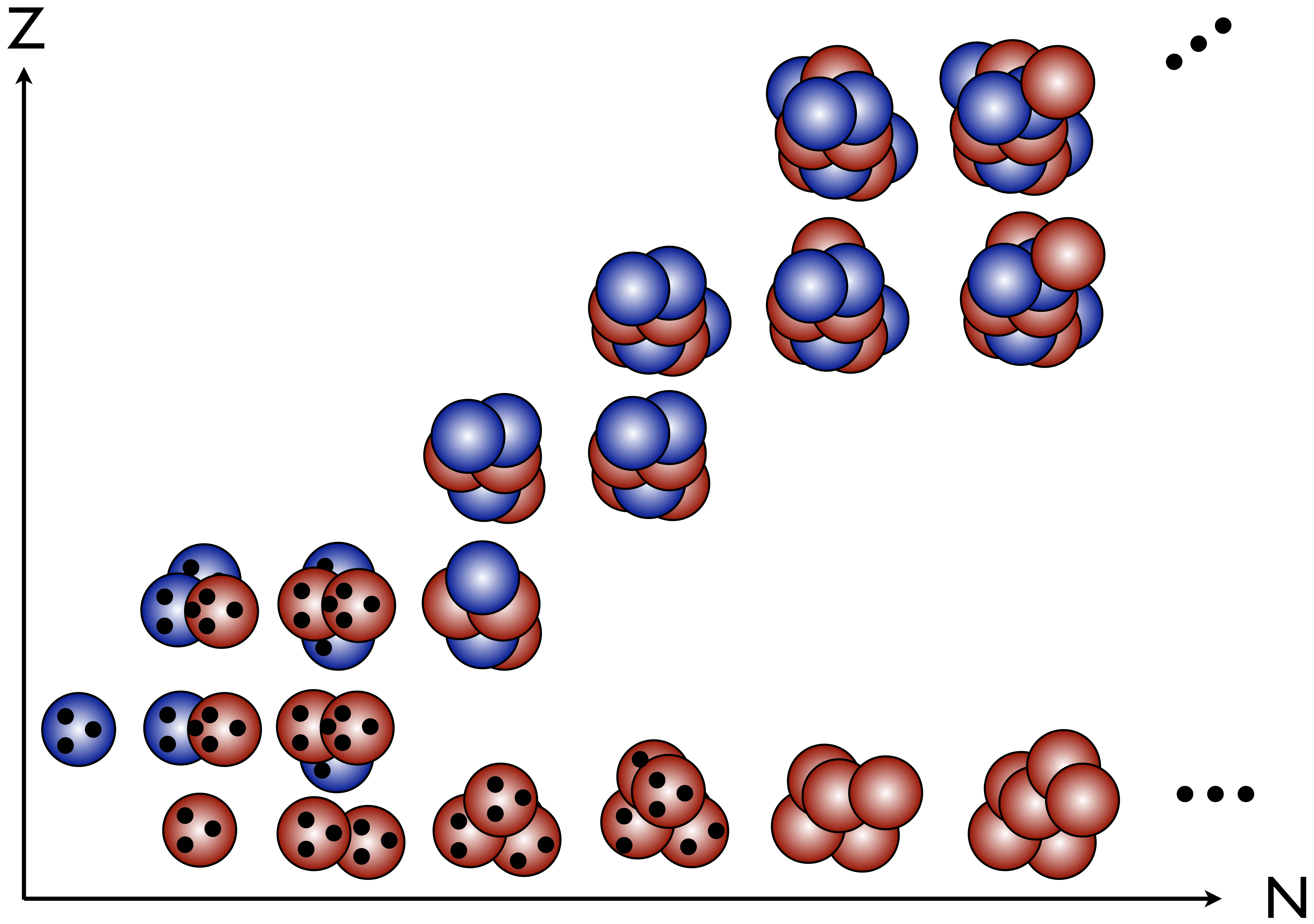
EIC

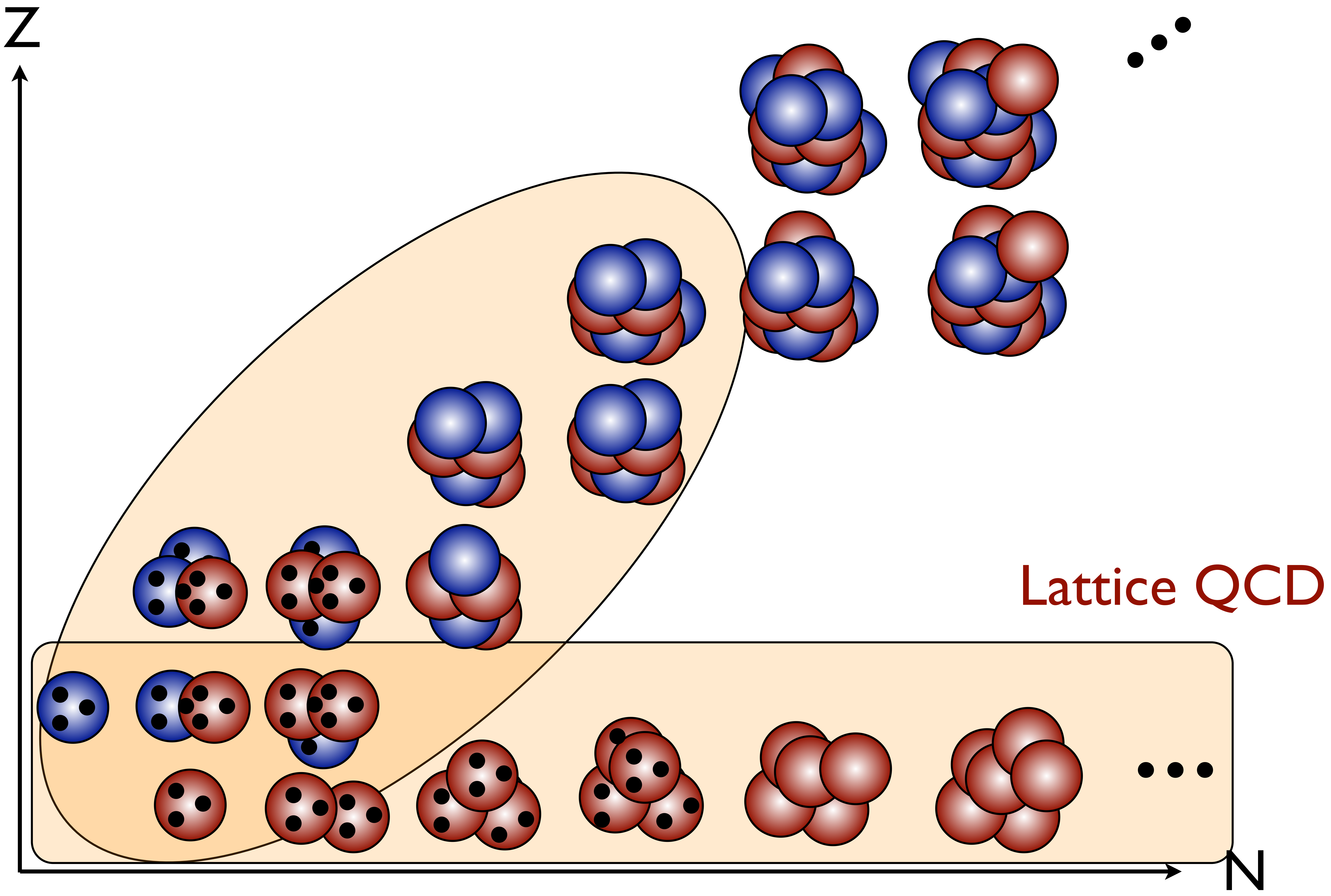


Science Questions

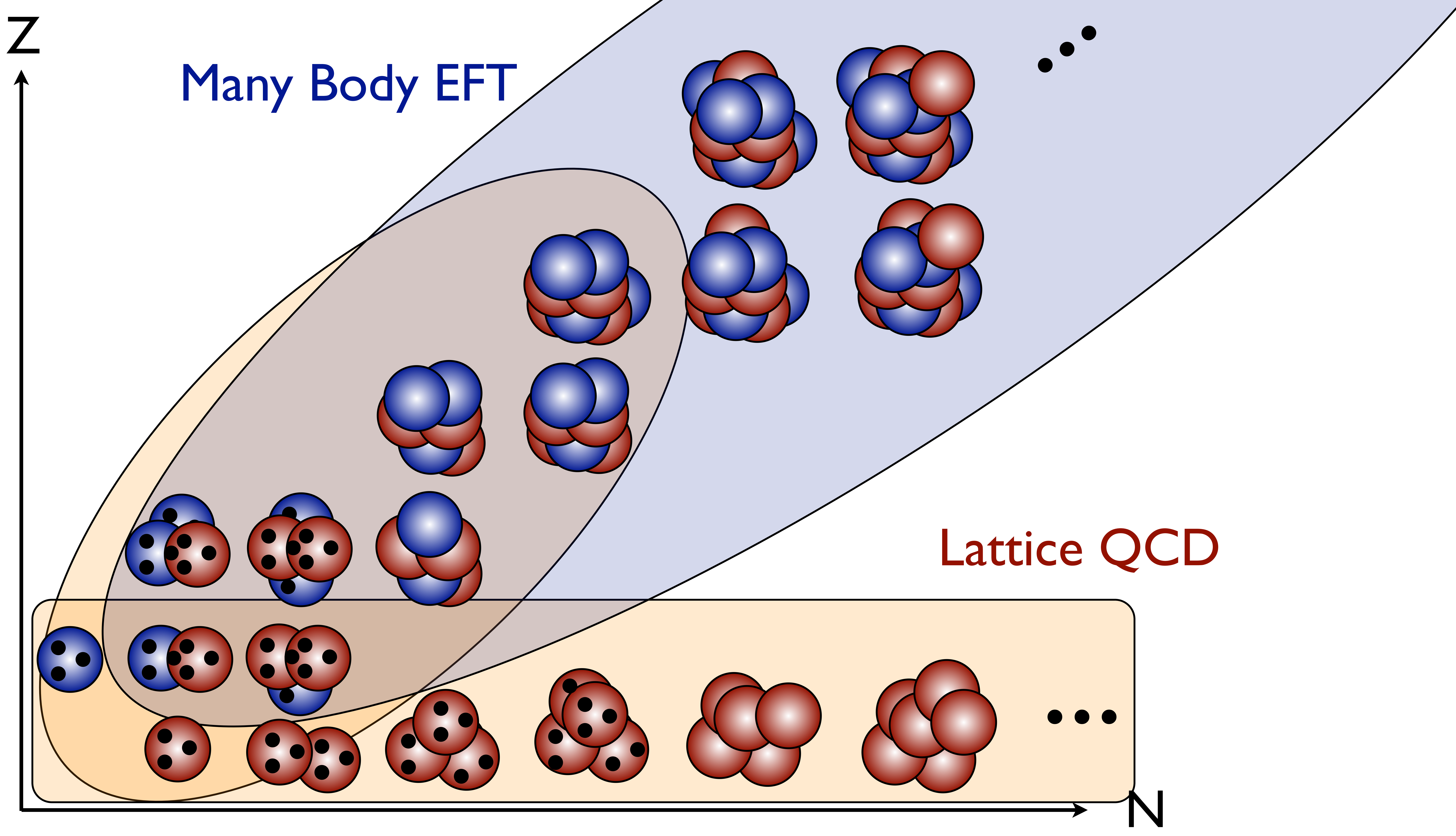


- Of course, we will not use LQCD to directly compute most of these processes
- In each case, there are key pieces of information that are challenging or impossible to determine from experimental information alone - and which we can address with LQCD
- Success requires a coordinated effort between
  - Lattice QCD
  - Effective Field Theory (EFT)
  - Theories of many body nuclear physics
- Allowing for the propagation of a quantitative theoretical uncertainty, rooted in the Standard Model, into theories of nuclear physics
  eg. Drischler et al, PPNP 121 (2021) 103888 [1910.07961]


Z
N



Determine 2, 3, 4 body forces directly from QCD

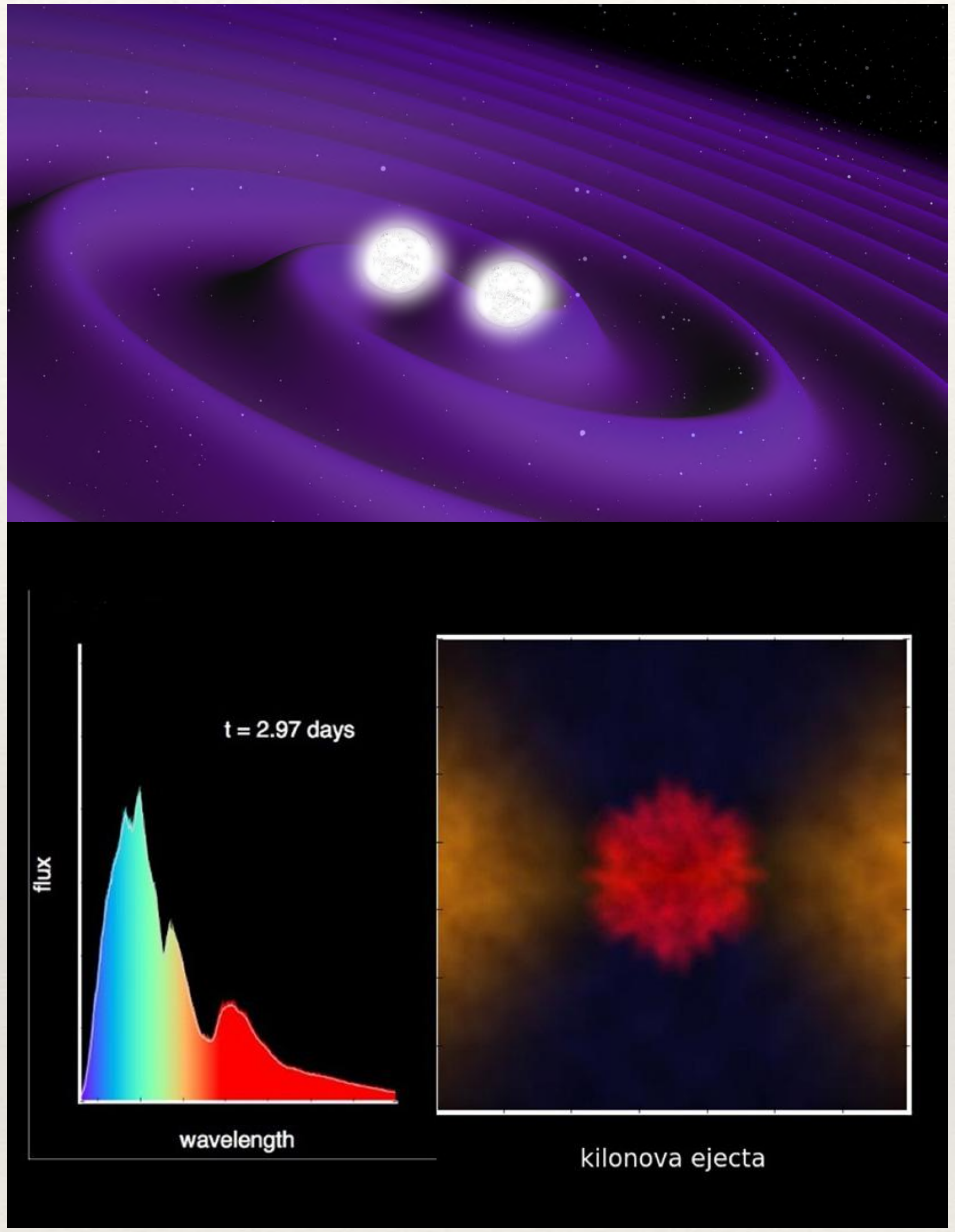


Determine 2, 3, 4 body forces directly from QCD

match onto many body effective field theory

Science Questions

Multi-messenger era and neutron-star mergers



- The ability to measure neutron star mergers has brought to reality the possibilities of constraining the nuclear equation of state with much better precision than previously possible
- It is difficult to make models with hyperons that can support the heavy ~2M neutron stars
- It is difficult to imagine that hyperons are irrelevant in the core of neutron stars (based upon the anticipated energy/density)
- The three-neutron interaction plays an important role in stabilizing neutron stars - but it is challenging to constrain
- Hyperon-Nucleon (YN) interactions are challenging to measure (since hyperons decay rapidly)
- If hyperons exist in neutron stars - it is probable that YNN interactions are also important
- The NNN and YN and YNN are interactions in principle we can determine with Lattice QCD

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \frac{1}{\mathcal{Z}}\int D\psi D\bar{\psi} DU \mathcal{O}(t)\mathcal{O}(0)e^{iS_M[\bar{\psi},\psi,U]}$$

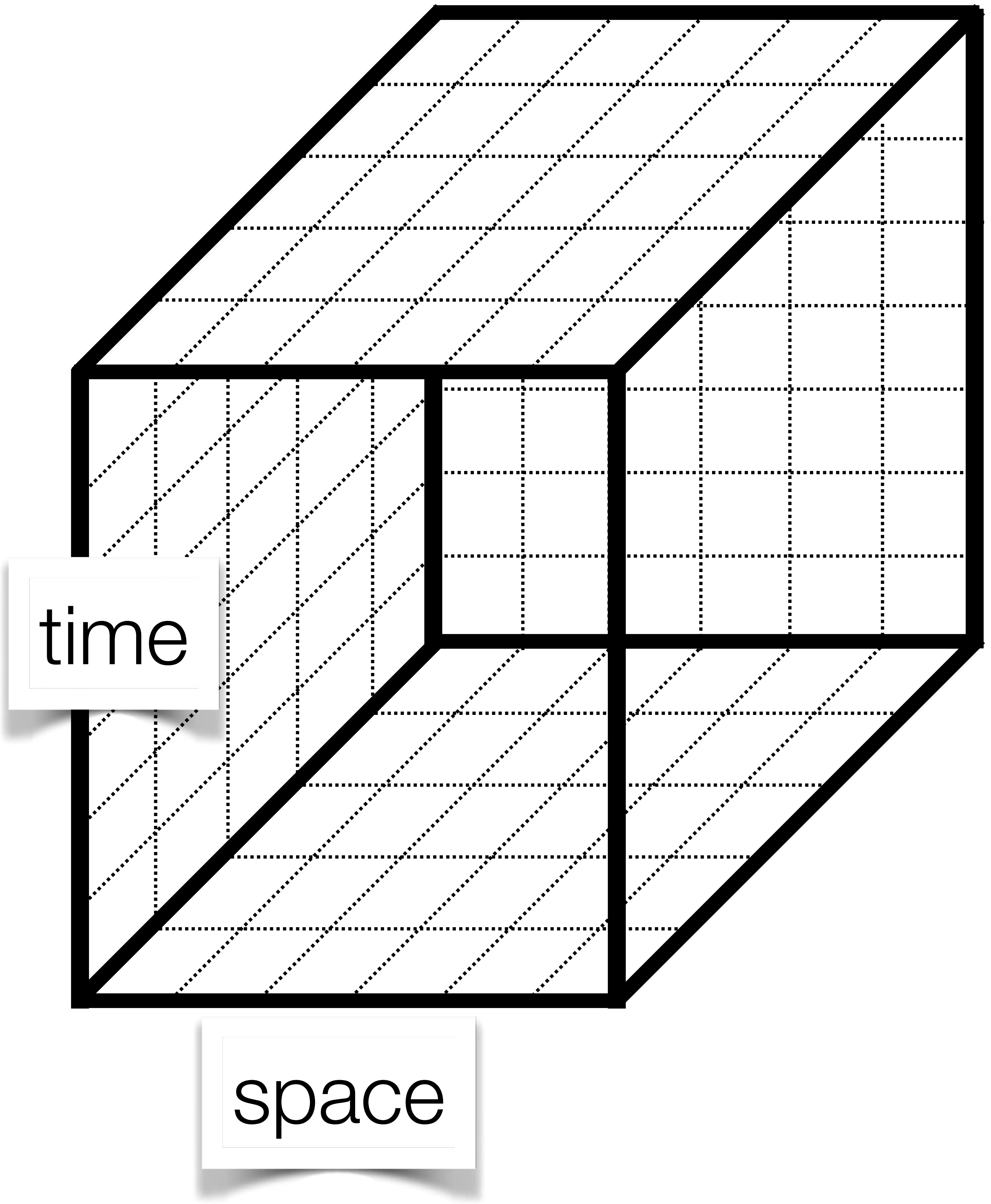
$$= \frac{1}{\mathcal{Z}}\int DU \det\left(\mathrm{i}\not{D} - \mathrm{M}\right)\mathcal{O}(\mathrm{t})\mathcal{O}(0)\mathrm{e}^{\mathrm{iS_M}[\bar{\psi},\psi,\mathrm{U}]}$$

Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \frac{1}{\mathcal{Z}}\int D\psi D\bar{\psi} DU \mathcal{O}(t)\mathcal{O}(0)e^{iS_M[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}}\int DU \det\left(i\not{D} - \mathrm{M}\right)\mathcal{O}(\mathrm{t})\mathcal{O}(0)\mathrm{e}^{\mathrm{iS_M}[\bar{\psi},\psi,\mathrm{U}]}$$

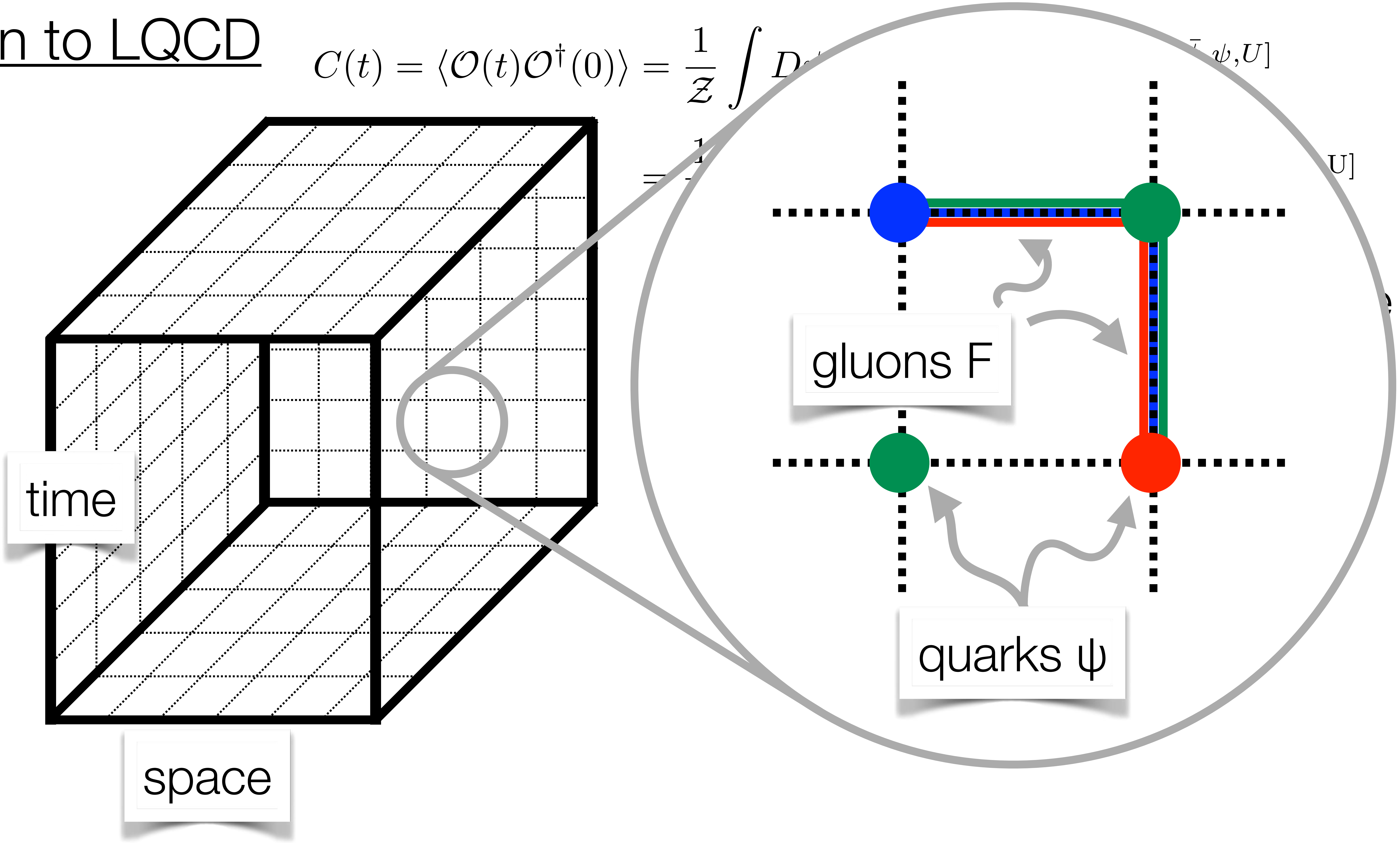


lattice
finite volume

Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \frac{1}{\mathcal{Z}}\int D$$

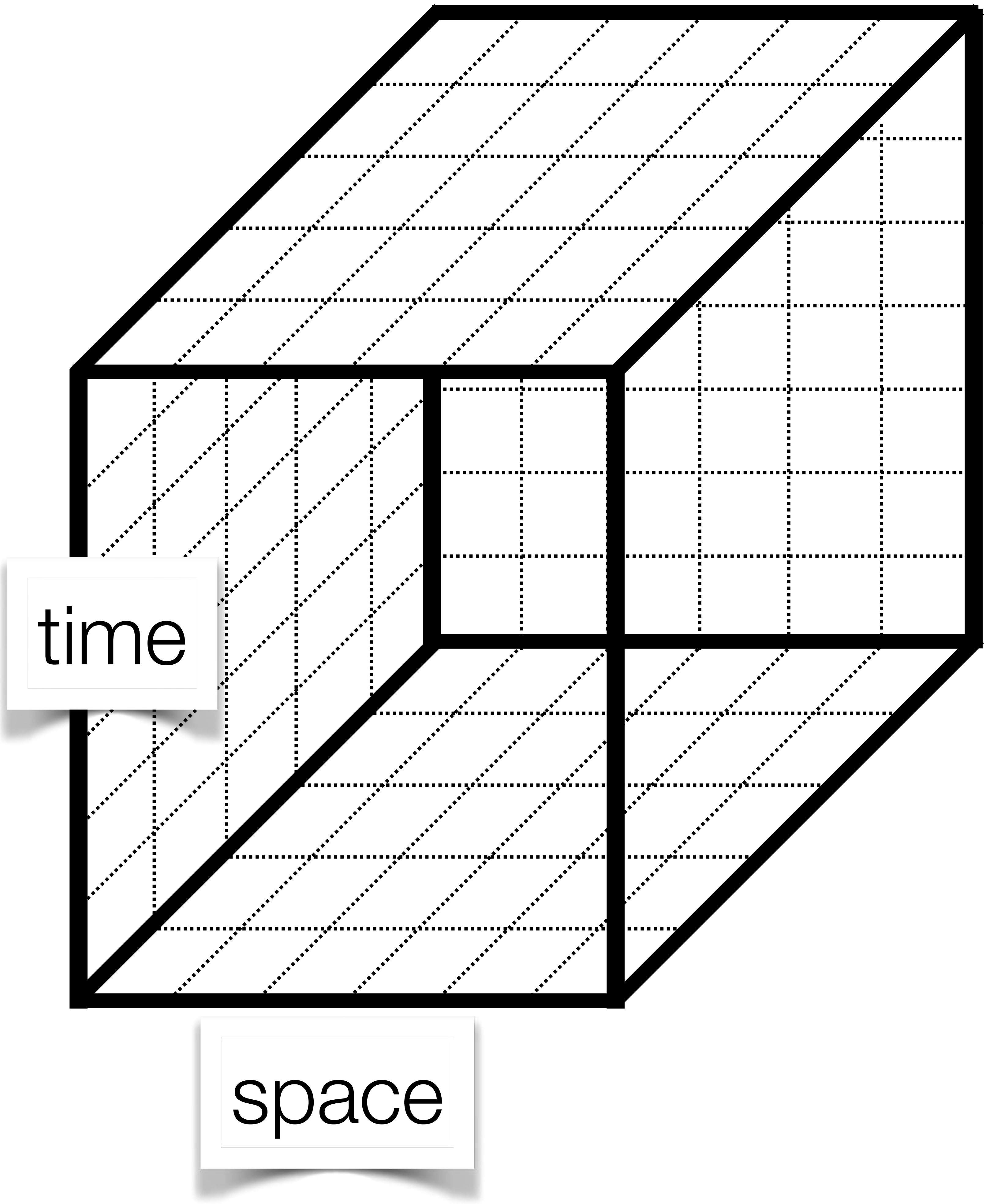


Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \frac{1}{\mathcal{Z}}\int D\psi D\bar{\psi} DU \mathcal{O}(t)\mathcal{O}(0)e^{iS_M[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}}\int DU \det\left(i\not{D} - M\right)\mathcal{O}(t)\mathcal{O}(0)e^{iS_M[\bar{\psi},\psi,U]}$$



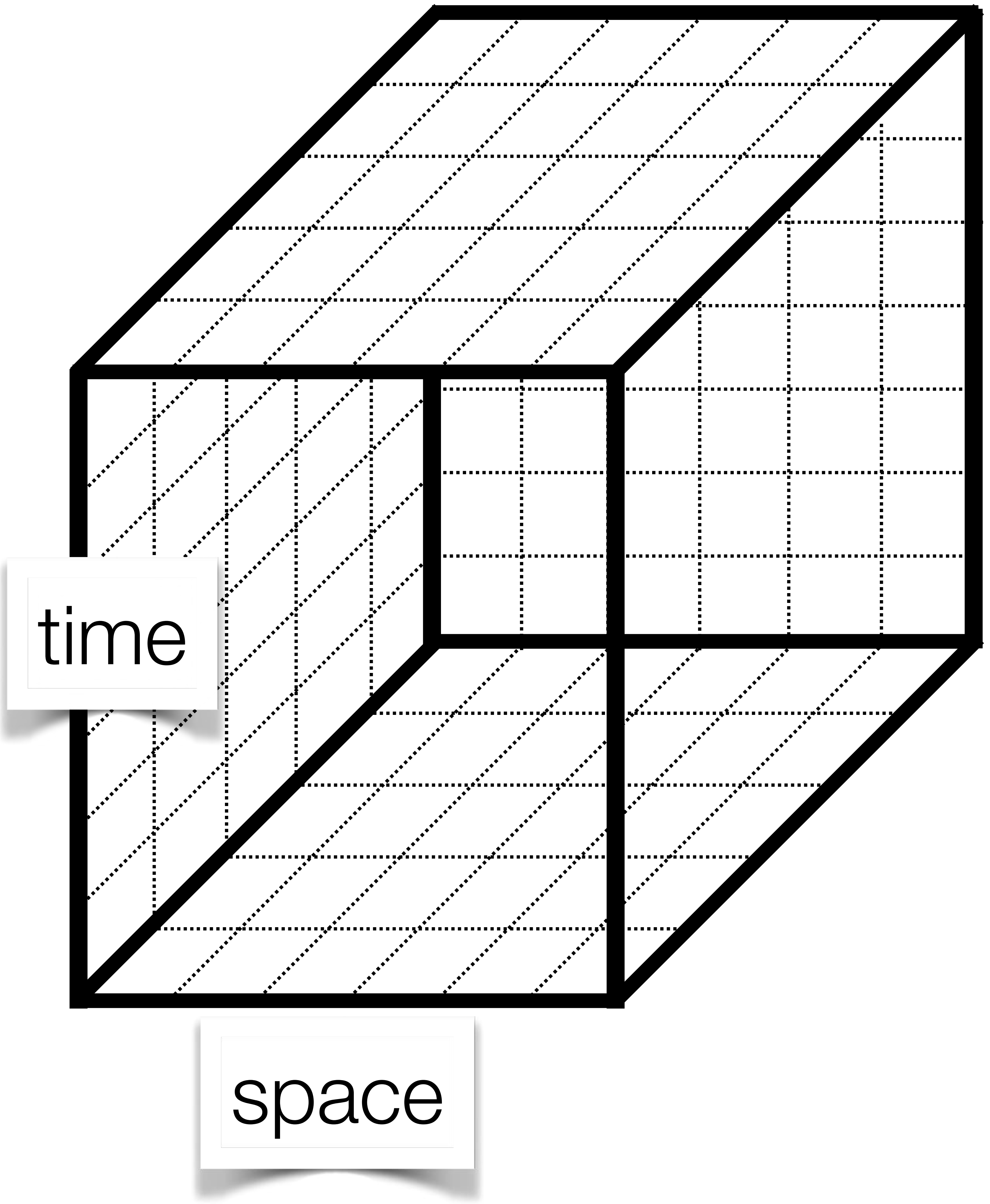
lattice
finite volume

Introduction to LQCD

$$C(t) = \left\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\right\rangle = \frac{1}{\mathcal{Z}}\int \mathcal{D}\psi\,\mathcal{D}\bar{\psi}\,\mathcal{D}U\;\mathcal{O}(t)\mathcal{O}^\dagger(0)e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}}\int \mathcal{D}U\,\det\left(\not{D}+M\right)e^{-S[U]}\;\mathcal{O}(t)\mathcal{O}^\dagger(0)$$

lattice
finite volume

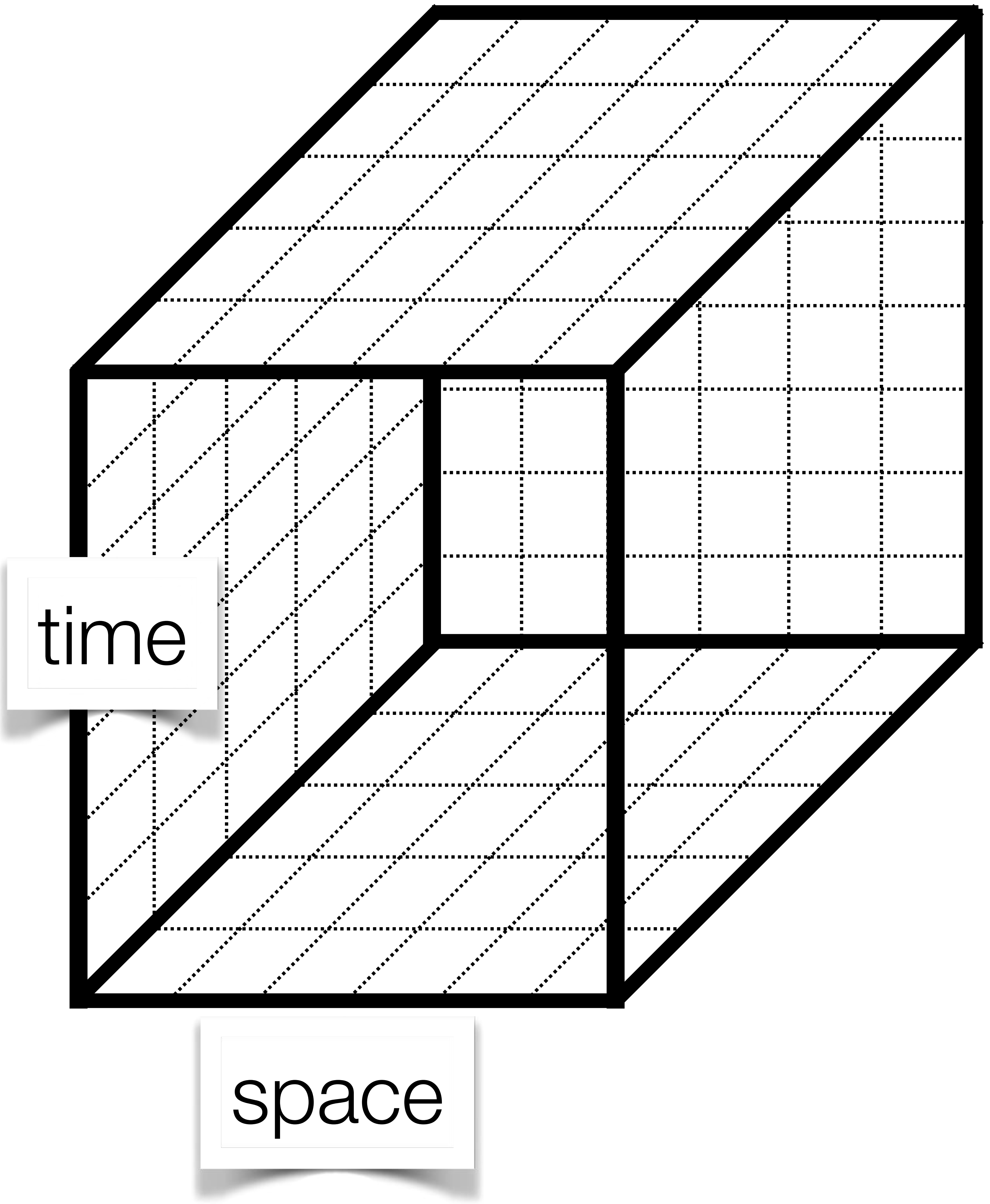


Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U\ \mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \underbrace{\det\left(\not{D} + M\right) e^{-S[U]}}_{\text{Probability}}\ \mathcal{O}(t)\mathcal{O}^\dagger(0)$$

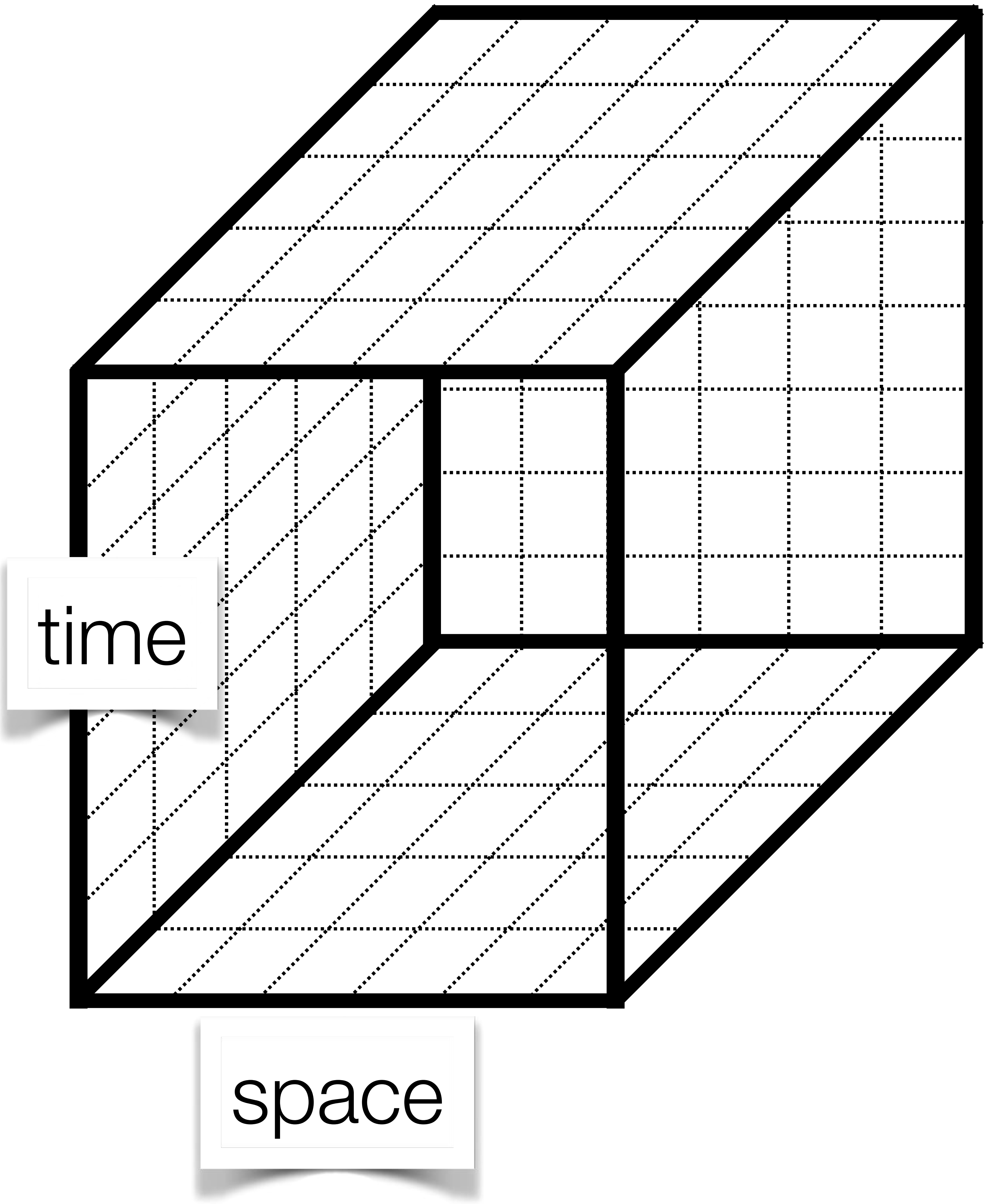


Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi \, \mathcal{D}\bar{\psi} \, \mathcal{D}U \; \mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \, \underbrace{\det\left(\not{D} + M\right) e^{-S[U]}}_{\text{Probability}} \; \mathcal{O}(t)\mathcal{O}^\dagger(0)$$



Probability

$$\{U_1, U_2, U_3, \ldots, U_N\}$$

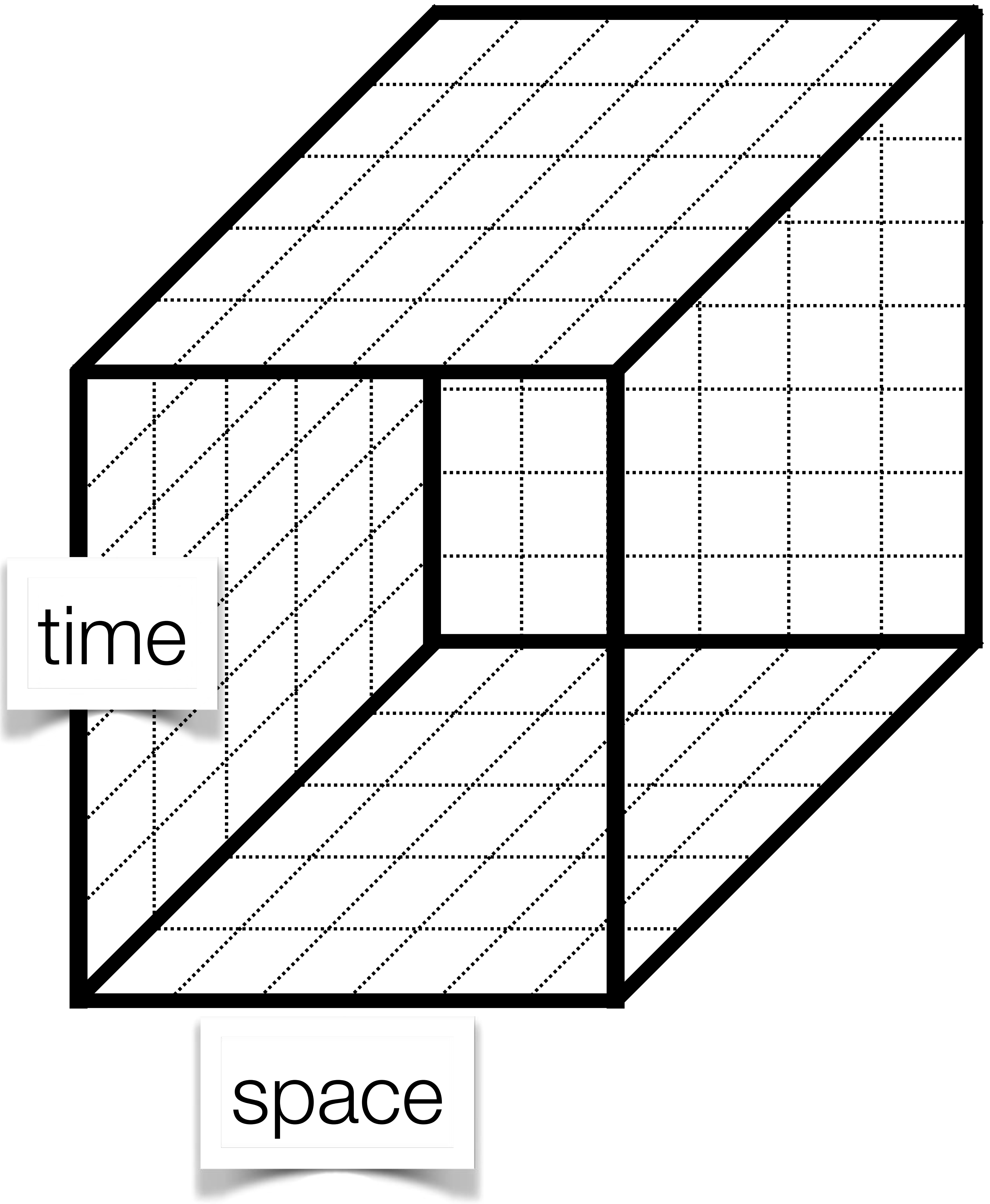
Markov Chain Monte Carlo

Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U\; \mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \underbrace{\det\left(\not{D} + M\right) e^{-S[U]}}_{\text{Probability}} \mathcal{O}(t)\mathcal{O}^\dagger(0)$$



$$\{U_1, U_2, U_3, \ldots, U_N\}$$

Markov Chain Monte Carlo

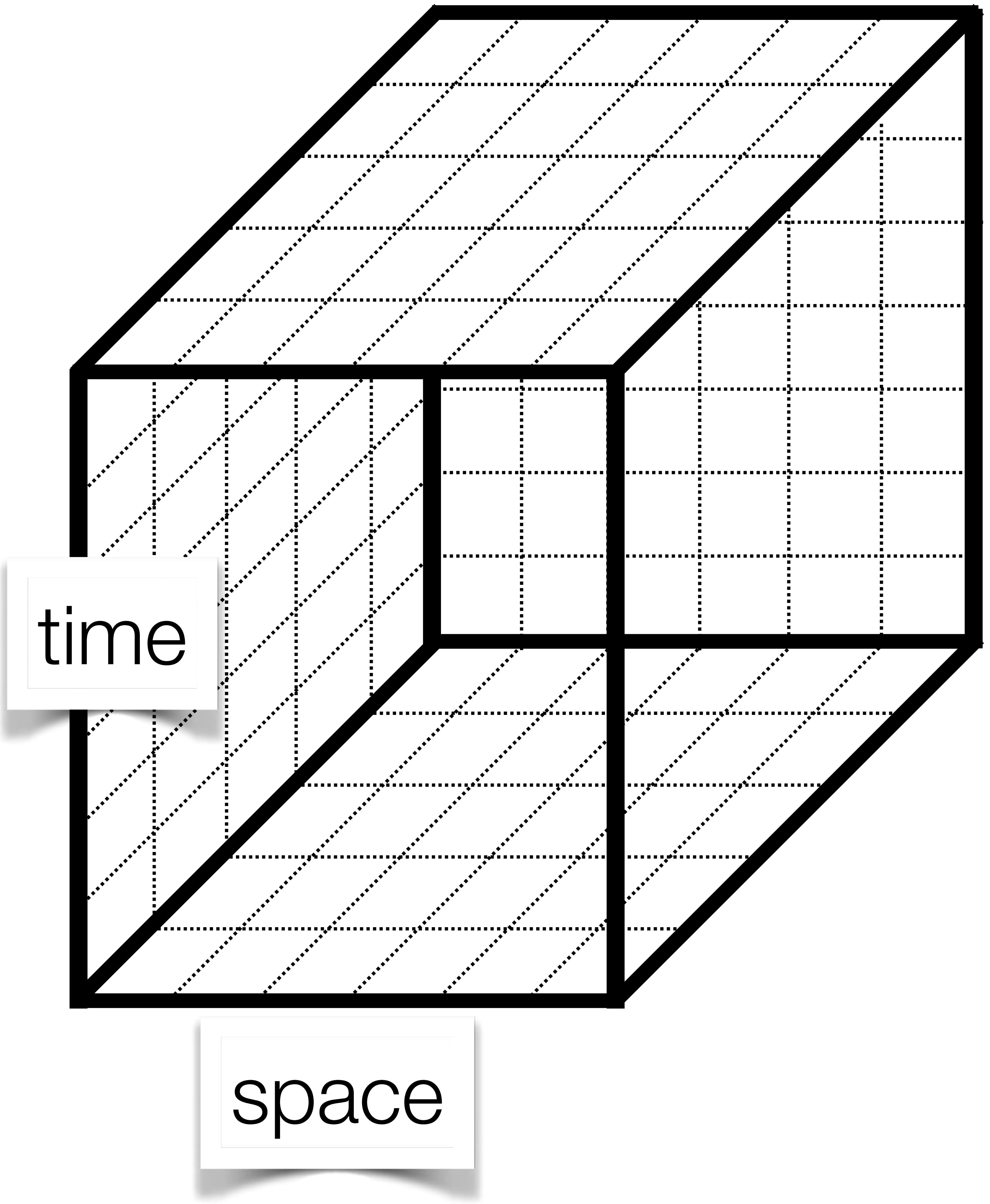
$$\approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(t)\mathcal{O}^\dagger(0)[U_i]$$

Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U\; \mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \underbrace{\det\left(\not{D} + M\right) e^{-S[U]}}_{\text{Probability}} \mathcal{O}(t)\mathcal{O}^\dagger(0)$$



Probability

$$\{U_1, U_2, U_3, \ldots, U_N\}$$

Markov Chain Monte Carlo

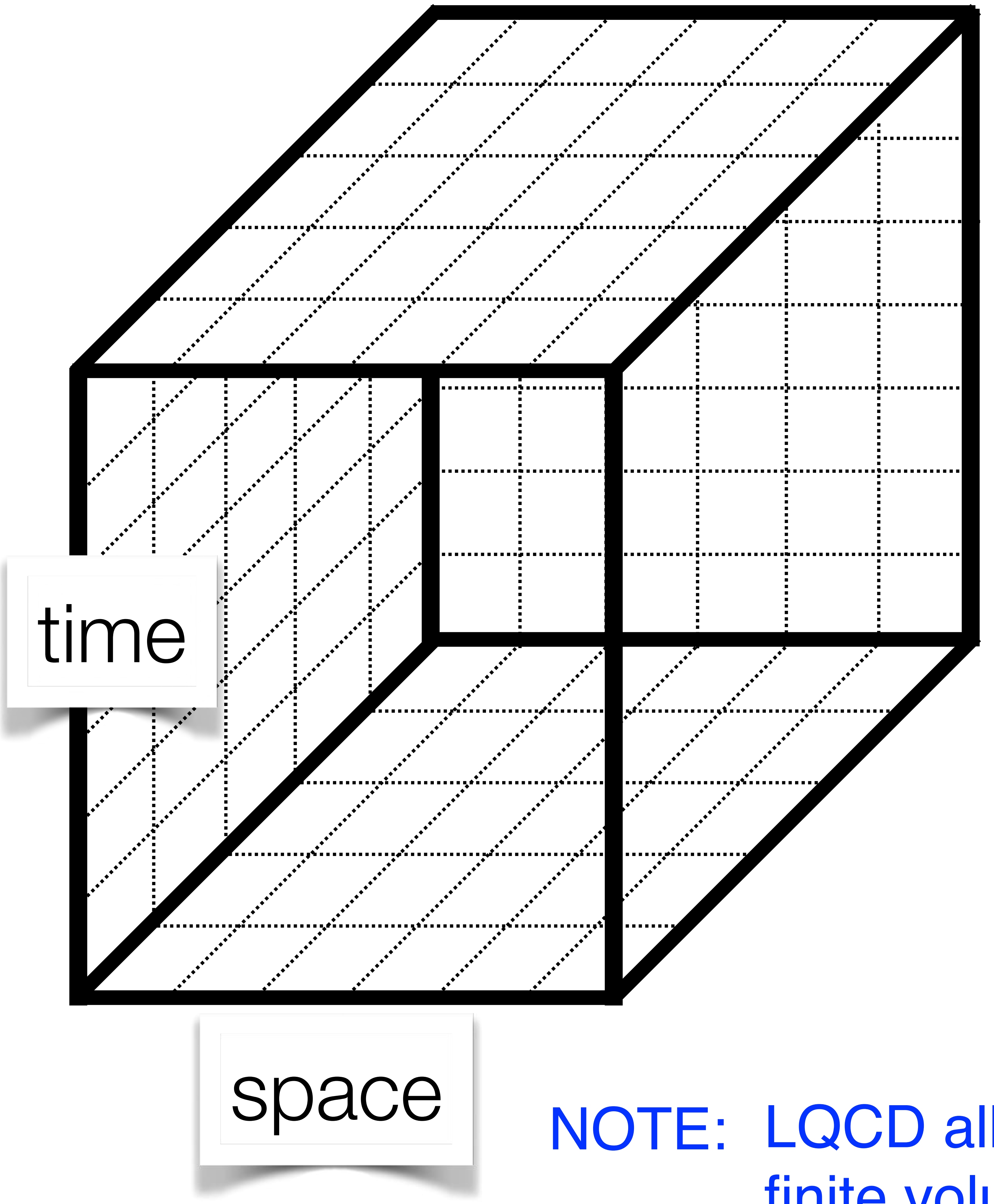
$$\approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(t)\mathcal{O}^\dagger(0)[U_i] + O\left(\frac{1}{\sqrt{N}}\right)$$

Slide adapted from E. Berkowitz

Introduction to LQCD

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi \, \mathcal{D}\bar{\psi} \, \mathcal{D}U \; \mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

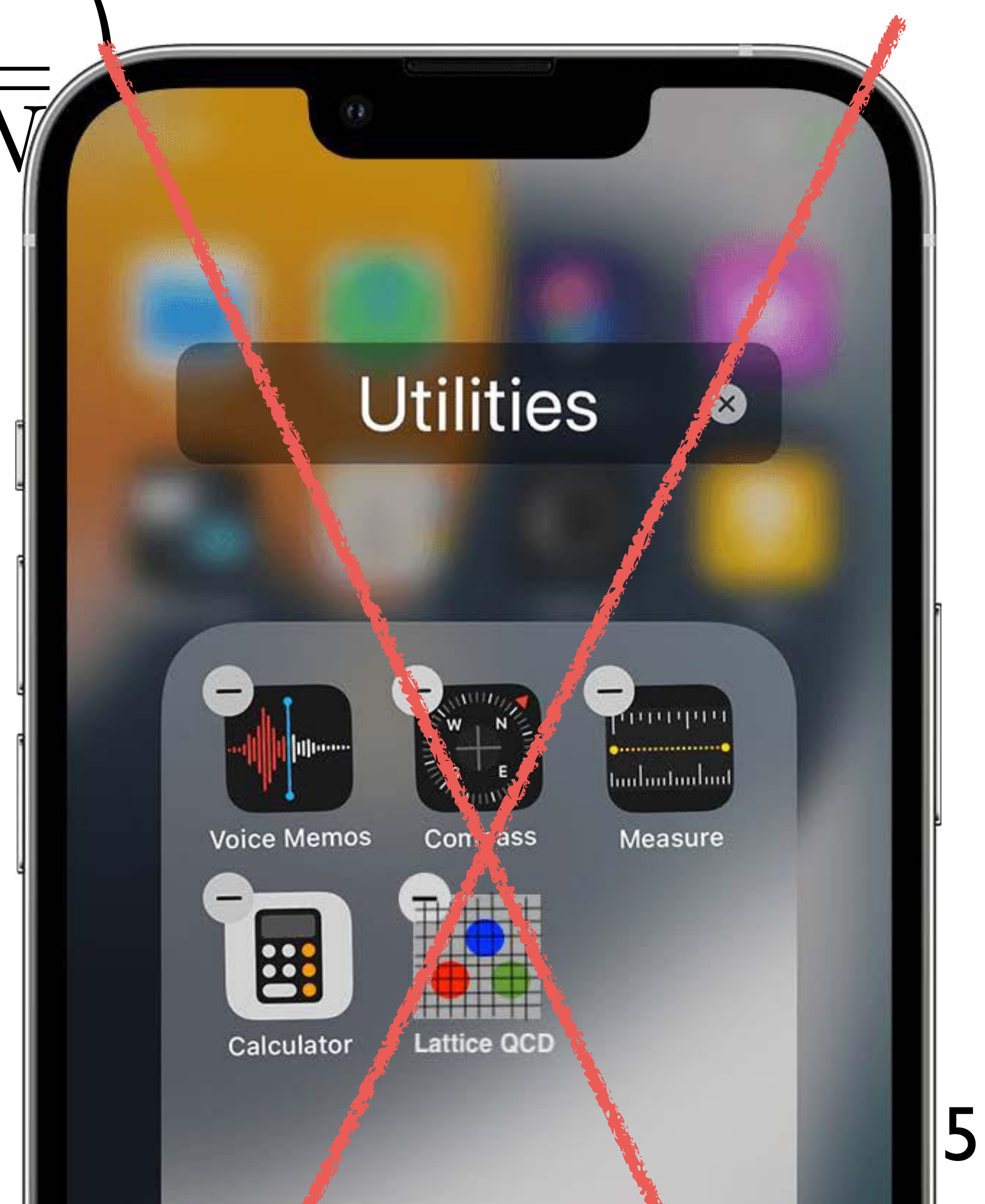
$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \, \underbrace{\det\left(\not{D} + M\right) e^{-S[U]}}_{\text{Probability}} \; \mathcal{O}(t)\mathcal{O}^\dagger(0)$$



$$\{U_1, U_2, U_3, \ldots, U_N\}$$

Markov Chain Monte Carlo

$$\approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(t)\mathcal{O}^\dagger(0)[U_i] \; + O\left(\frac{1}{\sqrt{N}}\right)$$

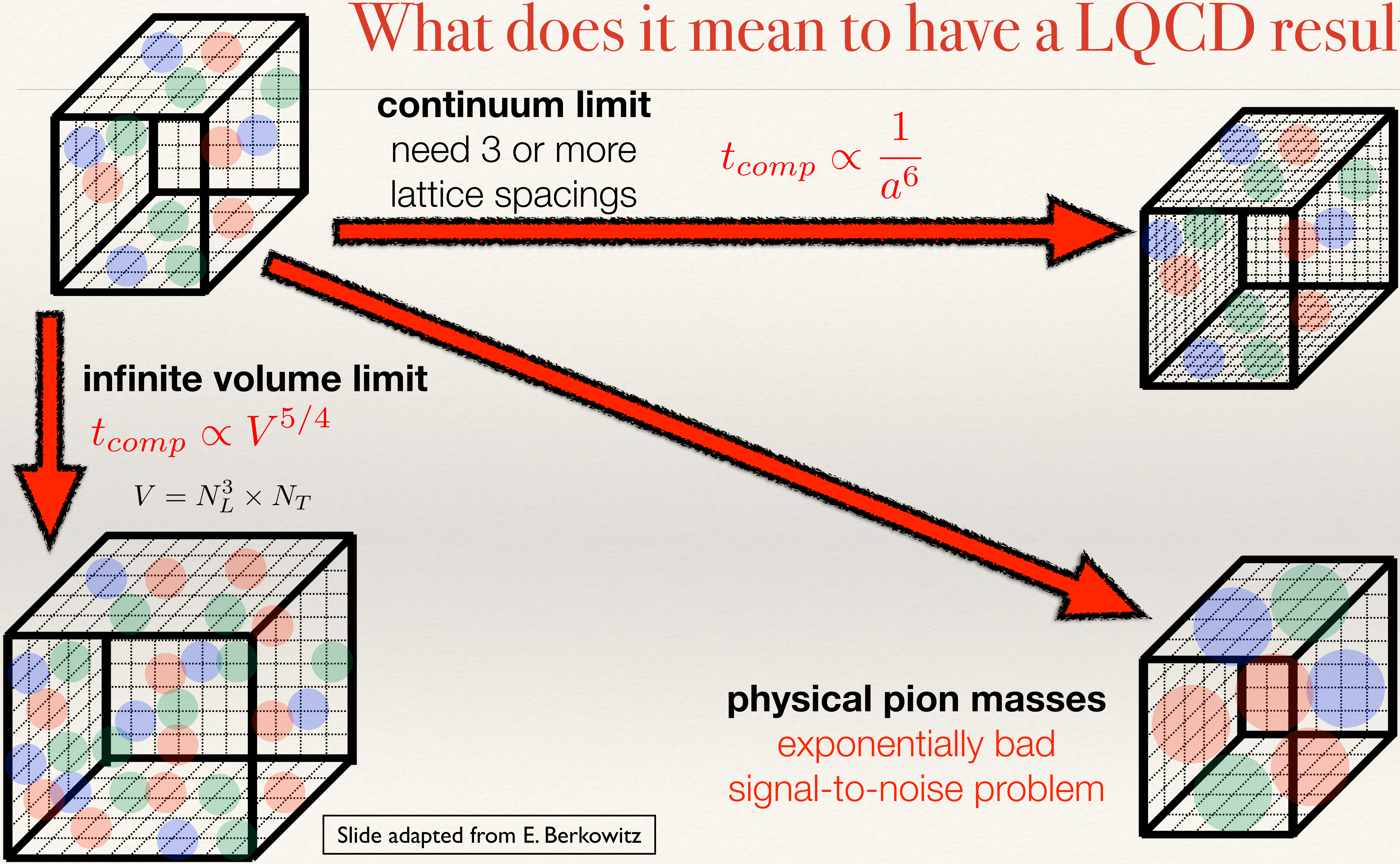


NOTE: LQCD allows us to compute Euclidean space, finite volume, correlation functions

Non-trivial numerical analysis (and sometimes formalism) to extract spectrum, matrix elements, form factors, …

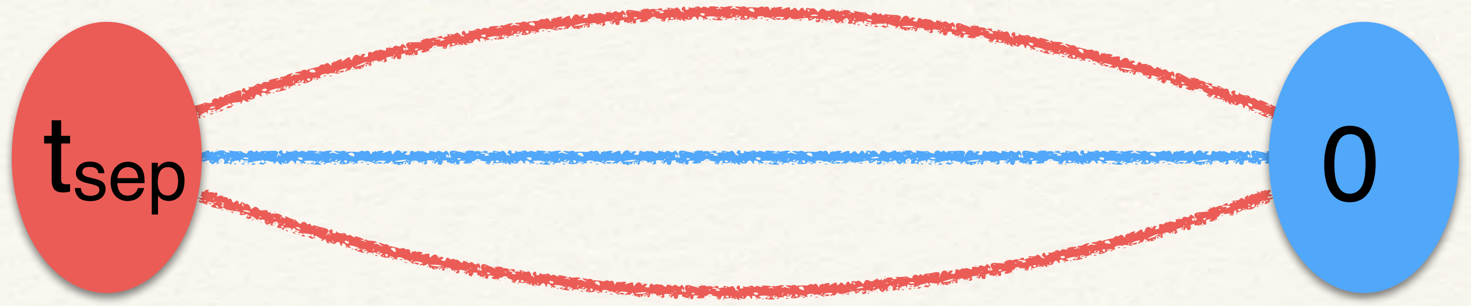
Slide adapted from E. Berkowitz

What does it mean to have a LQCD result?



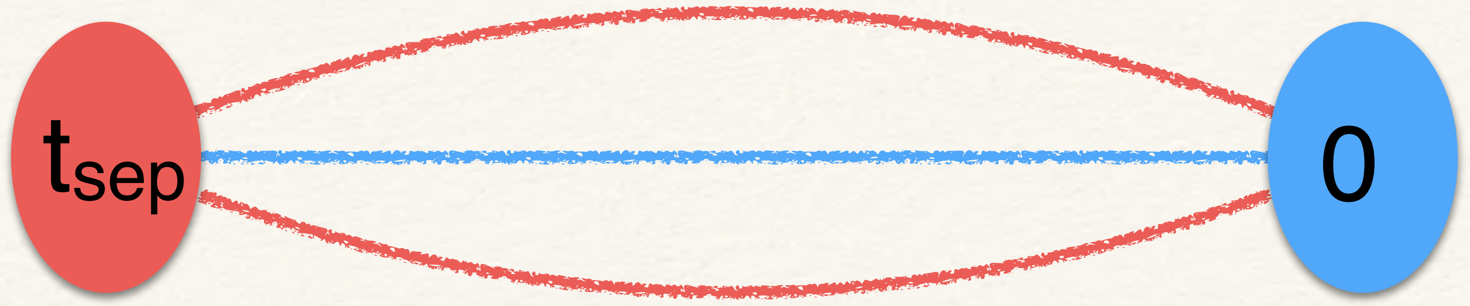
LQCD: 2 point functions

$$C(t,\mathbf{p}) = \sum_{\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{x}} \langle \Omega | O(t,\mathbf{x}) O^\dagger(0,\mathbf{0}) | \Omega \rangle$$



$$\begin{aligned}
C(t) &= \sum_{\mathbf{x}} \langle \Omega | O(t,\mathbf{x}) O^\dagger(0,\mathbf{0}) | \Omega \rangle && \text{focus on 0-momentum} \\
&= \sum_{\mathbf{x}} \langle \Omega | e^{\hat{H}t} O(0,\mathbf{x}) e^{-\hat{H}t} O^\dagger(0,\mathbf{0}) | \Omega \rangle && \text{time-evolve operator} \\
&= \sum_n \sum_{\mathbf{x}} \langle \Omega | e^{\hat{H}t} O(0,\mathbf{x}) e^{-\hat{H}t} | n \rangle \langle n | O^\dagger(0,\mathbf{0}) | \Omega \rangle && \text{multiply by 1,} \quad 1 = \sum_n |n\rangle\langle n| \\
&= \sum_n e^{-E_n t} \sum_{\mathbf{x}} \langle \Omega | O(0,\mathbf{x}) | n \rangle \langle n | O^\dagger(0,\mathbf{0}) | \Omega \rangle && \text{define vacuum to have 0-energy} \\
&= \sum_n e^{-E_n(\mathbf{p}=0)t} \langle \Omega | O(0) | n, \mathbf{p}=0 \rangle \langle n, \mathbf{p}=0 | O^\dagger(0) | \Omega \rangle \\
&= \sum_n e^{-E_n t} z_n z_n^\dagger && \text{sum of exponentials}
\end{aligned}$$

LQCD: 2 point functions



$$C(t, \mathbf{p}=0) = \sum_{\mathbf{x}} \langle \Omega | N(t, \mathbf{x}) N^\dagger(0, \mathbf{0}) | \Omega \rangle$$

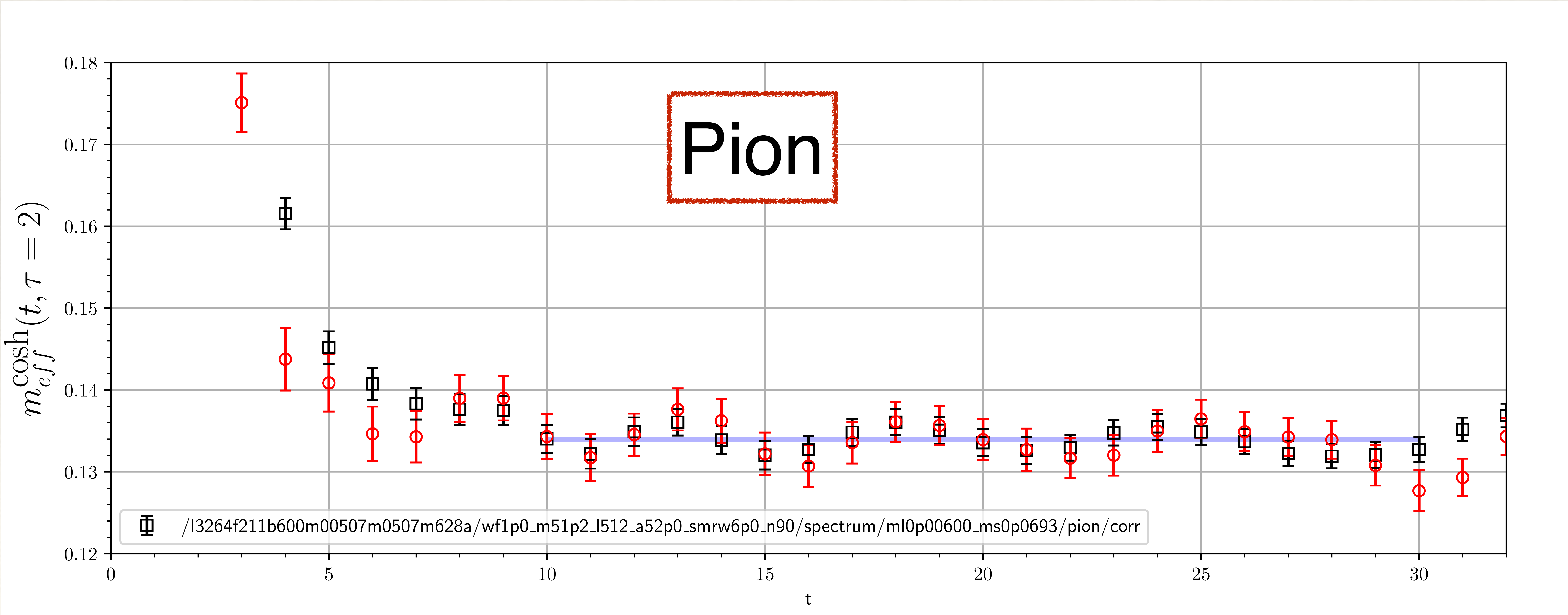
$$= A_0 e^{-E_0 t} \left(1 + \sum_{n>0} r_n e^{-\Delta_{n0} t} \right)$$

$$\Delta_{n0} = E_n - E_0$$

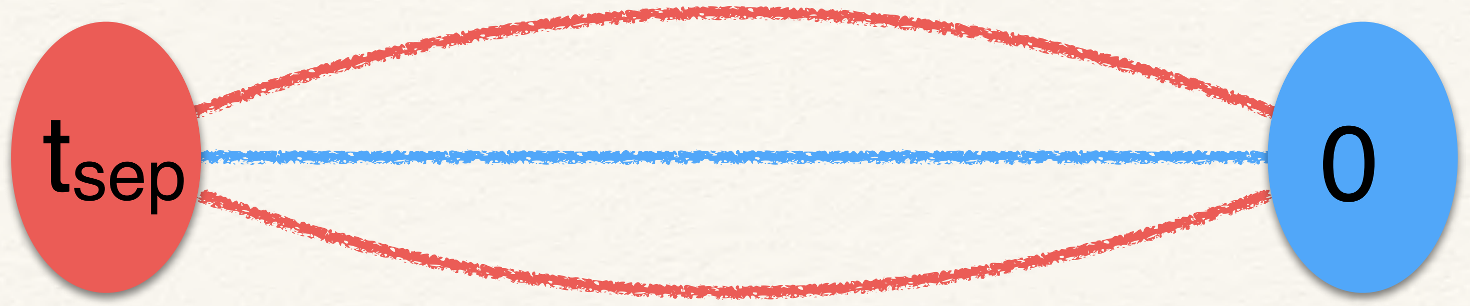
$$m_{\text{eff}}(t) = \ln \left(\frac{C(t)}{C(t+1)} \right) \underbrace{\longrightarrow}_{\text{large } t} E_0 + \sum_{n>0} r_n \left(e^{-\Delta_{n0} t} - e^{-\Delta_{n0} t+1} \right)$$

NOTE: if the creation operator is conjugate to the annihilation operator

$$r_n \geq 0$$



LQCD: 2 point functions



$$C(t, \mathbf{p}=0) = \sum_{\mathbf{x}} \langle \Omega | N(t, \mathbf{x}) N^\dagger(0, \mathbf{0}) | \Omega \rangle$$

$$= A_0 e^{-E_0 t} \left(1 + \sum_{n>0} r_n e^{-\Delta_{n0} t} \right)$$

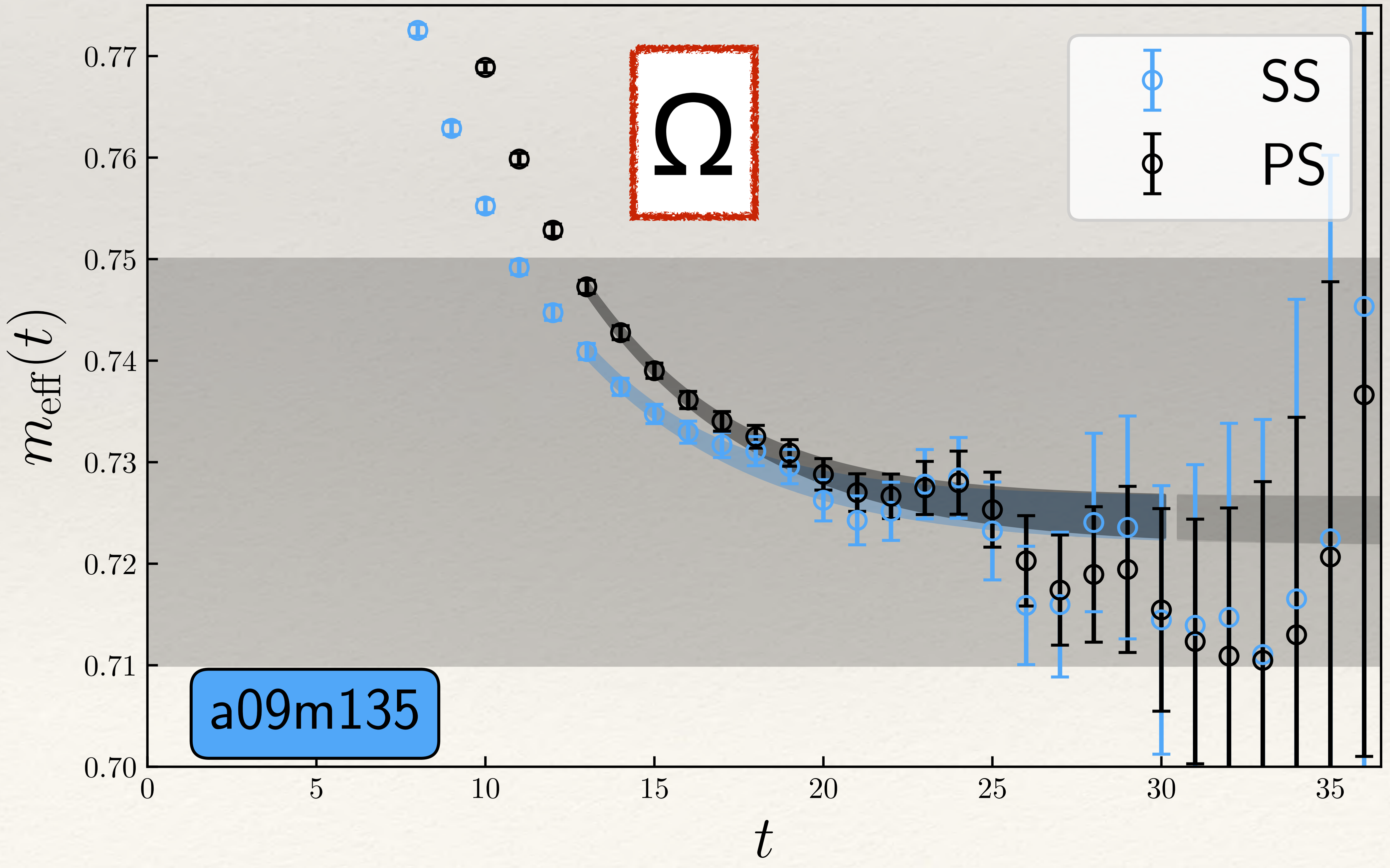
$$\Delta_{n0} = E_n - E_0$$

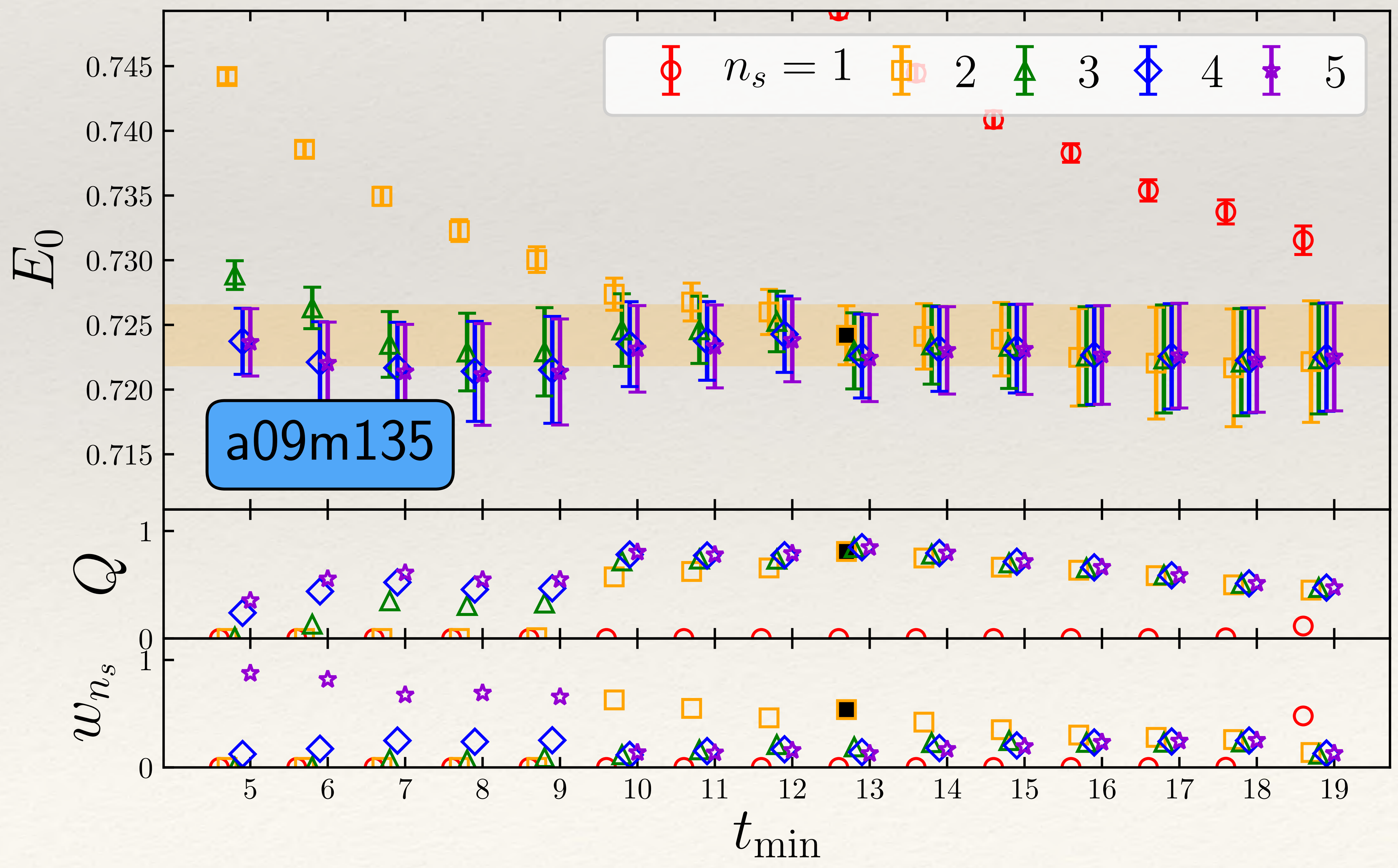
$$m_{\text{eff}}(t) = \ln\left(\frac{C(t)}{C(t+1)}\right) \underbrace{\longrightarrow}_{\text{large } t} E_0 + \sum_{n>0} r_n \left(e^{-\Delta_{n0} t} - e^{-\Delta_{n0} t + 1}\right)$$

NOTE: if the creation operator is conjugate to the annihilation operator

$$r_n \geq 0$$

but… signal-to-noise - can not simply "wait till long time" to get ground state (g.s.)

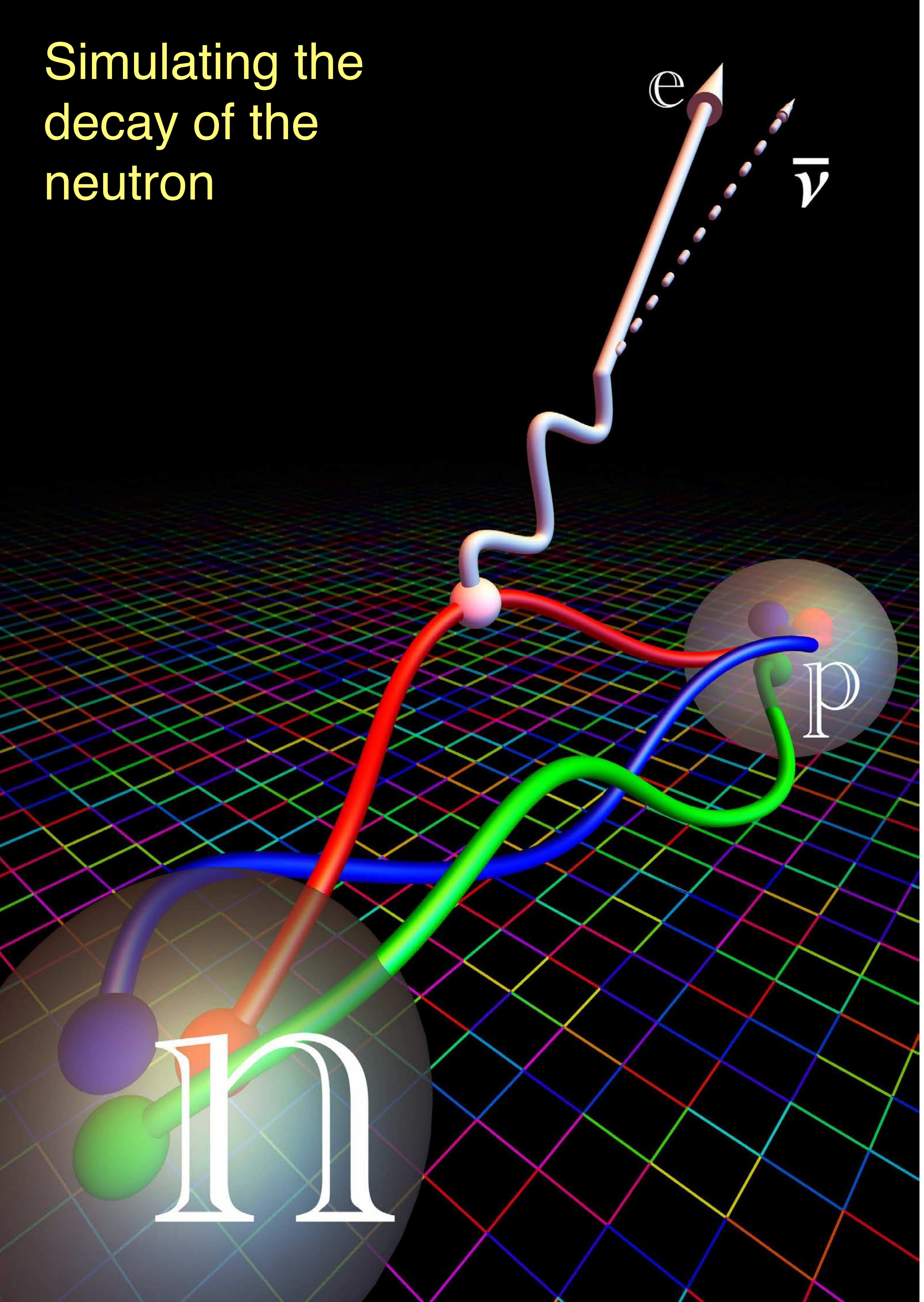


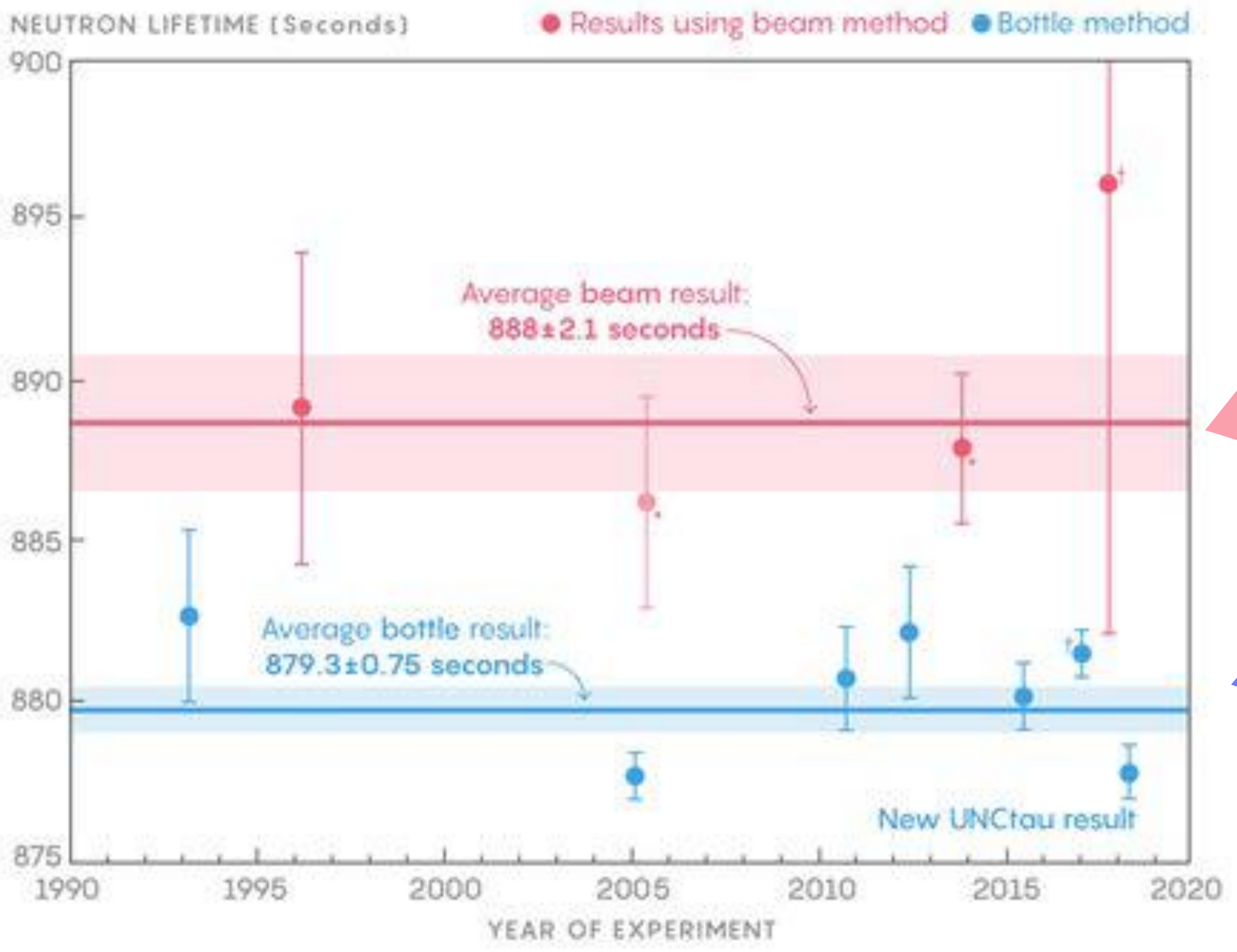


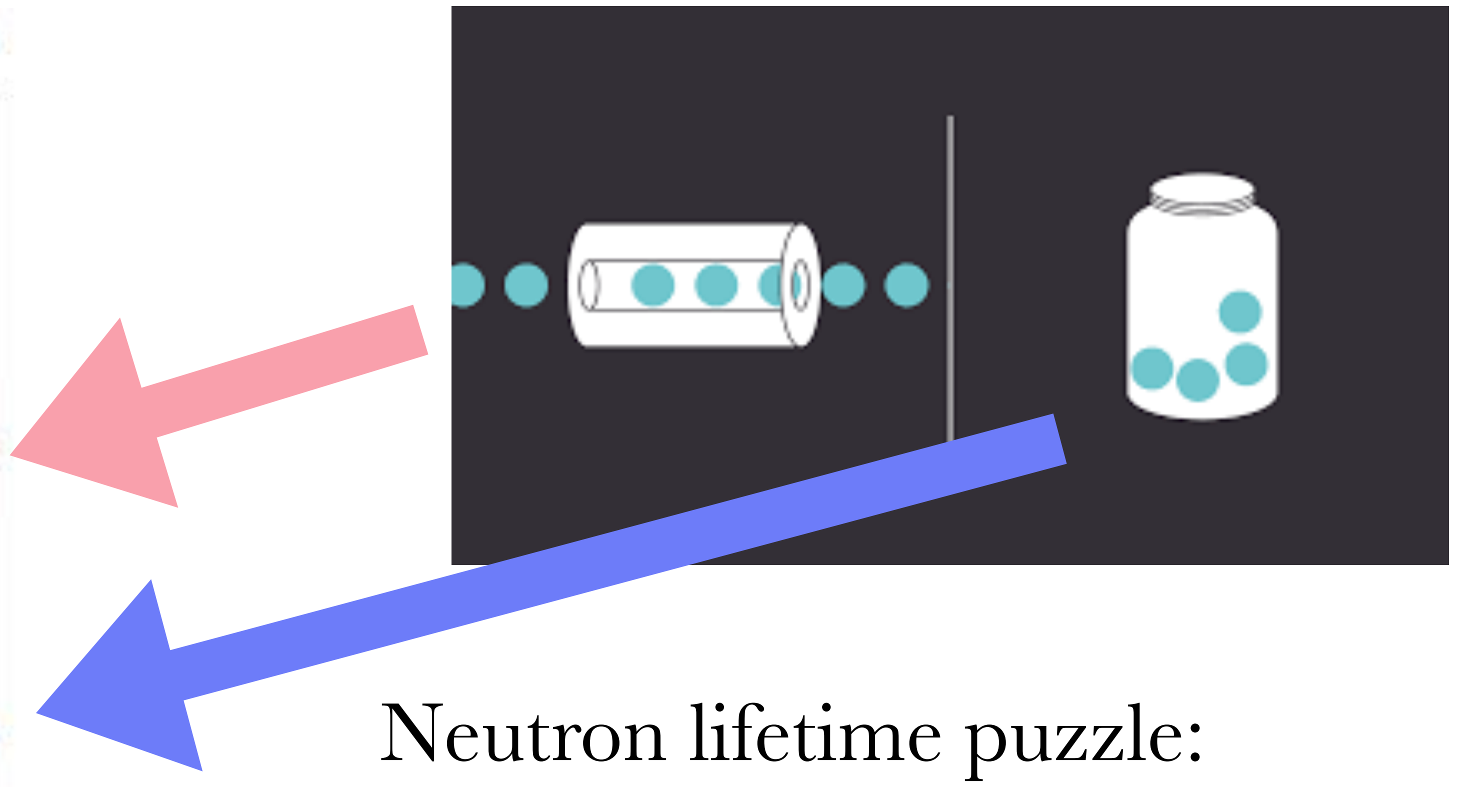
Selective Highlights

- ❑ The nucleon axial coupling g_A
- ❑ The nucleon axial form factor
- ❑ $\pi \to \pi$ from short-distance 4-quark/2-electron operators: $0\nu\beta\beta$
- ❑ BBN vs Isospin breaking

Simulating the decay of the neutron

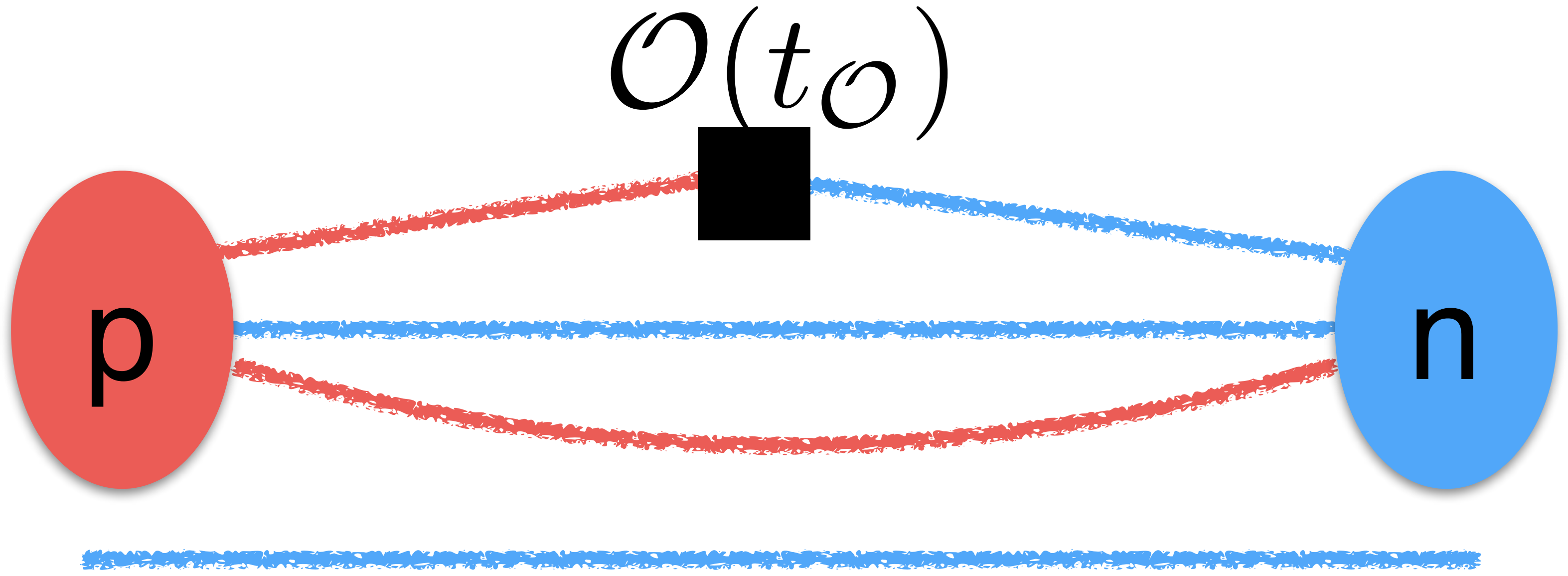






Neutron lifetime puzzle:
There is currently a 4-sigma discrepancy between the **beam** and **bottle** measurements of the neutron lifetime

$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{ud}|^2}{2\pi^3} m_e^5 (1 + 3g_A^2)(1 + RC) f$$



"$S_Q(t,0)$ = Quark Propagator"

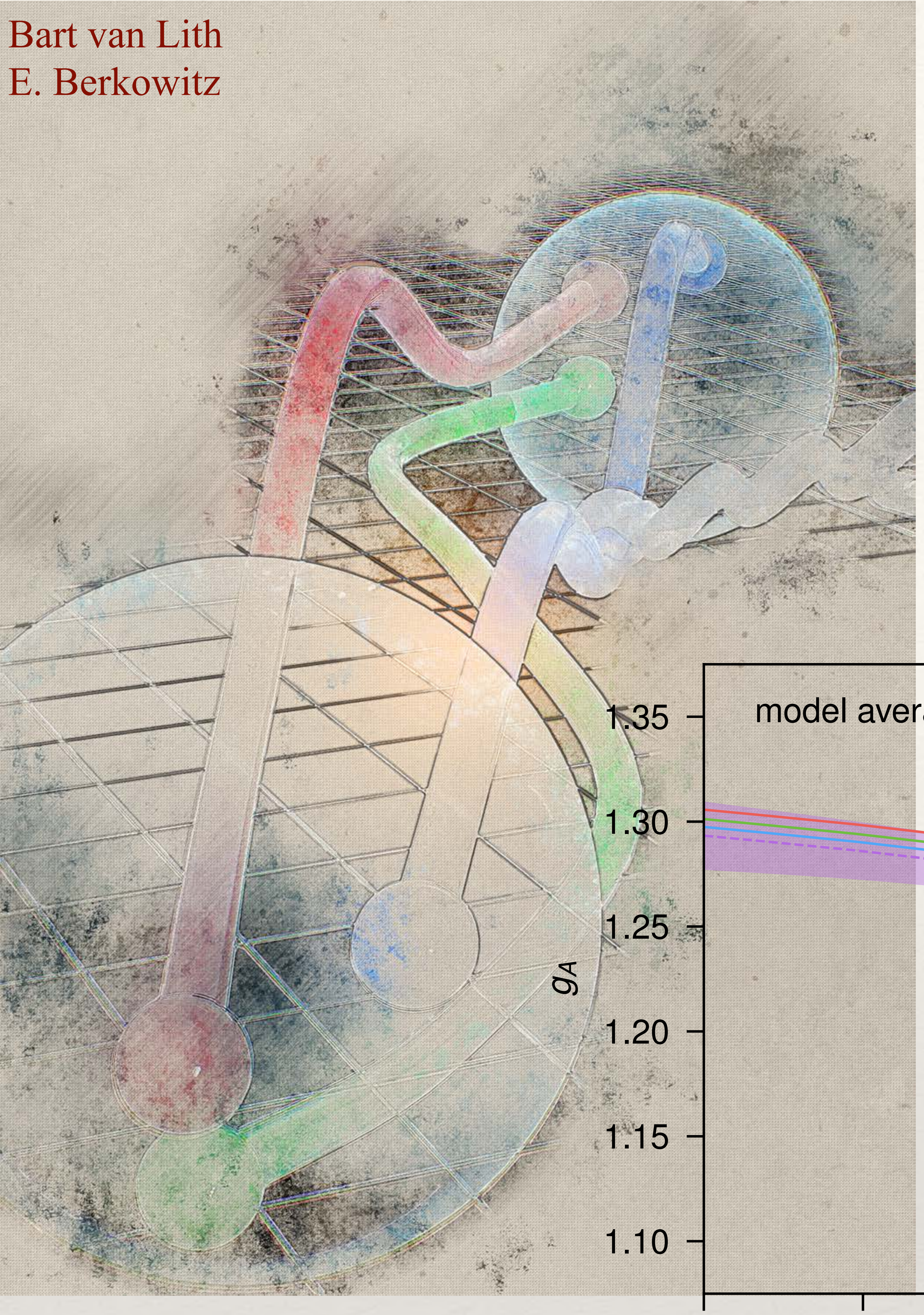
$$[D + M]_{y,z}\, S_{z,x} = \delta_{y,x}$$

Solve the Quark Propagators with Conjugate Gradient Matrix Multiplication

Known Matrix, Sparse, Large : ~400,000,000

GPUs are what allow us to do the calculations very efficiently

Bart van Lith
E. Berkowitz



LETTER

https://doi.org/10.1038/s41586-018-0161-8

Nature 558 (2018) no.7708, 91-94 [arXiv:1805.12130]

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

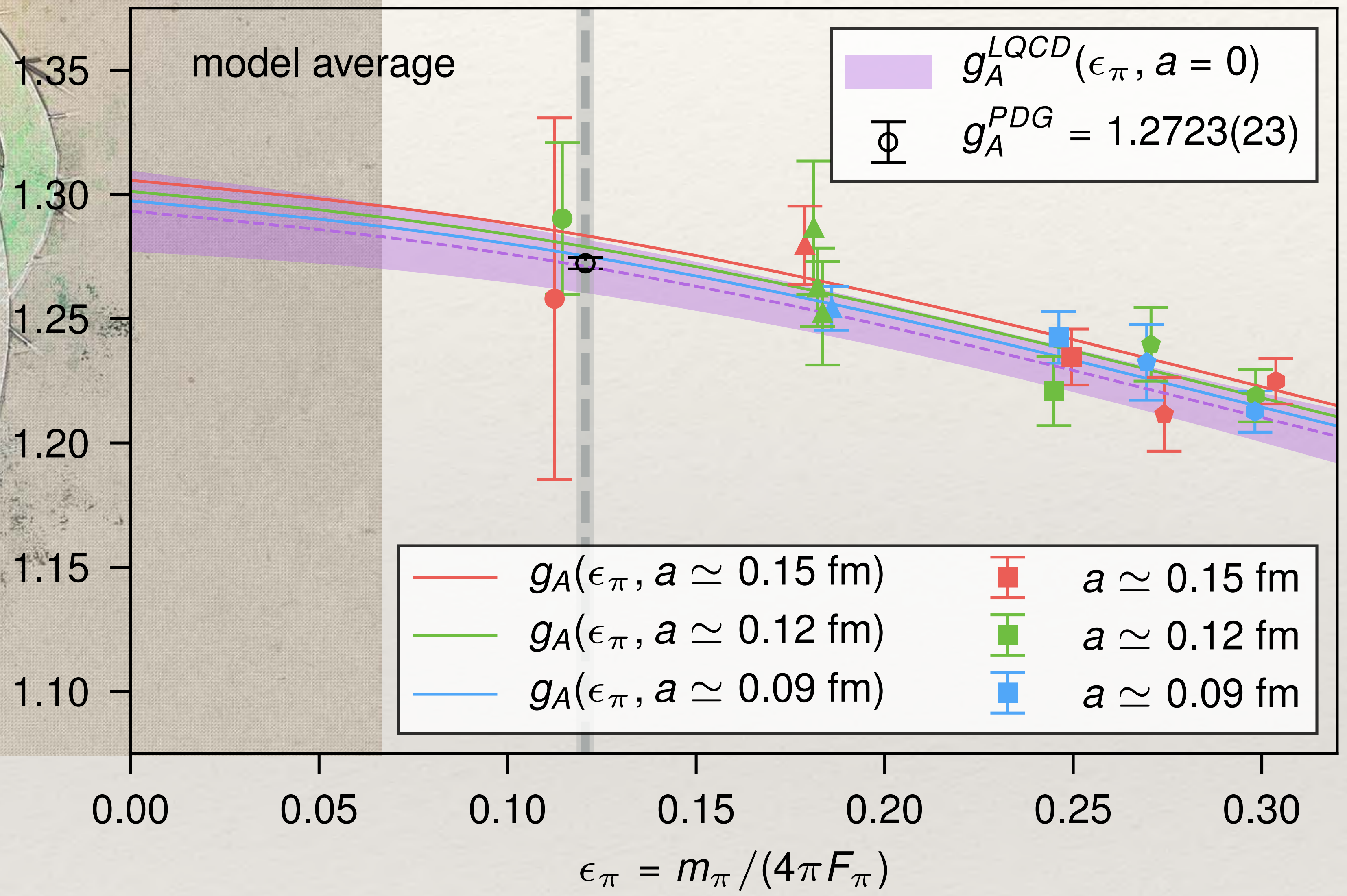
https://github.com/callat-qcd/project_gA

Lattice QCD Team

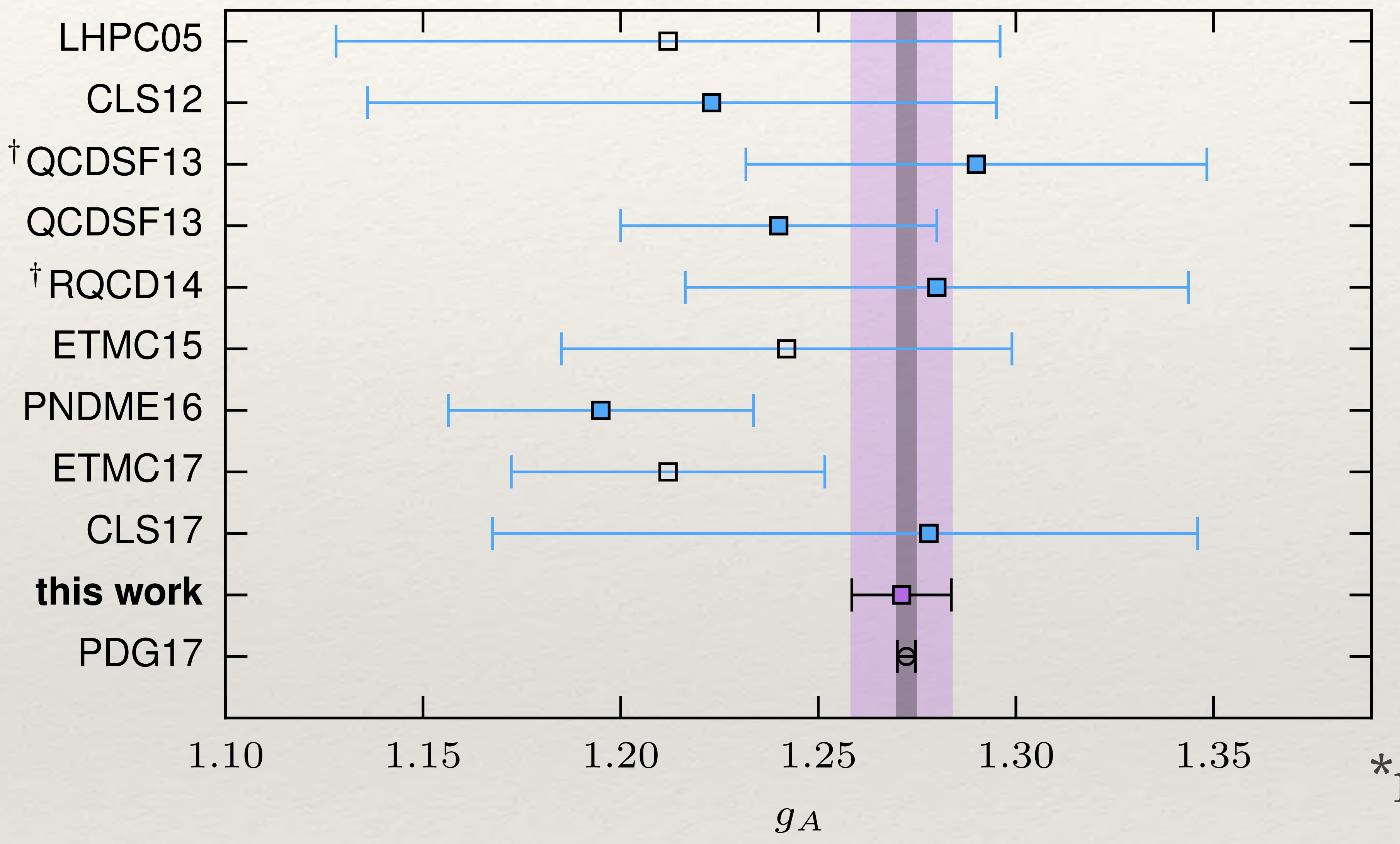
(postdoc, grad student)
Chia Cheng (Jason) Chang
Amy Nicholson
Enrico Rinaldi
Evan Berkowitz
Nicolas Garron
David Brantley
Henry Monge-Camacho
Chris Monahan
Chris Bouchard
Kate Clark
Bálint Joó
Thorsten Kurth
Kostas Orginos
Pavlos Vranas
André Walker-Loud

California Lattice Collaboration
(CalLat)
*not all in California

previously estimated to achieve 2% by 2020



LQCD results

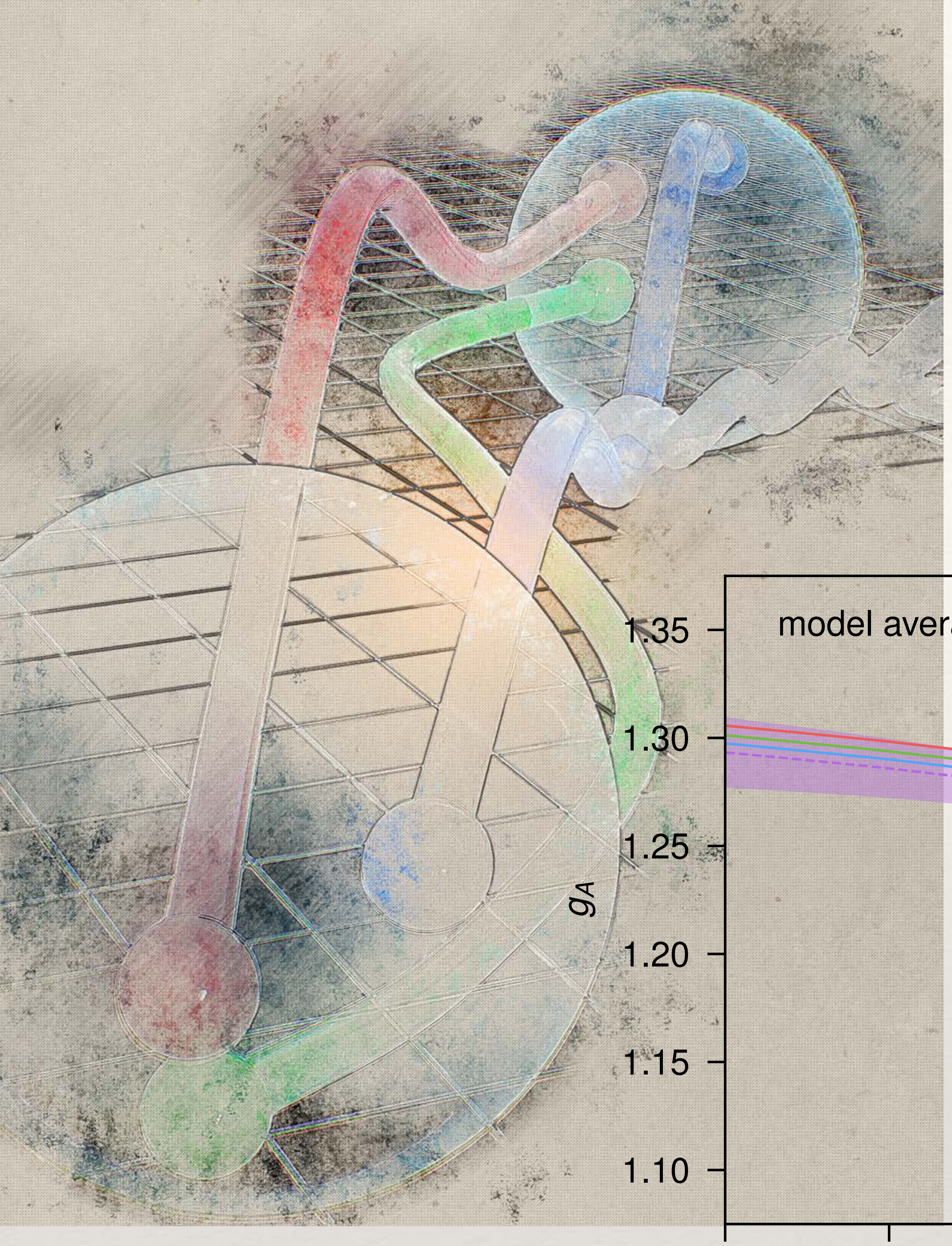


$$g_A^{\rm QCD} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$
$$= 1.2711(126)$$
$$g_A^{\rm UCNA} = 1.2772(020)$$

experiment factor of 6 more precise

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING
OAK RIDGE National Laboratory LEADERSHIP COMPUTING FACILITY
Lawrence Livermore National Laboratory
SciDAC Scientific Discovery through Advanced Computing
DOE Topical Collaboration Double Beta Decay
U.S. DEPARTMENT OF ENERGY Office of Science
NNSA National Nuclear Security Administration

Bart van Lith
E. Berkowitz



LETTER

https://doi.org/10.1038/s41586-018-0161-8

Nature 558 (2018) no.7708, 91-94 [arXiv:1805.12130]

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

https://github.com/callat-qcd/project_gA

Lattice QCD Team

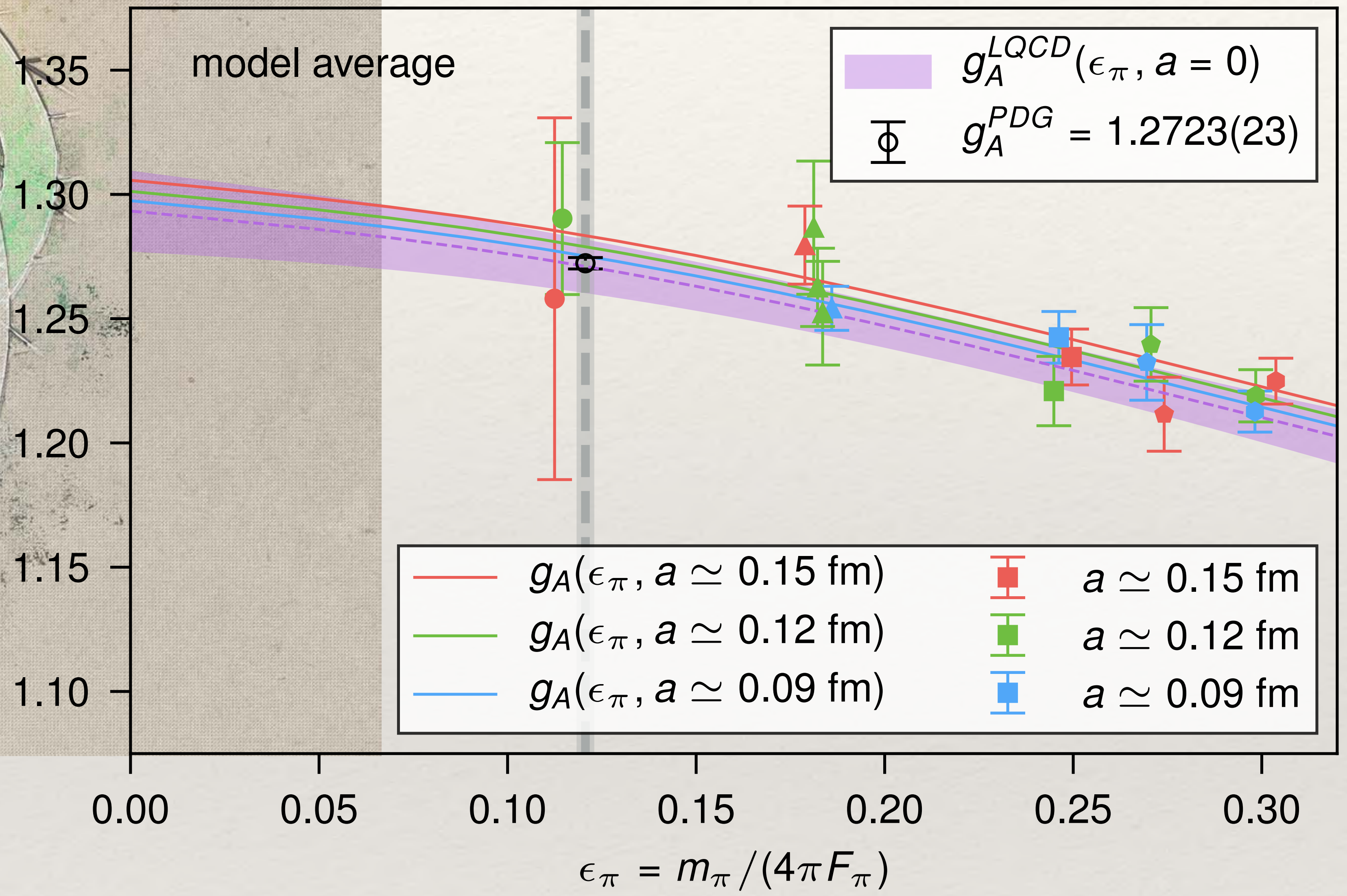
(postdoc, grad student)

Chia Cheng (Jason) Chang
Amy Nicholson
Enrico Rinaldi
Evan Berkowitz
Nicolas Garron
David Brantley
Henry Monge-Camacho
Chris Monahan
Chris Bouchard
Kate Clark
Bálint Joó
Thorsten Kurth
Kostas Orginos
Pavlos Vranas
André Walker-Loud

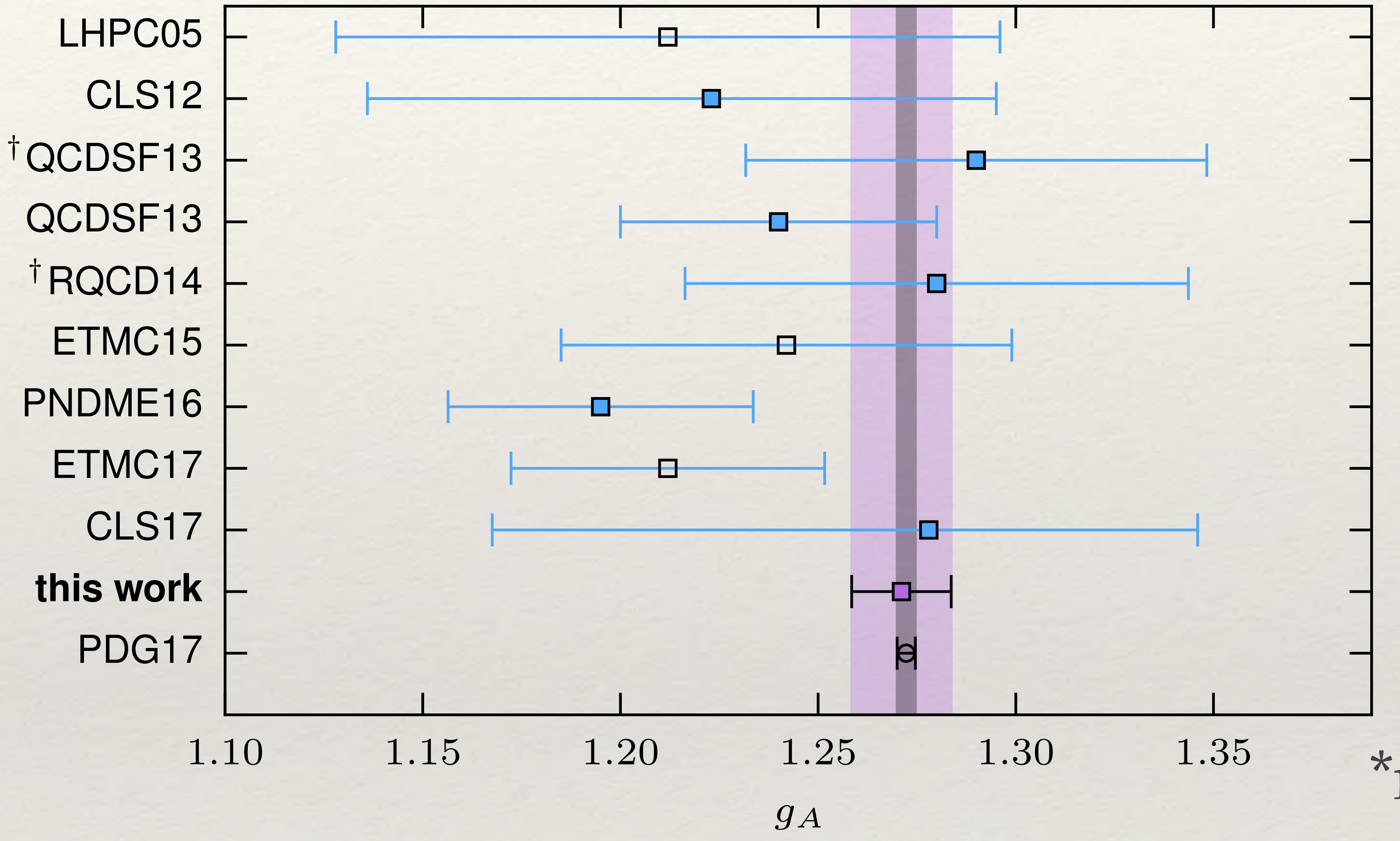
California Lattice Collaboration

(CalLat)
*not all in California

previously estimated to achieve 2% by 2020



LQCD results



$$g_A^{\rm QCD} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$

$$= 1.2711(126)$$

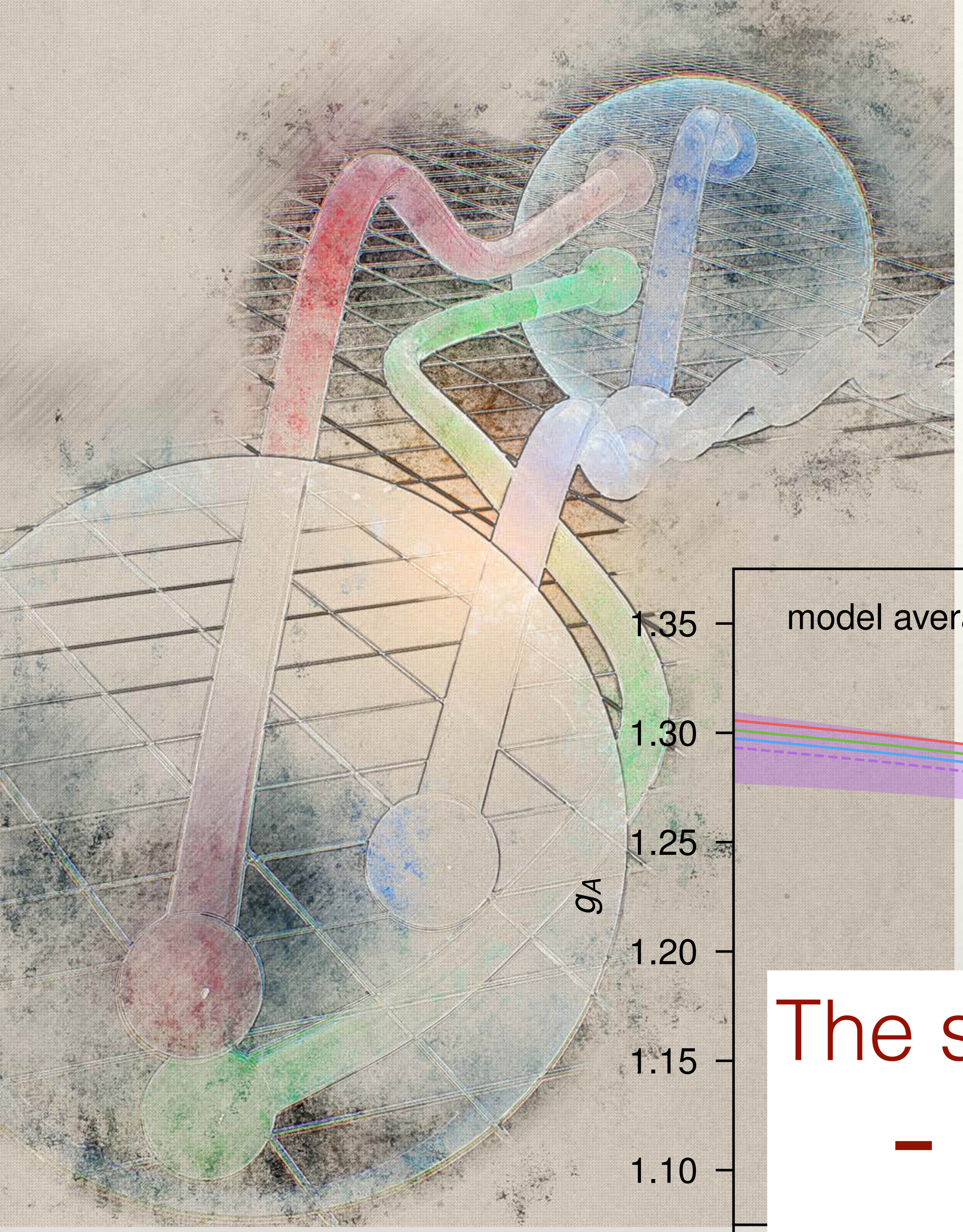
$$g_A^{\rm UCNA} = 1.2772(020)$$ ~~experiment factor of 6 more precise~~

$$g_A^{\rm PERKEO\ III} = 1.27641(0055)$$ experiment factor of 22 more precise

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING
OAK RIDGE National Laboratory | LEADERSHIP COMPUTING FACILITY
Lawrence Livermore National Laboratory
SciDAC Scientific Discovery through Advanced Computing
U.S. DEPARTMENT OF ENERGY | Office of Science
NNSA National Nuclear Security Administration

DOE Topical Collaboration
Double Beta Decay

Bart van Lith
E. Berkowitz



LETTER

https://doi.org/10.1038/s41586-018-0161-8

Nature 558 (2018) no.7708, 91-94 [arXiv:1805.12130]

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

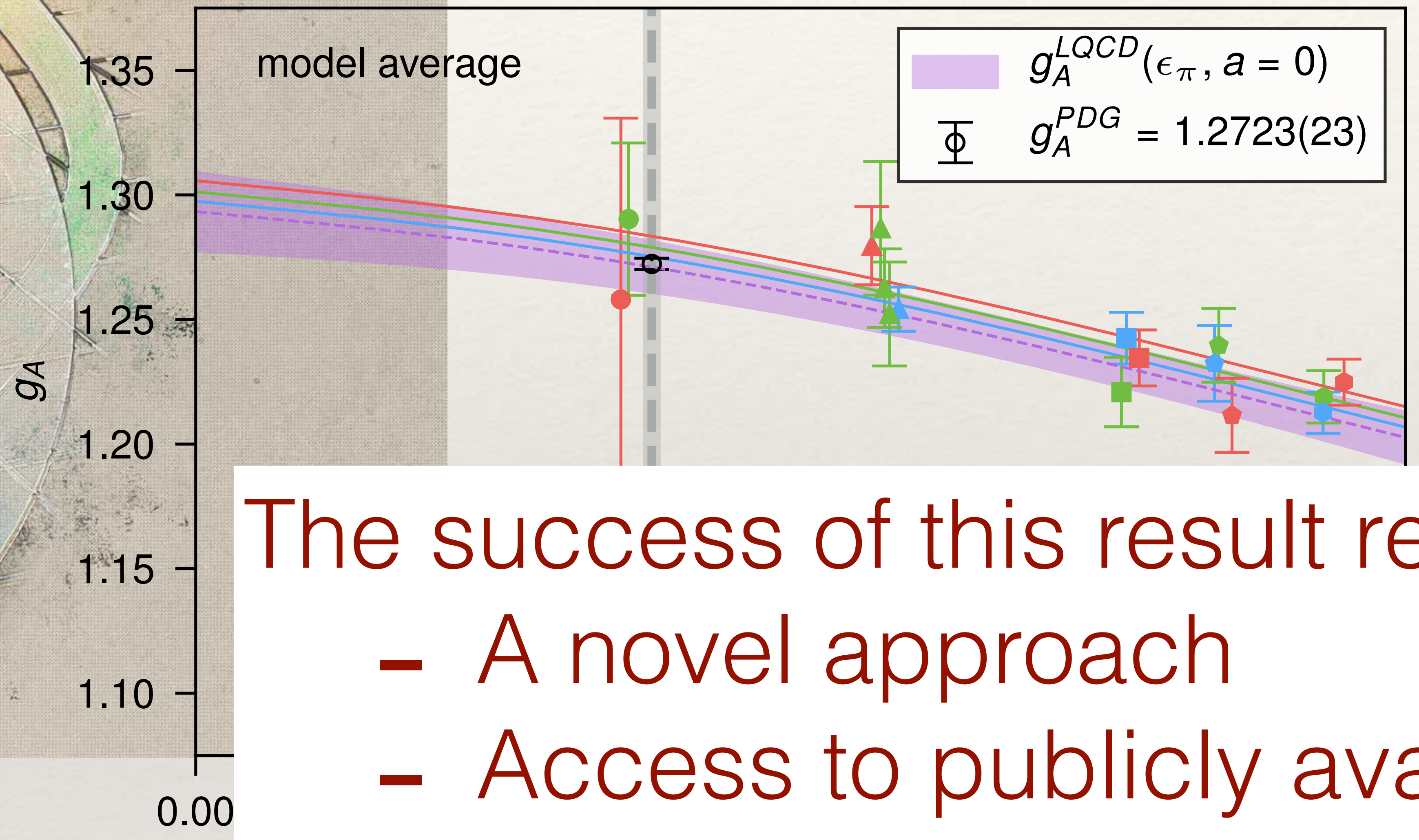
https://github.com/callat-qcd/project_gA

Lattice QCD Team

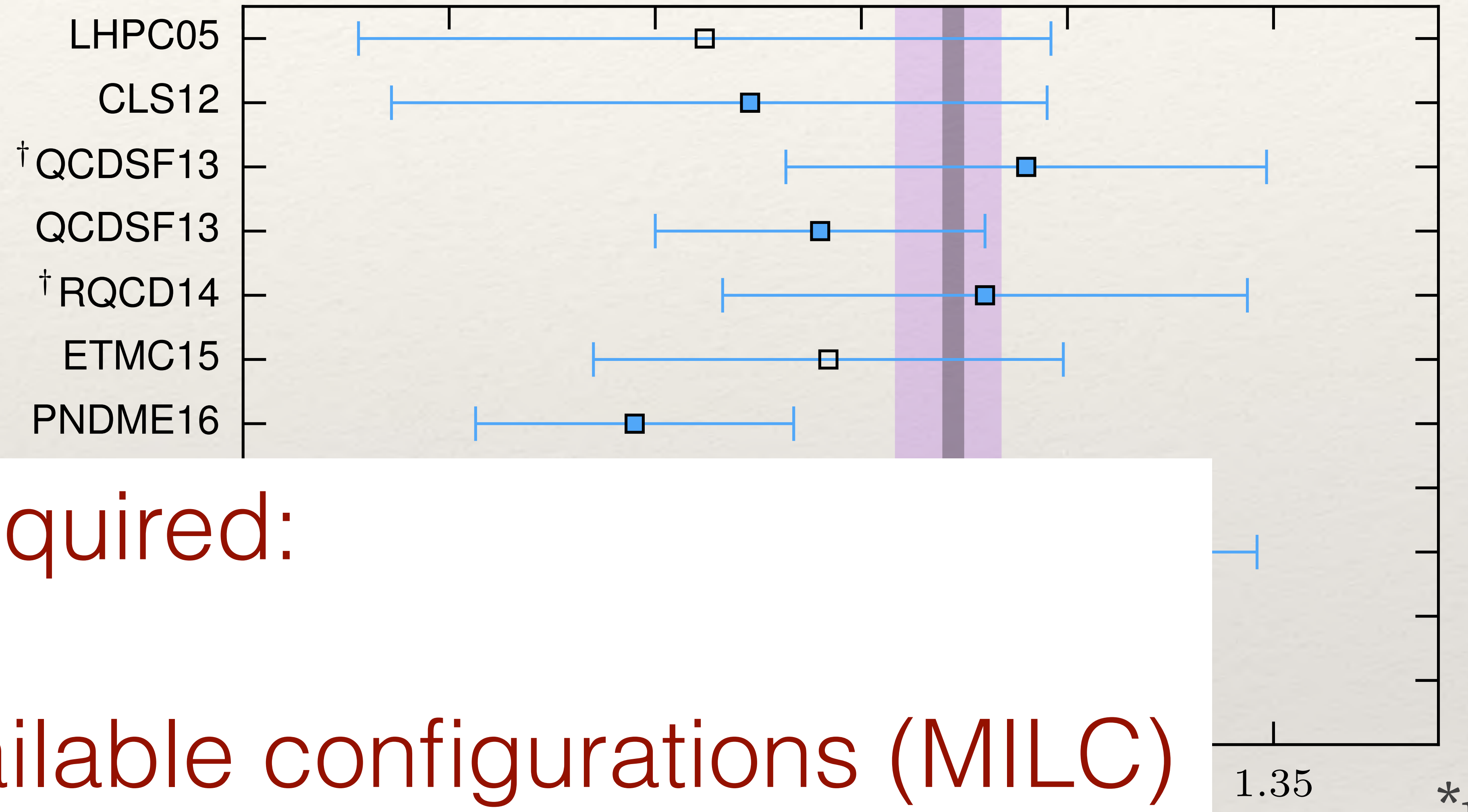
(postdoc, grad student)
Chia Cheng (Jason) Chang
Amy Nicholson
Enrico Rinaldi
Evan Berkowitz
Nicolas Garron
David Brantley
Henry Monge-Camacho
Chris Monahan
Chris Bouchard
Kate Clark
Bálint Joó
Thorsten Kurth
Kostas Orginos
Pavlos Vranas
André Walker-Loud

California Lattice Collaboration
(CalLat)
*not all in California

previously estimated to achieve 2% by 2020



LQCD results



The success of this result required:

- A novel approach
- Access to publicly available configurations (MILC)
- Ludicrously fast GPU code (Kate Clark of NVIDIA)
- Access to Leadership Class Computing (INCITE)

$$= 1.2711(126)$$

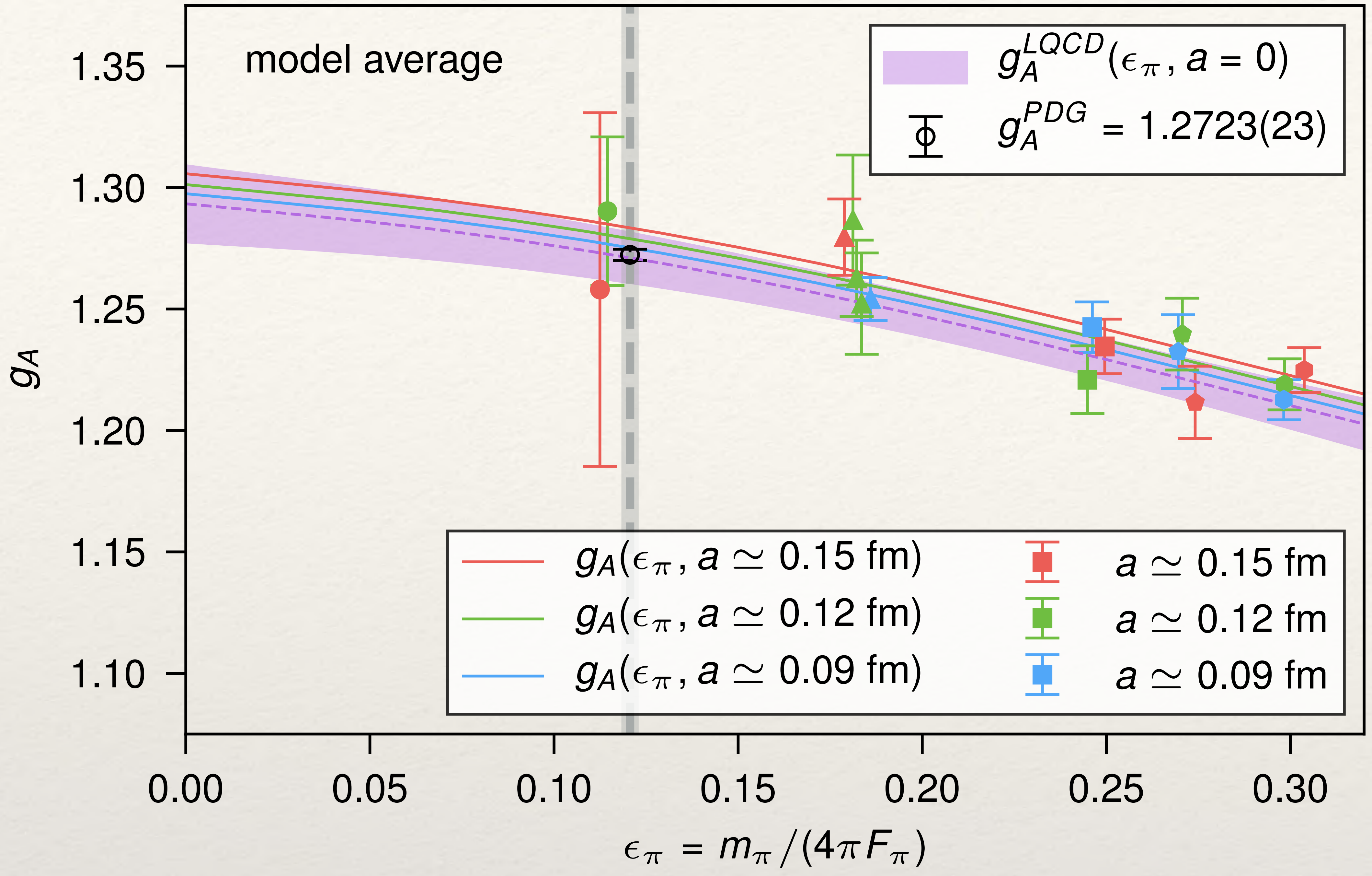
$$g_A^{\text{UCNA}} = 1.2772(020)$$ ~~experiment factor of 6 more precise~~

$$g_A^{\text{PERKEO III}} = 1.27641(0055)$$ experiment factor of 22 more precise

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING
OAK RIDGE National Laboratory LEADERSHIP COMPUTING FACILITY
Lawrence Livermore National Laboratory
SciDAC Scientific Discovery through Advanced Computing
DOE Topical Collaboration Double Beta Decay
U.S. DEPARTMENT OF ENERGY Office of Science
NNSA National Nuclear Security Administration

Nature 558 (2018) no. 7708, 91-94
Chang et al. [arXiv:1805.12130]

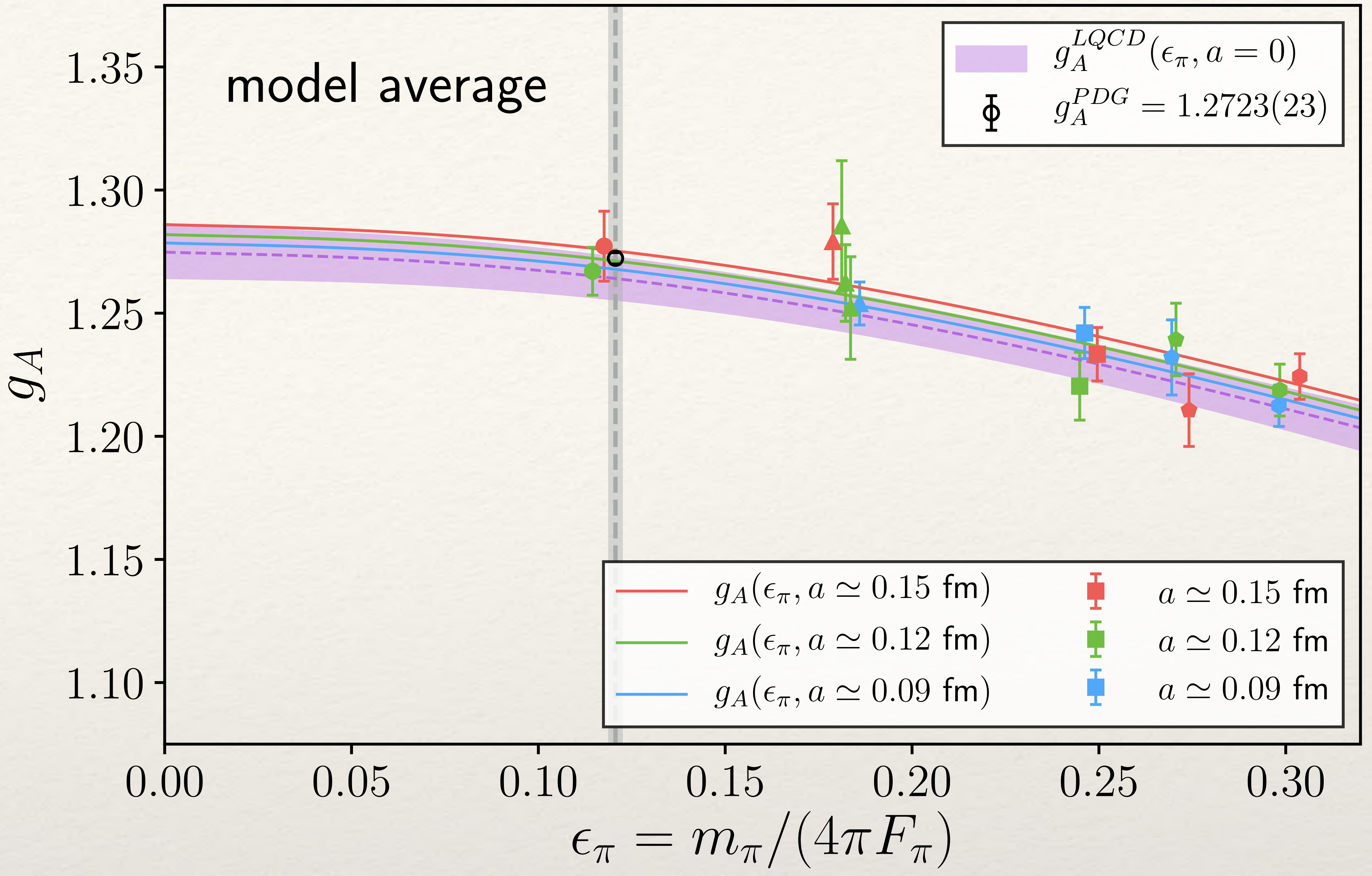
1 year on Titan (ORNL) + 2 years on GPU machines at LLNL



California Lattice Collaboration

Sierra Early Science

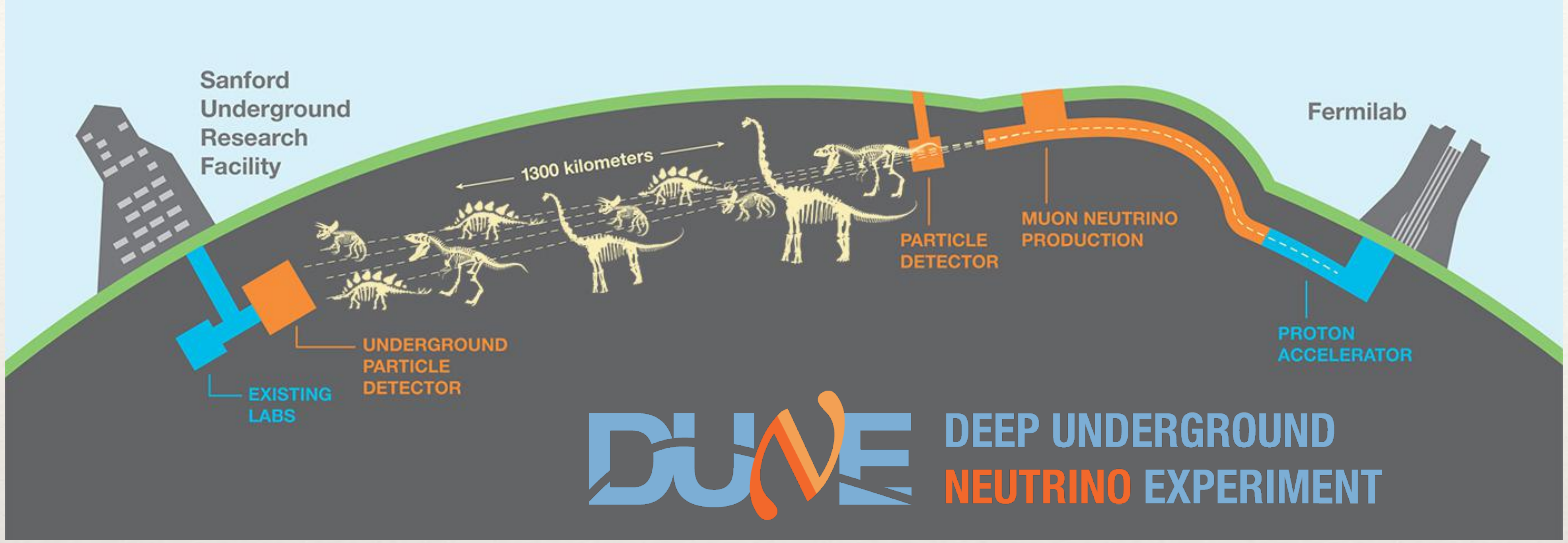
PRELIMINARY

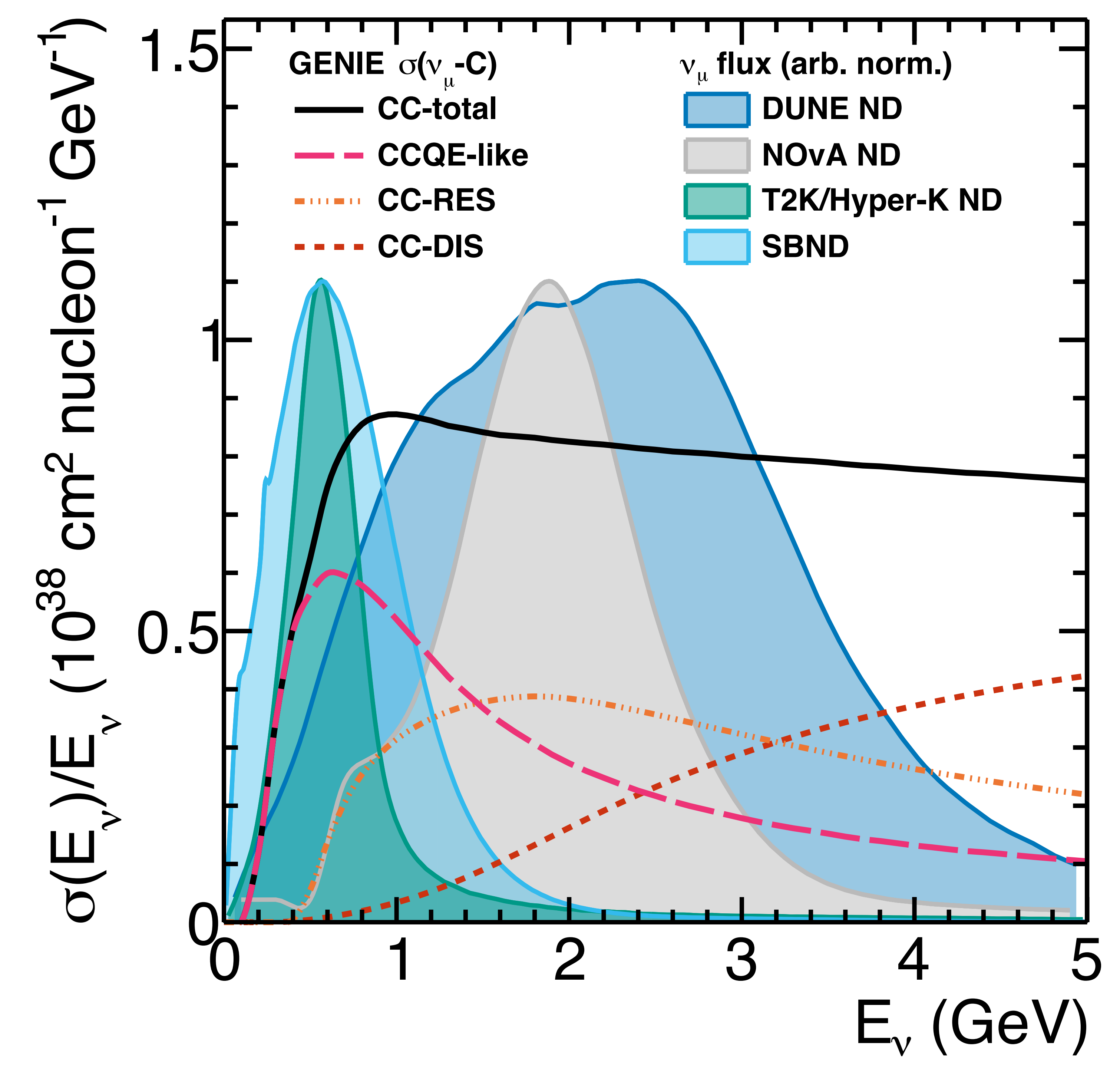


- The a12m130 (48^3 x 64 x 20) with 3 sources cost as much as all other ensembles combined
  - 2.5 weekends on Sierra → 16 srcs
  - Now, 32 srcs (un-constrained, 3-state fit)
- We generated a new a15m135XL (48^3 x 64) ensemble (old a15m130 is 32^3 x 48)
  - $M_\pi L = 4.93$ (old $M_\pi L = 3.2$)
  - $L_5 = 24$, $N_{src} = 16$
- We are running $g_A(Q^2)$ on Summit this year (DOE INCITE)
  - We anticipate improving g_A to ~0.5%

$$g_A = 1.2711(125) \rightarrow 1.2641(93) \;\; [0.74\%]$$

Nucleon Axial Form Factor





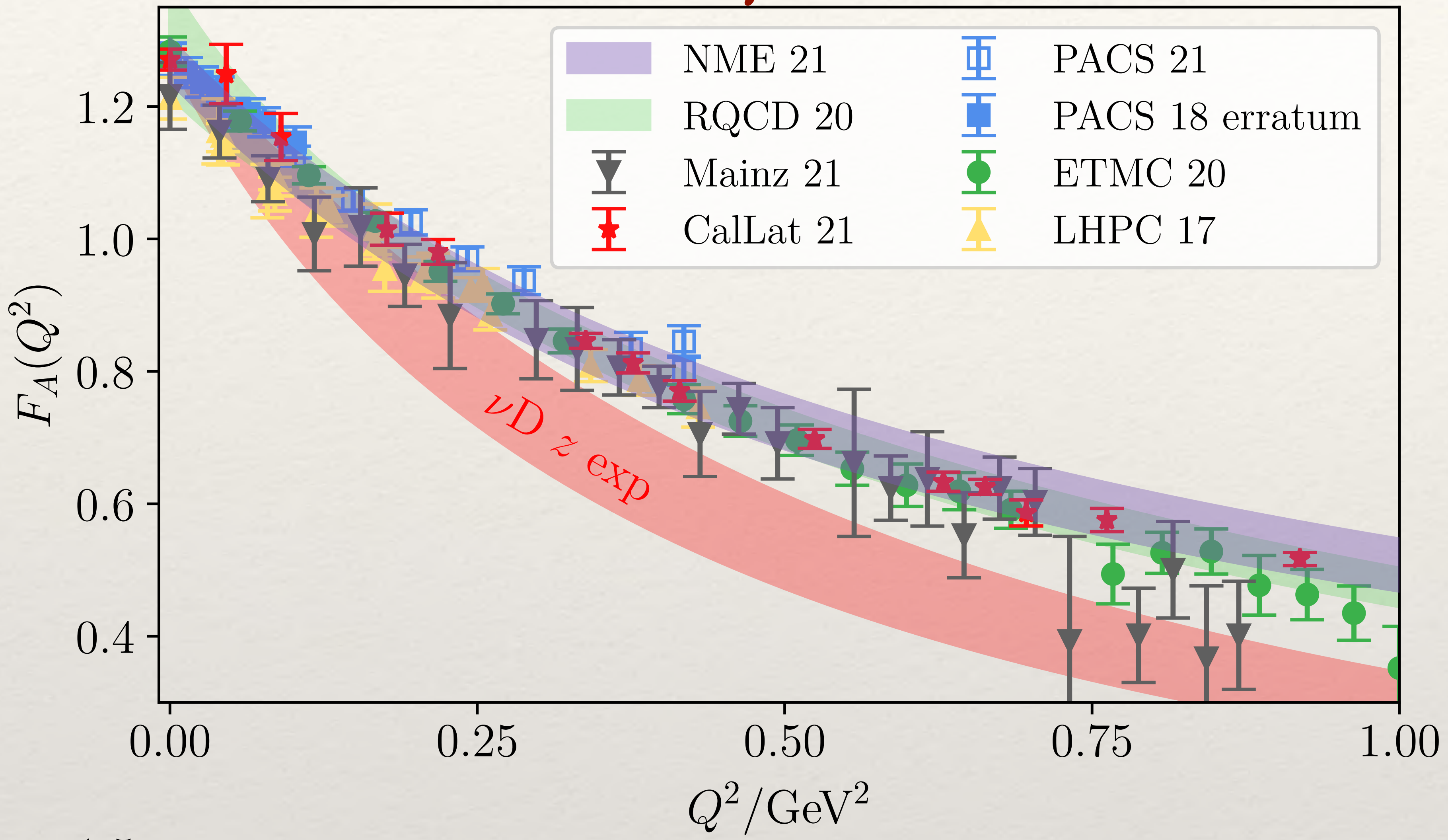
Unoscillated flux from different ν-A mechanisms

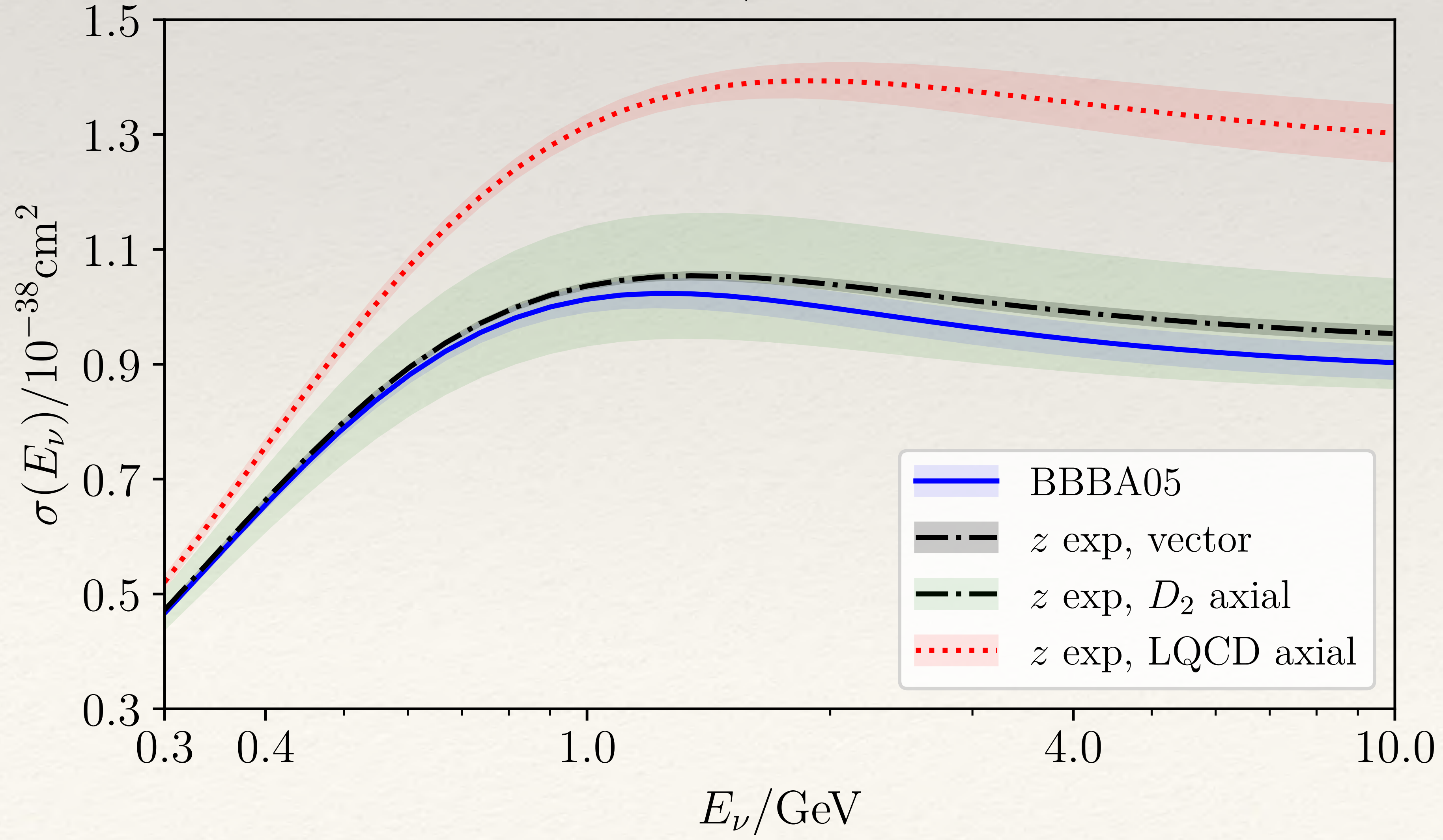
- DUNE and Hyper-K science goals reliant upon accurate and precise modeling of ν-A cross sections
  - The 50-year old pion-production model that is currently used in event generators was described by its authors as *naive and obviously wrong in its simplicity* [FKR]
  - No experimental path forward to improve these basic νN reactions
- With Lattice QCD, we can pin down certain contributions to the cross section to minimize the modeling uncertainty
  - $\nu n \to \ell p$, $\nu N \to \ell \Delta$, $\nu N \to \ell N \pi$, $\nu NN \to \nu NN$, …

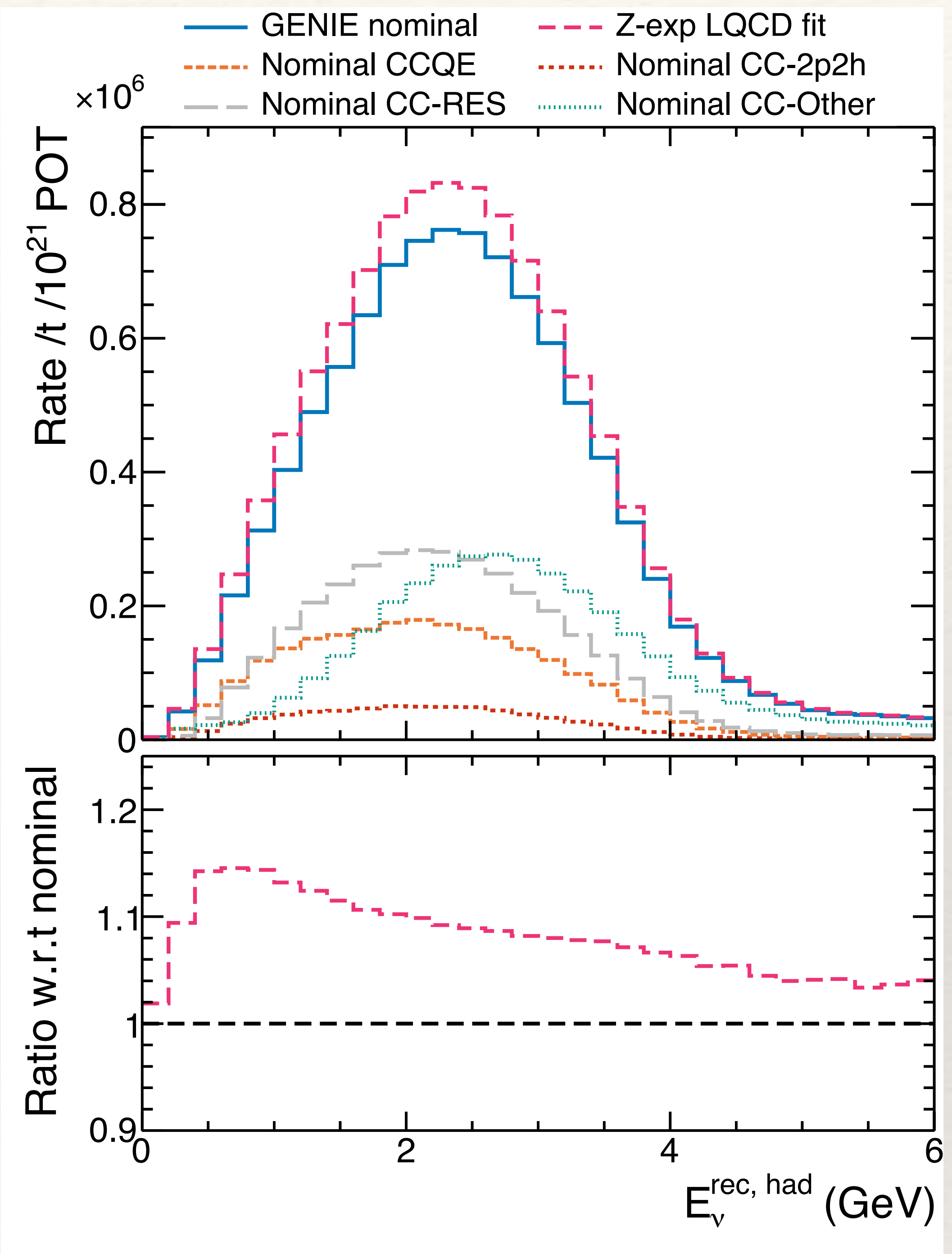
[FKR] Feynman, Kislinger, Ravndal PRD 3 (1971)

Nucleon Axial Form Factor

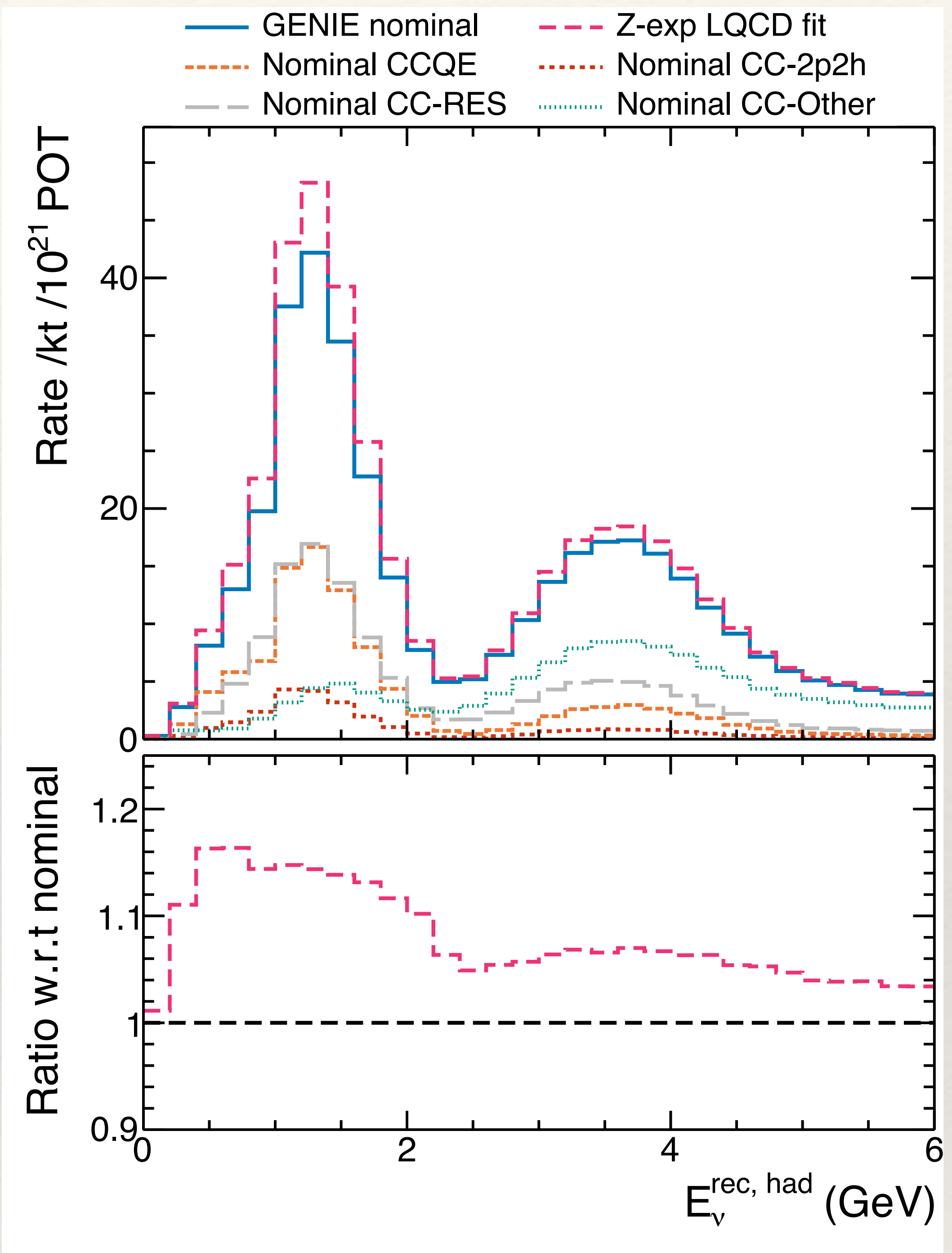
- Current lattice QCD results show significant tension for even the simplest quasi-elastic form factor - A. Meyer, A. Walker-Loud, C. Wilkinson, Ann. Rev. Nucl. Part. Sci. 72 (2022)







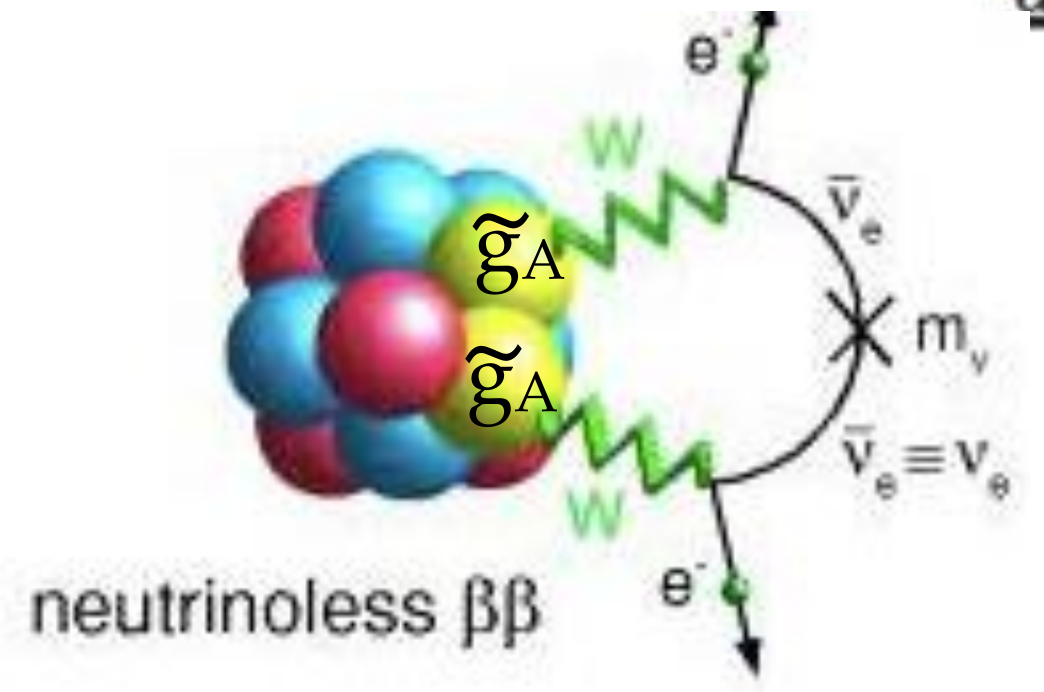
Near detector



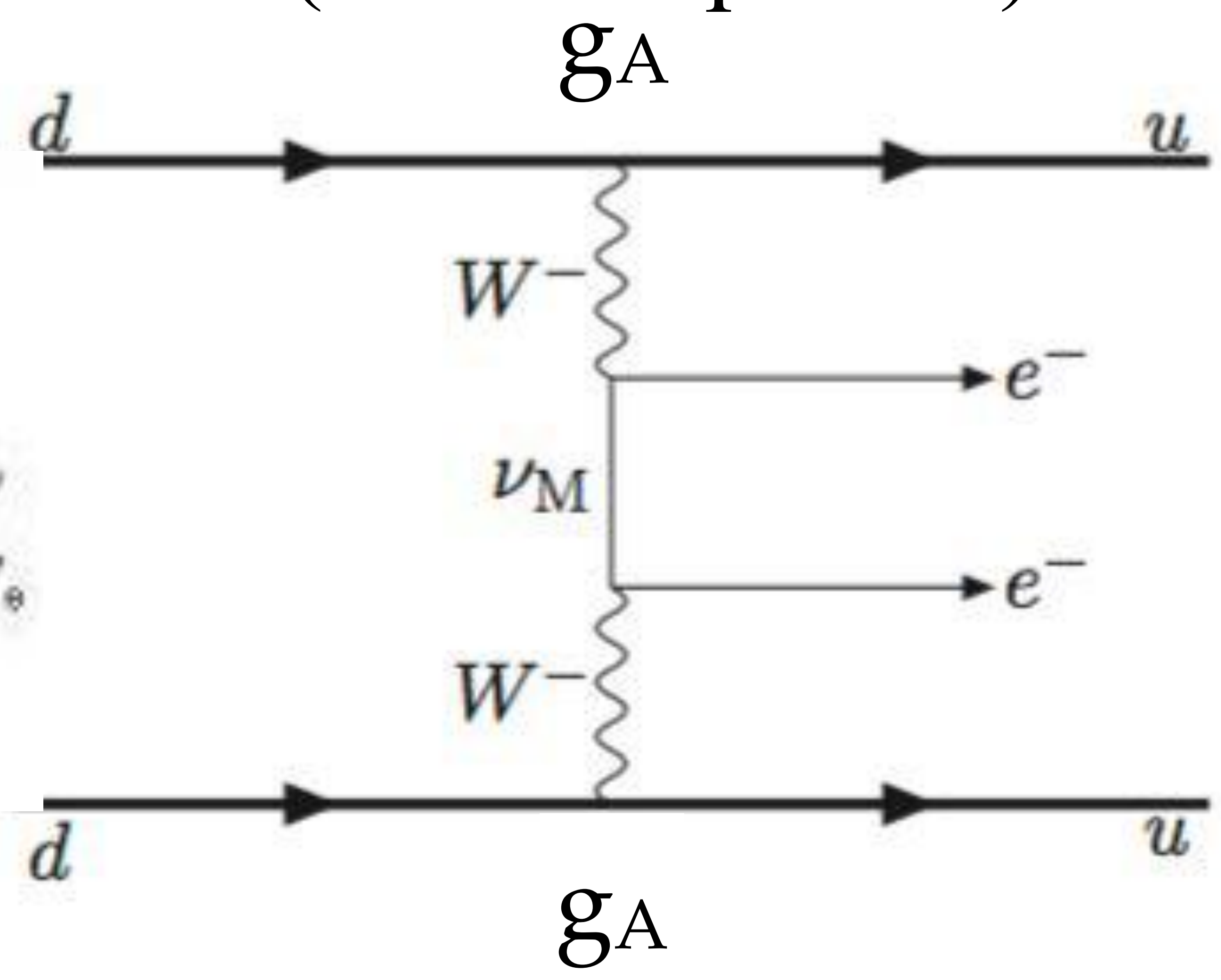
Far detector

- Within a couple years, lattice QCD will deliver "final" FA results
- We are not expecting any surprise systematics that will change this picture
- Frontier is the delta-resonance and pion-production amplitudes

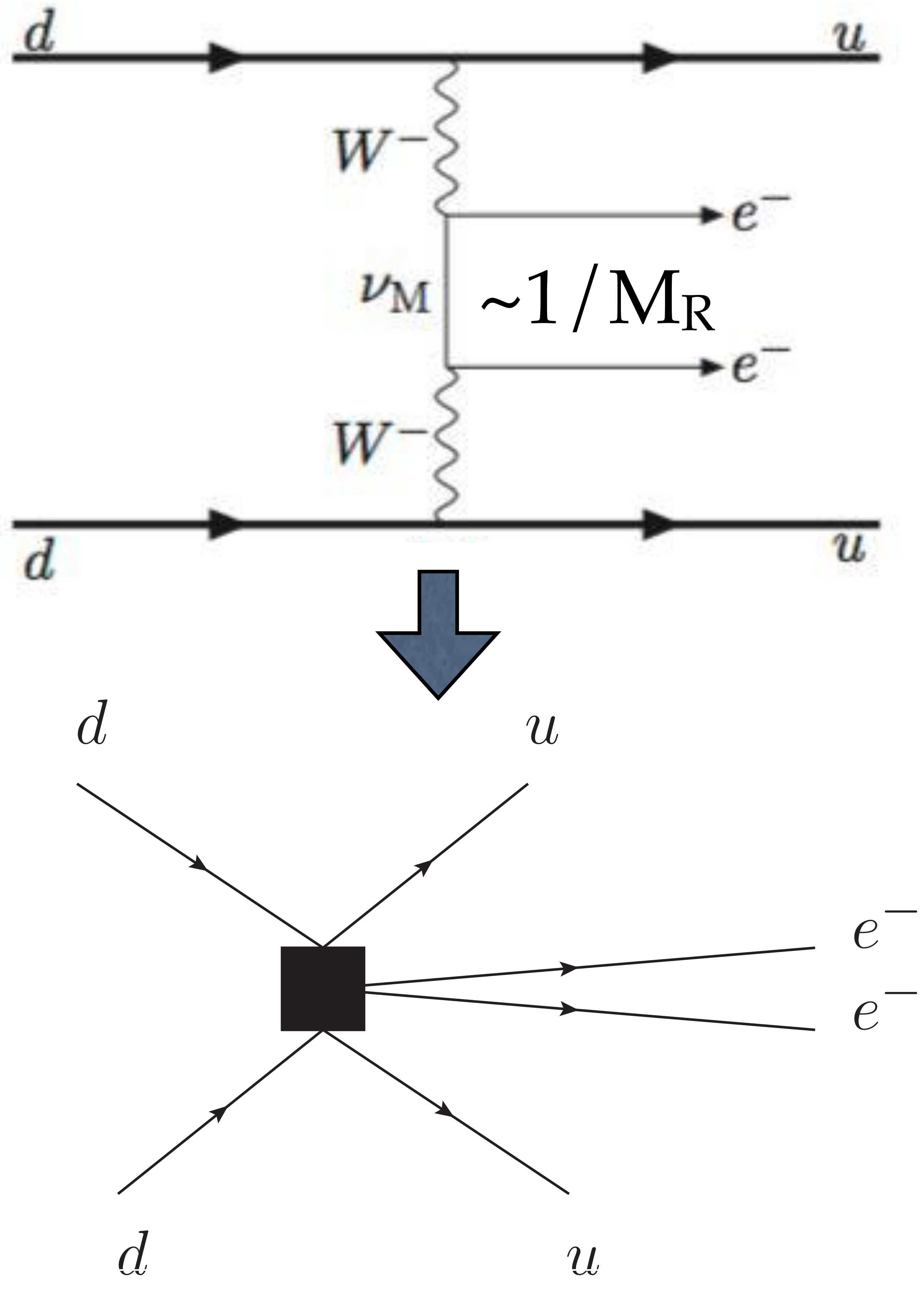
Neutrinoless Double Beta-Decay



long-range contribution (standard picture)



short-range contribution possibly equally/more important



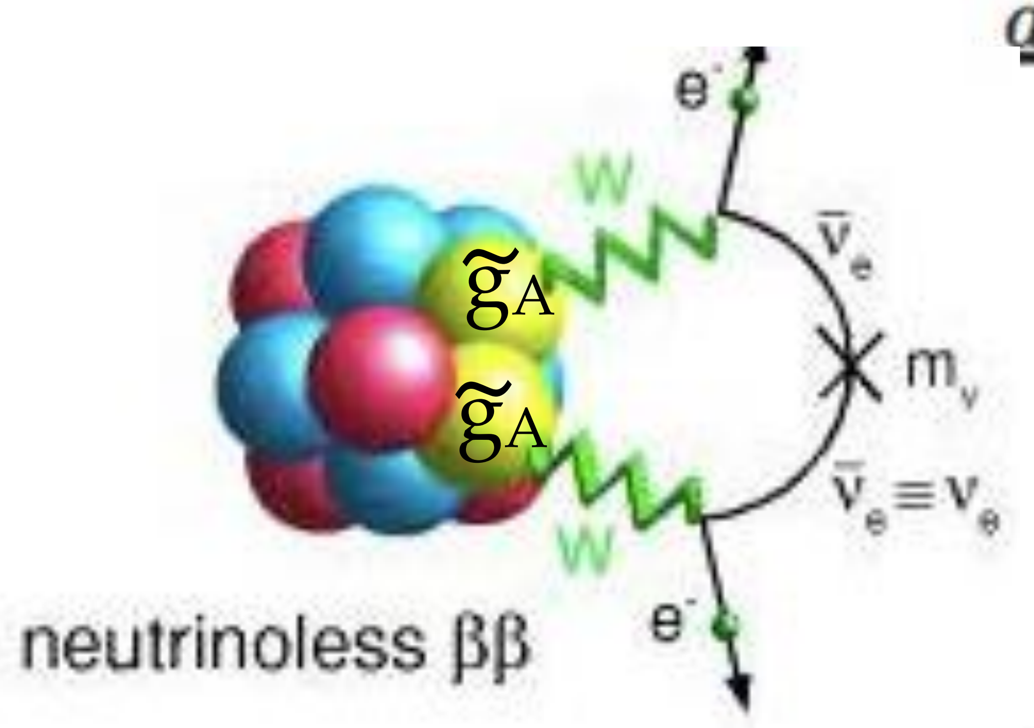
Long Range: lattice QCD can help understand "quenching" of g_A in a nucleus - although - see Gysbers et al. Nature Phys (2019) [1903.00047]

Short Range: lattice QCD is the ONLY theoretical tool we have to understand these contributions with quantified uncertainties

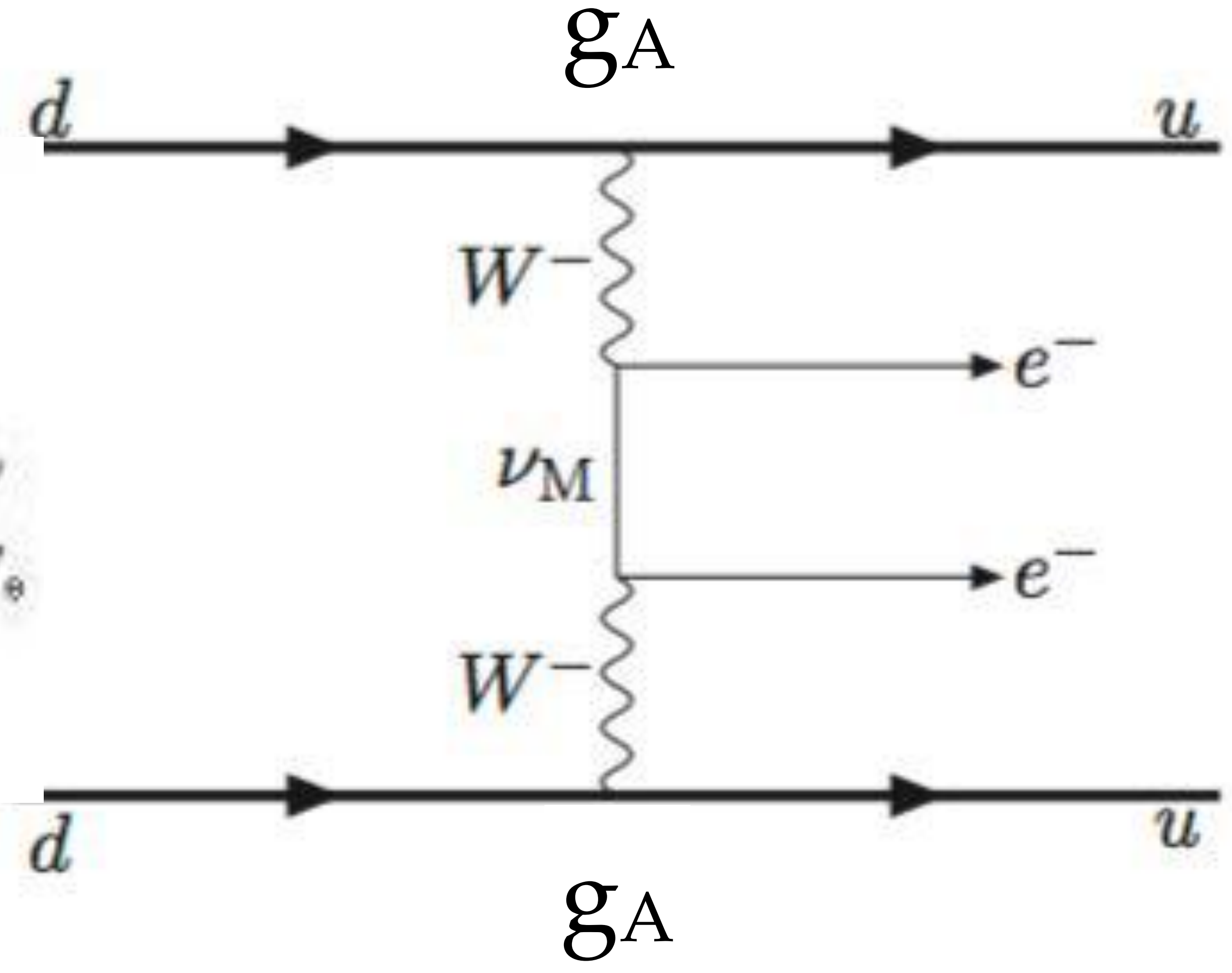
Lattice QCD: compute 2-nucleon matrix elements to determine unknown couplings/transition rates

Many Body Nuclear Effective Theory: take lattice QCD results as input and compute transition rate in nucleus (Haxton, others)

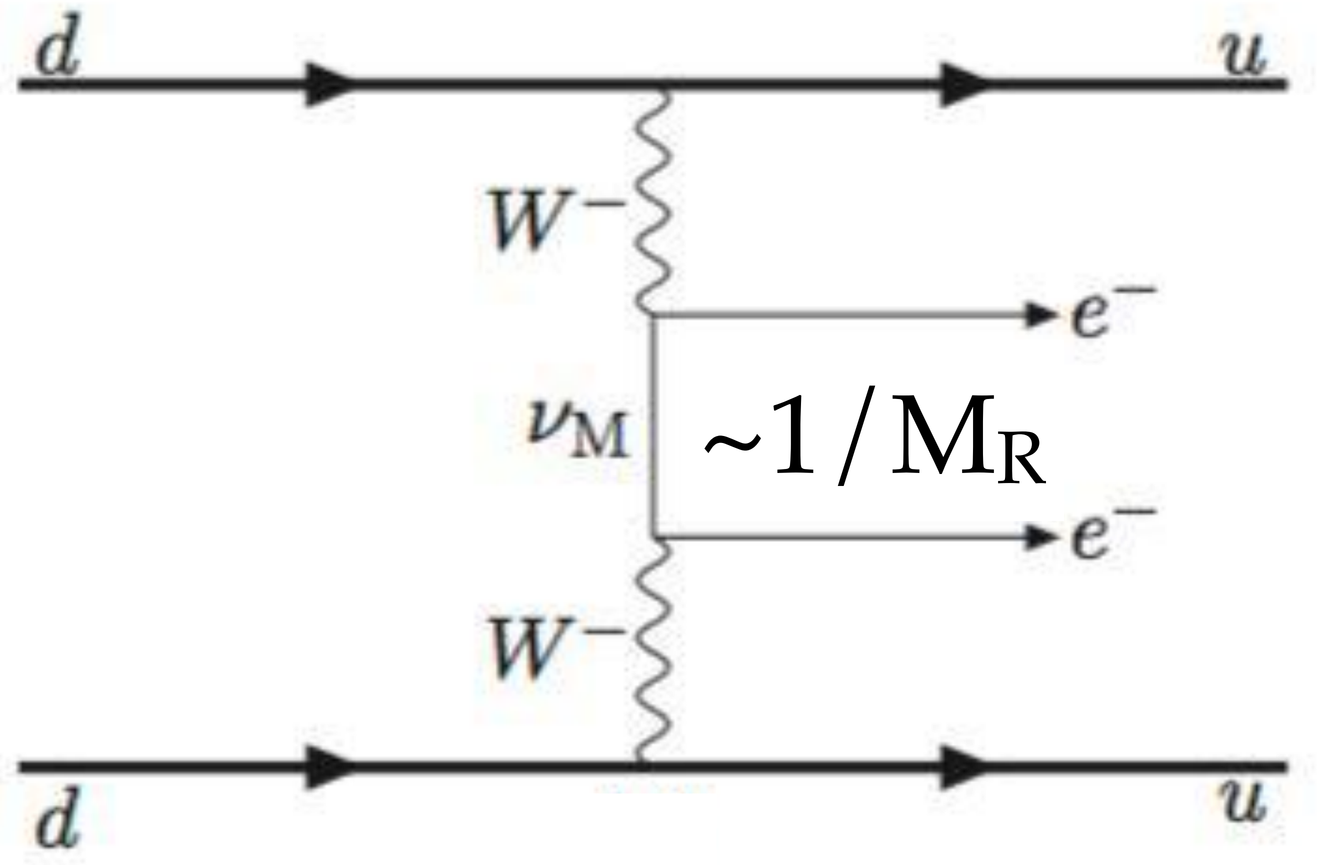
Neutrinoless Double Beta-Decay



long-range contribution
(standard picture)

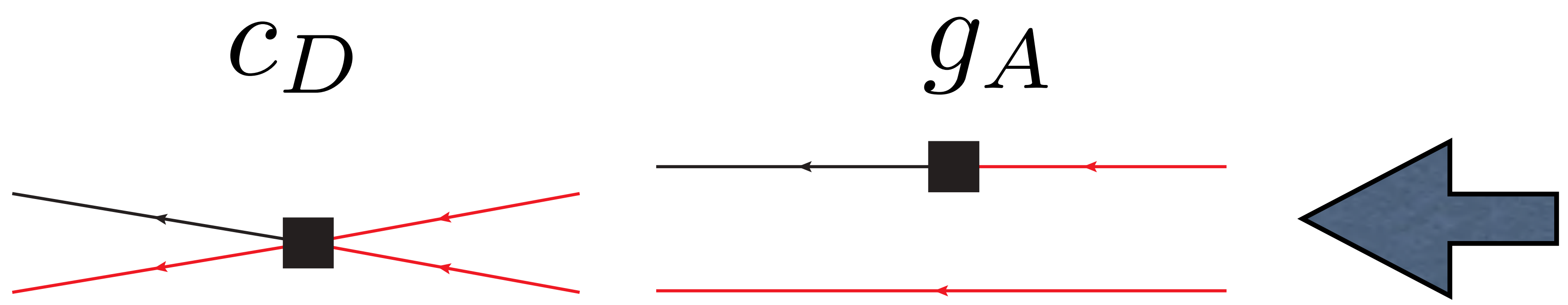


short-range contribution
possibly equally/more important

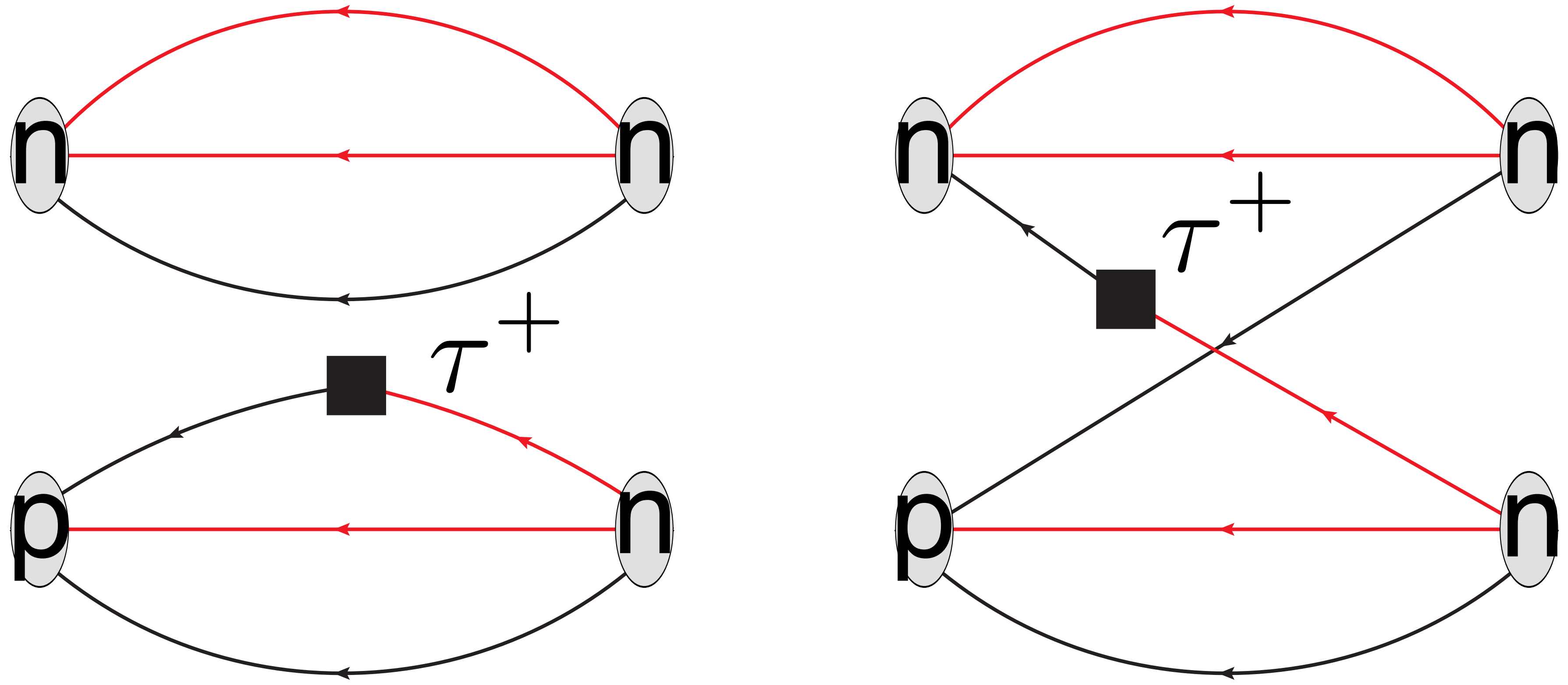


Long Range Contribution

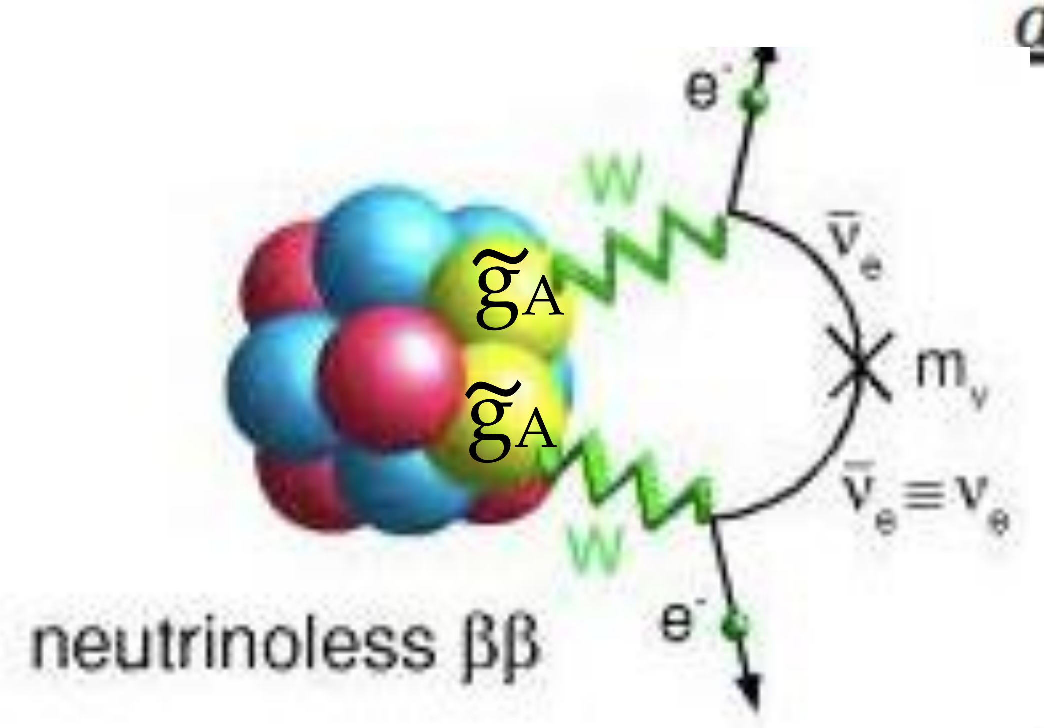
EFT Level



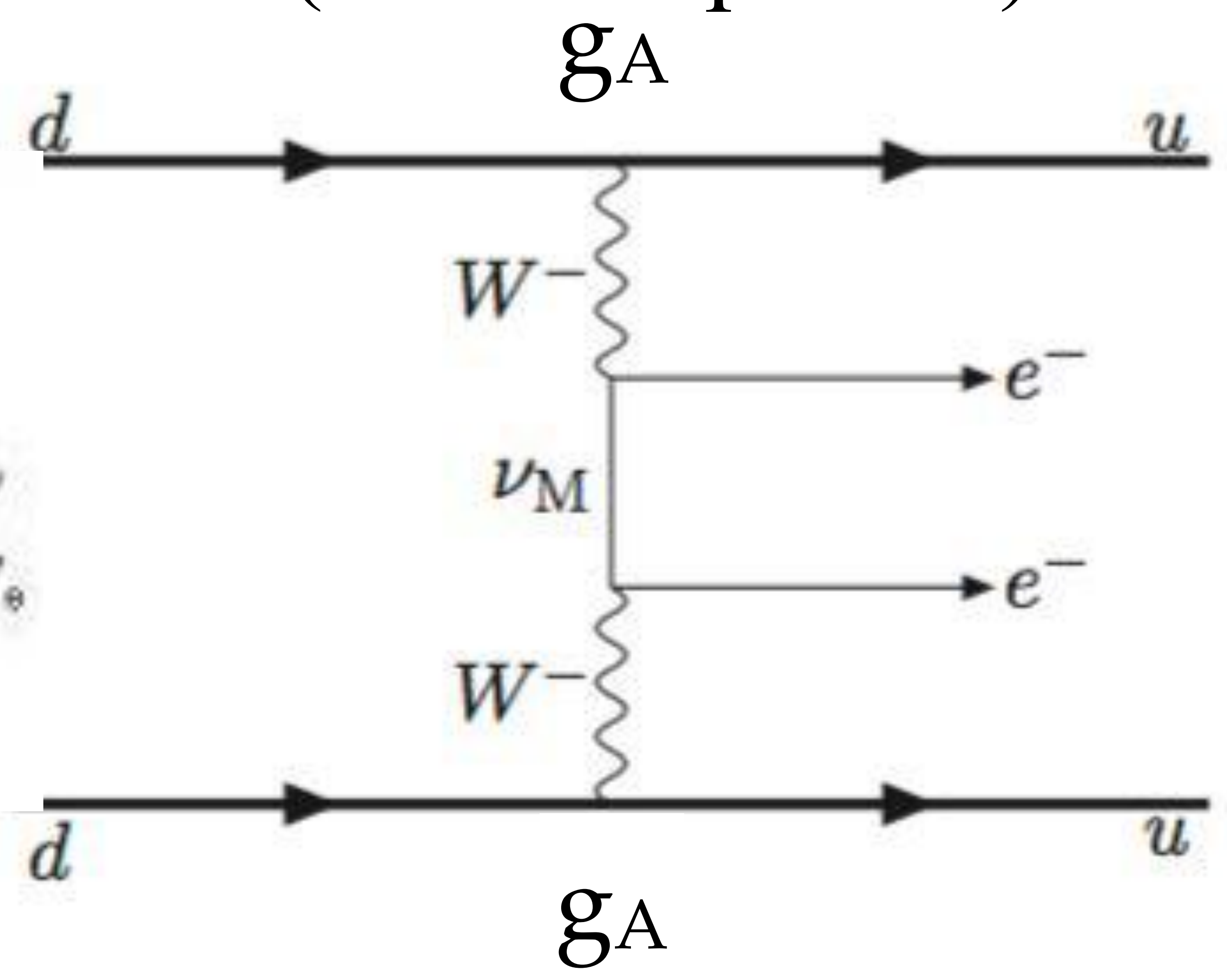
Lattice QCD



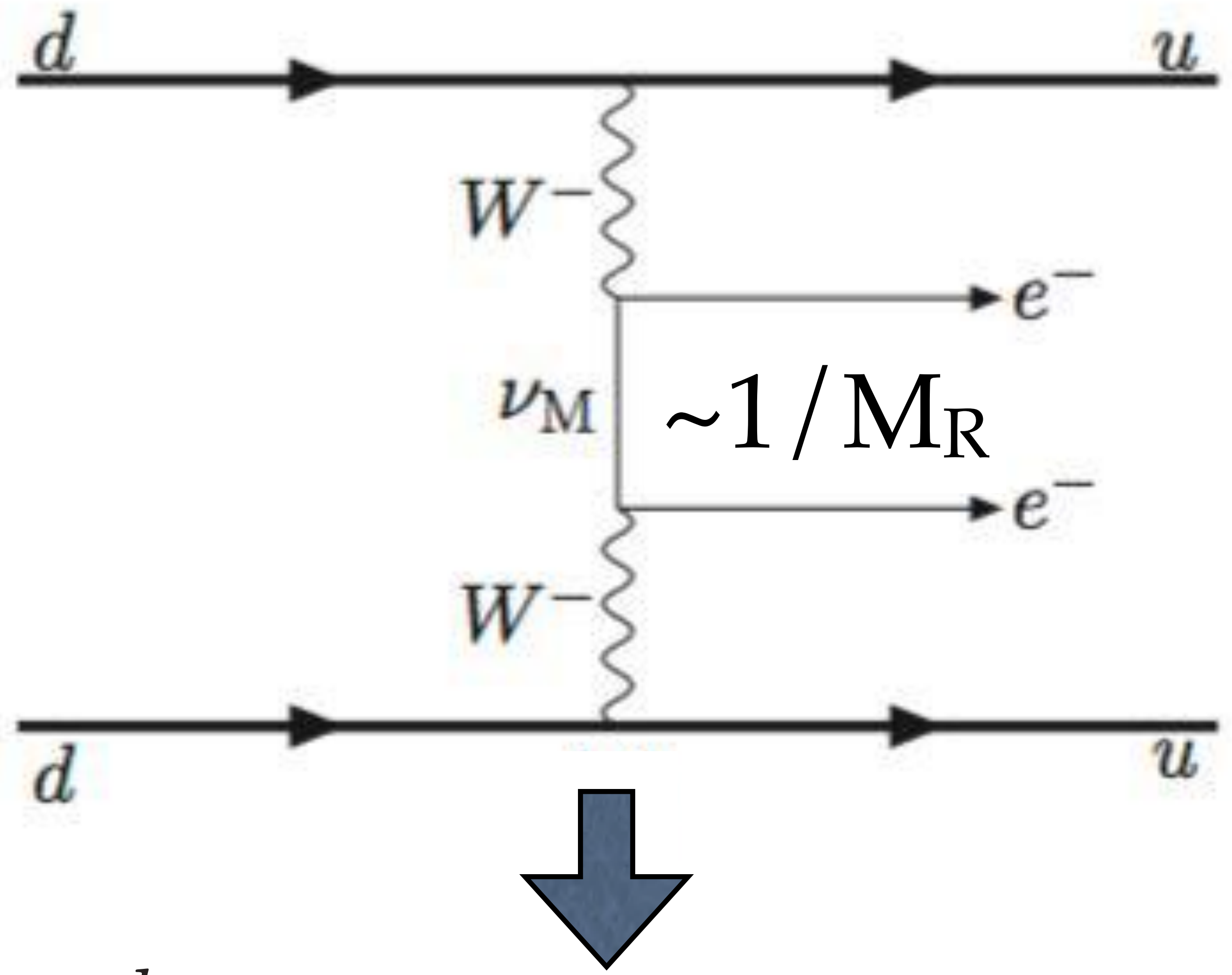
Neutrinoless Double Beta-Decay

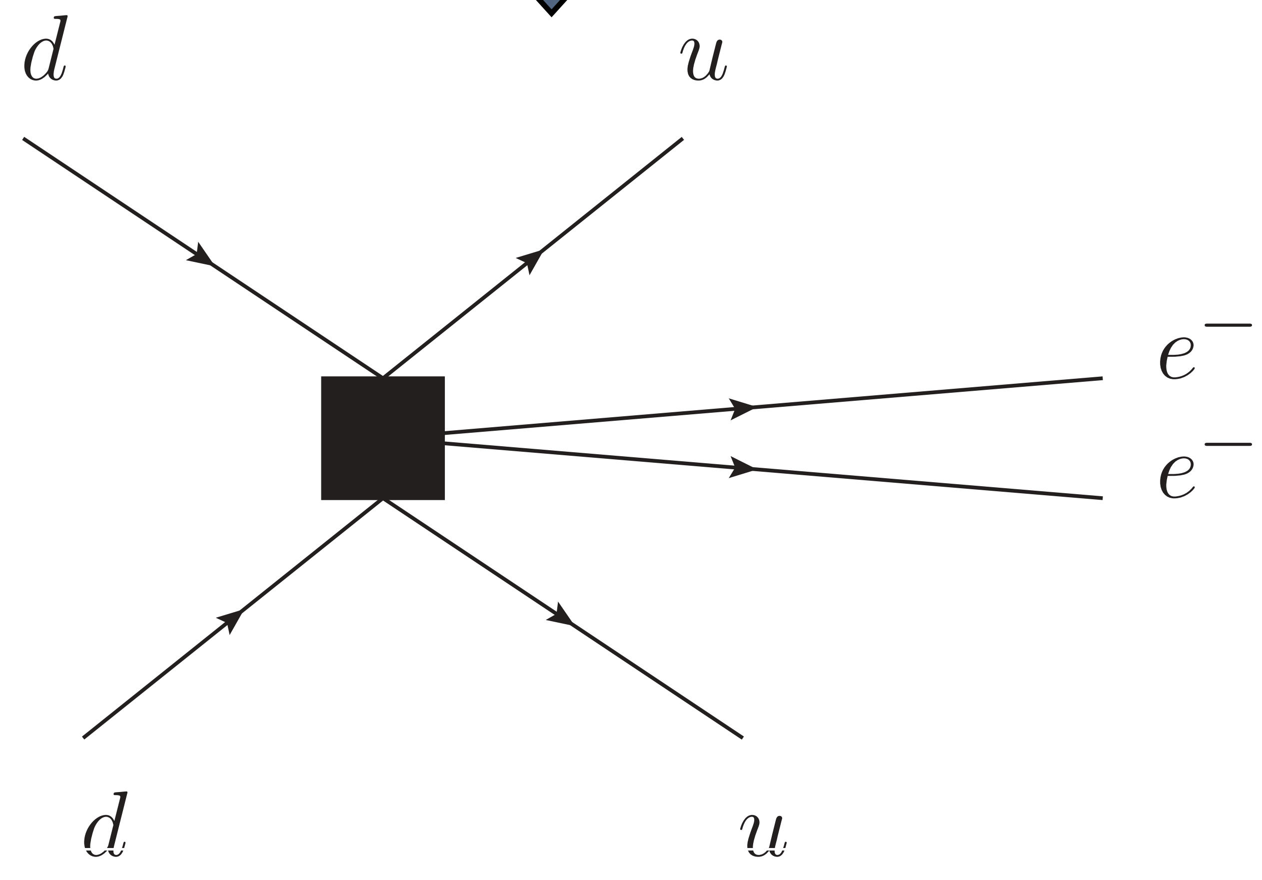


long-range contribution (standard picture)



short-range contribution possibly equally/more important



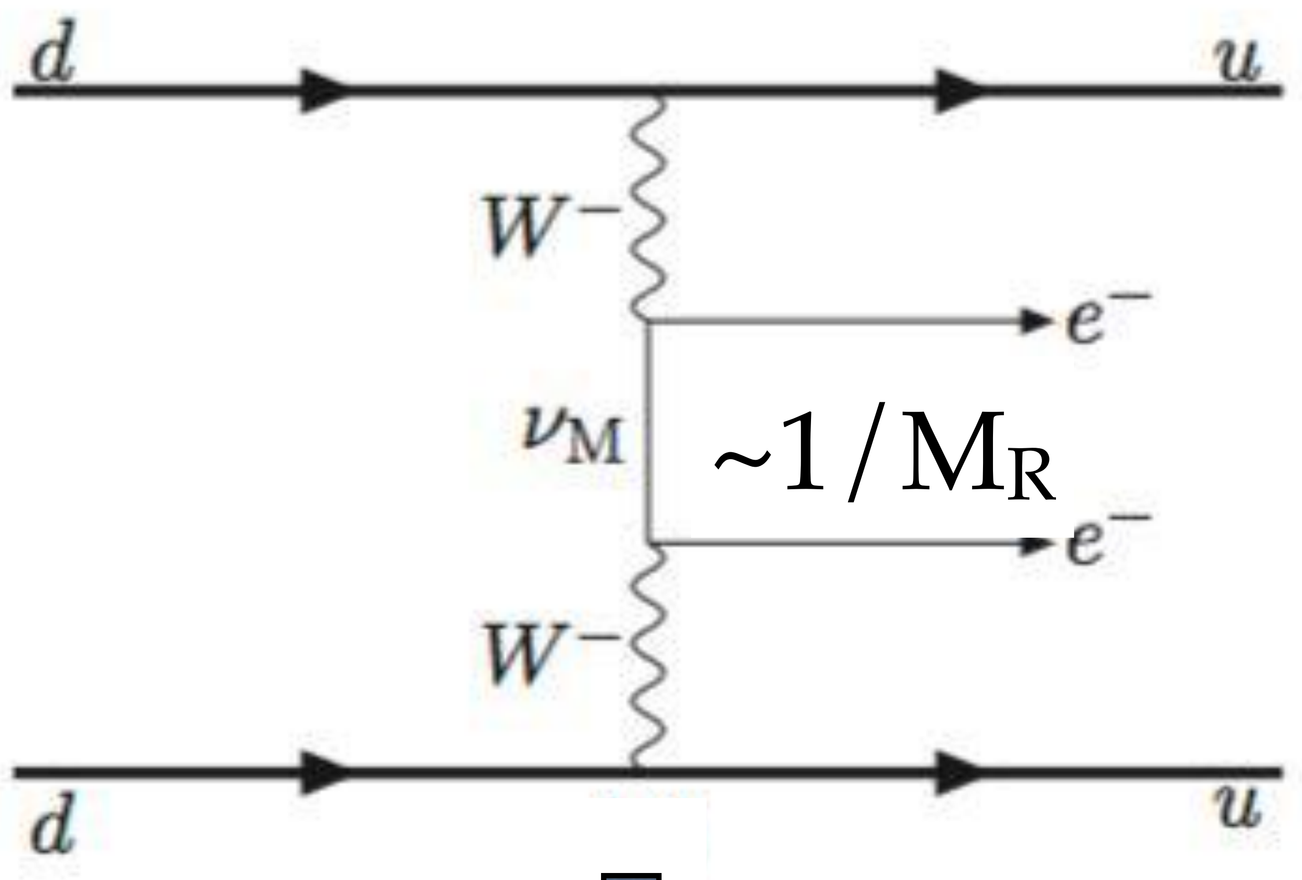


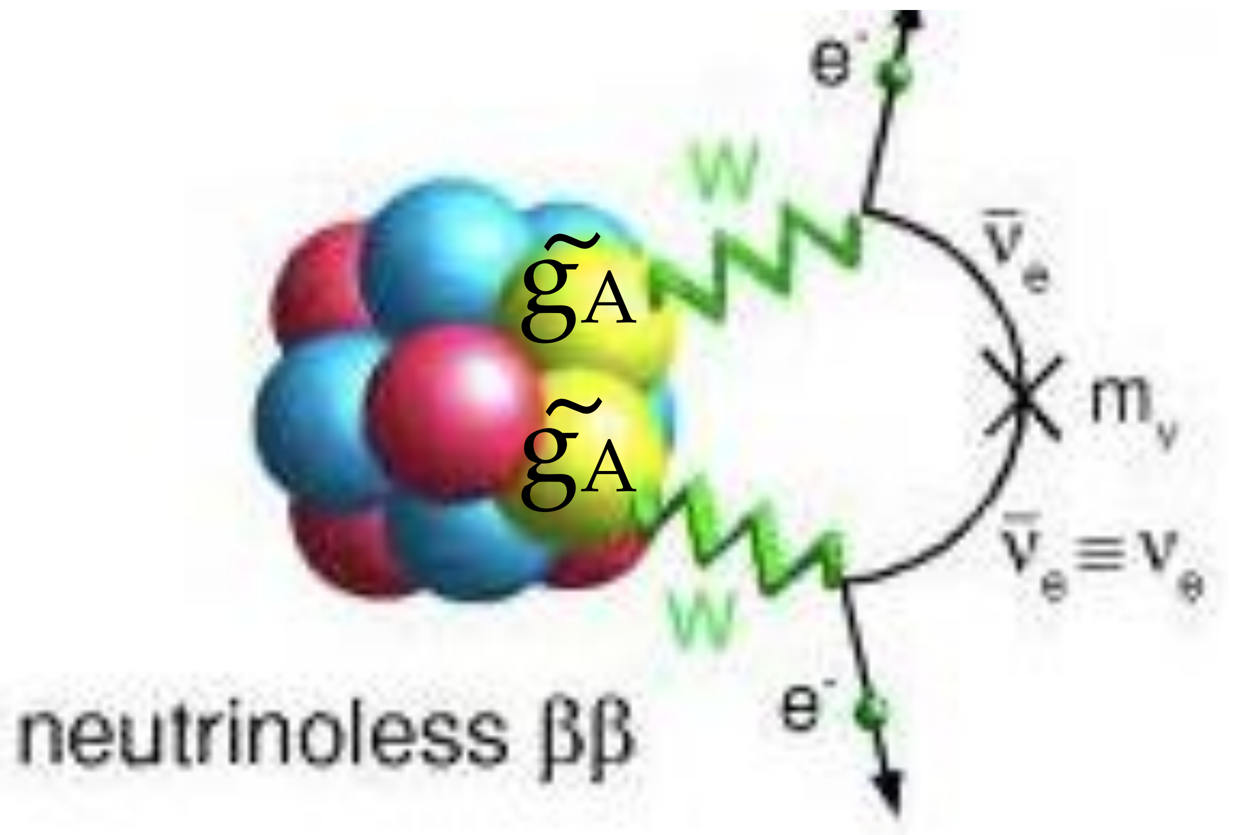
Short Range Contribution

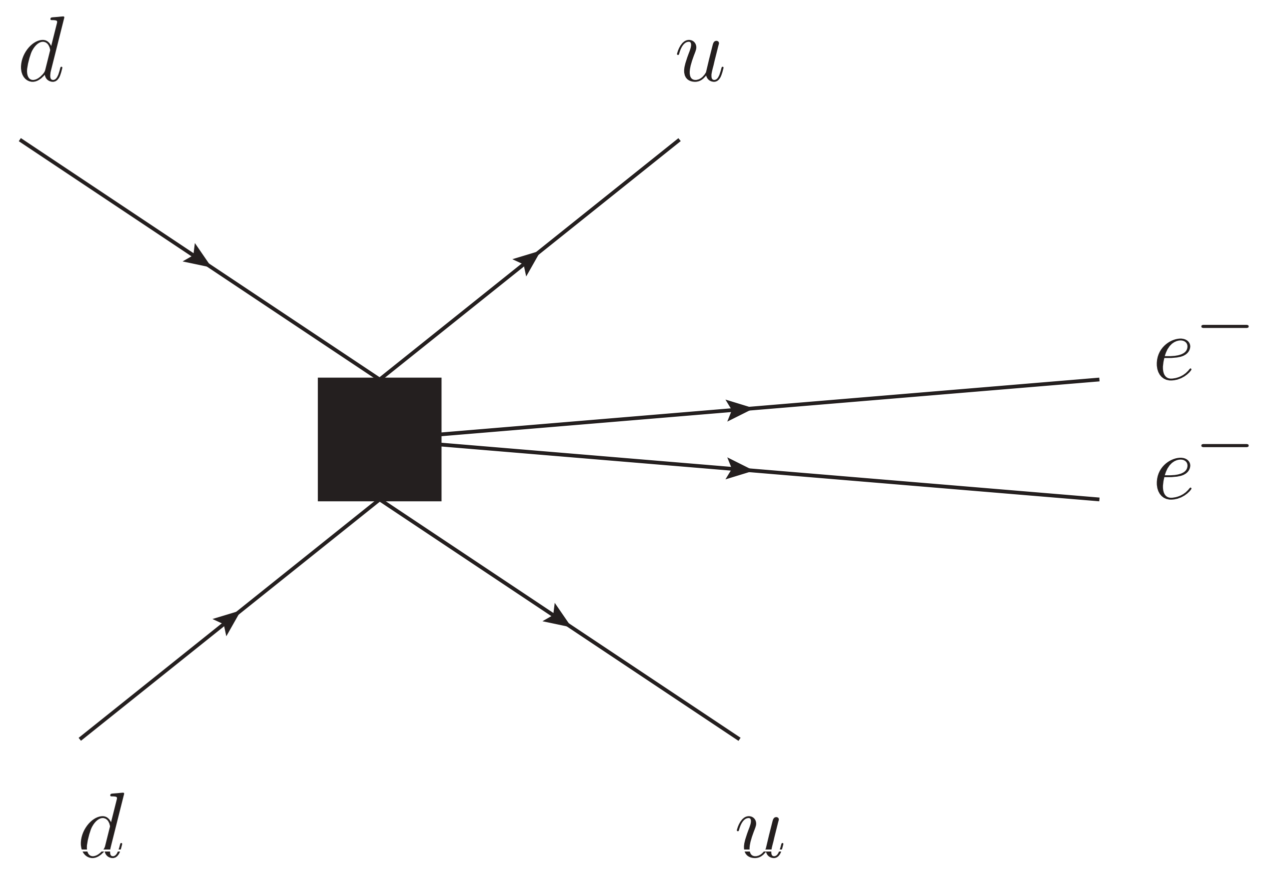
Need to know value of 4-quark matrix element in two-nucleon systems: LQCD is the only tool we have as we are not able to measure 0νββ in few-nucleon systems - so need fundamental theory calculation

Neutrinoless Double Beta-Decay

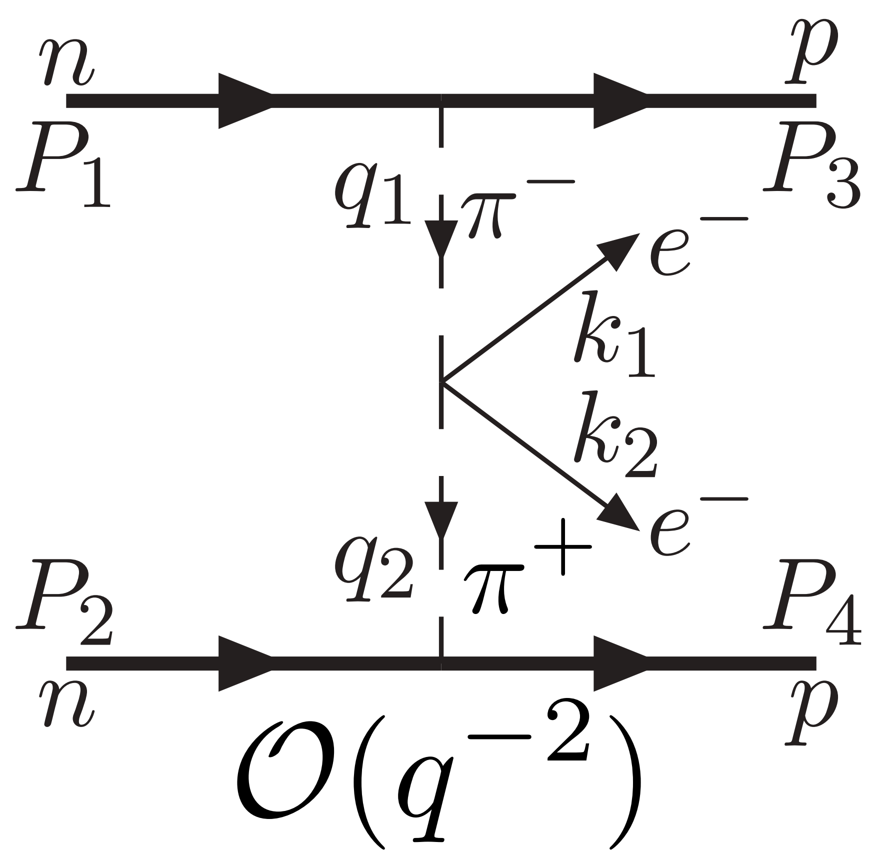
Short-range contribution: probe for heavy physics

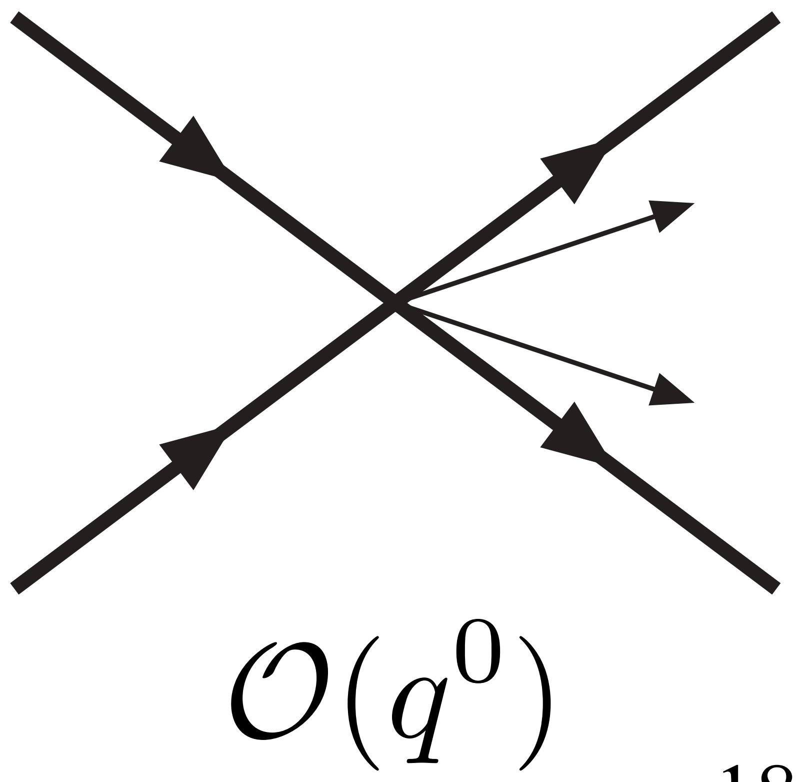






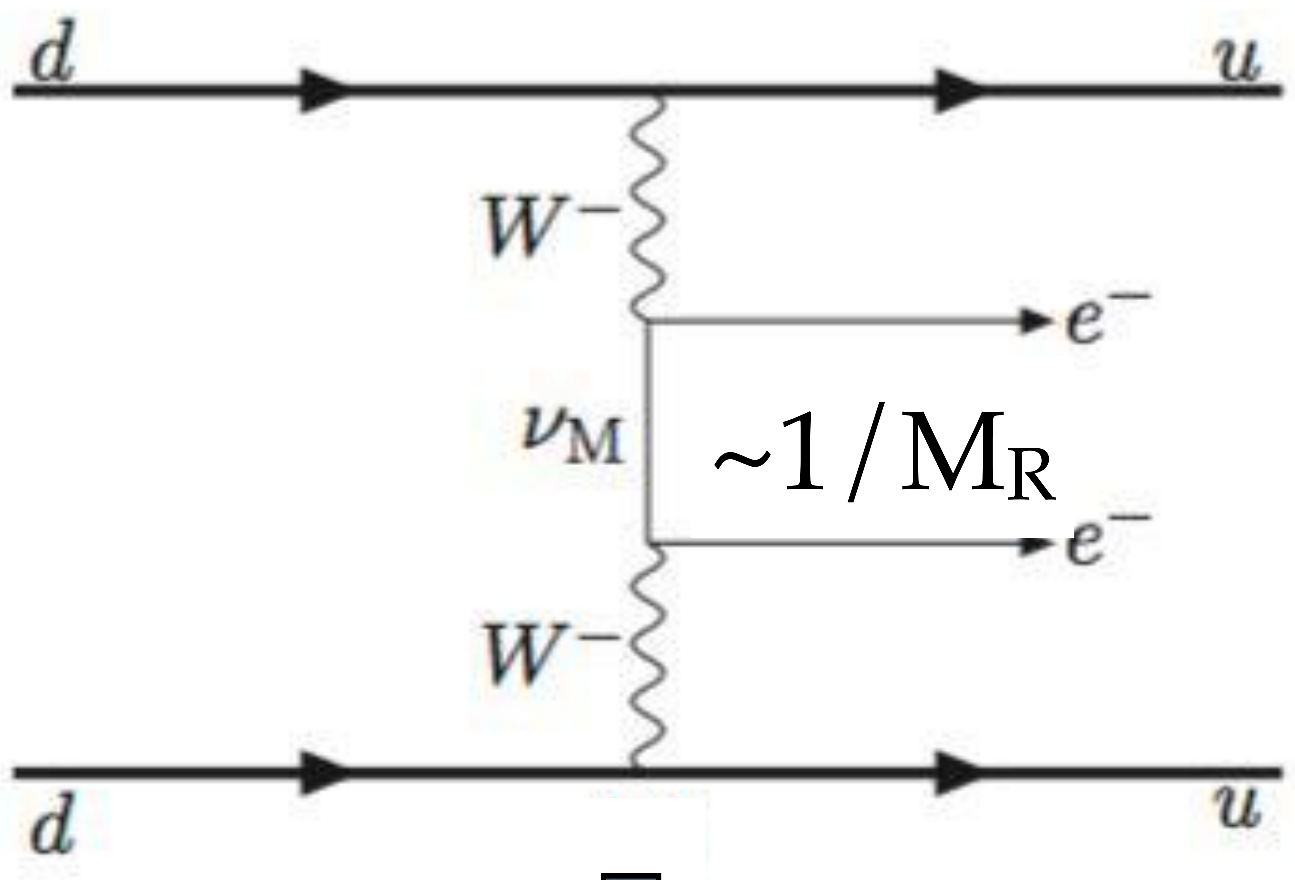
Effective Field Theory (π, N)
[Praezu, Ramsey-Musolf, Vogel]

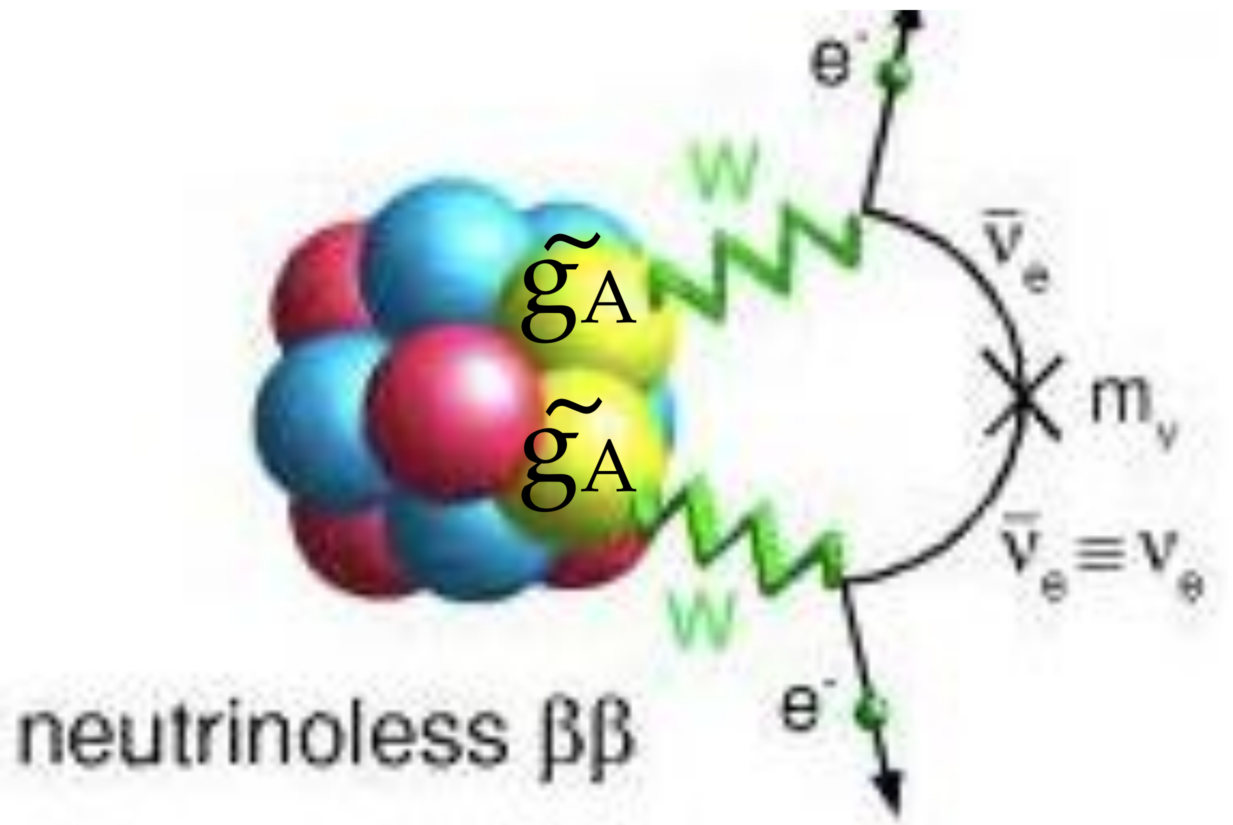


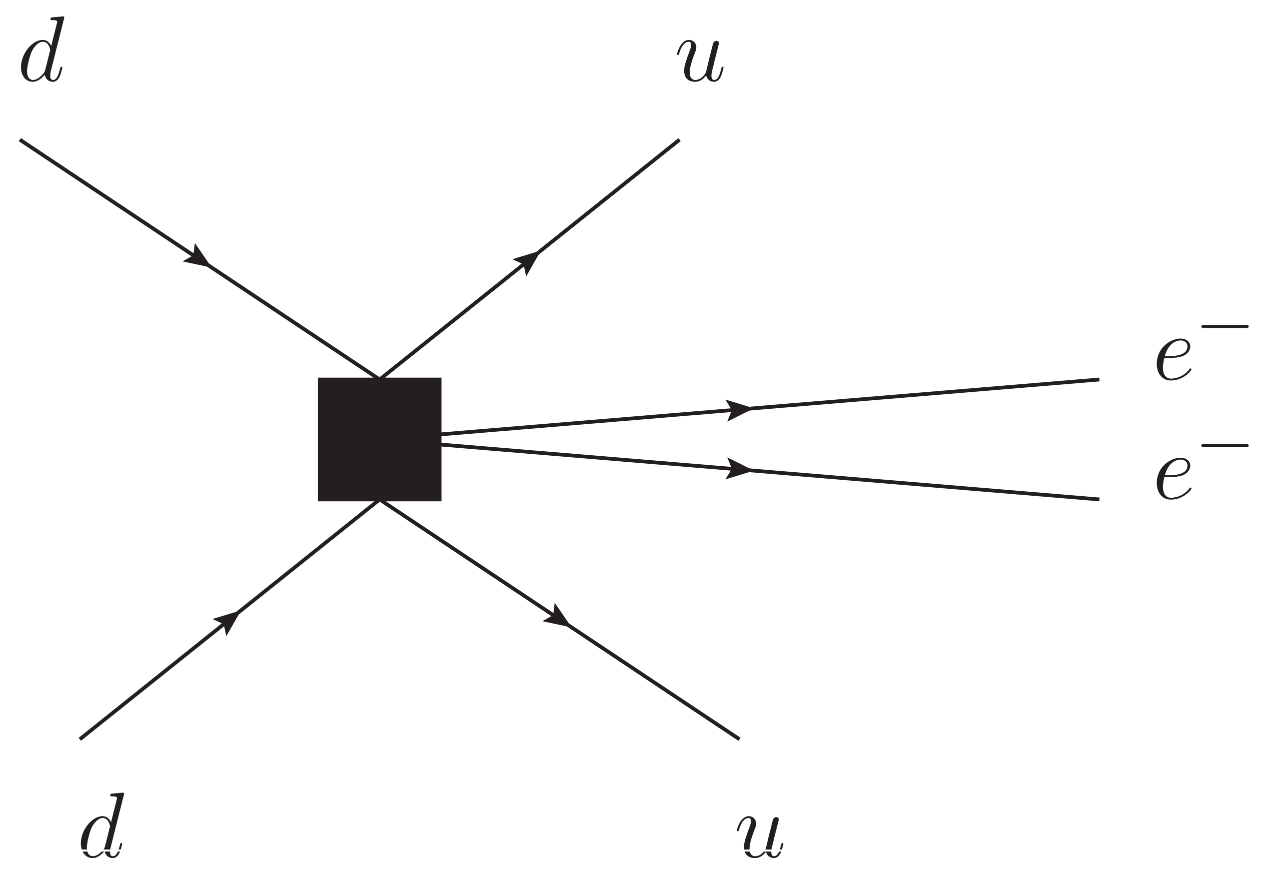


Neutrinoless Double Beta-Decay

Short-range contribution: probe for heavy physics

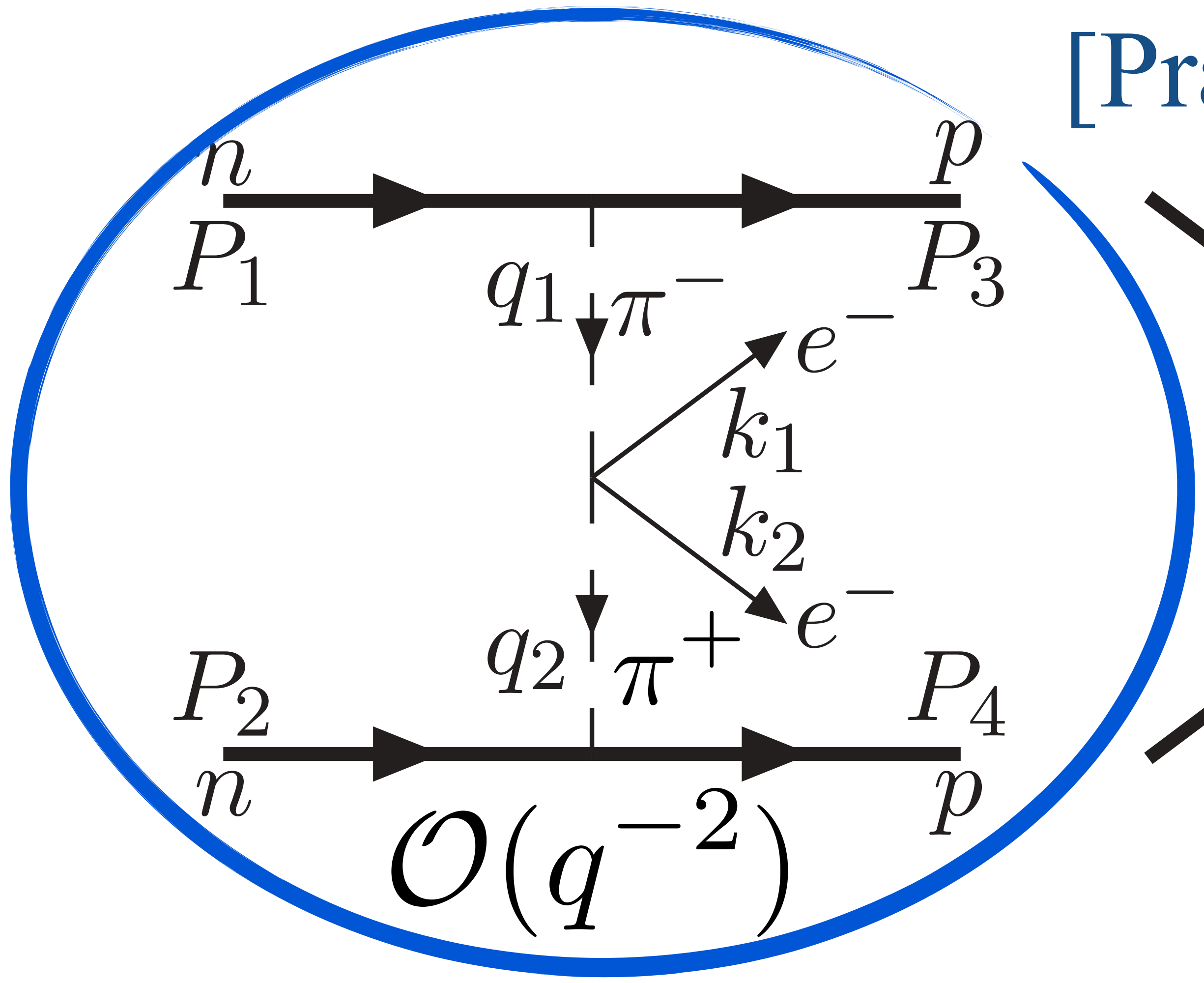


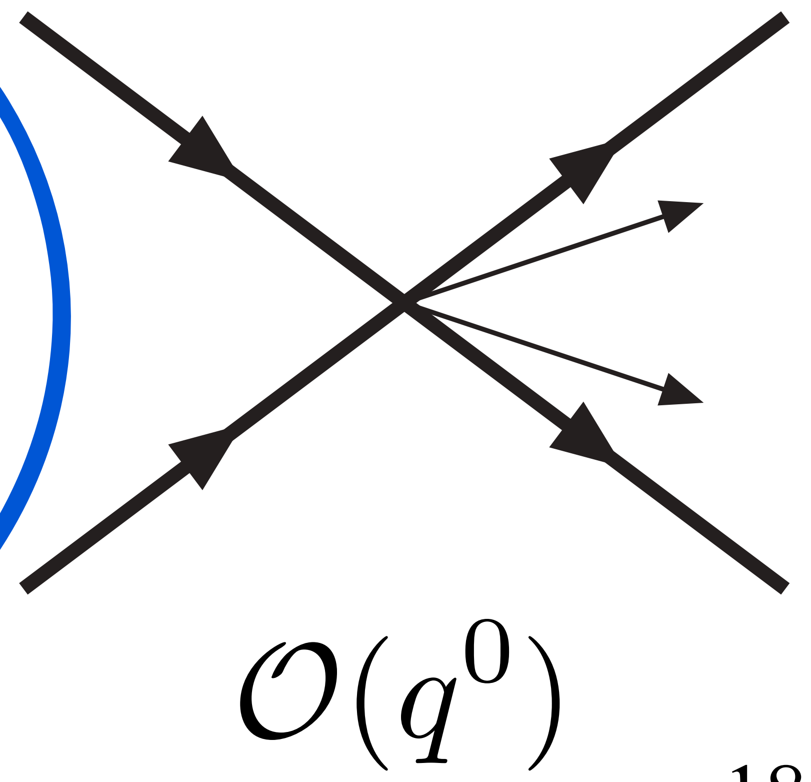




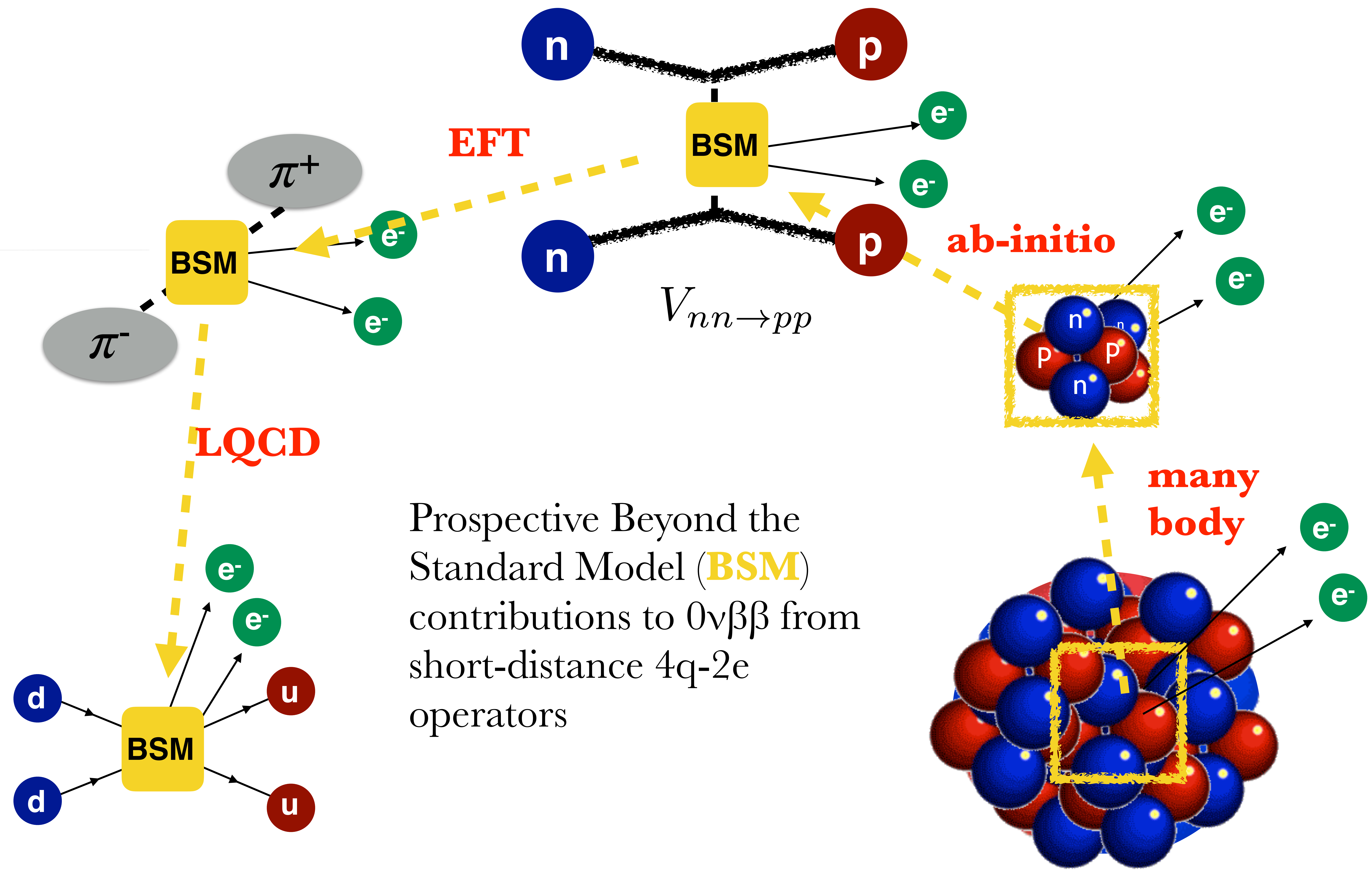
Effective Field Theory (π, N)

[Praezu, Ramsey-Musolf, Vogel]



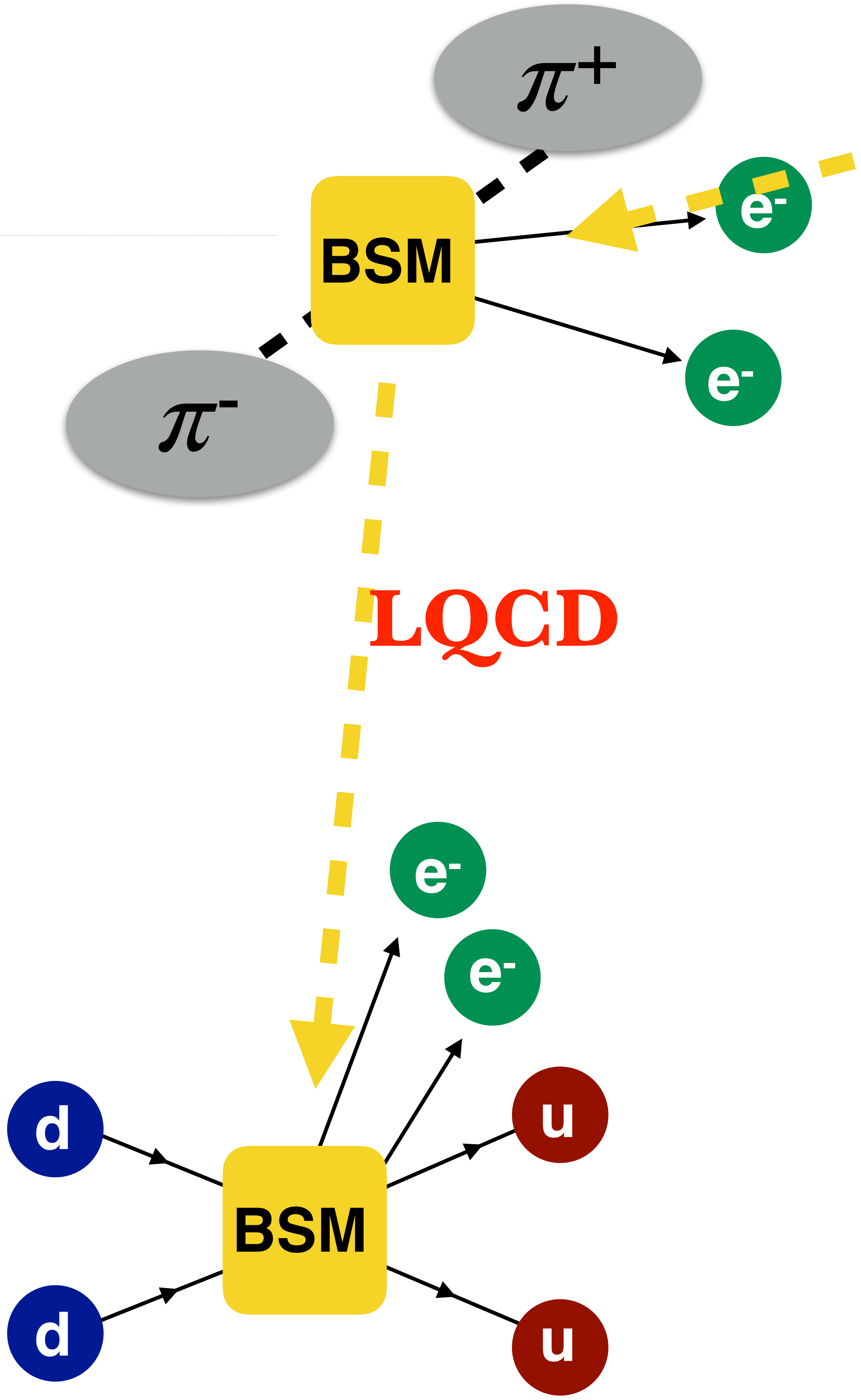


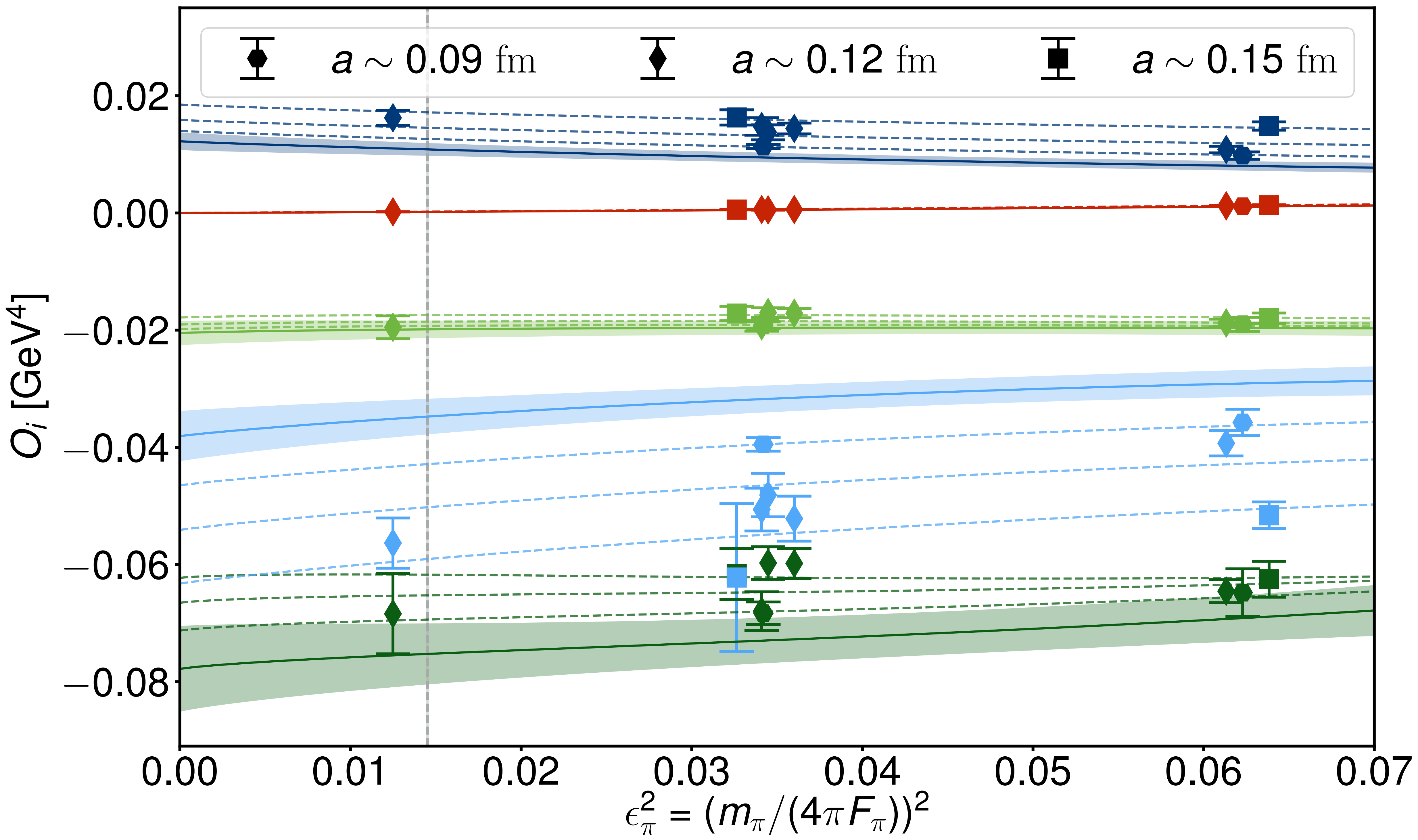
Lattice QCD for Neutrinoless Double Beta-Decay



Prospective Beyond the Standard Model (**BSM**) contributions to 0νββ from short-distance 4q-2e operators

Lattice QCD for Neutrinoless Double Beta-Decay



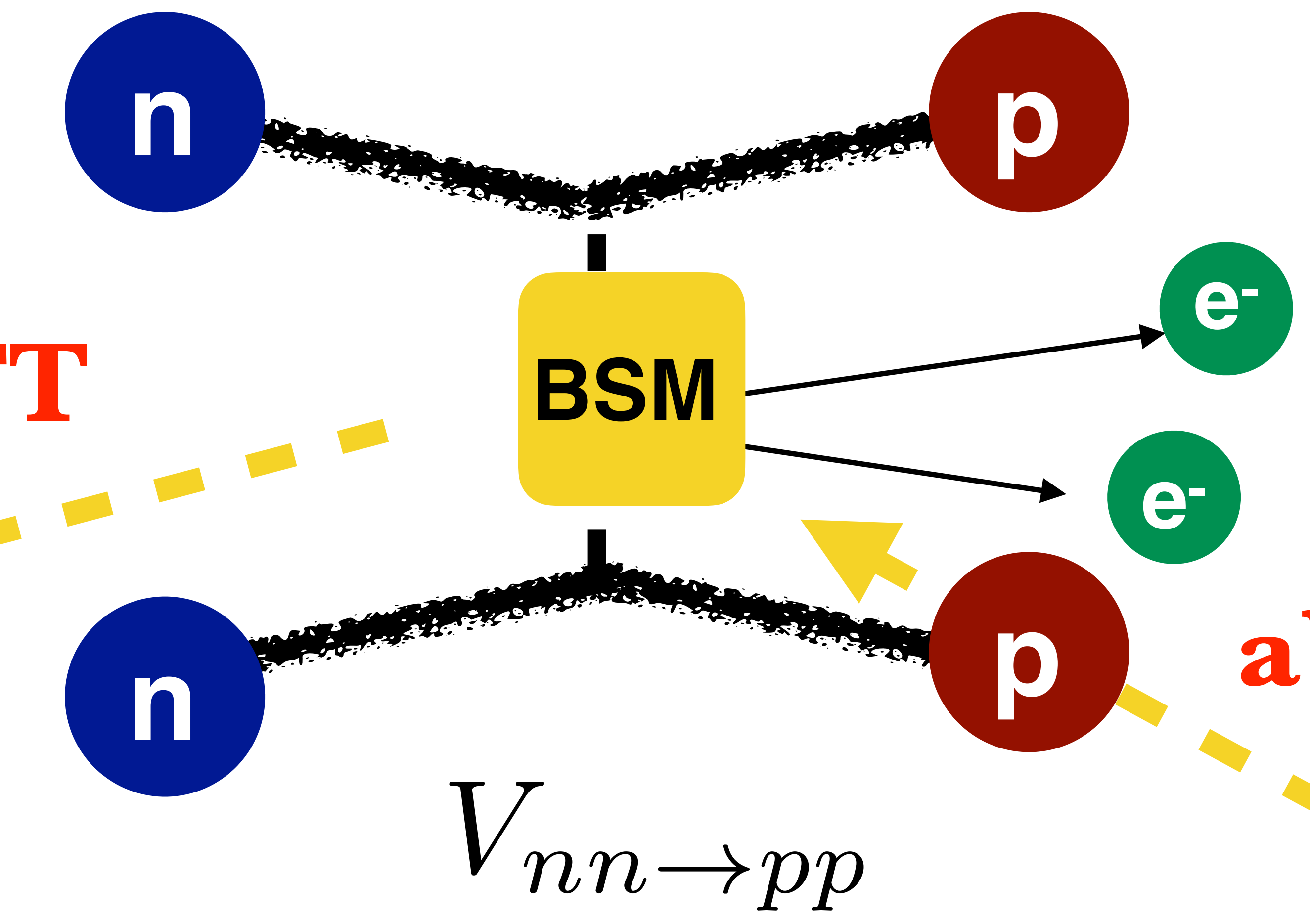


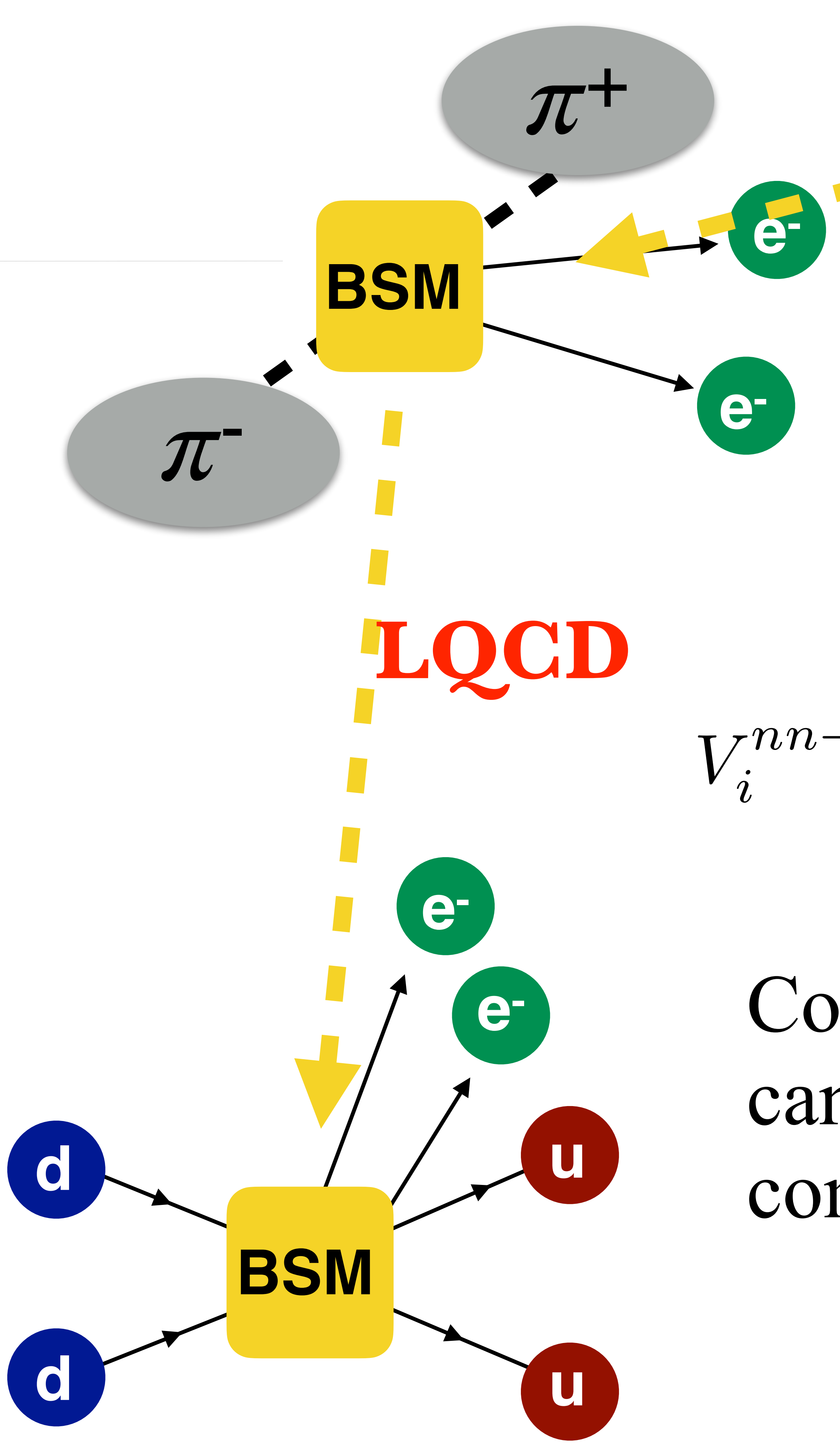
First (and complete) lattice QCD calculation of the $\pi^- \to \pi^+$ transition amplitude

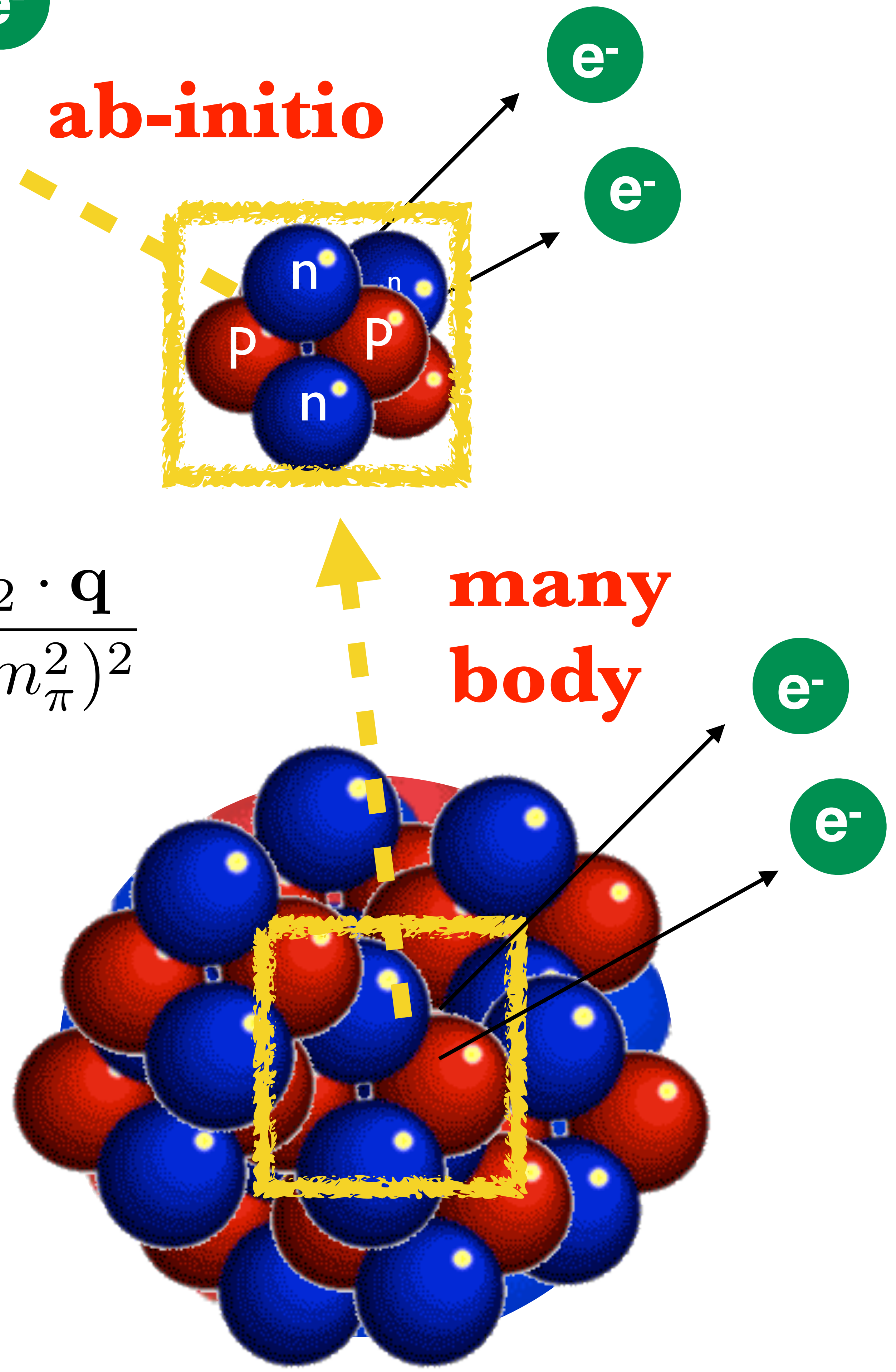
A. Nicholson, E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C.C. Chang, E. Rinaldi, M.A. Clark, B. Joó, T. Kurth, B.C. Tiburzi, P. Vranas, AWL

Phys. Rev. Lett. 121 (2018) 172501 [arXiv:1805.02634]

Lattice QCD for Neutrinoless Double Beta-Decay



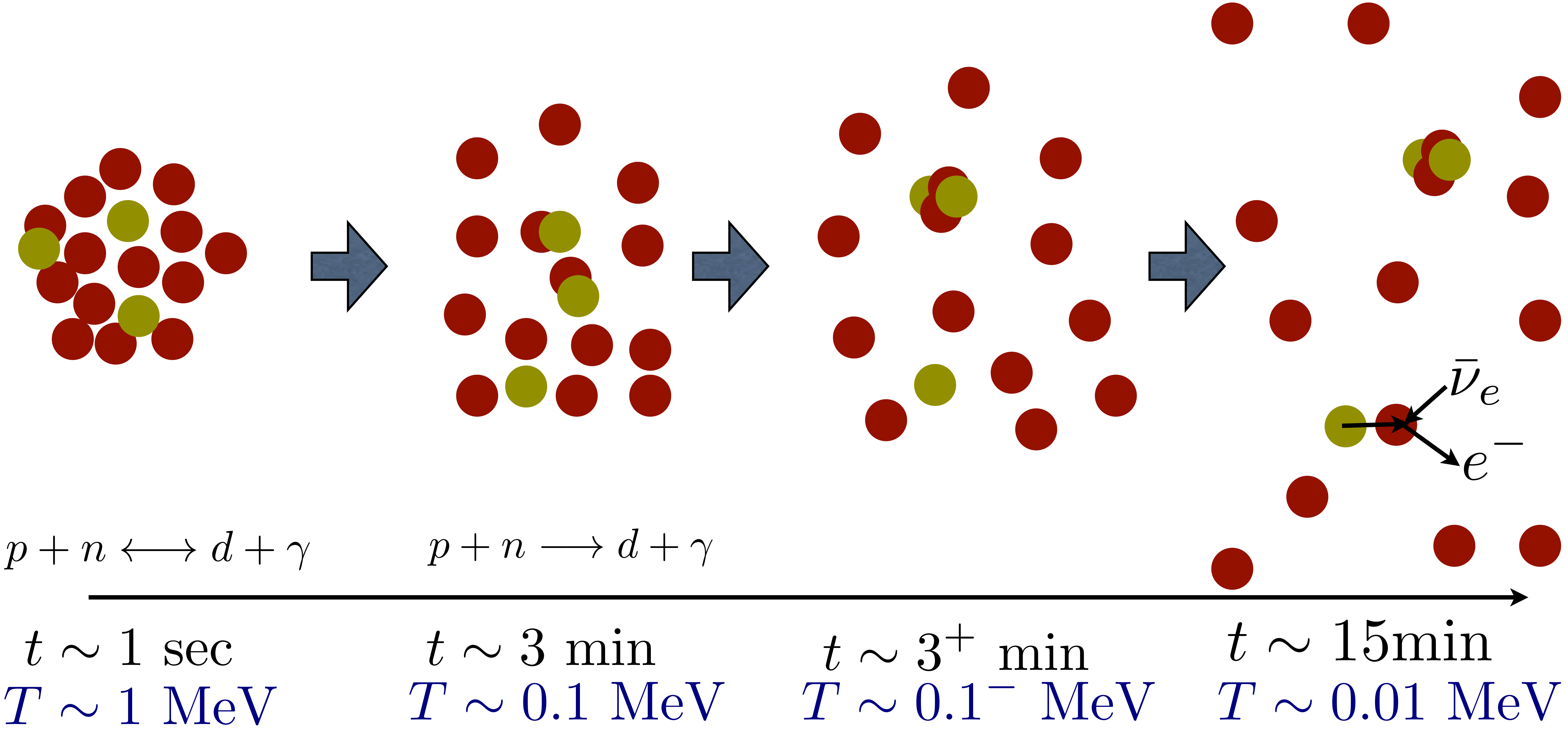




$$V_i^{nn\to pp}(|\mathbf{q}|) = -\mathcal{O}_i \frac{g_A^2}{4F_\pi^2} \tau_1^+ \tau_2^+ \frac{\sigma_1 \cdot \mathbf{q} \sigma_2 \cdot \mathbf{q}}{(|\mathbf{q}|^2 + m_\pi^2)^2}$$

Colleagues (Ken, Wick, others)
can take this potential and
compute the nuclear decay rate

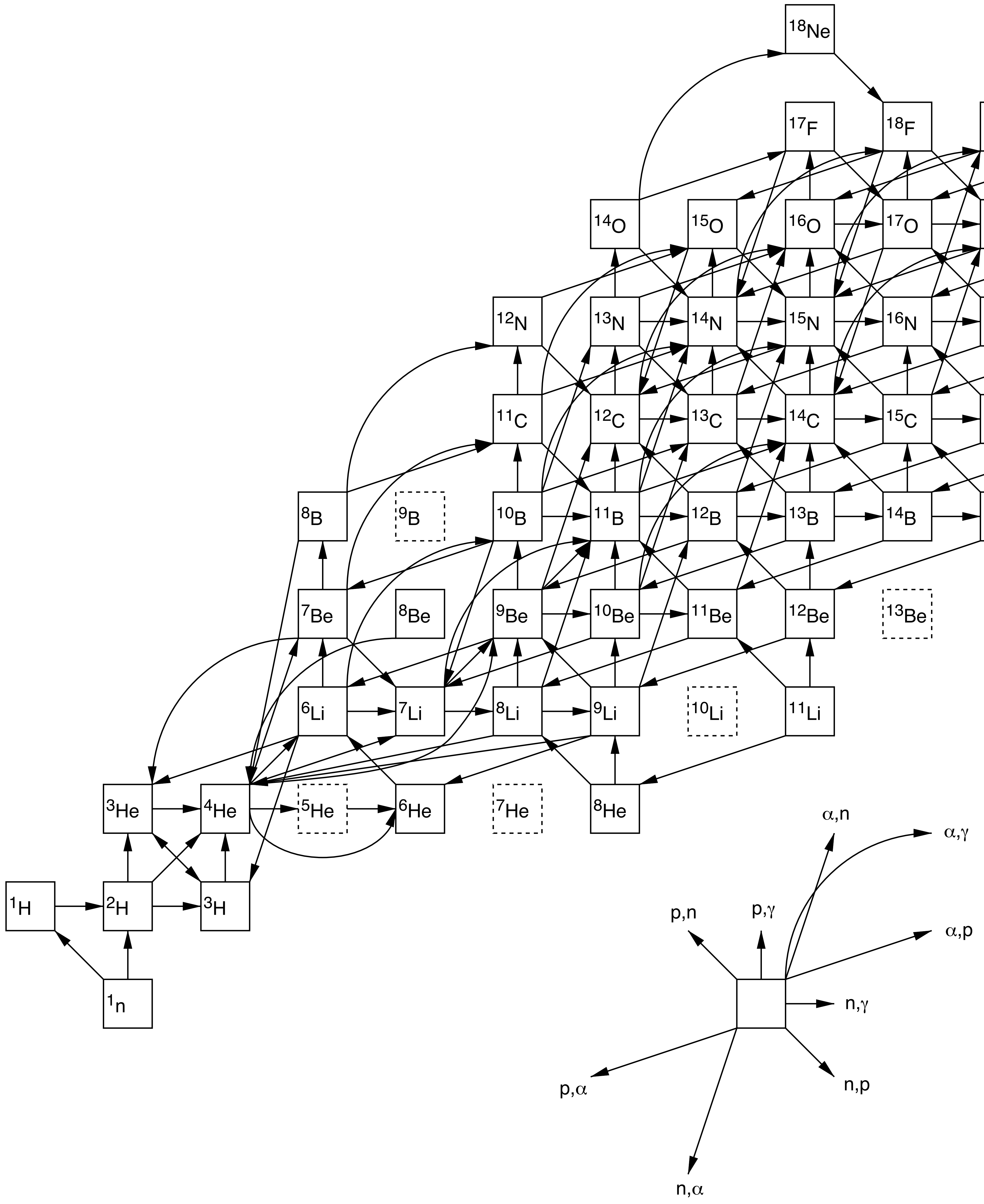
Primordial Abundance of Light Nuclei & Fine Tunings

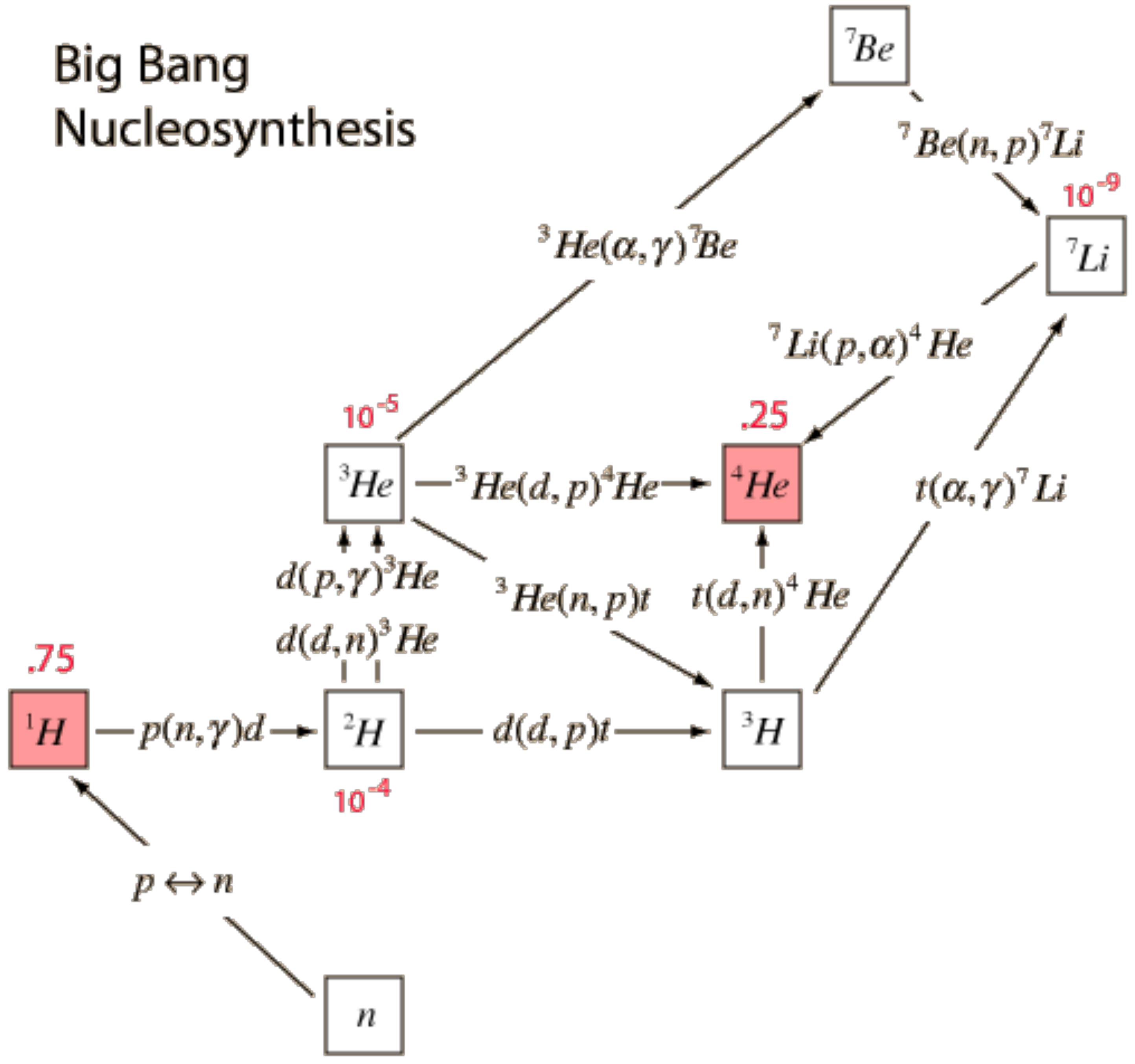


Light Ion reactions in early universe produce primordial abundances of light nuclei
reactions dominated by radiation
absence of bound A=5,8 nuclei limit synthesis (no ^{12}C)

Alpher, Gamow; Fermi, Turkevich; Hayashi; Alpher; Peebles; Hoyle, Tayler; Wagoner, Fowler, Hoyle; Kawano; Olive; ...

Primordial Abundance of Light Nuclei & Fine Tunings

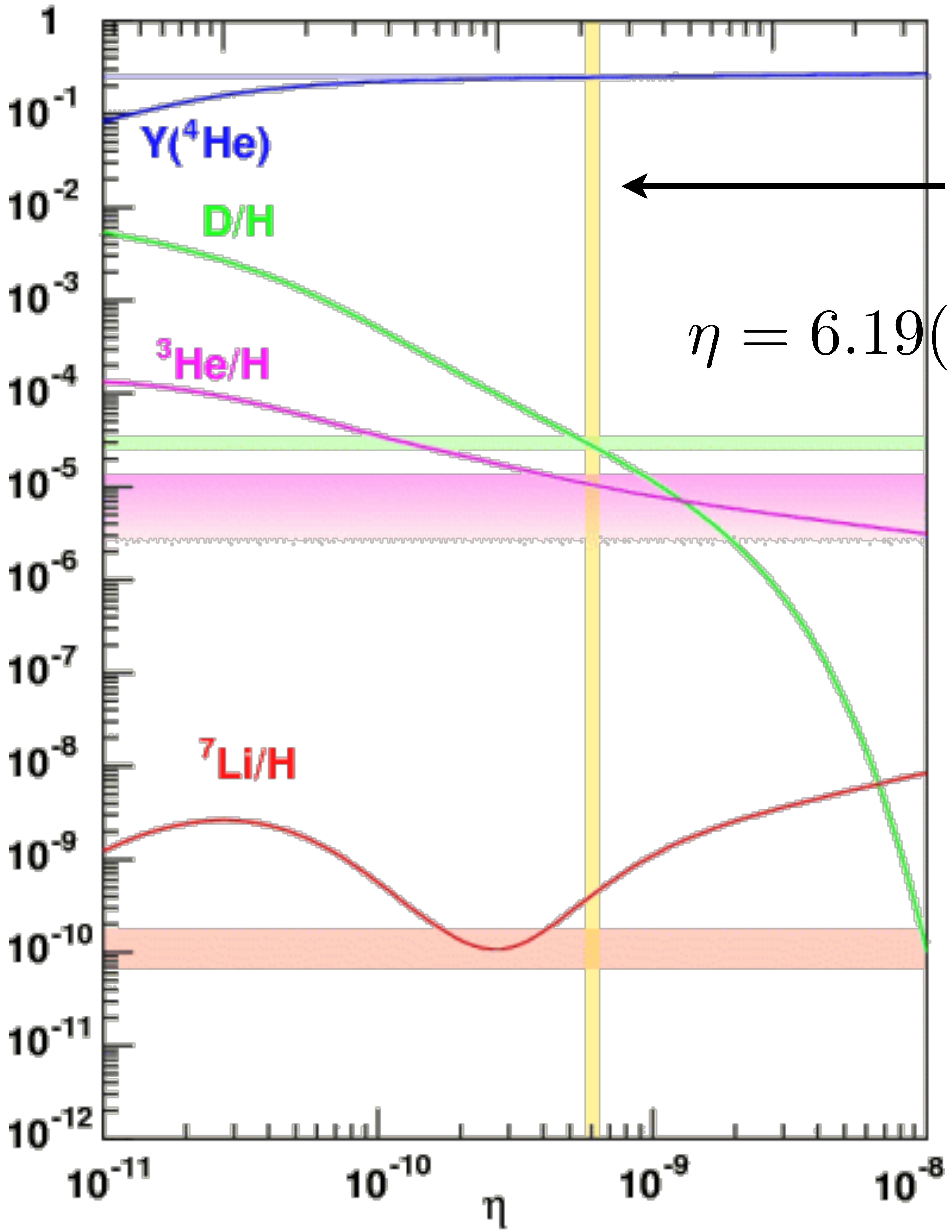




Primordial Abundance of Light Nuclei & Fine Tunings

Primordial Universe
(Mass Fraction)

~75% H
~25% ^{4}He

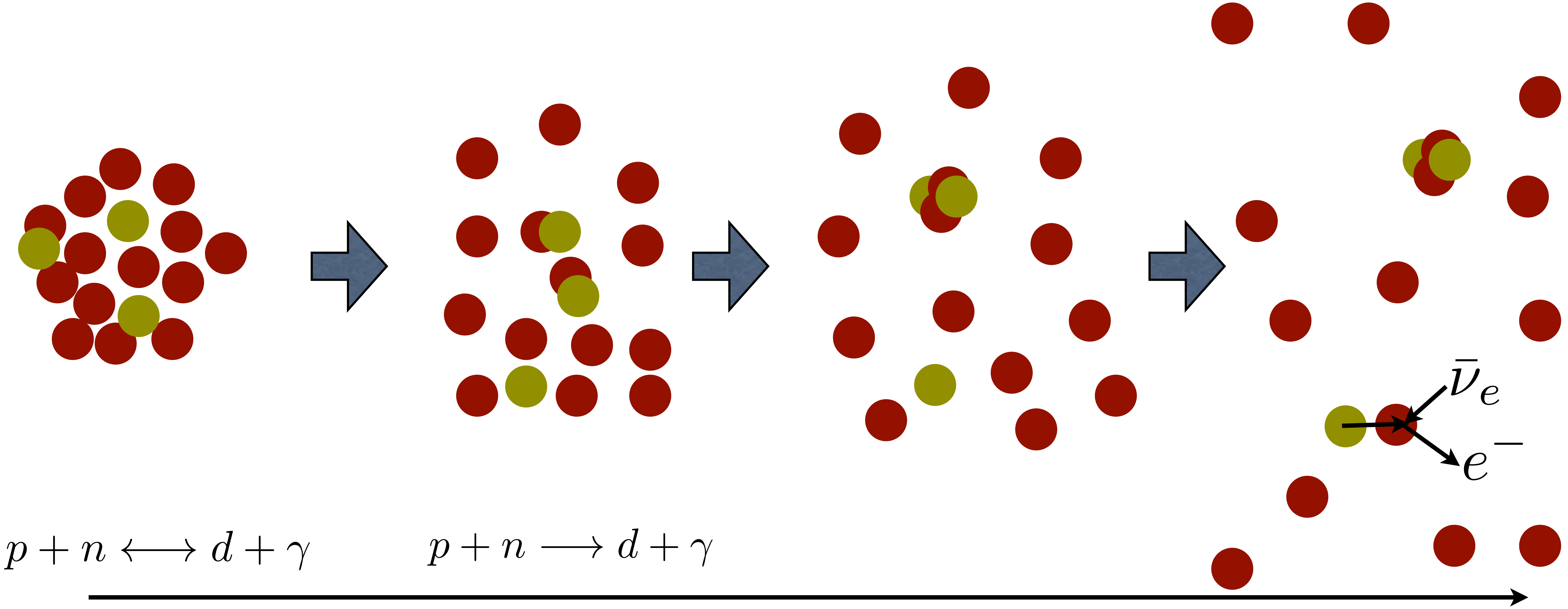


CMB

$$\eta = 6.19(15) \times 10^{-10}$$

$$\eta \equiv \frac{X_N}{X_\gamma}$$

Primordial Abundance of Light Nuclei & Fine Tunings



$t \sim 1$ sec	$t \sim 3$ min	$t \sim 3^+$ min	$t \sim 15$min
$T \sim 1$ MeV	$T \sim 0.1$ MeV	$T \sim 0.1^-$ MeV	$T \sim 0.01$ MeV

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

Initial conditions

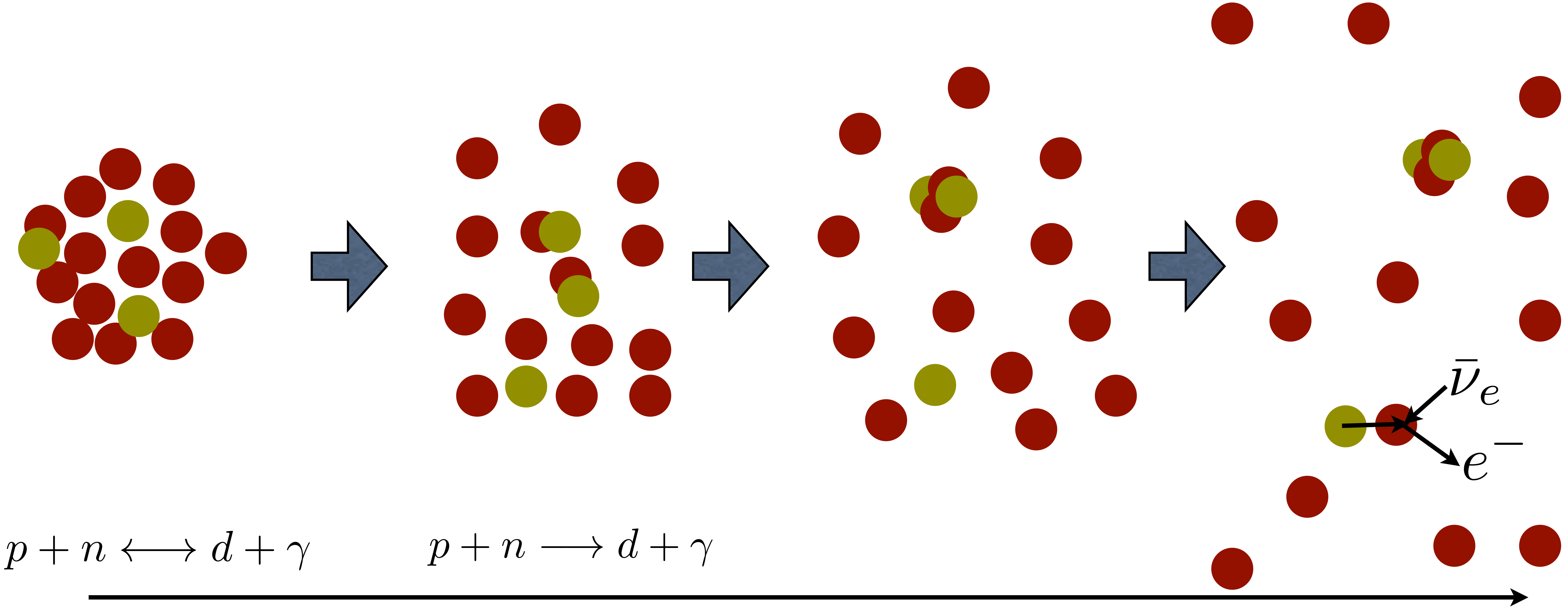
B_d

deuterium binding energy

τ_n

neutron lifetime

Primordial Abundance of Light Nuclei & Fine Tunings



$p + n \longleftrightarrow d + \gamma$ $\qquad$ $p + n \longrightarrow d + \gamma$

$t \sim 1$ sec	$t \sim 3$ min	$t \sim 3^+$ min	$t \sim 15$min
$T \sim 1$ MeV	$T \sim 0.1$ MeV	$T \sim 0.1^-$ MeV	$T \sim 0.01$ MeV

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

Initial conditions

focus on leading isospin breaking

τ_n

neutron lifetime

Big Bang Nucleosynthesis and $M_n - M_p$

initial conditions for ratio of neutron to protons exponentially sensitive to mass splitting

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

neutron lifetime very sensitive to mass splitting

$$\frac{1}{\tau_n} = \frac{(G_F \cos\theta_C)^2}{2\pi^3} m_e^5 (1 + 3g_A^2)\, f\left(\frac{M_n - M_p}{m_e}\right)$$

$$f(a) \simeq \frac{1}{15}\left(2a^4 - 9a^2 - 8\right)\sqrt{a^2 - 1} + a \ln\left(a + \sqrt{a^2 - 1}\right)$$

Griffiths "Introduction to Elementary Particles"

10% change in $M_n - M_p$ corresponds to ~100% change neutron lifetime

Big Bang Nucleosynthesis and $M_n - M_p$

$$M_n - M_p = 1.29333217(42)\ \mathrm{MeV}$$

two sources of isospin breaking in the Standard Model

quark mass

$$m_q = \hat{m}\mathbf{1} - \delta\tau_3$$

quark electric charge

$$Q = \frac{1}{6}\mathbf{1} + \frac{1}{2}\tau_3$$

at leading order in isospin breaking

$$M_n - M_p = \delta M^{\gamma}_{n-p} + \delta M^{m_d - m_u}_{n-p}$$

$$< 0 \qquad\qquad > 0$$

Big Bang Nucleosynthesis and $M_n - M_p$

PRELIMINARY

$$M_n - M_p = \delta M^{\gamma}_{n-p} + \delta M^{m_d - m_u}_{n-p}$$
$$= -178(04)(64)\ \mathrm{MeV} \times \alpha_{f.s.} + 1.08(6)(9) \times (m_d - m_u)$$

(lattice average)

Big Bang Nucleosynthesis (BBN) highly constrains variation of $M_n - M_p$ and hence variation of fundamental constants

- Observe gas clouds with low metalicity (very few heavy elements).
- Assume these are representative of nuclear abundances shortly after the Big Bang (for some quantities, extrapolations are required)
- Run BBN code, changing input parameters connected to QCD, and compare predicted abundances to observed

$$^4\mathrm{He}: \quad Y_p = 0.2449 \pm 0.0040$$
$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.53 \pm 0.04) \times 10^{-5}$$

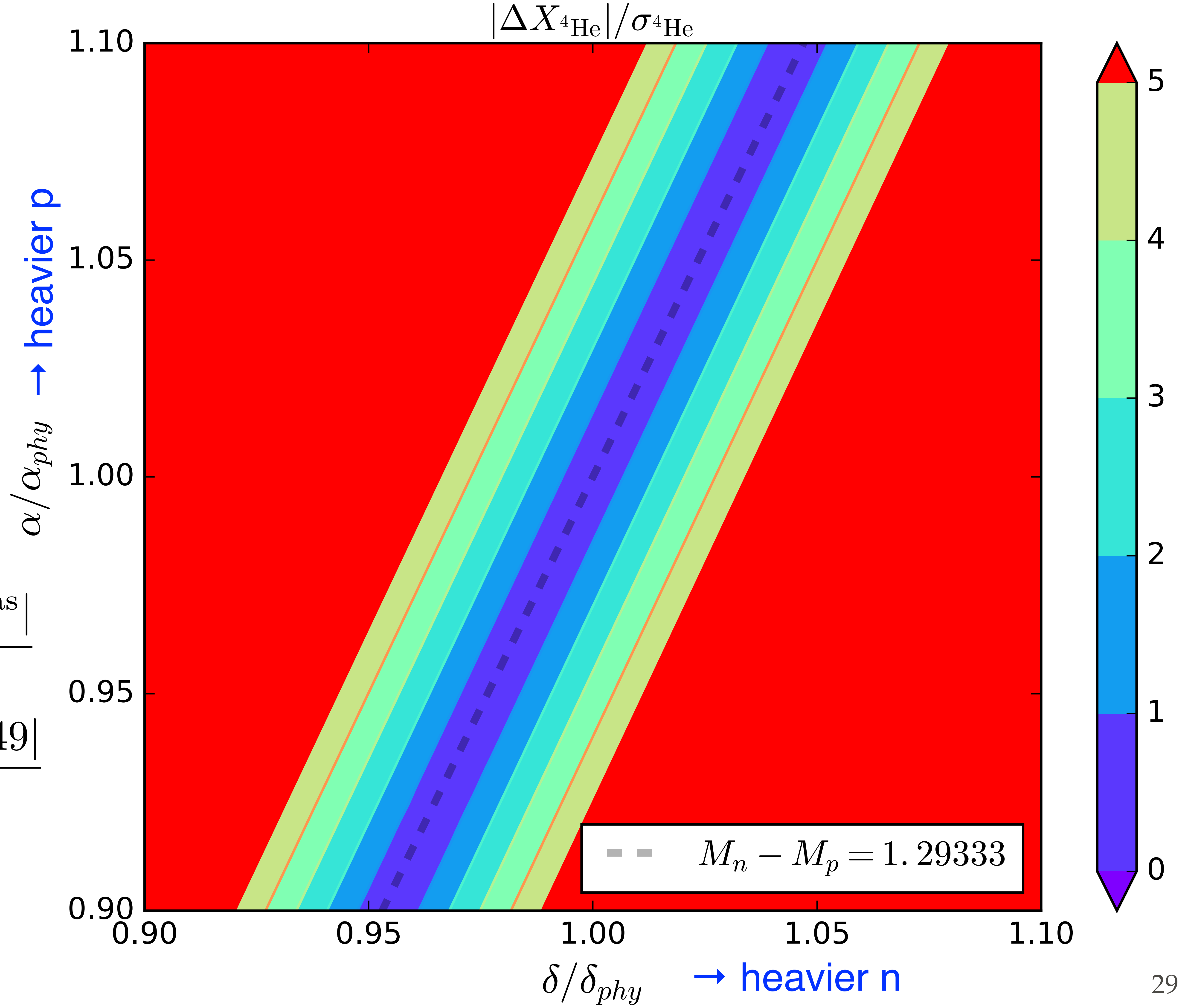
Big Bang Nucleosynthesis and $m_n - m_p$

Heffernan, Banerjee and AWL - 1706.04991

$$\delta M_{n-p} = \delta M^{\delta}_{n-p} + \delta M^{\gamma}_{n-p} = 2.39 \frac{\delta}{\delta^{\text{phys}}} - 1.10 \frac{\alpha_{f.s.}}{\alpha^{\text{phys}}_{f.s.}} \text{ MeV}$$

- Comparing the variation of ^{4}He to the observed abundance
- ^{4}He tracks almost perfectly the nucleon mass splitting

$$\frac{|\Delta X_{^4\text{He}}|}{\sigma_{^4\text{He}}} = \frac{|Y_p(\delta, \alpha_{f.s.}) - Y_p^{\text{meas}}|}{\sigma_{Y_p}} = \frac{|Y_p(\delta, \alpha_{f.s.}) - 0.2449|}{0.0040}$$



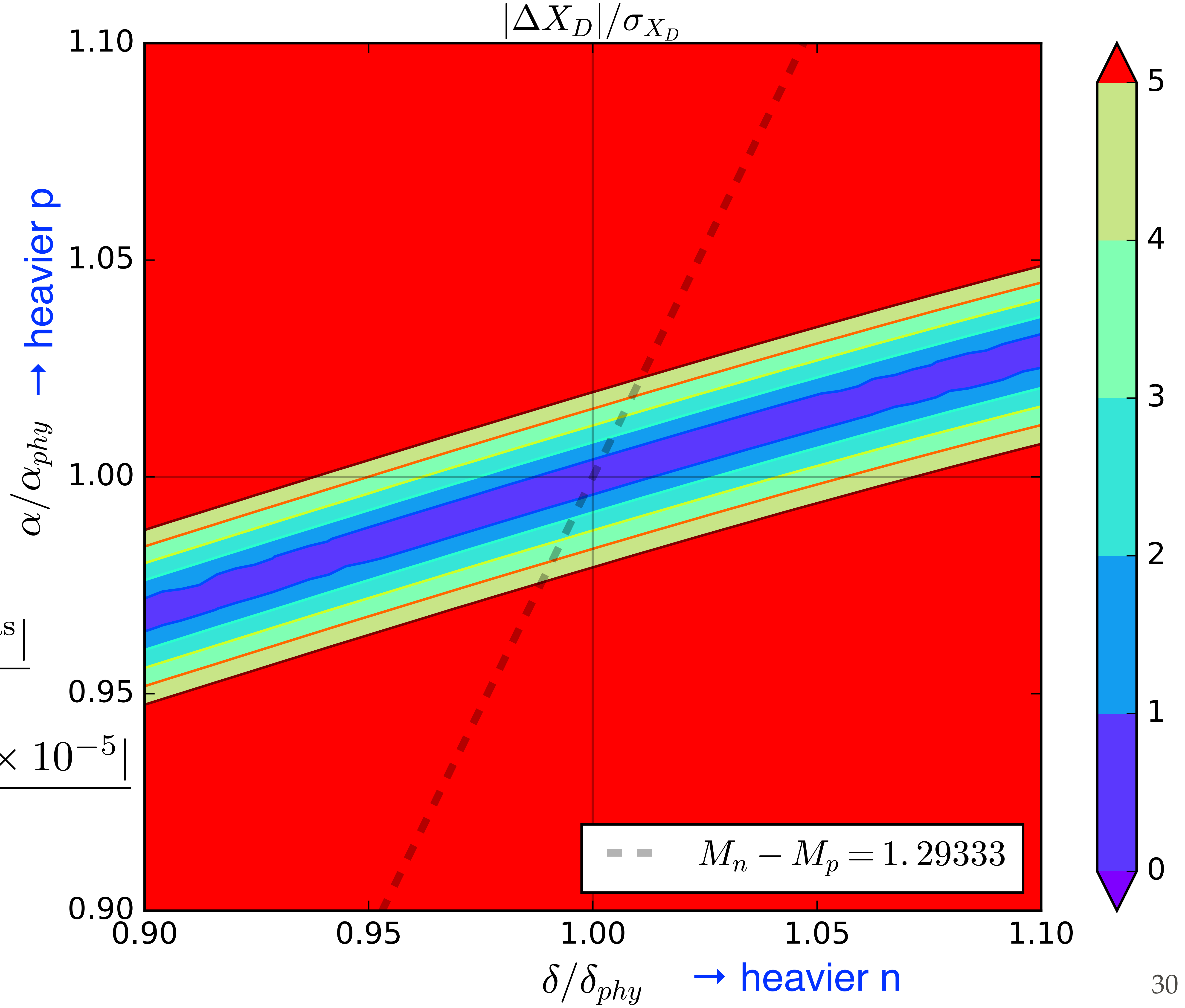
Big Bang Nucleosynthesis and $m_n - m_p$

Heffernan, Banerjee and AWL - 1706.04991

$$\delta M_{n-p} = \delta M^{\delta}_{n-p} + \delta M^{\gamma}_{n-p} = 2.39 \frac{\delta}{\delta^{\text{phys}}} - 1.10 \frac{\alpha_{f.s.}}{\alpha^{\text{phys}}_{f.s.}} \text{ MeV}$$

- Comparing the variation of Deuterium to the observed abundance
- electromagnetic effects in fusion cross sections are important, such that lines on constant D do not line up with M_n-M_p

$$\frac{|\Delta X_{\text{D}}|}{\sigma_{\text{D}}} = \frac{|X_D(\delta, \alpha_{f.s.}) - X_D^{\text{meas}}|}{\sigma_{X_D}} = \frac{|X_D(\delta, \alpha_{f.s.}) - 2.53 \times 10^{-5}|}{0.04 \times 10^{-5}}$$



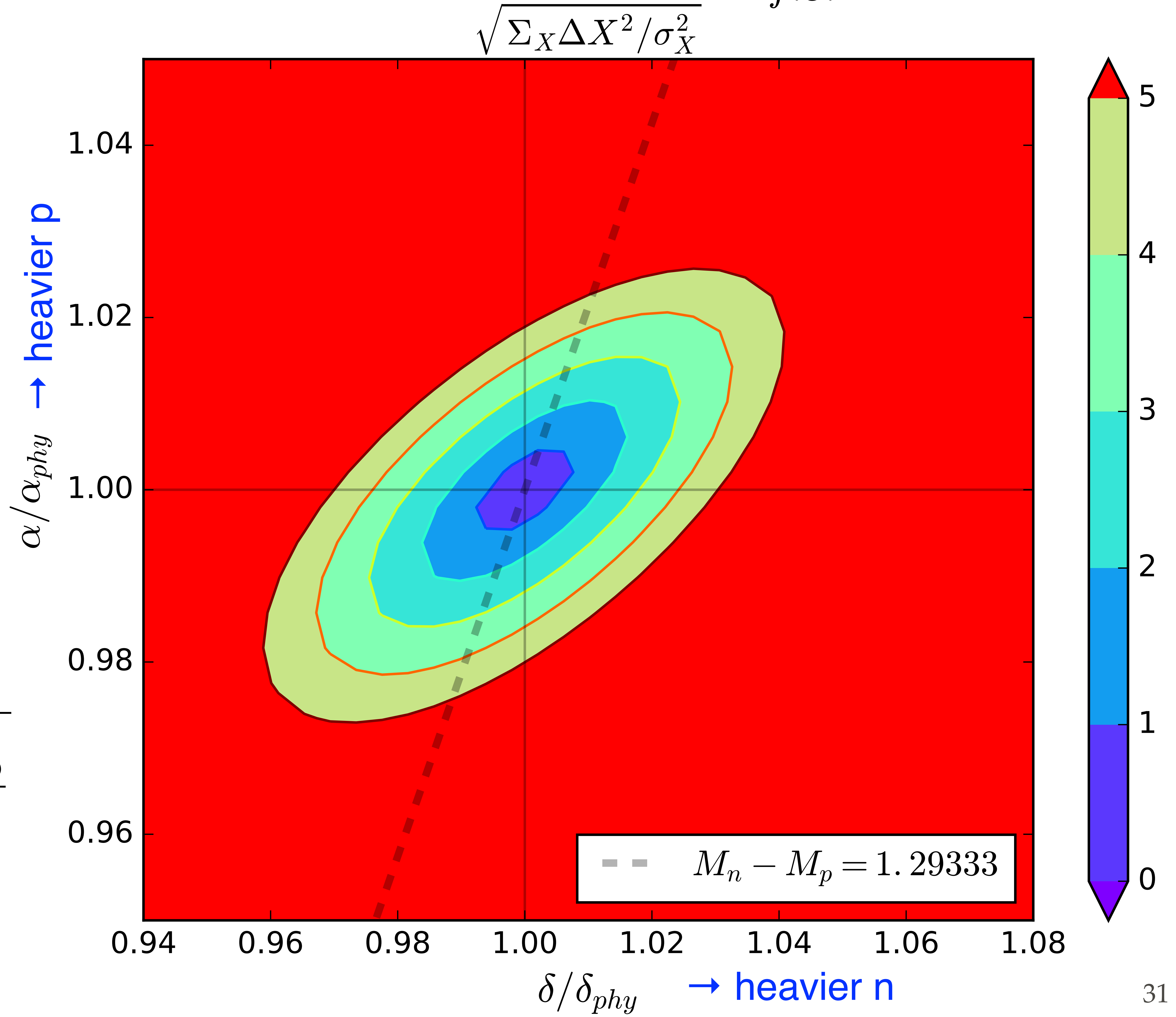
Big Bang Nucleosynthesis and $m_n - m_p$

Heffernan, Banerjee and AWL - 1706.04991

$$\delta M_{n-p} = \delta M^{\delta}_{n-p} + \delta M^{\gamma}_{n-p} = 2.39 \frac{\delta}{\delta^{\text{phys}}} - 1.10 \frac{\alpha_{f.s.}}{\alpha^{\text{phys}}_{f.s.}} \text{ MeV}$$

- The combined variation of D, ^{3}He and ^{4}He restrict possible primordial variations of isospin breaking to less than 2% at the 95% confidence level
- This places tight constraints on possible extensions of the Standard Model

$$\frac{\Delta X}{\sigma_X} = \sqrt{\frac{\Delta X^2_{^4\text{He}}}{\sigma^2_{^4\text{He}}} + \frac{\Delta X^2_{\text{D}}}{\sigma^2_{\text{D}}}}$$

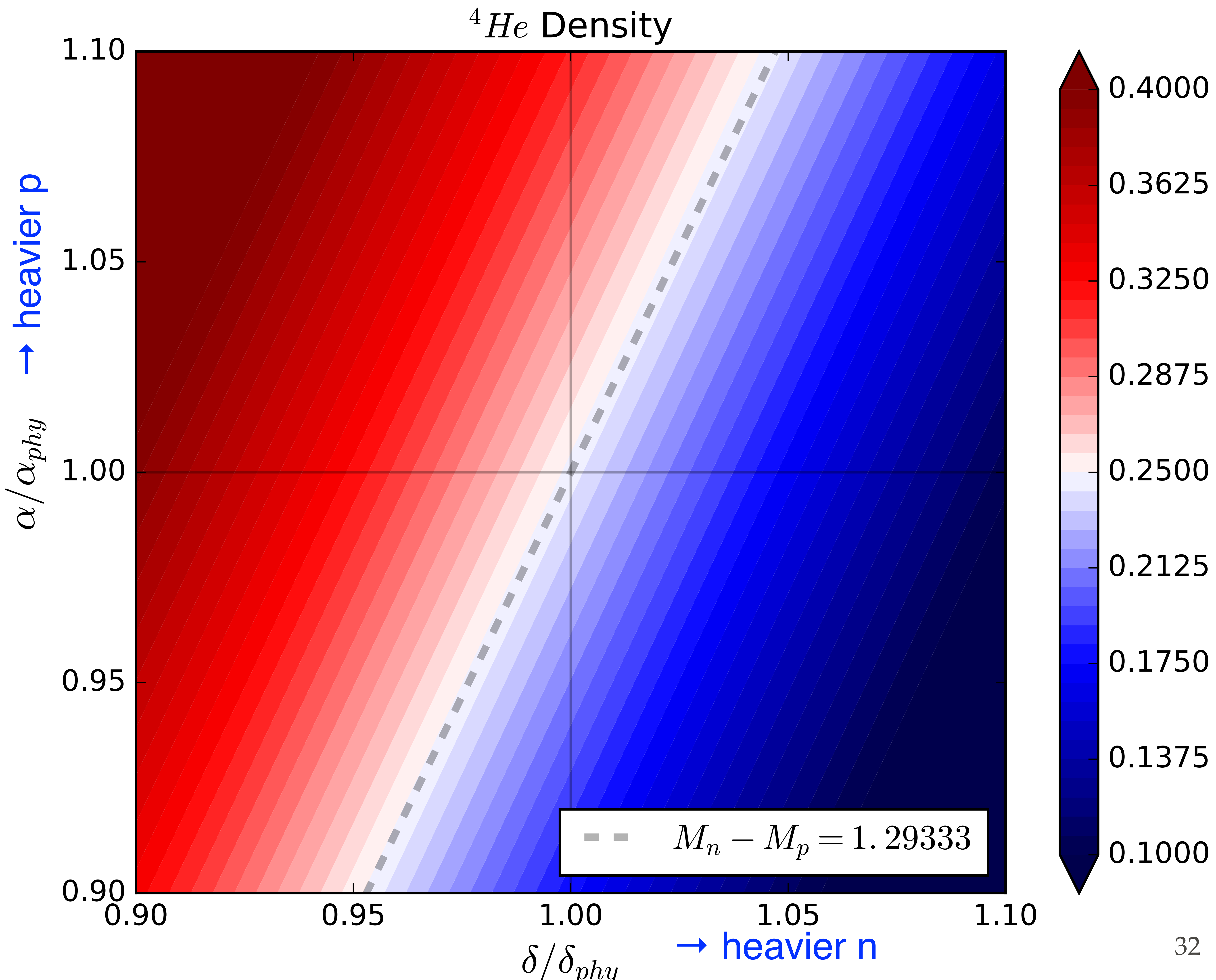


Big Bang Nucleosynthesis and $m_n - m_p$

Heffernan, Banerjee and AWL - 1706.04991

$$\delta M_{n-p} = \delta M_{n-p}^{\delta} + \delta M_{n-p}^{\gamma} = 2.39 \frac{\delta}{\delta^{\text{phys}}} - 1.10 \frac{\alpha_{f.s.}}{\alpha_{f.s.}^{\text{phys}}} \text{ MeV}$$

- For fun - we can see what the ^{4}He density would be for larger variations



Outlook

- We are now in the era in which lattice QCD is delivering precise single-nucleon quantities relevant to the nuclear physics program
  - nucleon charges (axial, scalar, tensor)
- In the next few years, we will see more dynamic quantities pinned down
  - form factors
  - radiative QED corrections to beta-decay
- The frontier for lattice QCD is moving towards the two-hadron processes
  - pi-N scattering, $N \to N\pi$ transition matrix elements, NN matrix elements, YN, (NNN) interactions, …
  - These two-hadron quantities (and notoriously two-nucleon) suffer from more extreme systematic challenges
    - The last couple years have seen the application of more sophisticated methods known to work for $\pi\pi$-scattering, to the NN problem: most likely, nearly all previous NN calculations (and their matrix elements) are unquantifiable wrong

Thank You