Chiral Perturbation Theory and Lattice QCD

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Effective Field Theory and Lattice QCD for Fundamental Nuclear Physics Research

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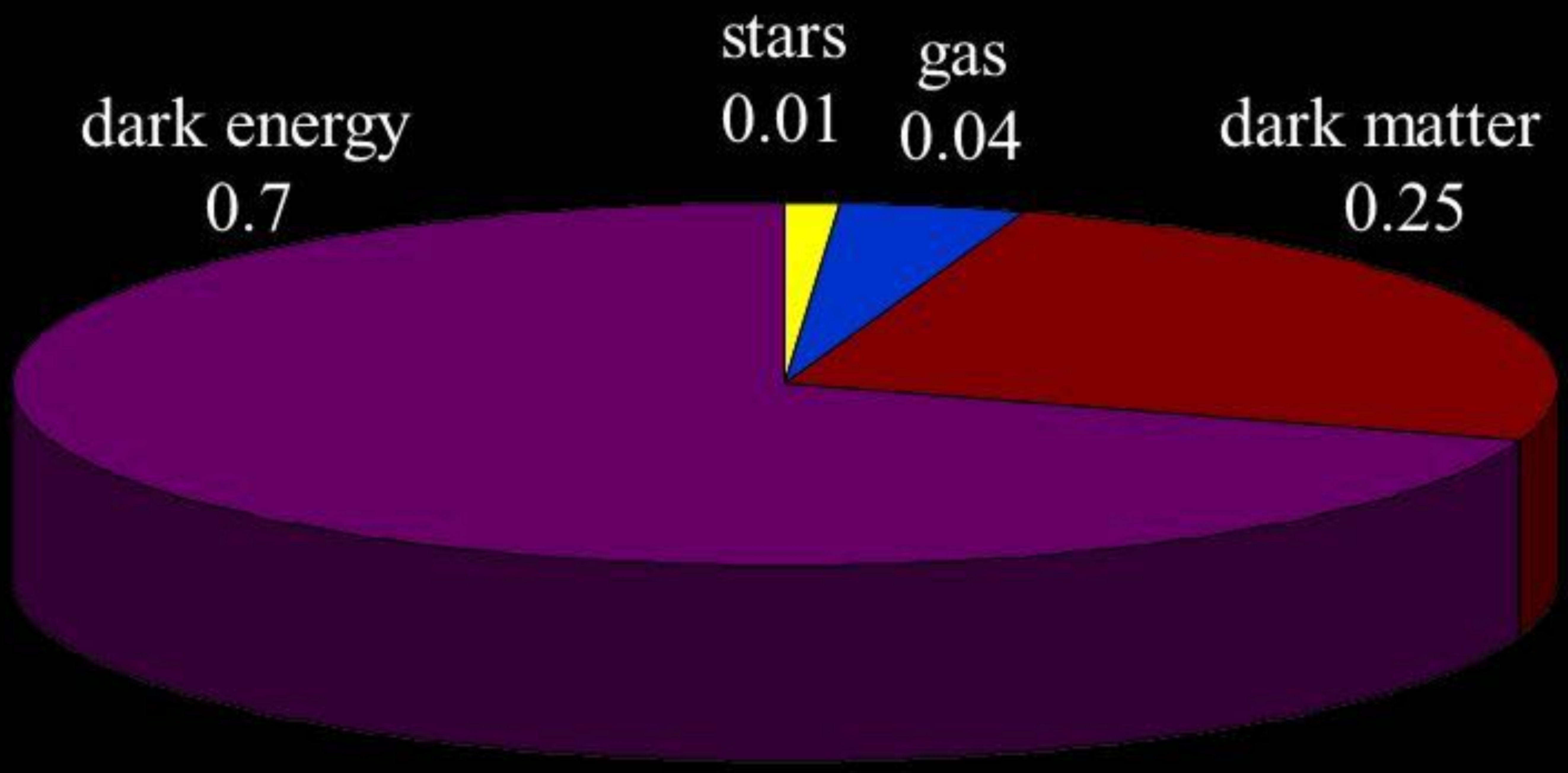
This Talk

- What are the driving science questions we are trying to understand?
- Why is it challenging to apply LQCD to nucleons and nuclei?
- Why is this an exciting time to use LQCD for basic physics?

Science Drivers

- Understanding the emergence of nuclear physics from QCD and the electroweak interactions of the Standard Model (SM)
    - How finally tuned is the universe we live in?
        - Mn-Mp, Bd, triple alpha process, …
    - What is the pp fusion rate in the sun?
    - What is the strength of the three-neutron force?
    - …
- Testing the SM and its Fundamental Symmetries at low energies in nuclear environments (nuclei)
    - Why is the universe composed of matter?
        - neutrinoless double beta decay ($0\nu\beta\beta$), permanent electric dipole moments (EDMs)
    - Does Dark Matter interact with matter other than gravitationally?
    - …

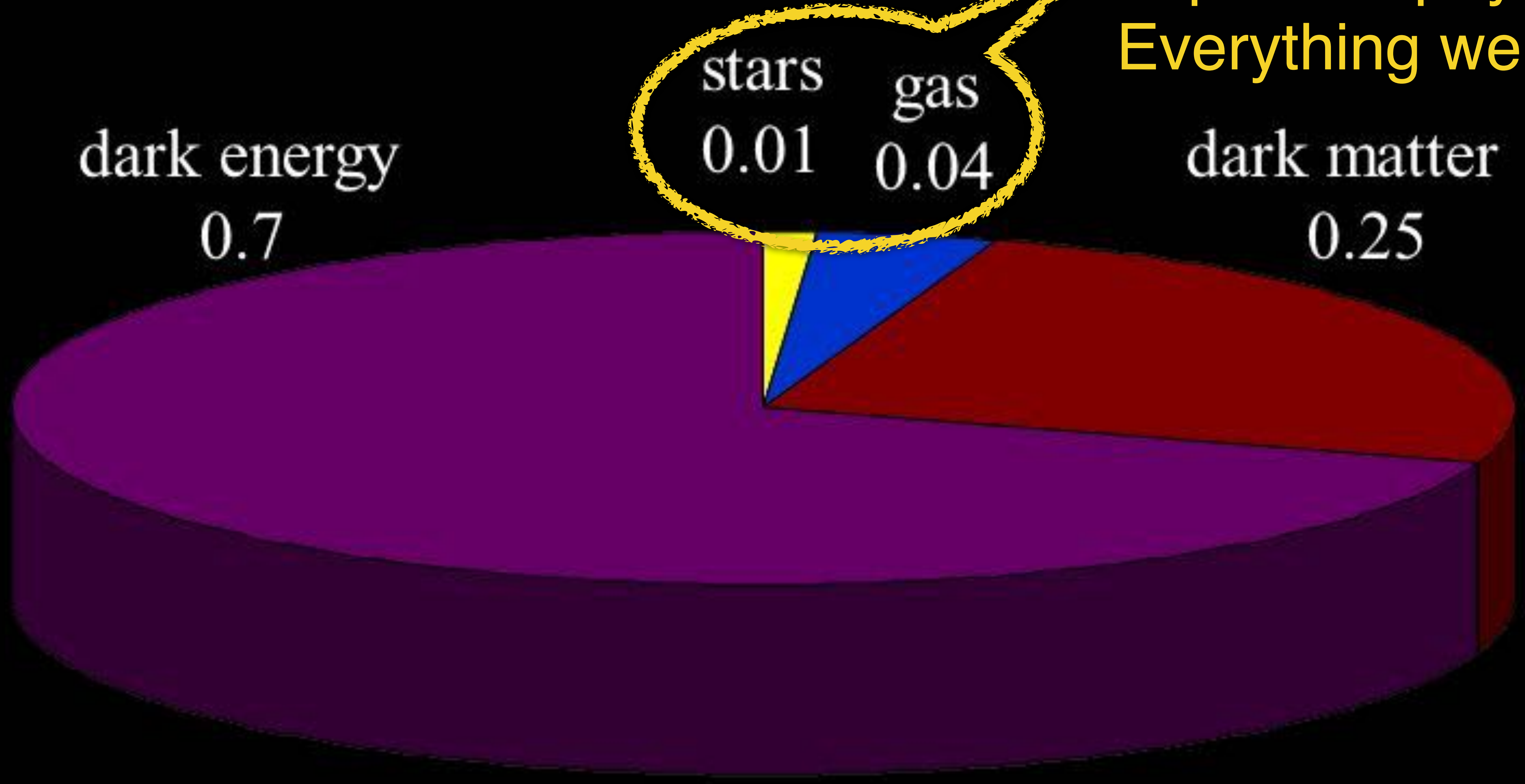
cosmic mass/energy budget



$$\Omega_{mass+energy} = 1 \text{ (or very close)}$$

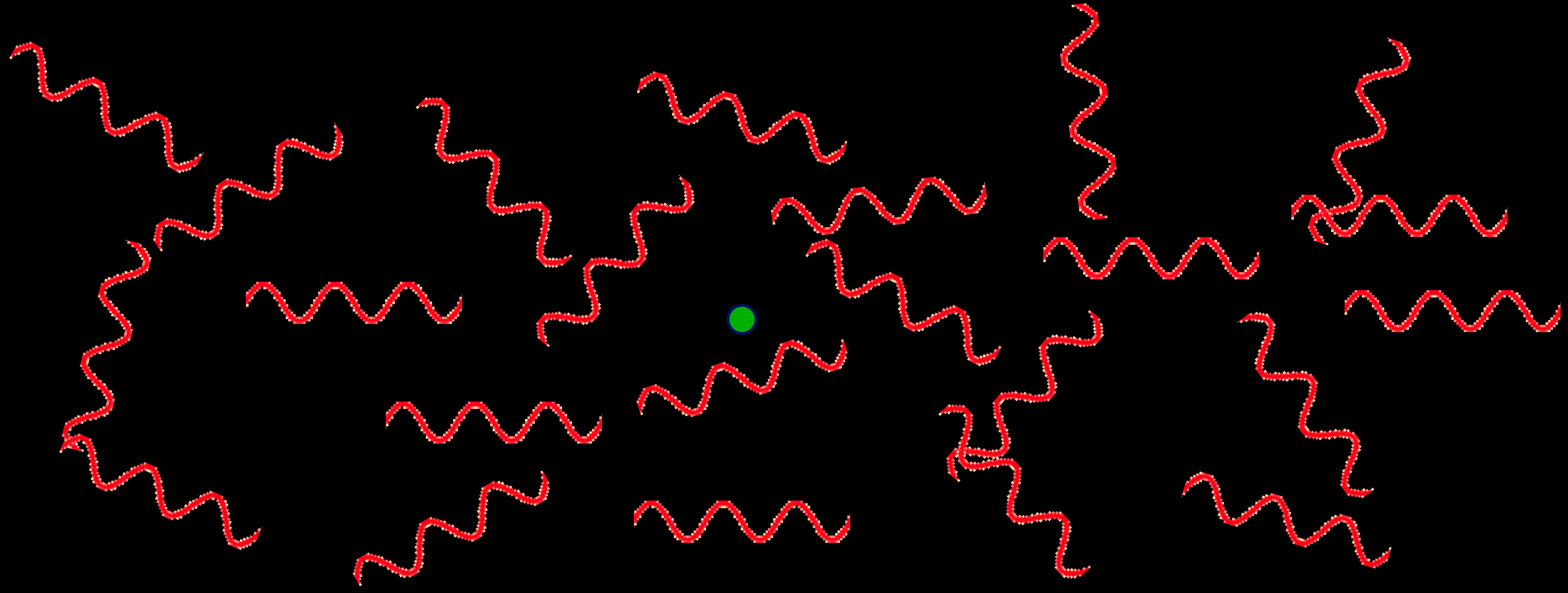
cosmic mass/energy budget

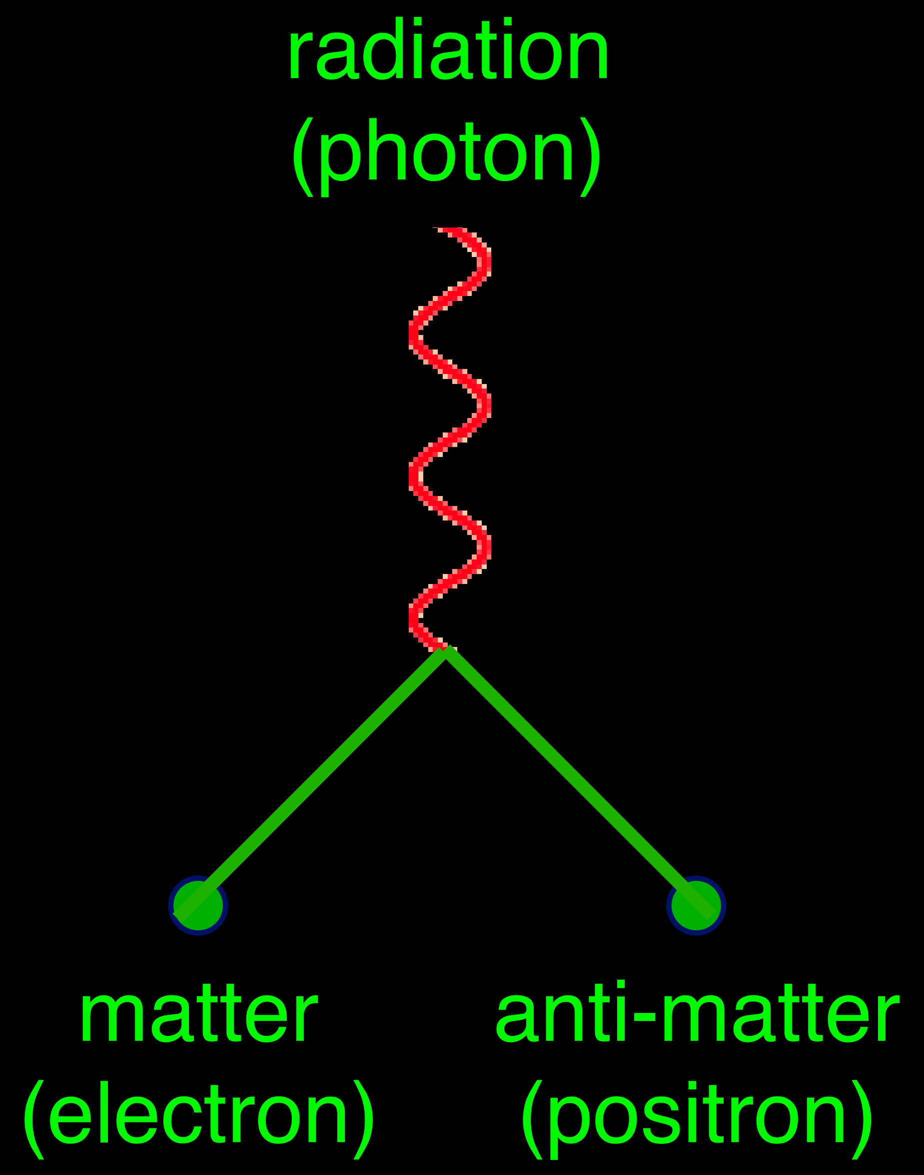
Standard Model
of particle physics
Everything we know…



$$\Omega_{mass+energy} = 1 \text{ (or very close)}$$

To the best of our knowledge, the Standard Model matter in the Universe is comprised entirely of matter and not anti-matter

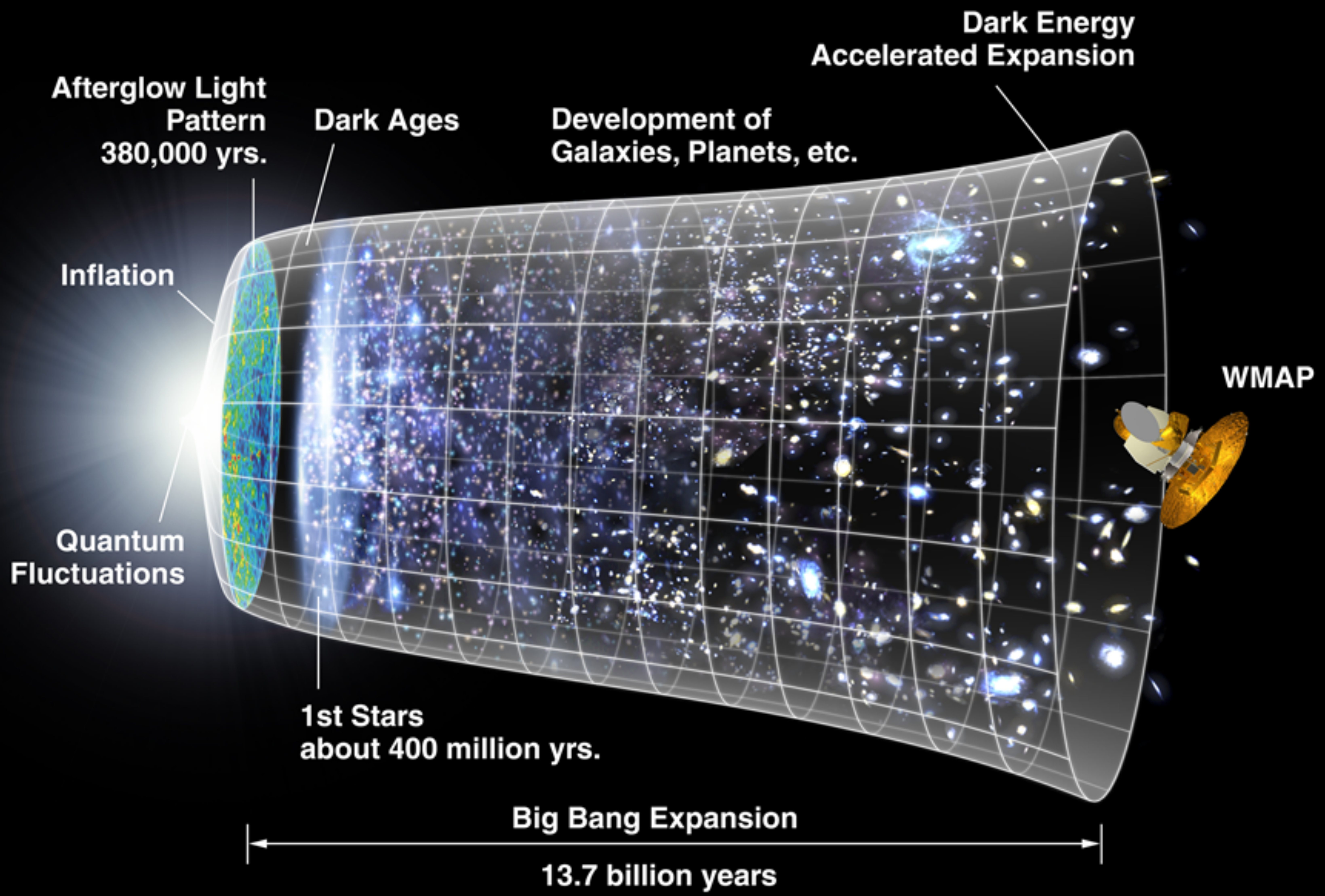




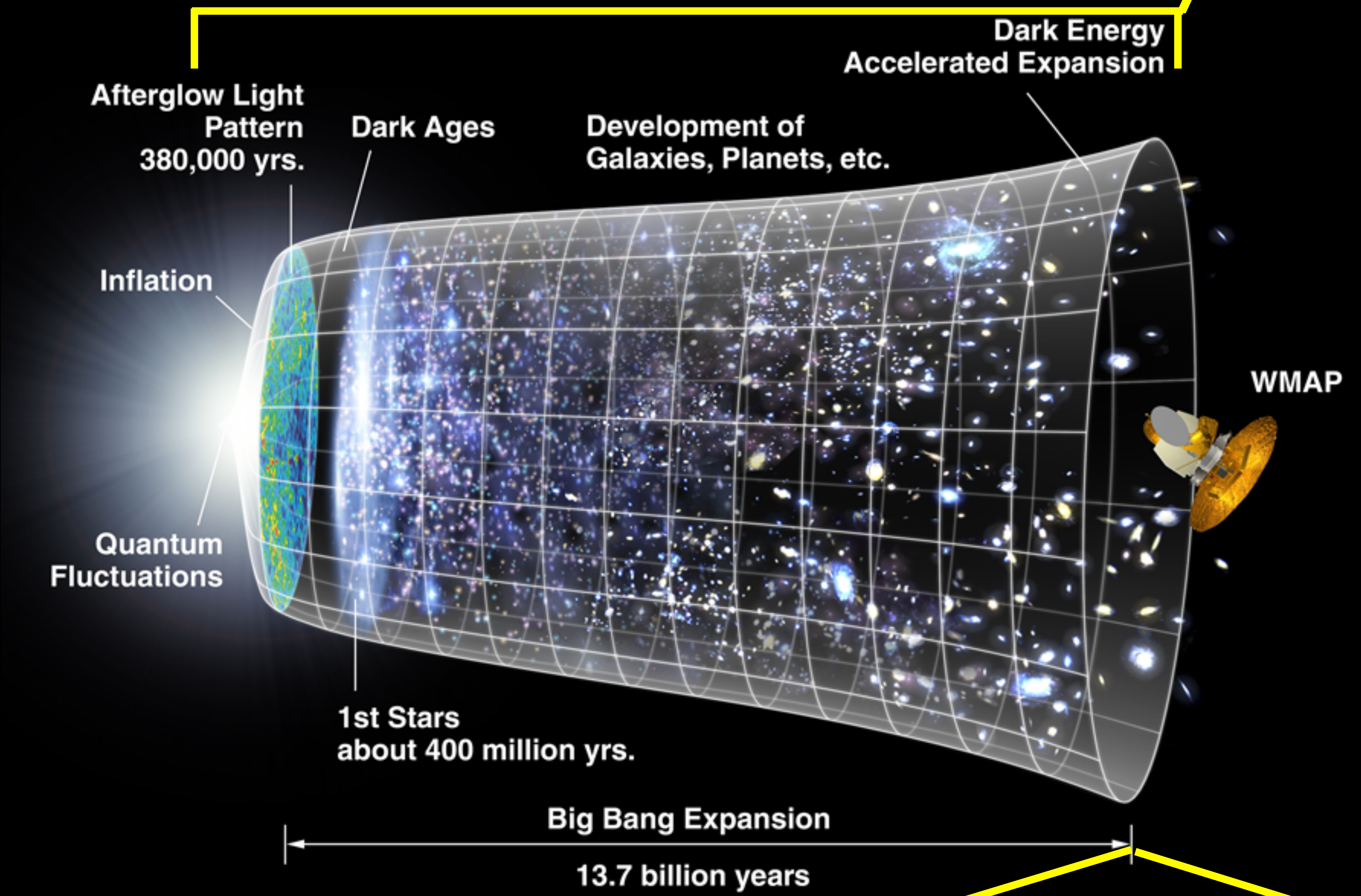
We observe there are more protons than anti-protons in the universe by an amount of roughly

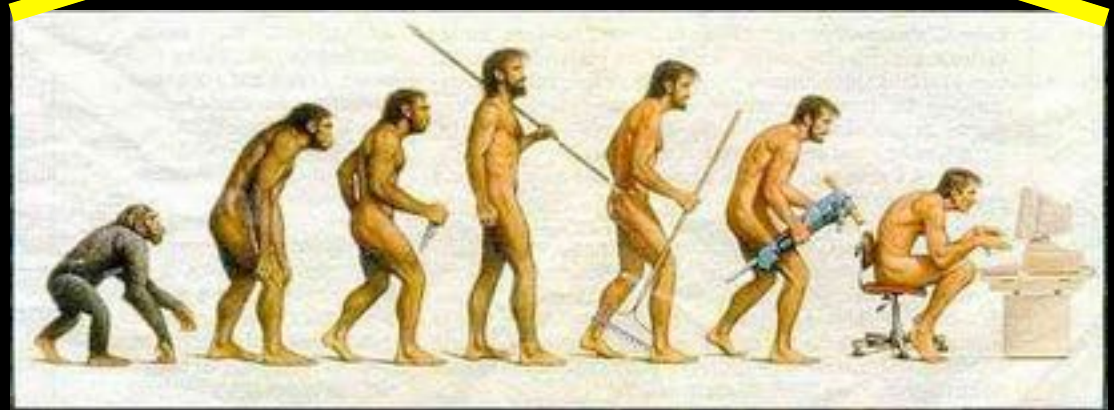
$$\frac{N_{proton} - N_{anti-proton}}{N_{photon}} \simeq 10^{-9}$$

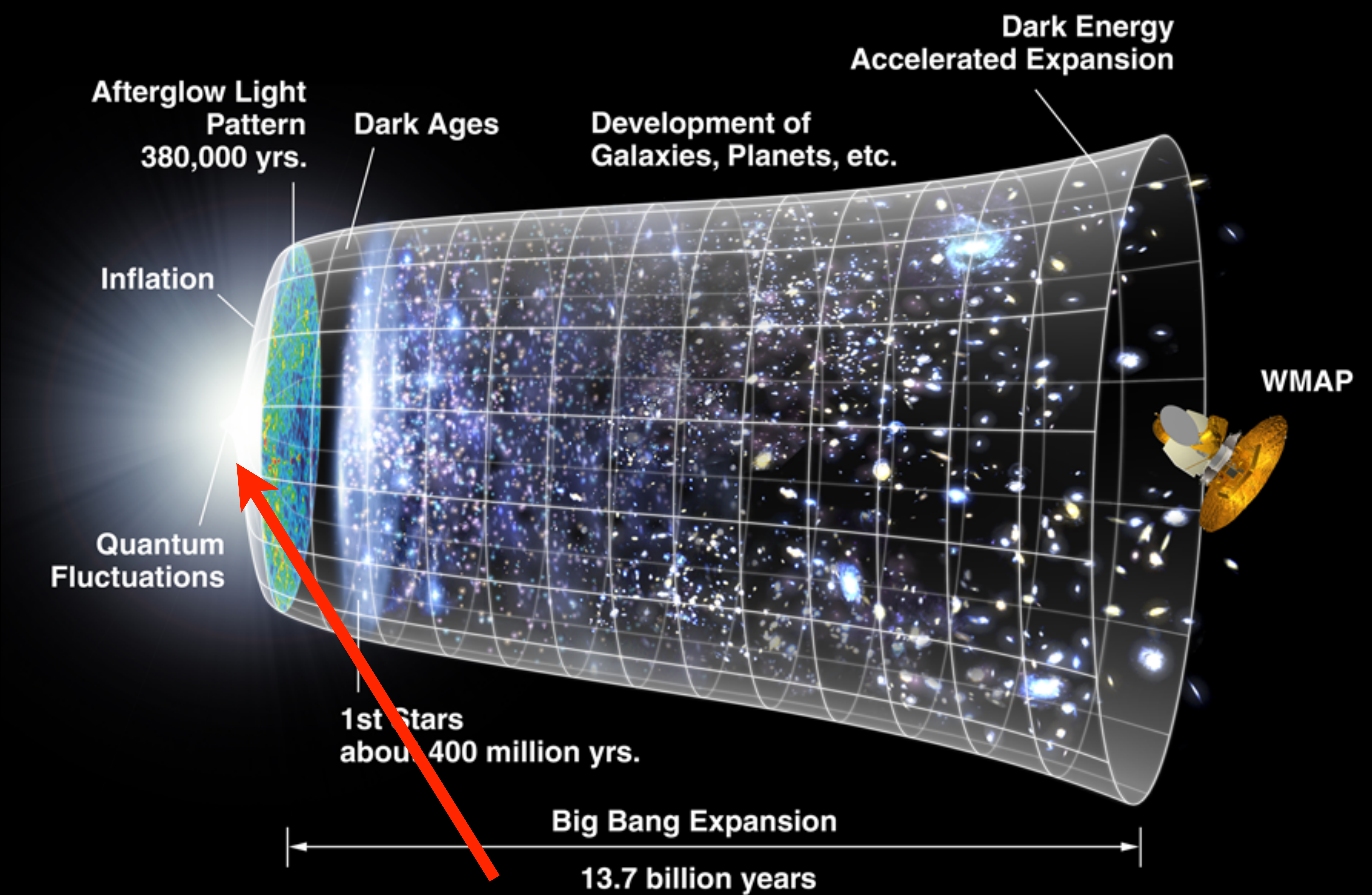
While tiny, this is still **10,000** times **or more** greater than we would predict with the Standard Model - why is there so much matter in the universe?


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Standard Model of Particle Physics





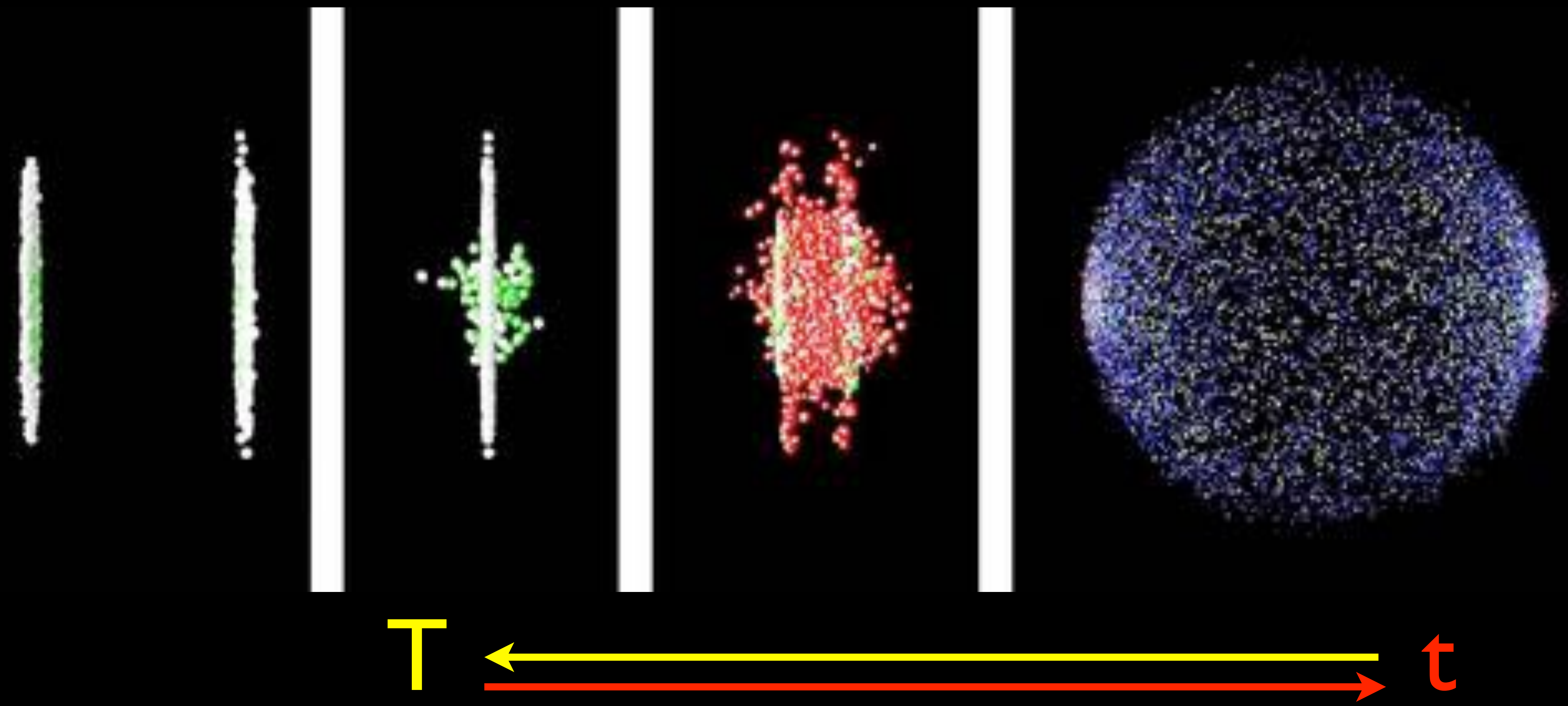


Formation of Matter

$T \simeq 1$ trillion K (10^{12} K)

$t \simeq 30$ micro seconds ($3\text{x}10^{-5}$ s)


Sextant 10/11
12:00 o'clock
Sextant 12/1
PHOBOS
10:00 o'clock
BRAHMS
2:00 o'clock
RHIC
4:00 o'clock
Sextant 6/7
STAR
(First sextant to be tested)
BOOSTER
G-2
LINAC
AGS
TANDEMS


T
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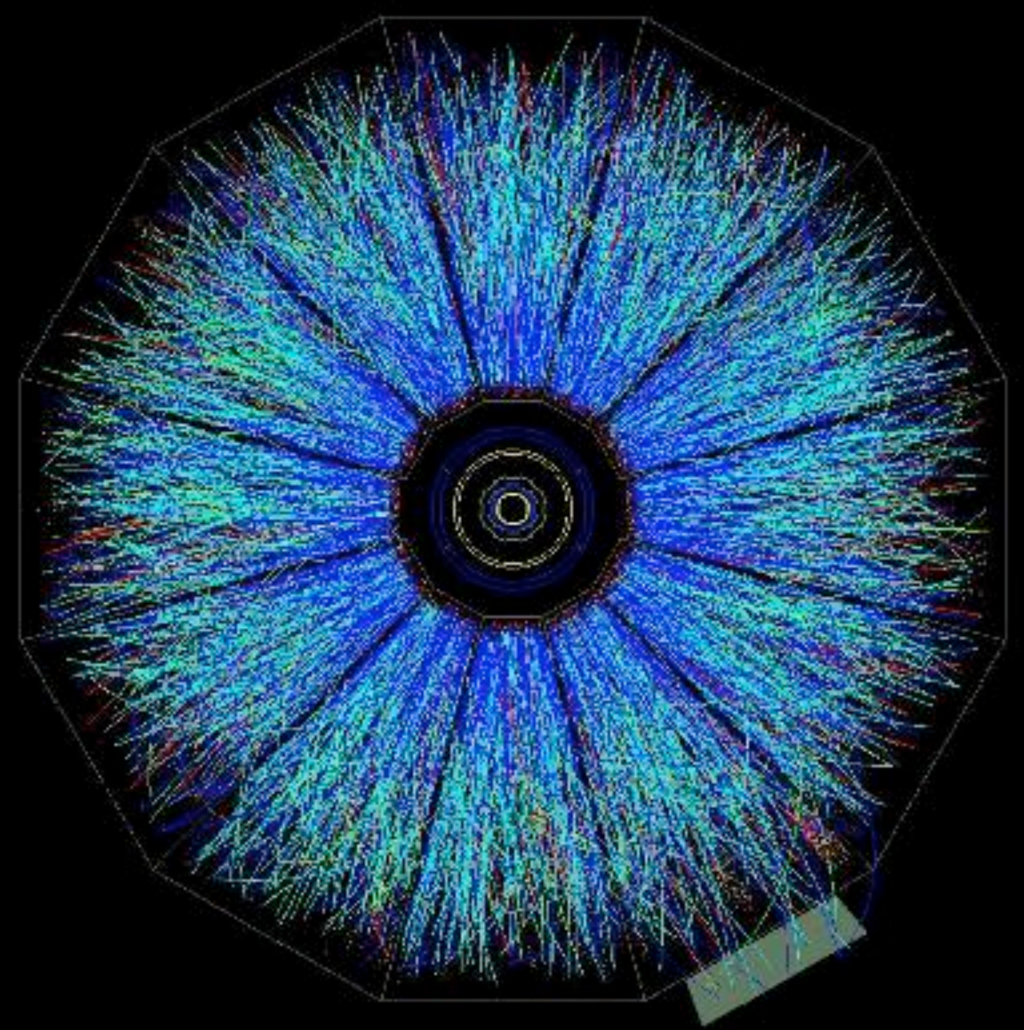
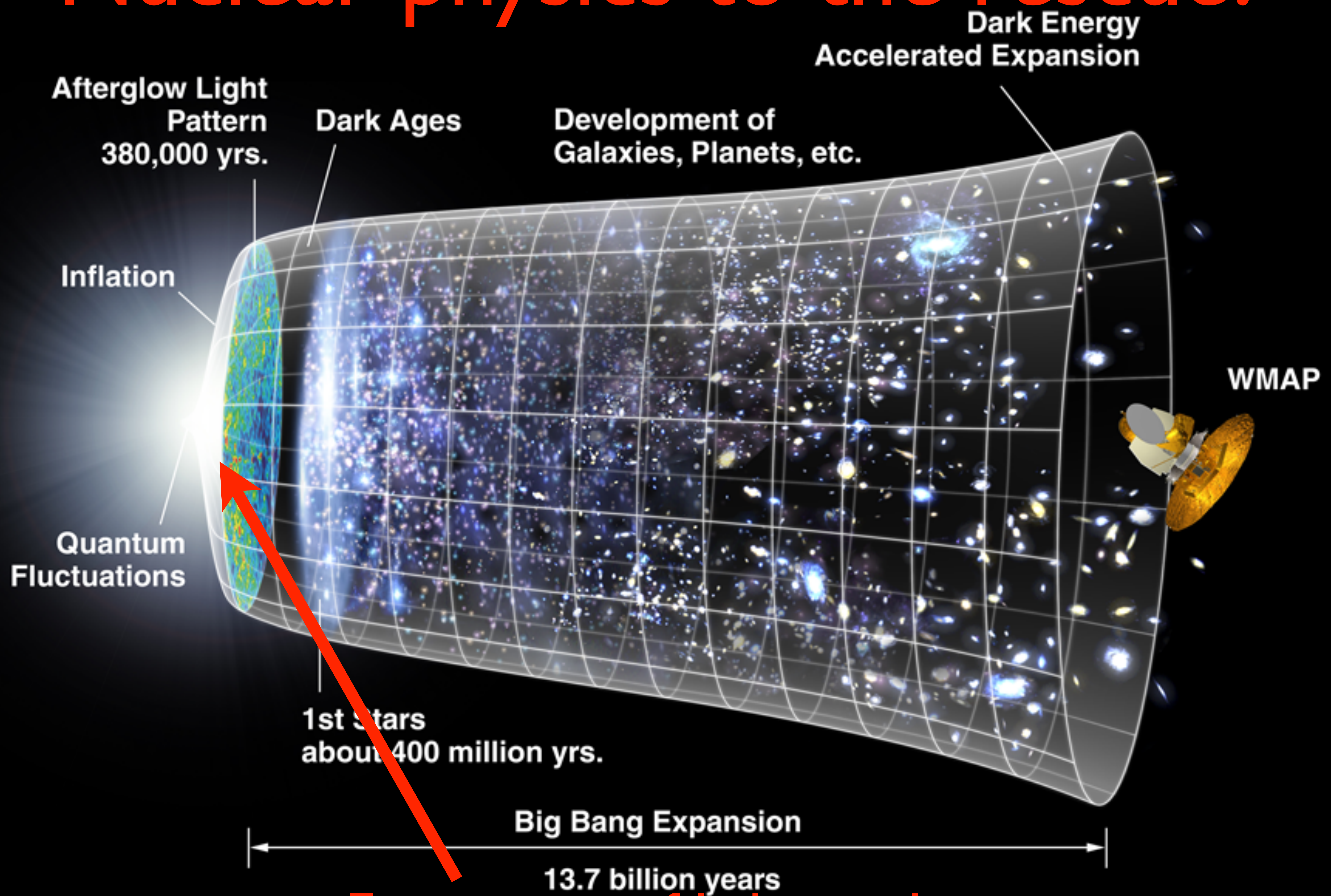


Nuclear physics to the rescue!

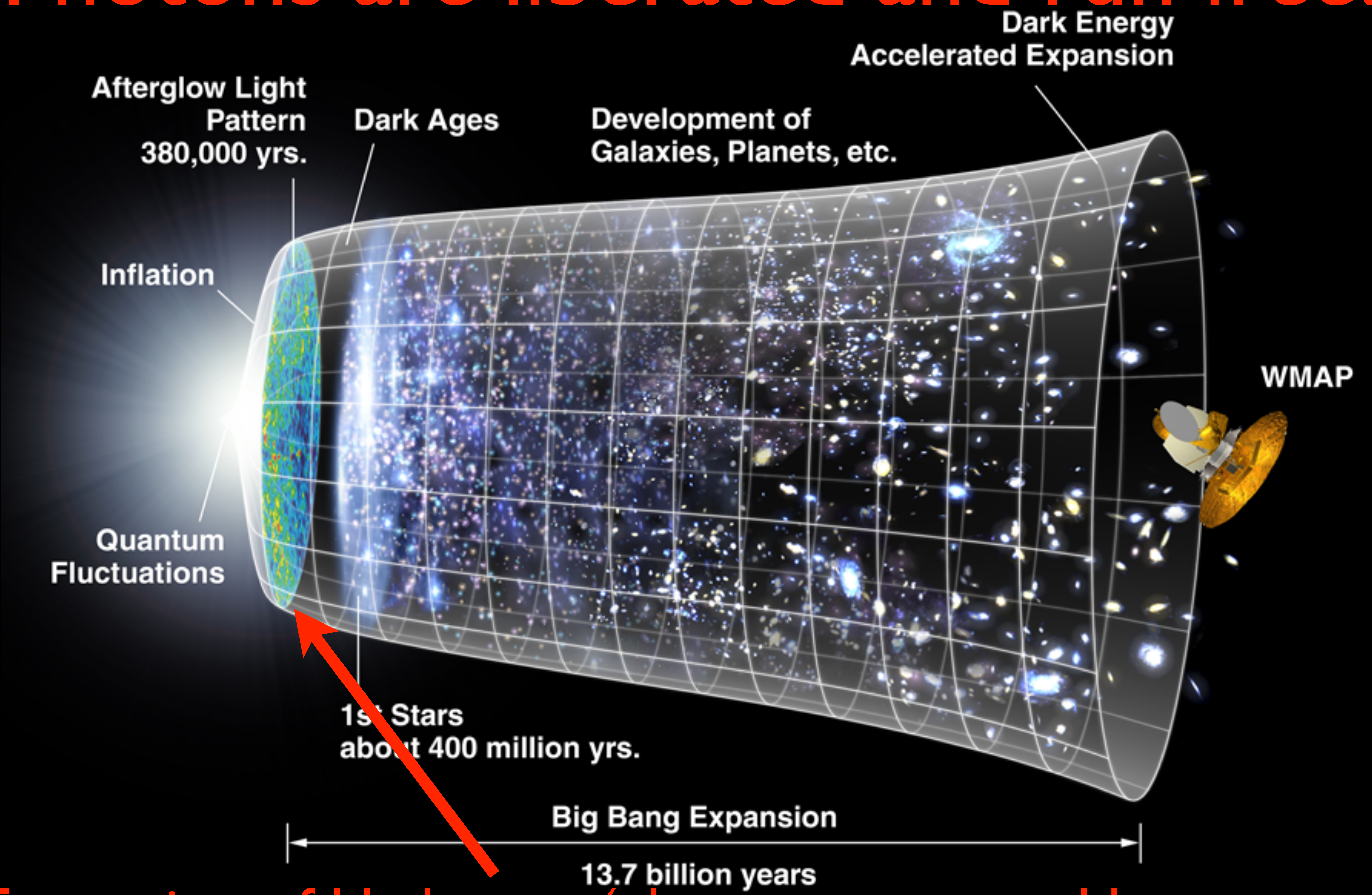


Formation of light nuclei

$T \simeq 1$ billion K (10^9 K)

$t \simeq 3$ minutes

Photons are liberated and run free!

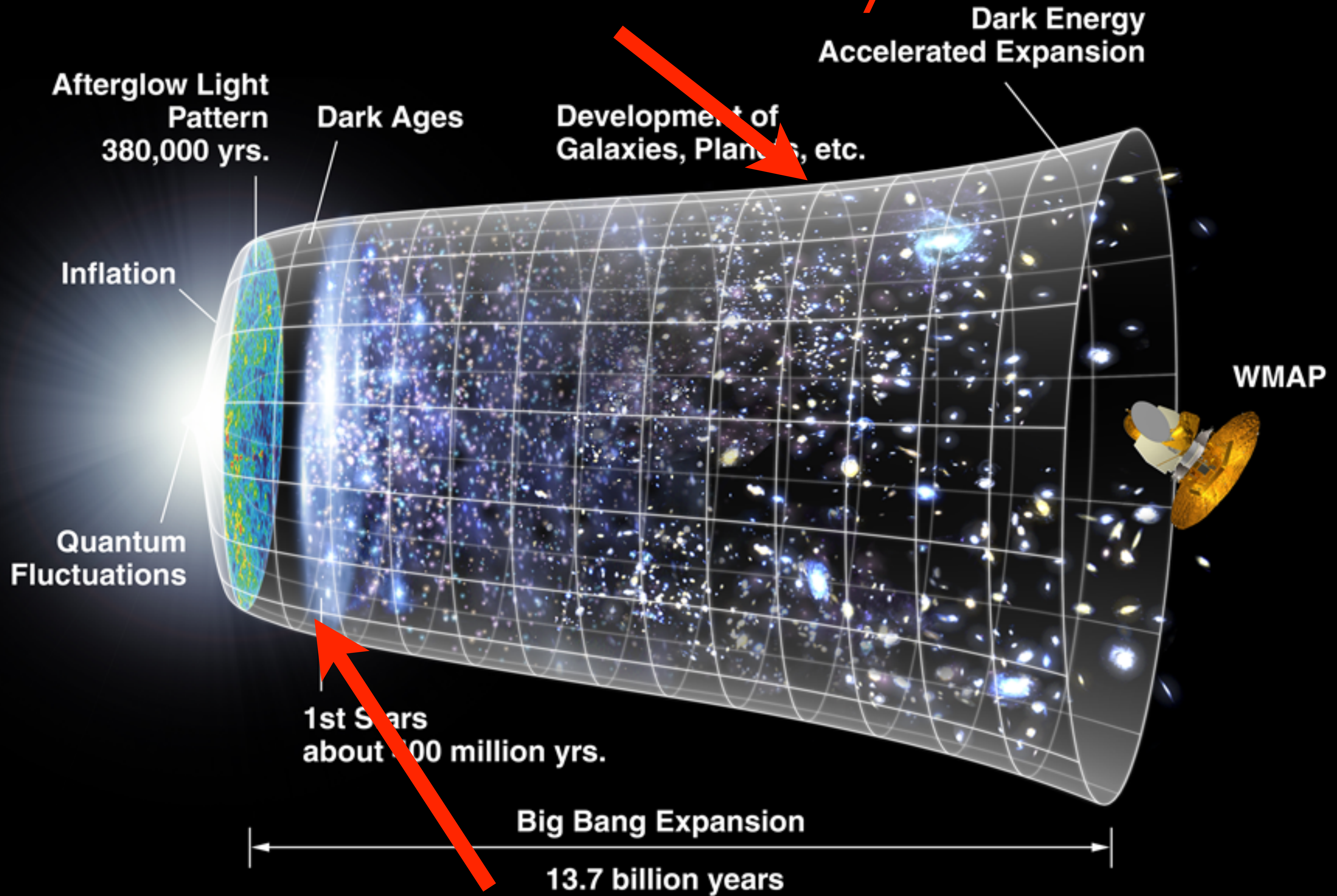


Formation of Hydrogen (electrons captured by protons)

$T \simeq 4{,}000$ K

$t \simeq 380{,}000$ years

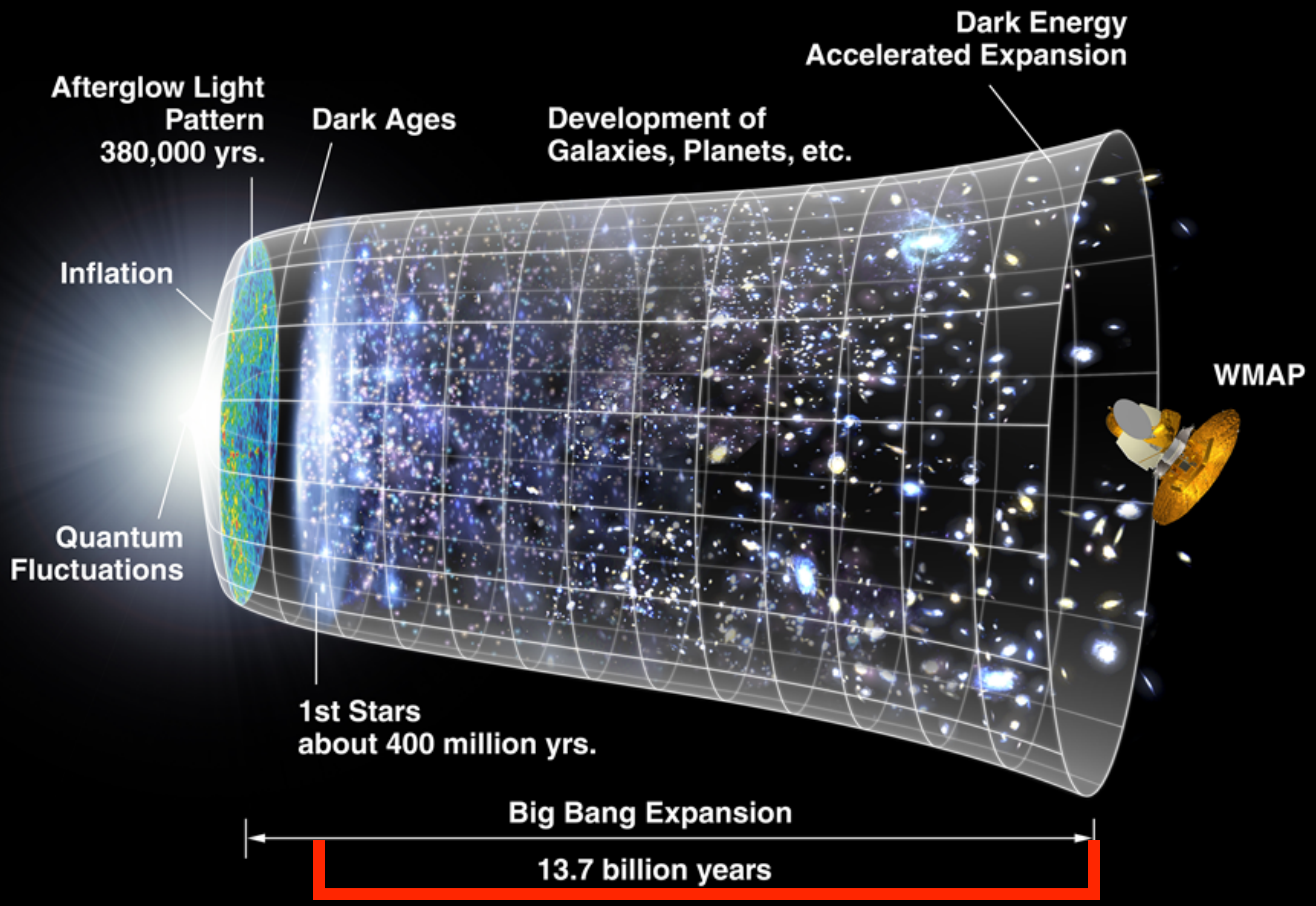
Formation of our solar system



Formation of first stars

$T \simeq 20$ K

$t \simeq 200$ Million years



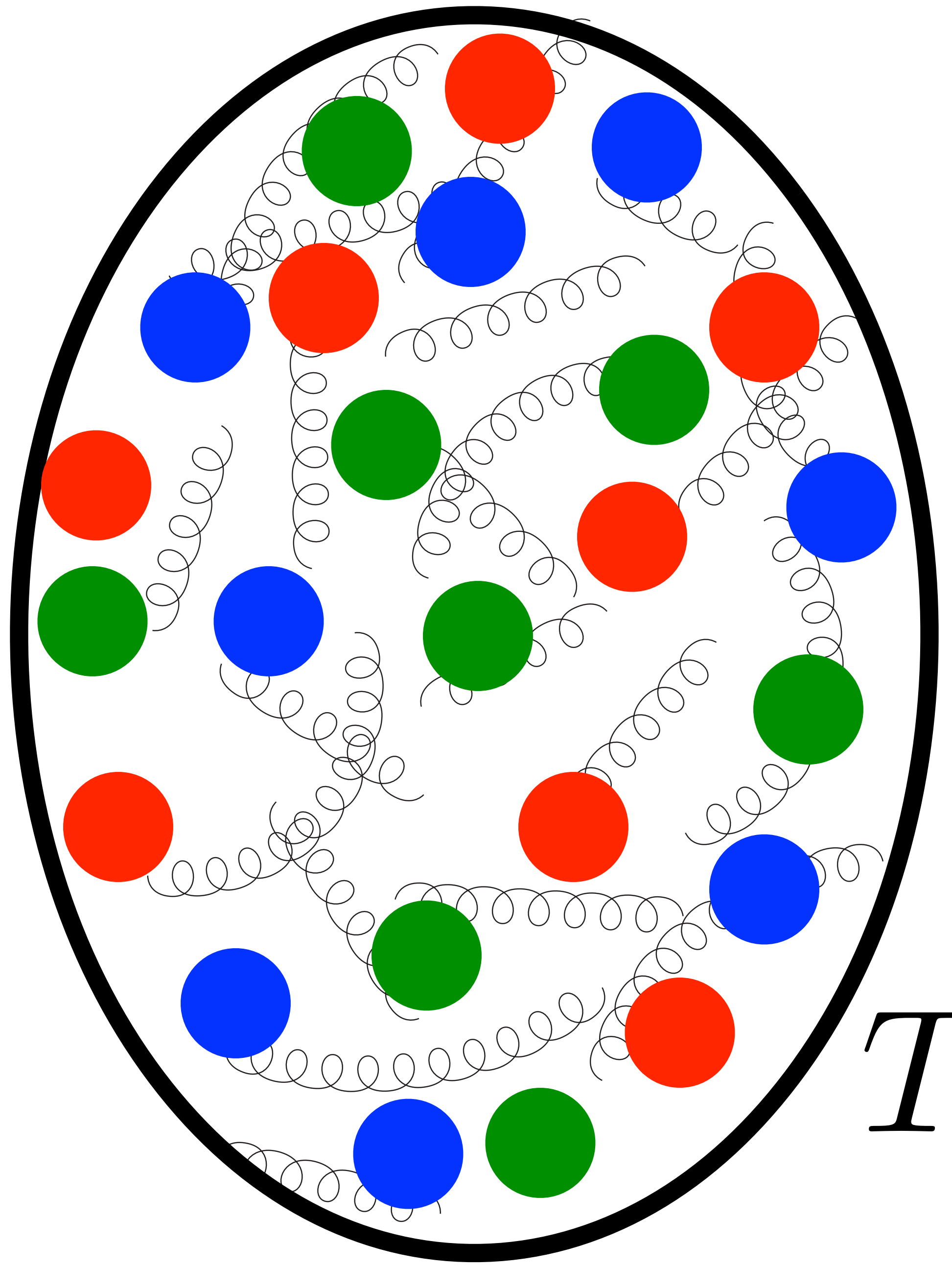
Death of stars, creation of heavy nuclei and *life*, creation of new, *ultradense* states of nuclear matter

From Quarks to Protons and Neutrons

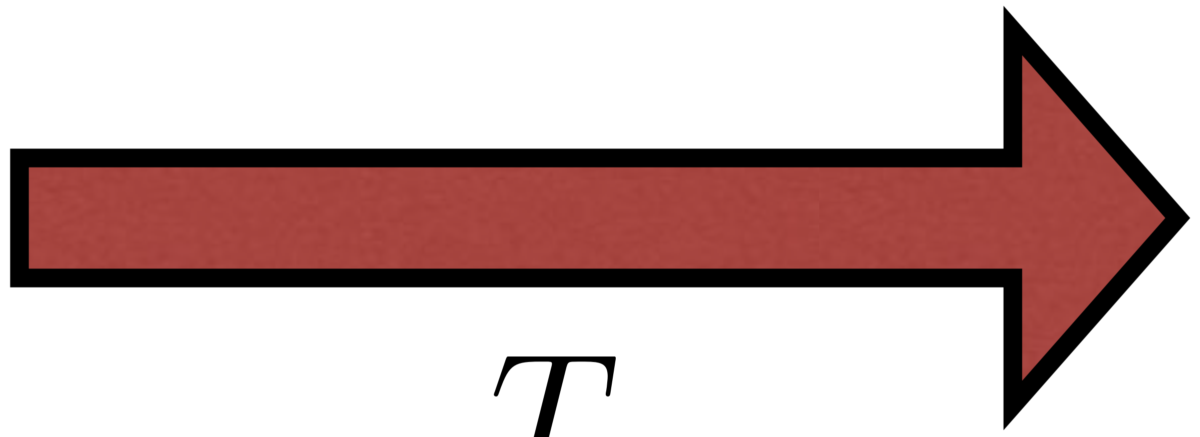
$$T \simeq 1 \text{ trillion K} \ \left(10^{12} \text{ K}\right)$$

$$t \simeq 30 \text{ micro seconds} \left(3.0 \times 10^{-5} s\right)$$

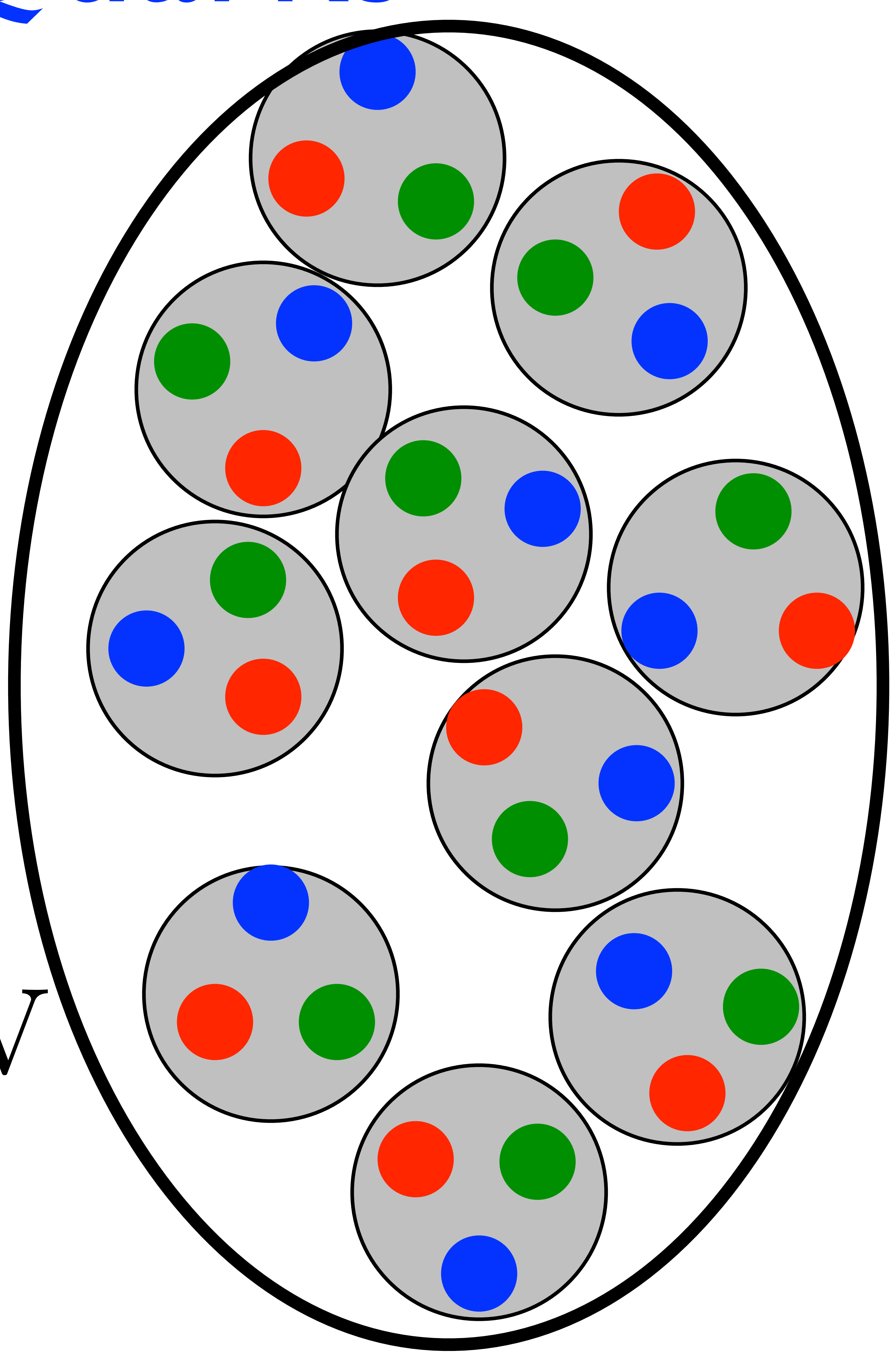
Confinement of Quarks



cooler



T_c



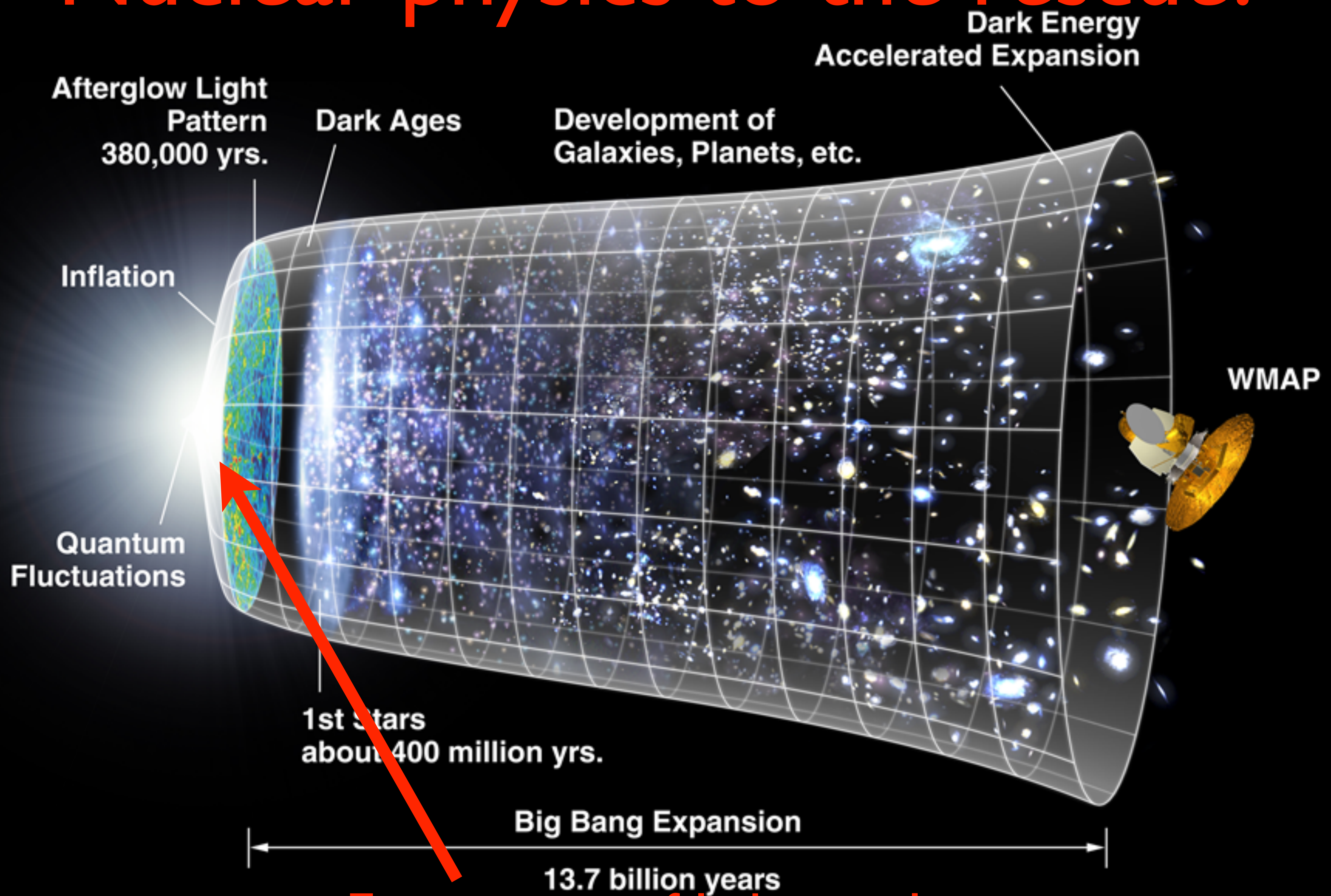
$$T_c \simeq 145 - 170 \text{ MeV}$$

$$\simeq 10^{12} K$$

computed by Budapest-Wuppertal and hot-QCD Lattice Collaborations with previous generation supercomputers

See lectures by Peter Petreczky

Nuclear physics to the rescue!



Formation of light nuclei

$T \simeq 1$ billion K (10^9 K)

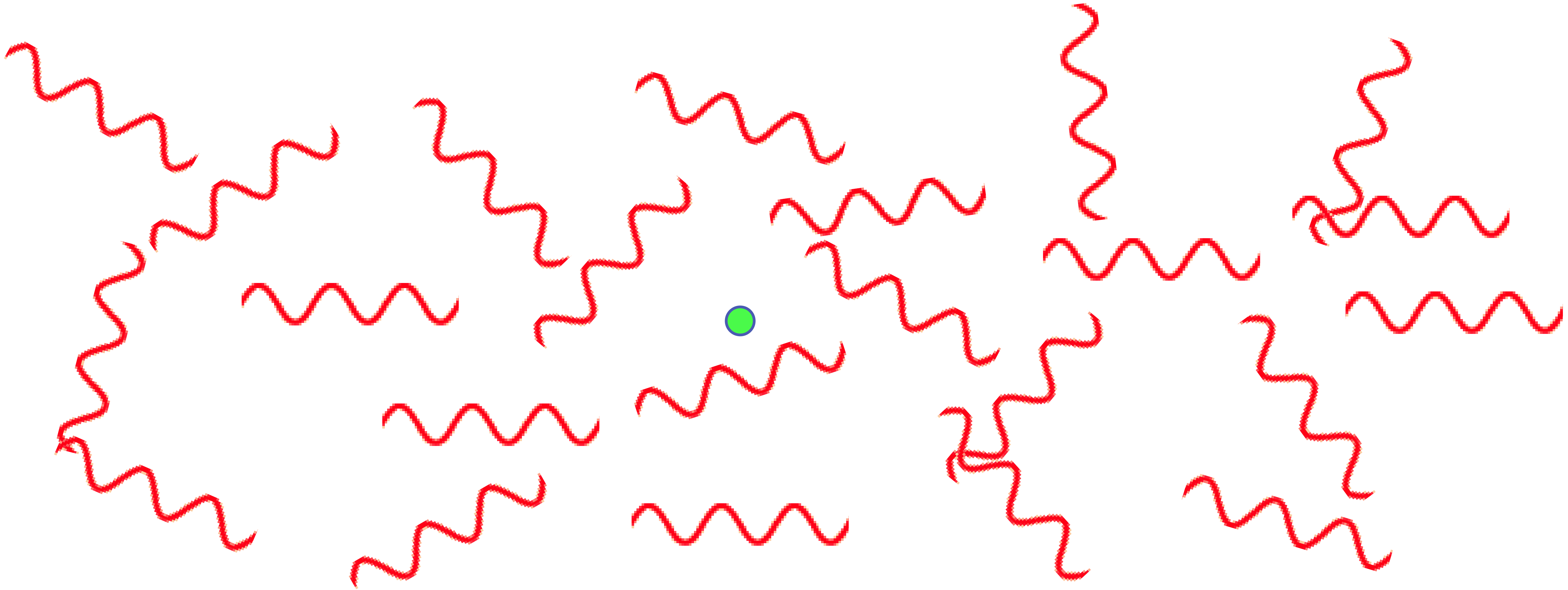
$t \simeq 3$ minutes

Big Bang Nucleosynthesis

$$T \simeq 1 \text{ trillion K} \rightarrow 1 \text{ billion K}$$

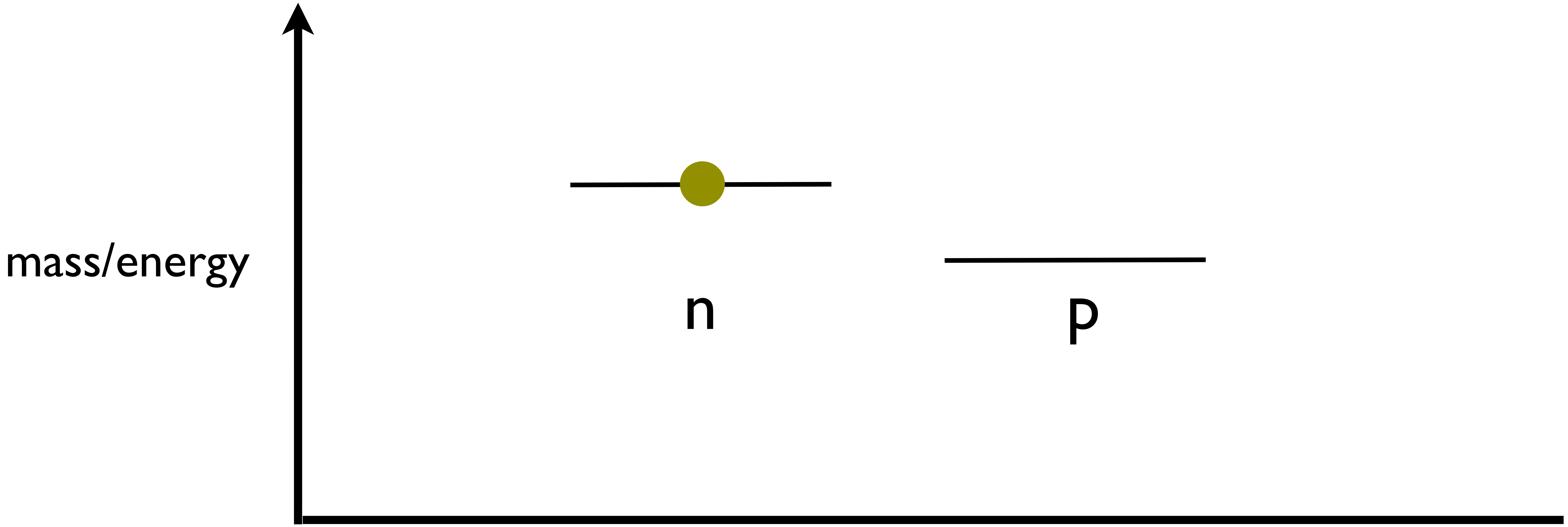
$$t \simeq 3 \times 10^{-5} s \rightarrow 3 \text{ min}$$

Our initial condition is a soup of radiation plus a small excess amount of matter, in the form of protons, neutrons, electrons and photons



$$\eta_{B/\gamma} \sim 10^{-9}$$

when systems cool, they settle into the lowest energy state

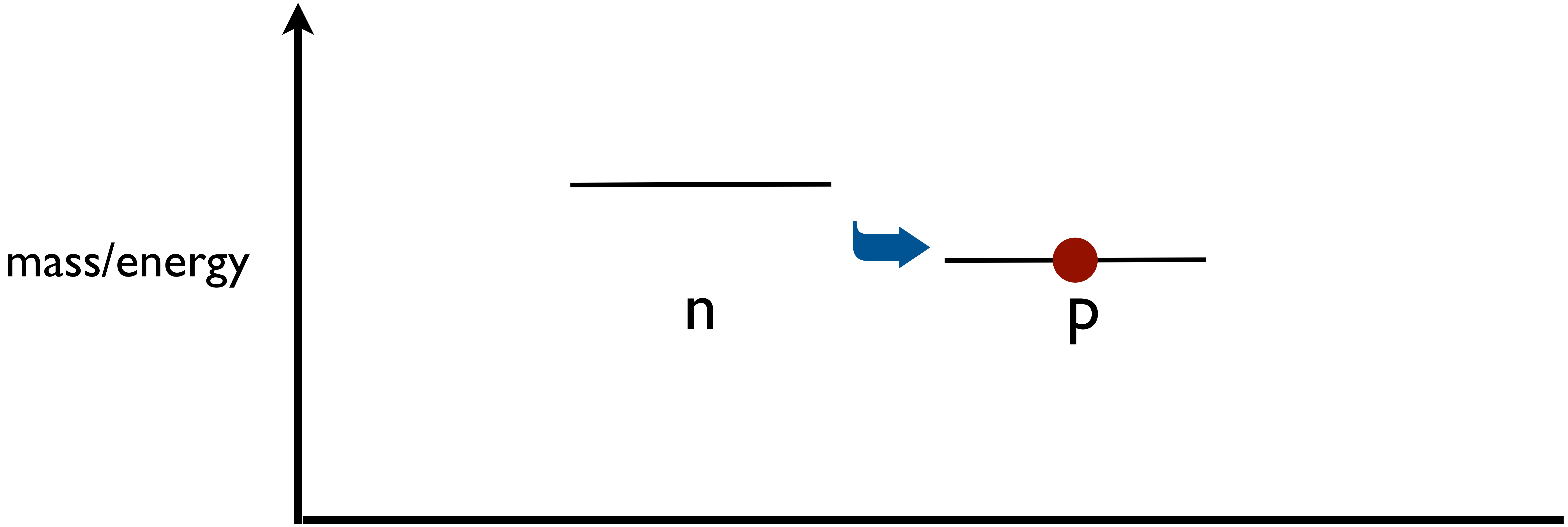


$$M_n - M_p = 1.29333217(42)\ \text{MeV}$$

$$E_{\text{Hydrogen}} = 13.6\ \text{eV}$$

$$\frac{M_n + M_p}{2} = 938.9187473(58)\ \text{MeV}$$

when systems cool, they settle into the lowest energy state

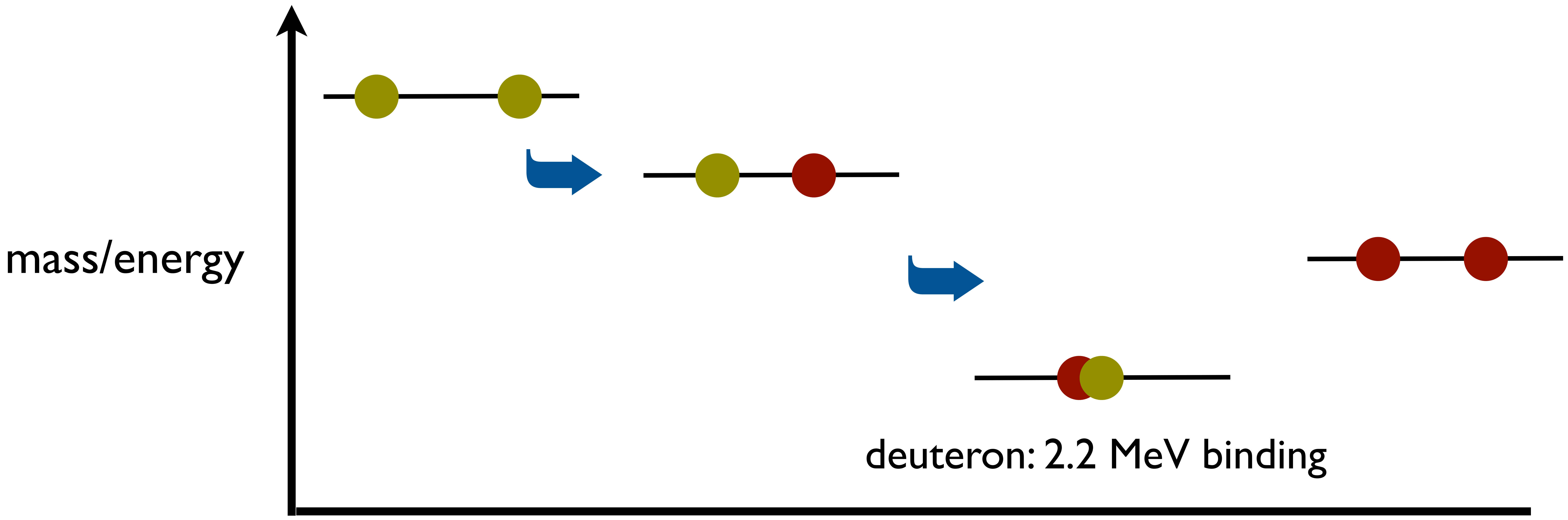


$\tau_n \sim 15 \text{ min}$

what prevented this from destroying all the neutrons?

if nothing else were to happen in the next few minutes,
our universe would be full of only Hydrogen

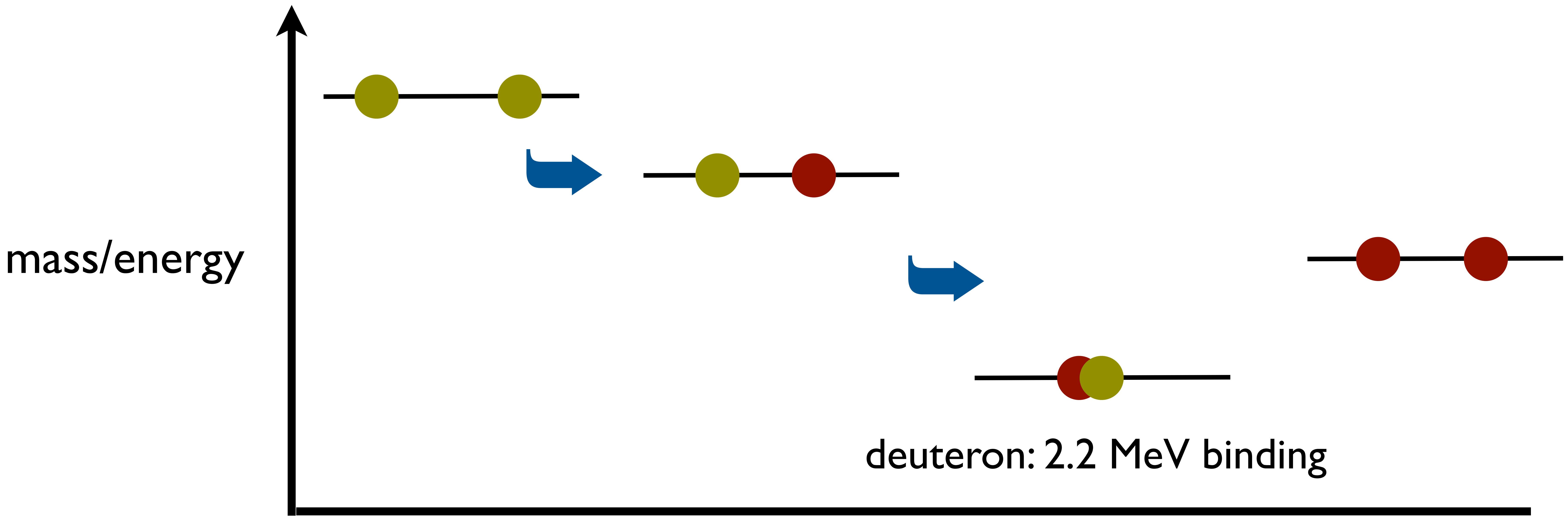
when systems cool, they settle into the lowest energy state

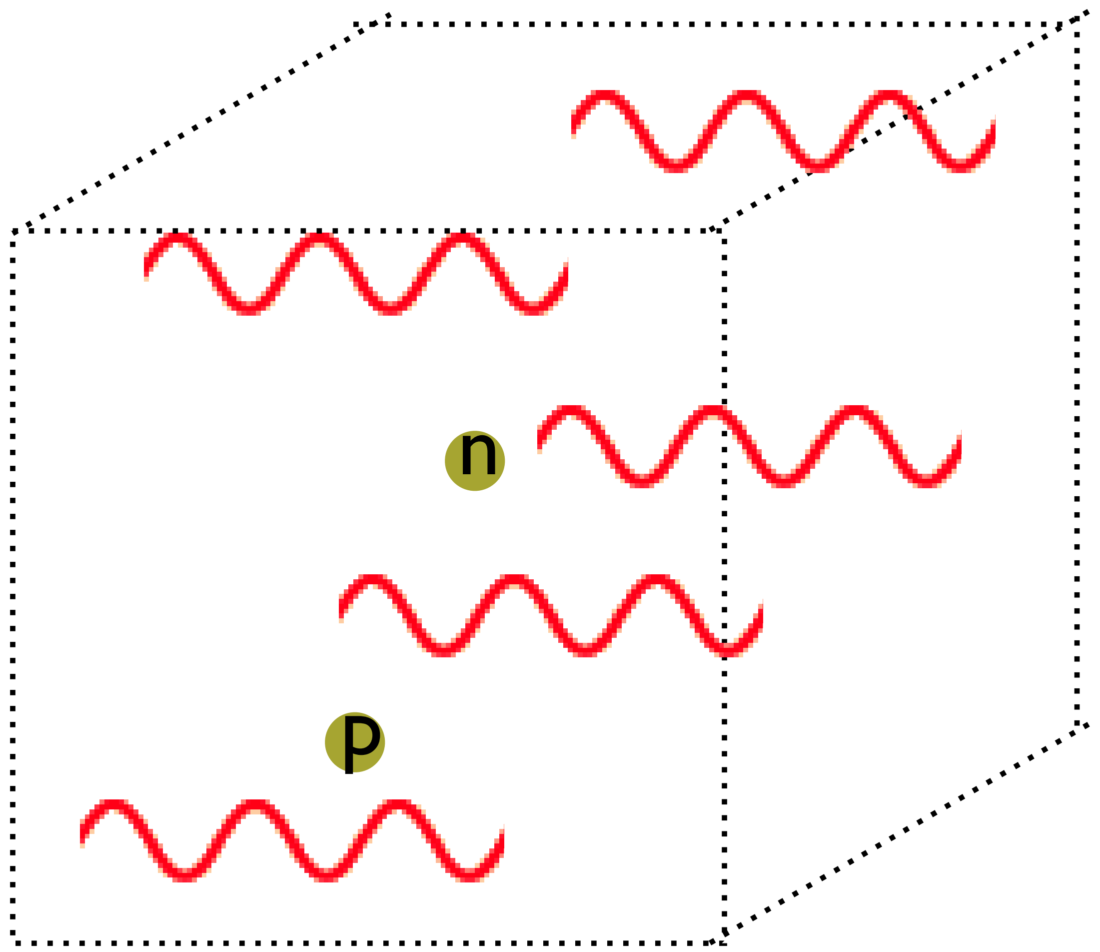


Answer: formation of nuclei

a system with protons and neutrons can collapse to a compact bound state, the deuteron: the attractive binding of a neutron and proton allows neutrons to survive when embedded in nuclei

The deuterium “bottleneck”





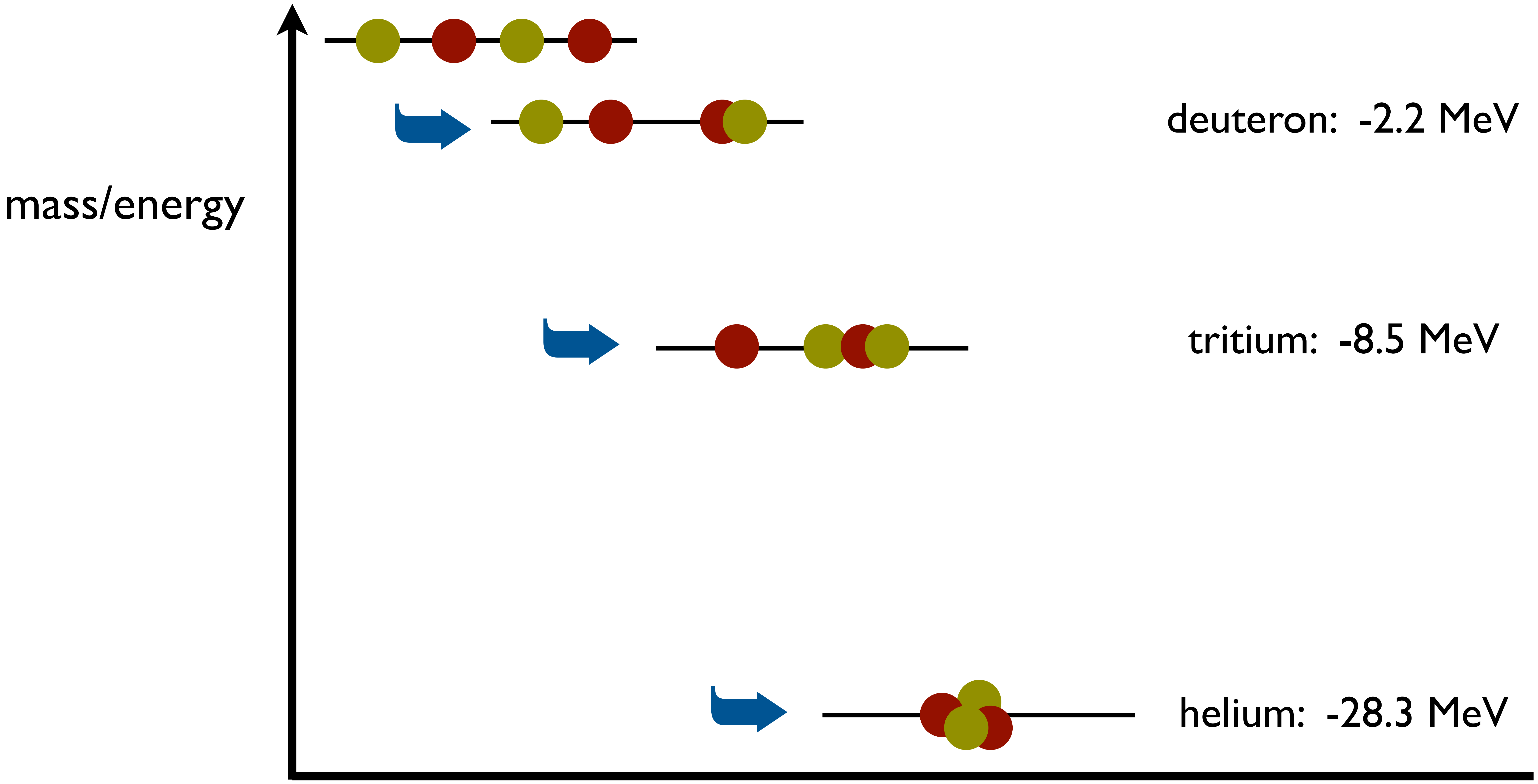
$$\eta_{B/\gamma} \sim 10^{-9}$$

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

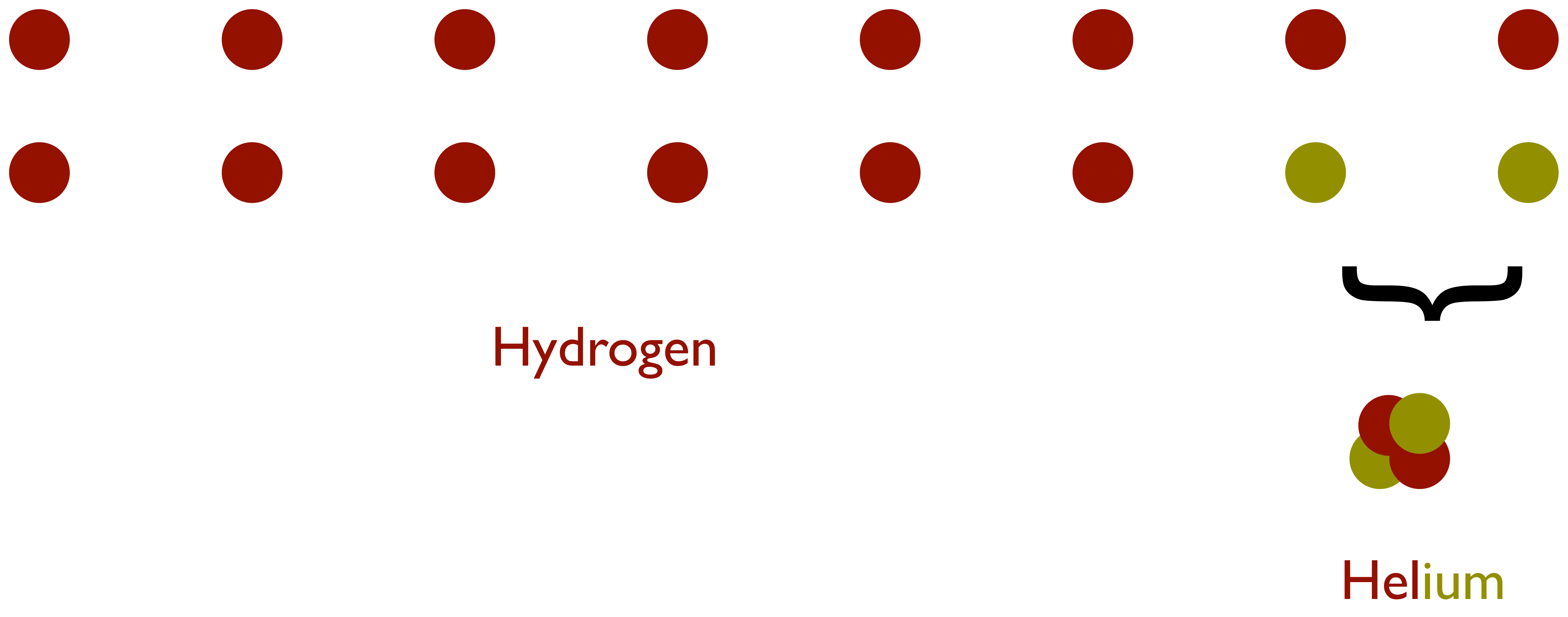
until T ≃ 100 keV (1 billion K),
t ≃ 3 min

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

The deuterium "bottleneck" is broken, neutrons flow into He

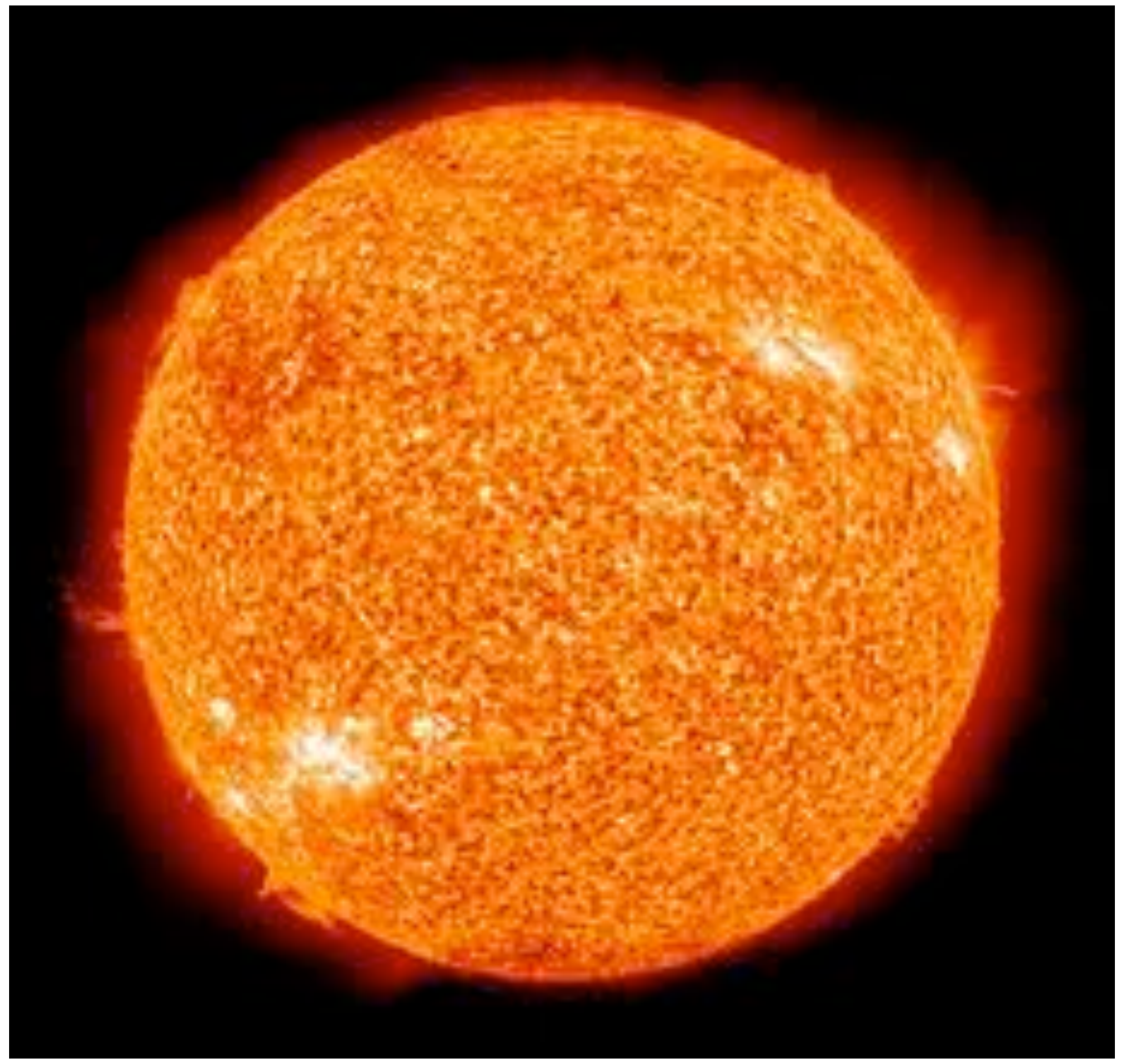


He stability: ↑,↓ protons and ↑,↓ neutrons can be packed together



The early universe contains 75% H and 25% ^{4}He by mass fraction

(“all” deuterium converted to ^{4}He)



Our understanding of Big Bang Nucleosynthesis is very sensitive to a few ingredients

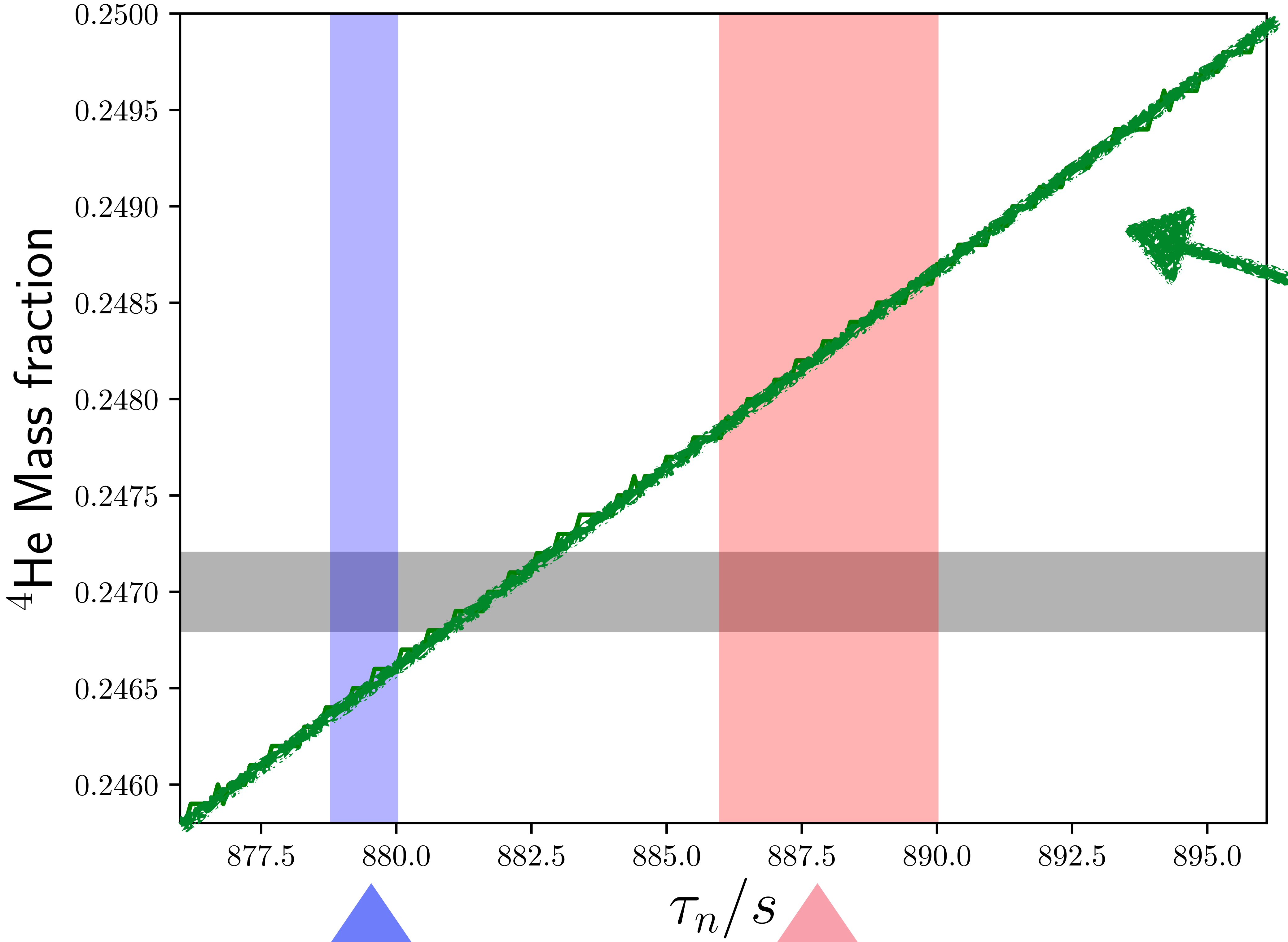
- The abundance of matter over antimatter $\eta_{B/\gamma} \sim 10^{-9}$
  A. Nicholson
- The neutron-proton mass splitting $M_n - M_p = 1.29333217(42)\ \mathrm{MeV}$
  A. Portelli, G. Martinelli
- The neutron lifetime $\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{ud}|^2}{2\pi^3} m_e^5 (1+3g_A^2)(1+RC) f_{V,A}$
- The deuteron binding energy $B_d \simeq 2.2\ \mathrm{MeV}$
  S. Aoki

The matter/antimatter asymmetry is an input ingredient while the other three quantities, to some degree, emerge from the Standard Model.

How sensitive are these quantities to variations of the input parameters of the SM?

With Lattice QCD and Effective Field Theory, we can answer these questions

This picture is also very sensitive to the lifetime of the neutron

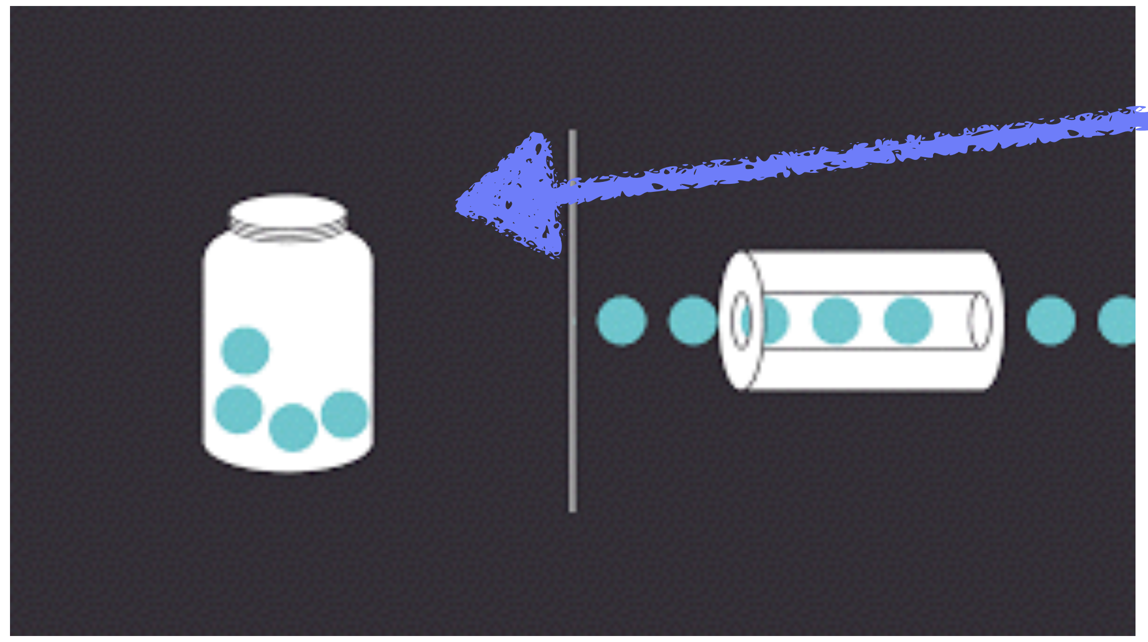


$$\tau_n = \frac{(5172.0 \pm 1.1)\ \text{seconds}}{1 + 3g_A^2}$$

Czarnecki, Marciano, Sirlin

Predicted primordial ^{4}He mass fraction of the universe as a function of the neutron lifetime

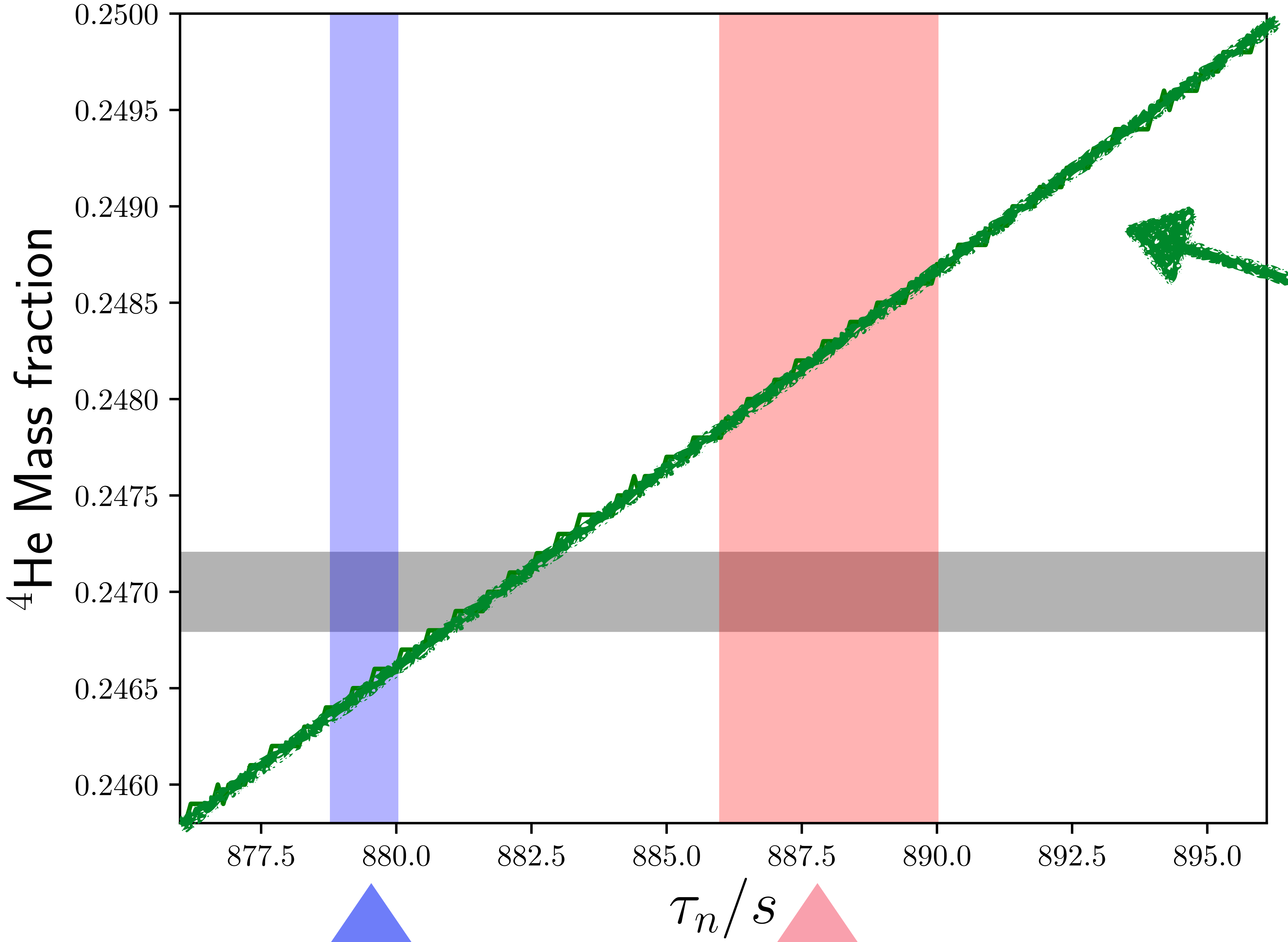
Observed primordial ^{4}He mass fraction of the universe



Two different methods of measuring the neutron lifetime disagree at the 99% level
bottle and beam

Is one of the experiments wrong? Or is there new physics hiding here?

This picture is also very sensitive to the lifetime of the neutron

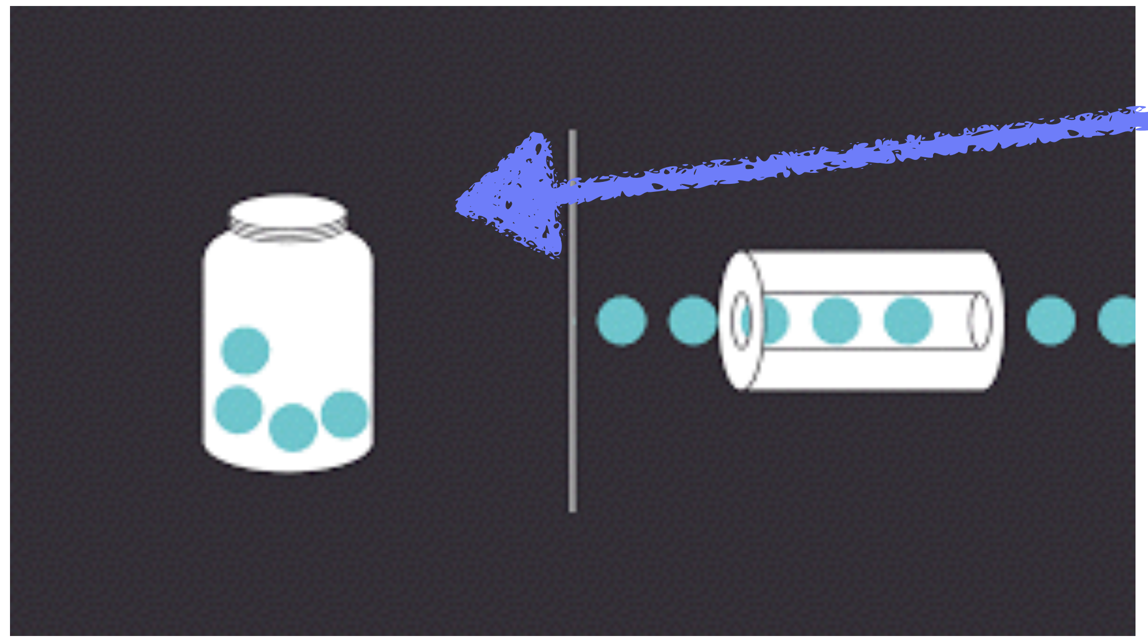


$$\tau_n = \frac{(5172.0 \pm 1.1)\ \text{seconds}}{1 + 3g_A^2}$$

Czarnecki, Marciano, Sirlin

with LQCD, we can provide this number
need 0.2% uncertainty to match precision of discrepancy 😱

Observed primordial ^{4}He mass fraction of the universe



Two different methods of measuring the neutron lifetime disagree at the 99% level
bottle and beam

Is one of the experiments wrong? Or is there new physics hiding here?

the binding energy of deuterium which is finely tuned (most nuclei have ~8 MeV binding per nucleon)!

$$B_d = 2.22\ \texttt{MeV}$$

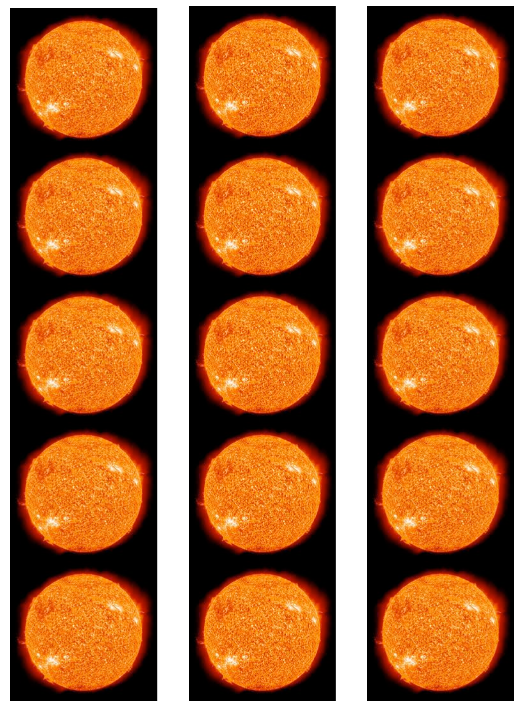
What if

$B_d \ll 2.22$ MeV

more finely tuned

all neutrons decay - no helium

mostly hydrogen stars?



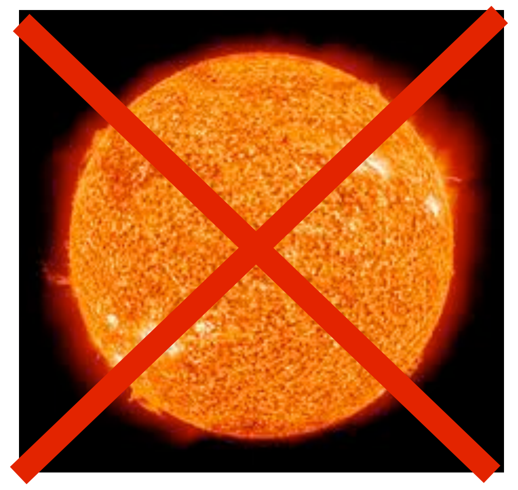
Too many suns?

$B_d \gg 2.22$ MeV

natural scenario

all neutrons captured in deuterium and helium - no hydrogen

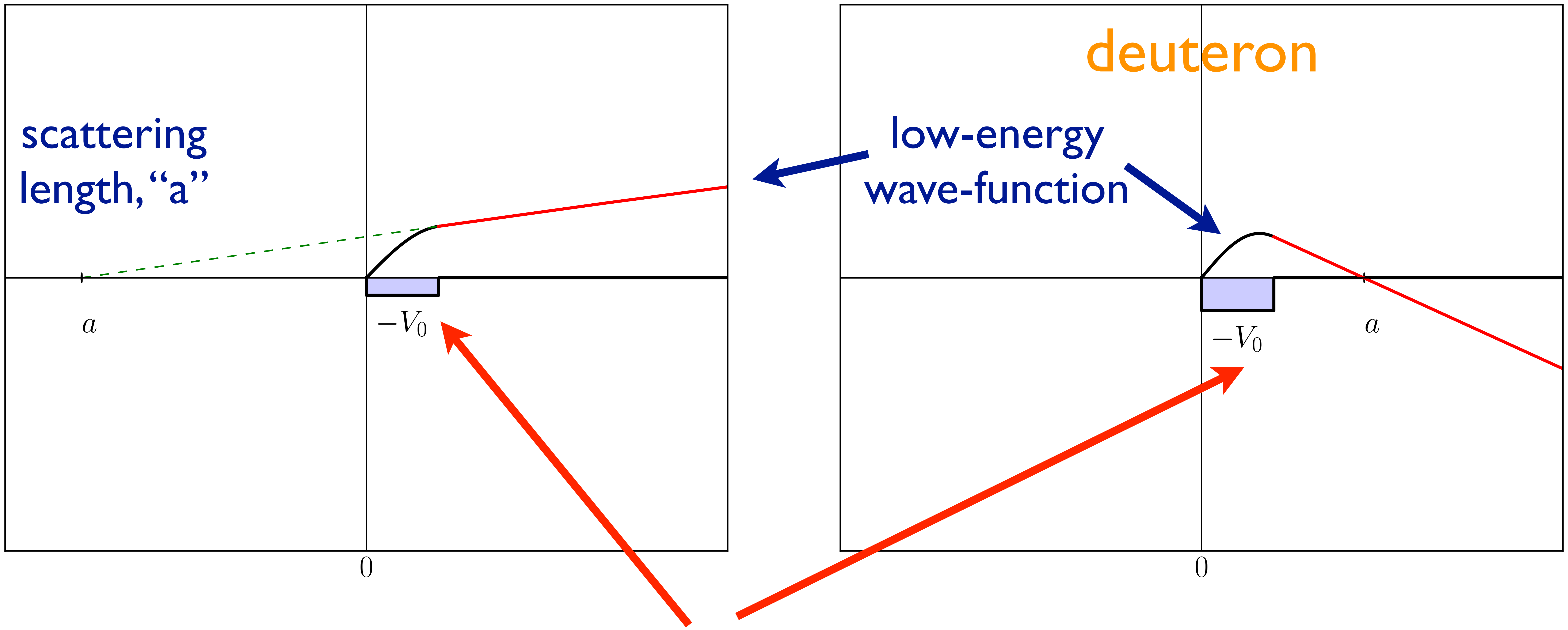
no stars like ours!



No Sun!

proton-neutron scattering at low energies

$^1S_0 : a \simeq -24\ \texttt{fm}$ $\quad$ $^3S_1 : a \simeq 5.5\ \texttt{fm}$

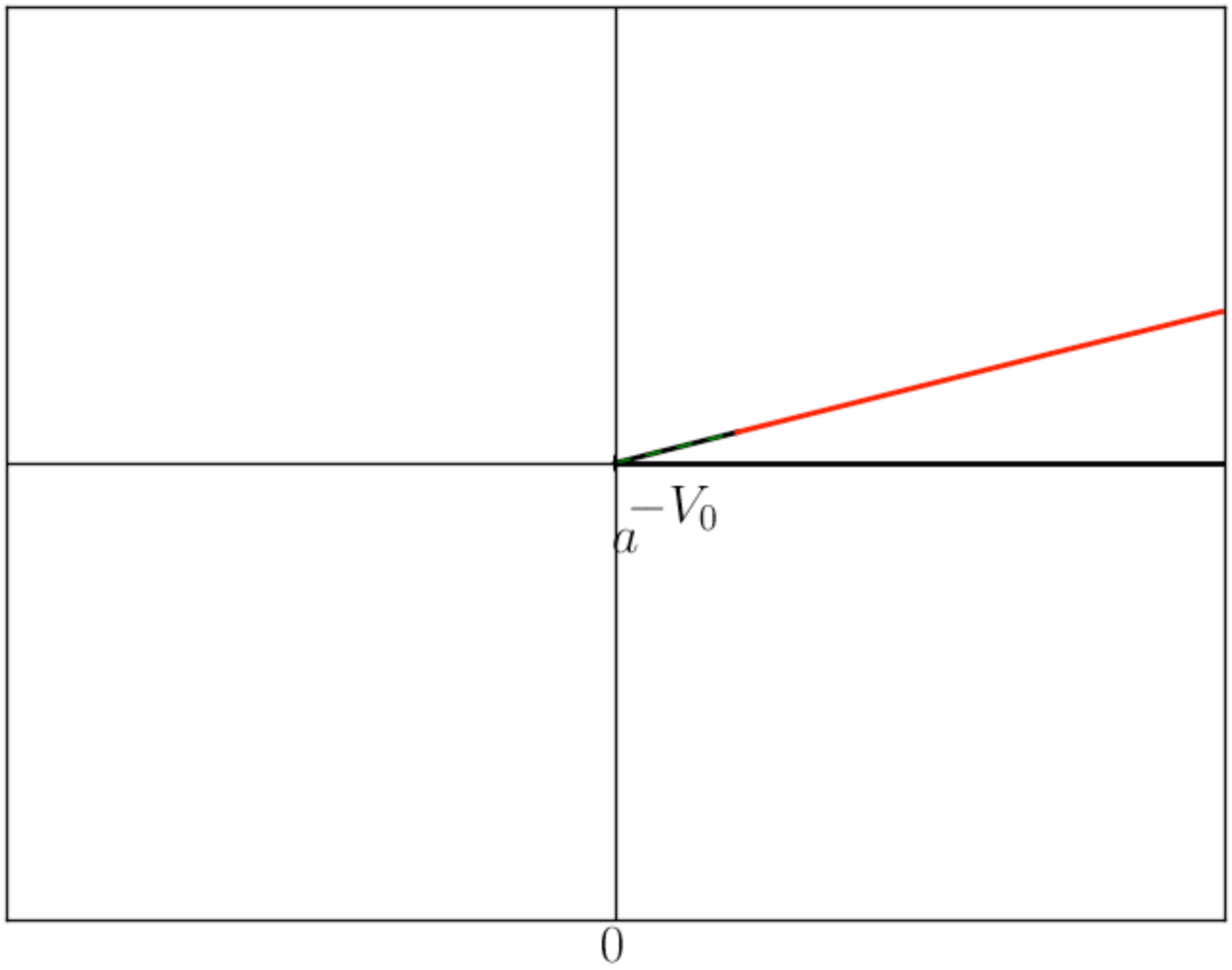


$$R_{NN} \sim 1.4\ \texttt{fm}$$

Fine tuning gives small deuteron binding energy

Solving QCD can help us determine the nature of this fine tuning

Finely tuned interactions
(like in AMO systems)



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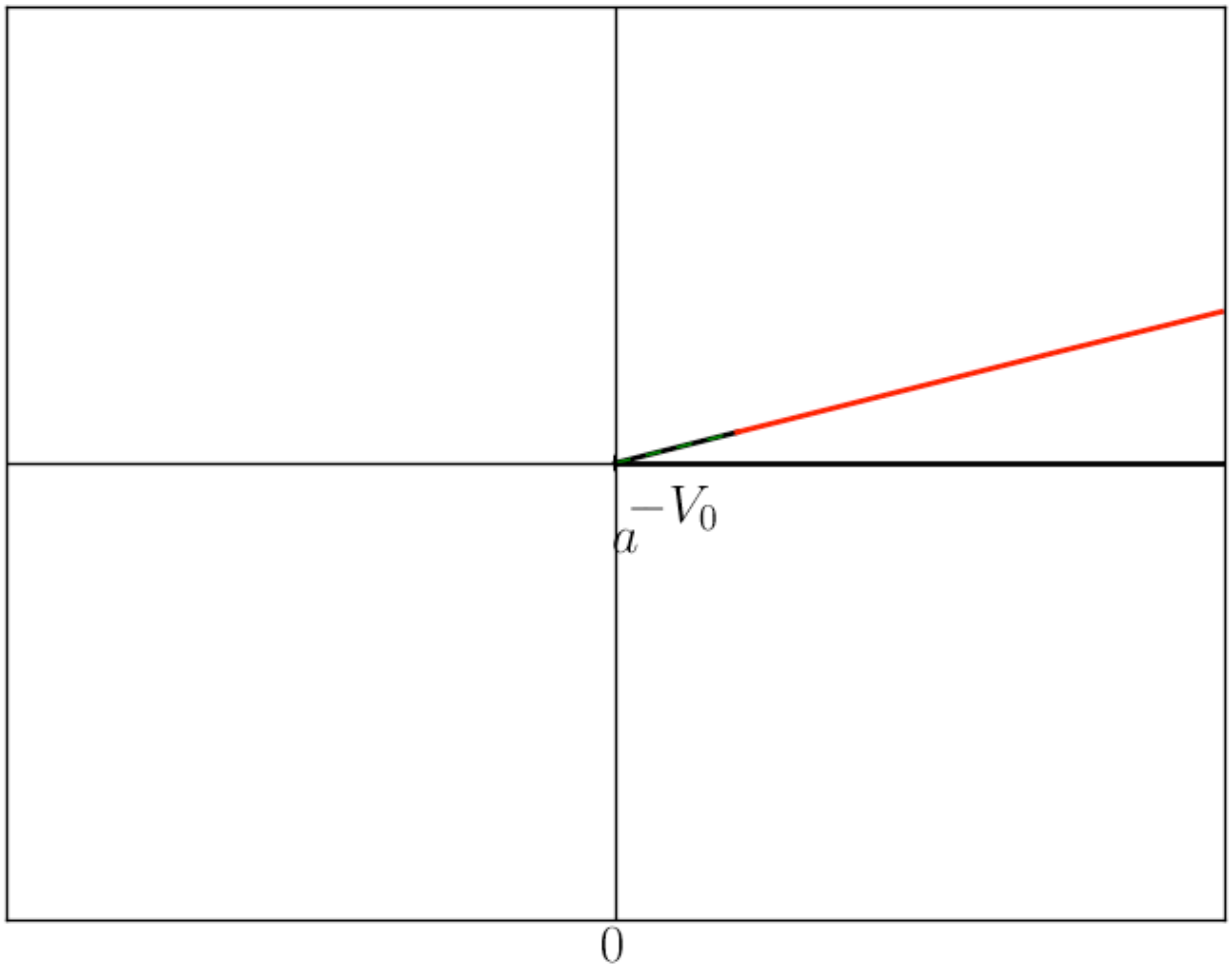

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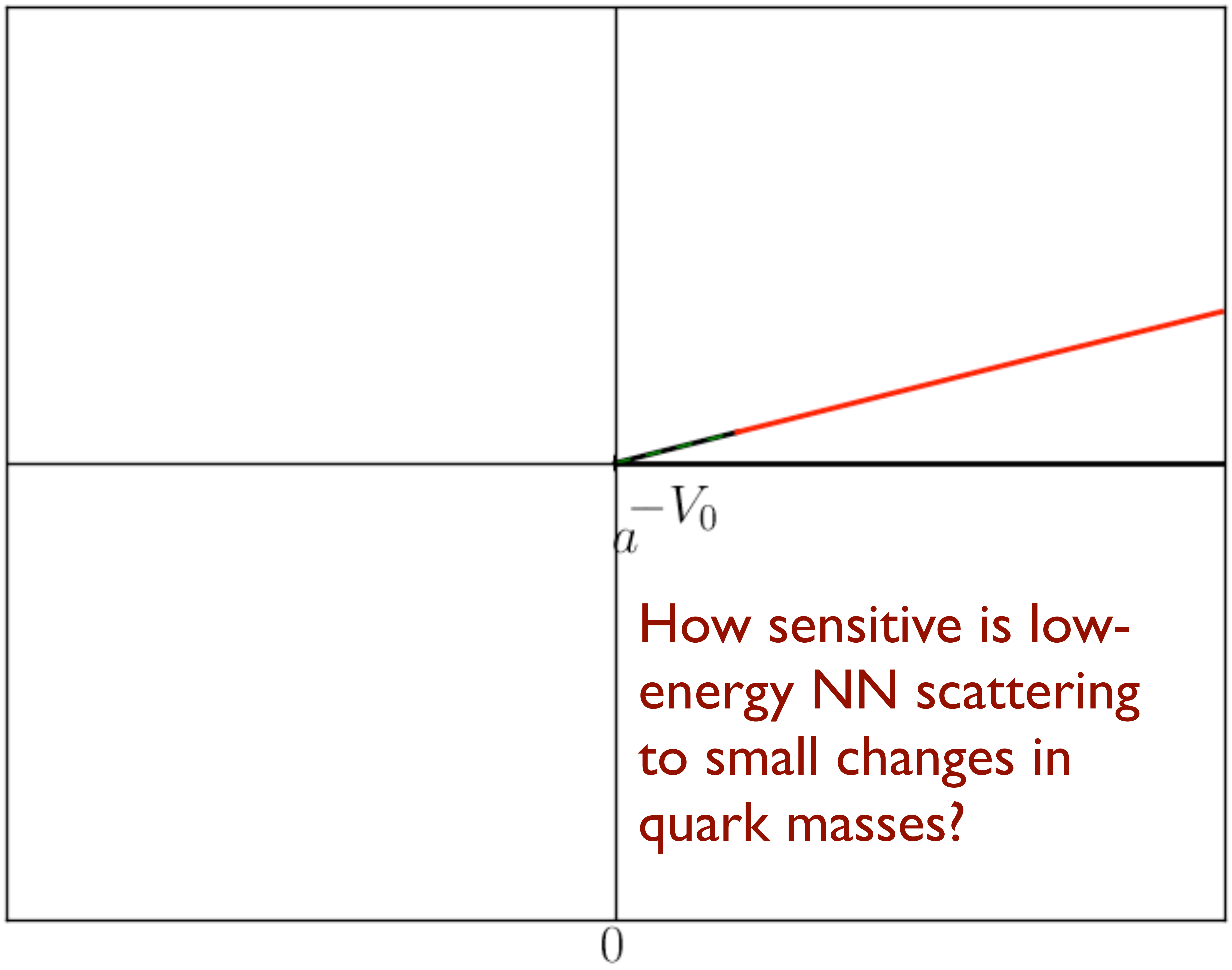
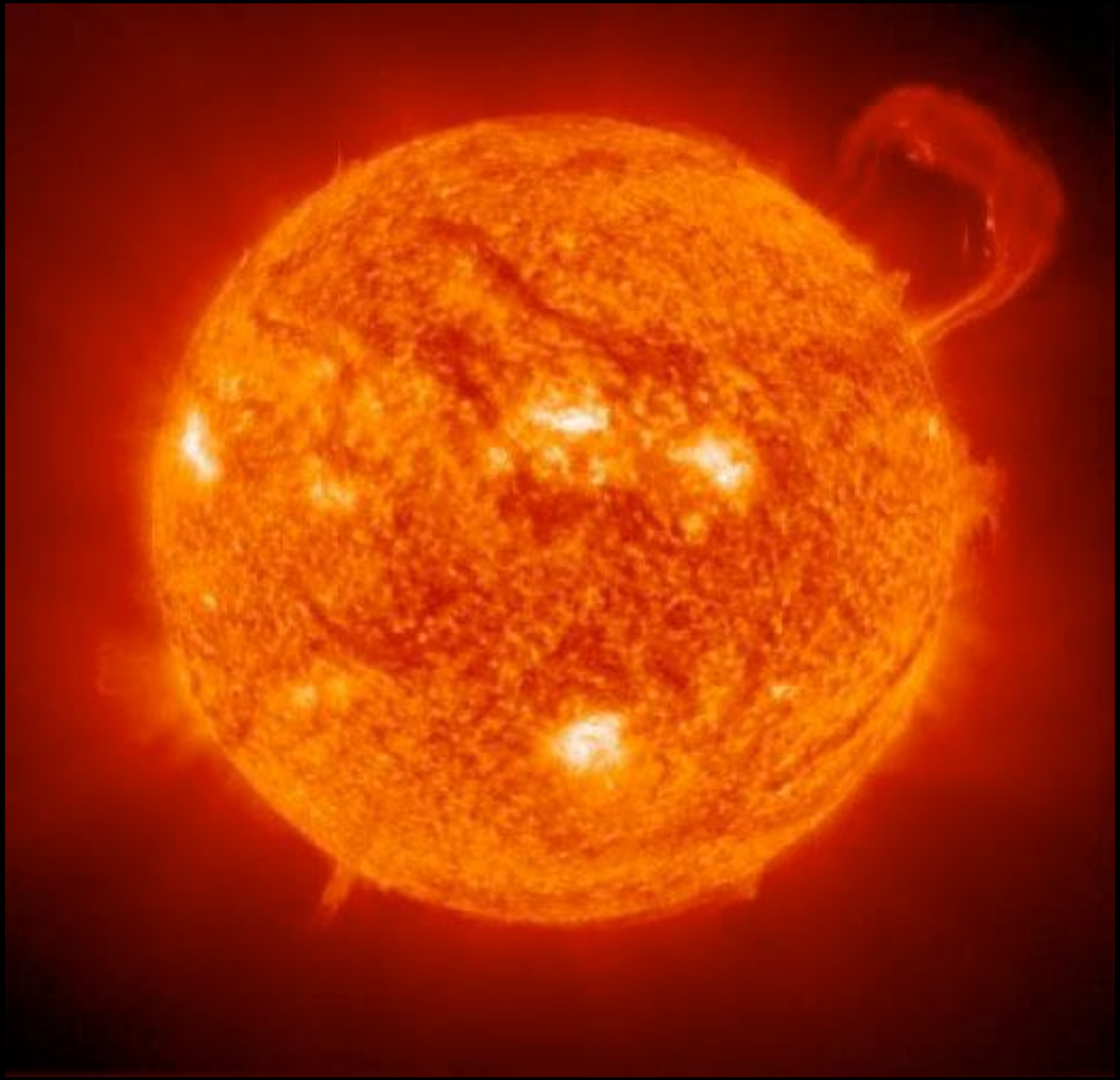


How sensitive is low-energy NN scattering to small changes in quark masses?

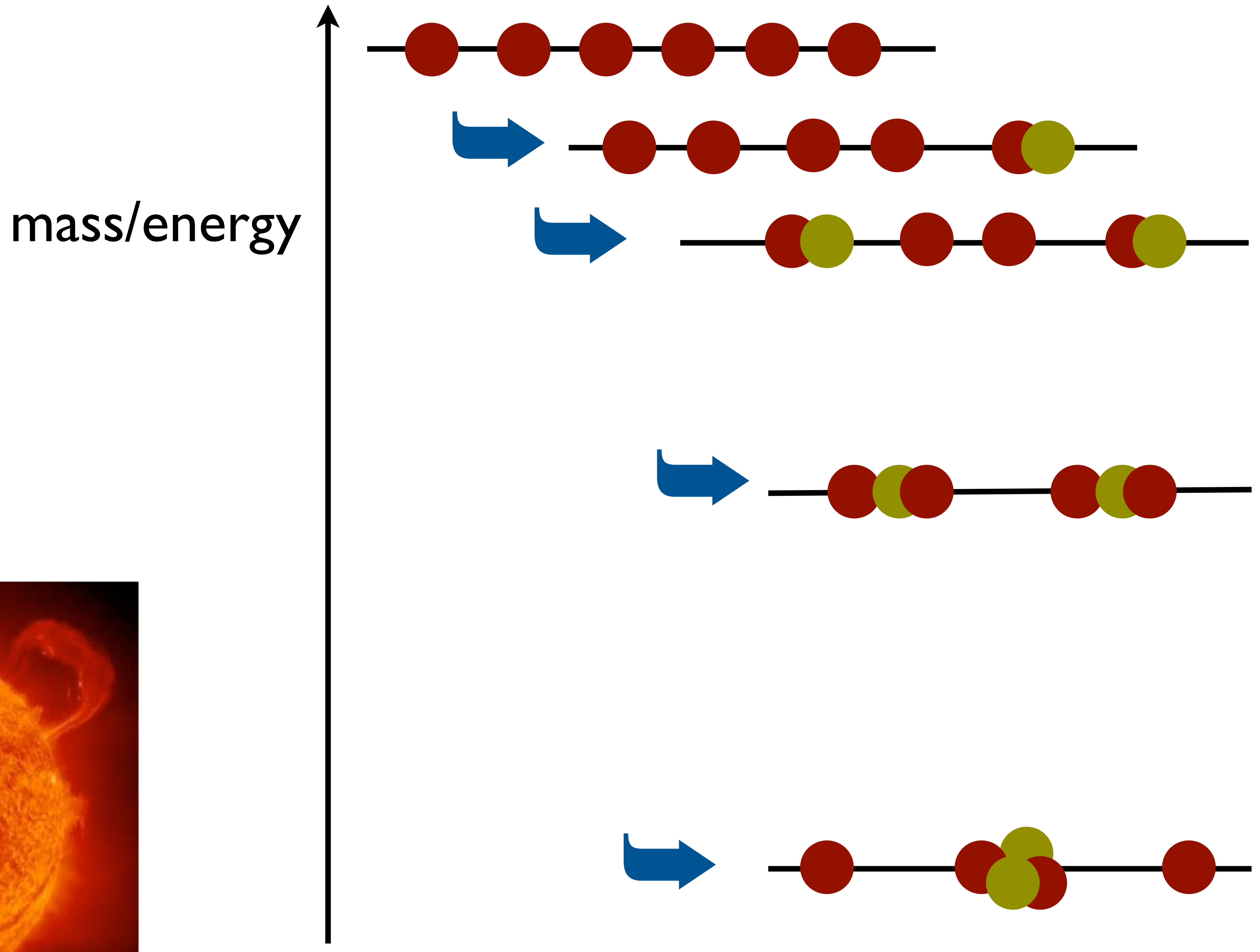
Solar Fusion



$$T \simeq 20 \text{ K}$$
$$t \simeq 200 \text{ Million years}$$

One needs neutrons and protons to make new nuclei.

Small stars burn protons only, manufacturing the needed neutrons



$$p + p \to d + \nu_e$$

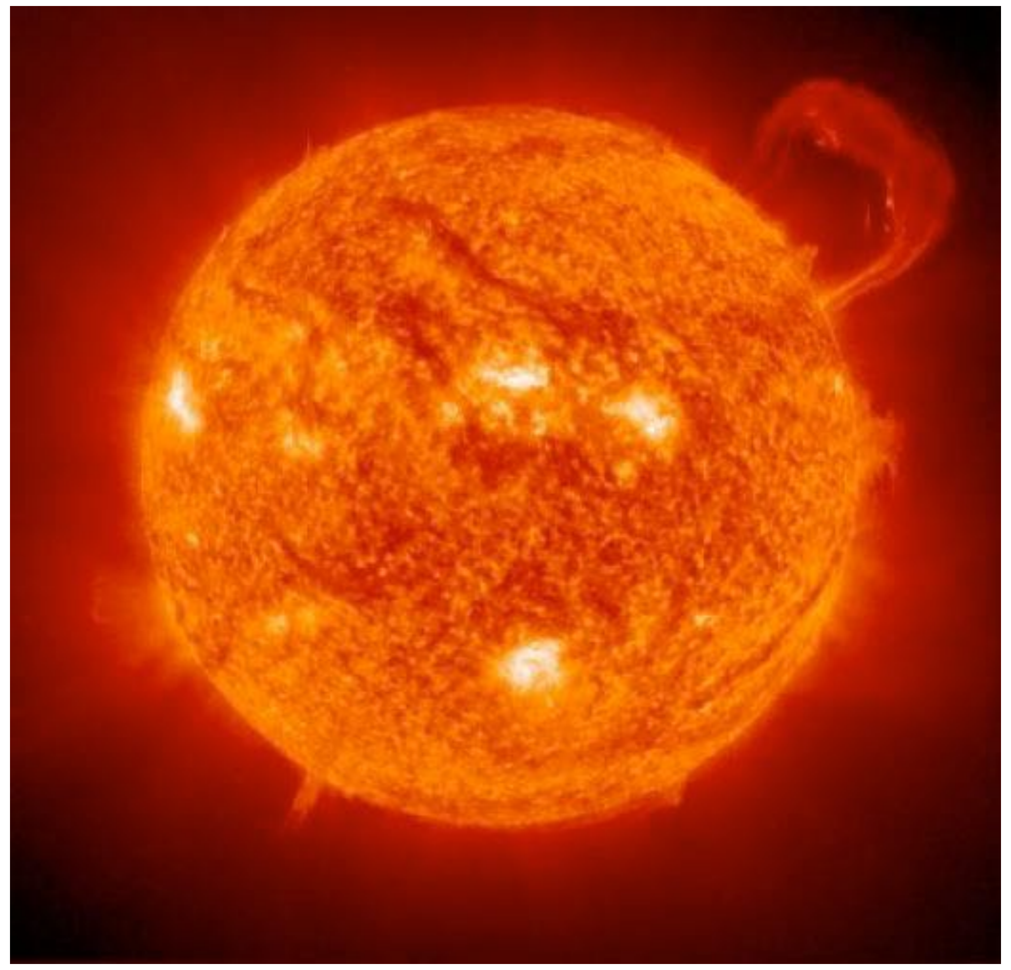
another bottleneck

deuteron: -1.2 MeV

2 deuterons: -2.4 MeV

2 ^{3}He: -12.4 MeV

helium: -28.3 MeV



pp chain

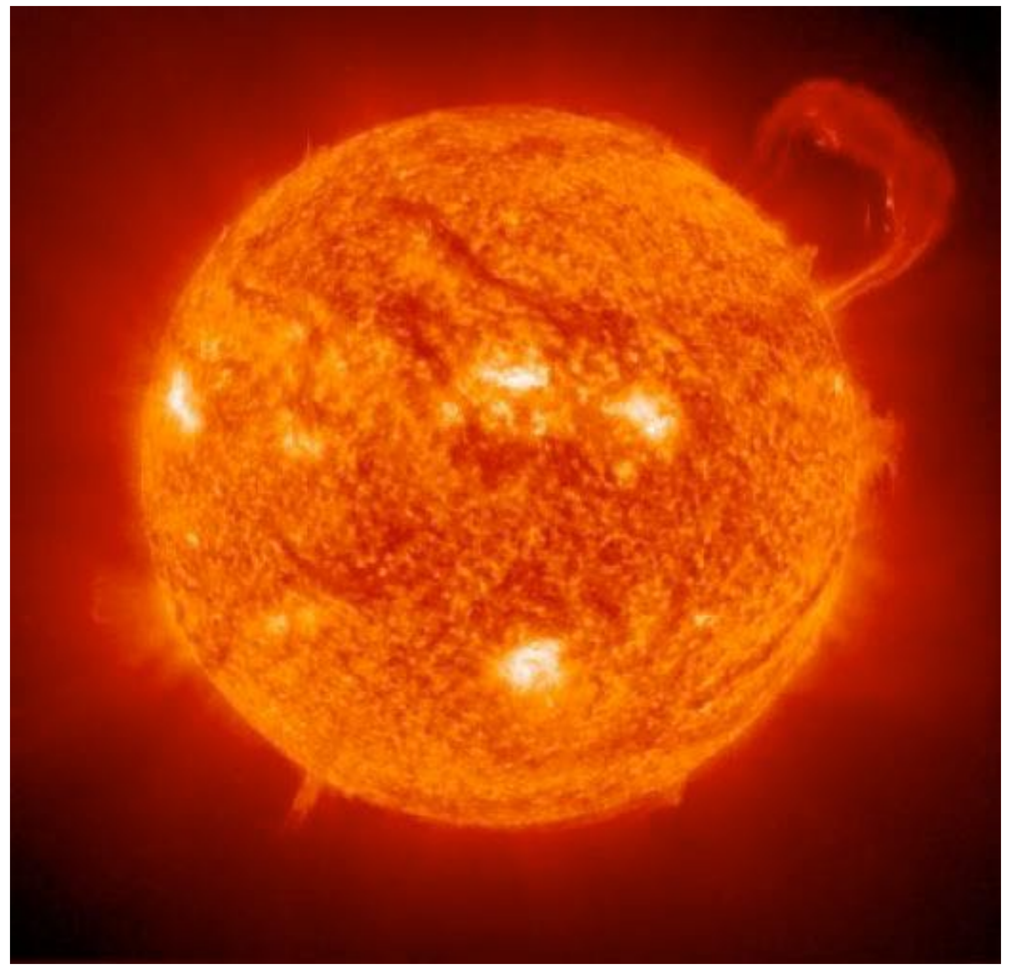
thermal energy to support star

This is how our Sun generates its energy

80% of all stars generate their energy by hydrogen burning

At its very center the Sun generates 275 watts/m^3 - similar to the energy generated by a compost (garbage) heap (of the same size)!

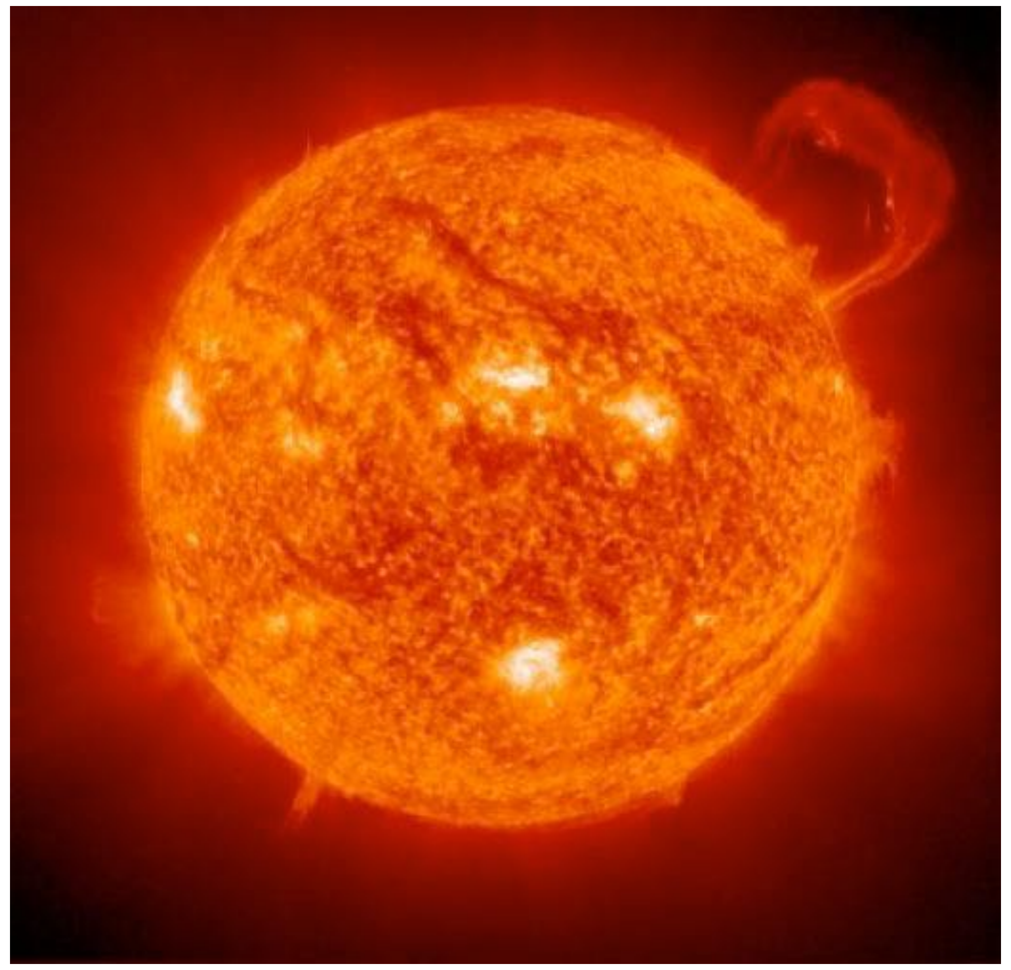
And this is why the Sun has burned for 4.6 b.y., and will burn for 5 b.y. more, fortunately -- a very big, very slow reactor



$$p + p \rightarrow d + \nu_e + e^+$$

This fundamental reaction can not be measured!
(Coulomb Repulsion)

We believe we know the rate, but we have not been able to predict it directly from the fundamental theory,
can we?



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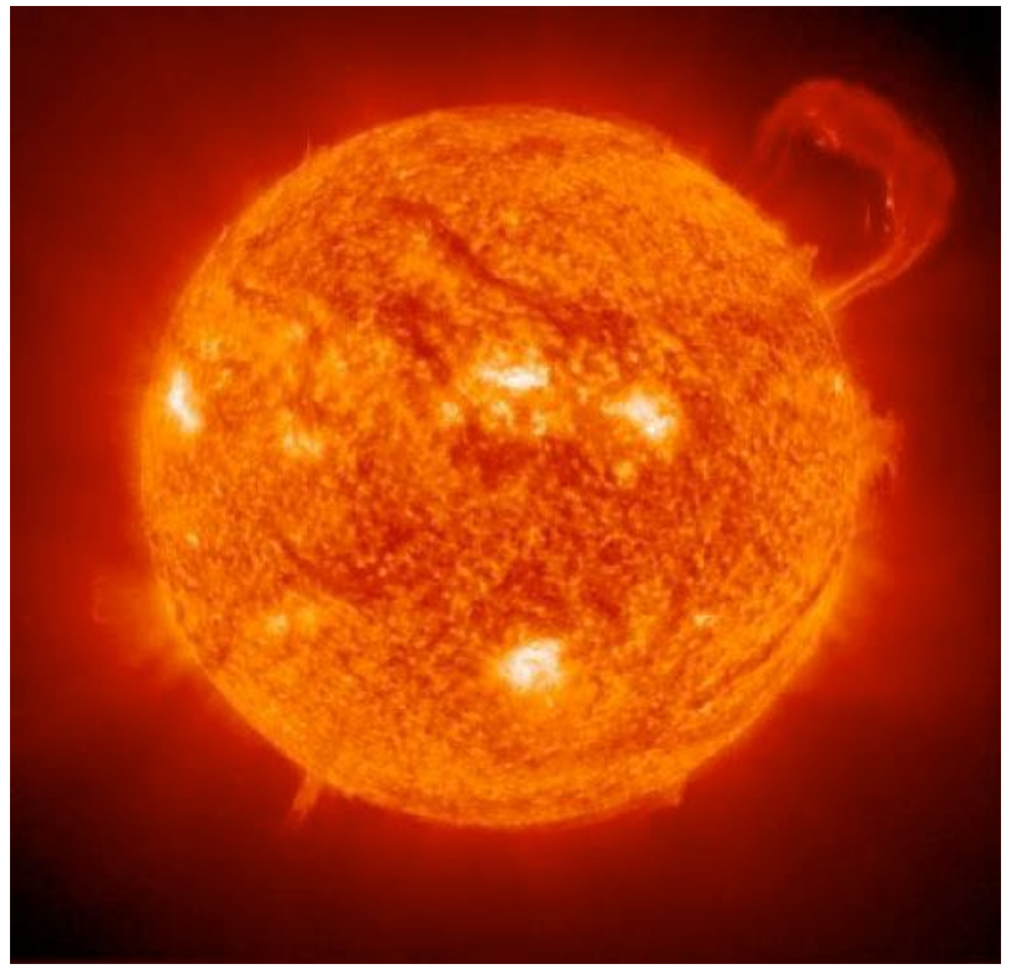
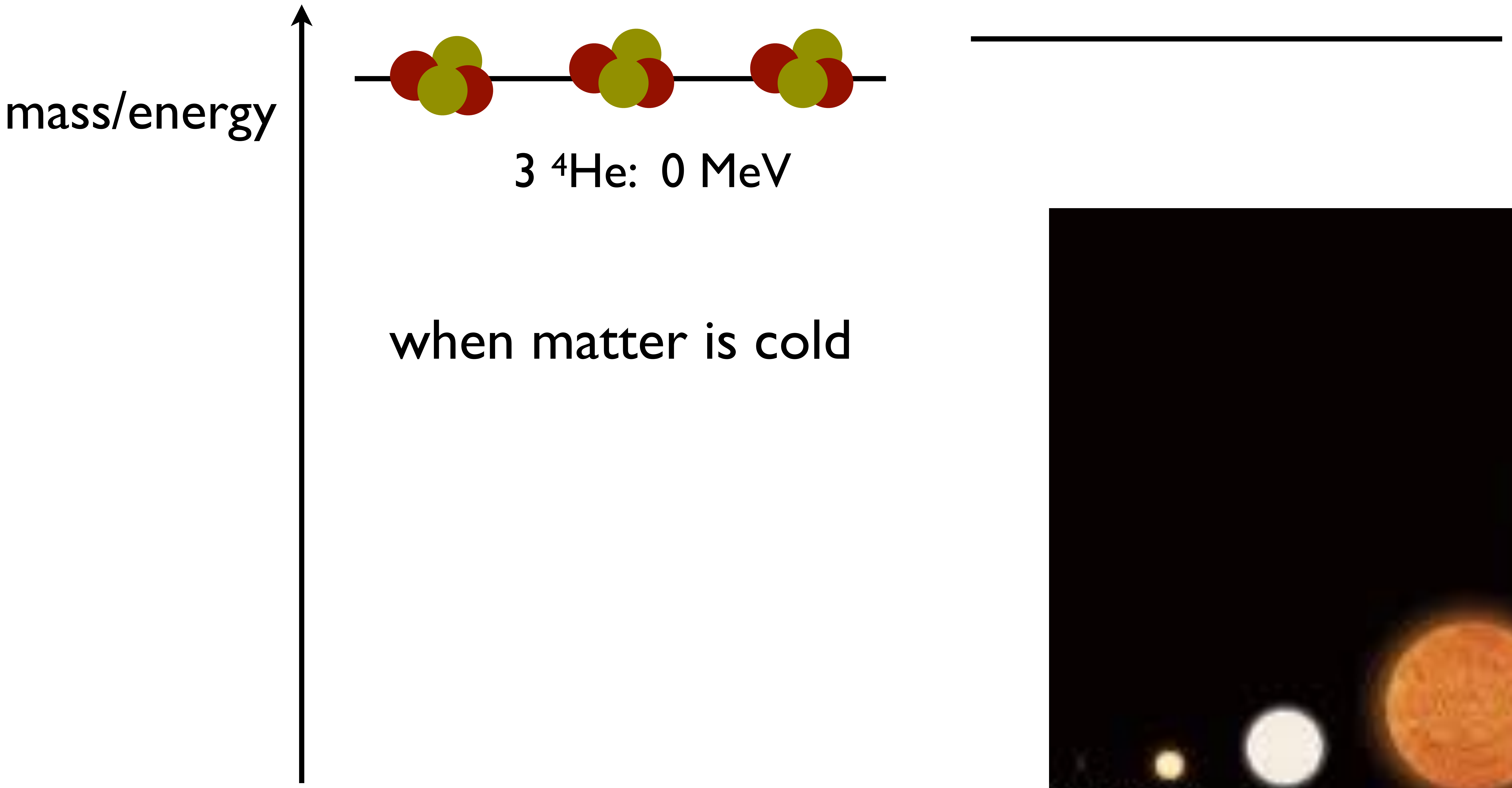


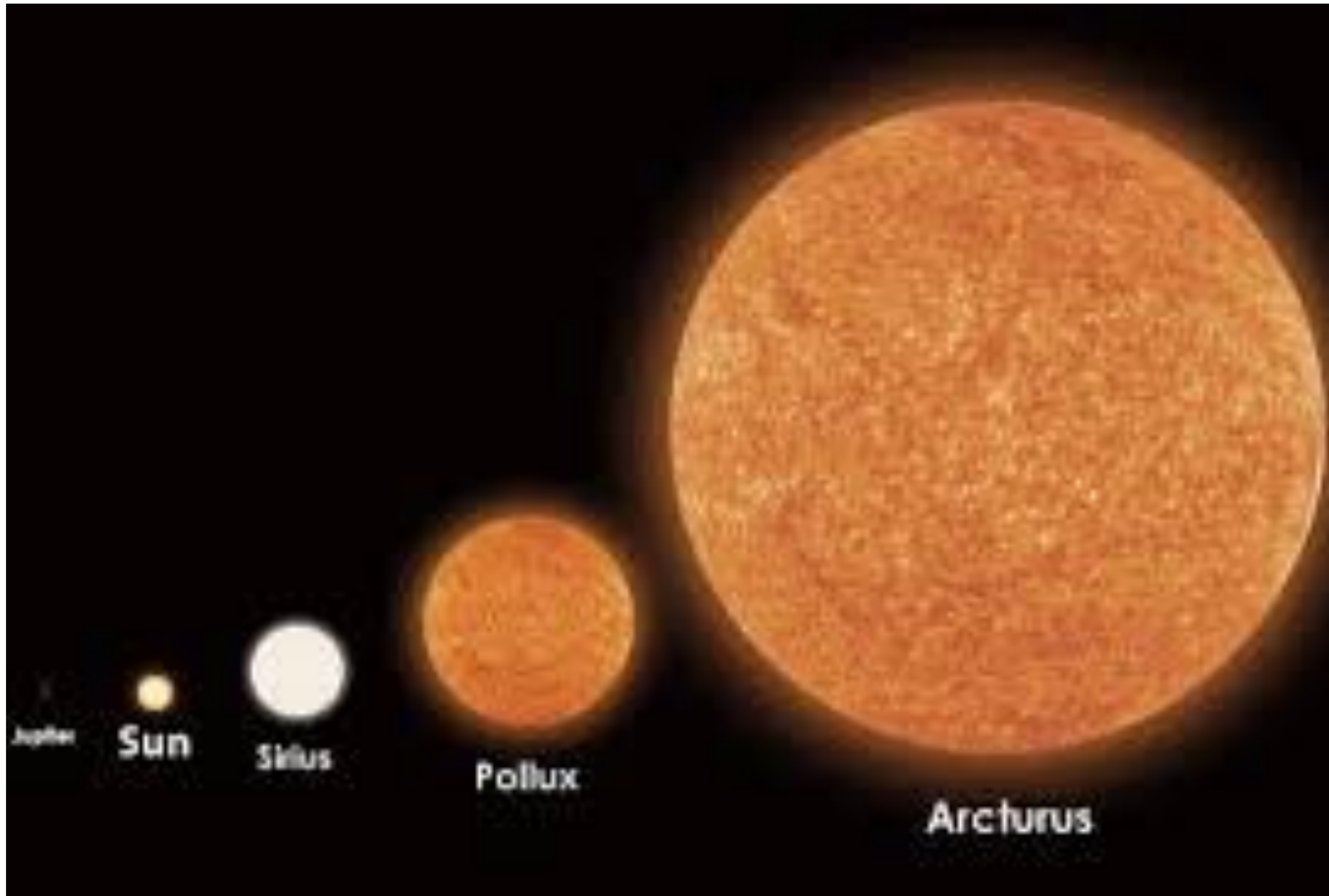
Yes!
With summit!
(or equivalent pre-exascale
super computer)

Large stars use He and neutrons to build new nuclei.

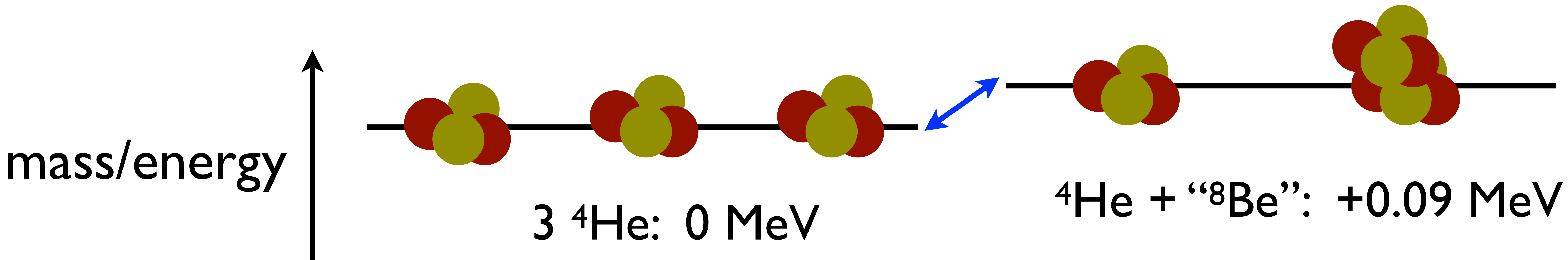
Higher temperatures and higher densities are needed.

The Big Bang could not do this because the density was too low.

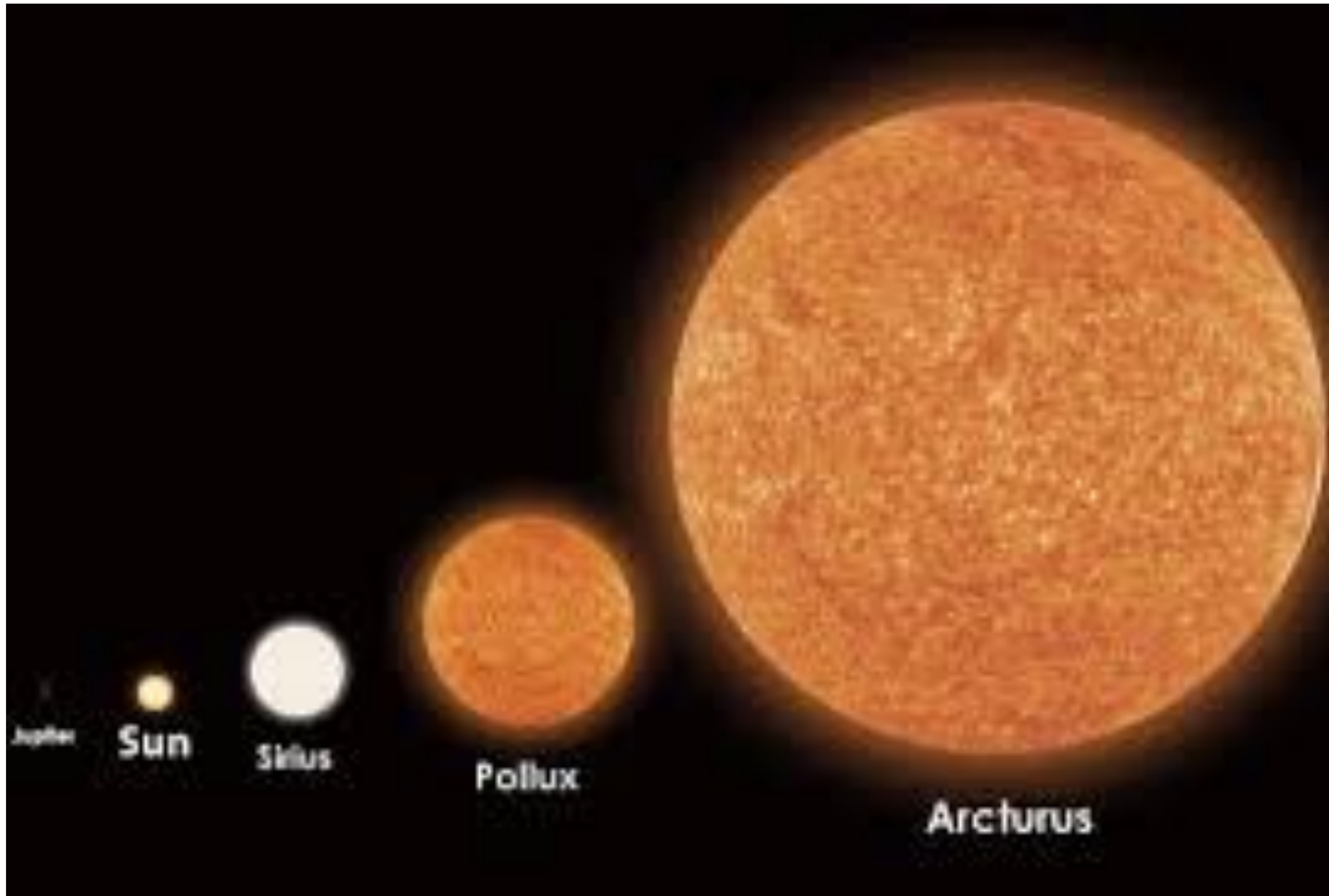




even more finely tuned

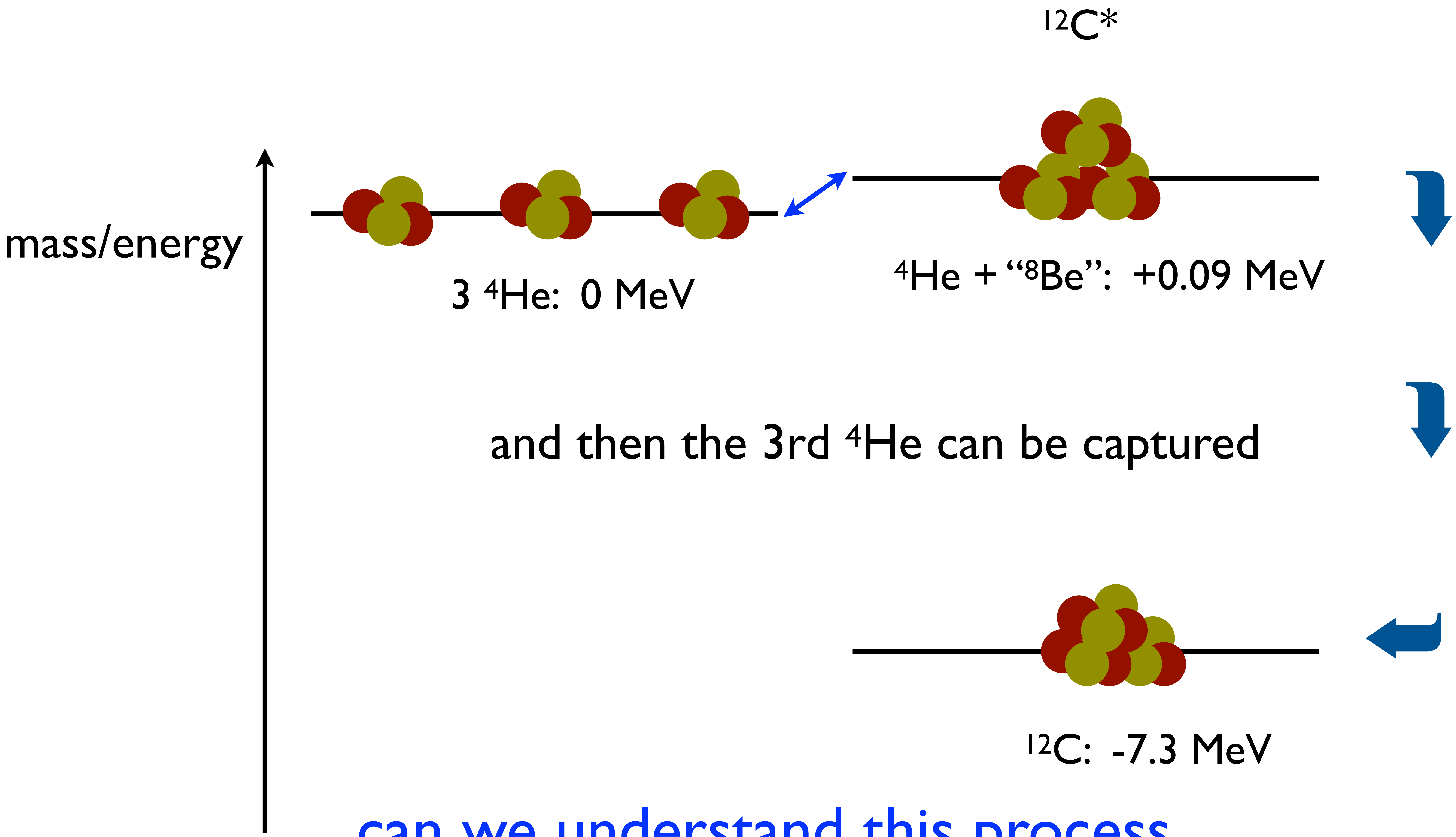


but when matter is
hot, T > 10^8 K



even more finely tuned - source of complex life

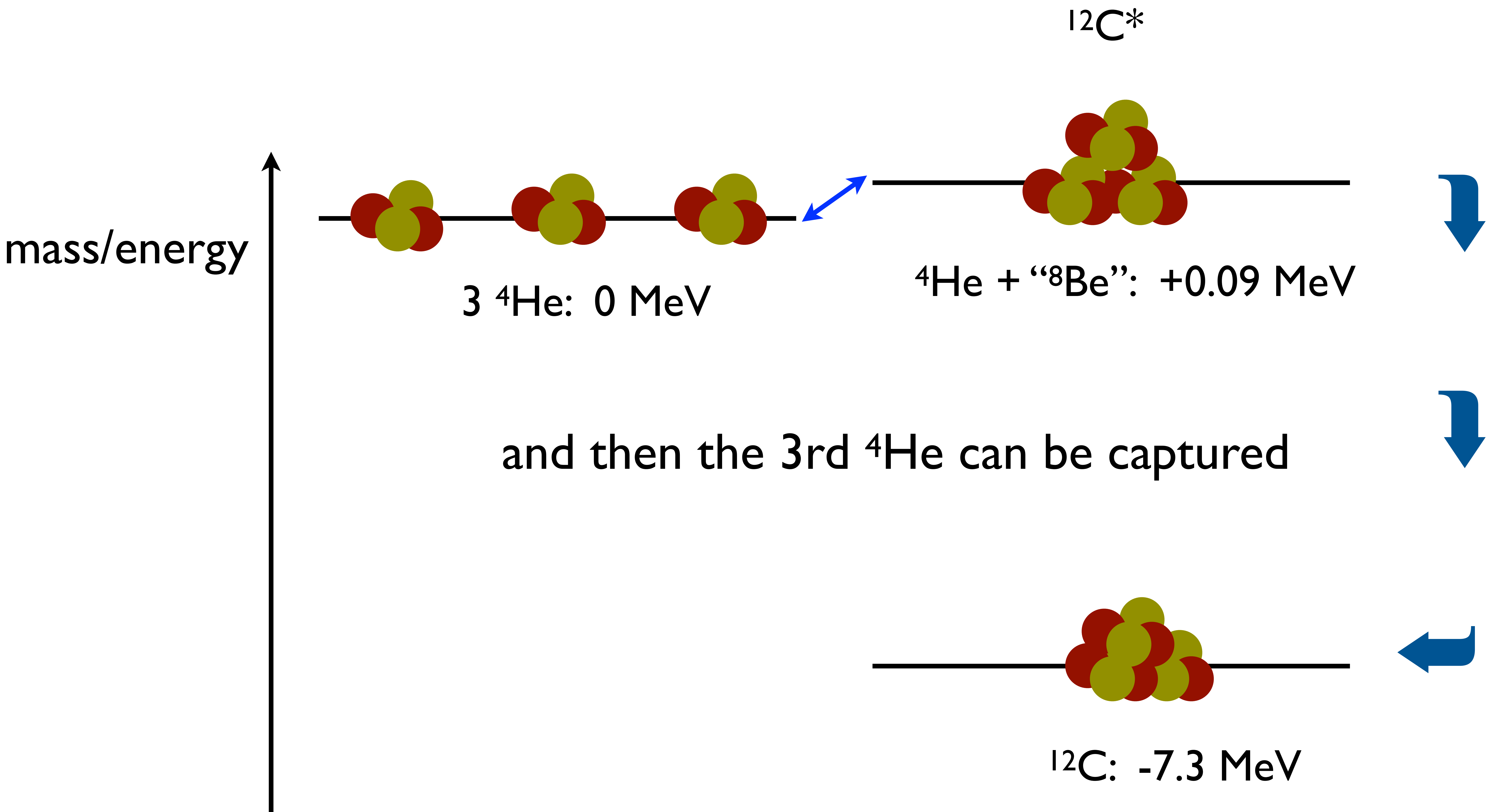
the triple-α process Hoyle State



can we understand this process from the fundamental theory?

even more finely tuned - source of complex life

the triple-α process Hoyle State



can we understand this process
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Yes!
maybe with summit!

even more finely tuned - source of complex life

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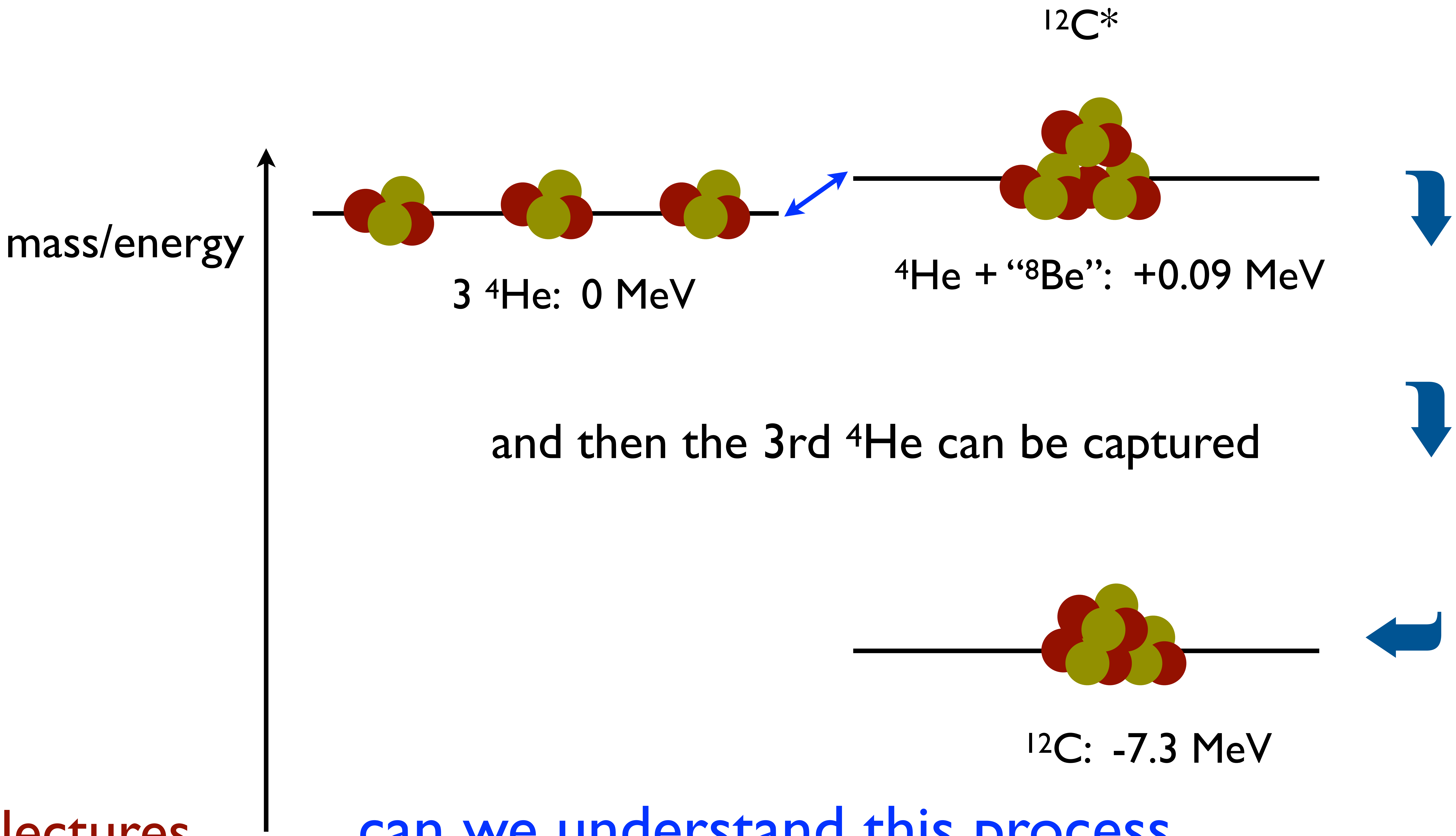
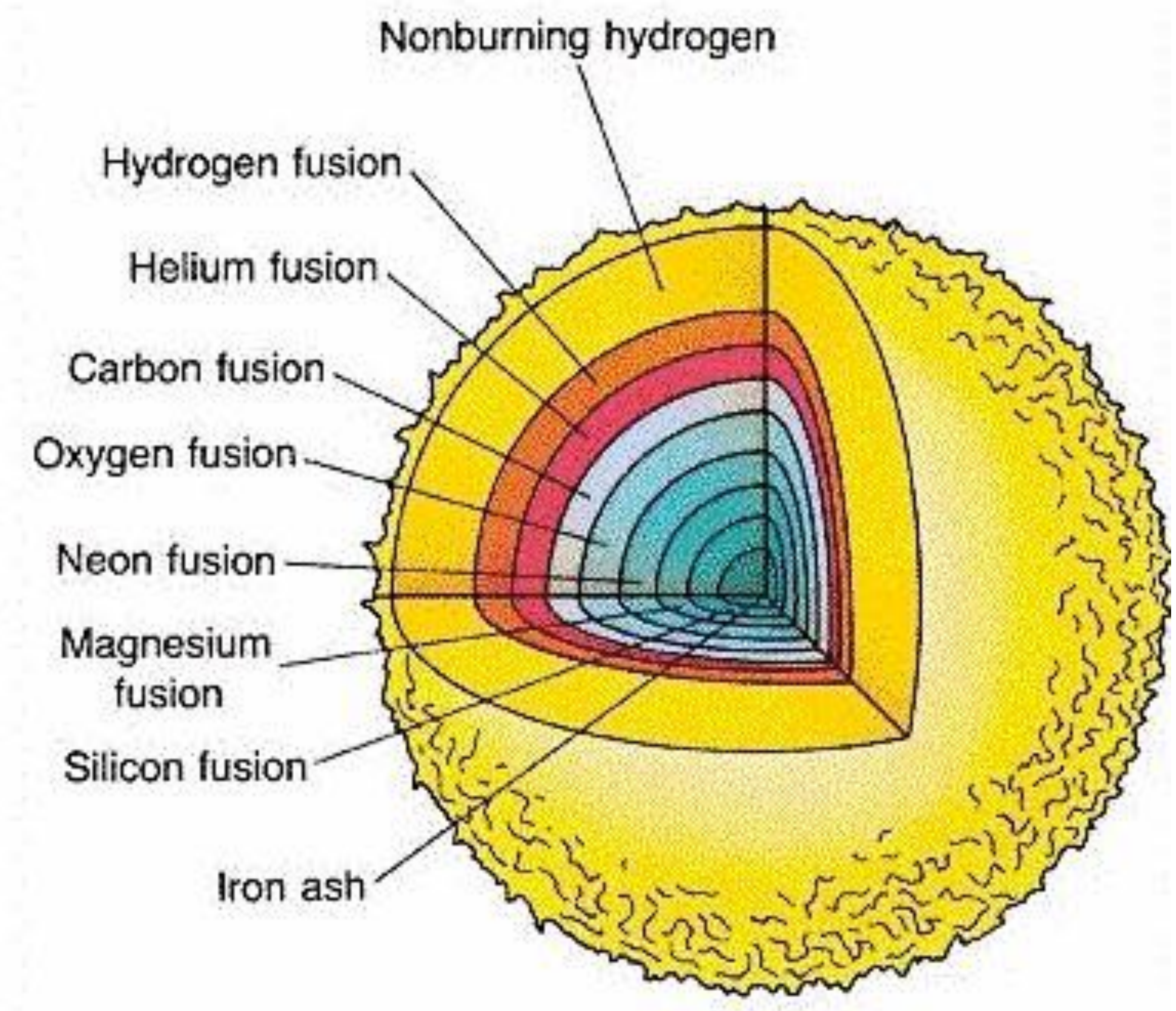


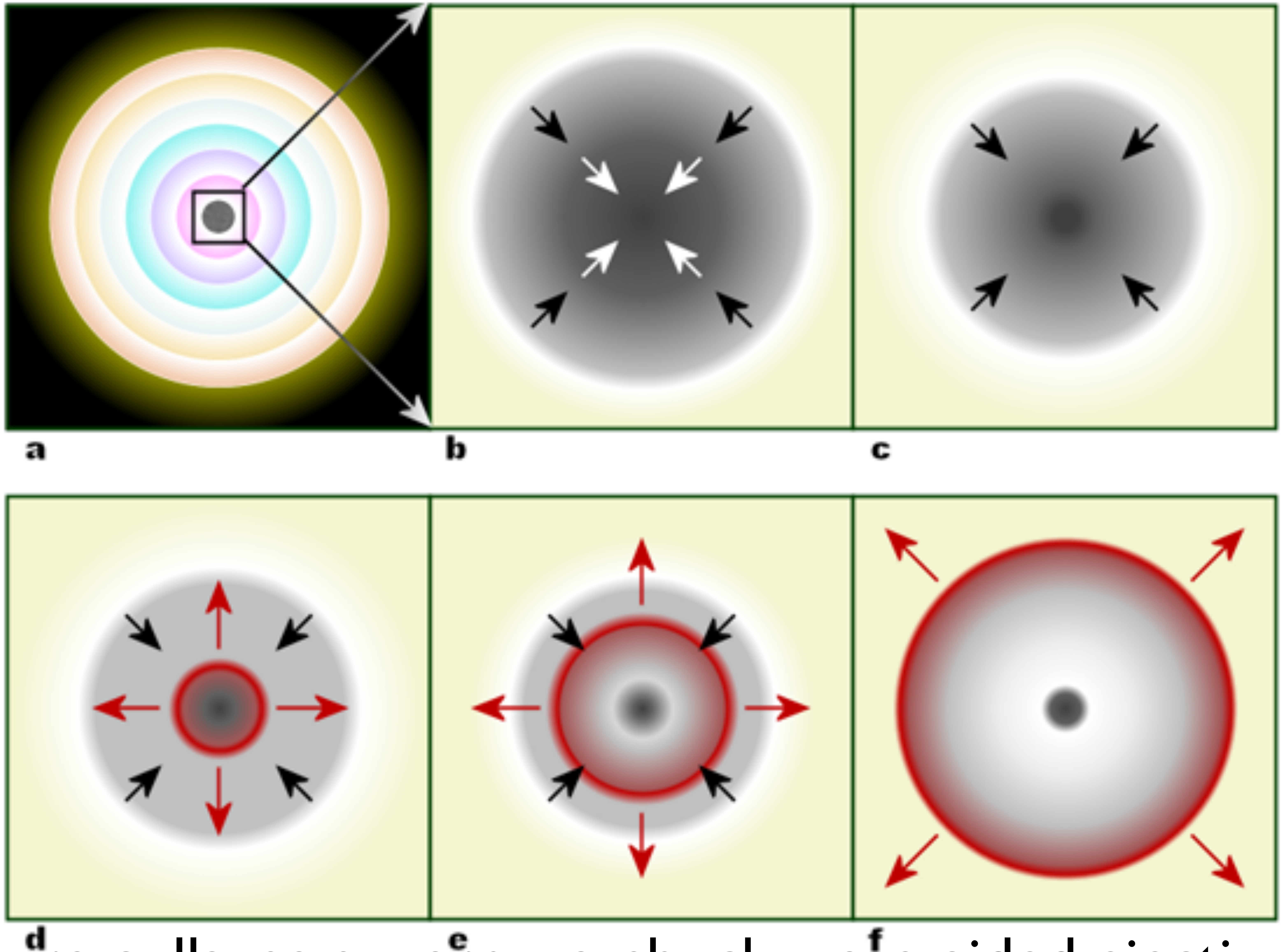
Also - see lectures by Ulf Meissner

can we understand this process from the fundamental theory?

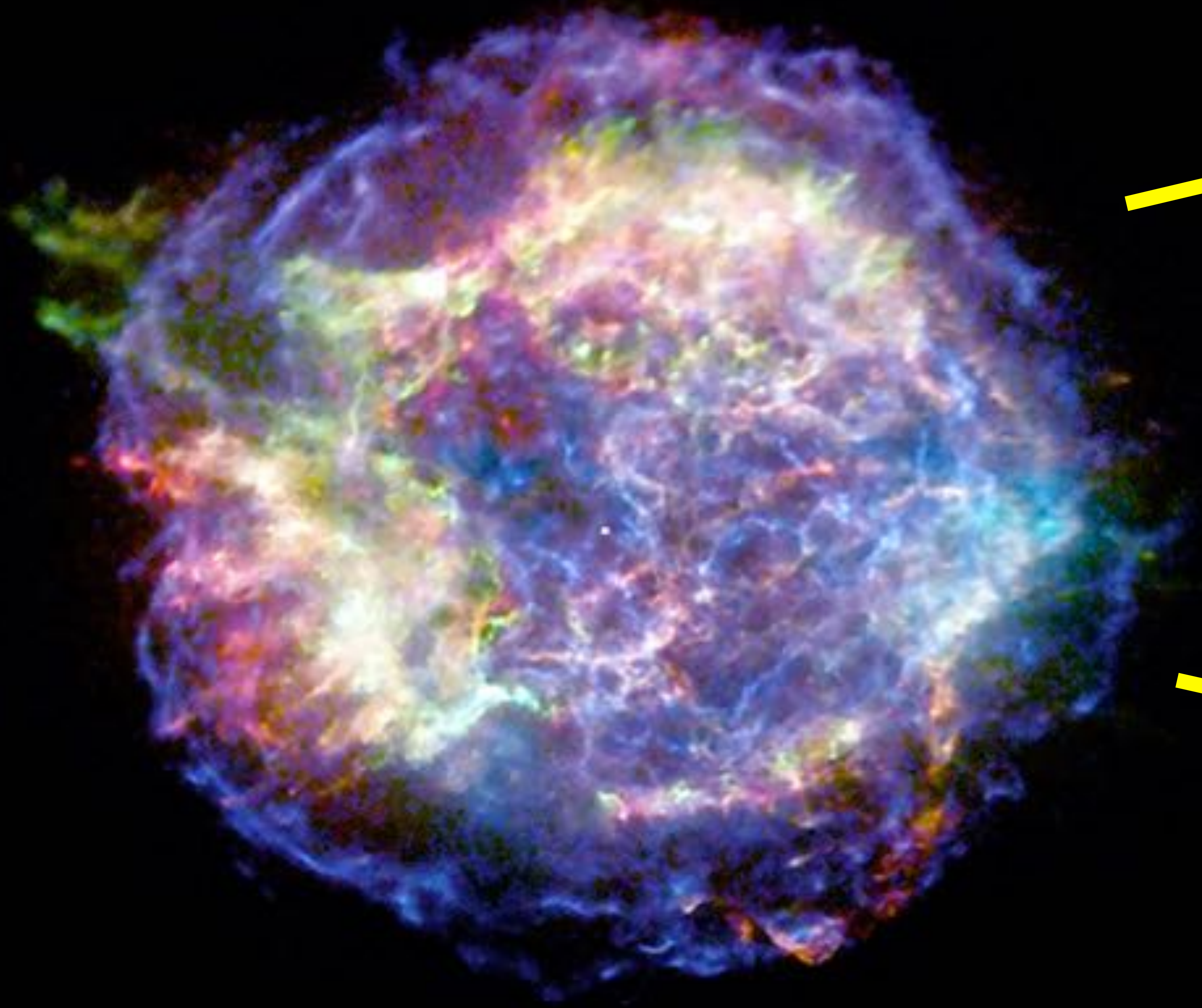
Yes! maybe with summit!



He, C, O, ... Si burning produces energy until Iron (Fe)



core collapse supernova, shock-wave-aided ejection of mantel



Supernova

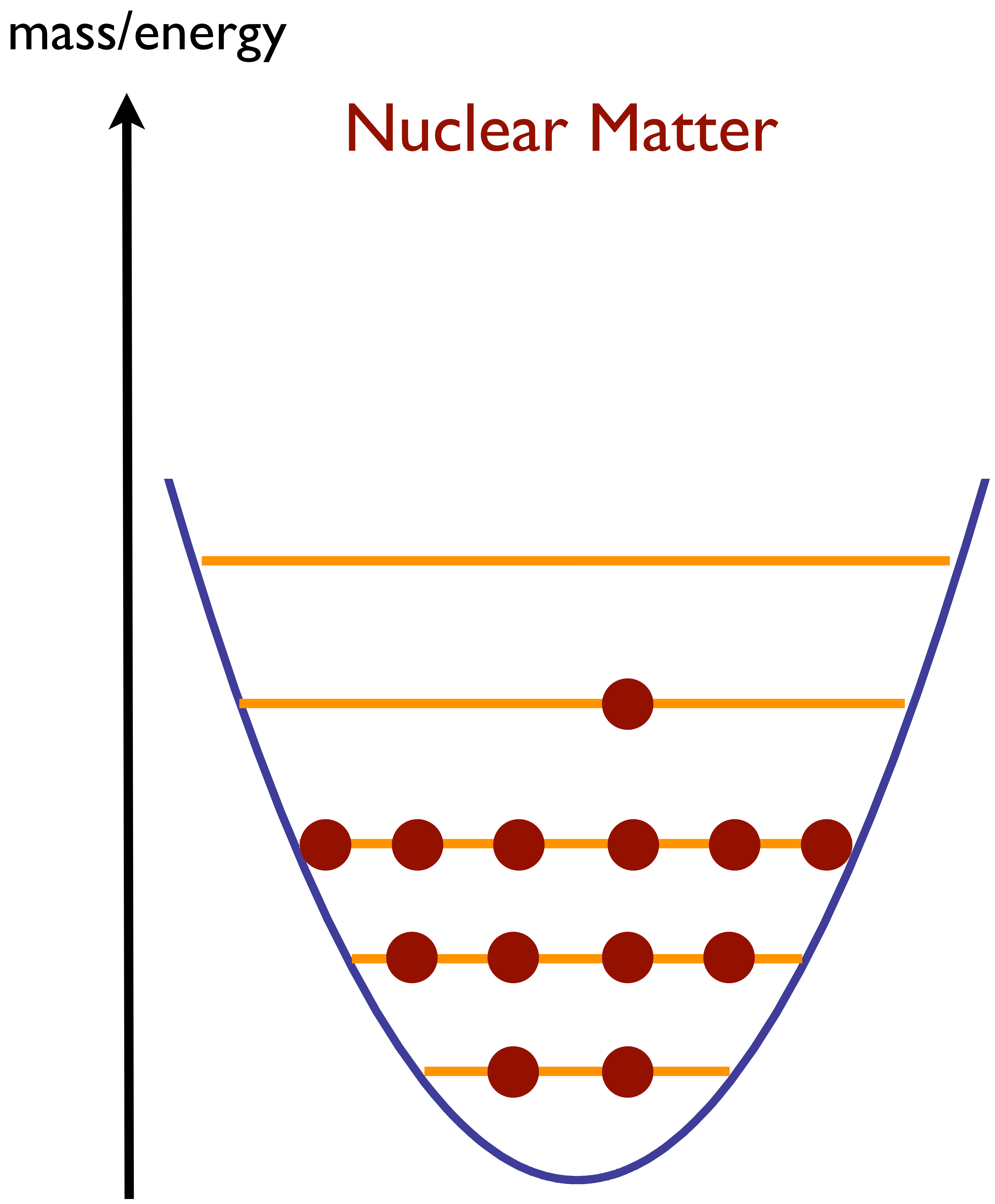
neutron star

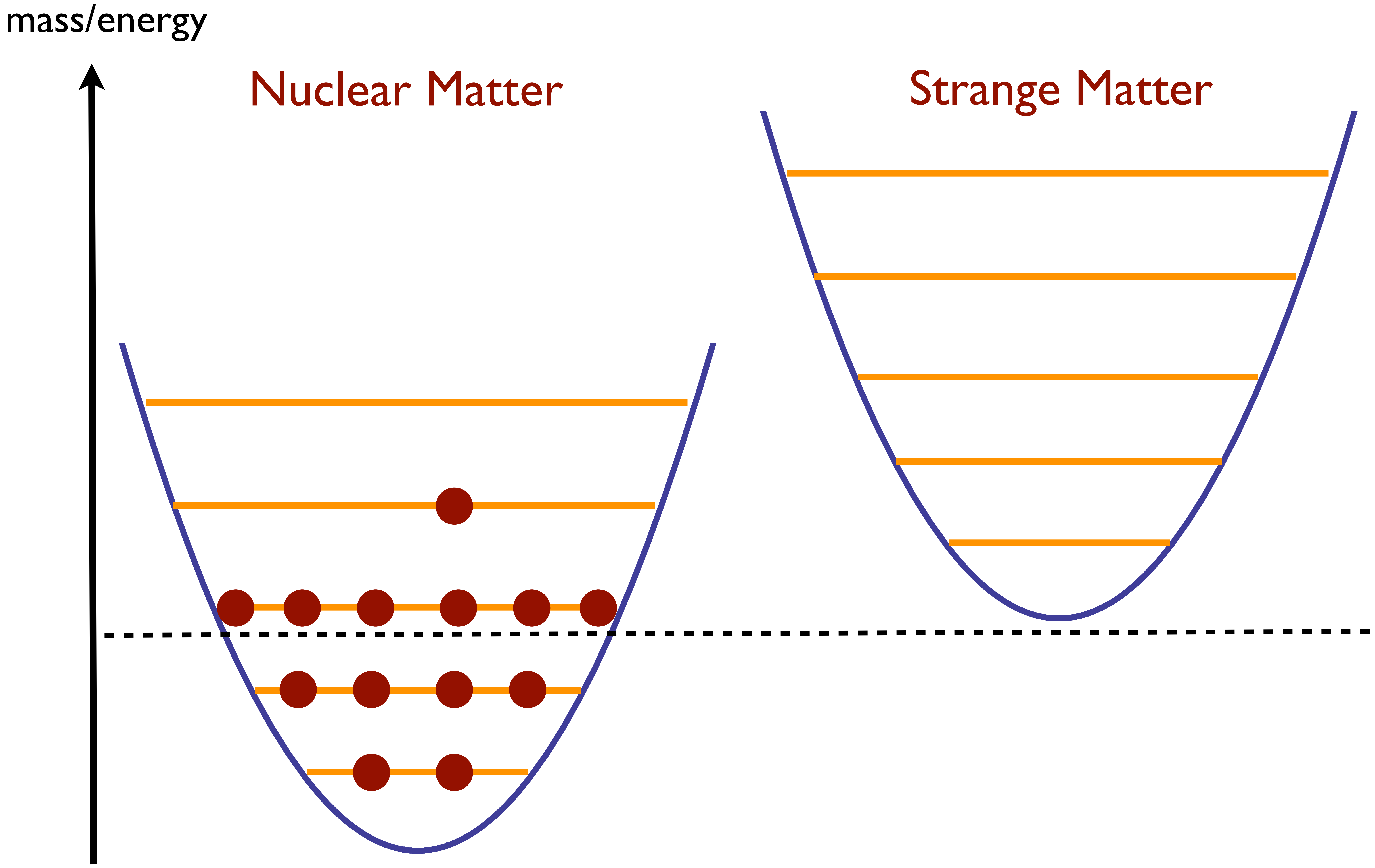
black hole

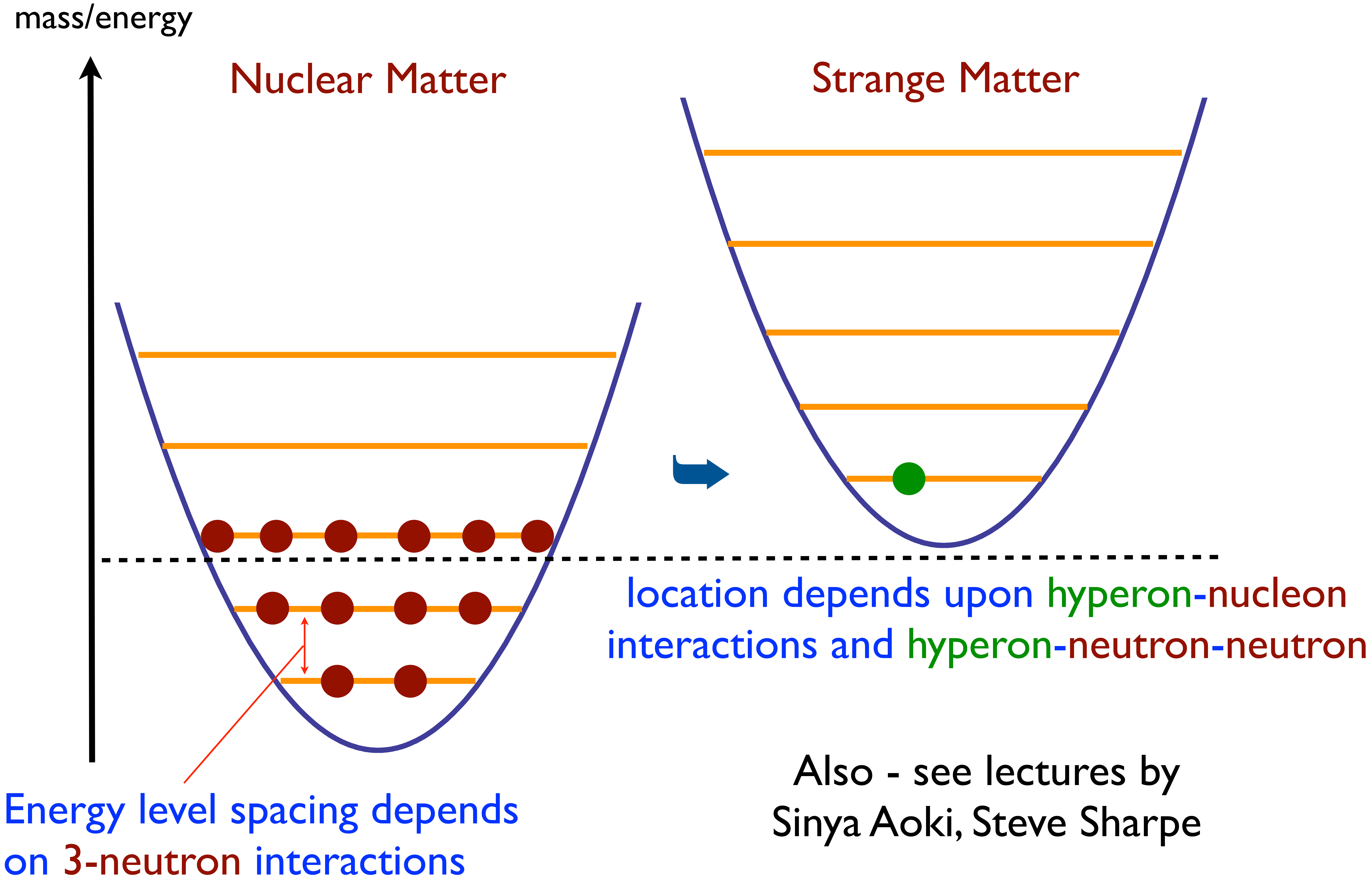
“We are all made of star stuff”

much coming from the ejecta of supernova

Nuclear Matter




mass/energy
Nuclear Matter
Strange Matter


mass/energy
Nuclear Matter
Strange Matter
location depends upon hyperon-nucleon
interactions and hyperon-neutron-neutron
Energy level spacing depends
on 3-neutron interactions
Also - see lectures by
Sinya Aoki, Steve Sharpe

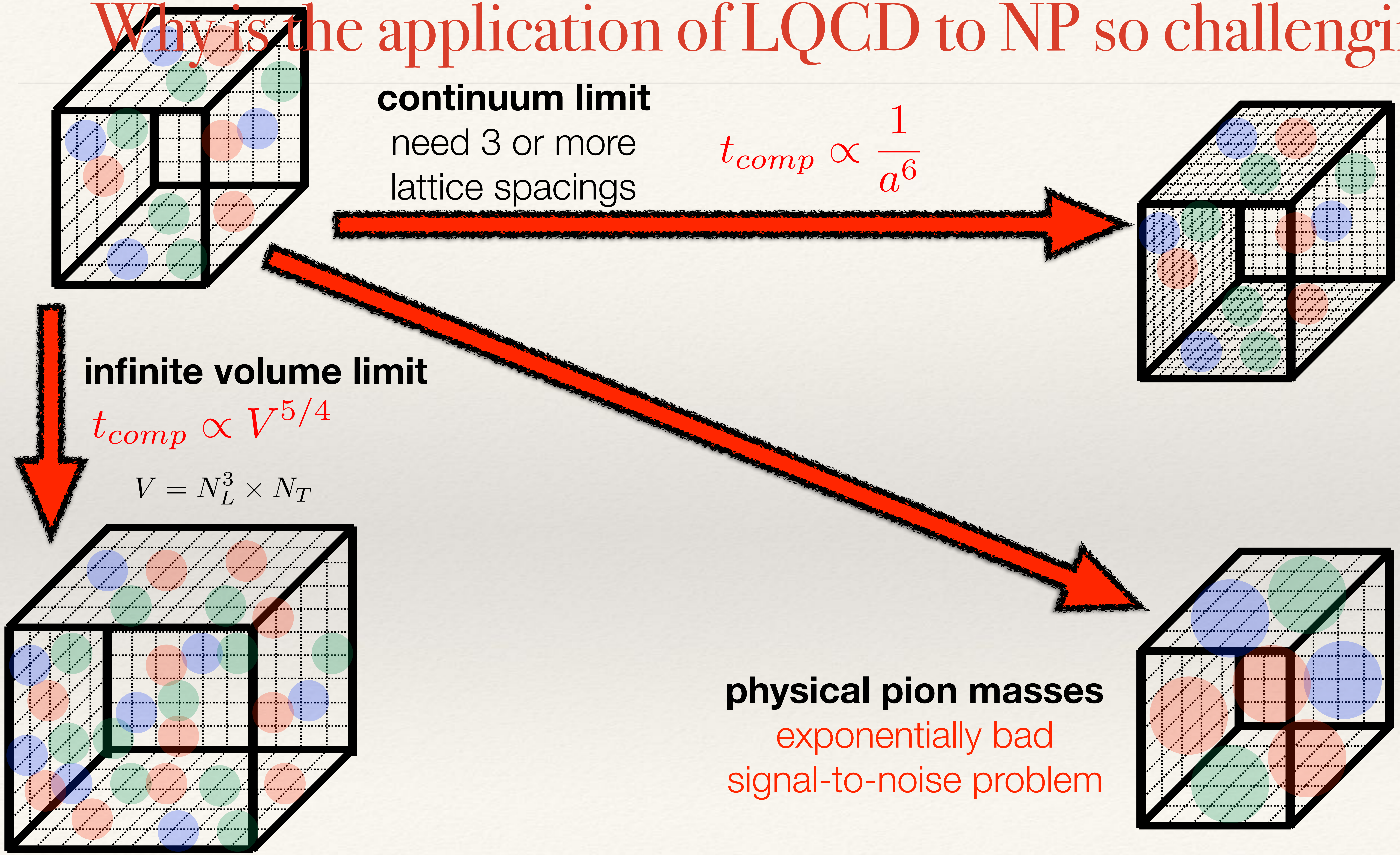
Can we understand properties of neutron stars directly from the fundamental theory?

Can we understand properties of neutron stars directly from the fundamental theory?

Yes! With FRONTIER

Why is the application of LQCD to NP so challenging?

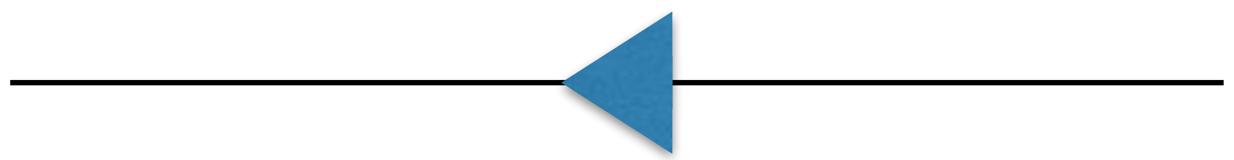
Why is the application of LQCD to NP so challenging?



LQCD challenges for NP

Most difficult challenge: an exponentially bad signal-to-noise problem

Parisi, Phys. Rep. 103 (1984) 203



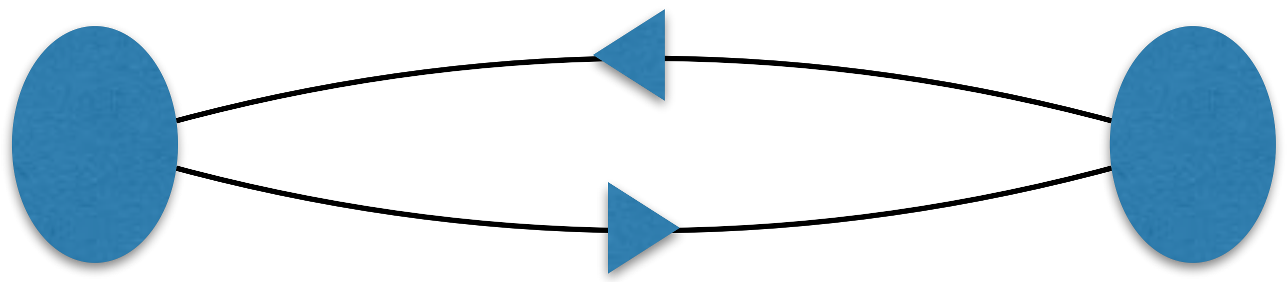
$$\sim e^{-\frac{1}{2}m_\pi t} + e^{-\frac{1}{3}m_N t} + \cdots$$

Lepage, TASI 1989

Each **quark propagator** carries information about pions and nucleons (conversations with David Kaplan)

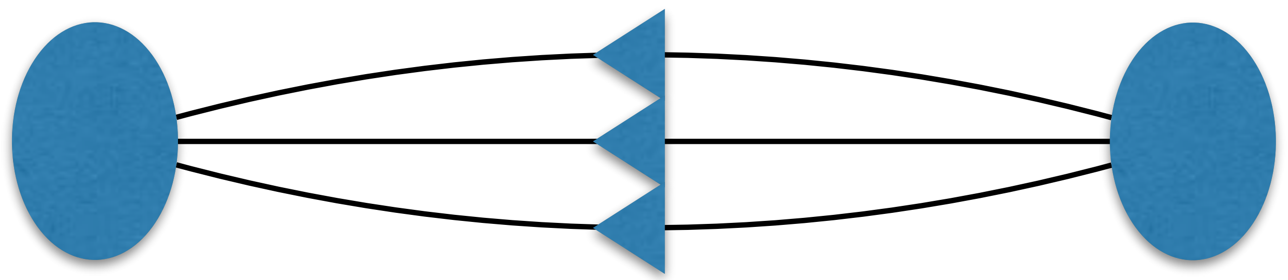
$$\lambda_\pi(t) \gg \lambda_N(t)$$

$$\lambda_i(t) \sim e^{-E_i t}$$



$$\bar{d}\gamma_5 u : C(t) = A_\pi e^{-m_\pi t} + \cdots$$

Large pion eigenvalues must cancel to expose small nucleon eigenvalues



$$(u^T C\gamma_5 d)u : C(t) = A_N e^{-m_N t} + \cdots$$

$$\frac{\text{Signal}}{\text{Noise}} \sim \sqrt{N}\exp\left[-A\left(m_N - \frac{3}{2}m_\pi\right)t\right]$$

exponential noise
power-law statistics

LQCD challenges for NP

2-point correlation function

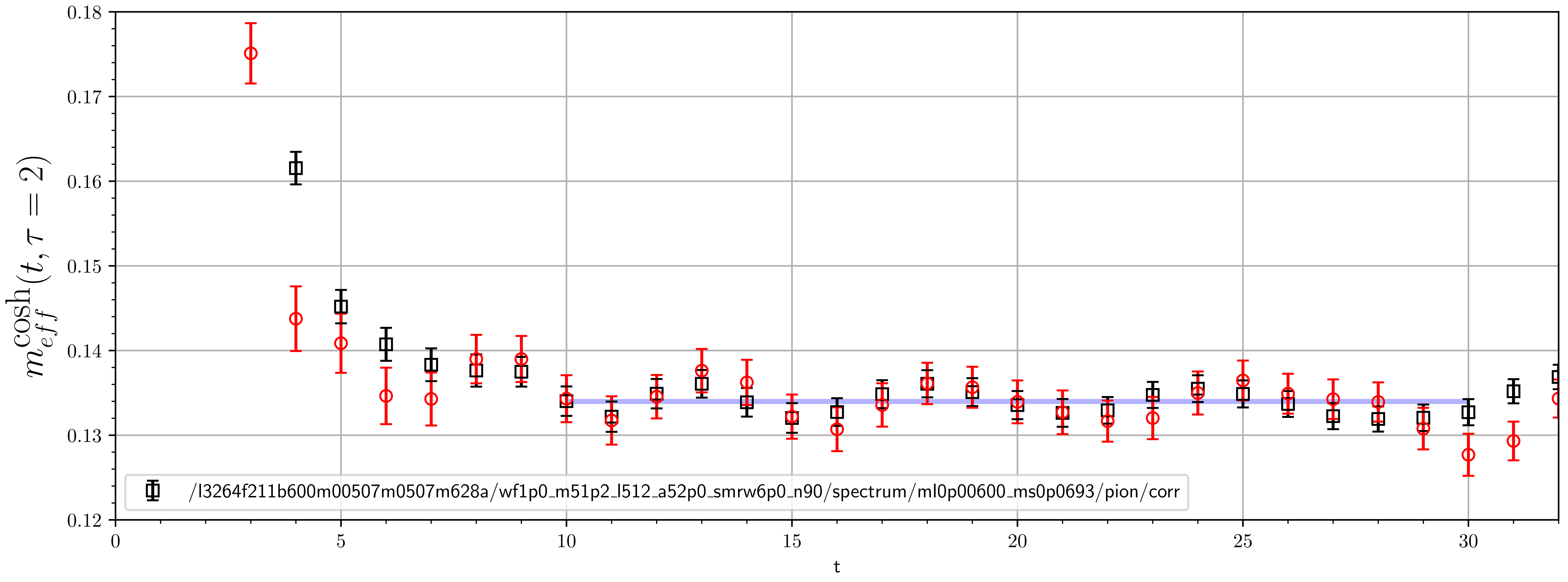
$$C(t) = \sum_n z_n z_n^\dagger e^{-E_n t}$$

$$m_{eff}(t) = \frac{1}{\tau} \ln\left(\frac{C(t)}{C(t+\tau)}\right)$$

For pions, need to consider leading finite temperature effects

$$C(t) = \sum_n z_n z_n^\dagger \left(e^{-E_n t} + e^{-E_n (T-t)}\right)$$

$$m_{eff}^{\cosh}(t,\tau) = \frac{1}{\tau}\cosh^{-1}\left(\frac{C(t+\tau)+C(t-\tau)}{2C(t)}\right)$$

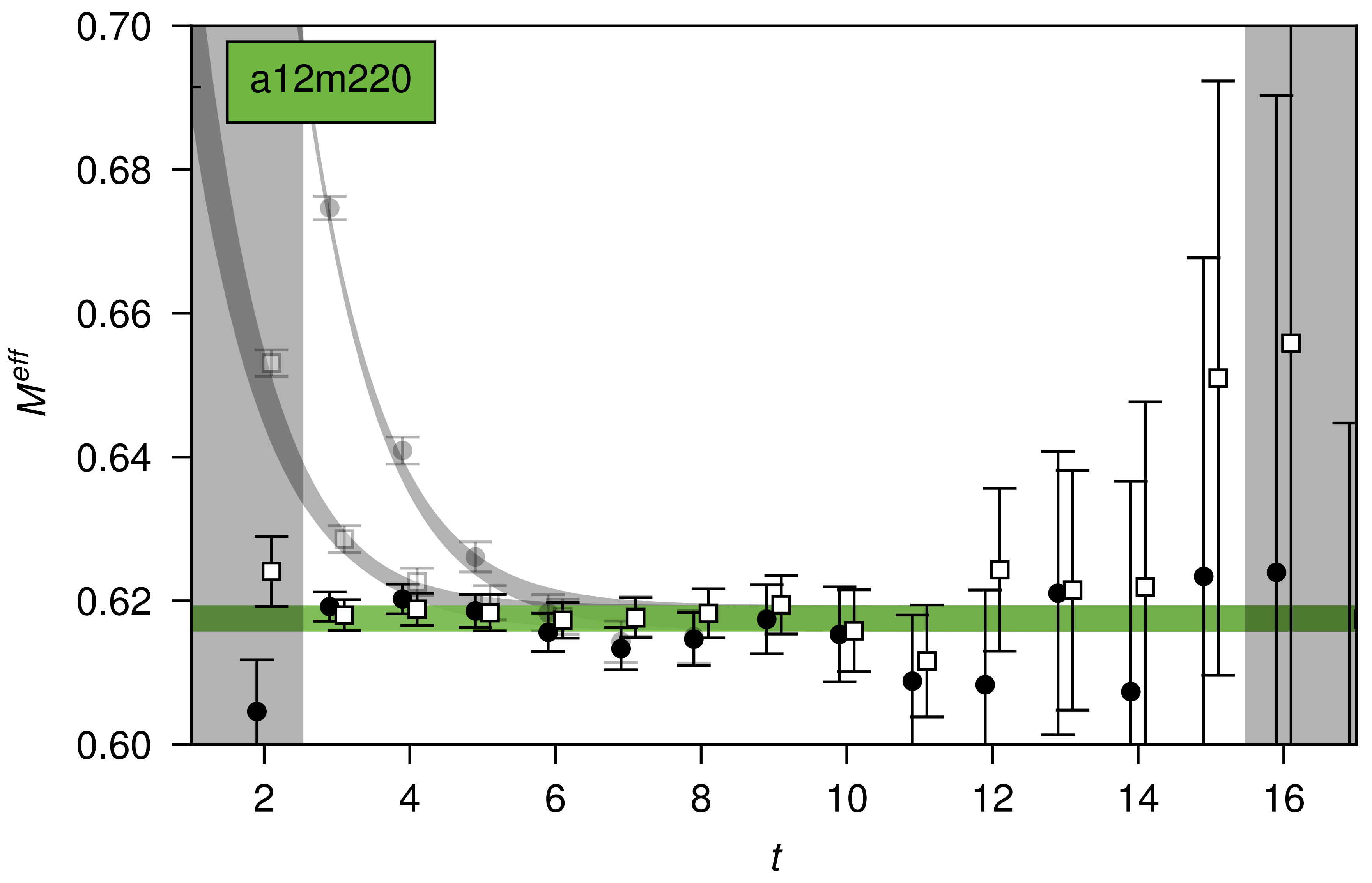


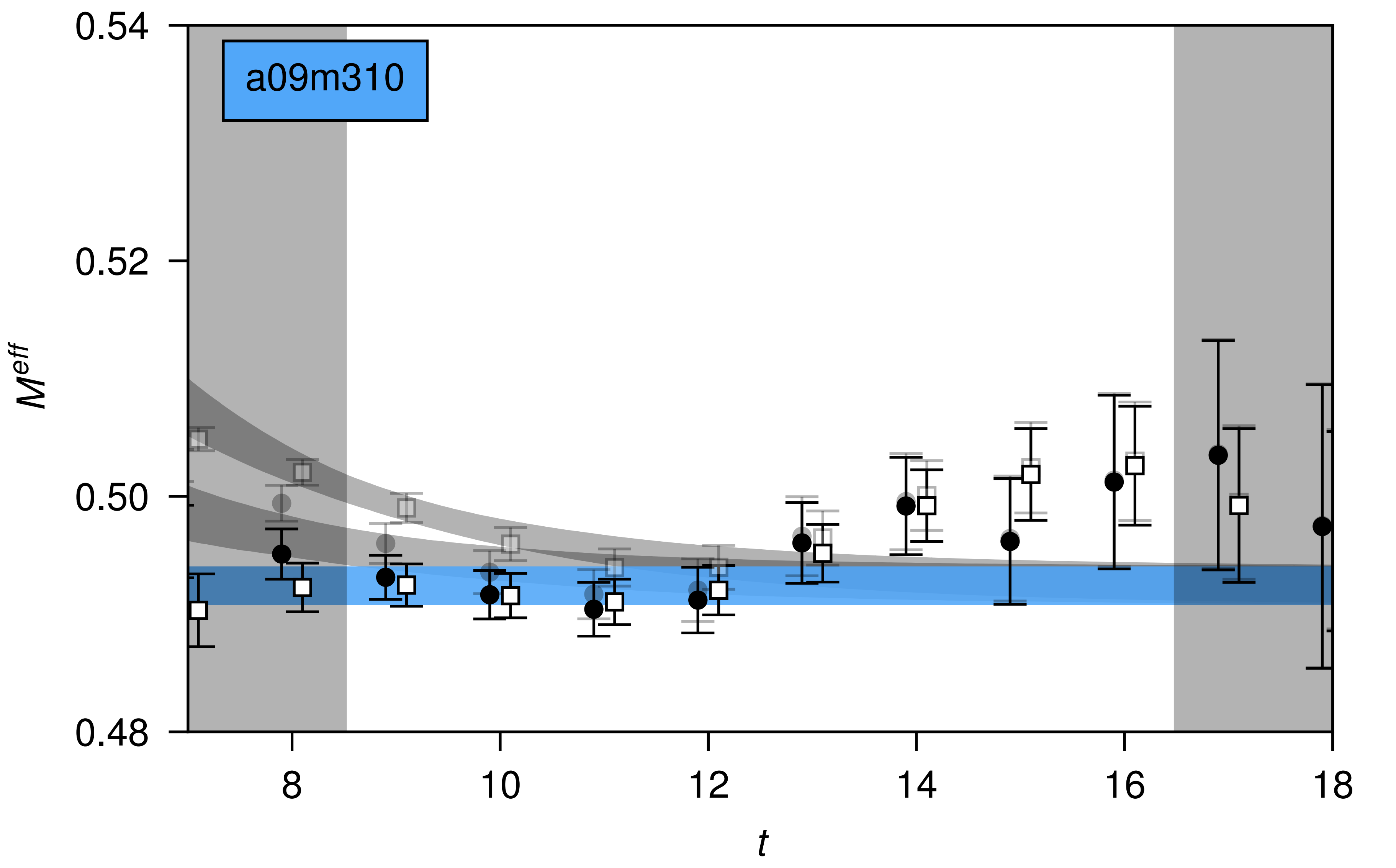
Effective mass of Pion 2-point correlation function
red and black “data” are from different choices of *interpolating* operators

Noise is constant in time - can determine very clean ground state (blue band)

LQCD challenges for NP

2-point correlation function





Two examples of nucleon effective mass

Noise is growing in time - can not simply go to the long-time limit without exponentially increasing the amount of statistics needed

$$\frac{Signal}{Noise} \to \sqrt{N_{state}} e^{-(m_N - \frac{3}{2} m_\pi) t}$$

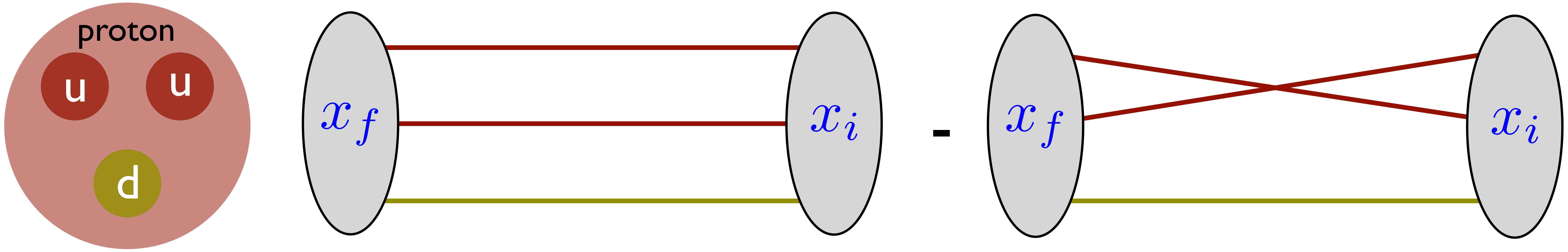
Correlated late-time fluctuations… what is the ground state?

Need sophisticated analysis to ensure you are not susceptible to correlated fluctuations

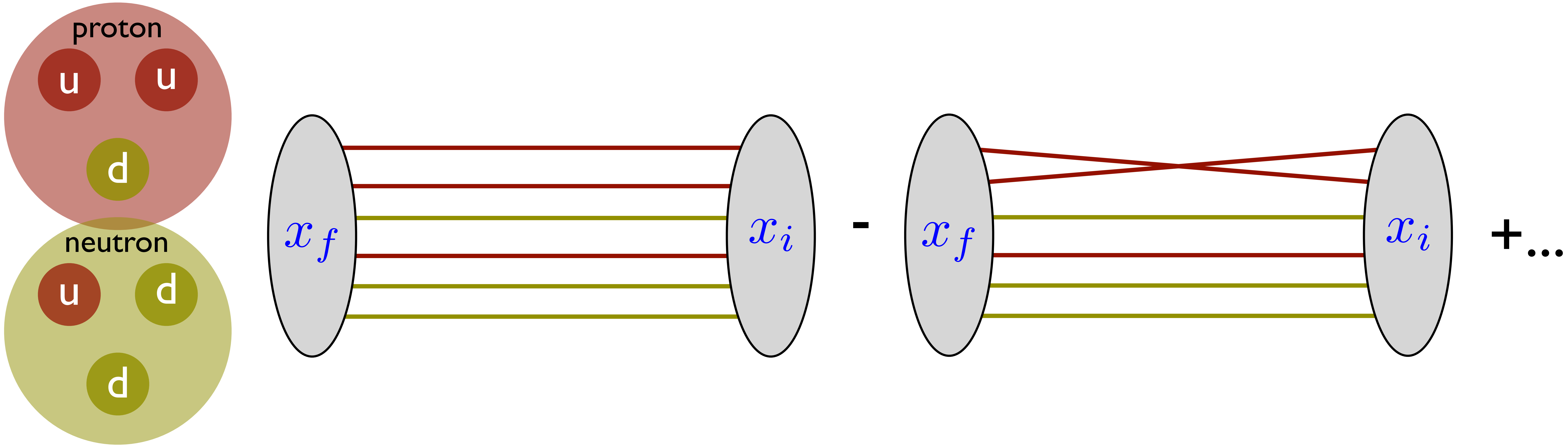
This problem is exacerbated with form-factor calculations (g_A) and 2+ nucleons

- quark contraction cost becomes dominant
- density of excited states grows significantly and gap becomes small (nuclear interaction energies instead of pion mass gap)

LQCD challenges for NP

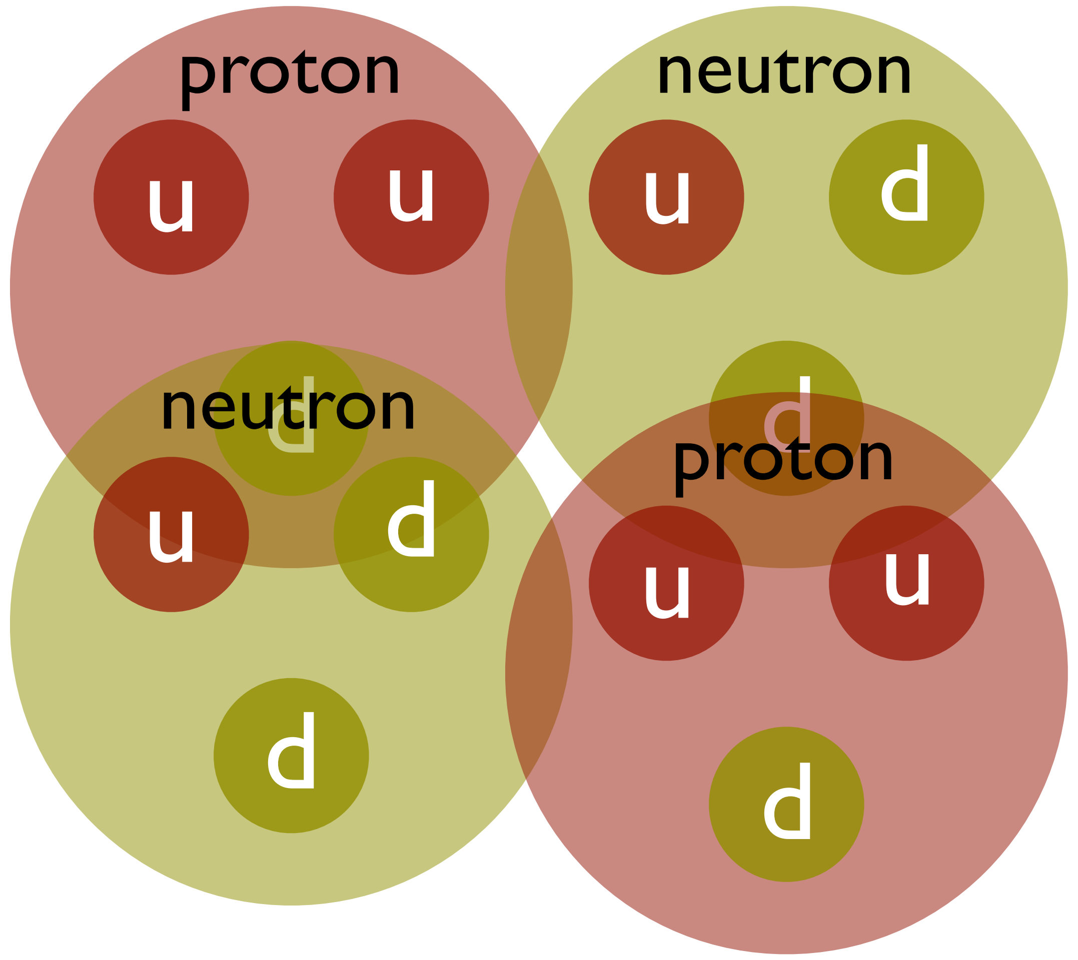


$2! \times 1! = 2$
contractions



$3! \times 3! = 36$
contractions

LQCD challenges for NP



+...

$$6! \times 6! = 518400$$

contractions

numerical cost exceeds HMC + props

quark-exchange diagrams are source of fermion sign problem

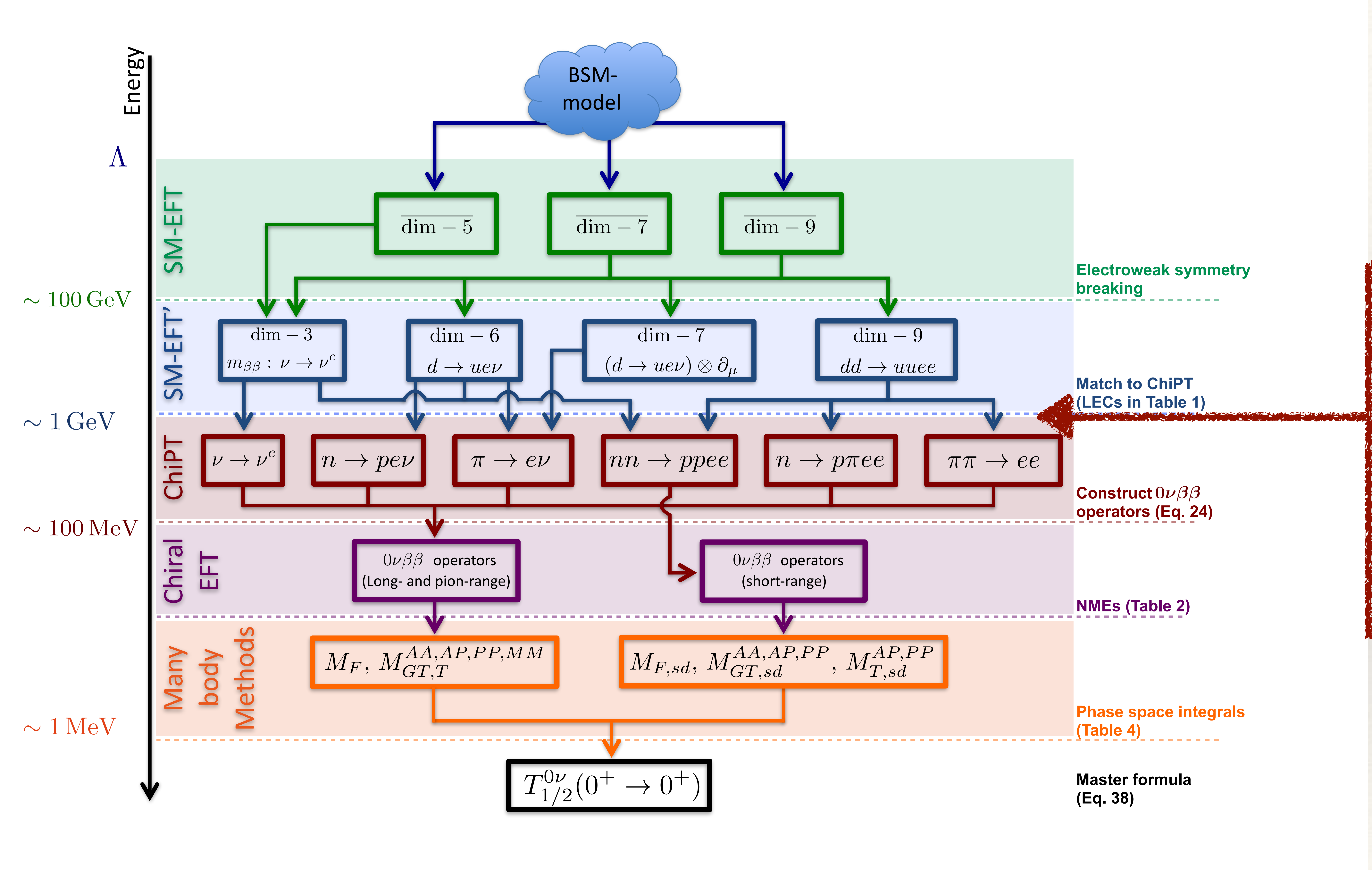
expensive AND noisy :(

There are clever solutions that reduce this cost significantly

Yamazaki, Kuramashi, Ukawa arXiv:0912.1383,
Doi, Endres arXiv:1205.0585, Detmold, Orginos arXiv:1207.1452
Günther, Toth, Varnhorst arXiv:1301.4895

But unfortunately, they only work with unrealistically simplistic interpolating operators in which all quarks originate from the same spacetime point, or are otherwise, identical

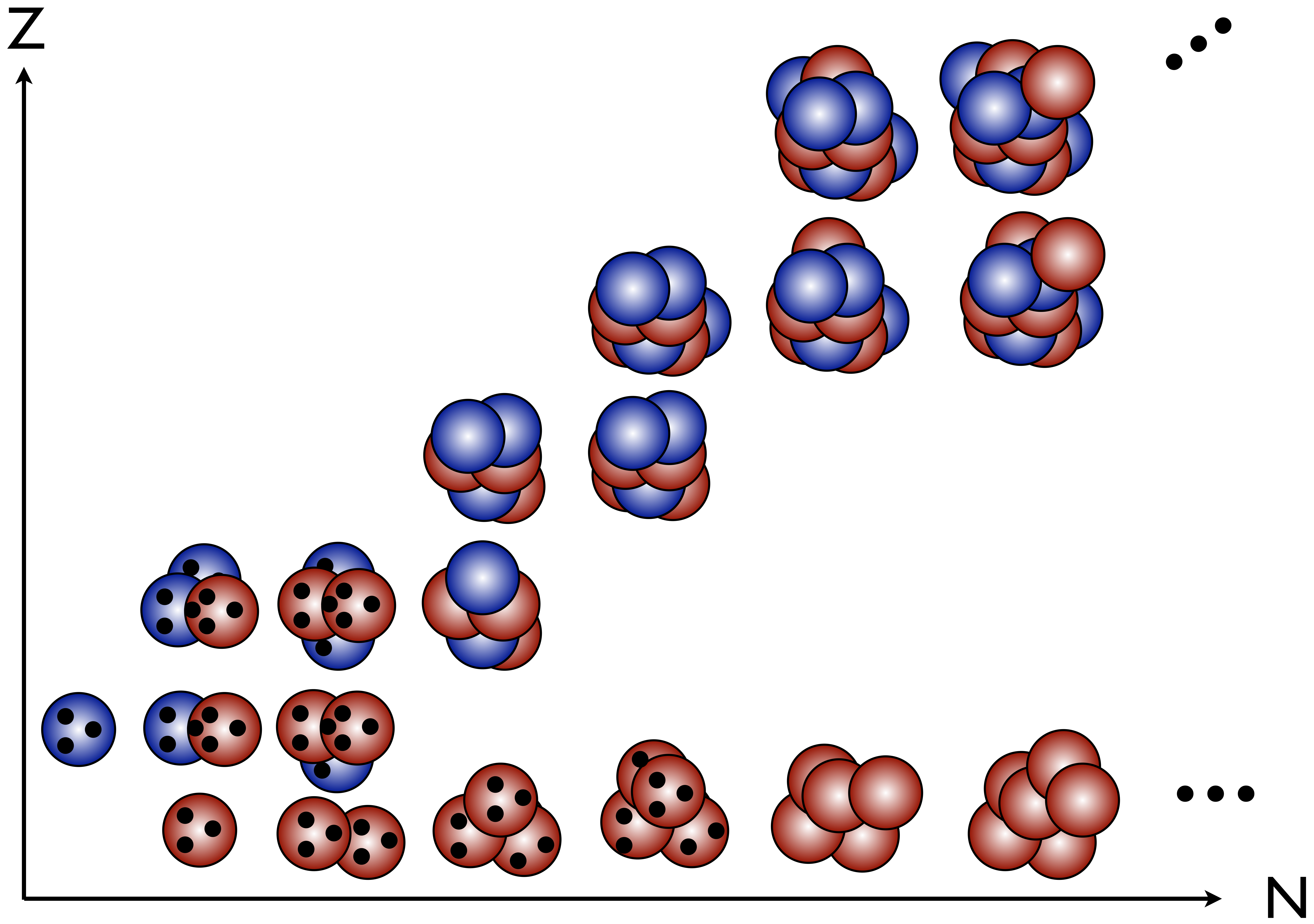
LQCD and EFT

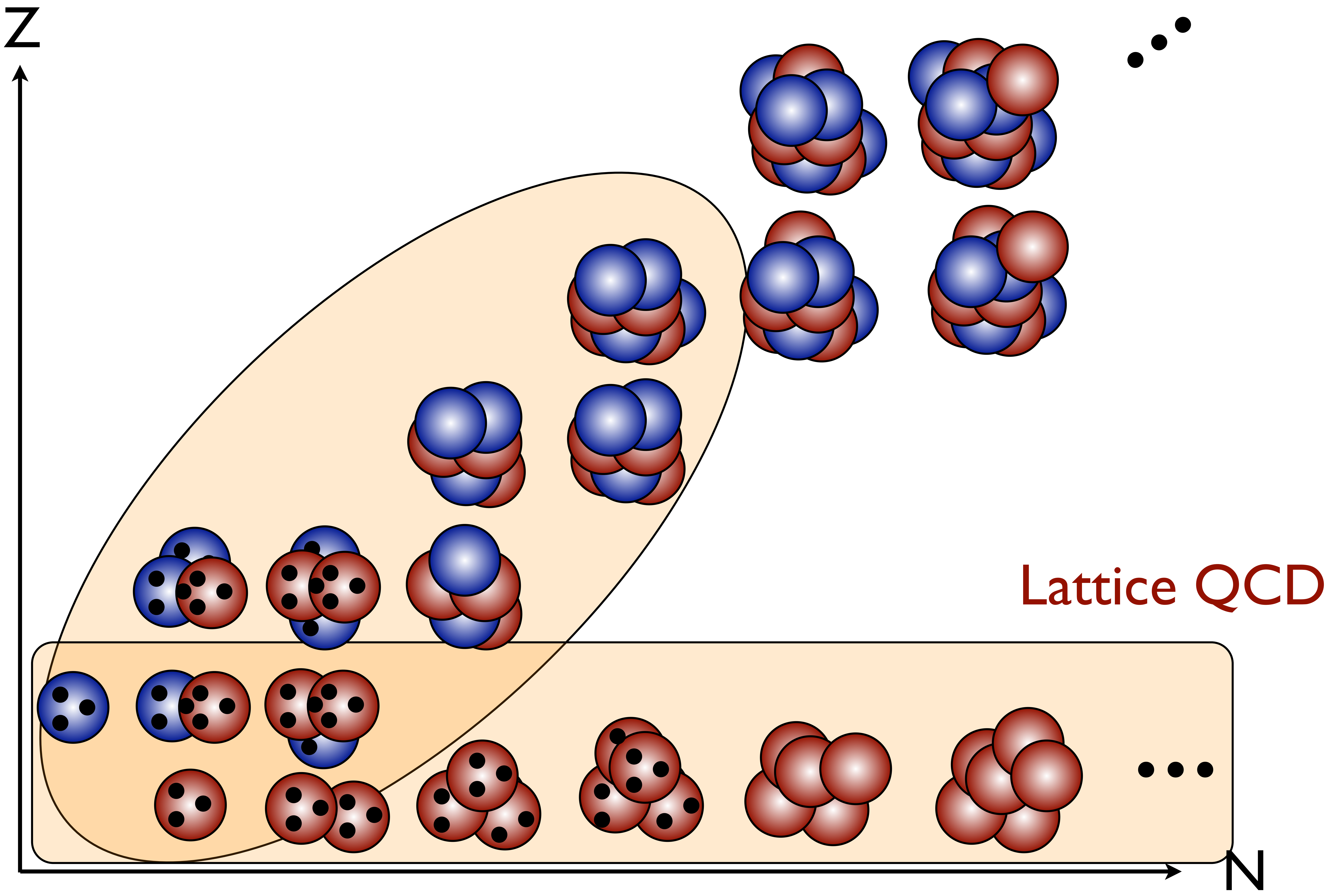


Example from 0νββ

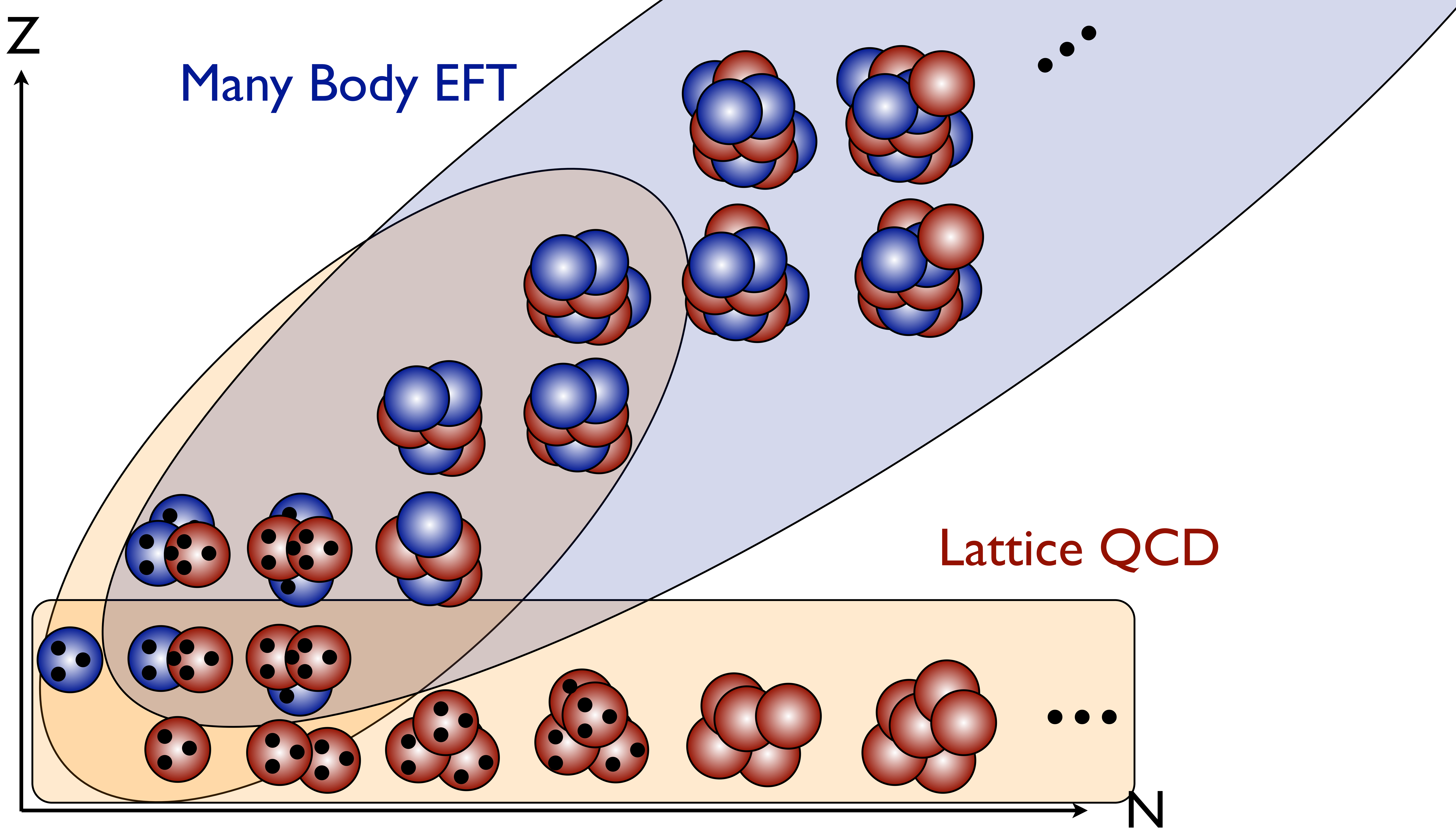
Cirigliano, Dekens, de Vries, Graesser, Mereghetti, arXiv:1806.02780

- LQCD is used at the interface between QCD-level operators and Chiral Perturbation Theory
- Combining LQCD + EFT greatly extends the reach of application and prediction


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

Chiral Perturbation Theory Overview

Jenkins & Manohar Phys. Lett. B 255 (1991)

HBχPT for M_N up to NNLO

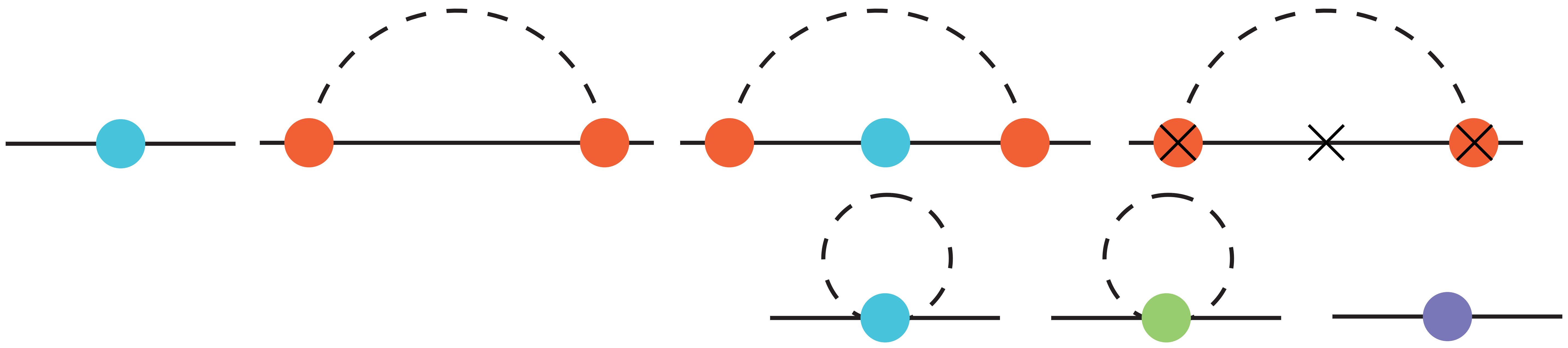
AWL arXiv:hep-lat/0405007
B.C. Tiburzi, AWL arXiv:hep-lat/0501018

$$\mathcal{L}_{N\pi} = \bar{N} iv\cdot D N - \frac{\alpha_N}{4\pi F}\bar{N}\mathcal{M}_+ N - \frac{\sigma_N}{4\pi F}\bar{N}N\,\mathrm{tr}(\mathcal{M}_+) + 2g_A^{\mathrm{LO}}\bar{N}S\cdot\mathcal{A}N$$

$$-\bar{N}\frac{D_\perp^2}{2M_0}N + g_A^{\mathrm{LO}}\left(\bar{N}\frac{i\overleftarrow{D}\cdot S}{M_0}v\cdot\mathcal{A}N + \bar{N}v\cdot\mathcal{A}\frac{S\cdot i\overrightarrow{D}}{M_0}N\right) + \frac{b_A}{4\pi F}\bar{N}N\,\mathrm{tr}(\mathcal{A}\cdot\mathcal{A}) + \frac{b_{vA}}{4\pi F}\bar{N}N\,\mathrm{tr}(v\cdot\mathcal{A}v\cdot\mathcal{A})$$

$$+\frac{b_1}{(4\pi F)^3}\bar{N}\mathcal{M}_+^2 N + \frac{b_2}{(4\pi F)^3}\bar{N}N\,\mathrm{tr}(\mathcal{M}_+^2) + \frac{b_3}{(4\pi F)^3}\bar{N}\mathcal{M}_+N\,\mathrm{tr}(\mathcal{M}_+) + \frac{b_4}{(4\pi F)^3}\bar{N}N[\mathrm{tr}(\mathcal{M}_+)]^2$$

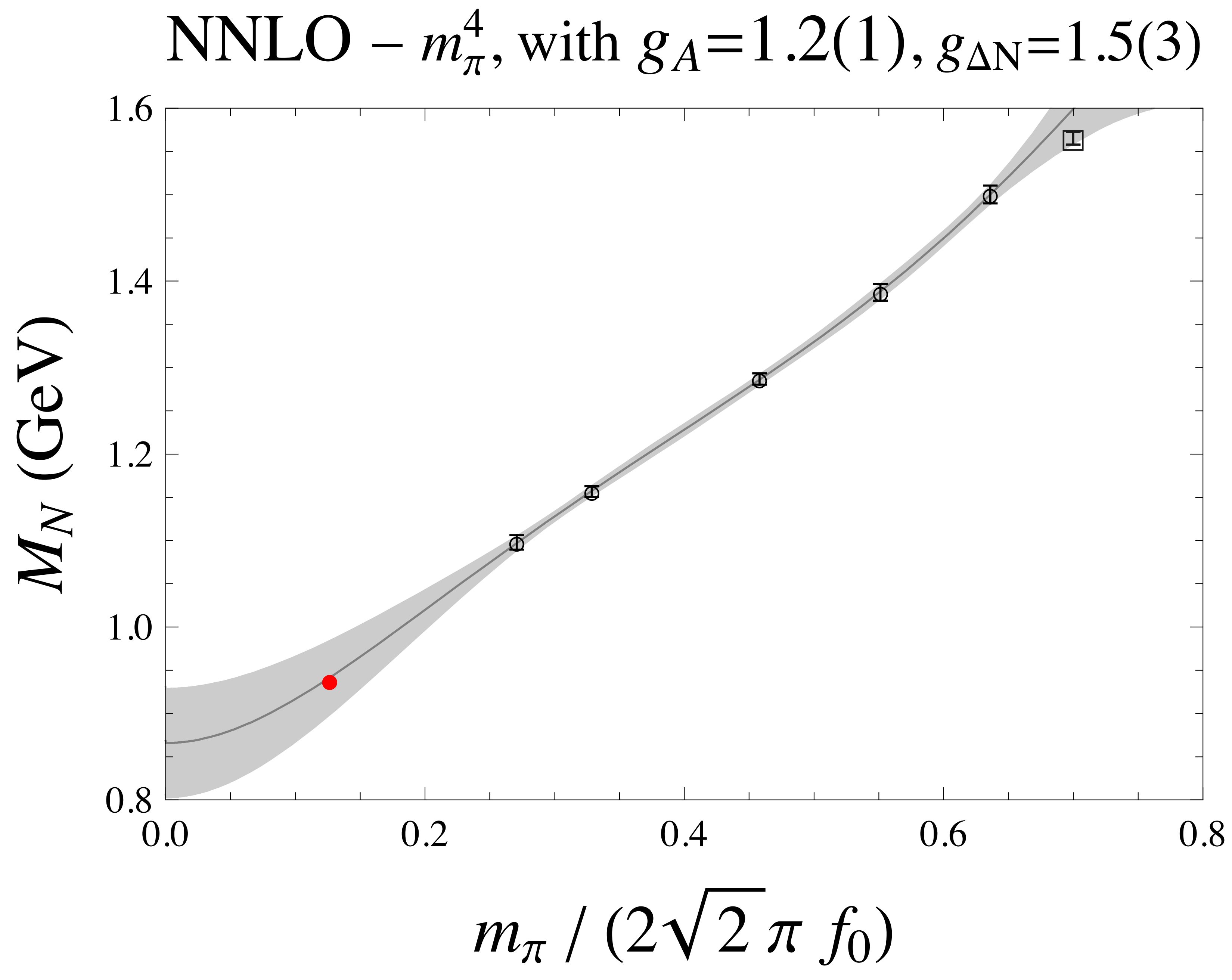
$\Delta M_N =$

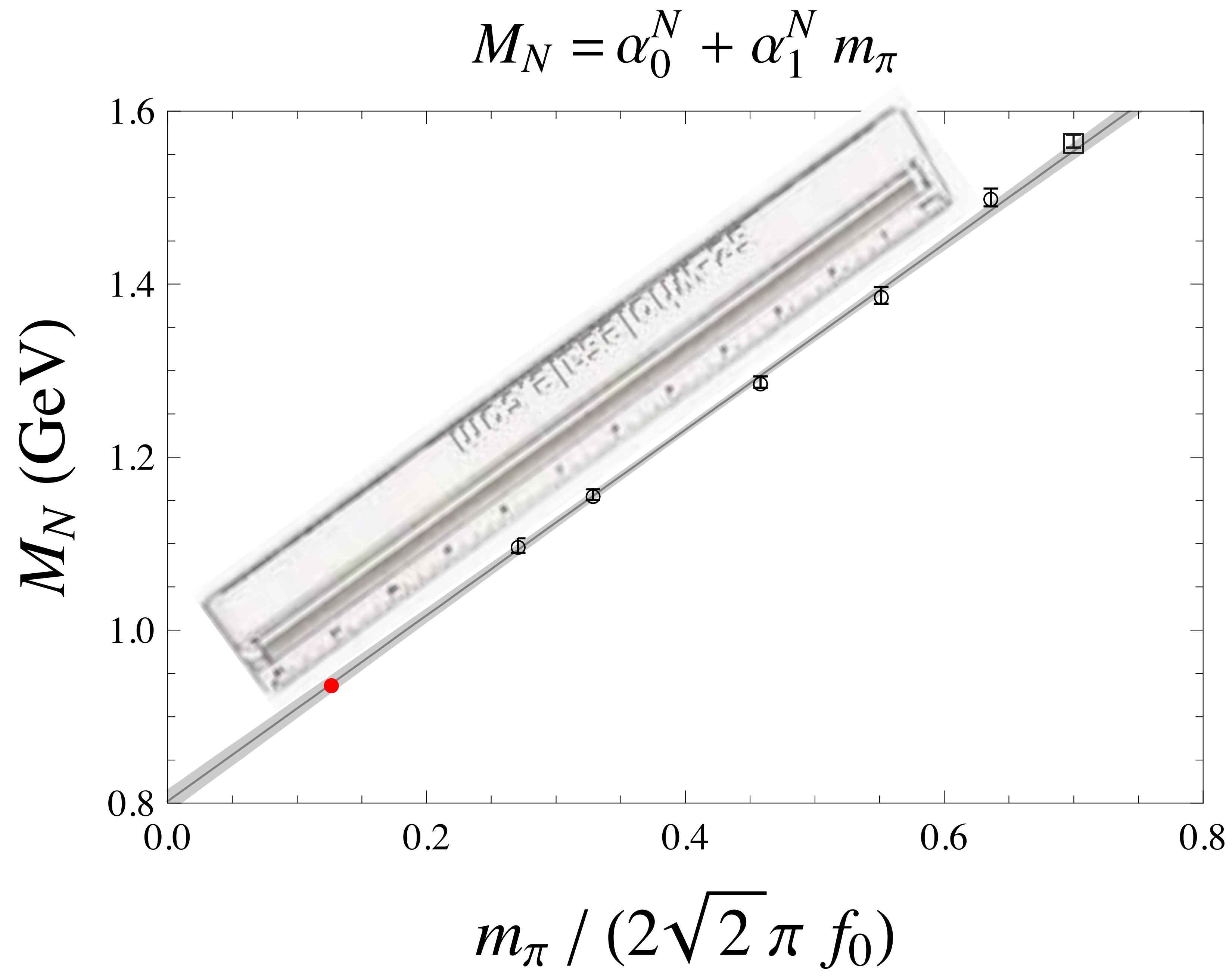


LO NLO NNLO

$$\frac{m_\pi^2}{4\pi F_\pi} \qquad -\frac{3\pi g_A^2}{2}\frac{m_\pi^3}{(4\pi F_\pi)^2} \qquad \frac{m_\pi^4}{(4\pi F_\pi)^3}\ln\left(\frac{m_\pi^2}{(4\pi F_\pi)^2}\right) \qquad \frac{m_\pi^4}{(4\pi F_\pi)^3}$$

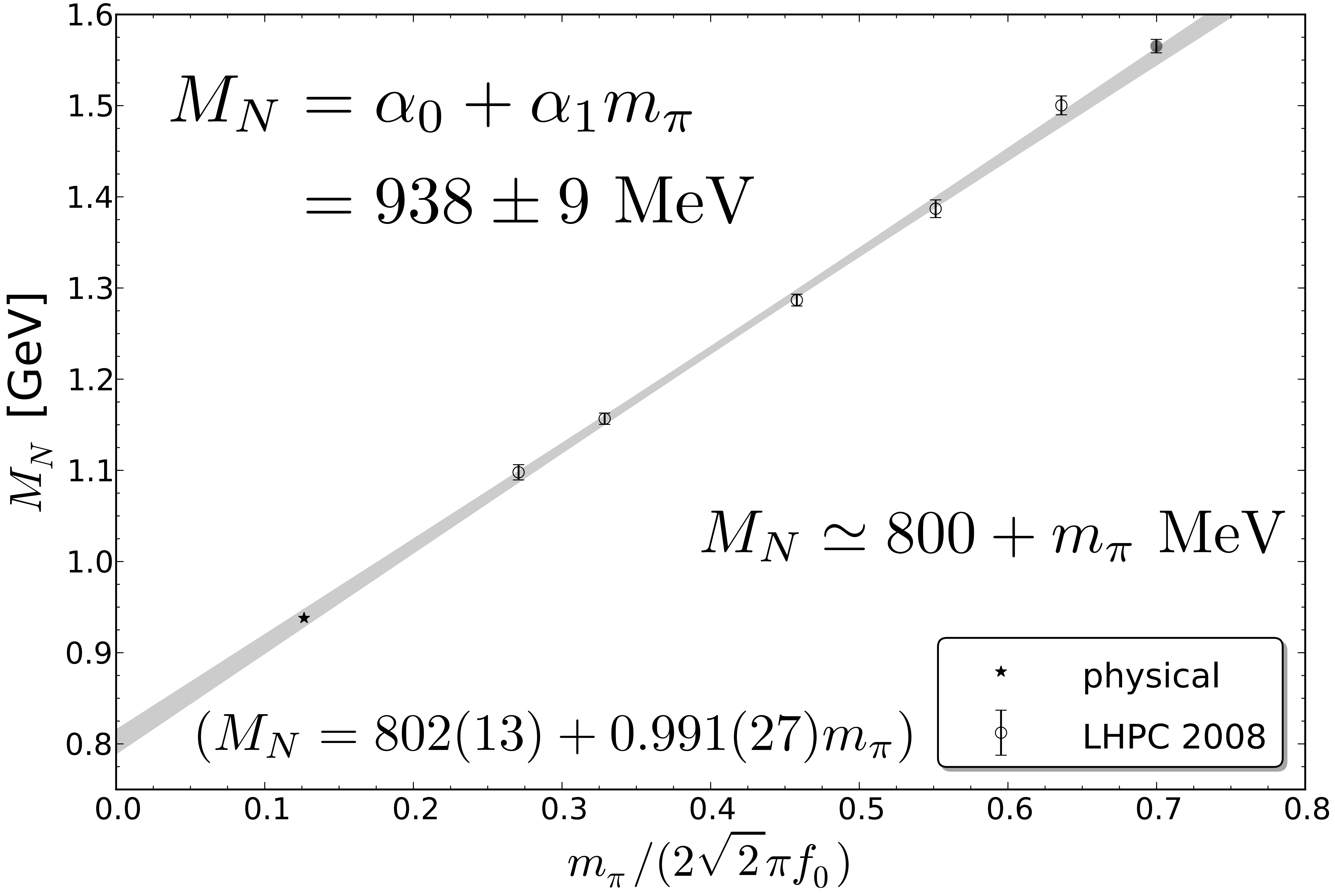
M_N OLD 2008 work: LHPC 0806.4549





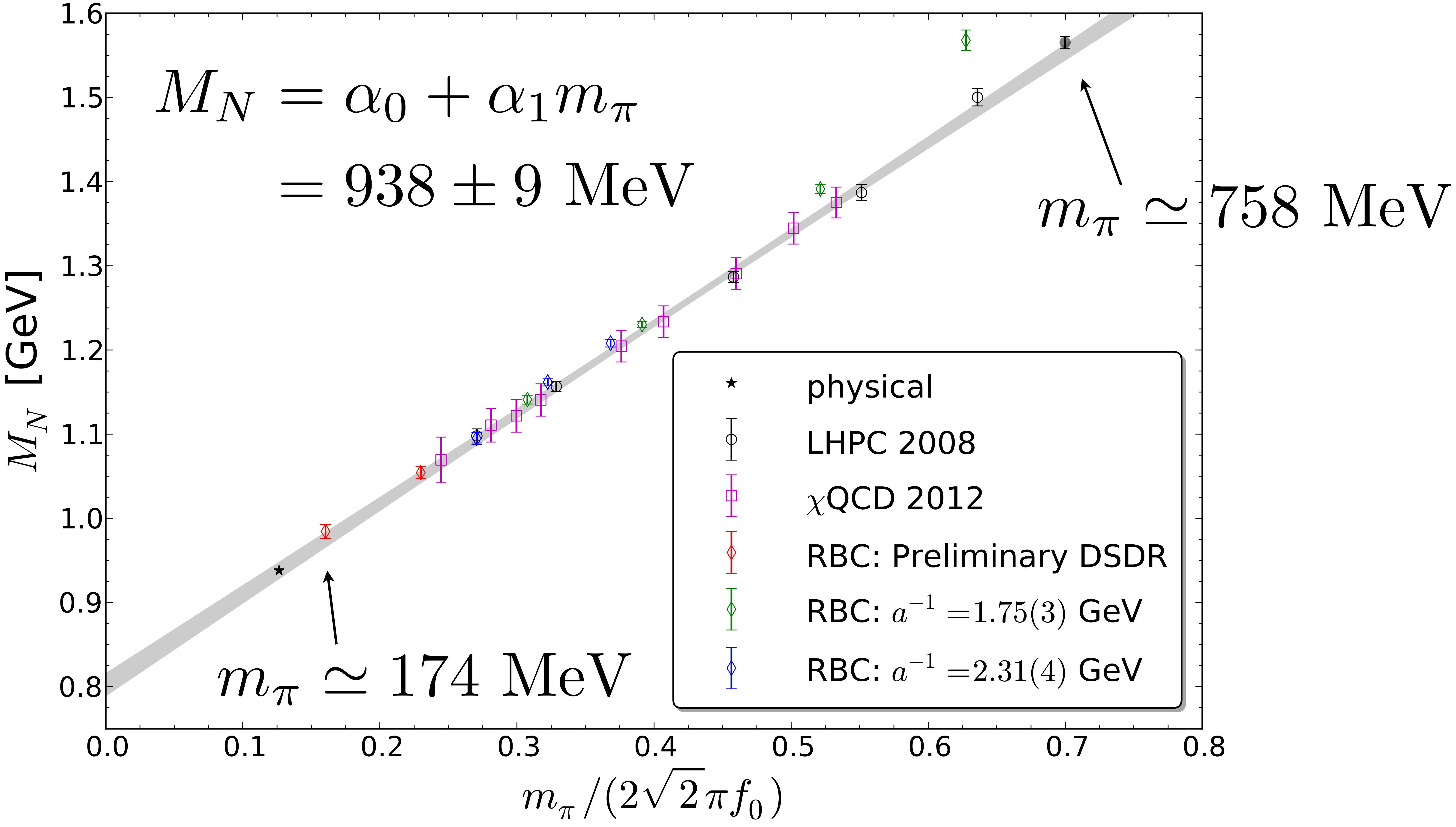
- Is this a lattice artifact? Or a conspiracy of QCD?
- All lattice calculations in 2008 with 2+1 dynamical fermion showed this linear pion mass dependence

What is the status now (2012)?



Physical point NOT included in fit

What is the status now (2012)?



Taking this seriously yields

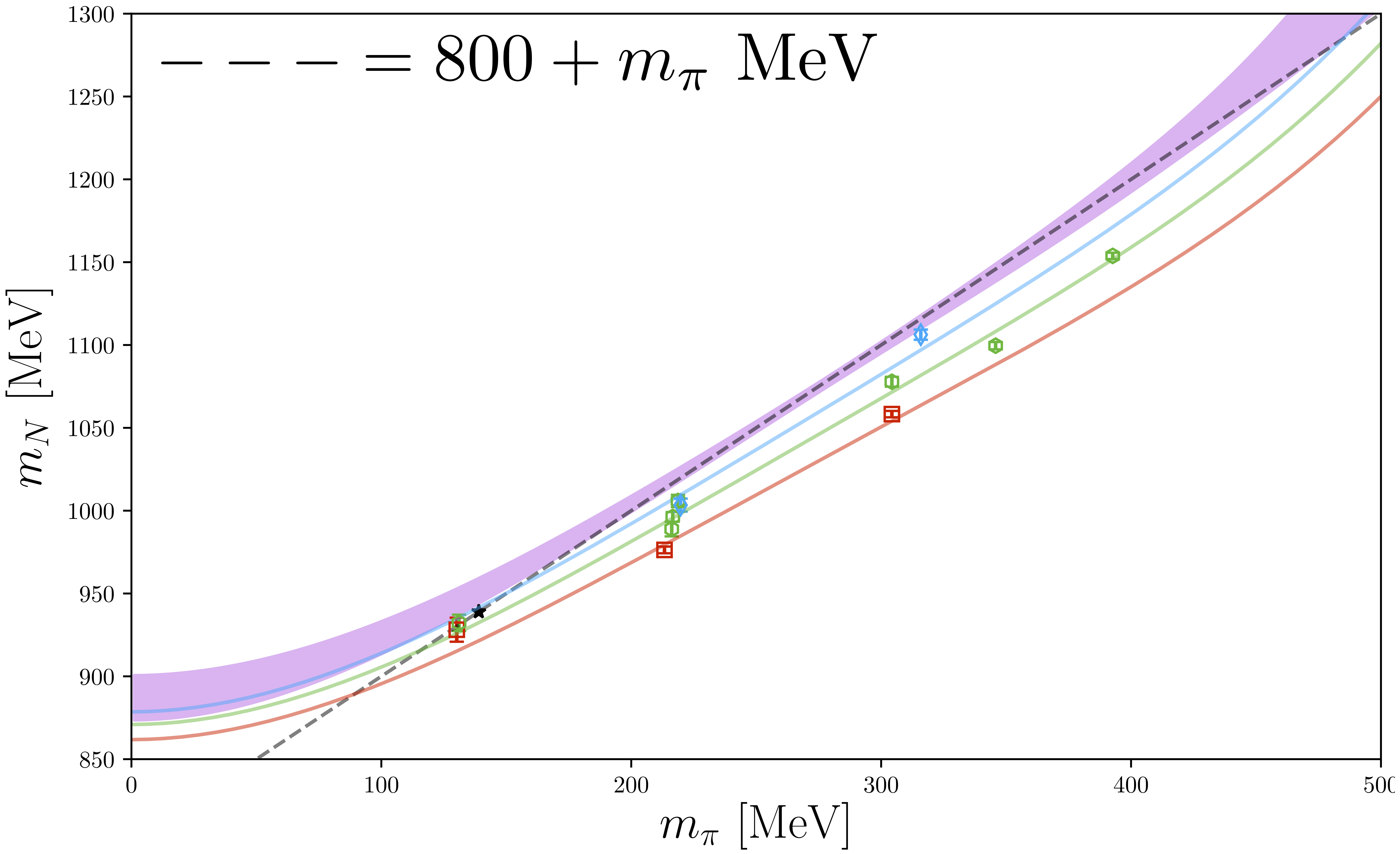
$$\sigma_{\pi N} = 67 \pm 4 \text{ MeV}$$

$$M_N \simeq 800 + m_\pi \text{ MeV}$$

$$(M_N = 802(13) + 0.991(27) m_\pi)$$

M_N

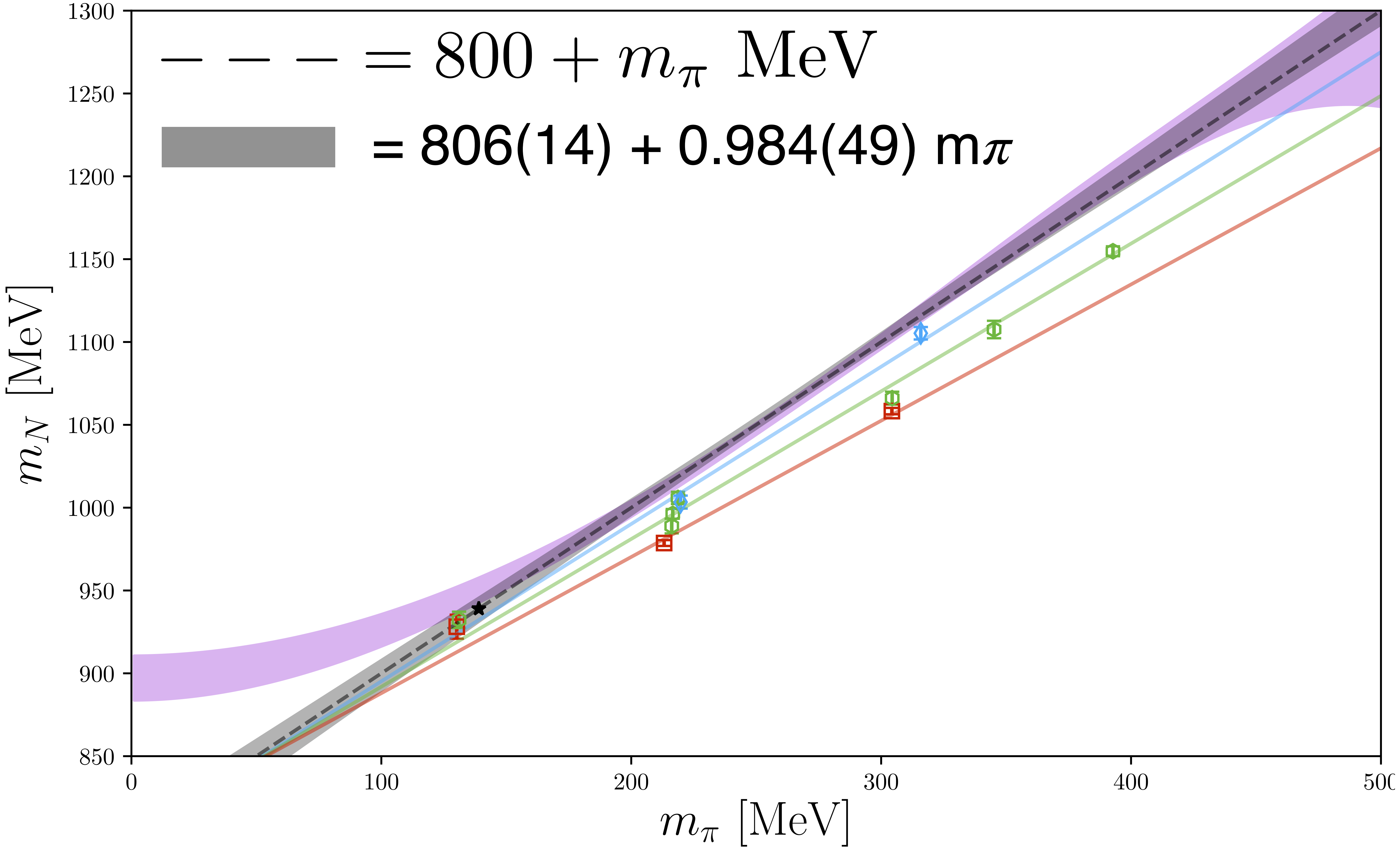
work in progress



- NNLO fit $O(m_\pi^4) + a^2/\omega_0^2 + a^2/\omega_0^2 \times m_\pi^2/(4\pi F)$
- gA taken from our calculation
- continuum, infinite volume extrapolated mass is consistent with RULER

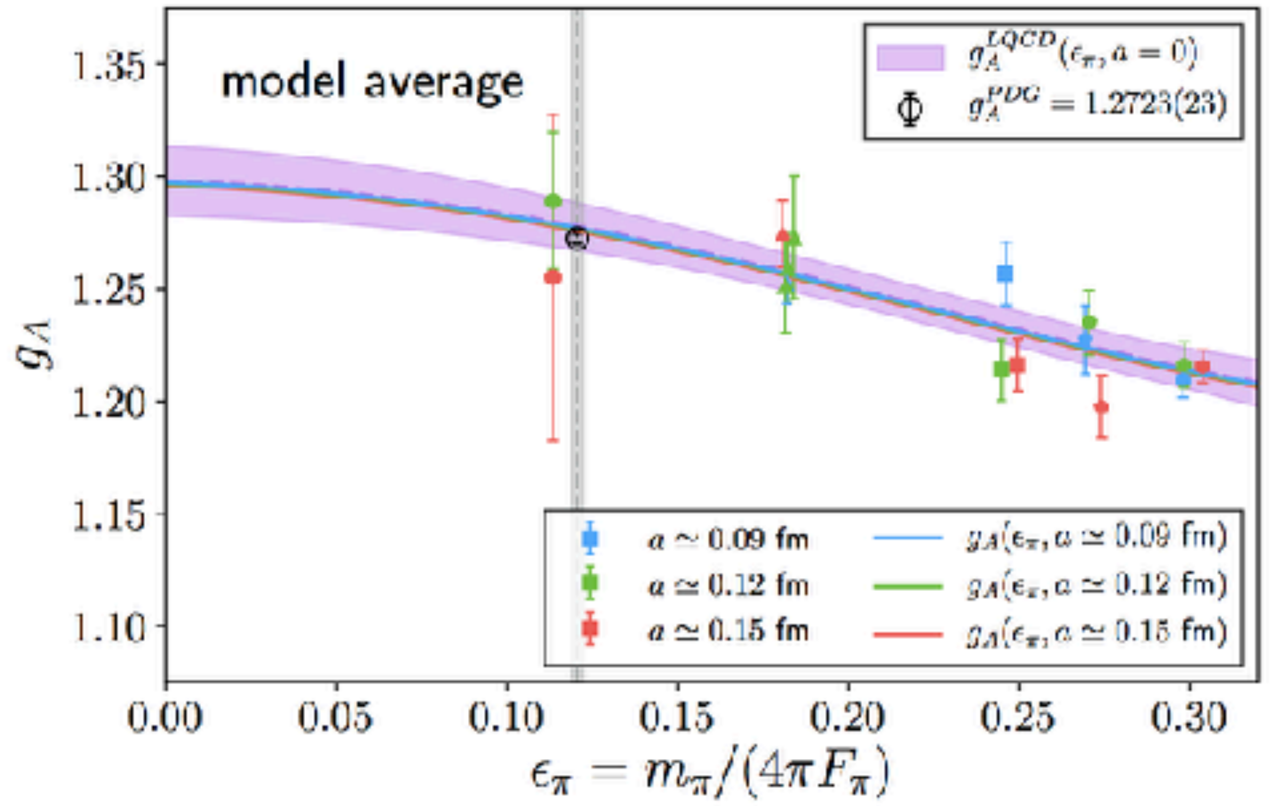
M_N

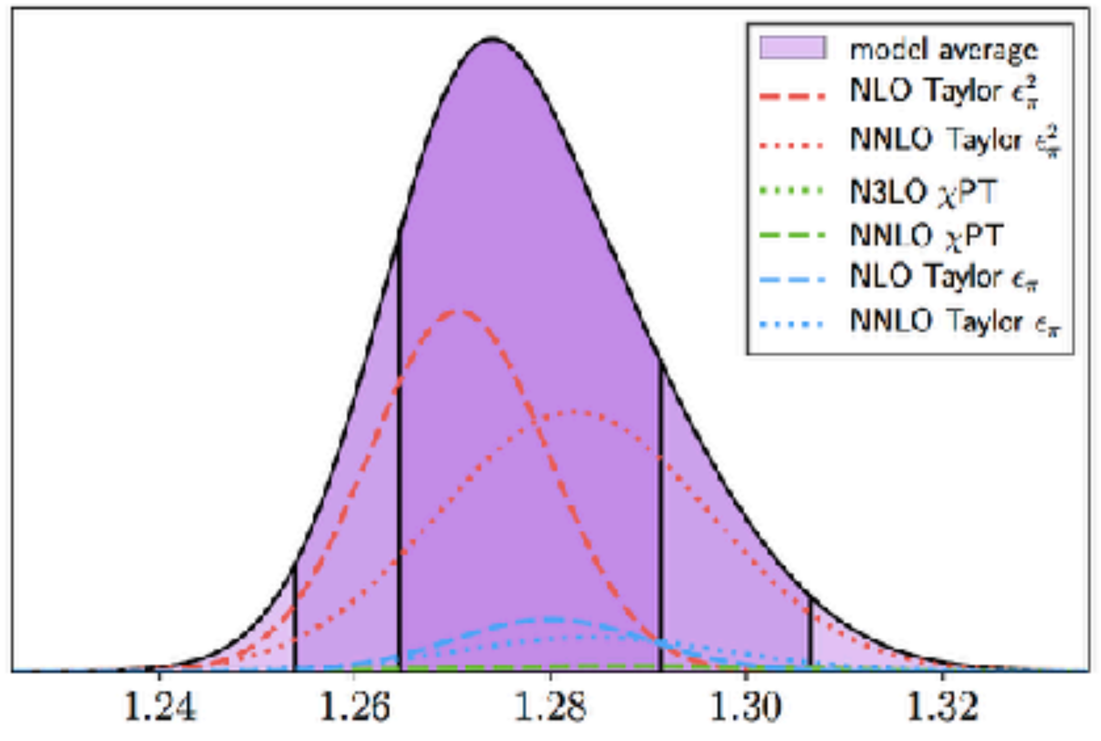
work in progress



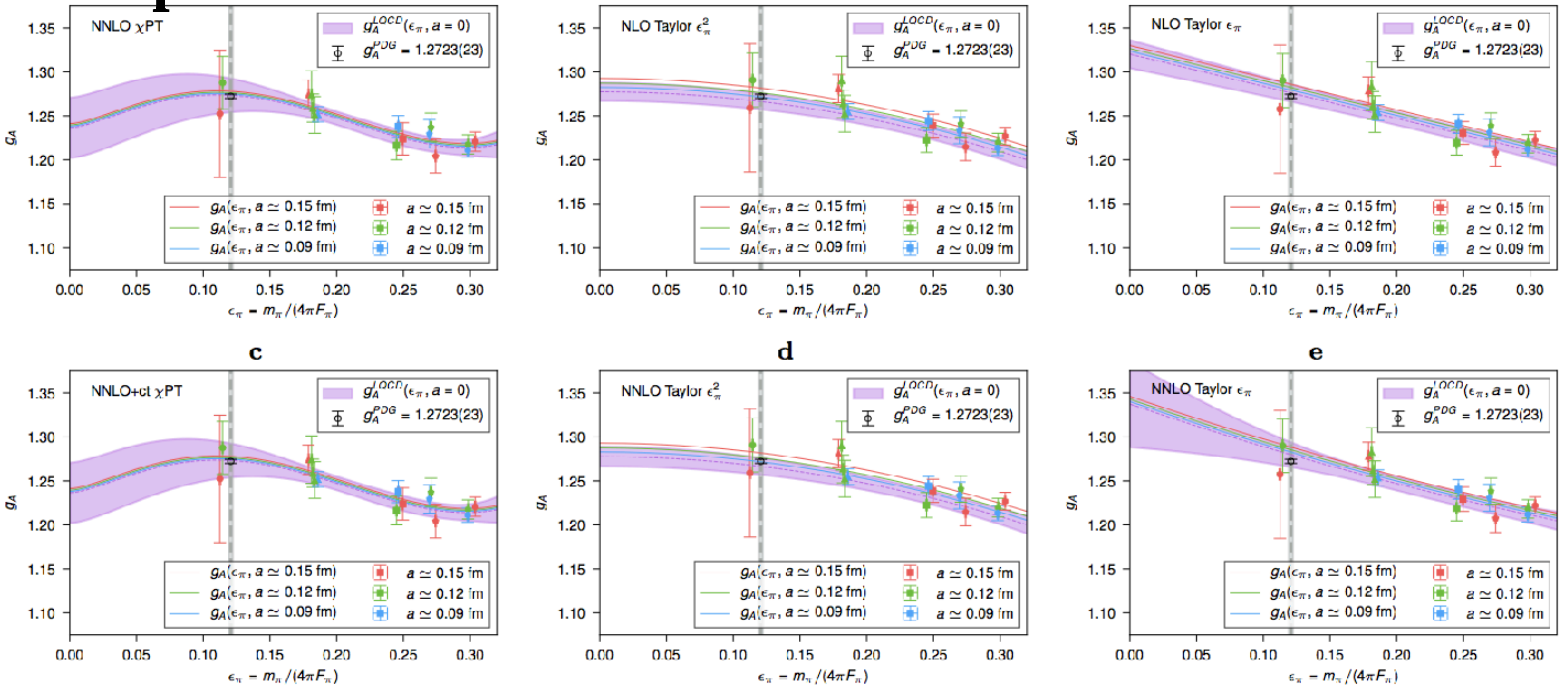
- Ruler applied to our new MDWF on HISQ results
- $M_N = c_0 + c_1\ m_\pi + a_2\ a^2 + c_{am,2}\ a^2 m_\pi$

Analysis Details





Extrapolations



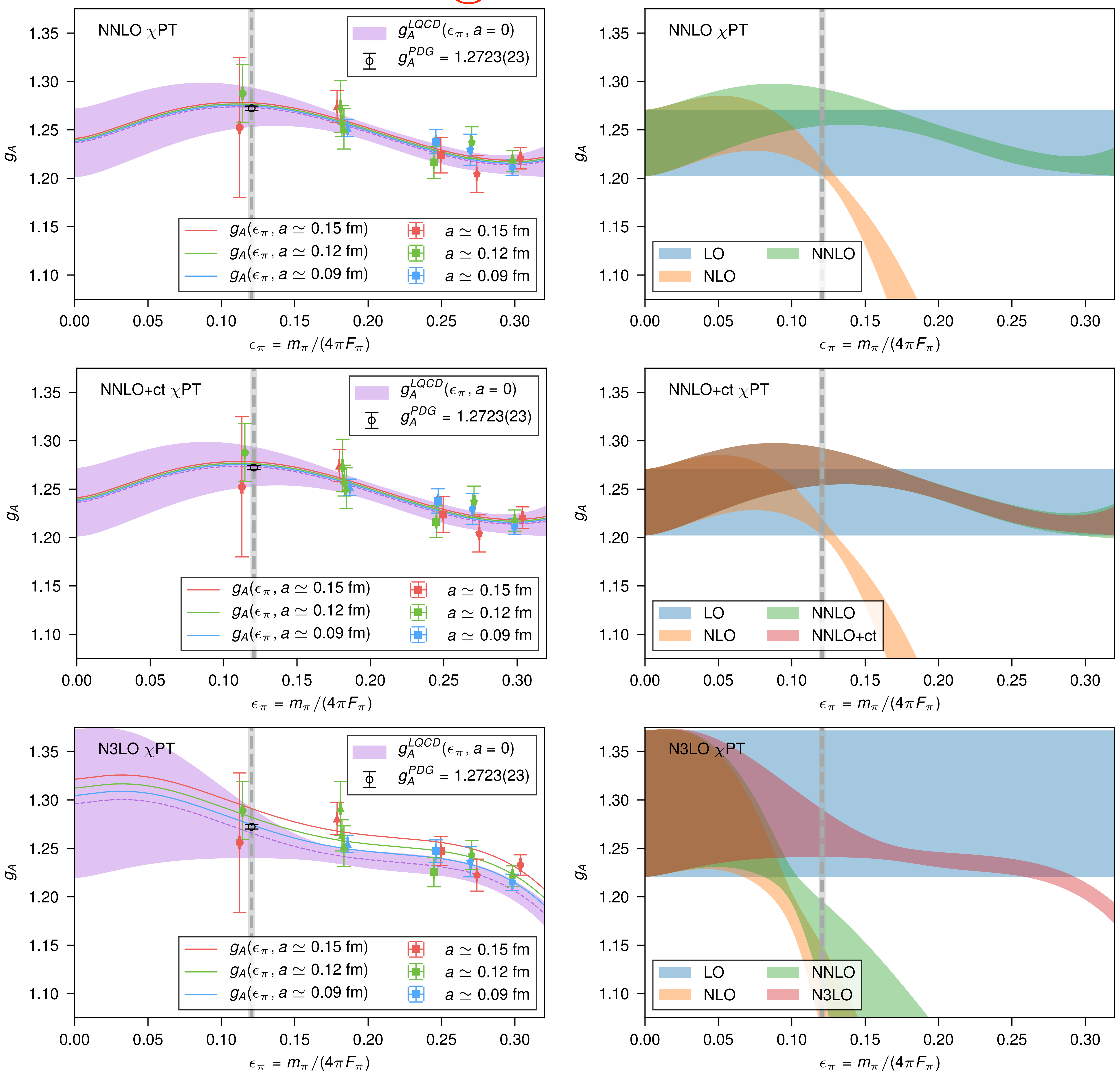
Fit	χ^2/dof	$\mathcal{L}(D\|M_k)$	$P(M_k\|D)$	$P(g_A\|M_k)$
NNLO χPT	0.727	22.734	0.033	1.273(19)
NNLO+ct χPT	0.726	22.729	0.033	1.273(19)
NLO Taylor ϵ_π^2	0.792	24.887	0.287	1.266(09)
NNLO Taylor ϵ_π^2	0.787	24.897	0.284	1.267(10)
NLO Taylor ϵ_π	0.700	24.855	0.191	1.276(10)
NNLO Taylor ϵ_π	0.674	24.848	0.172	1.280(14)
average				1.271(11)(06)

f

$$g_A = g_0 - \epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + c_2\epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3$$

$$\begin{aligned}
\text{NNLO } \chi\text{PT}: &\quad \text{Eq. (S8)} + \delta_a + \delta_L \\
\text{NNLO+ct } \chi\text{PT}: &\quad \text{Eq. (S8)} + c_4\epsilon_\pi^4 + \delta_a + \delta_L \\
\text{NLO Taylor } \epsilon_\pi^2: &\quad c_0 + c_2\epsilon_\pi^2 + \delta_a + \delta_L \\
\text{NNLO Taylor } \epsilon_\pi^2: &\quad c_0 + c_2\epsilon_\pi^2 + c_4\epsilon_\pi^4 + \delta_a + \delta_L \\
\text{NLO Taylor } \epsilon_\pi: &\quad c_0 + c_1\epsilon_\pi + \delta_a + \delta_L \\
\text{NNLO Taylor } \epsilon_\pi: &\quad c_0 + c_1\epsilon_\pi + c_2\epsilon_\pi^2 + \delta_a + \delta_L
\end{aligned}$$

convergence of the chiral expansion…



$$g_A = g_0 - \epsilon_\pi^2 (g_0 + 2g_0^3) \ln(\epsilon_\pi^2) + c_2 \epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3$$

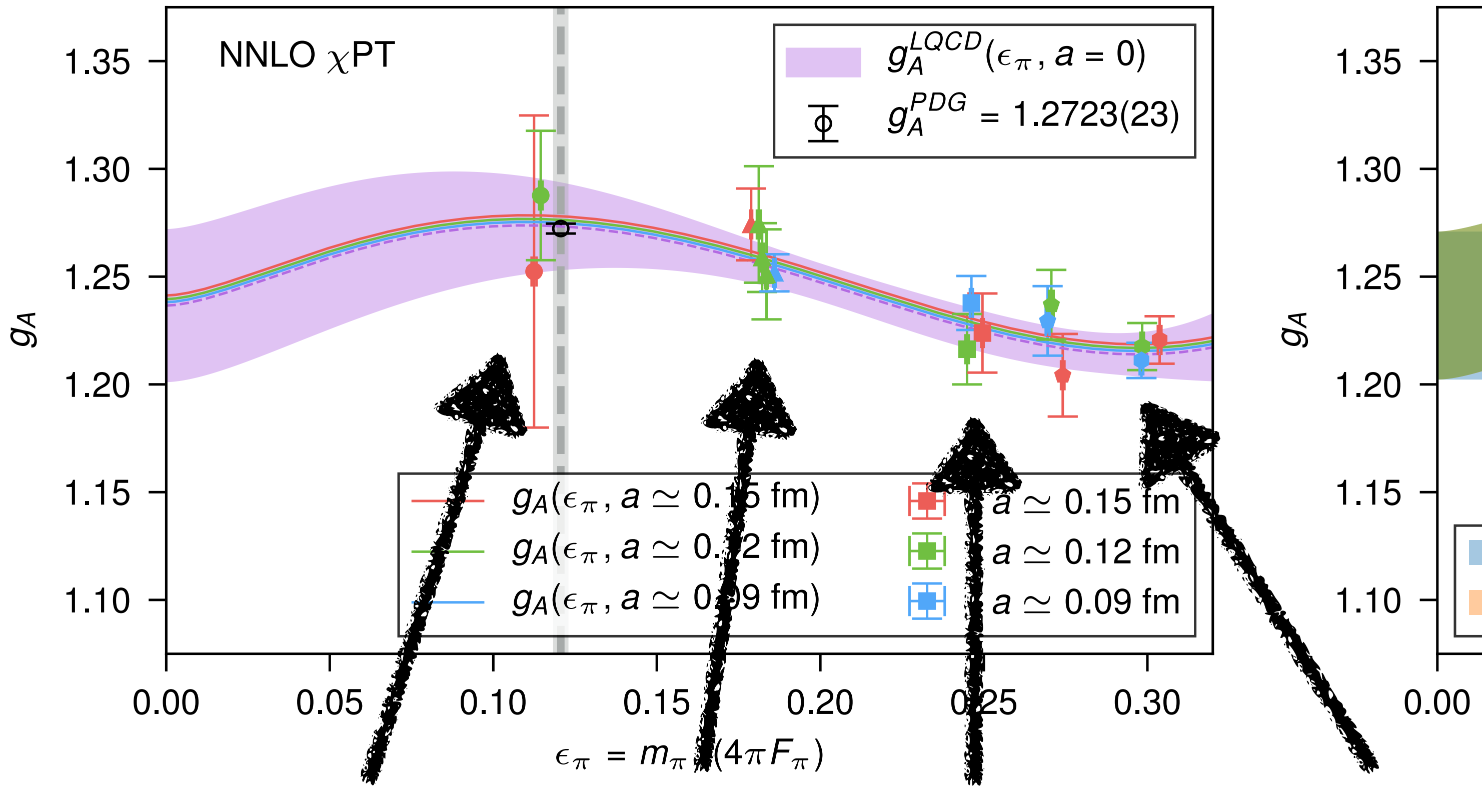
$$\epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

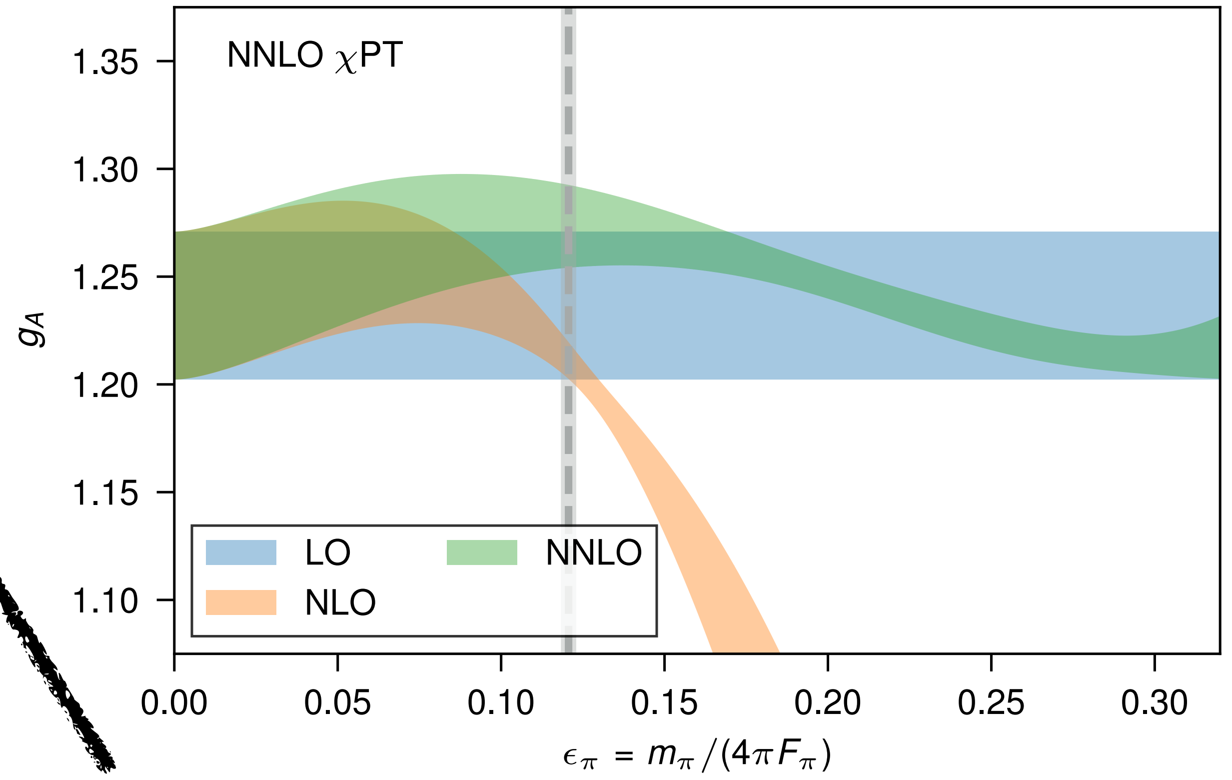
$$g_A = g_0 - \epsilon_\pi^2 (g_0 + 2g_0^3) \ln(\epsilon_\pi^2) + c_2 \epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3 + c_4 \epsilon_\pi^4$$

$$g_A = g_0 - \epsilon_\pi^2 (g_0 + 2g_0^3) \ln(\epsilon_\pi^2) + c_2 \epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3 + \epsilon_\pi^4 \Big[c_4 + \tilde{\gamma}_4 \ln(\epsilon_\pi^2) + \left(\frac{2}{3} g_0 + \frac{37}{12} g_0^3 + 4 g_0^5 \right) \ln^2(\epsilon_\pi^2) \Big]$$

Bernard and Meissner (CD06)
Phys.Lett.B639 [hep-lat/0605010]
F —> F_π

convergence of the chiral expansion…





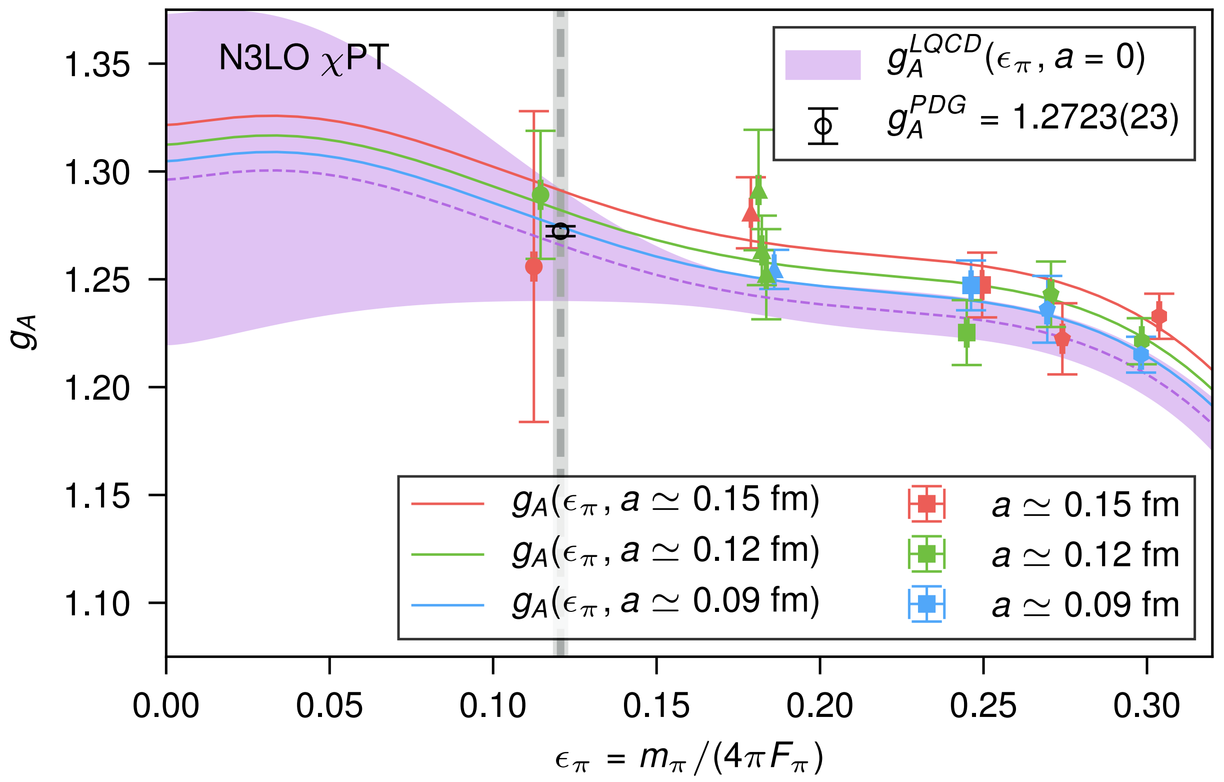
$$g_A = g_0 - \epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + c_2\epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3$$

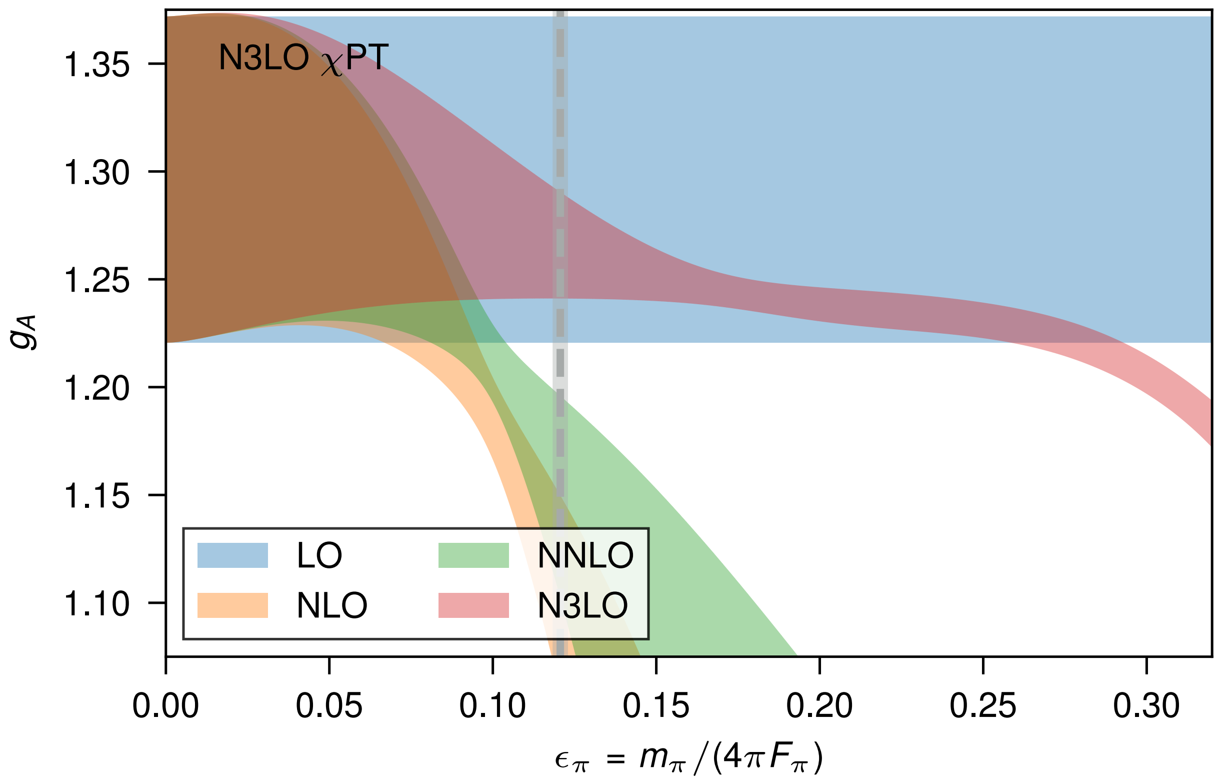
$$\epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

$m_\pi \sim 130$ MeV 220 310 400

can we trust extrapolation of quantities with chiraly-enhanced behavior?

if the single nucleon is not converging, would you trust chiral extrapolations of two or more nucleons?





$$g_A = g_0 - \epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + c_2\epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3 + \epsilon_\pi^4\left[c_4 + \tilde{\gamma}_4 \ln(\epsilon_\pi^2) + \left(\frac{2}{3}g_0 + \frac{37}{12}g_0^3 + 4g_0^5\right)\ln^2(\epsilon_\pi^2)\right]$$

Bernard and Meissner (CD06)
Phys.Lett.B639 [hep-lat/0605010]
F —> F_π

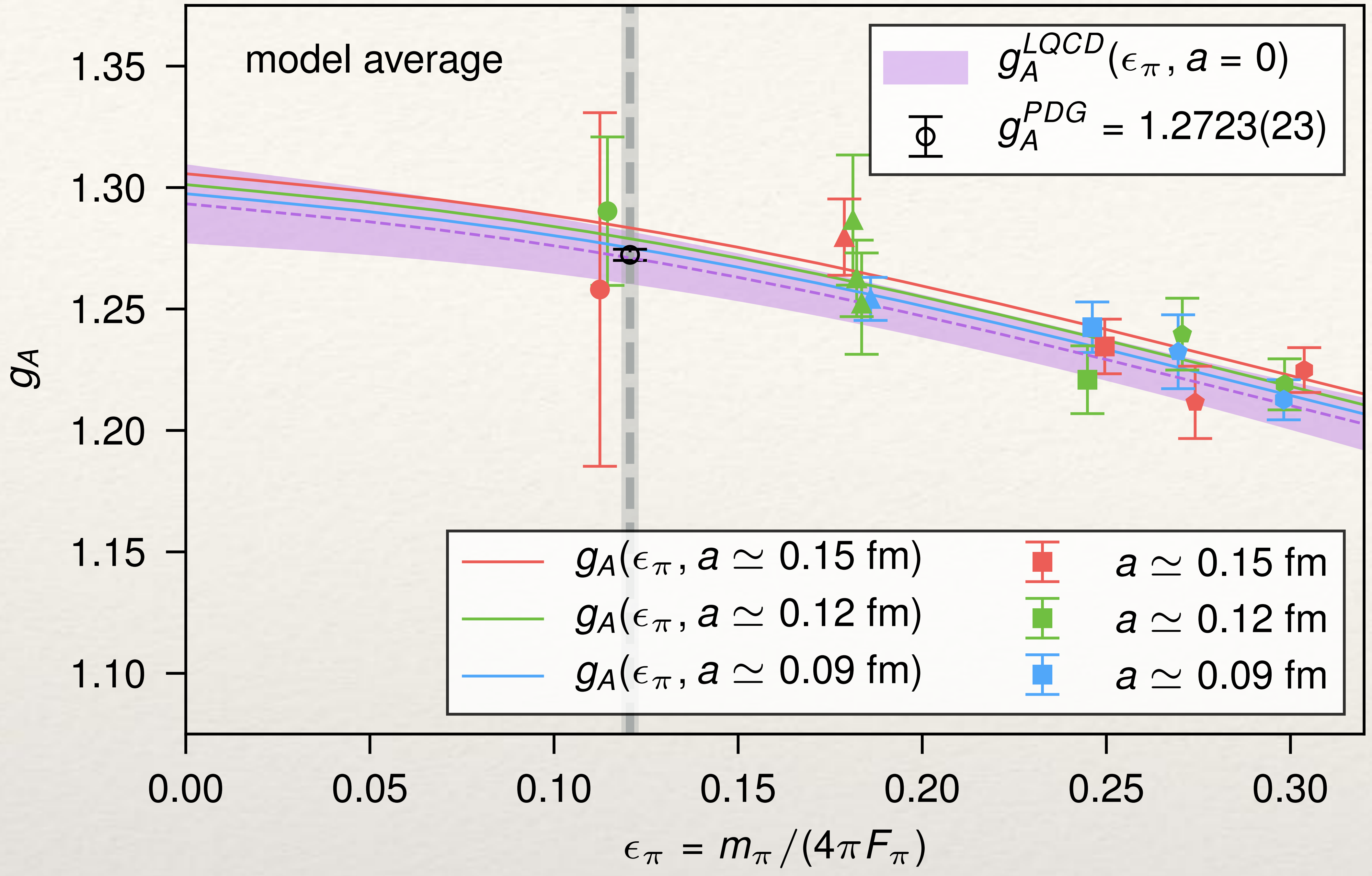
Assignment

- What is causing all the trouble for SU(2) baryon chiral perturbation theory?
  - Large Nc arguments show a cancellation between nucleon and delta loops for g_A, BUT, they add "coherently" for M_N
- What is the range of convergence of SU(2) baryon chiral perturbation theory?

Why is this an exciting time for LQCD and NP?

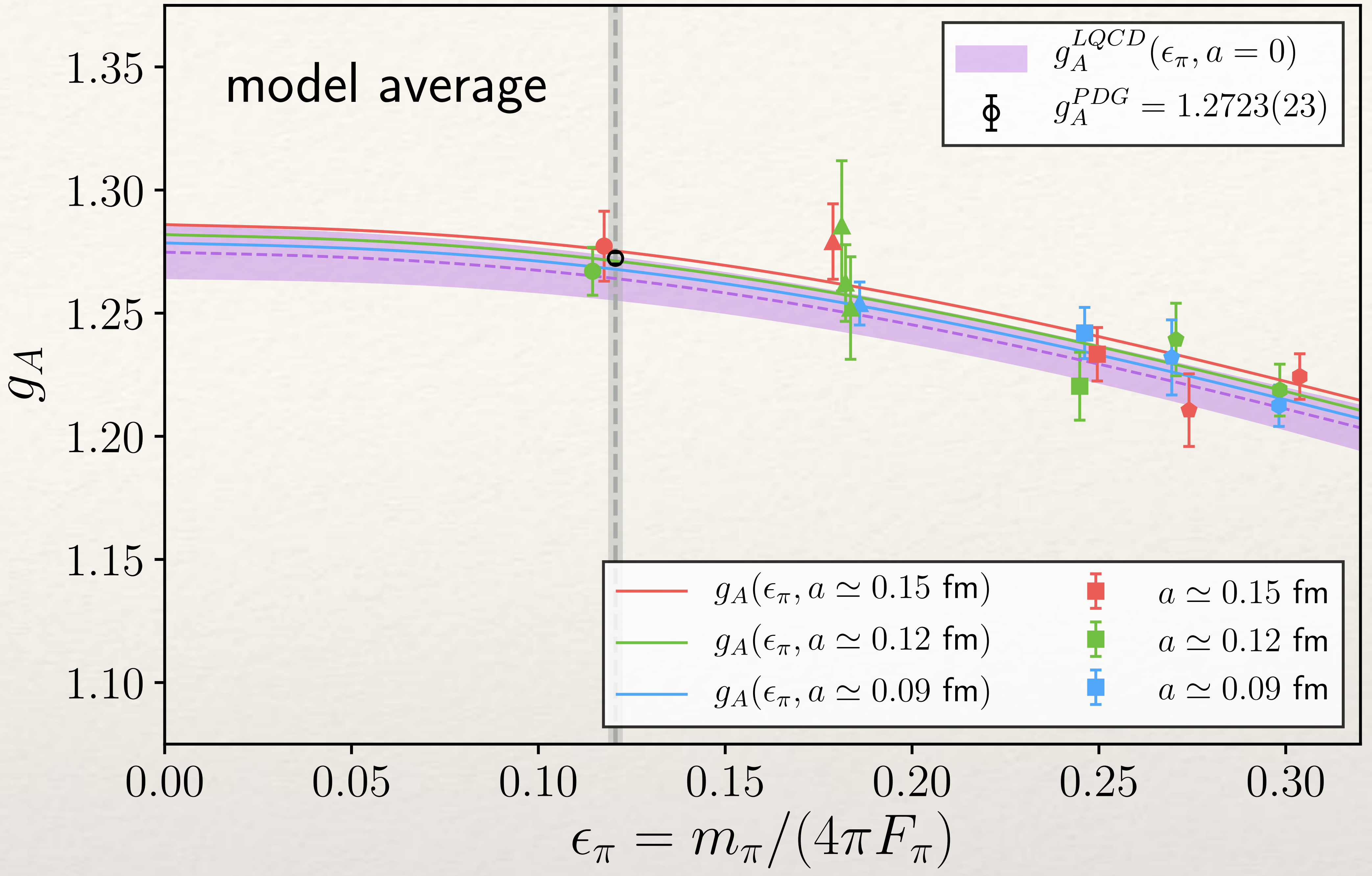
Chang et al. [arXiv:1805.12130]

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



Sierra Early Science

PRELIMINARY



California Lattice Collaboration

- 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%

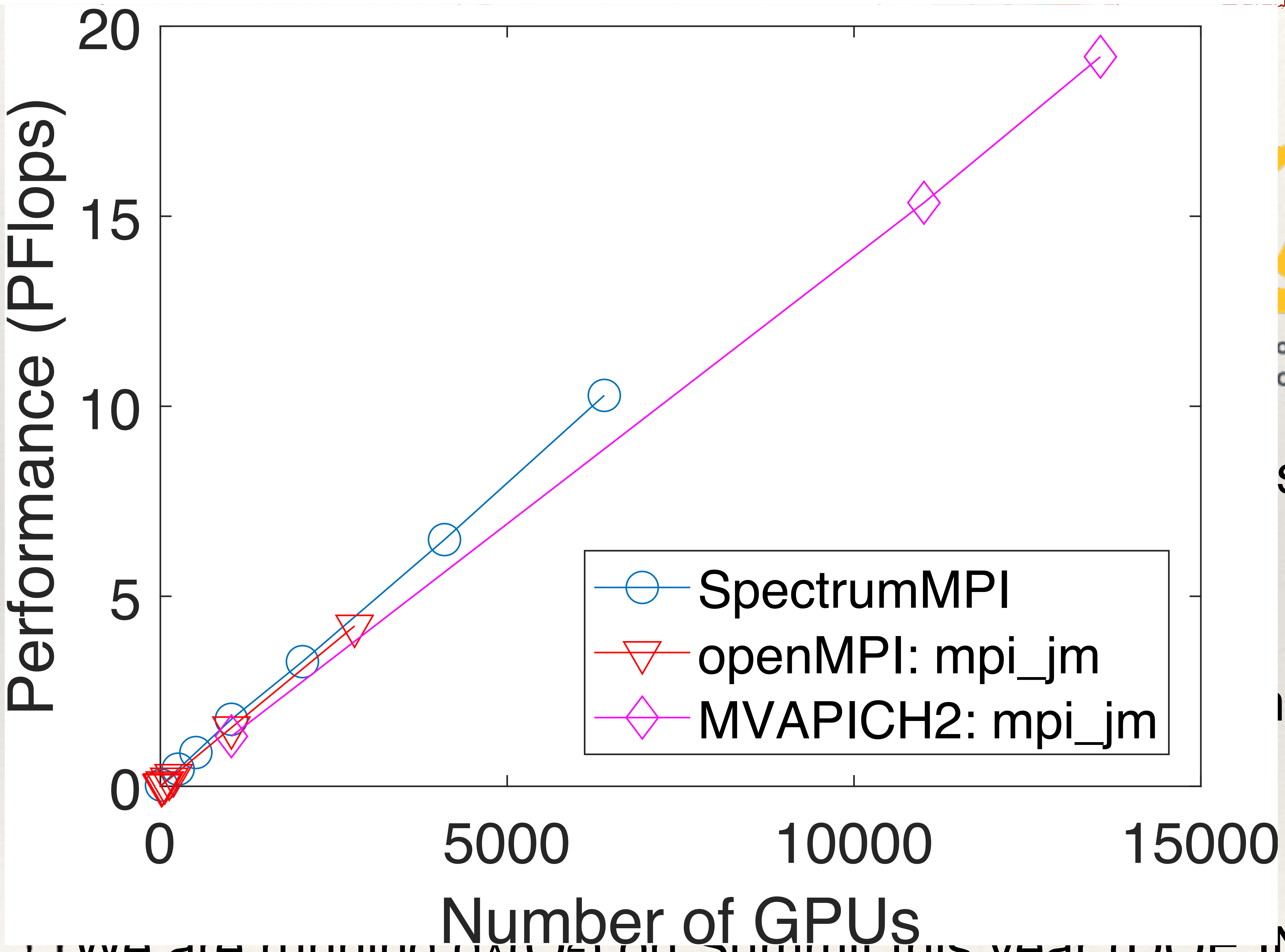
$g_A = 1.2711(125) \rightarrow 1.2641(93)$ [0.74%]

Chang et al. [arXiv:1805.12130]

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

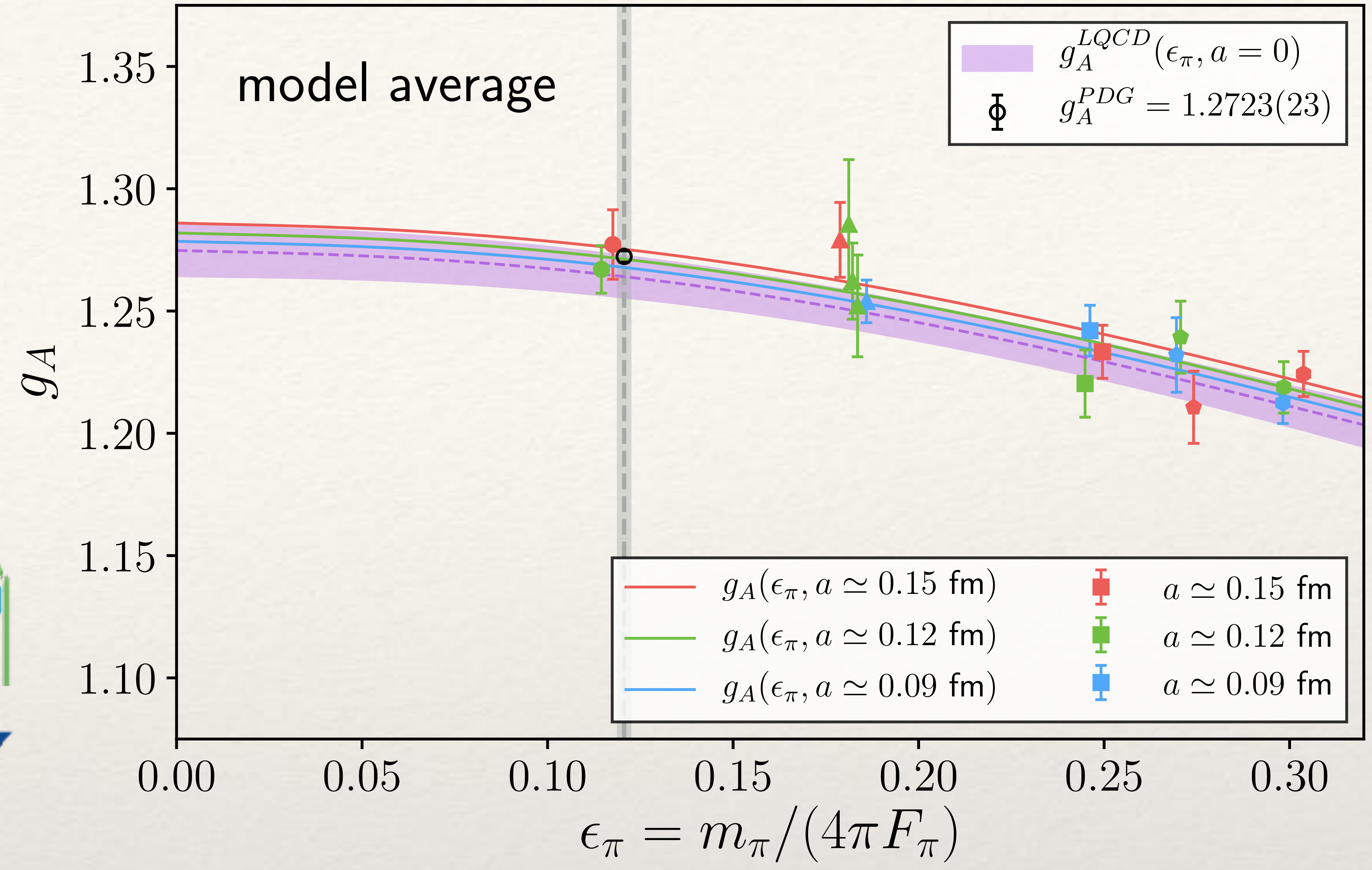
Simulating the *weak* death of the neutron in a femtoscale universe with near-Exascale computing

Berkowitz, Clark, Gambhir, McElvain, Nicholson, Rinaldi, Vranas, Walker-Loud, Chang, Joó, Kurth, Orginos



Sierra Early Science

PRELIMINARY



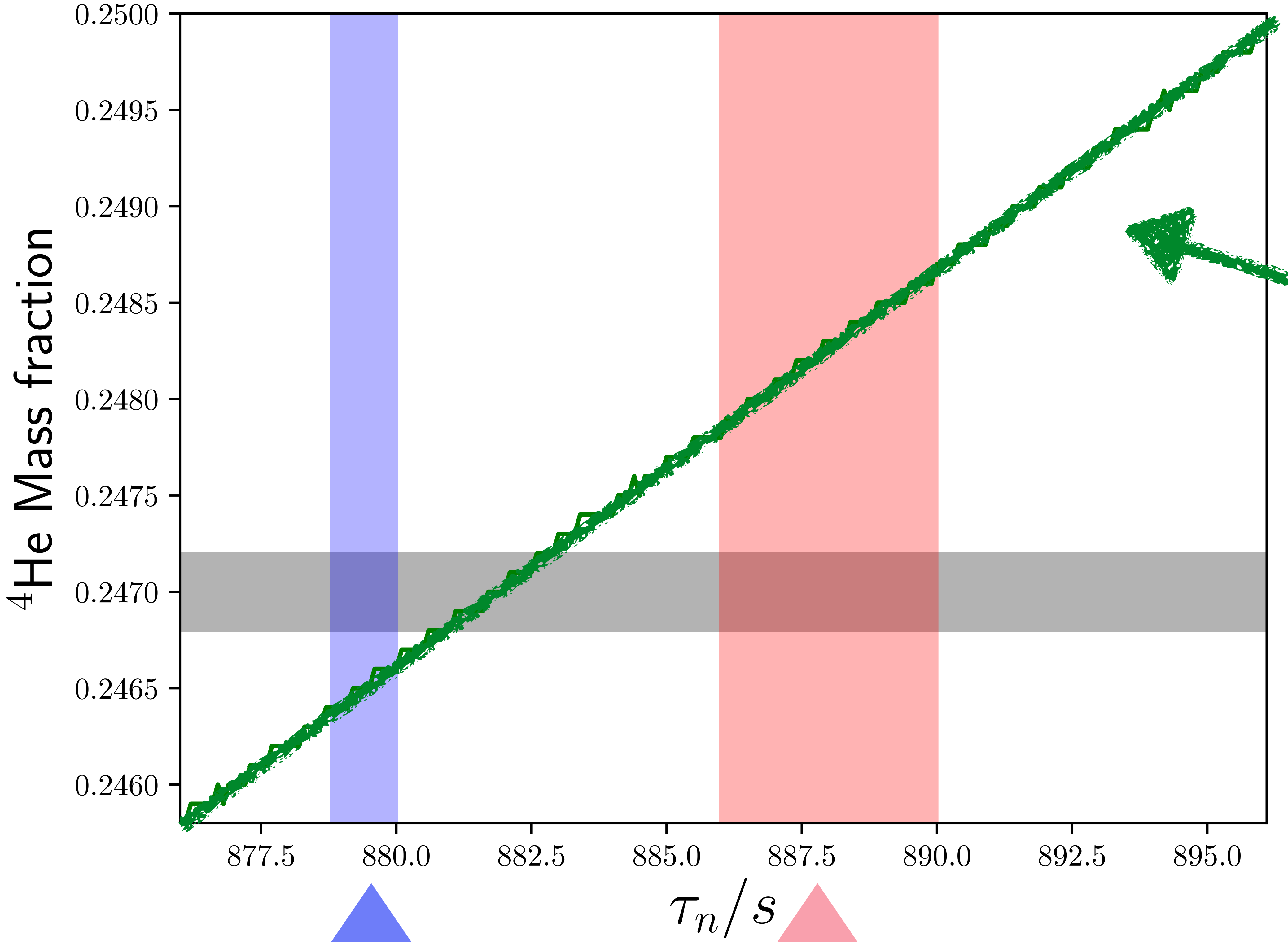
s much as all other ensembles combined

ble (old a15m130 is $32^3 \times 48$)

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

- We are running $g_A(Q^2)$ on Summit this year (DOE INCITE)
  - We anticipate improving g_A to ~0.5%

Why is understanding the neutron lifetime interesting?

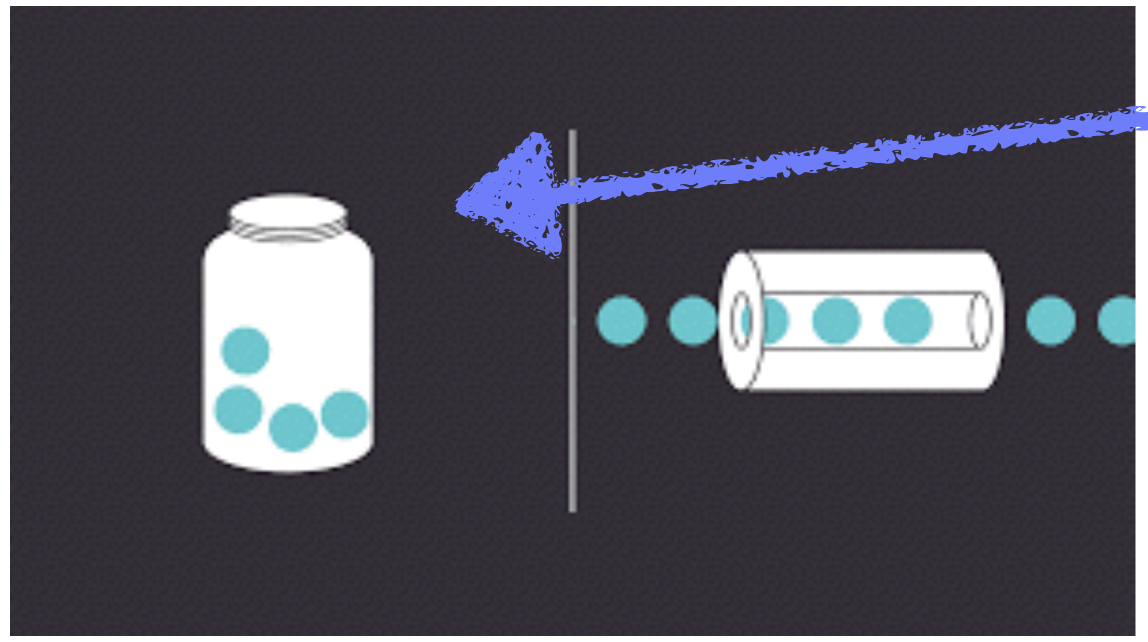


$$\tau_n = \frac{(5172.0 \pm 1.1)\ \text{seconds}}{1 + 3g_A^2}$$

Czarnecki, Marciano, Sirlin

Predicted primordial ^{4}He mass fraction of the universe as a function of the neutron lifetime

Observed primordial ^{4}He mass fraction of the universe

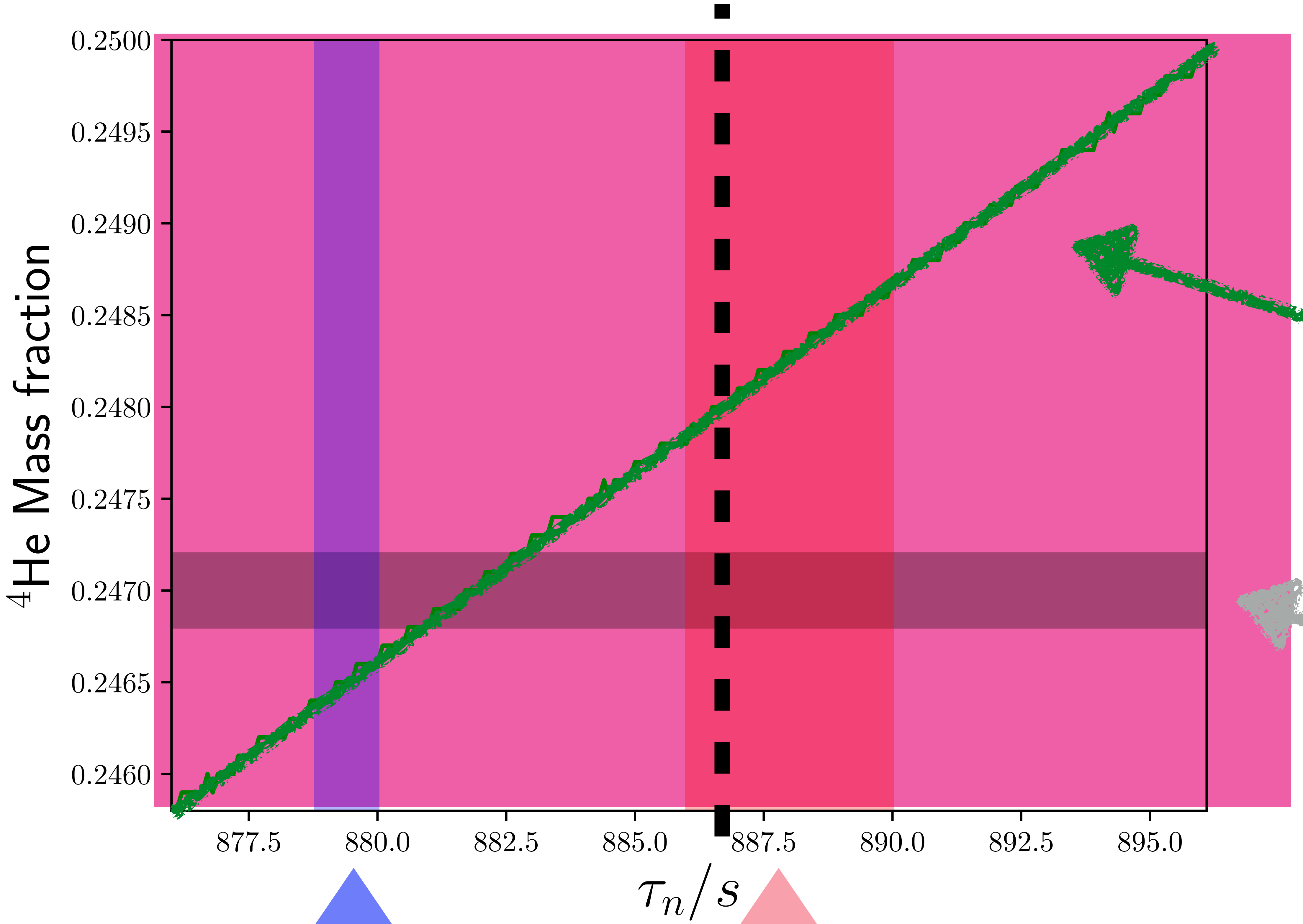


Two different methods of measuring the neutron lifetime disagree at the 99% level

bottle and beam

Is one of the experiments wrong? Or is there new physics hiding here?

Why is understanding the neutron lifetime interesting?



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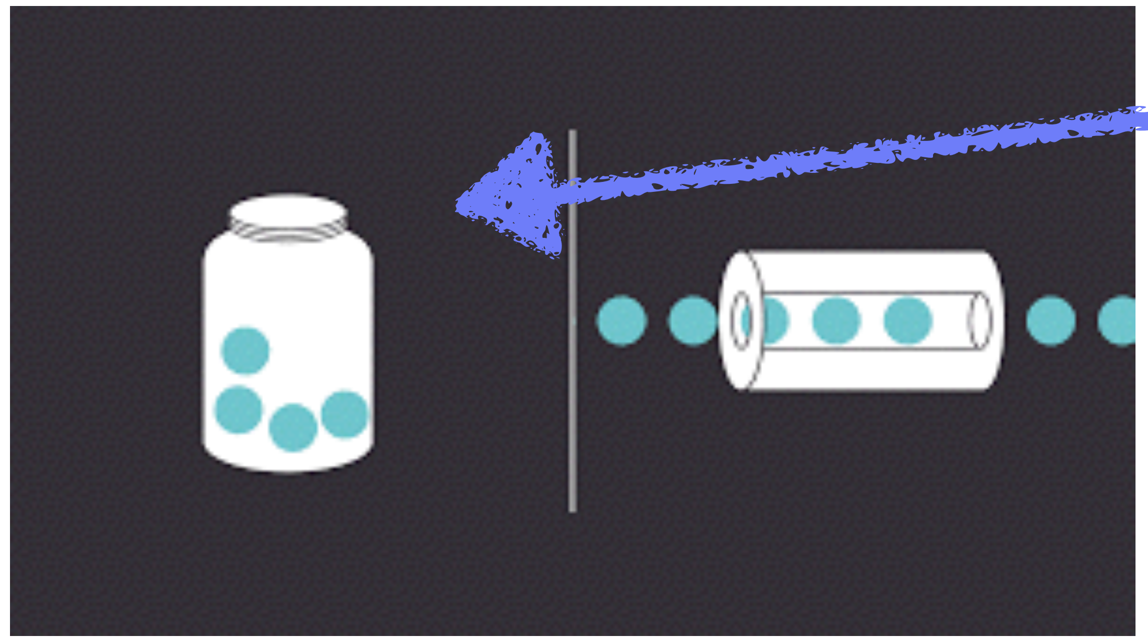

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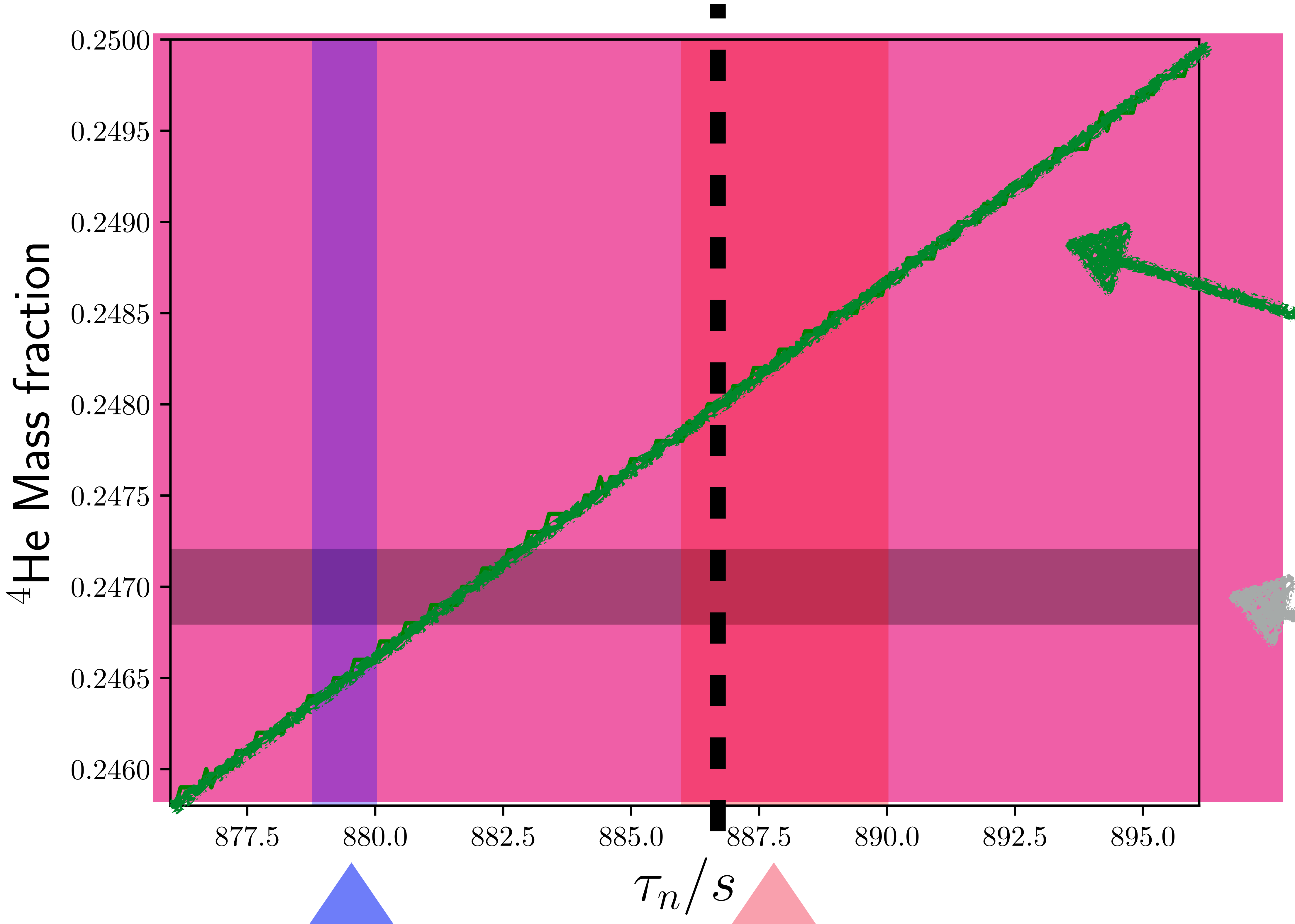

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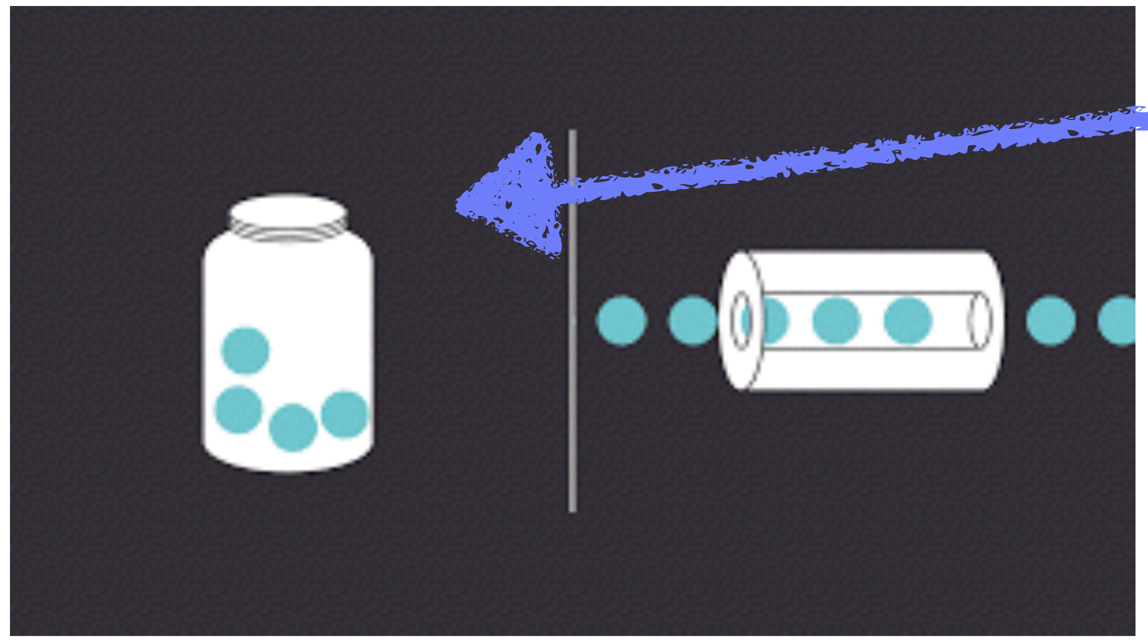
Can we reduce the uncertainty to a discriminating level?



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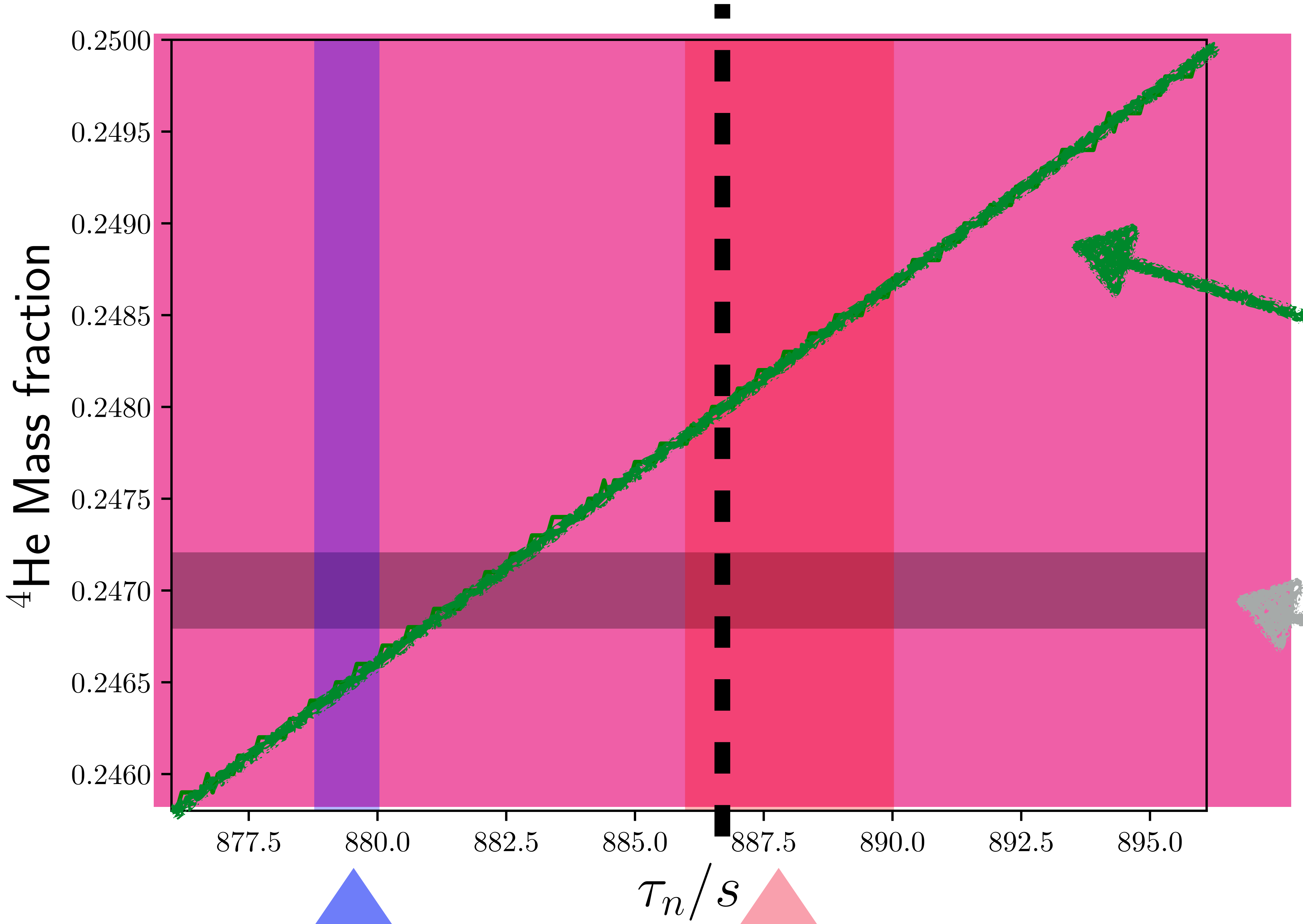

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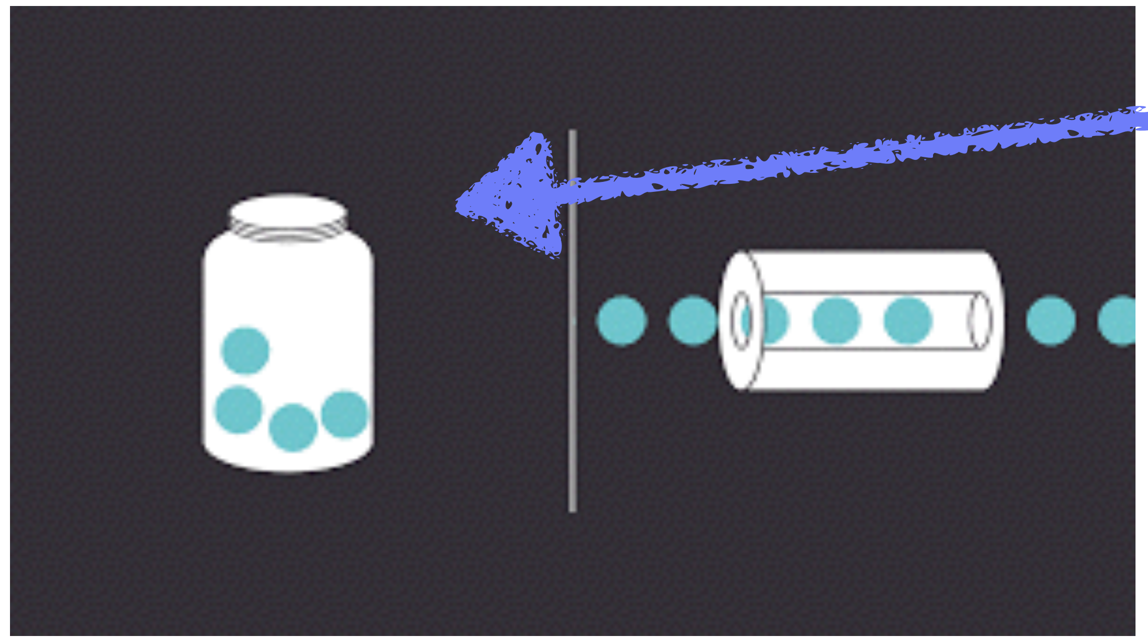
Can we reduce the uncertainty to a discriminating level?

Yes!

With summit!

Two different methods of measuring the neutron lifetime disagree at the 99% level

bottle and beam



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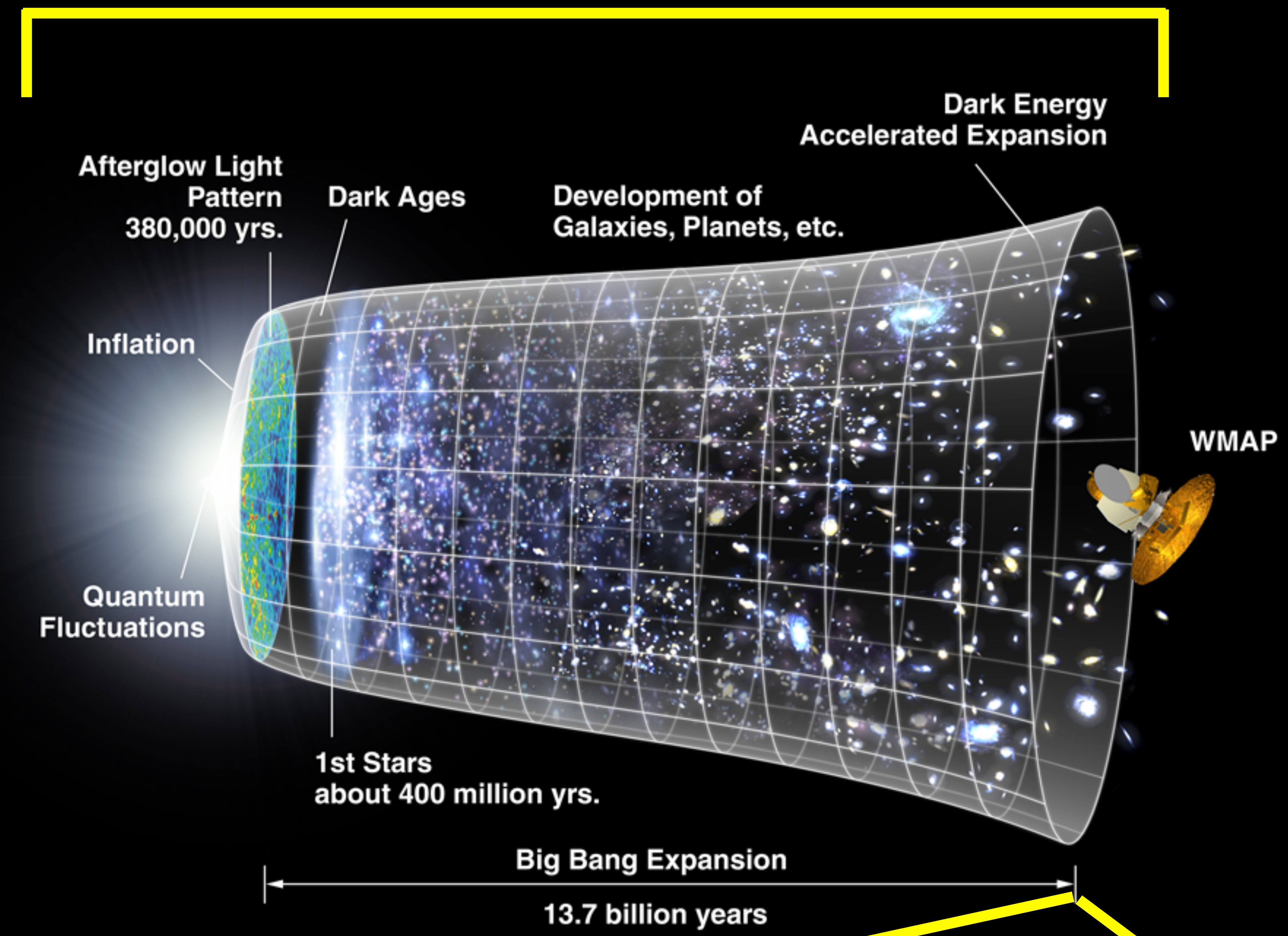
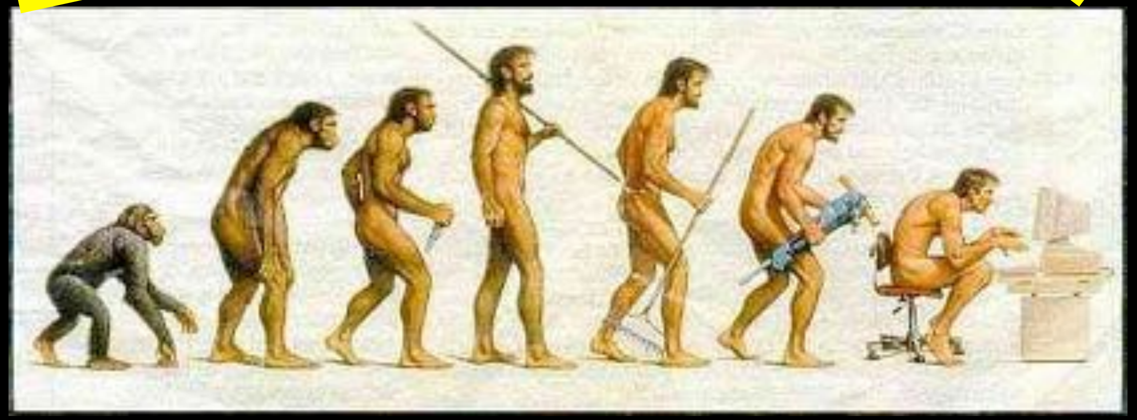
Standard Model of Particle Physics





- This is a very exciting time for basic science research with high-performance-computing
- The application of LQCD to NP is very challenging
  - Progress is very rewarding
  - Necessary for a coordinated effort with Effective Theories of NP - great opportunity to interface and learn other computational methods
- Summit is **disruptively** faster than Titan
  - we are still learning to expand our vision of what can be accomplished
  - Very exciting time to get involved: applications to NP which connect to experiment are just beginning