The H-dibaryon from Lattice QCD

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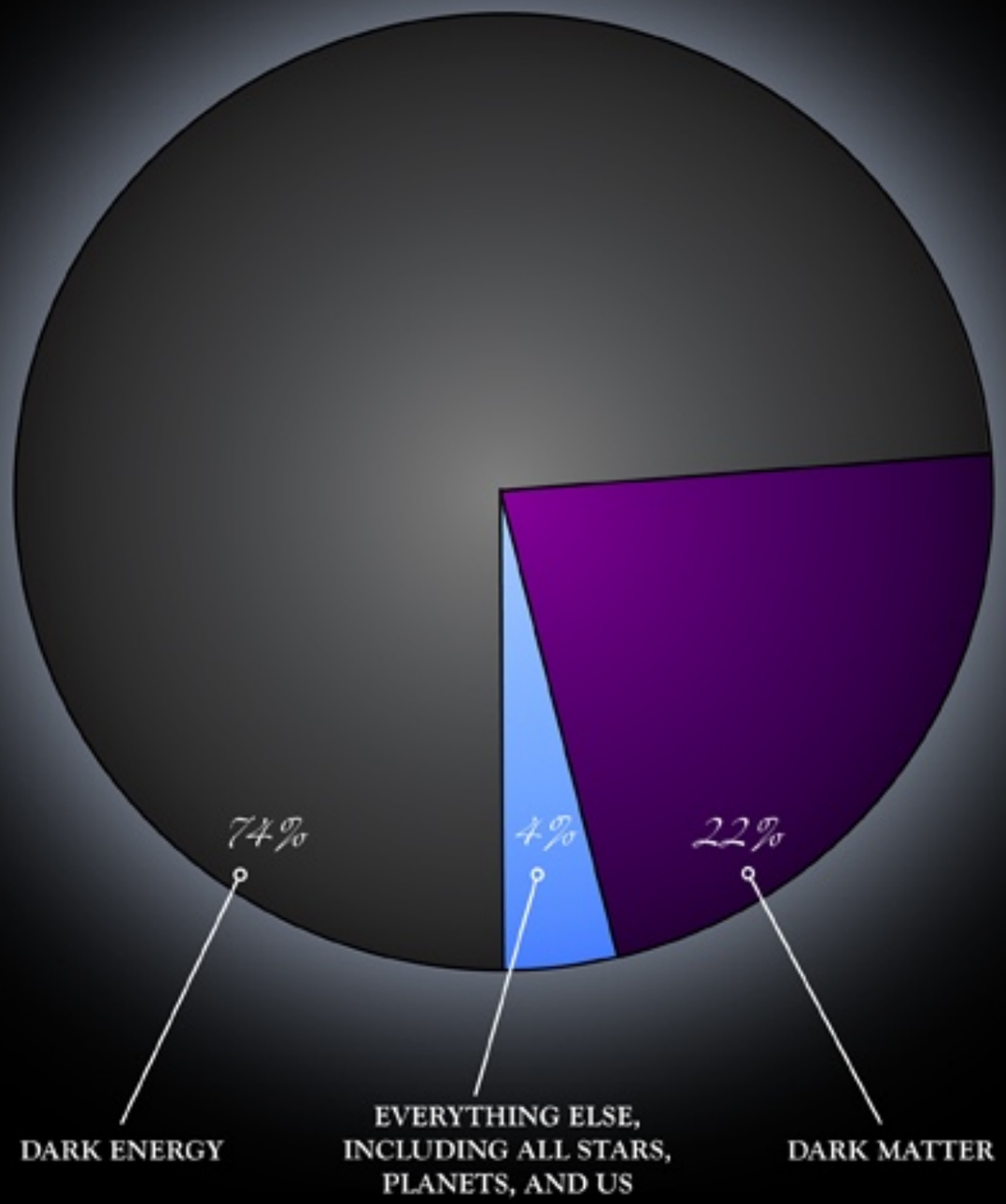
NPLQCD

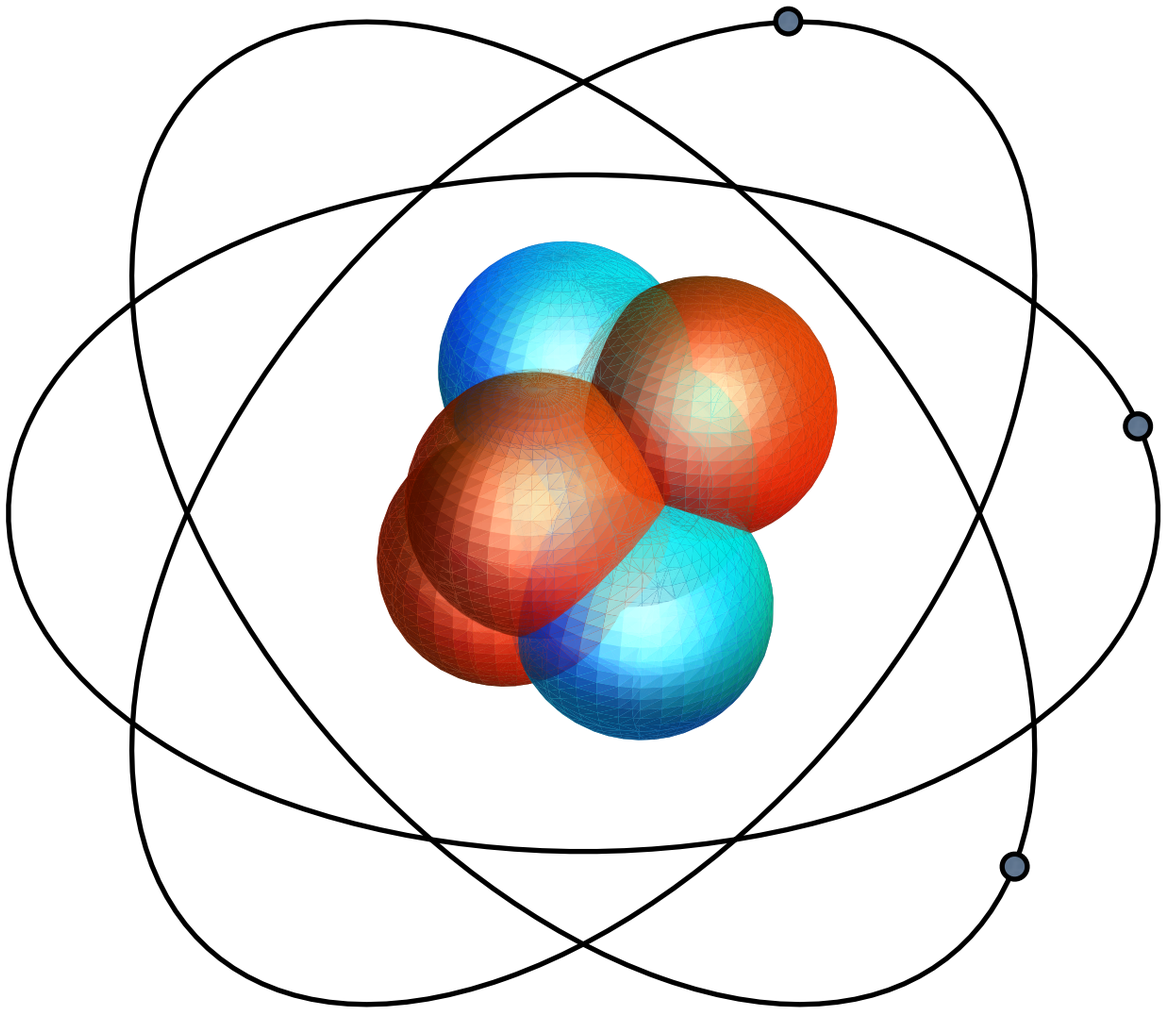
BNL 3/2/2012

Outline

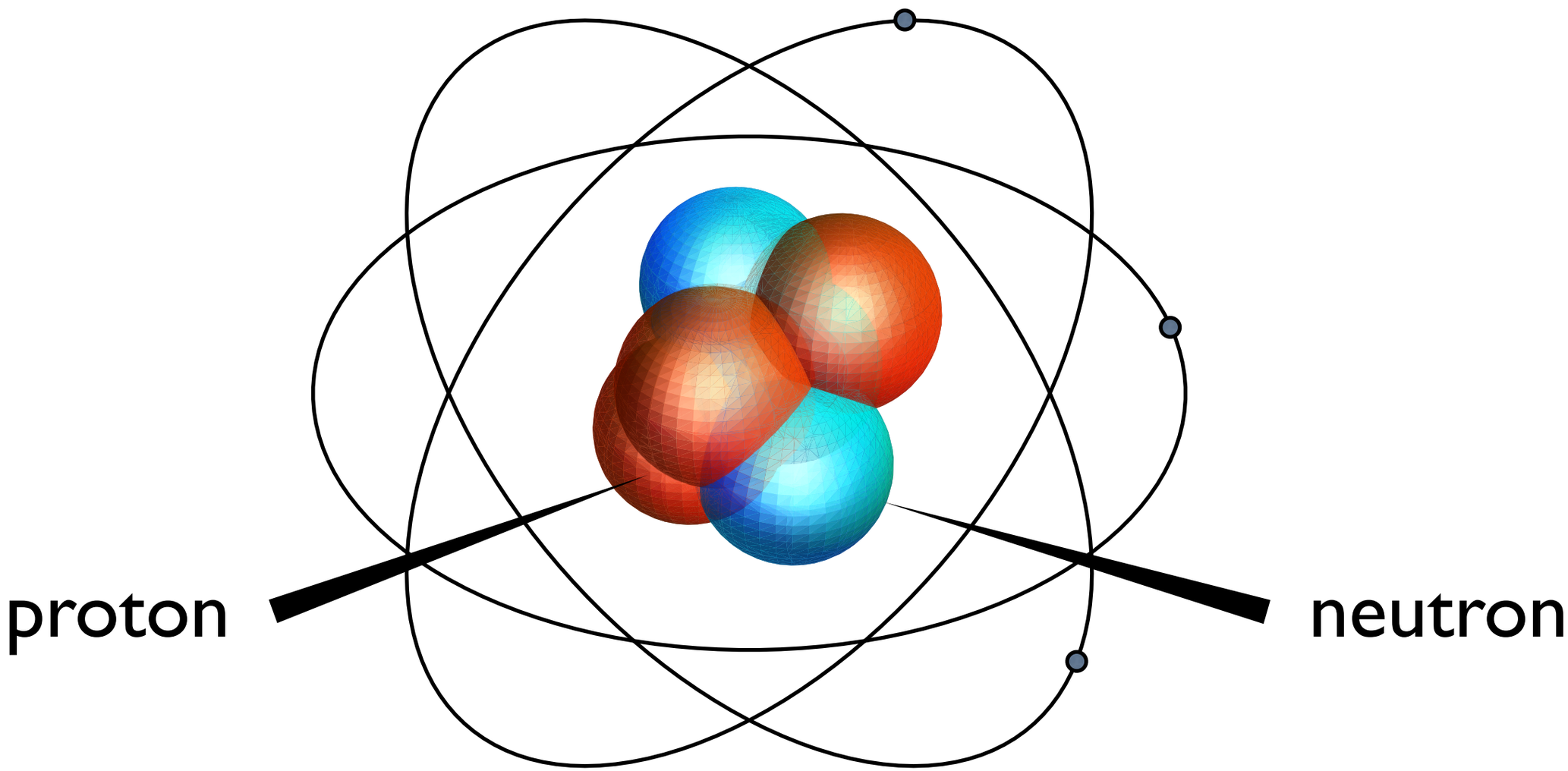
- QCD, Lattice QCD and Nuclear physics
- Road-map to the exa-scale
- The deuteron and helium
- Hypernuclear physics
- Conclusion


74%
4%
22%
DARK ENERGY
EVERYTHING ELSE, INCLUDING ALL STARS, PLANETS, AND US
DARK MATTER

4% is ATOMS!



4% is ATOMS!

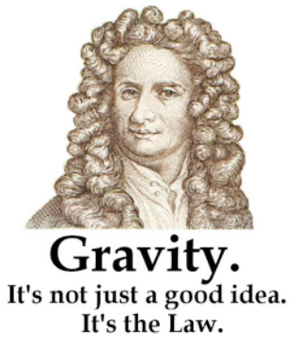


Lithium-6

The Nature of the Visible Matter in the Universe

Dictated by the Standard Model:

gravity



electromagnetism:QED

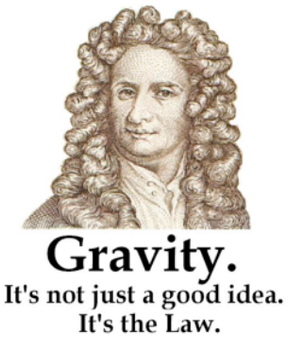
weak interaction

strong interaction: QCD

The Nature of the Visible Matter in the Universe

Dictated by the Standard Model:

easy! { gravity

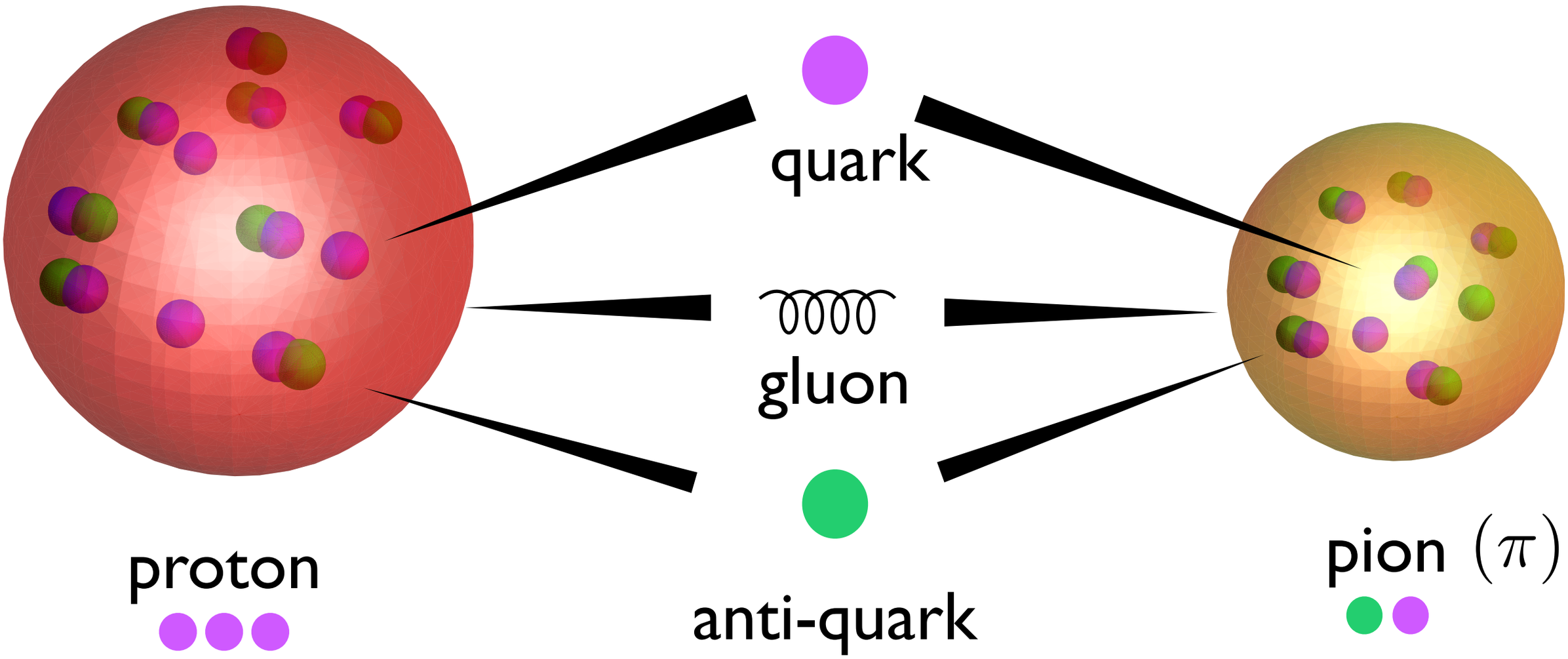


electromagnetism:QED

weak interaction

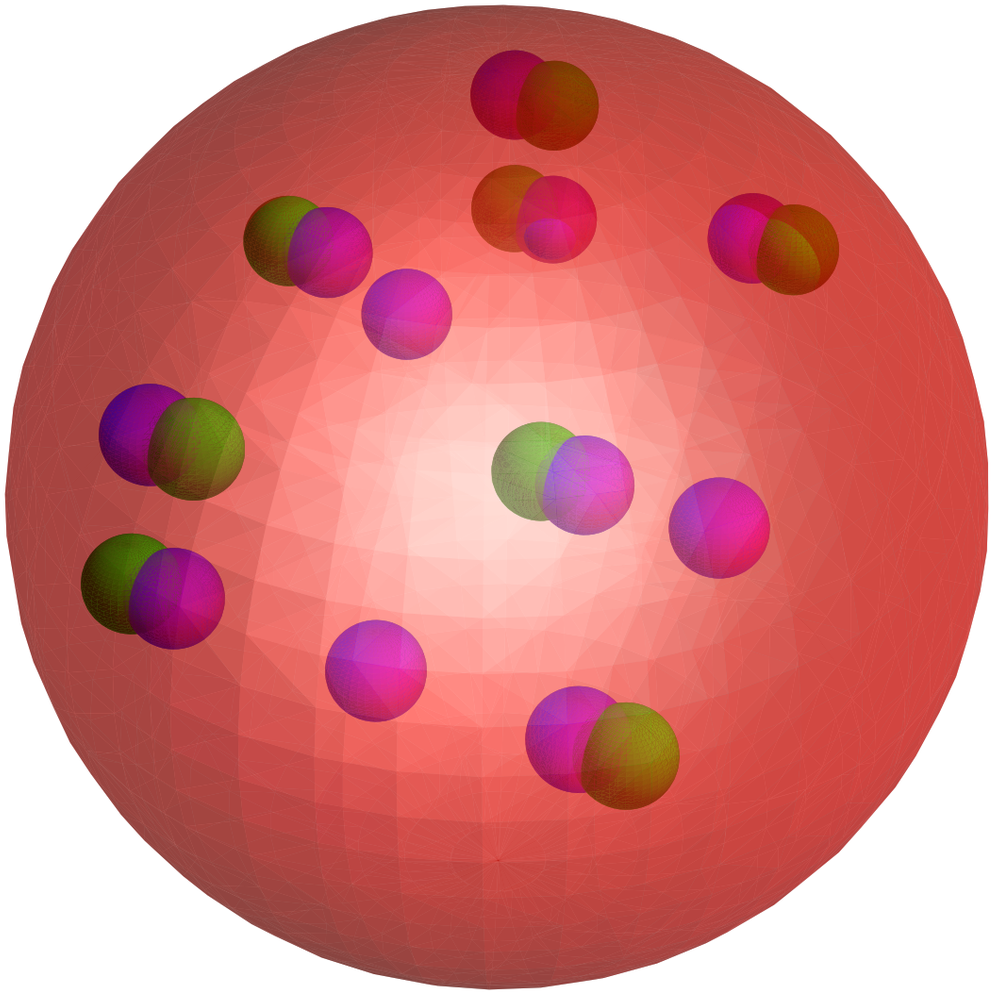
hard! { strong interaction: QCD

Quantum Chromodynamics



QCD = rules for making hadrons from quarks and gluons

Complicated strong coupling problem!



proton

Mass Budget

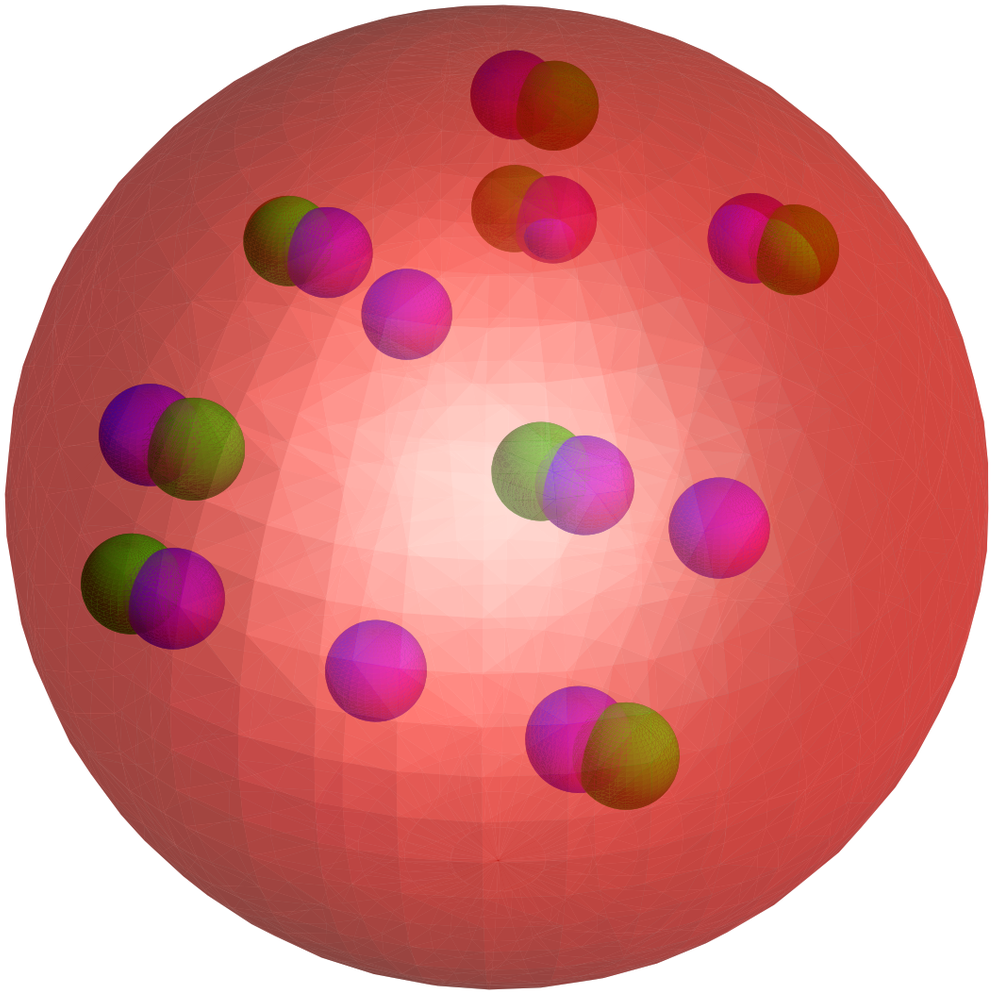
$$\text{gluon mass} = 0$$

$$\text{up quark mass} \sim 3 \text{ MeV}$$

$$\text{down quark mass} \sim 5 \text{ MeV}$$

$$\text{proton mass} \sim 940 \text{ MeV}$$

Complicated strong coupling problem!



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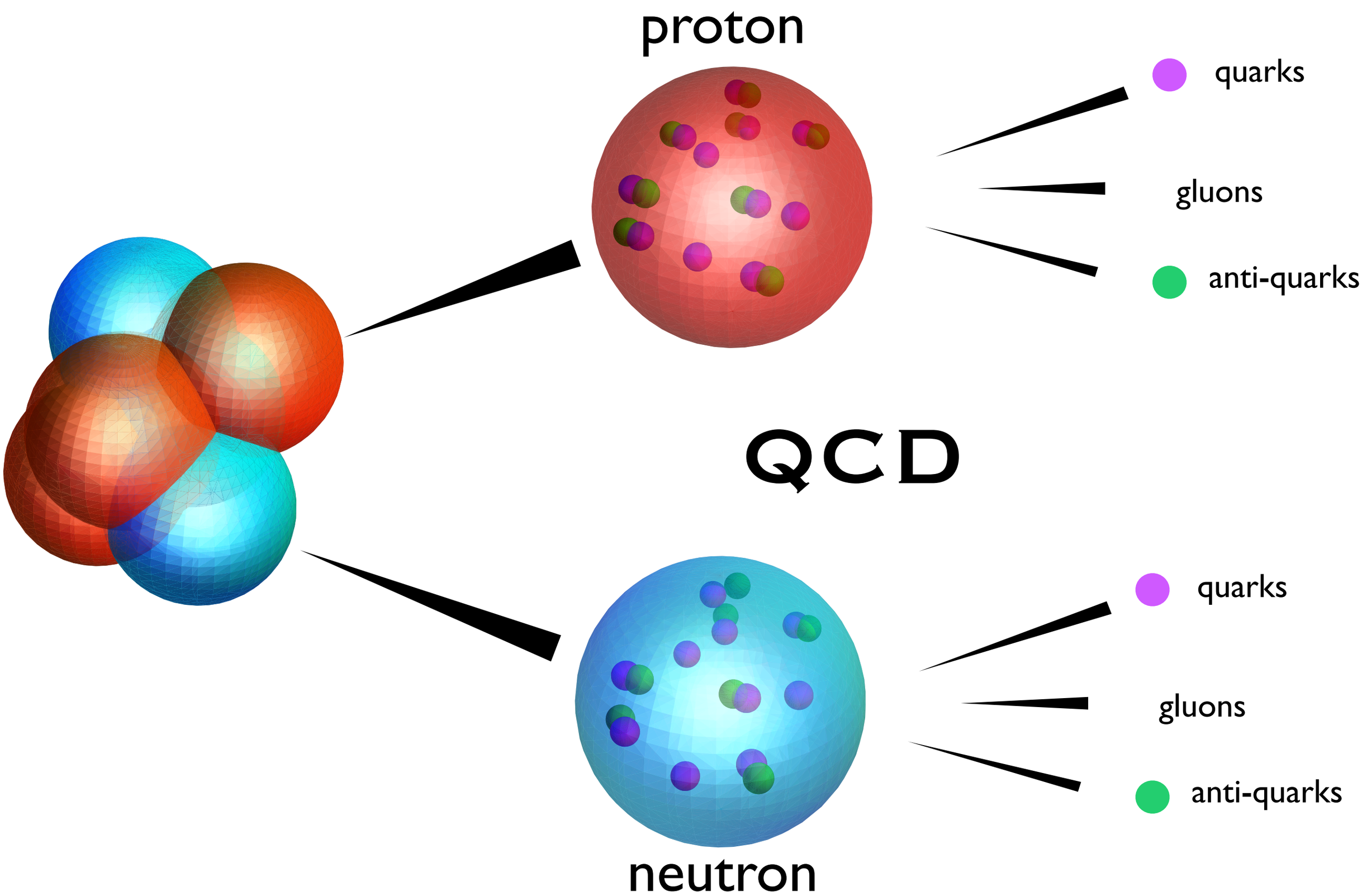
$$\text{down quark mass} \sim 5 \text{ MeV}$$

$$\text{proton mass} \sim 940 \text{ MeV}$$

~ 4% is QCD interactions!

Nuclear Physics: two layers of complexity!!

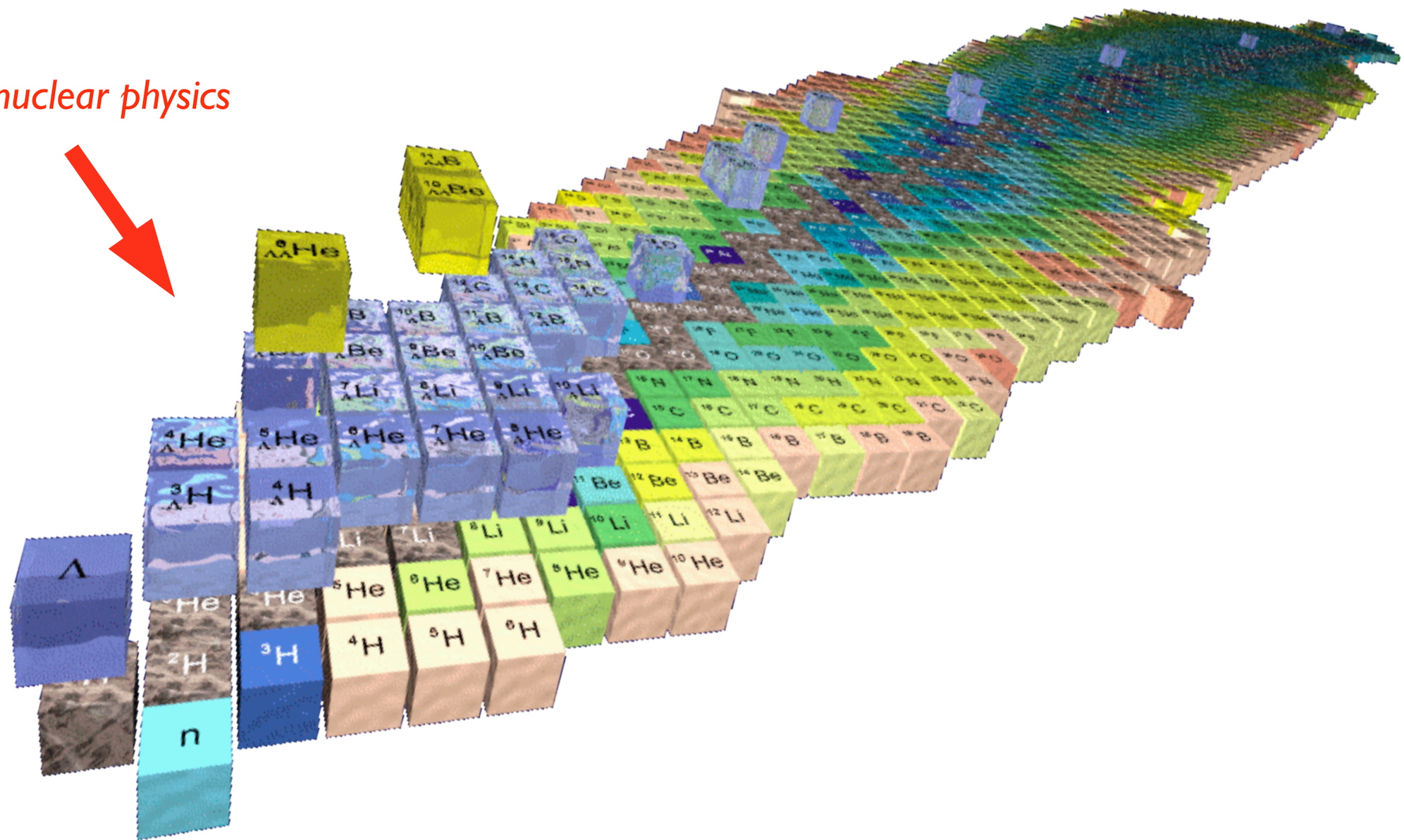


Why do it?

- Nuclear physics with quantifiable uncertainties!
- Dependence on fundamental parameters of nature:

$$\alpha_s \qquad \alpha_e \qquad m_u \qquad m_d \qquad m_s$$

Hypernuclear physics


Λ
n
^{2}H
^{3}H
^{4}H
^{5}H
^{6}H
$^3_\Lambda$H
$^4_\Lambda$H
$^4_\Lambda$He
$^5_\Lambda$He
$^6_\Lambda$He
$^7_\Lambda$He
$^8_\Lambda$He
$^7_\Lambda$Li
$^8_\Lambda$Li
$^9_\Lambda$Li
$^{10}_\Lambda$Li
$^9_\Lambda$Be
$^{10}_\Lambda$Be
$^{10}_\Lambda$B
$^{11}_\Lambda$B
$^{12}_\Lambda$B
$^{12}_\Lambda$C
$^{13}_\Lambda$C
$^{14}_\Lambda$C
$^{14}_\Lambda$N
$^{15}_\Lambda$N
$^{16}_\Lambda$O
$^{17}_\Lambda$O
$^{18}_\Lambda$O
$^{12}_\Lambda$B
$^{10}_\Lambda$Be
$^6_{\Lambda\Lambda}$He
^{5}He
^{6}He
^{7}He
^{8}He
^{9}He
^{10}He
^{7}Li
^{8}Li
^{9}Li
^{10}Li
^{11}Li
^{12}Li
^{11}Be
^{12}Be
^{13}Be
^{14}Be
^{13}B
^{14}B
^{15}B
^{16}B
^{17}B
^{18}B
^{19}B
^{15}C
^{16}C
^{17}C
^{18}C
^{19}C
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^{16}N
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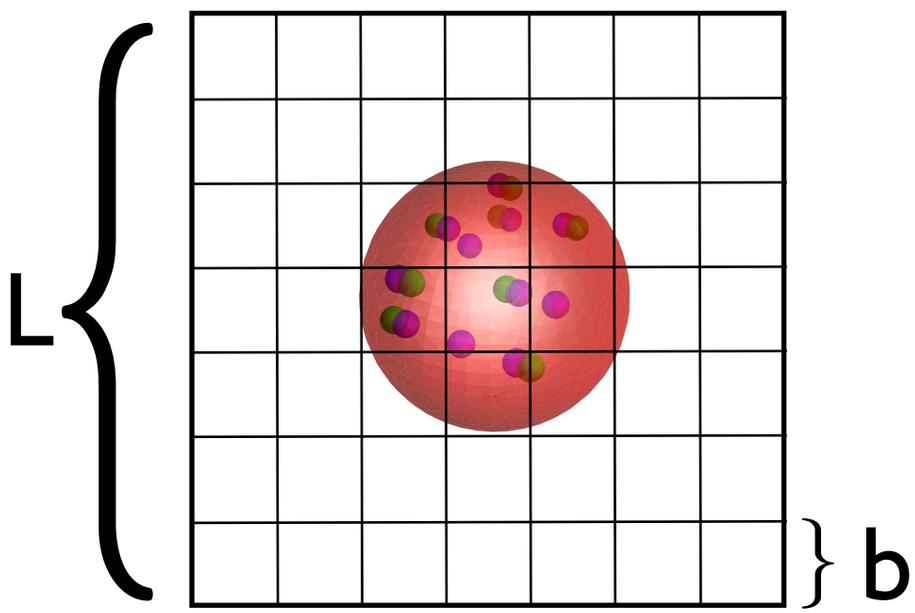
^{36}N
^{37}N
^{38}N
^{39}N
^{40}N
^{41}N
^{42}N
^{43}N
^{44}N
^{45}N
^{46}N
^{47}N
^{48}N
^{49}N
^{50}N
^{51}N
^{52}N
^{53}N
^{54}N
^{55}N

Lattice QCD = QCD on a grid or lattice



volume: $M_\pi L \gg 1$

lattice spacing: $b \ll M_N^{-1}$

Can use Effective Field Theory to extrapolate in L and b!

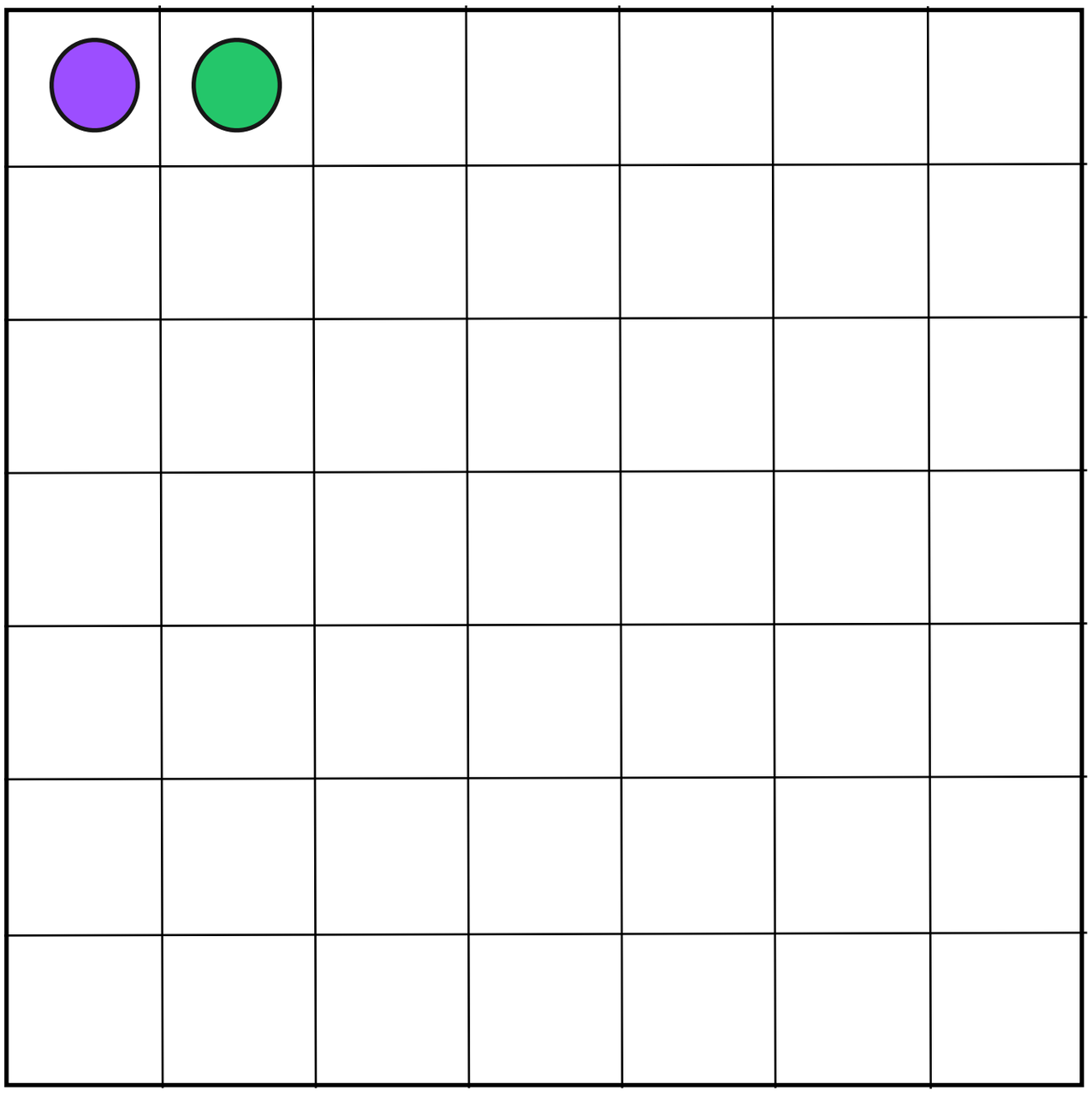
(systematic uncertainties fully controlled)

Why is nuclear physics hard?

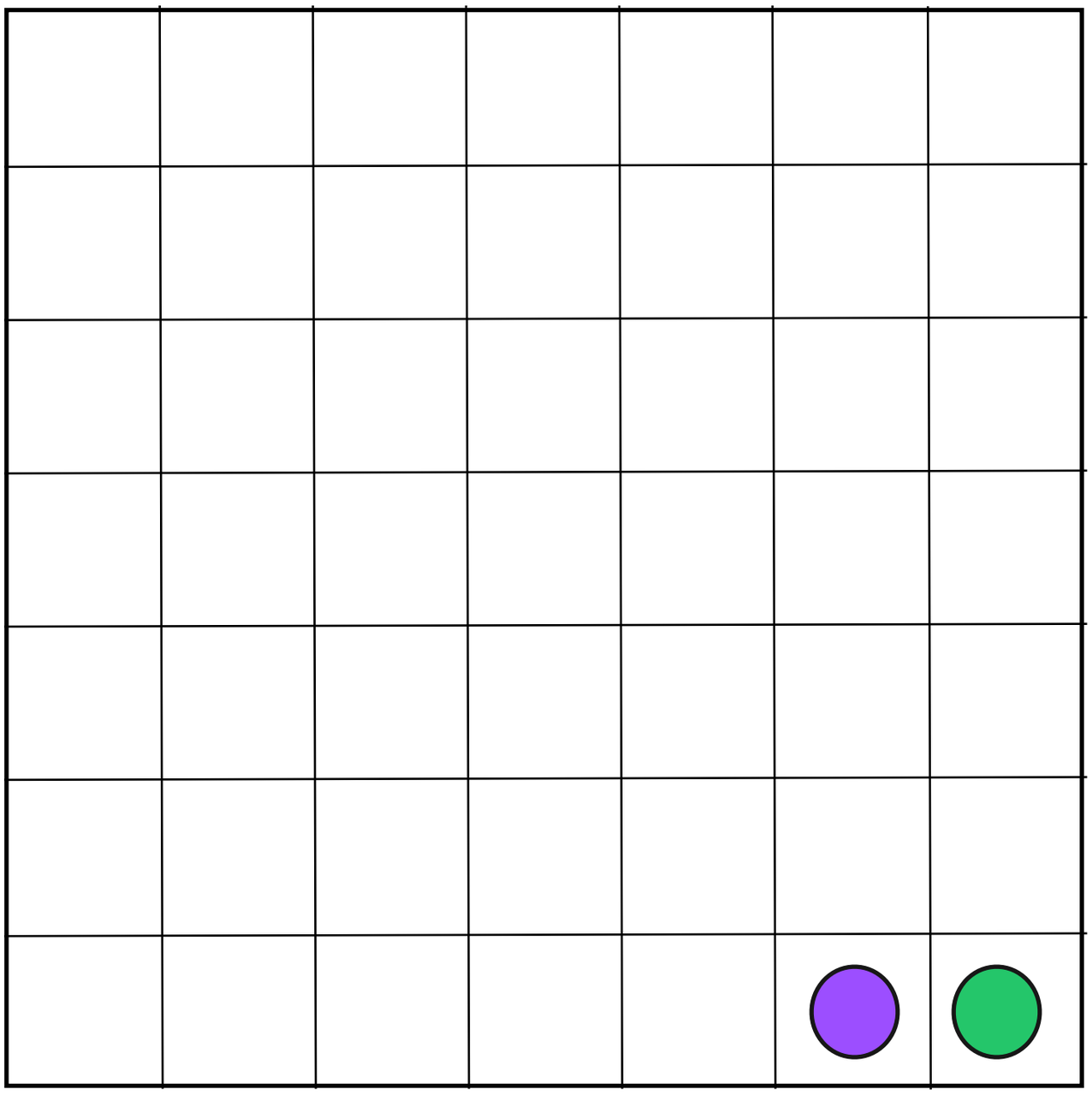
Why is nuclear physics hard?

- Signal/noise and statistics
- Excited level resolution
- Number of contractions

SIGNAL

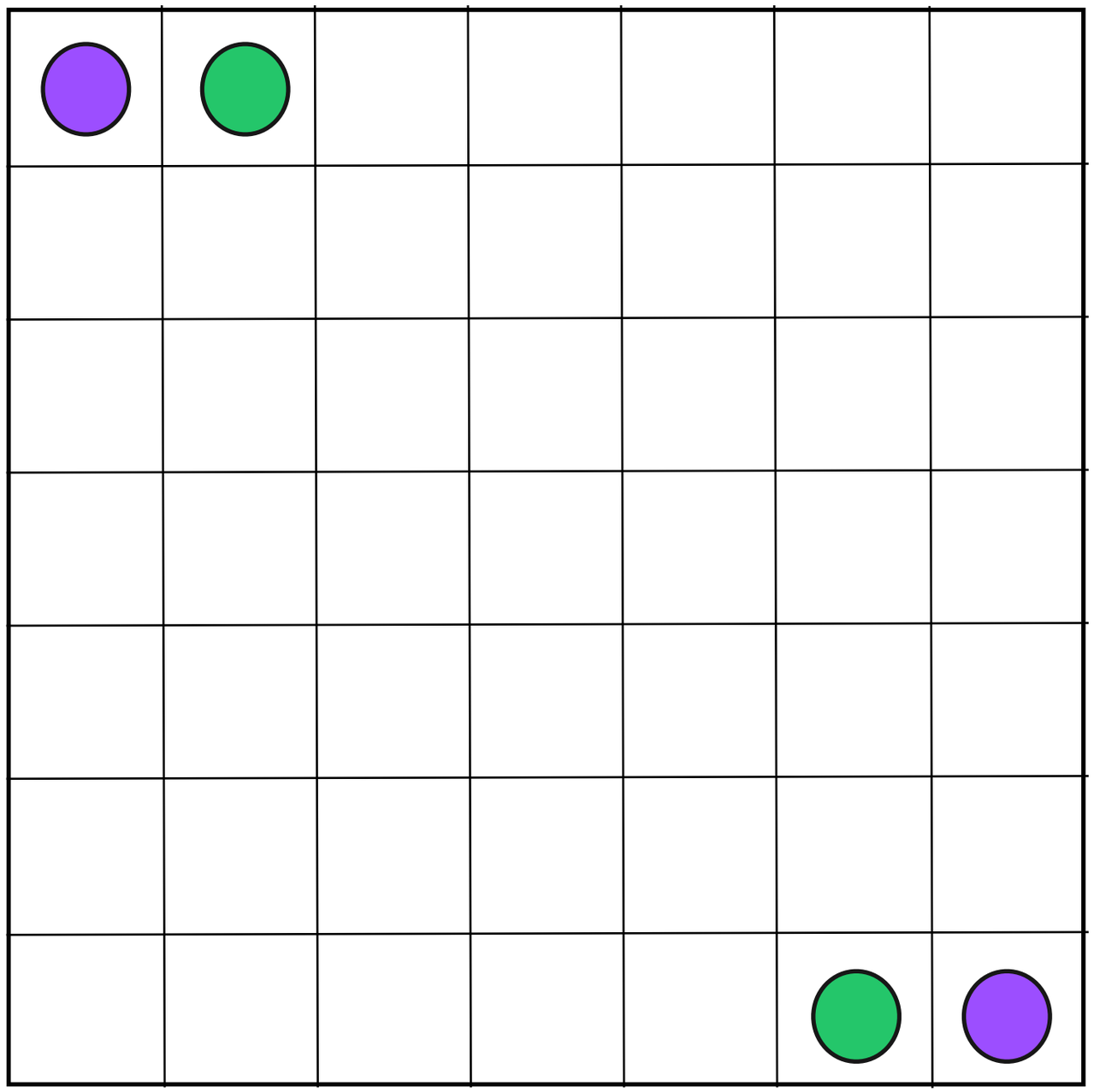


SIGNAL

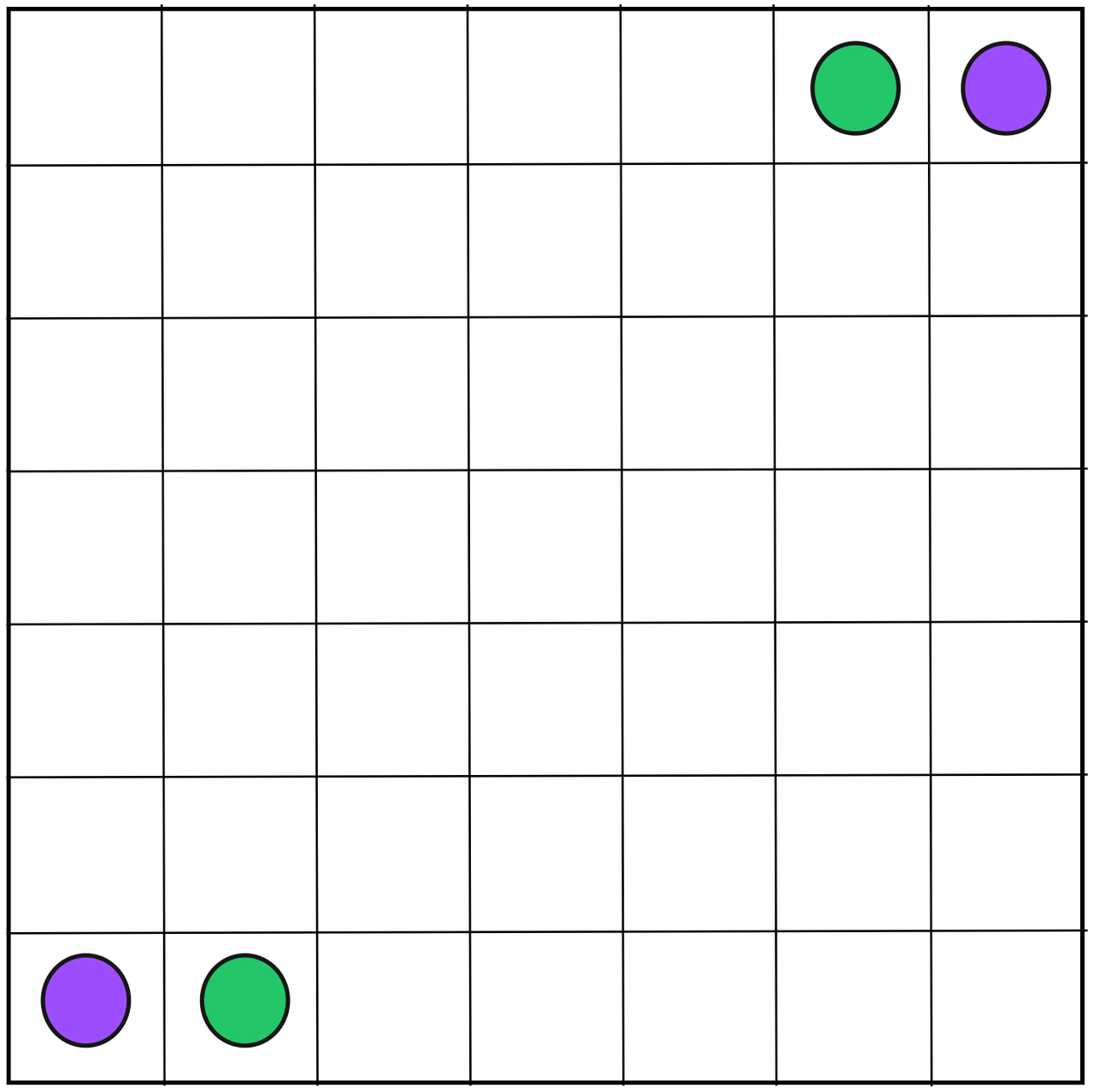


$$\sim e^{-M_\pi t}$$

NOISE

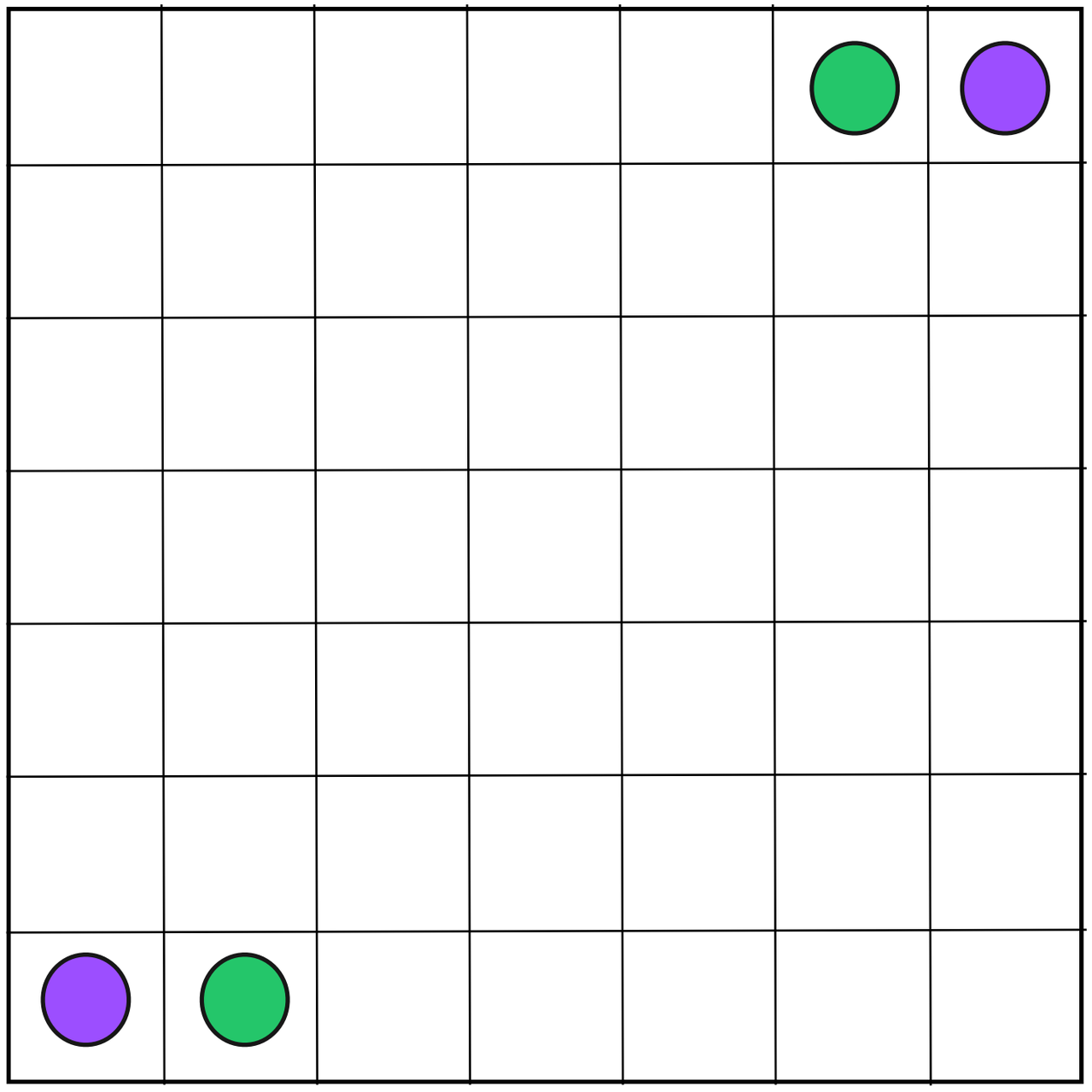


NOISE



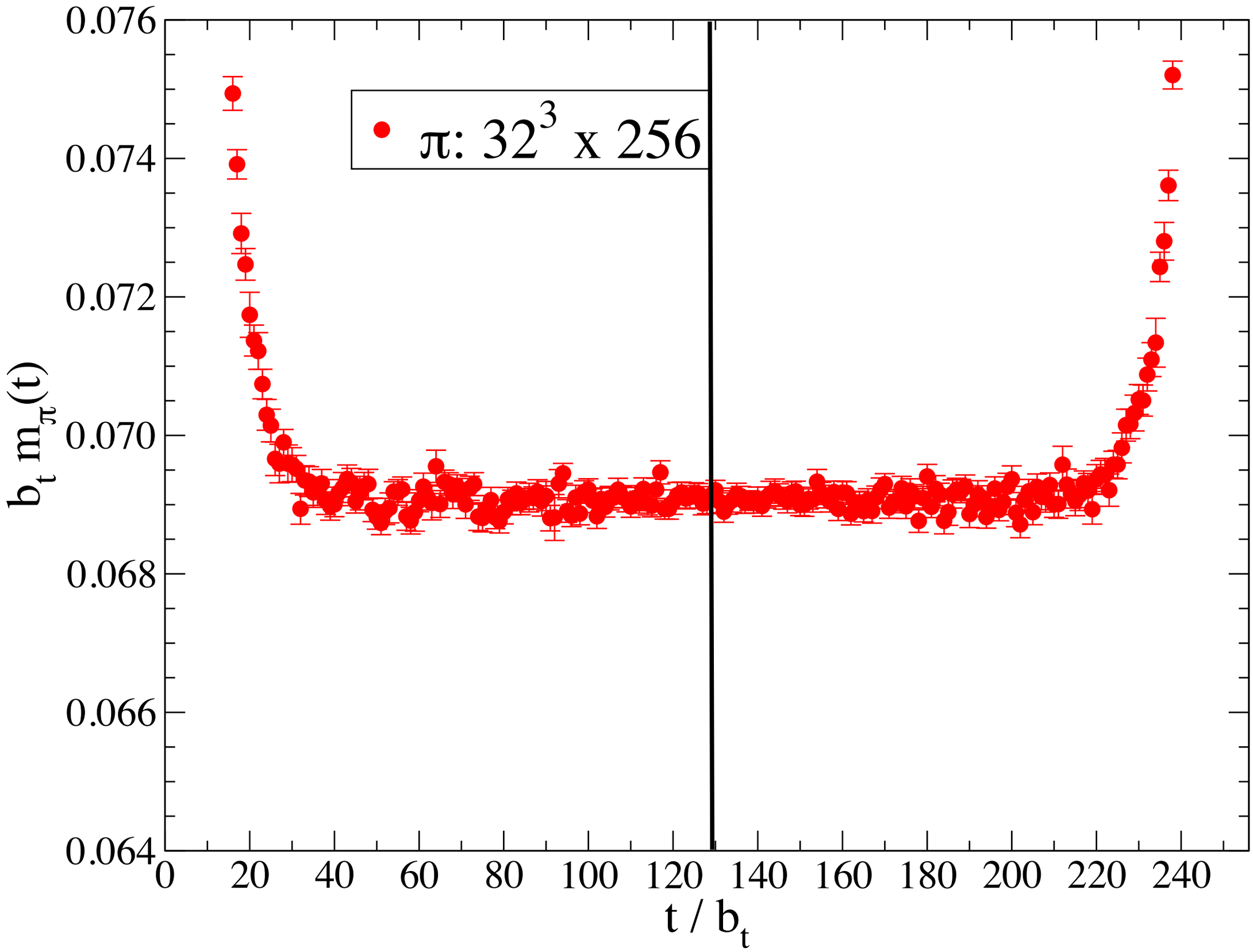
$$\sim e^{-2M_\pi t}$$

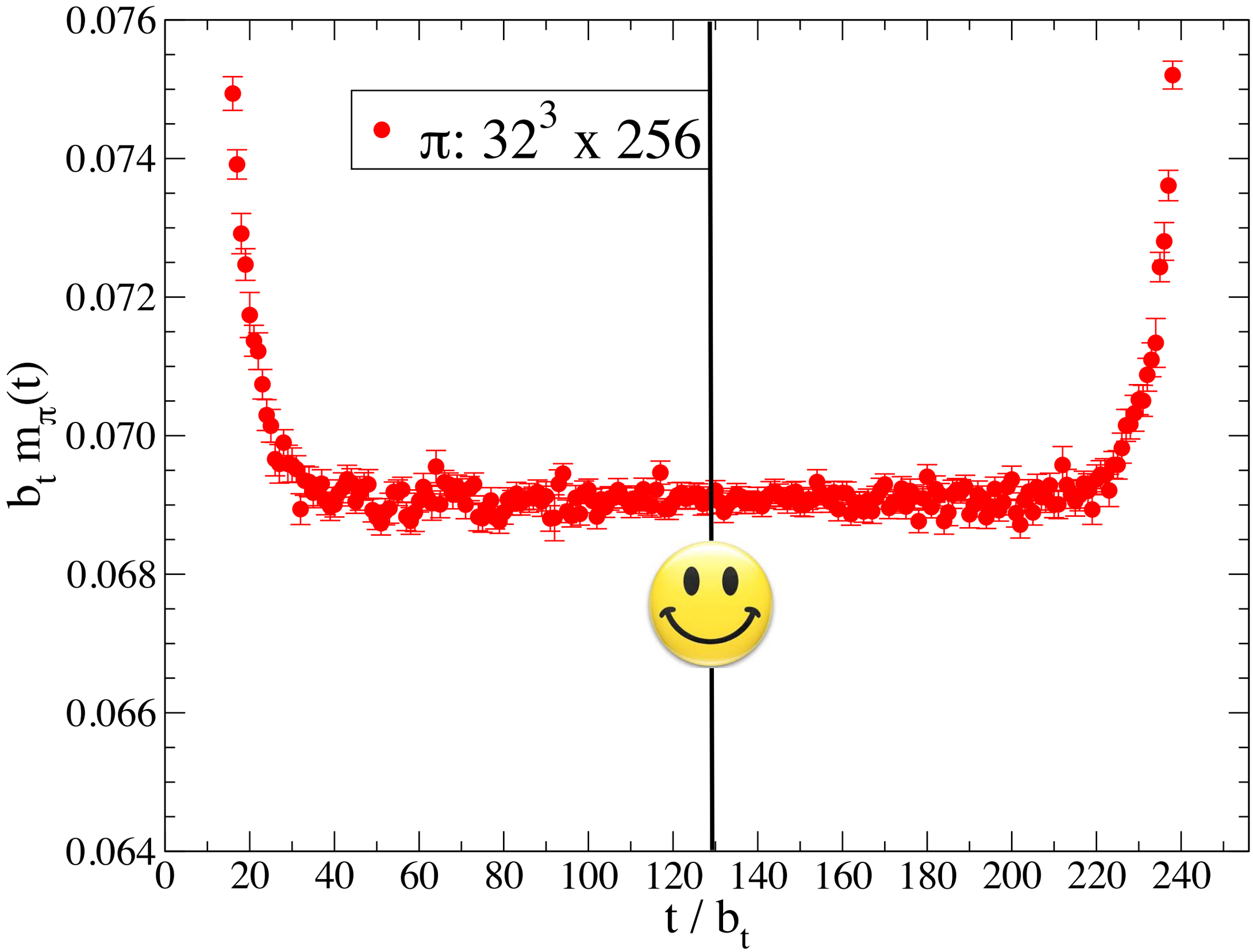
NOISE



$$\sim e^{-2M_\pi t}$$

$$\text{signal/noise} \sim 1$$


π: 32^3 x 256
0.076
0.074
0.072
0.070
0.068
0.066
0.064
b_t m_π(t)
0
20
40
60
80
100
120
140
160
180
200
220
240
t / b_t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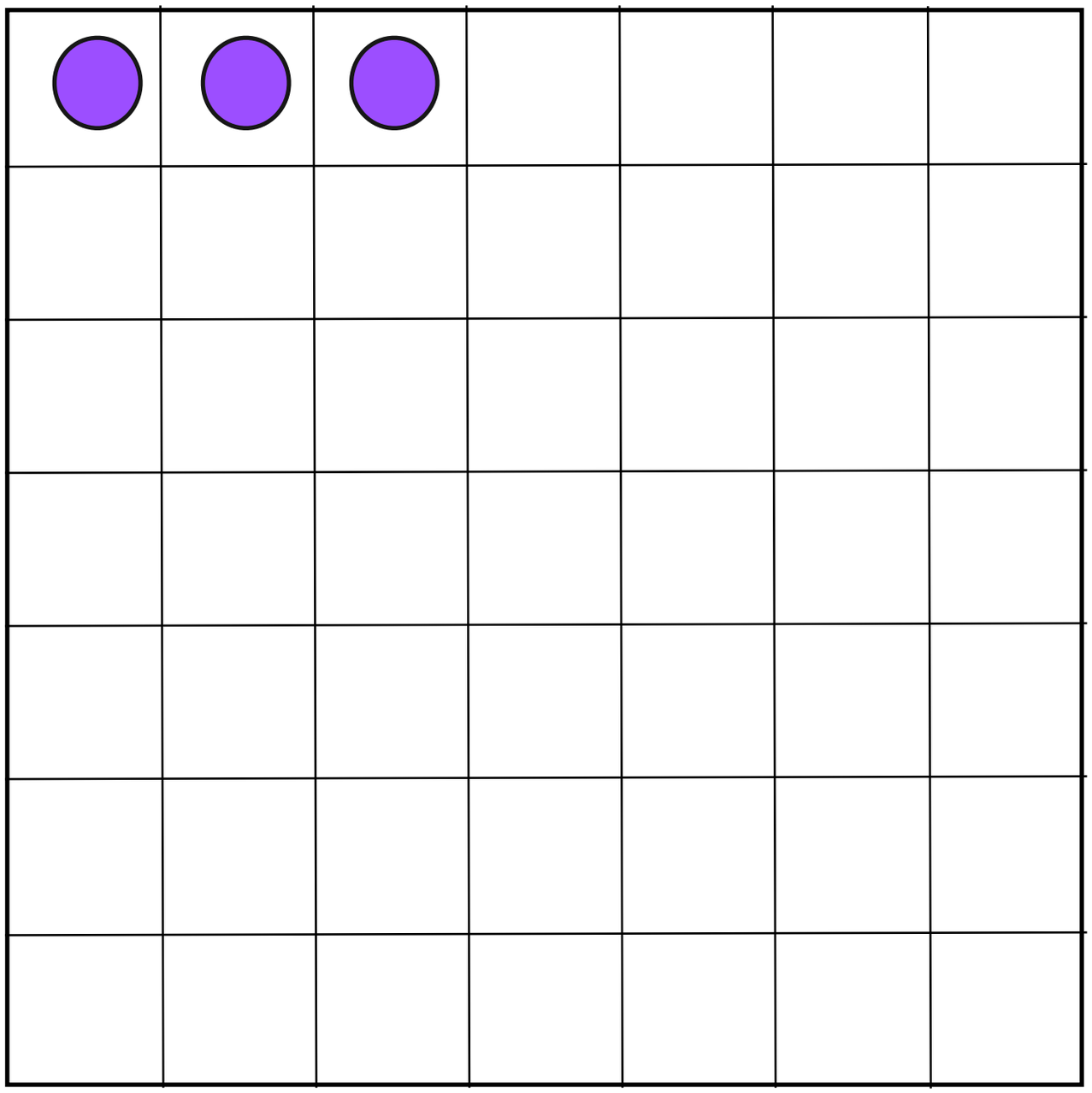
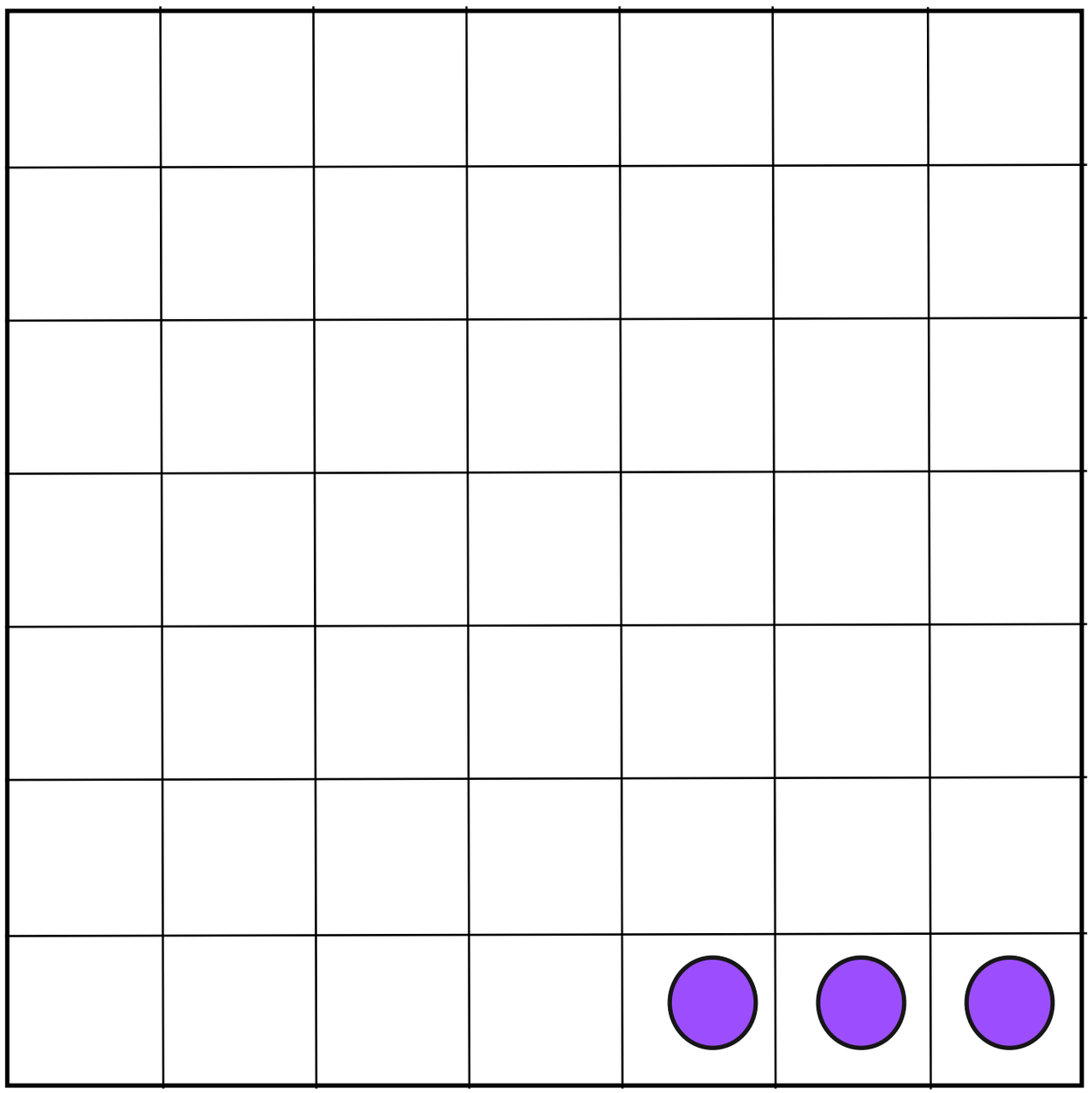
SIGNAL

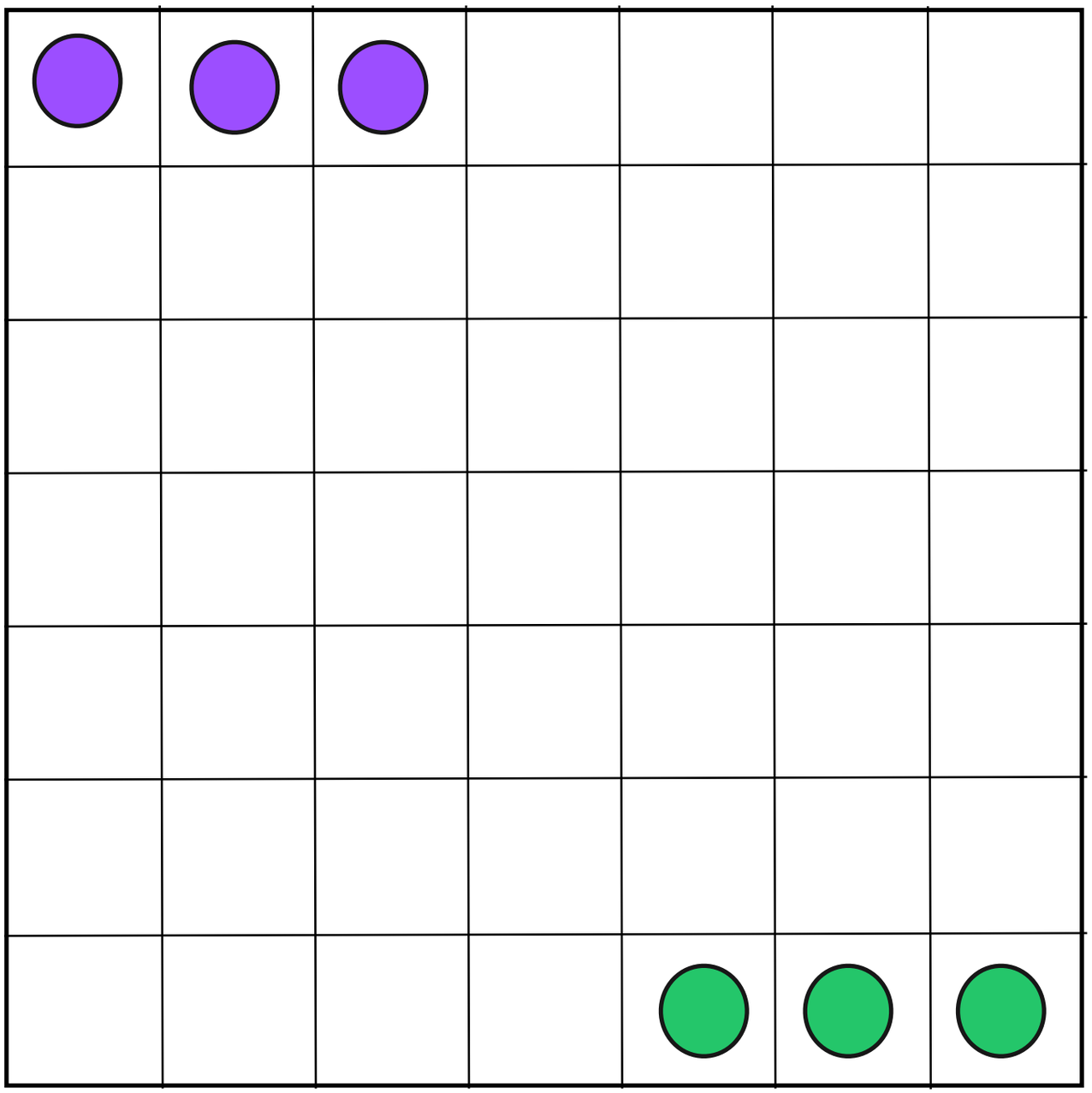


SIGNAL

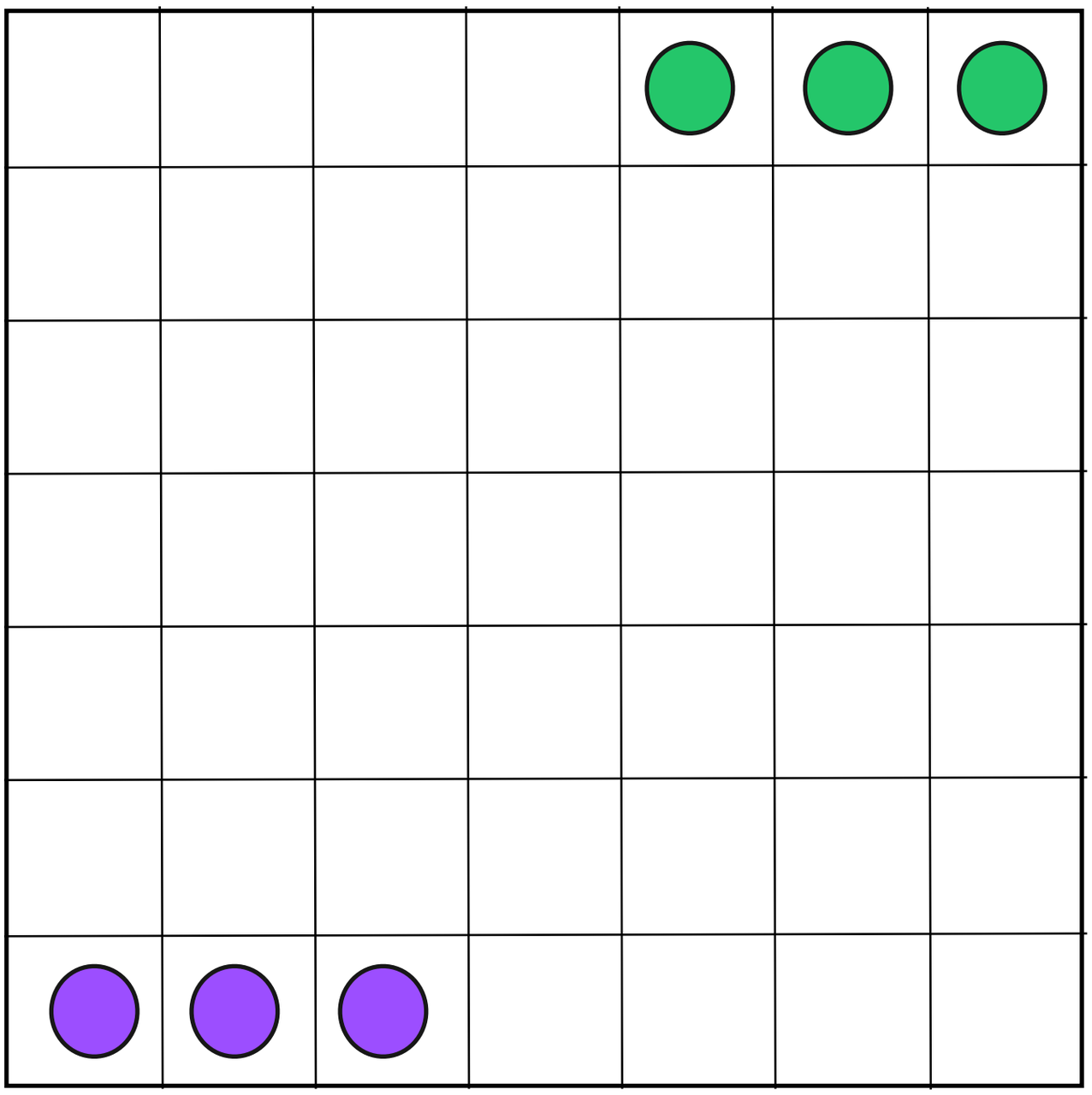


$$\sim e^{-M_N t}$$

NOISE

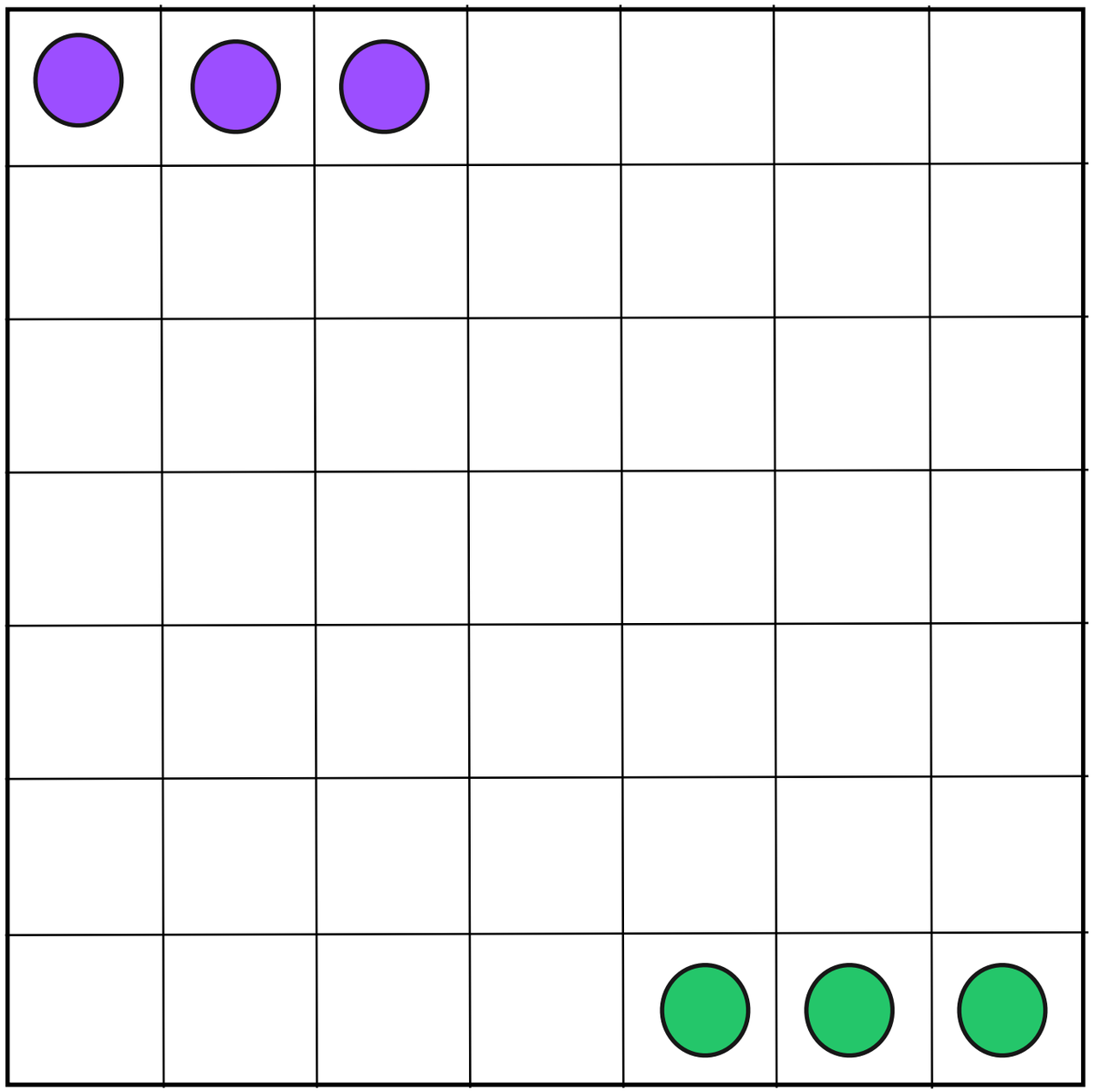


NOISE

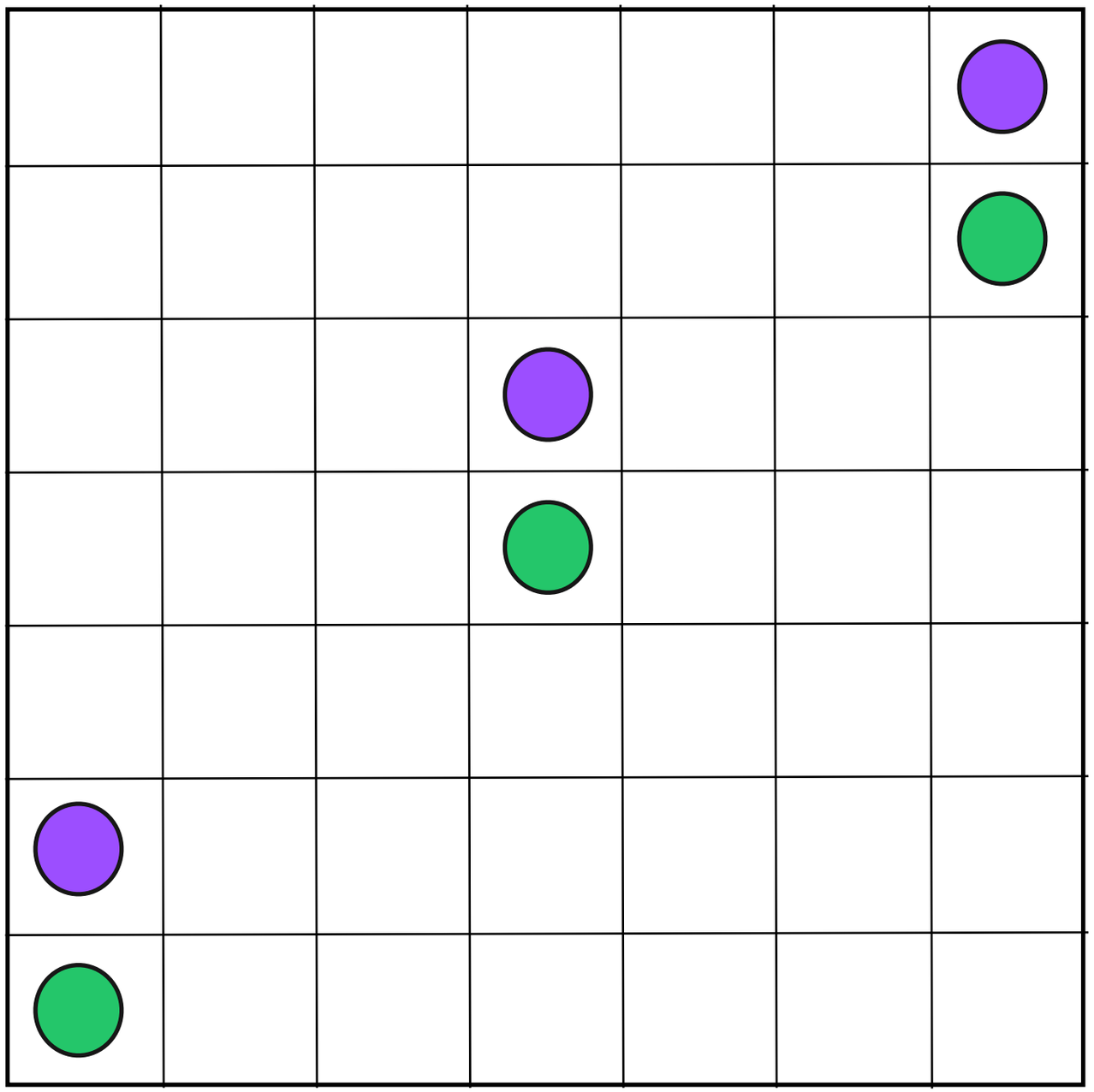


$$\sim e^{-2M_N t}$$

NOISE

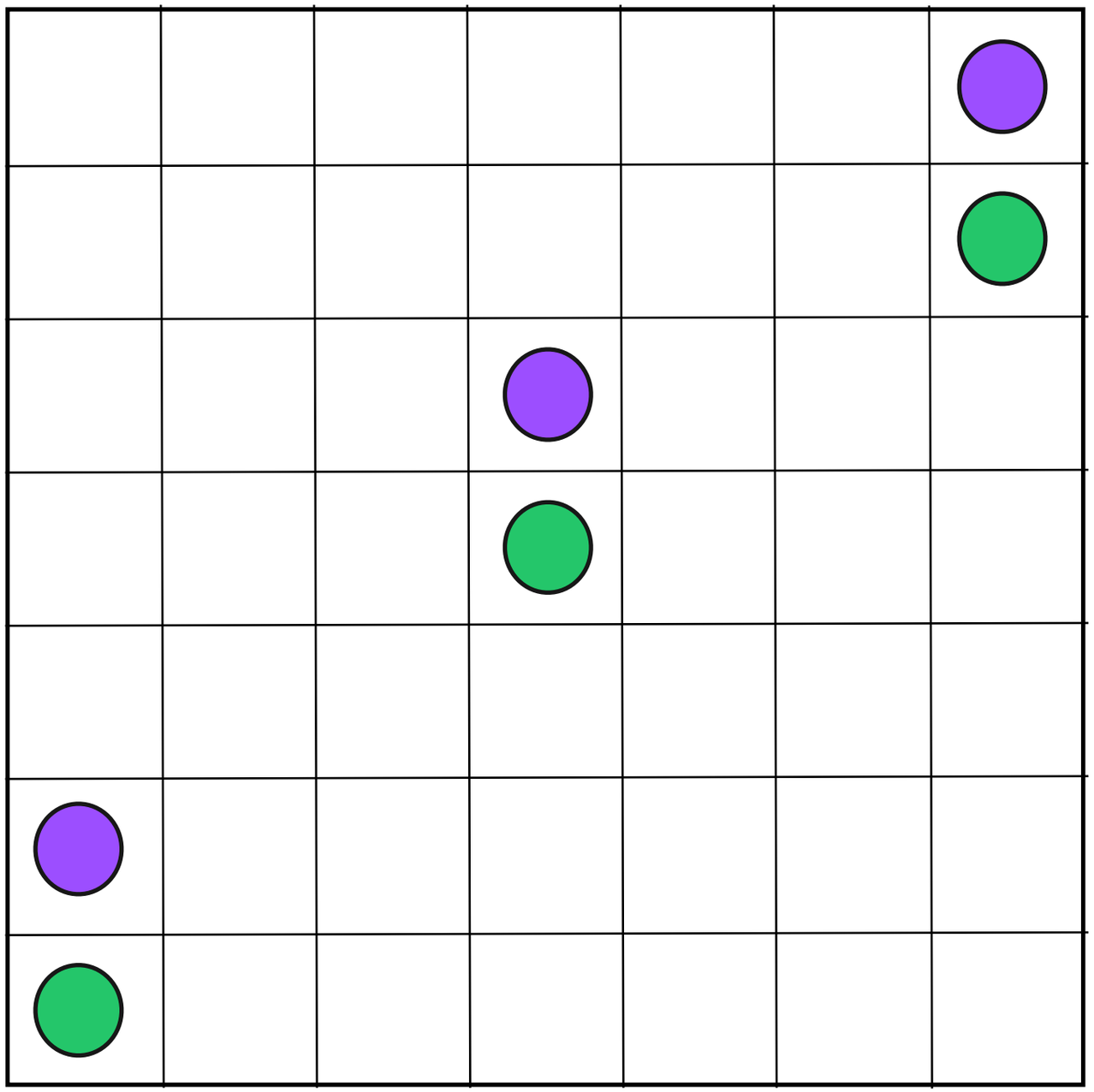


NOISE



$$\sim \quad e^{-3M_\pi t}$$

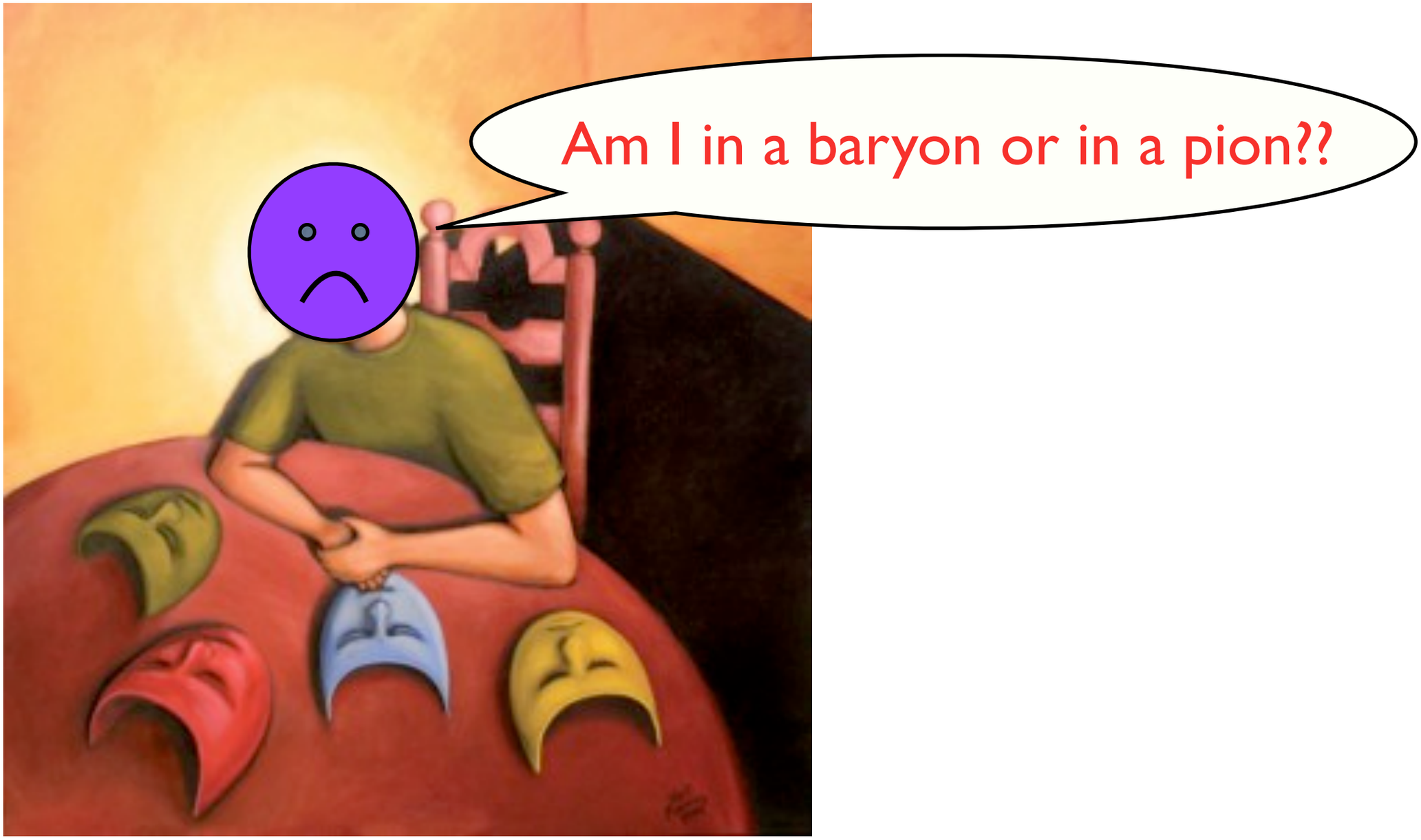
NOISE

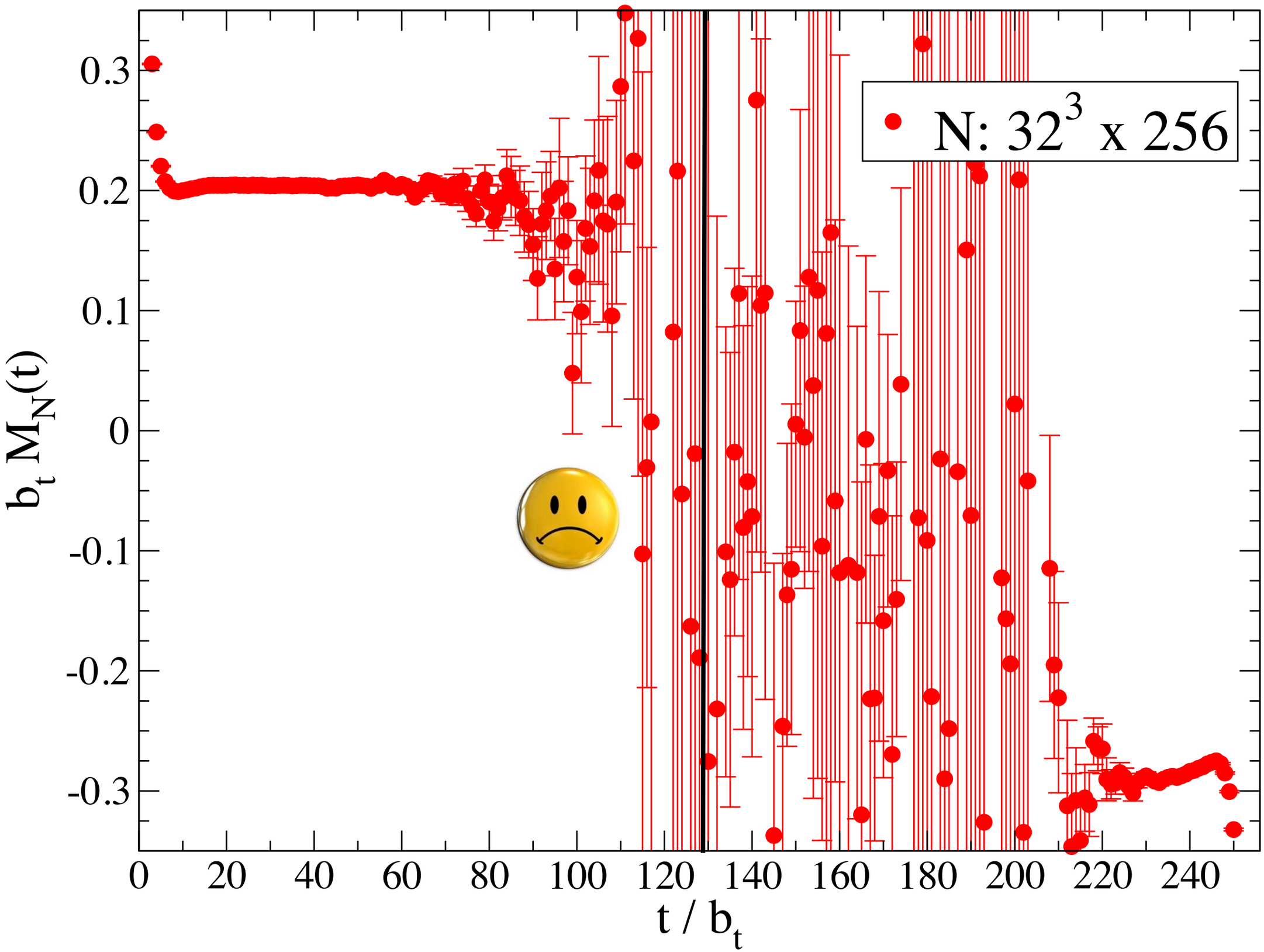


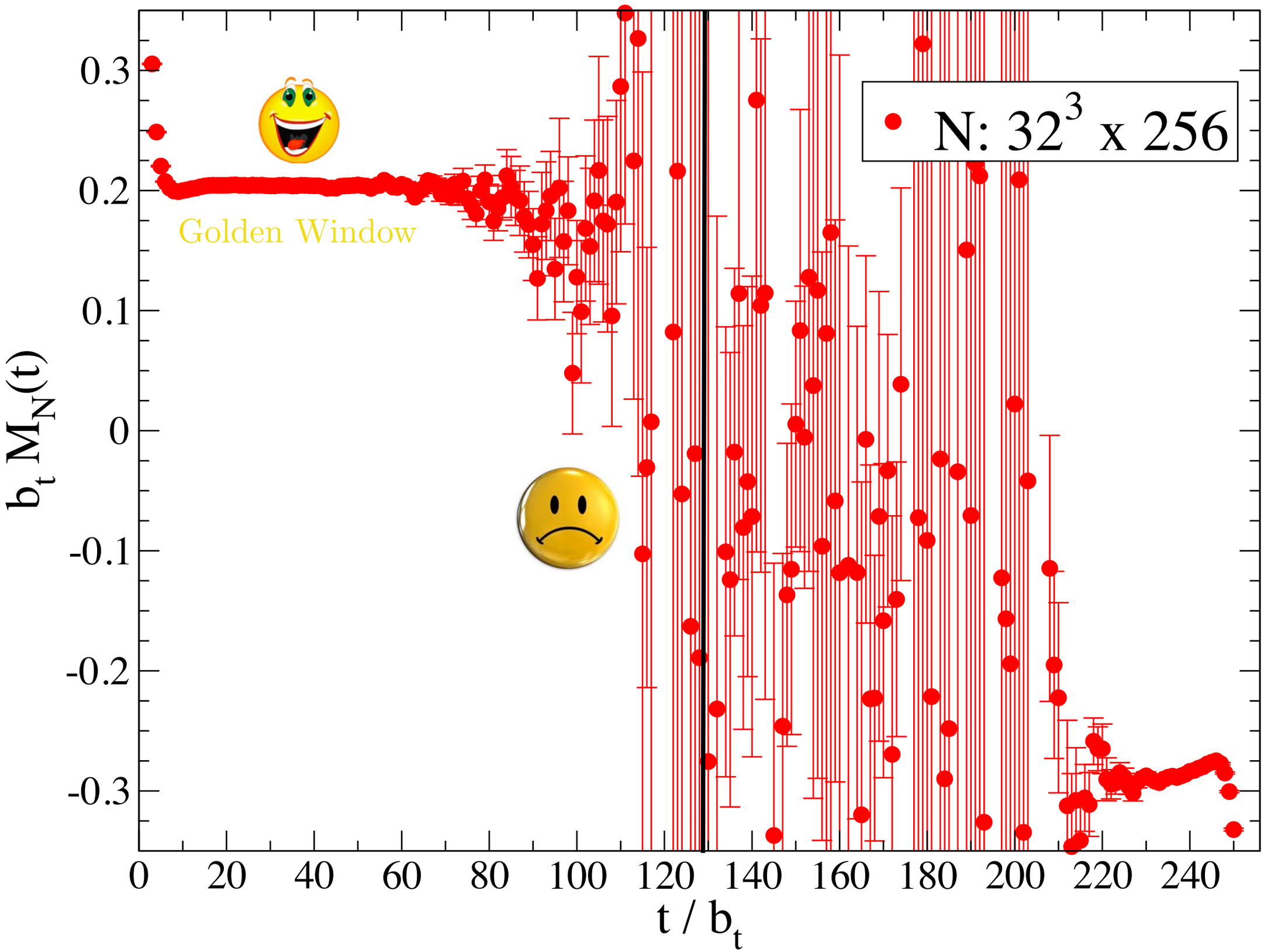
$$\sim \quad e^{-3M_\pi t}$$

$$\text{signal/noise} \ \sim \ e^{-(M_N - \frac{3}{2}M_\pi)t}$$

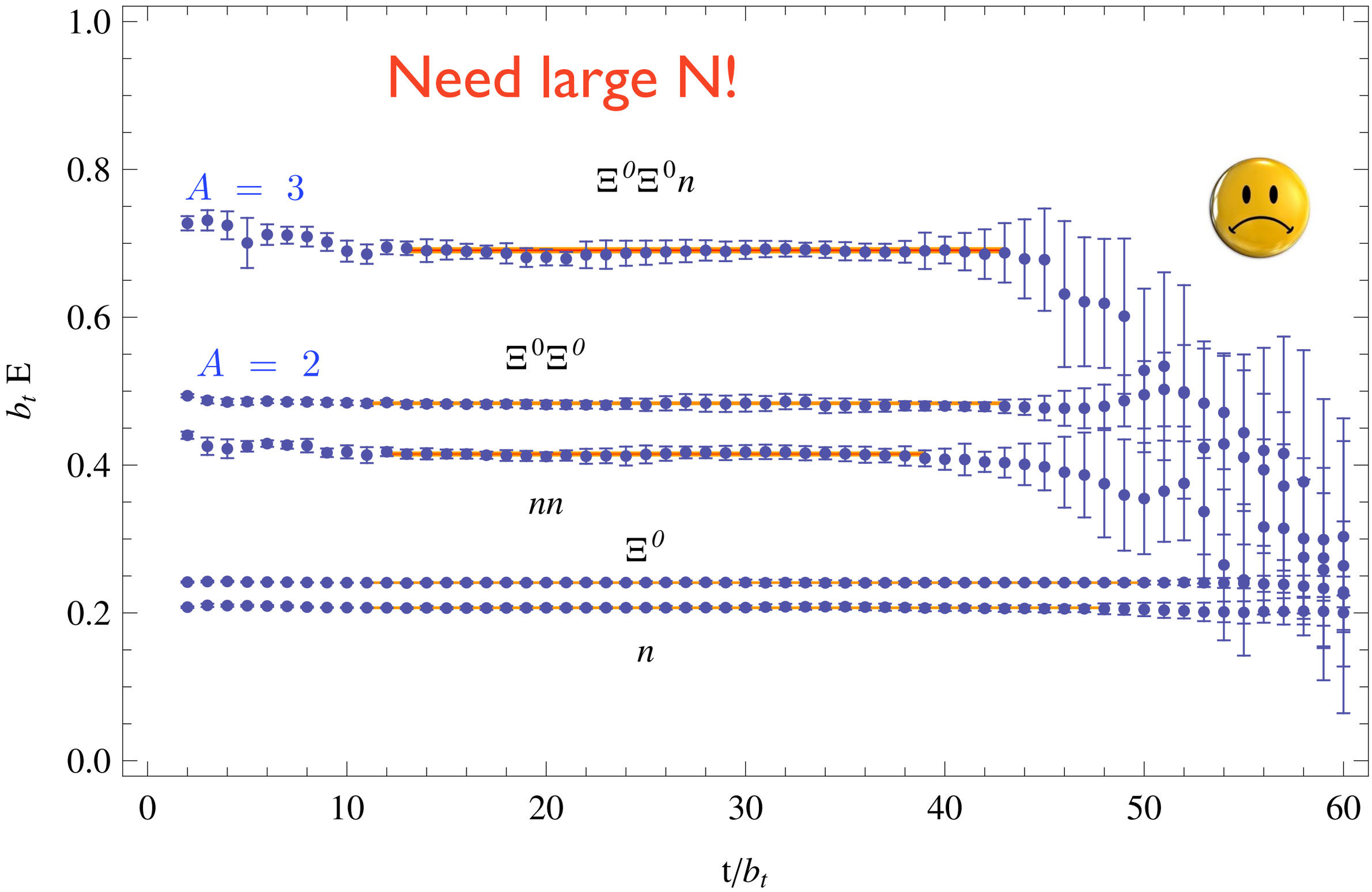
signal/noise problem = quark identity crisis!

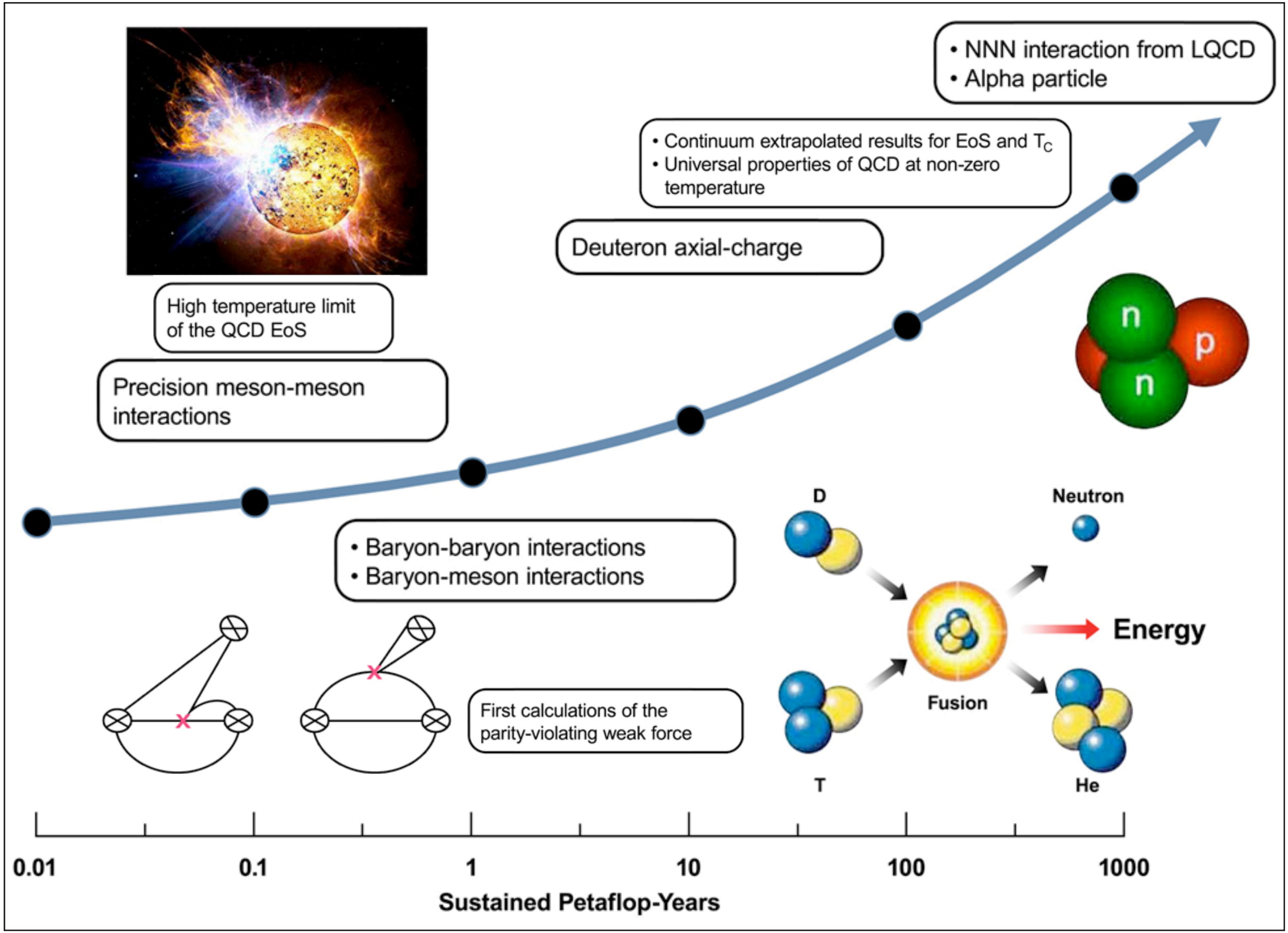


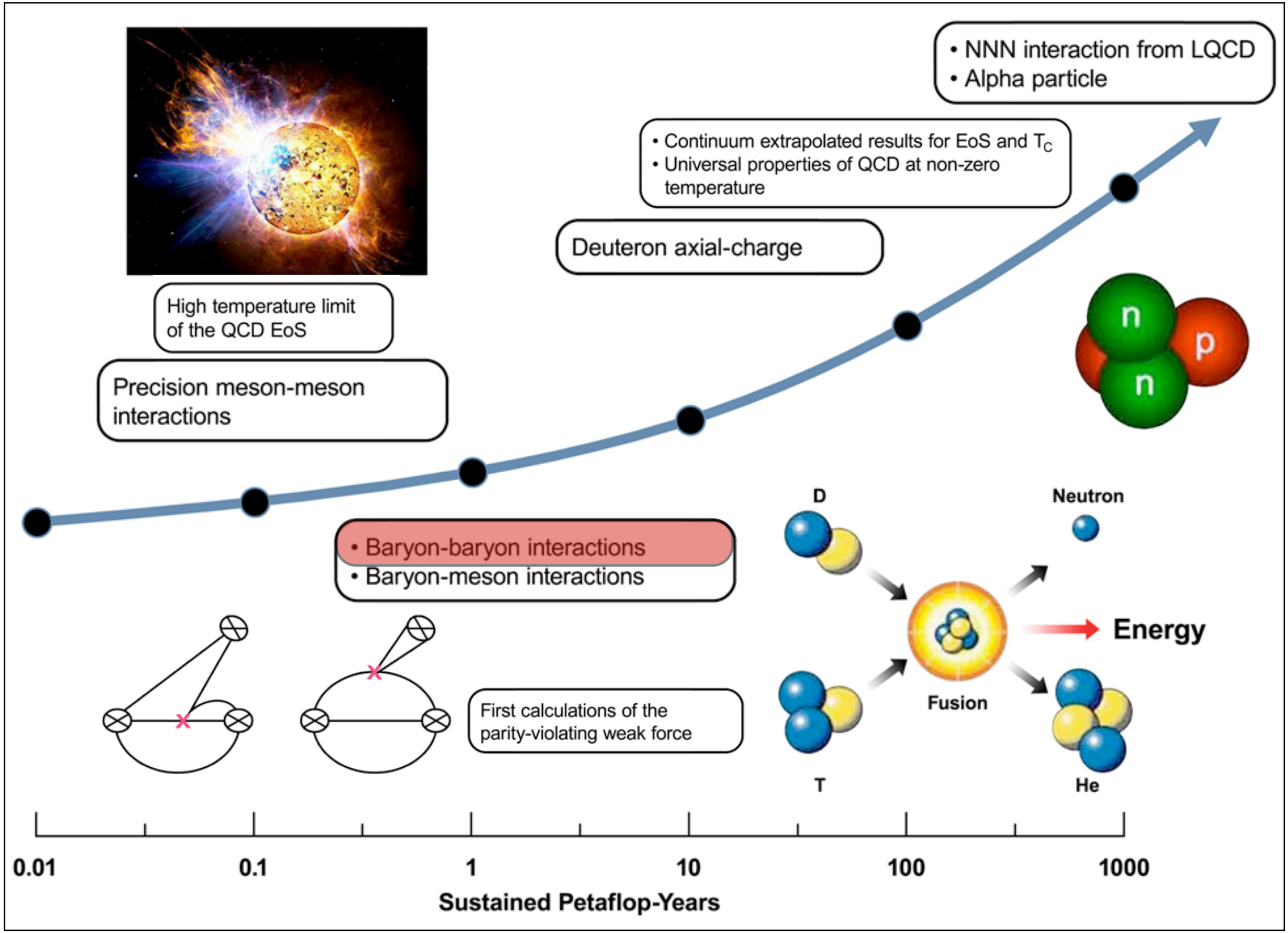

N: 32^3 x 256
$b_t M_N(t)$
t / b_t
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
20
40
60
80
100
120
140
160
180
200
220
240


N: 32^3 x 256
Golden Window
$b_t M_N(t)$
t / b_t
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
20
40
60
80
100
120
140
160
180
200
220
240

"Golden window" persists to $A > 1$




• NNN interaction from LQCD
• Alpha particle
• Continuum extrapolated results for EoS and T_C
• Universal properties of QCD at non-zero temperature
Deuteron axial-charge
High temperature limit of the QCD EoS
Precision meson-meson interactions
n
p
n
• Baryon-baryon interactions
• Baryon-meson interactions
D
Neutron
Energy
Fusion
T
He
First calculations of the parity-violating weak force
0.01
0.1
1
10
100
1000
Sustained Petaflop-Years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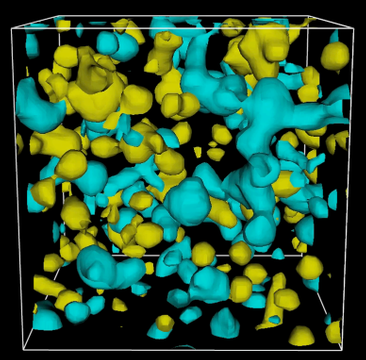
Energy
Fusion
T
He
First calculations of the parity-violating weak force
0.01
0.1
1
10
100
1000
Sustained Petaflop-Years

$N_f = 2+1$ *Anisotropic Clover*

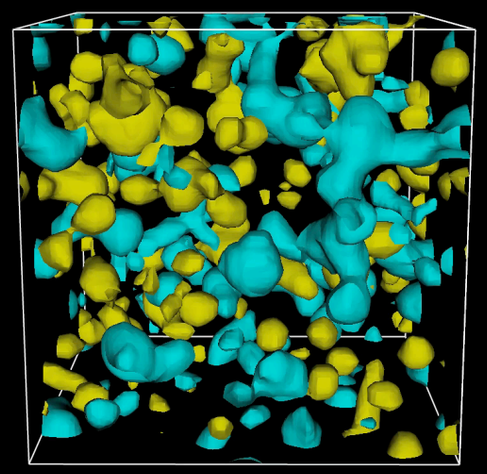
$m_\pi \sim 389$ MeV $\quad b_s \sim 0.1227(8)$ fm $\quad b_s/b_t = 3.500(32)$

$L \sim 2$ fm



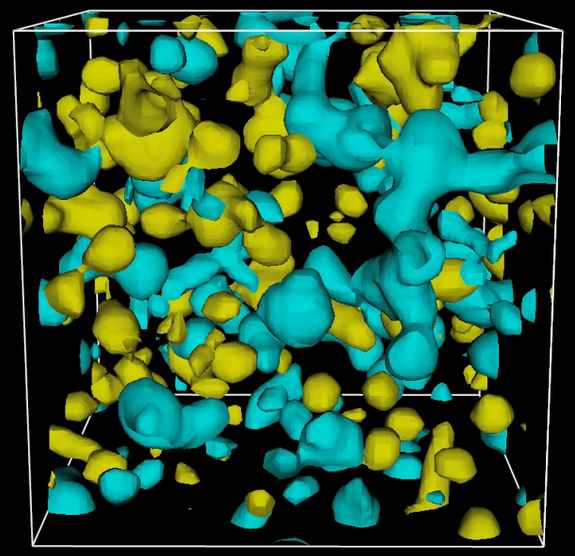
$16^3 \times 128$

$L \sim 2.5$ fm



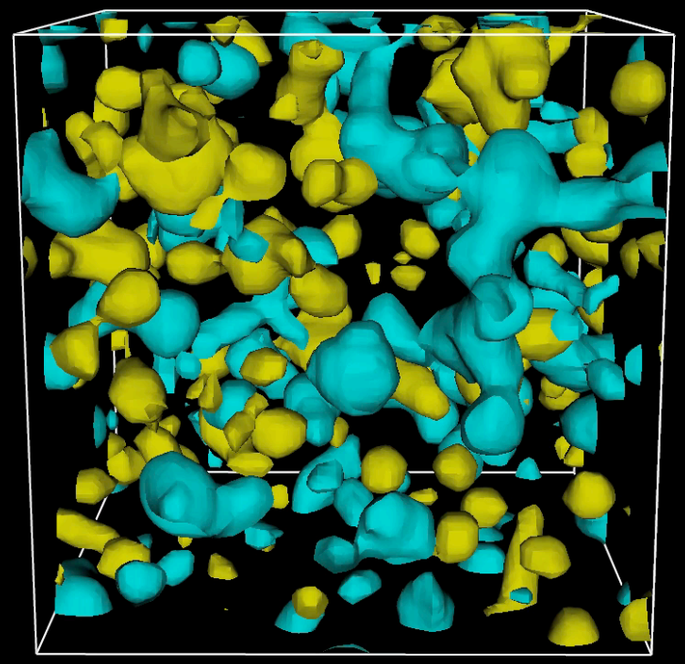
$20^3 \times 128$

$L \sim 3$ fm



$24^3 \times 128$

$L \sim 4$ fm

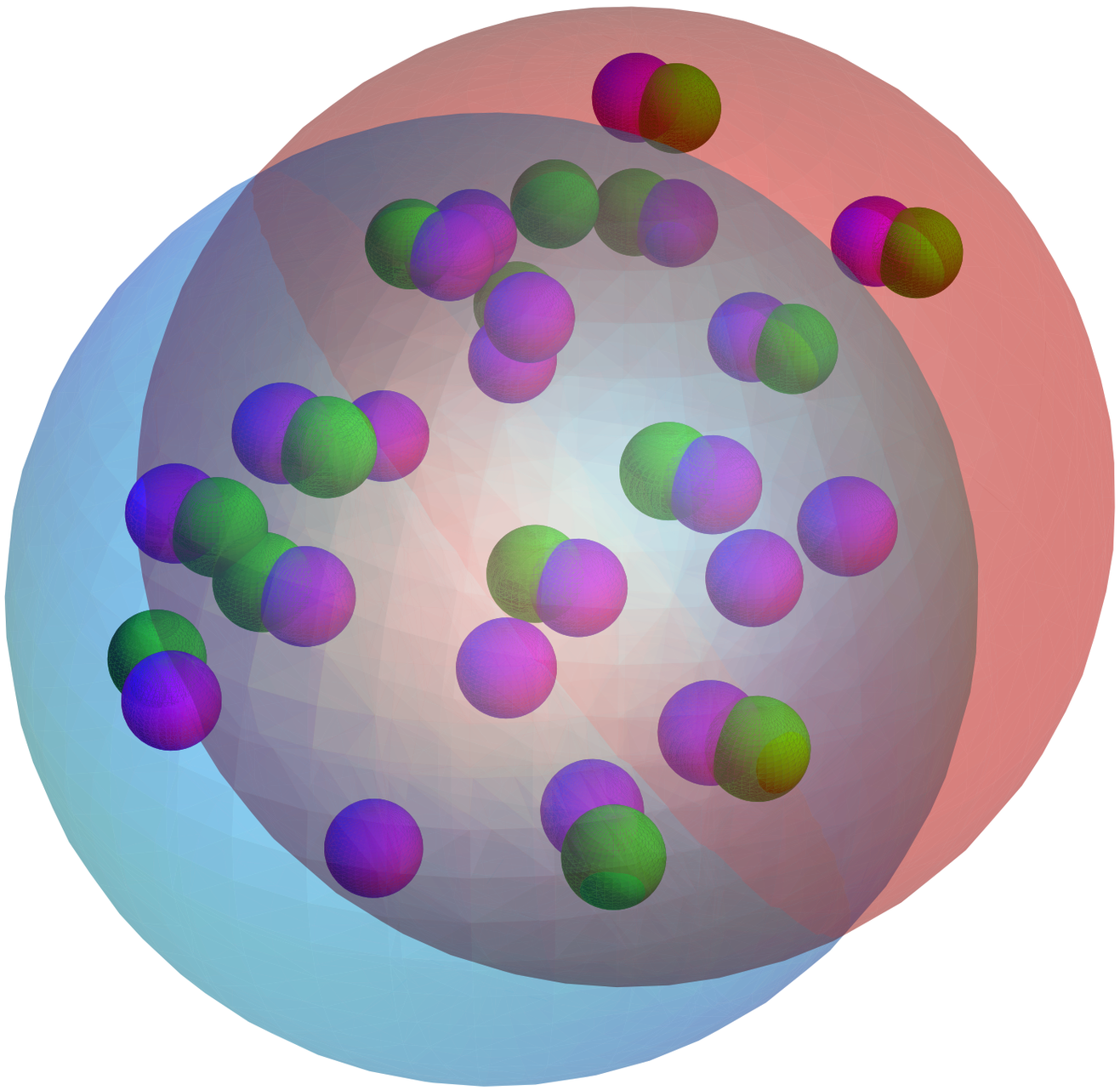


$32^3 \times 256$

Ensemble	Number of cfgs	Average Number of Sources per cfg
16^3 X 128	2001	224
20^3 X 128	1195	364
24^3 X 128	2215	180
32^3 X 256	774	174

High statistics!

The simplest nucleus:



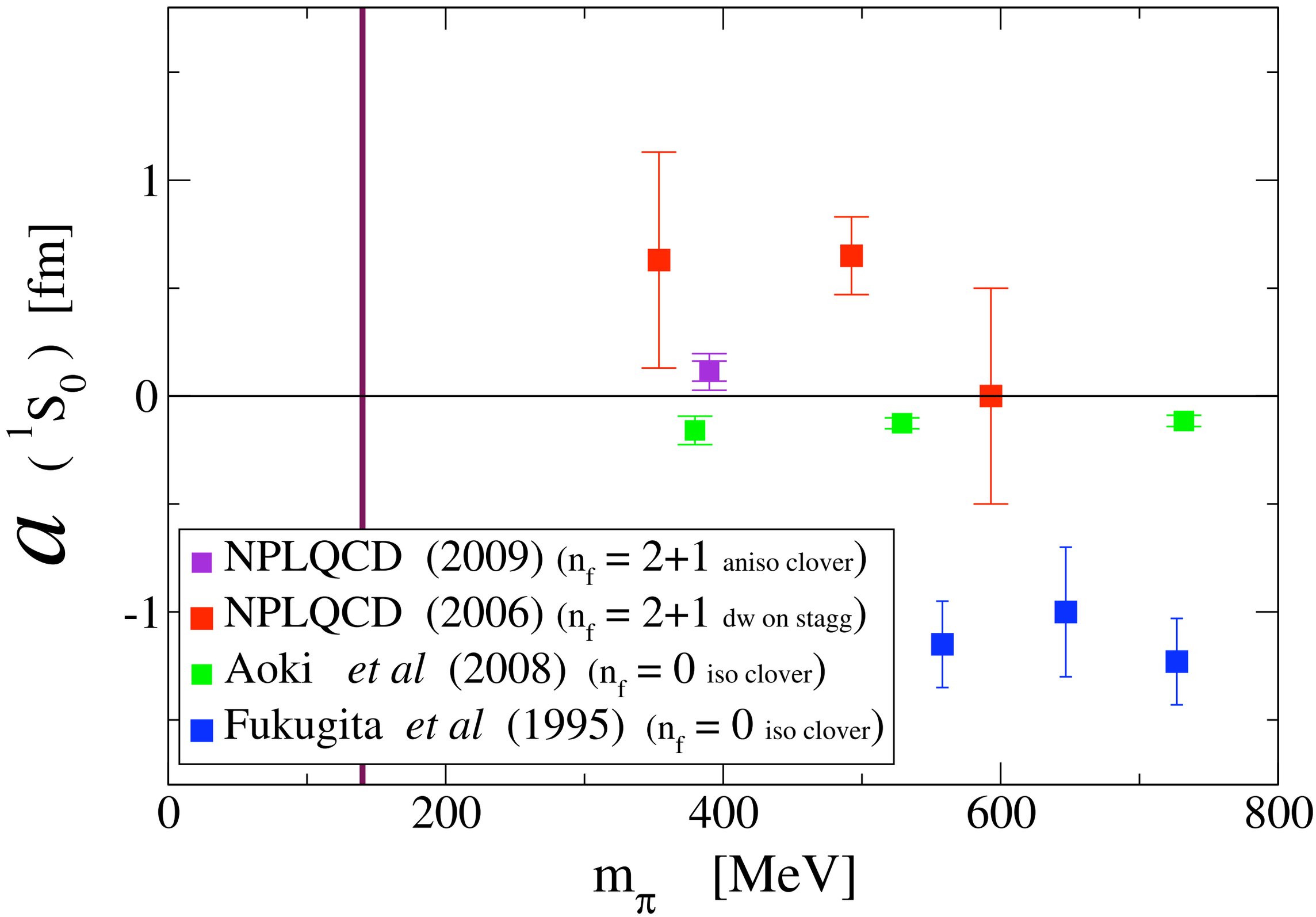
Fundamental benchmark for Lattice QCD!

$$B_d = 2.224644(34)\ \mathrm{MeV}$$

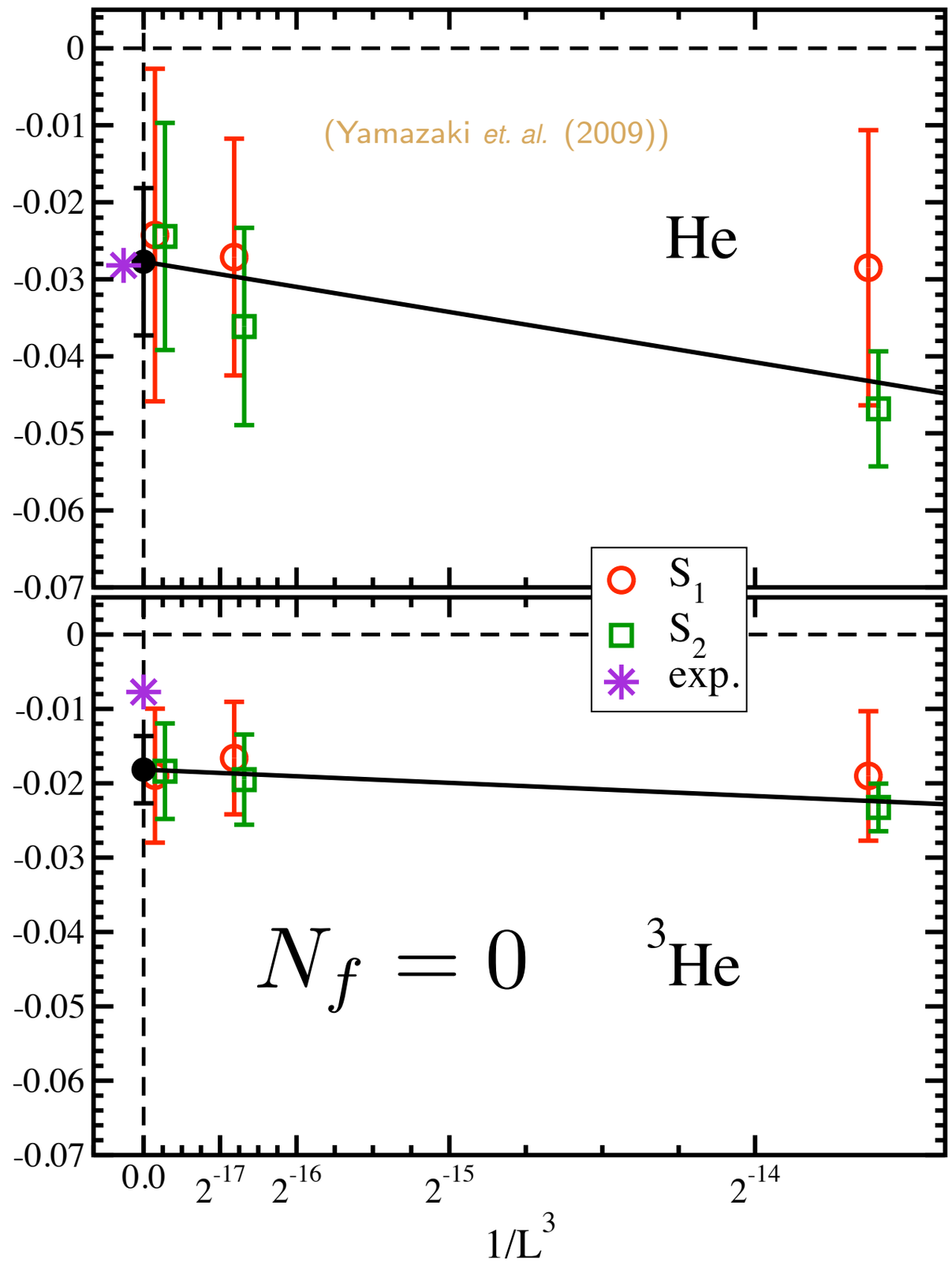
deuteron

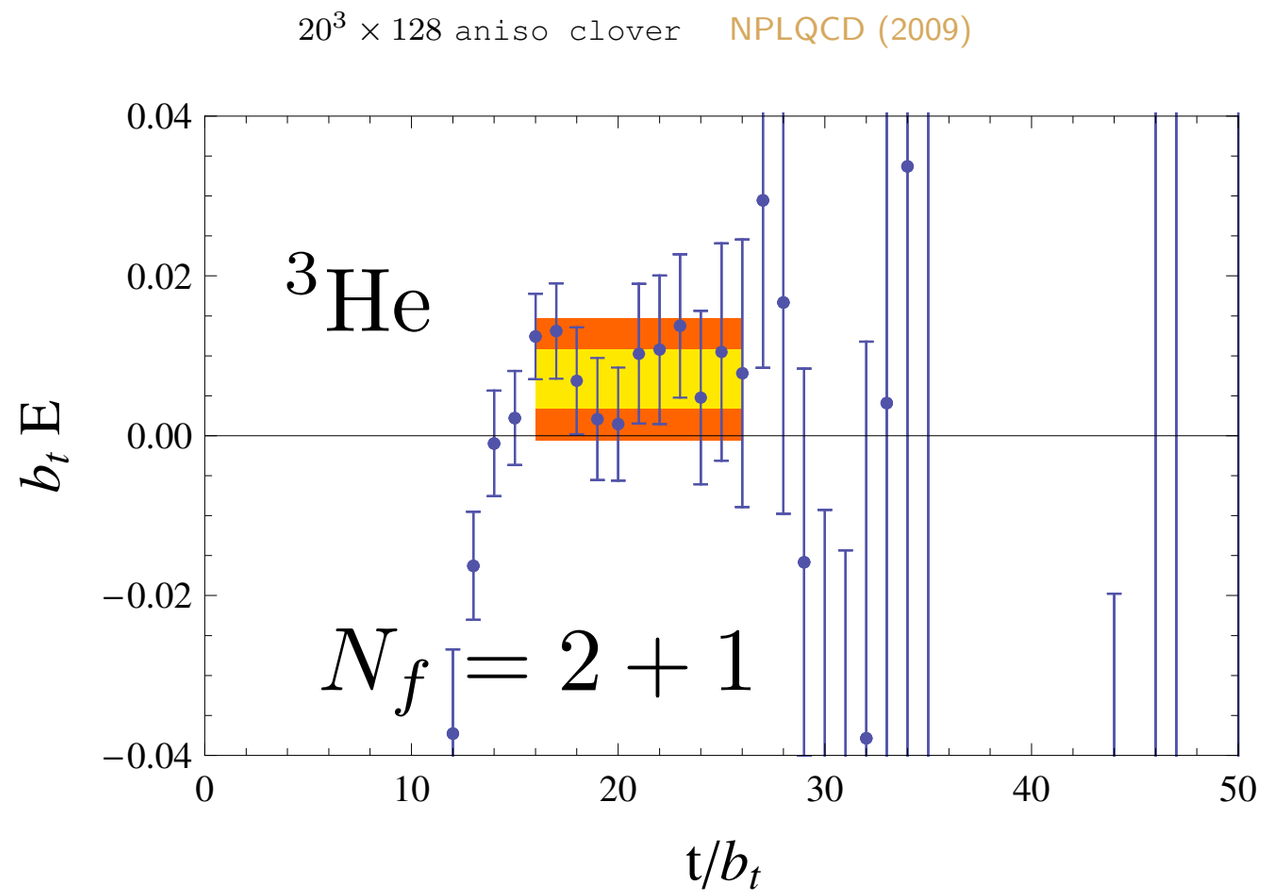
Deuteron binding still ambiguous..

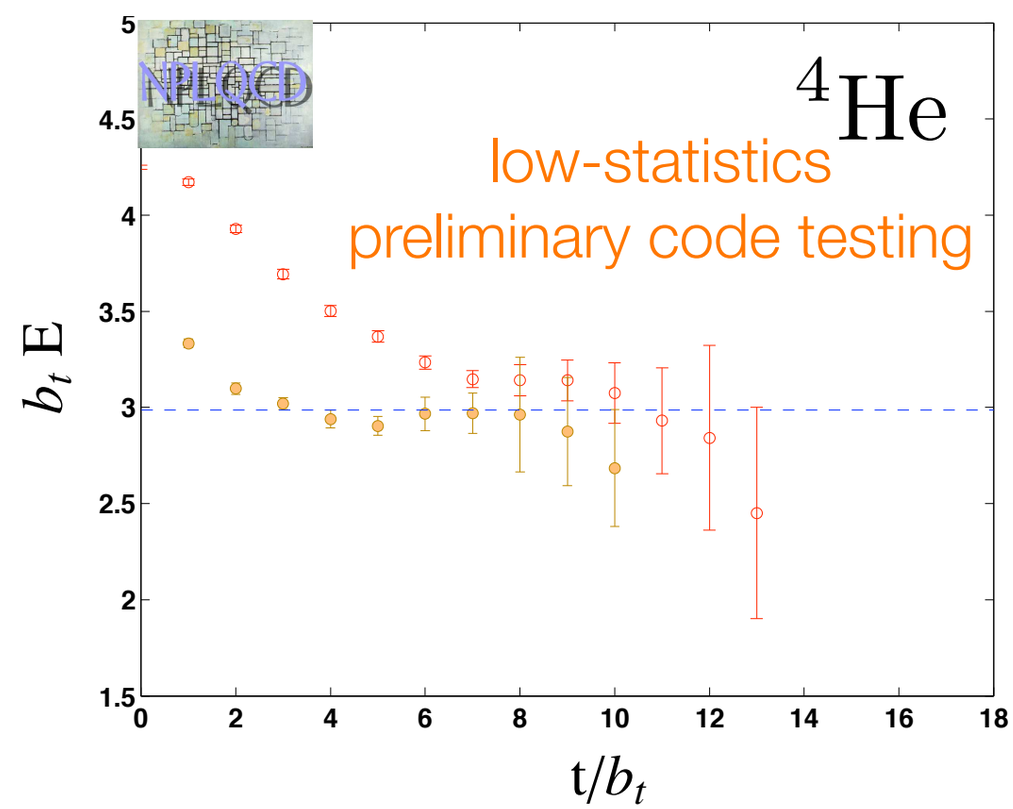
NN scattering



A > 2 nuclei:

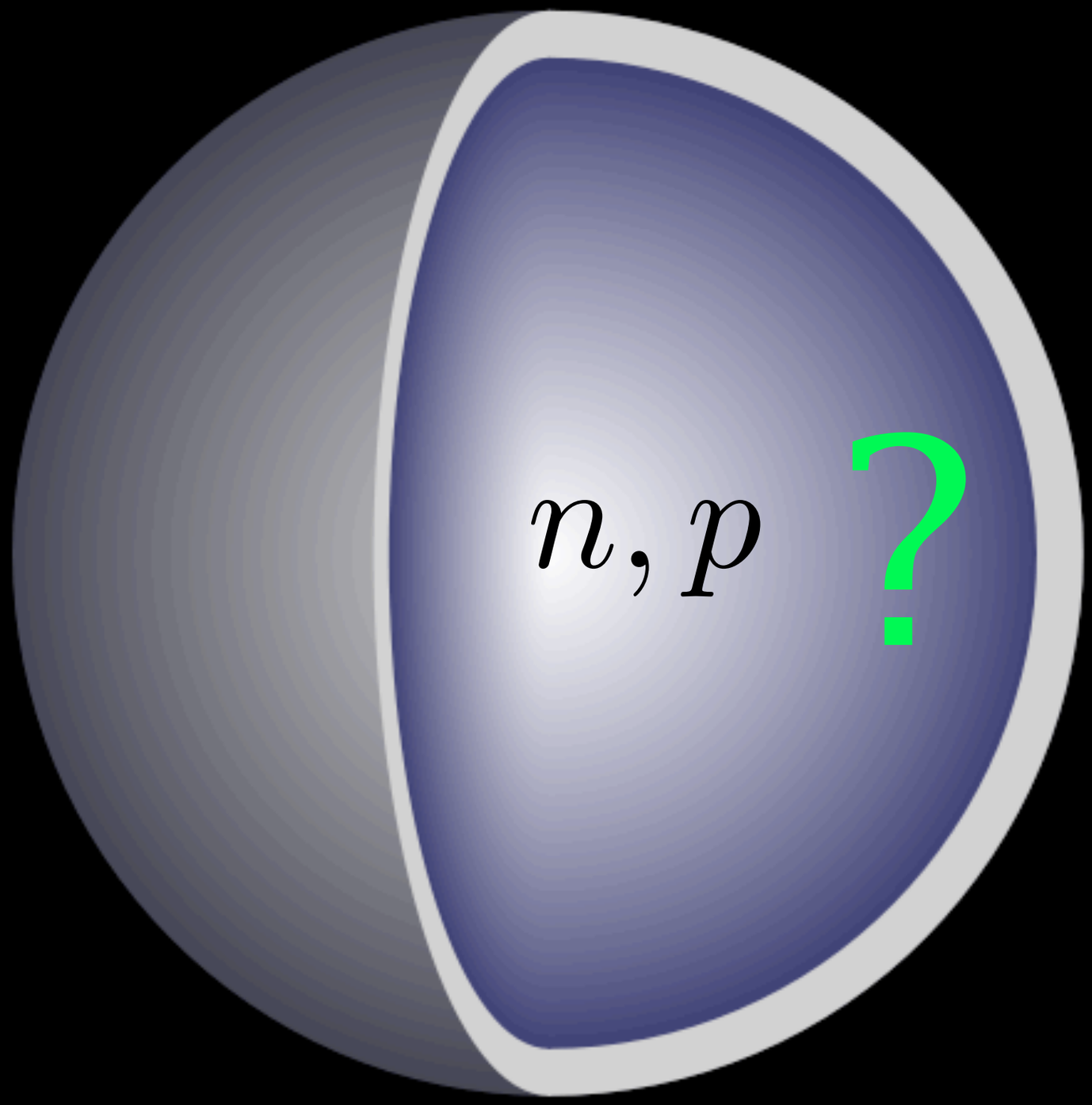

(Yamazaki et. al. (2009))
He
S_1
S_2
exp.
$N_f = 0$
^{3}He
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
0.0
2^{-17}
2^{-16}
2^{-15}
2^{-14}
$1/L^3$


$20^3 \times 128$ aniso clover
NPLQCD (2009)
^{3}He
$N_f = 2 + 1$
b_t E
t/b_t
0.04
0.02
0.00
−0.02
−0.04
0
10
20
30
40
50

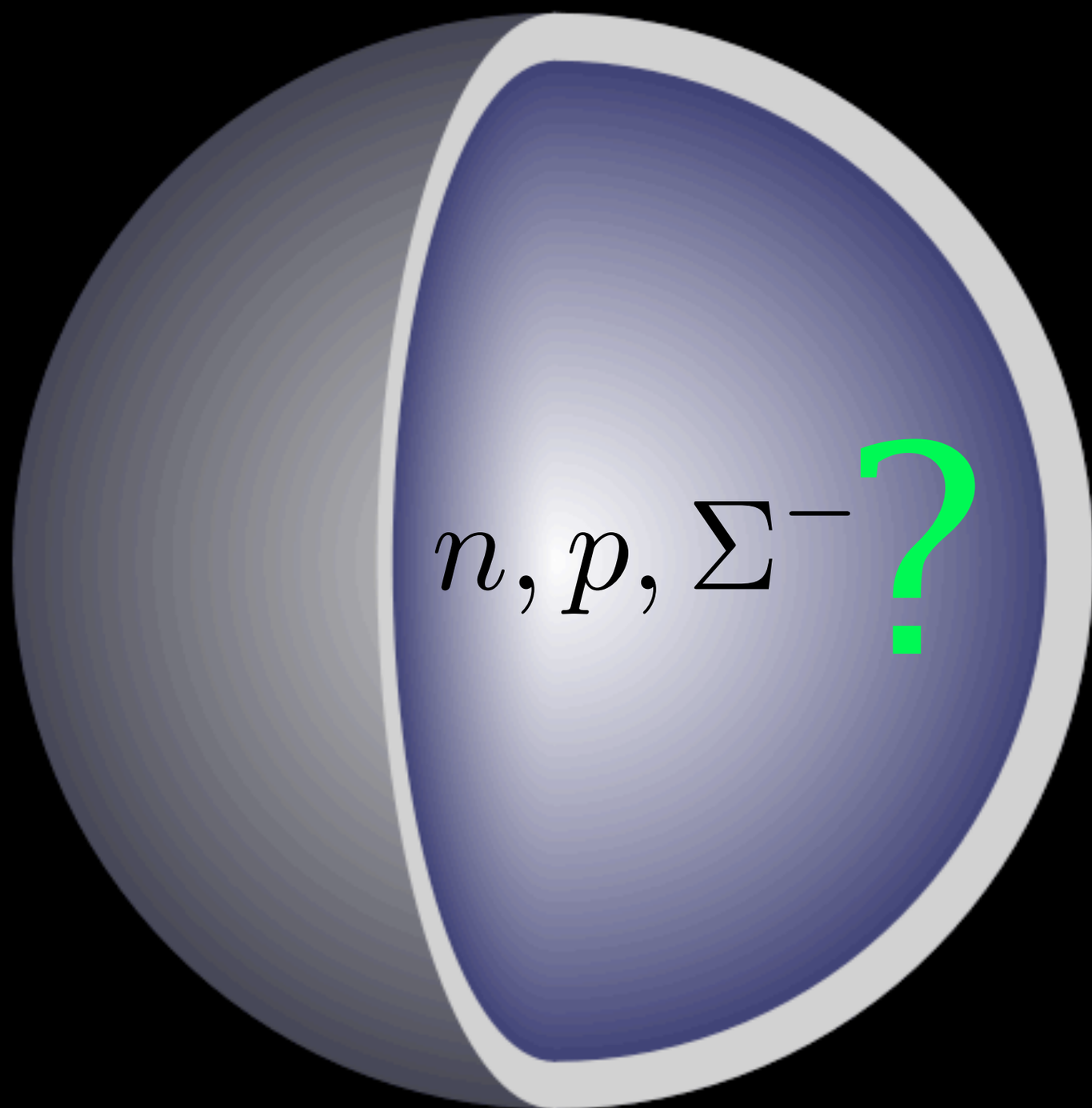

NPLQCD
^{4}He
low-statistics
preliminary code testing
b_t E
t/b_t
5
4.5
4
3.5
3
2.5
2
1.5
0
2
4
6
8
10
12
14
16
18

What can we measure that we do not know?

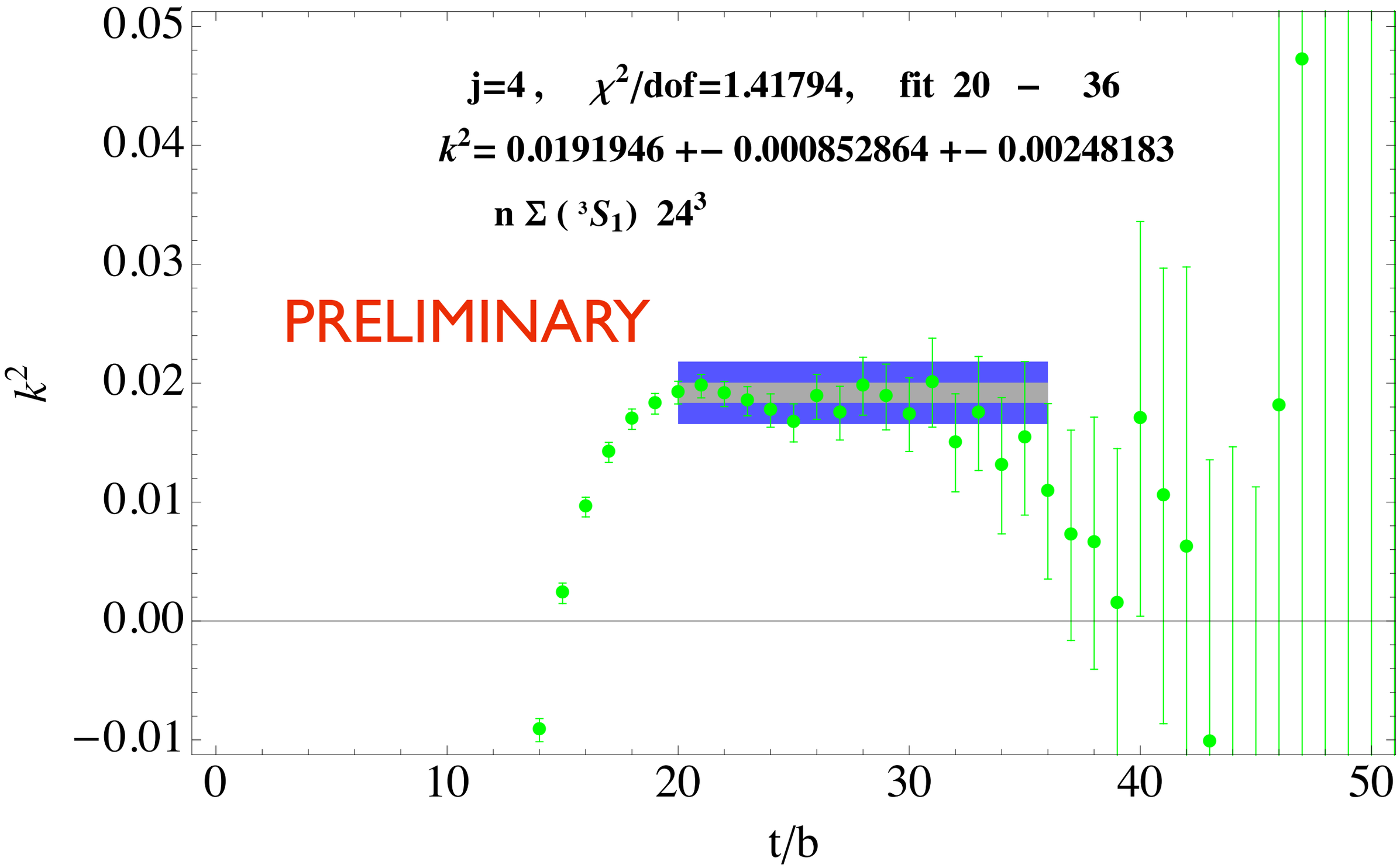
Neutron Star Core



Neutron Star Core



Nucleon-hyperon interactions



Is there an H-dibaryon?

In SU(3) limit:

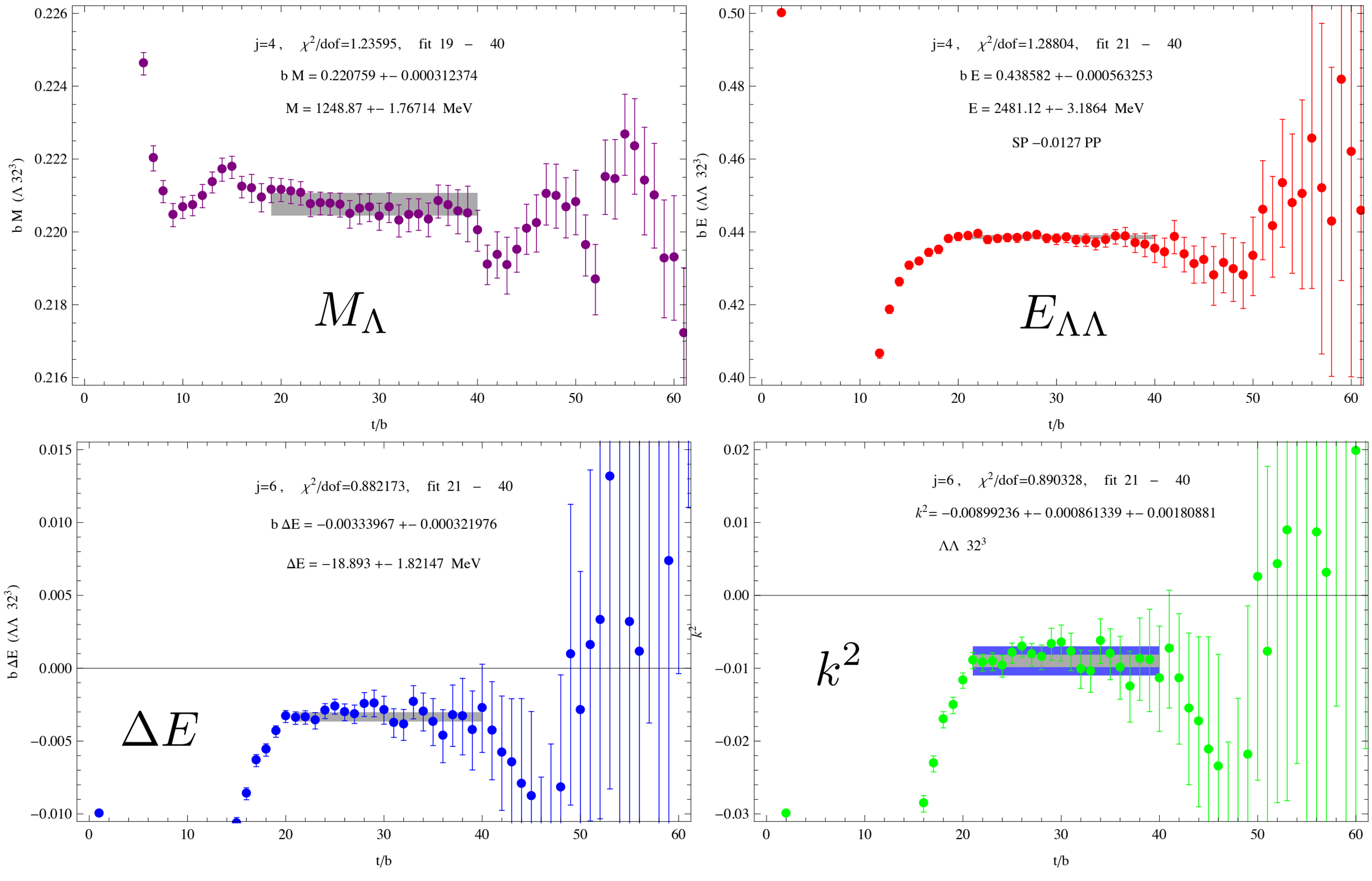
$$(\mathbf{8} \otimes \mathbf{8})_S = -\sqrt{\frac{1}{8}}\Lambda\Lambda + \sqrt{\frac{3}{8}}\Sigma\Sigma + \sqrt{\frac{4}{8}}N\Xi$$

With SU(3) breaking:

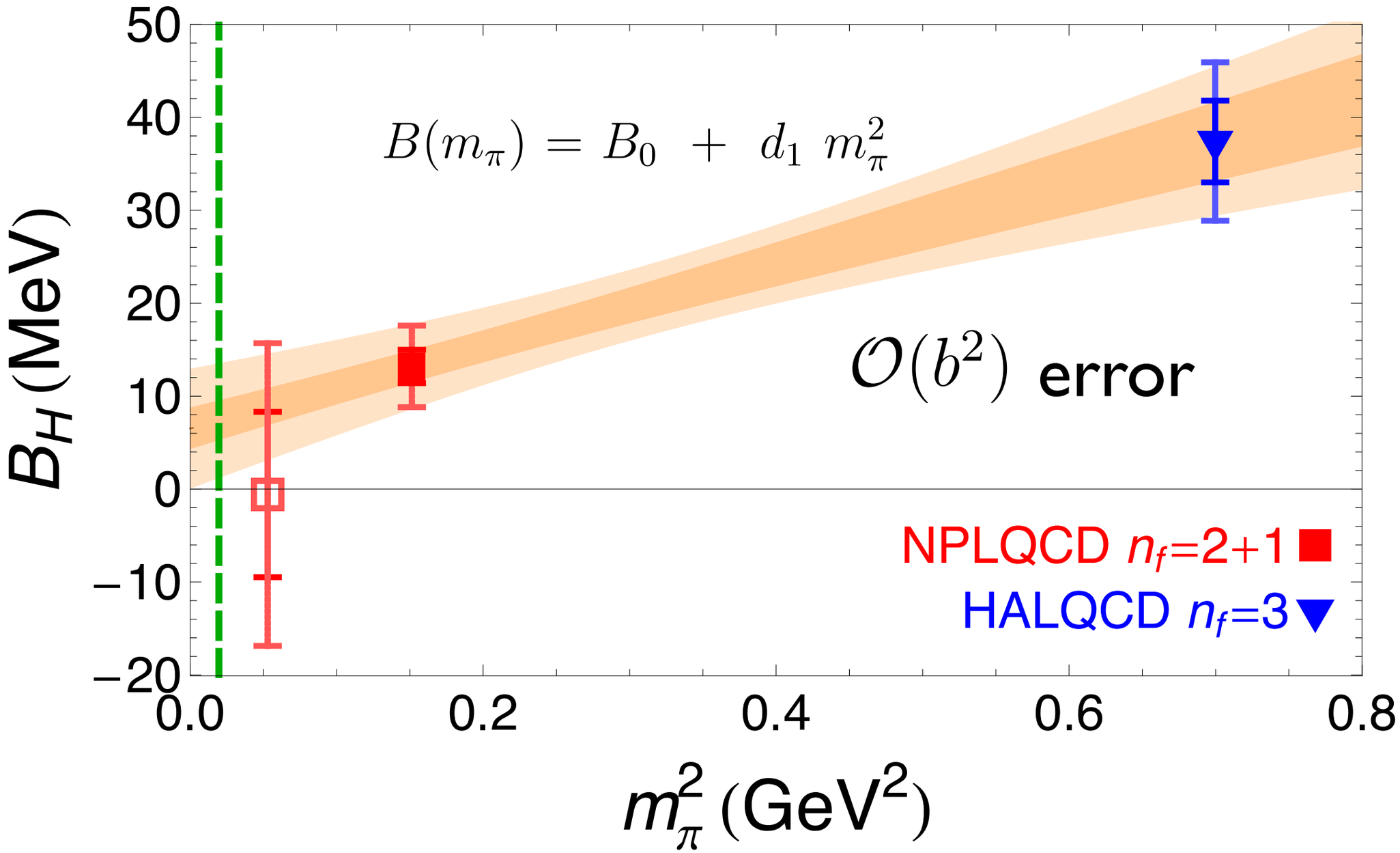
$\Lambda\Lambda - \Sigma\Sigma - N\Xi$ coupled channels!

Need isolated G.S.!

$32^3 \times 256$



Evidence for binding



$$B_H^{\text{quadratic}} = 7.4 \pm 2.1 \pm 5.8 \text{ MeV}$$

三三 bound!!

Soon will be competitive with EFT and models!

Conclusion

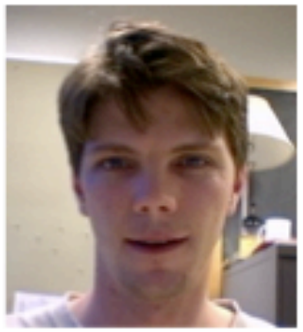
- A Golden Age for nuclear physics is imminent! But need to run big machines a long time to do nuclear physics!

- Few-hadron systems are currently under intense investigation. Calculation of deuteron properties is a major outstanding benchmark. The H-dibaryon and $\Xi\Xi$ systems are bound at unphysical quark masses. Results on hyperon-nucleon scattering are forthcoming.

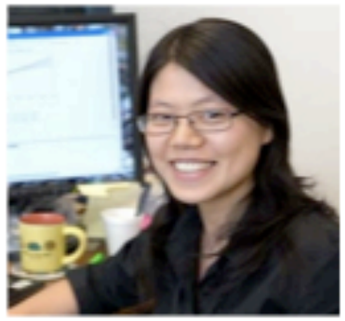
- Naive chiral extrapolation of the existing lattice data indicate that at 2-sigma level H can be unbound or independent of the quark masses: need $m_\pi \sim 200 - 250 \text{ MeV}$ AND smaller lattice spacing to claim control of continuum limit!

Silas Beane
New Hampshire

Emmanuel Chang
Barcelona



William Detmold
Willam+Mary



Huey-Wen Lin
U. of Washington

Tom Luu
LLNL

Kostas Orginos
William+Mary

Assumpta Parreno
Barcelona

Marton Savage
U. of Washington

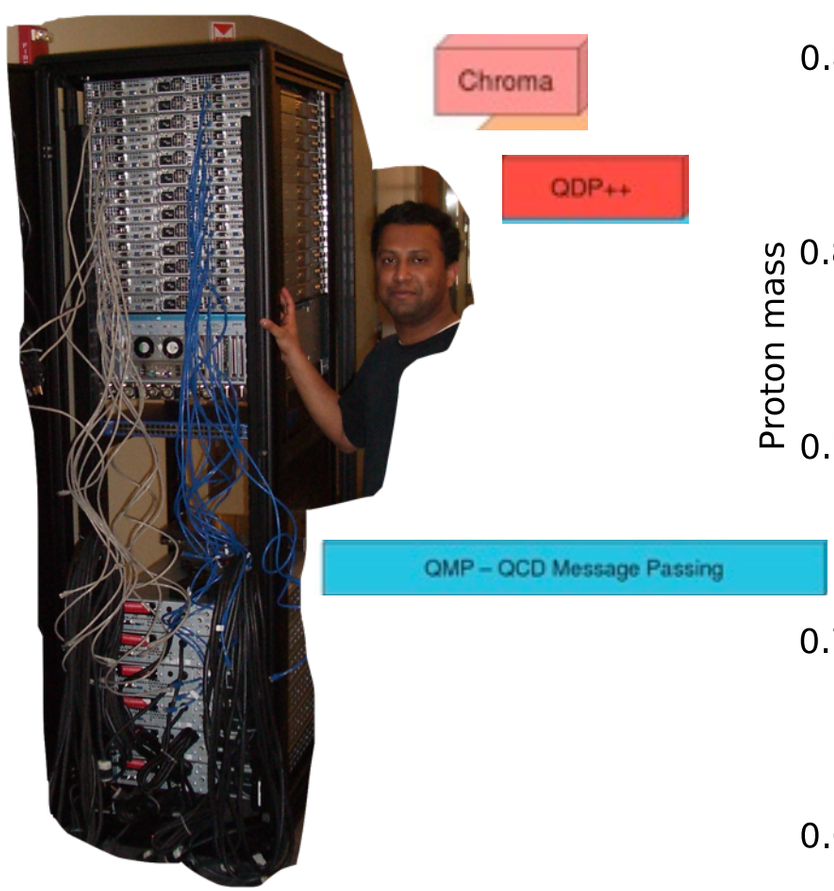
Aaron Torok
Indiana

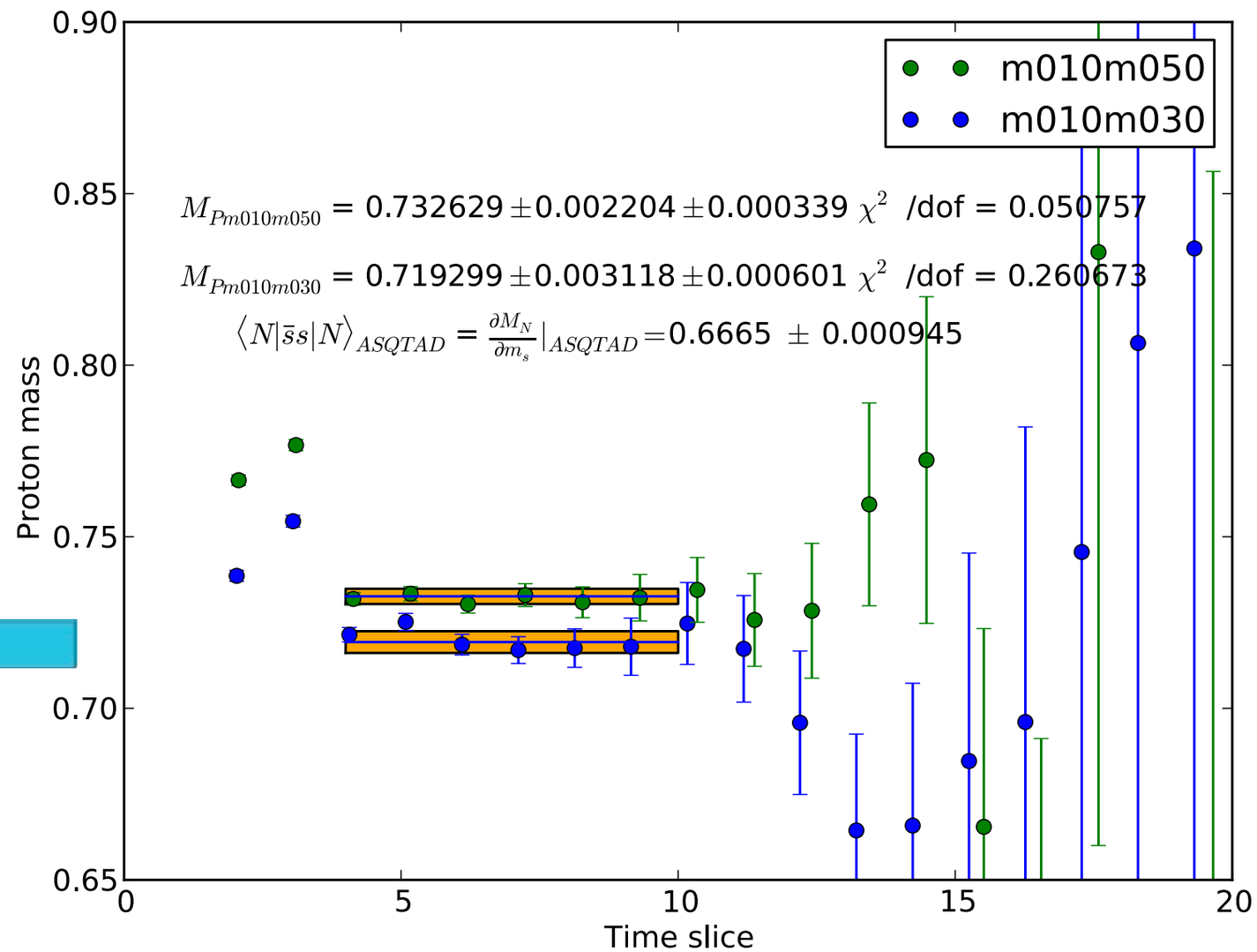
Andre Walker-Loud
LBNL

+

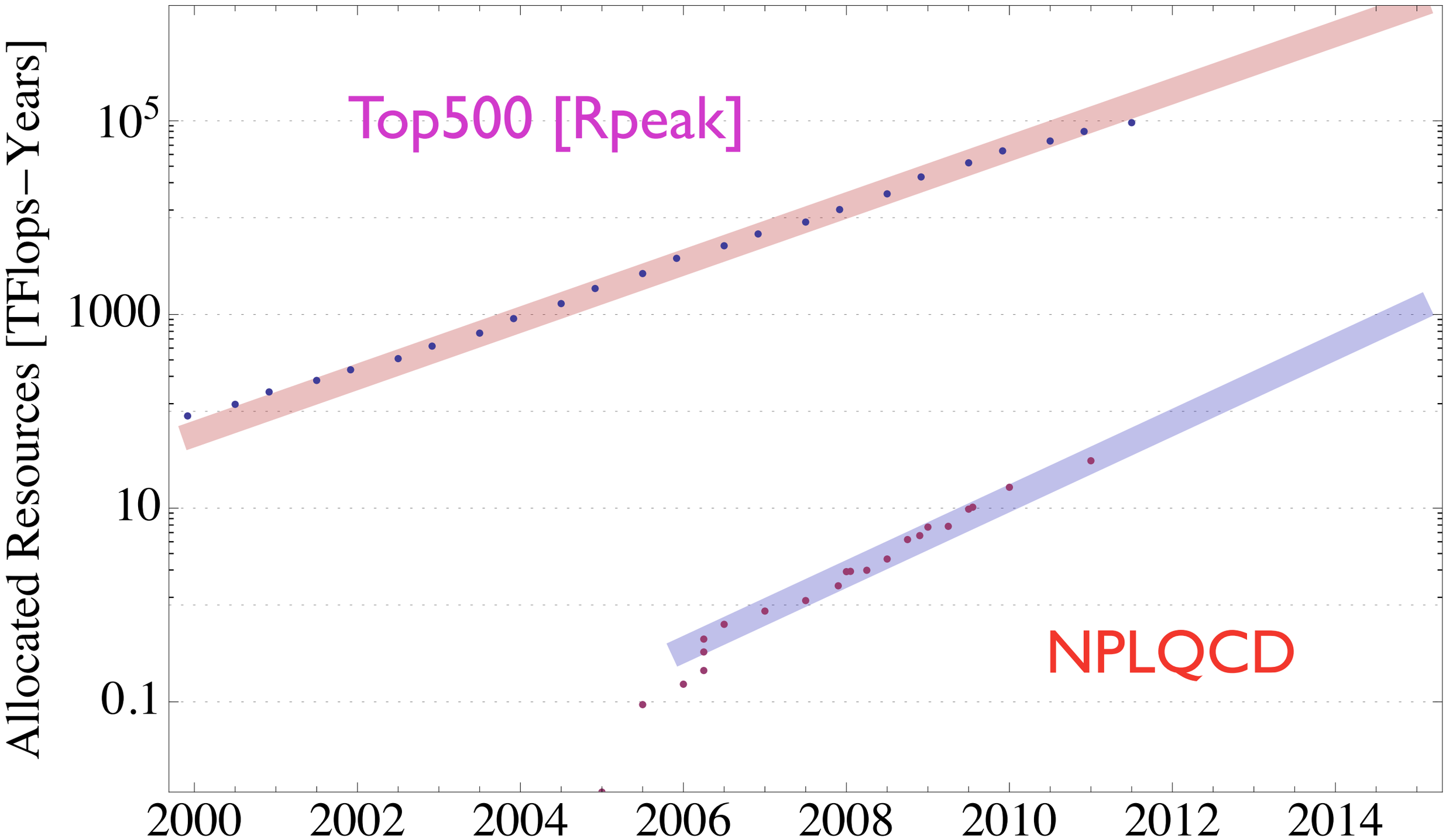
Parikshit Junnarkar
New Hampshire

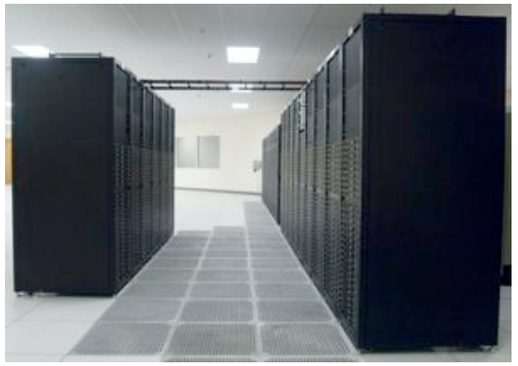
Endeavour photo album





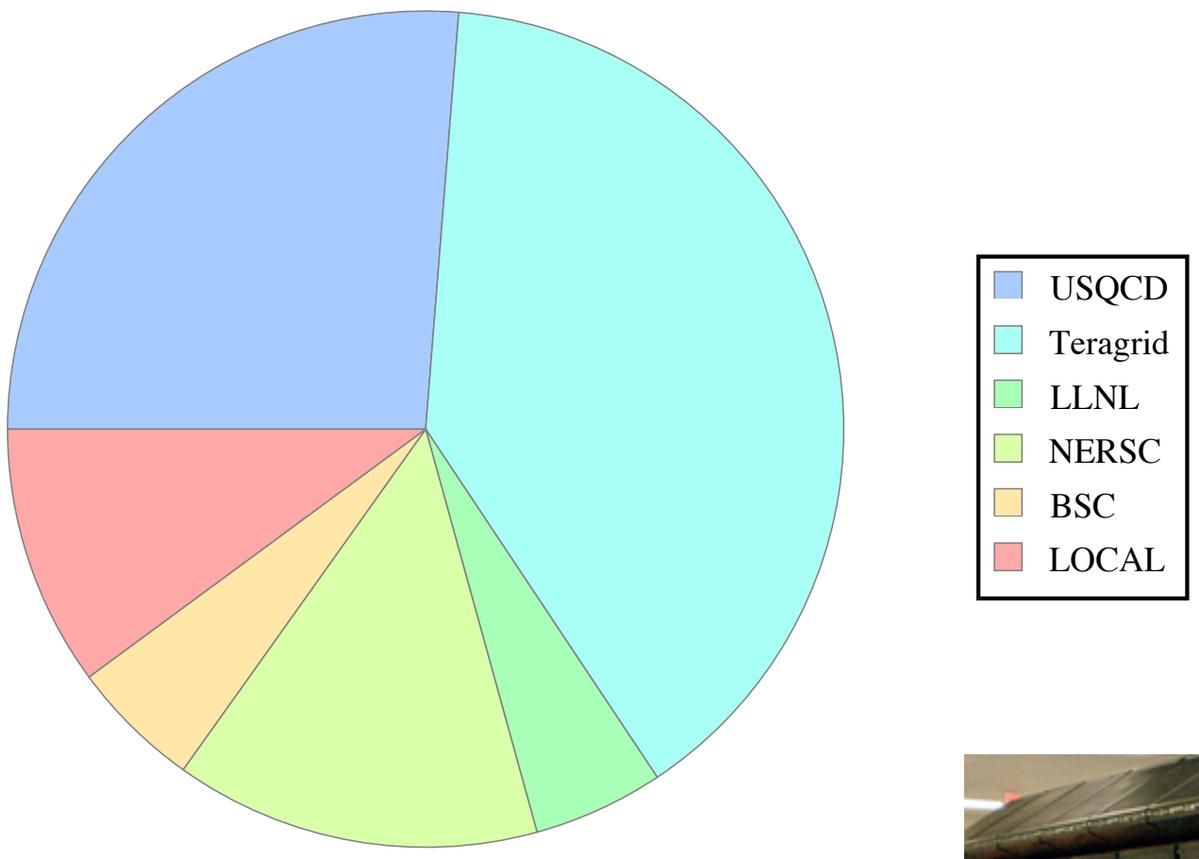
How we compare...

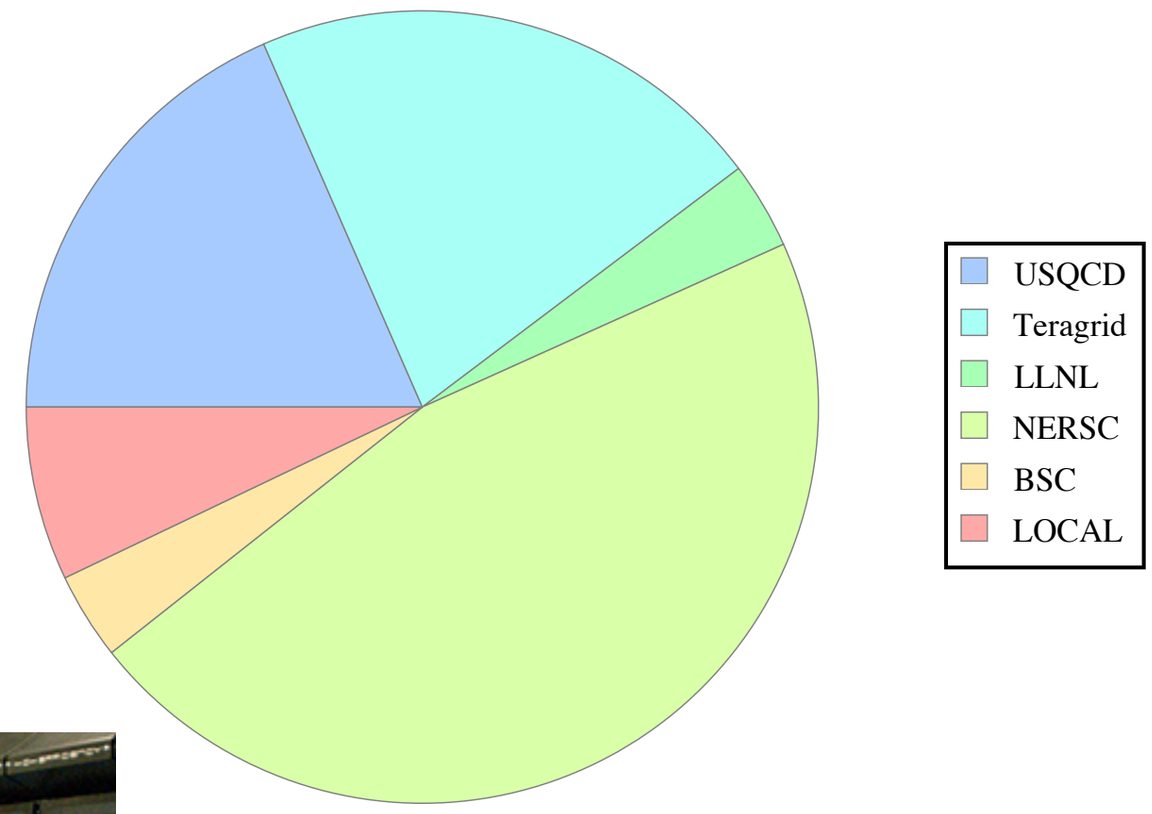




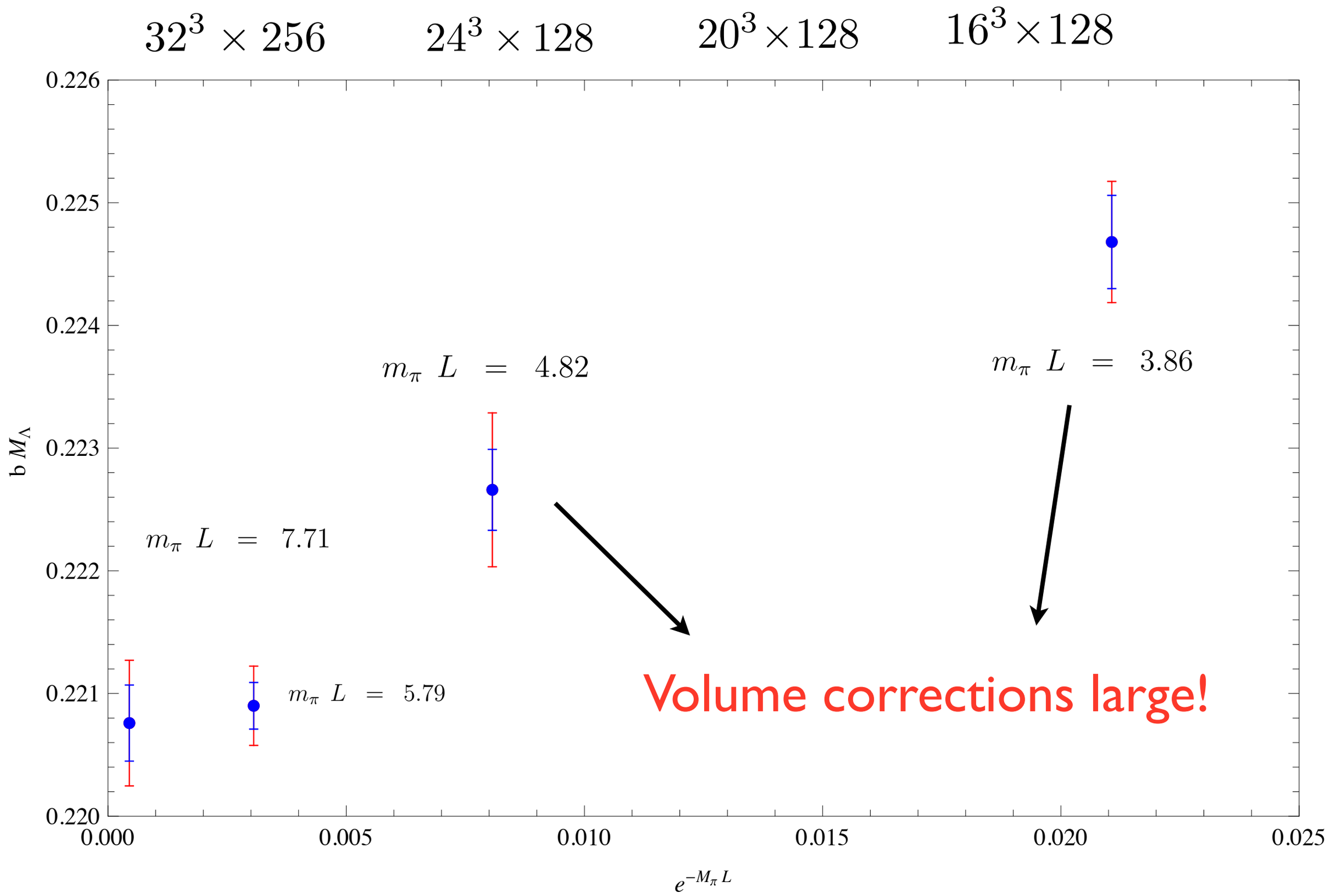
2009 NPLQCD

2011 NPLQCD

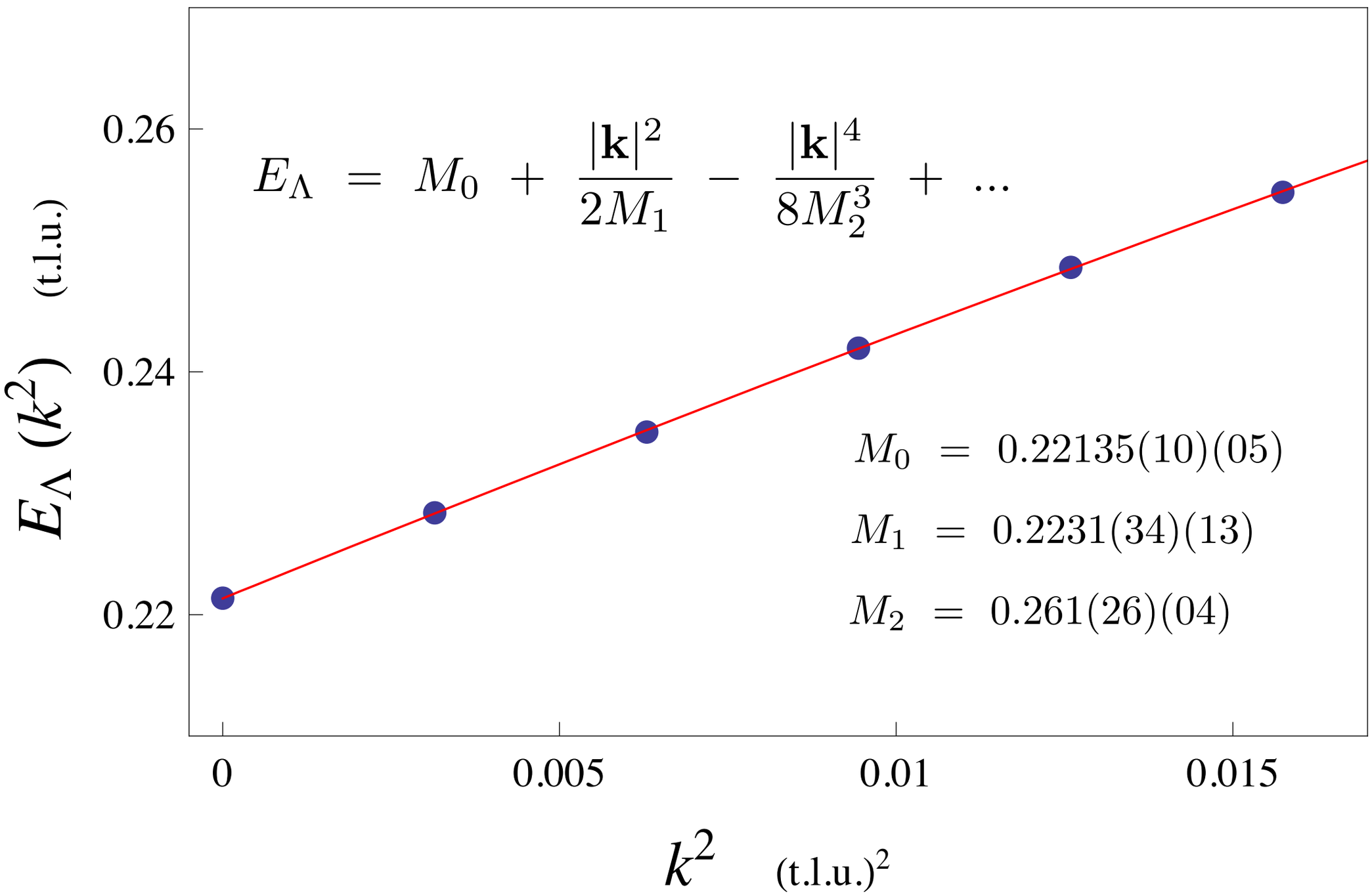




Volume dependence of the Λ mass



Energy-Momentum Relation



Special relativity satisfied!