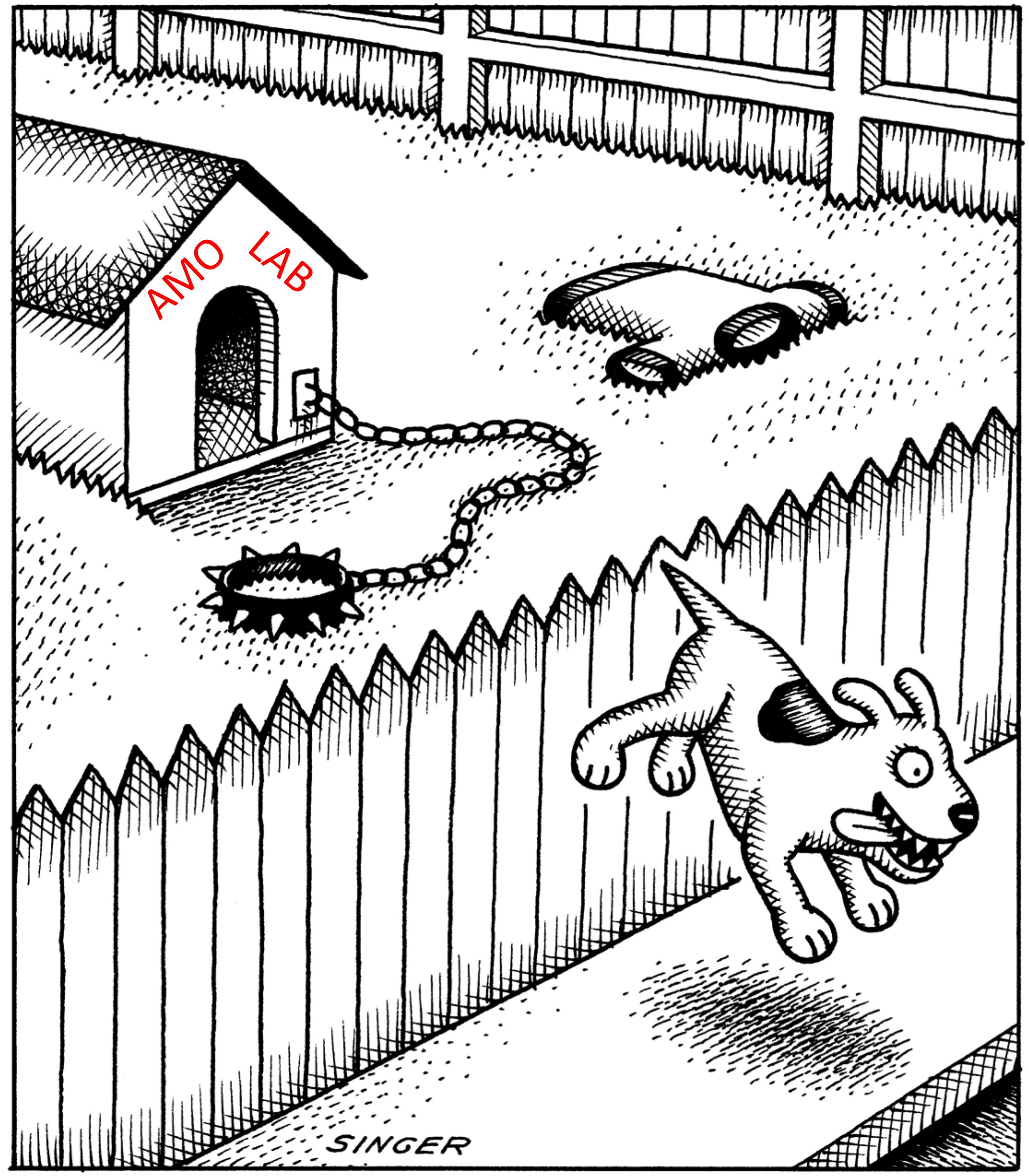
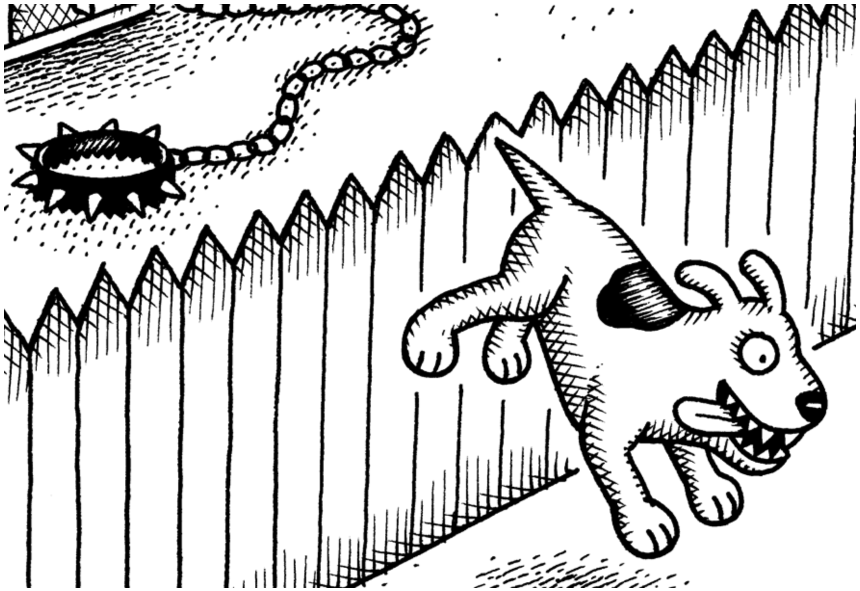
When Atomic Physicists Escape:

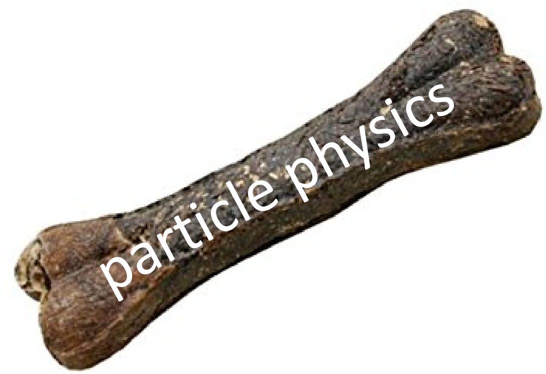
Baryogenesis; Materials; Liquids



artist: Andy Singer

Cagle.com

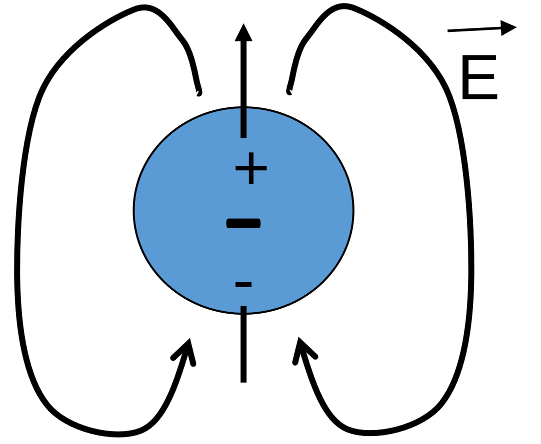



particle physics

As of 2013, the electron electric dipole moment eEDM was already known to be small

$d_e < 10^{-27}$ e-cm

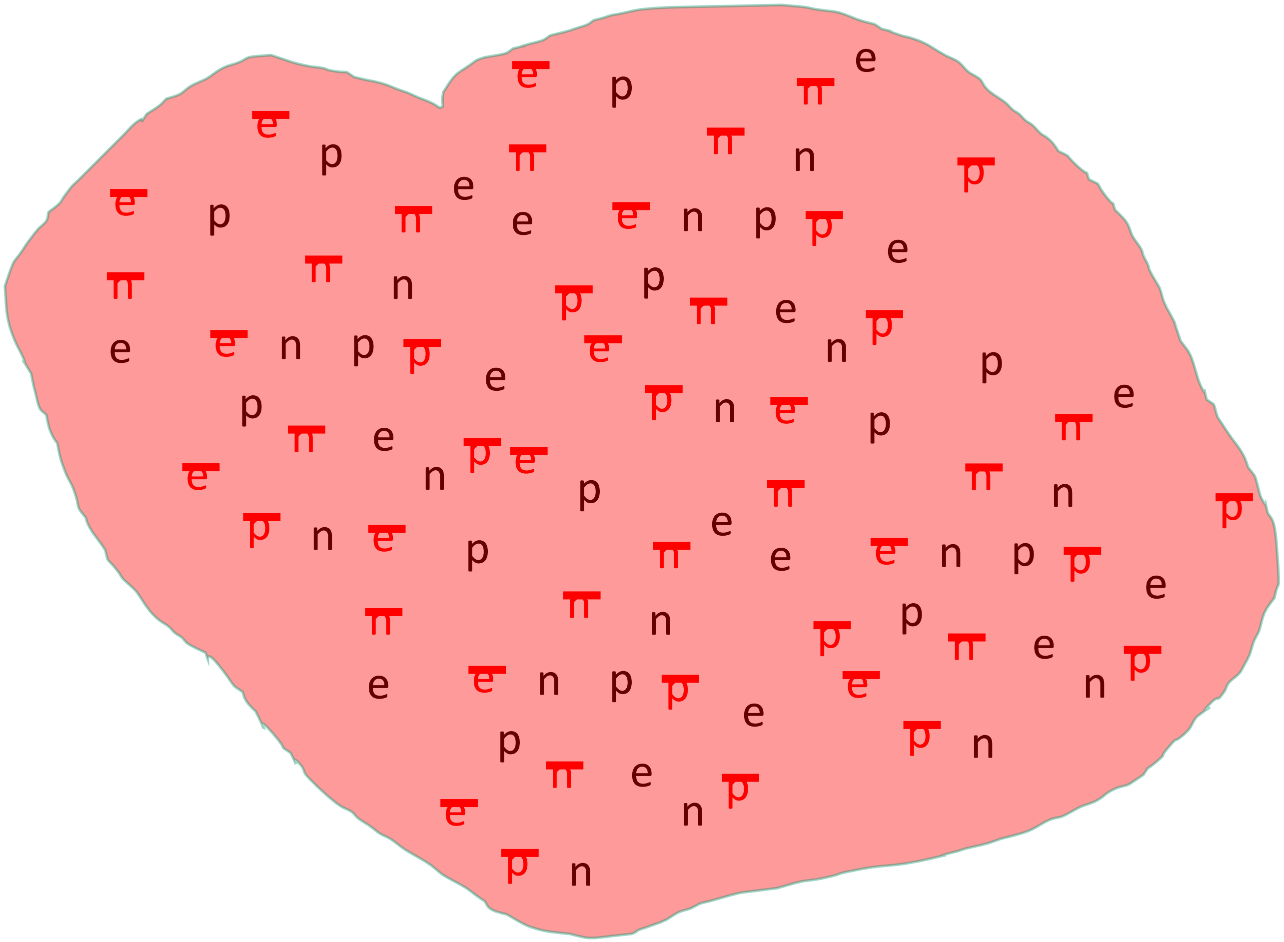
$< 10^{-14}\, e\, r_{classical}$ (Berkeley, Imperial)



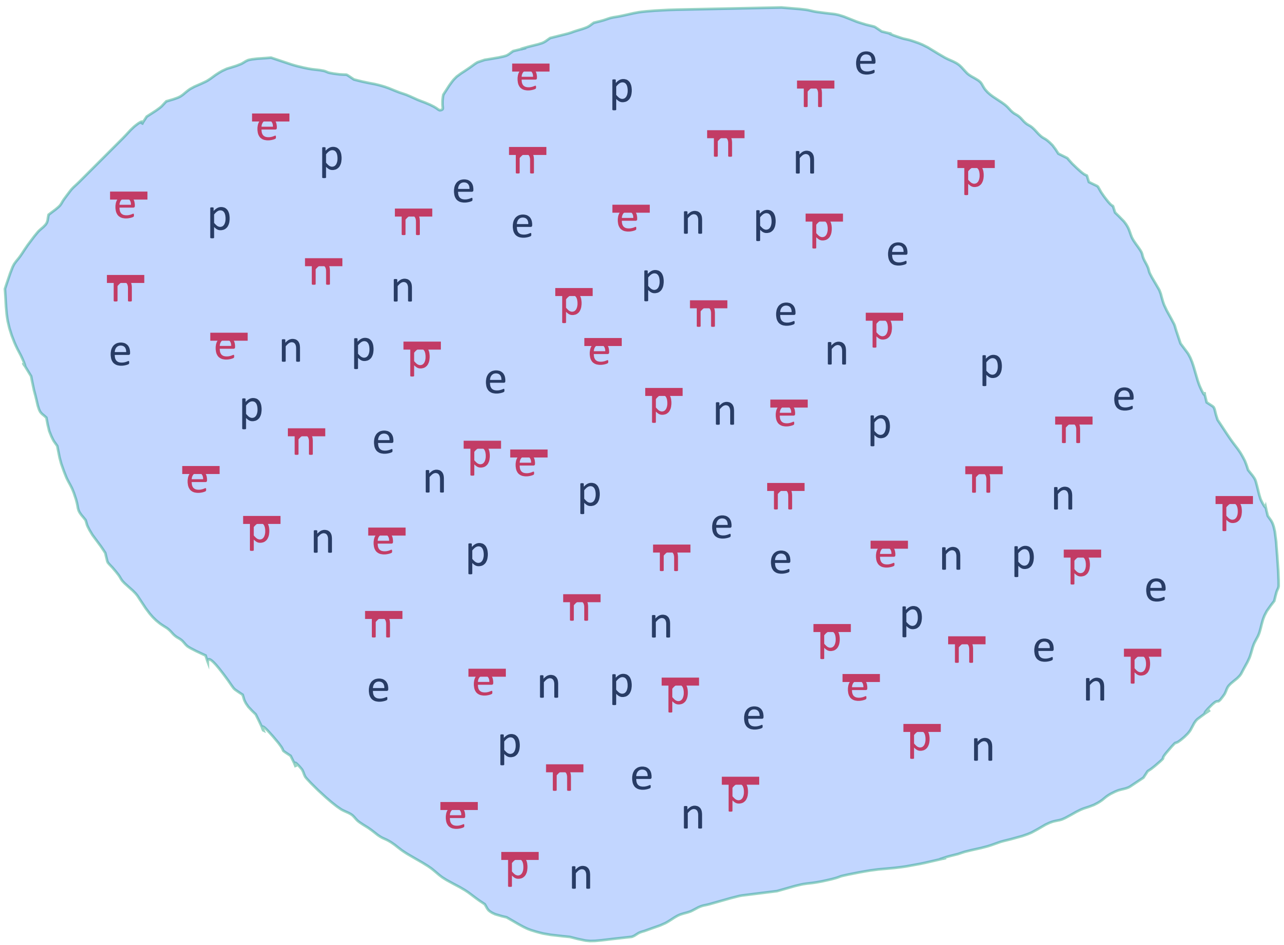
Why do better?

The situation, approximately
14 billion years before right now:

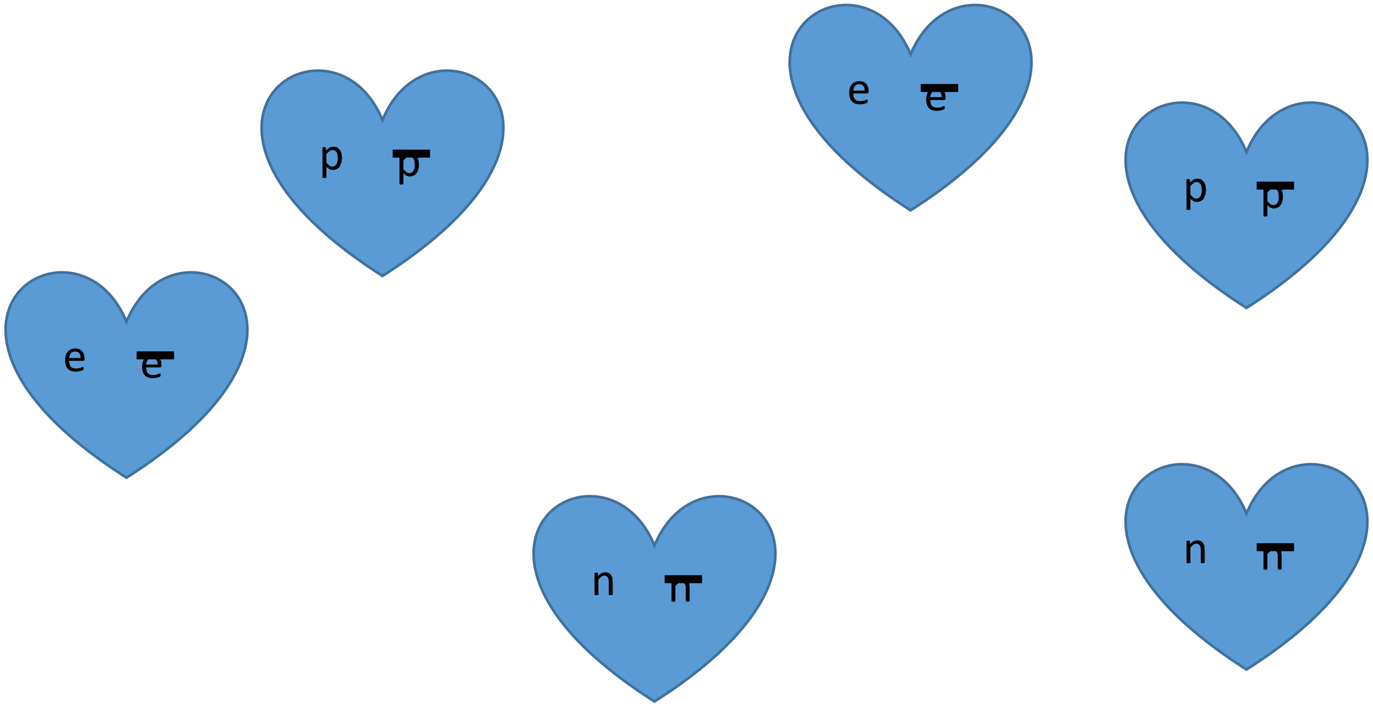
Then, shortly thereafter:

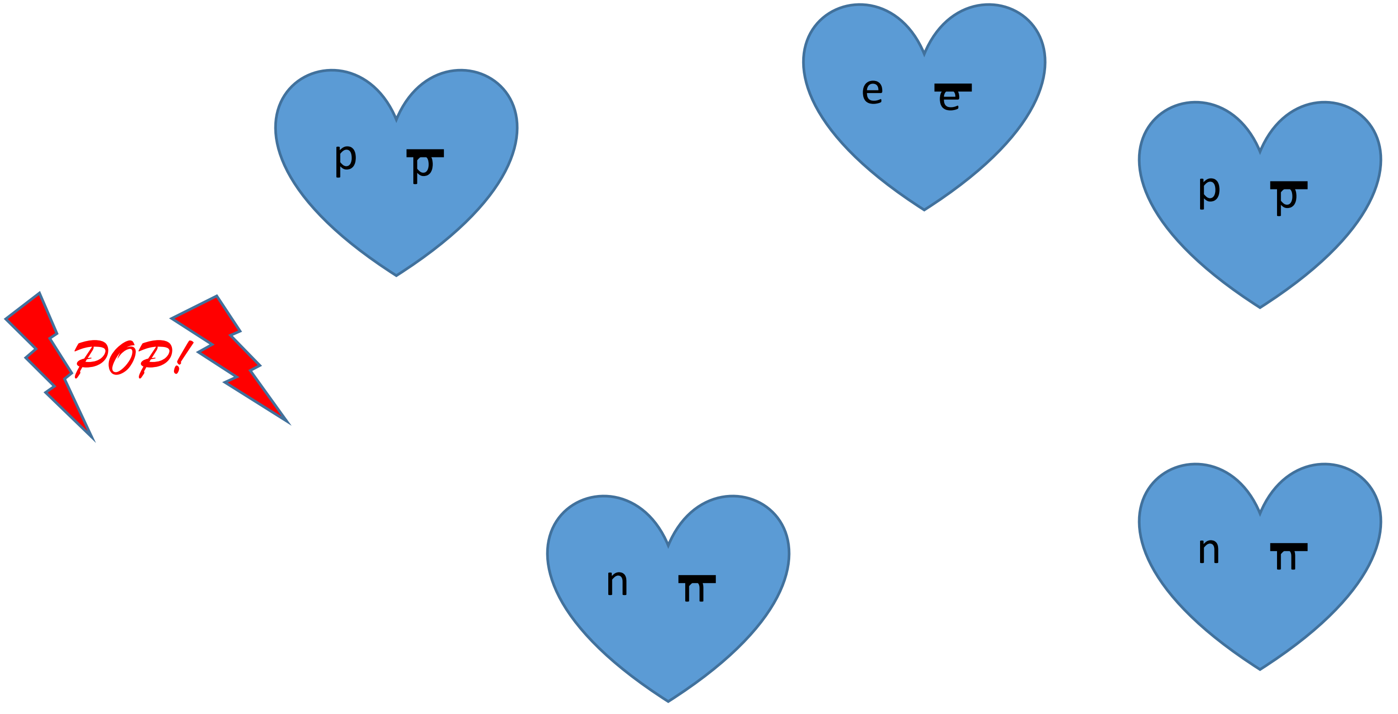


Then, the universe expanded and cooled:

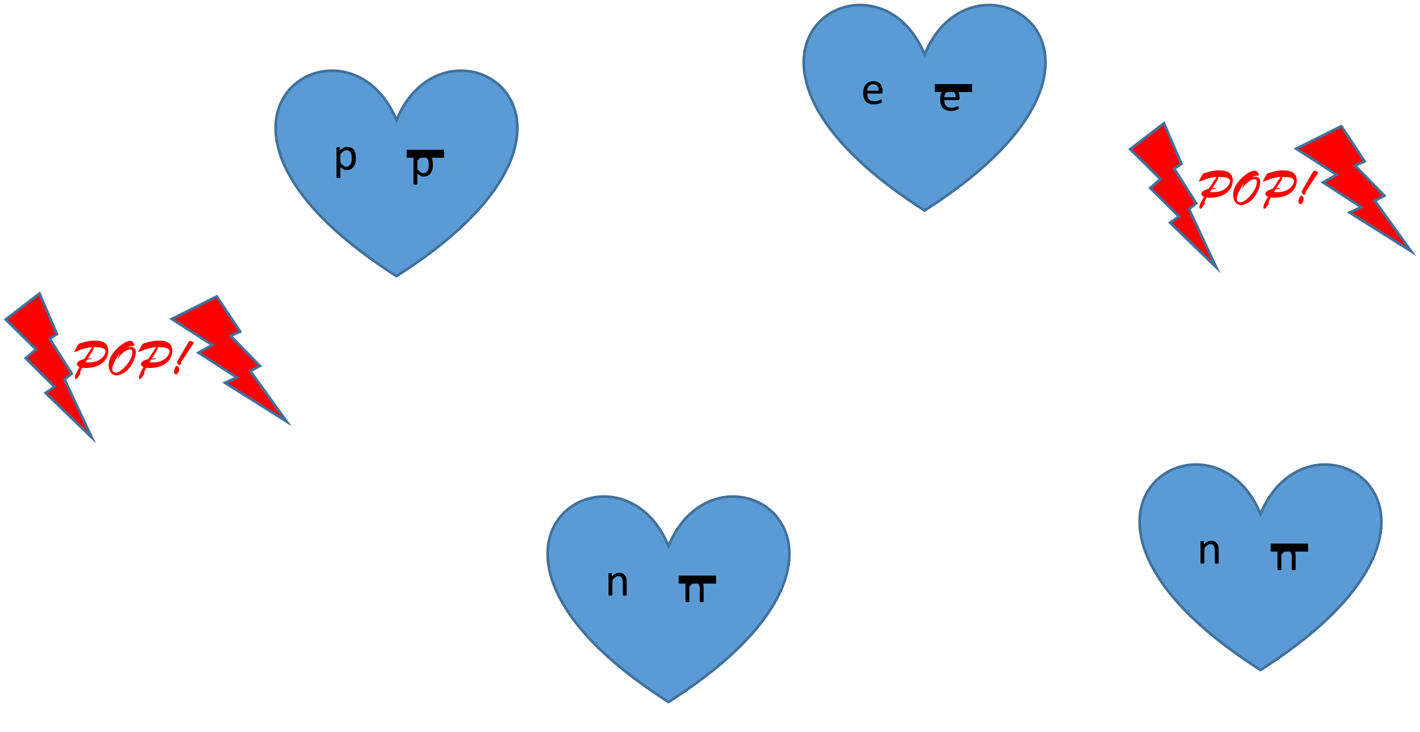


Then, true love!:





p $\bar{p}$
e $\bar{e}$
p $\bar{p}$
POP!
n $\bar{n}$
n $\bar{n}$



e $\bar{e}$
p $\bar{p}$
POP!
POP!
n $\bar{n}$
n $\bar{n}$


POP!

POP!

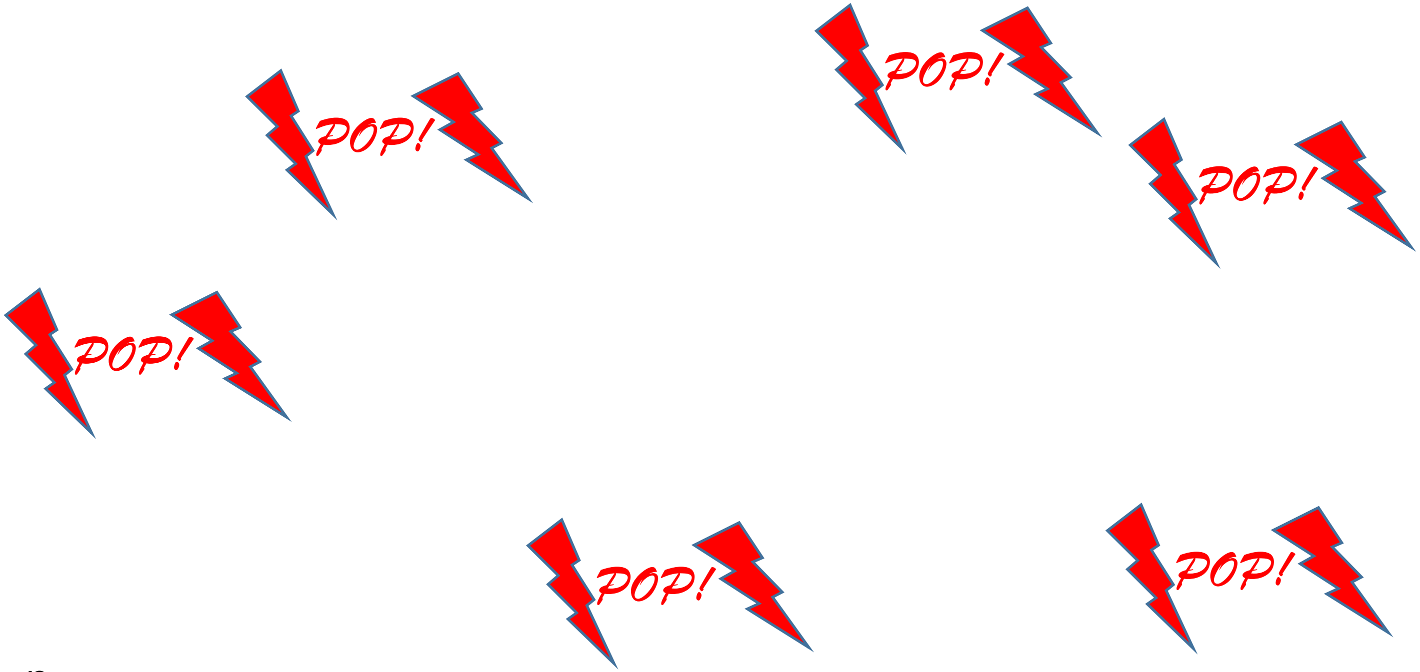
POP!

POP!

POP!

POP!

e



p

n

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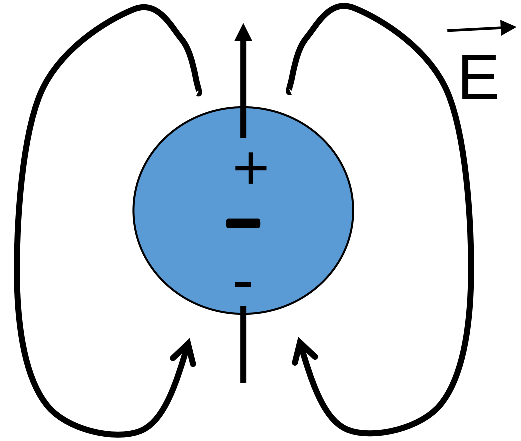
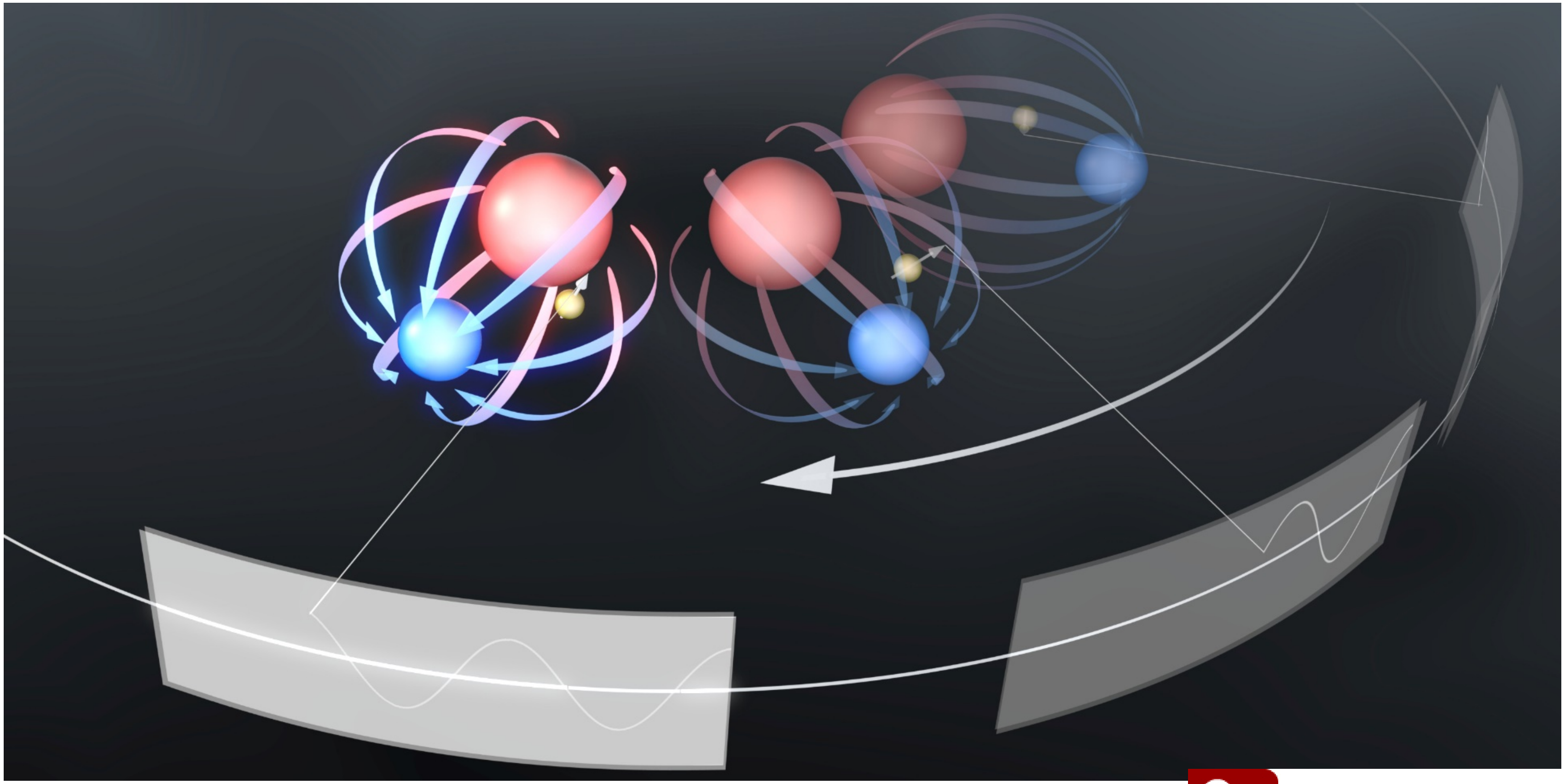
$d_e < 10^{-27}$ e-cm
$< 10^{-14}\ e\ r_{classical}$ (Berkeley, Imperial)



Why do better?

After the big bang cooled, most matter and antimatter annihilated, but *tiny* bit of matter left over, hooray!   Why?
There is CP violation in known present-day particle physics but not enough. Where is it hiding?

Measuring electron EDM using molecular ions



JILA eEDM collaboration

- *Dr. Yan Zhou*
- *Dr. Yuval Shagam*
- *Kia Boon Ng*
- *Will Cairncross*
- *Dan Gresh*
- *Tanya Roussy*
- *Fatemeh Abbasi-Razgaleh*
- *Jeff Meyers, Kevin Boyce*
- ***Jun Ye***
- *Eric Cornell*

Local theory: John Bohn

Non local Theory: Bob Field

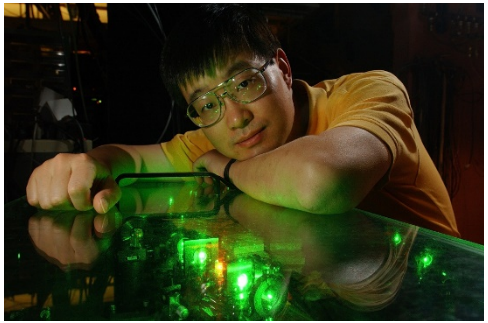
Still Less Local Theory

St. Petersberg quantum chemistry group

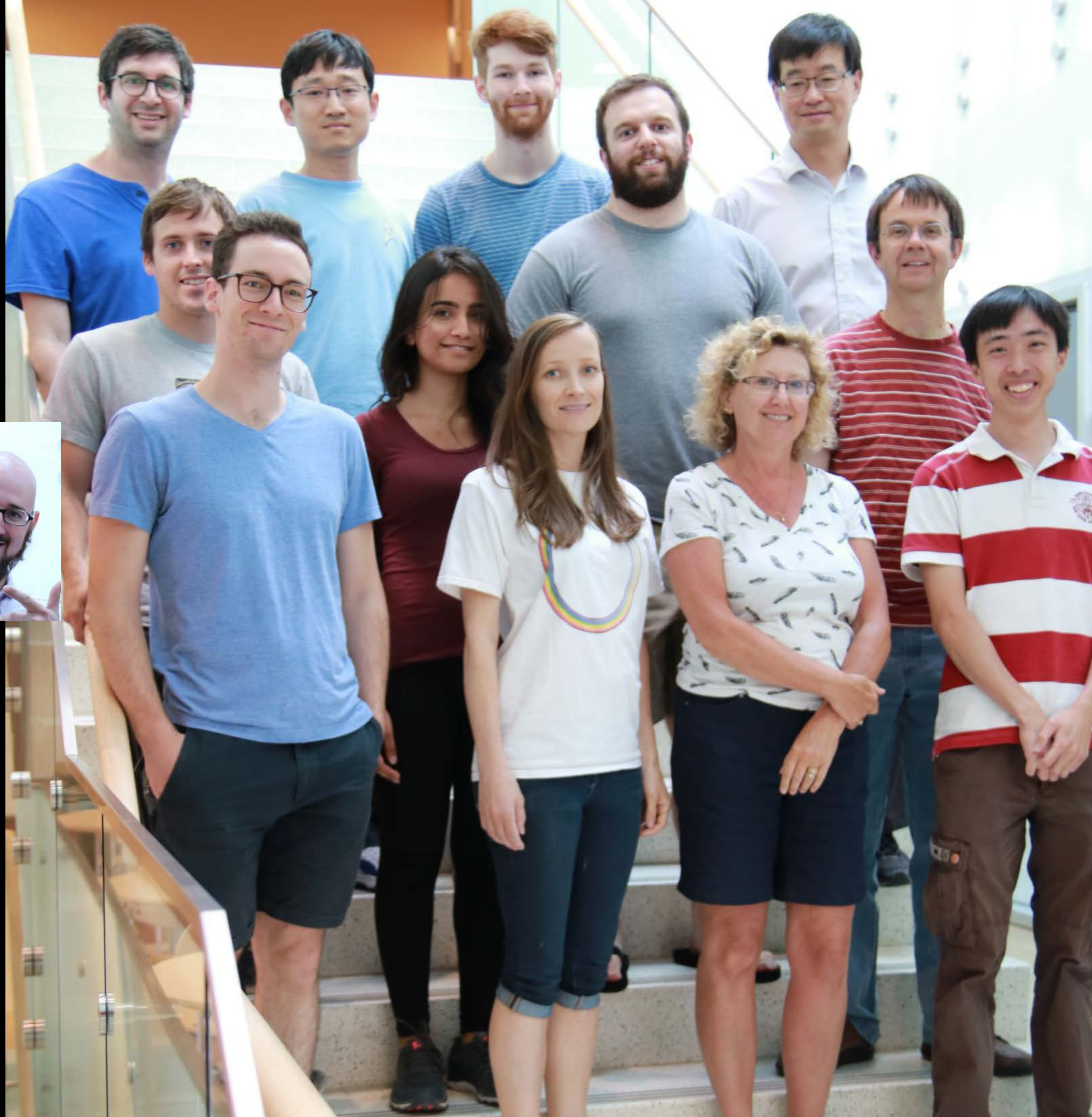
Past Group Members

- Laura Sinclair
- Kang-Kuen Ni
- Kevin Cossel
- Russ Stutz
- Aaron Leanhardt
- Yiqi Ni
- Huanqian Loh
- Matt Grau

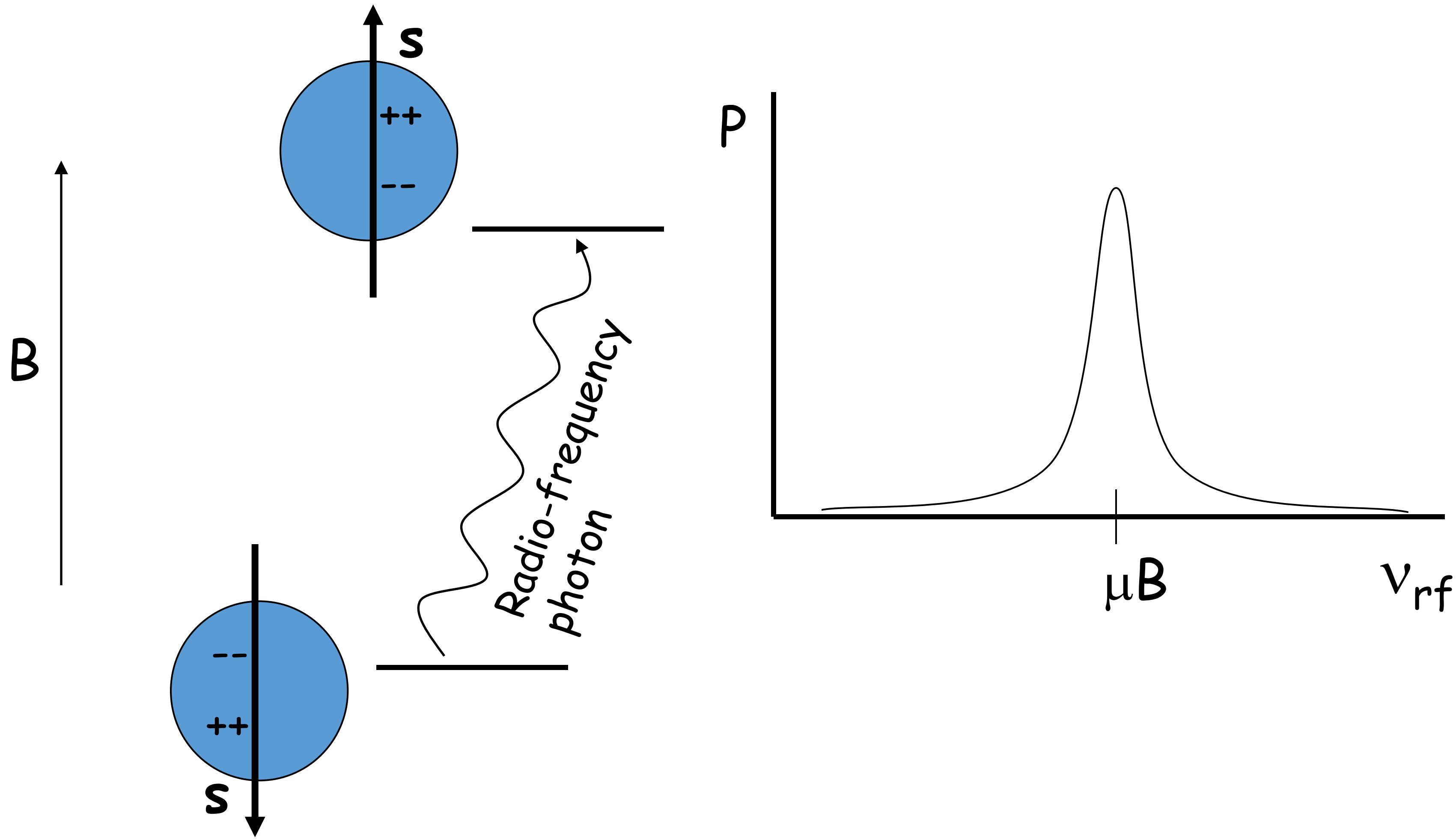
Thanks: NSF/PFC, NIST,
and Marsico Foundati



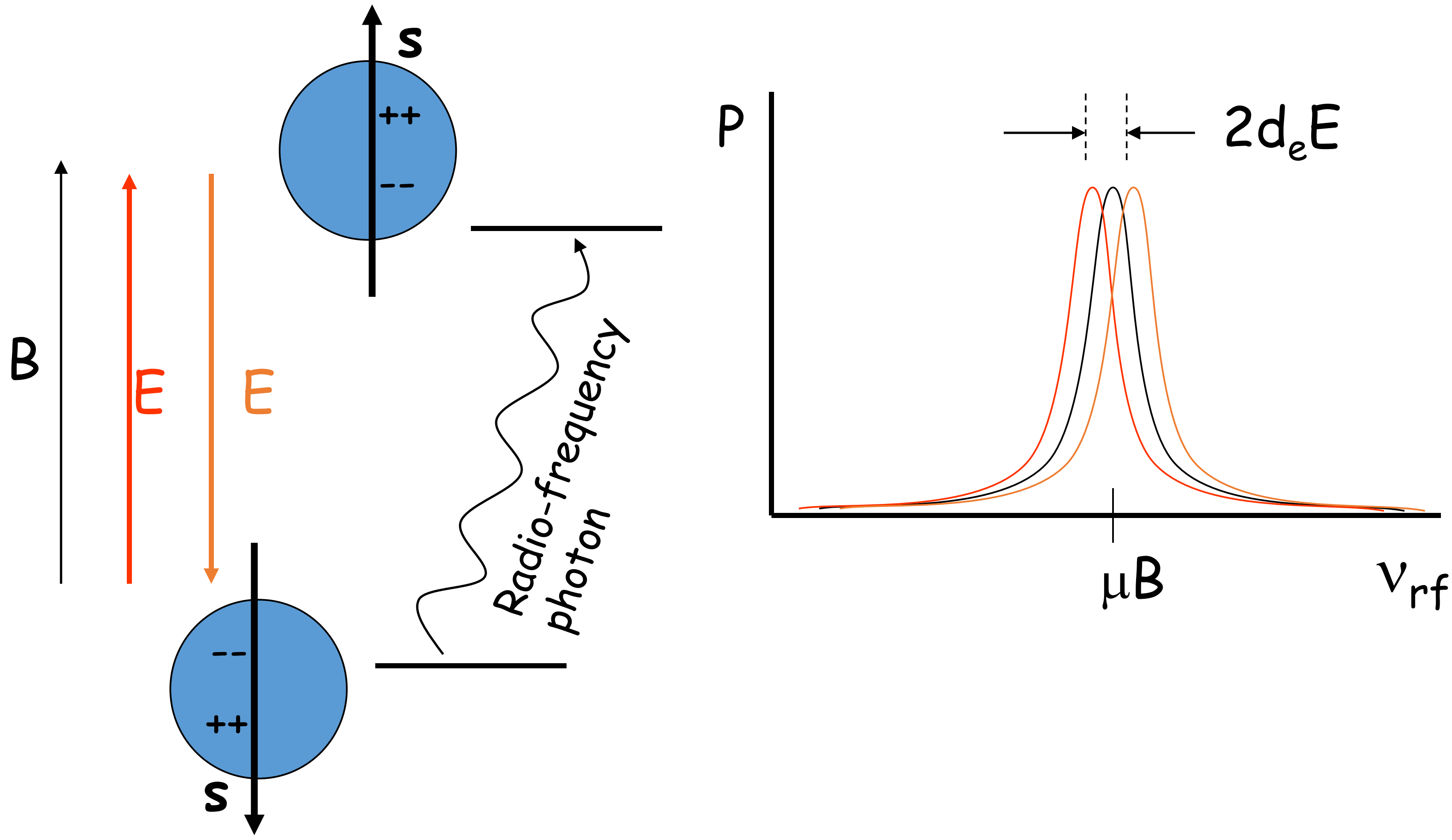


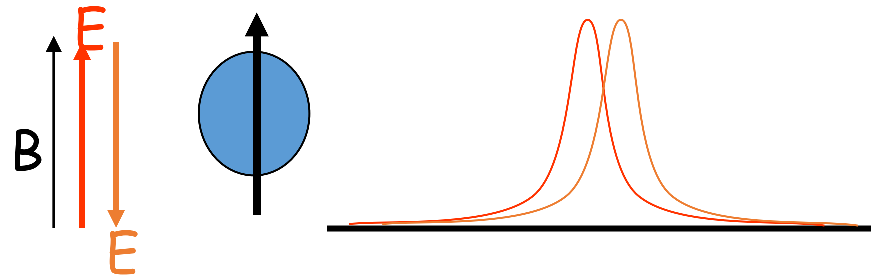



How to measure eEDM? First, how do we measure eMDM?



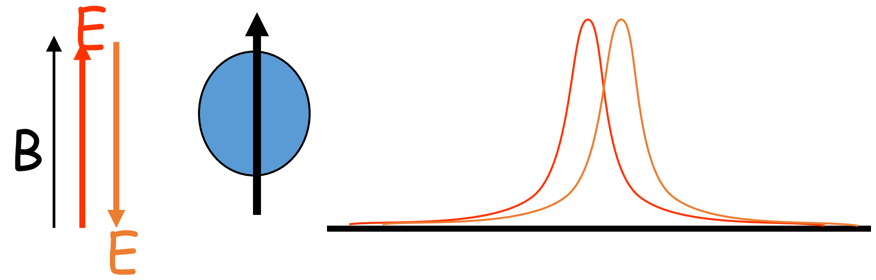
How to measure eEDM?





E
B
E

Figure-of-merit:
What makes a good EDM experiment?



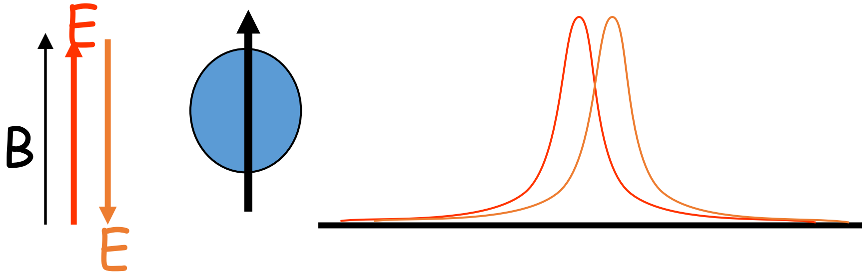
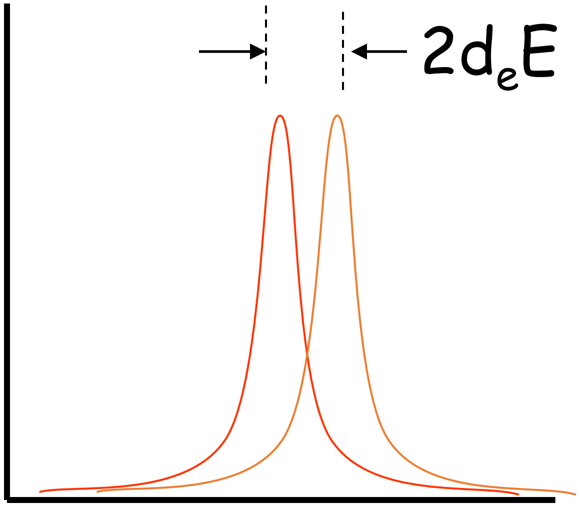
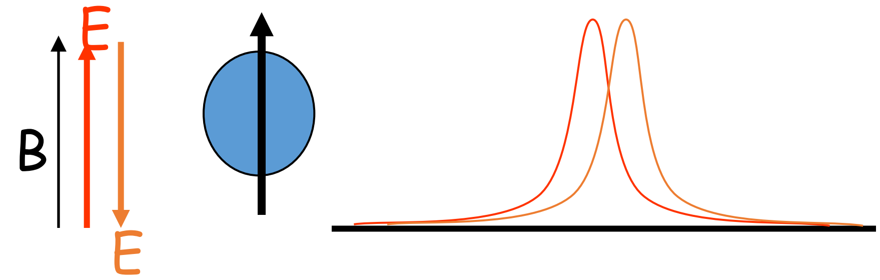


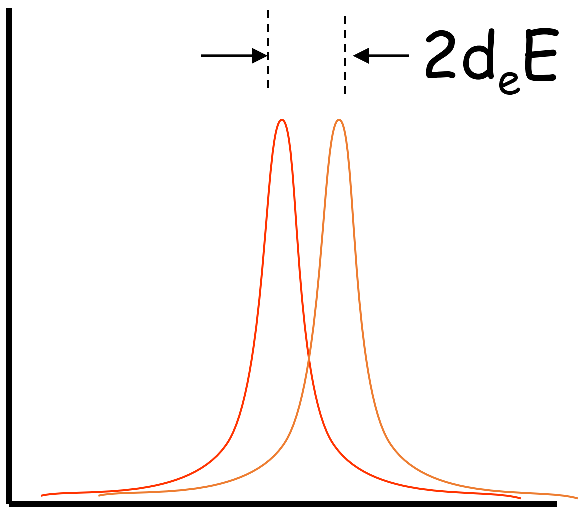
Figure-of-merit:
What makes a good EDM experiment?



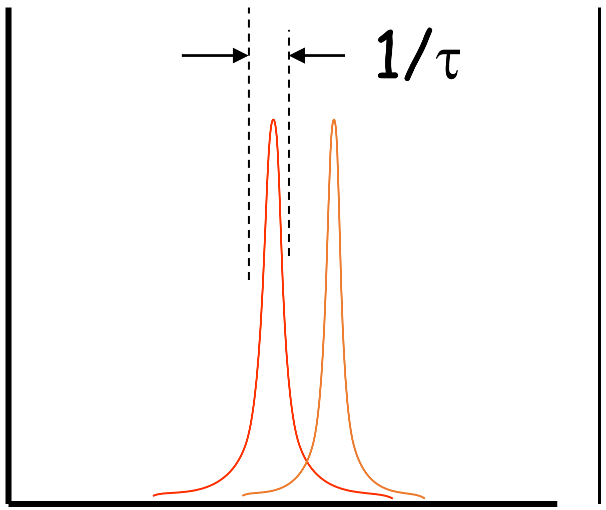
Big Electric Field!

Figure-of-merit:
What makes a good EDM experiment?





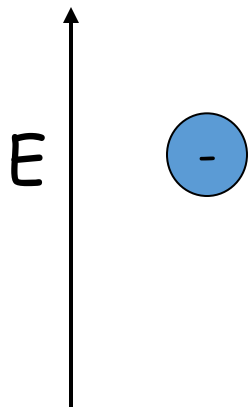
Big Electric Field!



Long Coherence Time (narrow resonances)!

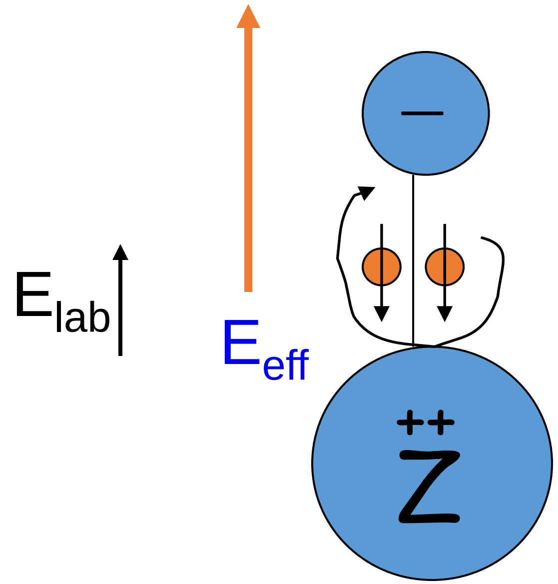
Problem:

Big E, long τ.   Electron accelerates quickly, and is gone????



Our approach. 1. Use molecule for big E_{eff}

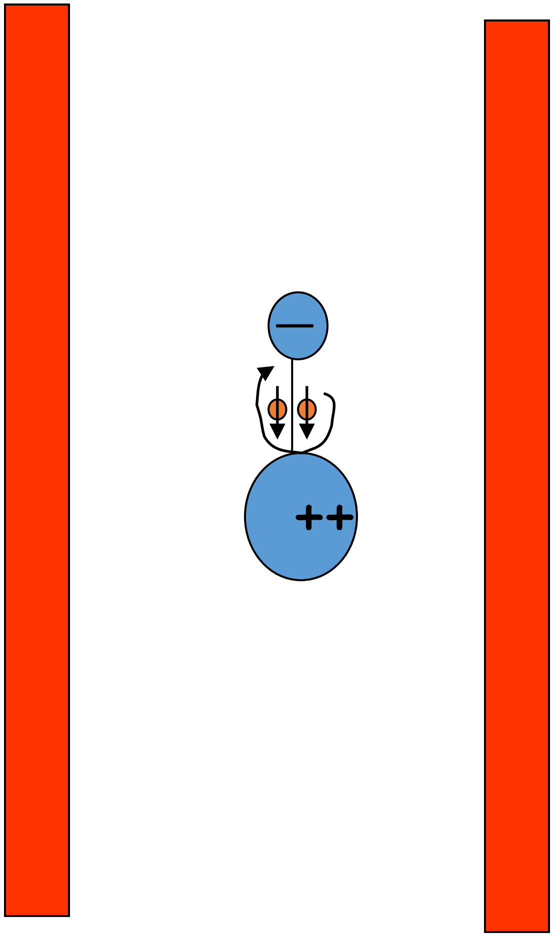
(we follow Hinds and Demille in this)



$E_{lab} = 10$ V/cm $\quad E_{eff} > 10^{10}$ V/cm

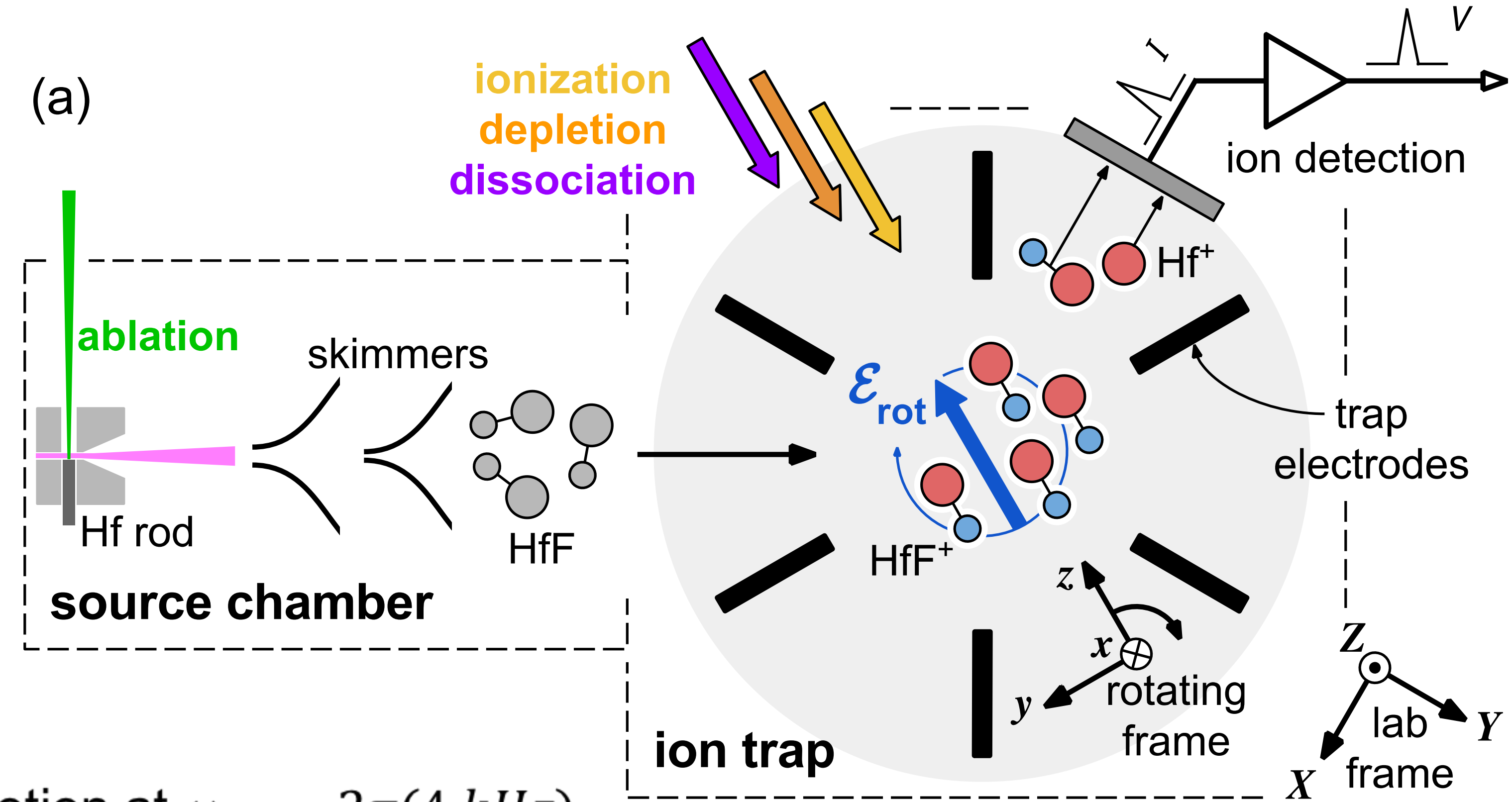
Our approach. 2. Use trapped ion for long τ

(atomic spectroscopy in ion traps sees many seconds)



We will work in an ion trap.

Apparatus

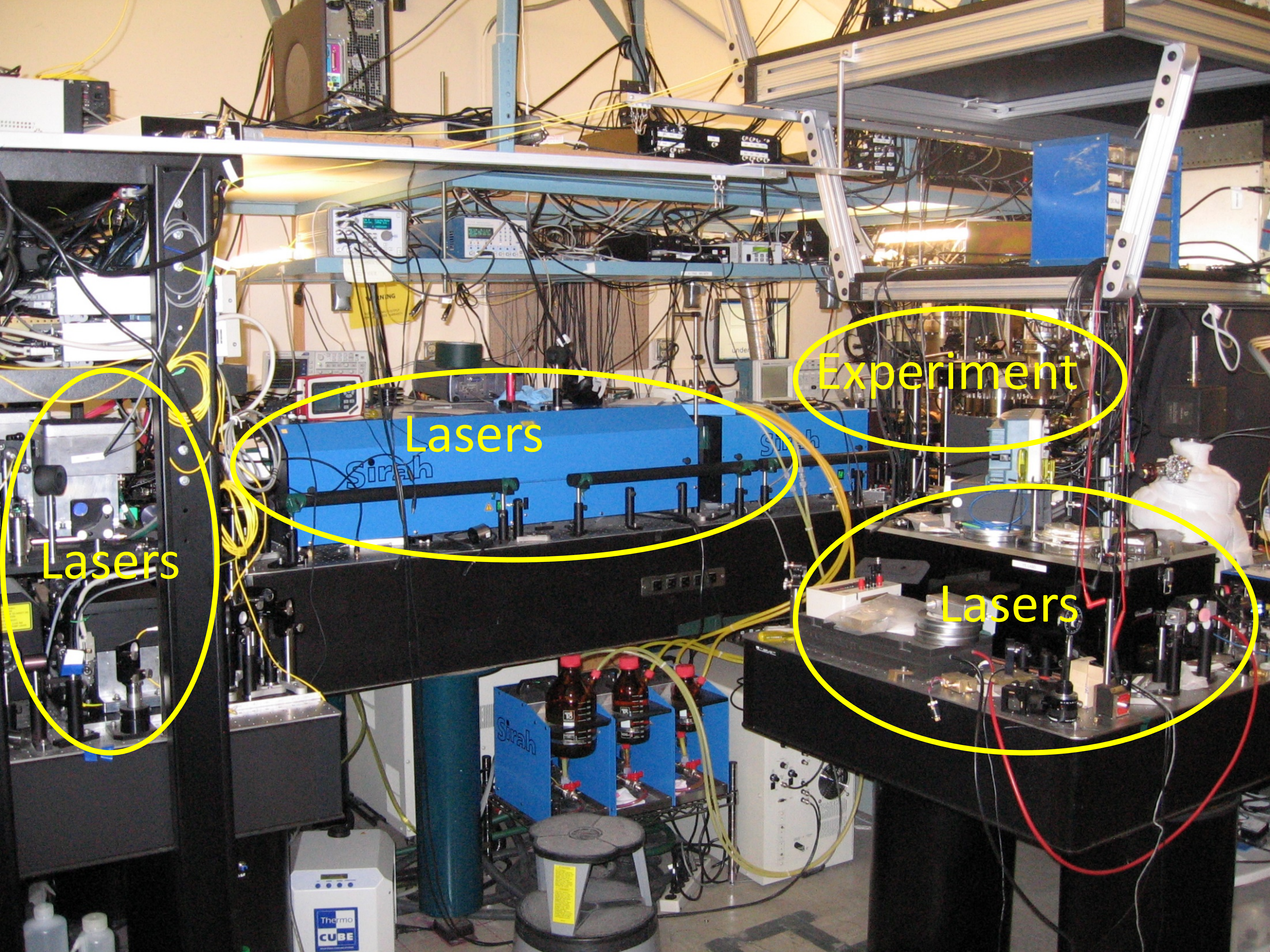


Secular trap motion at $\omega_{Sec} \sim 2\pi(4\ kHz)$

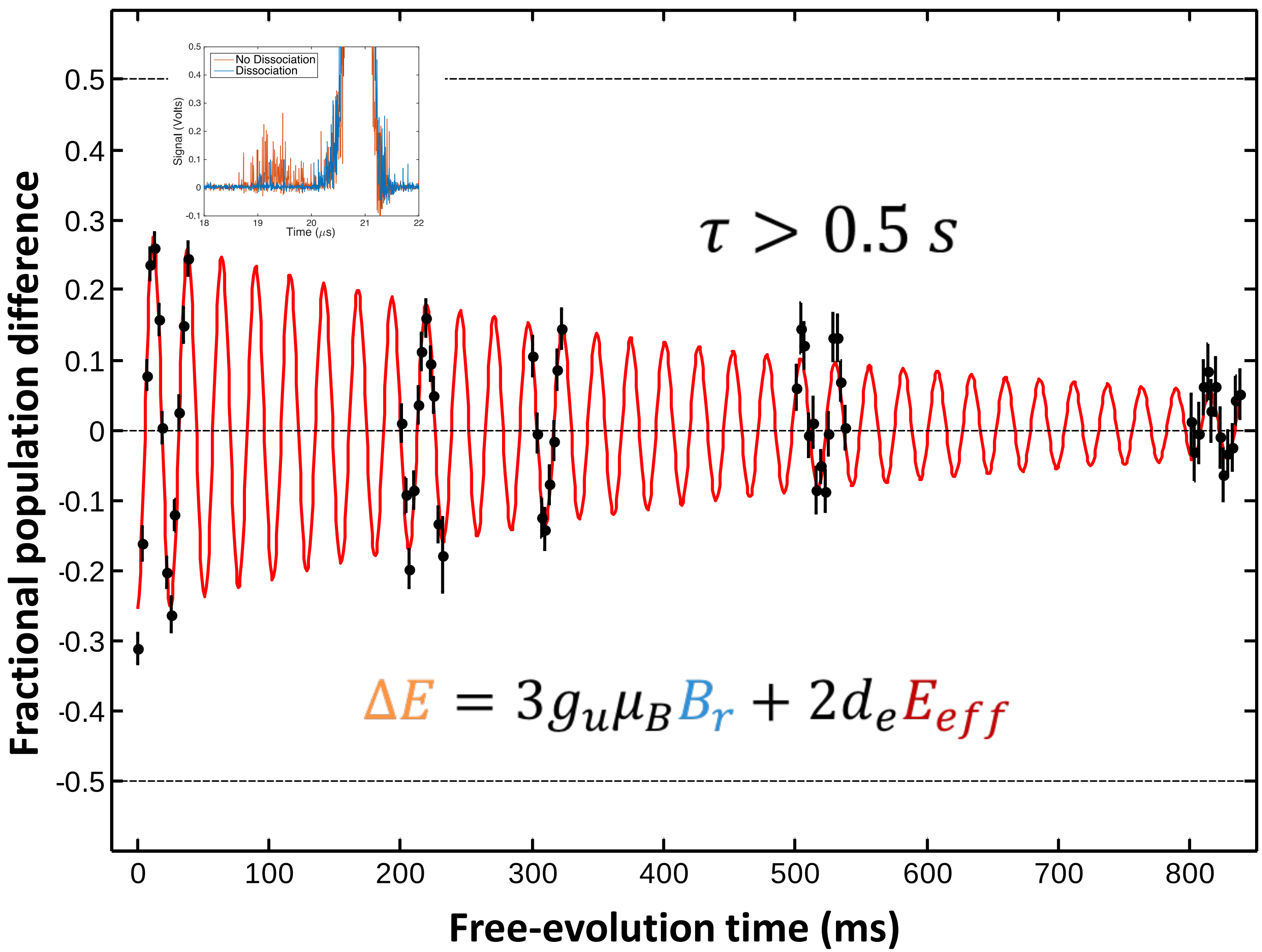
"RF" micromotion at $\omega_{rf} = 2\pi(50\ kHz)$

Rotational micromotion at $\omega_{rot} = 2\pi(250\ kHz)$

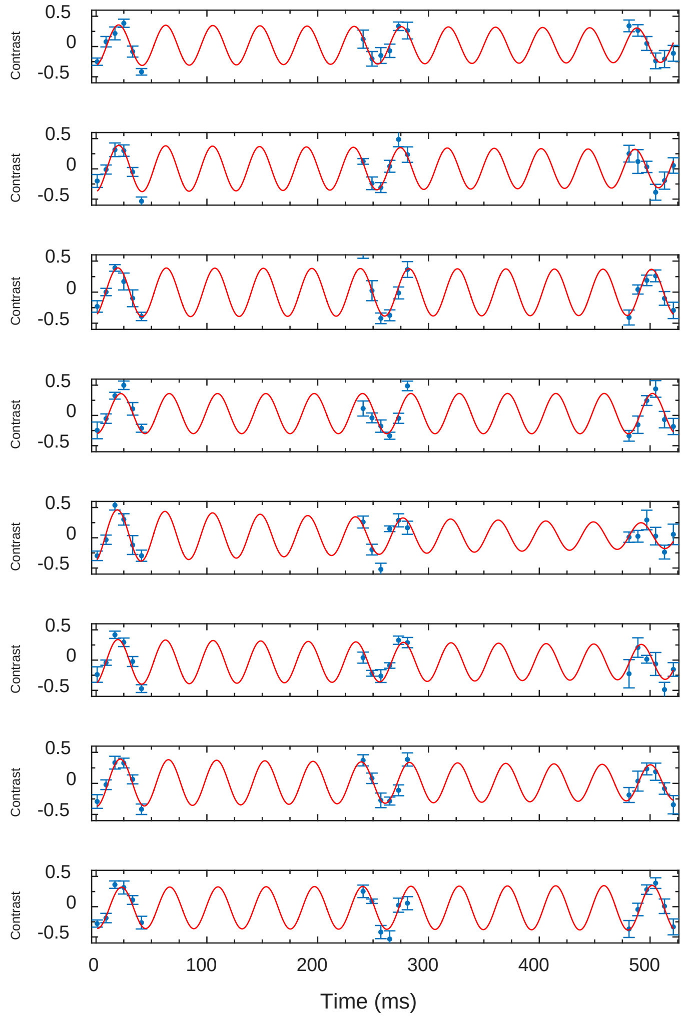
Rotating magnetic field: <u>not sensitive to DC fields</u>

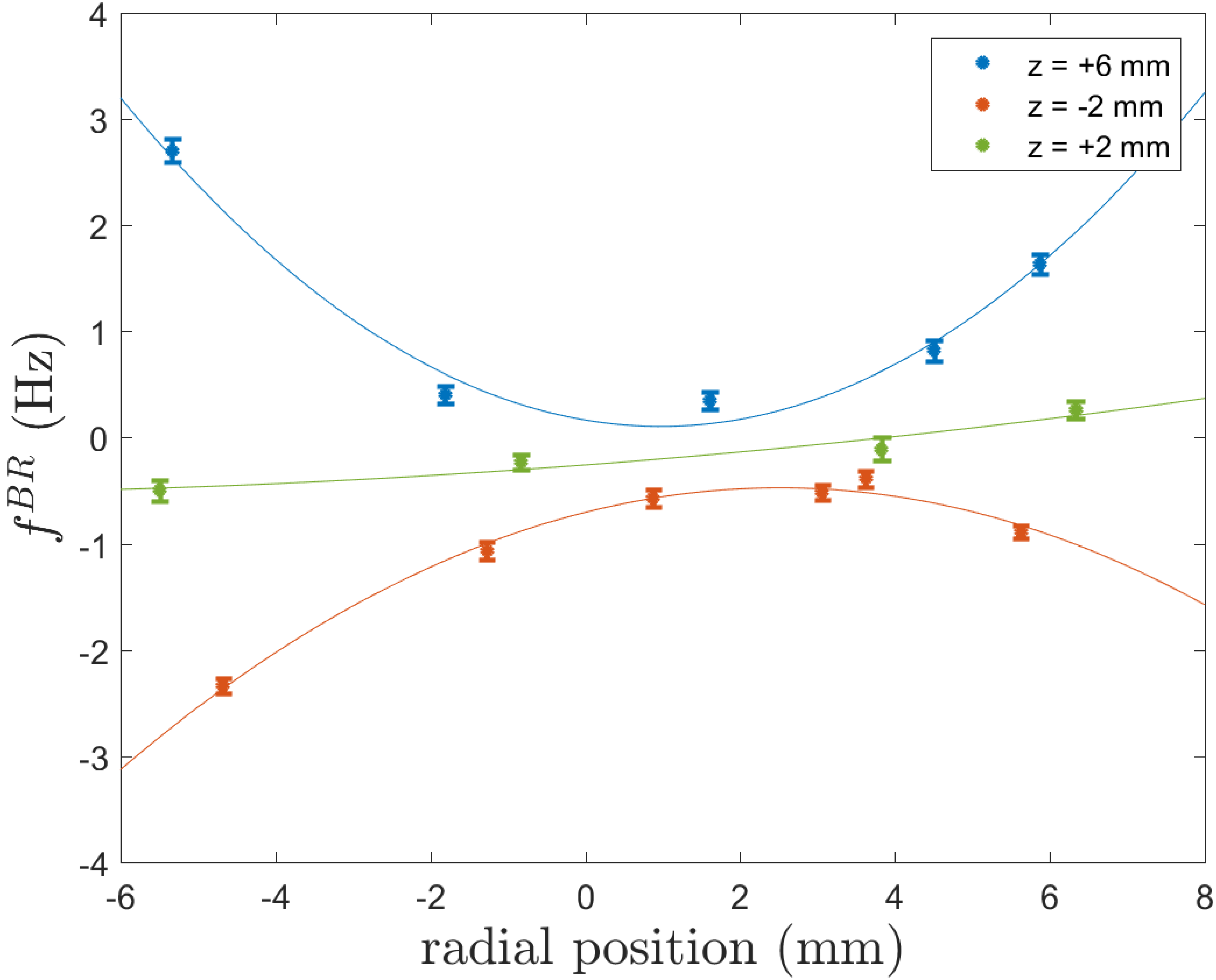

Experiment
Lasers
Lasers
Lasers

Ramsey Fringe – Electron Spin Resonance

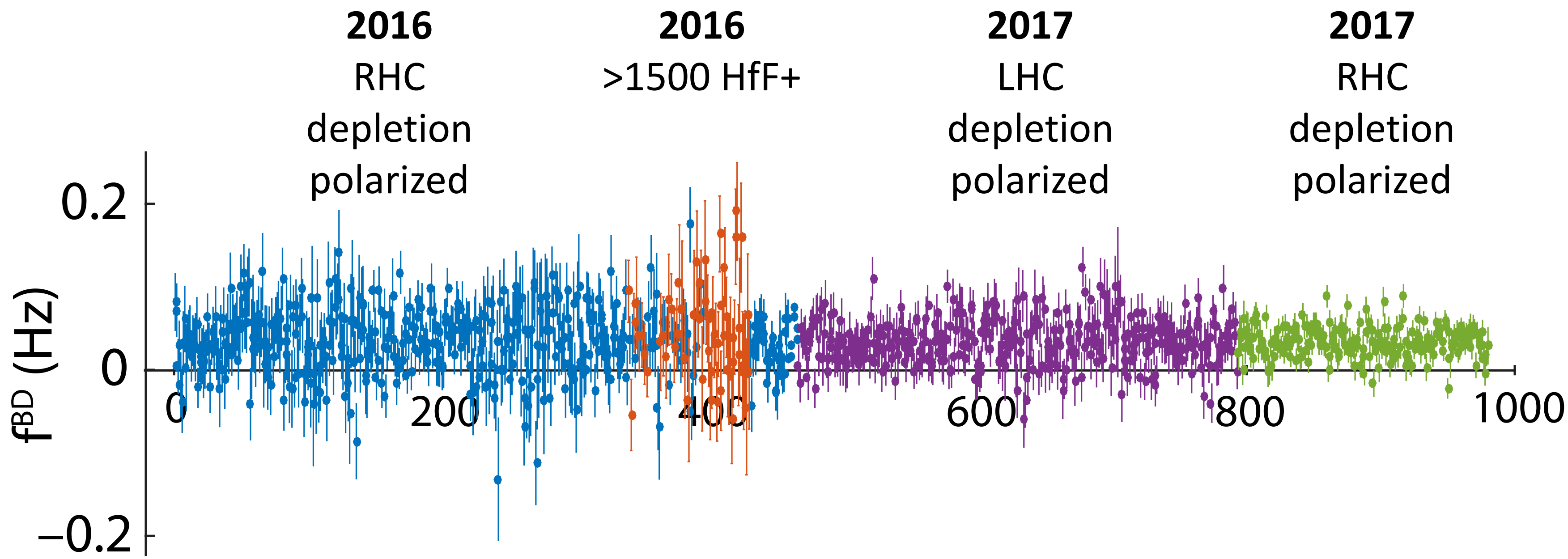


$\vec{B}$	$\vec{E}_{eff}$	$\vec{R}$	f^0	f^B	f^D	f^R	f^{BD}	f^{BR}	f^{DR}	f^{BDR}
↓	↓	↺	+	−	−	−	+	+	+	−
↓	↓	↻	+	−	−	+	+	−	−	+
↓	↑	↺	+	−	+	−	−	+	−	+
↓	↑	↻	+	−	+	+	−	−	+	−
↑	↓	↺	+	+	−	−	−	−	+	+
↑	↓	↻	+	+	−	+	−	+	−	−
↑	↑	↺	+	+	+	−	+	−	−	−
↑	↑	↻	+	+	+	+	+	+	+	+



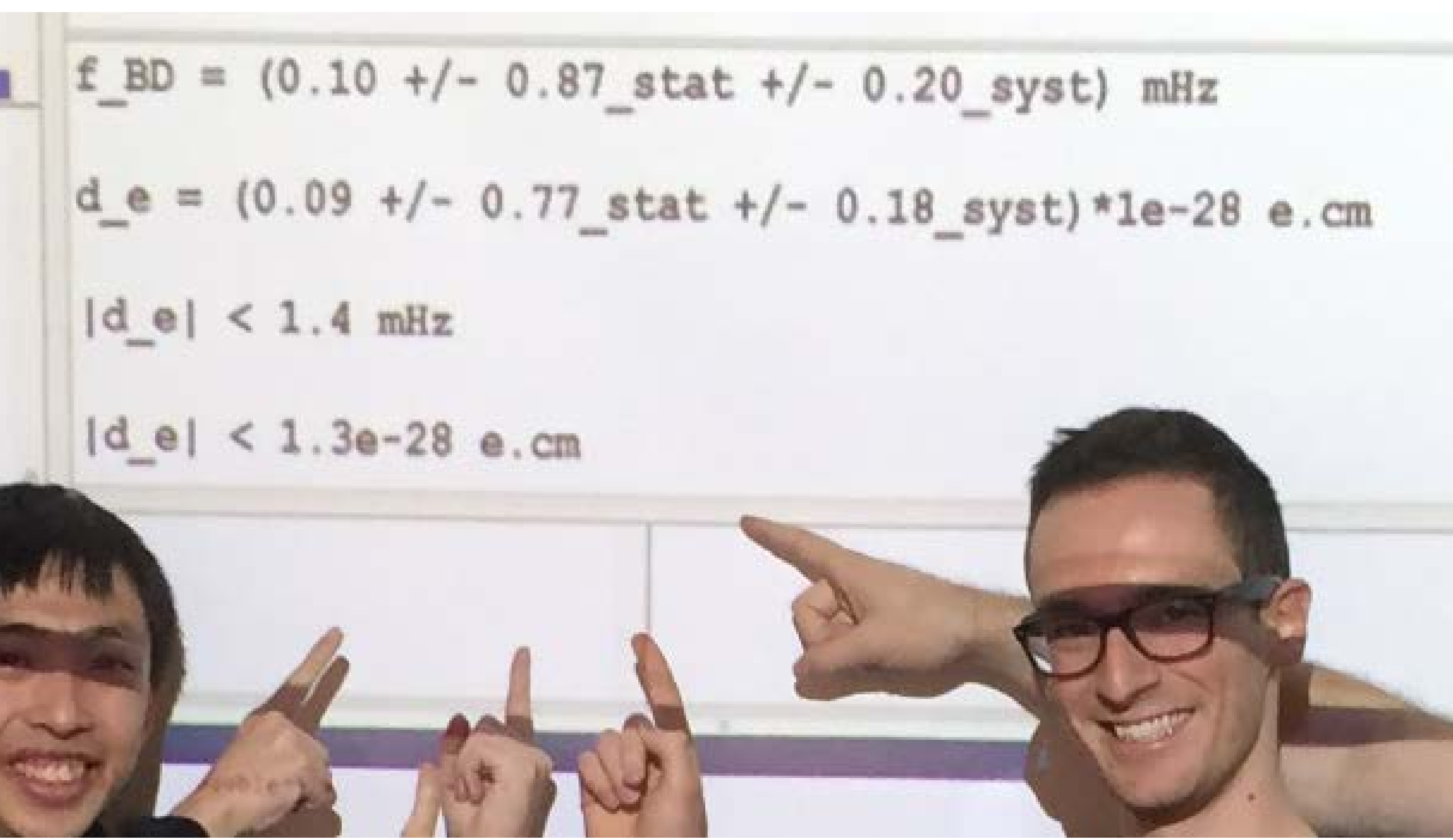


z = +6 mm
z = -2 mm
z = +2 mm
f^{BR} (Hz)
radial position (mm)
4
3
2
1
0
-1
-2
-3
-4
-6
-4
-2
0
2
4
6
8



Frequency channel	All data	2017 only
f^{R}	2.6(9) mHz	3(1) mHz
f^{DR}	–0.6(8) mHz	–1(1) mHz
f^{BD}	34.5(8) mHz	34.4(1.0) mHz
f^{BDR}	0.4(9) mHz	–0.3(1.0) mHz


Systematics
Parametric plot
Histogram
Normal Probability Plot
Expression
Correction
Uncertainty
Total
f_BD = (0.10 +/- 0.87_stat +/- 0.20_syst) mHz
d_e = (0.09 +/- 0.77_stat +/- 0.18_syst)*1e-28 e.cm
|d_e| < 1.4 mHz
|d_e| < 1.3e-28 e.cm
%% Process data
%% Find the EDM channel and apply the blind.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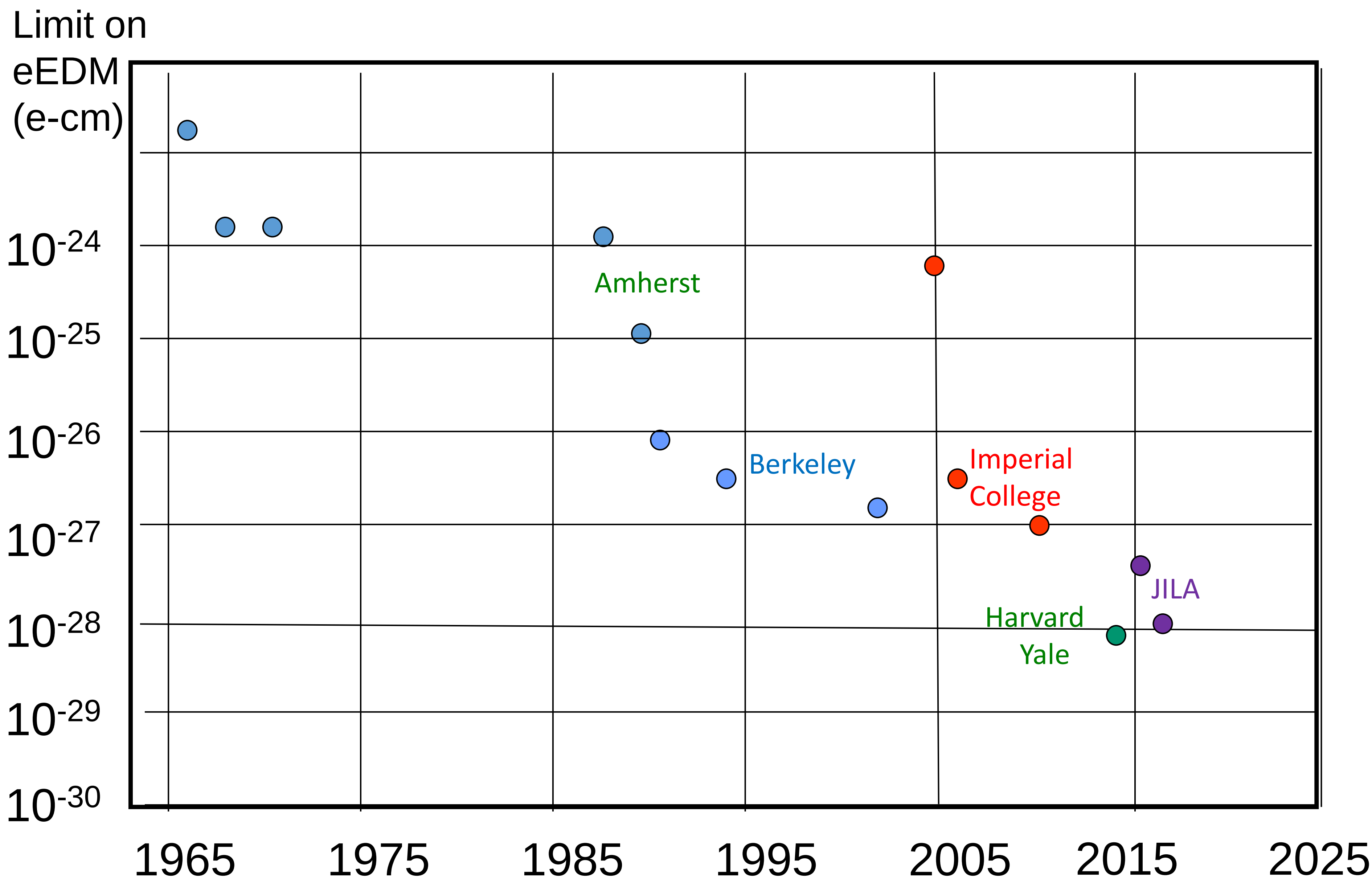
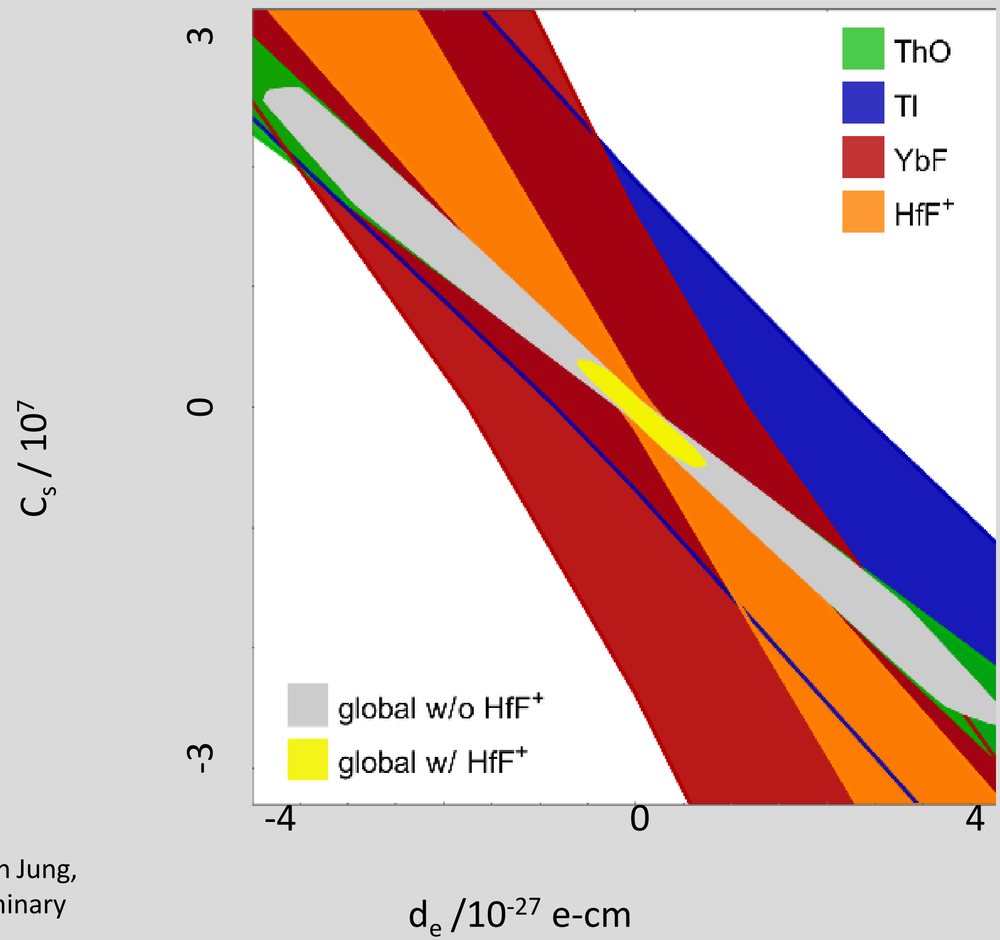


Limit on eEDM (e-cm)
10-24
10-25
10-26
10-27
10-28
10-29
10-30
Amherst
Berkeley
Imperial College
JILA
Harvard Yale
1965
1975
1985
1995
2005
2015
2025



Martin Jung,
Preliminary

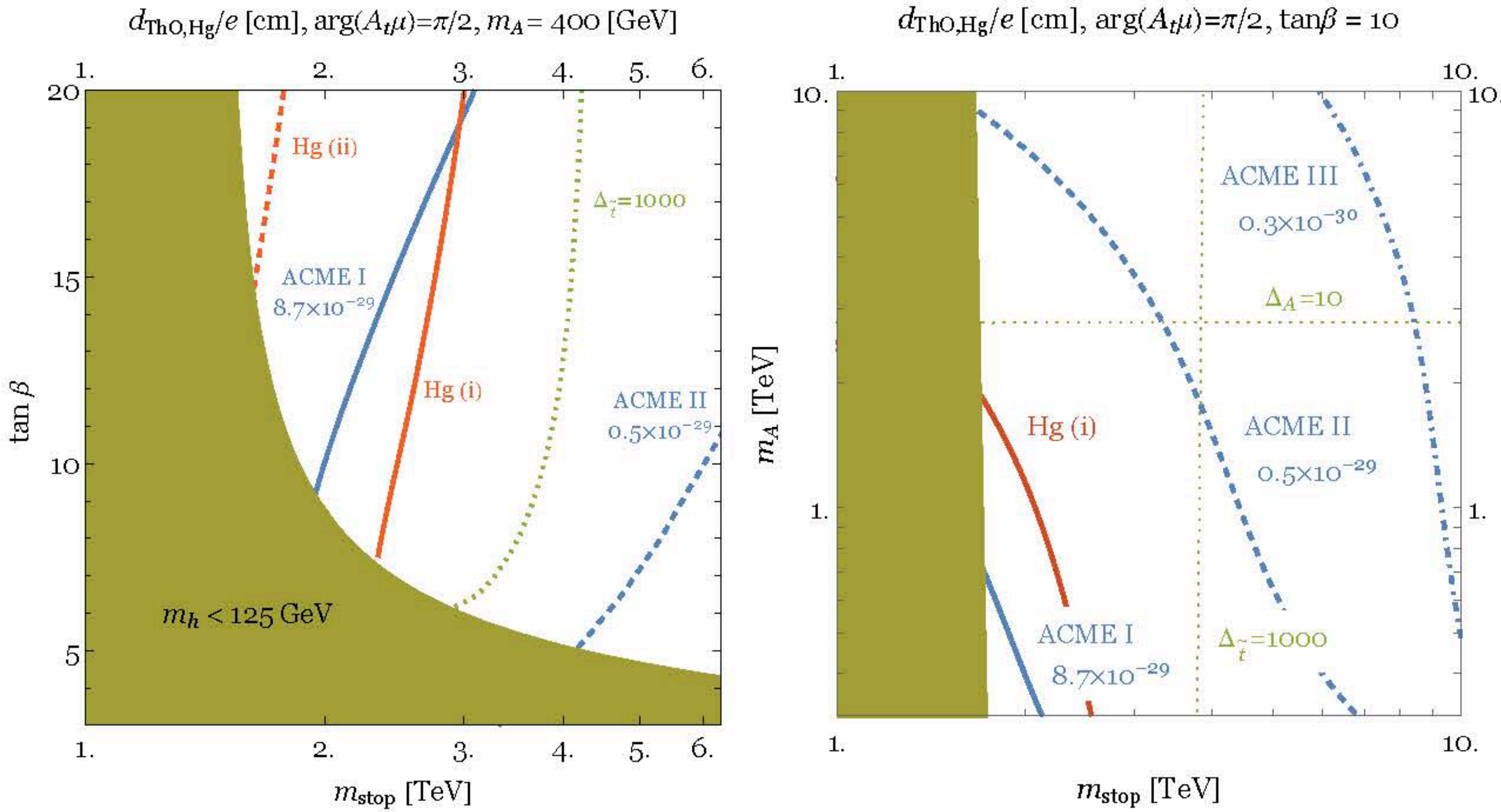
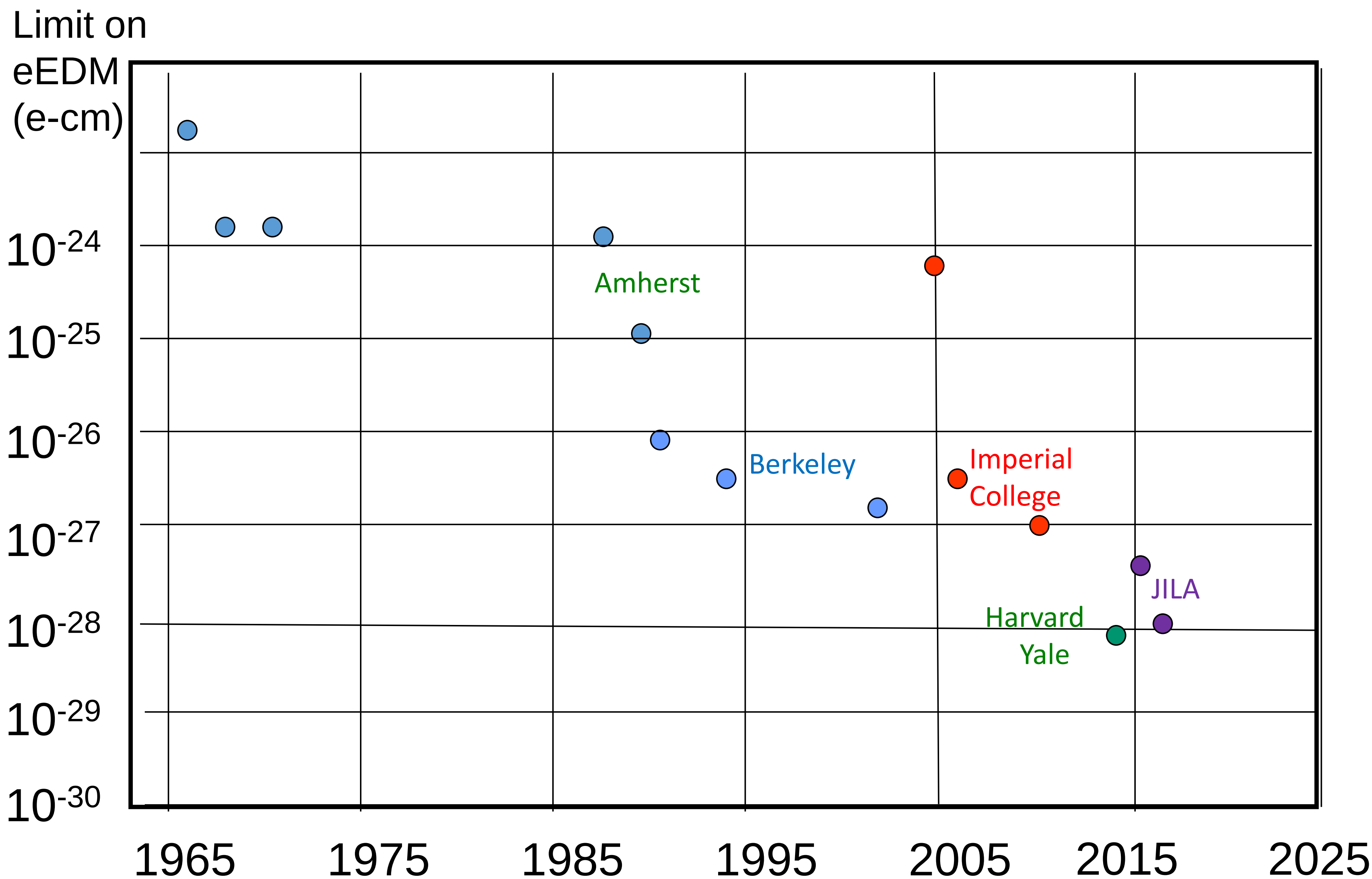


Figure 9: EDM constraints on the stop parameter space in the MSSM, where stop loops with large A-term lift the Higgs mass to 125 GeV. The horizontal axis shows the common stop soft mass $m_{\mathrm{stop}} = \widetilde{m}_{Q_3} = \widetilde{m}_{u_3}$. At left we fix $m_A = 400$ GeV and vary $\tan\beta$ on the vertical axis; at right we fix $\tan\beta = 10$ and vary m_A on the vertical axis. In the brown/green shaded region, no choice of A_t is sufficient to achieve the correct Higgs mass. In the rest of the parameter space, at each point we choose A_t to achieve $m_h = 125$ GeV. Regions of parameter space to the left of the solid blue contours are excluded by measurements of ThO. Red solid and dashed contours denote the mercury EDM constraints for the cases (i) and (ii) discussed in Appendix C), respectively. The blue dashed and dot-dashed contours ("ACME II" and "ACME III") are future projections. The dotted green lines display the st
tree-level Higgs fine tuning (26). We have fixed $|\mu| = 350$ GeV in these figures.

Nakai and Reece (2017)


Limit on eEDM (e-cm)
10-24
10-25
10-26
10-27
10-28
10-29
10-30
1965
1975
1985
1995
2005
2015
2025
Amherst
Berkeley
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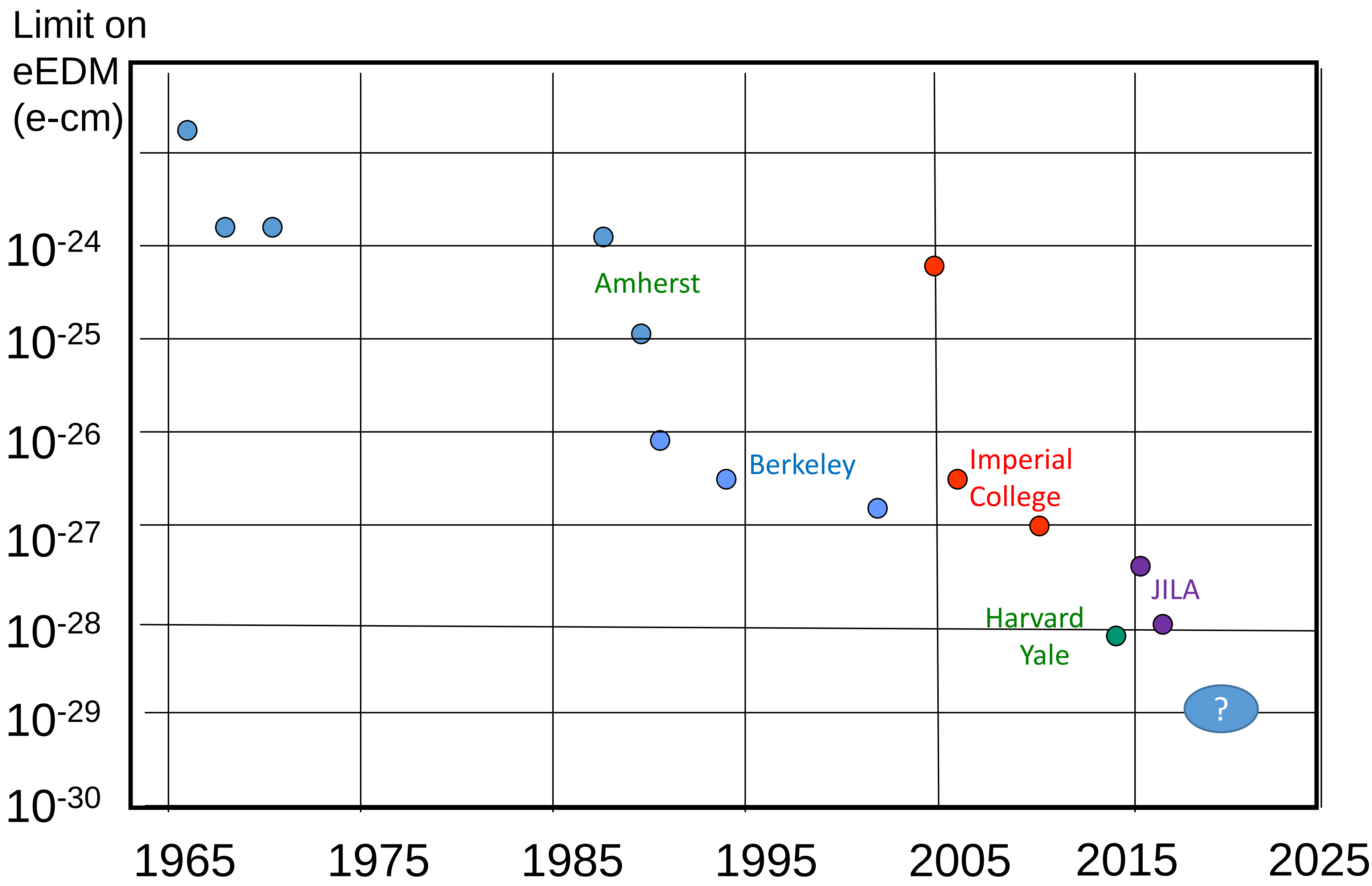
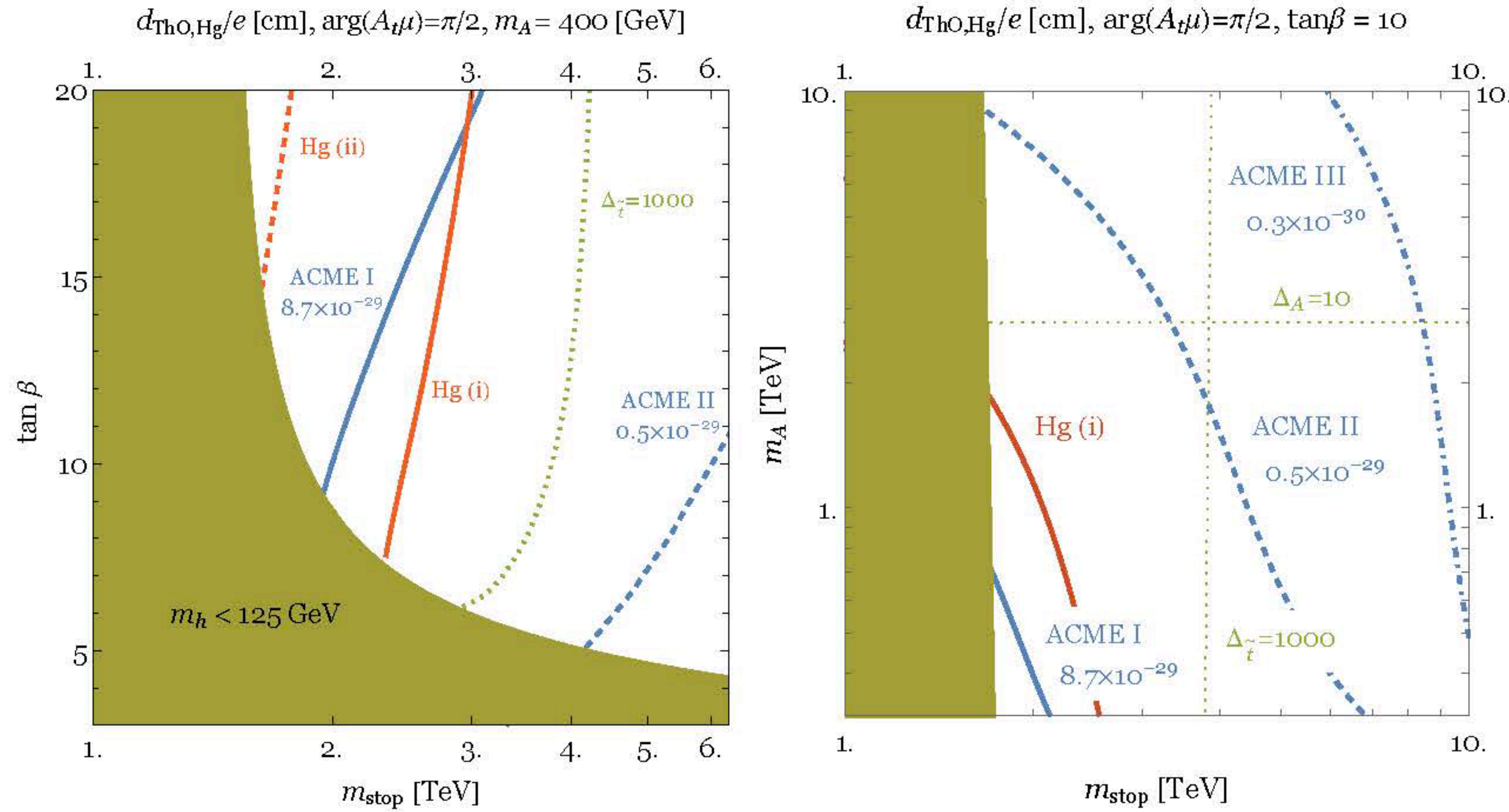


Limit on
eEDM
(e-cm)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
Amherst
Berkeley
Imperial
College
JILA
Harvard
Yale
?
1965
1975
1985
1995
2005
2015
2025



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tree-level Higgs fine tuning (26). We have fixed $|\mu| = 350$ GeV in these figures.

Nakai and Reece (2017)

Many other “AMO type” particle physics work. H. Muller

other electric dipole moment experiments in Harvard/Yale, Penn State

electric dipole moments of mercury atom, or radium atom, of neutron.

anomalies in *magnetic* moments

time-varying physical “constants”.

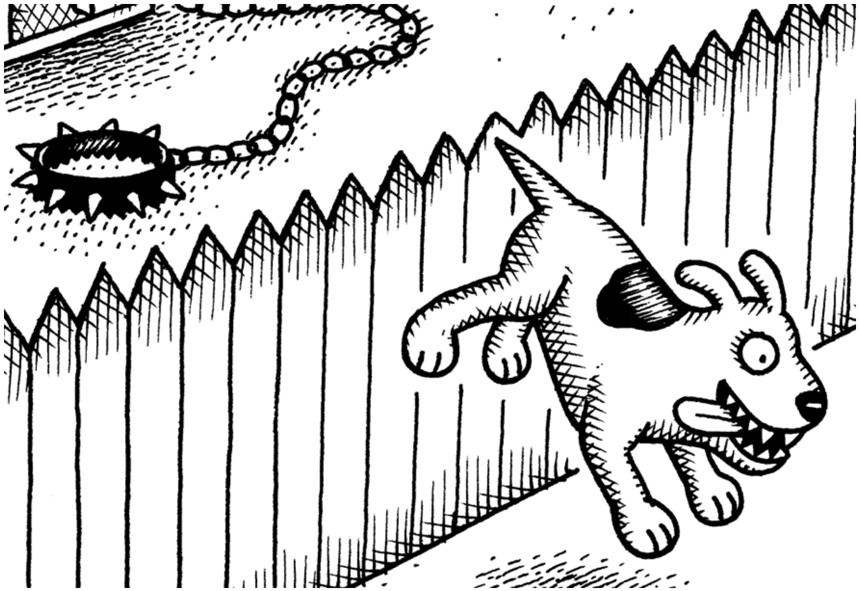
CPT violation? Gravity and antimatter? F. Sorrentino

search for axions

tests of gravitational theory. I Carusotto. G. Rosi. V. Fleurov

And let us recall the “O” in AMO. Optical detection of gravitational waves @
LIGO, VIRGO, maybe LISA? Optical gryoscopes. B Patricelli. D. Virgilio.

…




Materials Simulation

cold-atom capabilities:

methods: lasers, evap cooling; individual atom detection

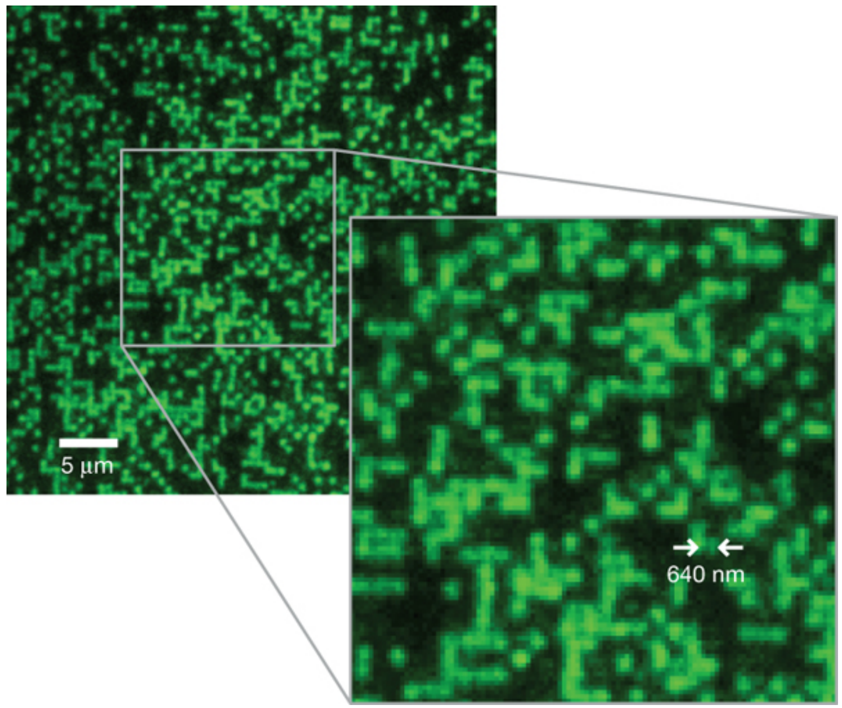
confining potentials : magnetic, or optical. harmonic or square or lattice.

bosons and fermions. tunable interactions. reduced dimemsions.

many of these things changeable in real time, dynamically

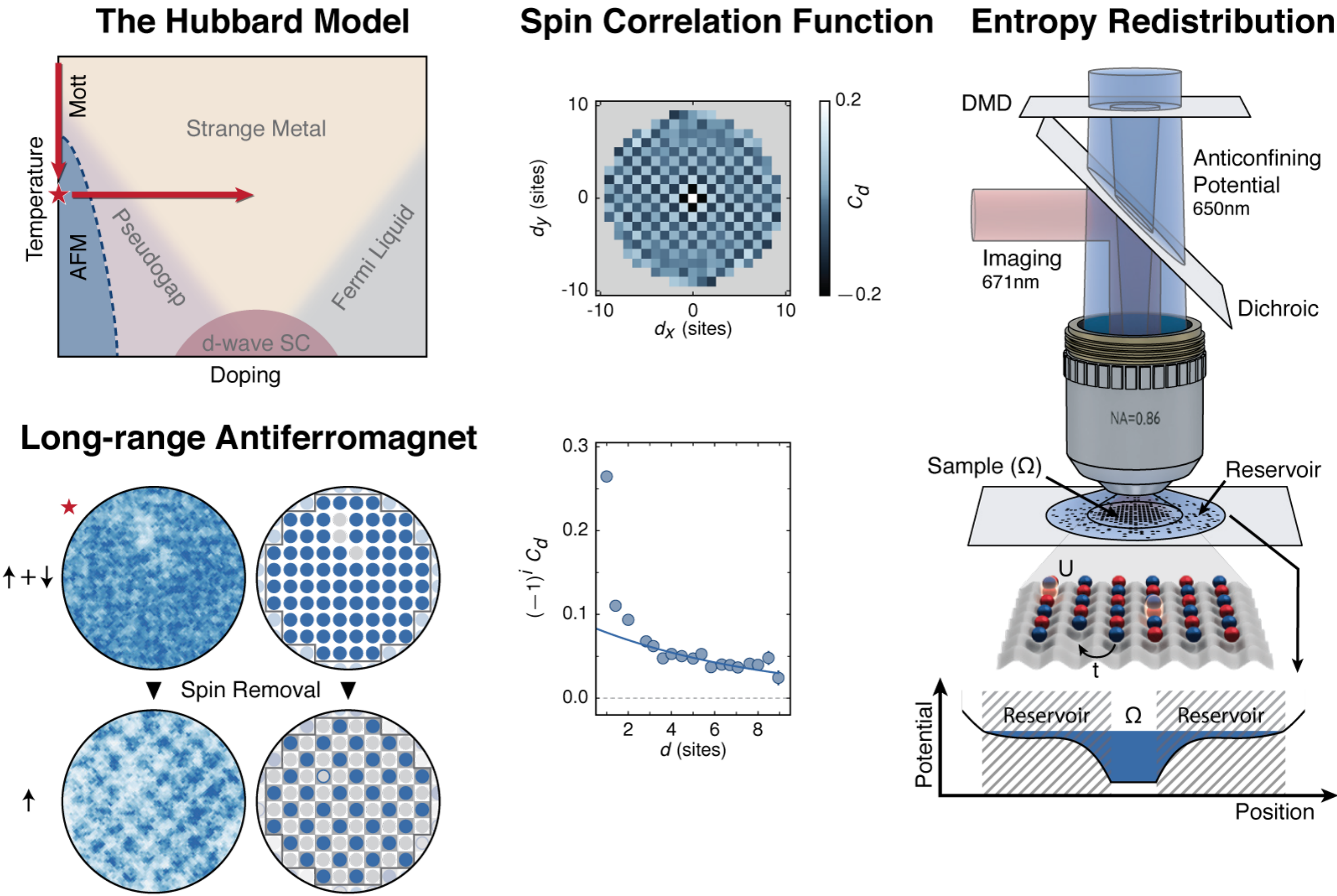
more recently, synthetic magnetic field.

Site-resolved imaging of single atoms on a 640-nm-period optical lattice, loaded with a high density Bose–Einstein condensate.



WS Bakr *et al.* *Nature* **462**, 74-77 (2009) doi:10.1038/nature08482

nature


The Hubbard Model
Mott
Strange Metal
Temperature
AFM
Pseudogap
Fermi Liquid
d-wave SC
Doping
Long-range Antiferromagnet
↑+↓
Spin Removal
↑
Spin Correlation Function
10
0
-10
d_y (sites)
d_x (sites)
0.2
−0.2
C_d
0.3
0.2
0.1
0.0
$(-1)^i C_d$
2
4
6
8
d (sites)
Entropy Redistribution
DMD
Anticonfining
Potential
650nm
Imaging
671nm
Dichroic
NA=0.86
Sample (Ω)
Reservoir
U
t
Reservoir
Ω
Reservoir
Potential
Position

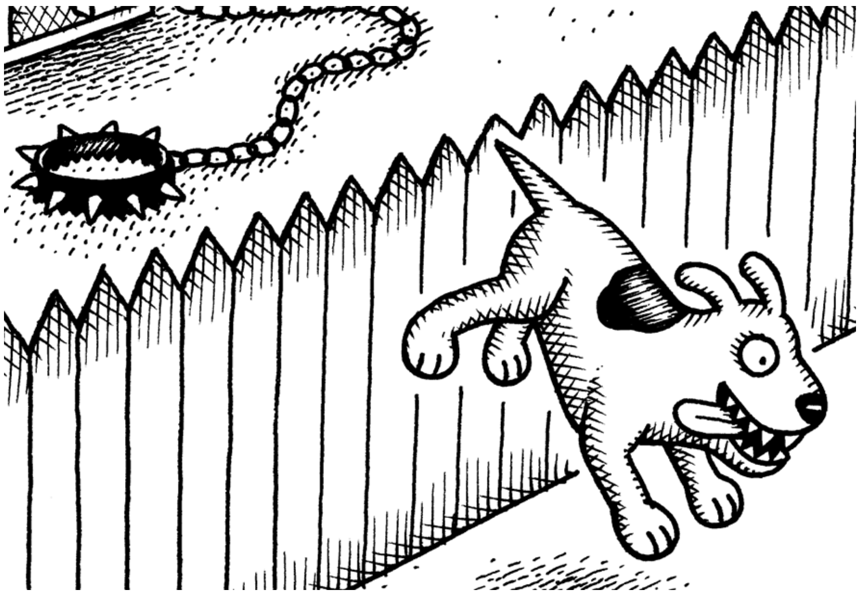
cold-atom capabilities:

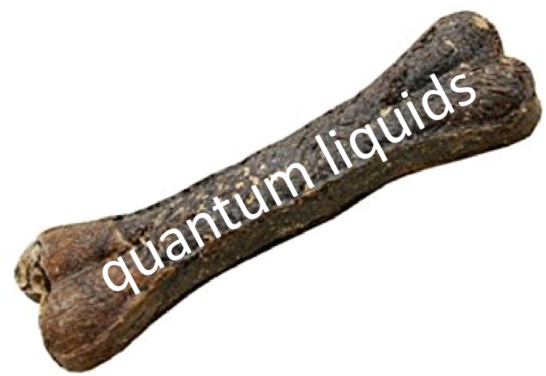
methods: lasers, evaporative cooling.; individual atom detection

containers : magnetic, or optical. harmonic or square *or lattice*.

bosons and fermions. tunable interactions. reduced dimemsions.
many of these things changeable in real time, dynamically
more recently, synthetic magnetic field.
Few body, many body.

See talks from: M Koehl. G. Rossini. V. Fleurov




quantum liquids

liquids:

Where most chemistry happens.

Where all life happens.

liquids:

Where most chemistry happens.

Where all life happens.

macroscopic definition: has a free surface.

liquids:

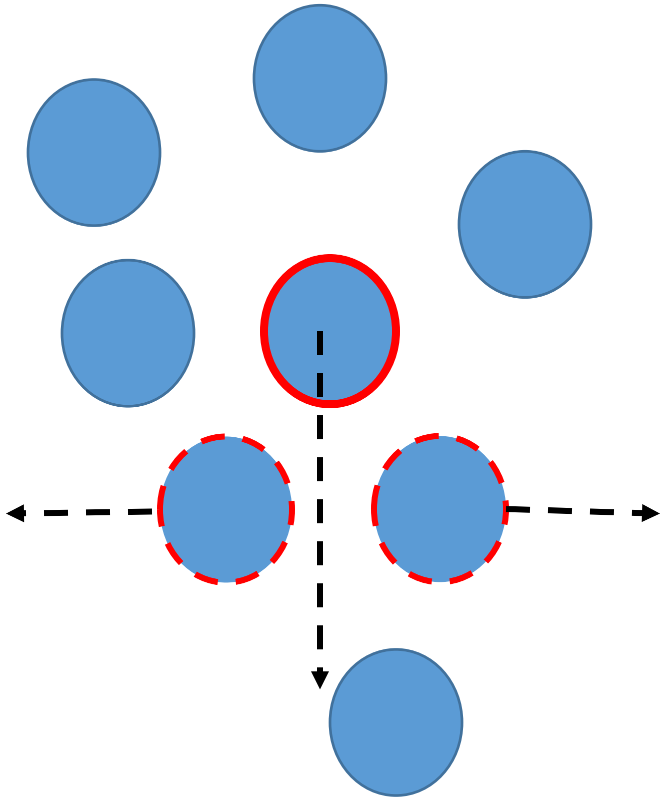
Where most chemistry happens.

Where all life happens.

macroscopic definition: has a free surface.

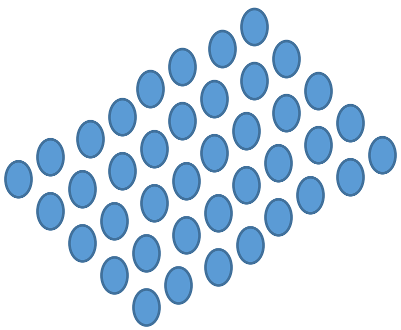
but microscopically…

microscopically,
a liquid is
where
one atom can
move only if
some other
atoms get out of
the way.



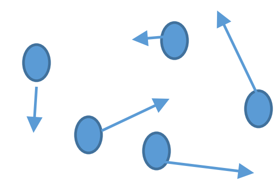
As physicists, we often like to approach a problem perturbatively. We start with…

A solid: lattice at T=0.



perturbatively add carriers, phonons, etc

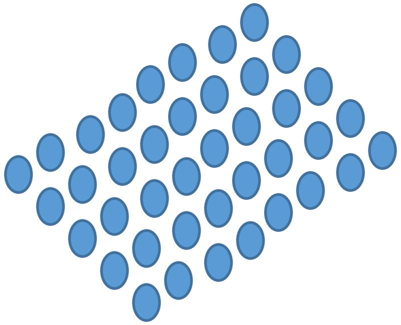
A gas: noninteracting molecules with good **k**.



perturbatively add rare k-changing collisions, mean field, etc

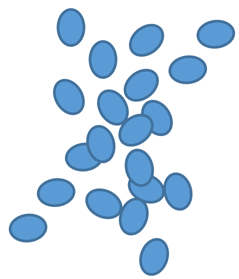
As physicists, we often like to approach a problem perturbatively. We start with…

A solid:
lattice at
T=0.



perturbatively
add carriers,
phonons, etc

A liquid:
??? Not T=0. No
single-atom **k**



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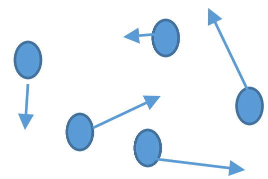
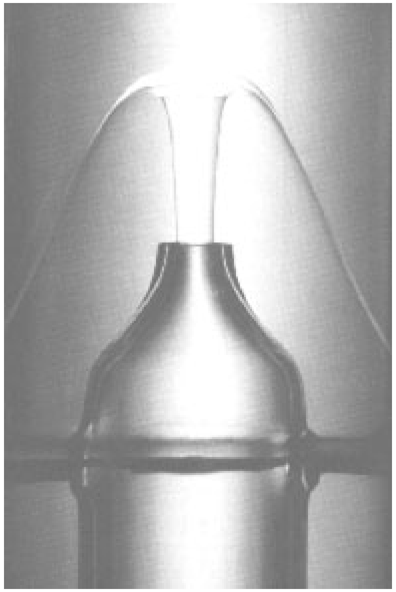
noninteracting
molecules with good **k**.



perturbatively add
rare k-changing
collisions, mean field,
etc

Except, superfluid liquid! Liquid at T=0!
Macroscopic physics very exotic.



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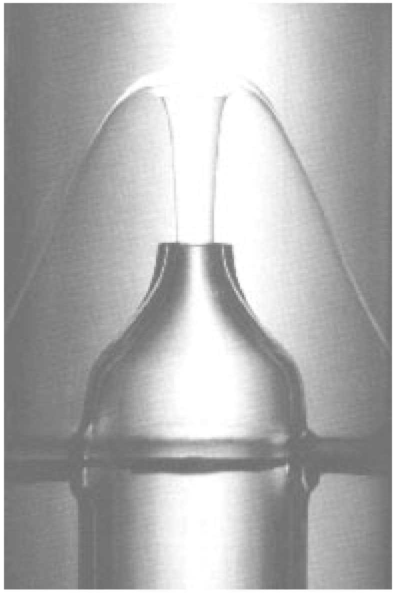
M*icroscopically* it's actually easier to understand than a regular liquid.



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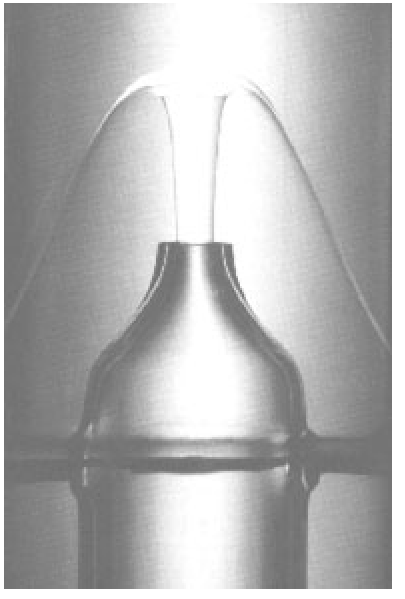


But comes only as liquid helium.
Microscopic probes are difficult.

Microscopic probes in Liquid Helium are tricky.

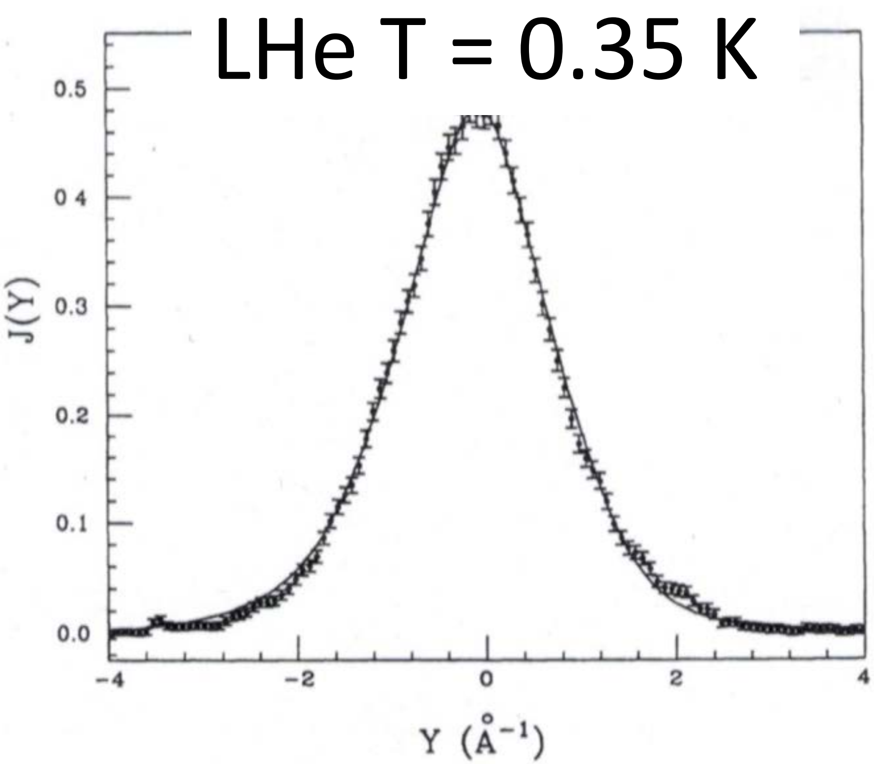


FIG. 8. Observed scattering at $T=0.35$ K. The dashed line is the GFMC prediction of Whitlock and Panoff broadened by the instrumental resolution function and by Silver's FSE broadening function.

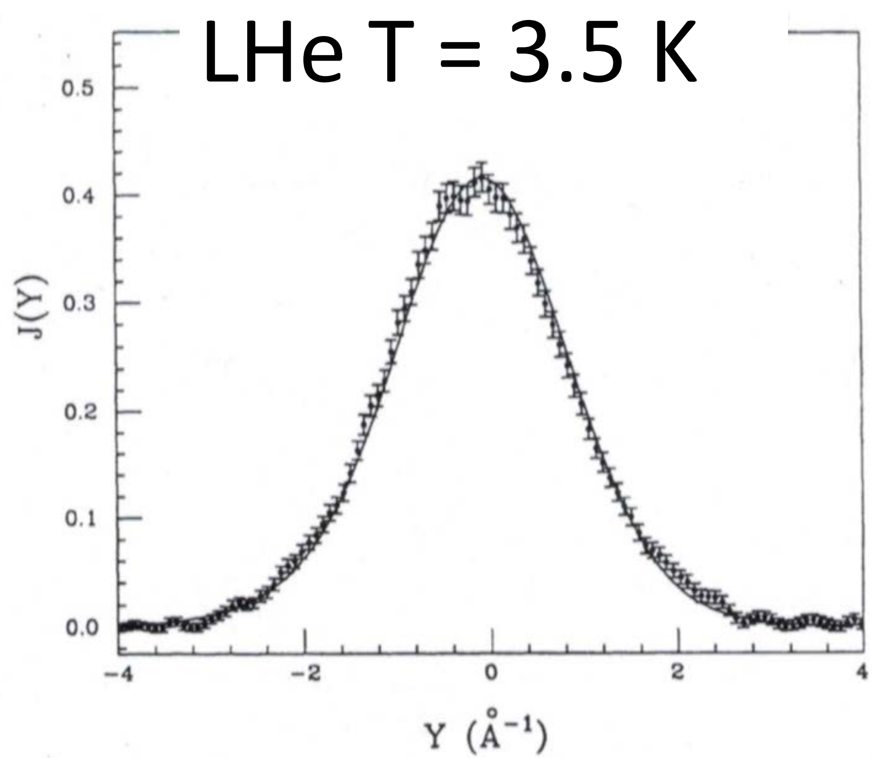


FIG. 7. Observed scattering at $T=3.5$ K. The dashed line is the PIMC prediction of Ceperley and Pollock broadened by the instrumental resolution function and by Silver's FSE broadening function.

Data from Sokol et al 1990.

Idea:
Ultracold atomic gases!
Many wonderful probes.
Tuneable interactions,
Tuneable dimensionalty,
Lots more experimental tools than LHelium

Q: Can we make them liquid like, and in that way learn something about liquids?

A: Maybe.

Work in progress!

Strongly interacting degenerate bose fluid:
A few-body approach to a many-body challenge

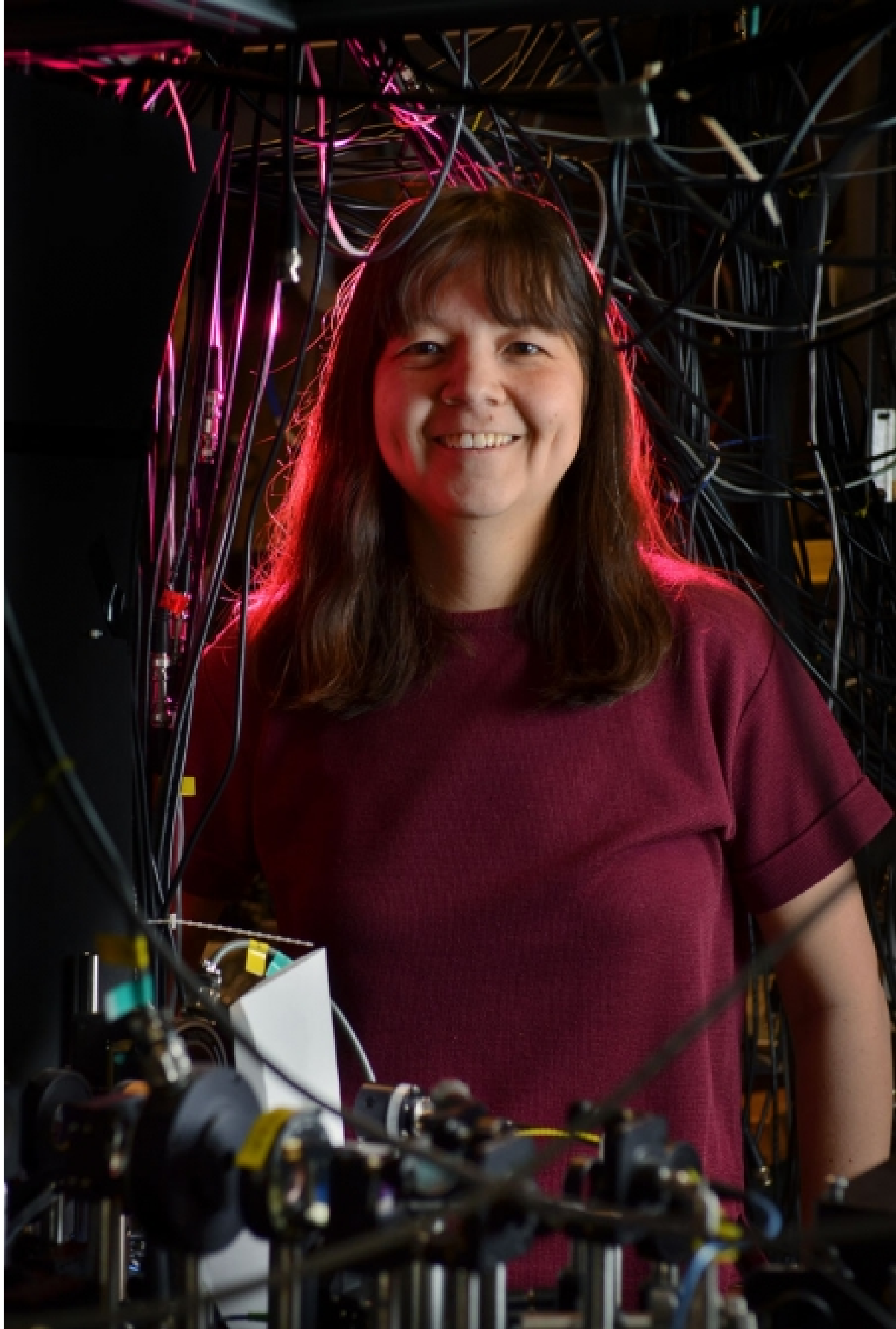
Cathy Klauss, Xin Xie
Carlos Lopez-Abadia

Debbie Jin, E.C
Jose d'Incao
visiting scientist:
Zoran Hadzibabic

former group members
Rob Wild, Phil Makotyn

Thanks: NSF, NIST, NASA

This portion of the talk is dedicated to the memory of Deborah S. Jin (1968-2016).



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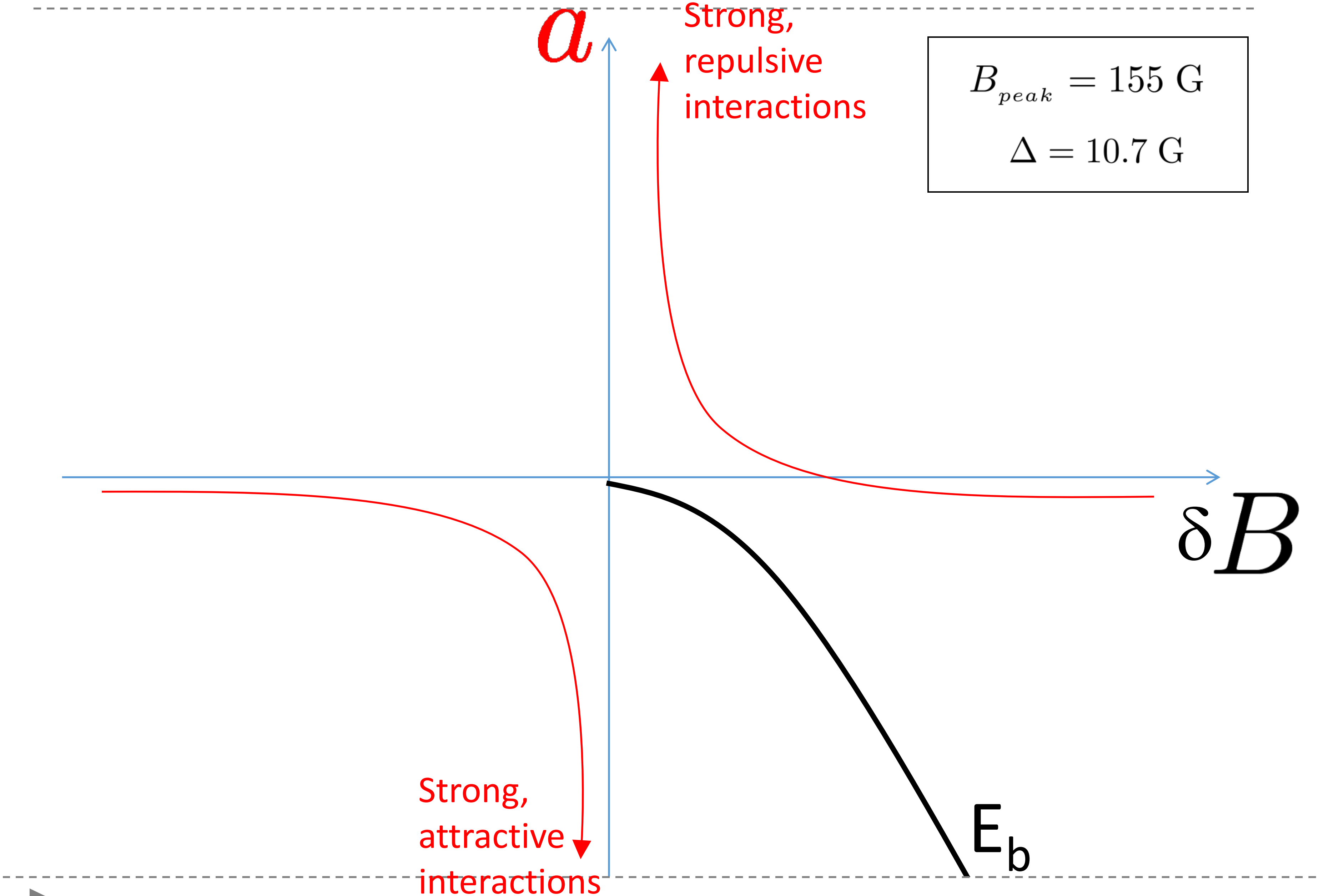
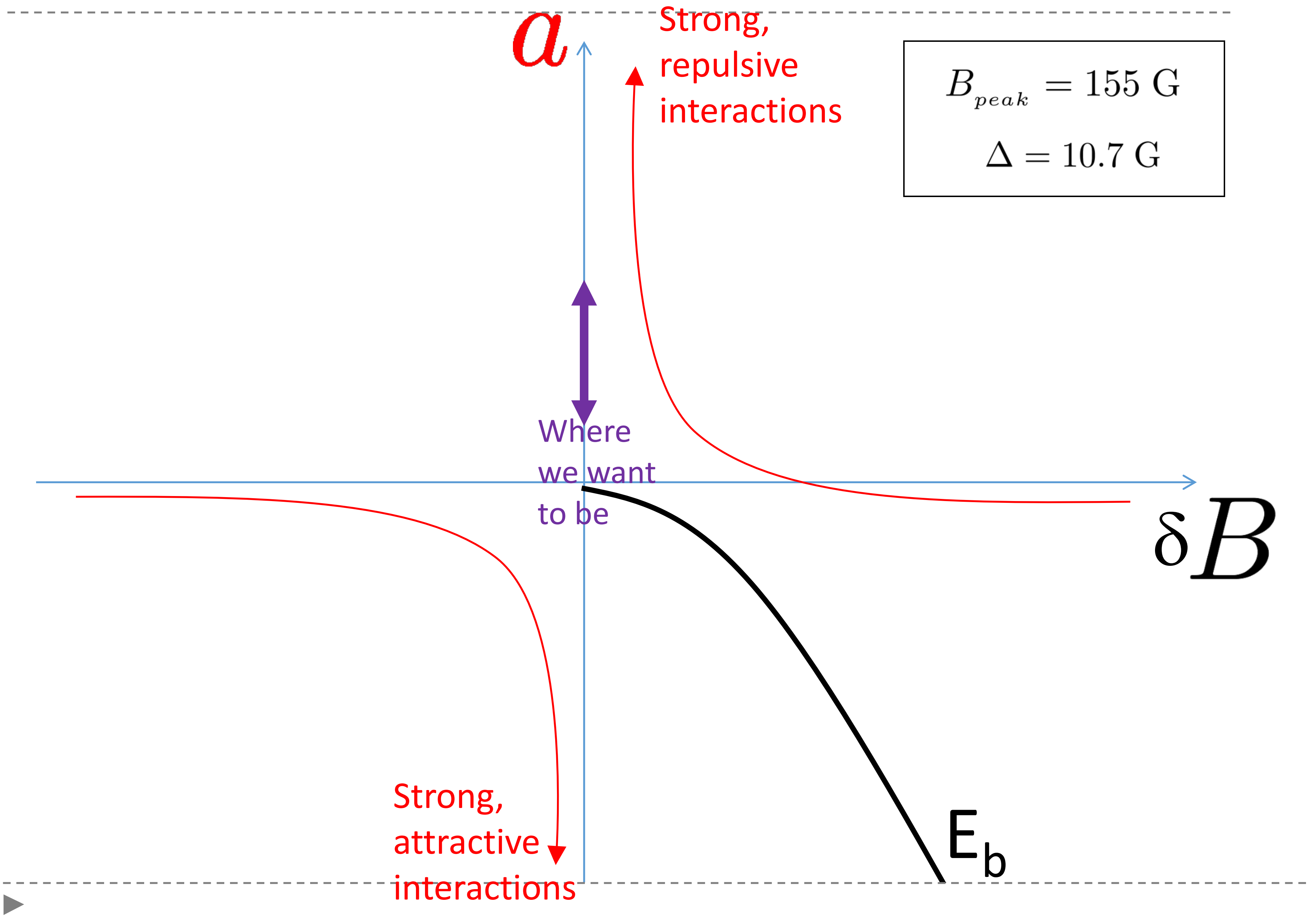
Feshbach Resonance



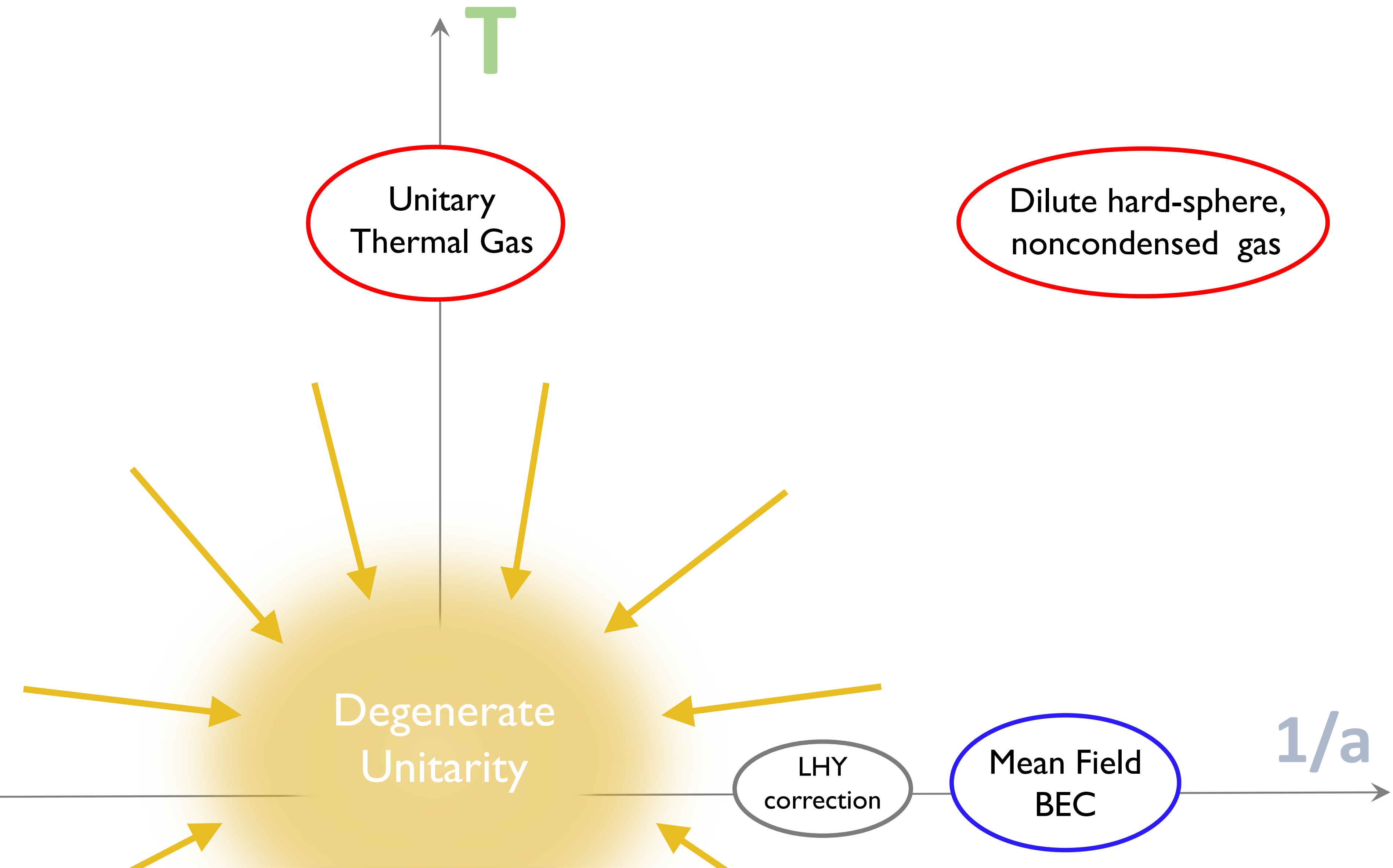
$$B_{peak} = 155 \text{ G}$$

$$\Delta = 10.7 \text{ G}$$

Feshbach Resonance

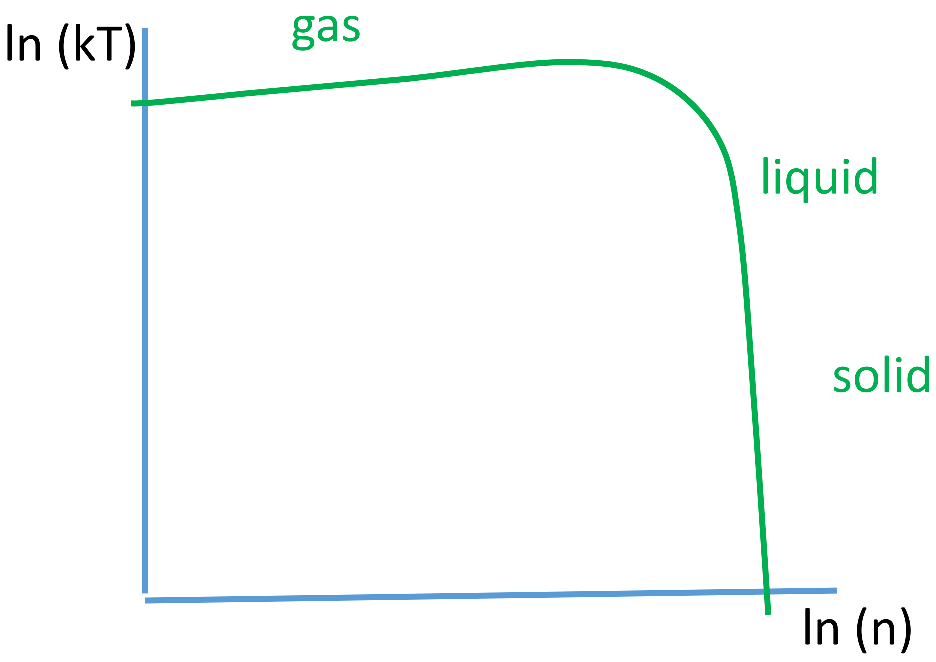


Cold Bosons: The Regimes



The 3-body recombination catastrophe.

Generic phase diagram



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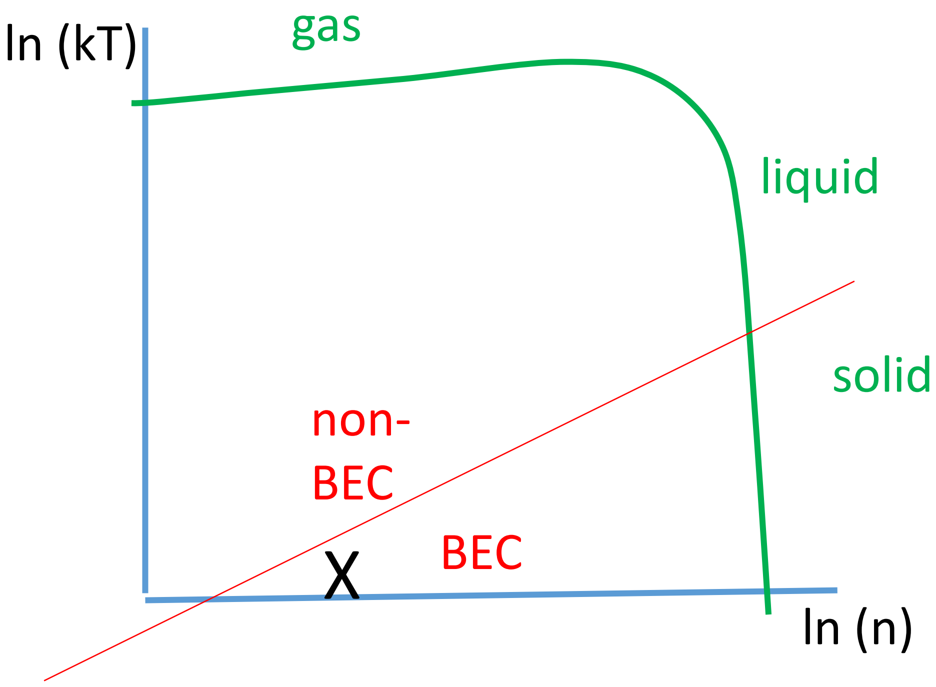


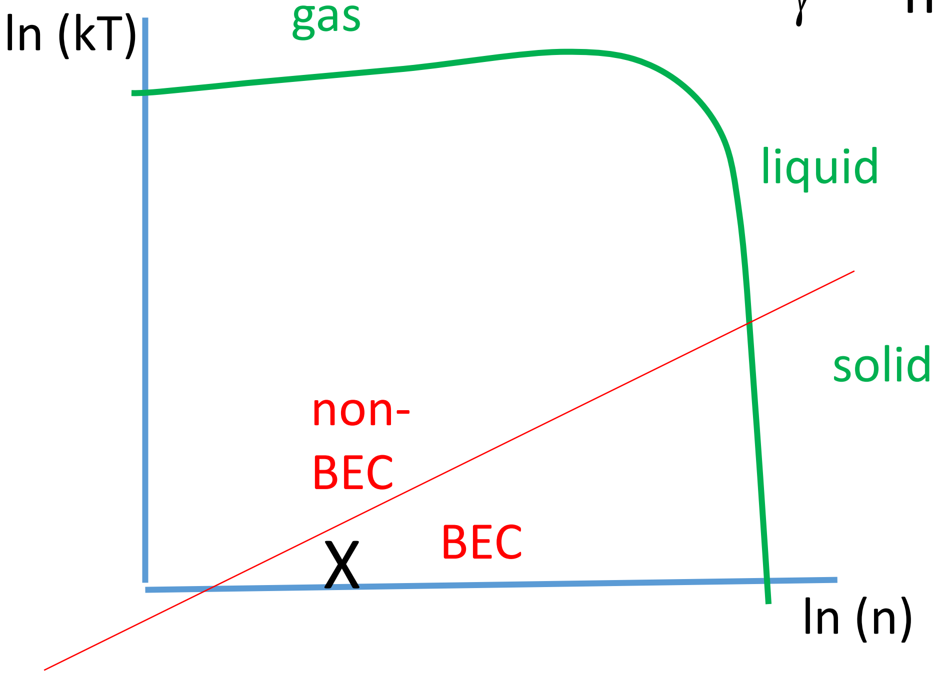
The 3-body recombination catastrophe.

Thermalization – two-body collisions

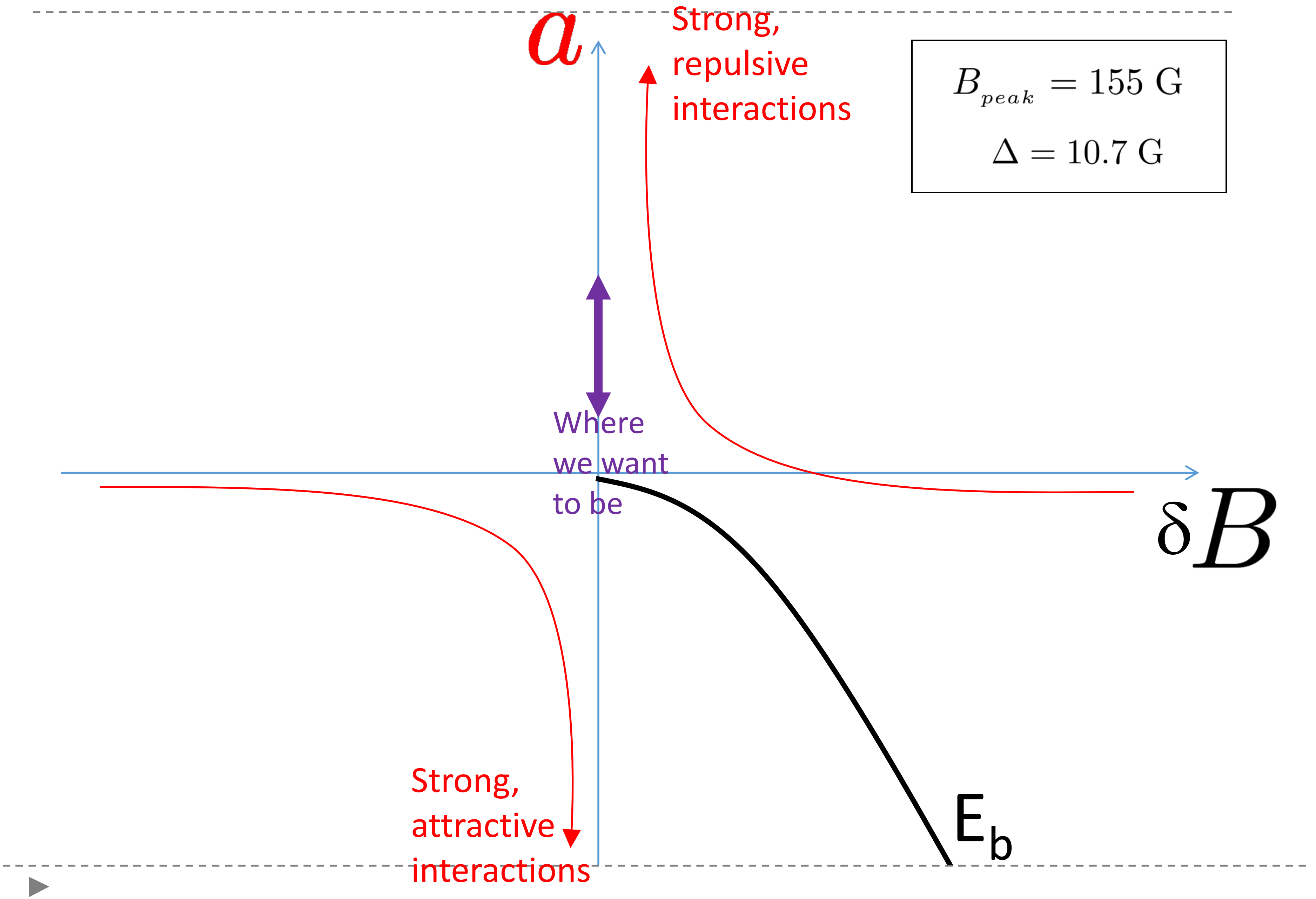
$\gamma \sim n a^2$

Decay – 3-body recombination

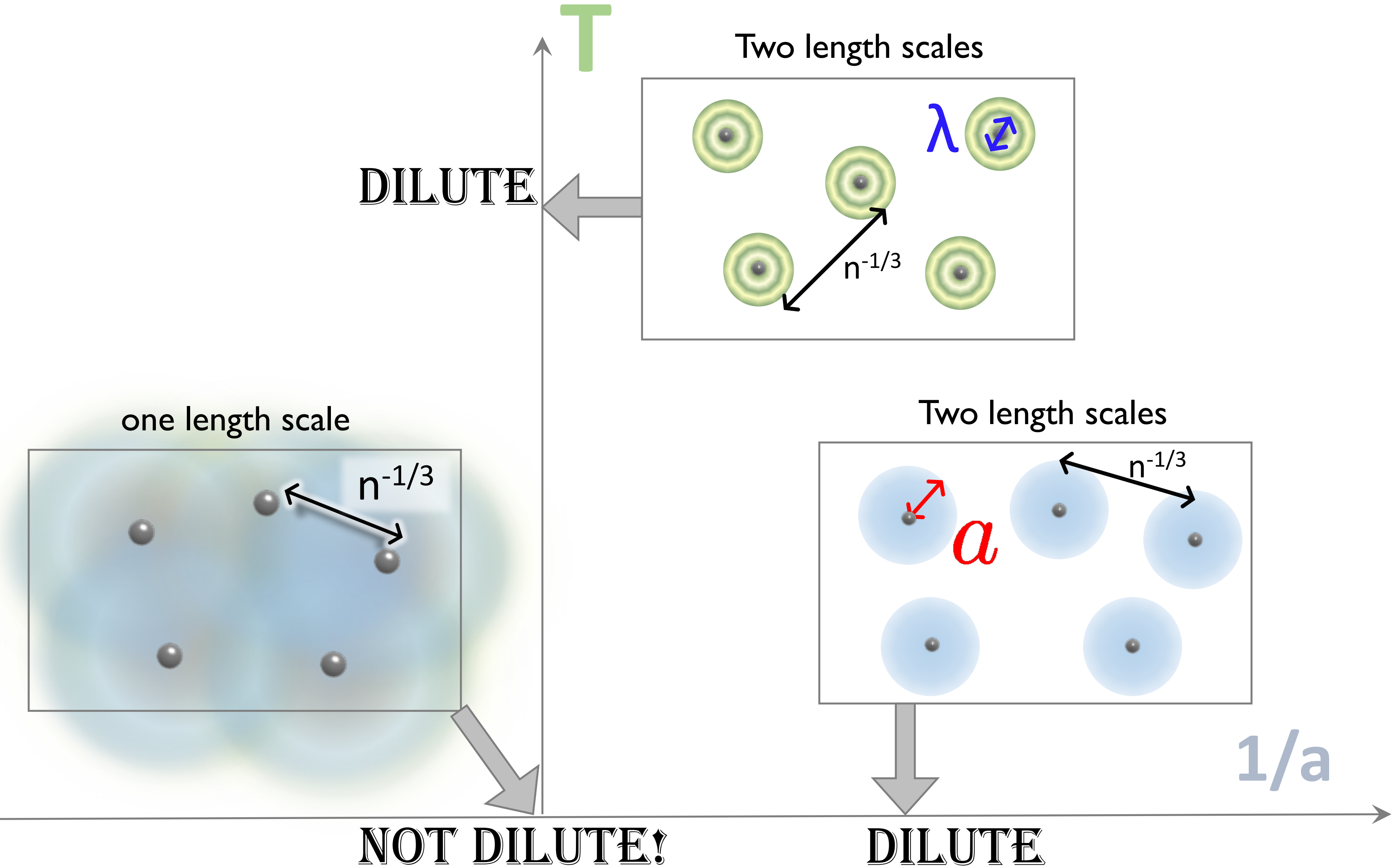
$\gamma \sim n^2 a^4$



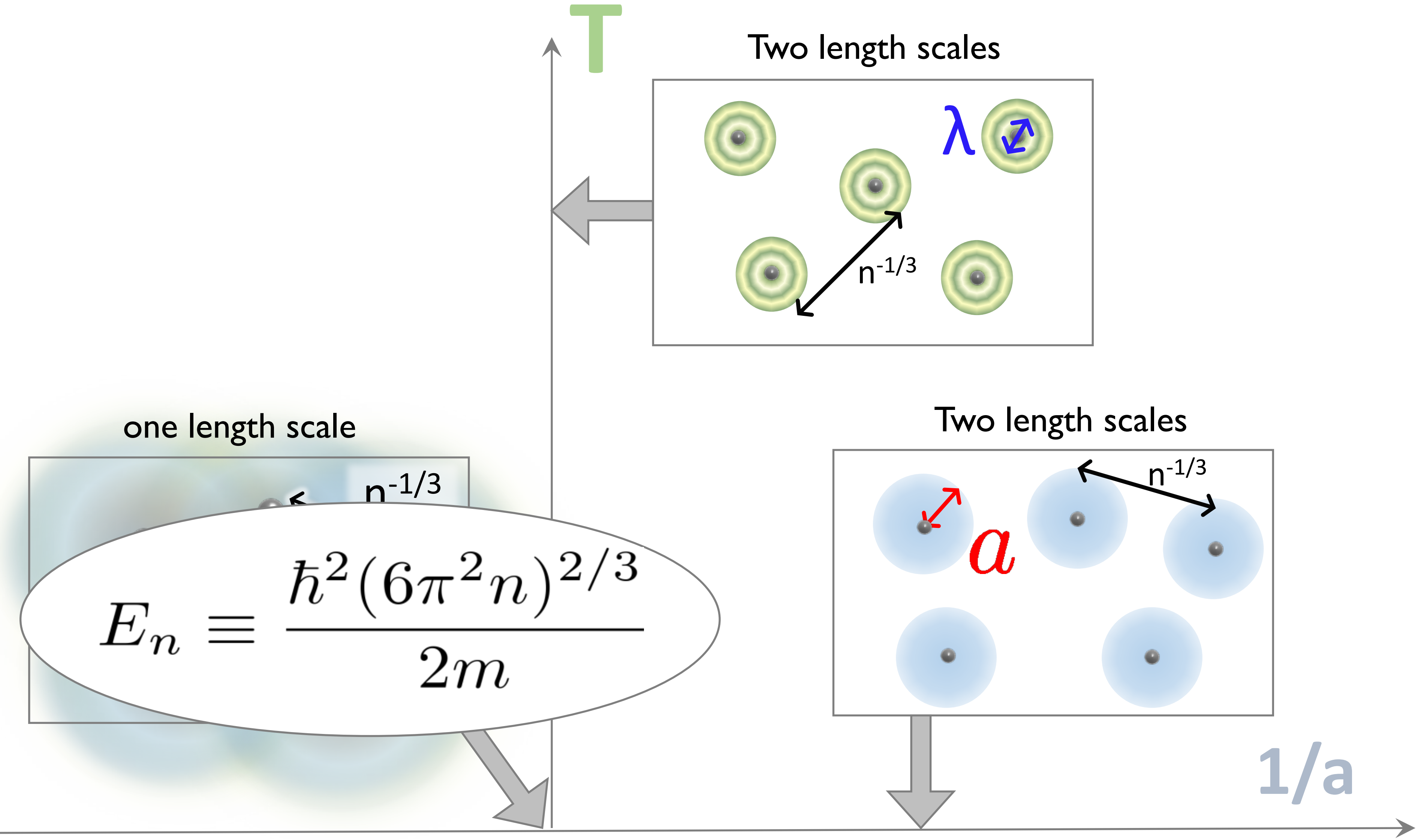
Feshbach Resonance



Degenerate Unitarity

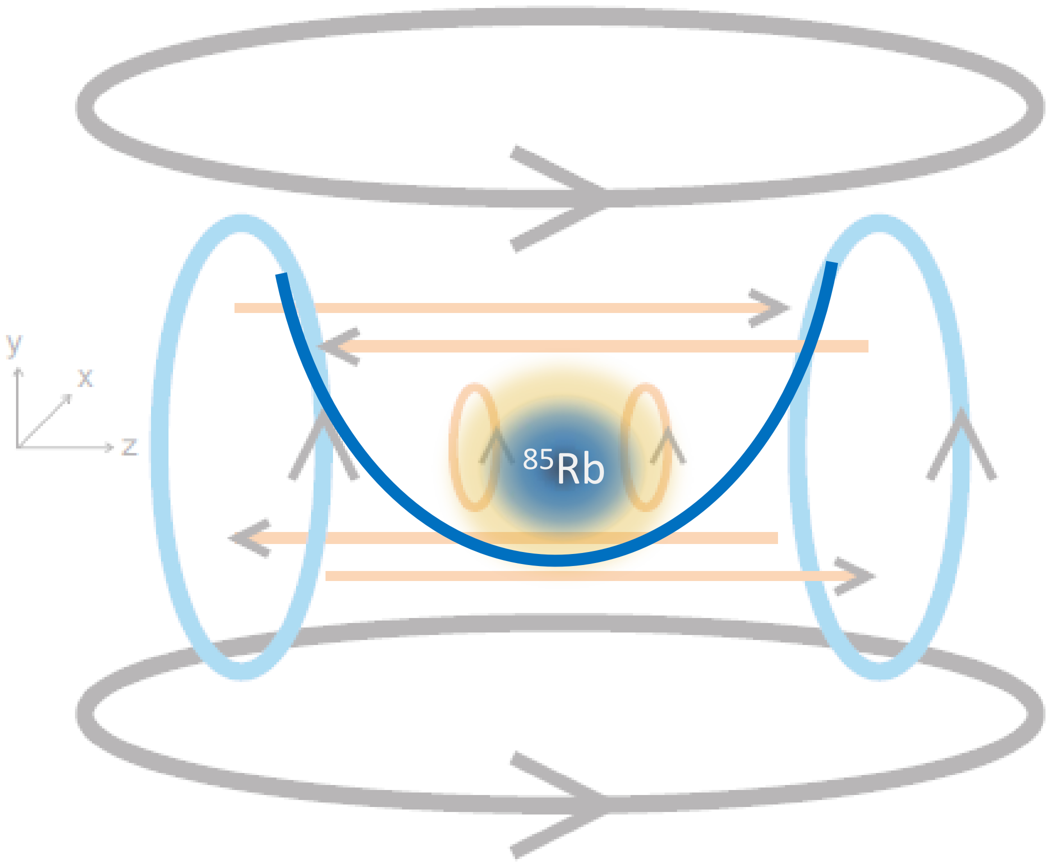


Degenerate Unitarity



$$E_n \equiv \frac{\hbar^2(6\pi^2 n)^{2/3}}{2m}$$

Basic spherical BEC setup



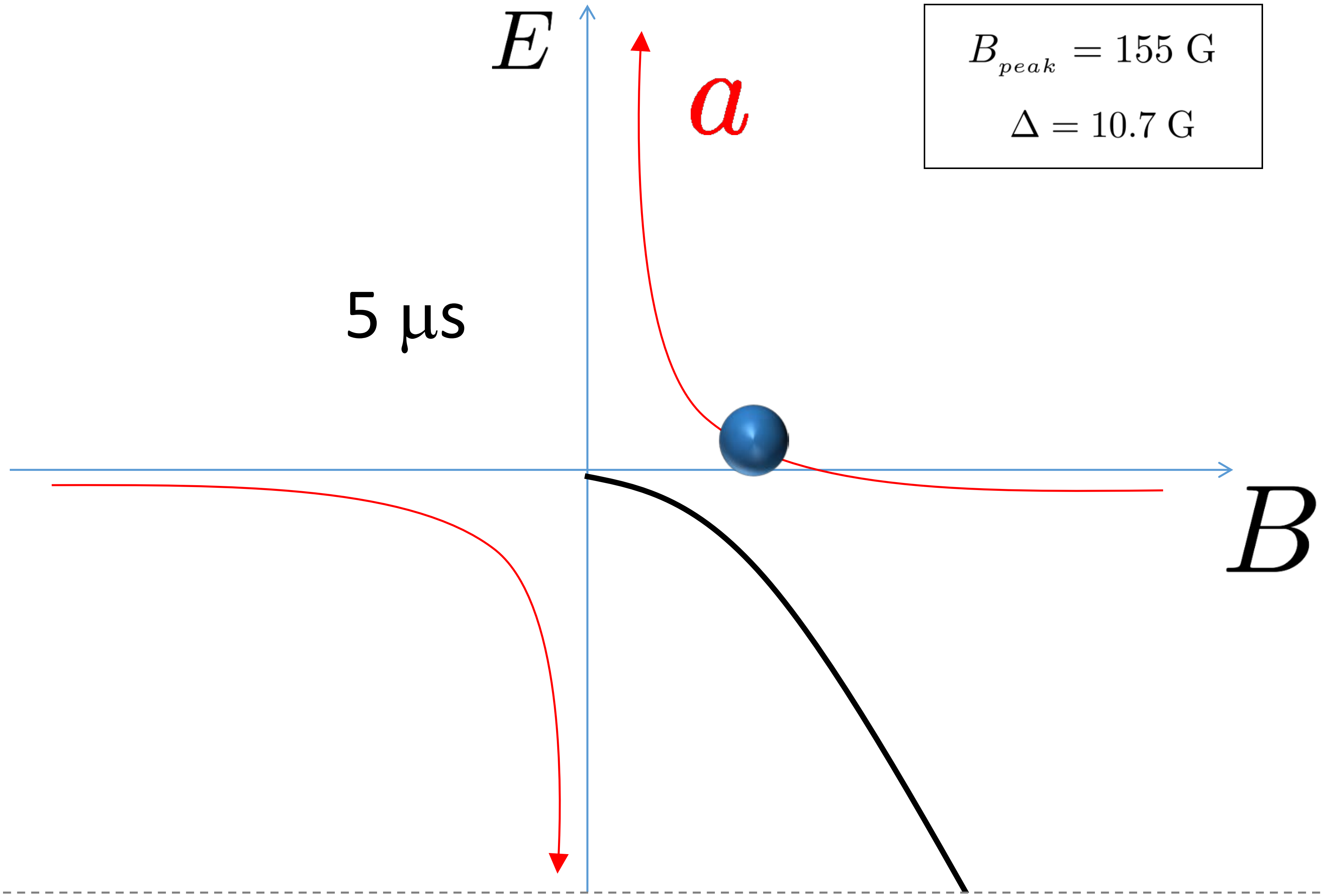
$$N_{BEC} = 6 \cdot 10^4$$

ω = 2 π 10 Hz

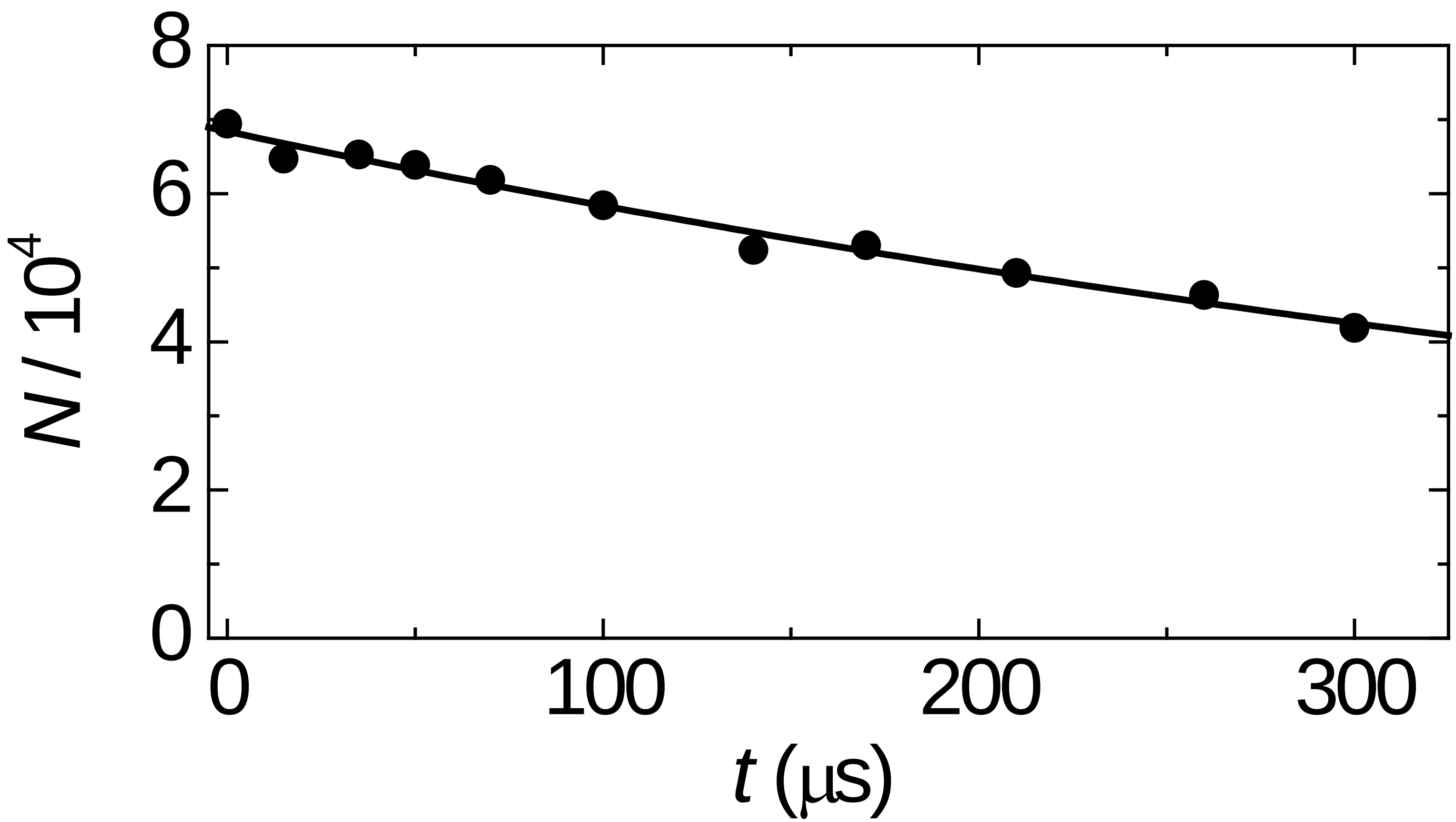
$$\langle n \rangle = 5 \cdot 10^{12}\ cm^{-3}$$

T<10 nK

Feshbach Resonance



Total atoms remaining v. time at unitarity



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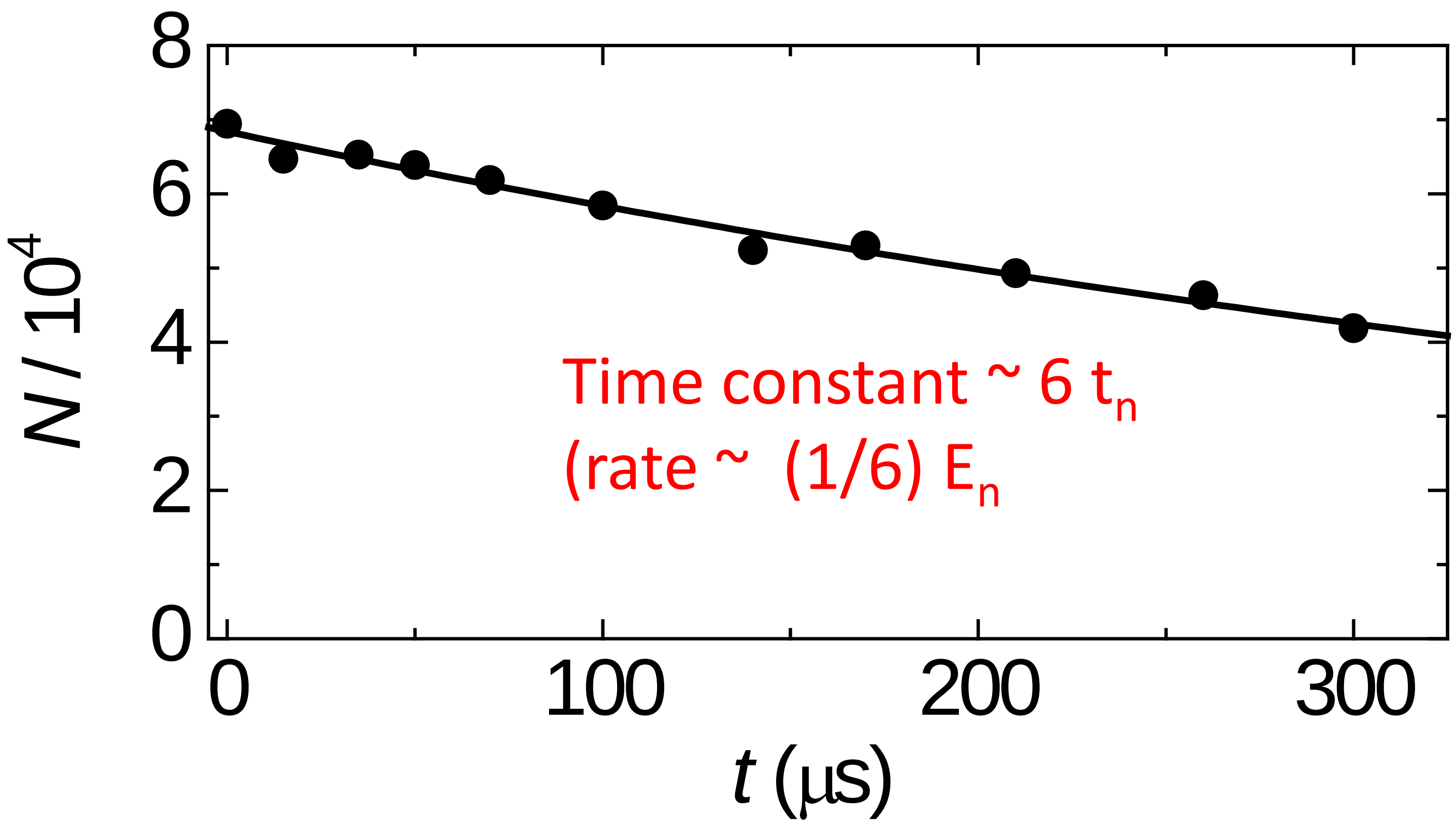
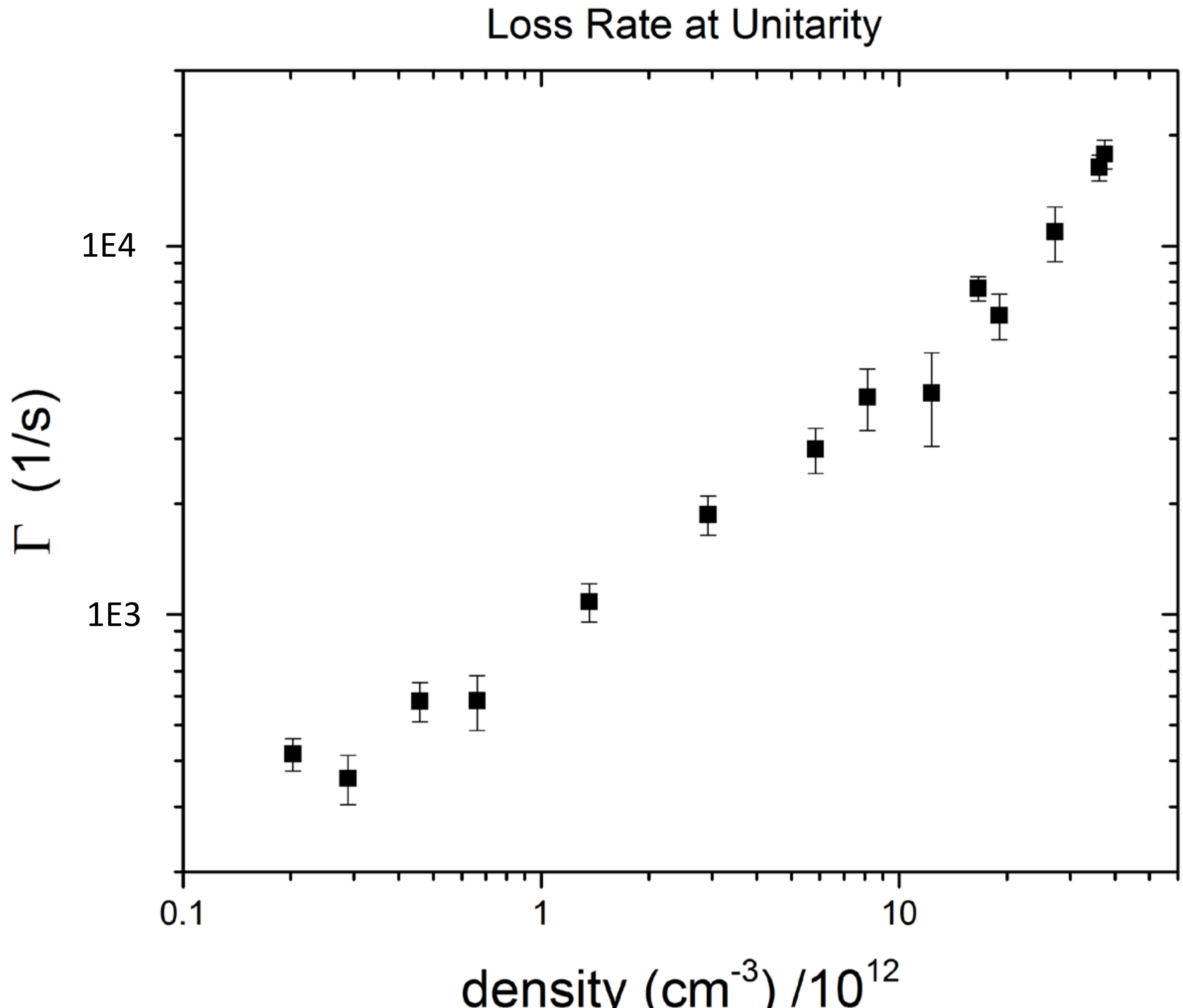
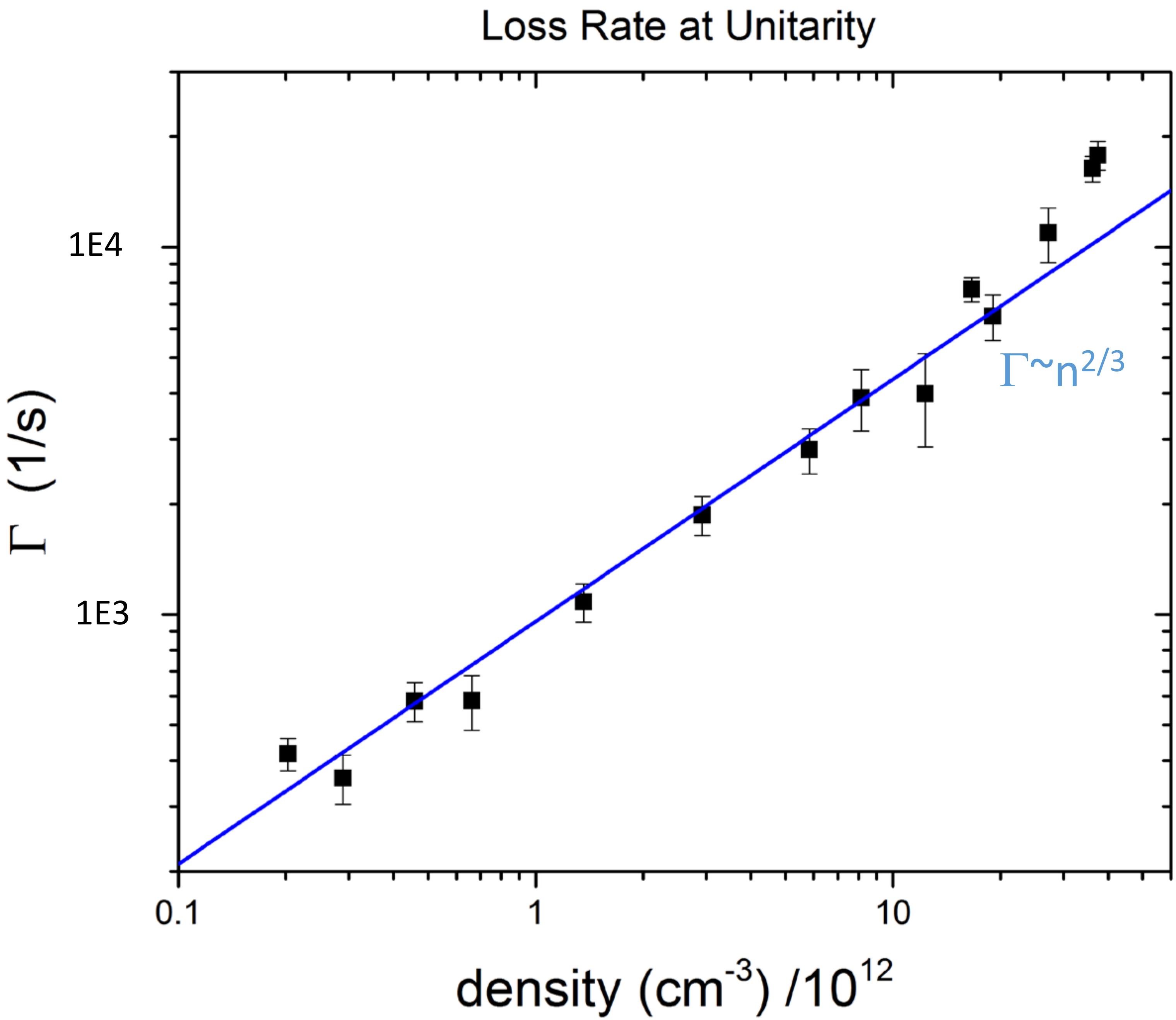
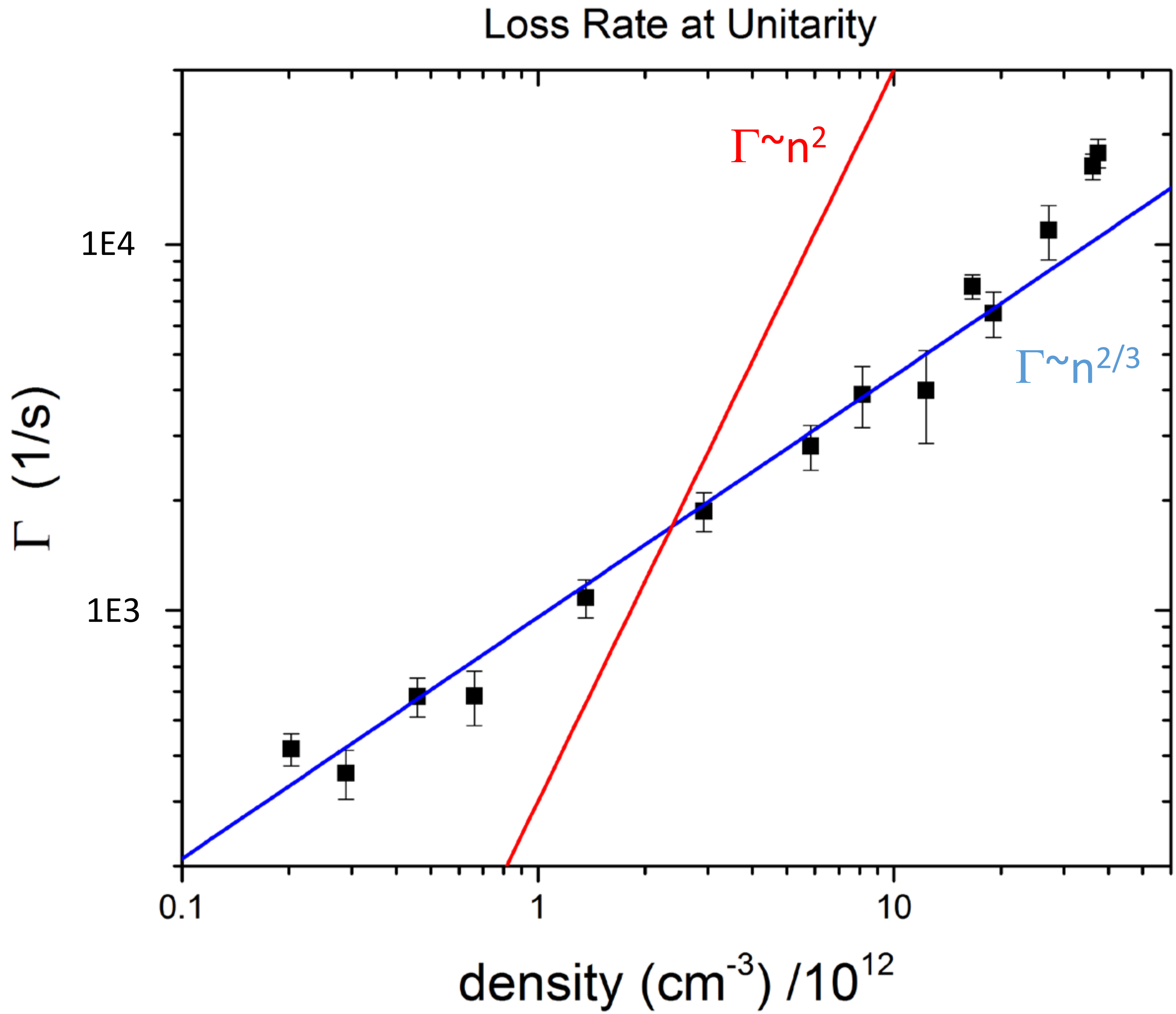



Loss Rate at Unitarity
1E4
1E3
Γ (1/s)
0.1
1
10
density (cm^-3) /10^12

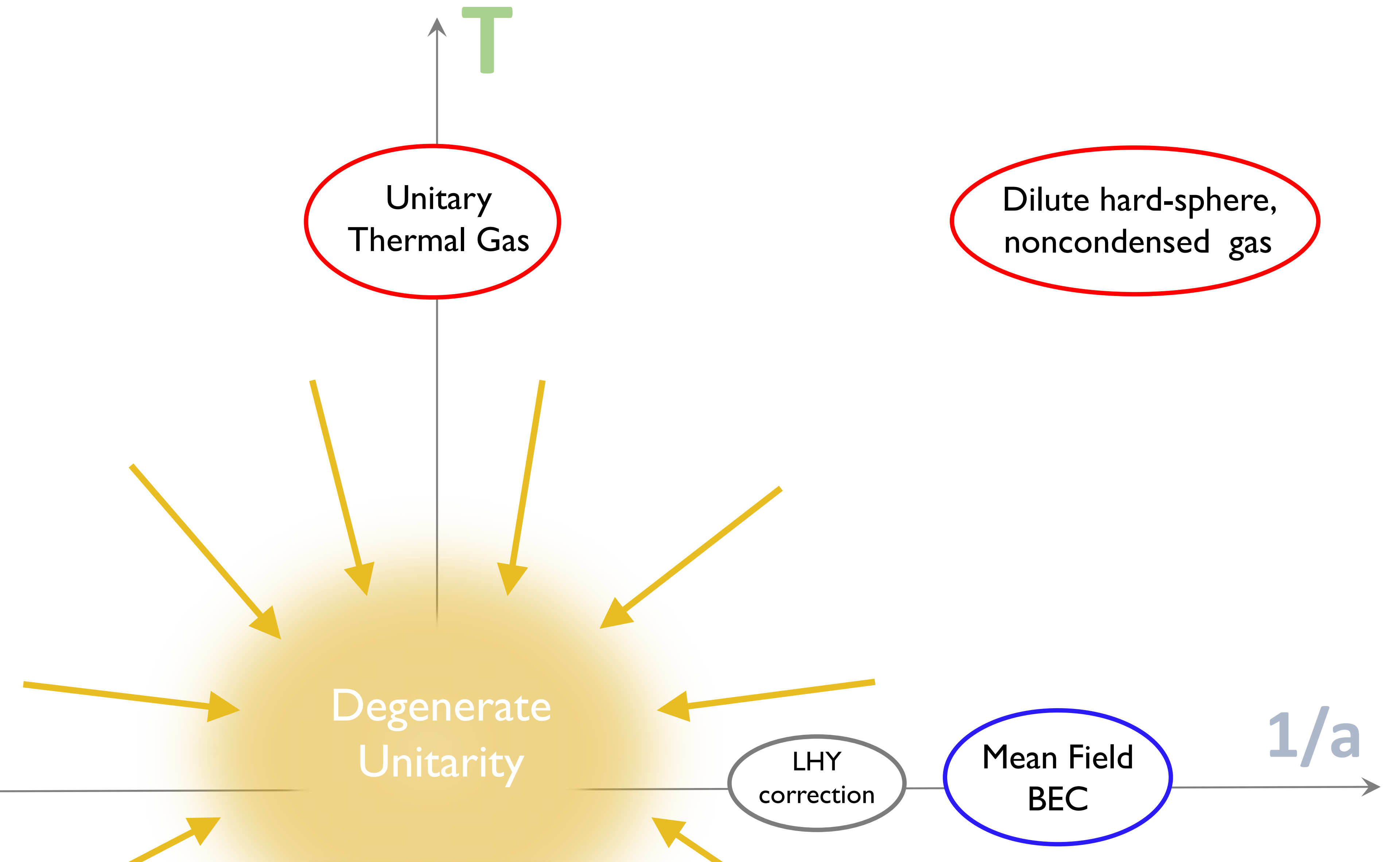


Loss Rate at Unitarity
1E4
1E3
Γ (1/s)
Γ~n2/3
0.1
1
10
density (cm-3) /1012



Loss Rate at Unitarity
Γ~n²
Γ~n^{2/3}
1E4
1E3
Γ (1/s)
0.1
1
10
density (cm⁻³) /10¹²

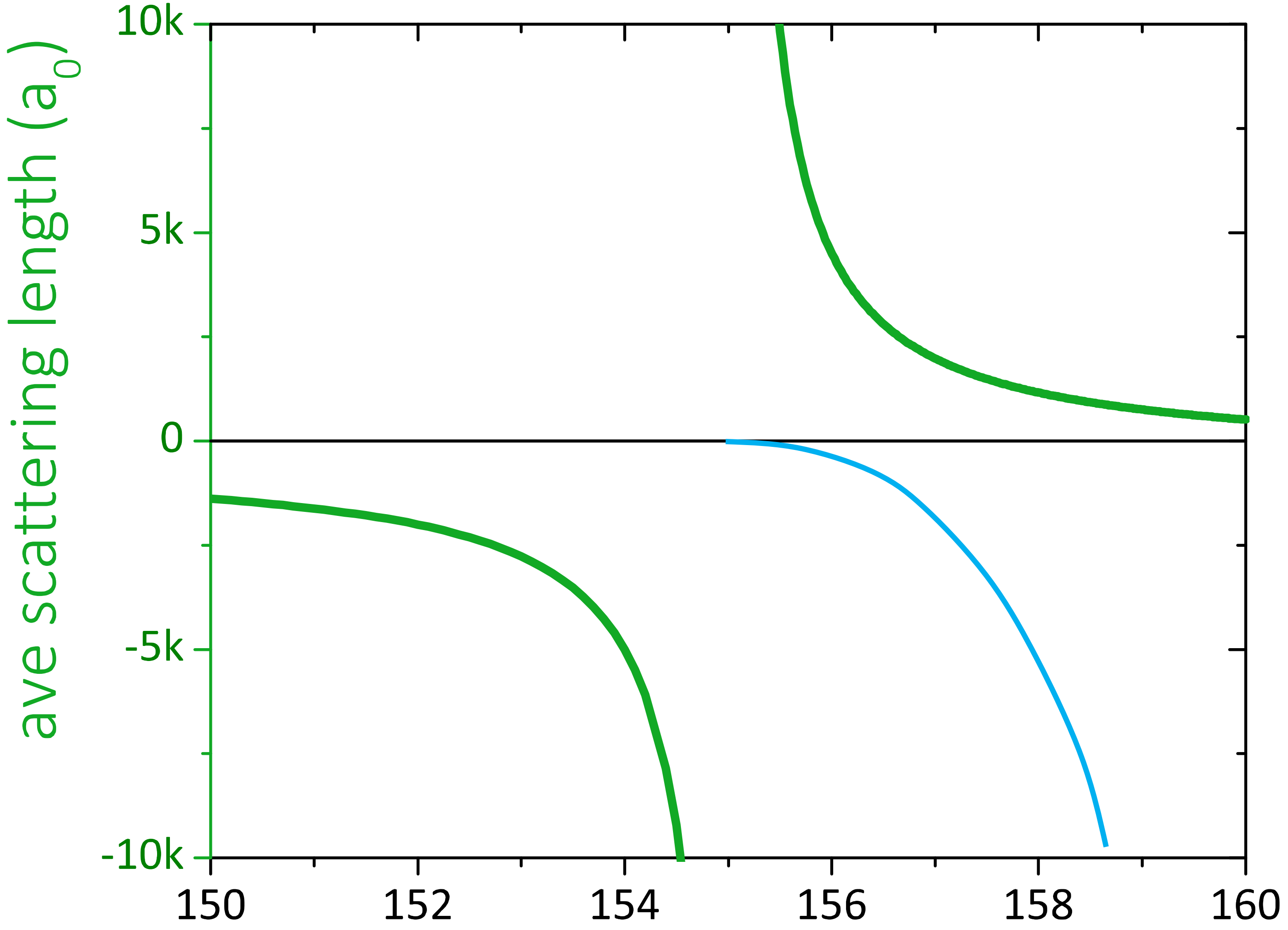
Cold Bosons: The Regimes

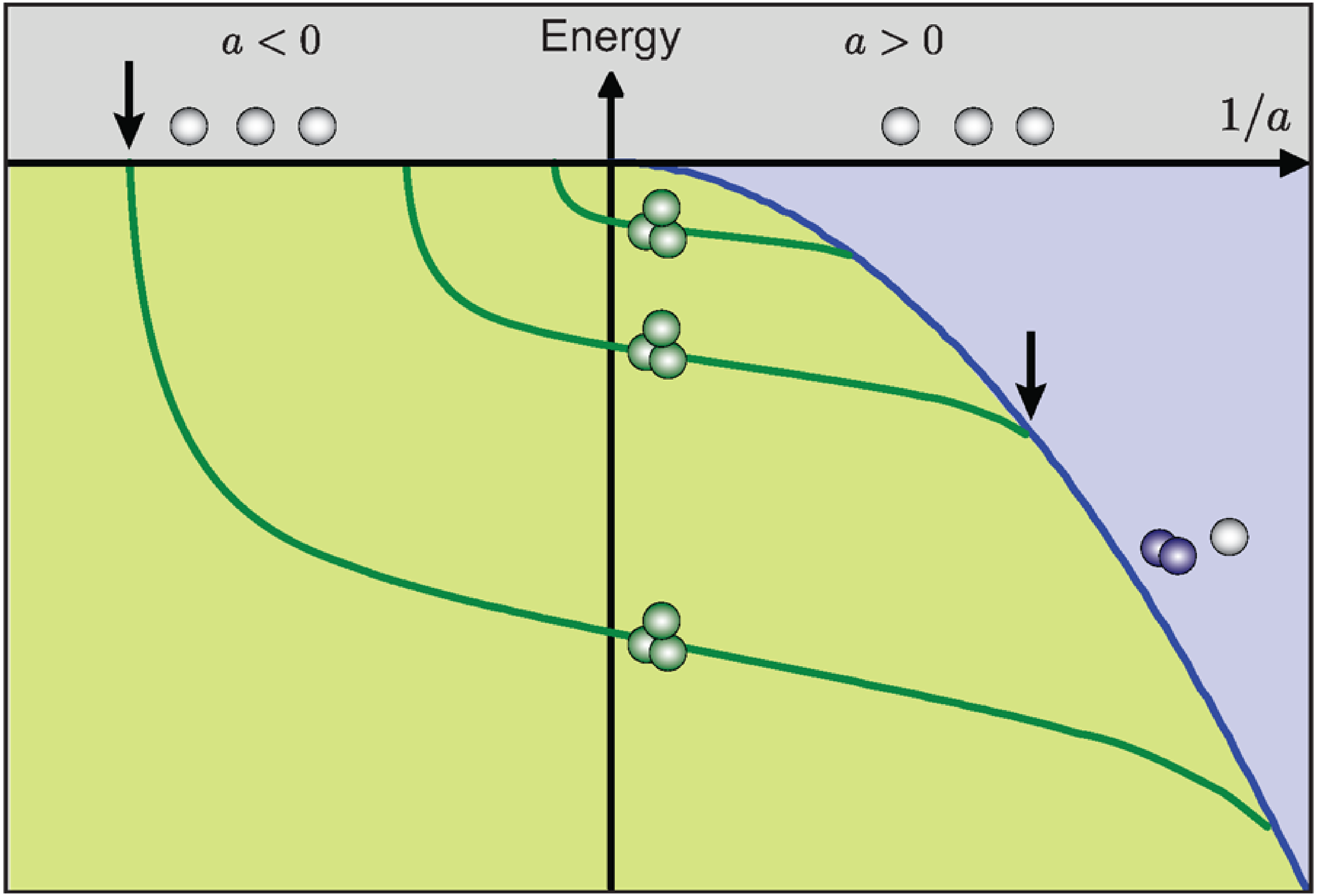


How can we learn more about
this short-lived (but not infinitely short-lived)
exotic, liquid-like *many-body* state?

First, let's review underlying *few-body* physics.

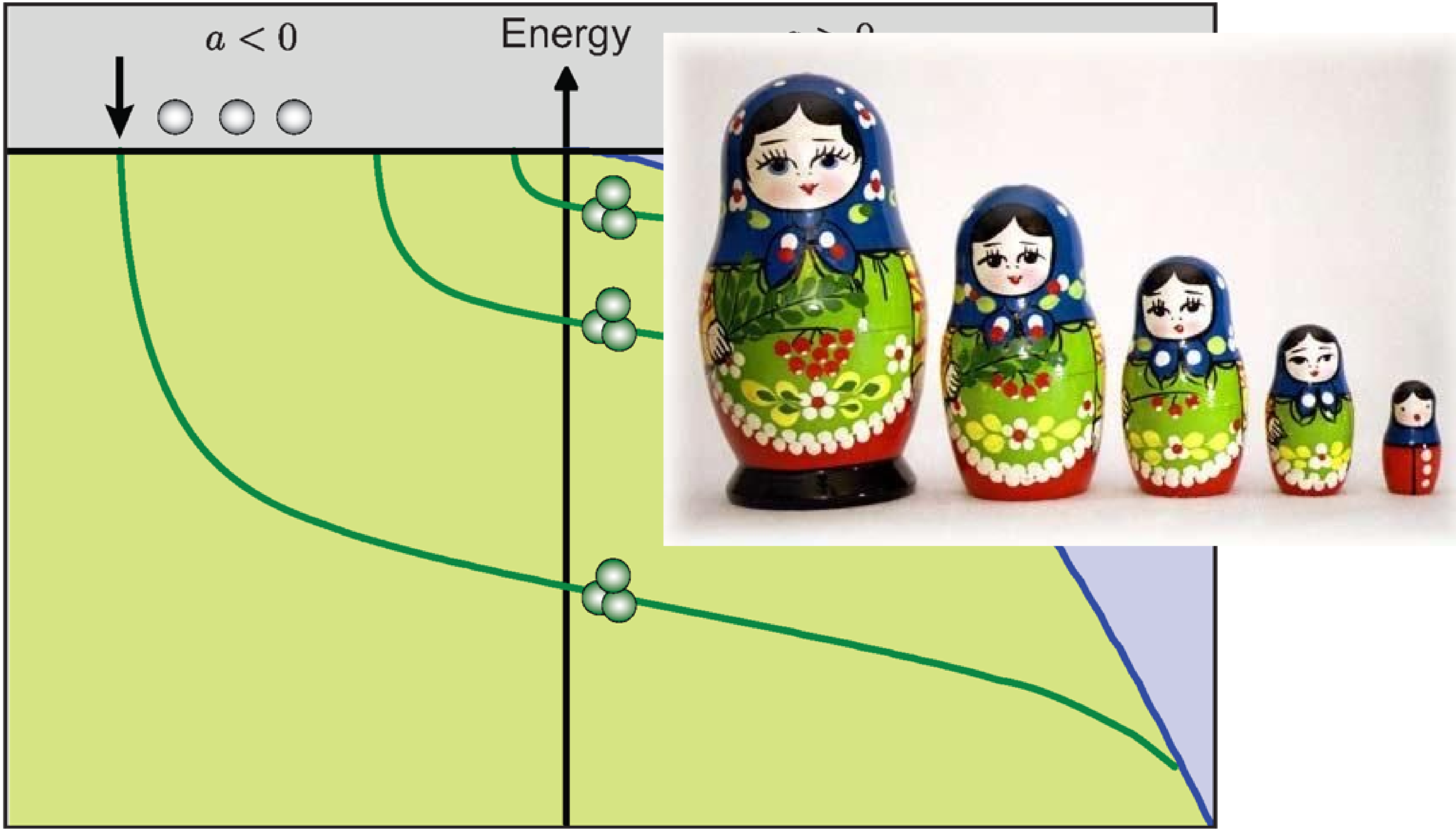
Feshbach Resonance: evidence for existence of…
a two-body boundstate!





From Ferlaino and Grimm (Phys. Today, 2010)

Three-body Efimov states



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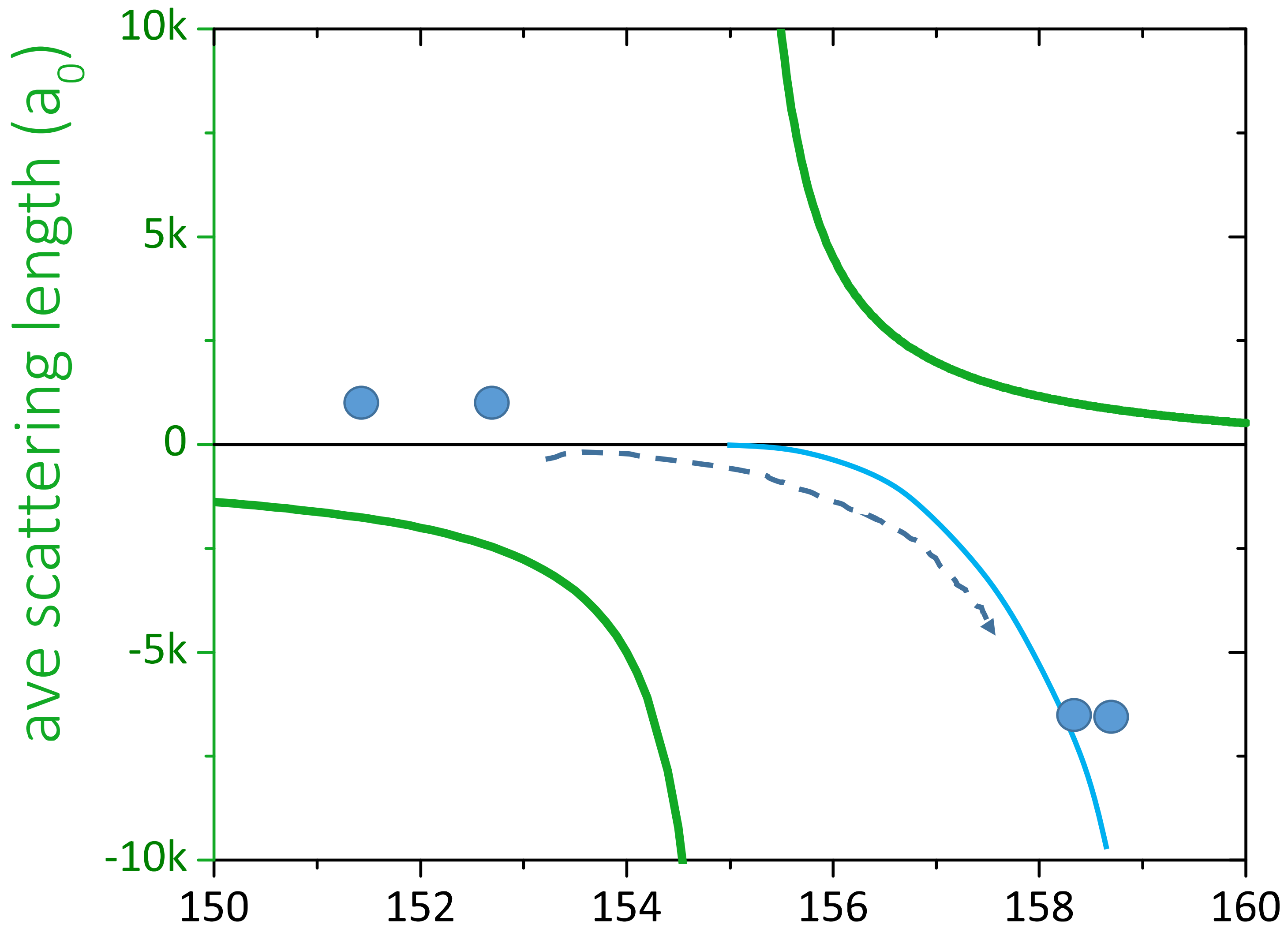
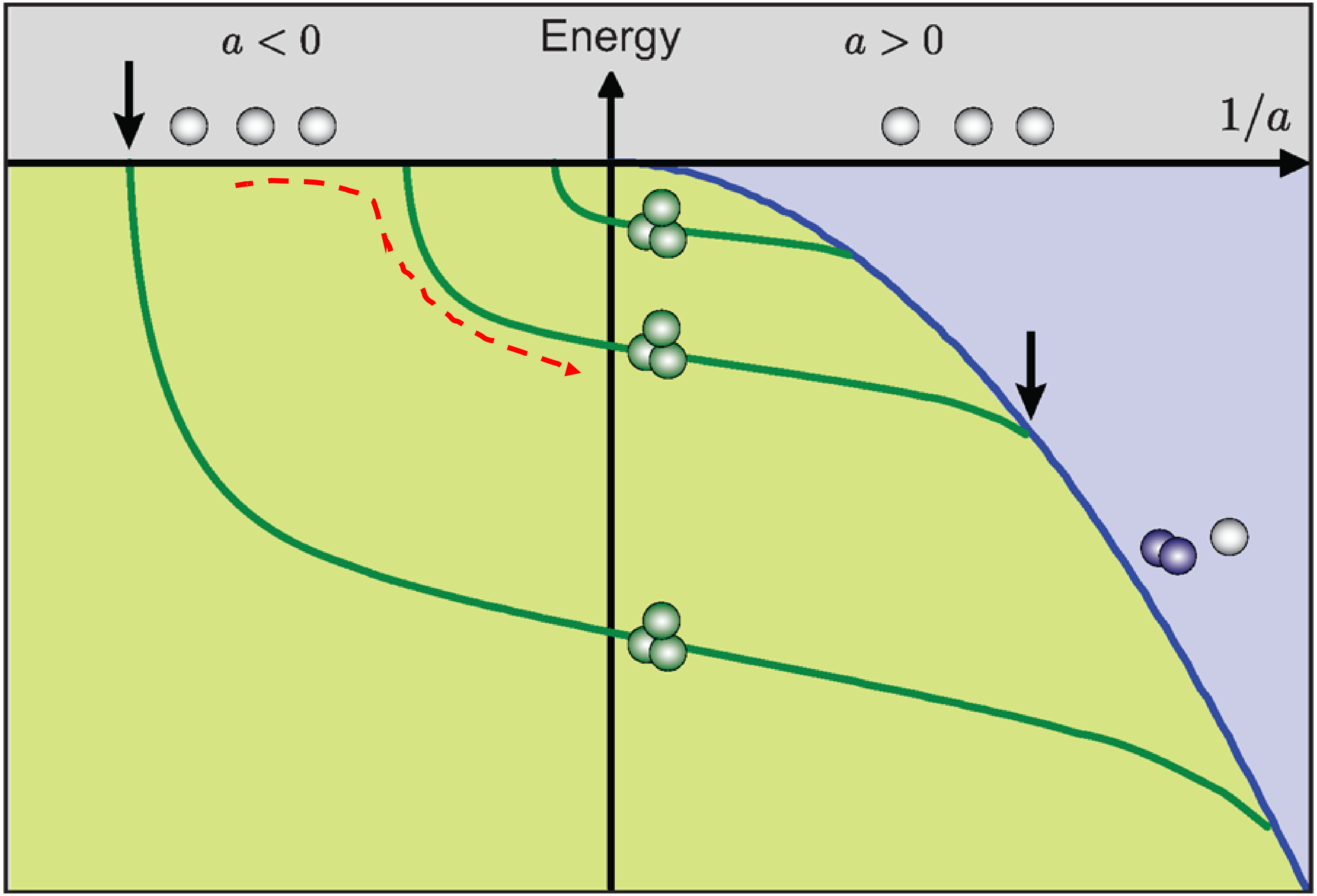


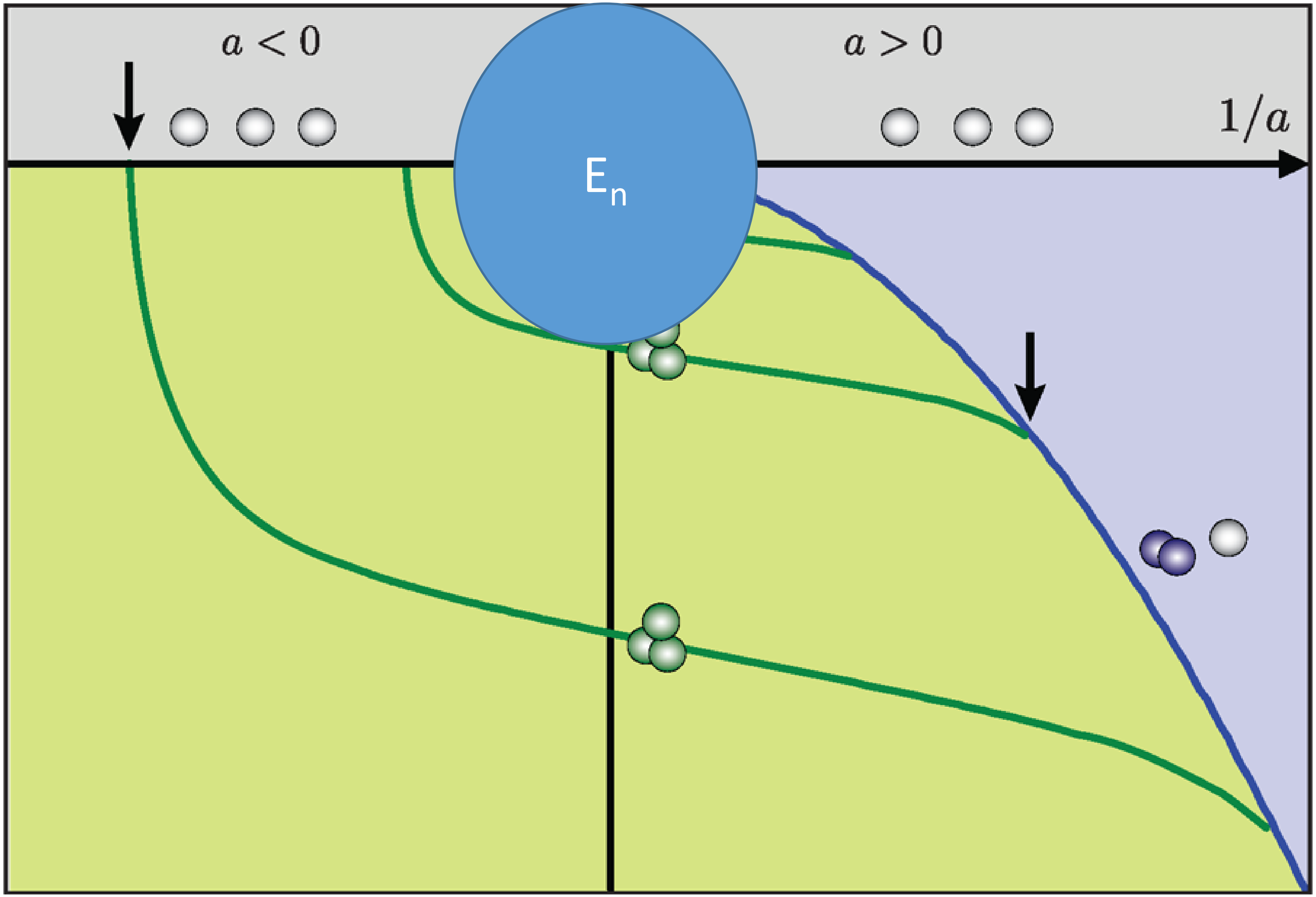
Various ways to create a population in the molecule state.



Enhanced loss (changes in imaginary part of scattering length) identifies curve crossing in bound states

Can we, instead, create a “population”?

From Ferlaino and Grimm (Phys. Today, 2010)



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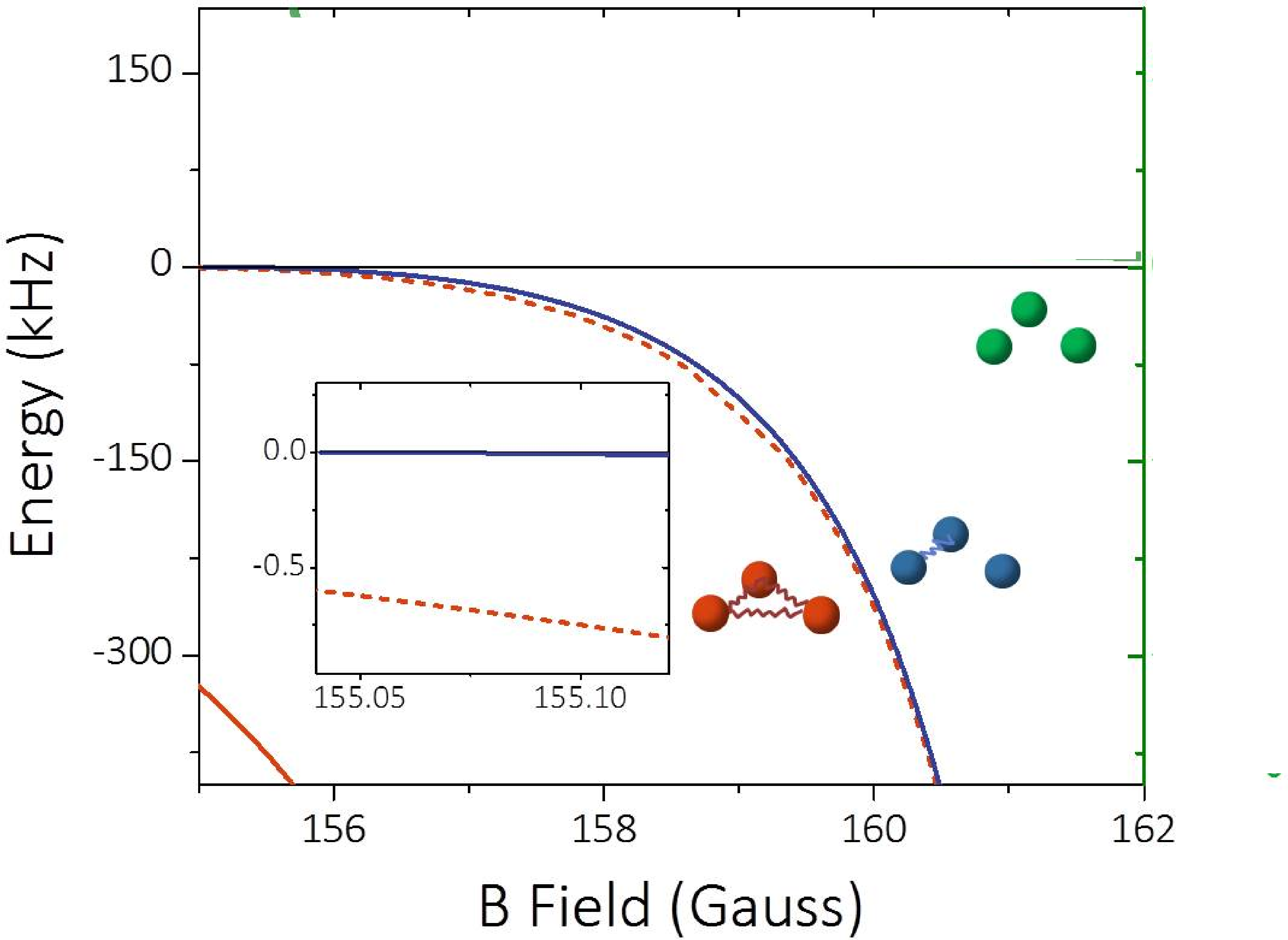
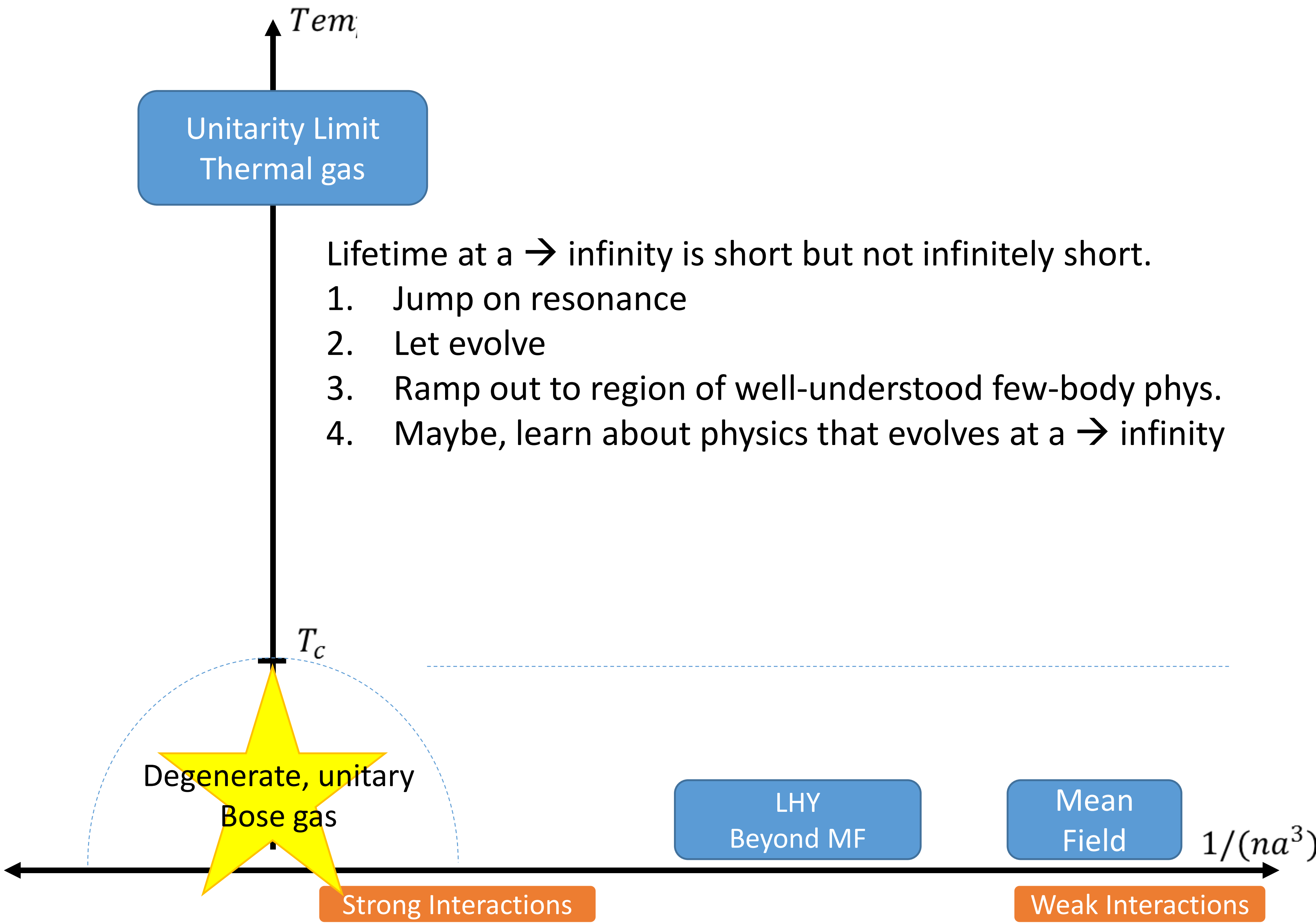
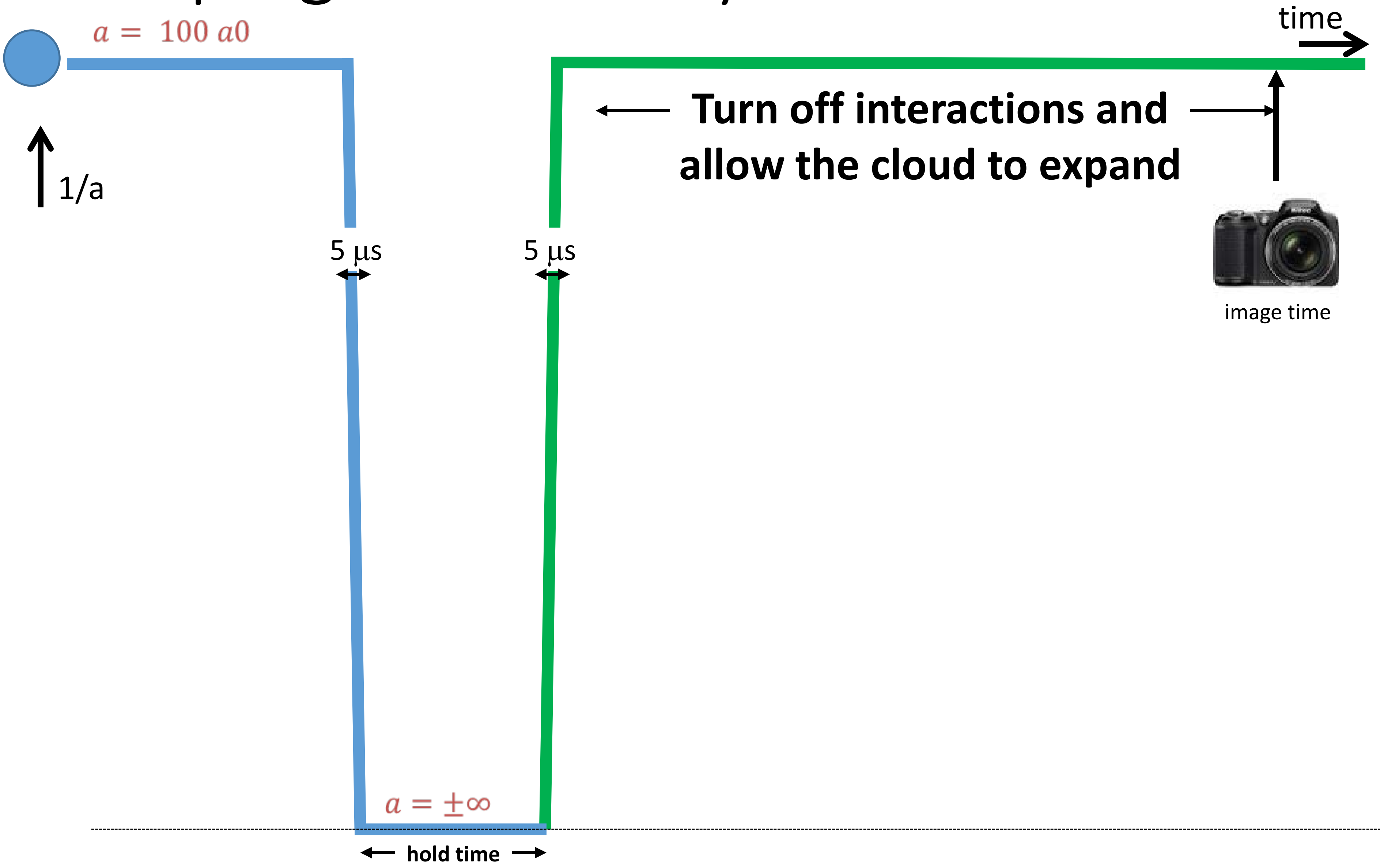
Three-body Efimov states

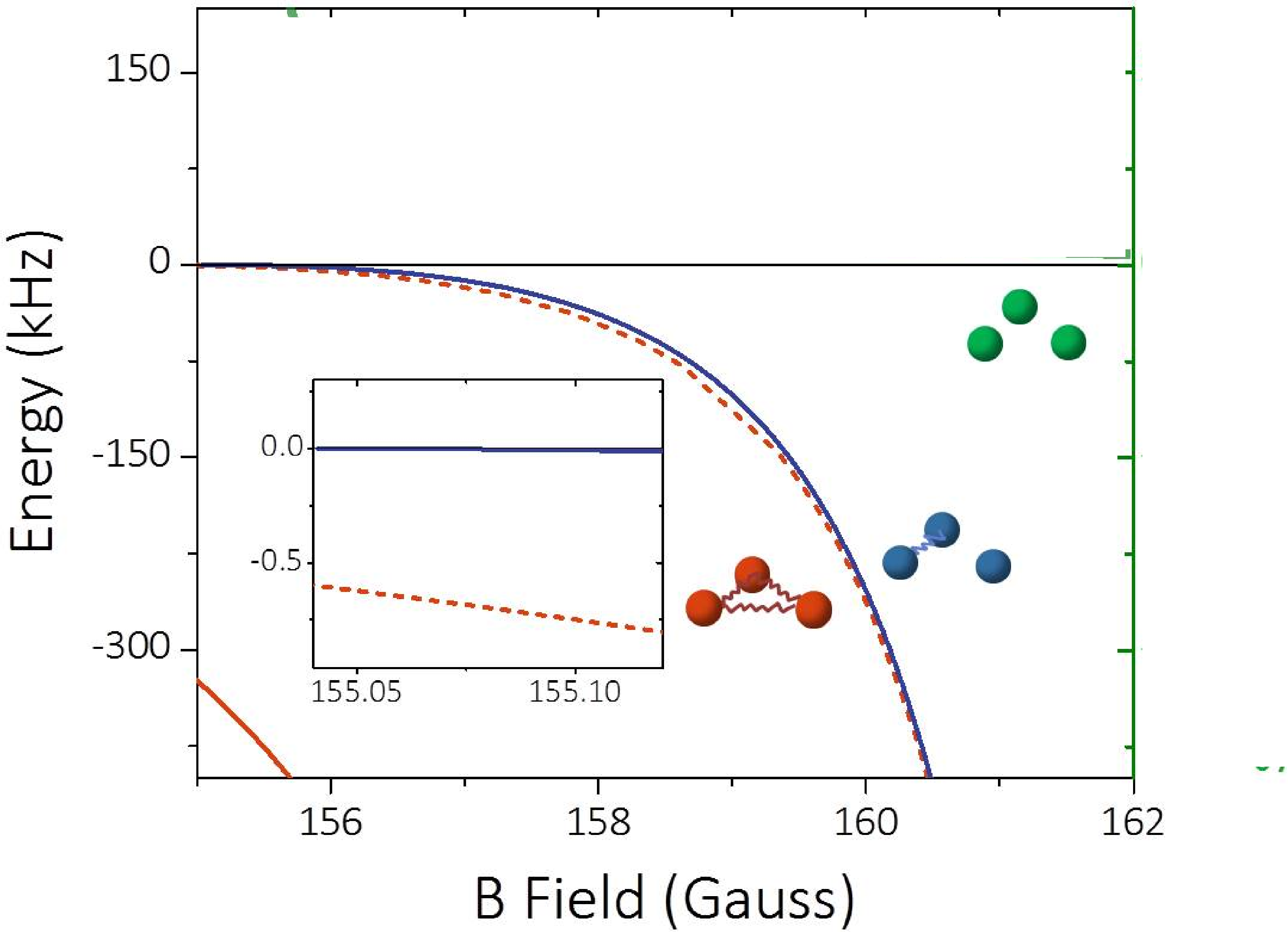

150
0
-150
-300
Energy (kHz)
0.0
-0.5
155.05
155.10
156
158
160
162
B Field (Gauss)



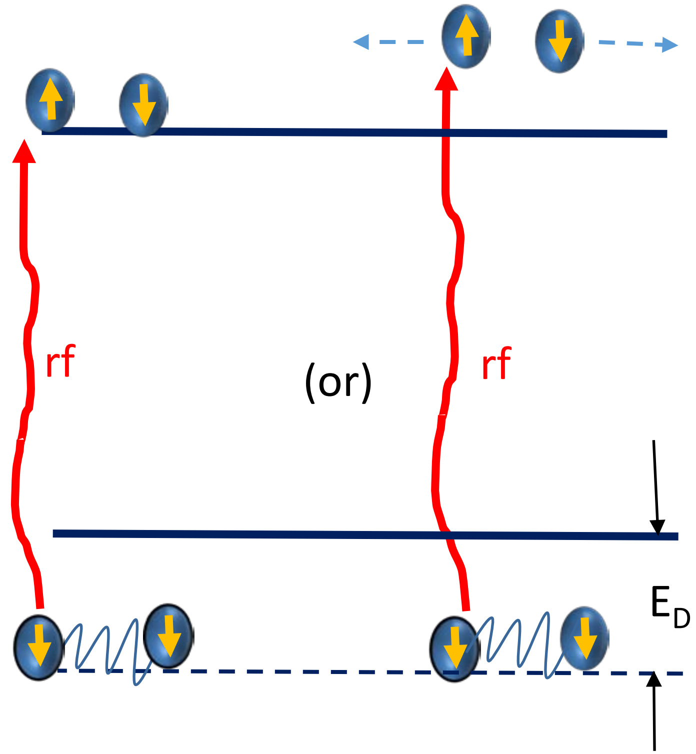
$Temp$
Unitarity Limit
Thermal gas
Lifetime at a → infinity is short but not infinitely short.
1. Jump on resonance
2. Let evolve
3. Ramp out to region of well-understood few-body phys.
4. Maybe, learn about physics that evolves at a → infinity
T_c
Degenerate, unitary
Bose gas
LHY
Beyond MF
Mean
Field
$1/(na^3)$
Strong Interactions
Weak Interactions

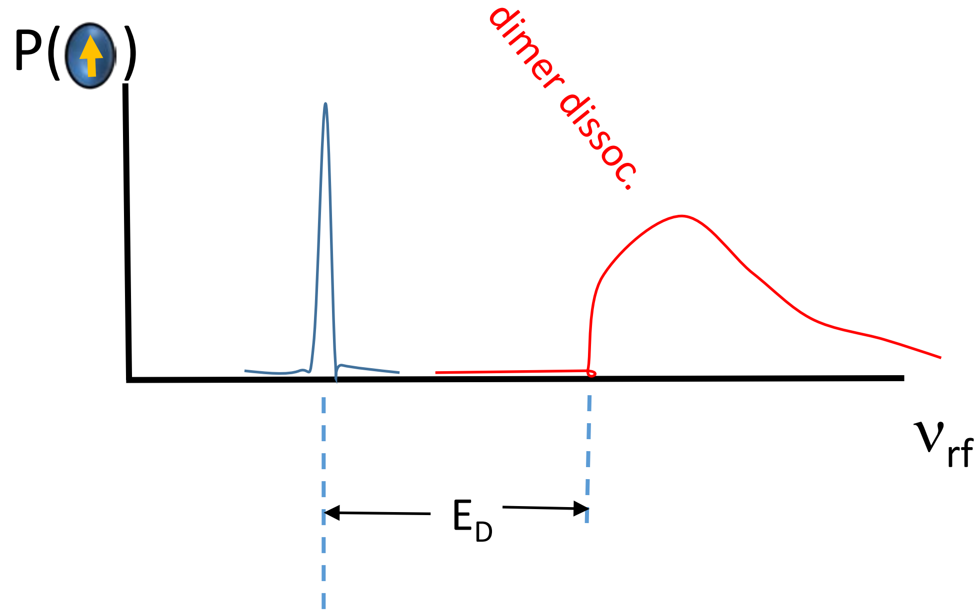
Jumping to Unitarity



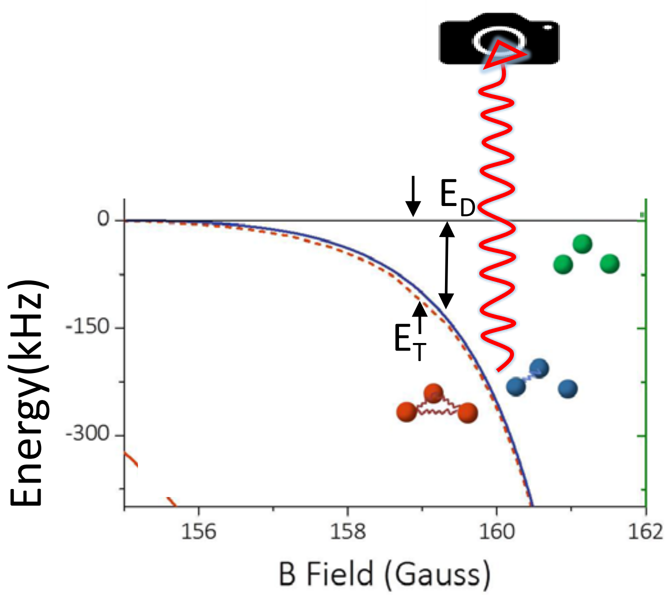


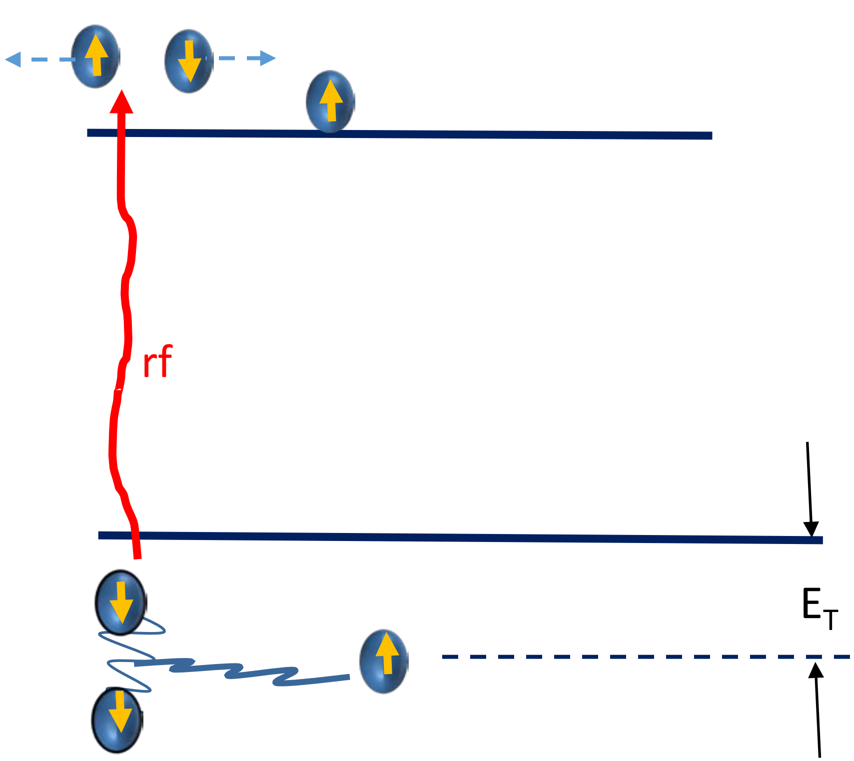
Energy (kHz)
150
0
-150
-300
0.0
-0.5
155.05
155.10
156
158
160
162
B Field (Gauss)

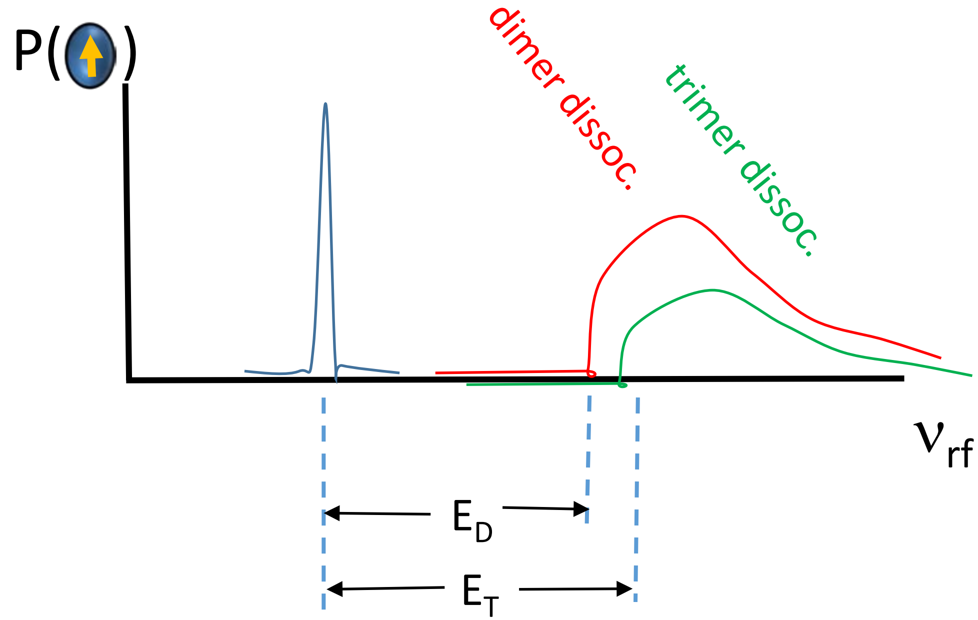




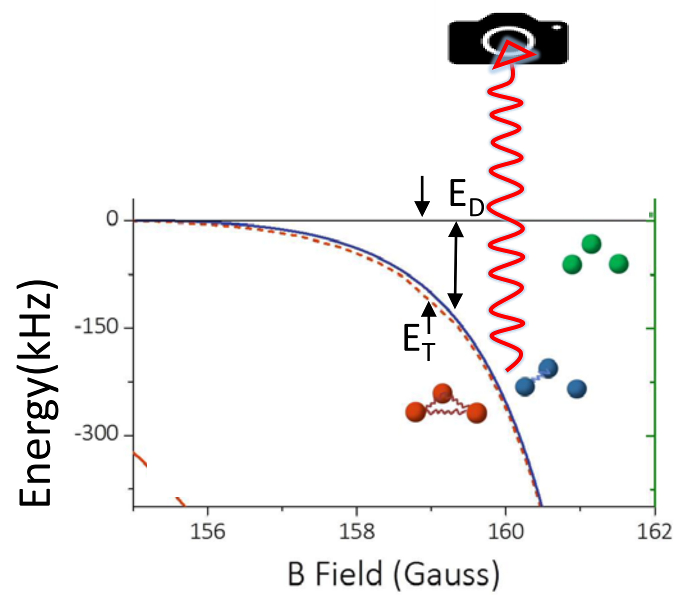
Dimer Dissociation

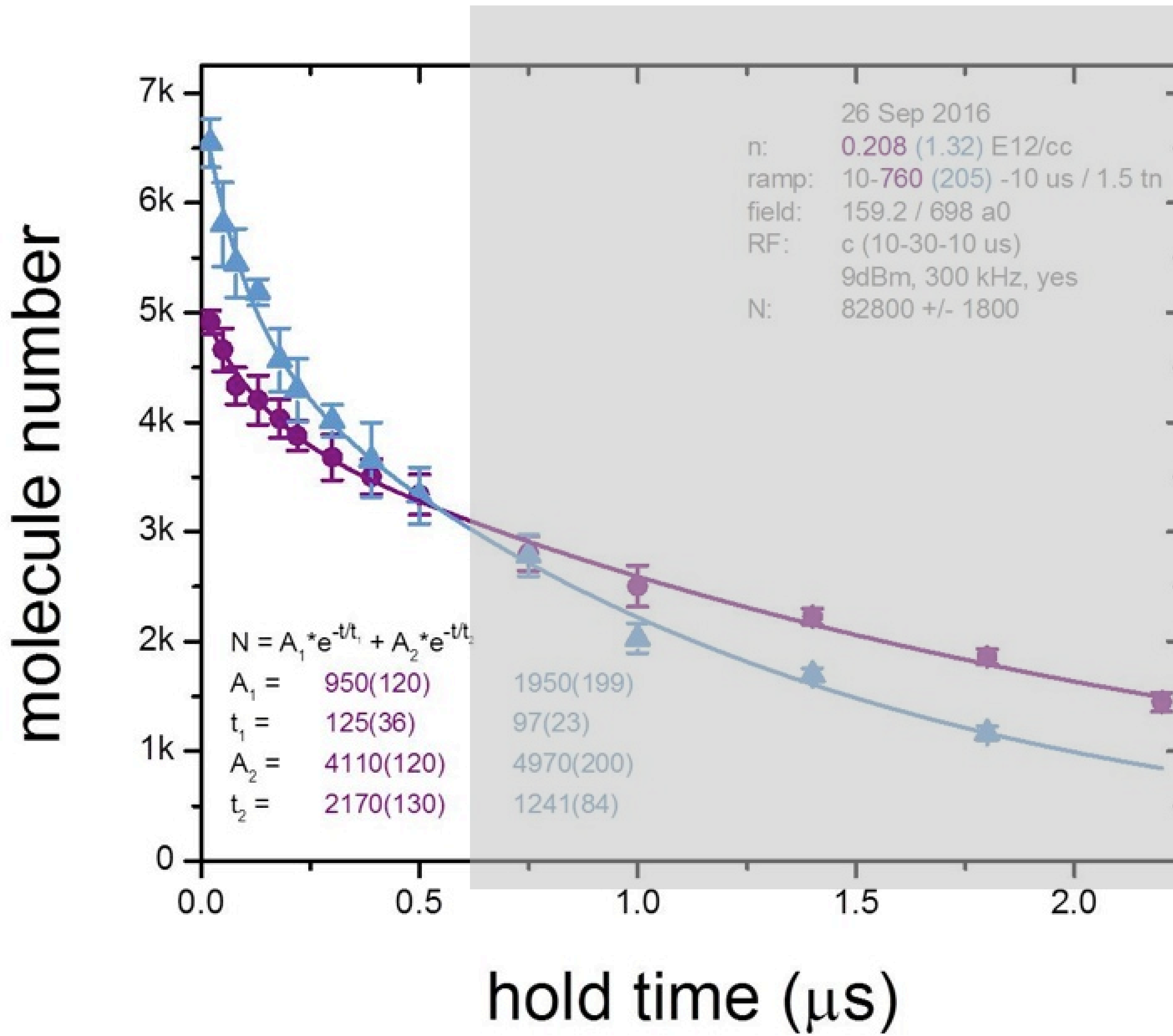




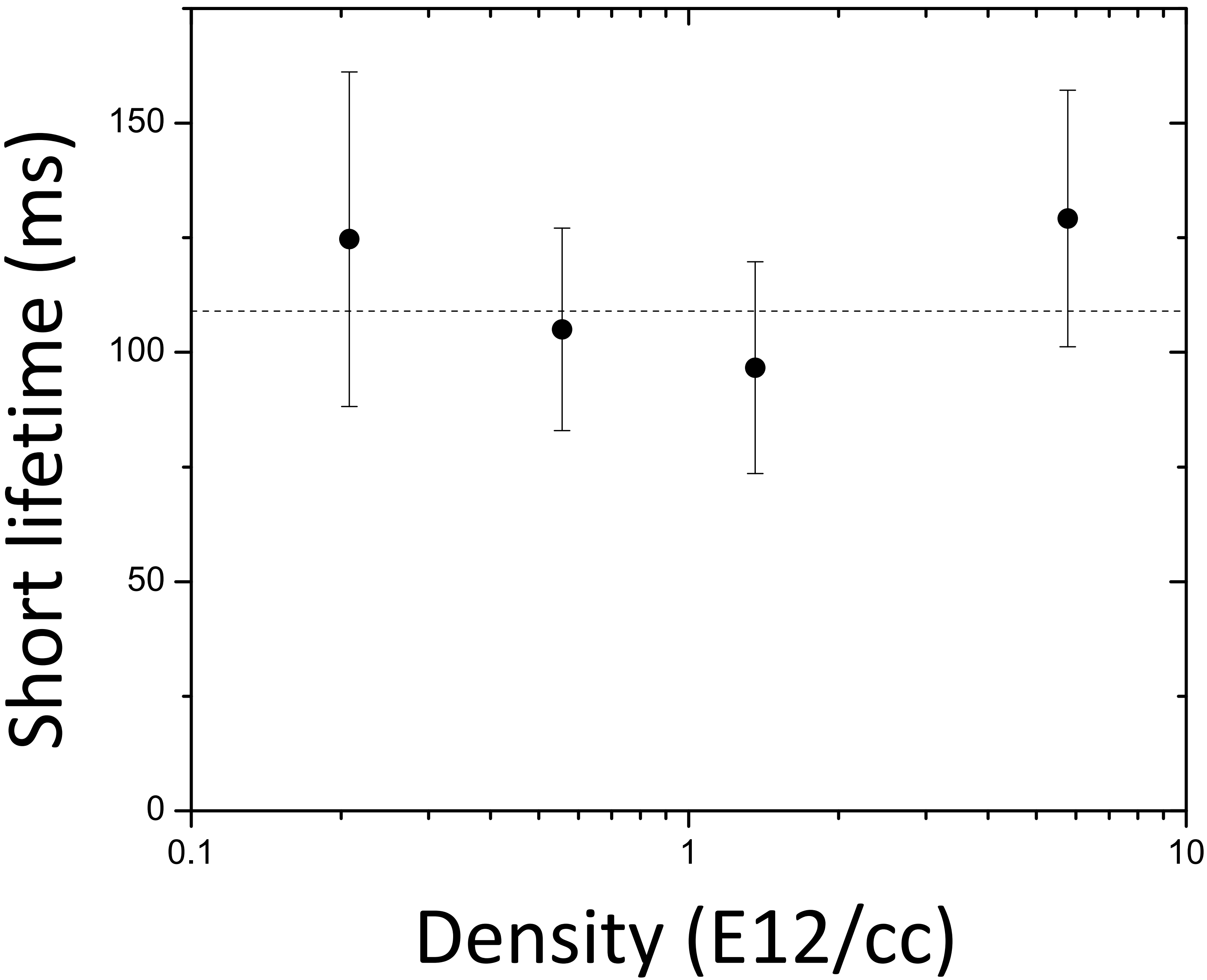


Trimer Dissociation





26 Sep 2016
n: 0.208 (1.32) E12/cc
ramp: 10-760 (205) -10 us / 1.5 tn
field: 159.2 / 698 a0
RF: c (10-30-10 us)
9dBm, 300 kHz, yes
N: 82800 +/- 1800
N = A1*e-t/t1 + A2*e-t/t2
A1 = 950(120) 1950(199)
t1 = 125(36) 97(23)
A2 = 4110(120) 4970(200)
t2 = 2170(130) 1241(84)
molecule number
hold time (μs)
0
1k
2k
3k
4k
5k
6k
7k
0.0
0.5
1.0
1.5
2.0

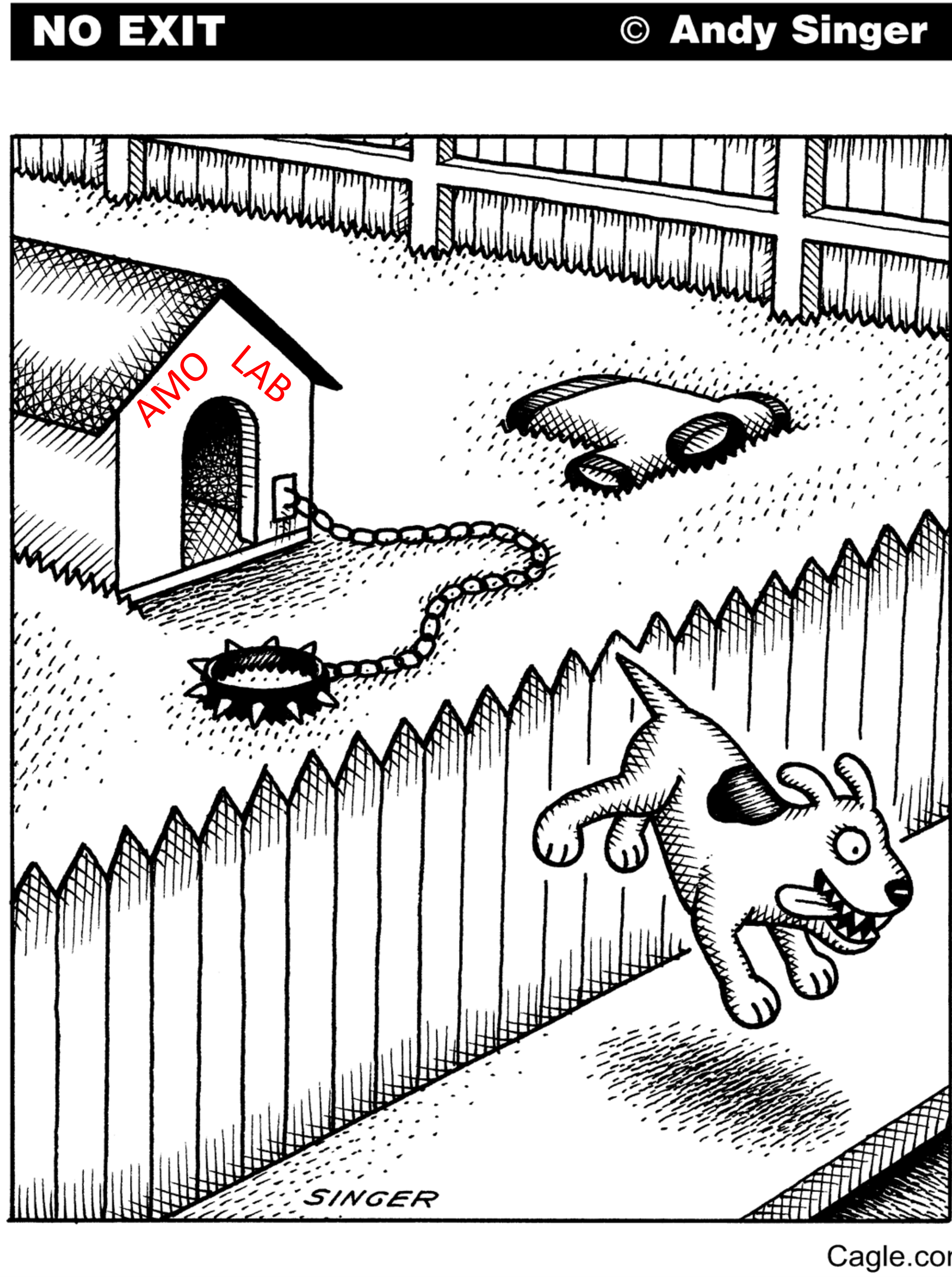


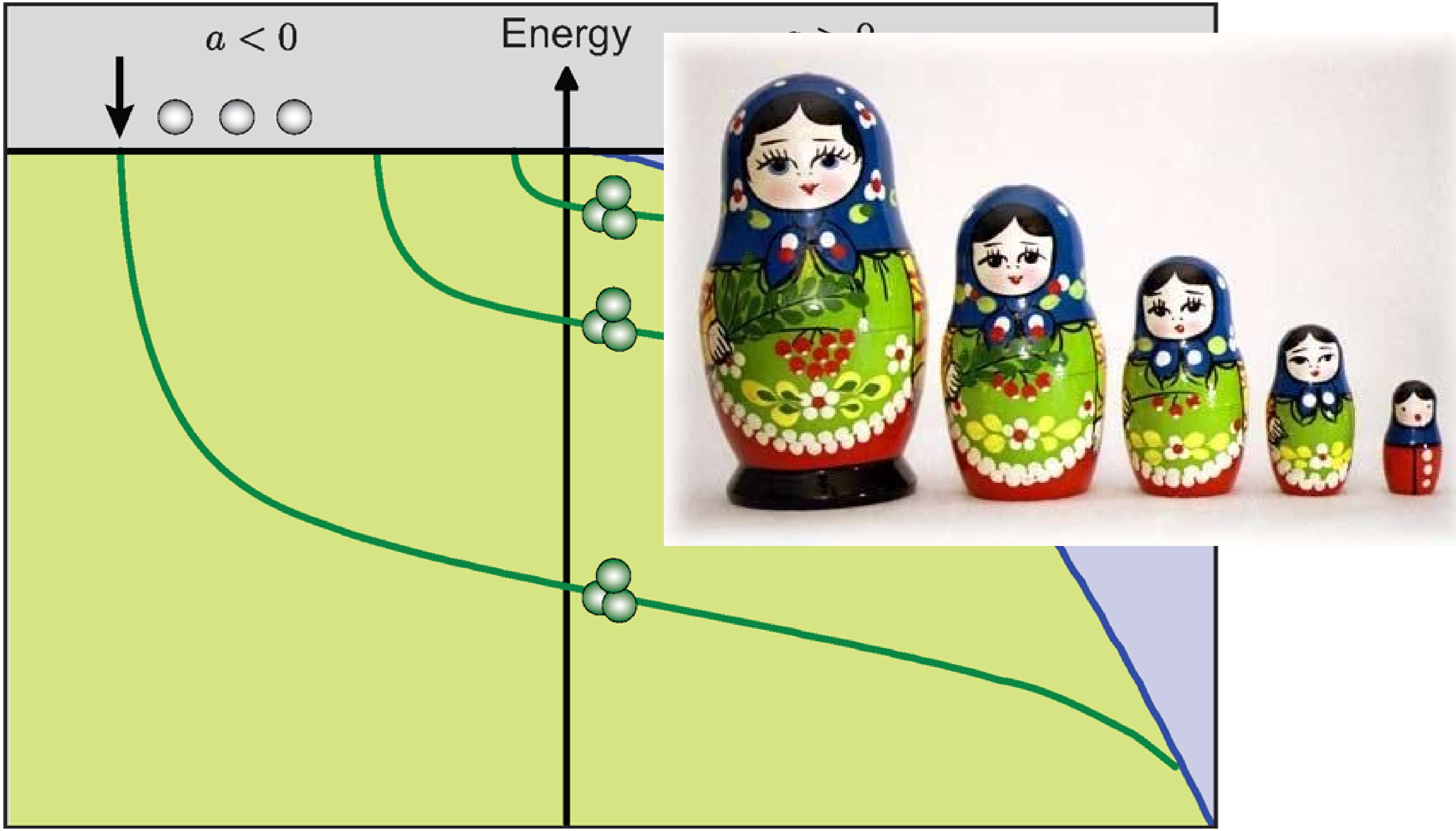
Short lifetime (ms)
150
100
50
0
0.1
1
10
Density (E12/cc)

When Atomic Physicists Escape:

Baryogenesis;

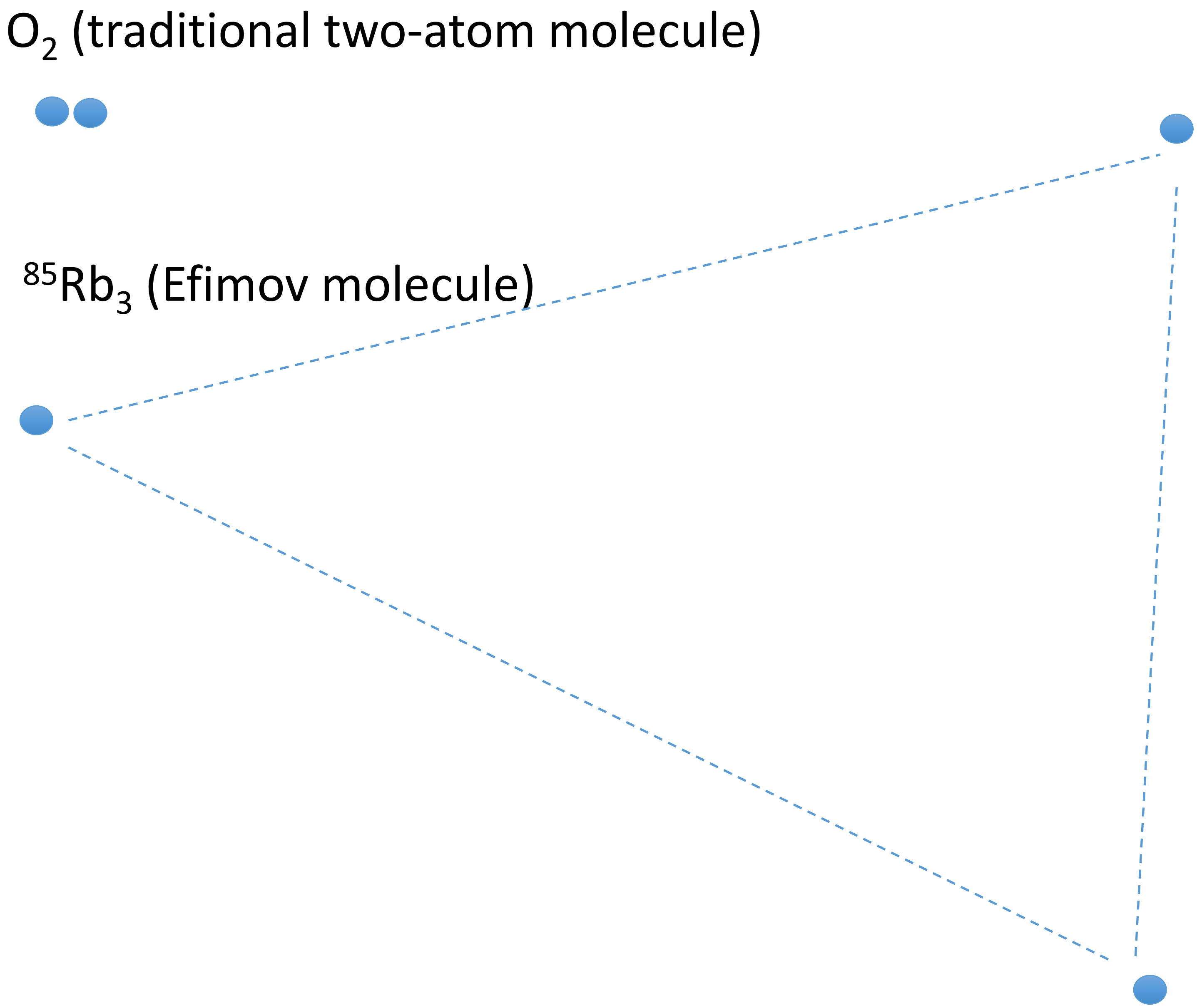
Materials; Liquids

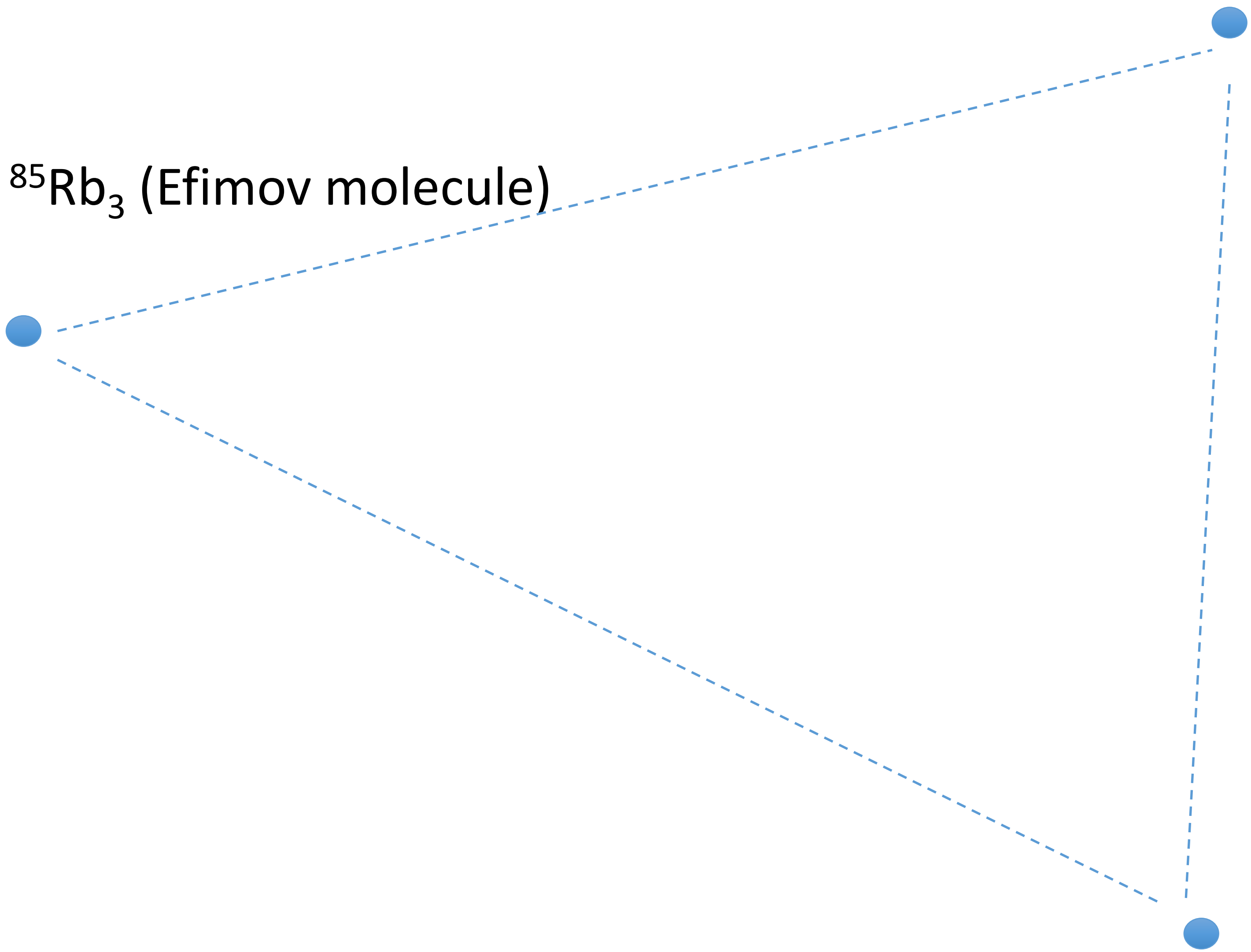




From Ferlaino and Grimm (Phys. Today, 2010)

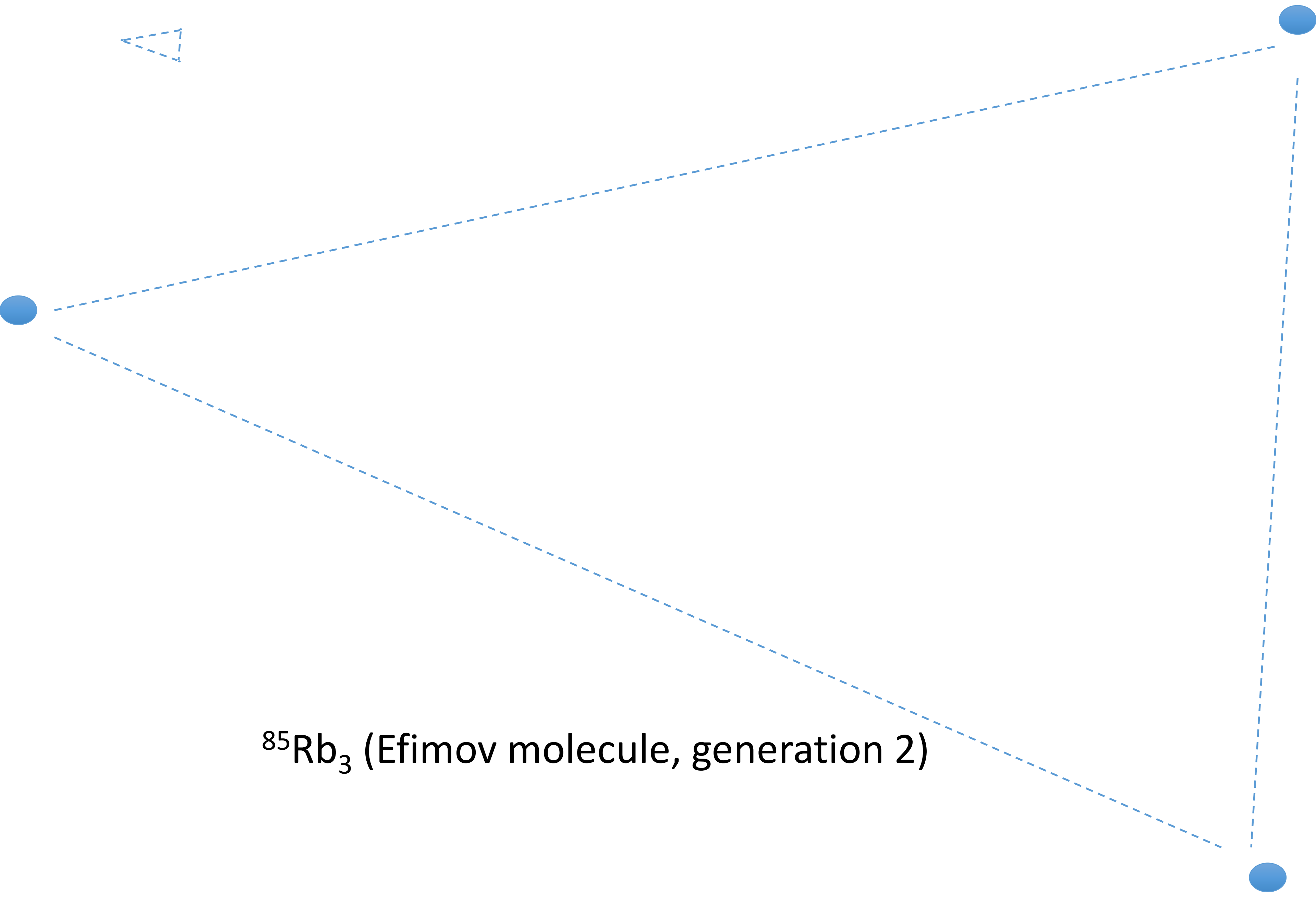
Three-body Efimov states


O_2 (traditional two-atom molecule)
$^{85}Rb_3$ (Efimov molecule)

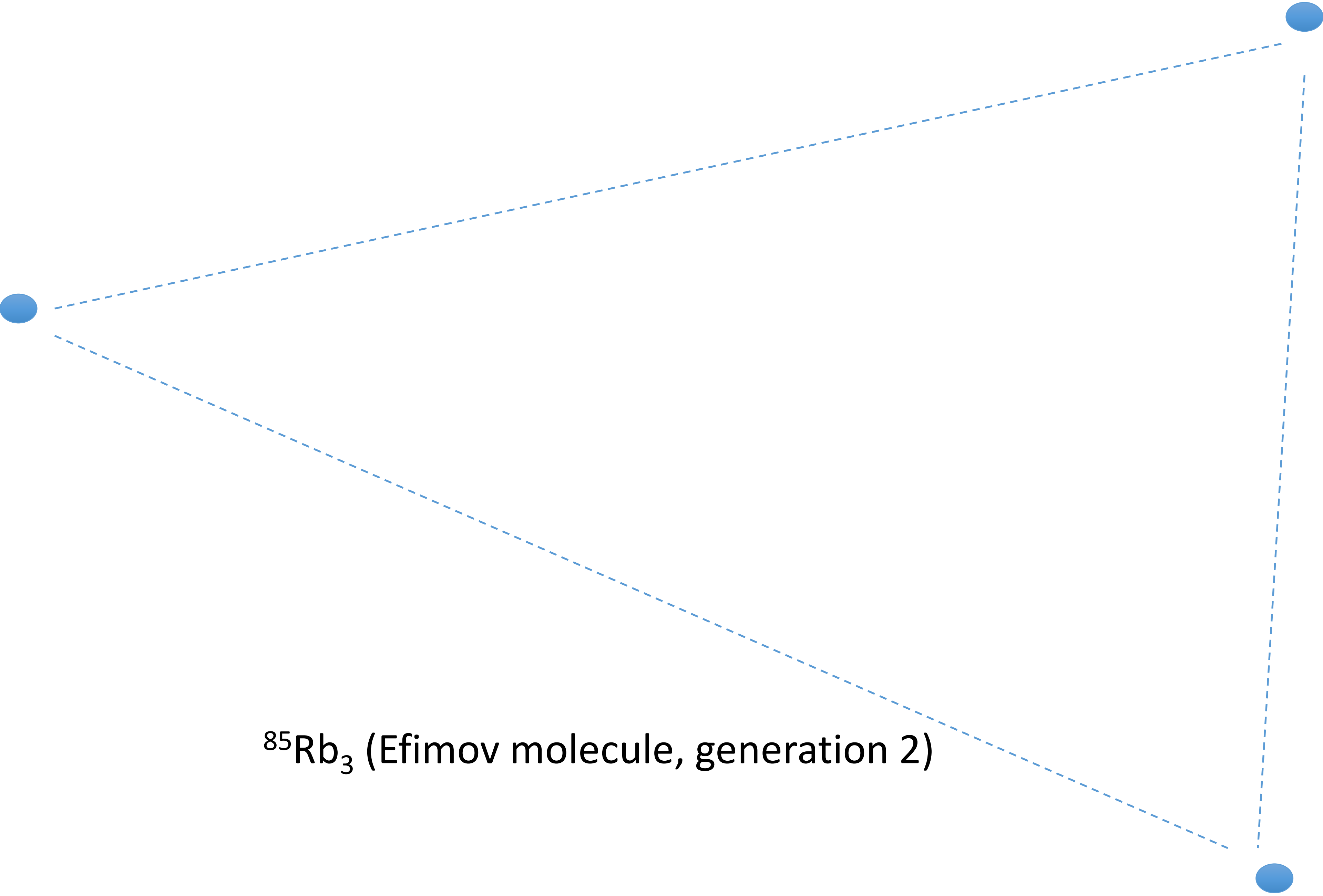

$^{85}Rb_3$ (Efimov molecule)

$^{85}Rb_3$ (Efimov molecule, generation 1)

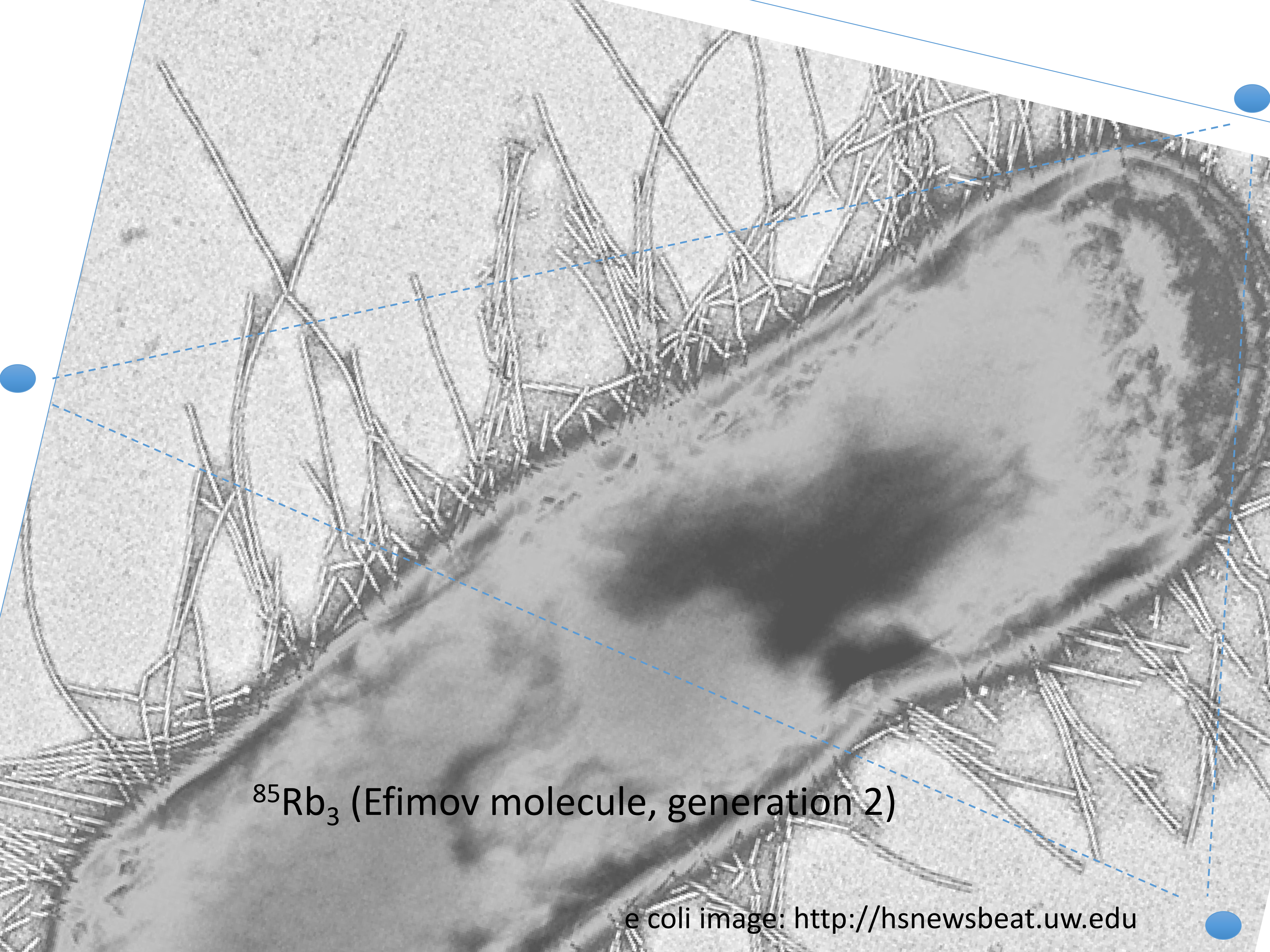
$^{85}Rb_3$ (Efimov molecule, generation 1)

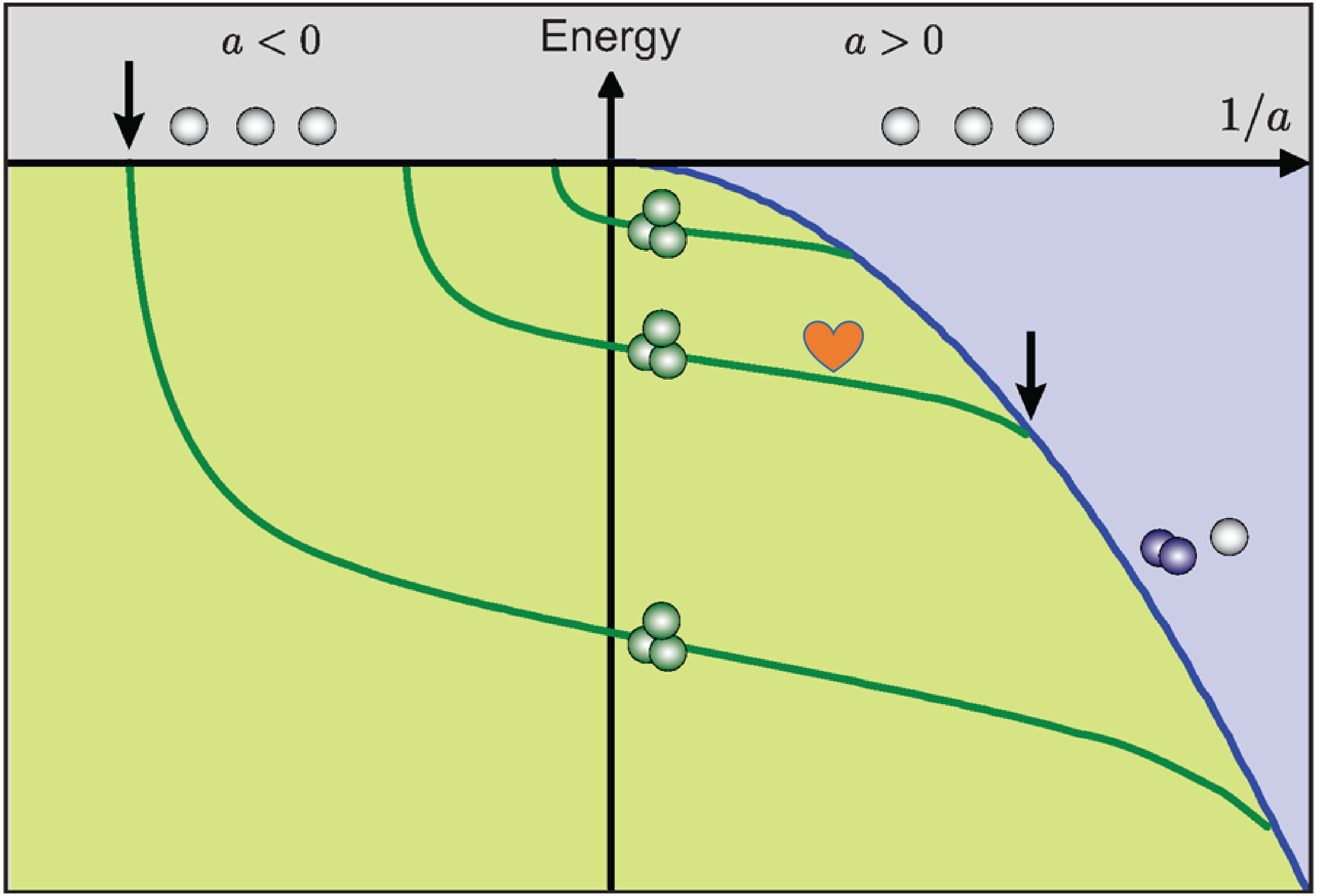


From one “generation” to next,
linear size increases x 22.7
binding energy decreases x 22.7^2 = 500
volume increases x 22.7^3 = 12000



$^{85}Rb_3$ (Efimov molecule, generation 2)


$^{85}Rb_3$ (Efimov molecule, generation 2)
e coli image: http://hsnewsbeat.uw.edu



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binding energy decreases x $22.7^2 = 500$
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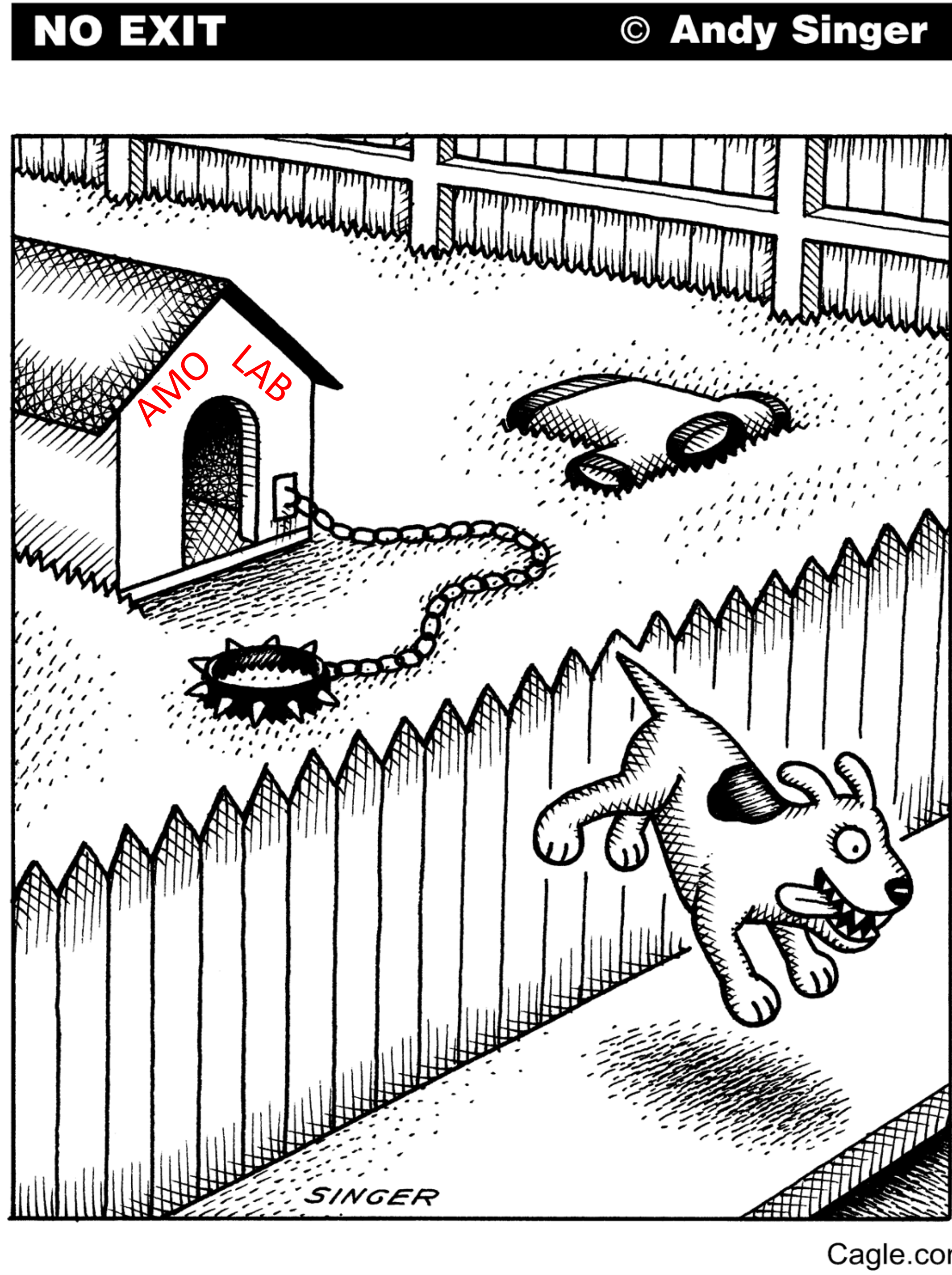
NASA
Armstrong
Collins
Slayton

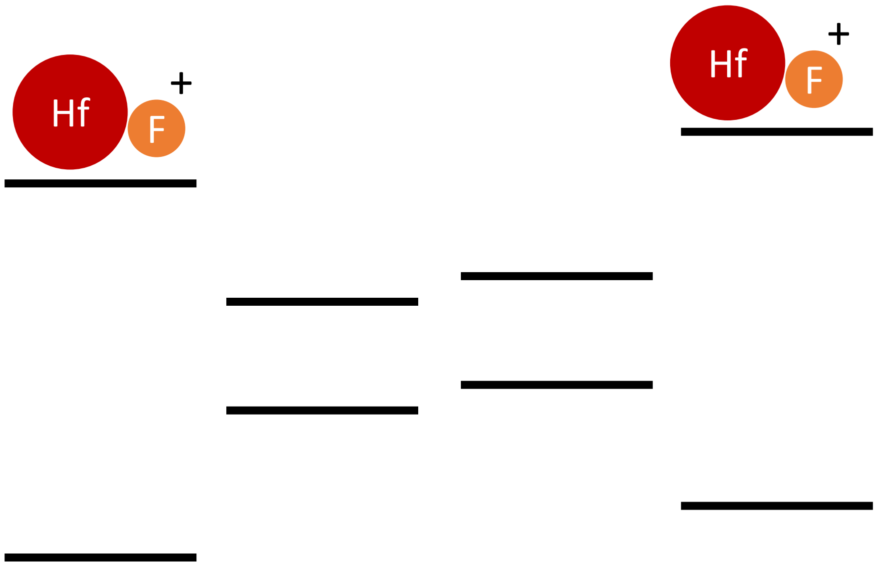
When Atomic Physicists Escape:

Baryogenesis; Materials; Liquids



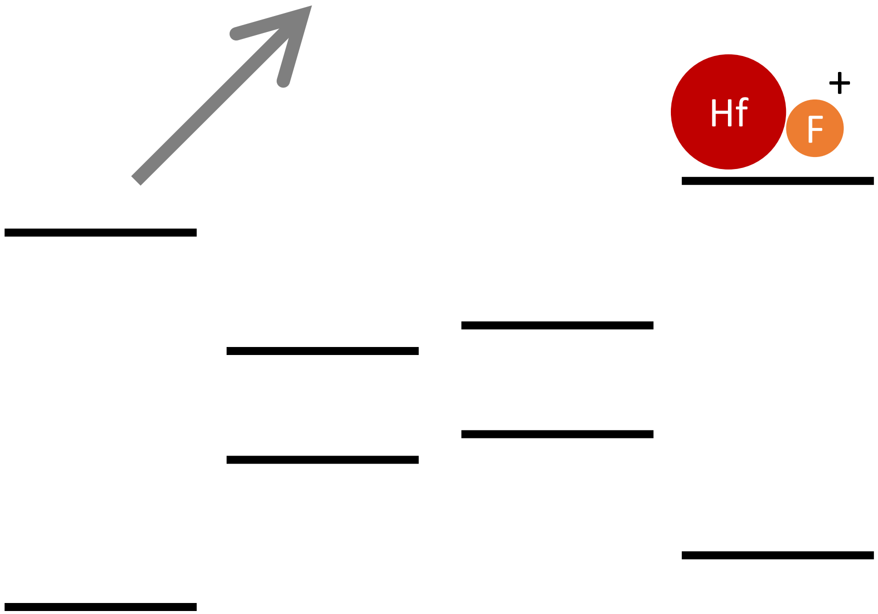
Ramsey Sequence

Transfer lasers prepare population in a single pair of Stark states



Ramsey Sequence

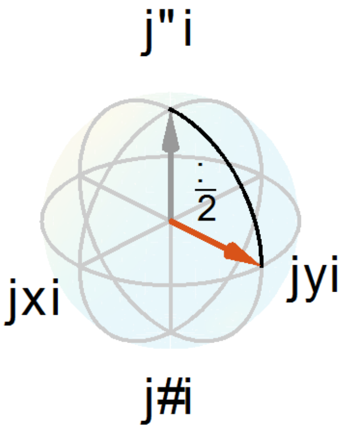
Optically deplete the population of one m_F level using strobed circularly polarized light

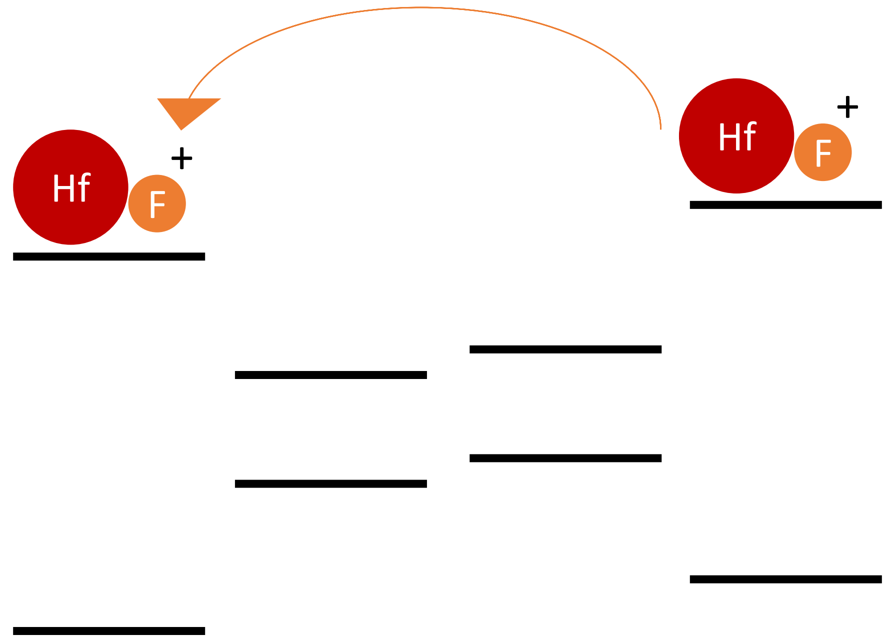


Ramsey Sequence

$\pi/2$ pulse puts system into the superposition

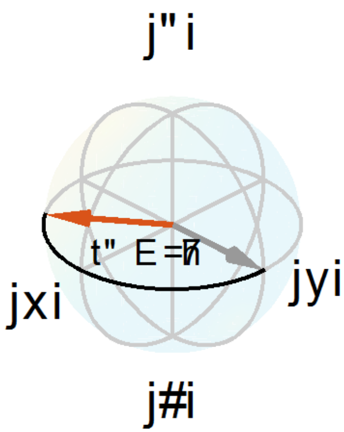
$$\left|m_F = -\frac{3}{2}\right\rangle + \left|m_F = +\frac{3}{2}\right\rangle$$



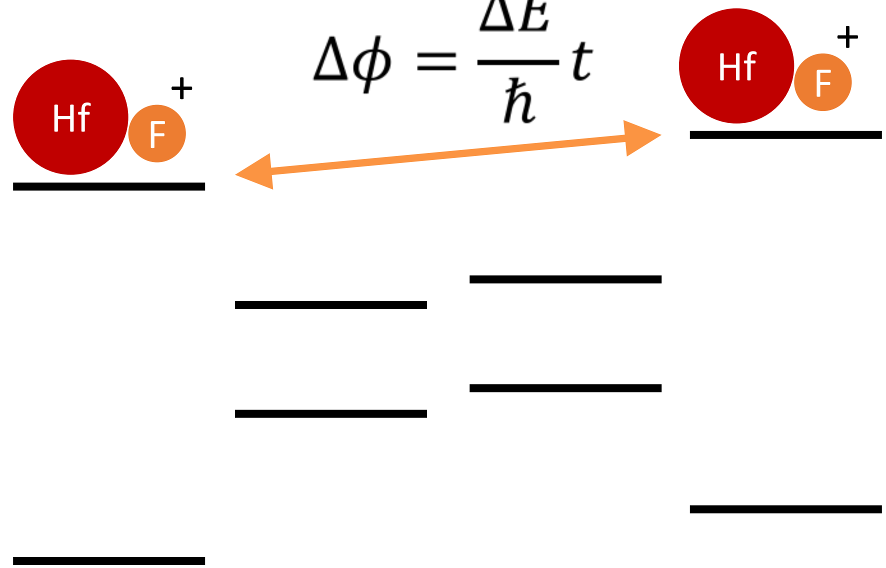


Ramsey Sequence

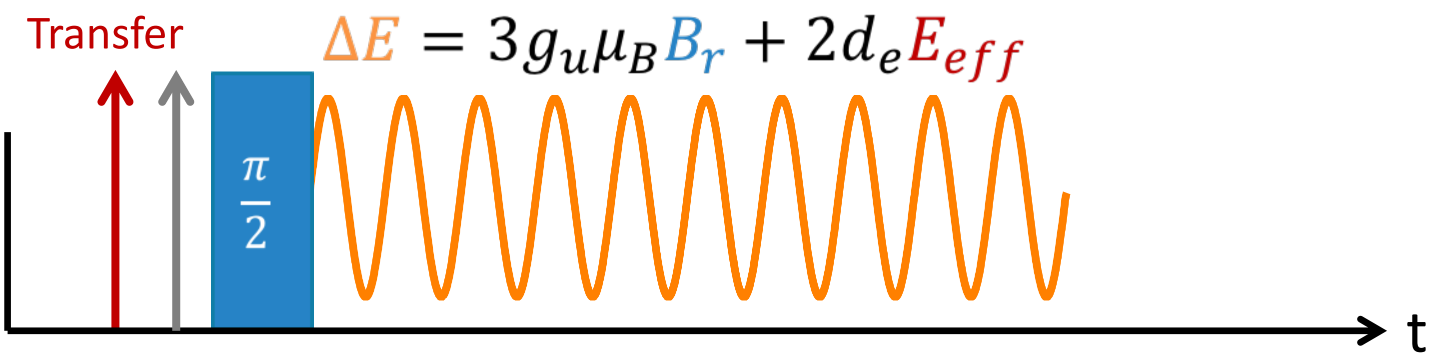
Free evolution



$$\Delta\phi = \frac{\Delta E}{\hbar} t$$

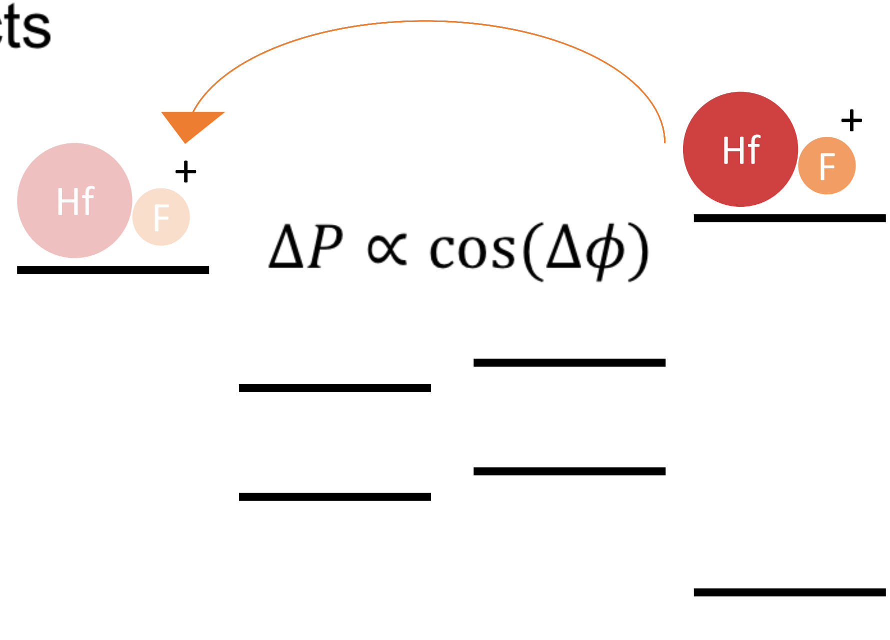


$$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$$

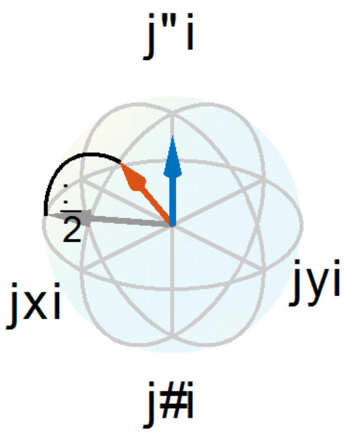


Ramsey Sequence

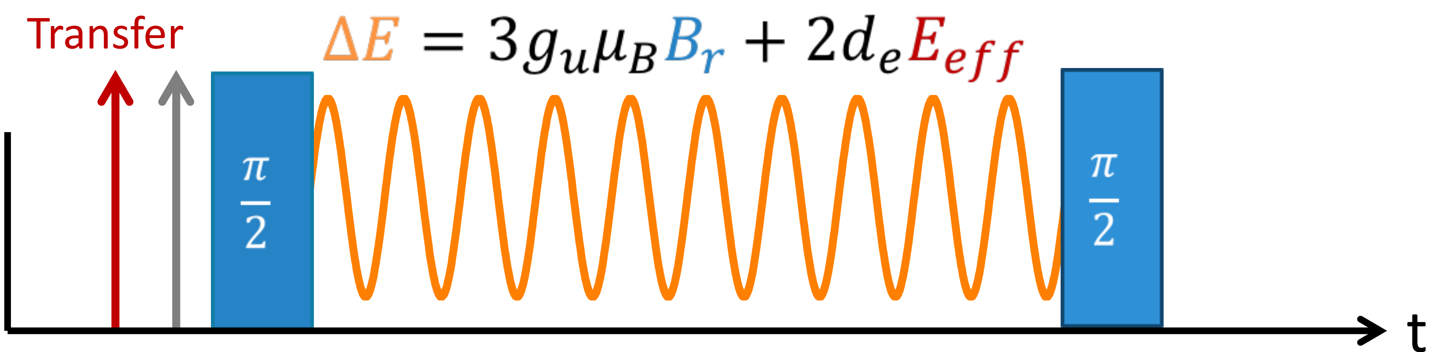
A second $\pi/2$ pulse projects the phase onto population



$$\Delta P \propto \cos(\Delta\phi)$$

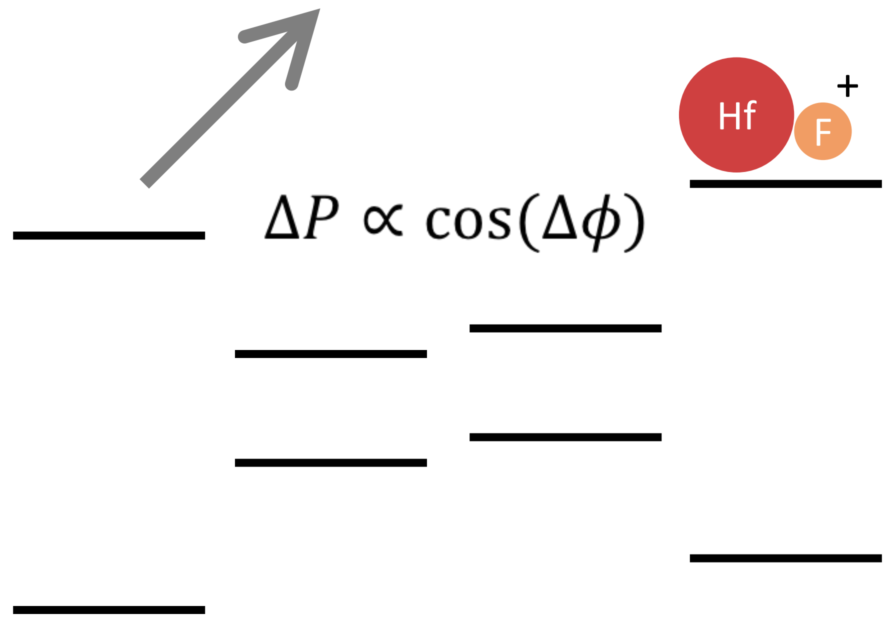


$$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$$



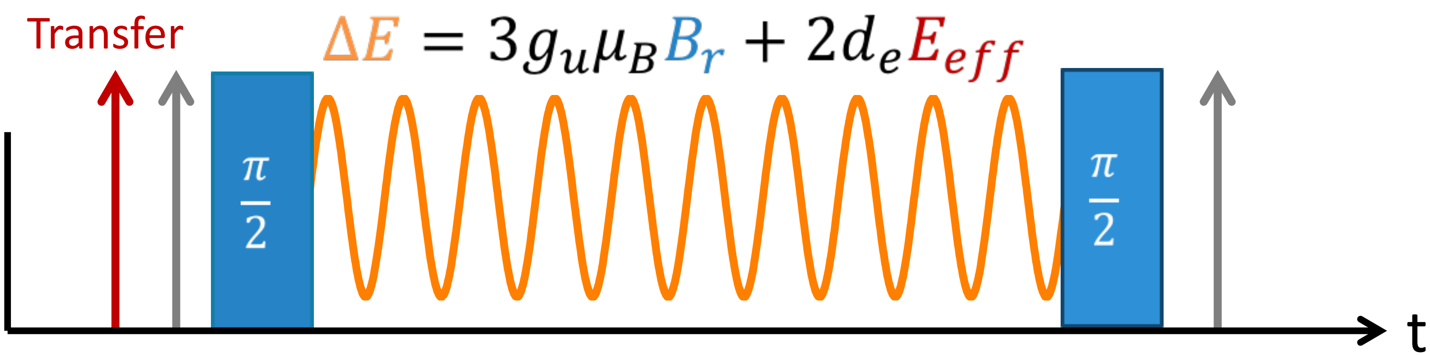
Ramsey Sequence

Optically deplete population out of one of the m_F levels



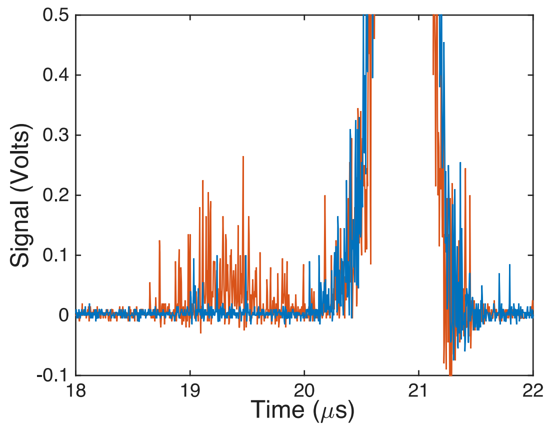
$$\Delta P \propto \cos(\Delta\phi)$$

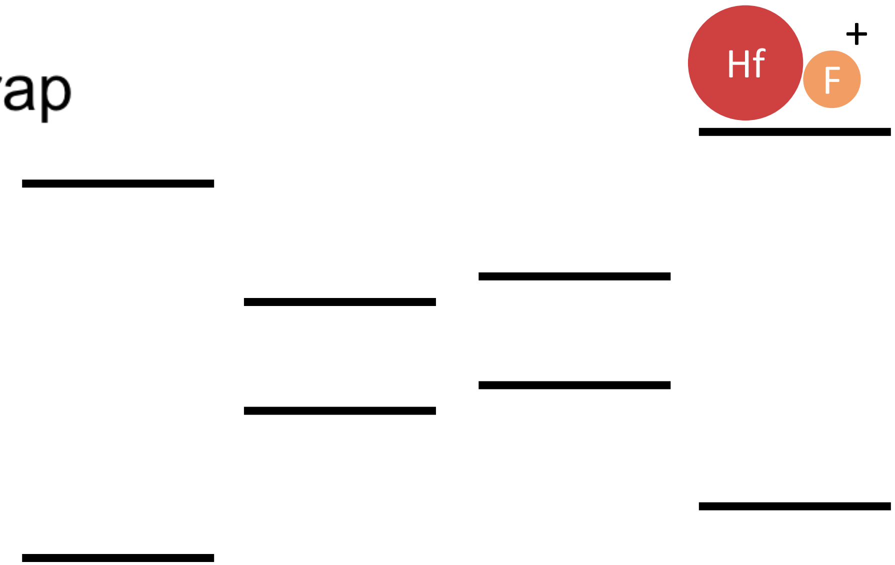
$$\Delta E = 3g_u\mu_B B_r + 2d_e E_{eff}$$



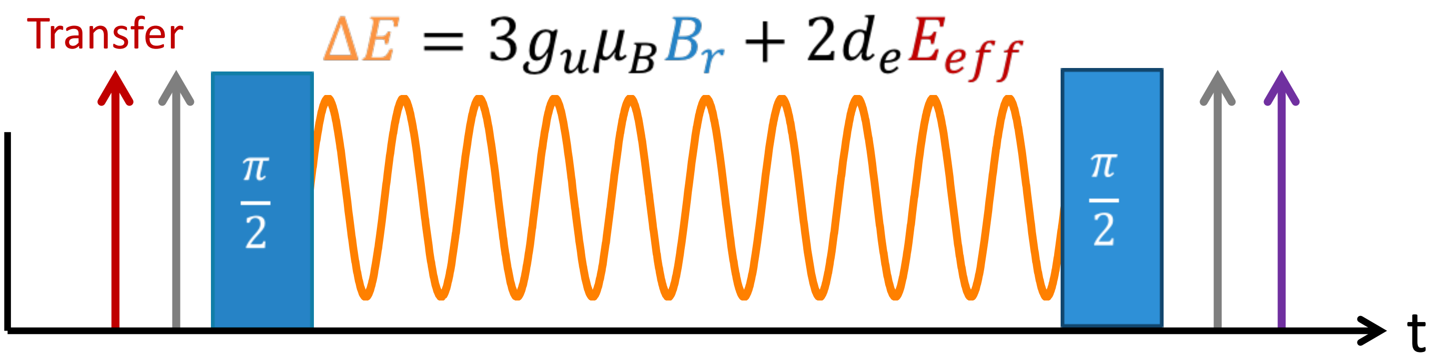
Ramsey Sequence

Dissociate all of the ions in the $J = 1$ level, and count Hf^+ ions in the trap

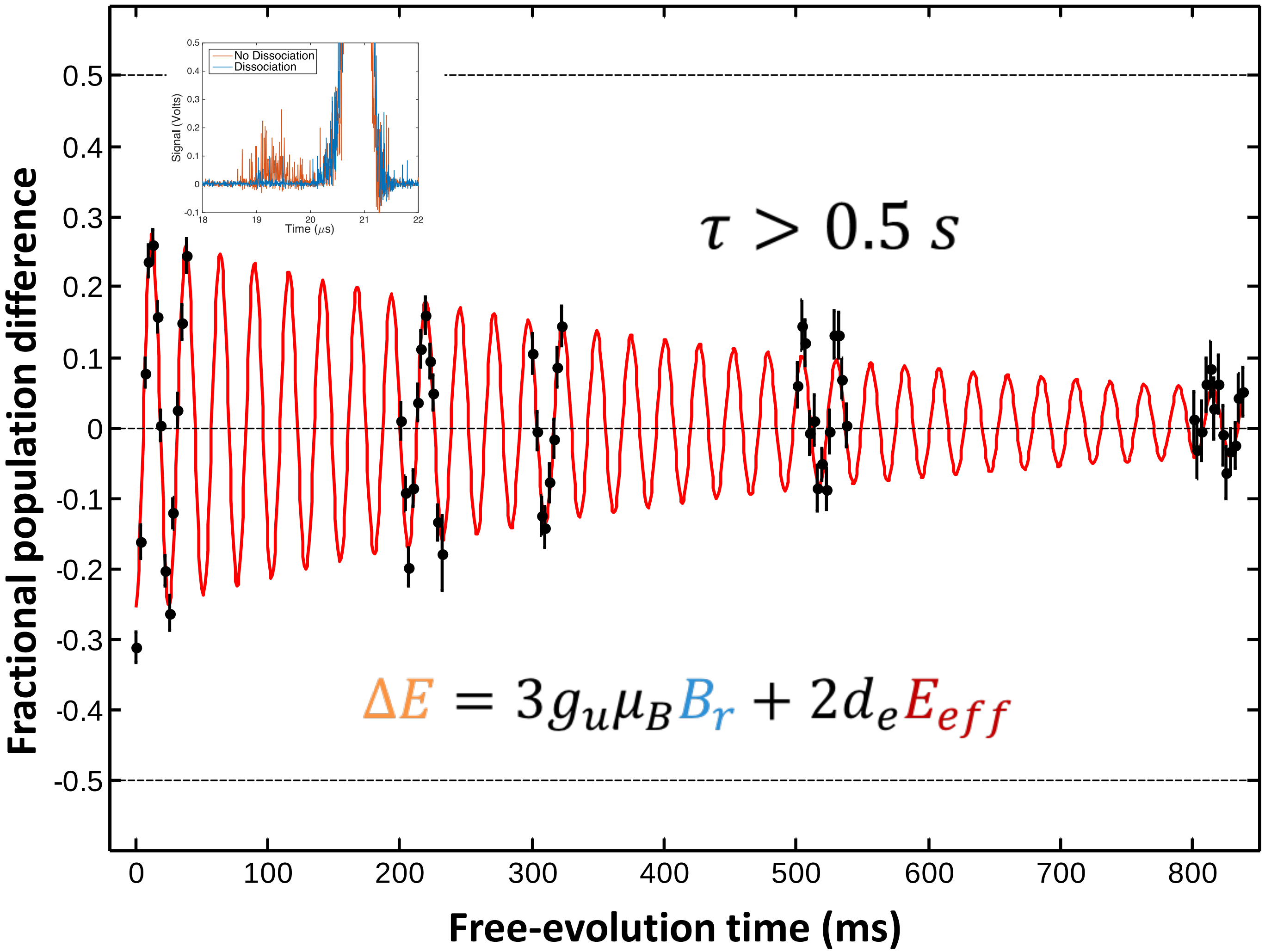




$$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$$

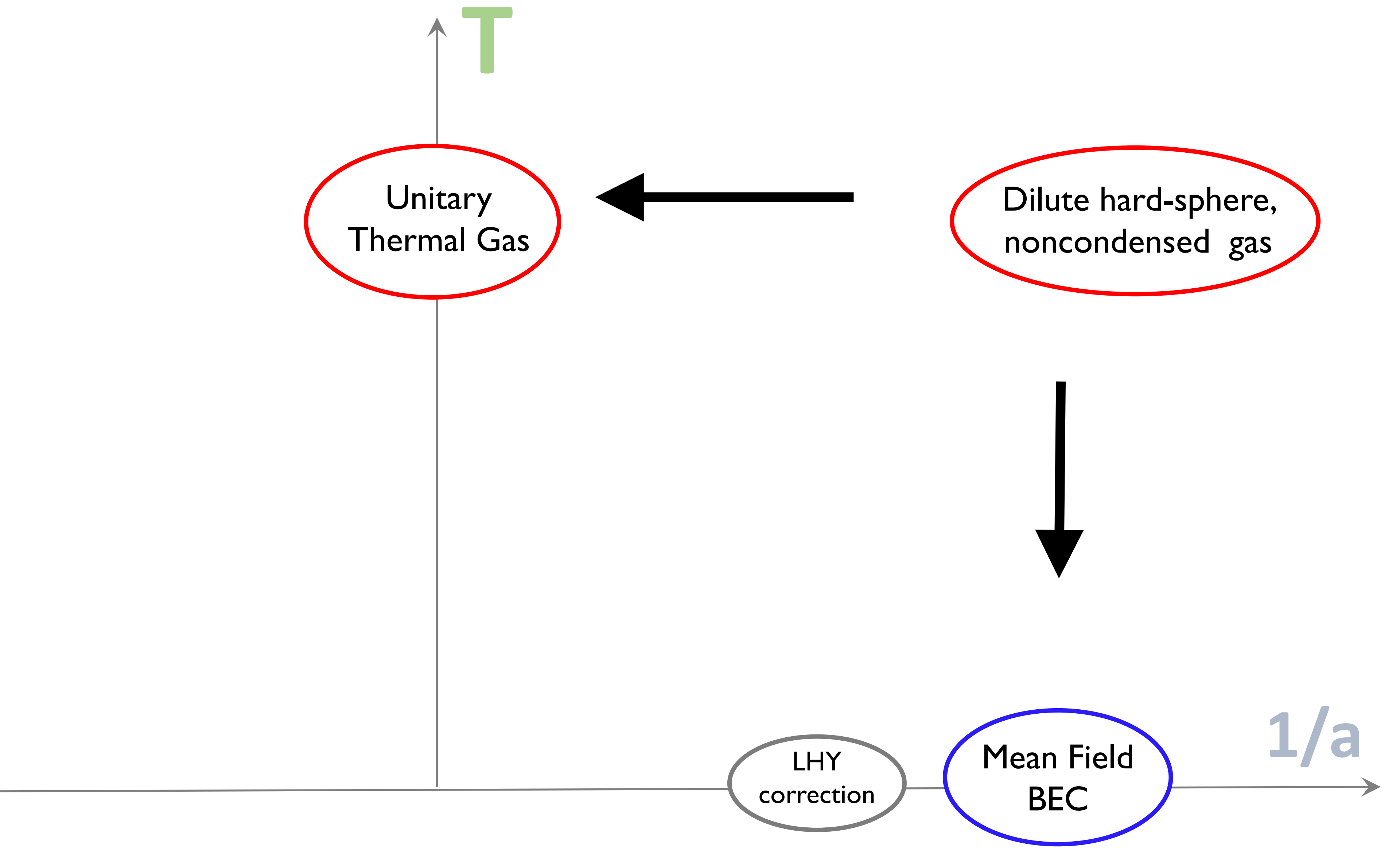


Ramsev Fringe

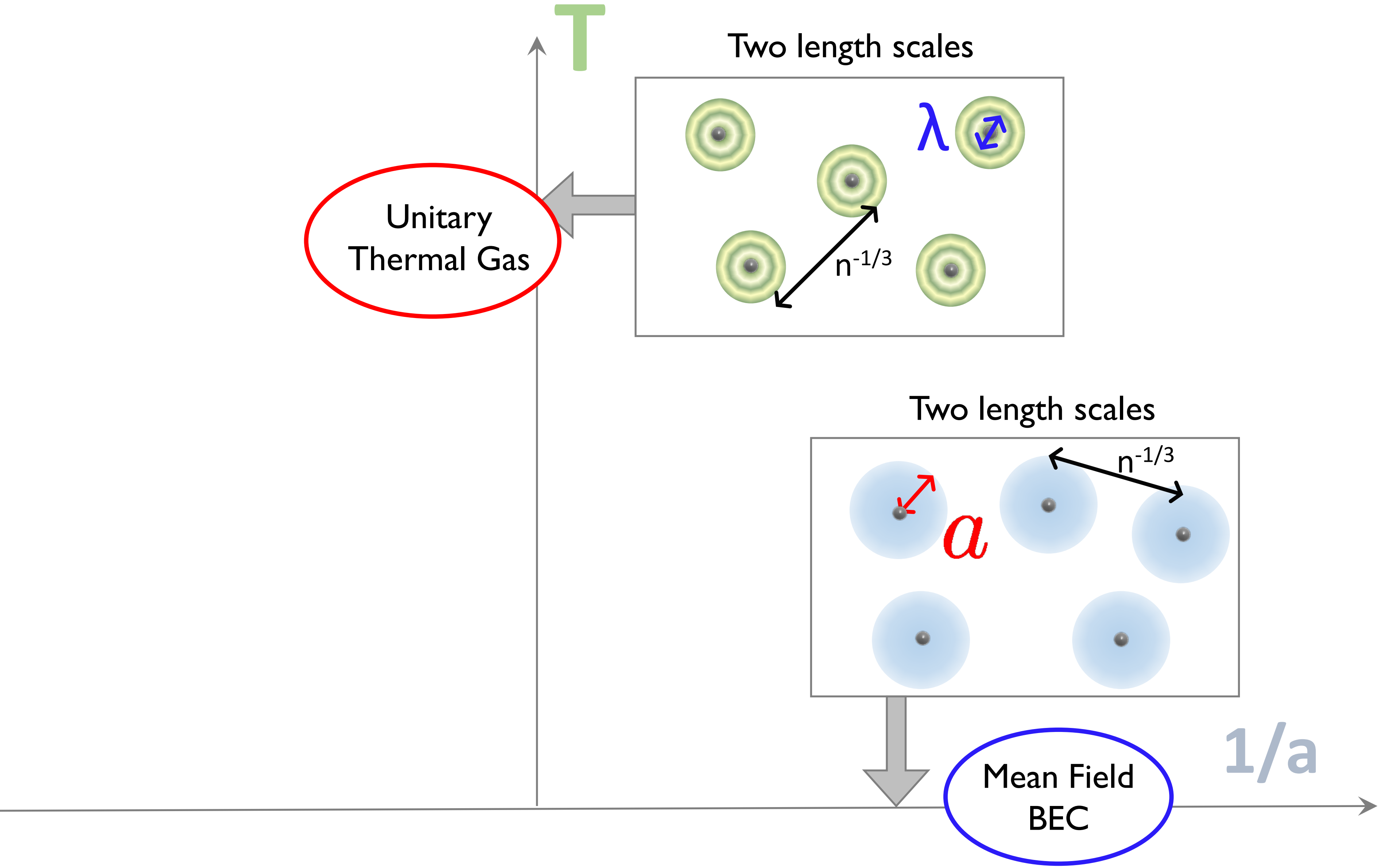


Cold Bosons: The Regimes

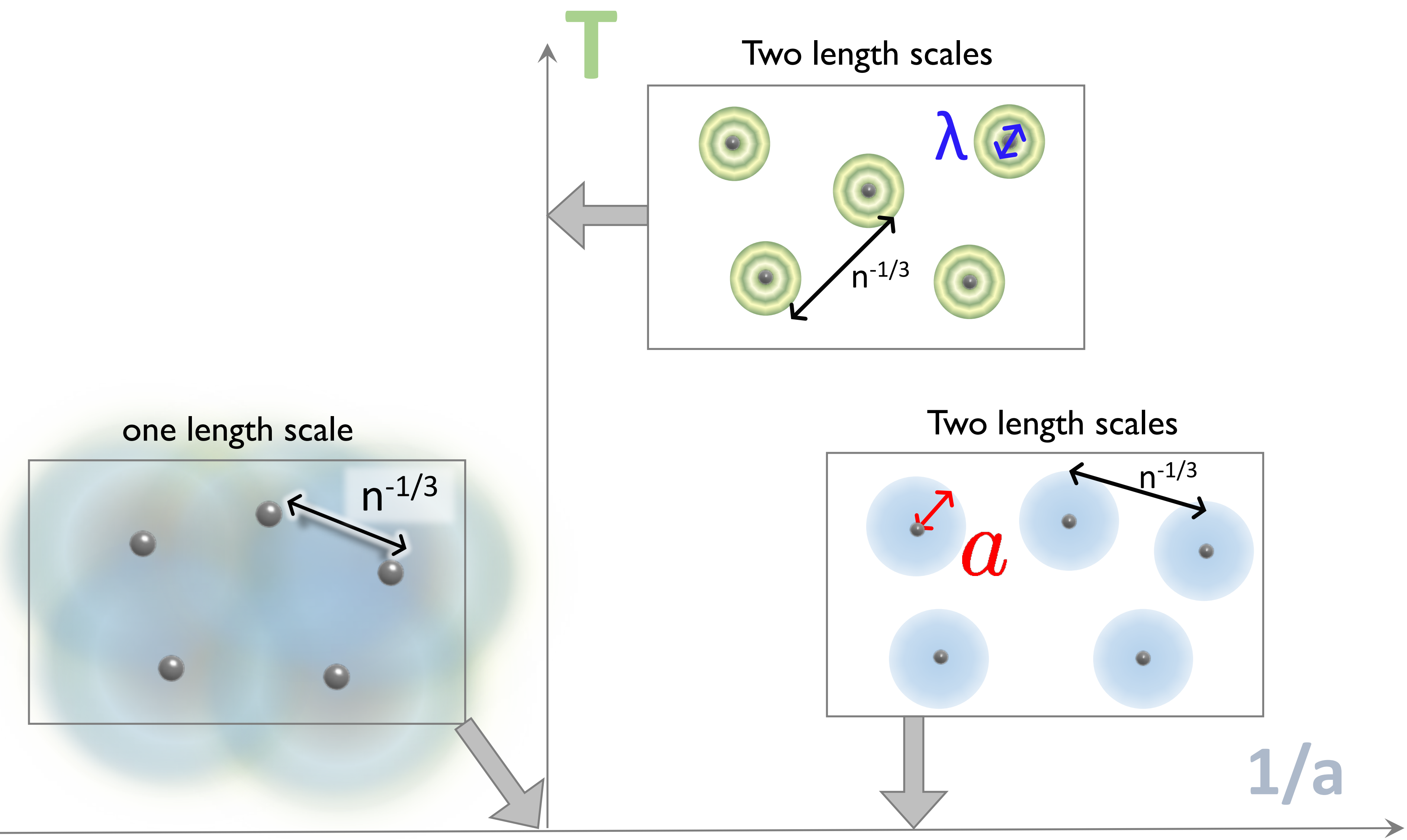
Cold Bosons: The Regimes



Degenerate Unitarity



Degenerate Unitarity: Why is it interesting?



Three boson inelastic loss: The Regimes

T

confirmed by
Paris group!

$\Gamma_3 \propto E_n\,(T_c/T)^2$

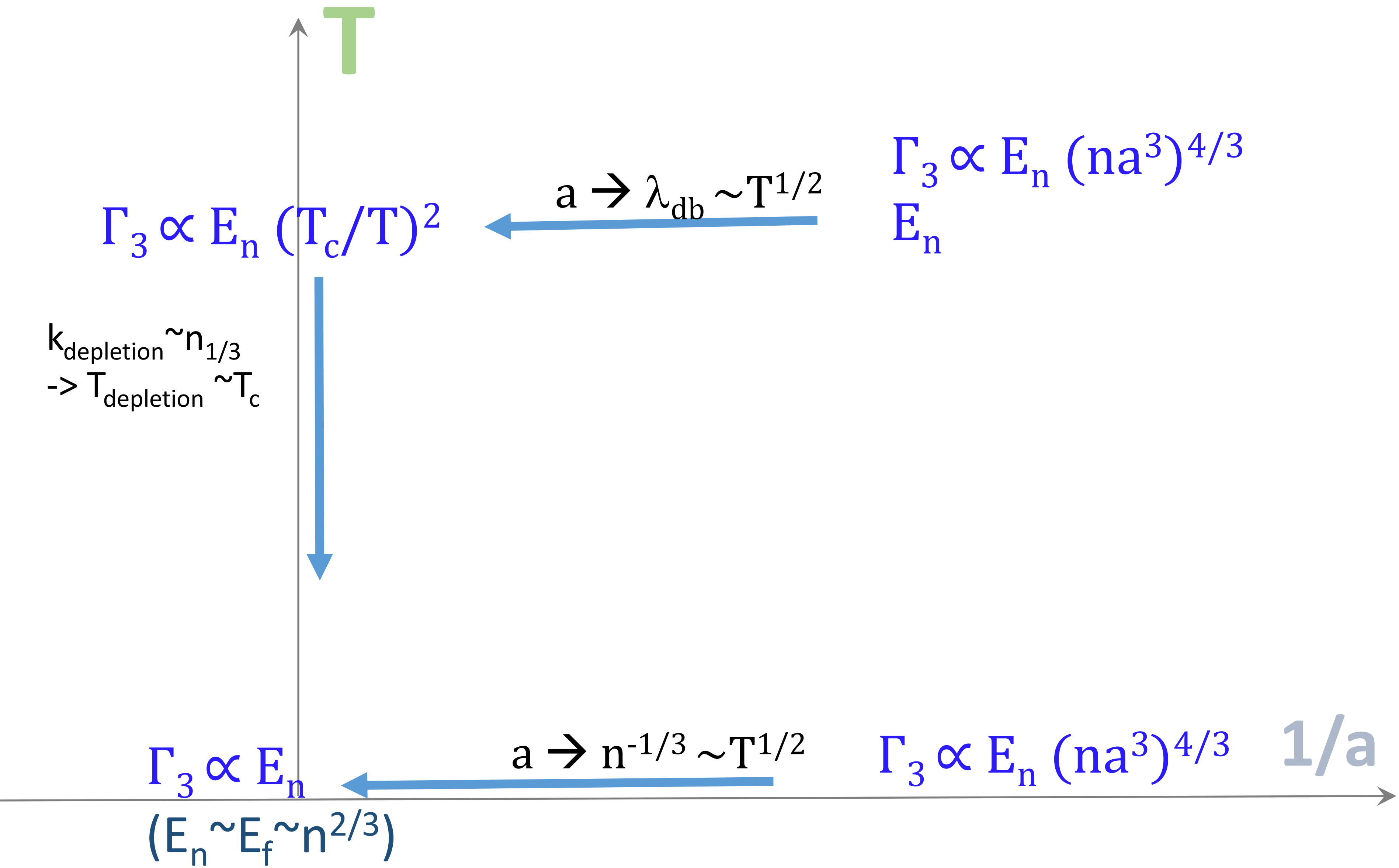
$a \rightarrow \lambda_{db} \sim T^{1/2}$

$\Gamma_3 \propto E_n\,(na^3)^{4/3}$

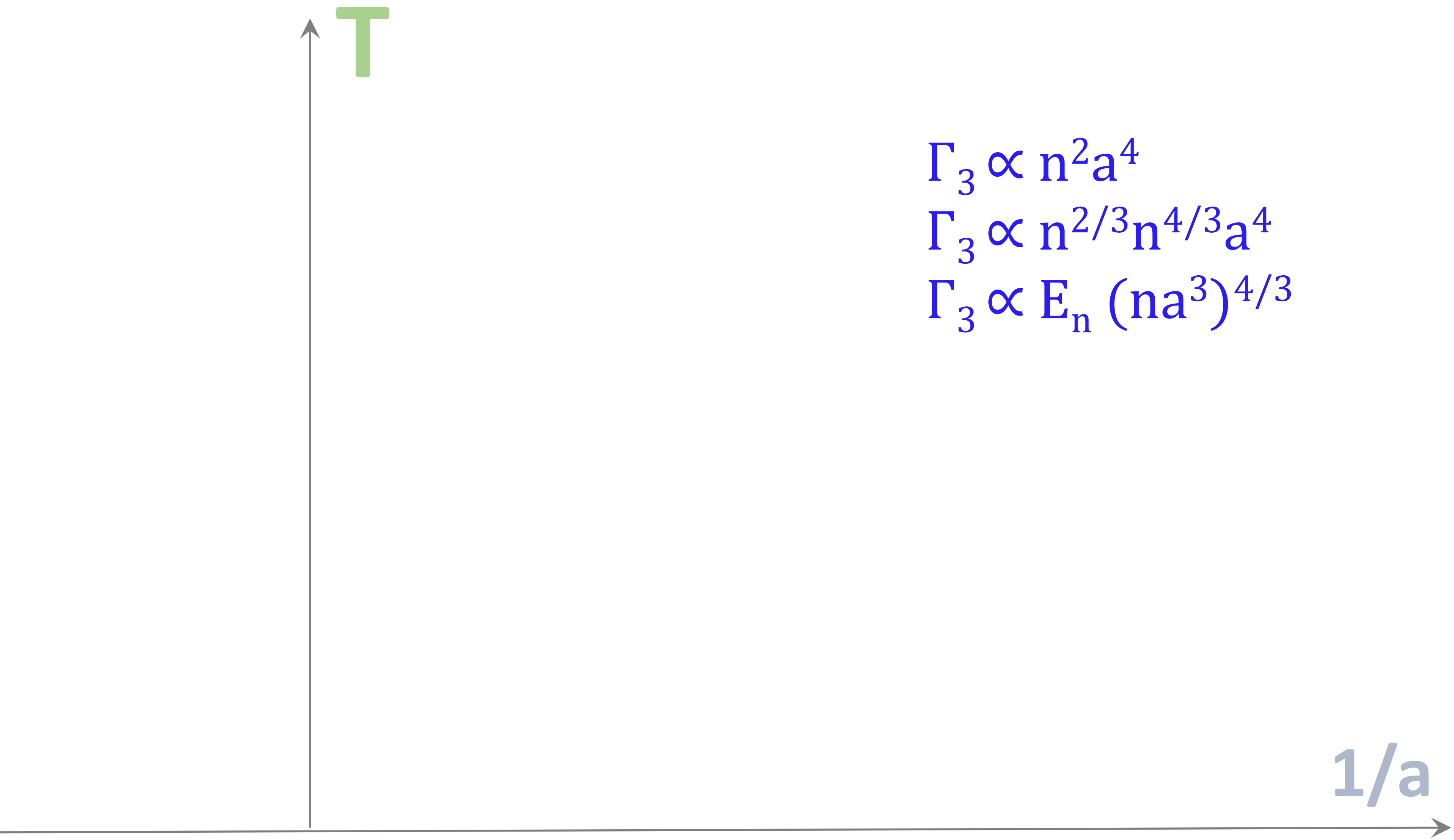
$\Gamma_3 \propto E_n\,(na^3)^{4/3}$

1/a

Three boson inelastic loss: The Regimes



Three boson inelastic loss: The Regimes



$\Gamma_3 \propto n^2 a^4$

$\Gamma_3 \propto n^{2/3} n^{4/3} a^4$

$\Gamma_3 \propto E_n \, (na^3)^{4/3}$