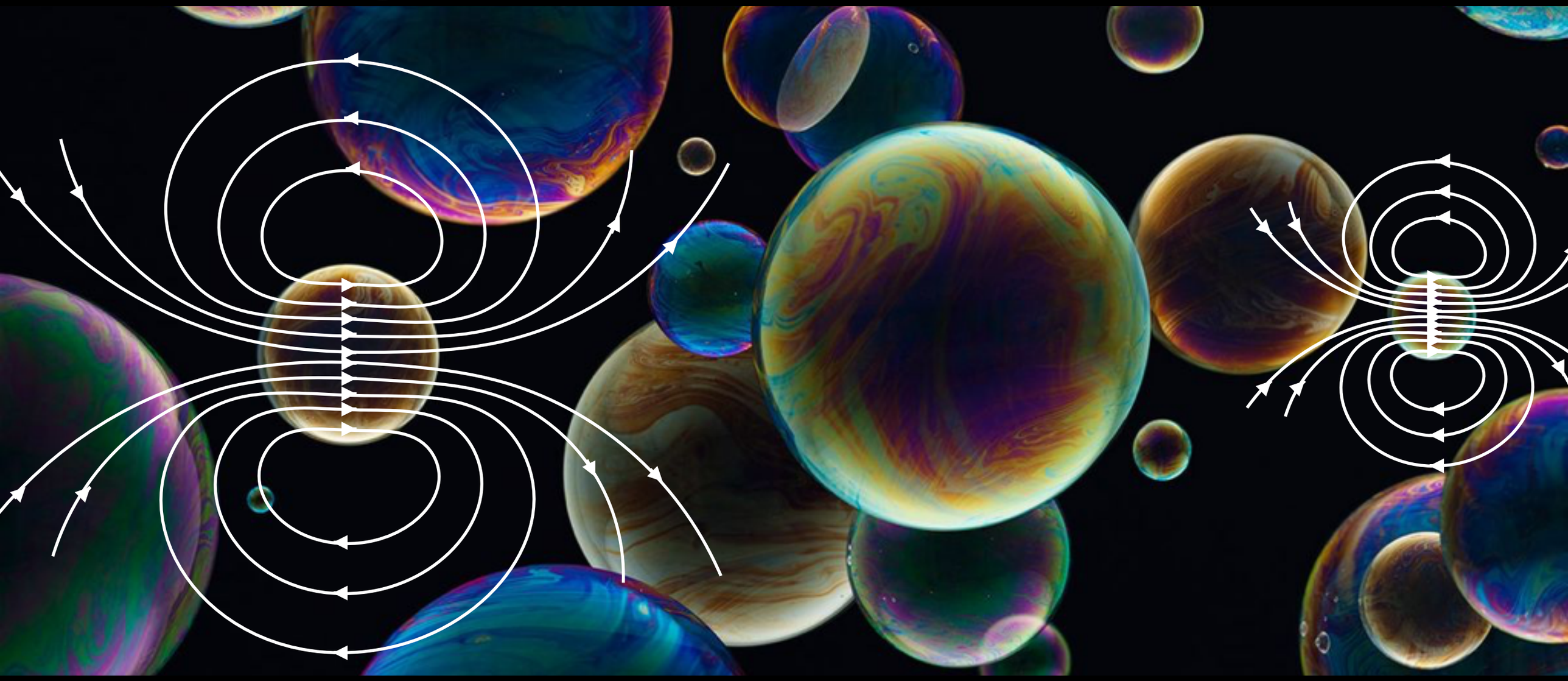
Single molecule magnets as Magnetic Bubble Chambers



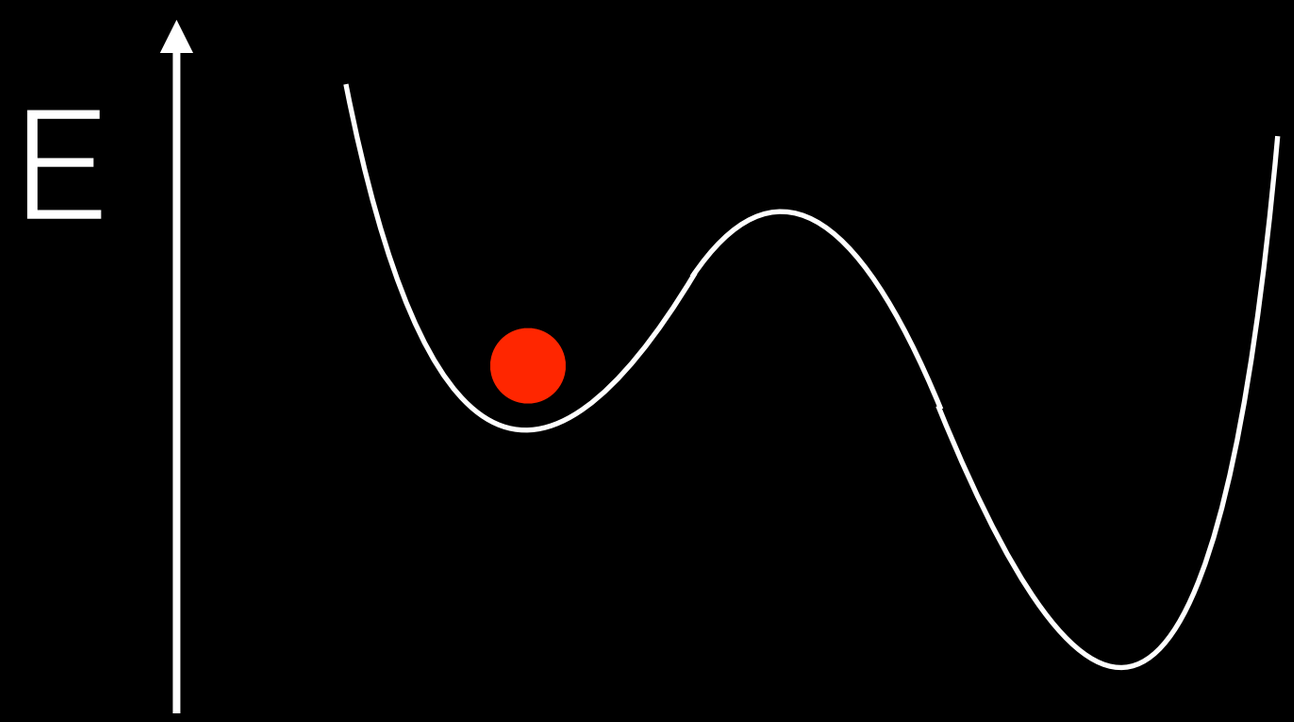
Tom Melia, LBNL & UC Berkeley
with Phil Bunting, Giorgio Gratta, Surjeet Rajendran

Sub-eV 2016, 7th-9th Dec, LBNL

arXiv:1612.xxxxx

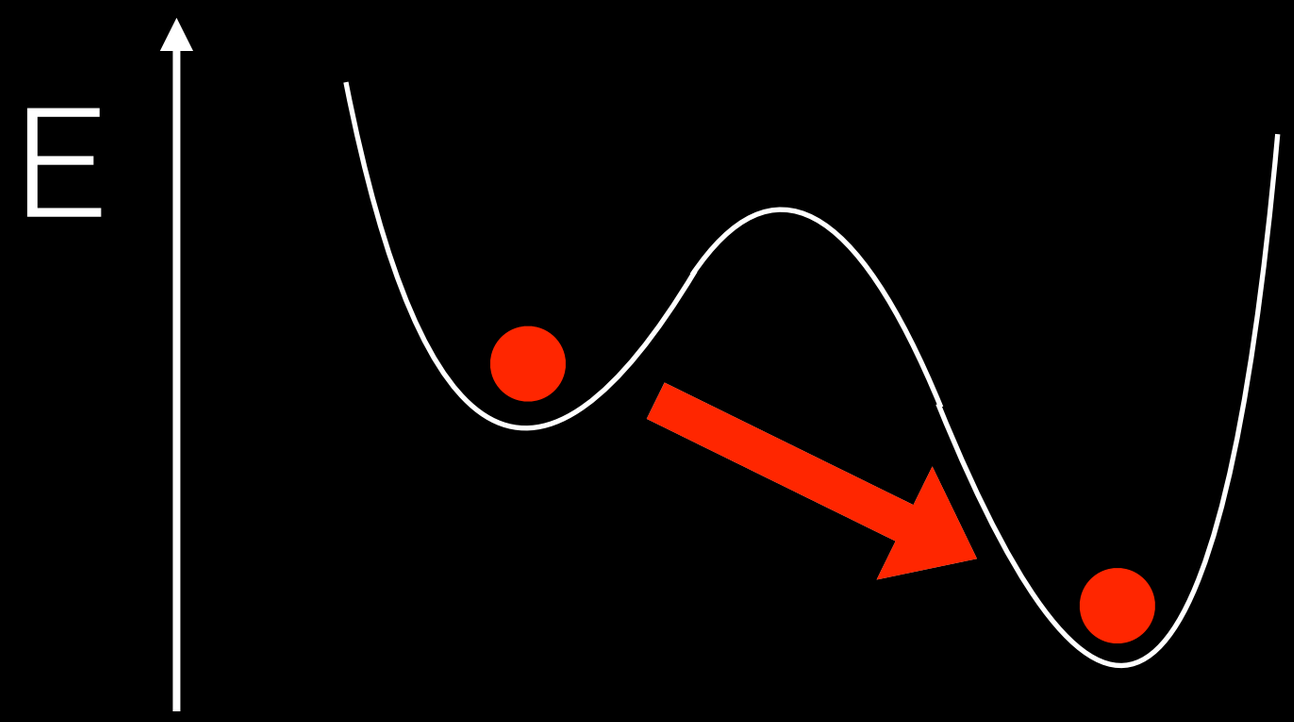
meV-eV—very small—energy deposits

Suggests investigating systems with possible intrinsic energy gain



Release of stored energy can set off some sort of avalanche

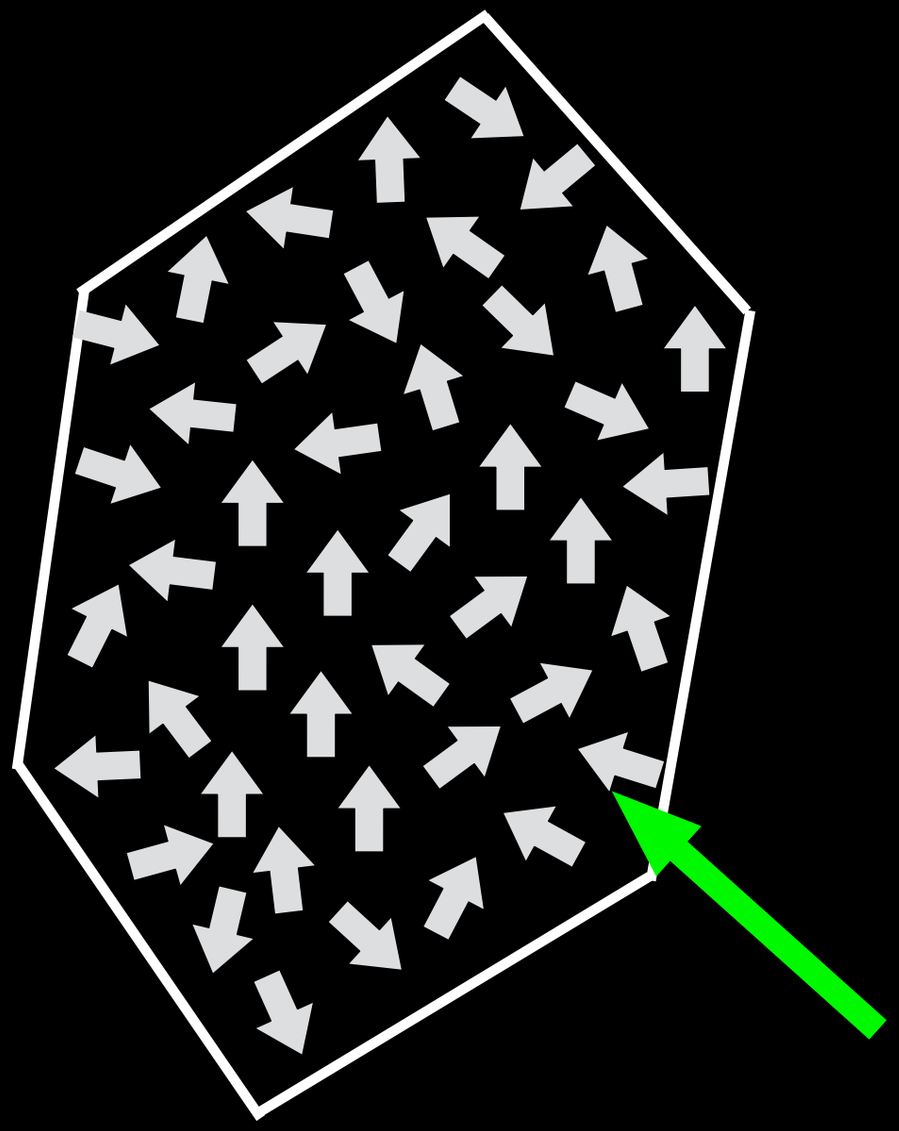
as happens in a bubble chamber



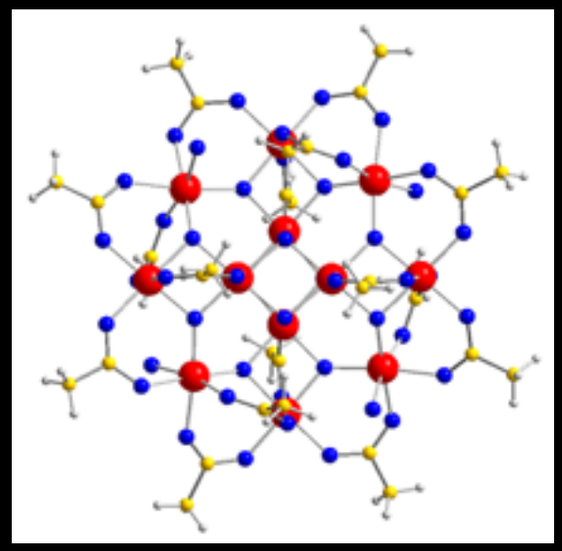
The detector itself acts as an amplifier

Ideally this doesn't destroy the detector

Single molecule magnet crystal

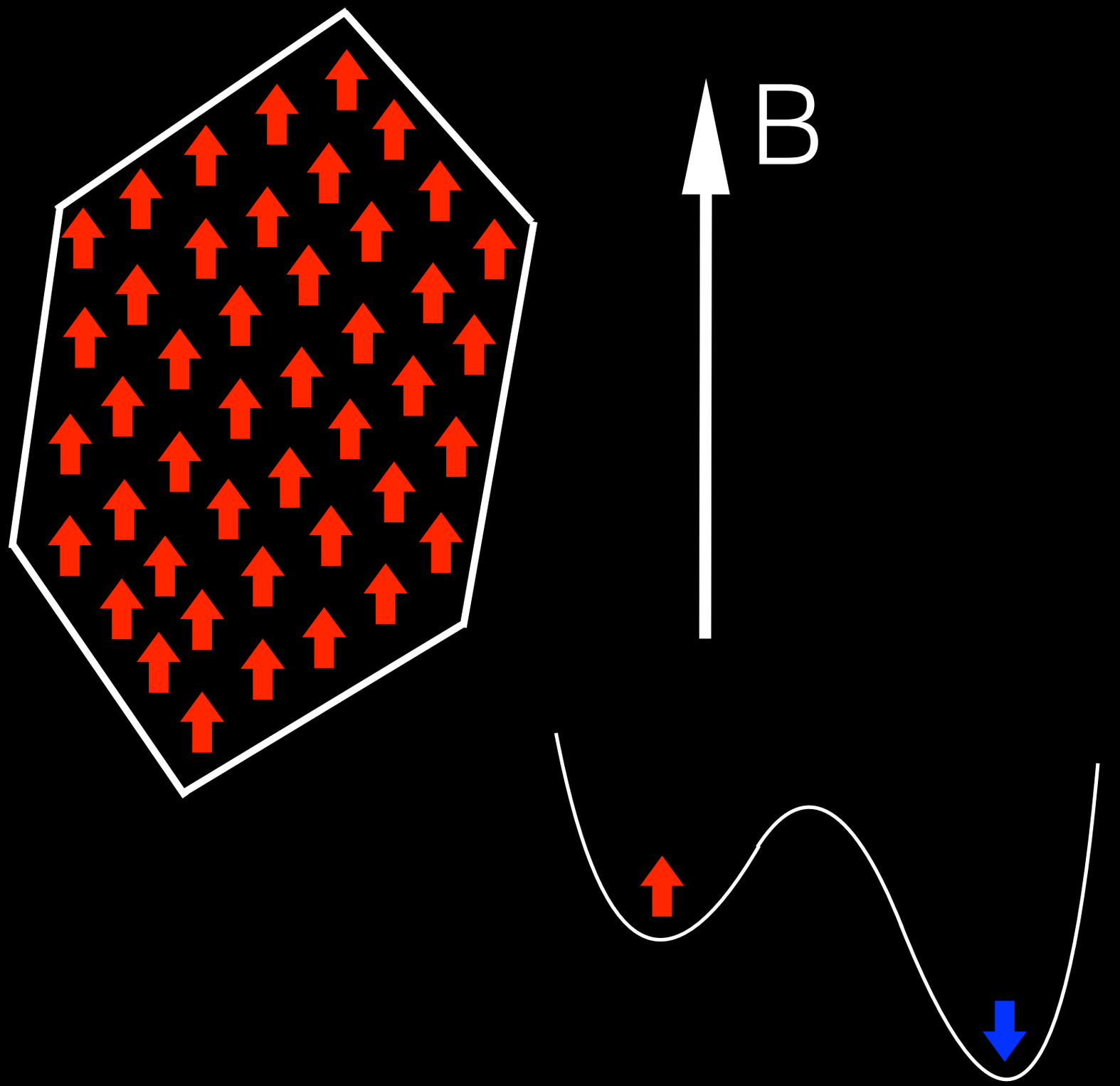


few micron to > mm

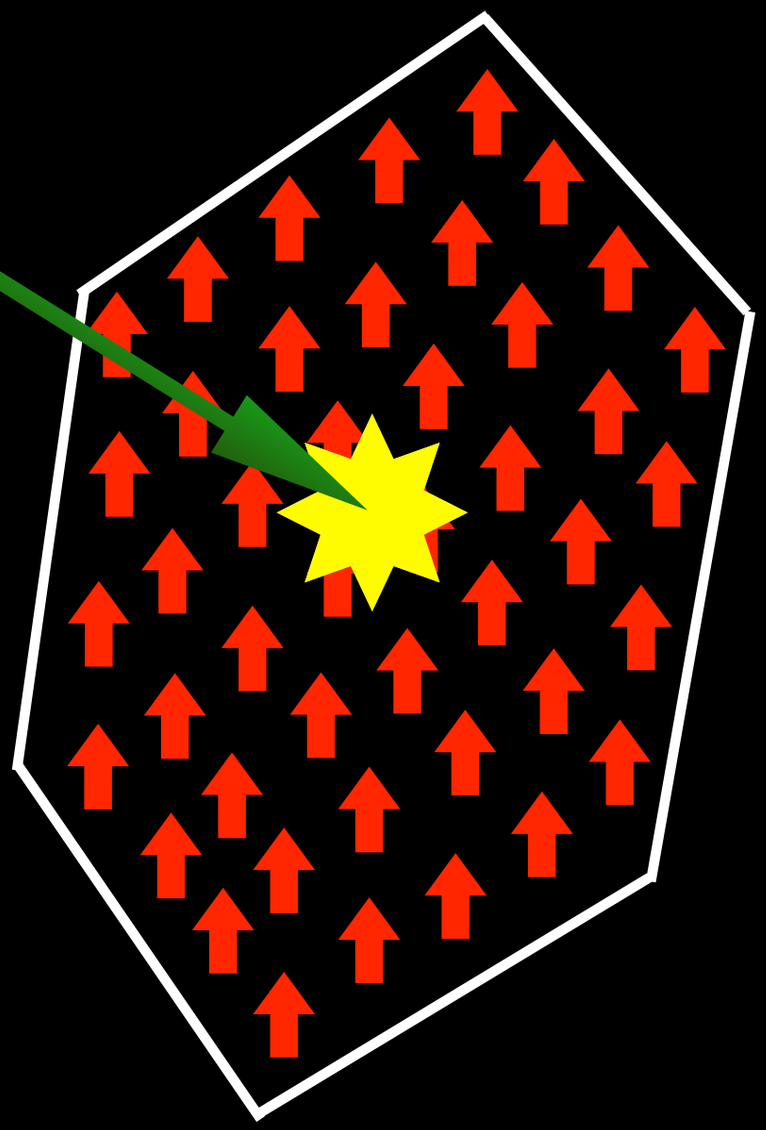


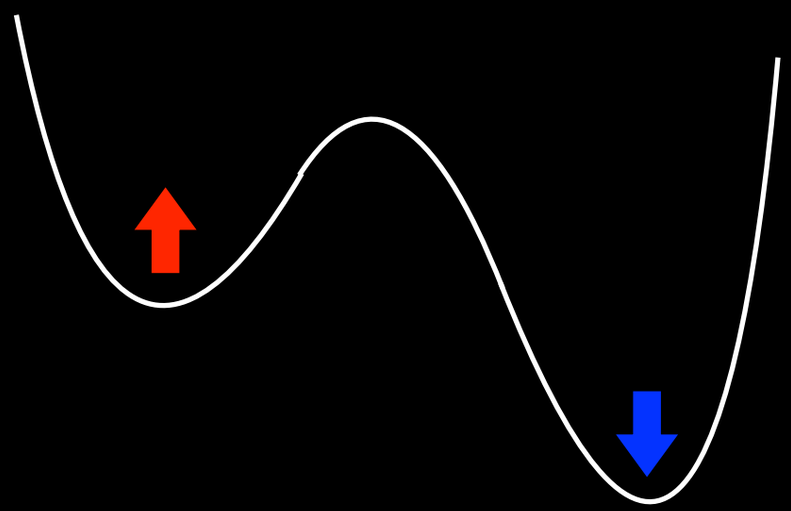
$10^{10\text{-}18}$ molecules with large rigid spin (J=10-50)

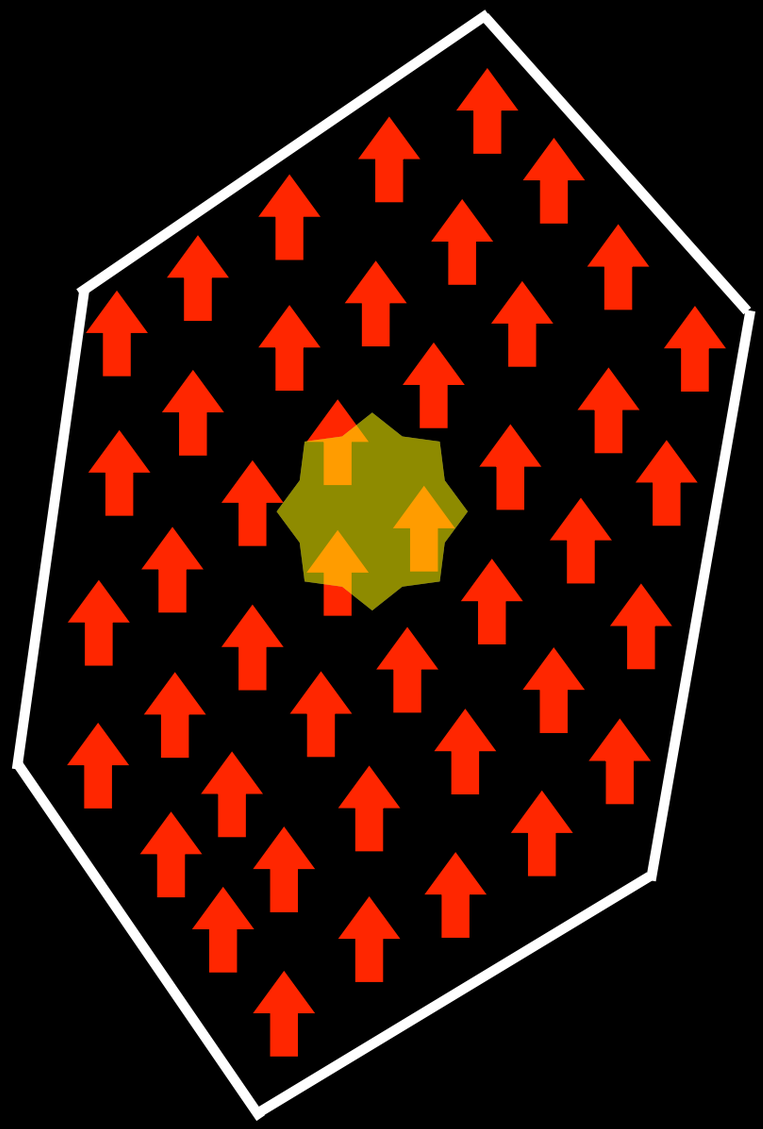
Single molecule magnet crystal

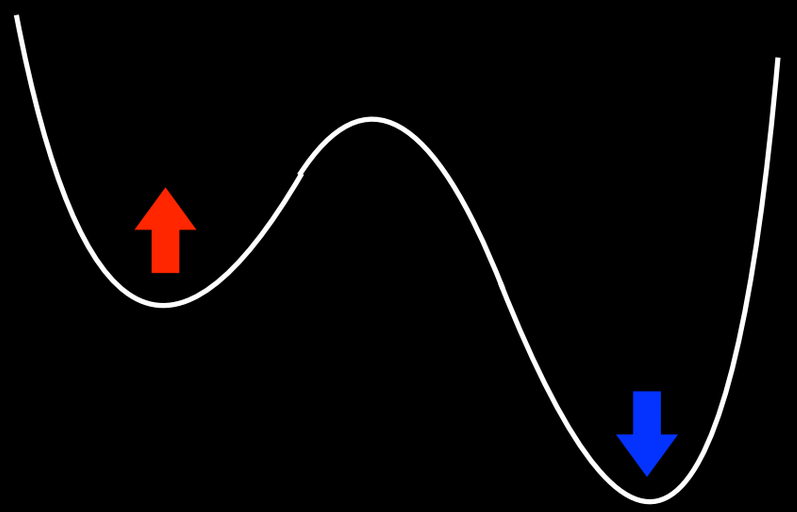


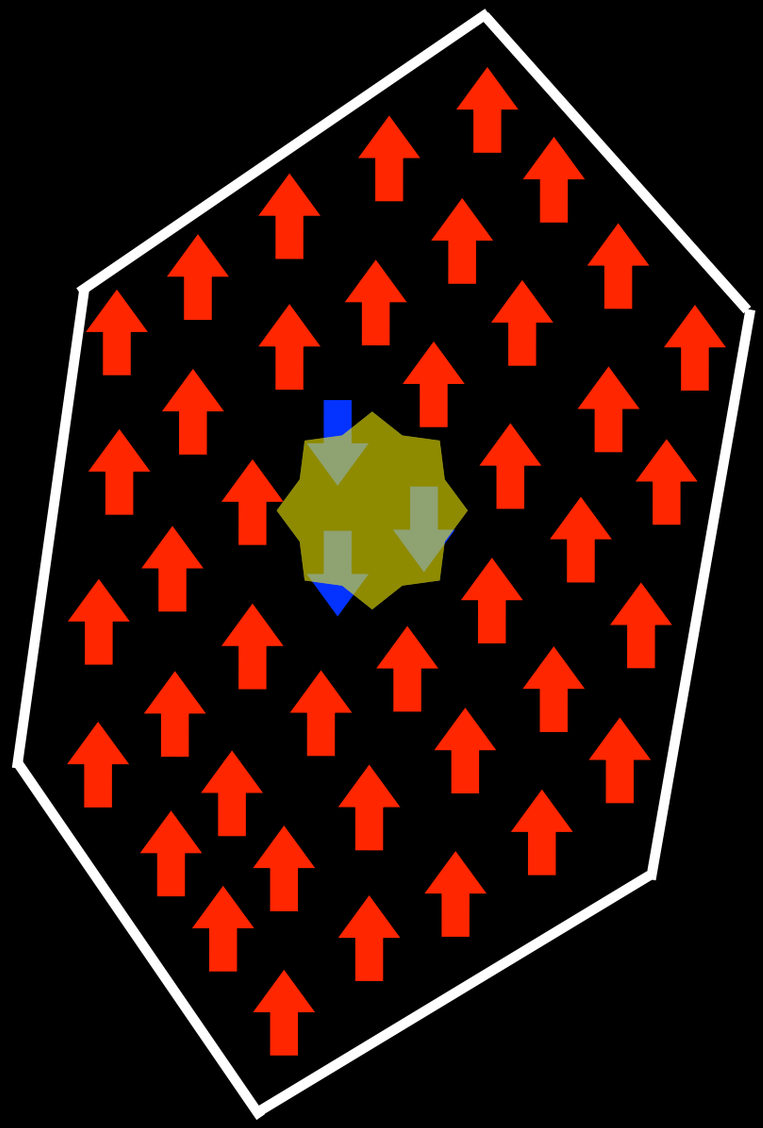
DM deposits energy

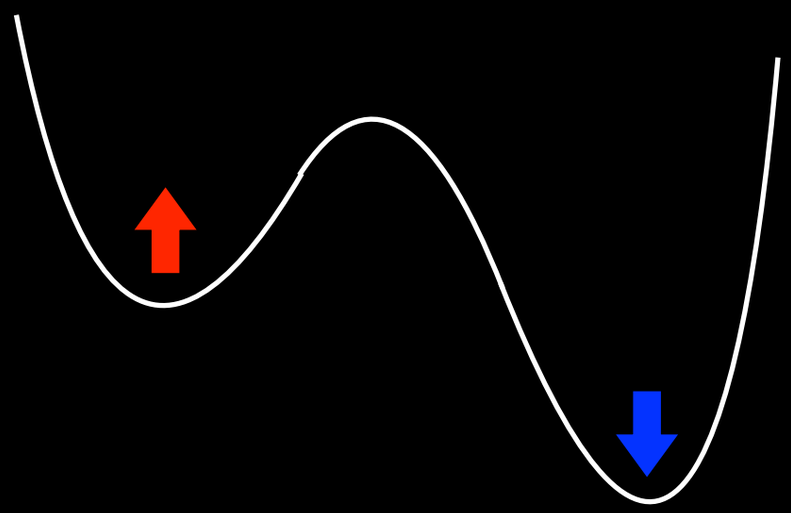






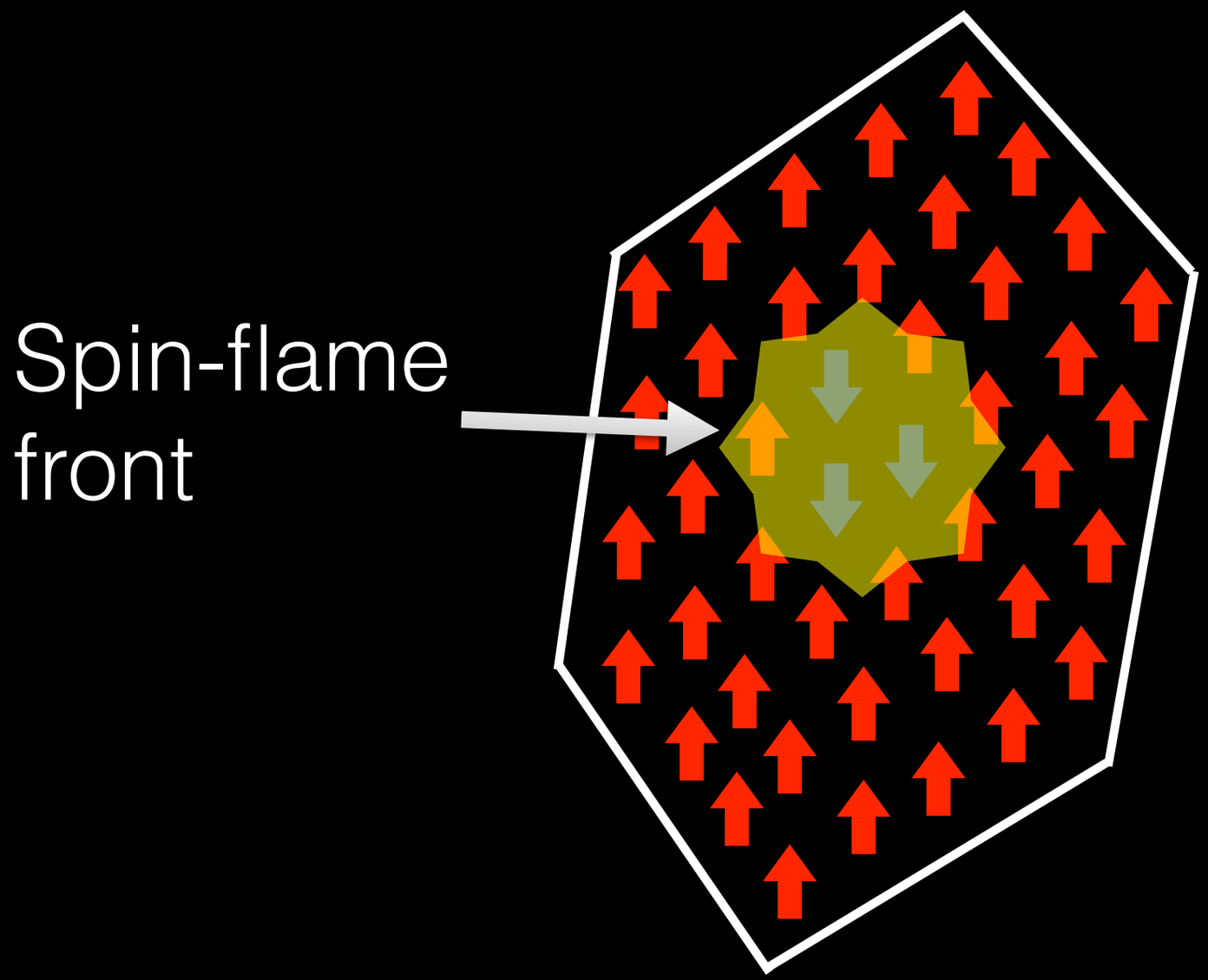


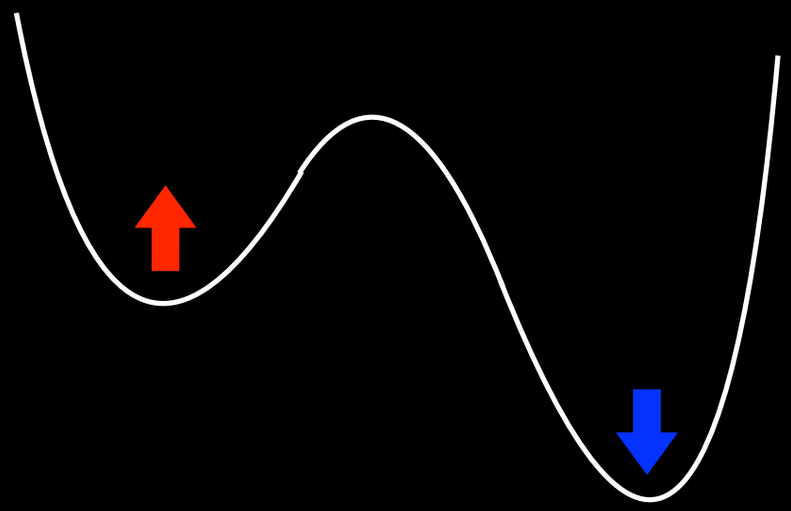




Zeeman energy released

Magnetic deflagration / Spin Avalanche

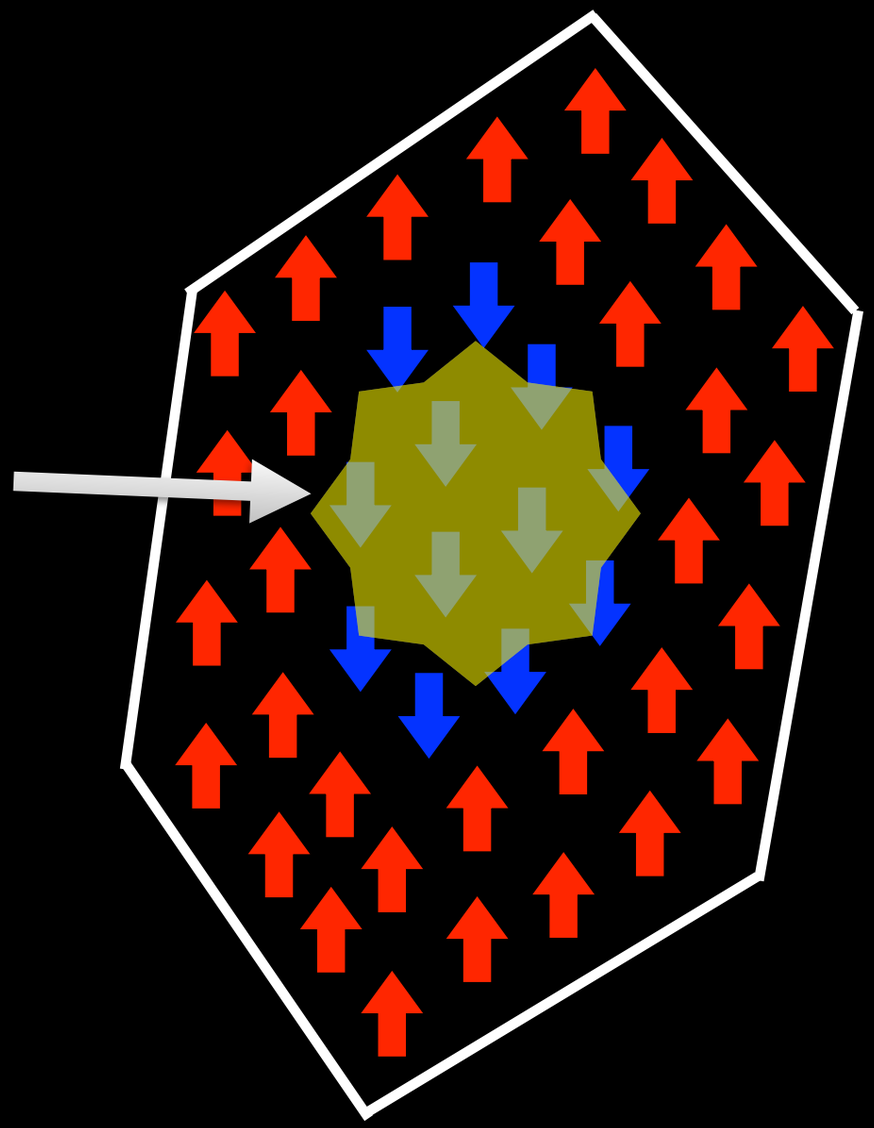




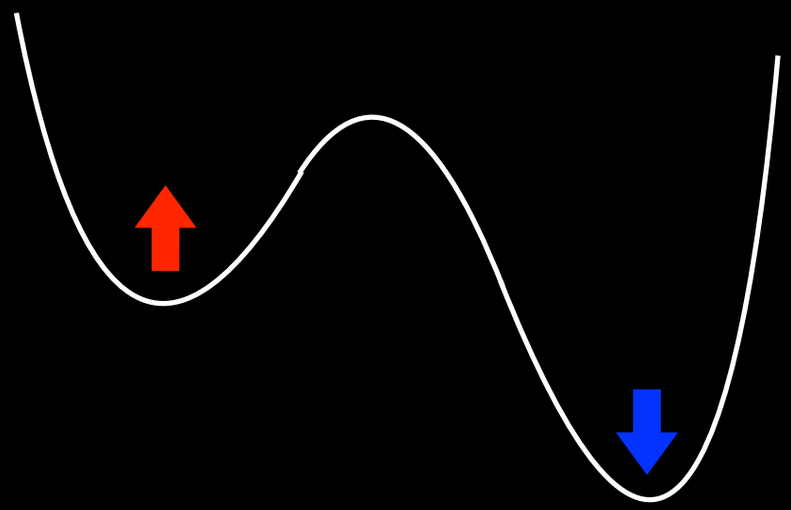
Zeeman energy released

Magnetic deflagration / Spin Avalanche

Spin-flame front

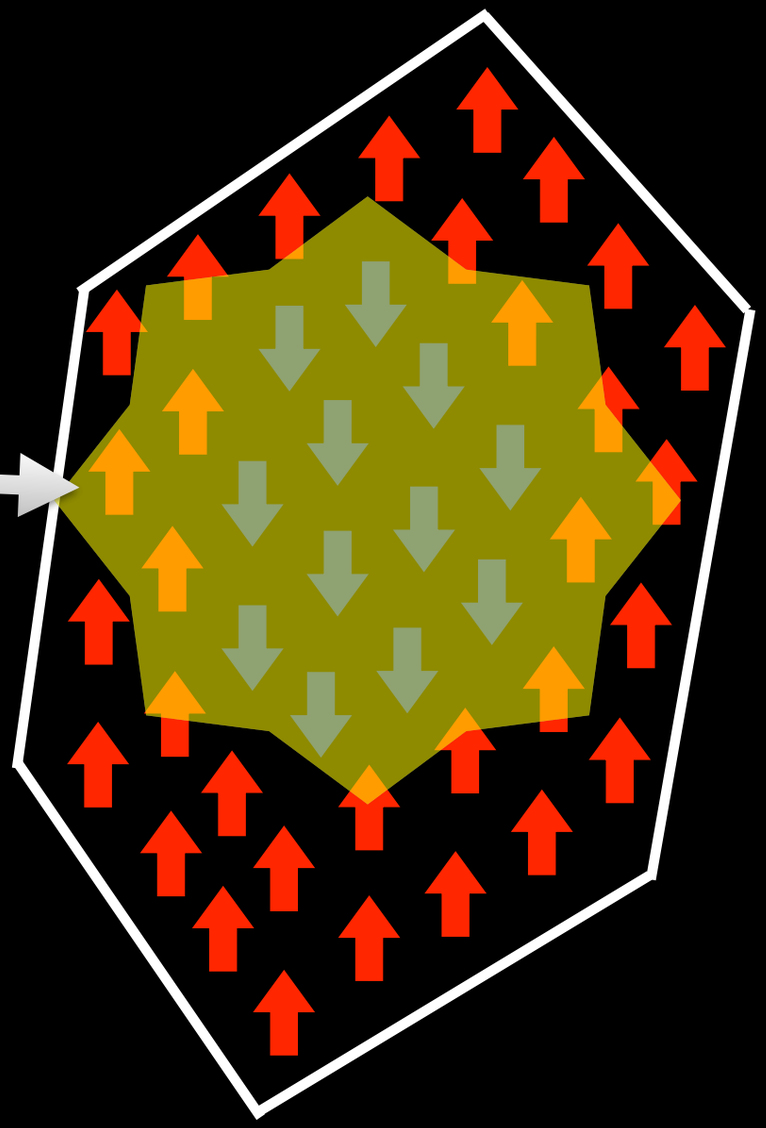


Zeeman energy released



Magnetic deflagration / Spin Avalanche

Spin-flame front



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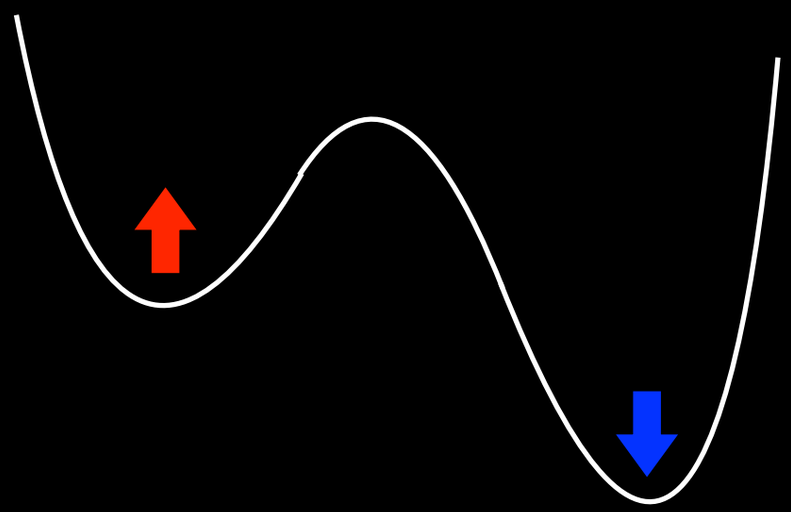
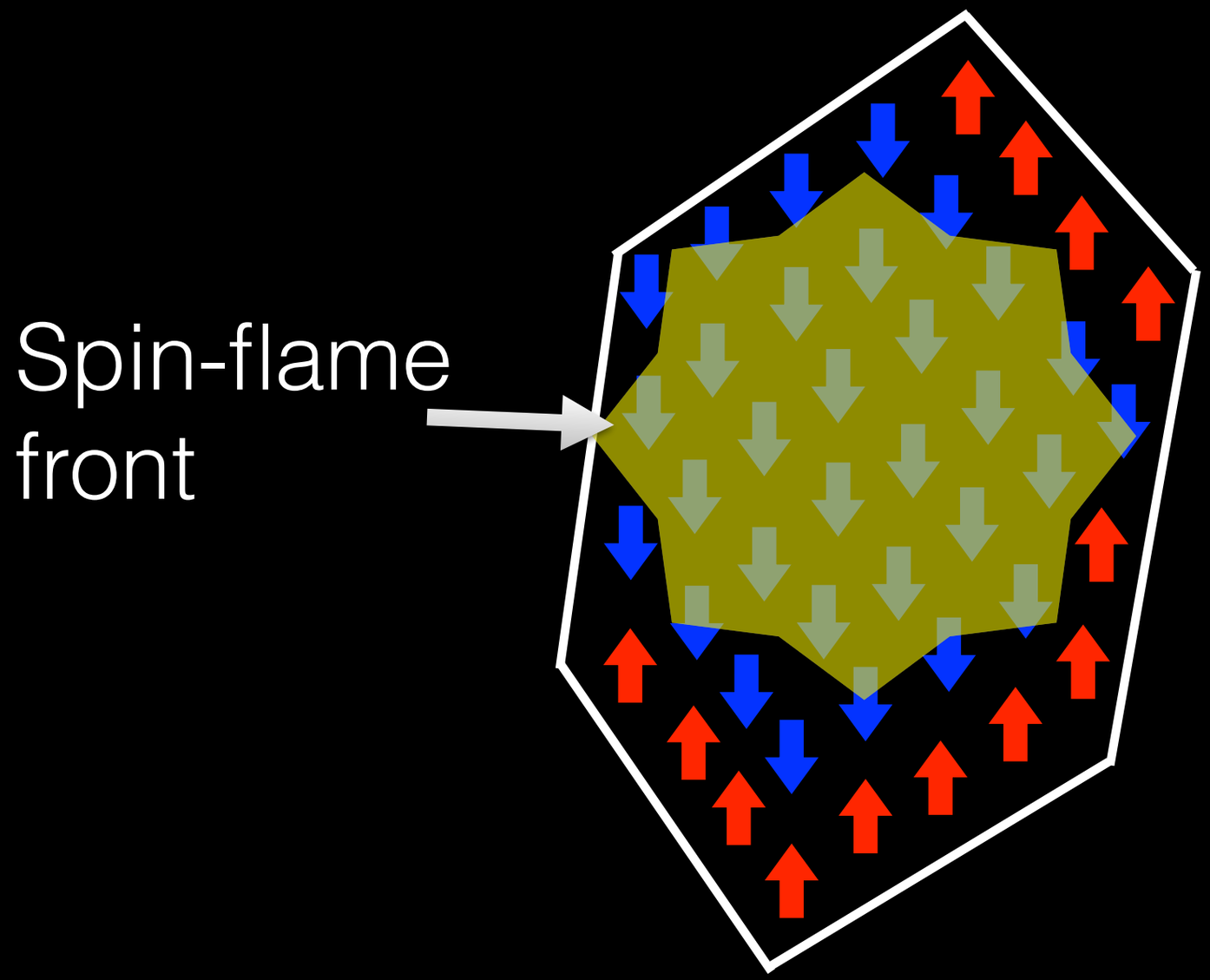
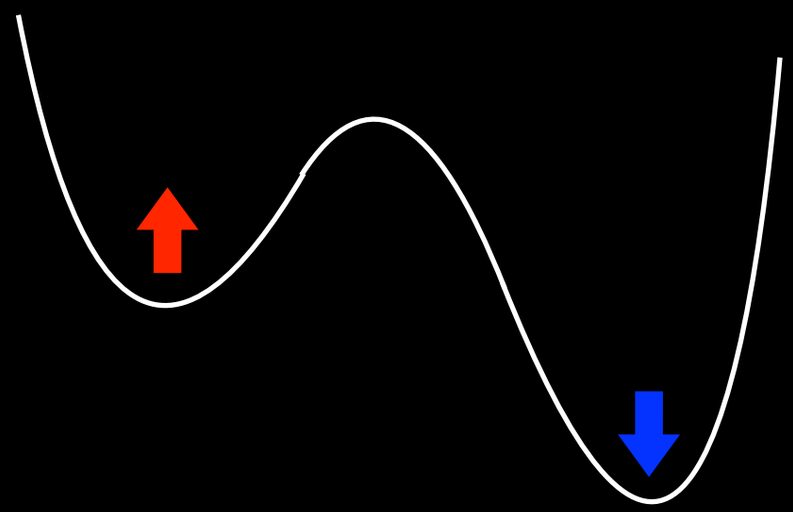


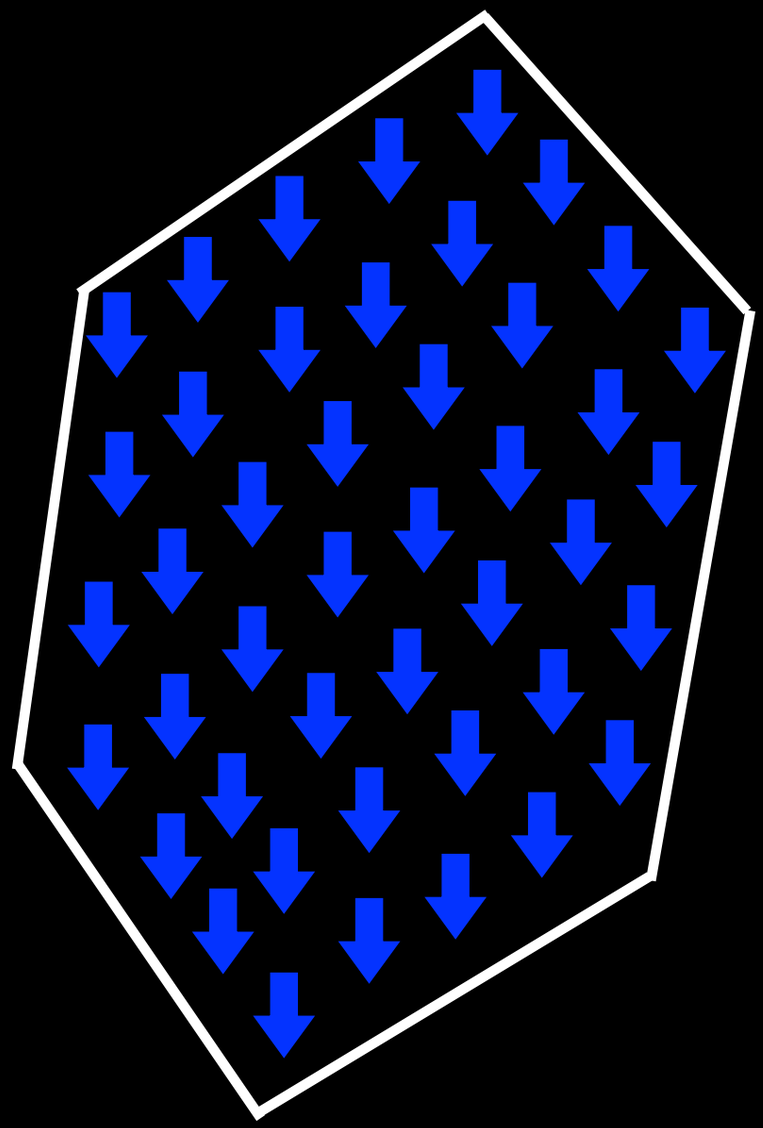
Magnetic deflagration / Spin Avalanche



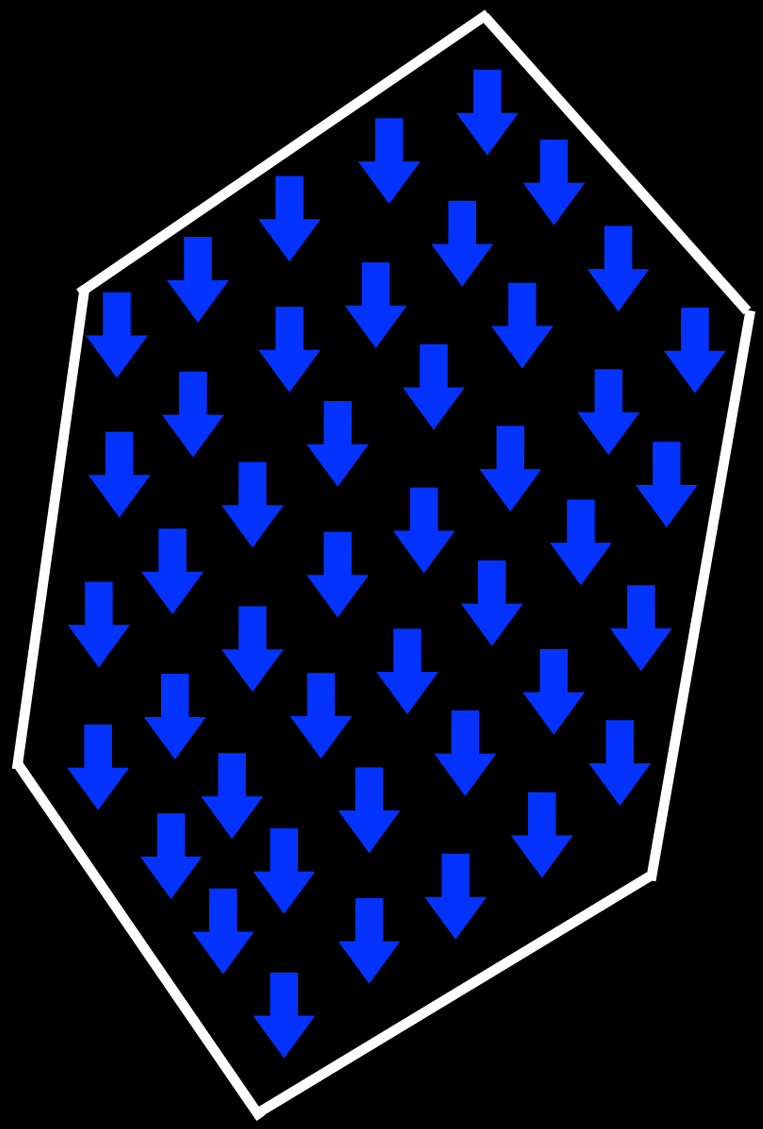


Zeeman energy released

Magnetic deflagration / Spin Avalanche



Magnetic deflagration / Spin Avalanche



Macroscopic change: amplification

Properties of single molecule magnets

& requirements for a DM detector

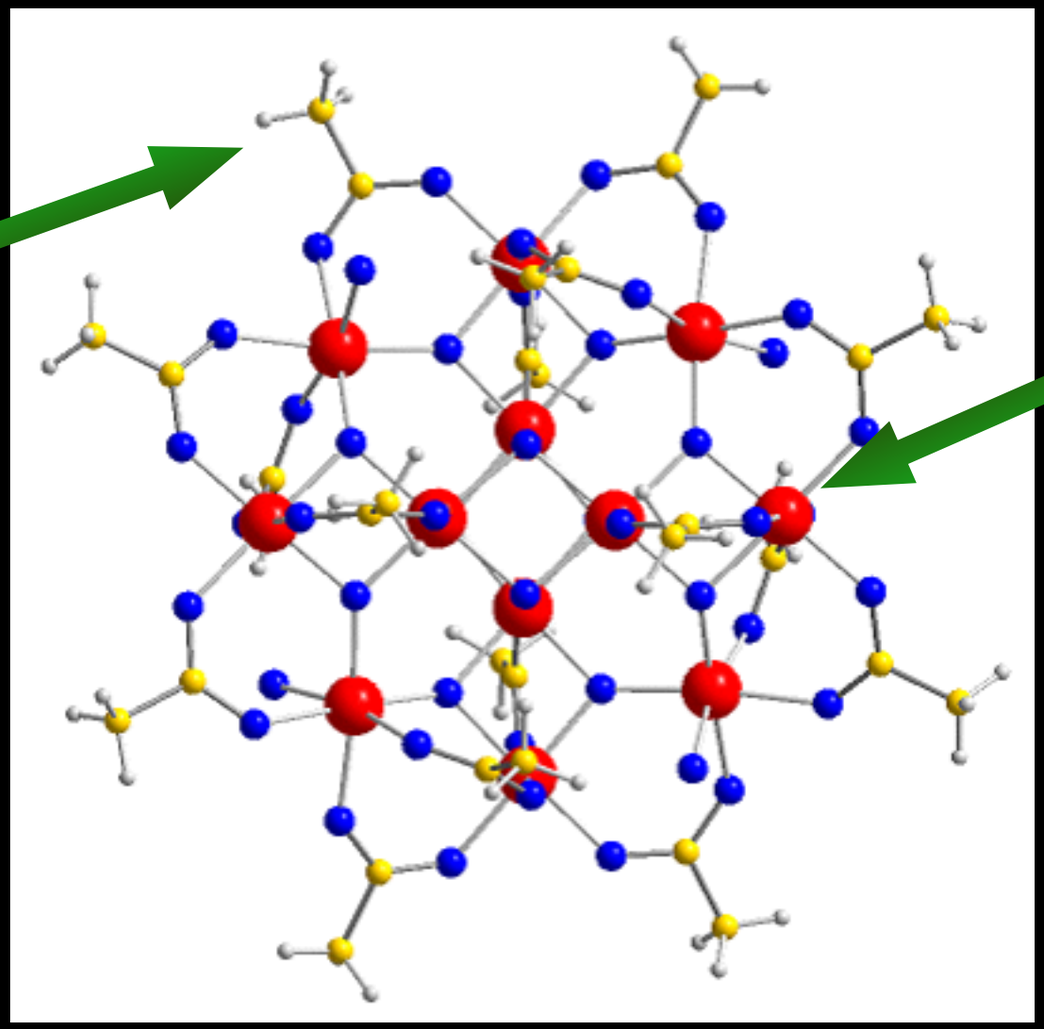
Chemistry

Mn12 - acetate

Acetate ligands

Provide ‘fluff’ to separate rigid spins on crystallization

Very weak magnet interaction



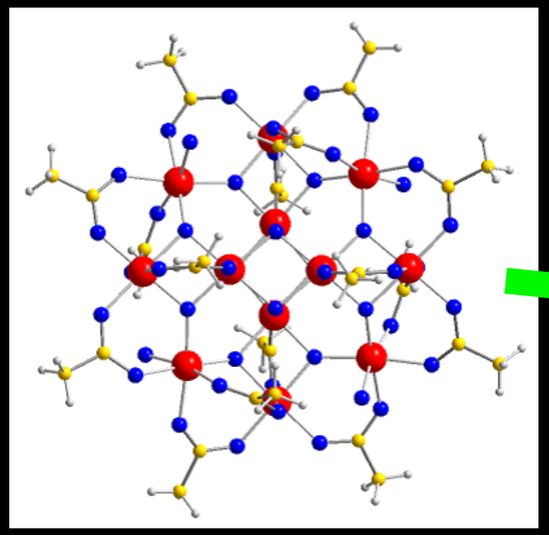
Manganese (red) ions

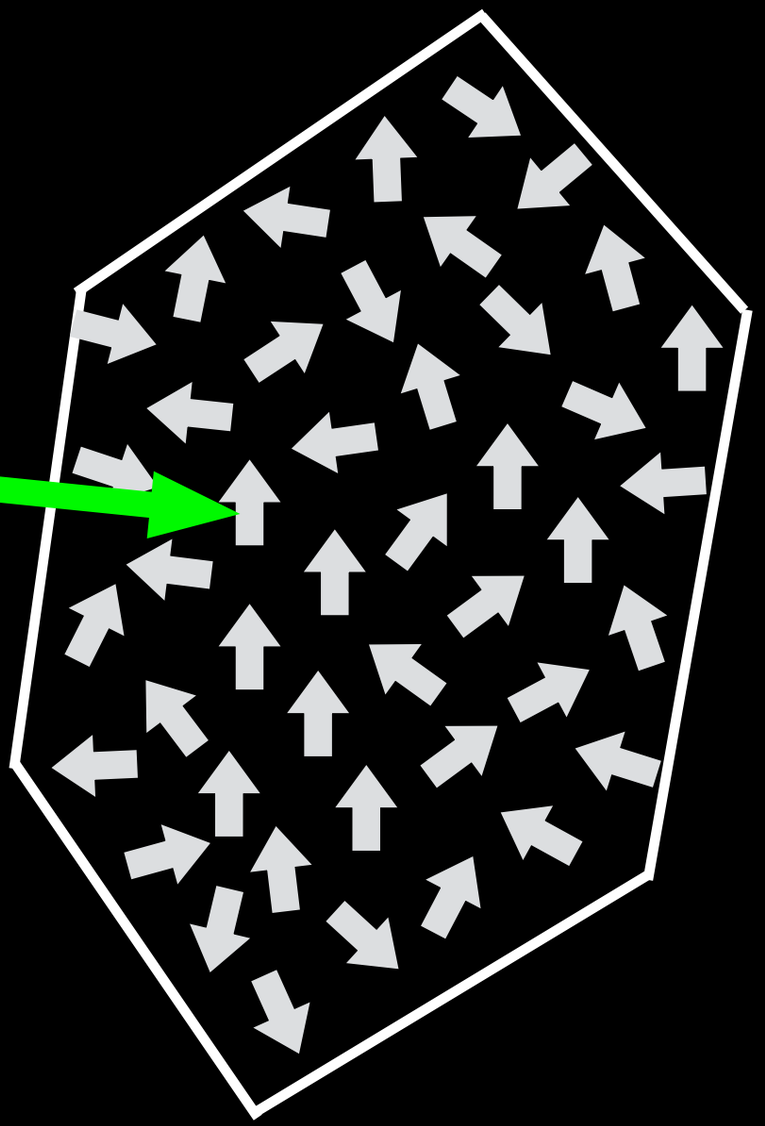
Strong exchange interactions mediated by (blue) oxygen bonds

Large rigid spin

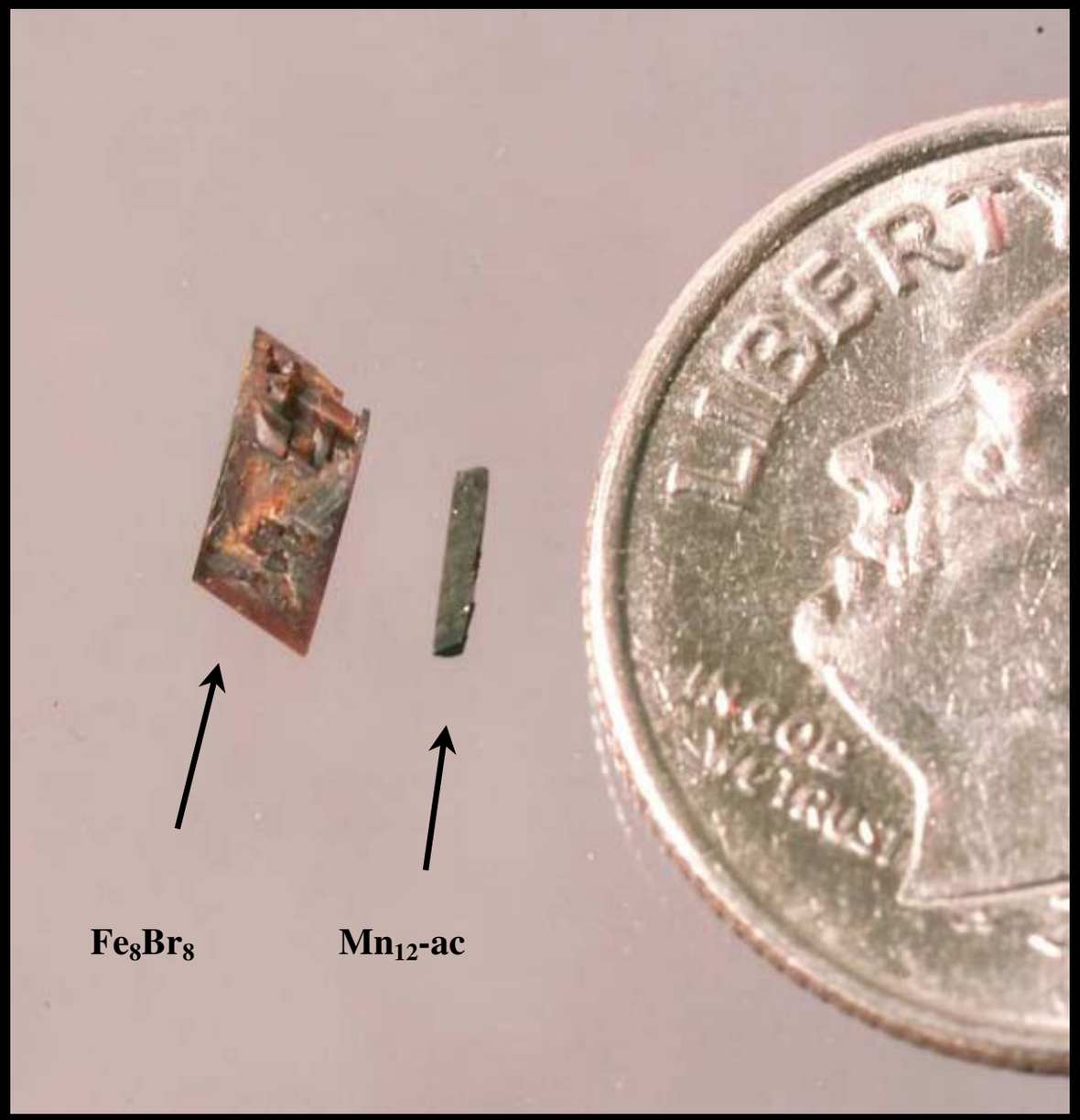
Chemistry

Essentially non-interacting nano-magnets





Chemistry



Source: Florida State University Thesis, Jeremy North, 2004

Crystals from few micron to >mm size

Very recent chemistry explosion

80s

First SMM synthesized

90s

Magnetic properties recognized

today

100s new SMMs synthesized

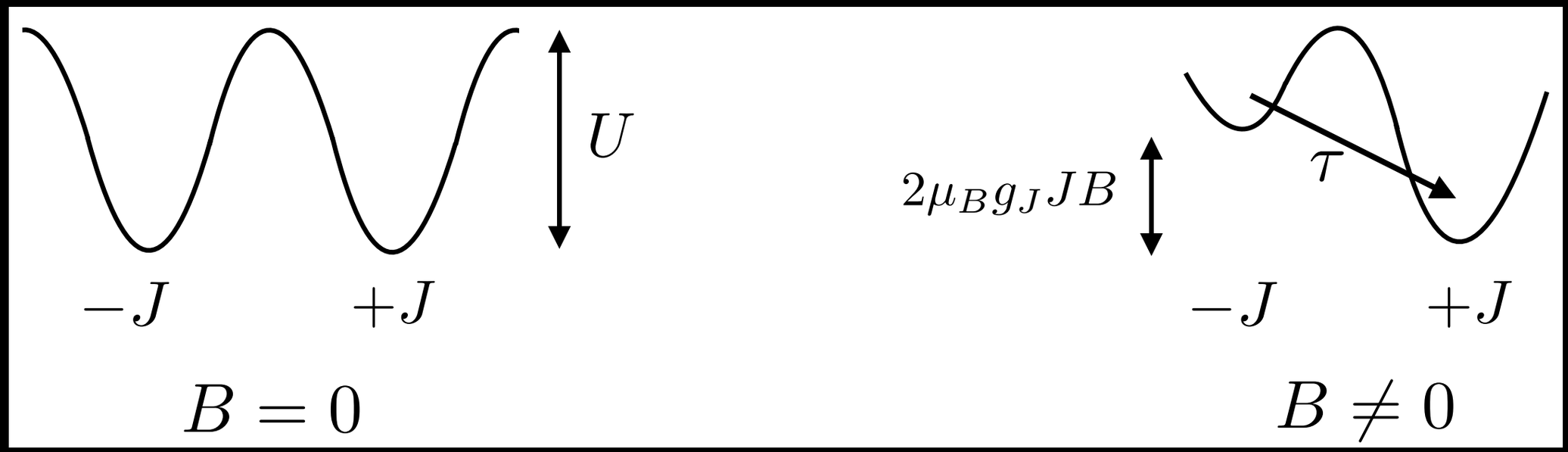
Tuning magnetic bubble chamber

Three intrinsic parameters important

U Energy barrier

τ_0 Relaxation time

J Spin



and external mag. field B

Zeeman E released

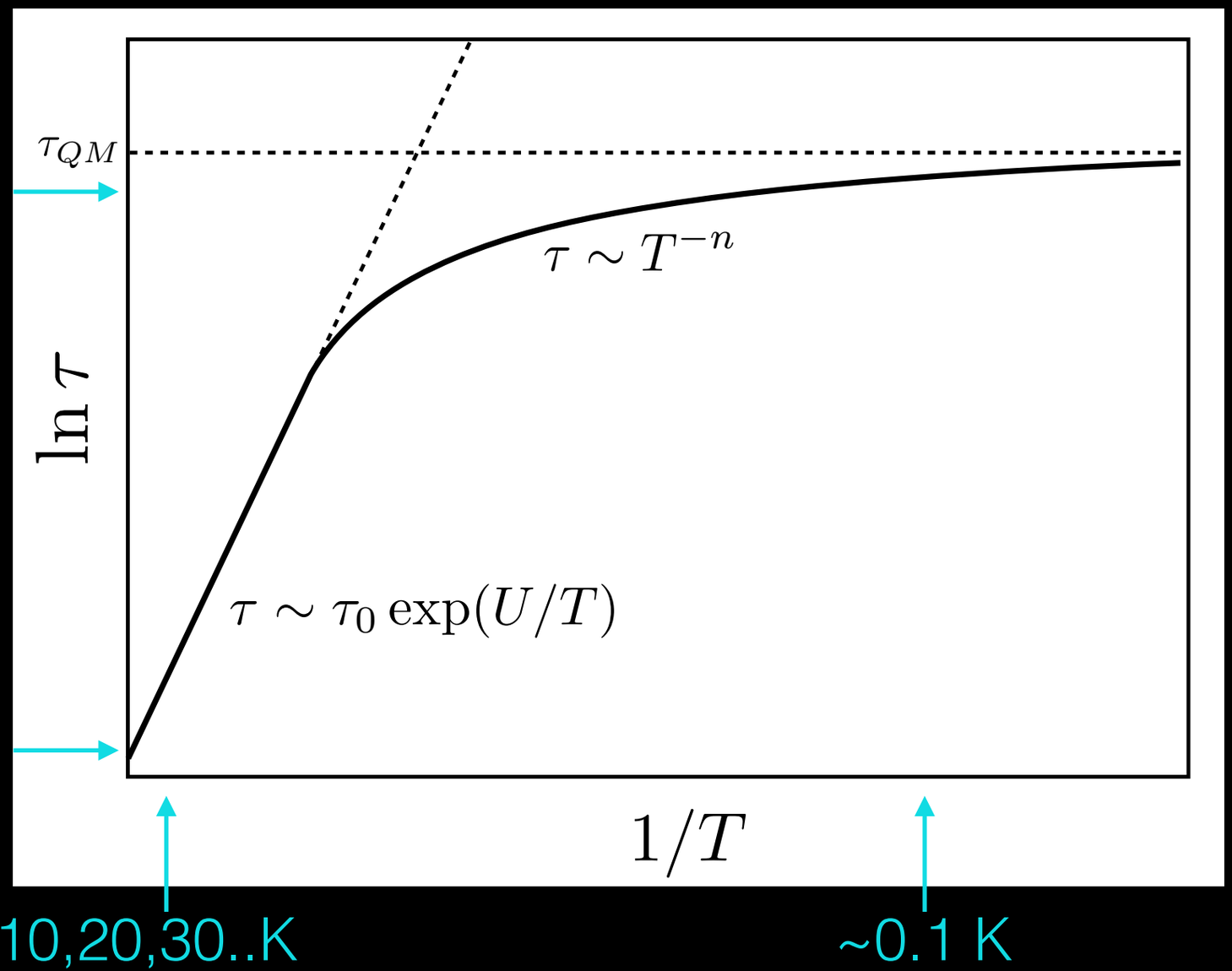
Tuning magnetic bubble chamber

Three intrinsic parameters important

U Energy barrier

τ_0 Relaxation time

J Spin



Tuning magnetic bubble chamber

Three intrinsic parameters important

U	τ_0	J
Energy barrier	Relaxation time	Spin
$\mathrm{few} - 800\ \mathrm{K}$	$10^{-6} - 10^{-14} s$	$\mathrm{few} - 50$

Synthesis—how easy (and cheap) is it to make them?

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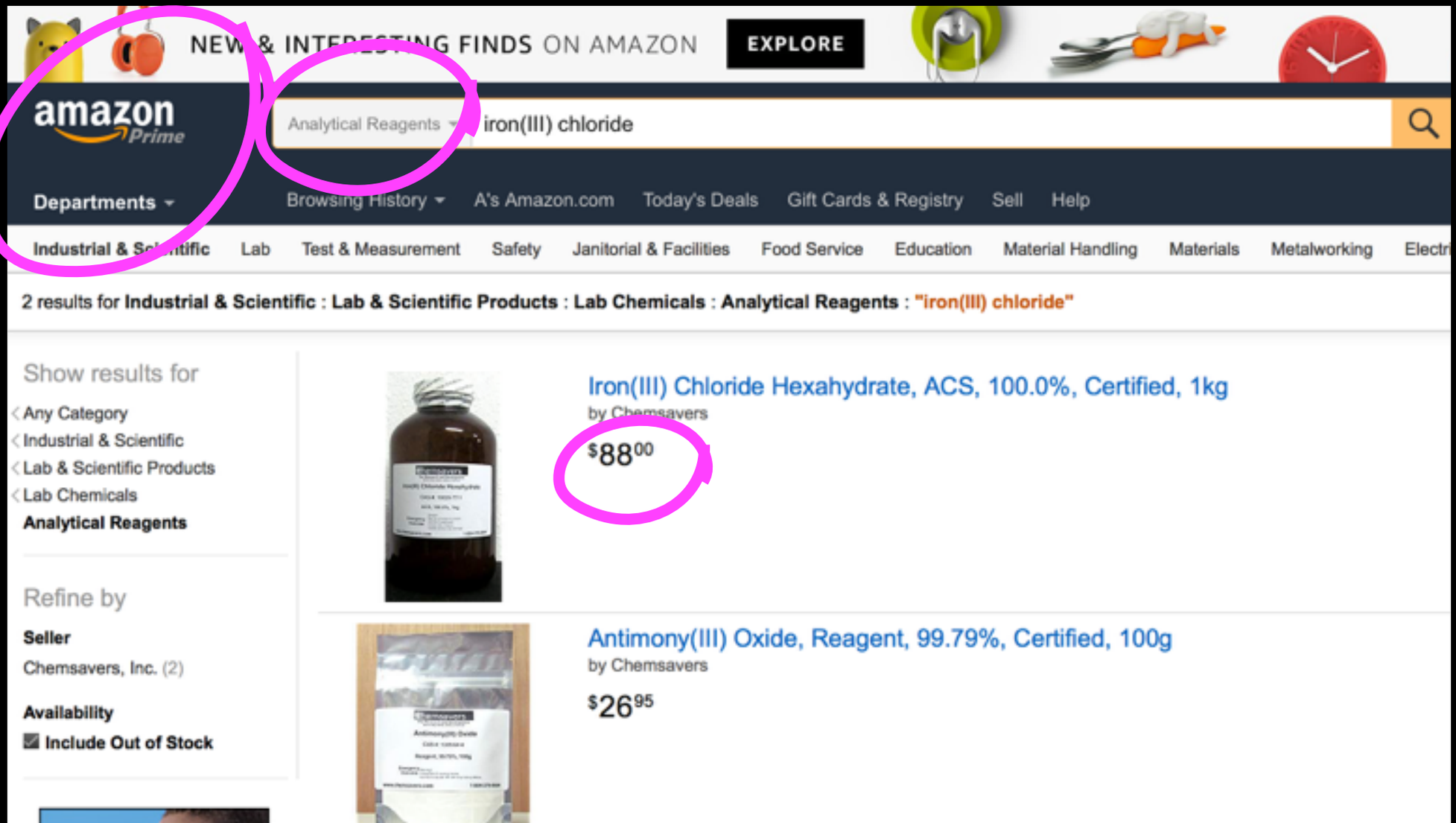
Typical synthesis:

Buy commercial reagents and solvents



Synthesis—how easy (and cheap) is it to make them?

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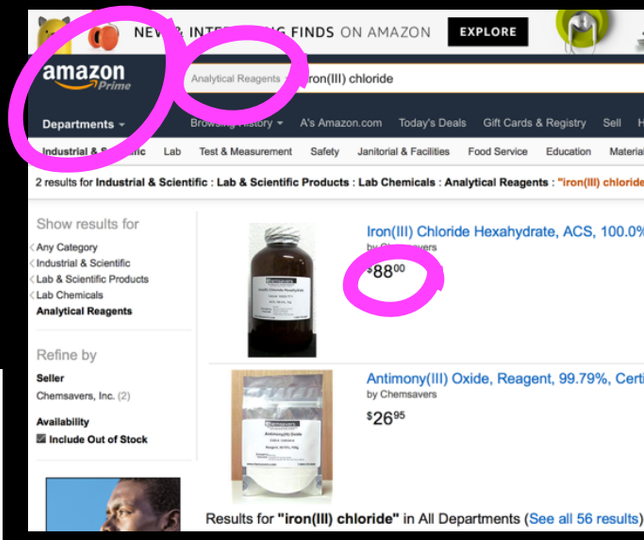
Mix solutions in some ratio, in a glovebox



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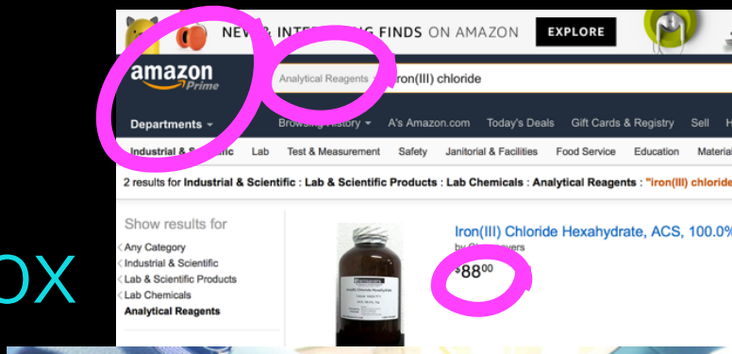
Heat to 240C, stir for an hour



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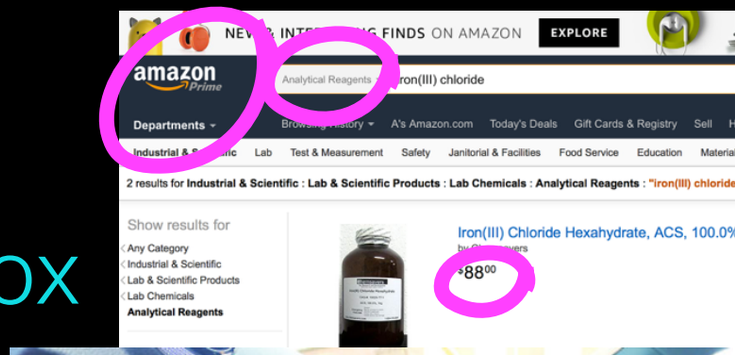
Cool while stirring



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Mix solutions in some ratio, in a glovebox

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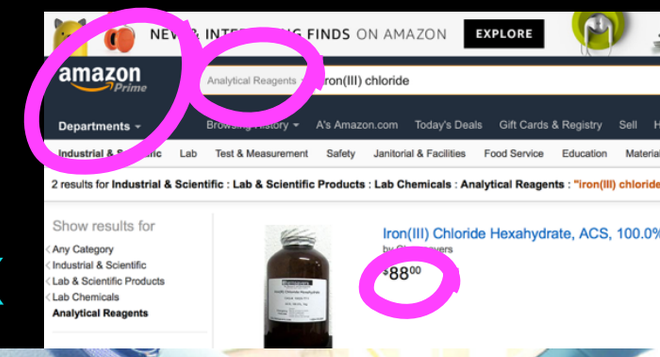
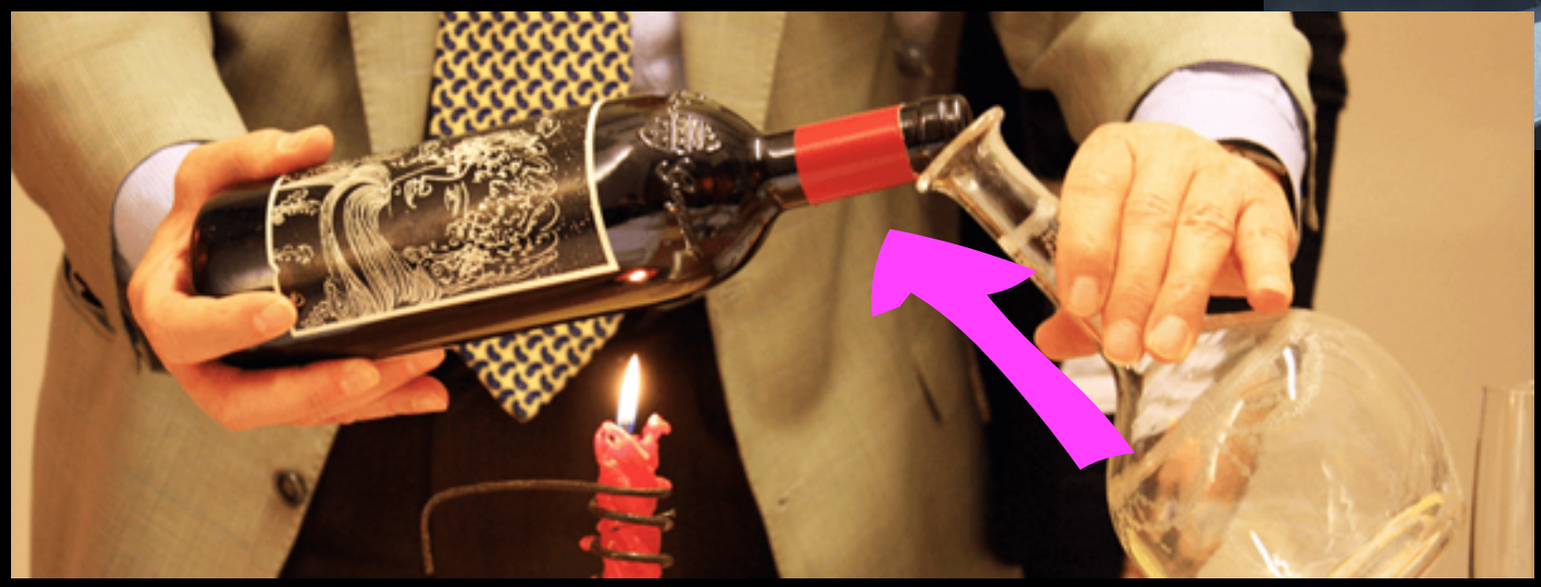
Cool while stirring

Decant





Synthesis—how easy (and cheap) is it to make them?

Typical synthesis:

Buy commercial reagents and solvents

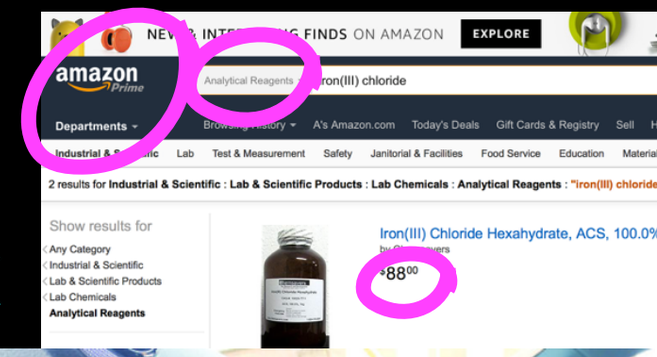
Mix solutions in some ratio, in a glovebox

Heat to 240C, stir for an hour

Cool while stirring

Decant

Dry with a flow of air



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Typical synthesis:

Buy commercial reagents and solvents

Mix solutions in some ratio, in a glovebox

Heat to 240C, stir for an hour

Cool while stirring

Decant

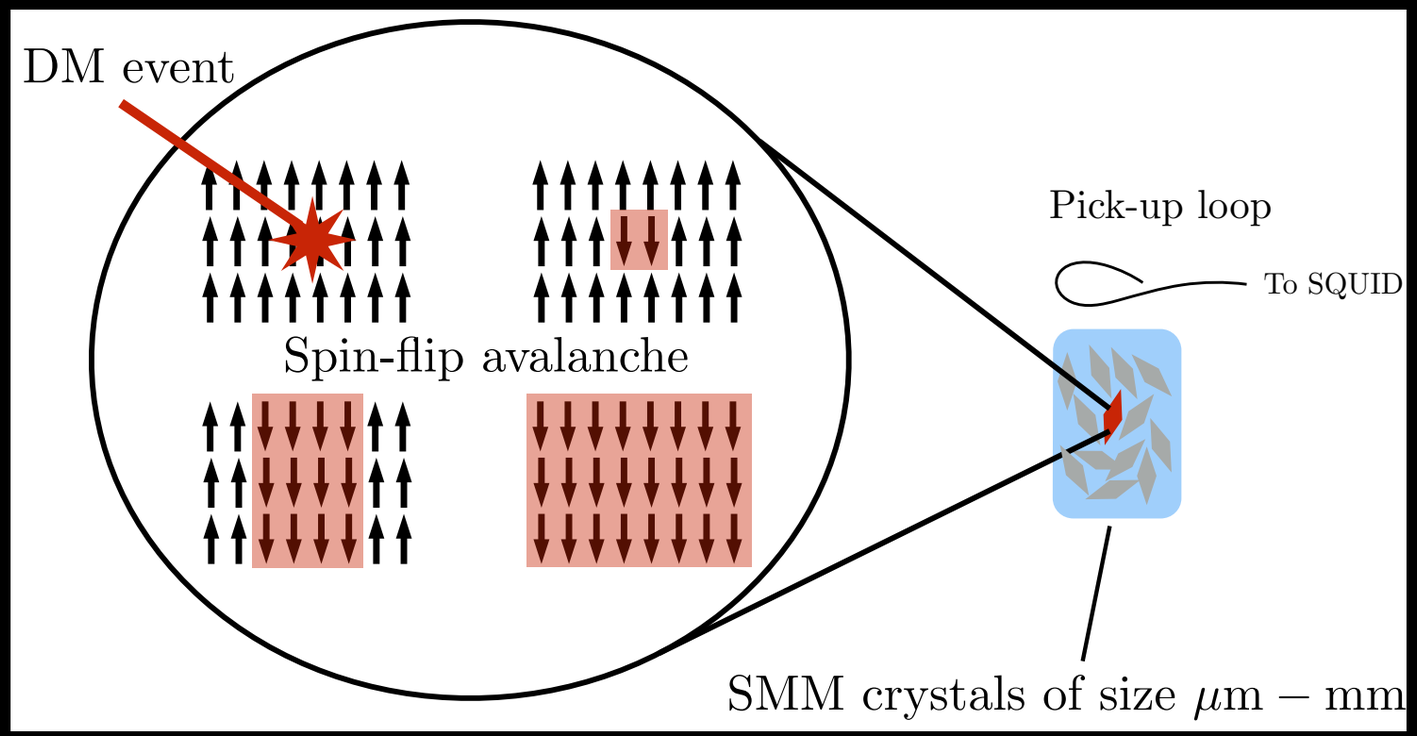
Dry with a flow of air

Synthesis—how easy (and cheap) is it to make them?

Typical synthesis:

& it doesn't have to be done pristinely! (see later)

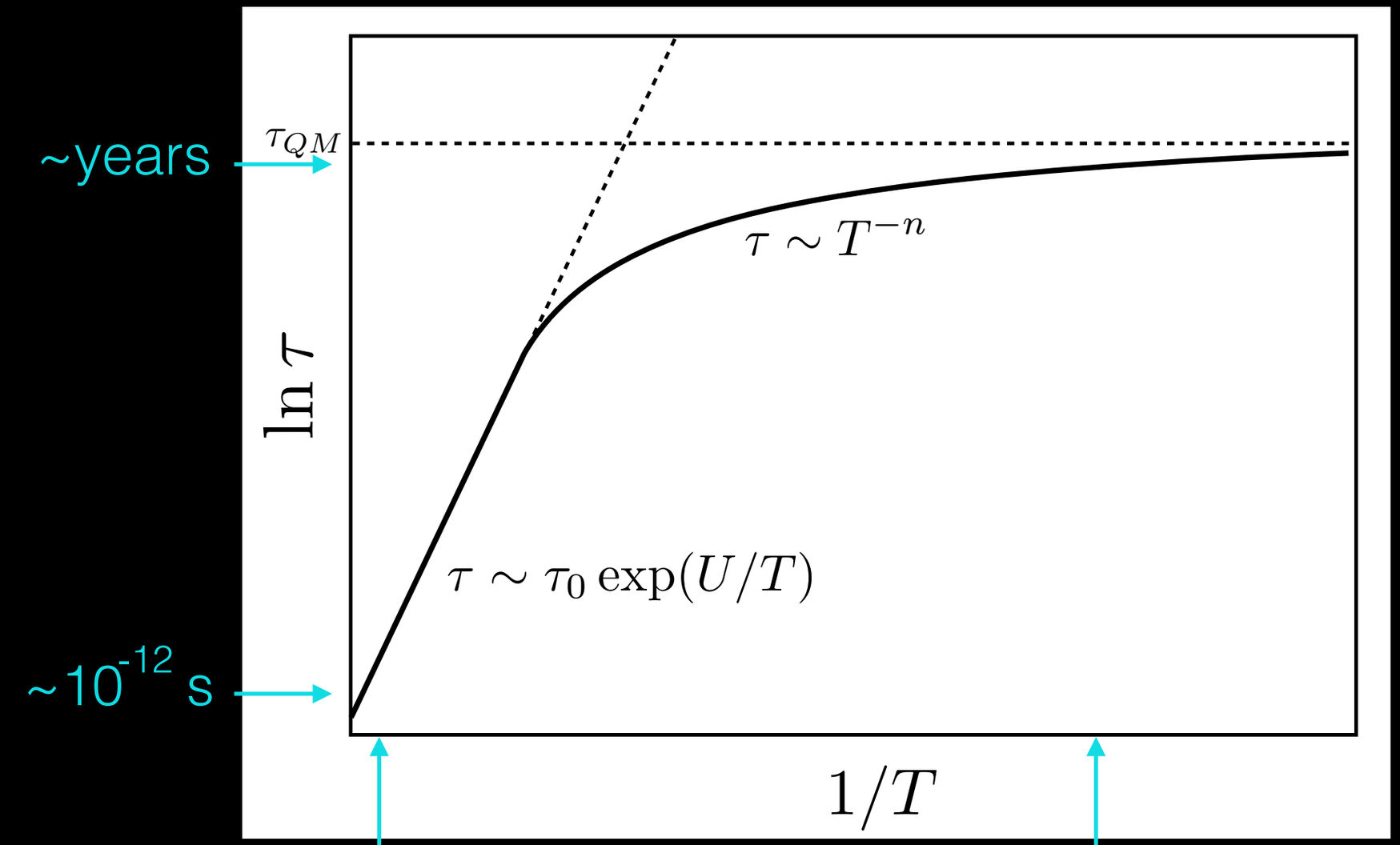
DM detector concept



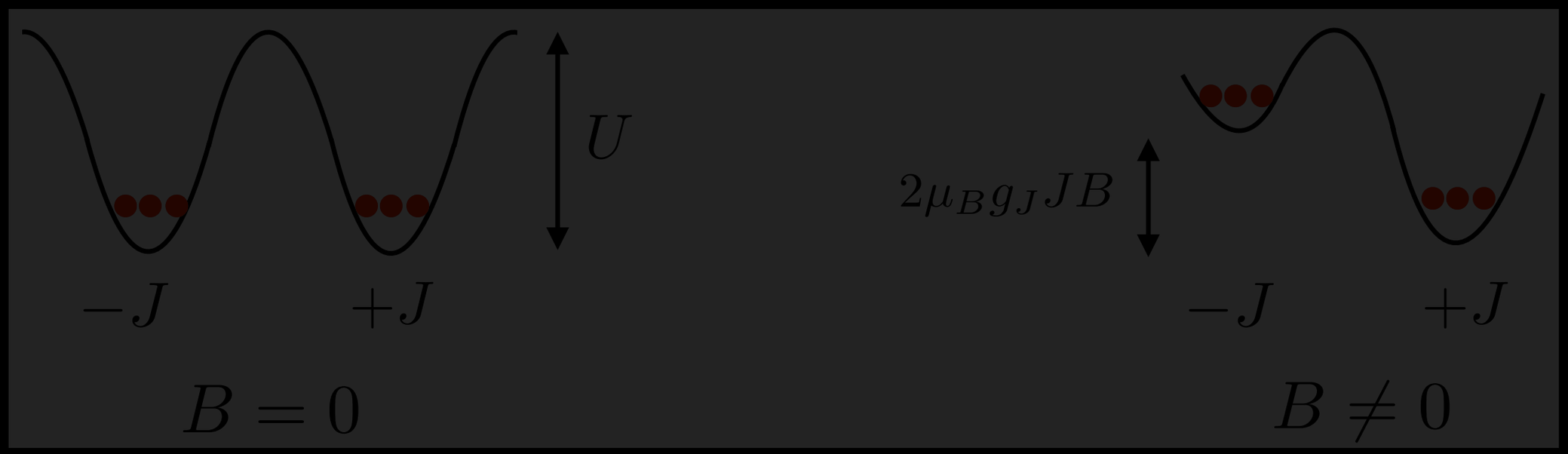
Preparation

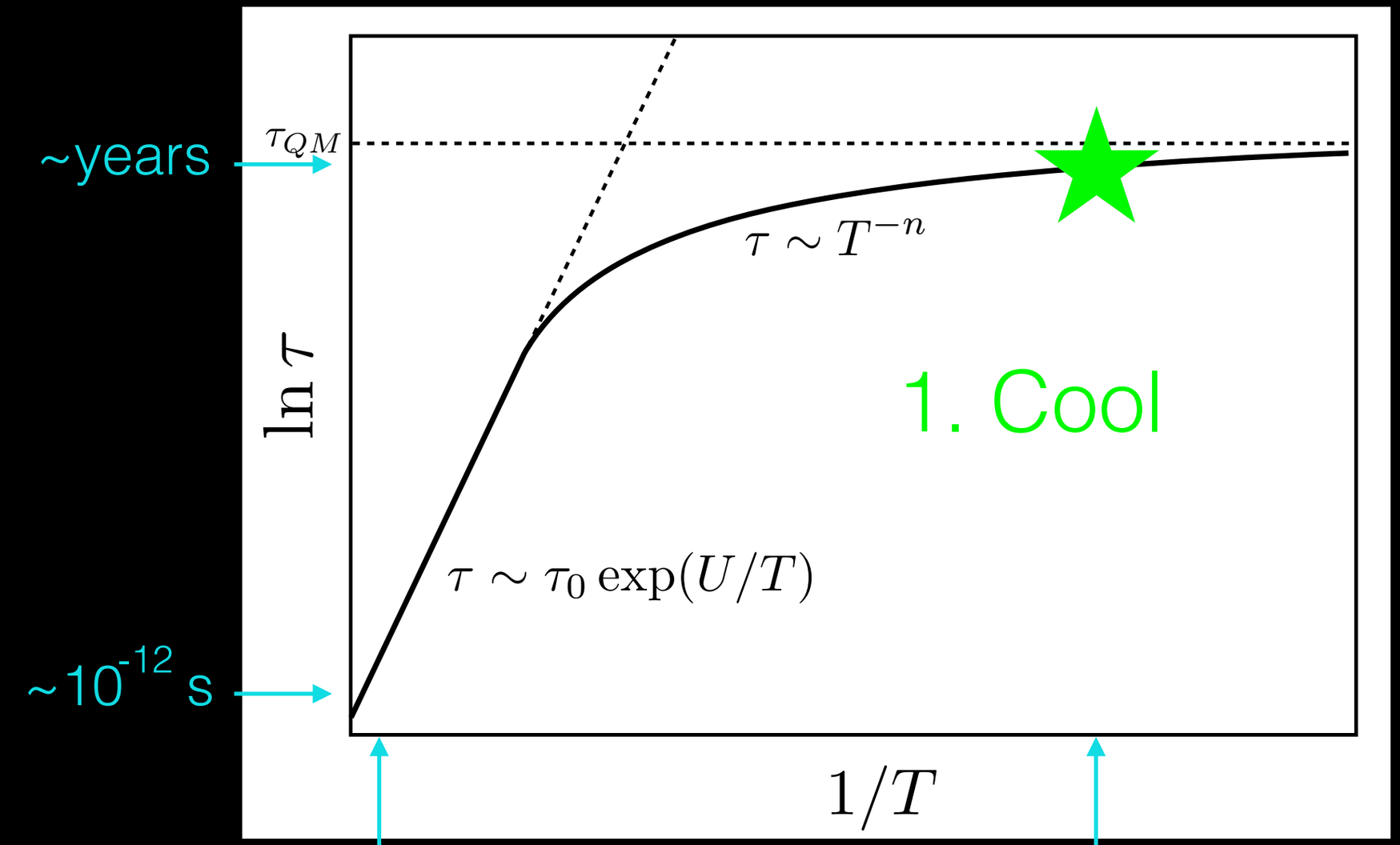
Tuning

Backgrounds



Preparation Tuning Backgrounds





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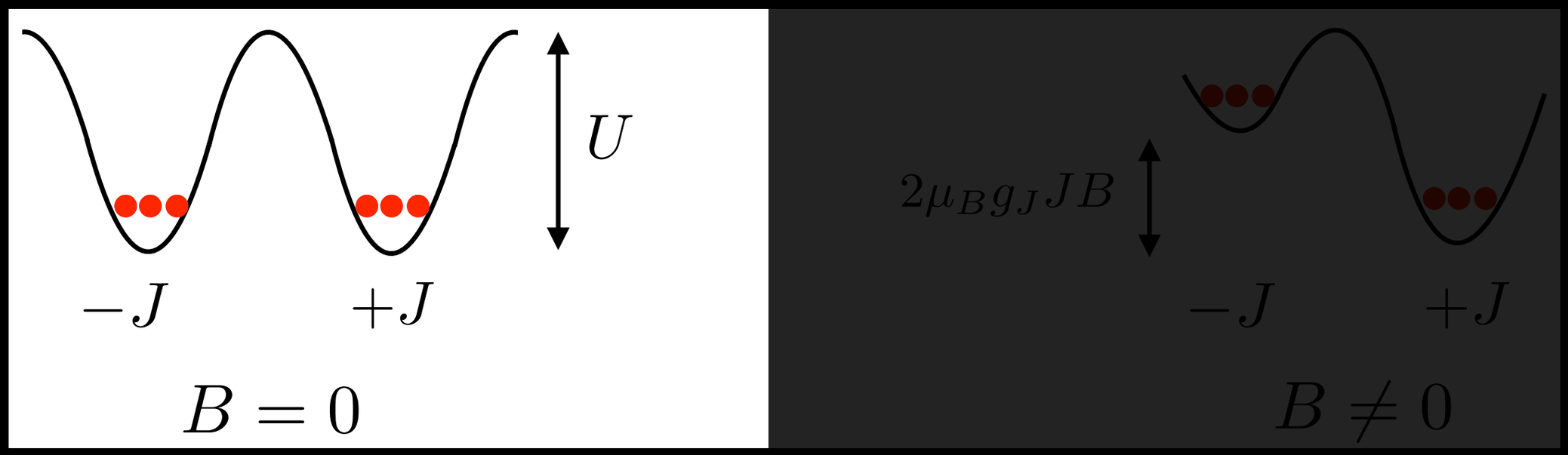
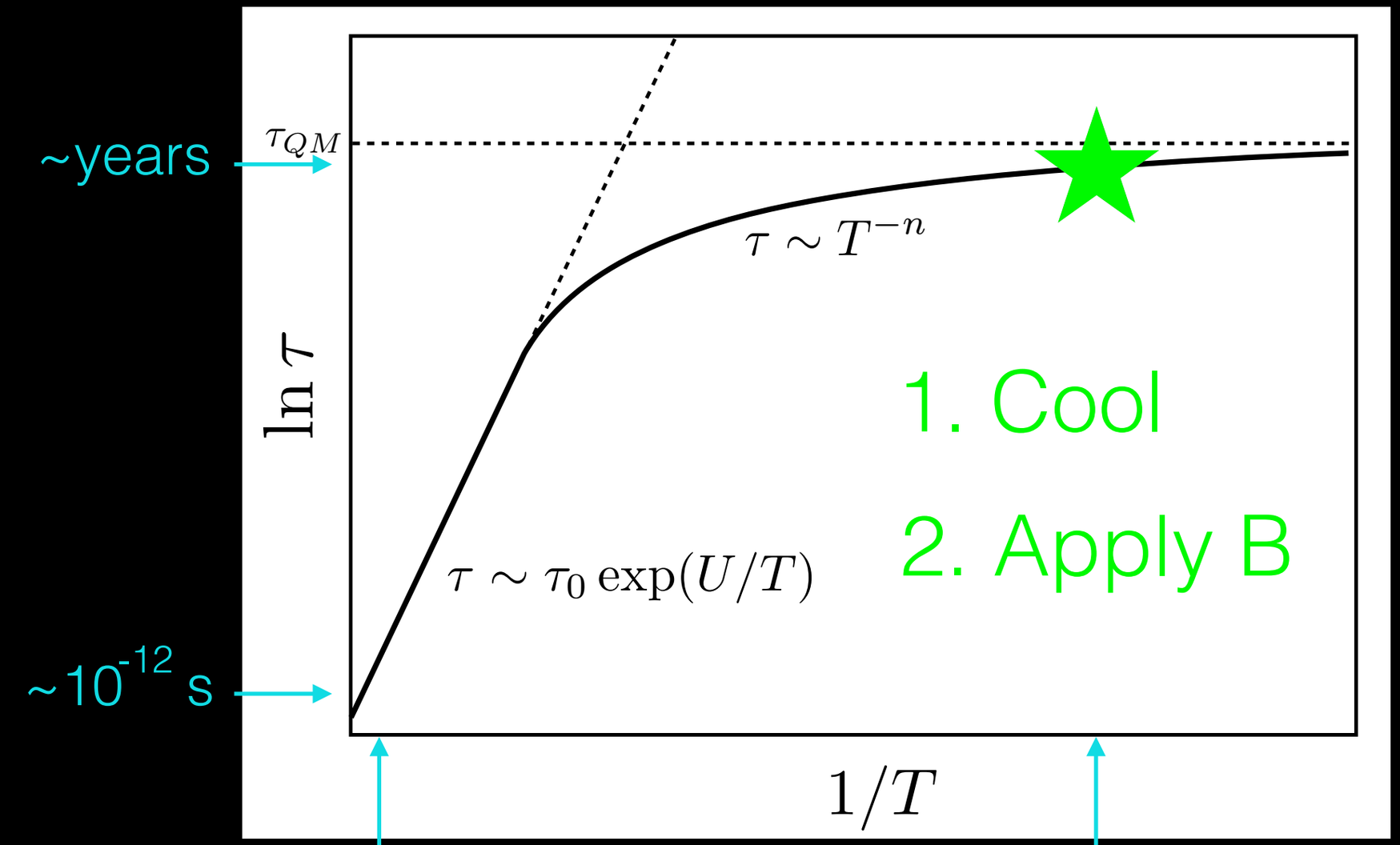
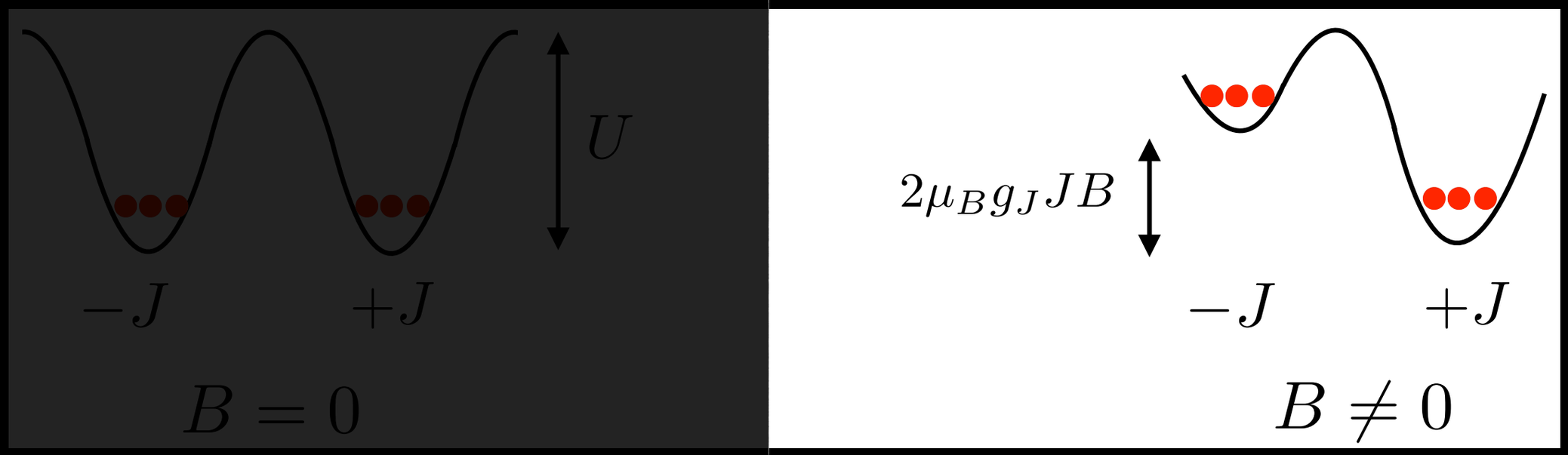
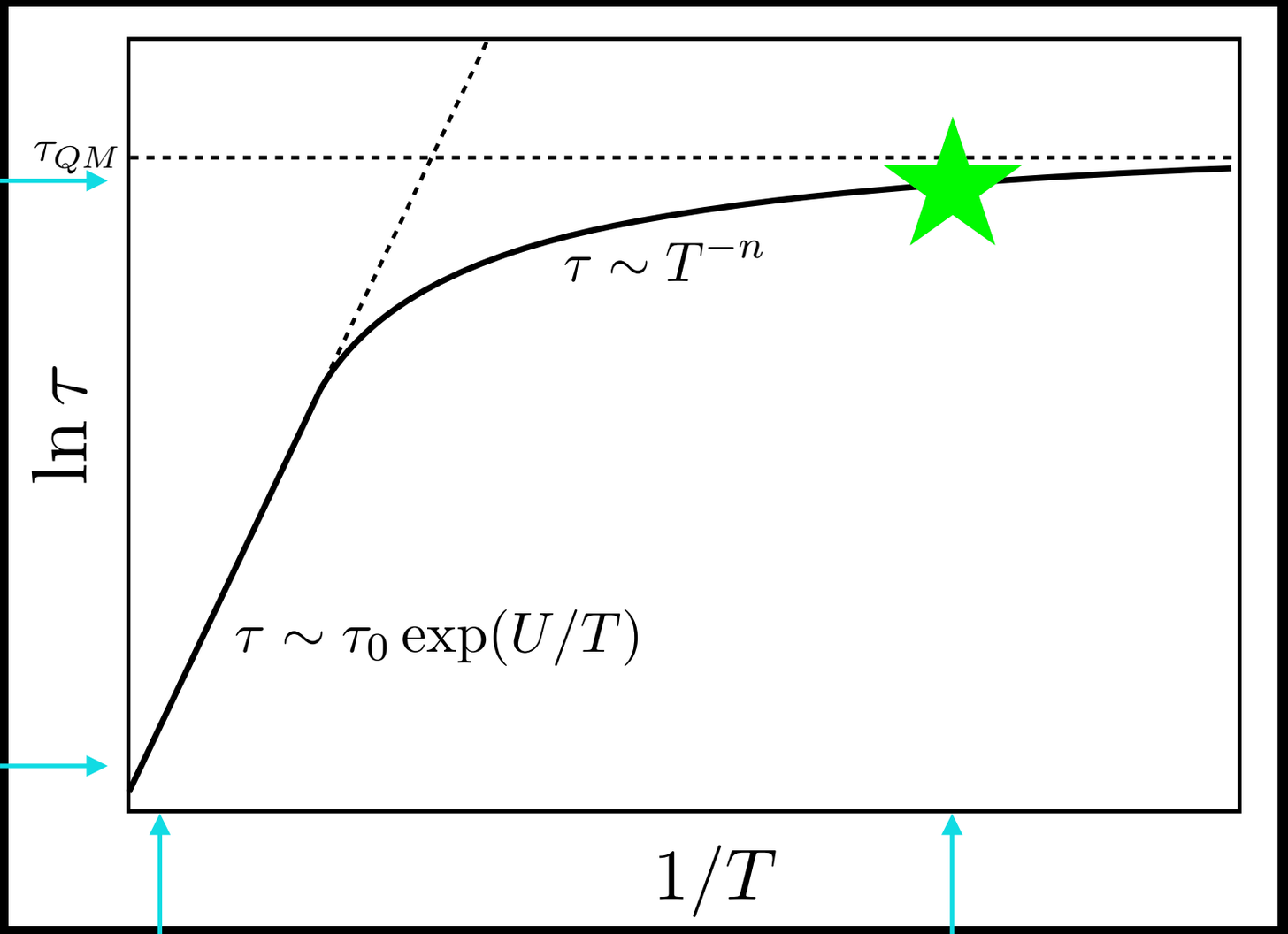




Preparation Tuning Backgrounds





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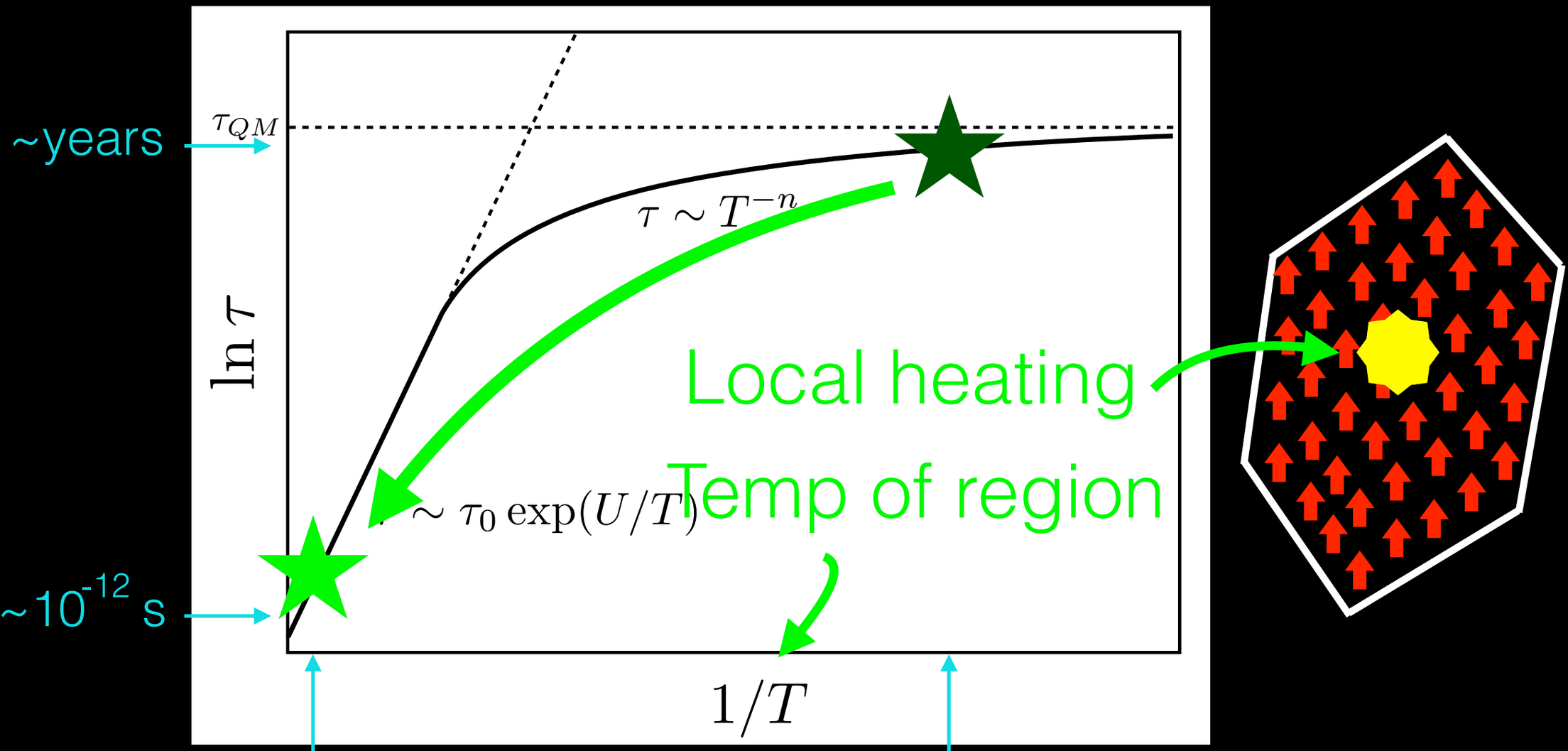

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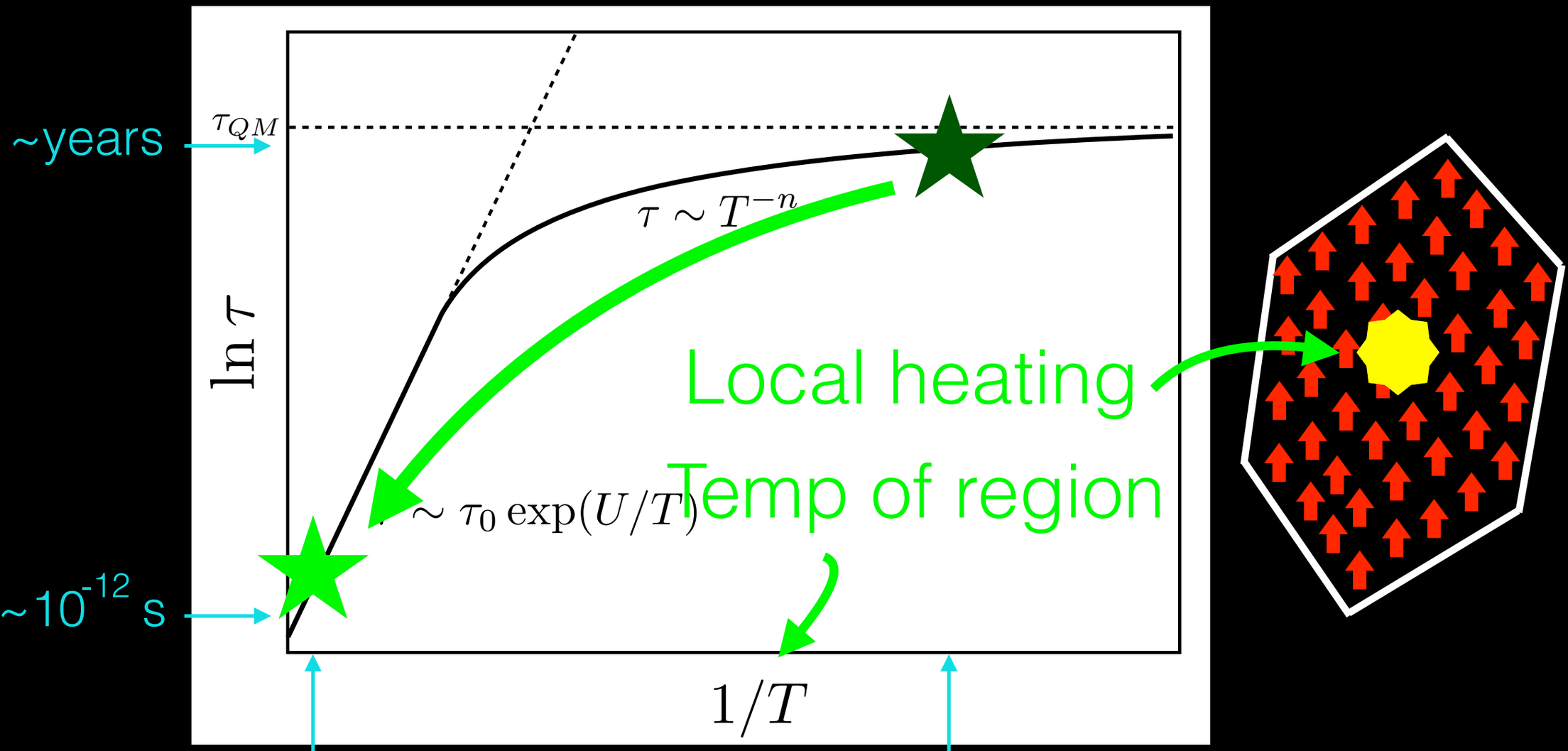


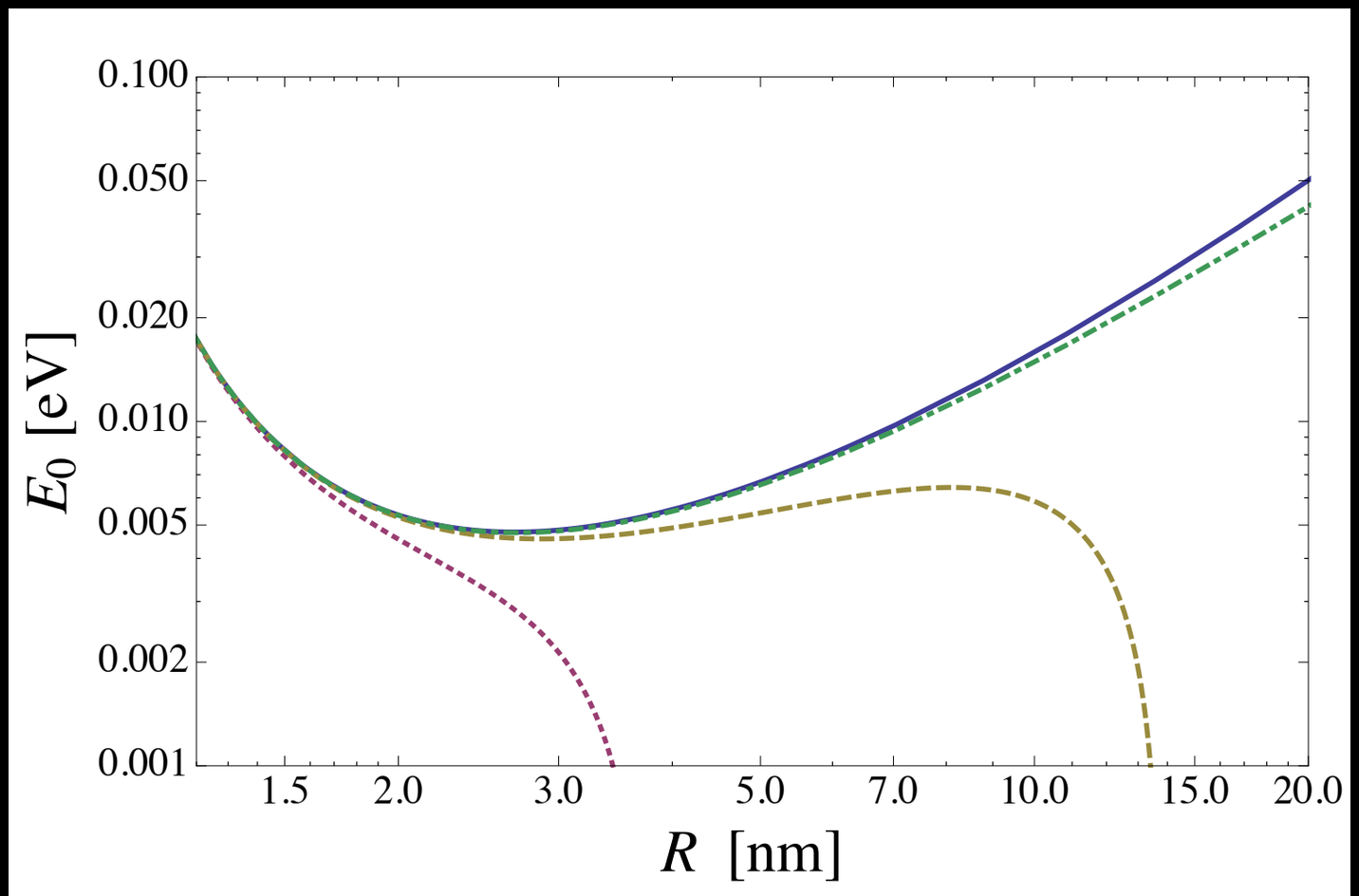
Preparation Tuning Backgrounds

Spins relax if $\tau \lesssim \tau_D$

~10^{-11} s for region a few spins long

magnetic relax time

thermal diff. time



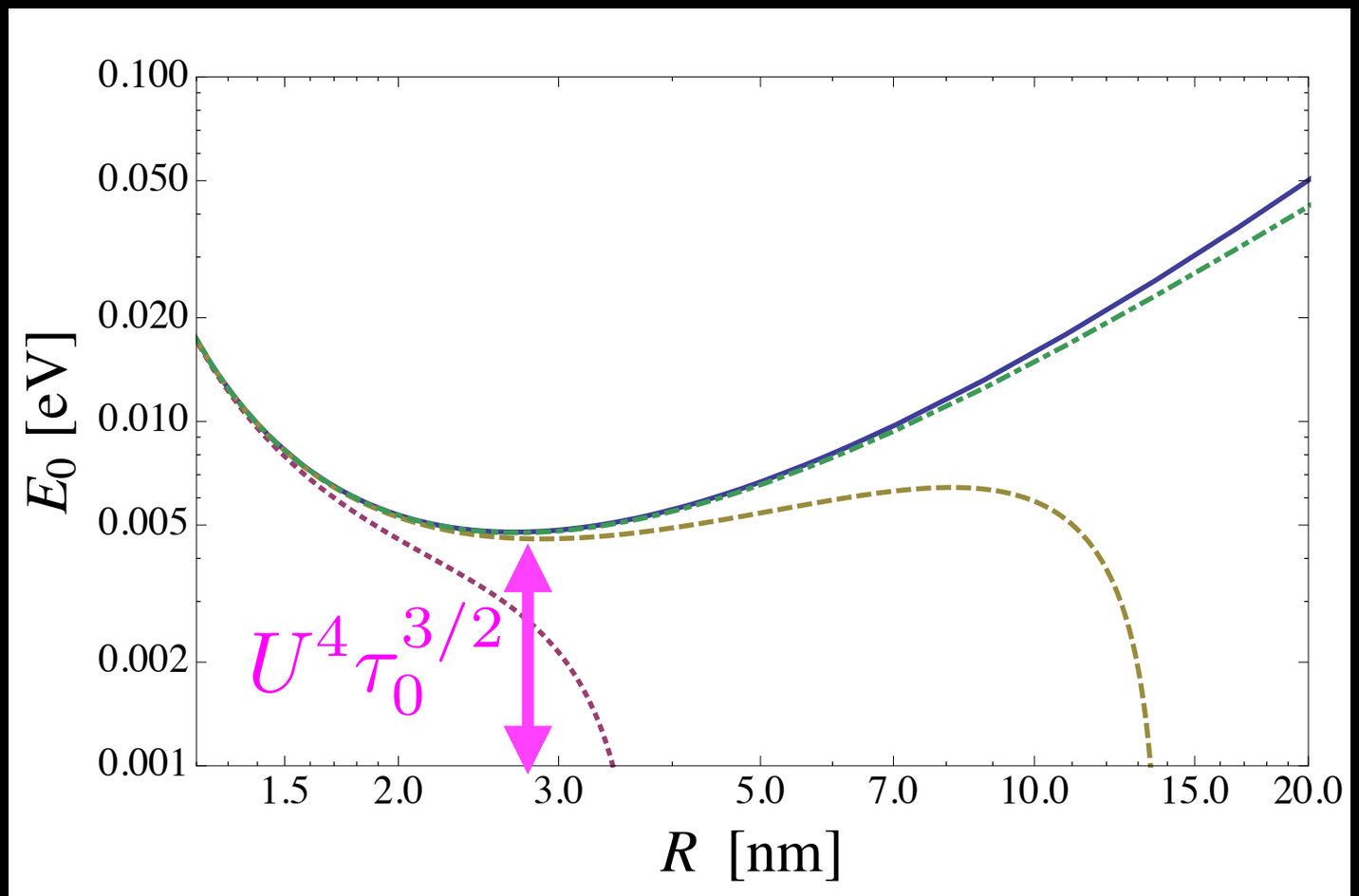
Preparation Tuning Backgrounds

‘Tuning equation’ for spin flip

Radius of region

Initial energy deposit

$$E_0 \gtrsim \frac{R^3(U - \mu_B g_J J B)^4}{\ln\left[\frac{R^2}{\tau_0}\right]^4}$$



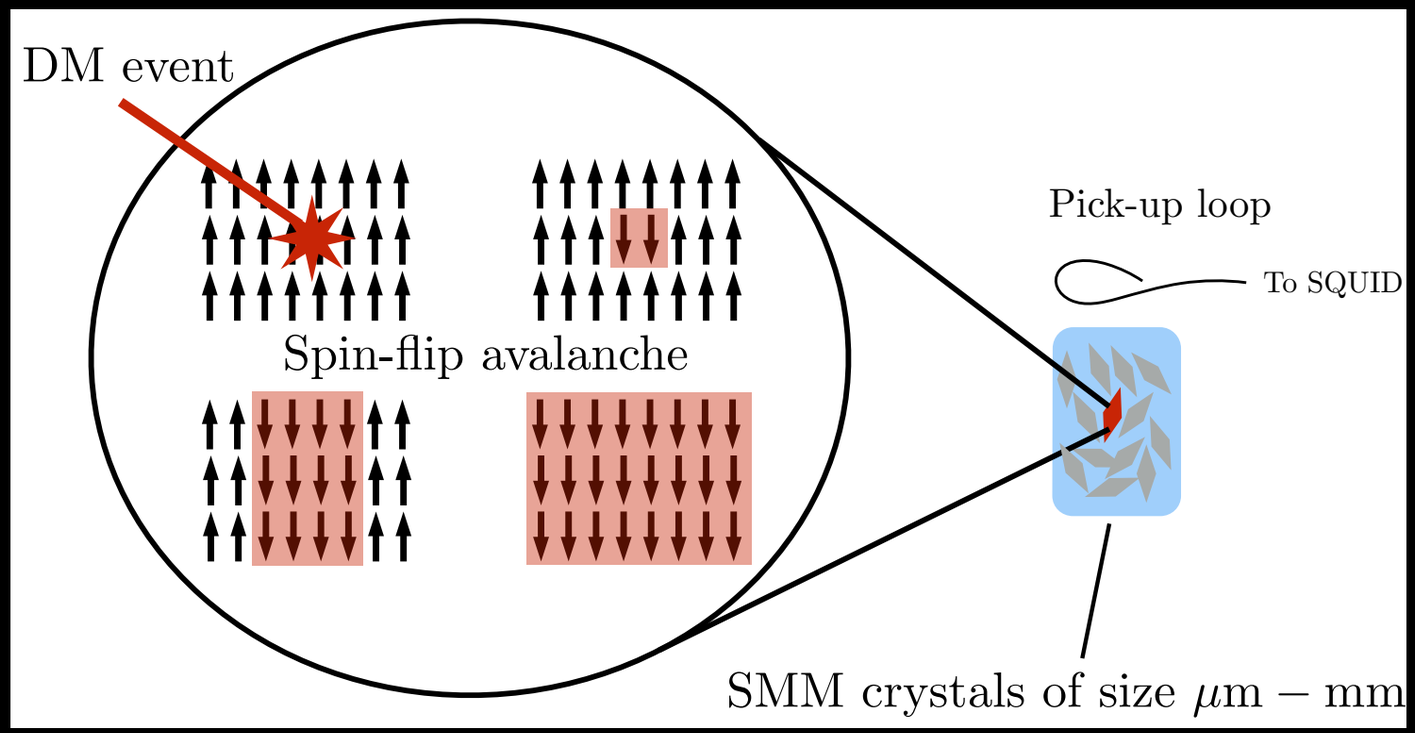
Preparation Tuning Backgrounds

‘Tuning equation’ for spin flip

Radius of region

Initial energy deposit

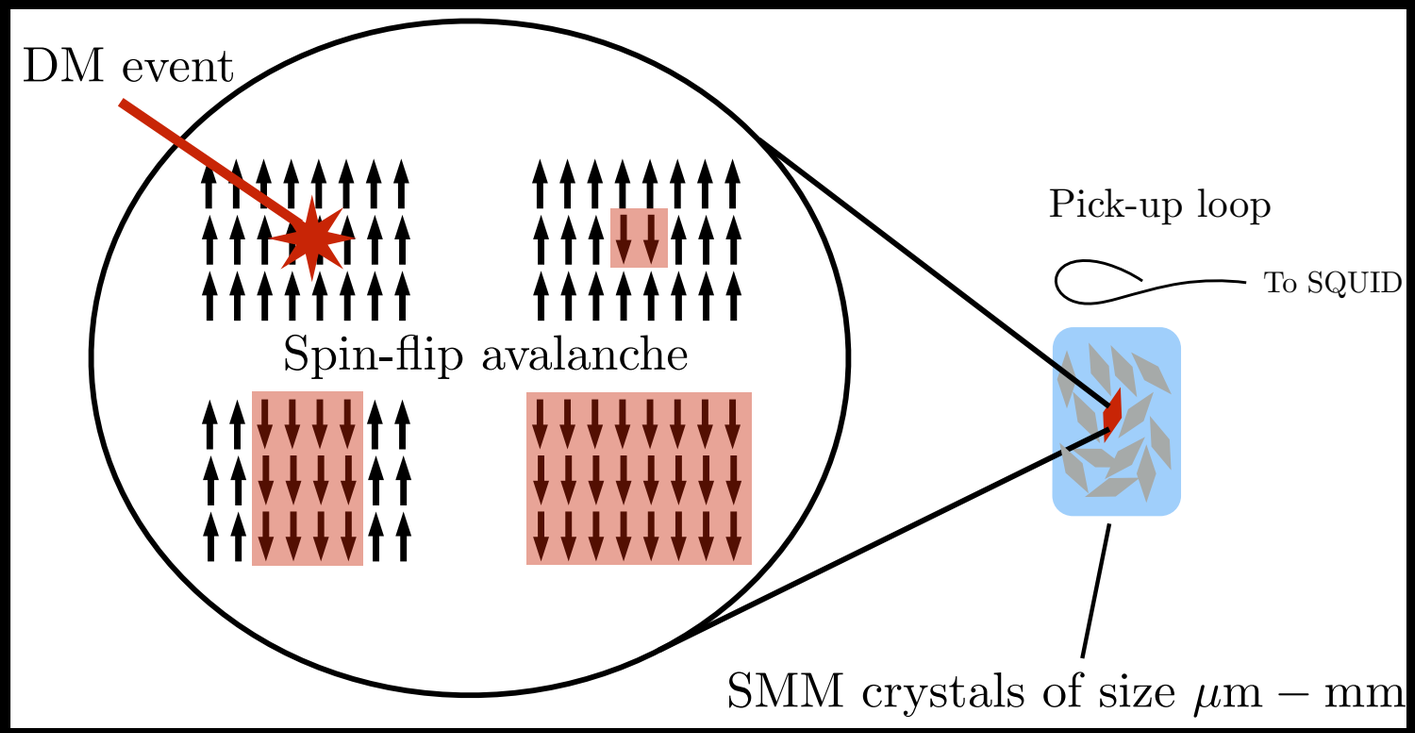
$$E_0 \gtrsim \frac{R^3 (U + \mu_B g_J J B)^4}{\ln\left[\frac{R^2}{\tau_0}\right]^4}$$



Preparation Tuning Backgrounds

One thing to demonstrate potential sensitivity…

…mainly comment here on feasibility to active veto

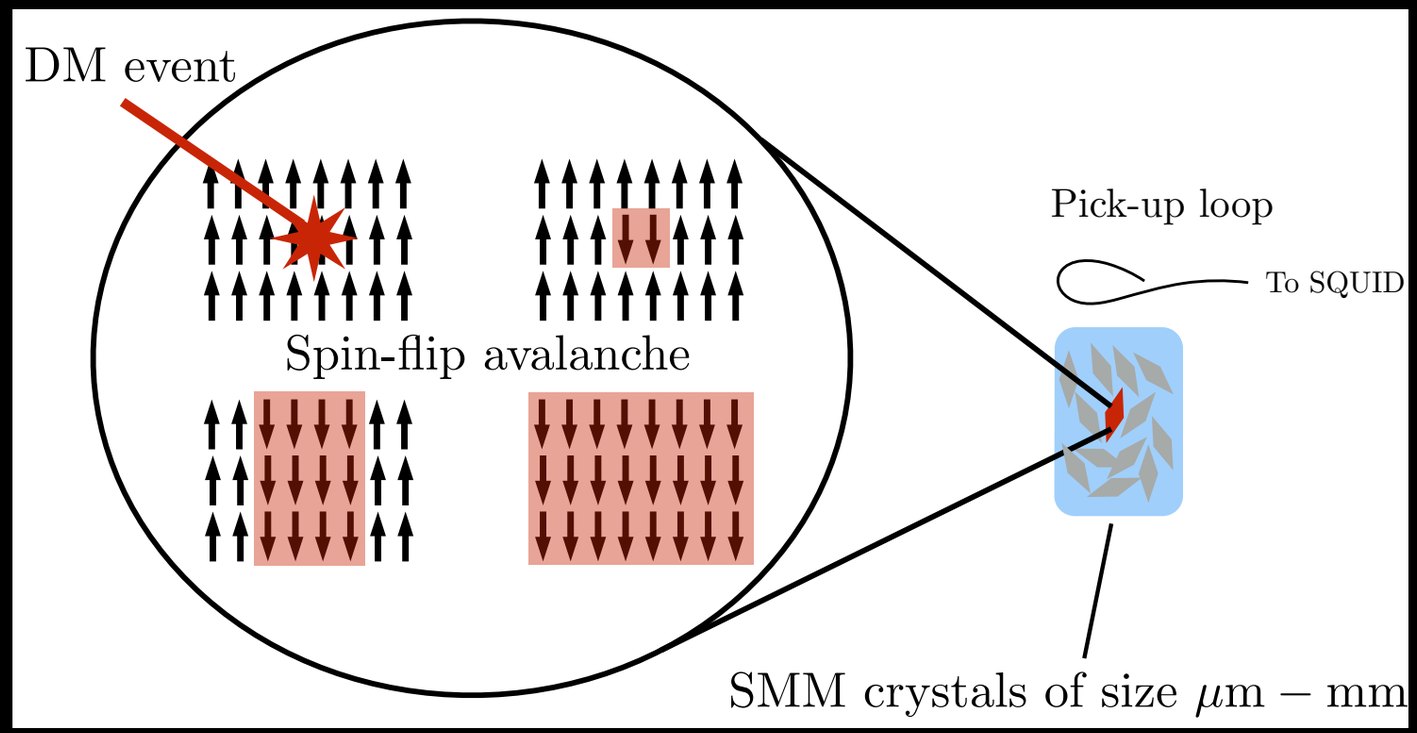


Preparation Tuning Backgrounds

The time it takes to detect spin avalanche (~few micron sized region), to turn off B field is ~10^{-5}s

Removes fuel for the avalanche, so it stops

radon, 1/m^2/s: for 10cm^3 detector, 1 every 100s



Preparation Tuning Backgrounds

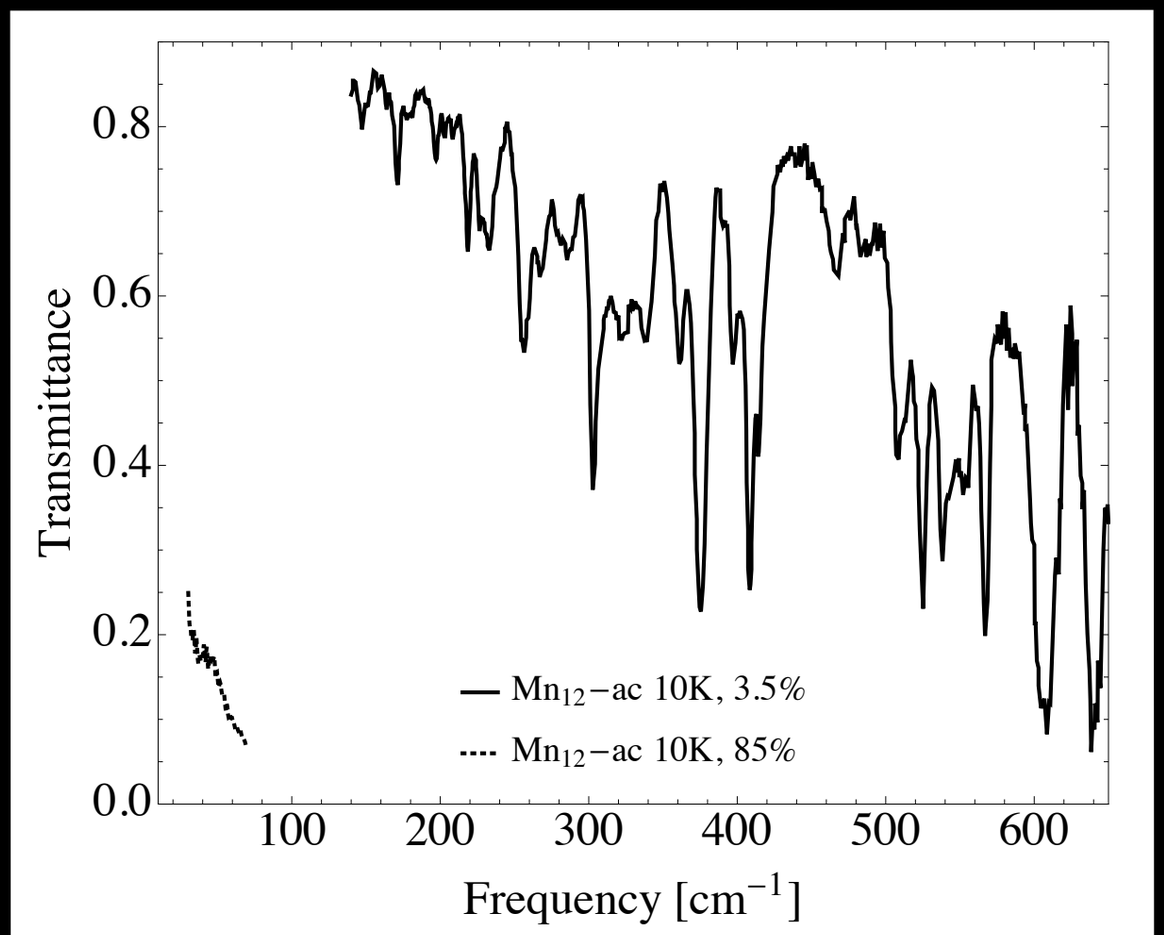
Two things to point out in light of discussions yesterday/today:

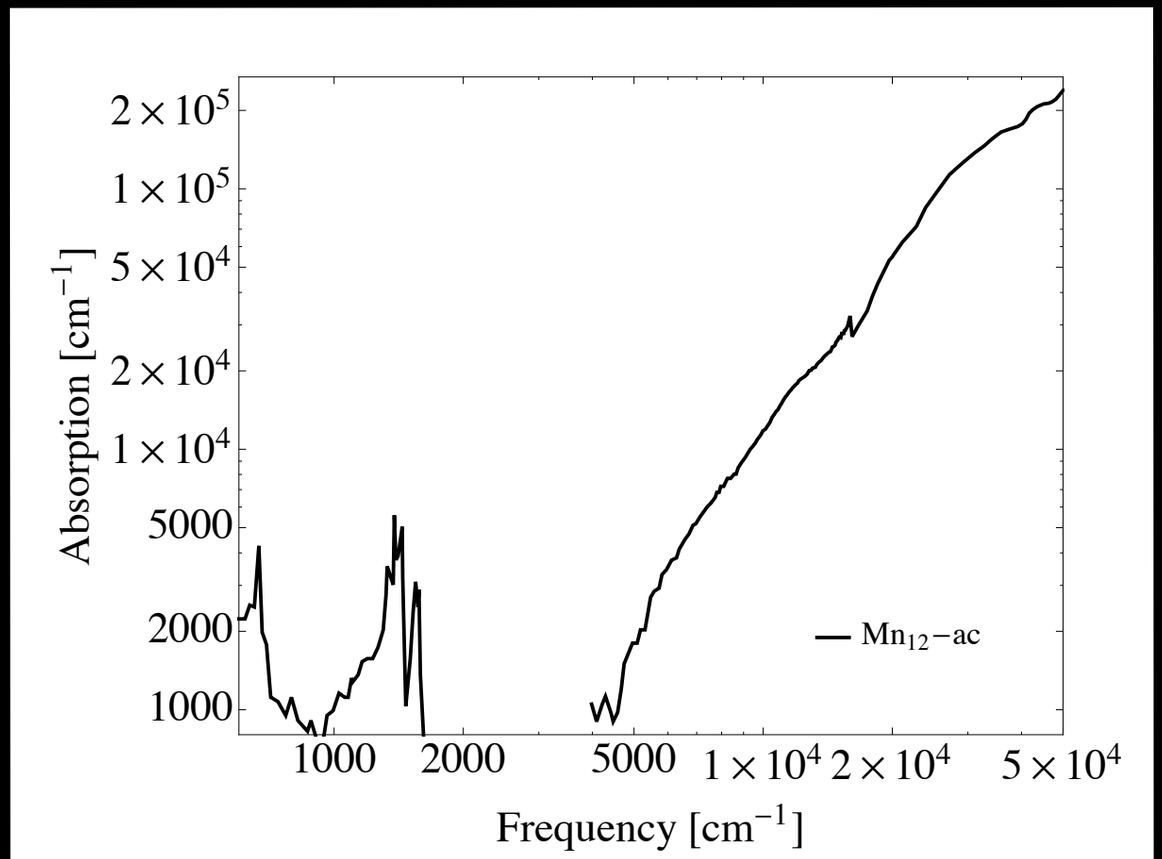
Many SMMs are scintillators

Mechanism not edge sensitive

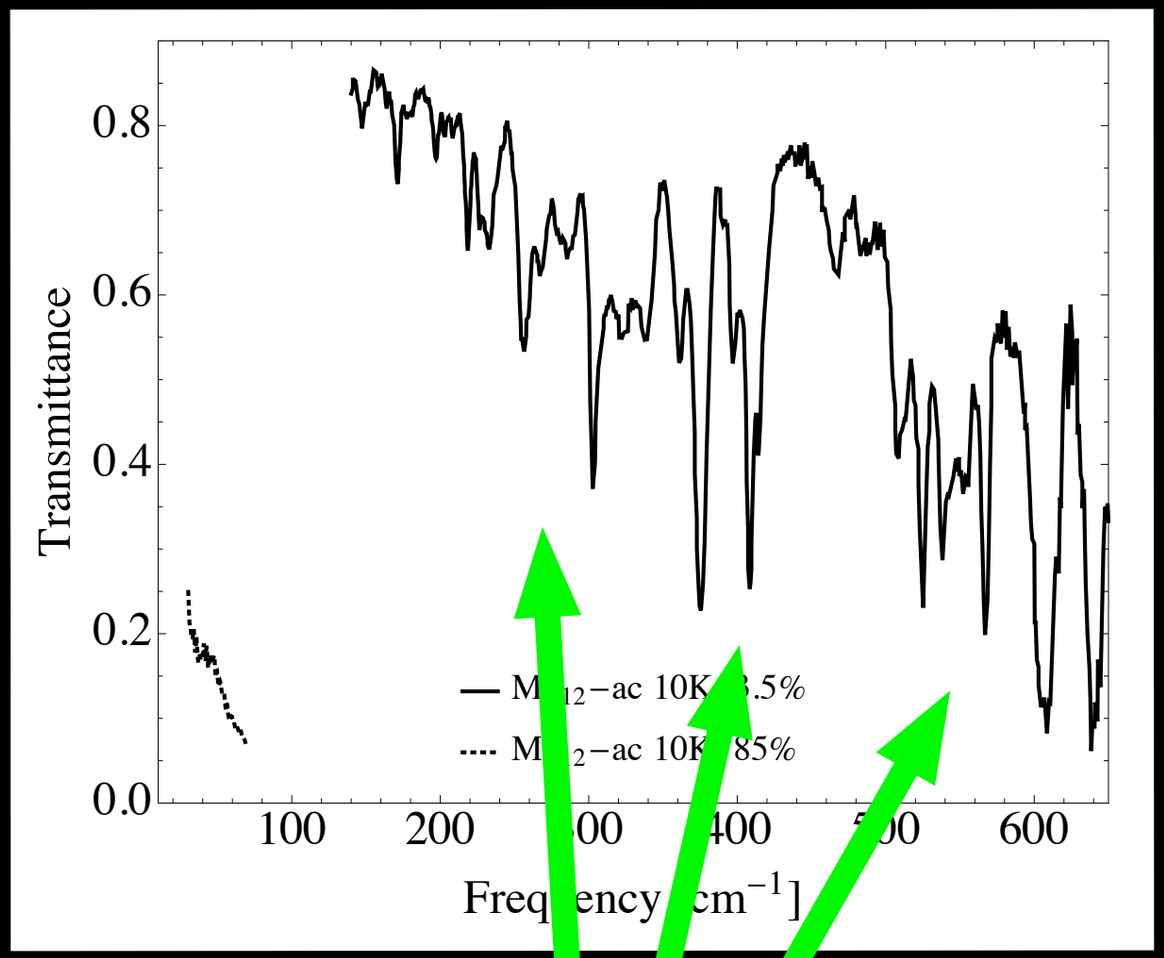
Sensitivity to DM parameter space

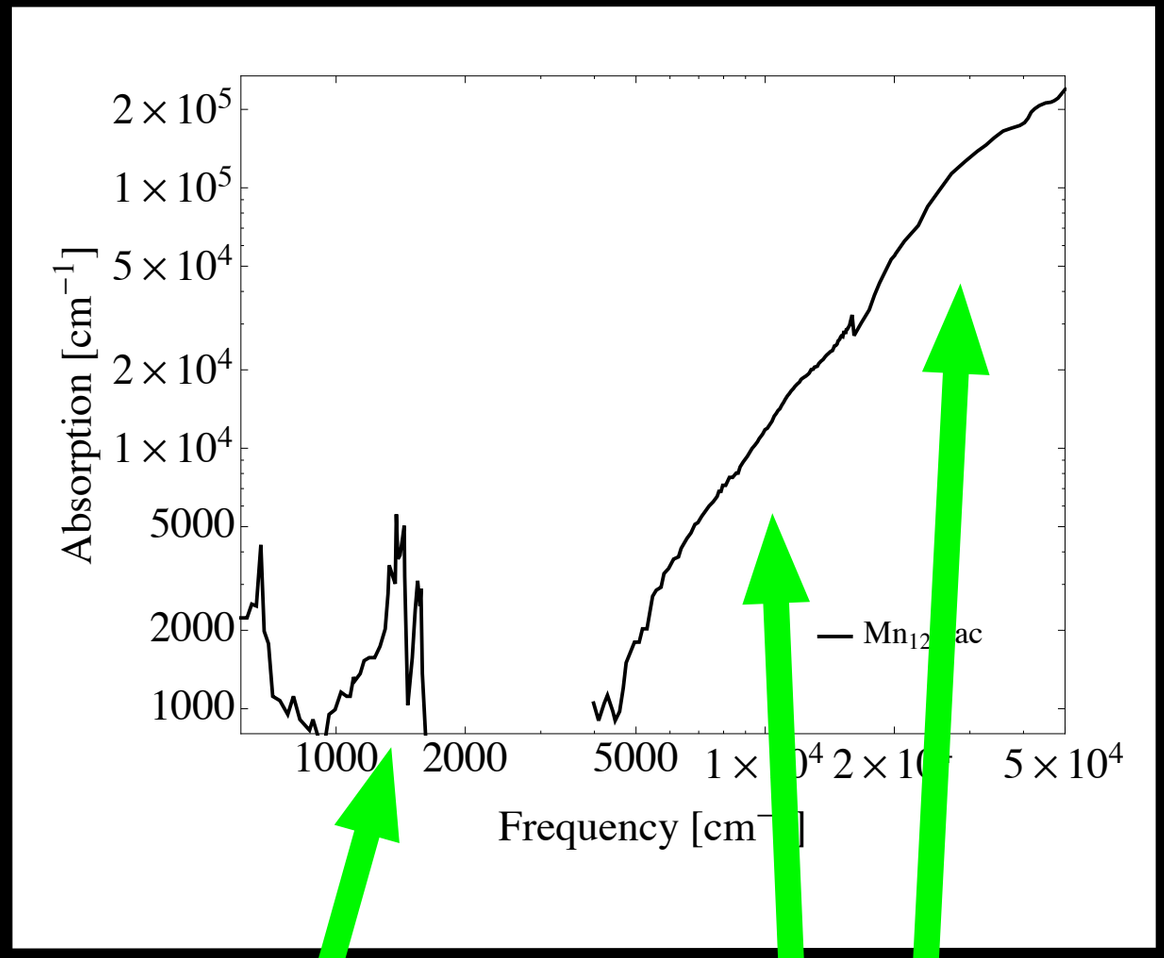
Absorption of dark photons





Absorption of dark photons





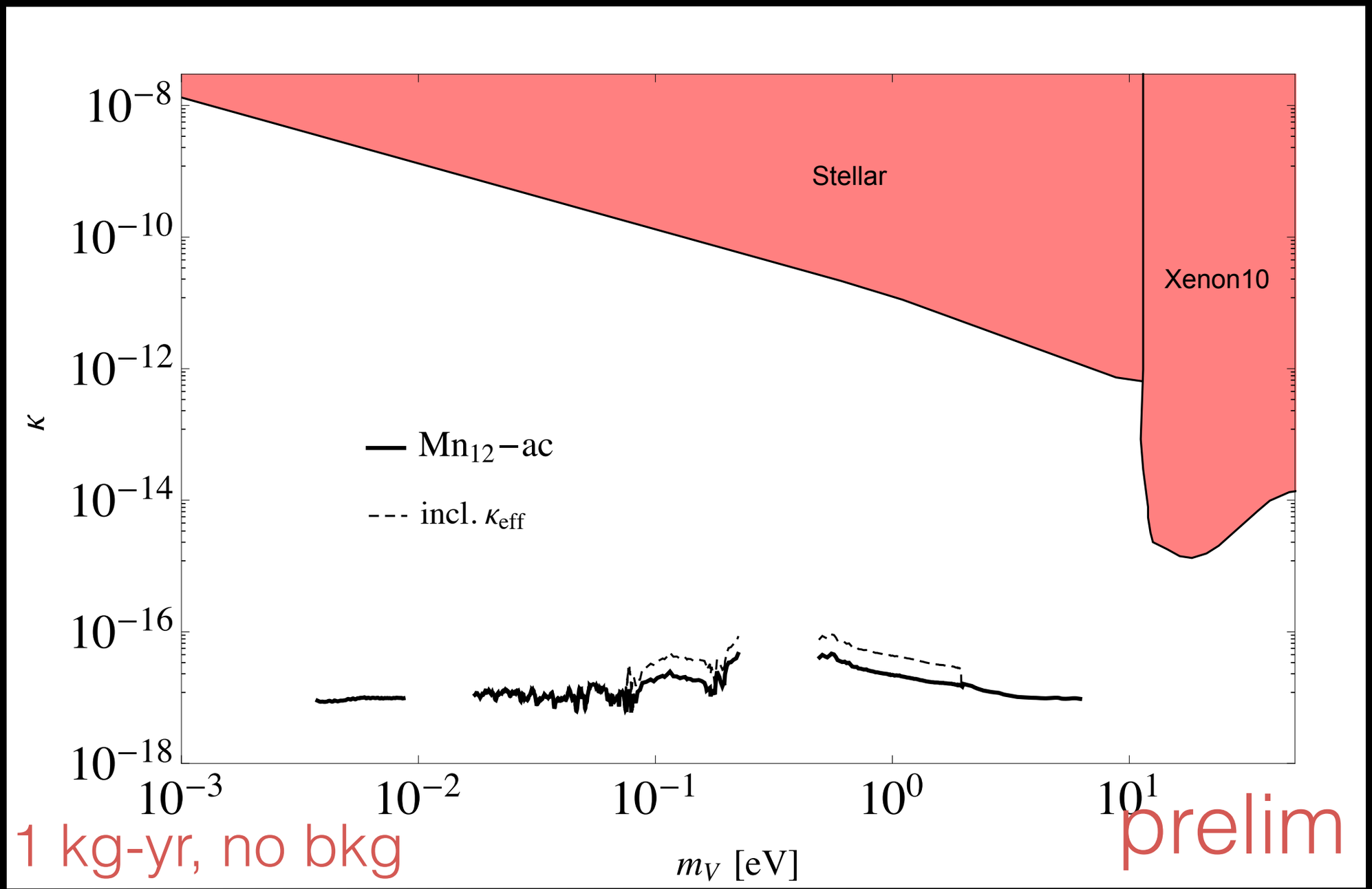
Mn-O crown vibrations

C=O vibrations

intra-molecular electronic shifts

Absorption of dark photons

$$\mathcal{L} \supset -\frac{1}{2}\kappa F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_V^2 A'_\mu A'^\mu$$

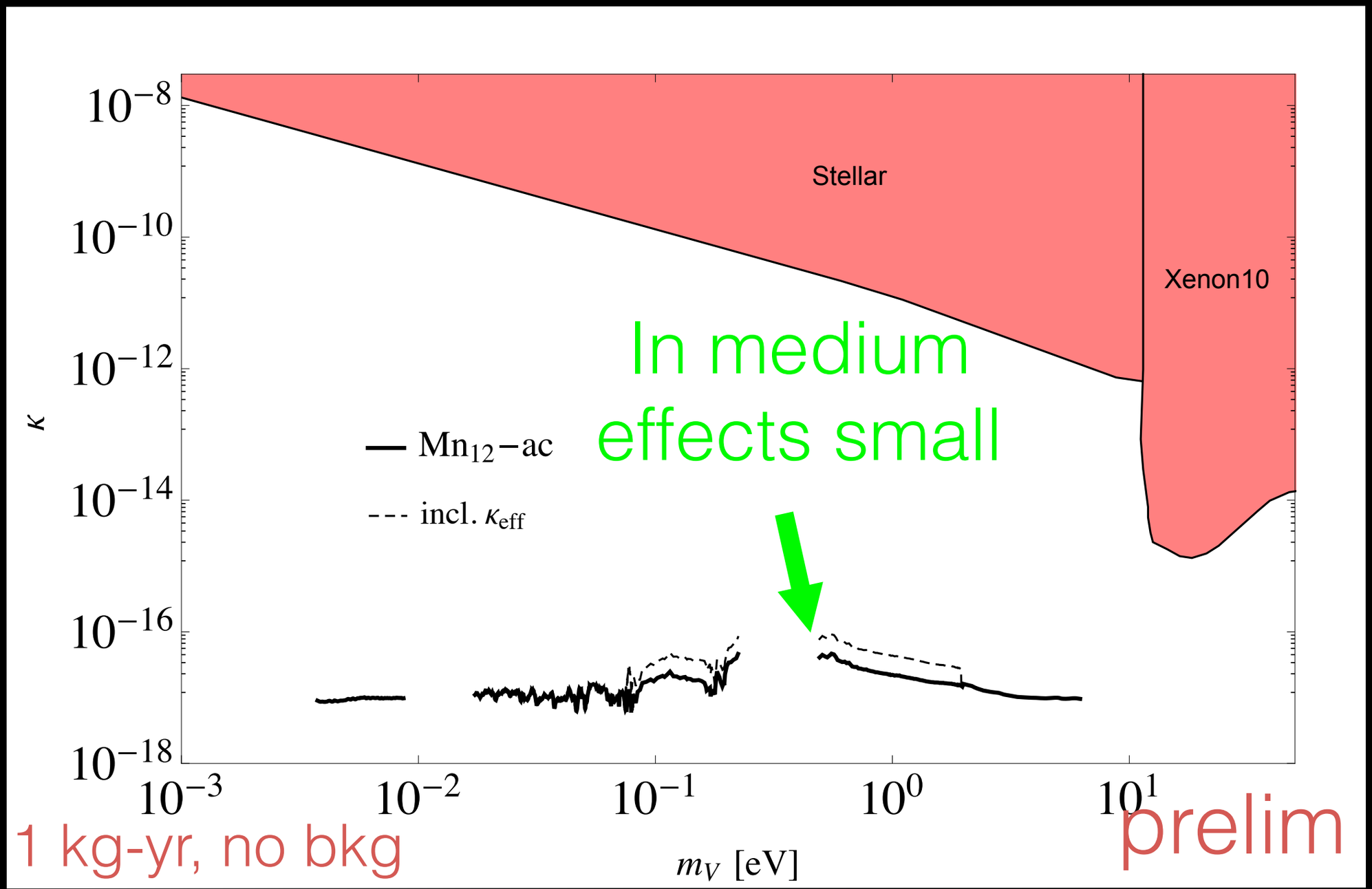


1 kg-yr, no bkg

prelim

Absorption of dark photons

$$\mathcal{L} \supset -\frac{1}{2}\kappa F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_V^2 A'_\mu A'^\mu$$



Localization, disorder

Absorbing in *intra*-molecular excitations

Impurities not an issue.. even *good* (open up more phonon modes, larger x-sec)

Some positive points…

Potential for sensitivity to meV-eV energy deposits

Can imagine a prototype with neutron gun & higher threshold

Chemistry—Physics x-discipline

Built-in amplification and ‘tuning’

General mechanism to trigger (heat) — disorder can be advantageous

Crystals are inexpensive and easy to synthesize

Many similar materials to explore (e.g. spin glasses)


Thanks for listening!