New Experimental Opportunities in Dark Matter Detection

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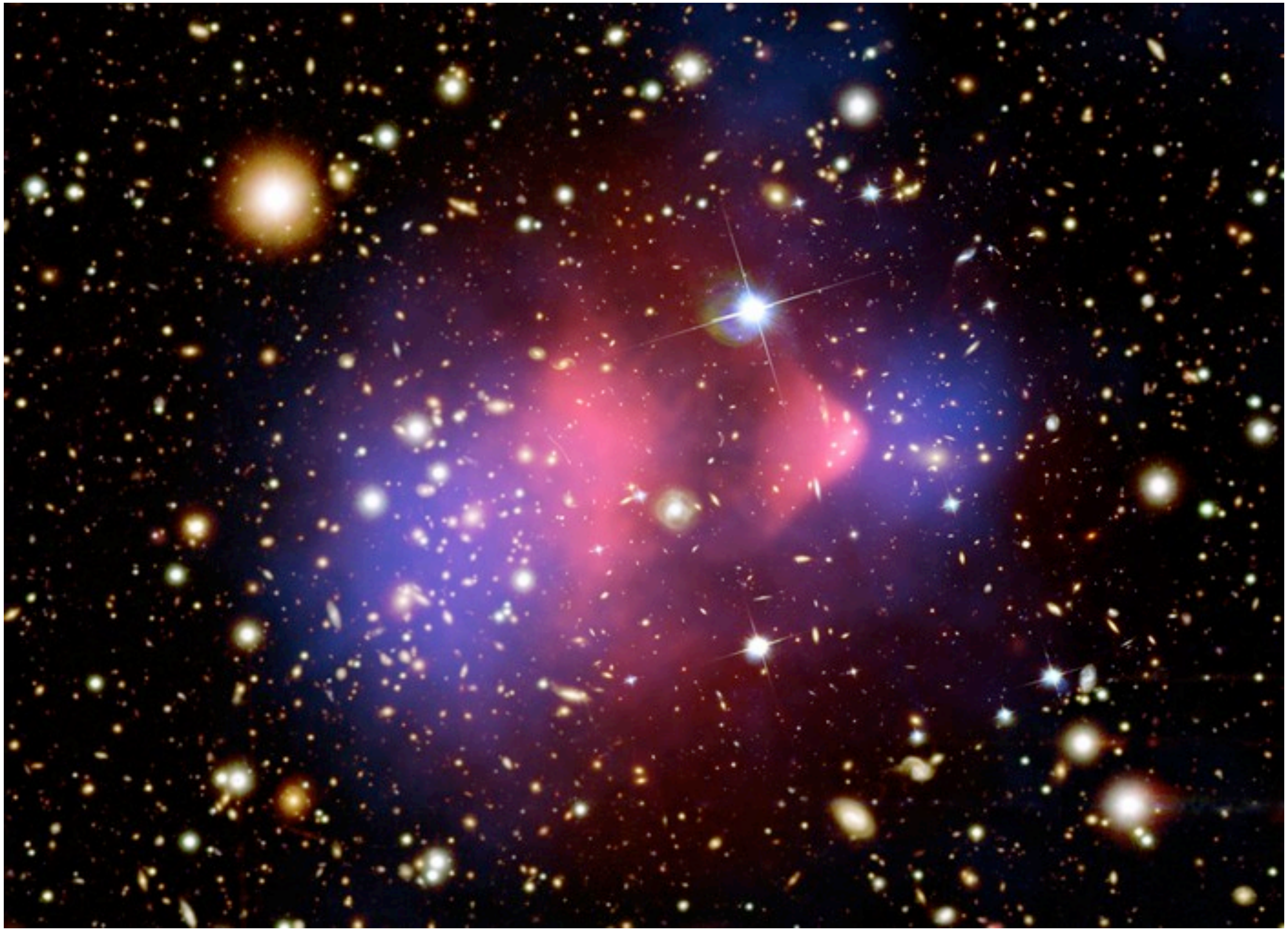
Stanford → Berkeley

Particle Dark Matter



Non-gravitational interactions

Detect these interactions?

Dark Matter Candidates

WIMP

M ~ 100 GeV.

Weak interactions.

e.g. Neutralino.

Ultra-light scalars

Derivative coupling.

Ultra-high energy physics.

e.g. Axions

Light fermions

M ~ keV.

High energy physics.

e.g. Gravitino.

How will we know?

Outline

WIMP

Theory Overview

Experimental Approaches

New Possibilities

Ultra-light scalars

Theory Overview

Experimental Approaches

New Possibilities

Light fermions

Theory and Experiment overlaps with WIMPs.

Will not be separately discussed in this talk.

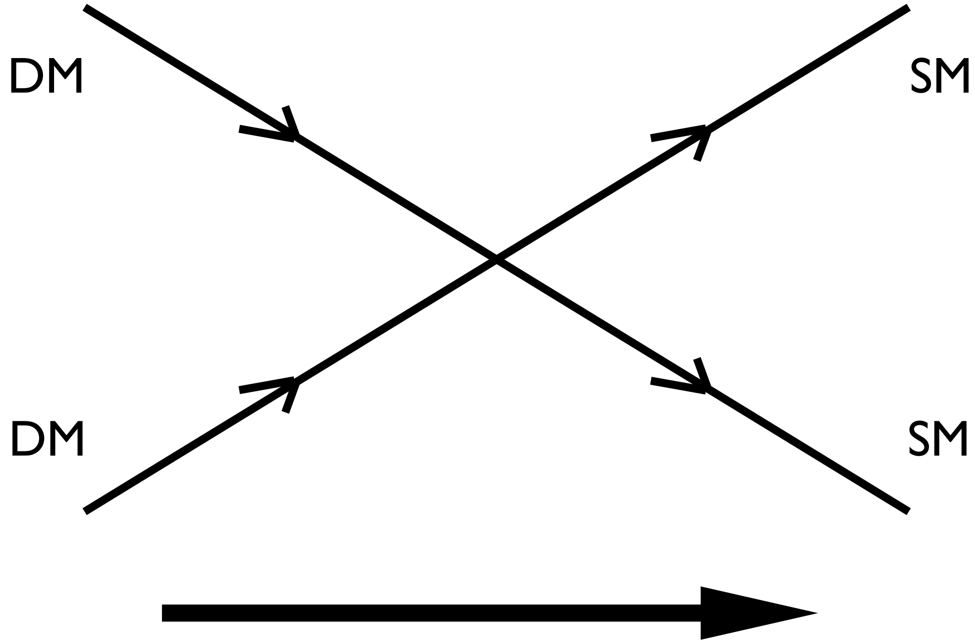
Weakly Interacting Massive Particle
(WIMP)

WIMP: Theory

Stable particles with mass ~ 100 GeV and weak-scale interactions

Easy to get them in BSM scenarios (low energy SUSY) LHC?

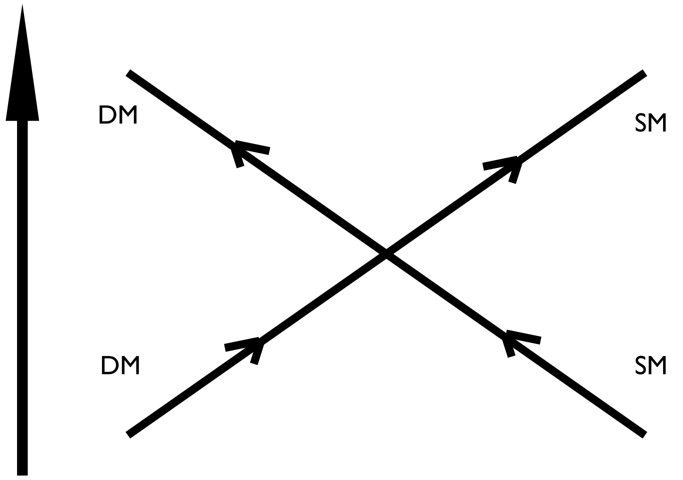
Simple Cosmology: Start in thermal equilibrium, follow physics



Abundance set by freeze out of annihilation

Right dark matter abundance!

WIMP: Experimental Approaches



Direct Detection

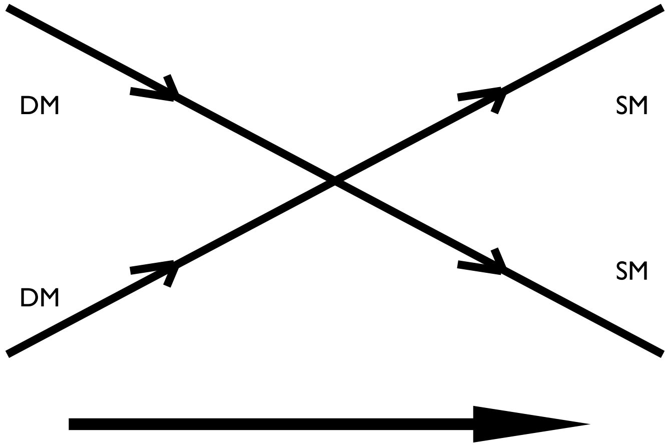
$M_{DM} \sim 100$ GeV, $v \sim 10^{-3}$

Weak cross-section

Reasonable rate to scatter in ultra-low background detectors

Deposit ~ 100 keV

Talks: M. Witherell, M. Pyle



Indirect Detection

Weak-scale annihilation

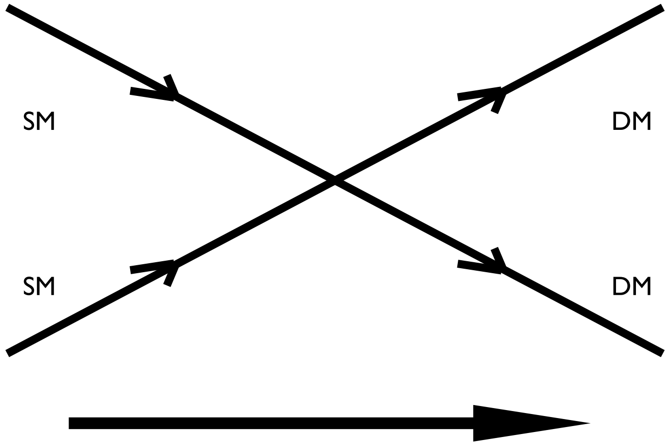
Observable production of high energy cosmic rays

Can also be produced by decay of dark matter

Cosmic ray detectors, effects on CMB

Similar features for light dark matter as well (e.g. X rays)

Talk: S. Klein



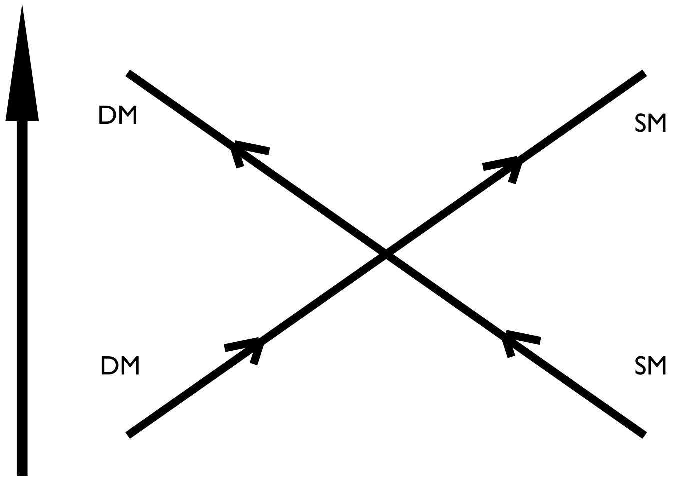
Direct Production

Colliders probe weak cross-sections

Above backgrounds in channels such as mono-jet or mono-photon

Talk: I. Hinchcliffe

WIMP: New Directions

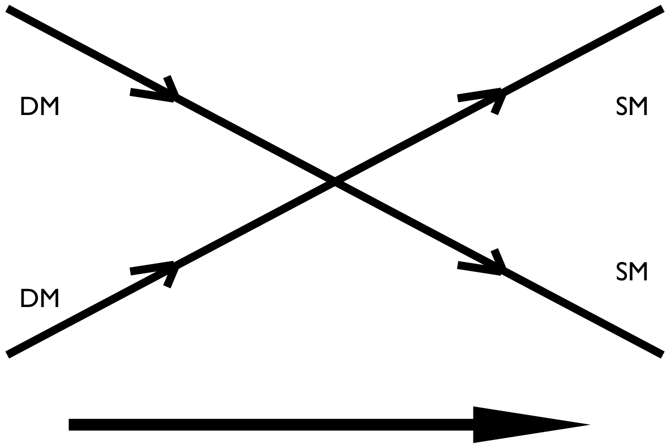


Direct Detection

Elastic scattering of heavy dark matter

Inelastic collisions

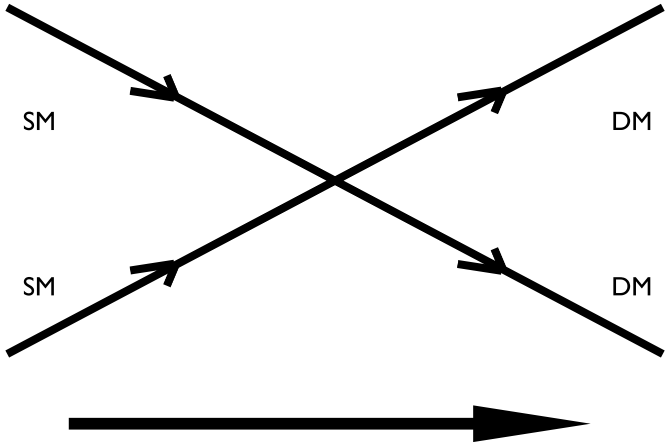
Light dark matter with semi-conductors



Indirect Detection

Galactic center, dwarf spheroids, multiple clusters

Focus on Bullet Cluster, Abell 520



Direct Production

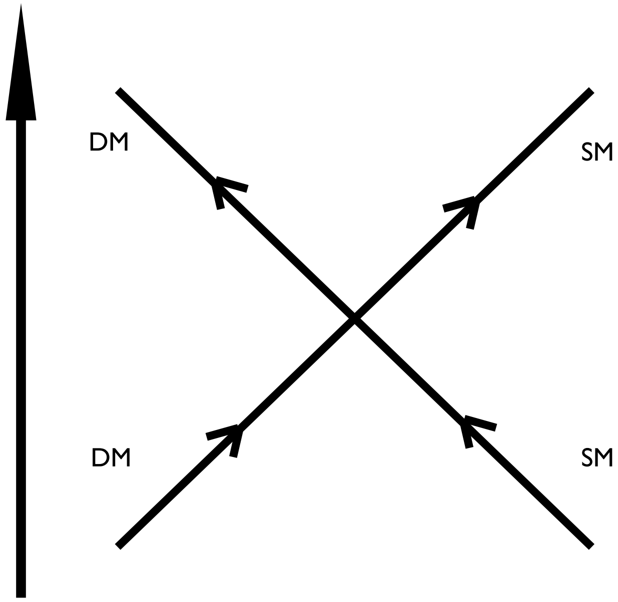
Focussed on LHC.

High luminosity may help for light but very weakly coupled particles (beam dumps)

Will not be discussed in this talk

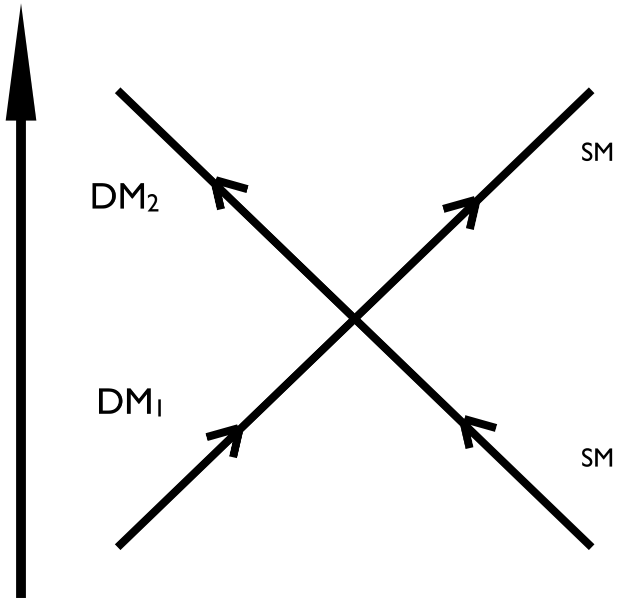
Inelastic WIMPs

Elastic Scattering



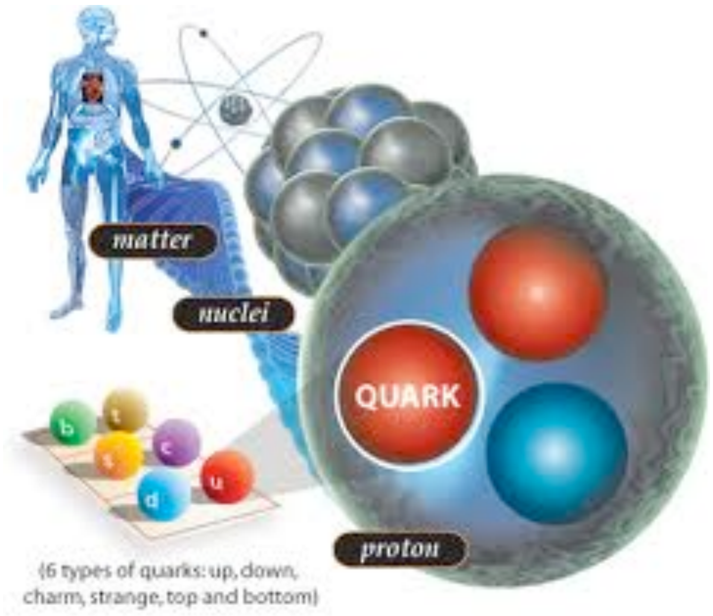
Energy deposited in collision set by kinetic energy

Inelastic Scattering



Collisions may involve transitions within dark sector (like atoms)

Energy deposited depends upon kinetic energy and transition splittings.



Inelastic Dark Matter

Why?

Why Not?

The SM, which is 5% of the universe, exhibits a lot of complexity

Dark matter may be similarly complex

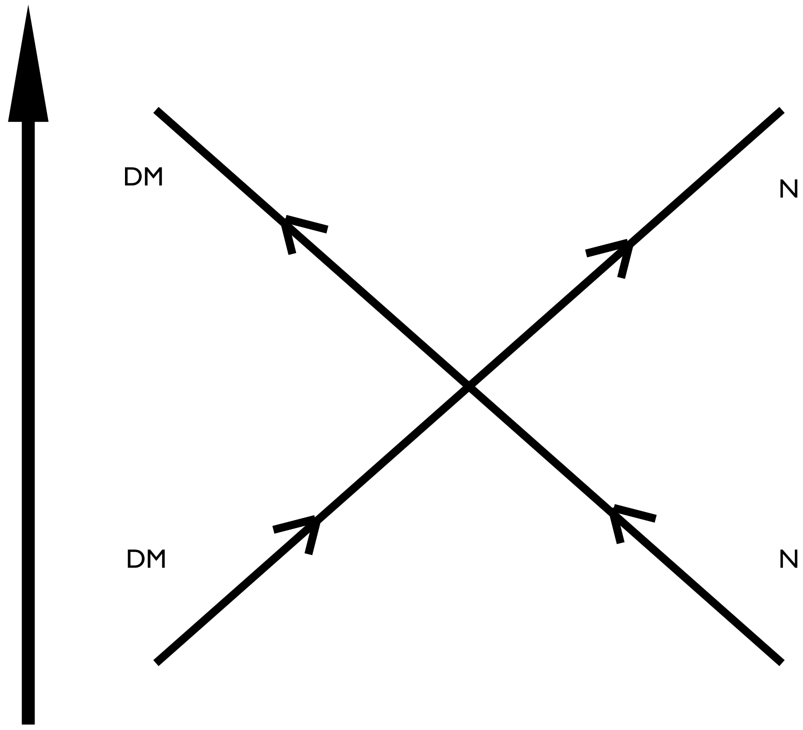
Very weak bounds on forces within the dark sector

Does this matter?

Yes - changes signals in detectors

Potential blind spots in searches

Nuclear Recoil Spectrum



Elastic Scattering

$$E_R \sim \frac{\mu^2}{m_N} v^2$$

$$\sim m_N v^2 \, (m_{DM} \gg m_N)$$

Less energy in lighter nuclei

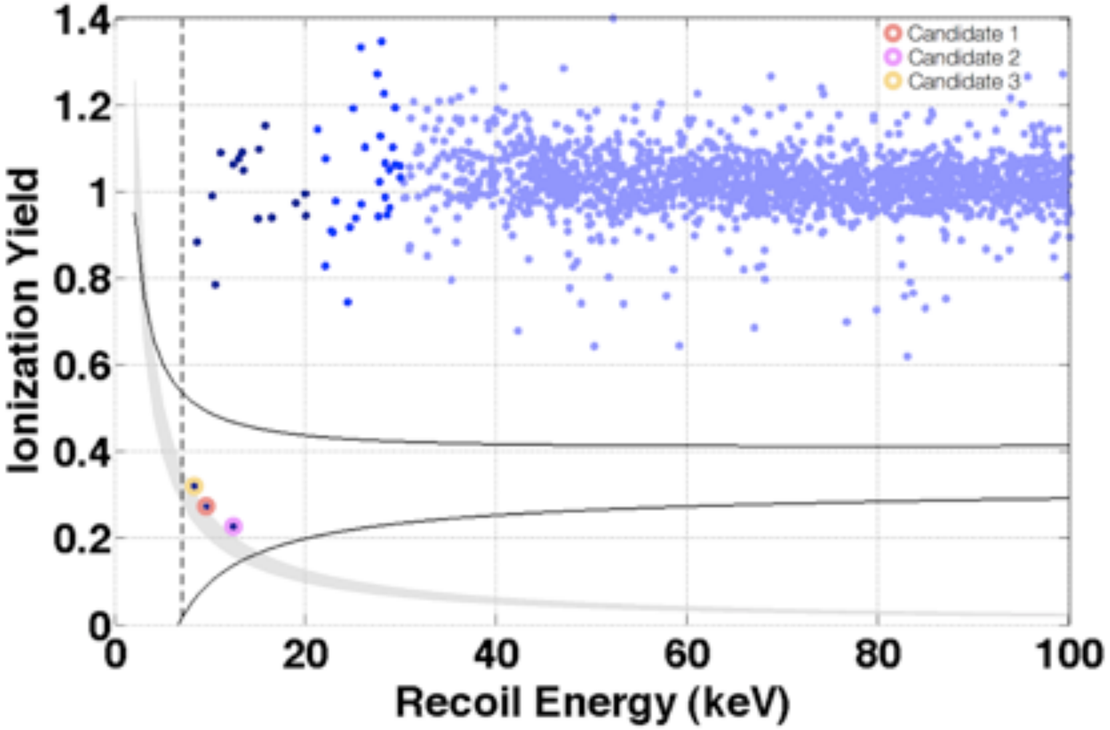
$$\sim \frac{m_{DM}^2}{m_N} v^2 \, (m_{DM} \ll m_N)$$

Less energy in heavier nuclei

Maxwell-Boltzmann velocity profile for dark matter

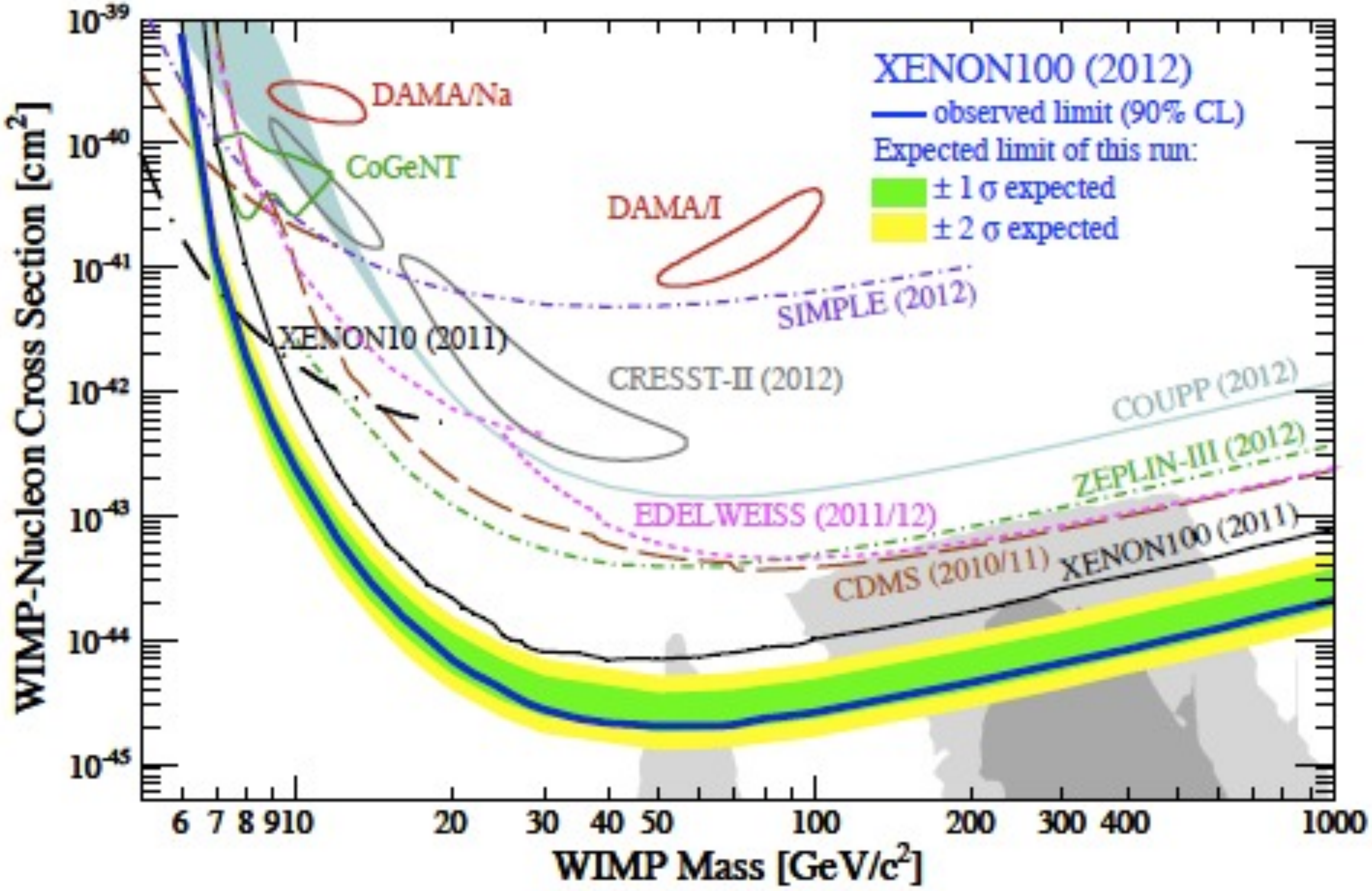
Spectrum rises exponentially at low velocities

Events analyzed between range of energies



Assumptions used to predict rate in different experiments

Dark Wars

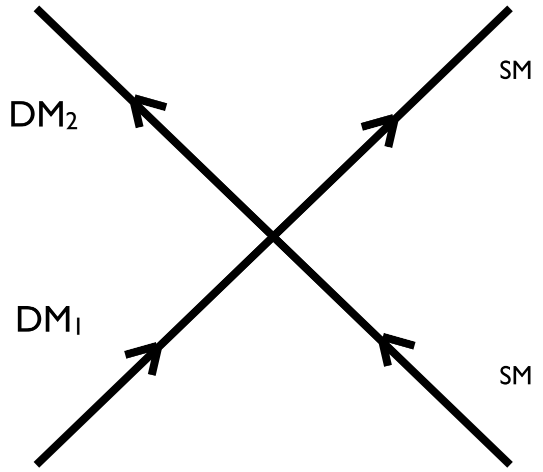


Expectations can change if the dark matter model is different

Inelastic Phenomenology

Endothermic

(hep-ph/0101138)



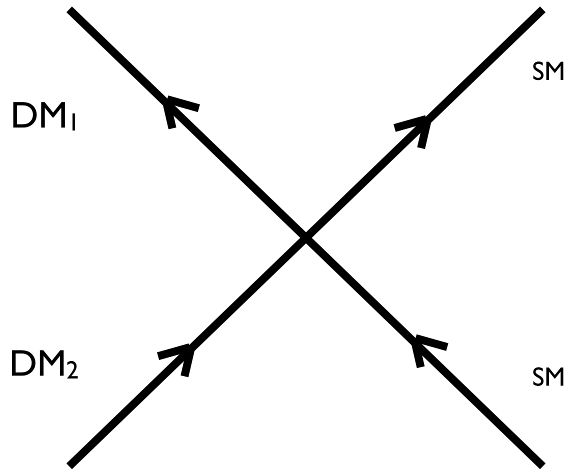
Upscattering

Larger CM energy
off heavy nuclei

Suppressed rate in
light nuclei

Exothermic

(1004.0937)



Downscattering

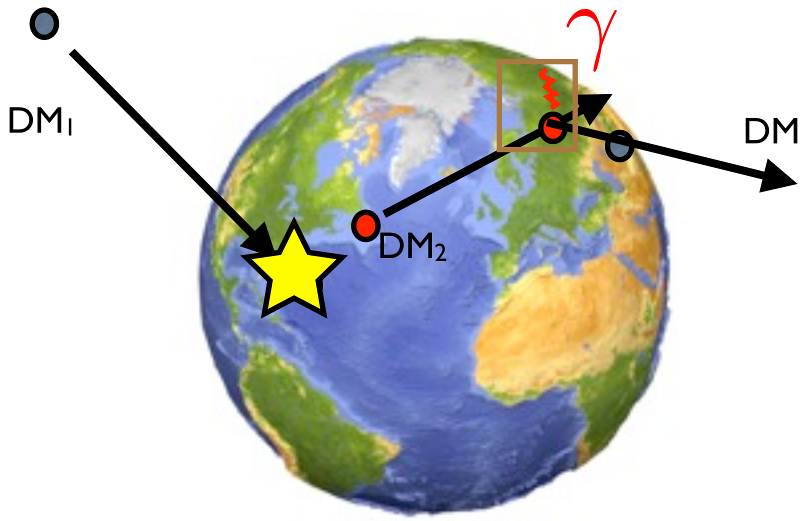
Deposits more energy
in lighter nuclei

Energy deposited in heavy targets
could be below detector thresholds

Split > 100 keV possible
Not analyzed by many experiments
(above analysis thresholds)

Luminous

(1008.1988)



Electromagnetic Energy
No nuclear recoil

Many experiments only
look for nuclear recoils

Electromagnetic events
vetoed

(except DAMA, COGeNT)

Not hard to realize theoretically (look at SM)

Wish List

Would be a shame to miss discovery because of theory prejudice

1. Enlarge analysis window to include higher energy events (> 100 keV)

2. Electron recoils/electromagnetic events
   Detectors have lots of events
   Mostly background
   Check for annual modulation

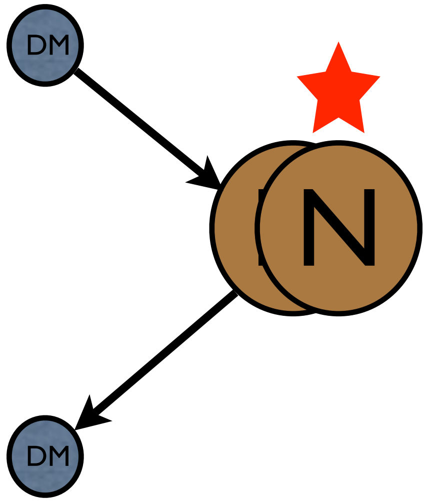
3. Lower thresholds

Light Dark Matter
with Semiconductors

(1108.5383, 1203.2531)

Light Dark Matter Challenge

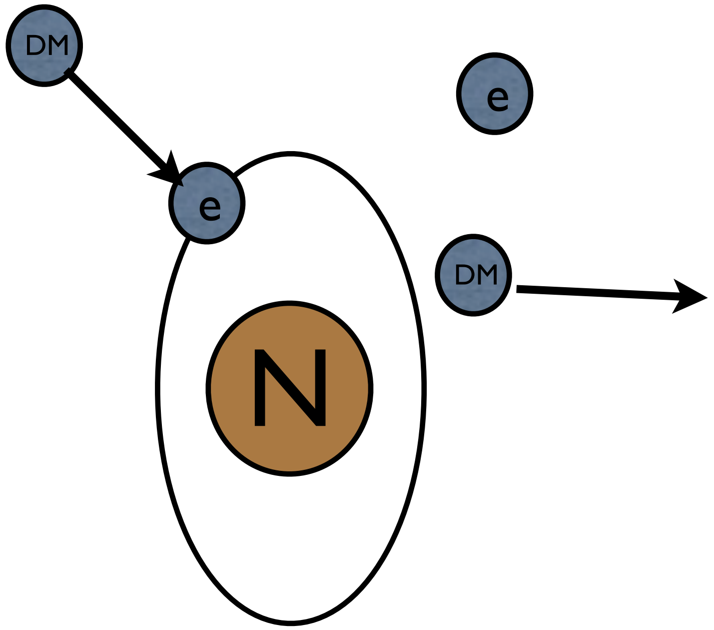
$$(m_{DM} \lessapprox 1\,\mathrm{GeV})$$



Nuclear Recoil: $E_R \sim \frac{m_{DM}^2}{m_N} v^2 \ll 1\,\mathrm{keV}$

Not much visible energy

Kick electrons?



Must ionize

For noble gases ~ 10 eV energy lost
by dark matter

$$\Longrightarrow \Delta P_{DM} \sim \frac{10\,\mathrm{eV}}{v} \sim 10\,\mathrm{keV}$$

Where does this momentum go?

Kinematic Bottleneck

$$\Delta P_{DM} \sim \frac{10\,\mathrm{eV}}{v} \sim 10\,\mathrm{keV}$$

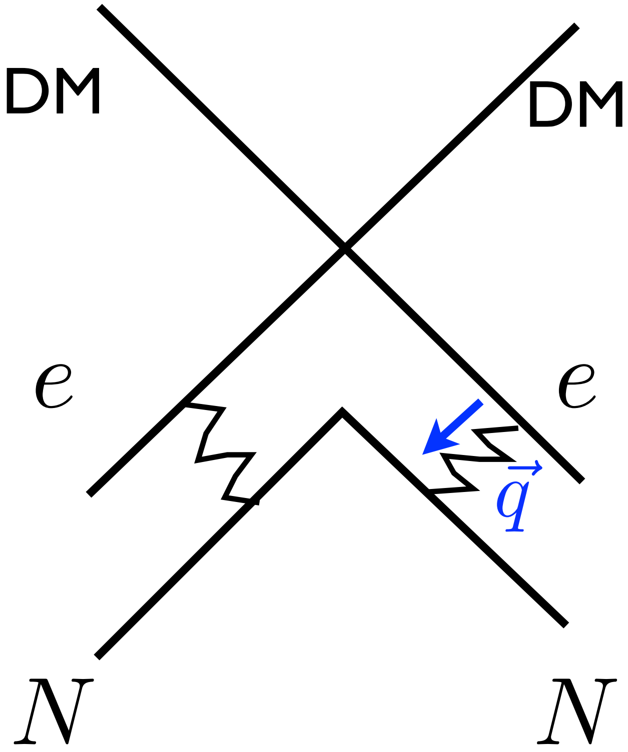
Can the electron carry it?

$$P_e \sim 10\,\mathrm{keV} \implies E_e \sim 90\ \mathrm{eV}$$

Larger than energy lost by dark matter

DM kicks electron, electron coupled to nucleus

Nucleus carries excess momentum (~ 10 keV)
Electron carries energy



Momentum transfer q limited by form factor

$$\propto \left(\frac{1}{q r_B}\right)^8 \approx \left(\frac{\mathrm{few\ keV}}{10\ \mathrm{keV}}\right)^8$$ (atoms i.e. noble gases)

Quite form factor suppressed

Semiconductor Advantage

Lower ionization energy (~ 1 eV)
Same Bohr radius (~ (few keV)$^{-1}$)

Energy lost by DM ~ 1 eV
Momentum (q) ~ 1 keV

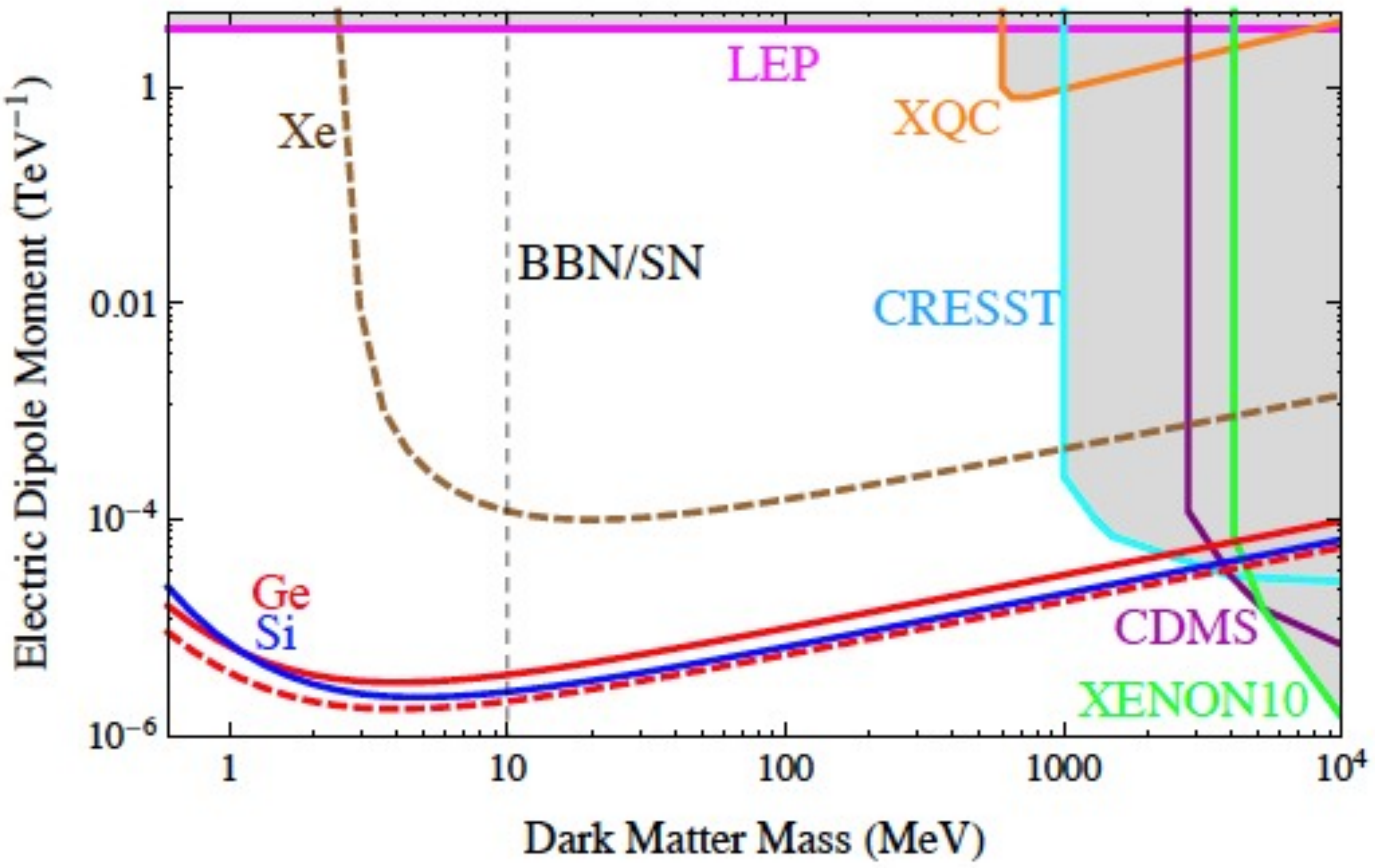
No form factor suppression!

Big advantage over noble gas detectors

Single ionization events detectable by CDMSLite

Background rejection (compton) also seems possible

Projected CDMSLite Sensitivity



Dark Matter scattering off electrons in semiconductors seems promising way for light dark matter

Indirect Detection

(in progress)

Cosmic Rays from Dark Matter

Dark Matter annihilations/decays yield flux of cosmic rays ($e^{\pm}$, photons, neutrinos)

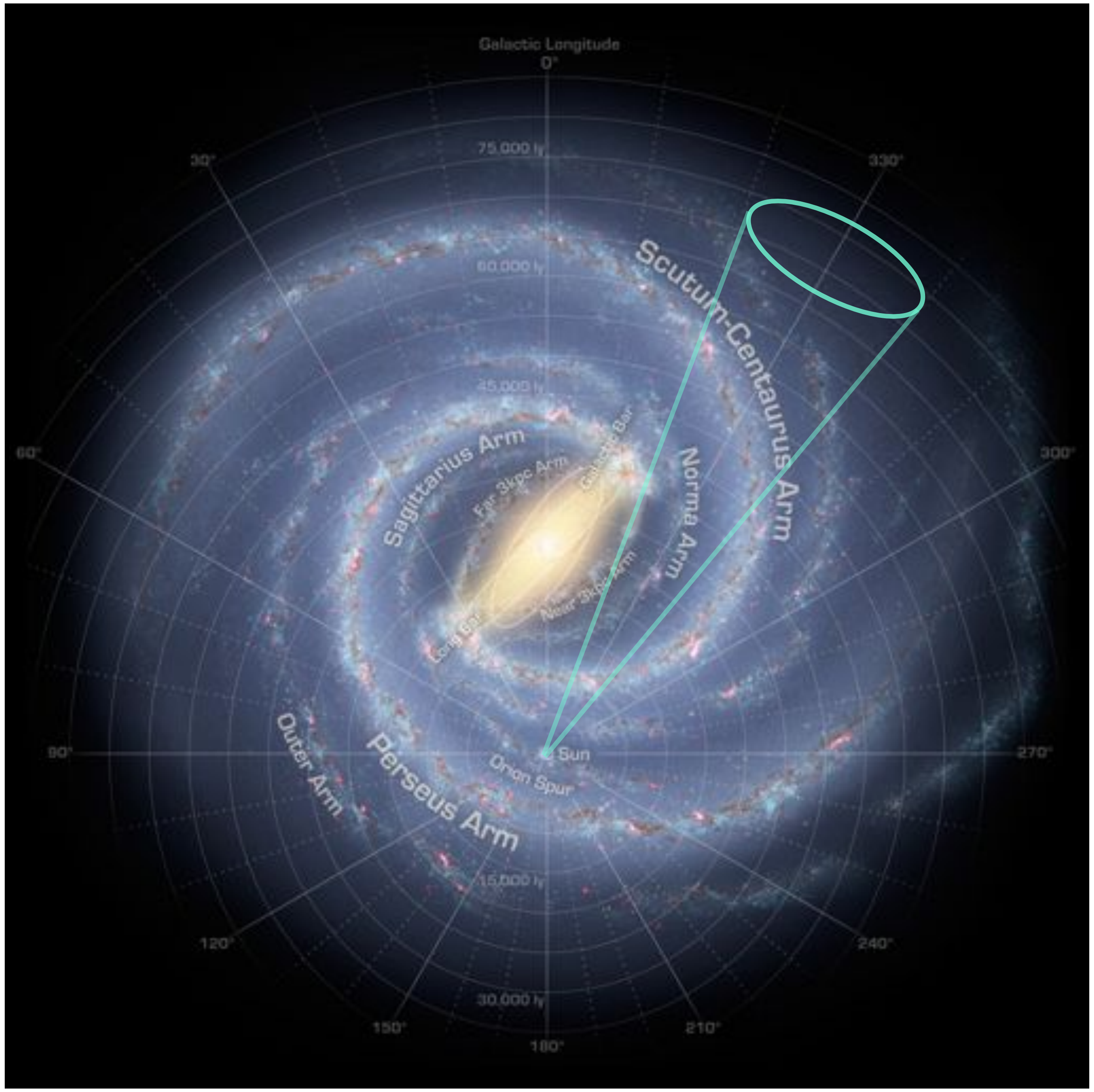
$$\int^{10\ \mathrm{kpc}} \frac{d^3r}{r^2} n_{\mathrm{DM}}^2 \langle \sigma v \rangle \sim (10\ \mathrm{kpc}) \left(\frac{0.3}{\mathrm{cm}^3} \frac{\mathrm{GeV}}{m_{\mathrm{DM}}} \right)^2 \left(3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}} \right)$$

$$\approx 10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1} \left(\frac{10\ \mathrm{GeV}}{m_{\mathrm{DM}}} \right)^2$$

Such a flux could be observable.

E.g. in a satellite or balloon experiment :

$$\sim (1\ \mathrm{m}^2)(1\ \mathrm{yr})(1\ \mathrm{sr}) \approx 3 \times 10^{11}\ \mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr}$$



X-rays, positrons/photons @ GeV, neutrinos >= TeV

(axion/sterile neutrino decays) (WIMP annihilation/decay)

Anomalies Everywhere

Chandra/XMM Newton

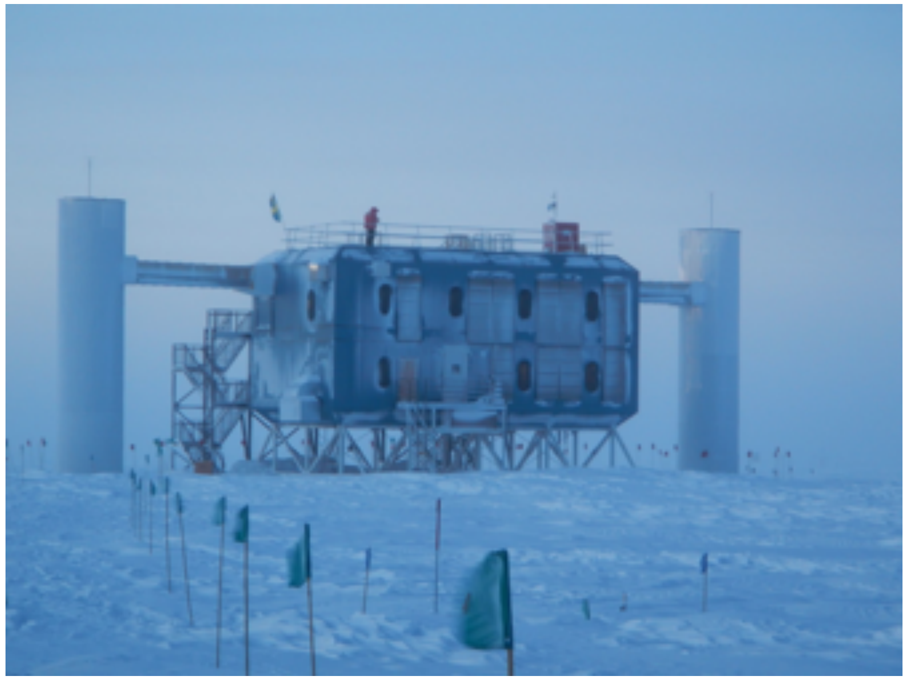
(3.55 keV line?)

PAMELA

(positron excess?)

Fermi (GLAST)

(lepton excess? 130 GeV line?)



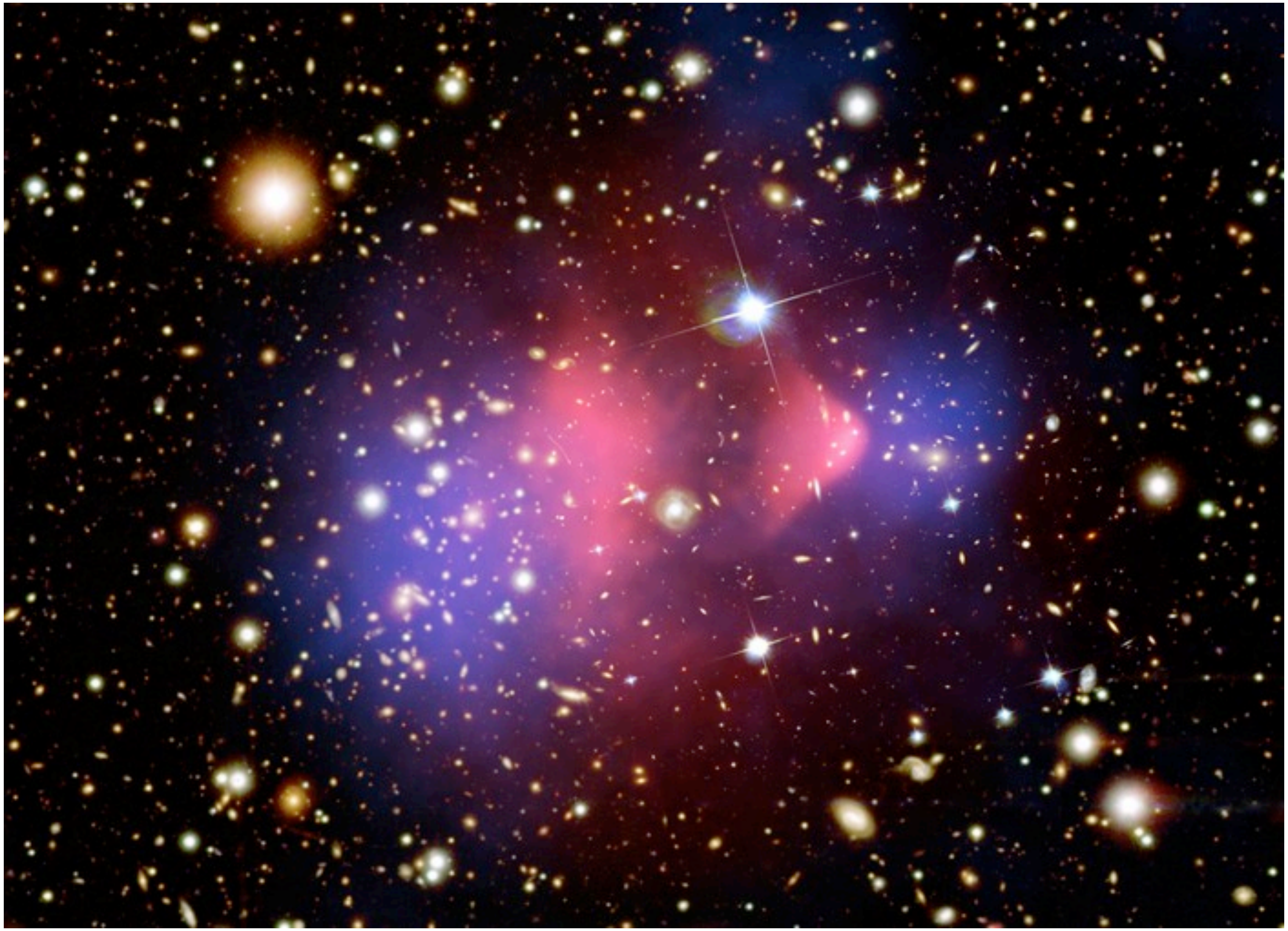
IceCube

(flux above 100 TeV?)

Astro vs Dark Matter?

Lines could be conclusive. But reasonable to get broad excesses.

Bullet Cluster: A Natural Vacuum Cleaner



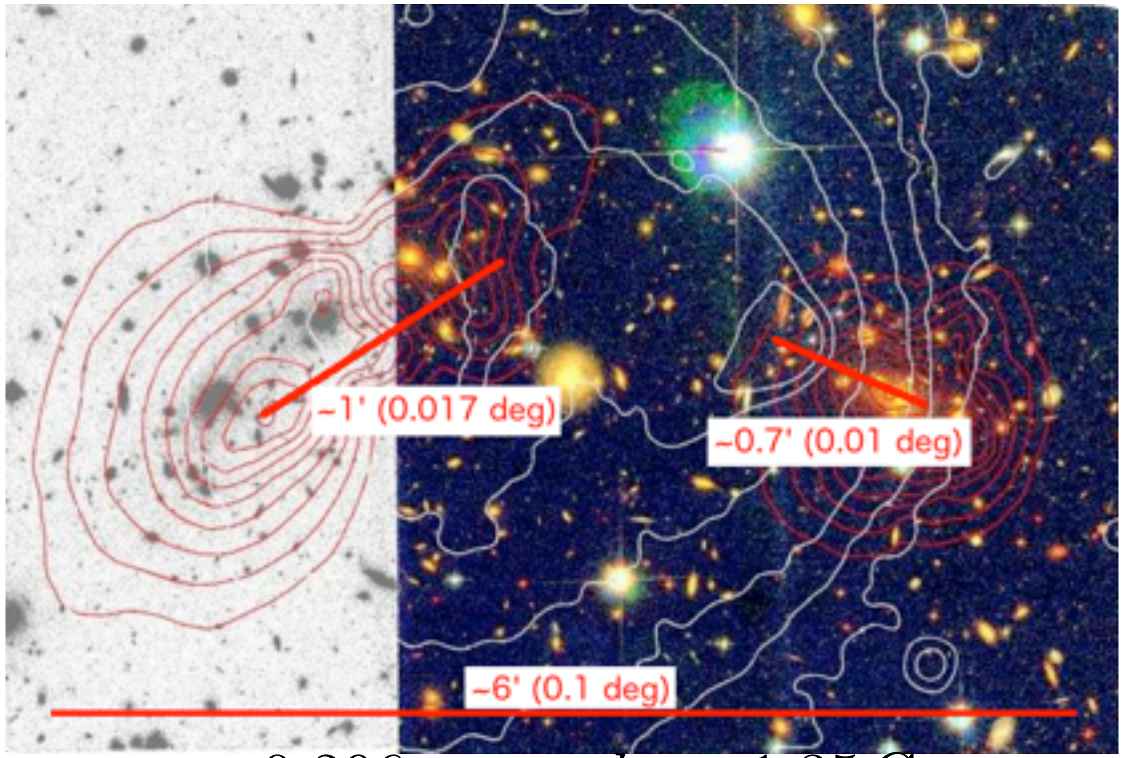
Clear separation of dark matter signal from gas backgrounds

Conclusive: Signal in dark matter region + nothing in gas

Separated Clusters

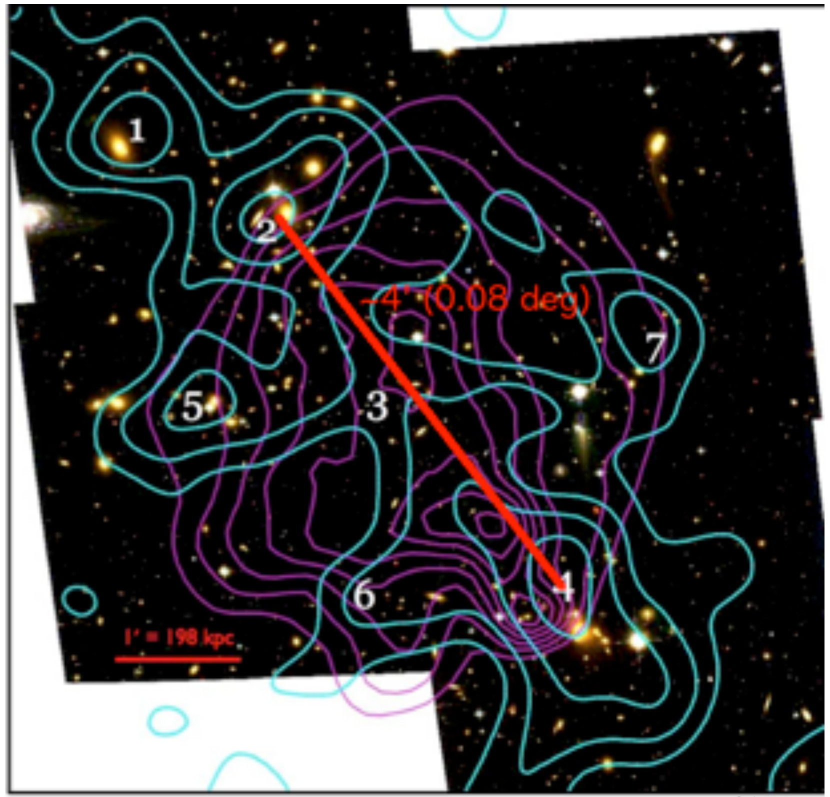
- Collision of galaxy clusters separates X-ray plasma (collisional) from stars and DM (non-collisional)
- Best known examples: Bullet Cluster (well understood), Abell 520 (highly separated but less well understood)

Bradac et al, Astrophys.J. 652 (2006)



$z = 0.296 \iff d_L = 1.35\,\mathrm{Gpc}$

Clowe et al, Astrophys.J. 758 (2012)



$z = 0.199 \iff d_L = 0.89\,\mathrm{Gpc}$

Substructures have $M_{\mathrm{DM}} \sim \mathrm{few} \times 10^{13} M_\odot$

$$\begin{aligned} M_{\mathrm{DM}}/M_{\mathrm{gas}} &\sim 5 \text{ (overall)} \\ &\sim 4 \text{ (Bullet gas blob)} \\ &\sim 23 \text{ (Bullet DM blob)} \end{aligned}$$

$$\begin{aligned} M_{\mathrm{DM}}/M_{\mathrm{gas}} &\sim 5 \text{ (overall)} \\ &\sim 8-9 \text{ (substr. 2,4)} \\ &\sim 2 \text{ (substr. 3)} \end{aligned}$$

Angular separations ~ 0.01 degrees

X-Rays

Instrumental Capabilities

- XMM-Newton (Chandra similar with less effective area)
  - angular resolution: 5"
  - effective area: ~400 cm^2 @ 5 keV
  - energy range: 0.15—15 keV
  - energy resolution: ~70 eV

Signal

$$\approx \frac{\frac{10^{14}\,M_\odot}{\mathrm{keV}}\,\frac{10^{-28}}{\mathrm{s}}}{4\pi\,(\mathrm{Gpc})^2}$$

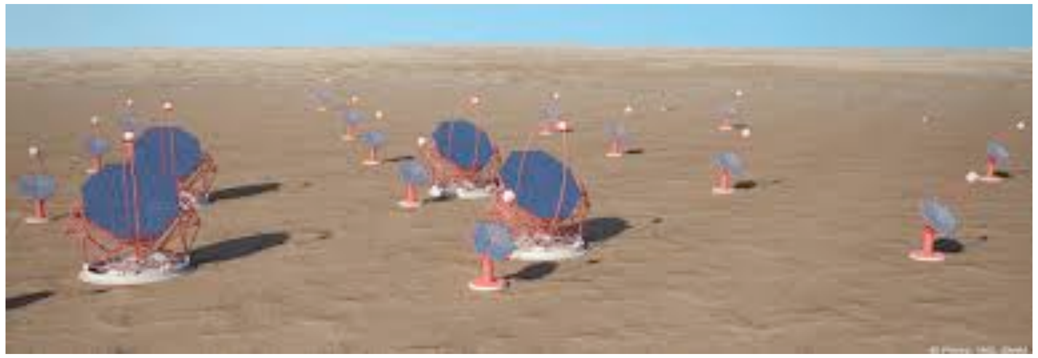
$$\approx \frac{10^{-7}}{\mathrm{cm}^2\,\mathrm{s}}$$

Angular resolution better than needed

Signal observable in ~ 7 hours

Comparable to background for line searches, may do better for broad excess

Gamma Rays



CTA

Signal

Instrumental Capabilities

- angular resolution: 0.03 degrees
- effective area: ~km^2 @ TeV
- energy range: 10 GeV —100 TeV

$$\approx \frac{\frac{10^{14} M_\odot}{\mathrm{TeV}} \frac{10^{-26}}{\mathrm{s}}}{4\pi\,(\mathrm{Gpc})^2}$$

$$\approx \frac{10^{-14}}{\mathrm{cm}^2\,\mathrm{s}}$$

Signal observable in ~ 50 hours

Average angular resolution may be enough for Abell 520, slightly better resolution necessary for bullet cluster.

Promising direction for proposed gamma ray instruments

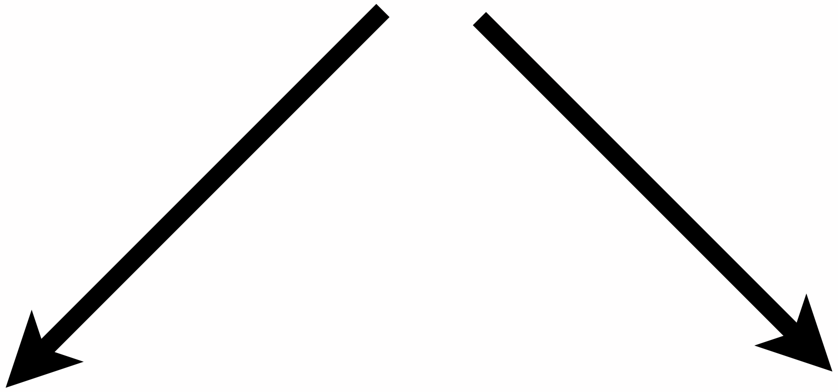
Axion Dark Matter

(1306.6088, 1306.6089)

Axions

Global symmetry broken at high scale f_a

Light Goldstone boson



Gauge Fields

$$\frac{a}{f_a} F \wedge F, \;\; \frac{a}{f_a} G \wedge G$$

Fermions

$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

string theory or extra dimensions naturally have axions from non-trivial topology

eg: reduction of higher dimensional gauge forms

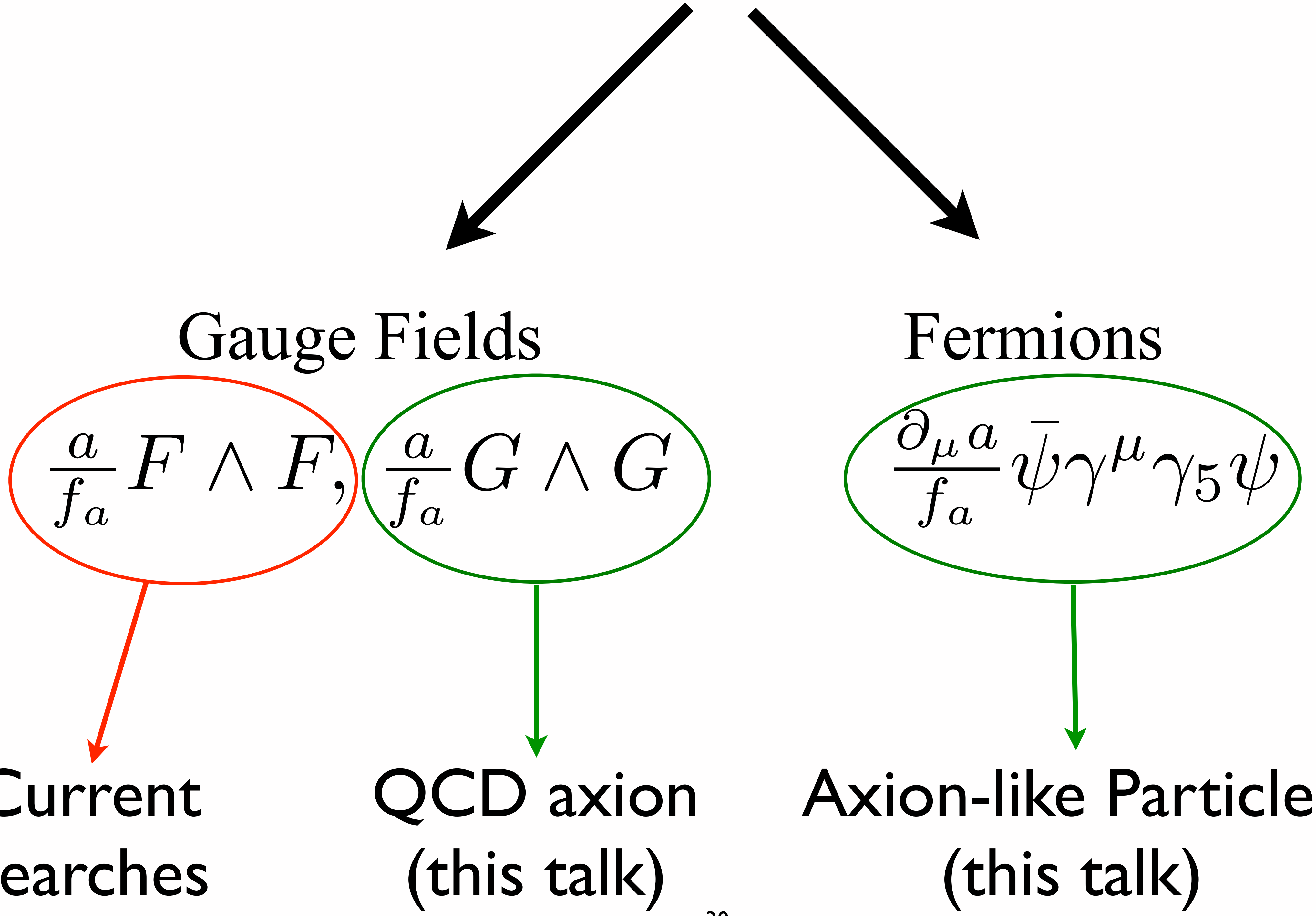
Svrcek & Witten (2006)

naturally expect large $f_a \sim$ GUT (10^{16} GeV), string, or Planck (10^{19} GeV) scales

Axions

Global symmetry broken at high scale *f_a*

Light Goldstone boson



Gauge Fields

$\frac{a}{f_a} F \wedge F,$

$\frac{a}{f_a} G \wedge G$

Fermions

$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$

Current Searches

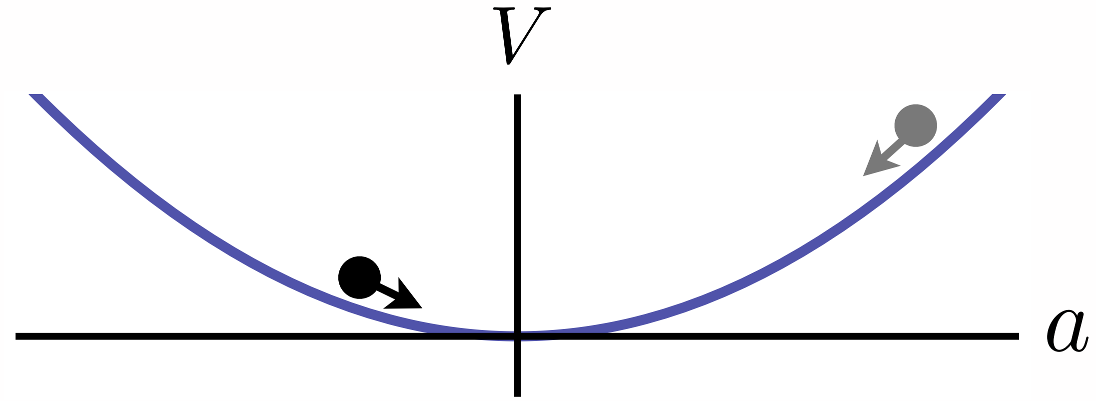
QCD axion (this talk)

Axion-like Particles (this talk)

Axion Dark Matter

Misalignment production:

Field has some initial value in the early universe,
oscillations carry energy density, natural dark matter.
For QCD axion mass turns on at $T \sim \Lambda_{QCD}$



$$a(t) \sim a_0 \cos(m_a t)$$

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

Axion easily produces correct abundance $\rho = \rho_{\rm DM}$

Many experiments search for WIMPs, only one (ADMX) can search for axion DM

Currently challenging to discover axions in much of parameter space

Important to find new ways to detect axions

Searching for Axion Dark Matter

heavy particle vs. light scalar field

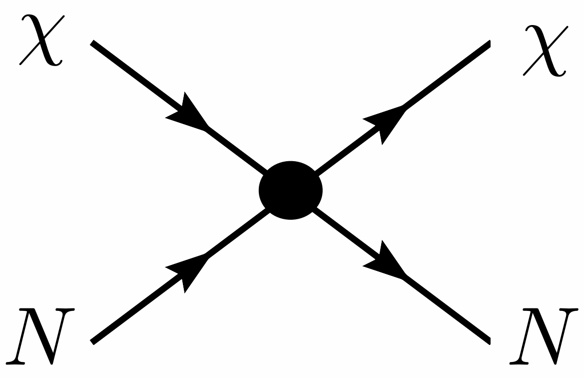
(WIMPs) (axions)

Search for single particle scattering

Large phase-space density

Described as classical field *a(t,x)*

Search for coherent effects of the entire field, not single hard-particle scatterings



Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, constraints most relevant for QCD axion, weak constraint on ALPs

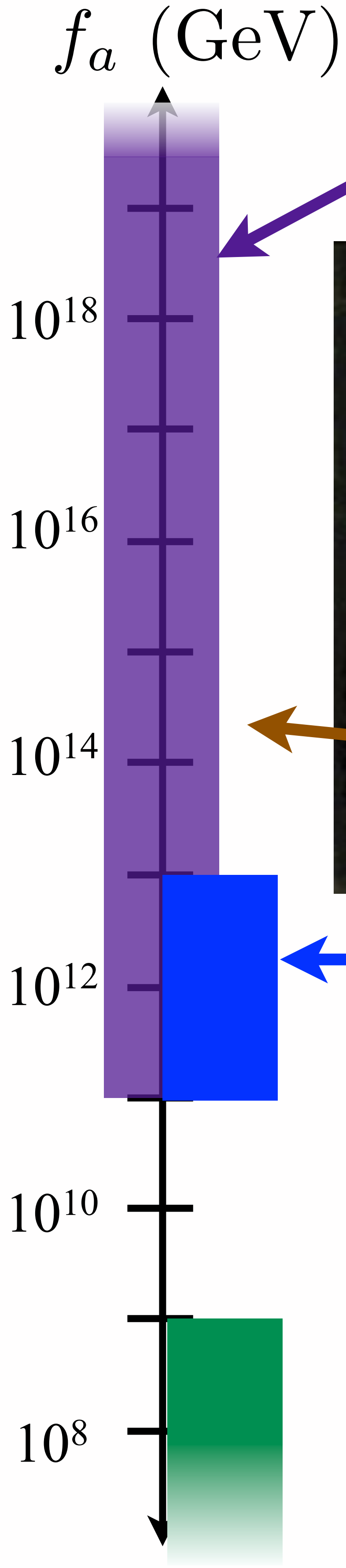
but this requires knowing physics all the way up to GUT scale $\sim 10^{16}\ \mathrm{GeV}$

constrains **one** cosmological history, **many** others possible
(including for QCD axion)

e.g. thermal monopole density, Fischler & Preskill (1983)
high temperature mass,
and many others e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

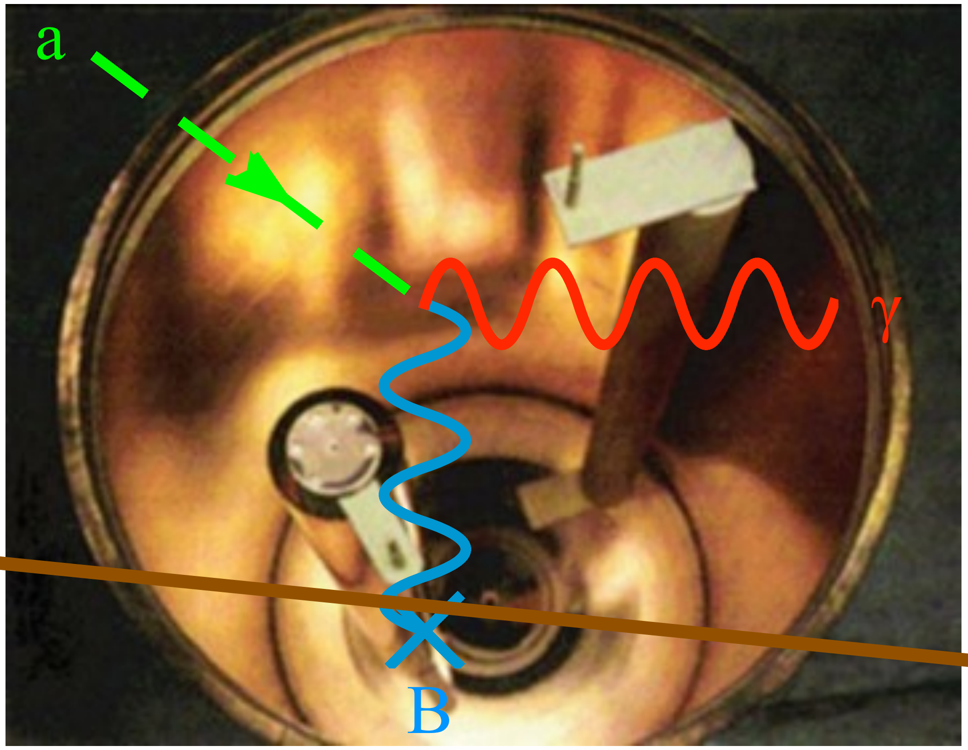
QCD axion offers unique probe of high energy cosmology,
an era difficult even for gravitational wave detectors

Constraints and Searches



Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$



axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

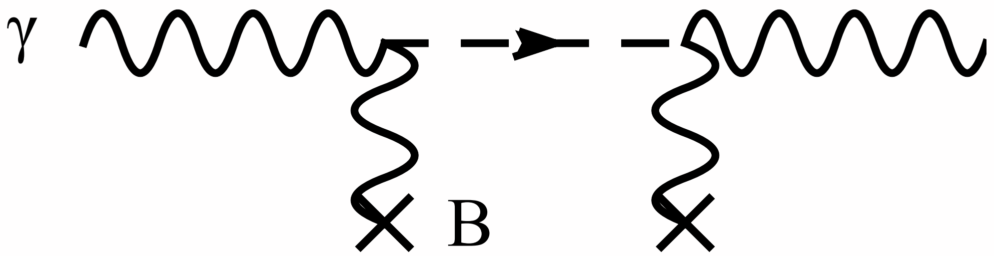
size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

S. Thomas

microwave cavity (ADMX)

laser experiments:



$\propto \frac{1}{f_a^4}$

axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

Other ways to search for light (high f_a) axions?

New Operators For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta \, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \theta \, e \, \mathrm{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \frac{a}{f_a} \, e \, \mathrm{cm}$

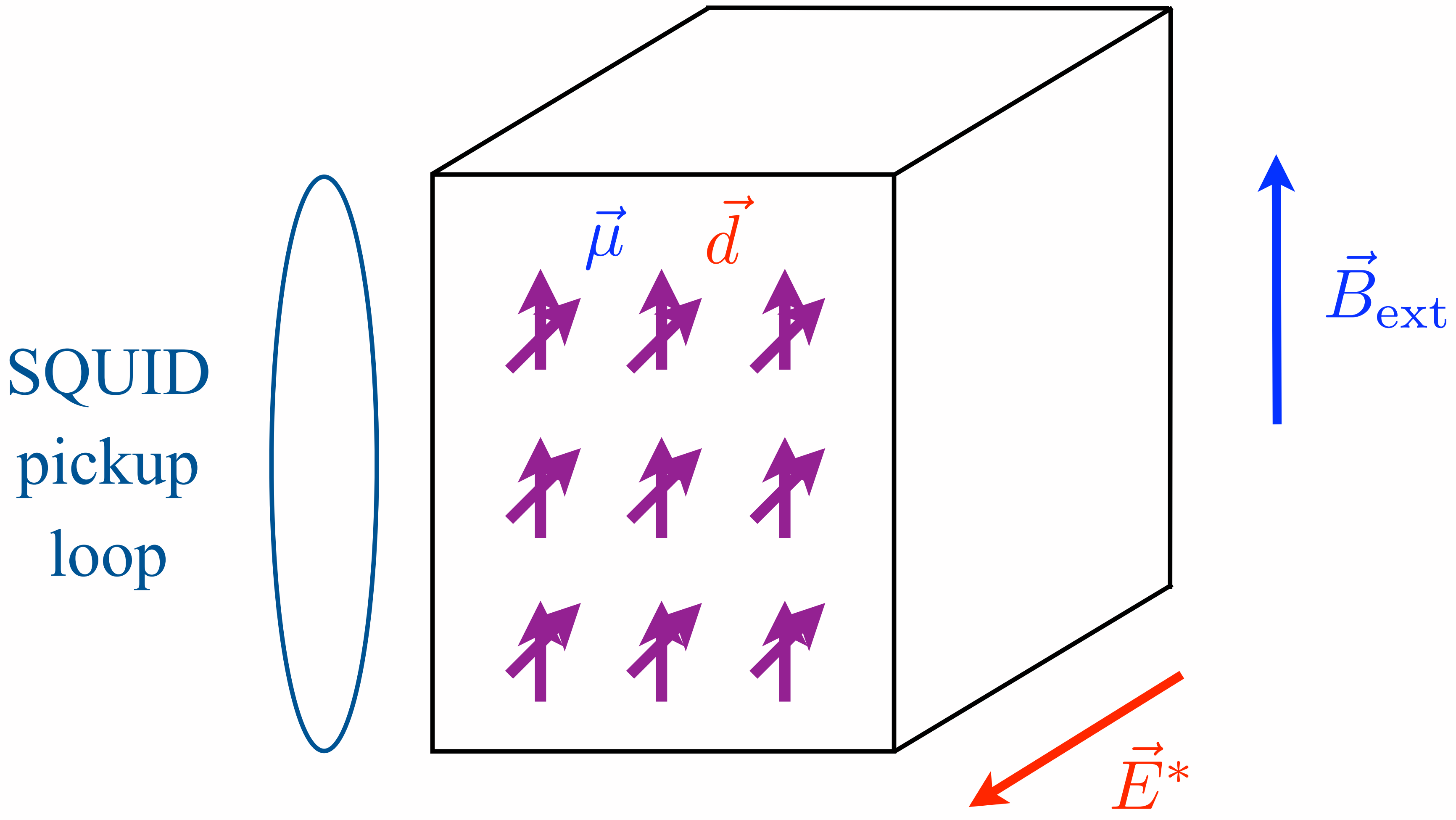
$a(t) \sim a_0 \cos\left(m_a t\right)$ with $m_a \sim \frac{(200 \text{ MeV})^2}{f_a} \sim \mathrm{MHz} \left(\frac{10^{16} \text{ GeV}}{f_a} \right)$

axion dark matter $\rho_{\mathrm{DM}} \sim m_a^2 a^2 \sim (200 \mathrm{MeV})^4 \left(\frac{a}{f_a} \right)^2 \sim 0.3 \, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

so today: $\left(\frac{a}{f_a} \right) \sim 3 \times 10^{-19}$ independent of f_a

axion gives all nucleons an oscillating EDM (kHz-GHz) independent of f_a,
a non-derivative operator

NMR Technique



high nuclear spin orientation achieved in several systems, persists for $T_1 \sim$ hours

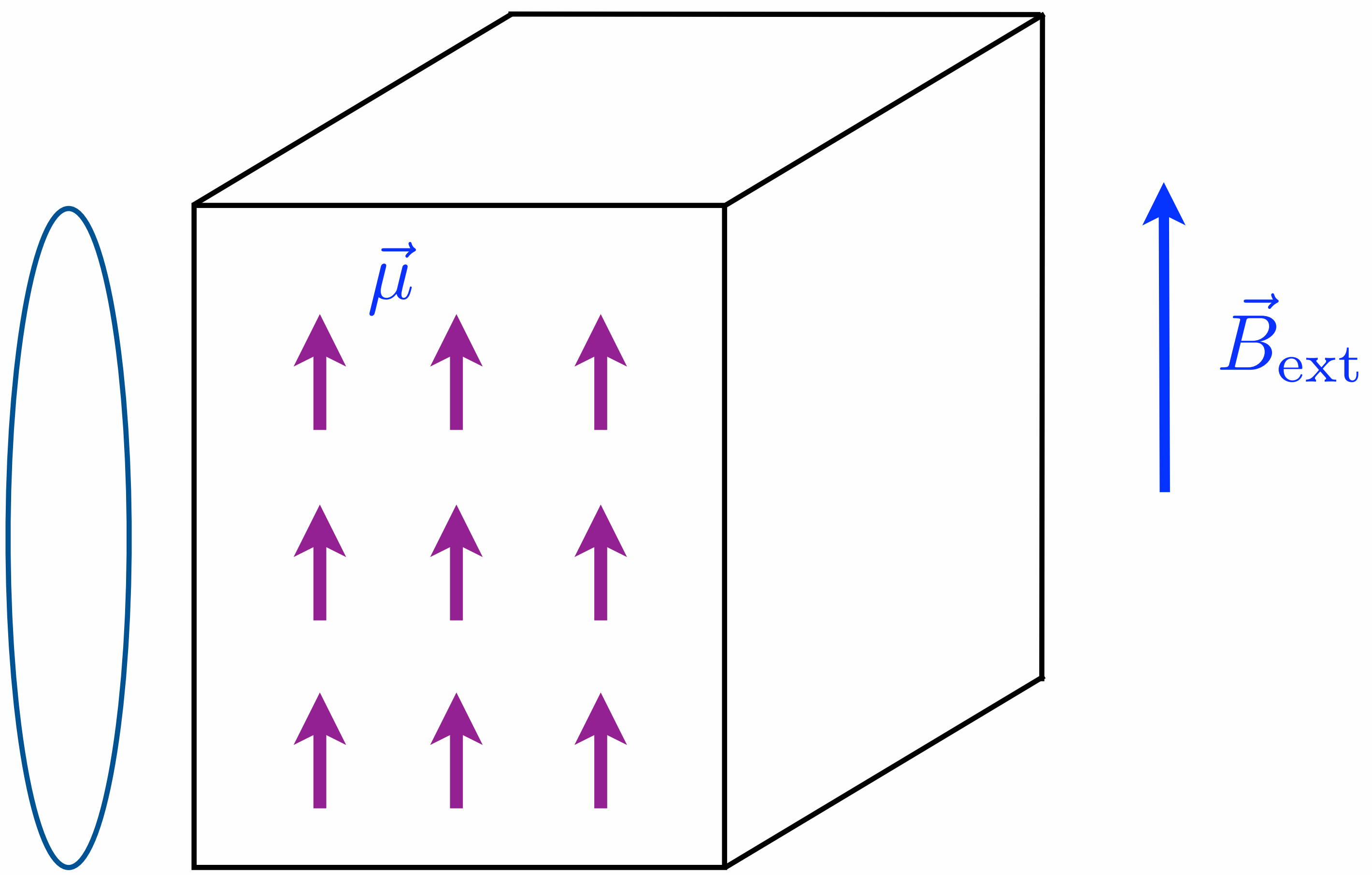
applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

Larmor frequency = axion mass $\Longrightarrow$ resonant enhancement

resonance ➜ scan over axion masses by changing B_{ext}

Magnetization Noise



a material sample has magnetization noise

noise arises from quantum spin projection

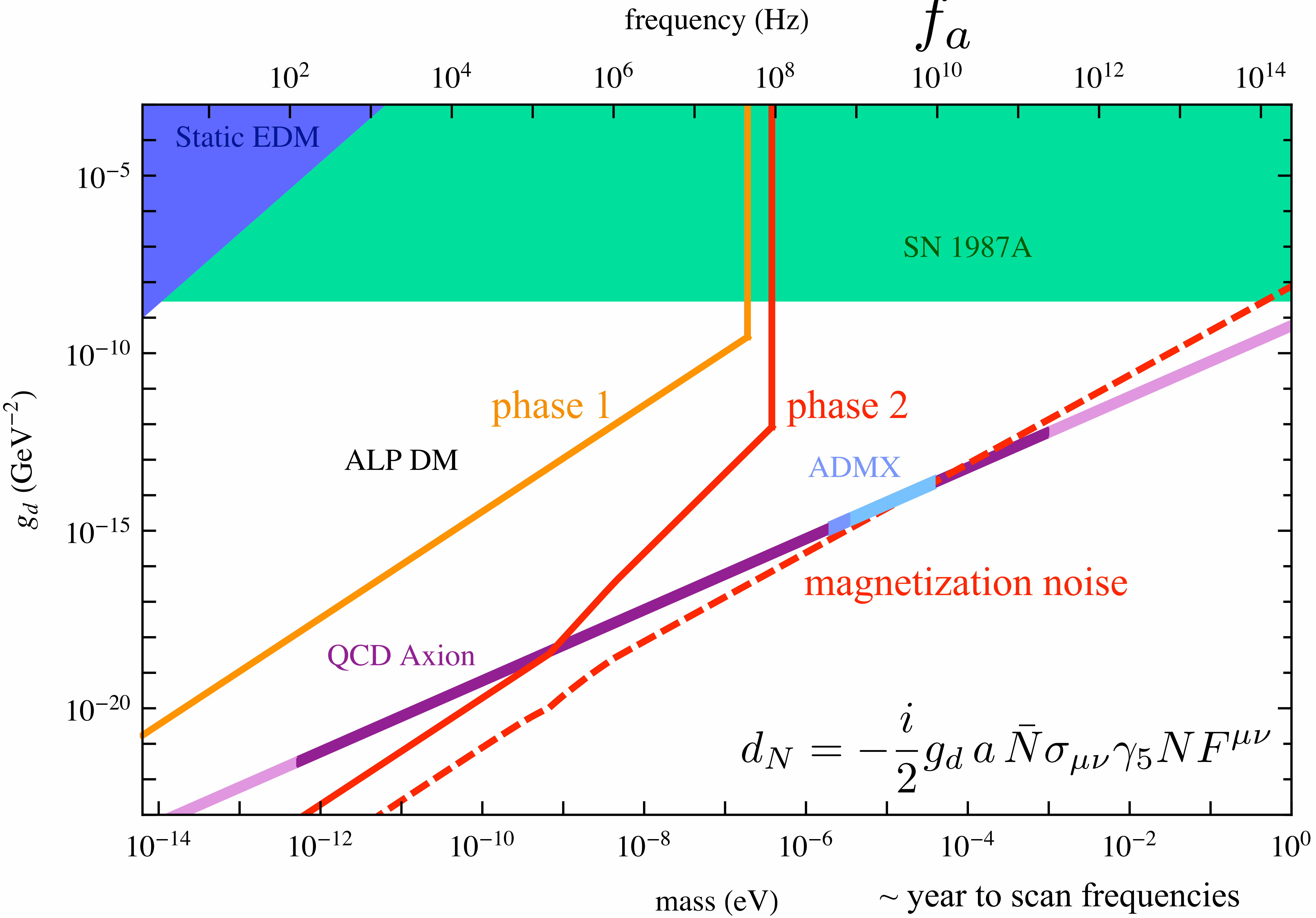
every spin necessarily has random quantum projection onto transverse direction

$$M_n(\omega) \sim \frac{\mu_N}{r^3}\sqrt{nr^3}\langle S(\omega)\rangle \sim \mu_N\sqrt{\frac{n}{V}}\langle S(\omega)\rangle$$

$S\left(\omega\right)$ is Lorentzian, peaked at Larmor frequency, bandwidth ~ $1/T_2$

T. Sleator, E. L. Hahn, C. Hilbert, and J. Clarke, PRL 55, 171742 (1985)

Axion Limits on $\frac{a}{f_a}G\widetilde{G}$

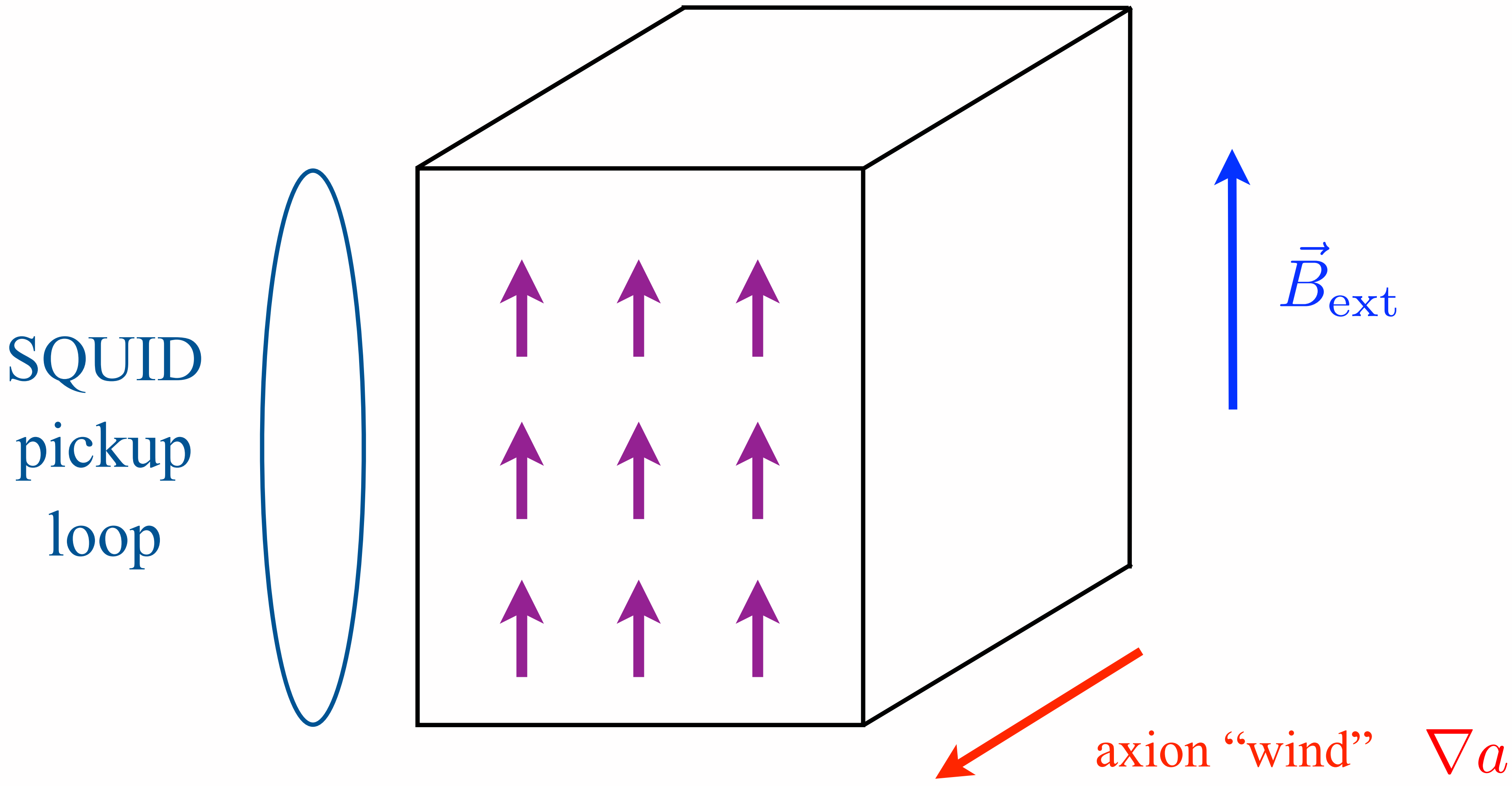


$$d_N = -\frac{i}{2} g_d\, a\, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

~ year to scan frequencies

Verify signal with spatial coherence of axion field

Axion Wind



use nuclear spins coupled to axion DM

$$g_{\rm aNN}\,(\partial_\mu a)\,\bar{N}\gamma^\mu\gamma_5 N \quad\Longrightarrow\quad H_N \supset g_{\rm aNN}\vec{\nabla}a.\vec{S}_N$$

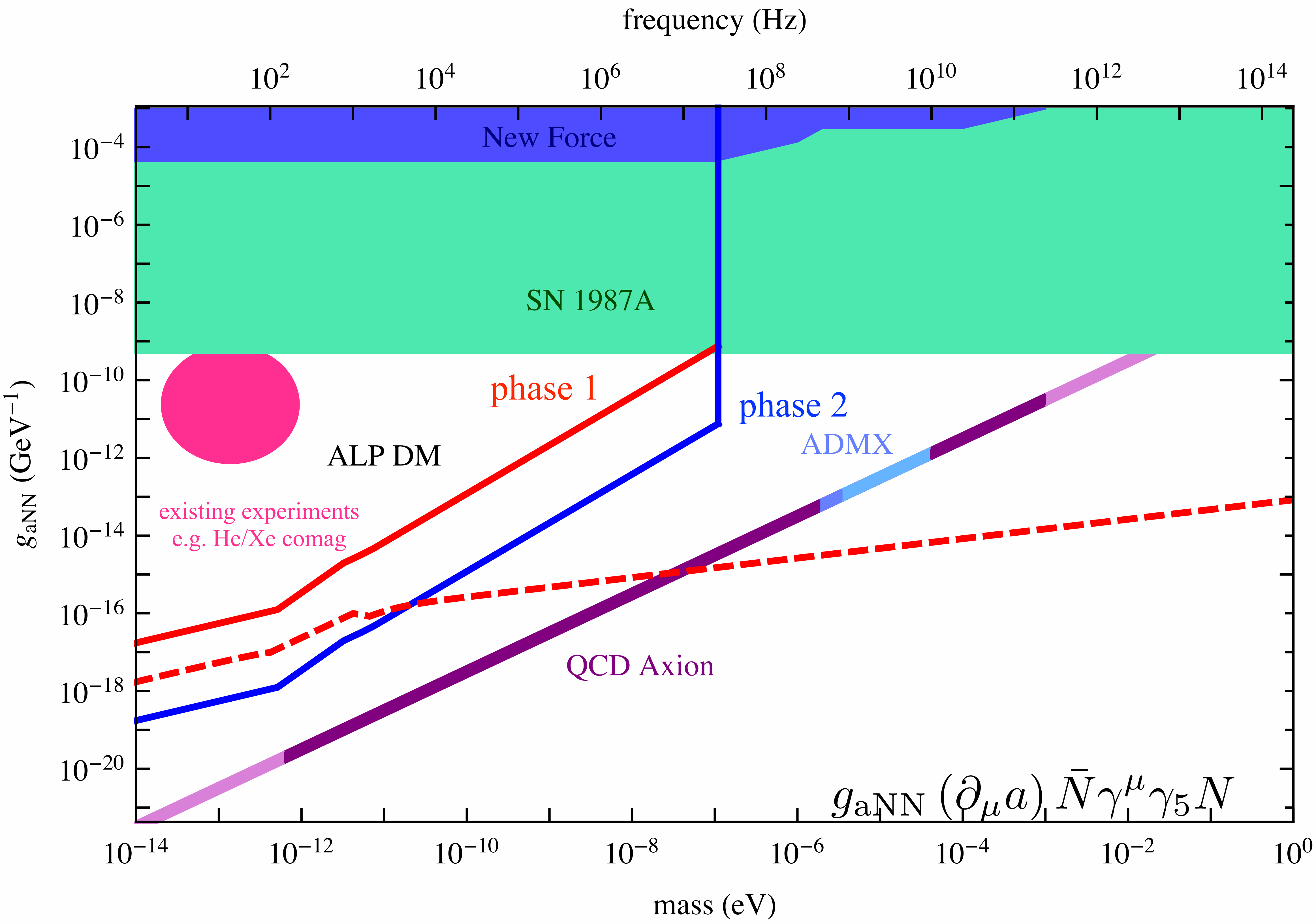
effects suppressed by v ~ 10^{-3}

Similar to EDM experiment but no Schiff suppression, no E-field (polar crystal)

makes a directional detector for axions (and gives annual modulation)

also works for any other spin-coupled DM (e.g. dark photon)

Limits on Axion-Nucleon Coupling



~ year to scan one decade of frequency

WIMPs

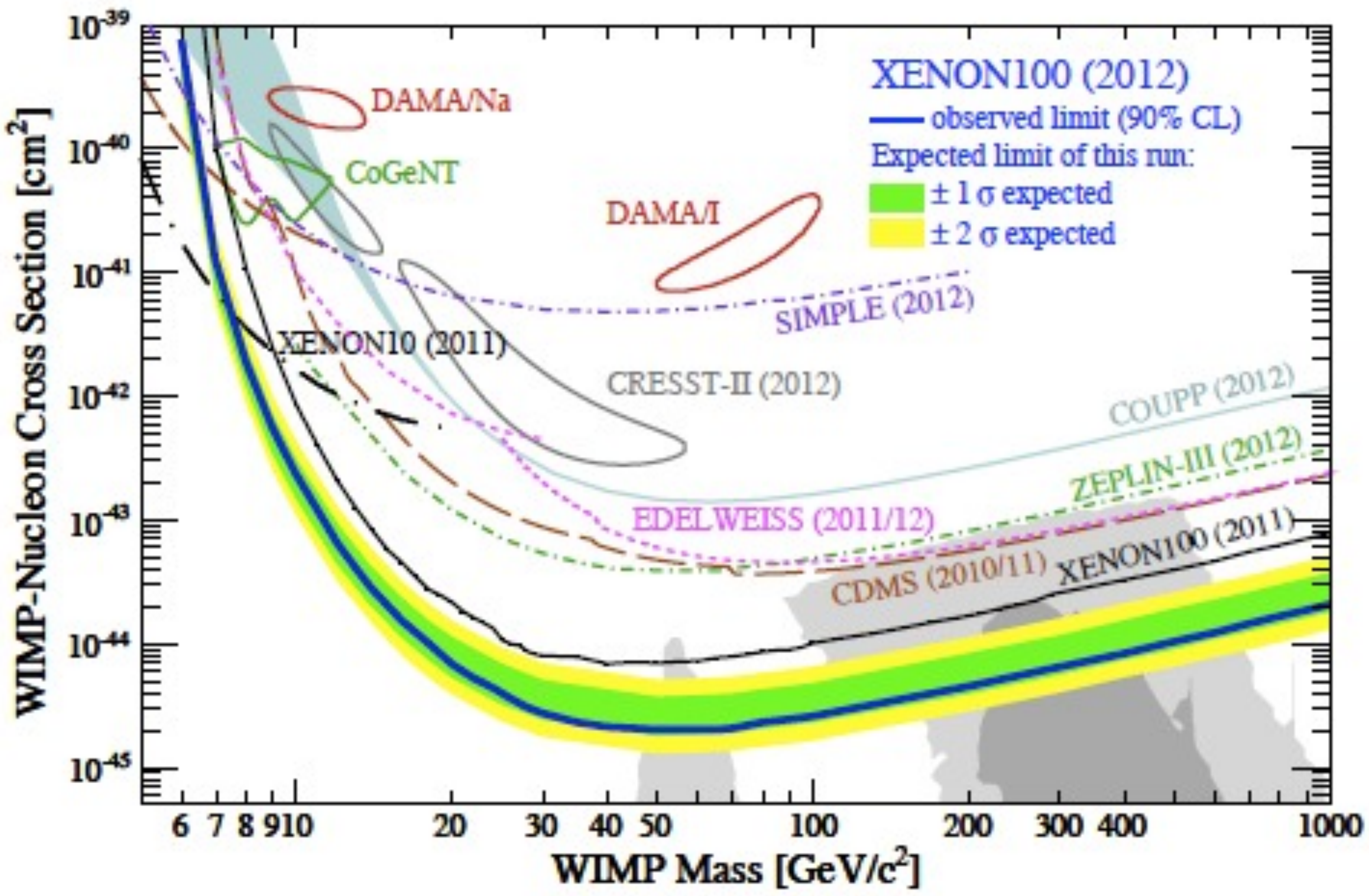
Hard scattering is good for heavy dark matter.

Goodman & Witten (1985): $\sigma \sim 10^{-38}\,\mathrm{cm}^2$

Z

h

W



Oscillating moments coupled to spin are natural for light dark matter.

(axions, dark photons...)

Summary

The Dark Matter Frontier

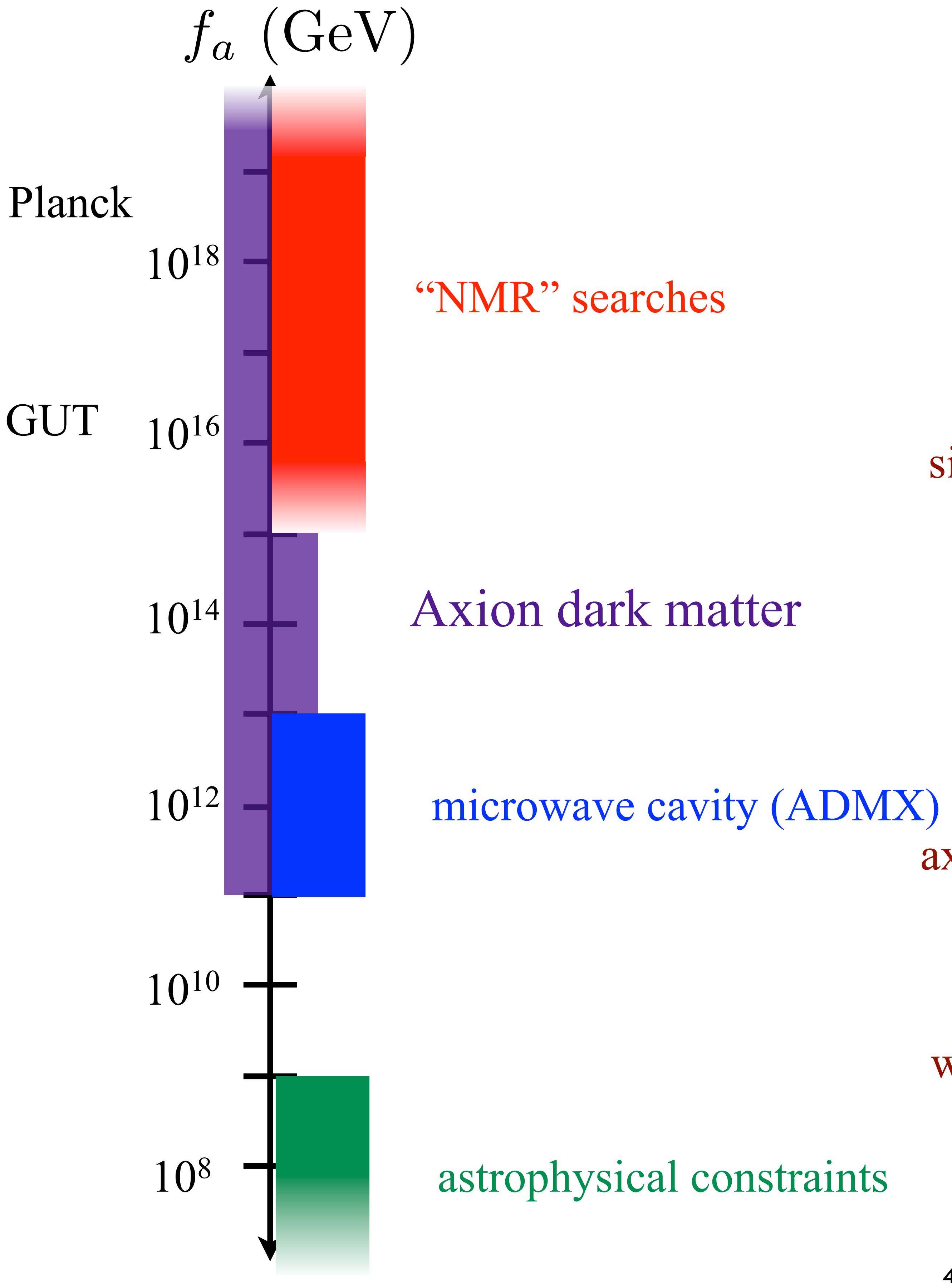
Proof of physics beyond standard model

Portal to new sectors

No reason to expect dark matter to be simple

Many new possibilities to go beyond present WIMP searches

CASPEr Discovery Potential



laboratory experiment

significant reach in kHz - 10 MHz
frequencies ➙ high f_a

technological challenges,
similar to early stages of WIMP detection, axions
deserve similar effort

technology broadly useful for community.

axion dark matter is very well-motivated, no other
way to search for light axions (high f_a)

would be both the discovery of dark matter and a
glimpse into physics at very high energies