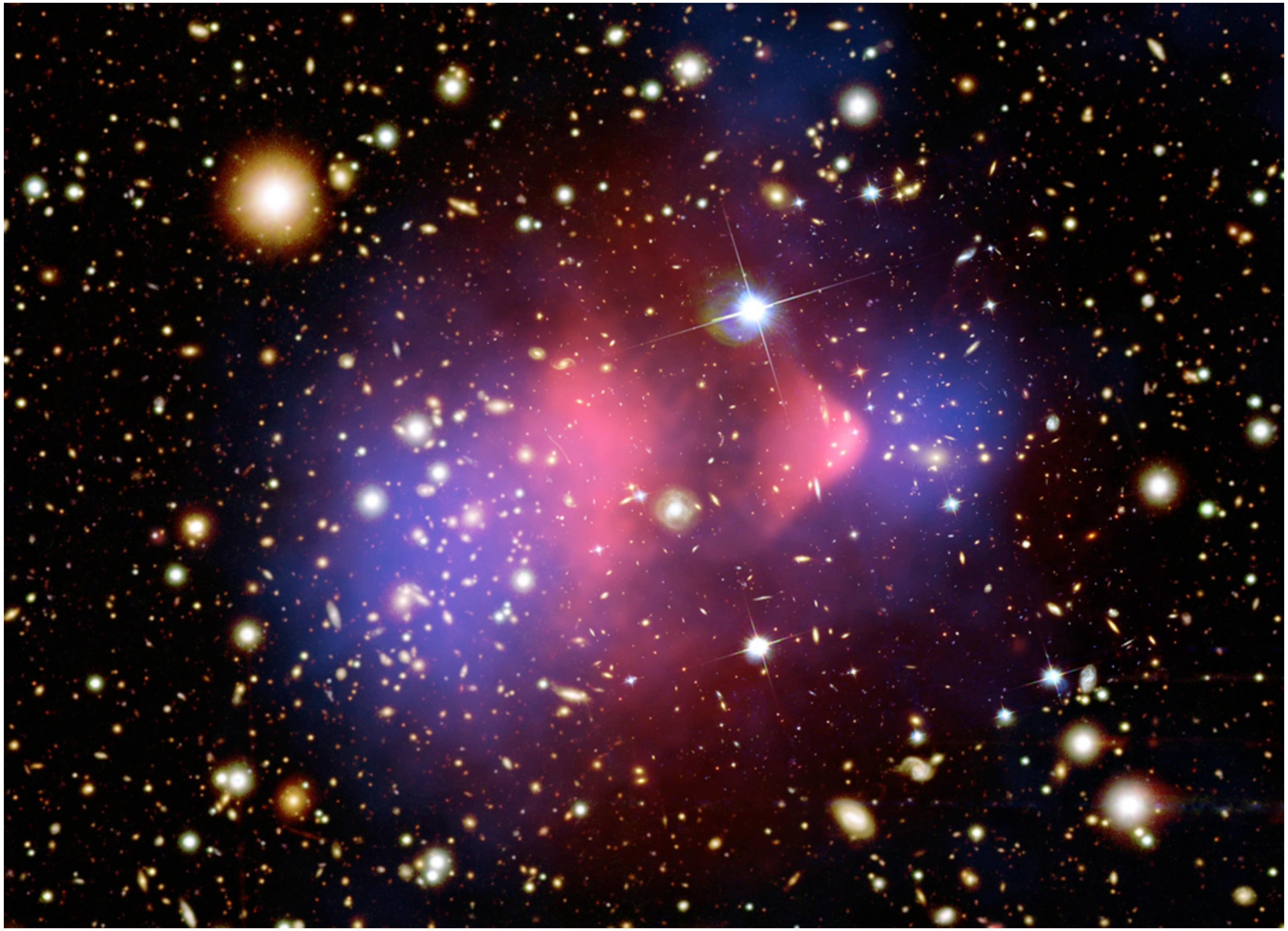
New Directions in Searching for the Dark Universe

Surjeet Rajendran,
UC Berkeley

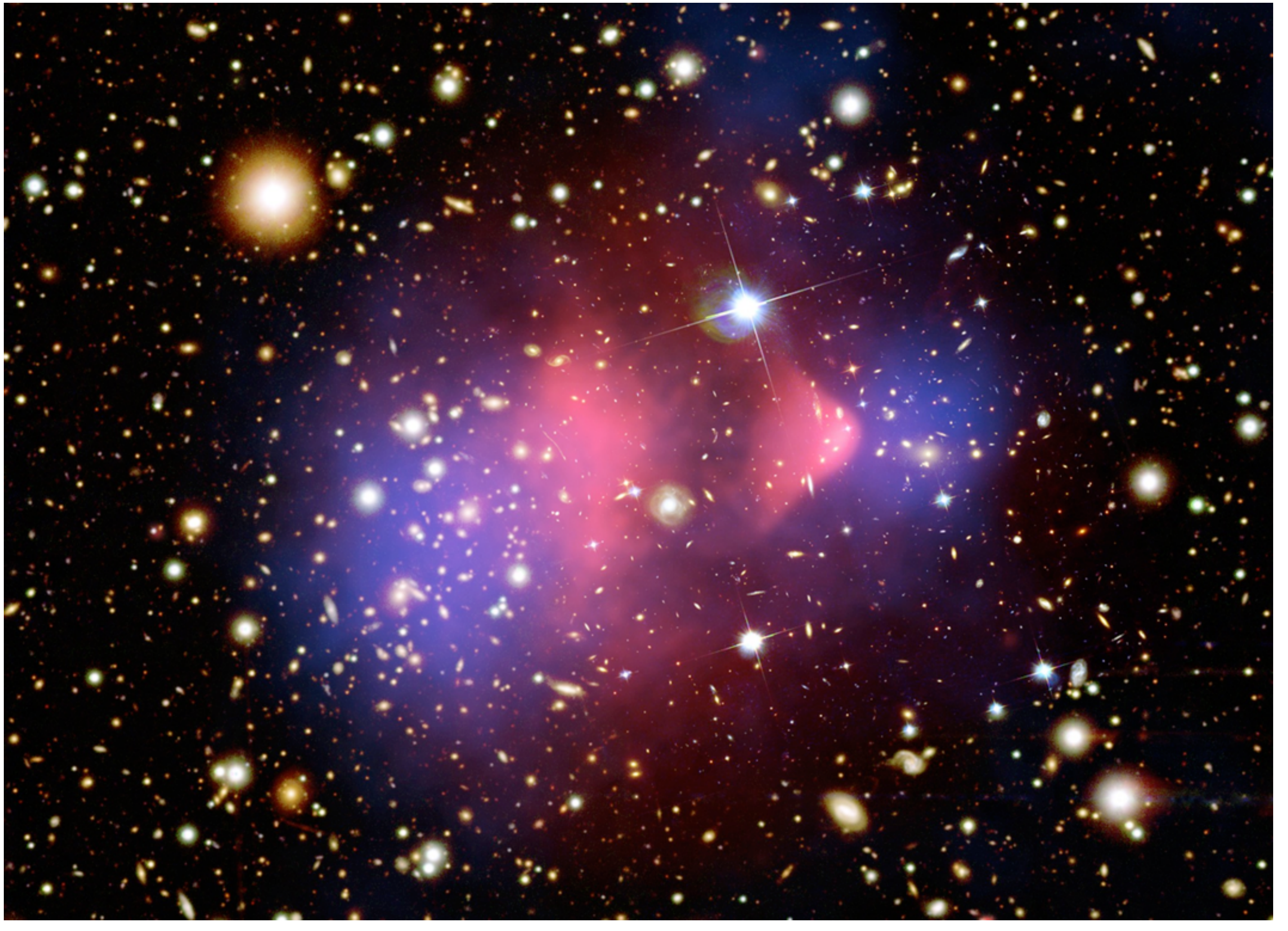
Dark Matter



A New Particle

Non gravitational interactions?

Dark Matter



A New Particle

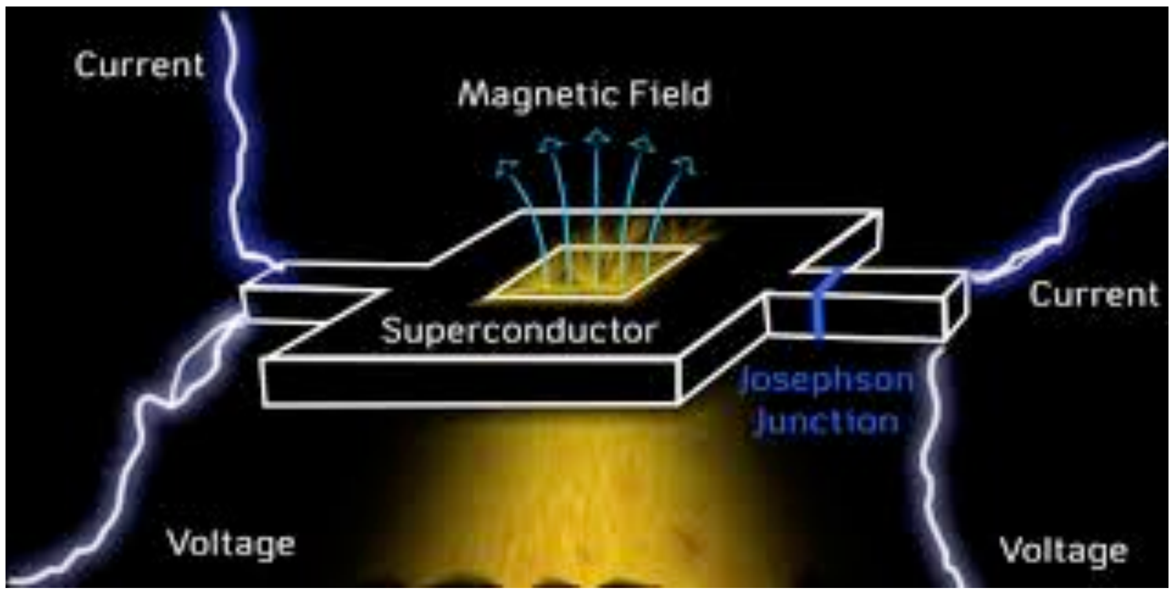
Non gravitational interactions?

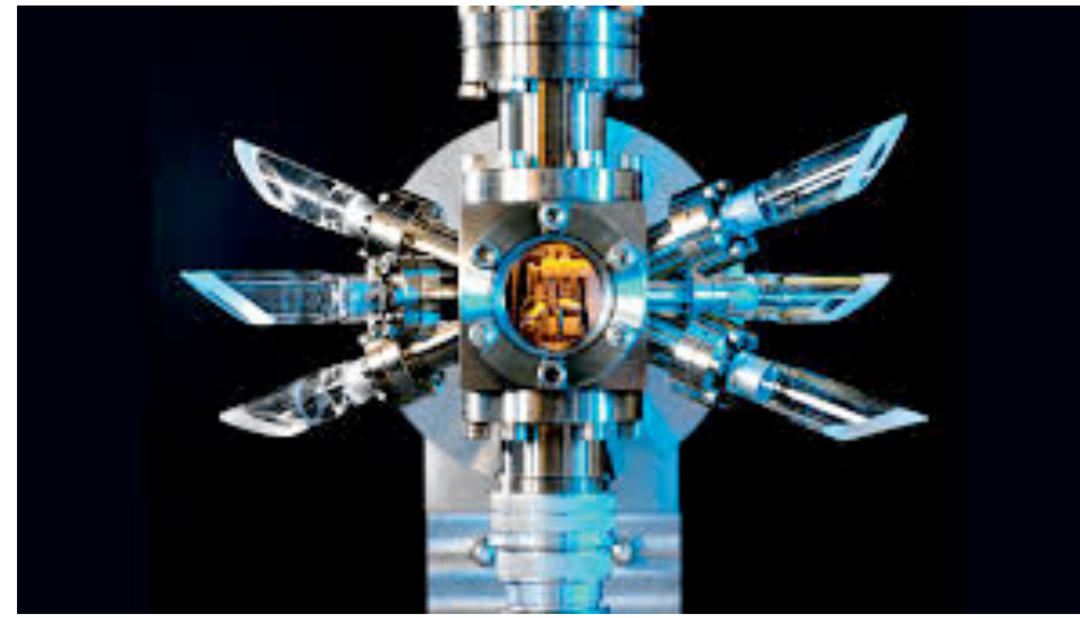
How do we detect them?

Weak effects. Need high precision

Precision Instruments

Impressive developments in the past two decades





$$\text{Magnetic Field} \lesssim 10^{-16} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$$

(SQUIDs, atomic magnetometers)

$$\text{Accelerometers} \lesssim 10^{-13} \frac{\mathrm{g}}{\sqrt{\mathrm{Hz}}}$$

(atom and optical interferometers)

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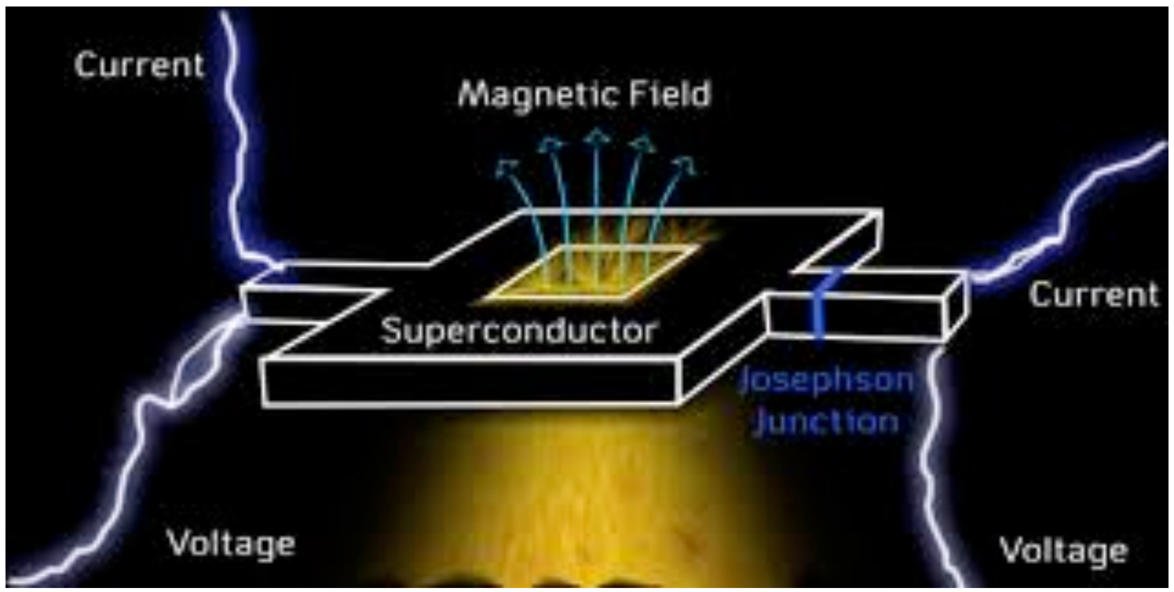

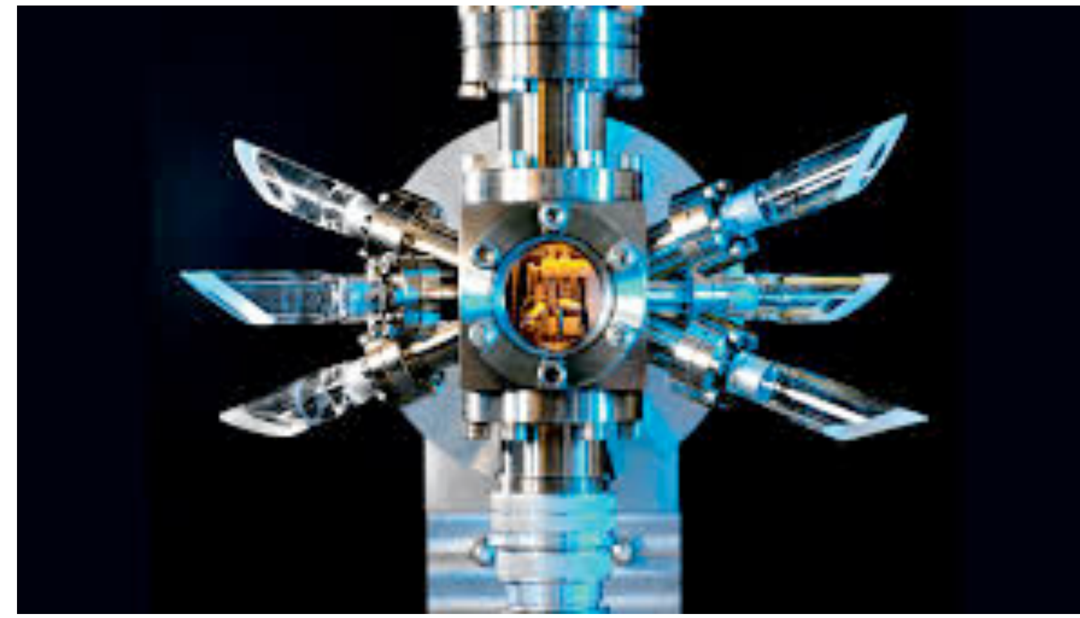

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Rapid technological advancements

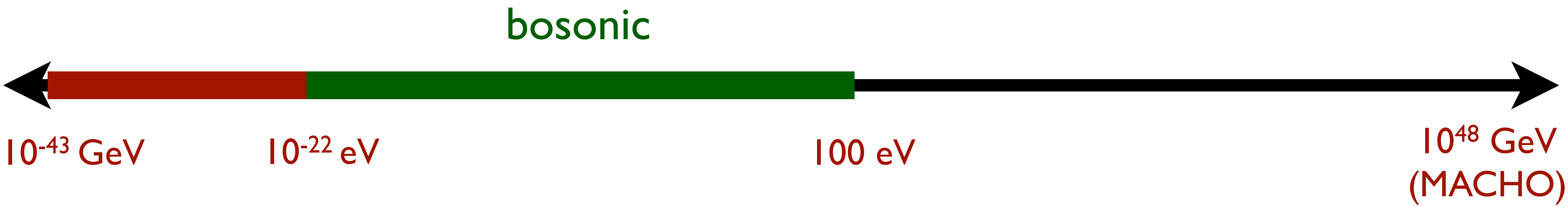
Use to detect new physics?

The Dark Matter Landscape

10^{-43} GeV

10^{48} GeV
(MACHO)

The Dark Matter Landscape



Fit in galaxy

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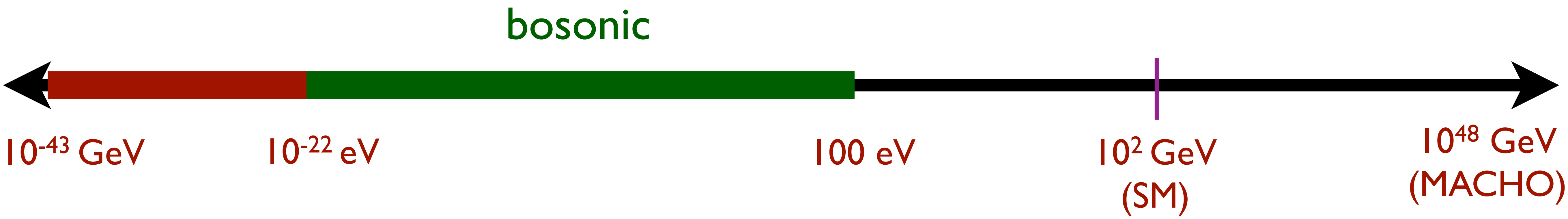

Fit in galaxy

Standard Model scale ~ 100 GeV

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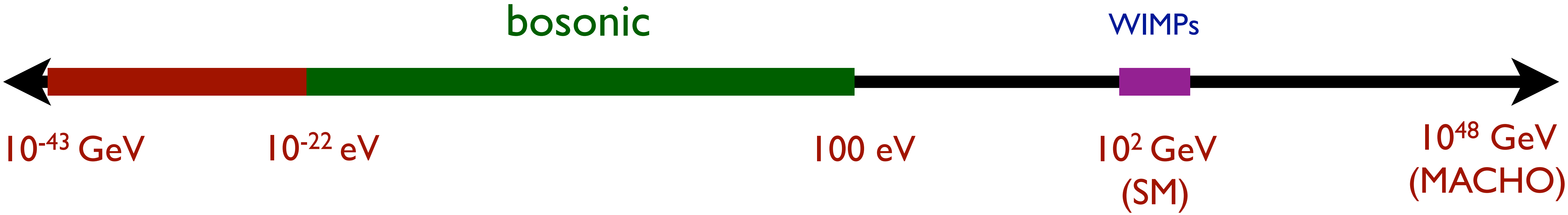

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One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

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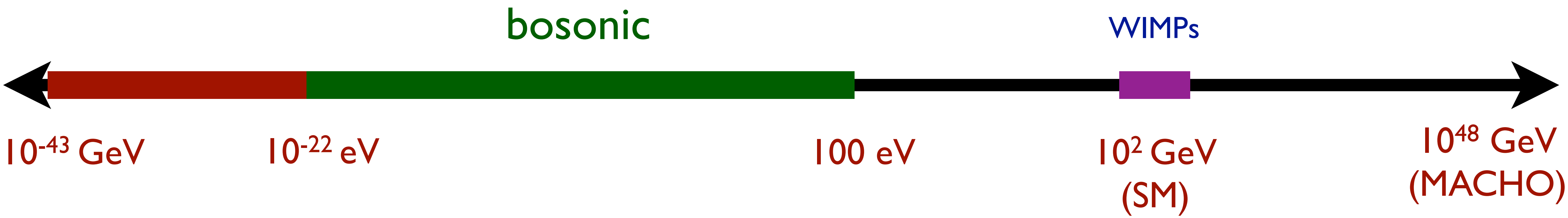

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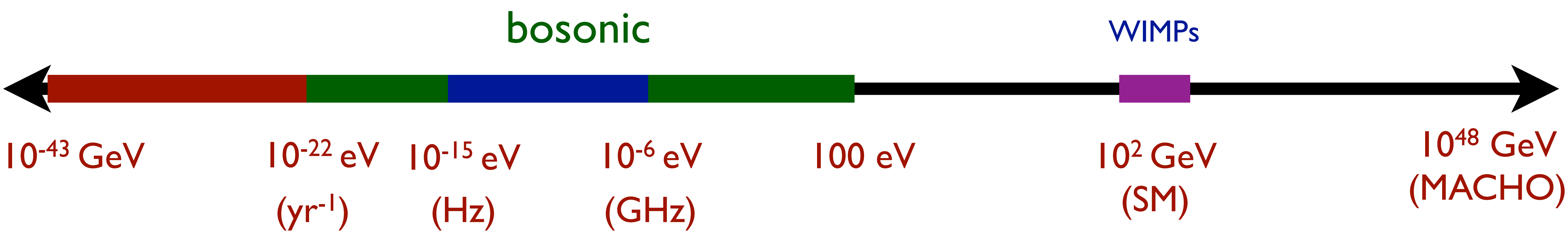

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How do we search for them?

Outline

1. Brief Theory Overview

2. Axion Detection with Nuclear Magnetic Resonance

3. Dark Photon Detection with Radios

4. Bosons with Accelerometers

5. Dark Blobs with White Dwarfs

6. Conclusions

Bosonic Dark Matter

Photons

$$\vec{E} = E_0 \cos(\omega t - \omega x)$$

Detect Photon by measuring time varying field

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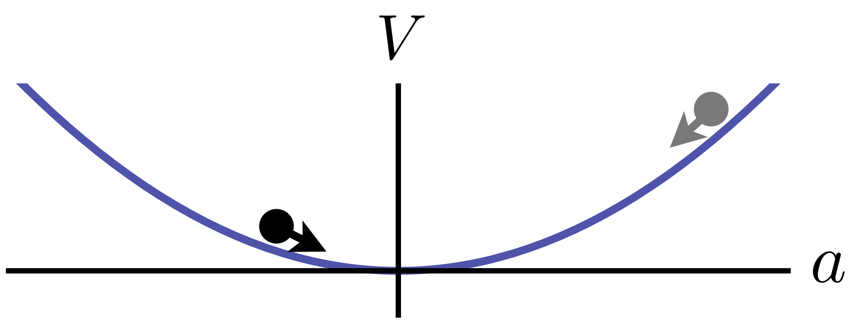
Dark Bosons

Early Universe:
Misalignment Mechanism



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

Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

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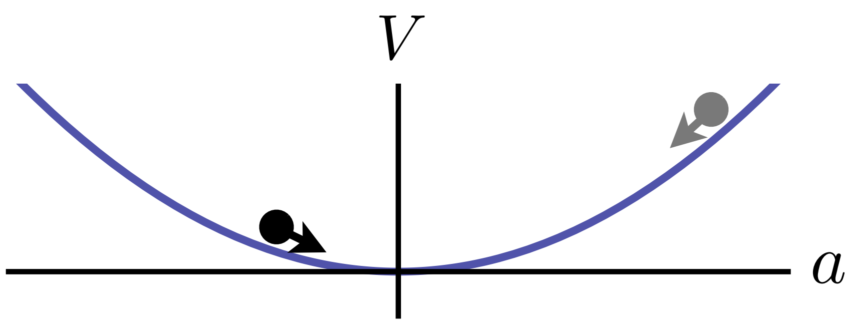

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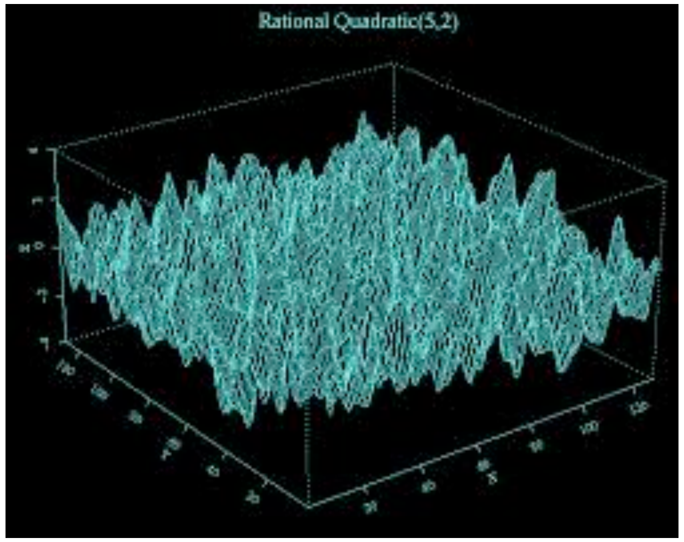
Today: Random Field



Correlation length $\sim 1/(m_a v)$

Coherence Time $\sim 1/(m_a v^2)$ ~ 1 s (MHz/m_a)

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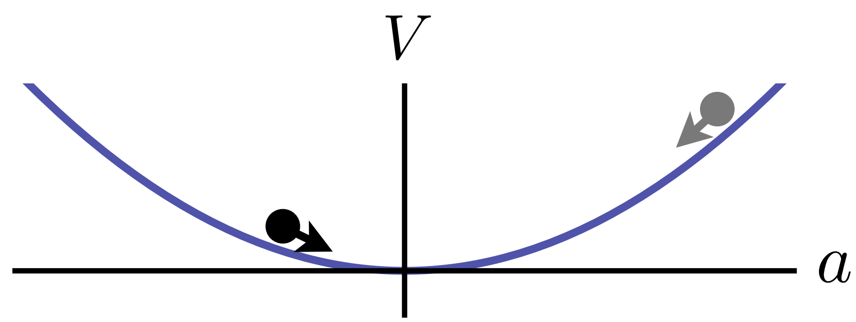

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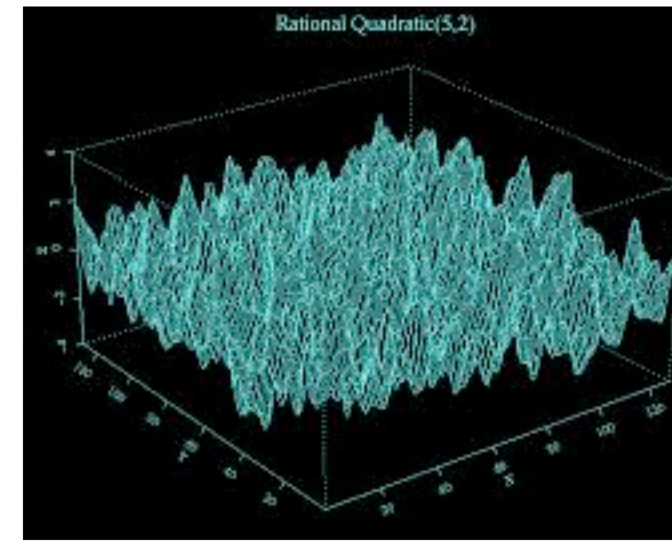

Correlation length ~ $1/(m_a v)$

Coherence Time ~ $1/(m_a v^2)$ ~ 1 s (MHz/m_a)

Detect effects of oscillating dark matter field

Resonance possible. Q ~ 10^6 (set by v ~ 10^{-3})

What kind of Bosons?

Naturalness. Structure set by symmetries.

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Spin 0

Axions and other goldstone bosons

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Electromagnetism	Nuclear Force	Nuclear Spin
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	QCD Axion	General Axions

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Anomaly free Standard Model couplings

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- Nuclear Spin $\left(\frac{F'_{\mu\nu}}{f_a} \bar{N} \sigma^{\mu\nu} N\right)$ Dipole moment
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$$\text{Hz} \lessapprox m_a \lessapprox \text{GHz}$$

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This Talk

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Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Peter Graham
Micah Ledbetter
Alex Sushkov

PRX **4** (2014) arXiv: 1306.6089
PRD **88** (2013) arXiv: 1306.6088
PRD **84** (2011) arXiv: 1101.2691

CASPEr: Axion Effects on Spin

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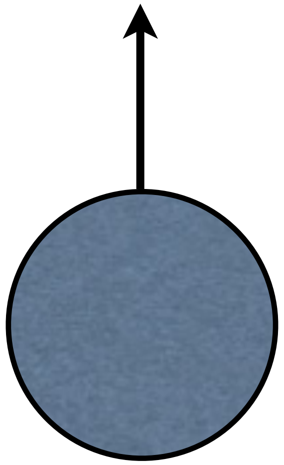
General Axions

Neutron



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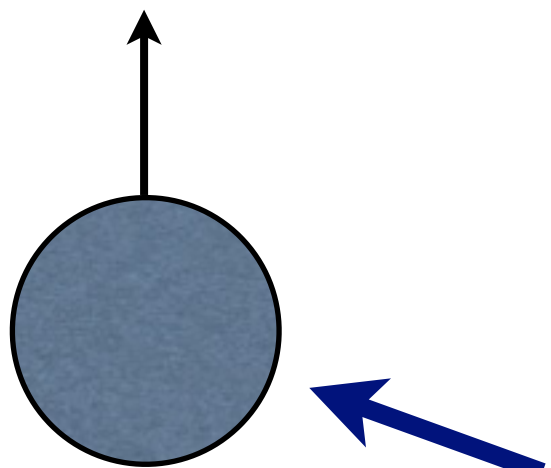
General Axions

Neutron in Axion Wind

$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$



$\vec{v}$

$$H_N \supset \frac{a}{f_a}\vec{v_a}.\vec{S}_N$$

Spin rotates about
dark matter velocity

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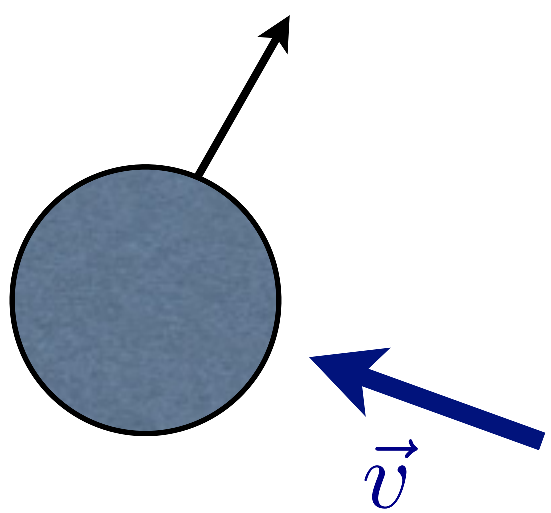

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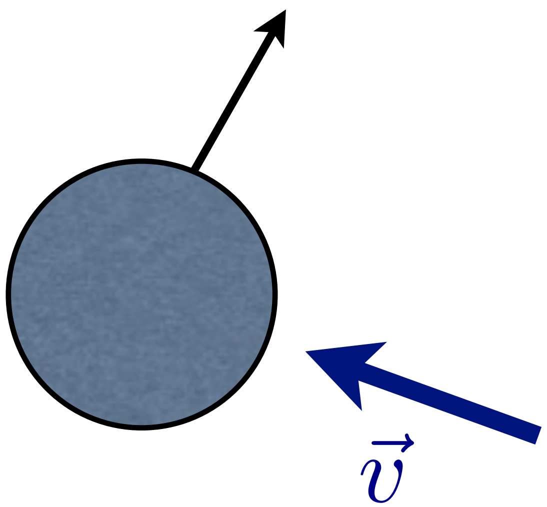

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Effective time varying
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$$B_{eff} \lessapprox 10^{-16}\,\cos\left(m_a t\right)\ \mathrm{T}$$

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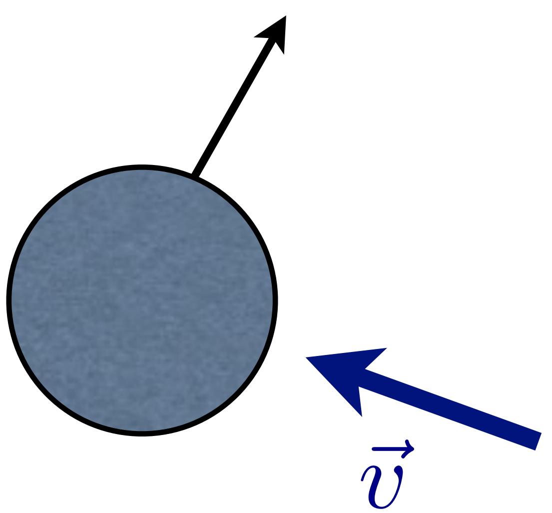

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Other light dark matter (e.g. dark photons) also induce similar spin precession

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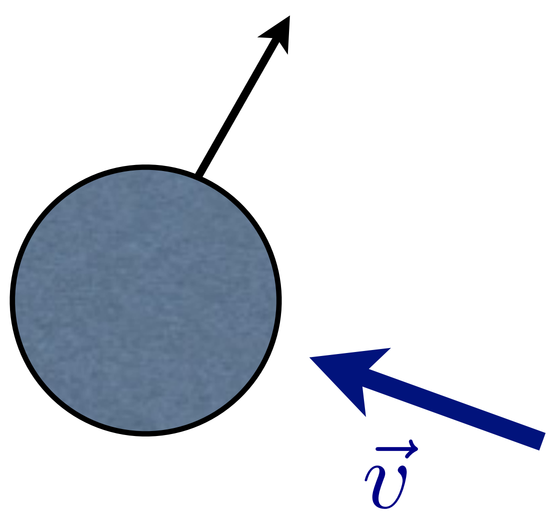

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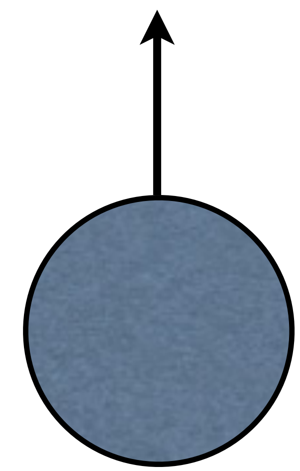

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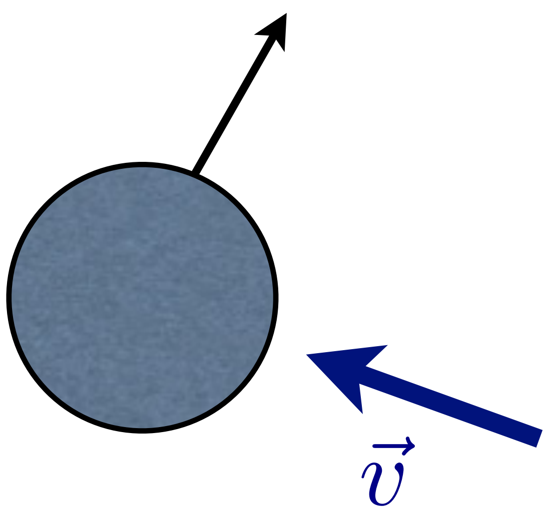

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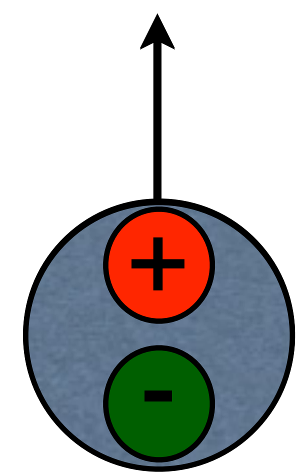

$$\left(\frac{a}{f_a}G\tilde{G}\right)$$

QCD axion induces electric dipole moment
for neutron and proton

Dipole moment
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Oscillating dipole: $d \sim 3 \times 10^{-34}\ \cos\left(m_a t\right)\ e\,\mathrm{cm}$

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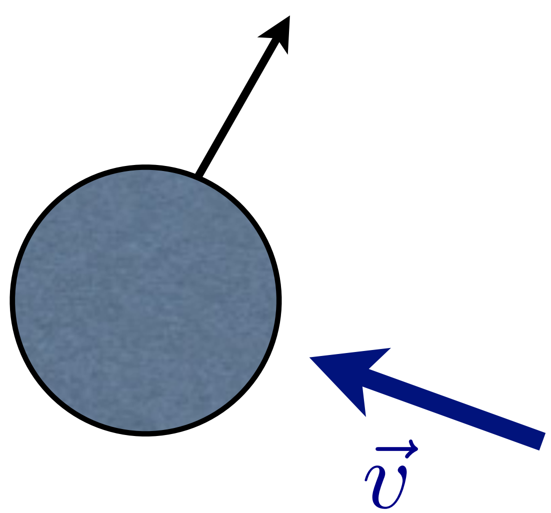

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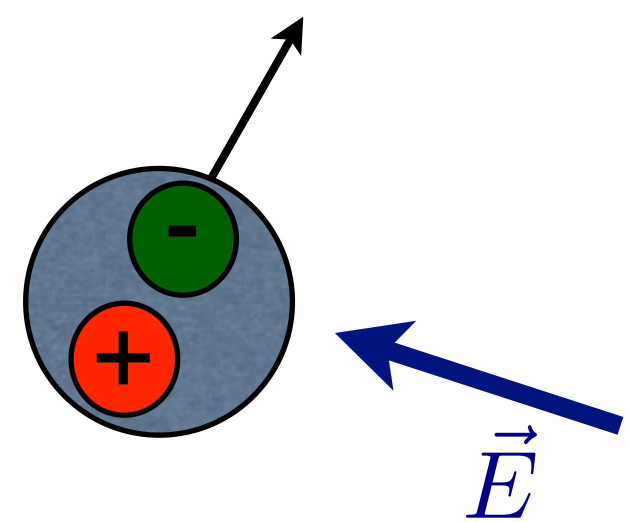

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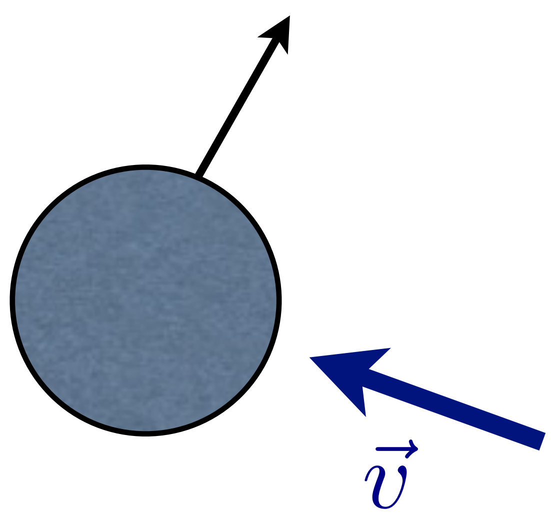

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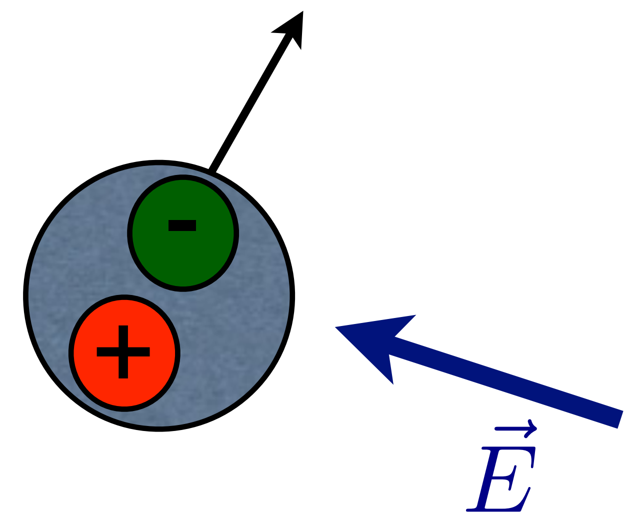

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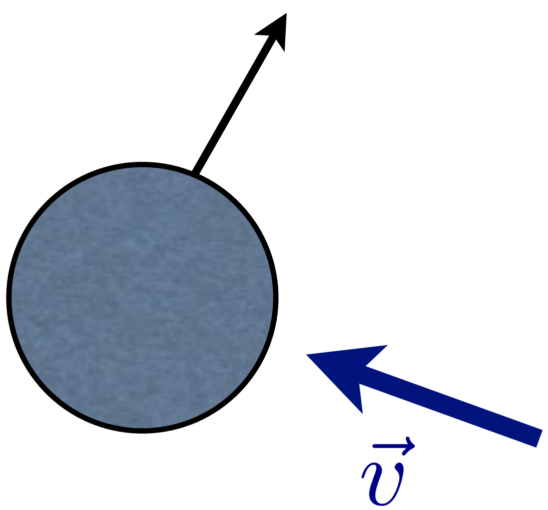

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Measure Spin Rotation, detect Axion

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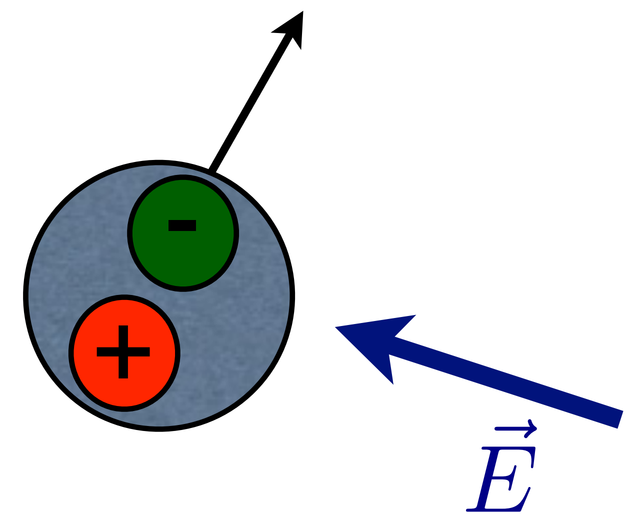

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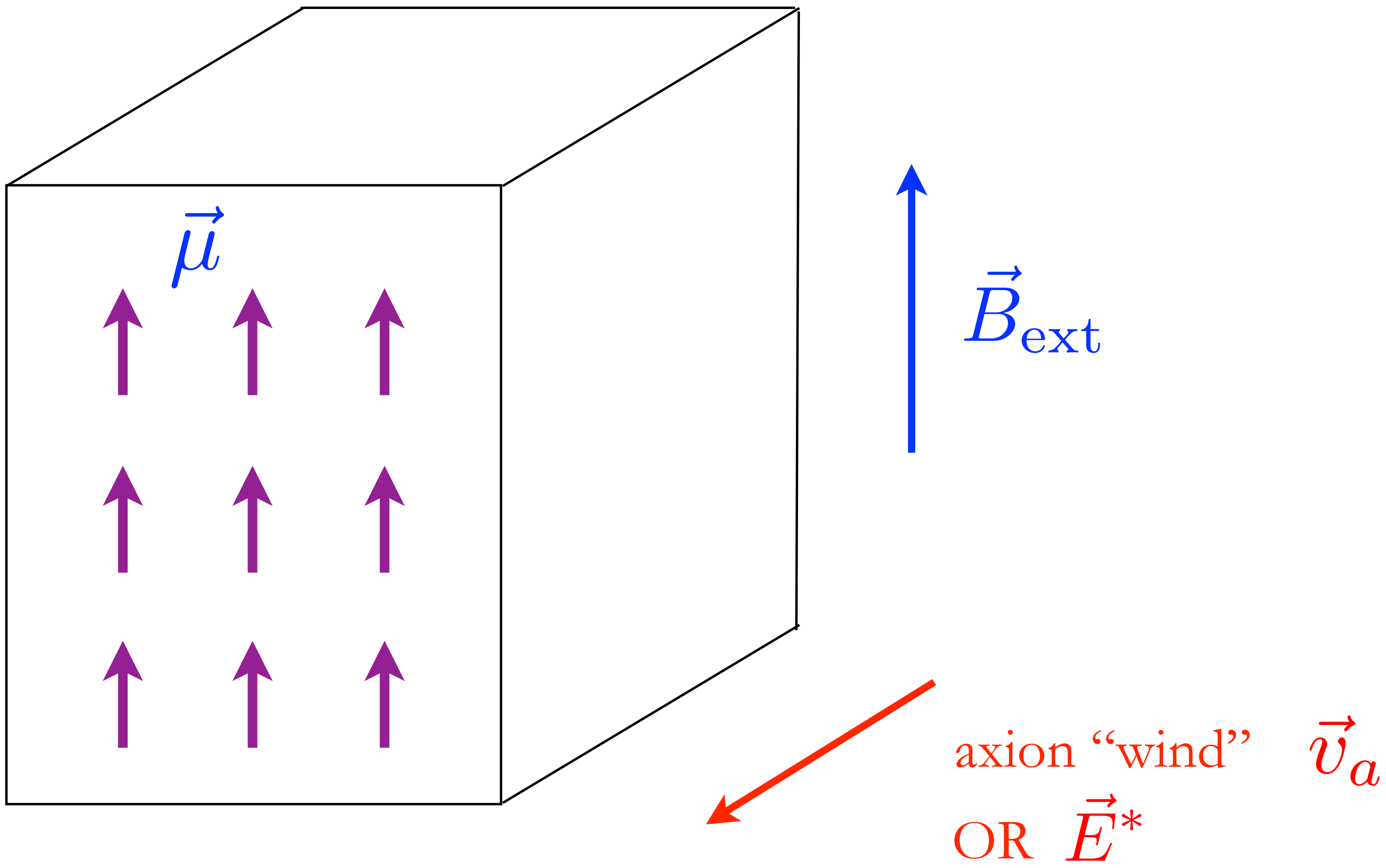
CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



Larmor frequency = axion mass ➔ resonant enhancement

CASPEr

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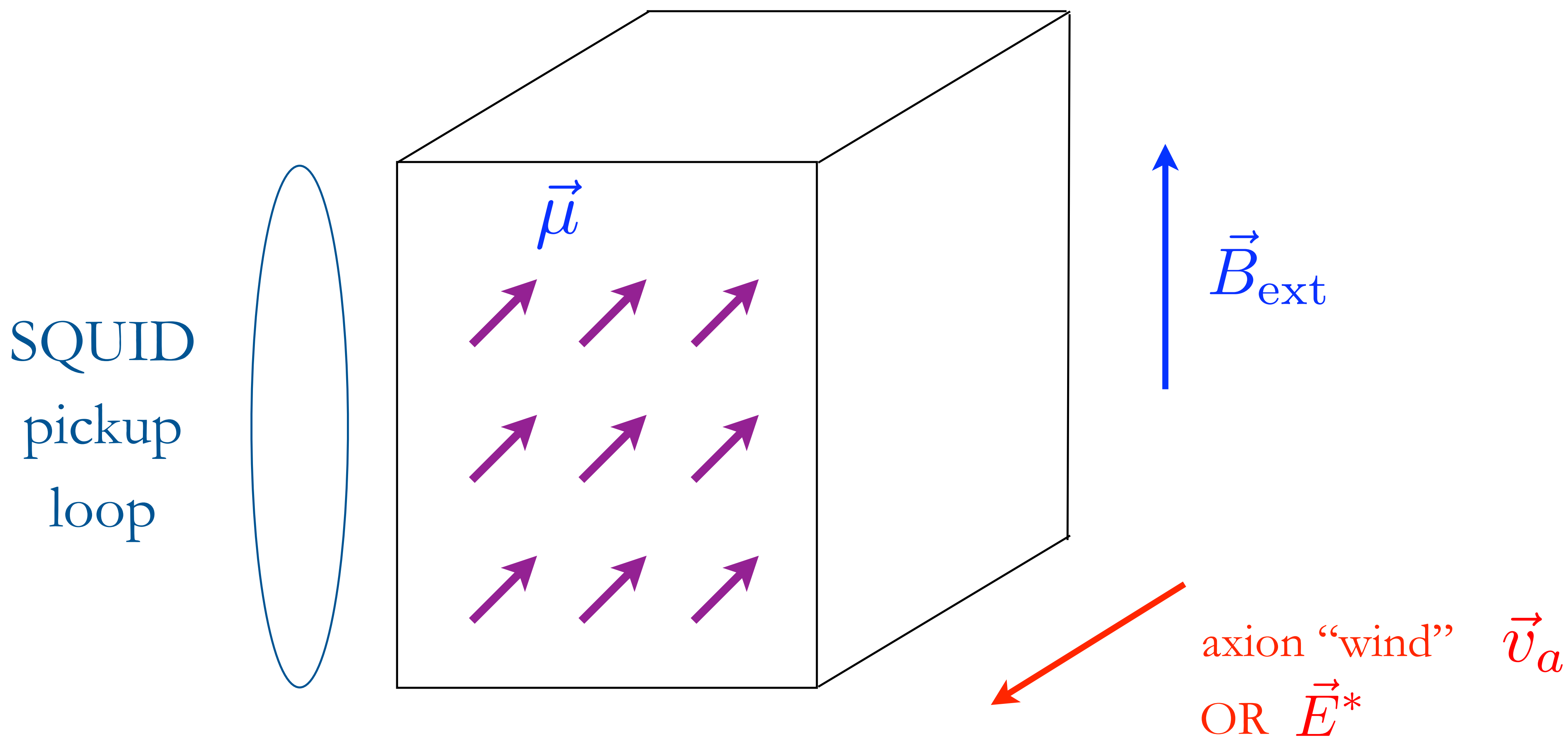


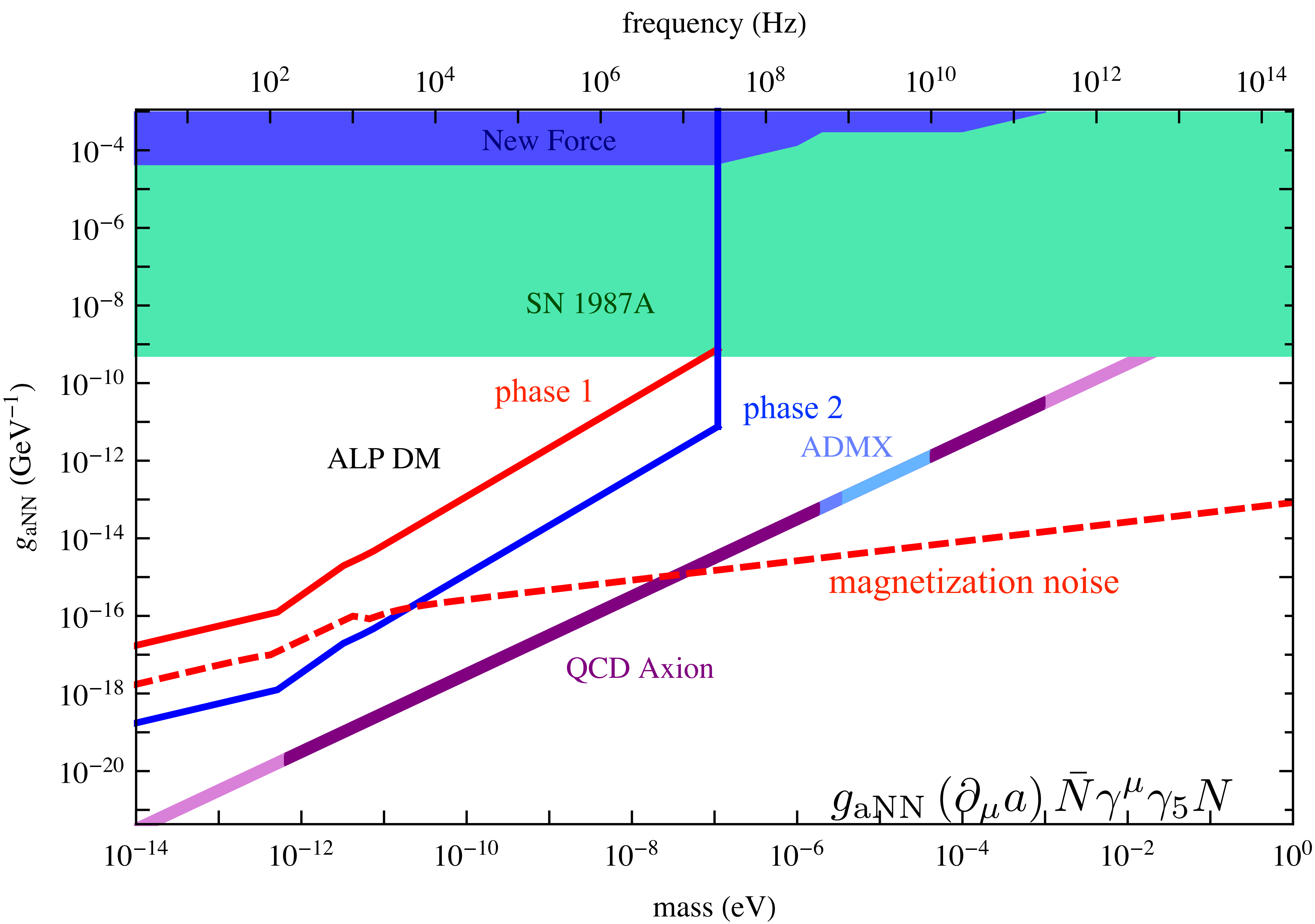
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

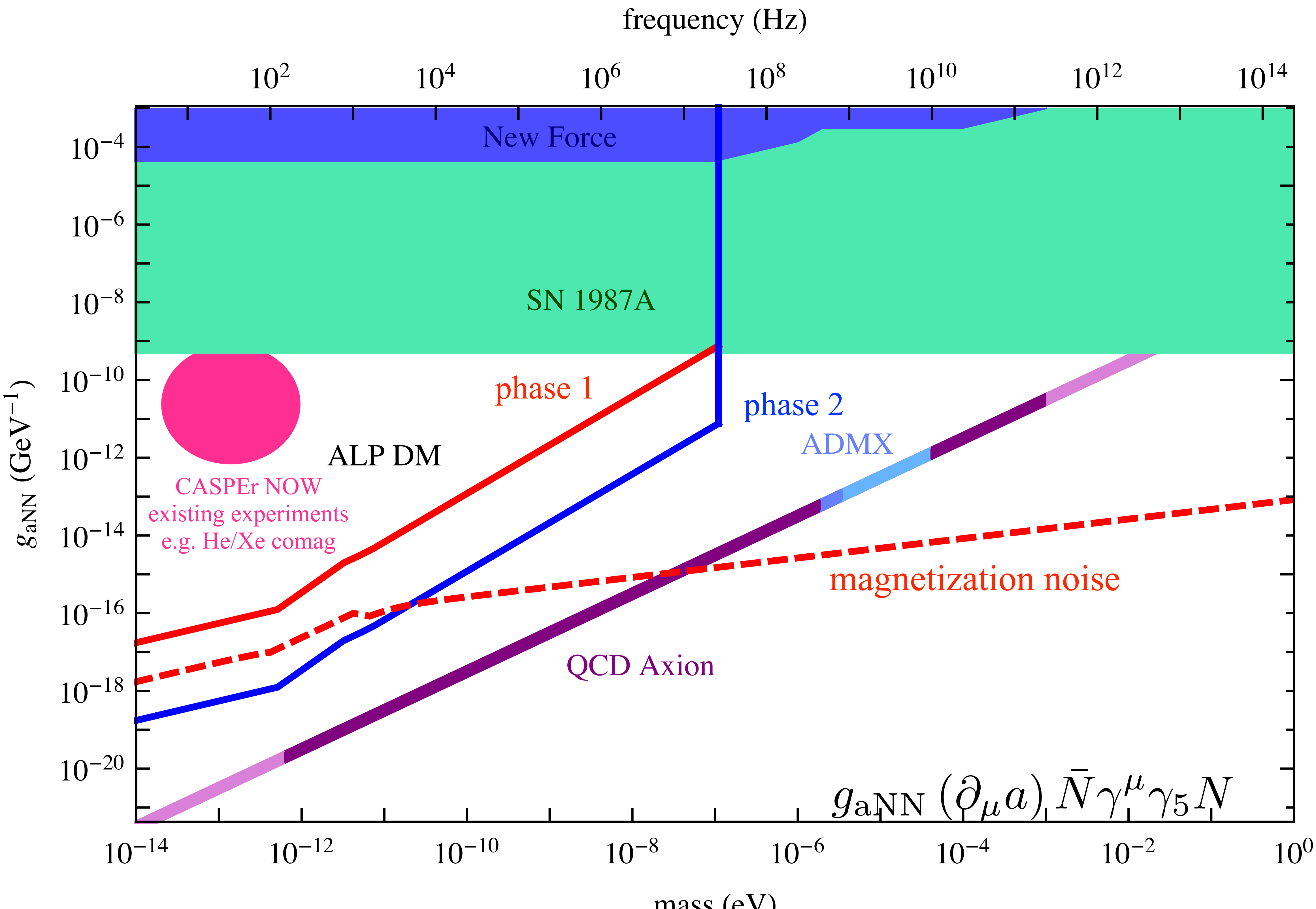
Example materials: LXe, ferroelectric $PbTiO_3$, many others

CASPEr-General Axions



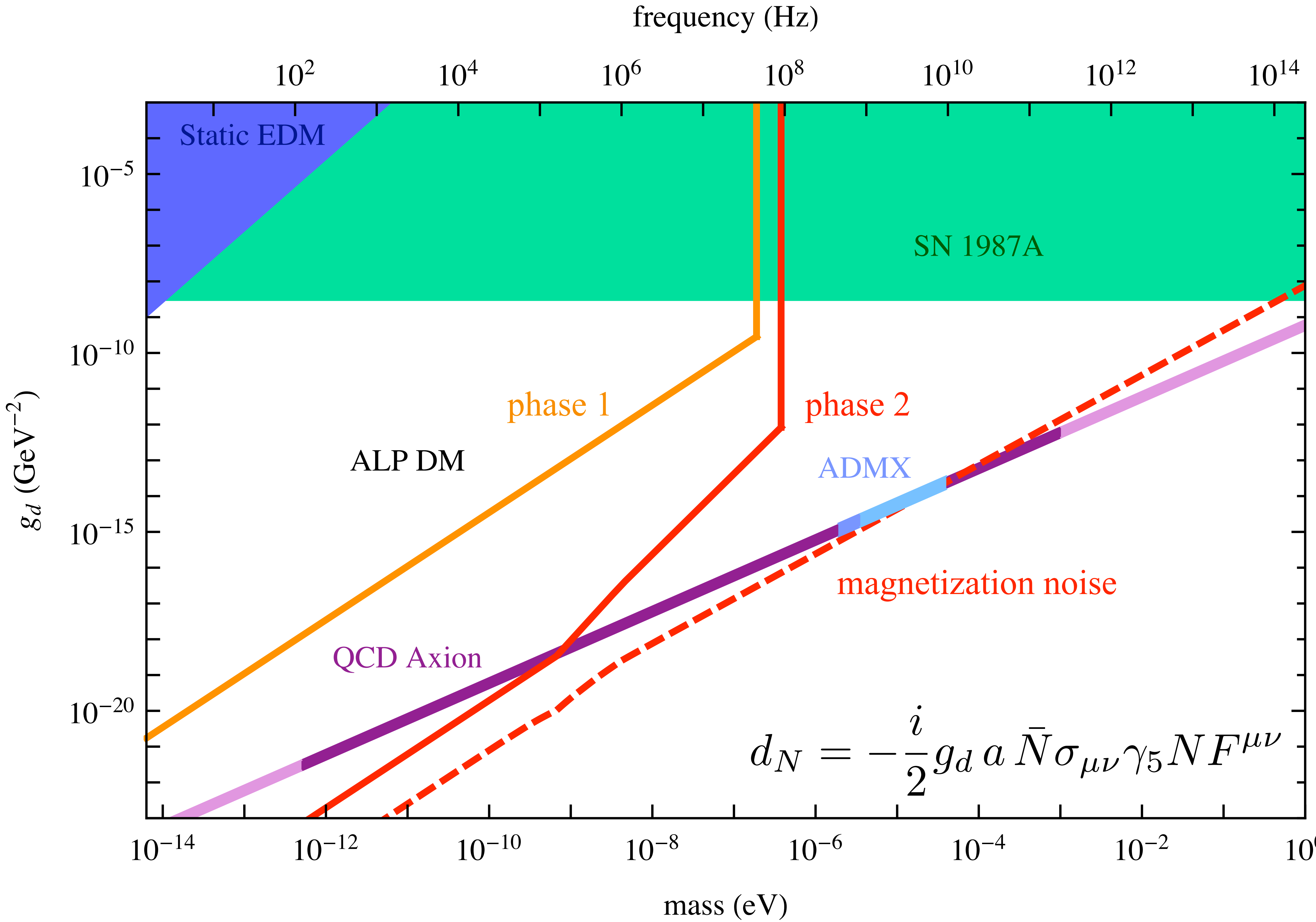
~ year to scan one decade of frequency

CASPEr-General Axions



~ year to scan one decade of frequency

CASPEr-QCD Axion



Verify signal with spatial coherence of axion field

Dark Photon Detection with a Radio

with

Peter Graham
Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Yue Zhao

arXiv: 1411.7382

Dark Photon Dark Matter

Many theories/vacua have additional, decoupled sectors, new U(1)'s

Natural coupling (dim. 4 operator): $\mathcal{L} \supset \varepsilon F F'$

mass basis:

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - eJ^\mu_{EM}\left(A_\mu + \varepsilon A'_\mu\right)$$

photon with small mass and suppressed couplings to all charged particles

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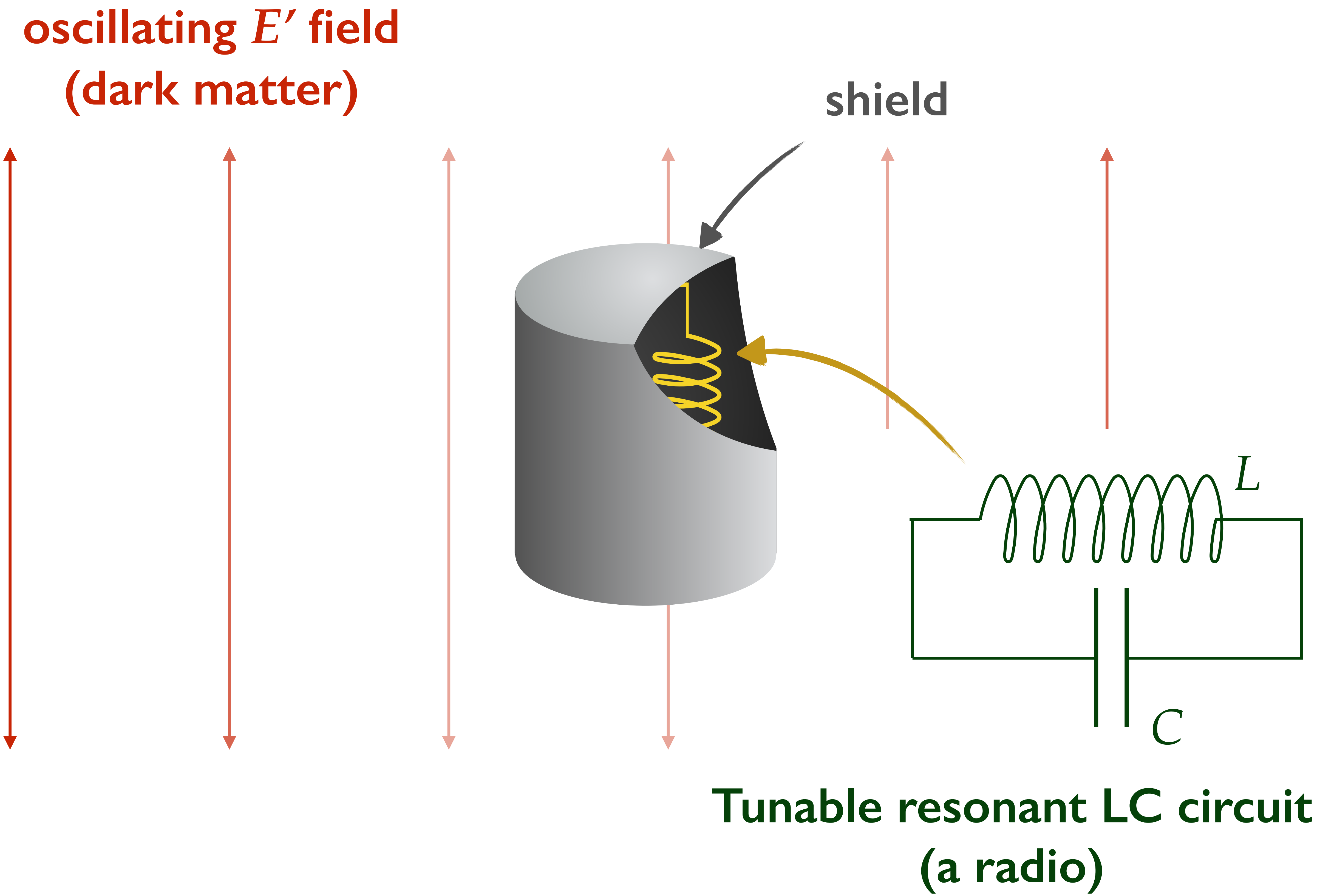
oscillating E' field (dark matter)

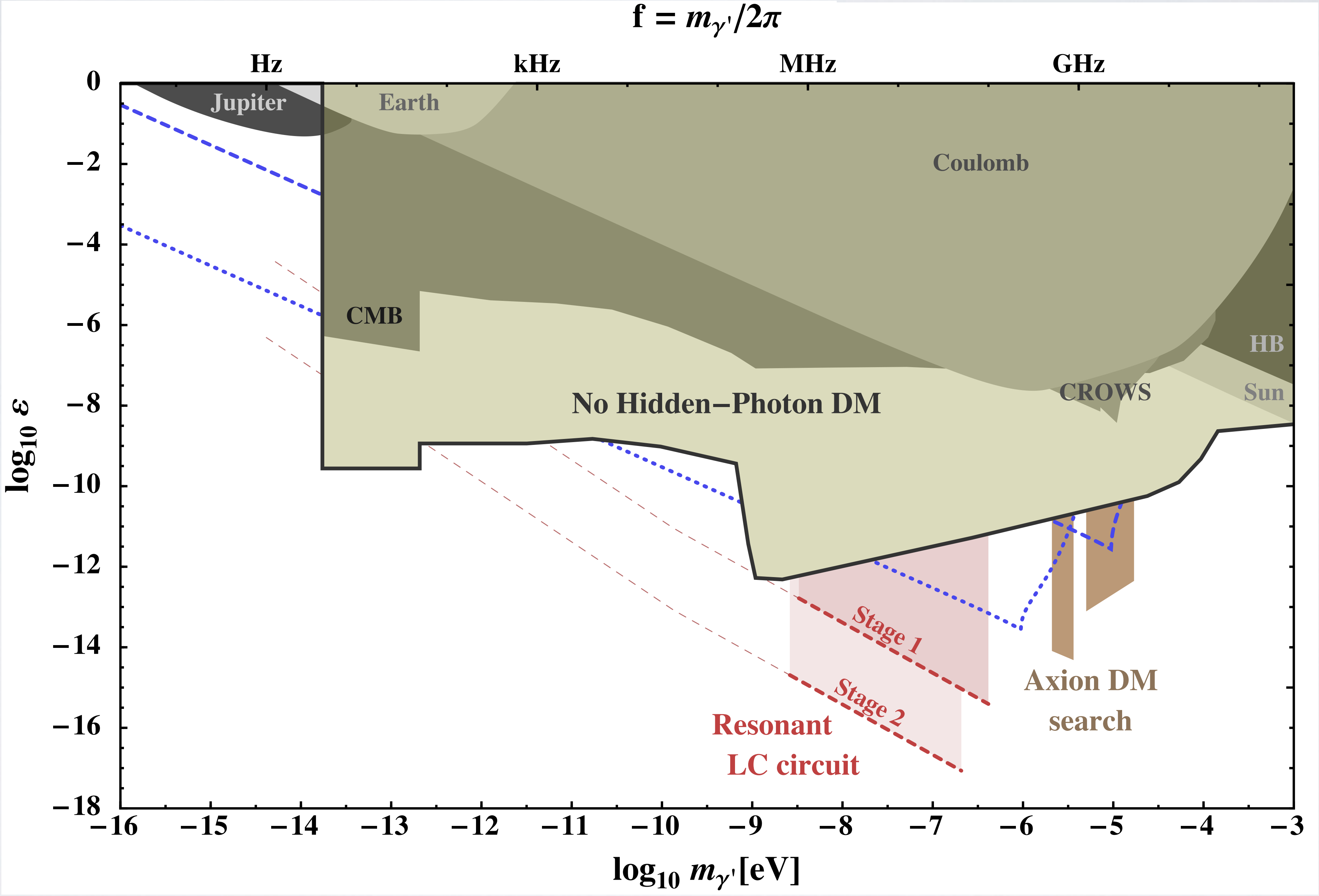
can drive current behind EM shield

Dark Matter Radio Station



EXPECTED REACH

Stage 1: size ~50 cm, T= 4K, $Q=10^6$, 1 year scan



Stage 2: size ~1 m, T= 10mK, $Q=10^6$, 1 year scan

B-L Dark Matter with Accelerometers

(under development)

with

Peter Graham
David Kaplan
Jeremy Mardon
William Terrano

B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - gJ^\mu_{B-L}A'_\mu$$

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

Force experiments constrain $g < 10^{-21}$

B-L Dark Matter

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Force experiments constrain $g < 10^{-21}$

oscillating E' field (dark matter)

can accelerate atoms

The Relaxion

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

Hierarchy problem solved through cosmic evolution - does not require any new physics at the LHC

ϕ is a light scalar coupled to higgs with small coupling g

$$\implies \frac{g\phi}{v} m_q \bar{q} q$$

$$\text{Dark matter } \phi \implies \phi = \phi_0 \cos\left(m_\phi \left(t - \vec{\mathrm{v}}.\vec{x}\right)\right)$$

Time variation of masses of fundamental particles

$$\implies \text{ force on atoms } \frac{g\nabla\phi}{v} m_q \sim \frac{g m_\phi \vec{\mathrm{v}}}{v} m_q$$

This force also violates the equivalence principle

B-L Dark Matter

Acceleration Per Baryon: $\frac{gE'}{m_n} \sim 10^{-10}\,\frac{\mathrm{m}}{\mathrm{s}^2}\left(\frac{g}{10^{-21}}\right)$

Atomic Accelerometers $\gtrapprox 10^{-12}\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$ (@ 1 Hz)

B-L Dark Matter

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Stanford Test Facility

Atomic Accelerometers $\gtrsim 10^{-12}\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$ (@ 1 Hz)

Dark Matter force depends upon net neutron number
Time dependent equivalence principle violation!

B-L Dark Matter

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Atomic Accelerometers $\gtrapprox 10^{-12}\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$ (@ 1 Hz)

Dark Matter force depends upon net neutron number
Time dependent equivalence principle violation!

Without extra work, Stanford facility probes $g \approxeq 10^{-26}$

Improvements possible with resonant schemes

Seems promising!

White Dwarves

A New Dark Matter Detector

Surjeet Rajendran

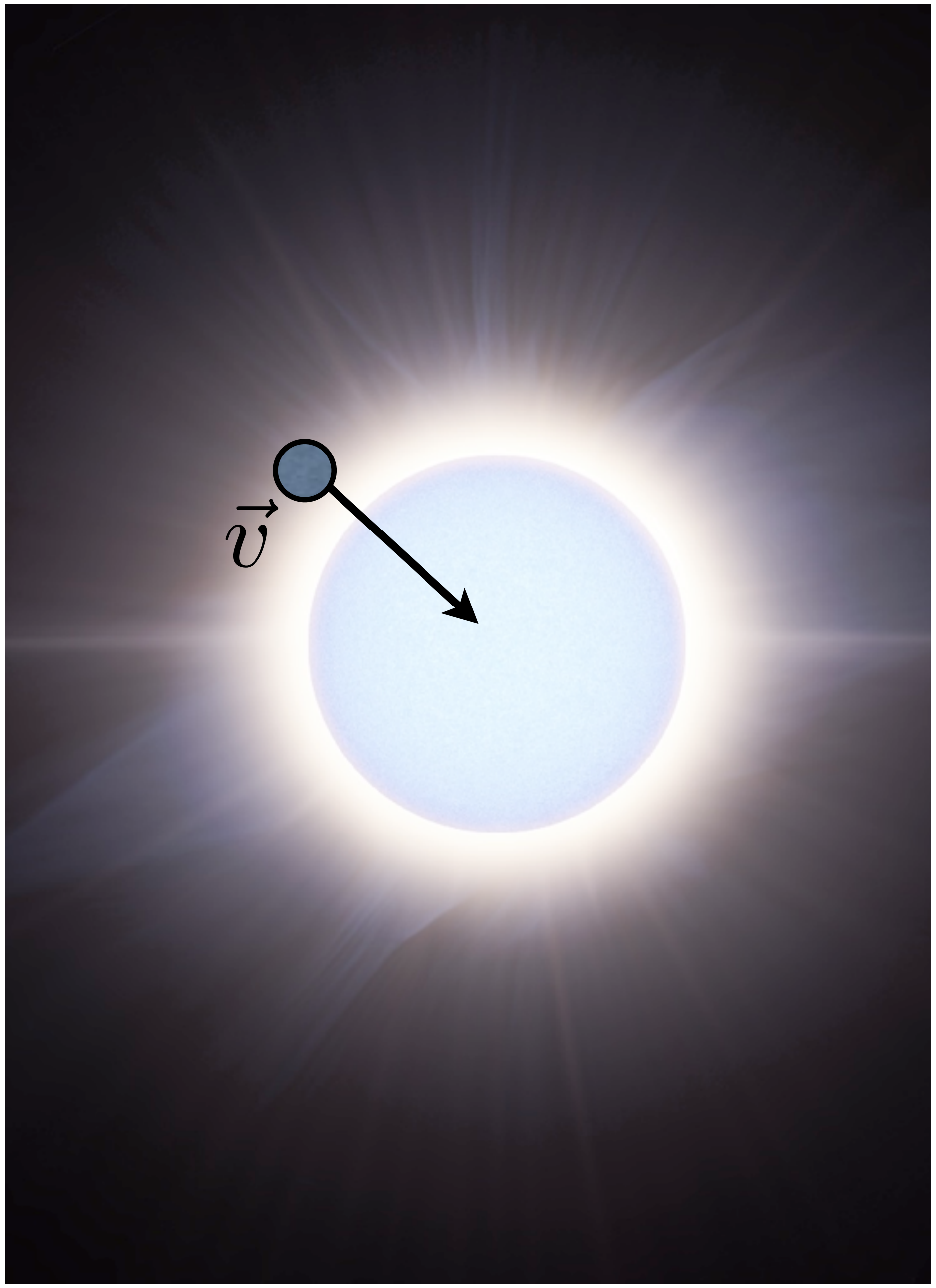
with

Peter Graham
Jaime Varela

arXiv:1505.04444

Exploding White Dwarfs: Basic Idea

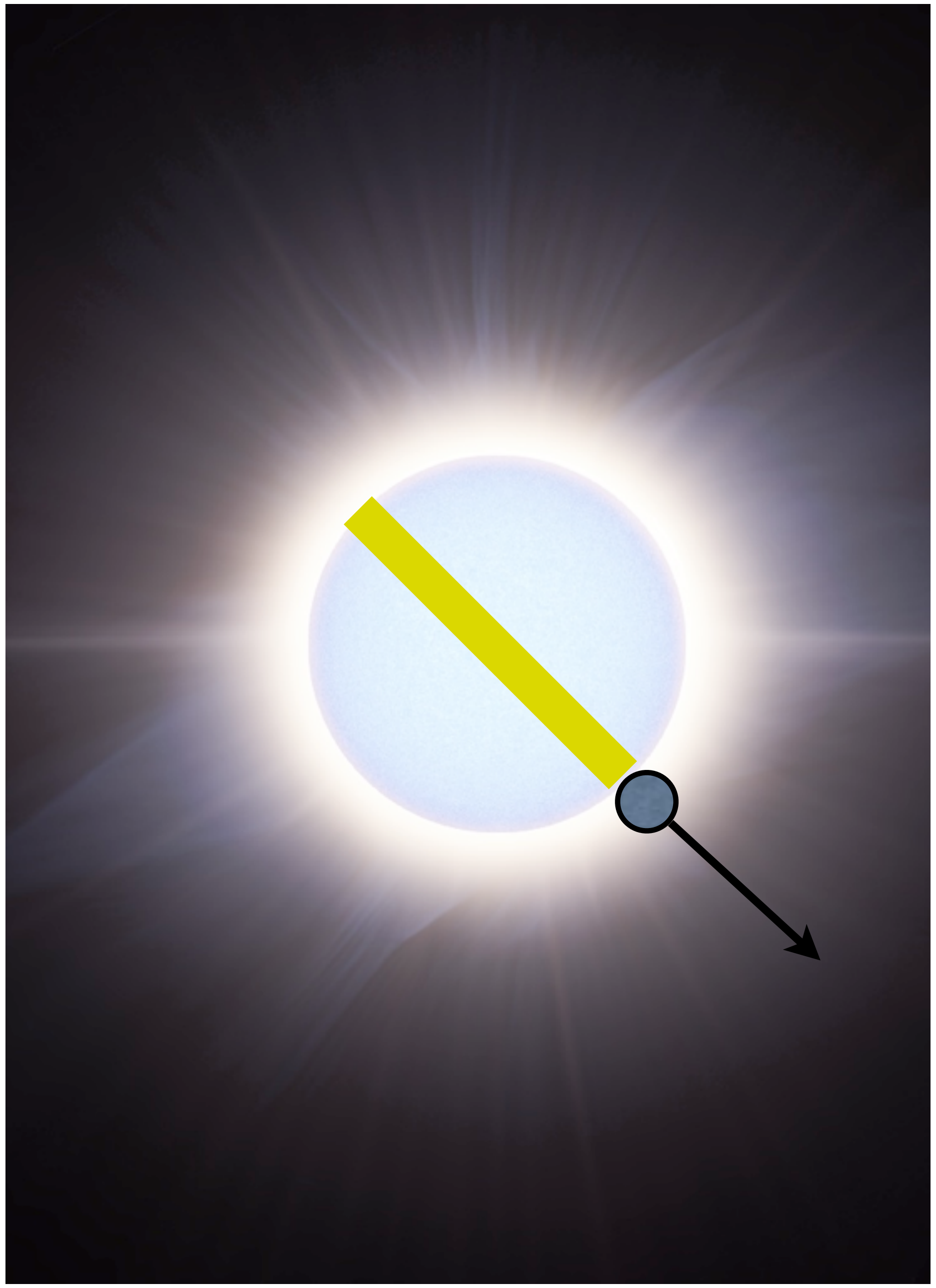
Exploding White Dwarfs: Basic Idea



Single dark matter event

e.g. transit of primordial black hole or Q ball through star

Exploding White Dwarfs: Basic Idea



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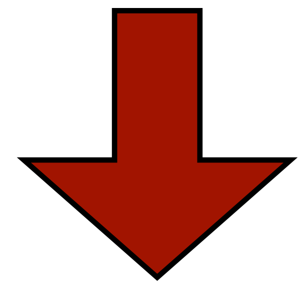

Localized energy deposition

Exploding White Dwarfs: Basic Idea

Single dark matter event

e.g. transit of primordial black hole or Q ball through star

↓

Localized energy deposition

↓

Triggers Type 1a Supernova, white dwarf explodes

Exploding White Dwarfs: Basic Idea

Single dark matter event

e.g. transit of primordial black hole or Q ball through star

↓

Localized energy deposition

↓

Triggers Type 1a Supernova, white dwarf explodes

Limits from sub-Chandrasekhar white dwarfs

Motivation

Dark Matter Interactions

Weak coupling with Standard Model

Dark Matter Interactions

Weak coupling with Standard Model

Self interactions?

Dark Matter Interactions

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Self interactions?

Weak

e.g. WIMPS, Axions...

Individual particles, large number density

Chance for events in human-scale detectors

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Strong

e.g. mirror QCD, neutron lighter than proton

- John March-Russell et.al (to appear), S.R. et.al. (to appear)

Large composite objects

Dark Matter Interactions

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Self interactions?

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e.g. WIMPS, Axions...

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e.g. mirror QCD, Q Balls, Primordial Black Holes

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Zero event rate in human scale detectors

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Large composite objects, very low number density

Zero event rate in human scale detectors

Large space-time volume detector needed

Exploding White Dwarfs: Basic Idea

Single dark matter event

White dwarf explodes as Type 1a supernova

Detector Capabilities

Area ~ (4000 km)^2 x 1000

Lifetime ~ 10^{10} yr

Event visible everywhere

Large space-time volume detector!

Exploding White Dwarfs: Basic Idea

Single dark matter event

White dwarf explodes as Type 1a supernova

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Area ~ $(4000\ \text{km})^2$ x 1000

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Good system for ultra heavy dark matter

Outline

1. Runaway fusion in White Dwarfs
2. Primordial Black Holes
3. Observational Constraints

Runaway Fusion in White Dwarfs

White Dwarf 101

Stellar remnant supported by electron degeneracy pressure

Electron degeneracy cannot support mass > 1.4 M_0

(Chandrasekhar Limit)

Densities ~ 10^6 gm/cm^3 for 0.5 M_0 to 10^9 gm/cm^3 for 1.3 M_0

Core is mainly Carbon/Oxygen

Also, Oxygen/Neon/Magnesium

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Core is mainly Carbon/Oxygen

Also, Oxygen/Neon/Magnesium

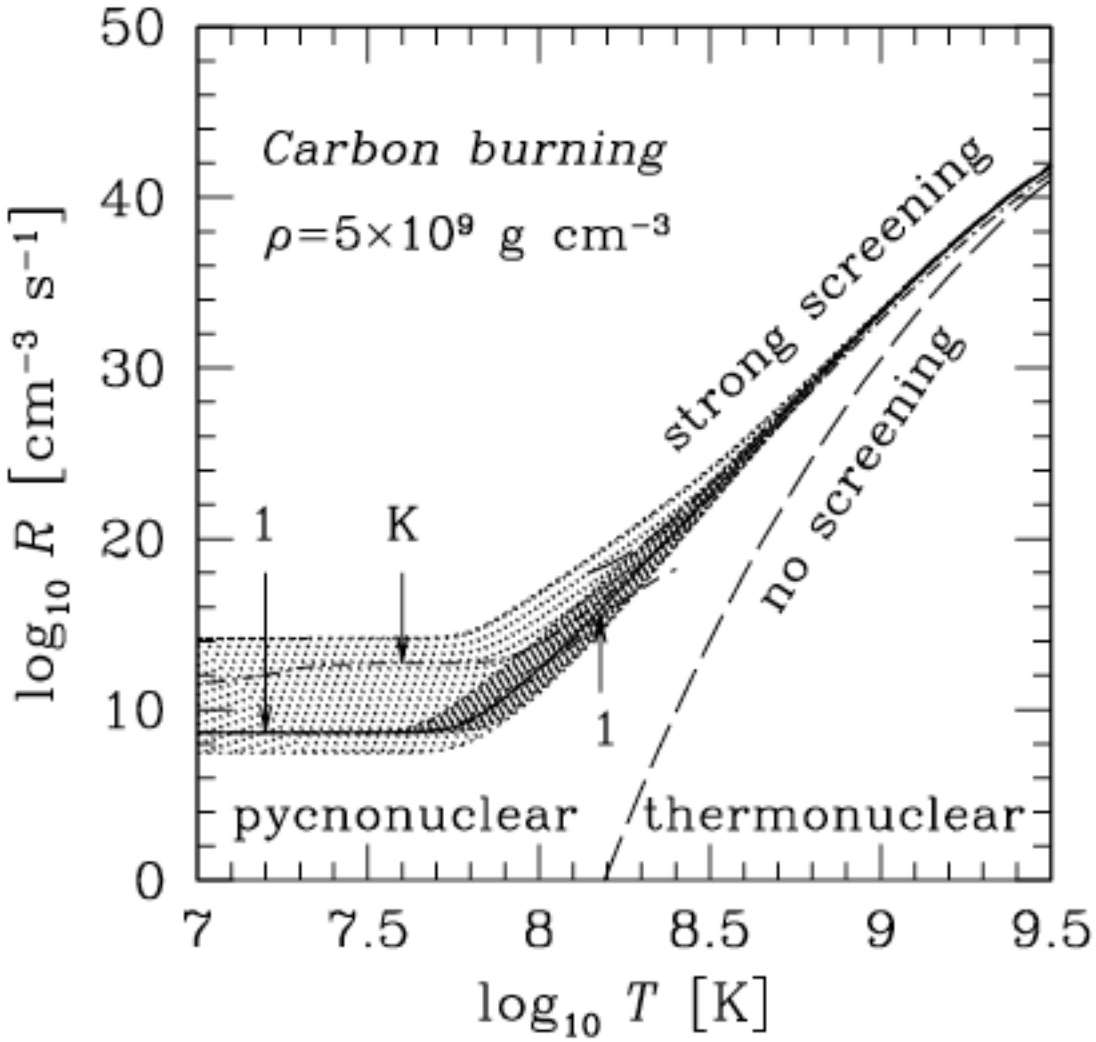
Core can still undergo fusion

As star gets close to 1.4 M_0, runaway fusion occurs causing Type 1a Supernova

Our bounds come from causing supernovae well below this mass

Runaway Fusion

Carbon Fusion Rate

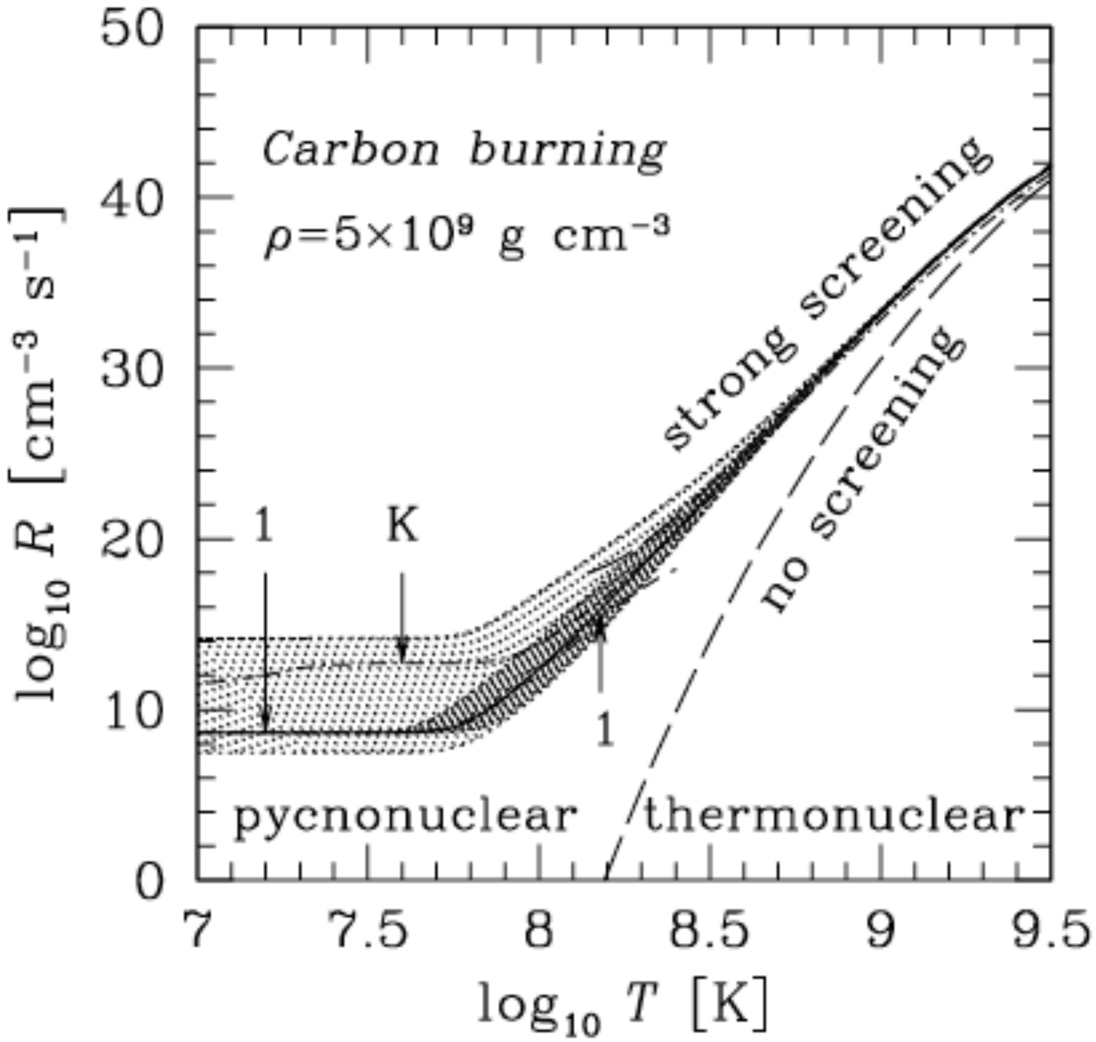


L.R. Gasques et.al. , Phys. Rev. C 72 (2005)

Fusion rates are exponentially sensitive to temperature

Runaway Fusion

Carbon Fusion Rate



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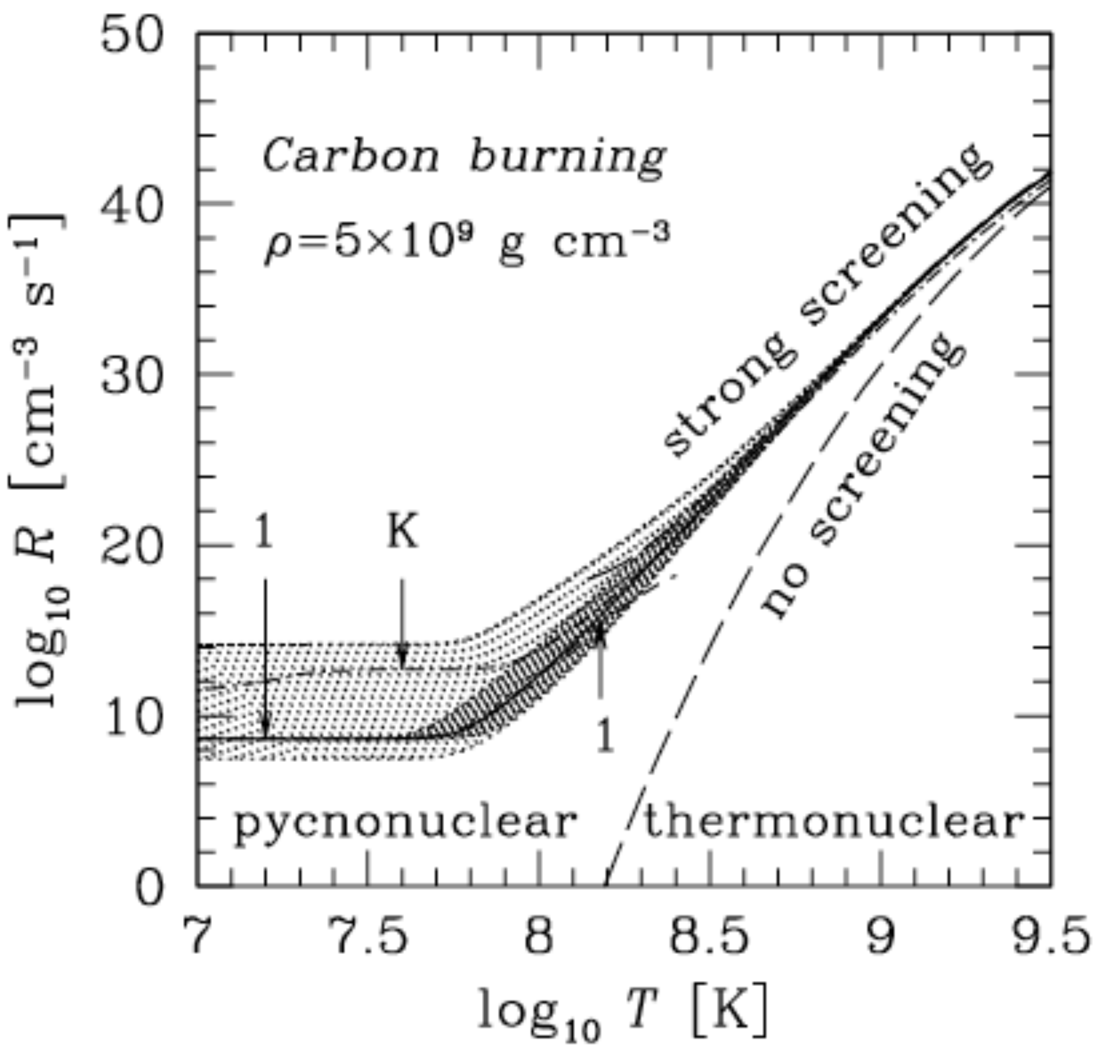
$$\frac{R(300\ \mathrm{keV})}{R(10\ \mathrm{keV})} \gtrsim 10^{30}$$

Runaway Fusion

Carbon Fusion Rate



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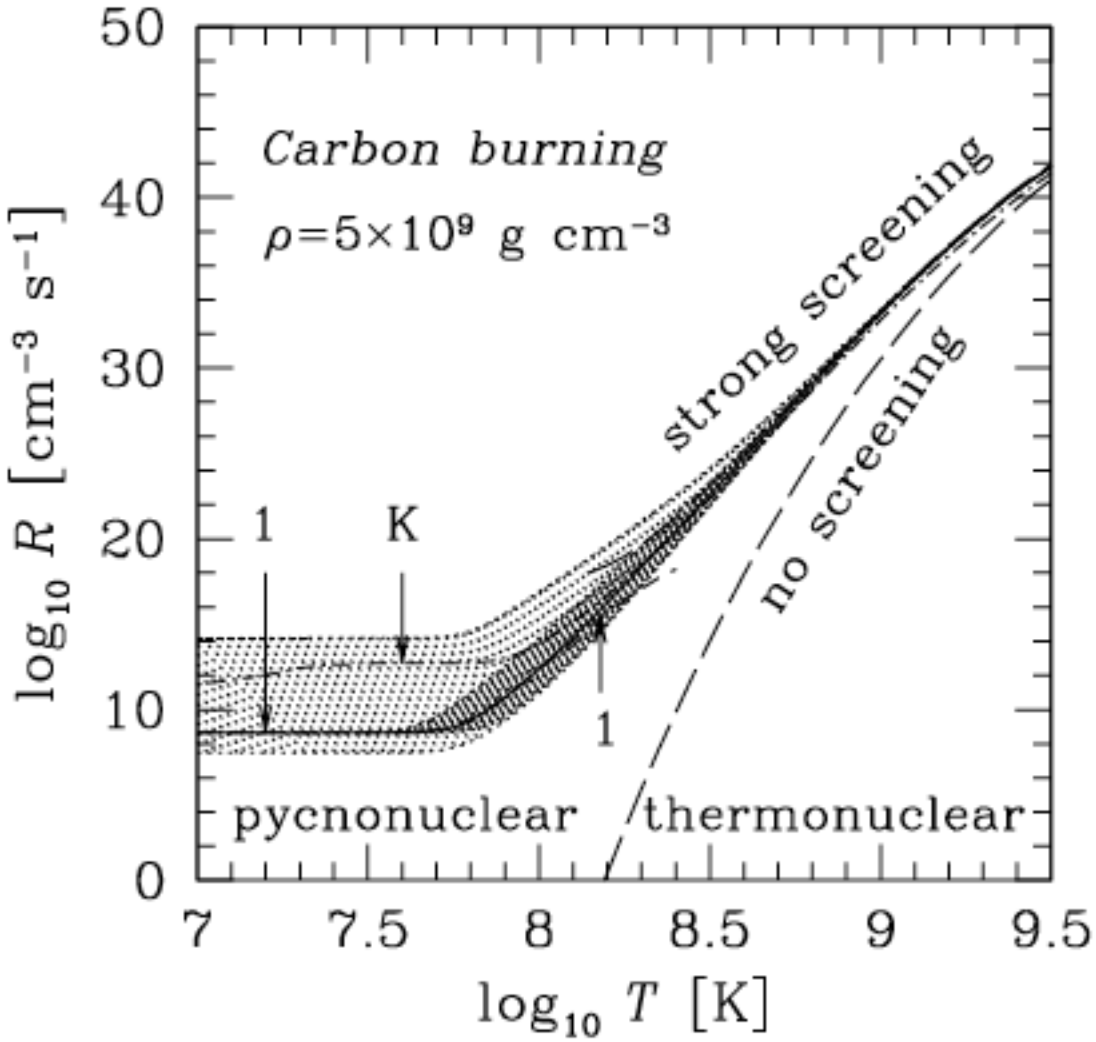
Each fusion releases ~ 10 MeV

Rapid Fusion of more Carbon

Runaway Fusion

Carbon Fusion Rate



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Rapid Fusion of more Carbon

Chain Reaction Possible

Small number of initial fusion reactions can trigger many more

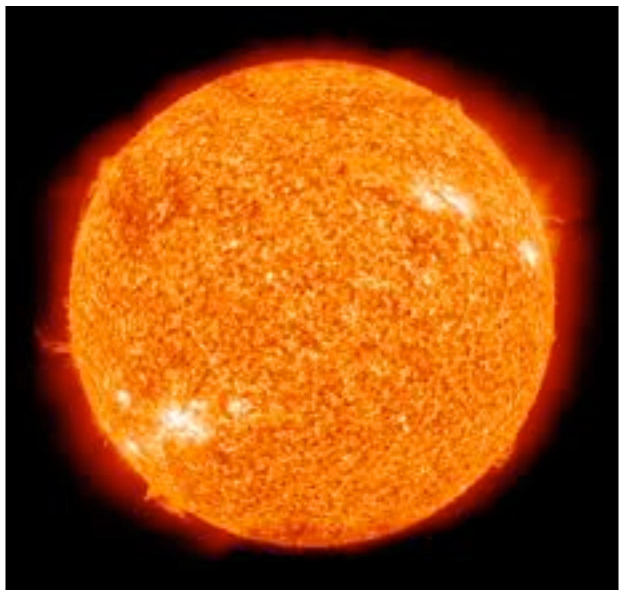
Runaway Fusion

Local Increase in Temperature

Runaway Fusion

Local Increase in Temperature

Sun



$$P \propto T$$

Temperature leads to expansion

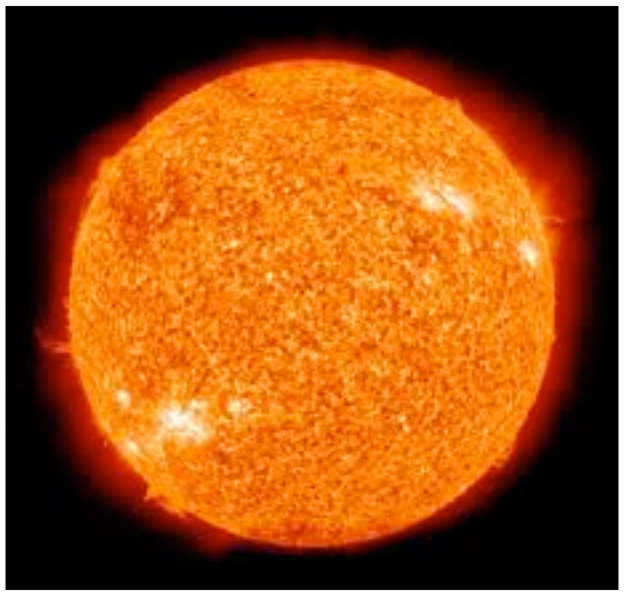
Expansion lowers density and cools medium

Decreases fusion. Stable equilibrium

Runaway Fusion

Local Increase in Temperature

Sun



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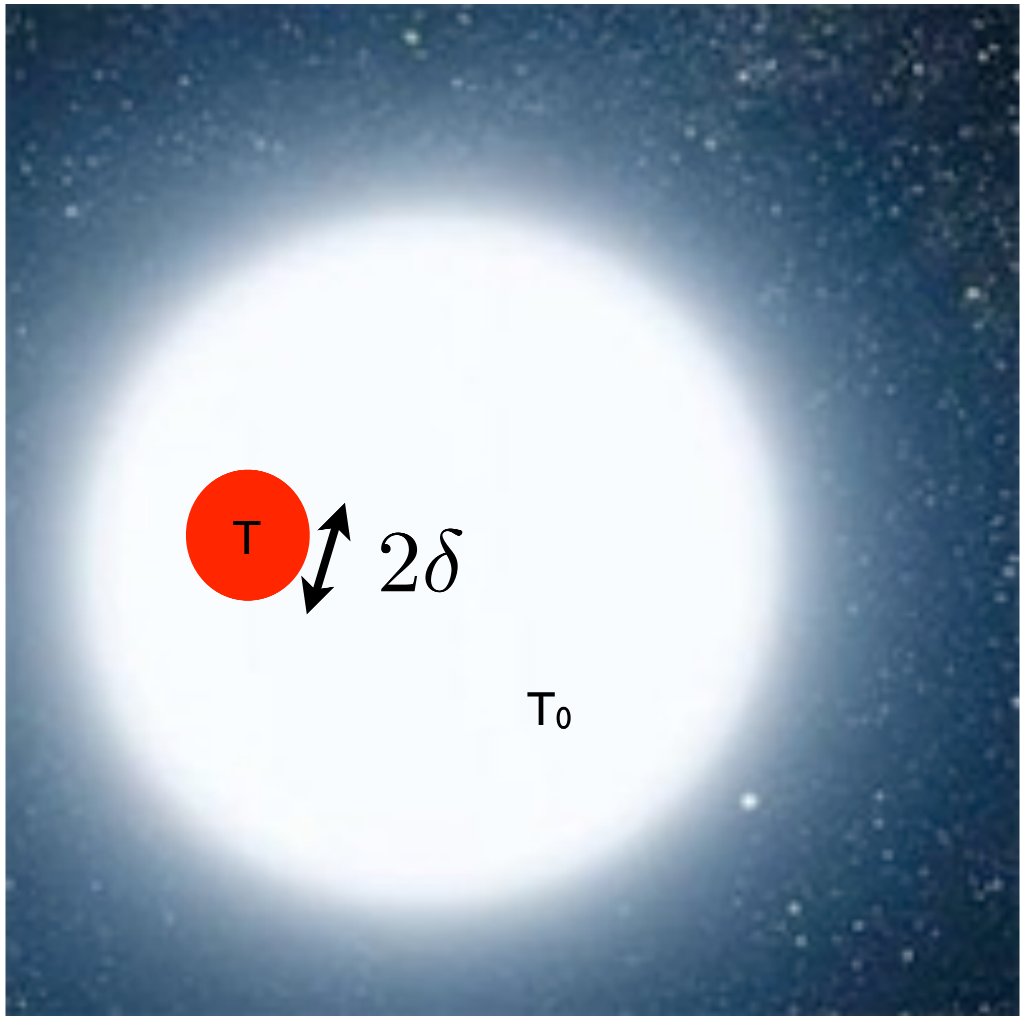
White Dwarf

Degenerate gas
Pressure and density independent of temperature

High T leads to higher rate of fusion

Absence of self-regulation. Explosive

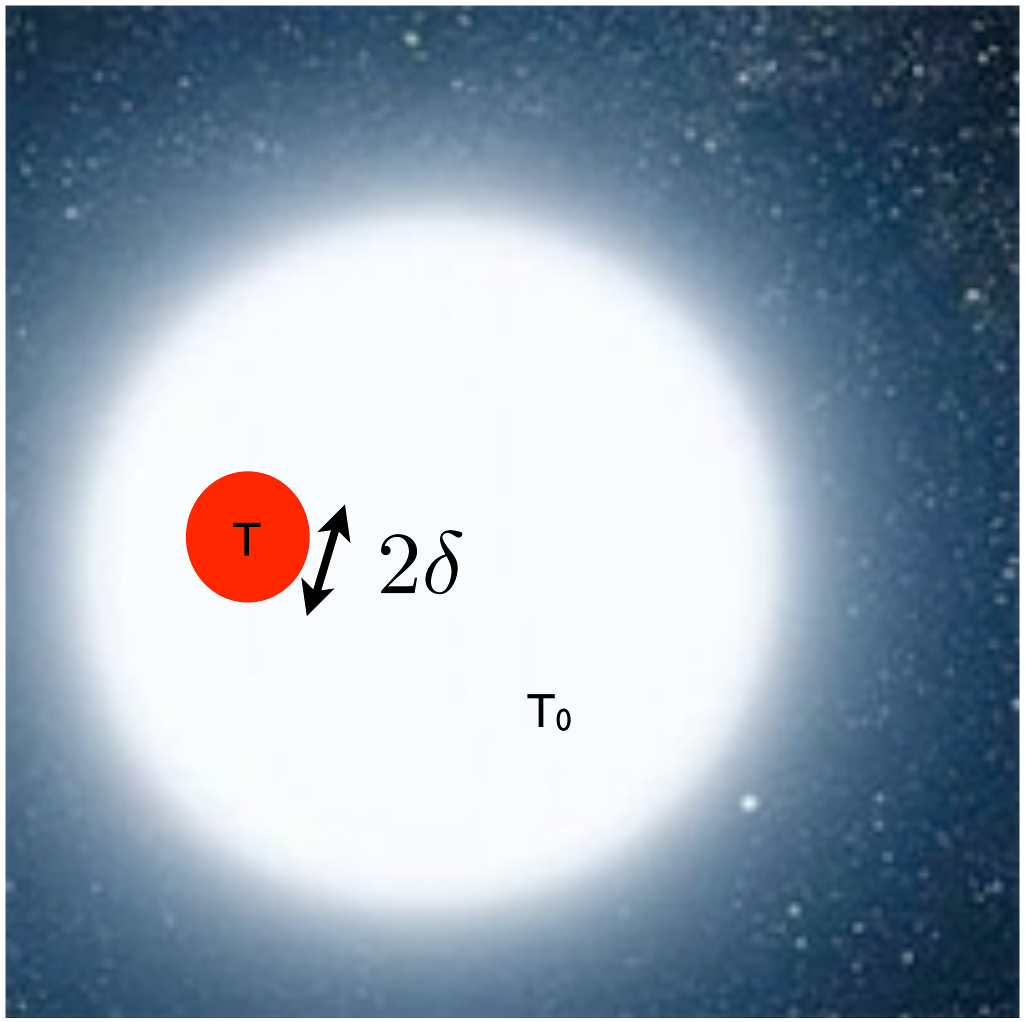
Triggering Runaway Fusion



Sphere of Radius δ

Set at $T \gg T_0$

Triggering Runaway Fusion



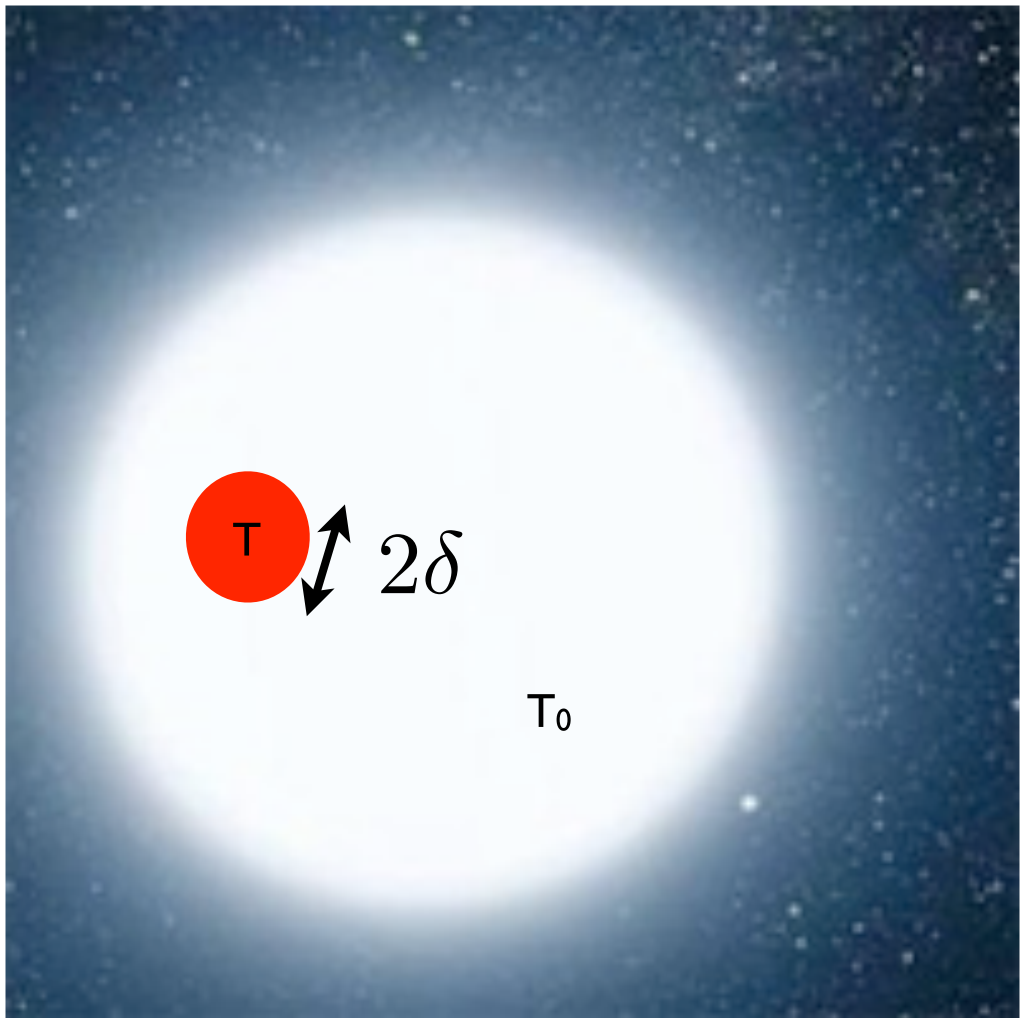
Sphere of Radius δ

Set at $T \gg T_0$

Heat dissipates out, lowering T

Fusion occurs, increasing T

Triggering Runaway Fusion



Sphere of Radius δ

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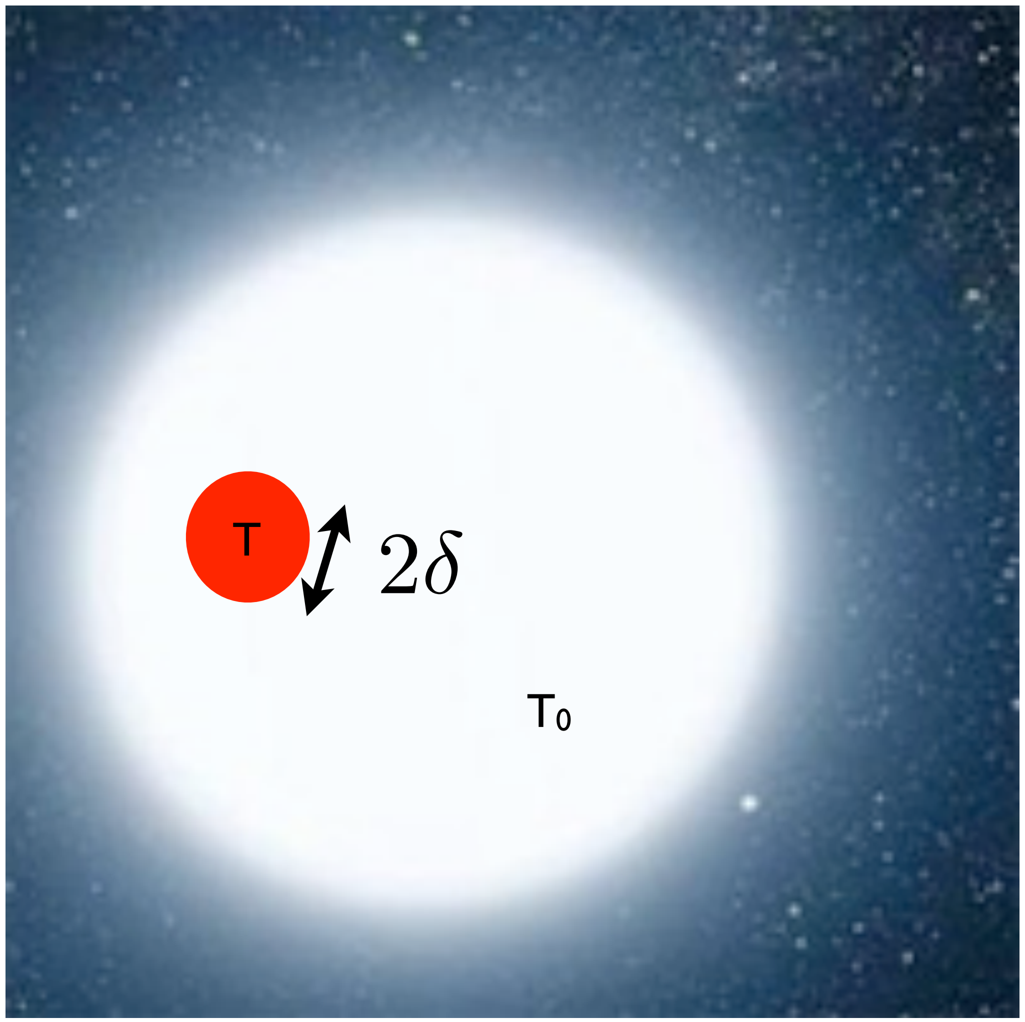
Two Possibilities

Dissipation rate > Fusion rate.
Trigger fizzles. No explosion.

Fusion rate > Dissipation rate.
Explosion.

Thermal Dissipation

The Heat Equation



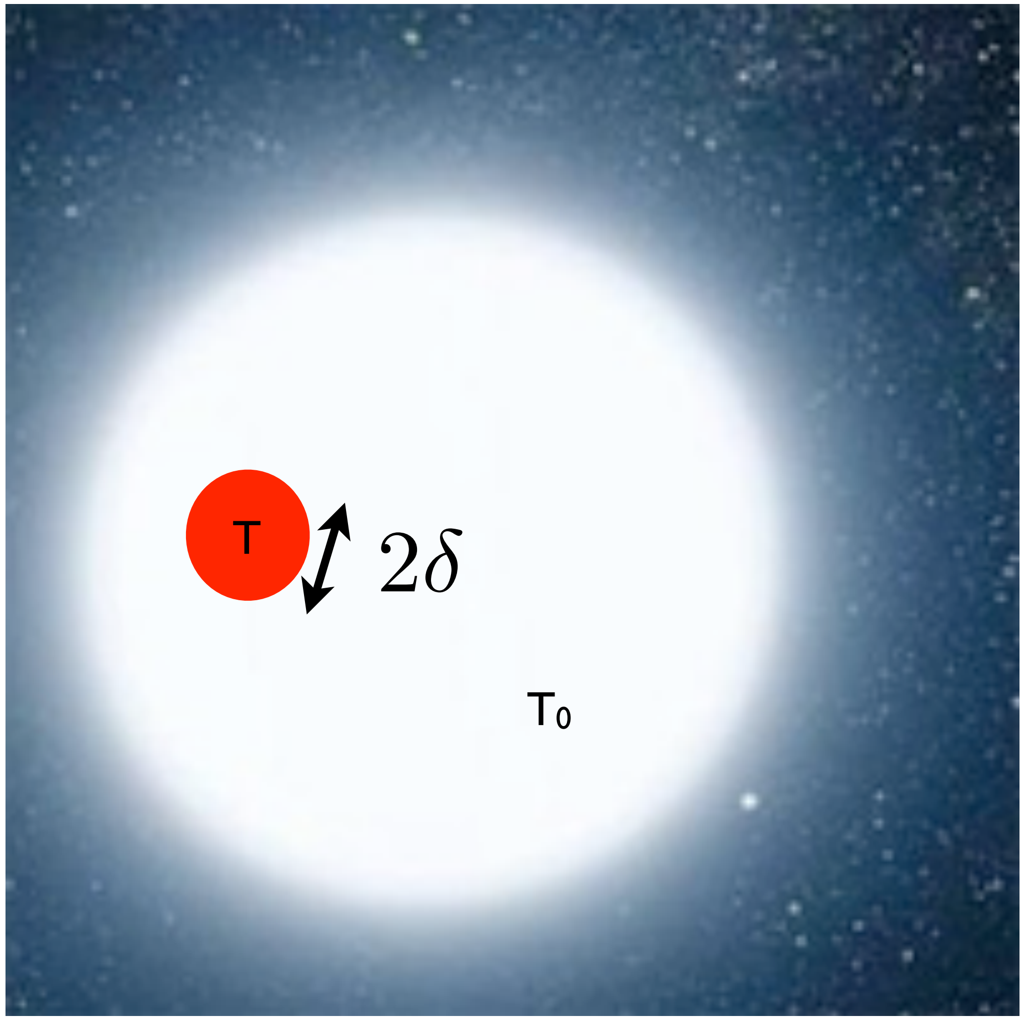
Given $T(0,r)$, find $T(t,r)$

$$\frac{\partial T}{\partial t} = \frac{1}{c_p \rho} \nabla . \left(K_{cd} \nabla T \right)$$

$K_{cd} =$ Conductivity of Carrier

Thermal Dissipation

The Heat Equation



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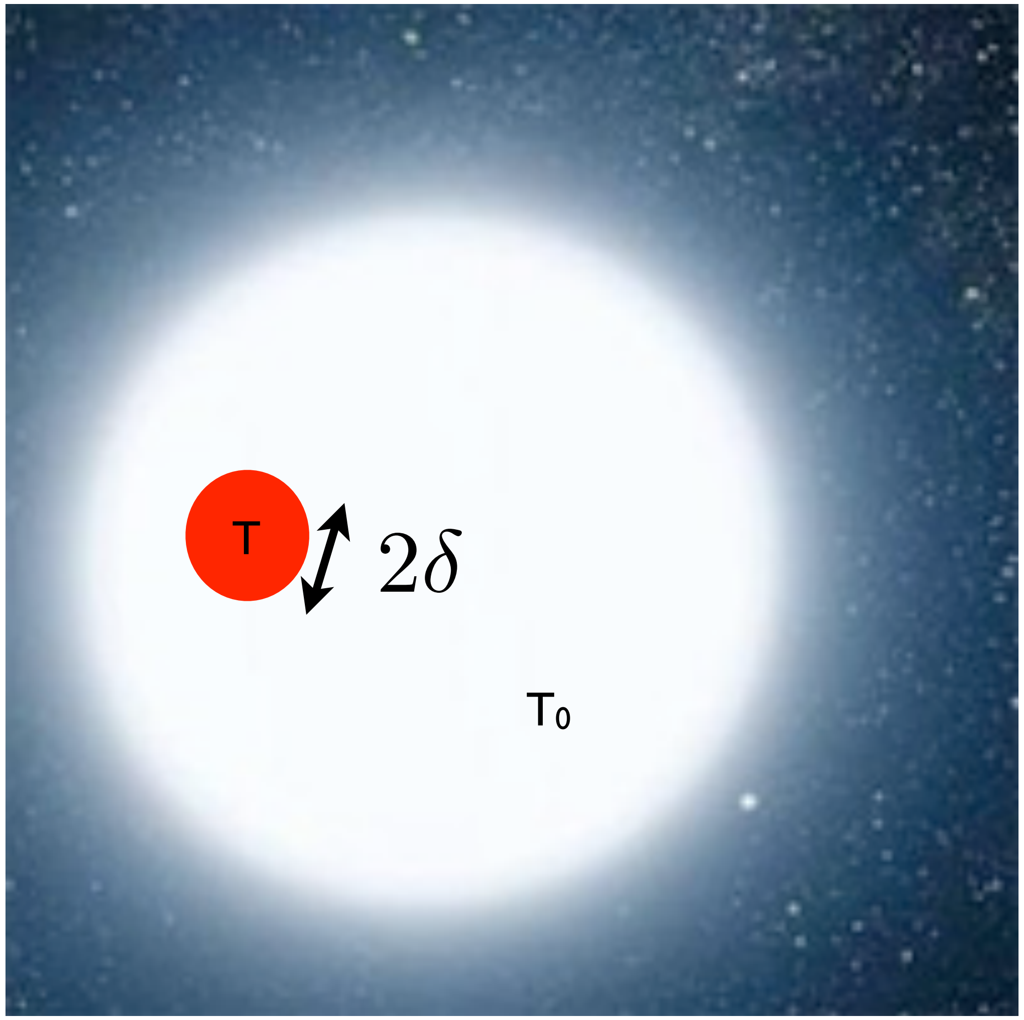
$$K_{cd} = \text{ Conductivity of Carrier}$$

Approximate Solution

$\mathcal{O}\left(1\right)$ change in T: Diffusion time scale τ

$$\tau \approxeq \frac{c_p \rho}{K_{cd}} \delta^2$$

Trigger Size



$\mathcal{O}(1)$ change in T: Diffusion time scale τ

$$\tau \approx \frac{c_p \rho}{K_{cd}} \delta^2$$

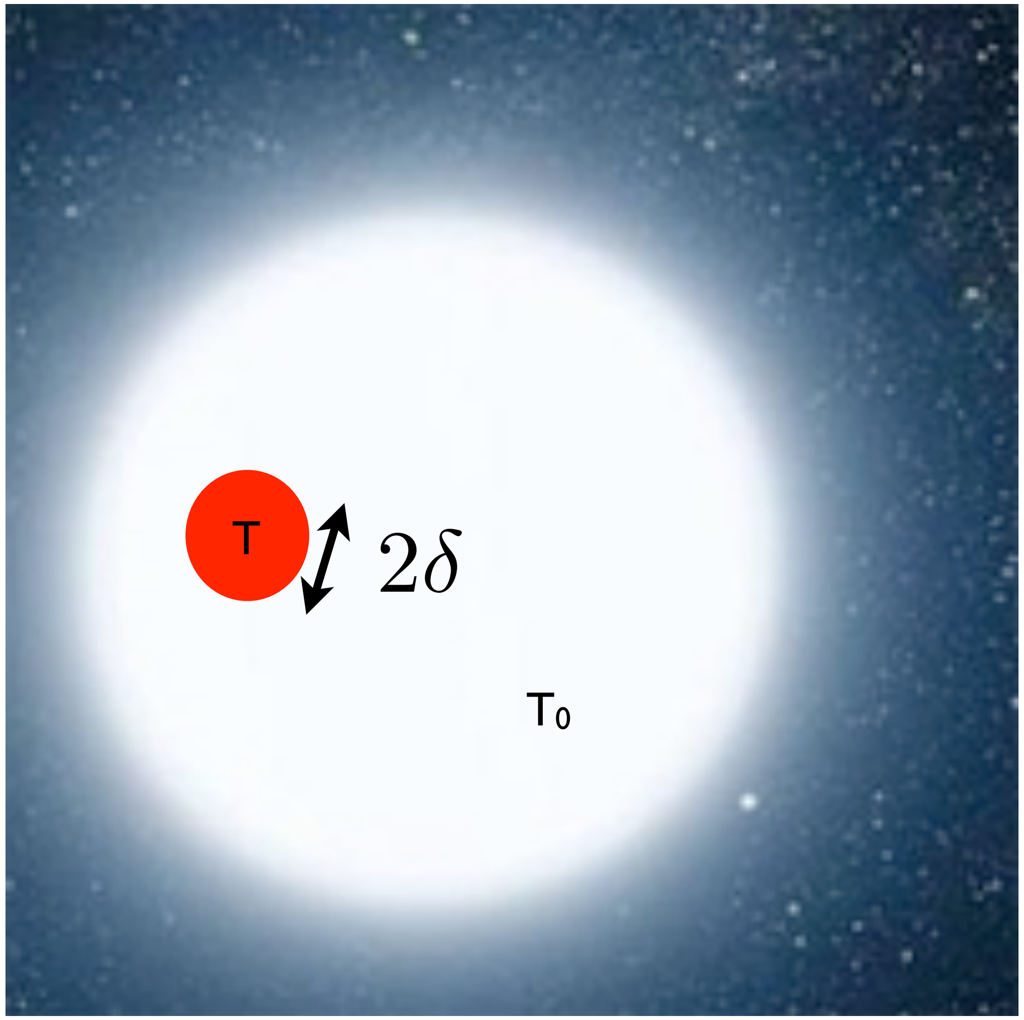
Larger δ, slower diffusion

Fusion Rate $R(T)$

Require $R(T)\,\tau \gtrapprox 1$

$\Longrightarrow$ Complete fusion within δ

Trigger Size



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Larger δ, slower diffusion

Fusion Rate $R(T)$

Require $R(T)\,\tau \gtrapprox 1$

$\Longrightarrow$ Complete fusion within δ

Fusion releases ~ 10 MeV energy. Larger region is now hotter.

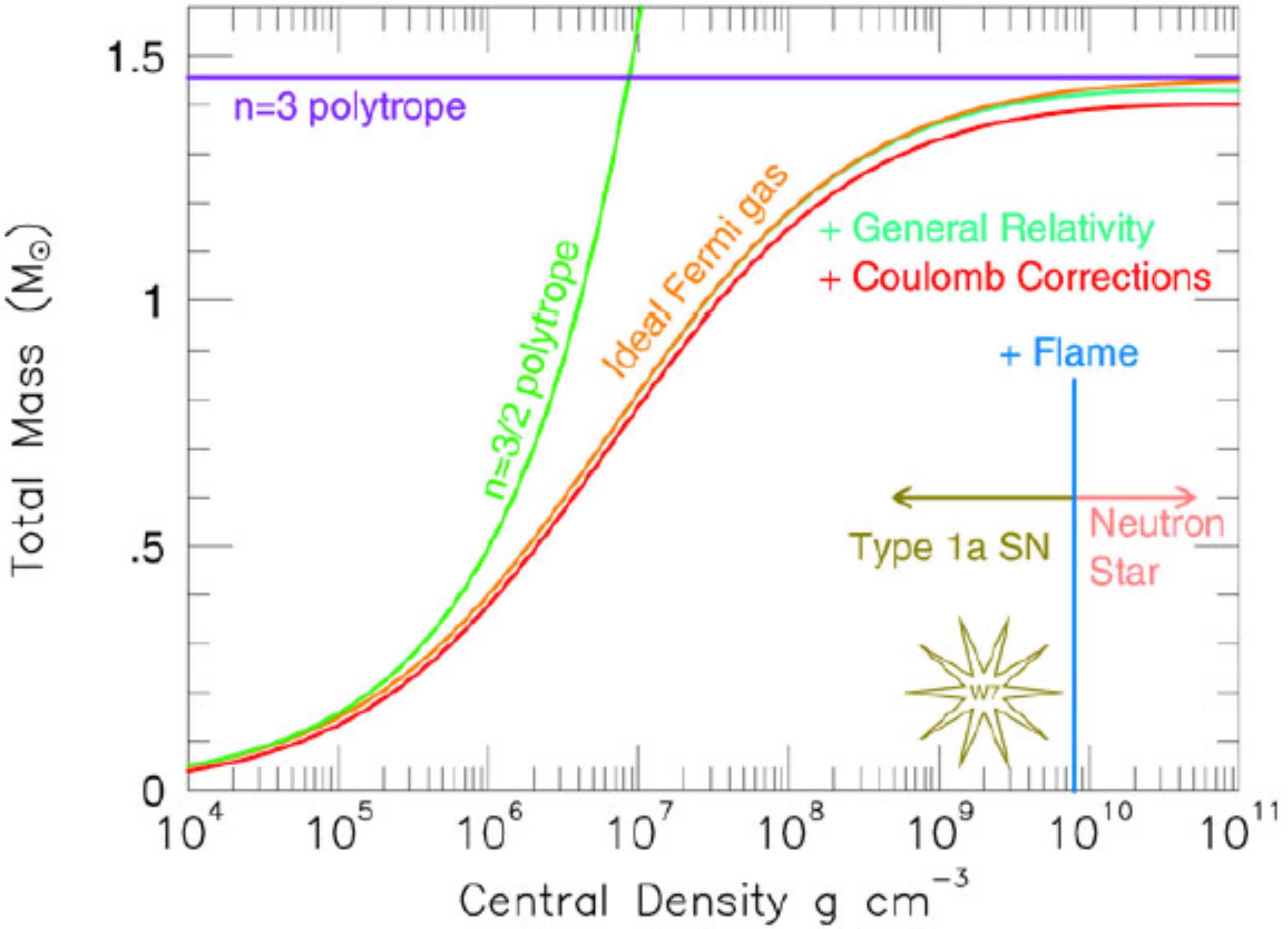
Slower diffusion, fixed fusion rate. Condition more easily satisfied.

Chain reaction!

Sets trigger size δ

The Bottomline

Exploding sub-Chandrasekhar White Dwarfs



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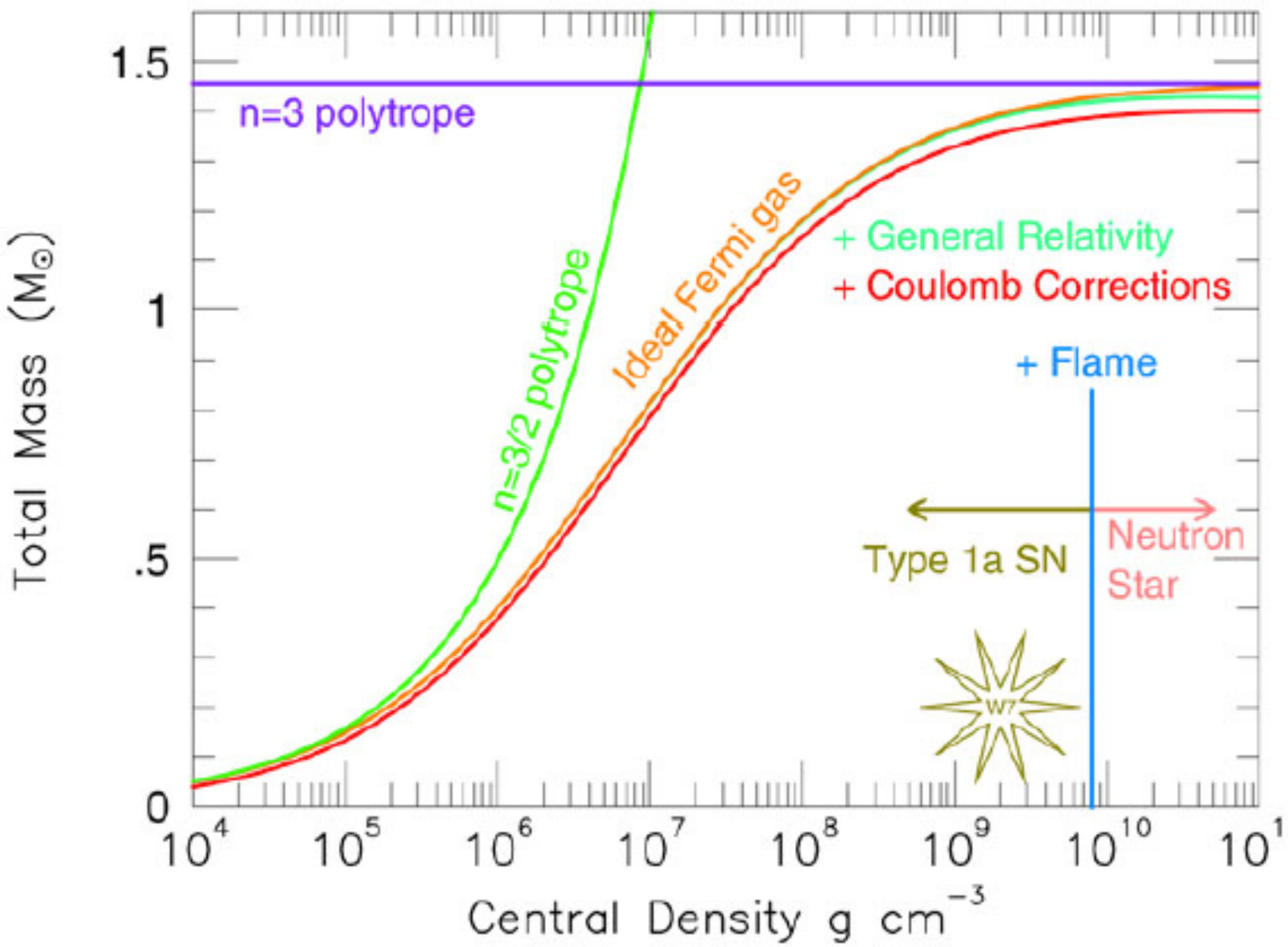

Trigger Temperature ~ 1 MeV

$$\delta \gtrsim 10^{-2}\ \mathrm{cm}\ @\ 0.7 M_\odot$$

$$\delta \gtrsim 10^{-4}\ \mathrm{cm}\ @\ 1.2 M_\odot$$

$$\delta \gtrsim 10^{-5}\ \mathrm{cm}\ @\ 1.3 M_\odot$$

Primordial Black Holes

Transit of Primordial Black Hole

$$10^{24}\ \text{gm} \gtrapprox M_{BH} \gtrapprox 10^{17}\ \text{gm}$$

$$10^{-4}\ \text{cm} \gtrapprox R_{BH} \gtrapprox 10^{-11}\ \text{cm}$$

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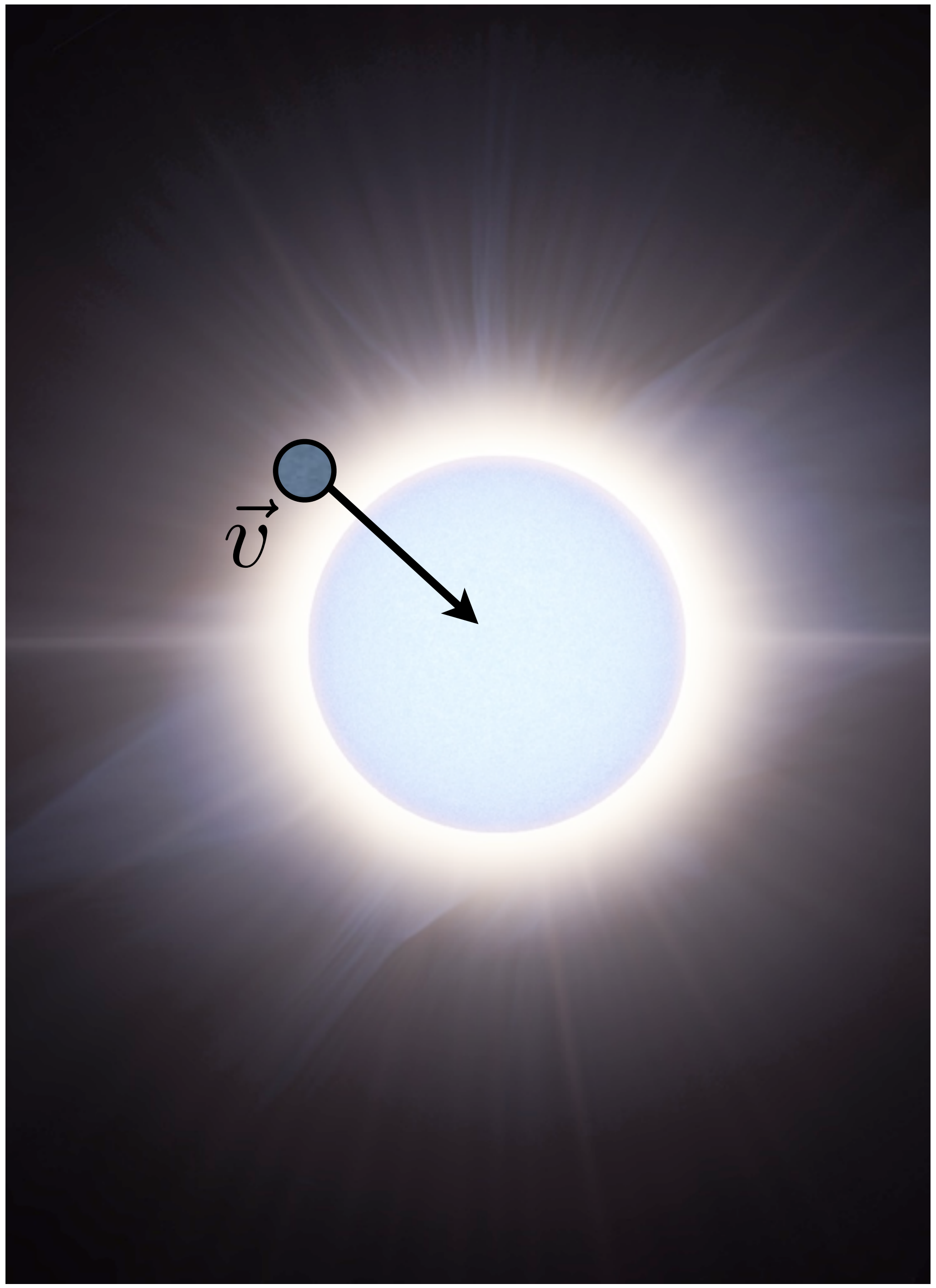

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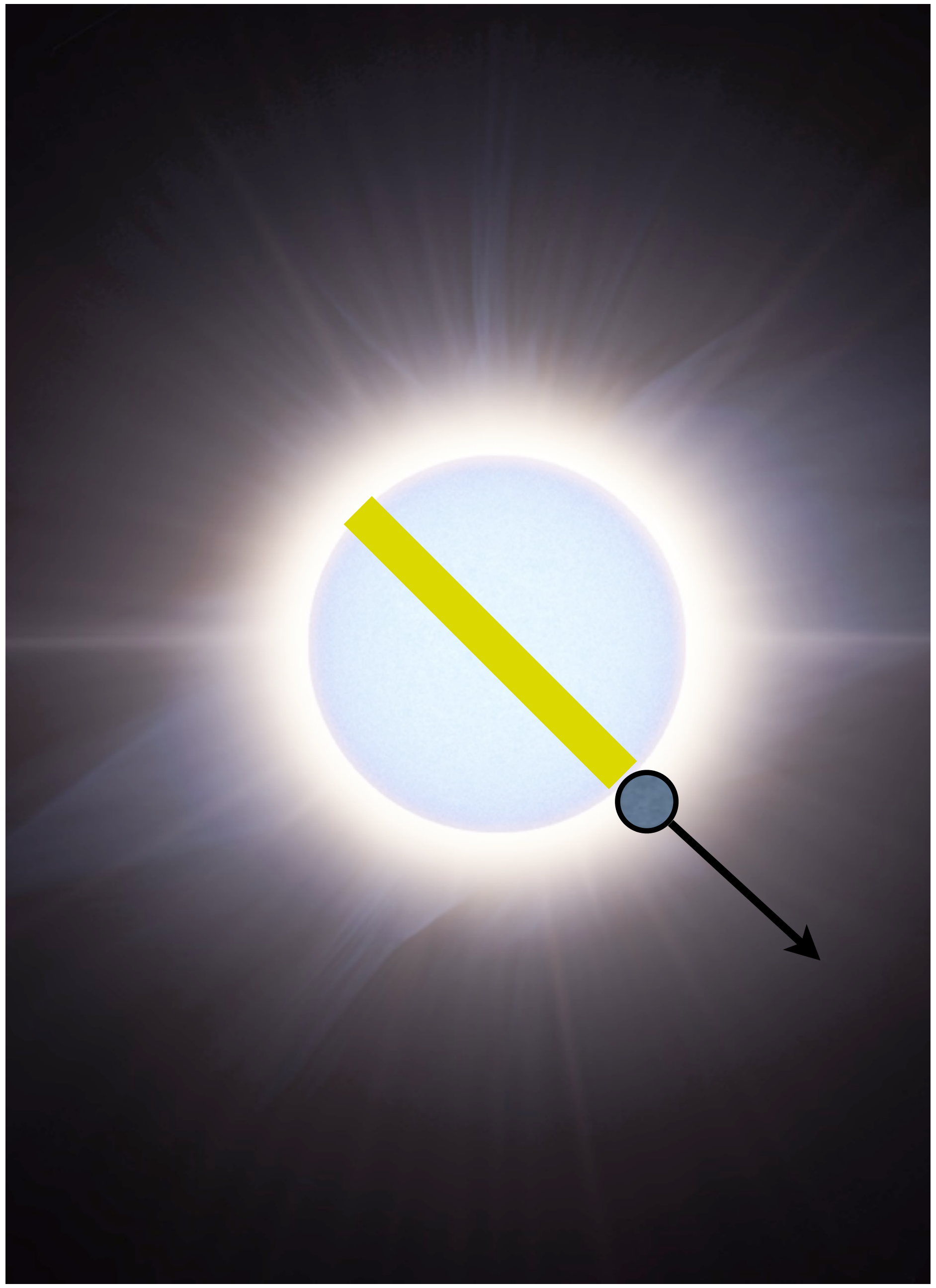

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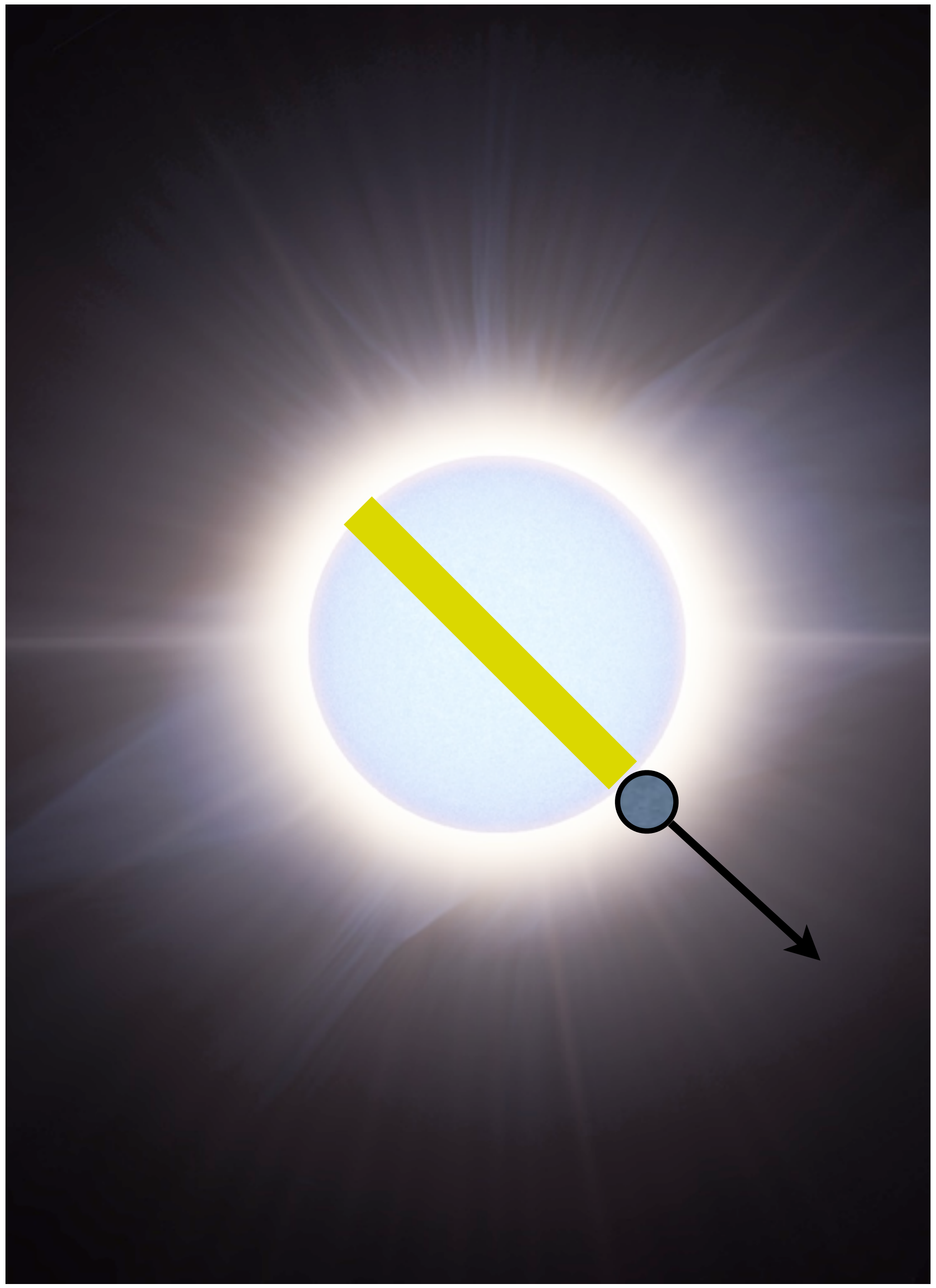
Tiny black hole
Tiny gravitational perturbation
Goes through star

Transit of Primordial Black Hole



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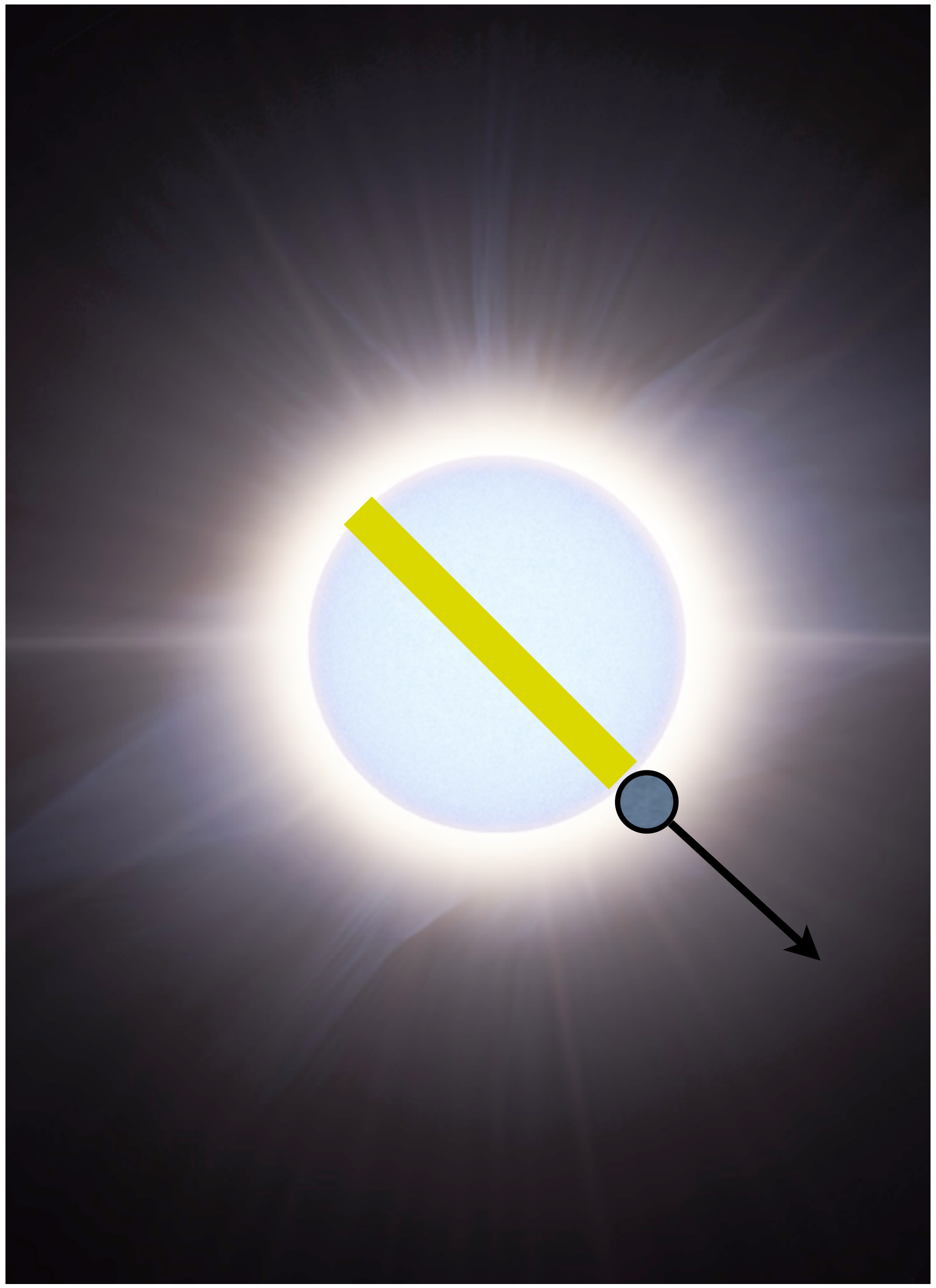
Tiny gravitational perturbation
Goes through star

Gravitational pull significant on tiny region near black hole

Localized heating (dynamical friction)

Transit of Primordial Black Hole



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Tiny black hole
Tiny gravitational perturbation
Goes through star

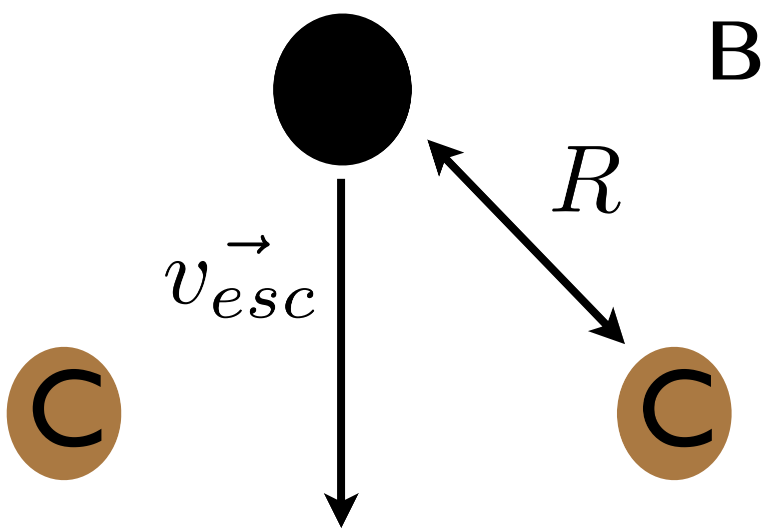
Gravitational pull significant on tiny region near black hole

Localized heating (dynamical friction)

Supernova if heating > trigger

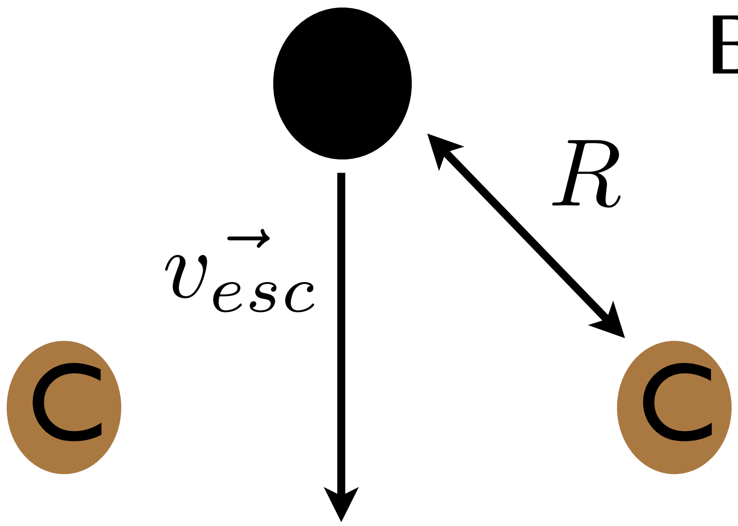
Heating by Black Hole

(Dynamical Friction)



Black hole enters star at escape velocity ~ 10^{-2}

Heating by Black Hole
(Dynamical Friction)



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$$v_{esc} > c_s$$

Instant approximation holds

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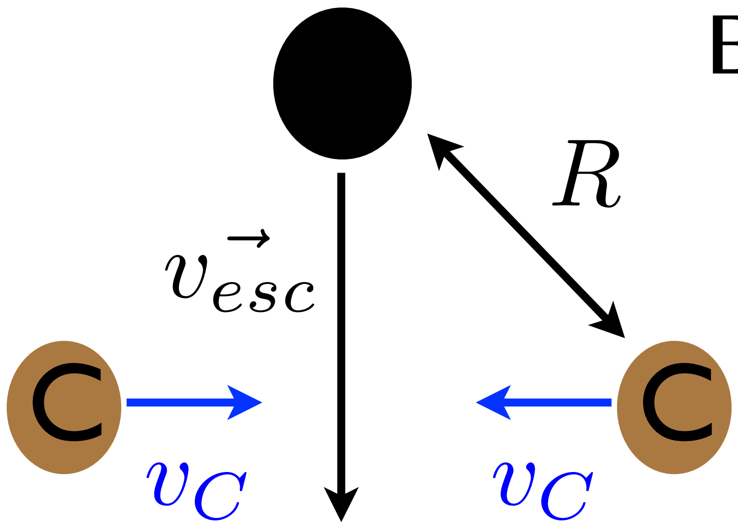

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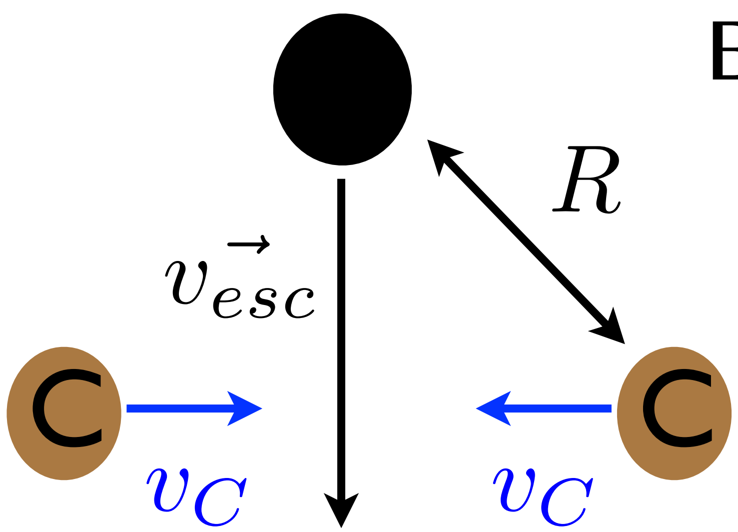
$$v_C \approx \left(\frac{GM_{BH}}{R^2} \right) \times \frac{R}{v_{esc}}$$

Heating by Black Hole

(Dynamical Friction)



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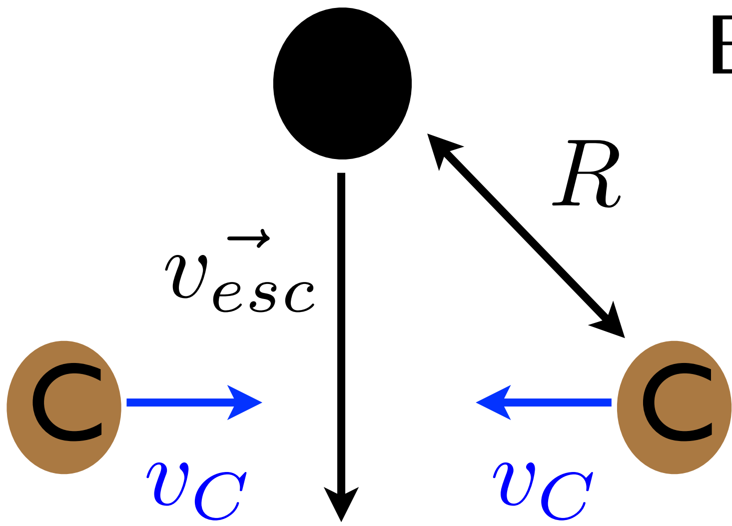
$$T_C \approx m_C v_C^2 \gtrapprox 1 \text{ MeV} \implies v_C \gtrapprox 10^{-2}$$

$$R \lessapprox 10^4 R_{BH} \approxeq 10^{-5} \text{ cm} \left(\frac{M_{BH}}{10^{19} \text{ gm}}\right)$$

Heating by Black Hole

(Dynamical Friction)



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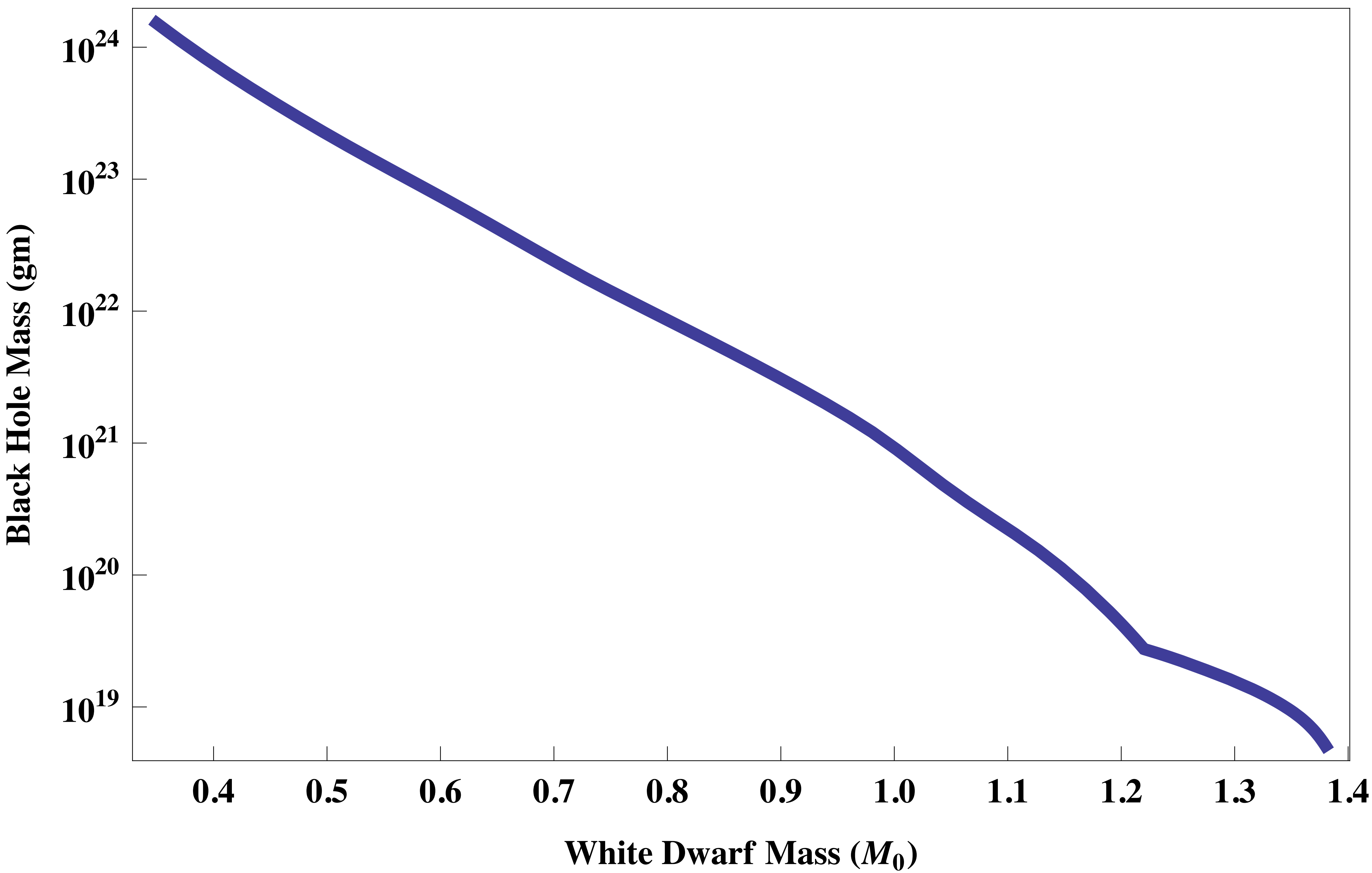
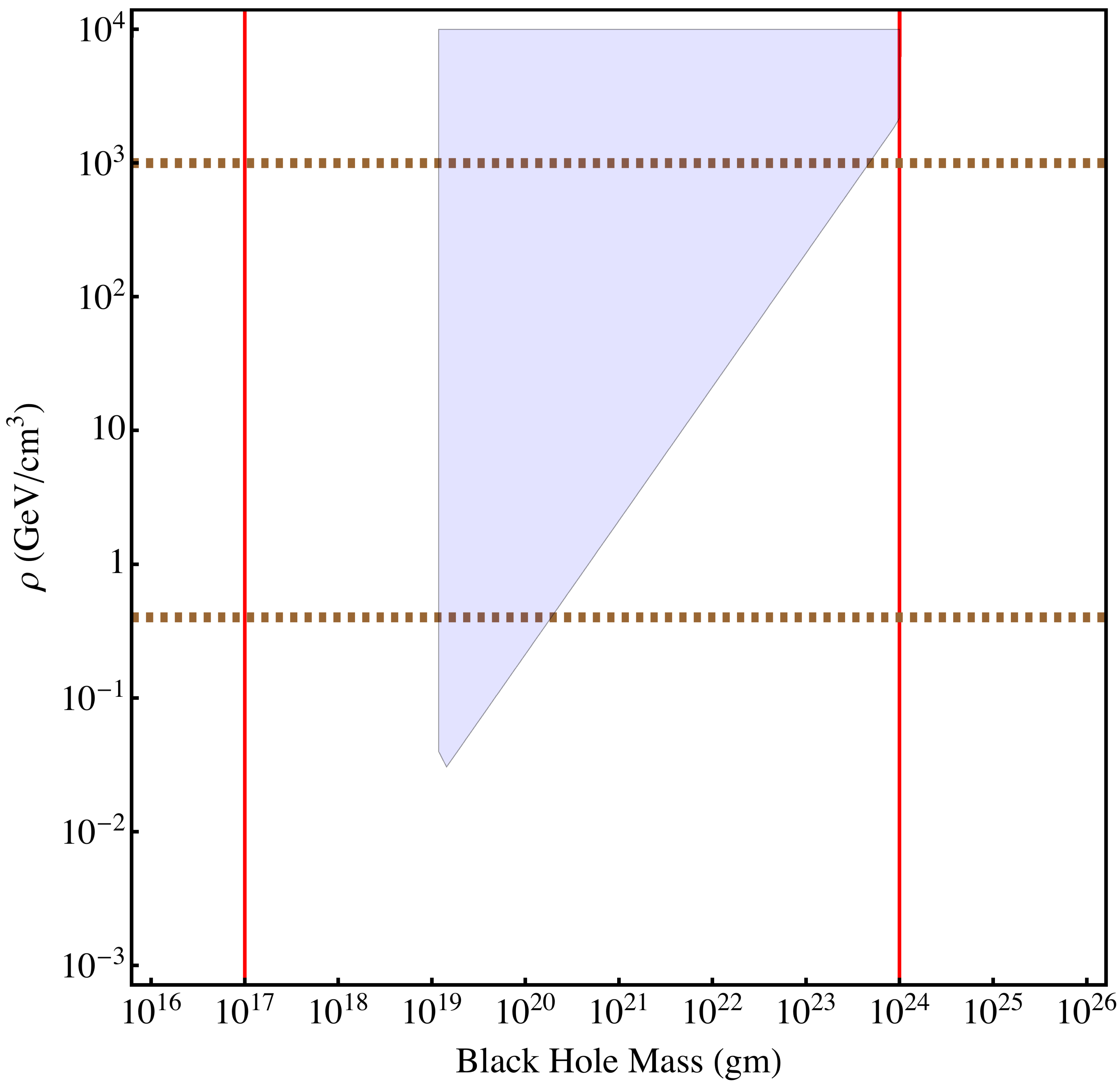
Compare with trigger size

White Dwarf Destroyers



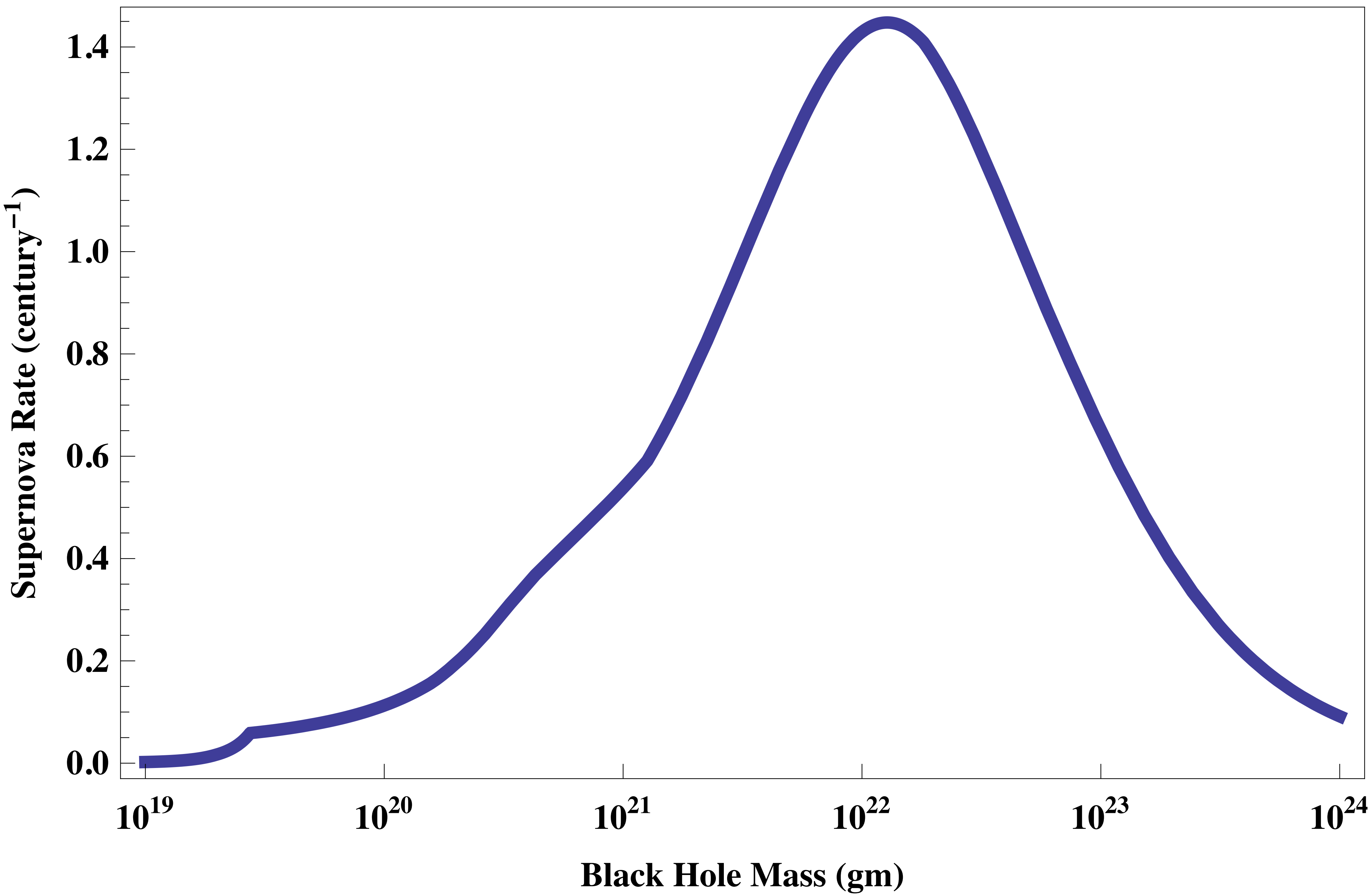
Observational Constraints

Black Hole Capture Rate

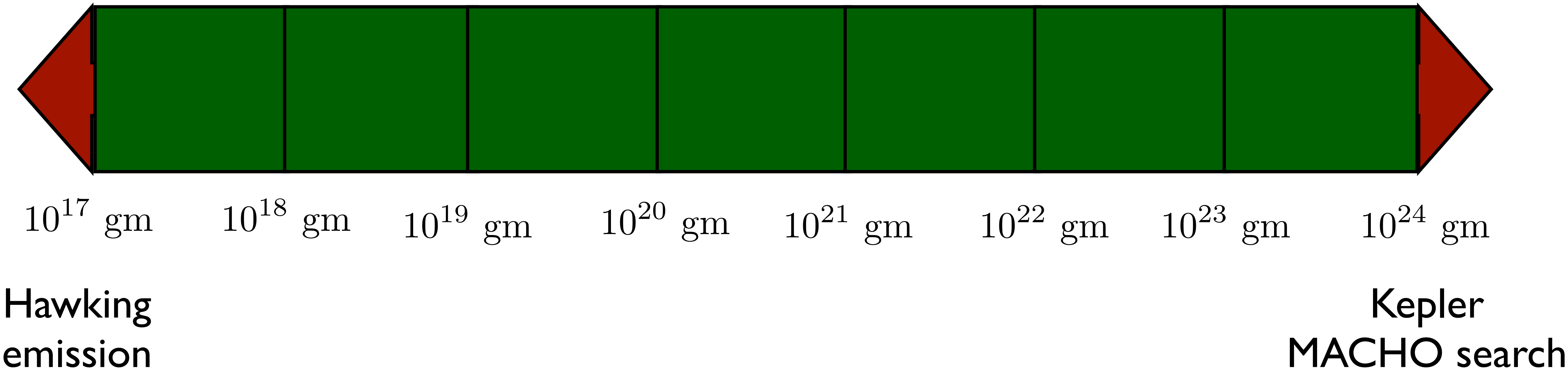


Black hole transits white dwarf within 1/5th of the age of the universe

Supernova Rate



Constraints on Primordial Black Holes



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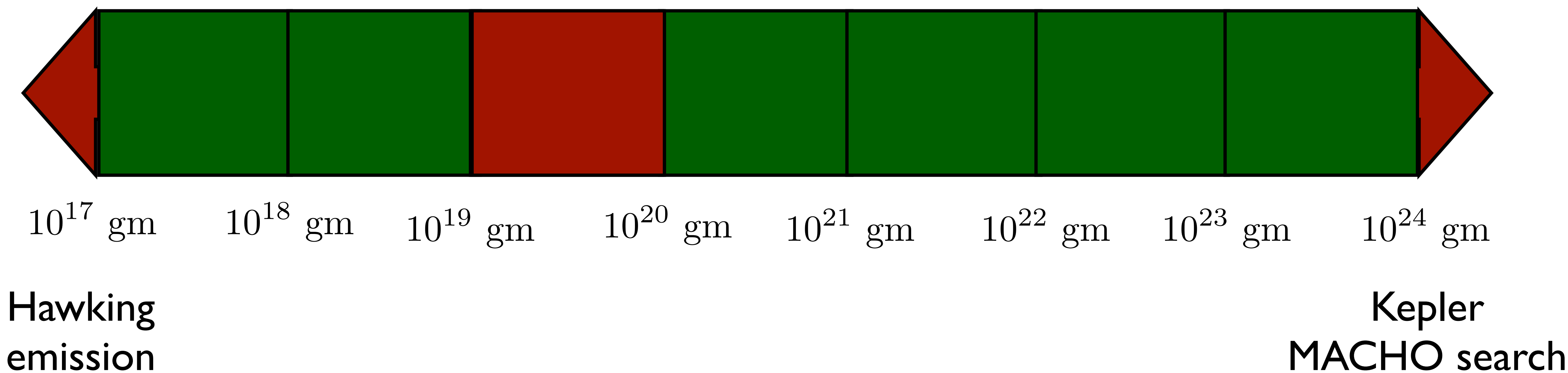

Existence of certain heavy (> 1.28 M_0) white dwarfs (e.g. RX J0648.0 - 4418)

Local population distribution of heavy (> 1.15 M_0) fits falling gaussian

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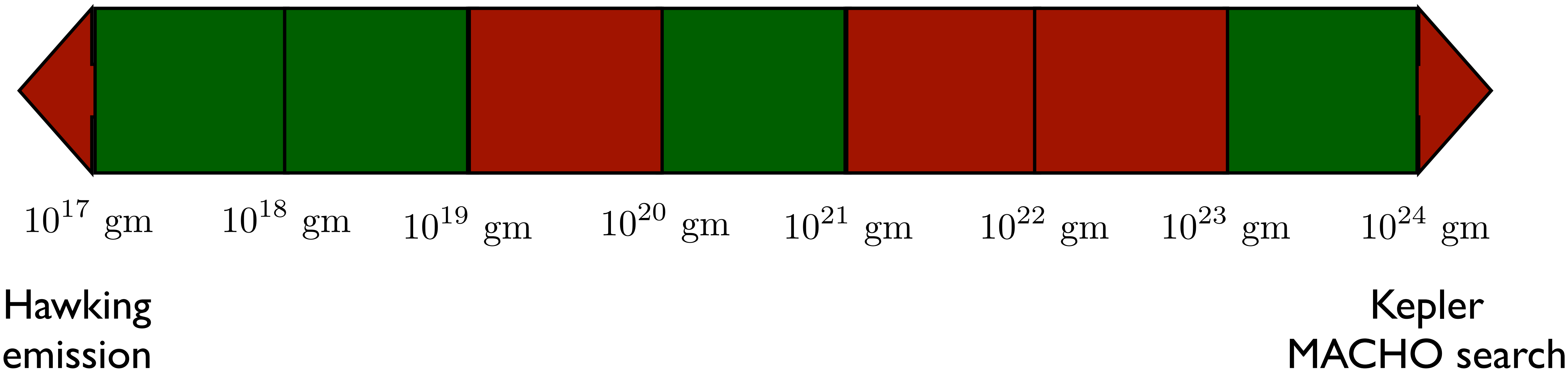

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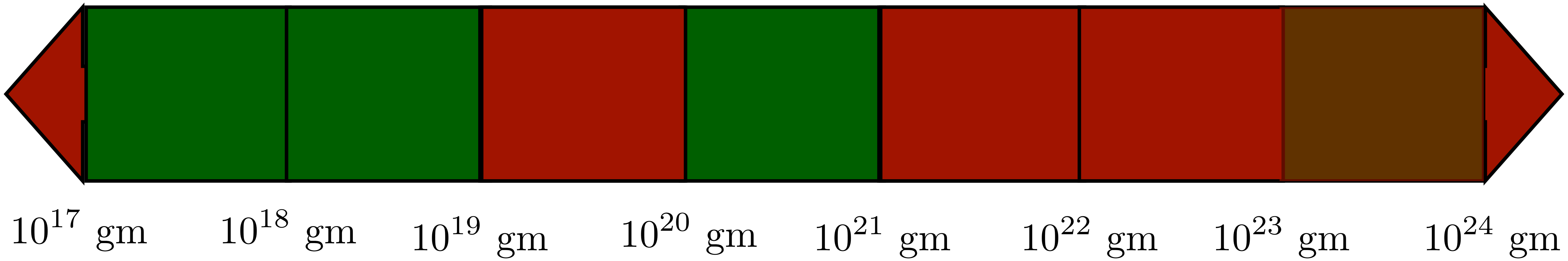

Hawking emission

Kepler MACHO search

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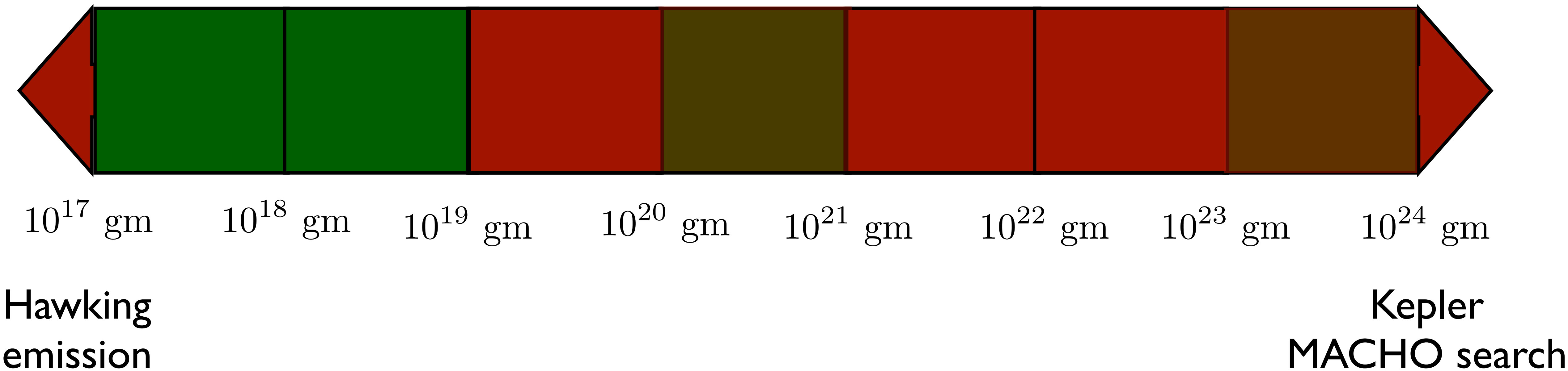

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Blows up stars > 1.0 M_0.
Inconsistent with NuStar observations of 1.2 M_0 in galactic center

Conclusions

WIMPs

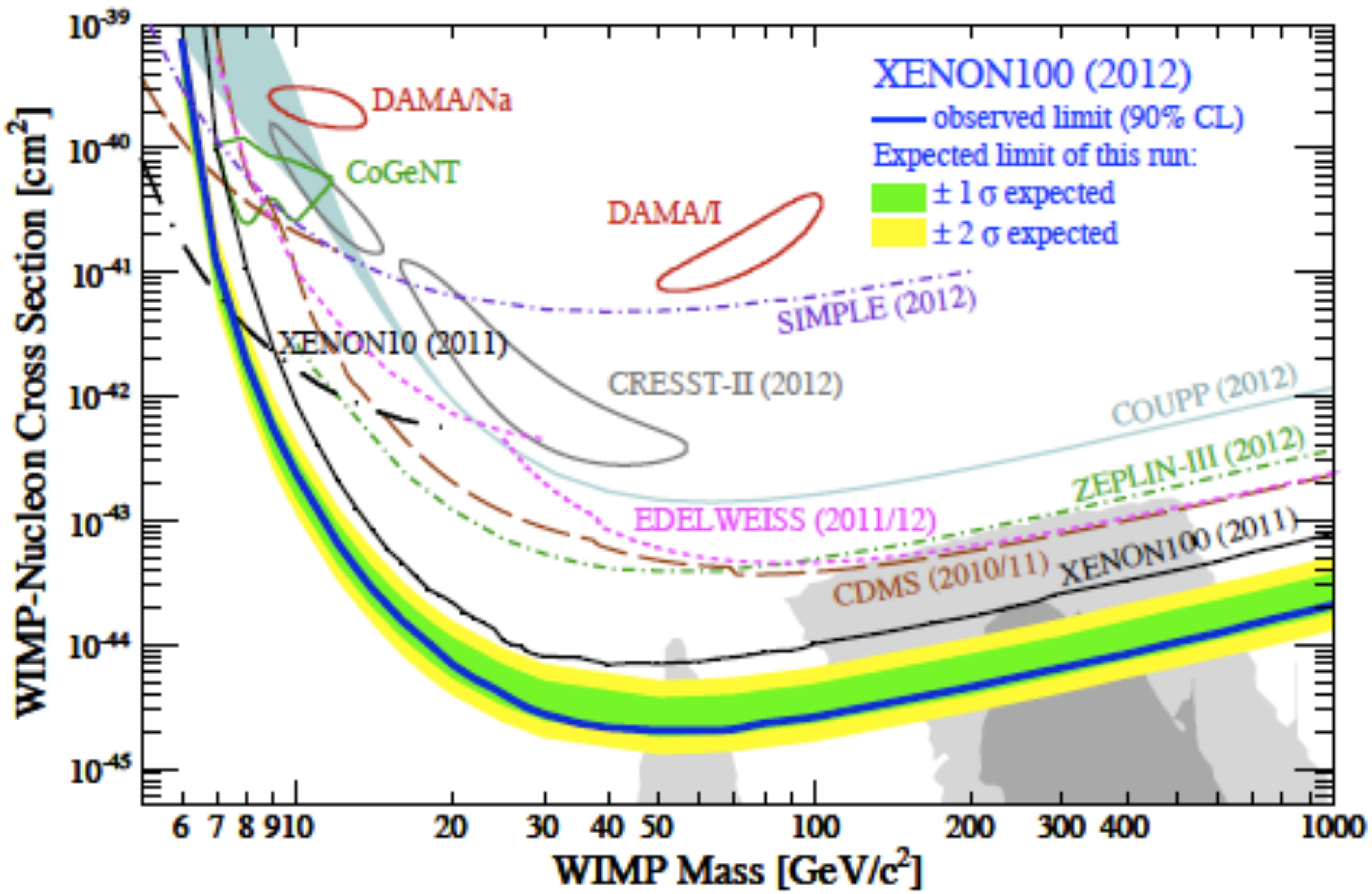
Scalable

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

Z

h

W



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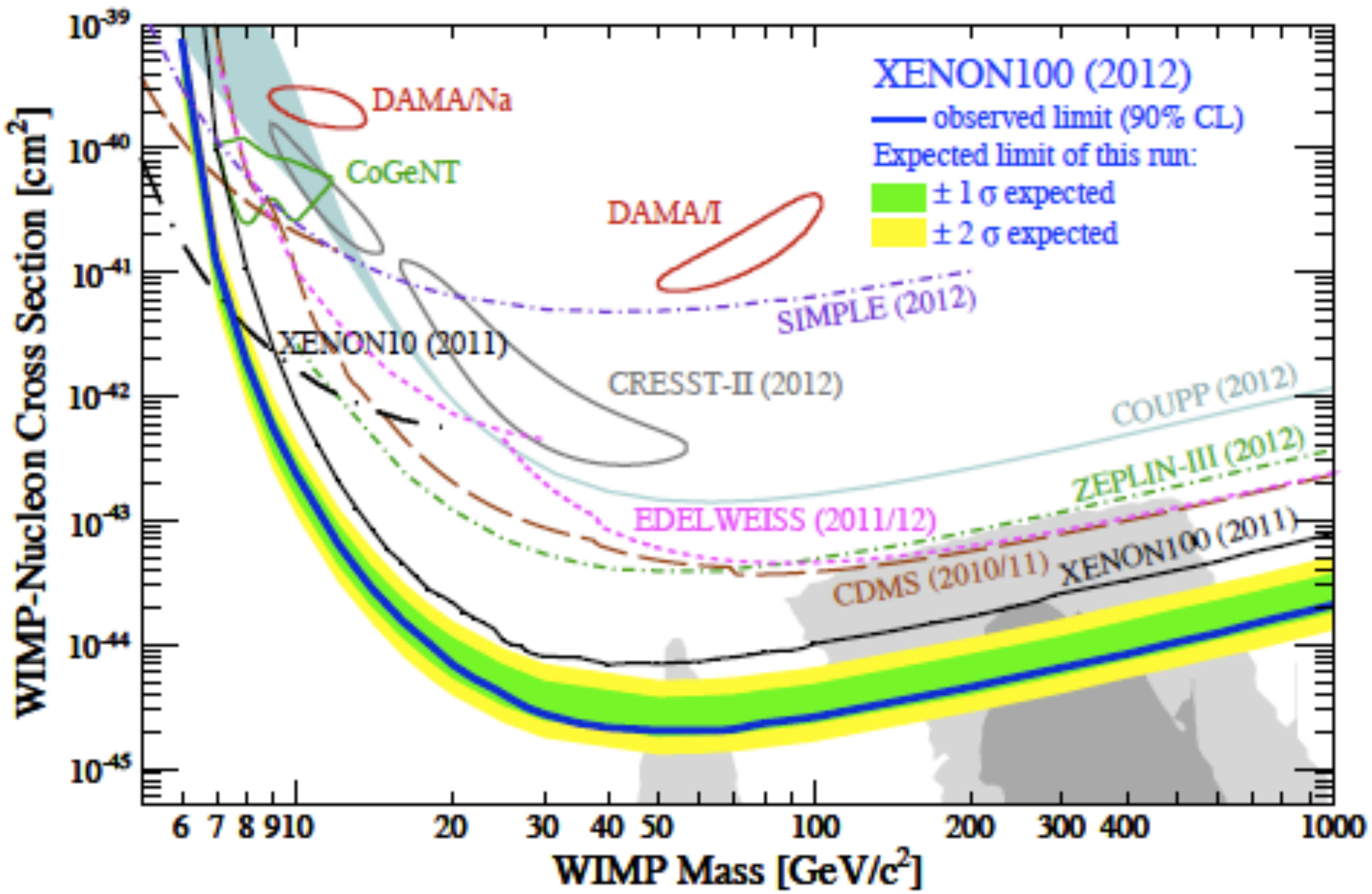
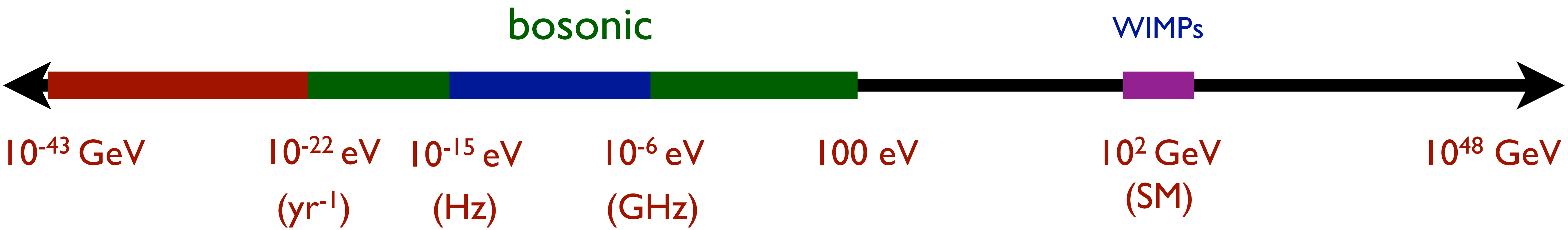


Similar approach seems possible in searching for oscillating fields

The Dark Matter Landscape



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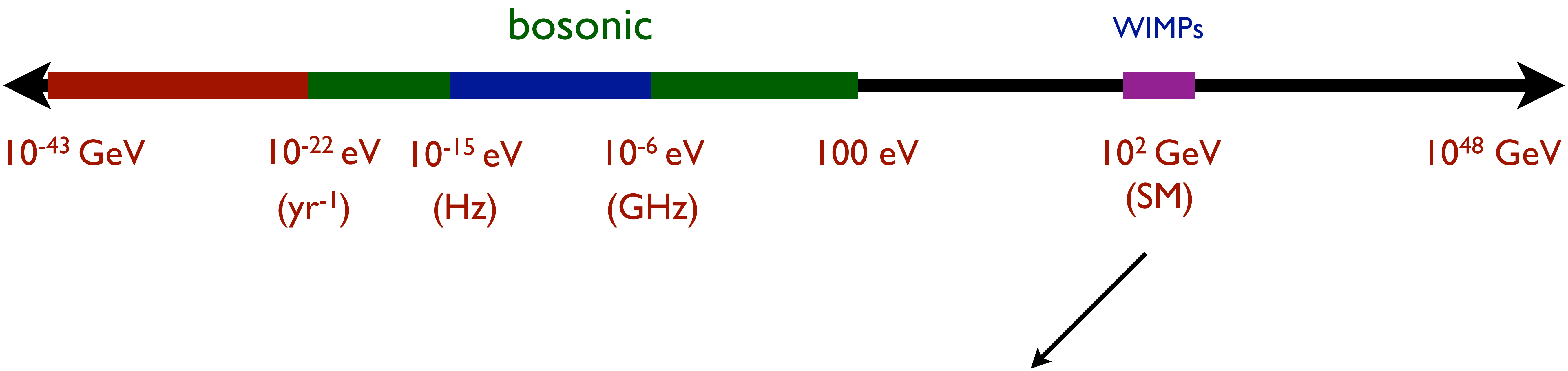
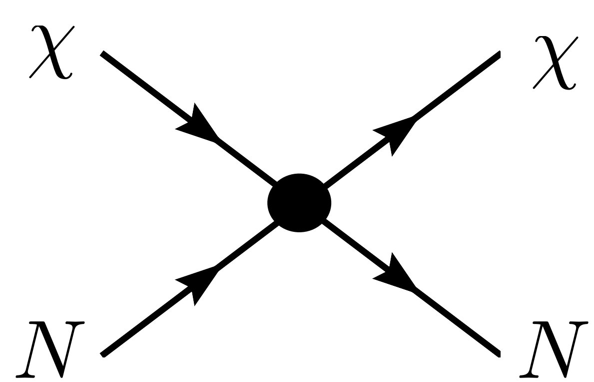


Search for single, hard
particle scattering



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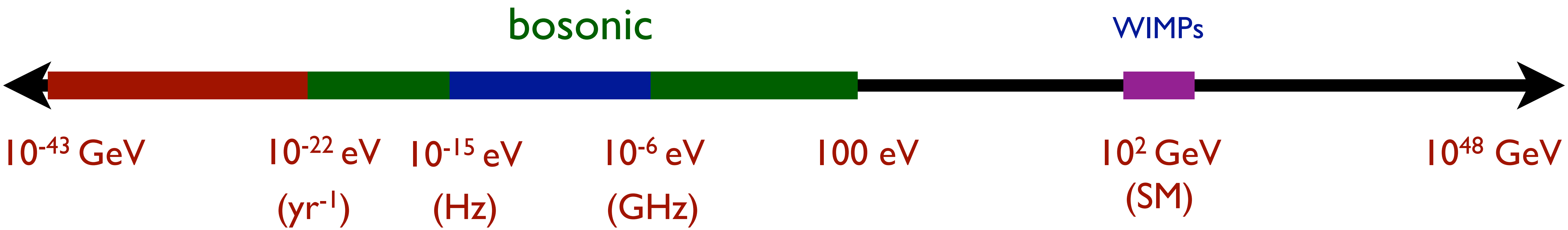
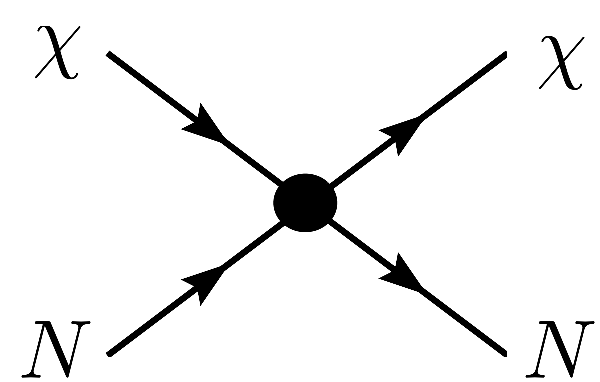


Time dependent moments of coherent classical field

Search for single, hard particle scattering

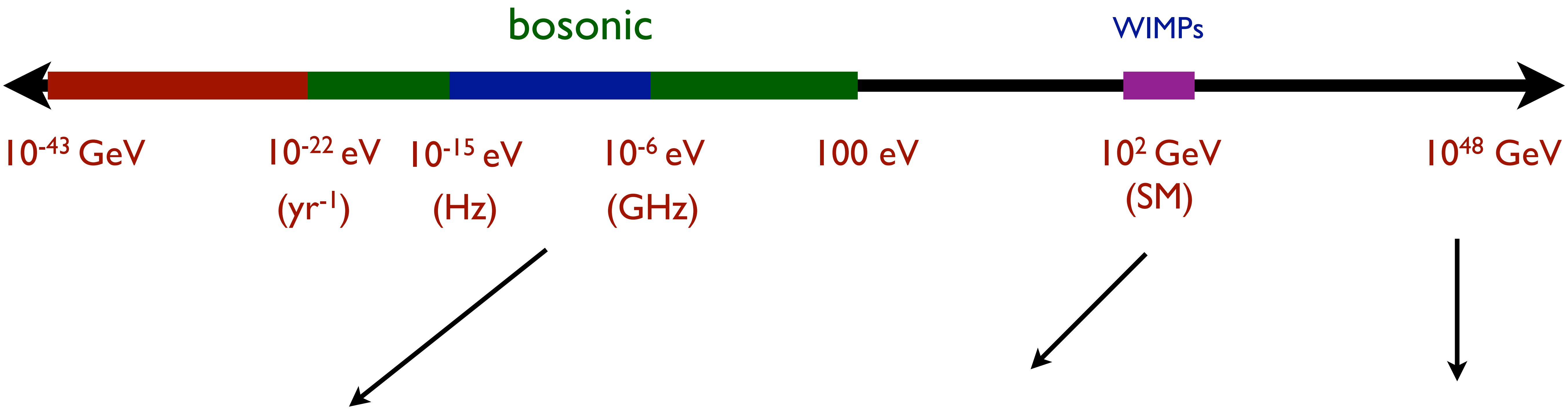
Interactions restricted by symmetry



Frequencies can naturally be lab accessible (Hz - GHz)

Lab-scale experiments

The Dark Matter Landscape



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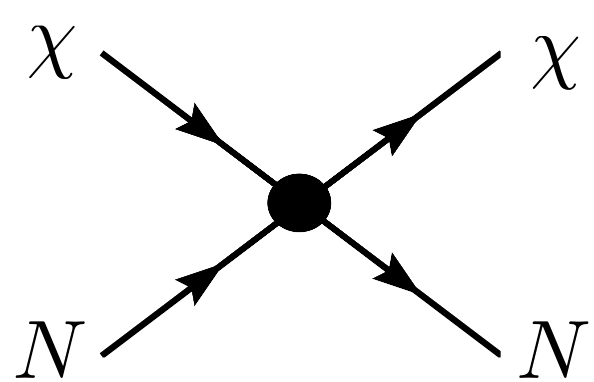
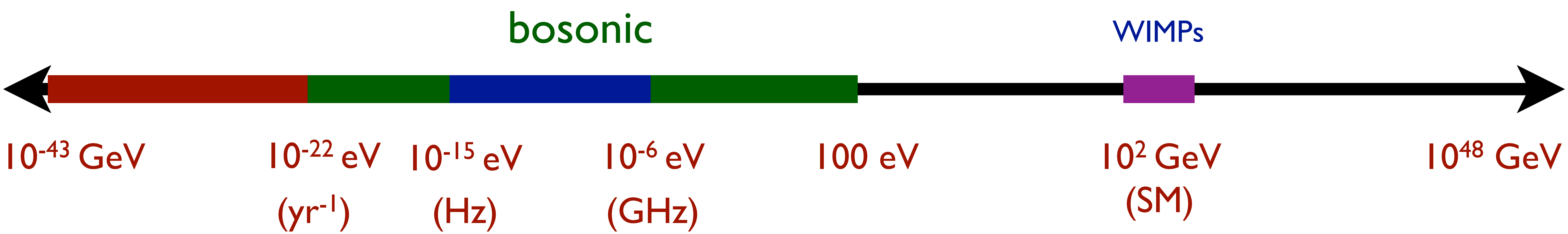


Low number density

Spectacular single events

The Dark Matter Landscape



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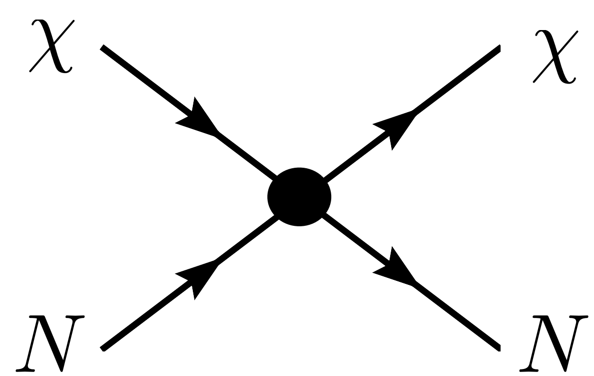

Low number density

Spectacular single events

How do we cover full range?

Backup

A Different Operator 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 $d \sim 3 \times 10^{-16} \, \frac{a}{f_a} \, e \, \mathrm{cm}$

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

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

Conclusions and Future Directions

White dwarfs are nuclear bombs waiting to explode

Localized heat injection sufficient to trigger explosion

Ideal for studying ultra-massive dark matter states

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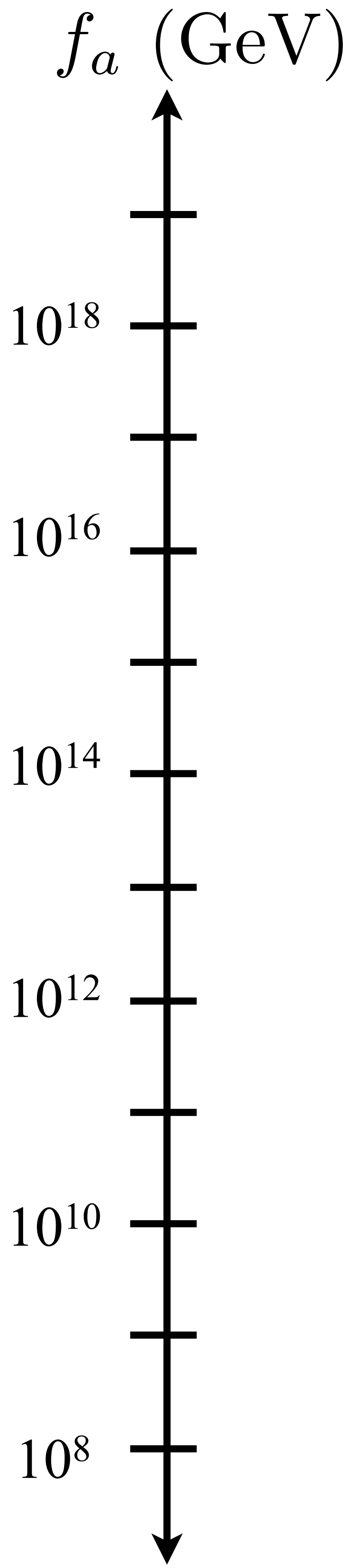
Significant constraints on primordial black holes

Constrain Q balls, annihilations of ultra-massive composite states

Accumulation of dark matter in star, leading to compact core. Localized heating possible.

Constraints and Searches



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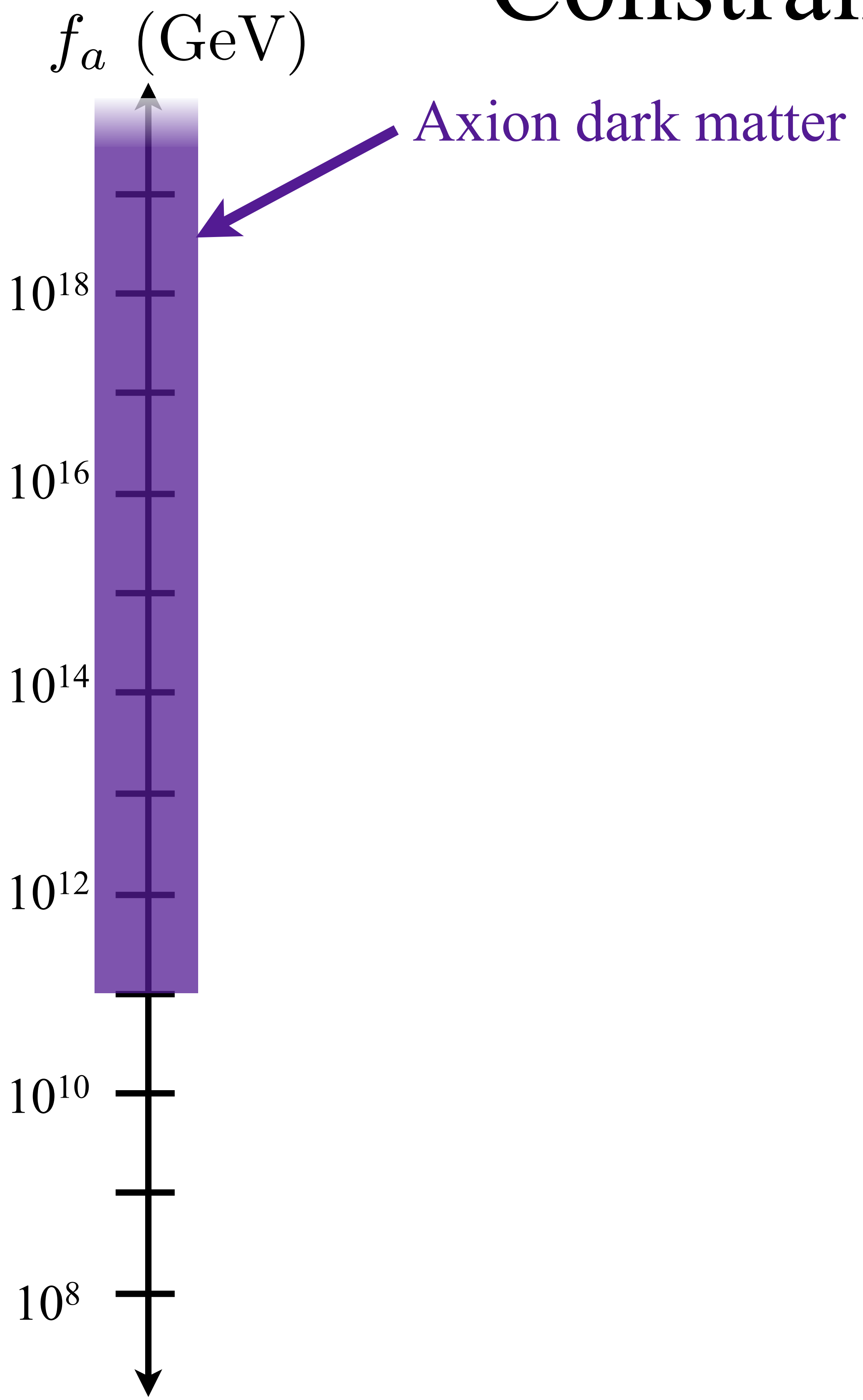

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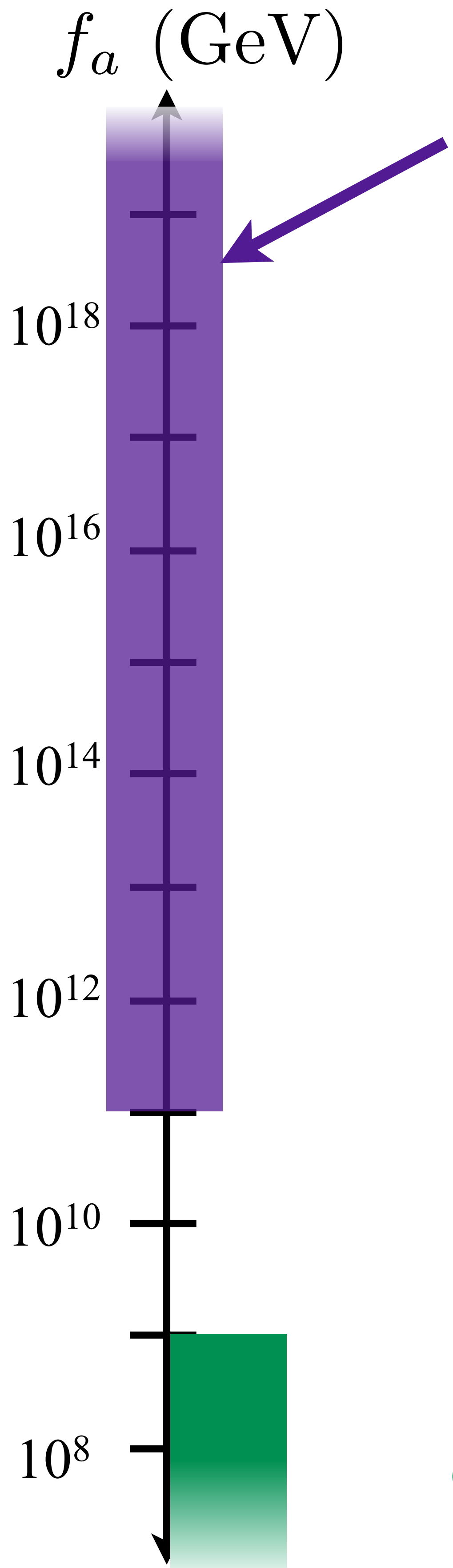
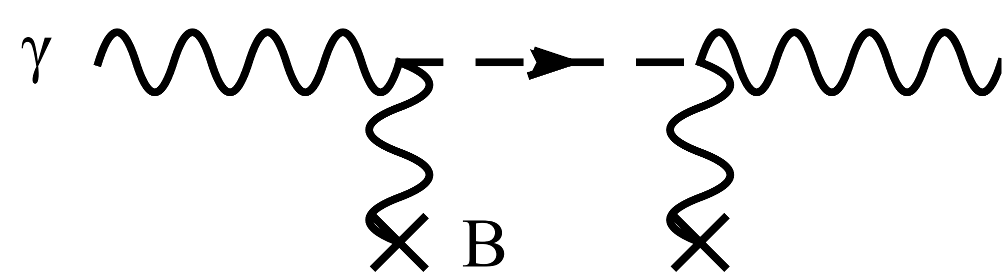


Axion dark matter

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

laser experiments:



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

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

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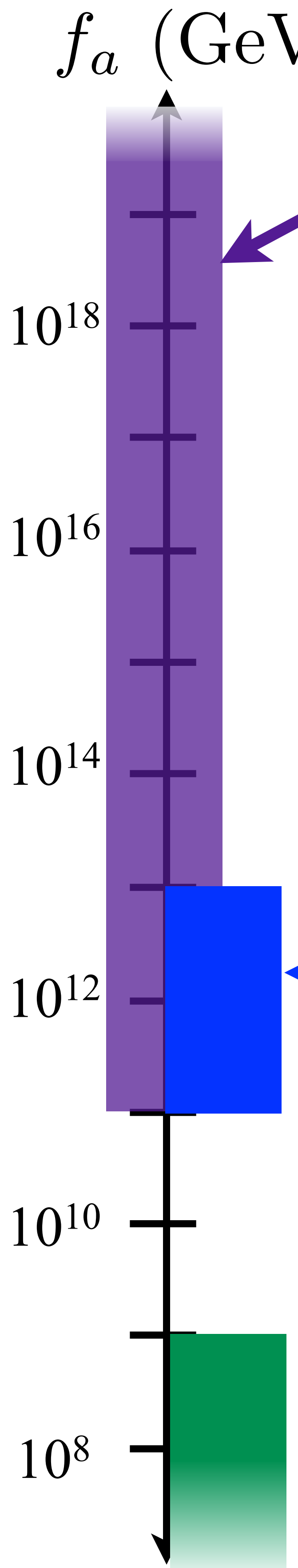

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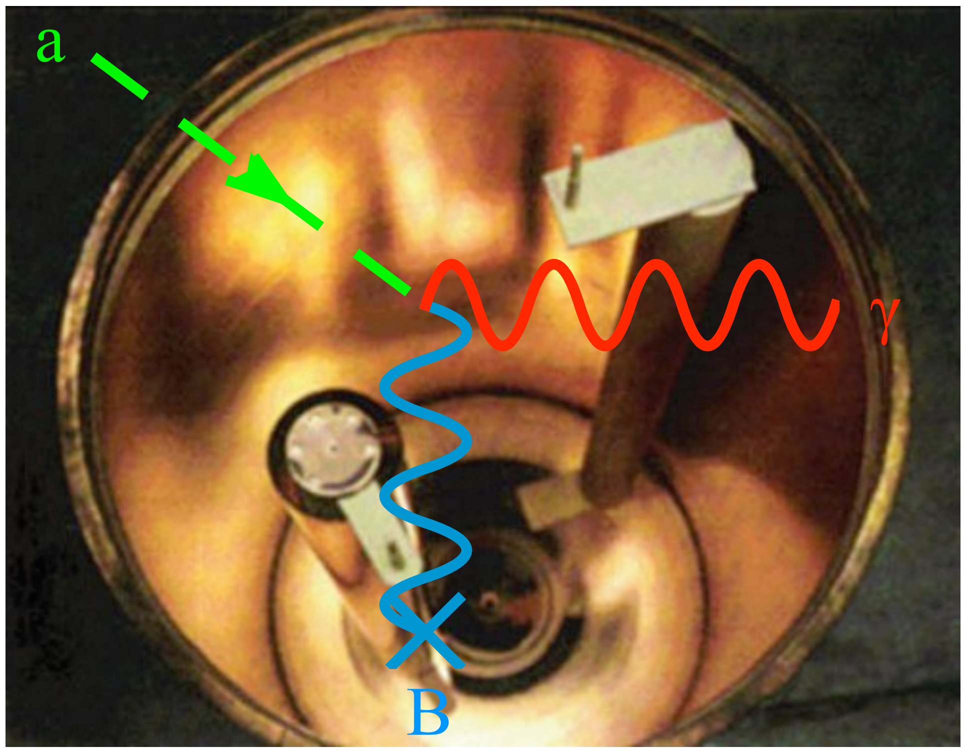

axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

size of cavity increases with f_a

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

microwave cavity (ADMX)

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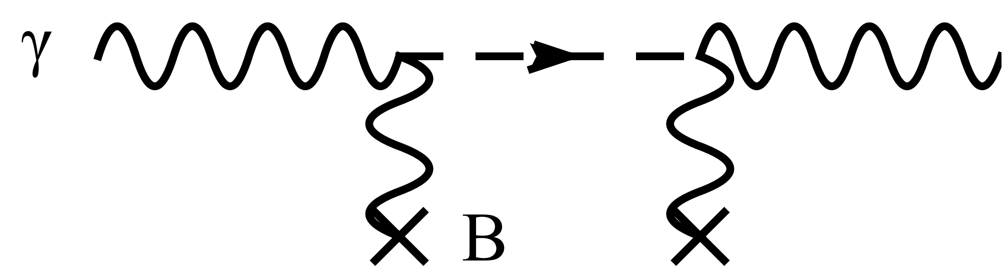

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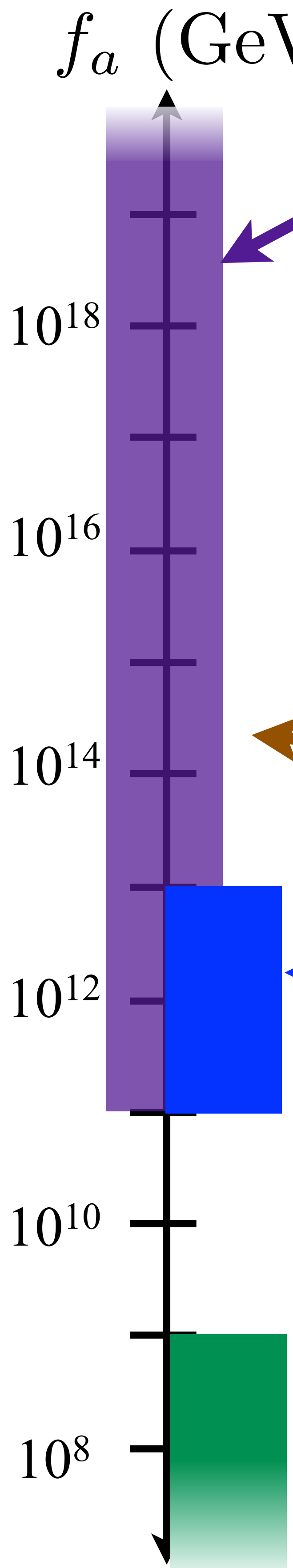

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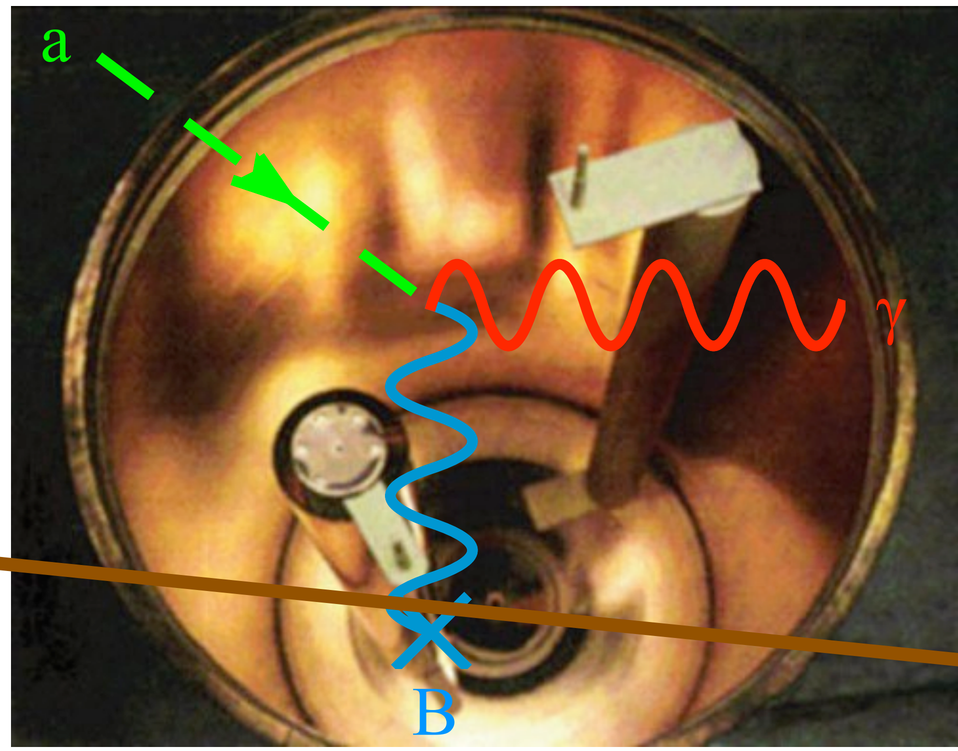

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S. Thomas

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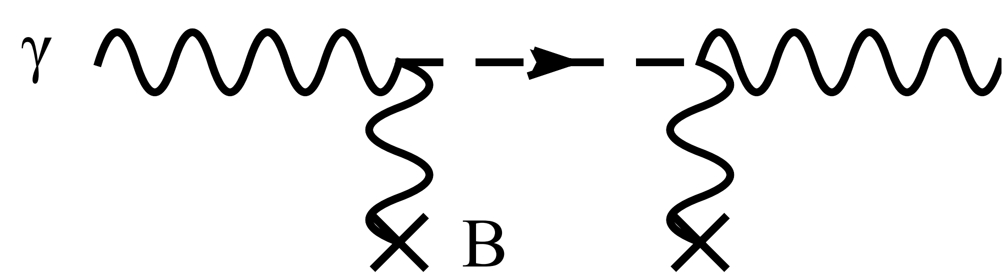

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Other ways to search for light (high f_a) axions?

Axions and the CMB

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

$$H_{\mathrm{inf}} \sim 10^{14}\ \mathrm{GeV}$$

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, weak constraint on ALPs probed by CASPEr.

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for QCD axion, constrains **one** cosmological history.

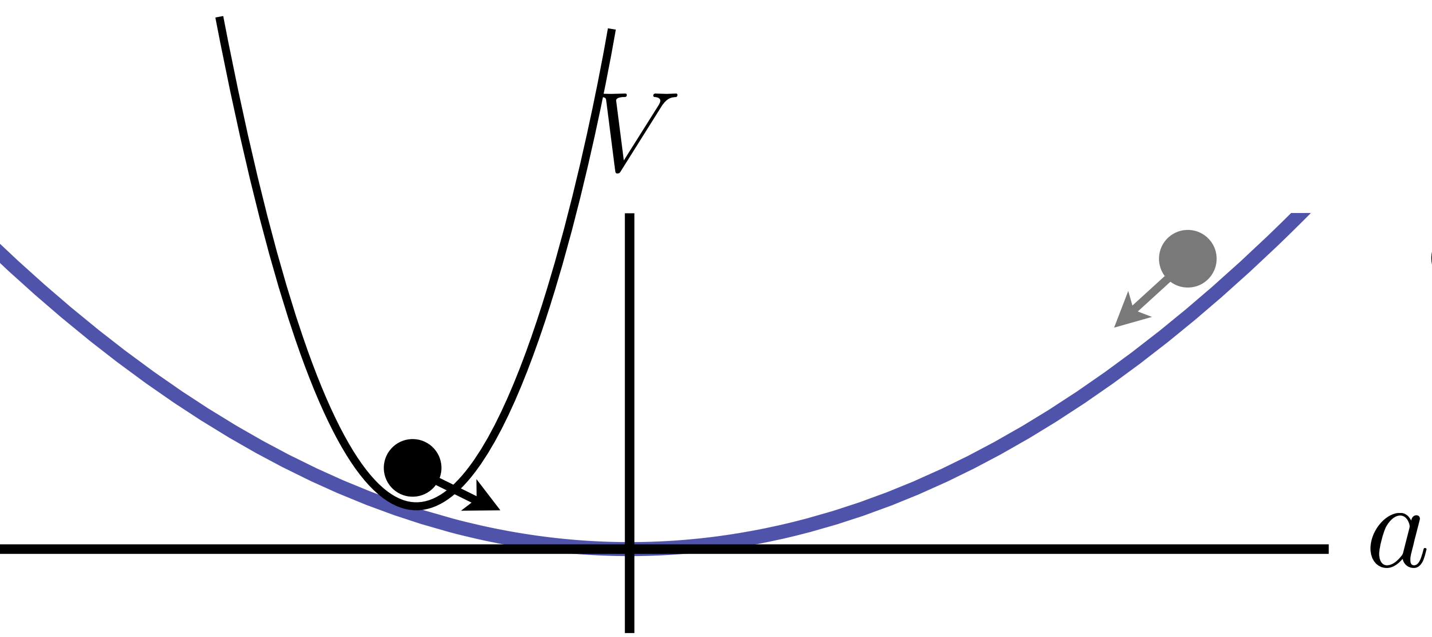
Requires knowing physics all the way up to GUT scale $\sim 10^{16}\ {\rm GeV}$

many others possible.

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.

Need not be on during inflation.



Axion oscillates earlier, damps to high temperature minimum.

Misalignment of minima gives axion dark matter.

Dark matter from choice of parameters instead of initial conditions.

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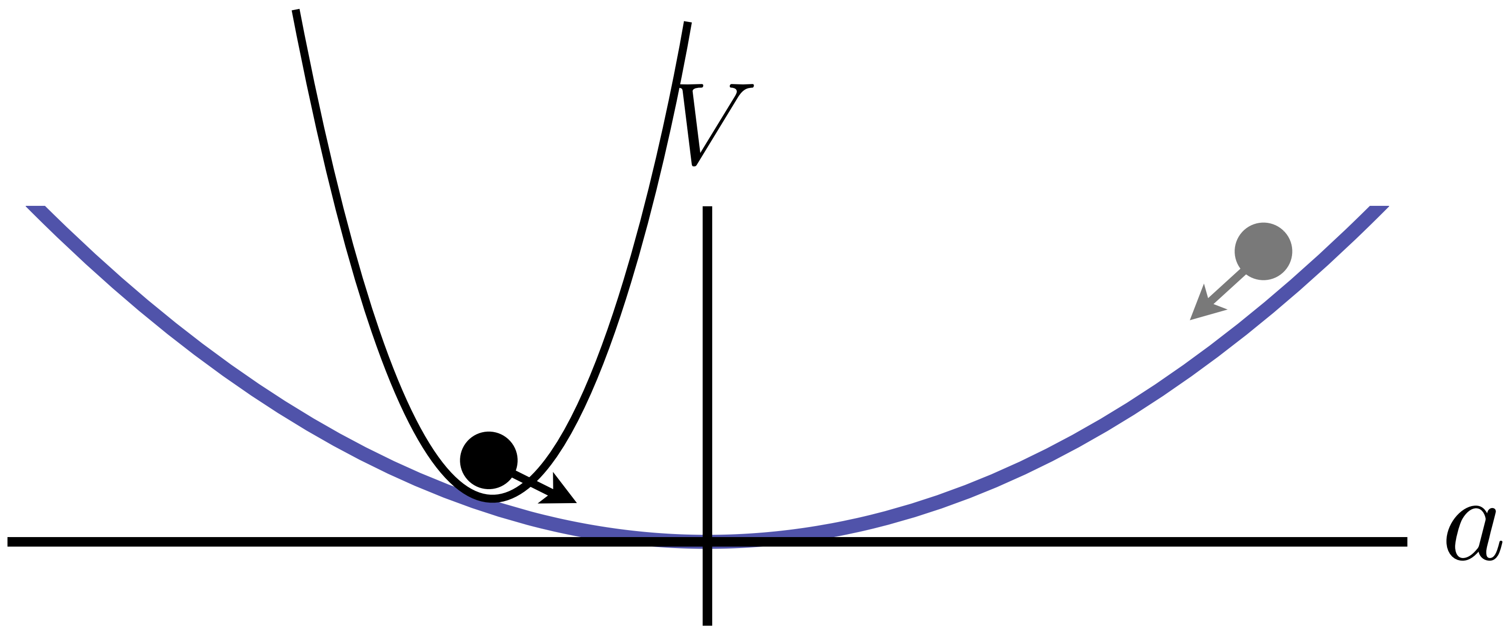

e.g. thermal monopole density,
high temperature mass,
and many others

Fischler & Preskill (1983)

e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

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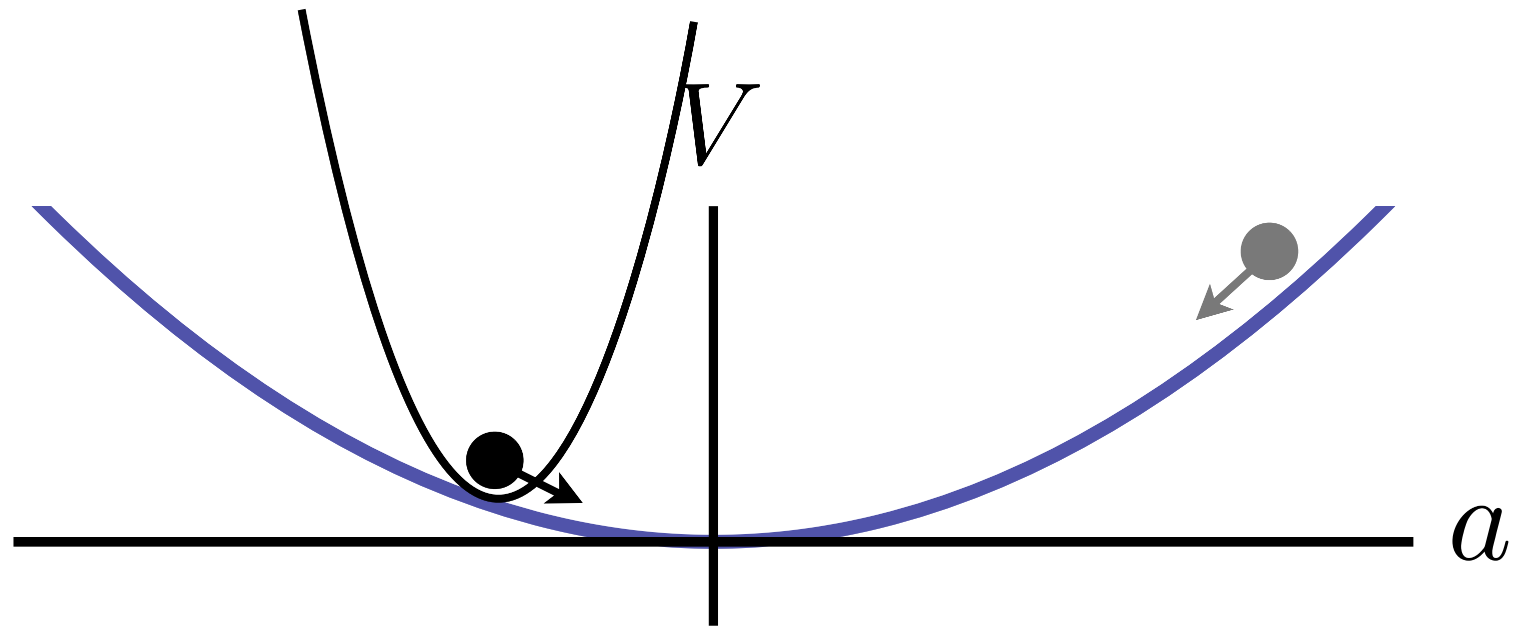

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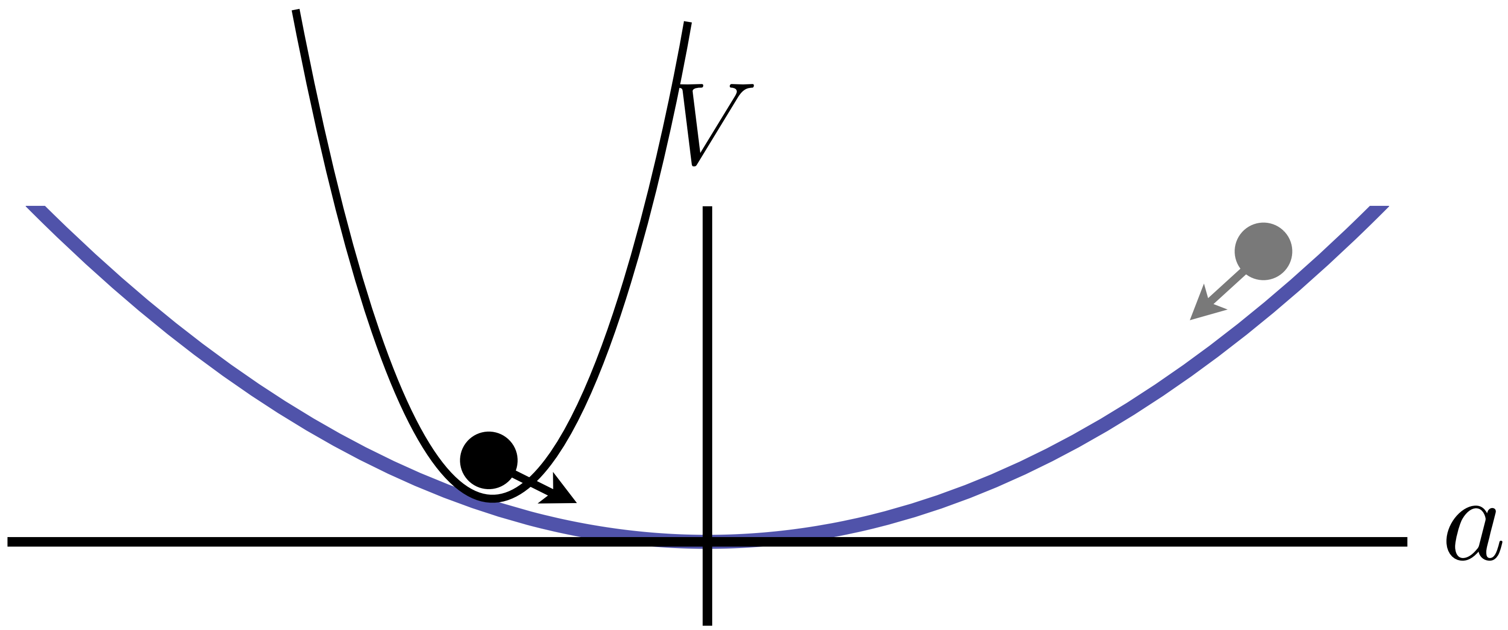

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