Searching for Ultra-Heavy Dark Matter

Surjeet Rajendran,
UC Berkeley

(with Dorota Grabowska and Tom Melia)

The Dark Matter Landscape

10^{-43} GeV

10^{48} GeV

The Dark Matter Landscape

bosonic

10^{-43} GeV

10^{-22} eV

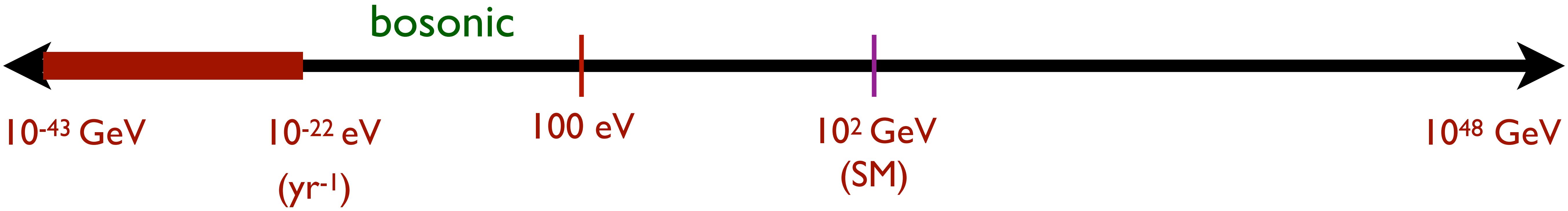
(yr^{-1})

100 eV

10^{48} GeV

Fit in galaxy

The Dark Matter Landscape



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Fit in galaxy

Standard Model scale ~ 100 GeV

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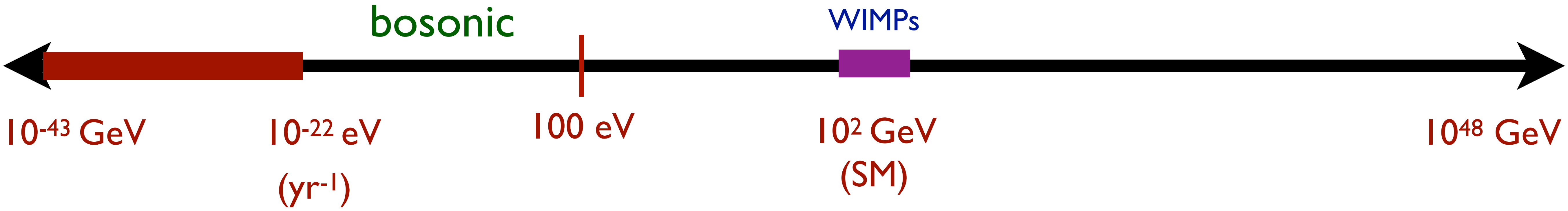

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WIMPs

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

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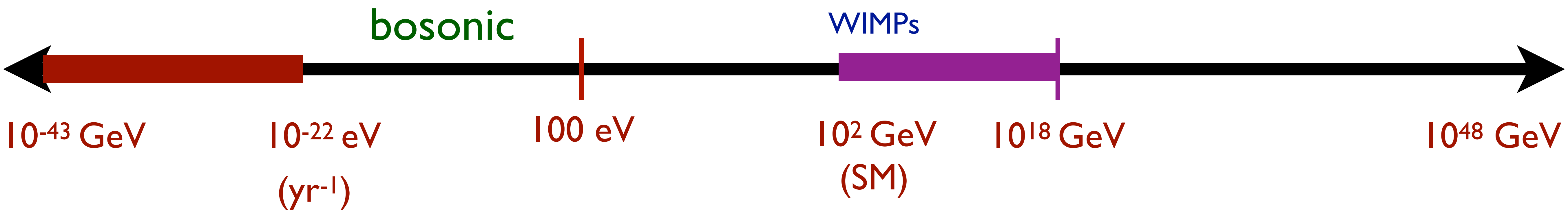

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WIMP Experiments: Sensitive up to 10^{18} GeV

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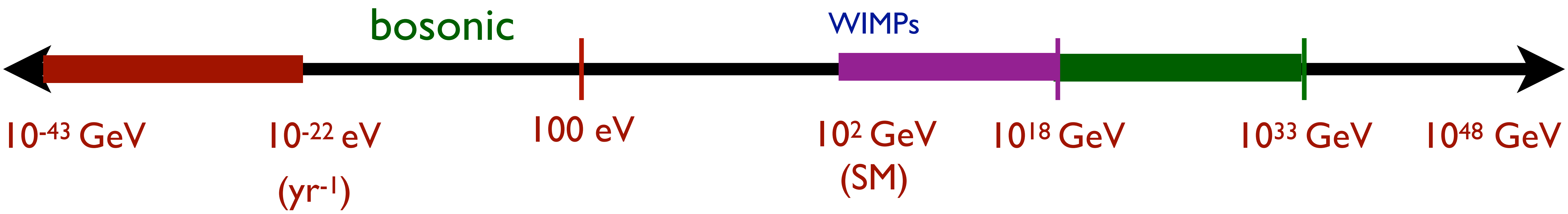

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Weakly Interacting Massive Particles (WIMPs)

WIMP Experiments: Sensitive up to 10^{18} GeV

What if dark matter is super heavy?

Low number density - need large detectors.

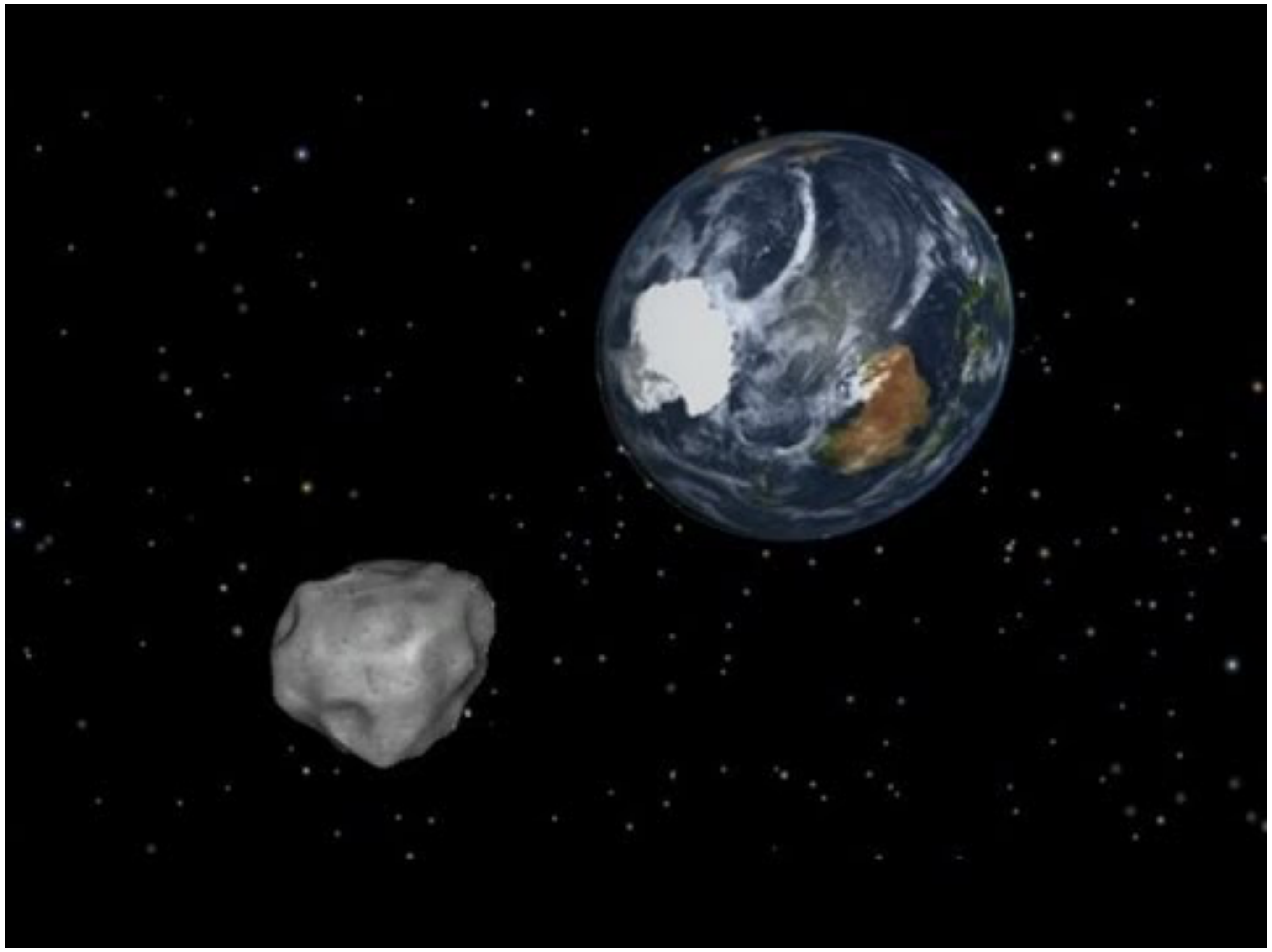
Terrestrial: up to 10^{33} GeV

Outline

1. Theory and Phenomenology
2. Constraints
3. Detection

Ultra-heavy Dark Matter?

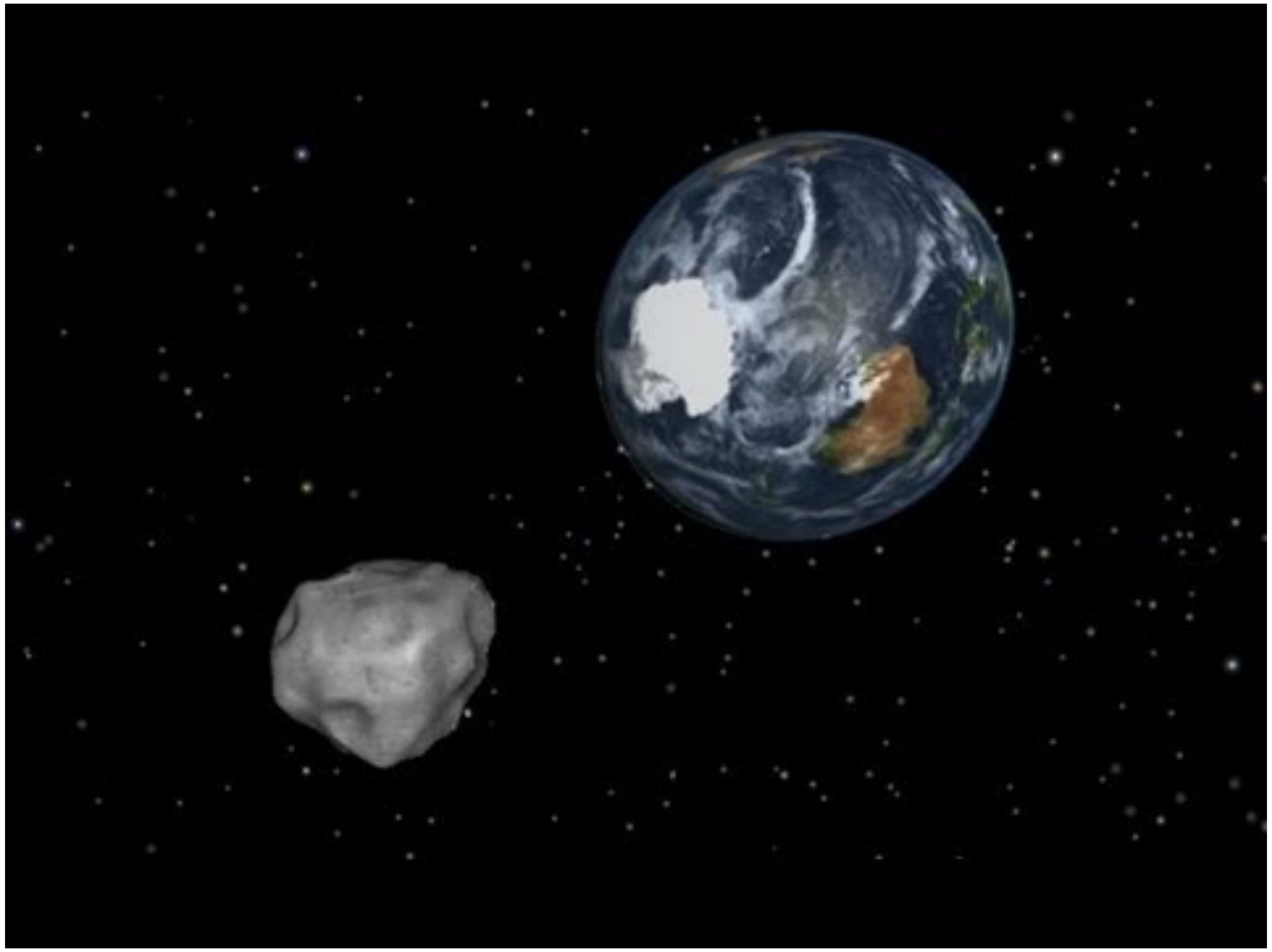
Large composite blob



Weak constraints on self-interactions of dark matter

Strong self-interactions in dark sector

Ultra-heavy Dark Matter?



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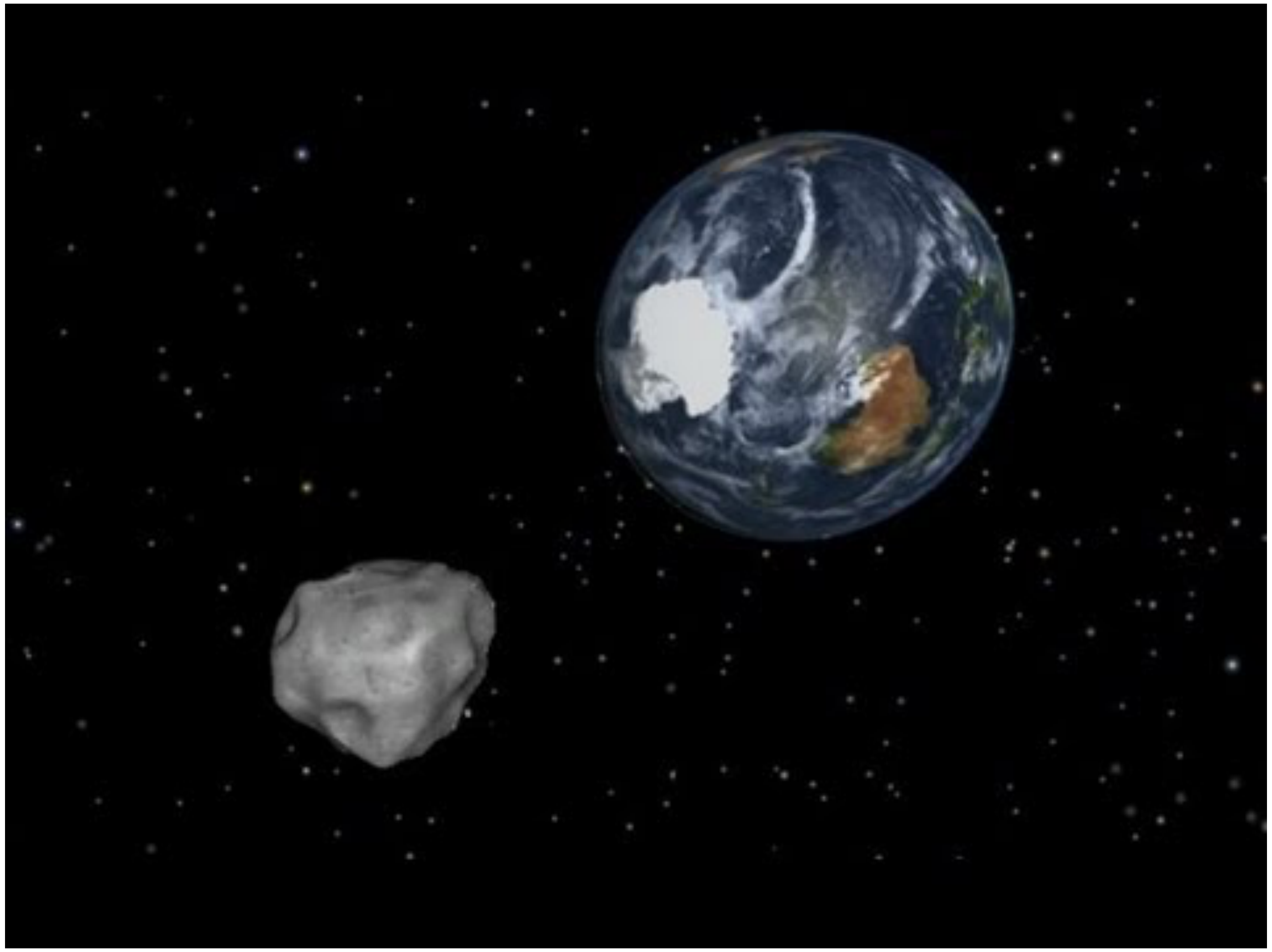

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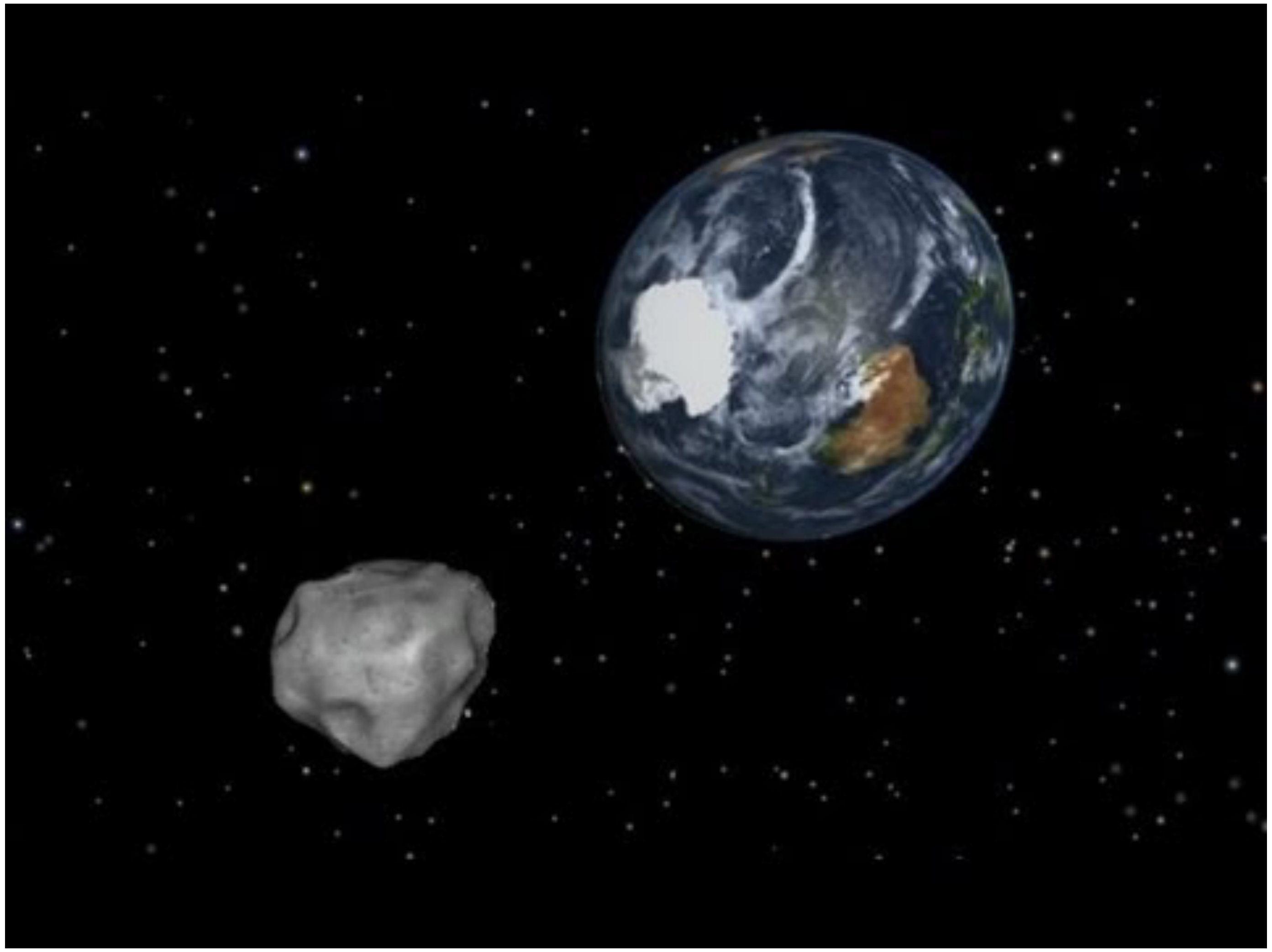

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Weak constraints on self-interactions of dark matter

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Efficient nucleosynthesis? Primordial production? Galactic evolution?

Observational Effects?

Key Point: Lots of dark matter partons packed into single blob

Rare but potentially spectacular transit

What does the blob look like?

Self-Interaction Scale Λ, Parton Mass ~ Λ

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Fermionic

Bosonic

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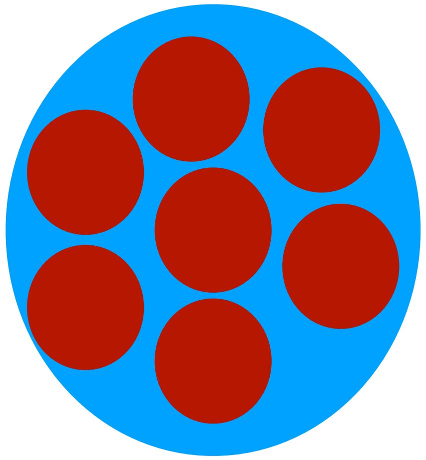

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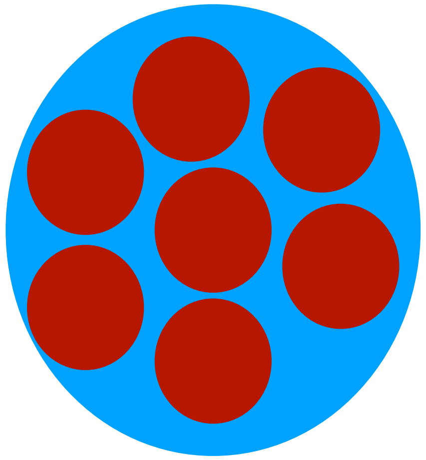

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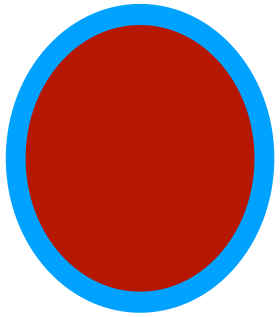

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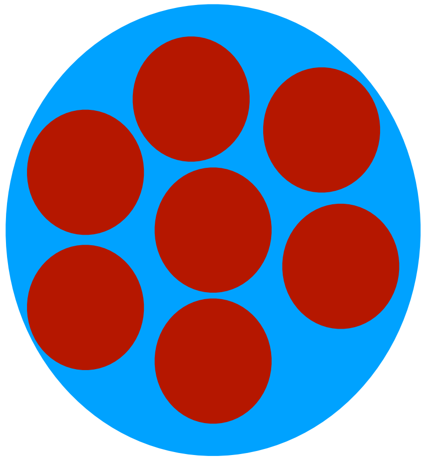

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$$\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi$$

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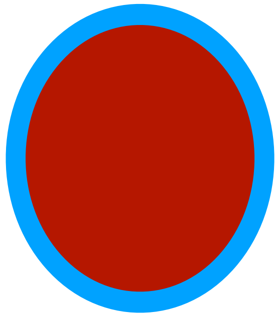

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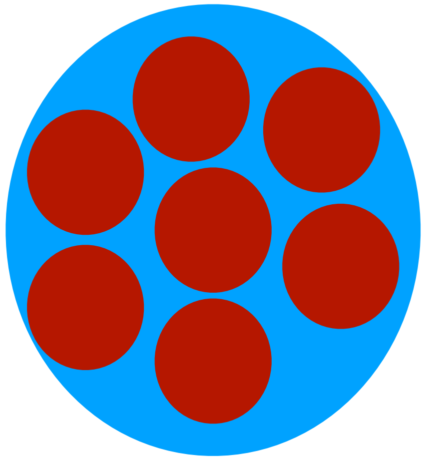

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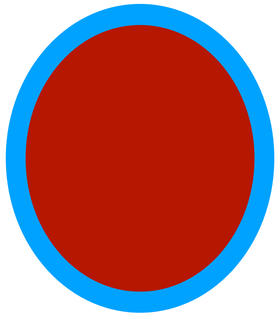

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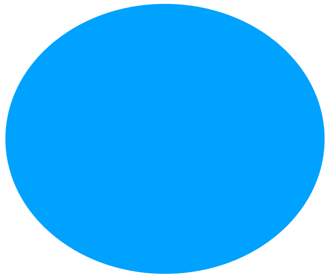
Standard Model Interactions

$$+\mu^2\phi^2 + g_N \phi \bar{N} N + \frac{1}{f_a}\partial_\nu \phi \bar{N} \gamma^\nu \gamma_5 N + \frac{\phi}{\alpha M} F_{\mu\nu} F^{\mu\nu}$$

Observational Effects



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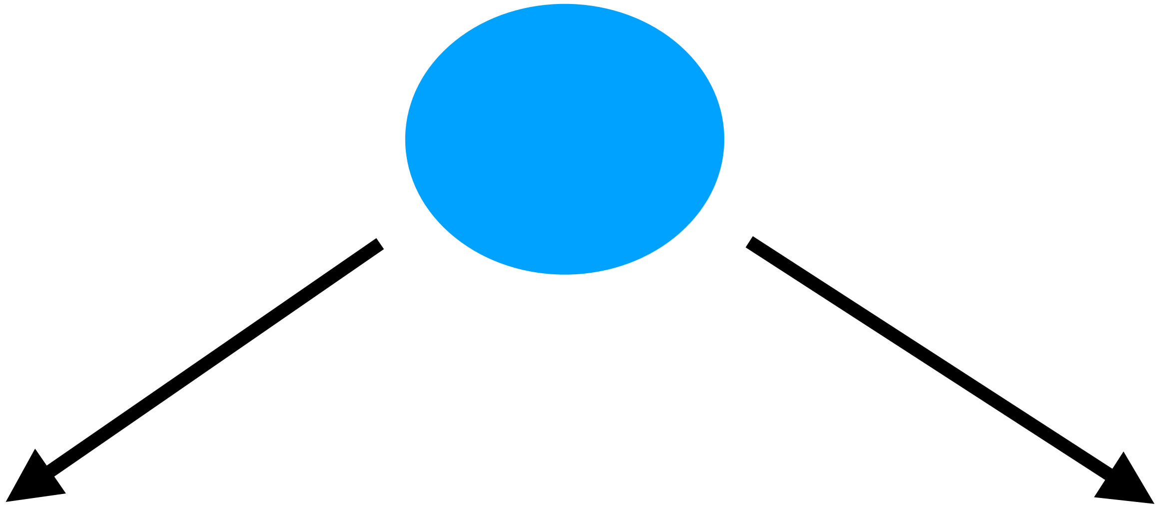

Short Range

$\mu^{-1} < \lambda_p$

Long Range

$\mu^{-1} > \lambda_p$

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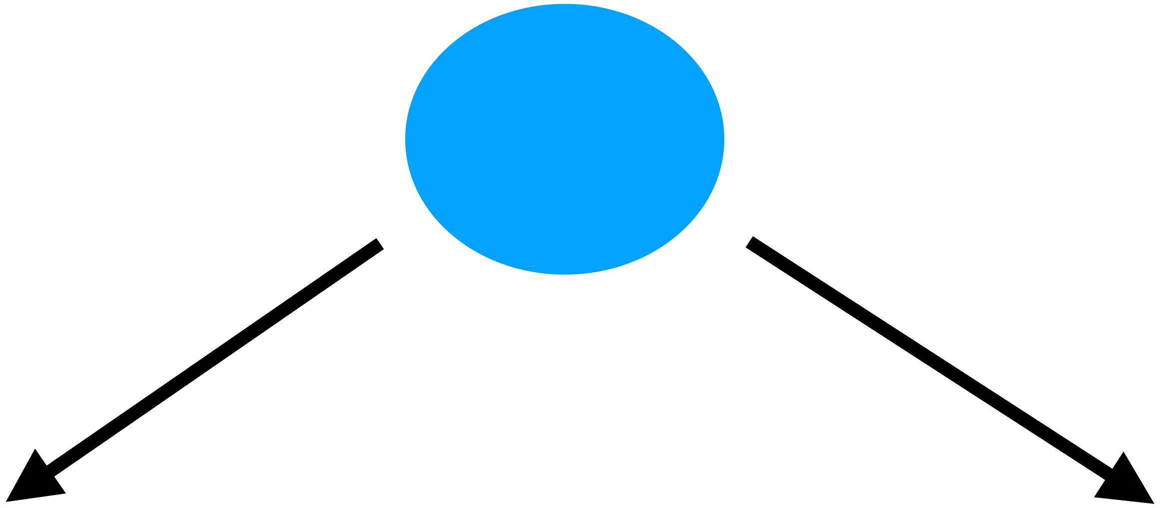

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Dark Matter scatters,
deposits energy.
Calorimetry

Compositeness could
enable multiple scattering

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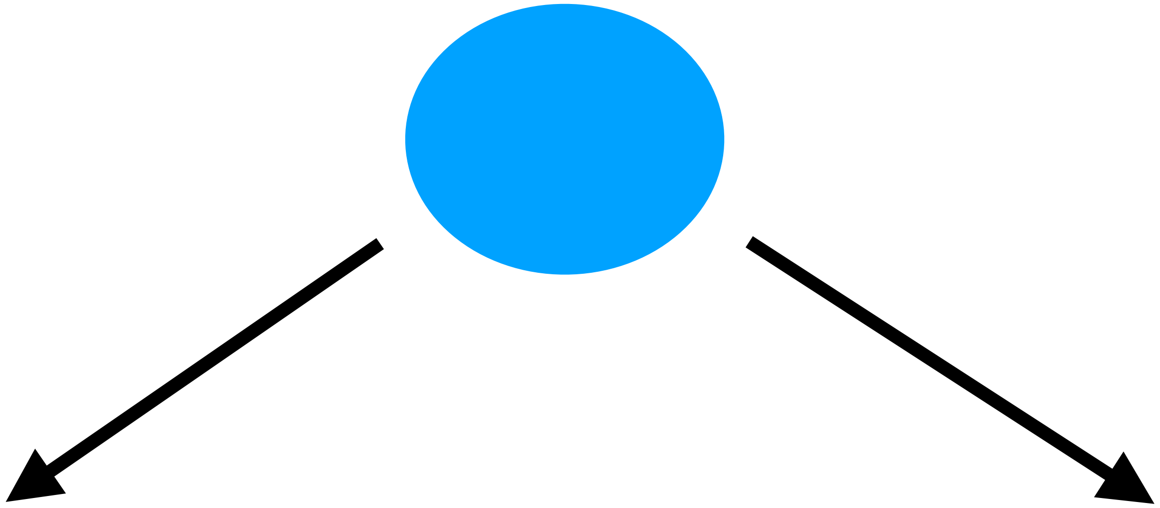

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Blob sources classical field

Use detectors of ultra-light
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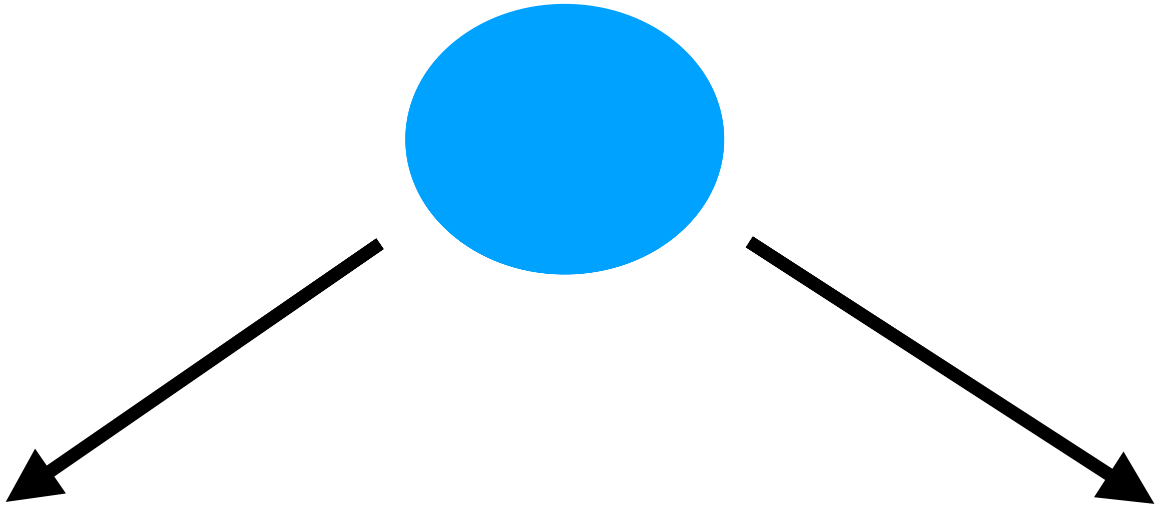

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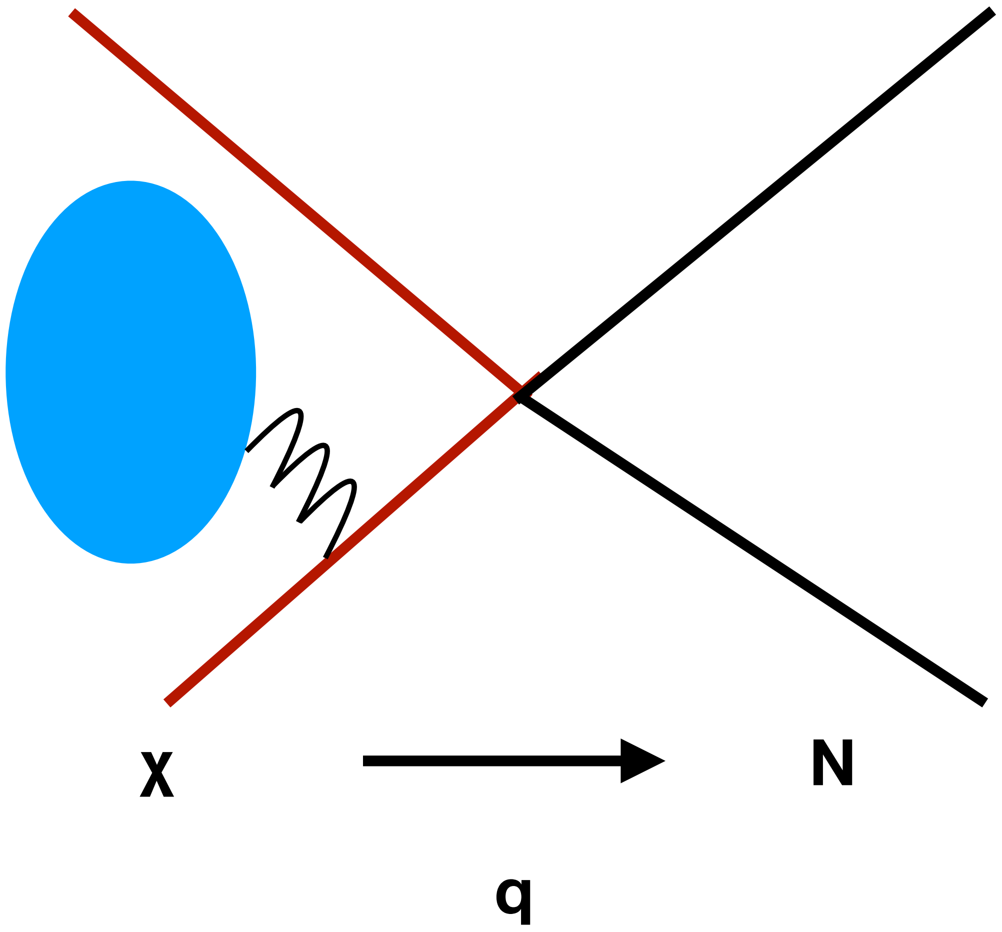
Leverage: $c > v_{dm} > v_{human}$

Constraints?

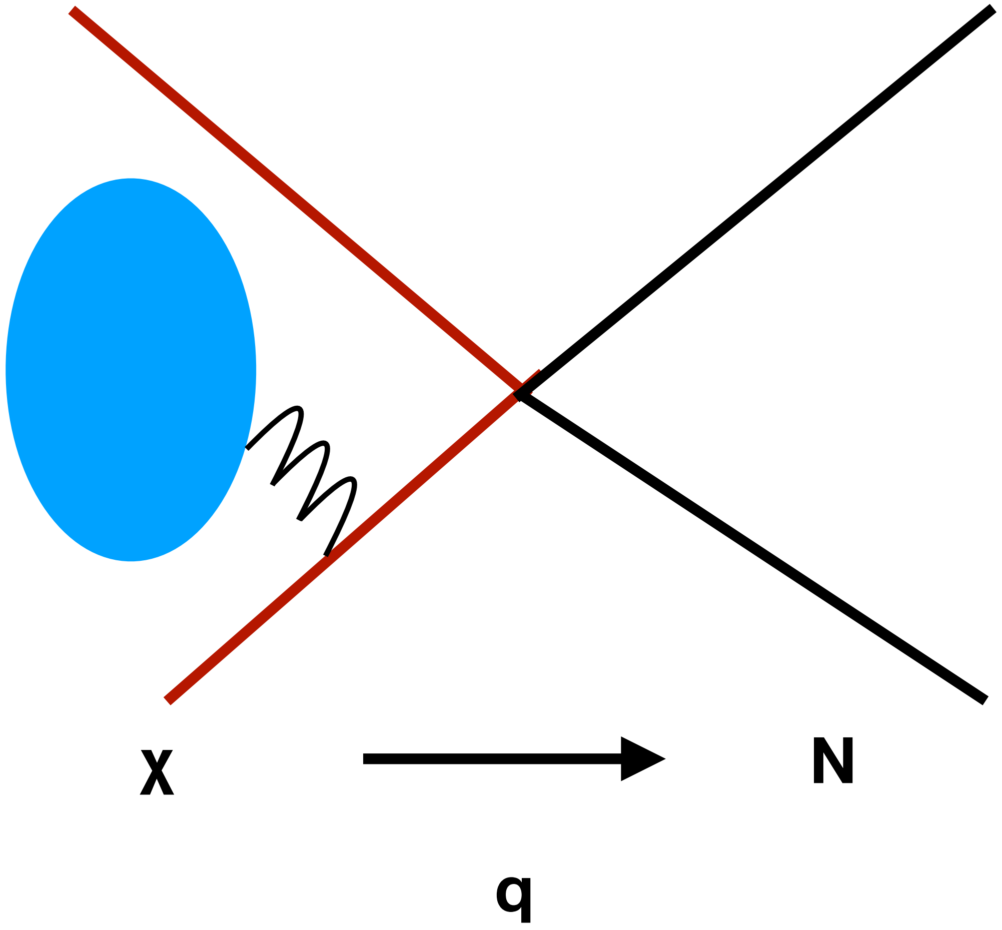
Short Range



Scattering at the partonic level

Parton transfers momentum to blob

Short Range



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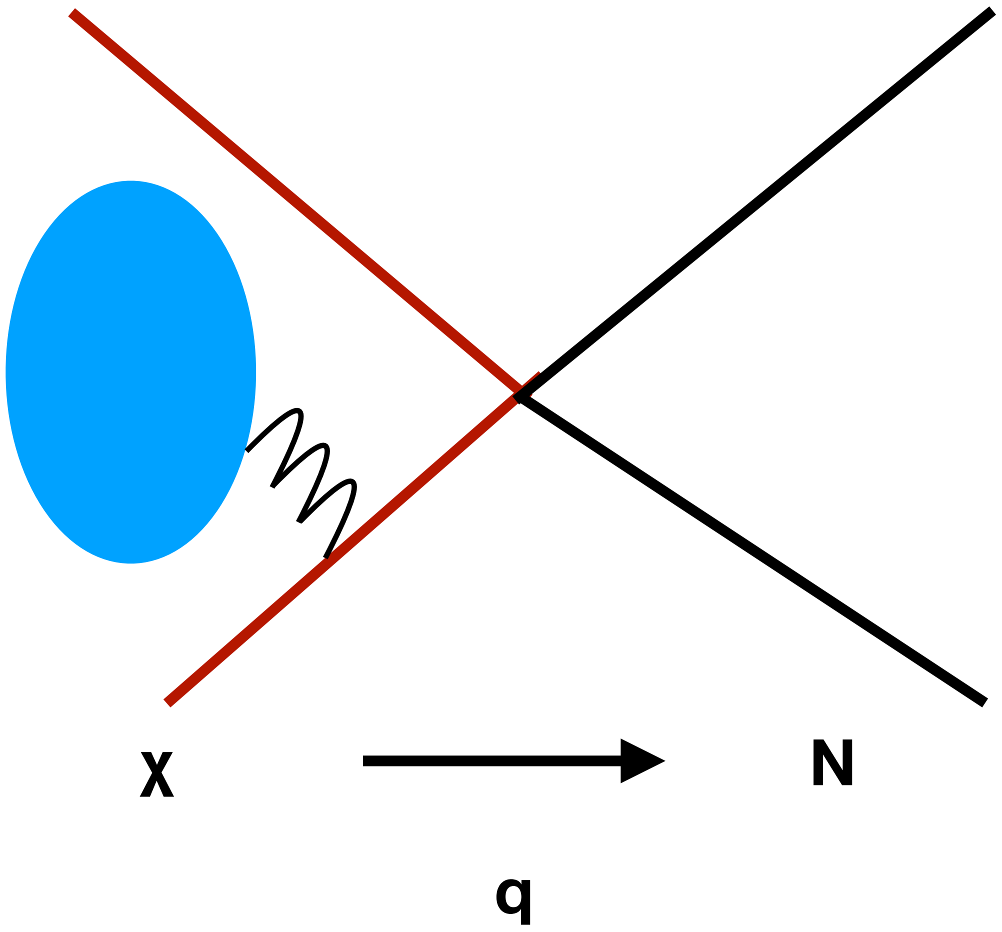
Form factor for $q \gg 1/r_\chi \sim \Lambda$

$M \gg m_N$, kinematics set by m_N

$q = \mathrm{Min}[m_N v, \Lambda]$

Short Range



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Key Point: $\Lambda < 300$ keV => soft energy transfer, no ionization

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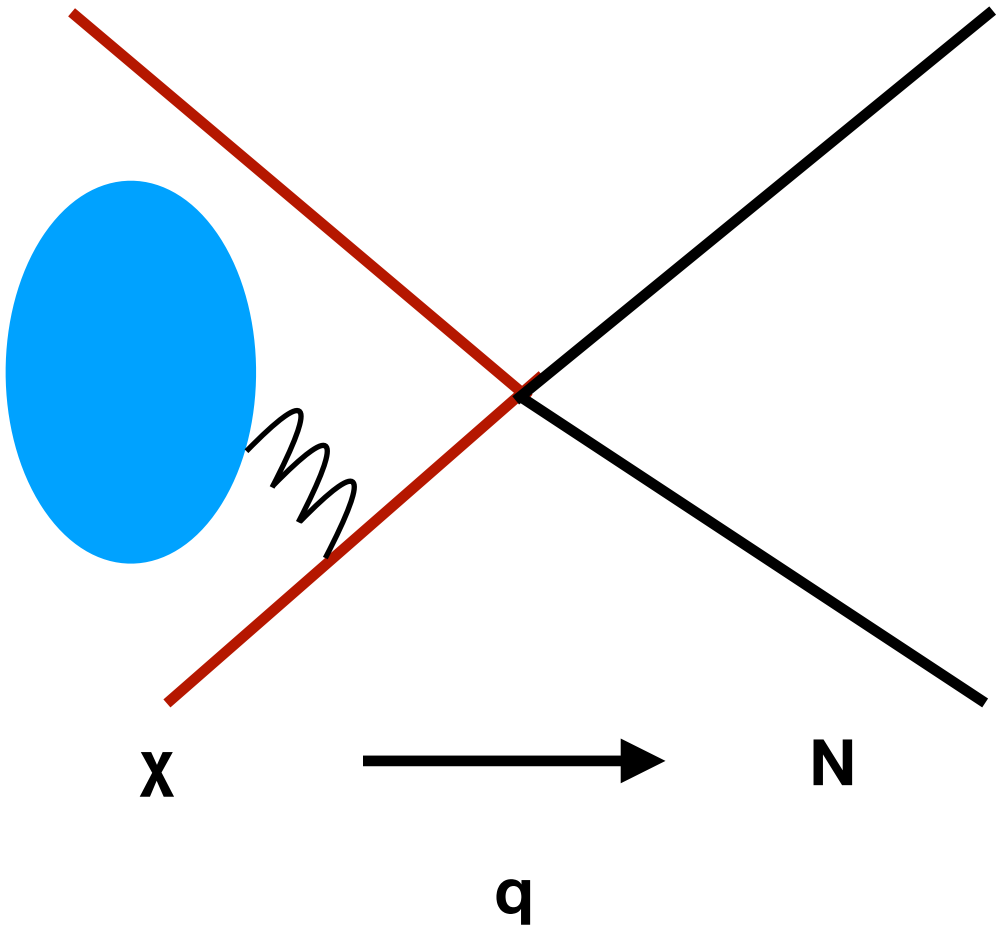

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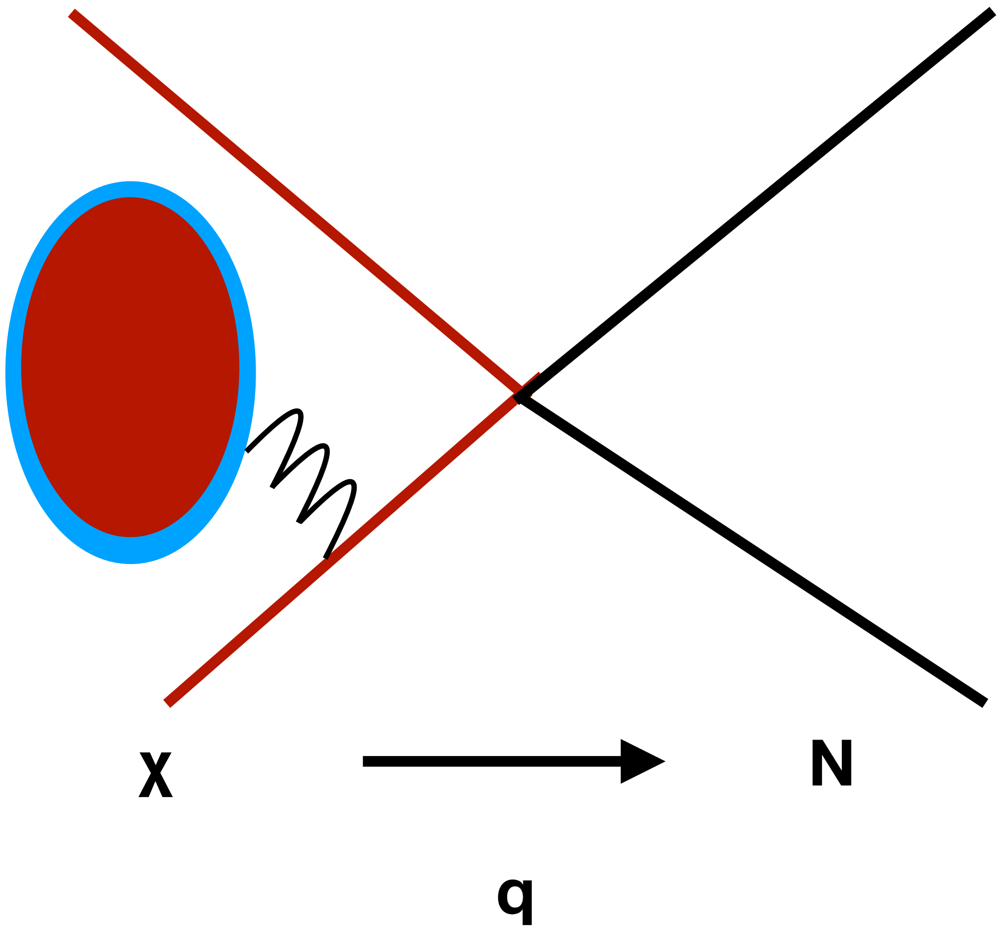
This Work: $10\ \mathrm{keV} < \Lambda < 10\ \mathrm{MeV}$

Goal: Robust parameter space, targeted experimental signals

Short Range: Bosonic Blob



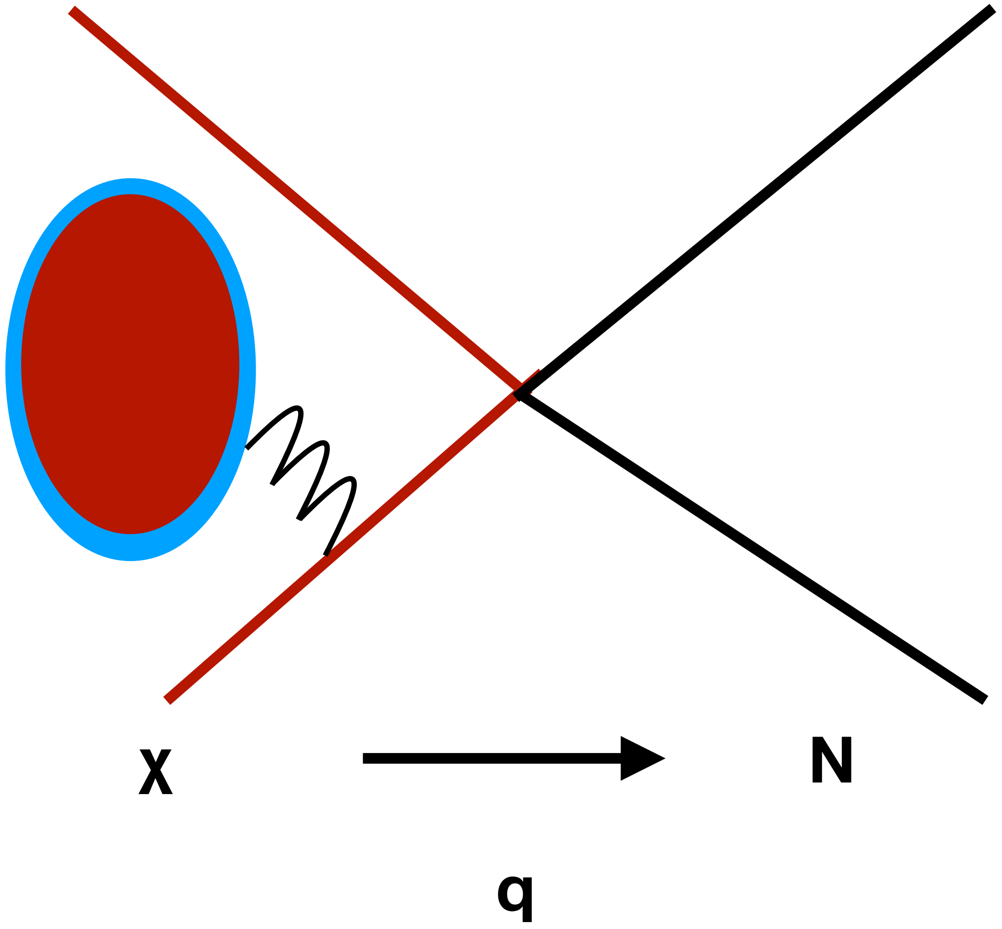
$R \sim 1/\Lambda$

10 keV $< \Lambda <$ 10 MeV => $q \sim 1/R$

Cross-section Coherently Enhanced

Easily geometric $\sigma = 1/\Lambda^2$

Short Range: Bosonic Blob



R ~ 1/Λ

10 keV < Λ < 10 MeV => q ~ 1/R

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$$\frac{dE}{dx} = \eta_m \left(\frac{\Lambda^2}{m_N}\right)\frac{1}{\Lambda^2} = \frac{\eta_m}{m_N} \sim \mathrm{keV/cm}$$

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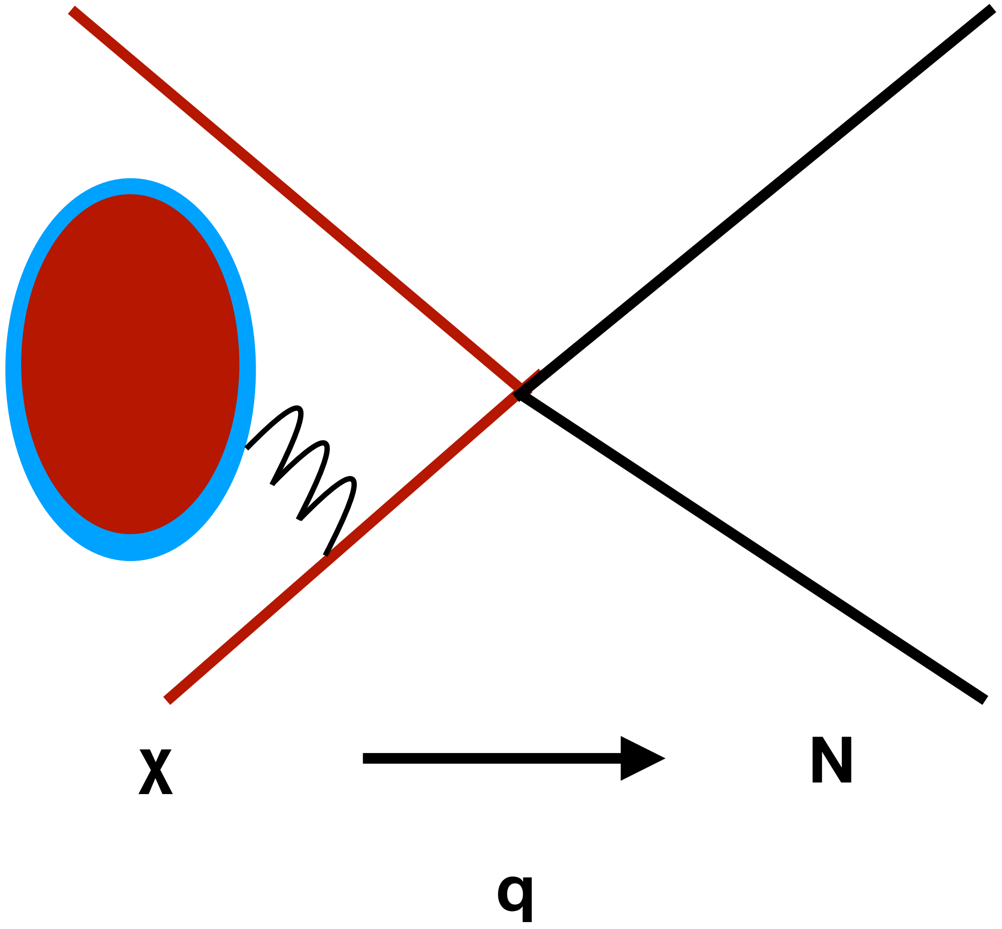

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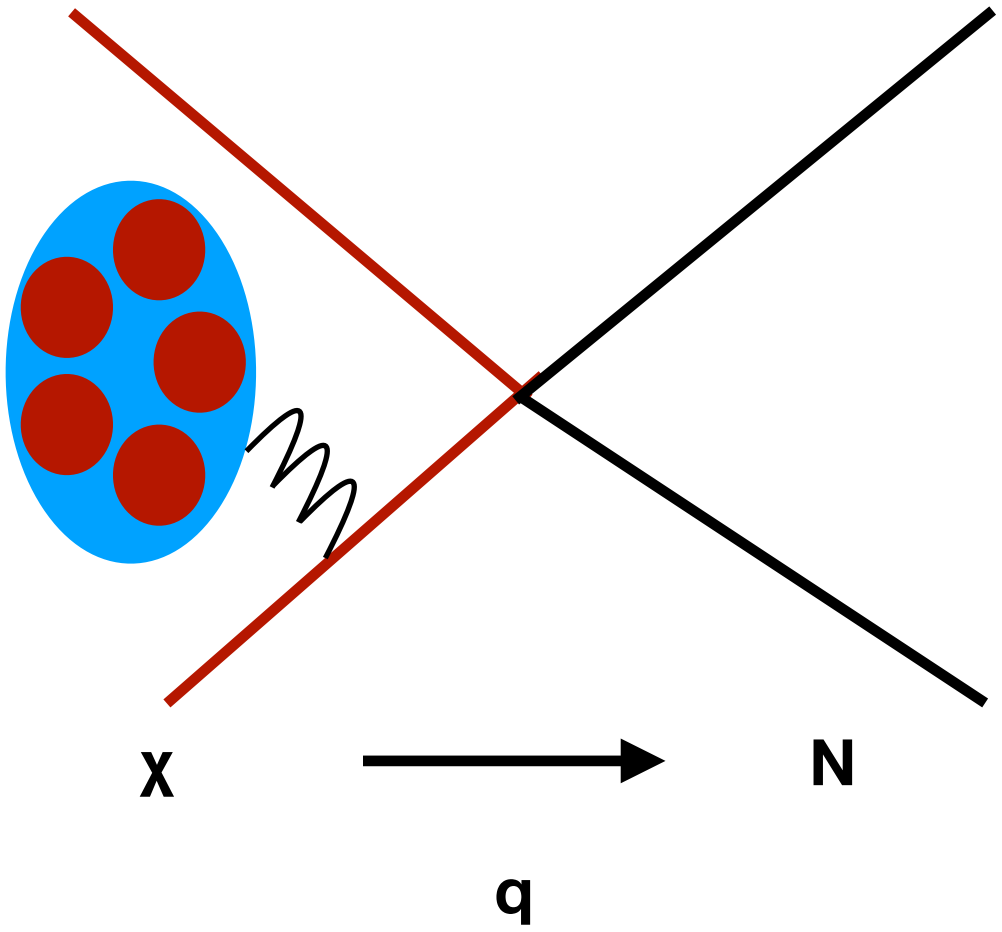
Form depends on Λ - ionize for Λ > 300 keV, heat below that

Short Range: Fermionic Blob



$R \sim N^{1/3}/\Lambda$

Coherent enhancement only for soft scattering => low energy deposition

Lots of partons => multiple scattering possible

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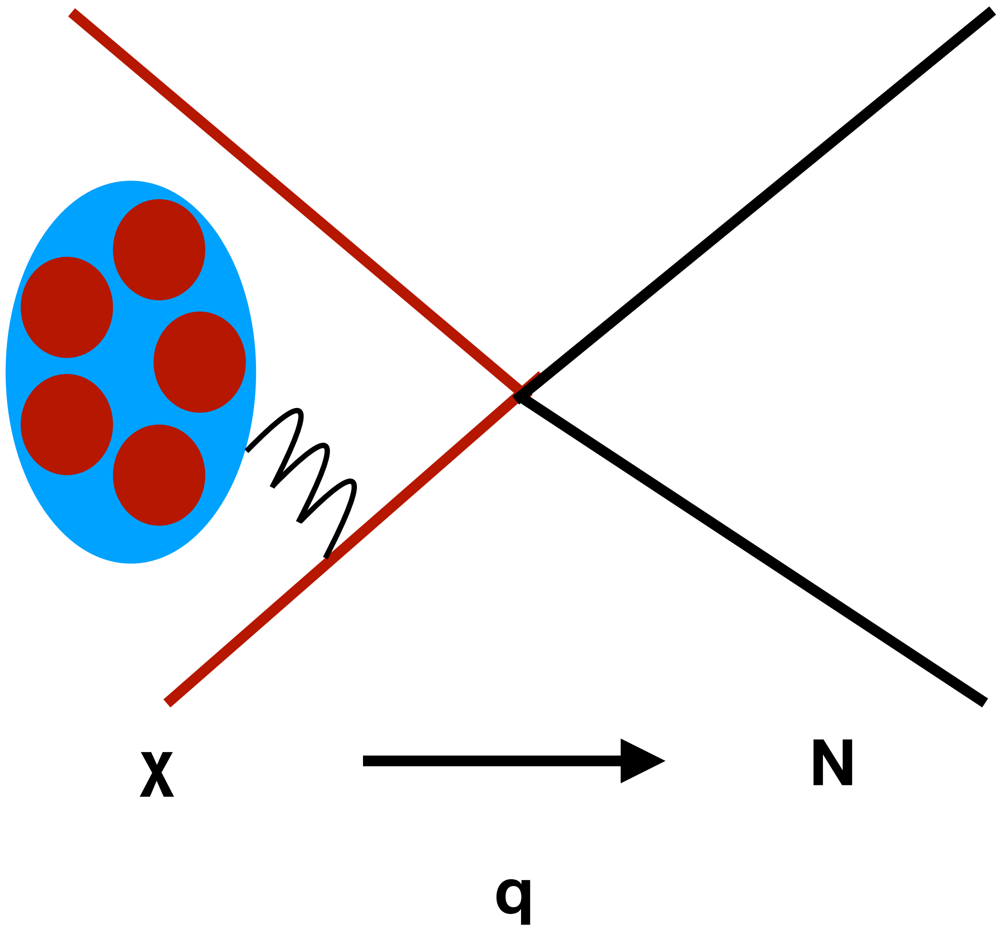

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$$\frac{dE}{dx} = \eta_m \left(\frac{M}{\Lambda}\right) \left(\frac{g_\chi^2 g_N^2 m_N^2}{\mu^4}\right) \left(\frac{\Lambda^2}{m_N^2 v_x^2}\right) \left(\frac{\Lambda^2}{m_N}\right)$$

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Long Range

Take Range $1/\mu \gg$ Blob size R

Blob sources classical field $g_\chi N/r$

Long Range

Take Range 1/μ >> Blob size R

Blob sources classical field g_χ N/r

$$g_N\phi\bar{N}N$$

Exerts Force

Energy Loss in Medium due to dynamical friction

$$\frac{dE}{dx} \sim 2\pi \int_0^{\frac{1}{\mu}} dr\, r\, \eta_m m_N \left(\frac{F\left(r\right)}{m_N}\frac{r}{v}\right)^2$$

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(when adiabatic)

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$$\frac{1}{f_a} \partial_\nu \phi \bar{N} \gamma^\nu \gamma_5 N$$

Causes Spin Precession

$$\delta\theta \sim \frac{g_\chi N}{f_a r v}$$

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Causes Spin Precession

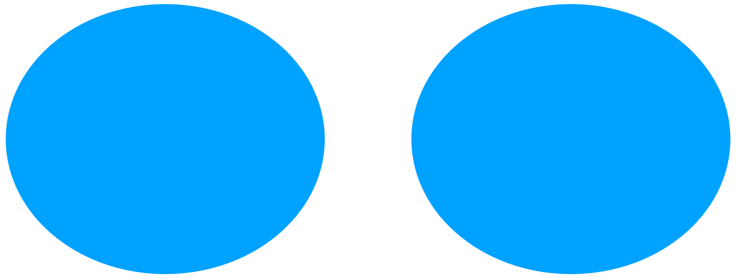
$$\delta\theta \sim \frac{g_\chi N}{f_a r v}$$

$$\frac{\phi}{\alpha M} F_{\mu\nu} F^{\mu\nu}$$

Induces Strain

$$h \sim \frac{g_\chi N}{r M}$$

Constraints



Bullet Cluster Bounds.
For short range, no constraints on bosons.

Not relevant if blob < 10 percent of dark matter

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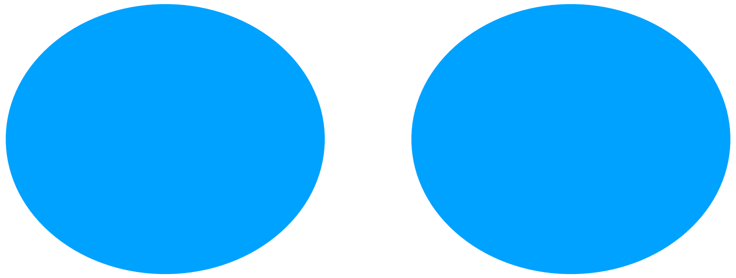

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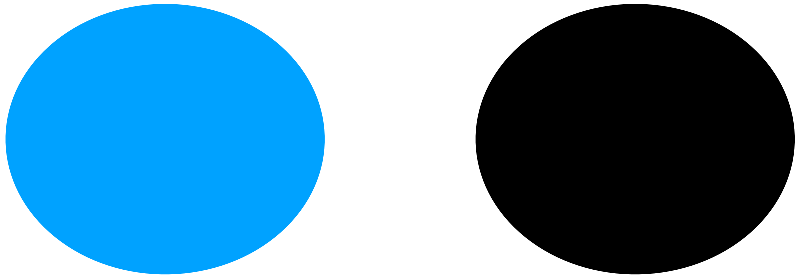

Blob - baryon friction bounded by BAO. Not a significant constraint.

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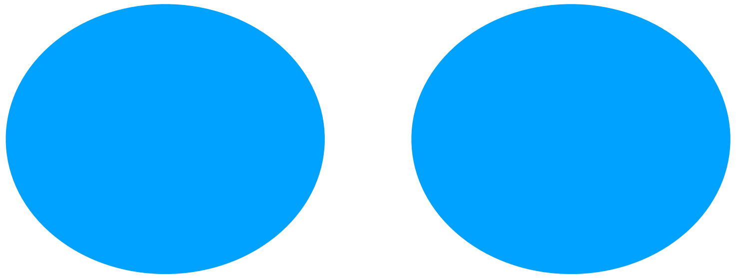

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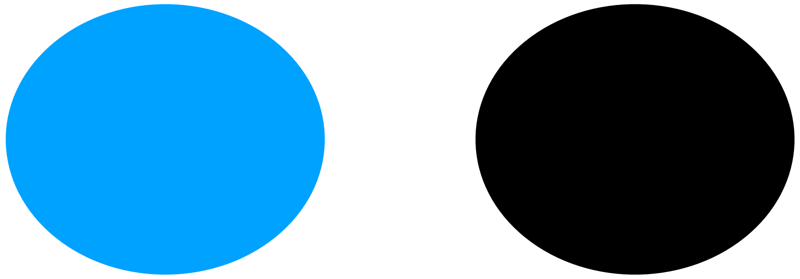

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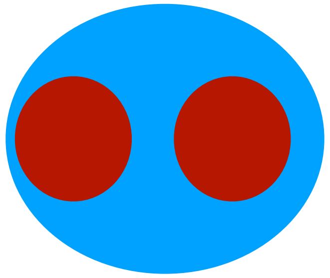


No instability from ϕ

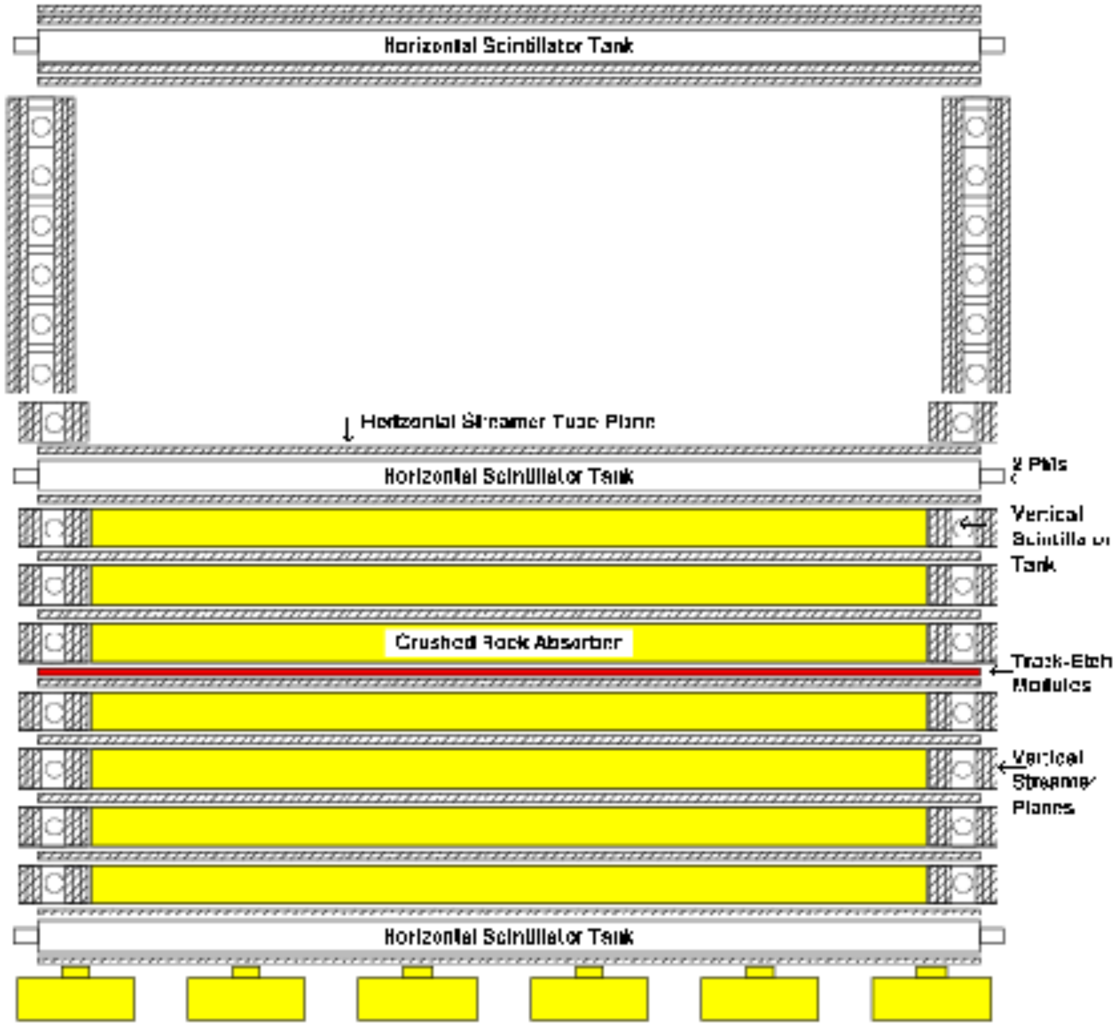
$$g_\chi \lessapprox \frac{1}{\sqrt{N}}$$

(bosonic)

$$g_\chi \lessapprox \frac{1}{N^{\frac{1}{3}}}$$

(fermionic)

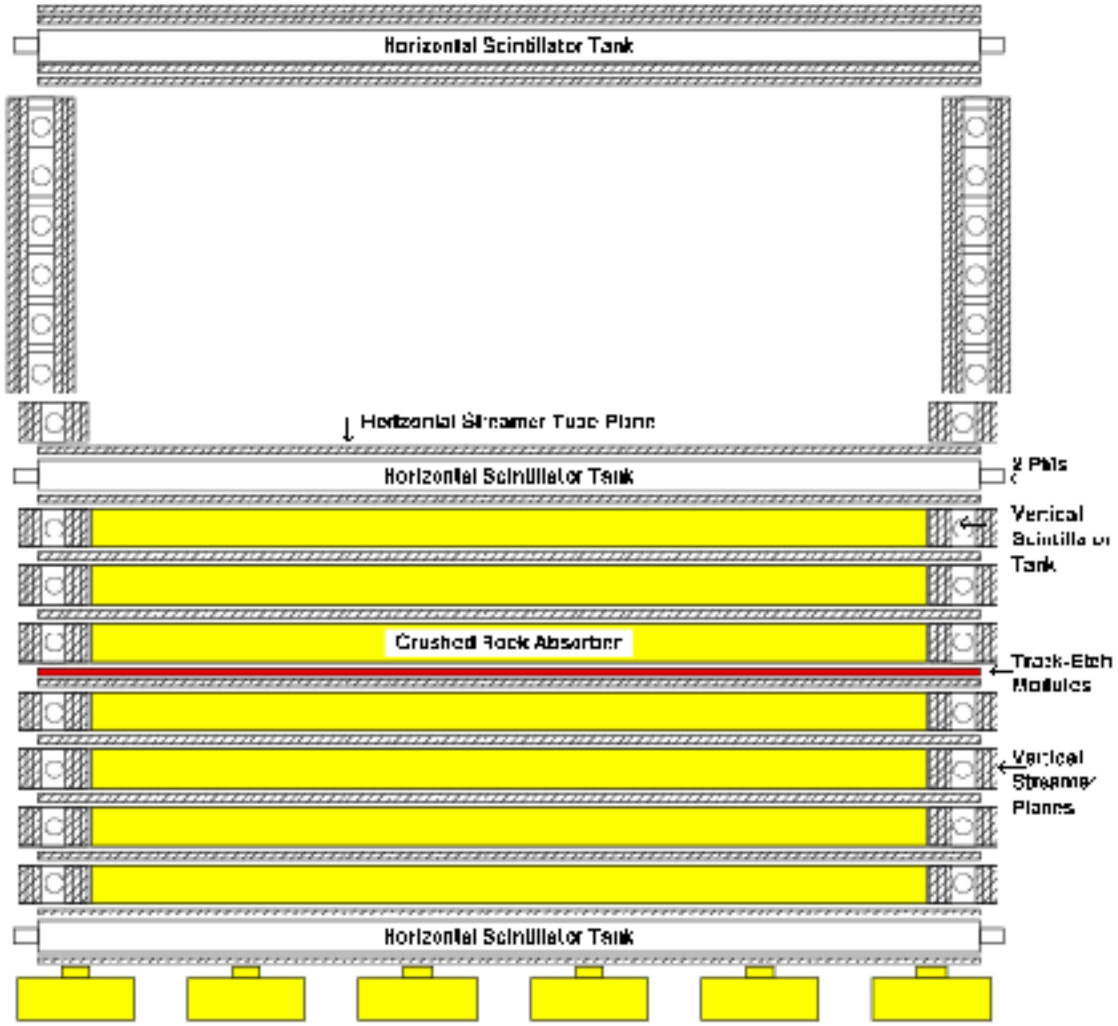
Constraints



MACRO Monopole Search
(~ 80 x 10 x 10 m^3)

Energy Threshold: 6 MeV/cm
+
Scintillation

Constraints



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(~ 80 x 10 x 10 m^3)

Energy Threshold: 6 MeV/cm
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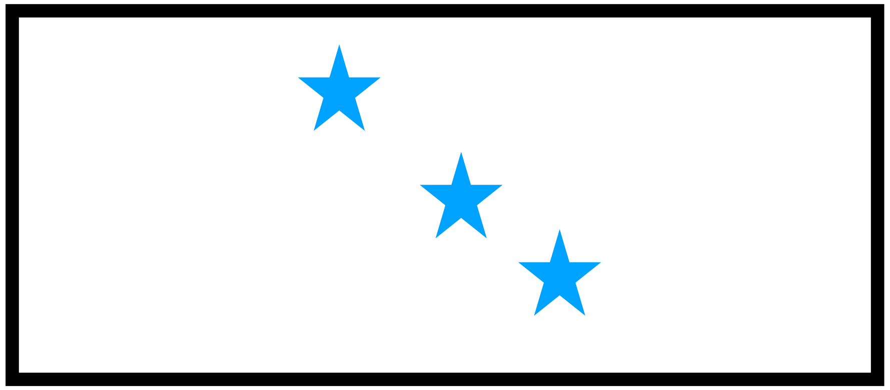
Mediator coupling to Standard Model constrained by new force searches, astrophysical bounds on light particles, collider limits

Detection

Short Range

Ionization
($\Lambda > 300$ keV)



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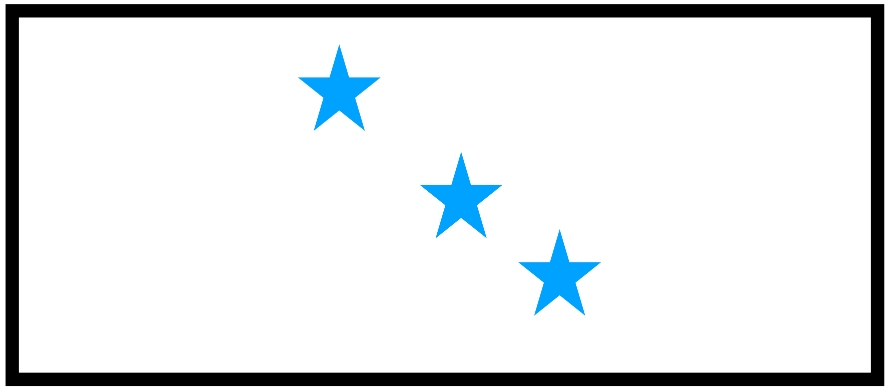

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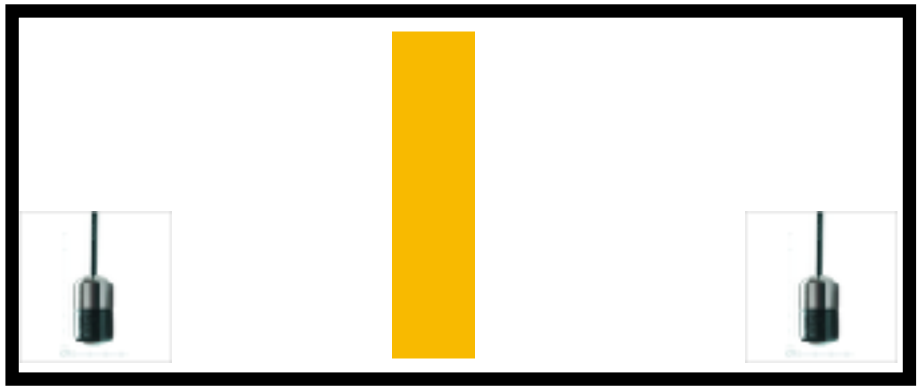
Huge Volume?



Hydrophones: $dE/dx \sim$ keV/A

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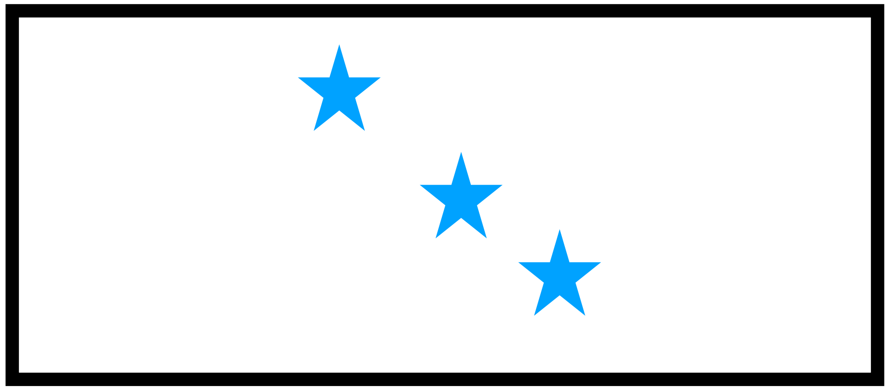

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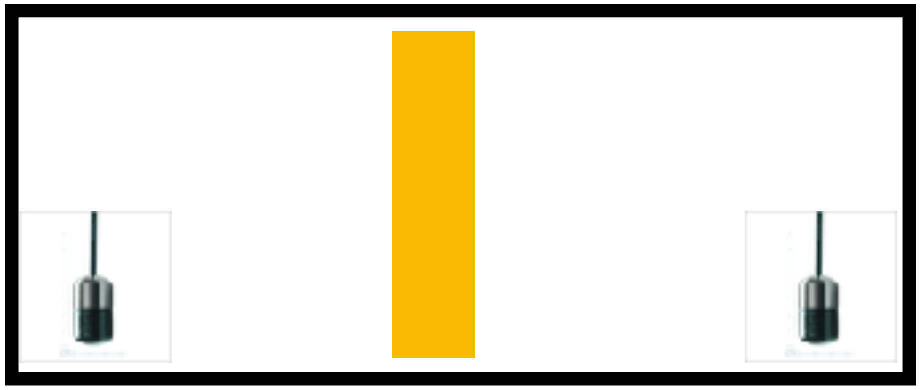
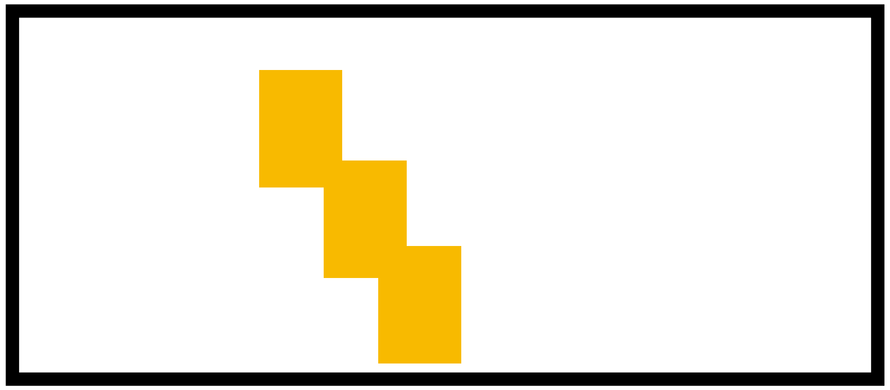


Hydrophones: dE/dx ~ keV/A

Acoustic
(Λ < 300 keV)



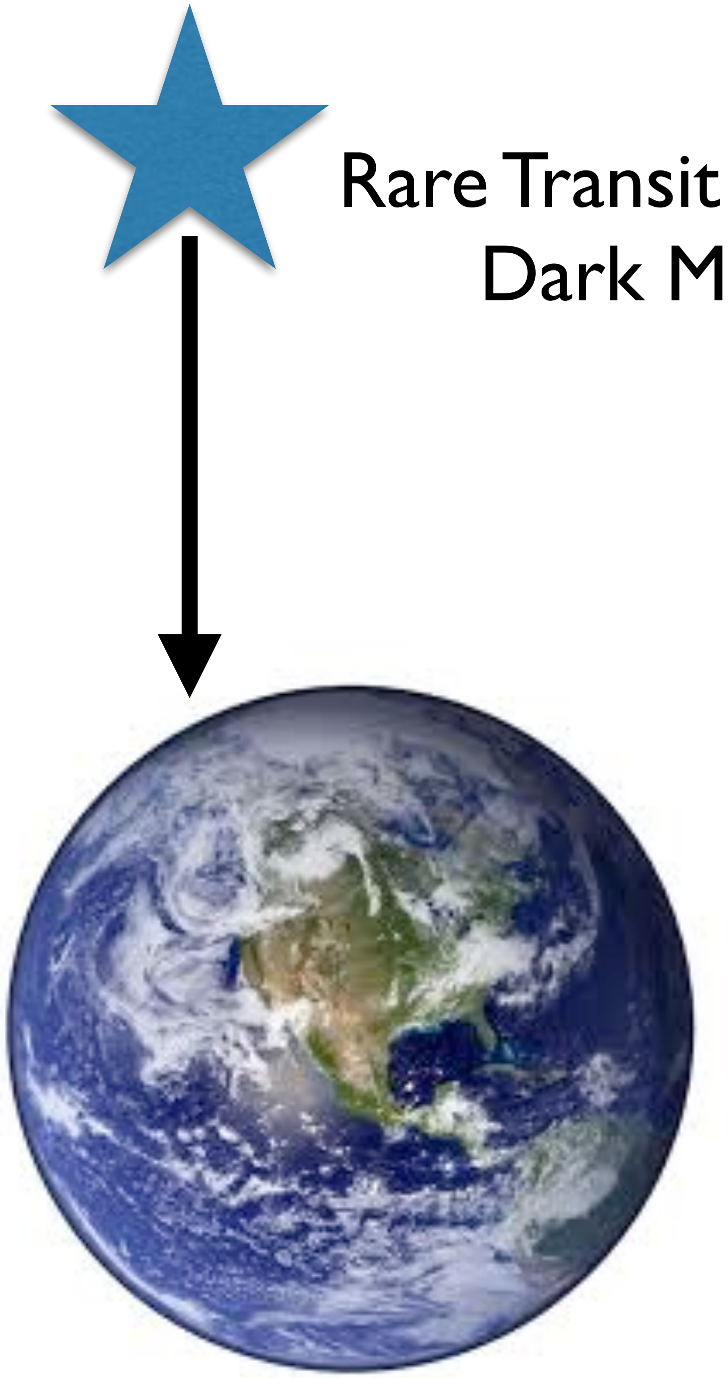
Low threshold calorimeter like CDMS

Line of hot cells

Energy depositions ~ keV/cm

Detection

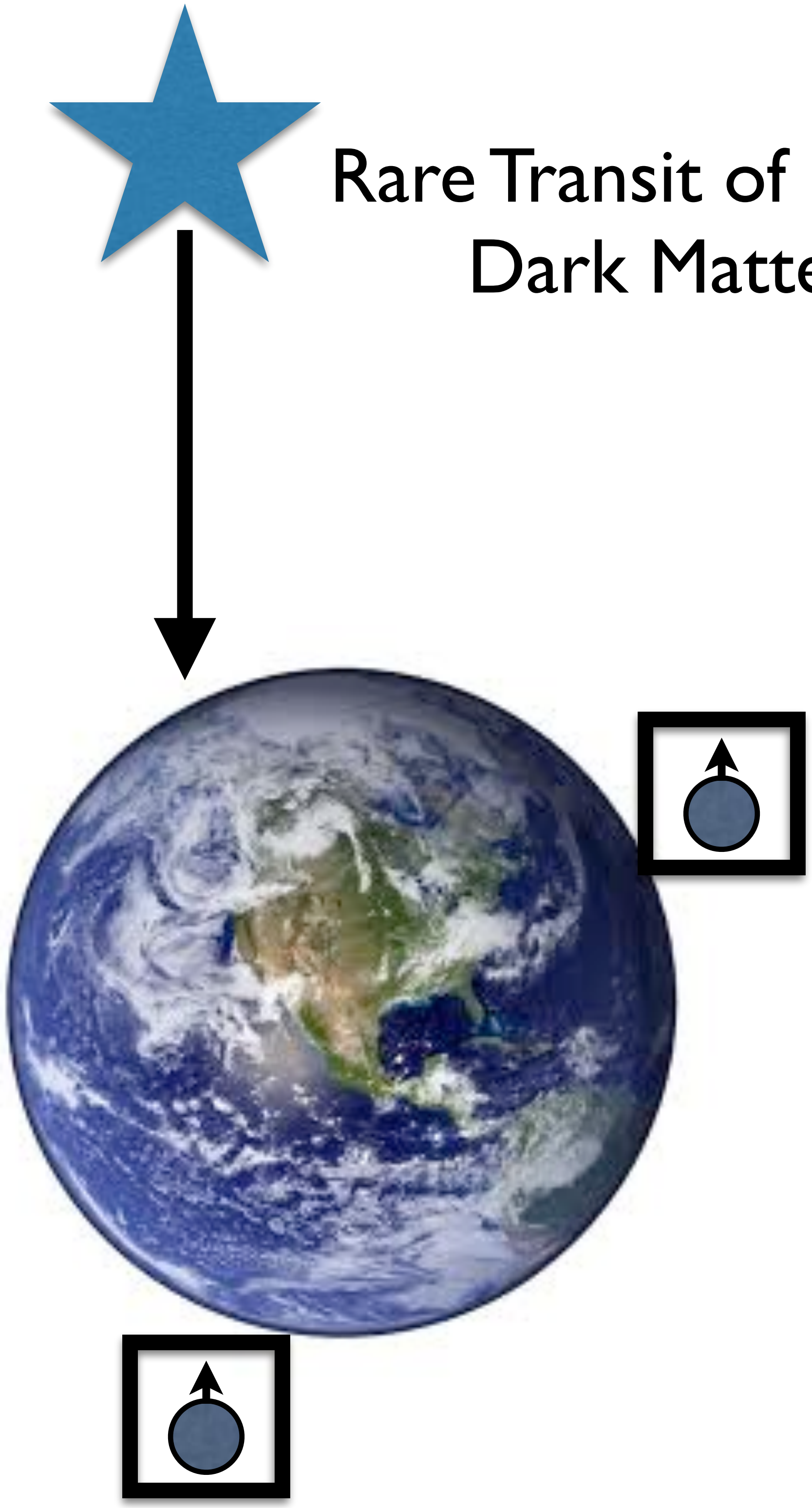
Long Range



Rare Transit of Heavy
Dark Matter

Detection

Long Range



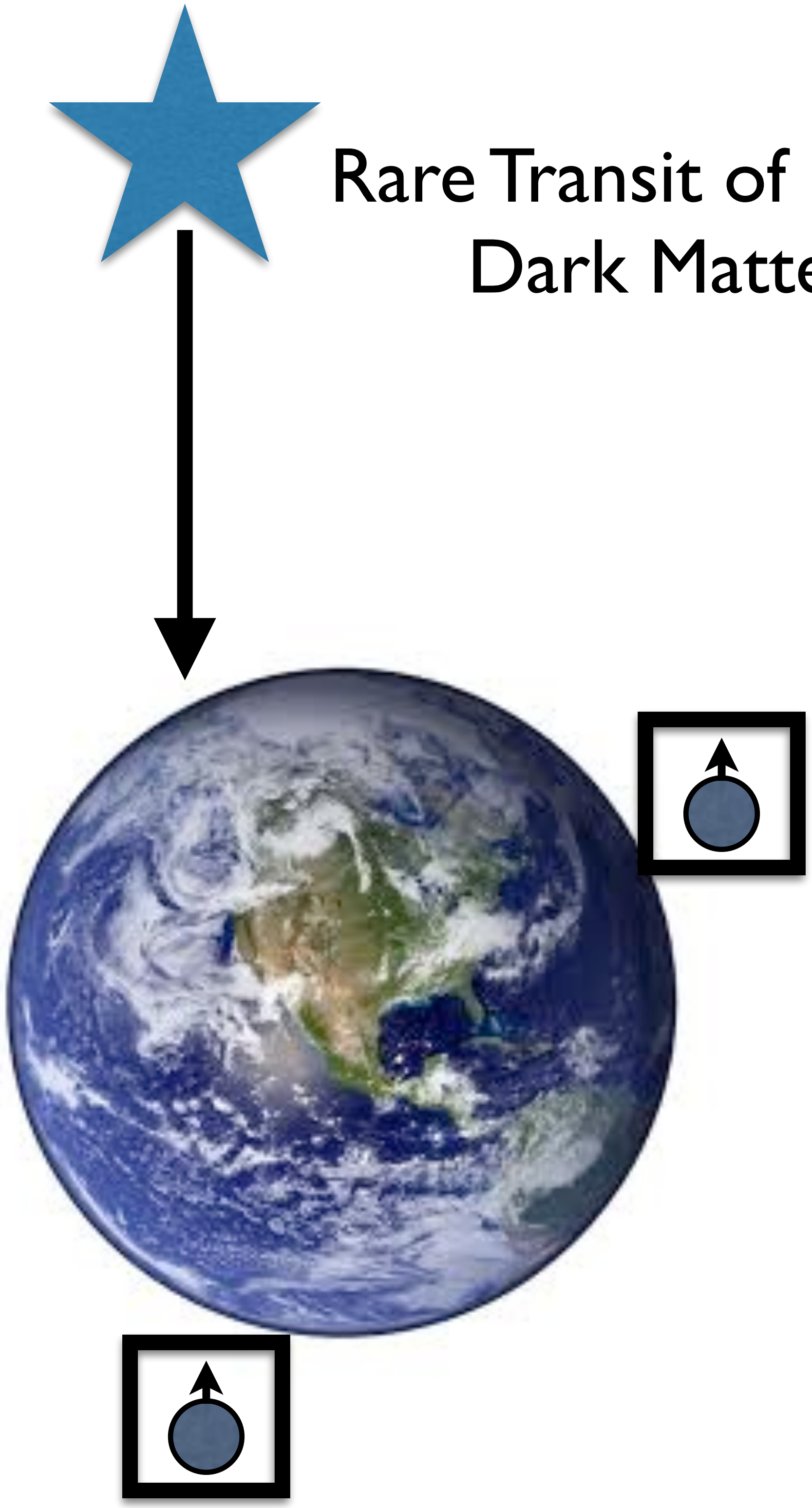
Rare Transit of Heavy Dark Matter

Classical field created by dark matter - correlated excitation of multiple detectors

Same class of effects as light dark matter - excitation of currents, spin precession, acceleration, variation of fundamental constants

Detection

Long Range



Rare Transit of Heavy Dark Matter

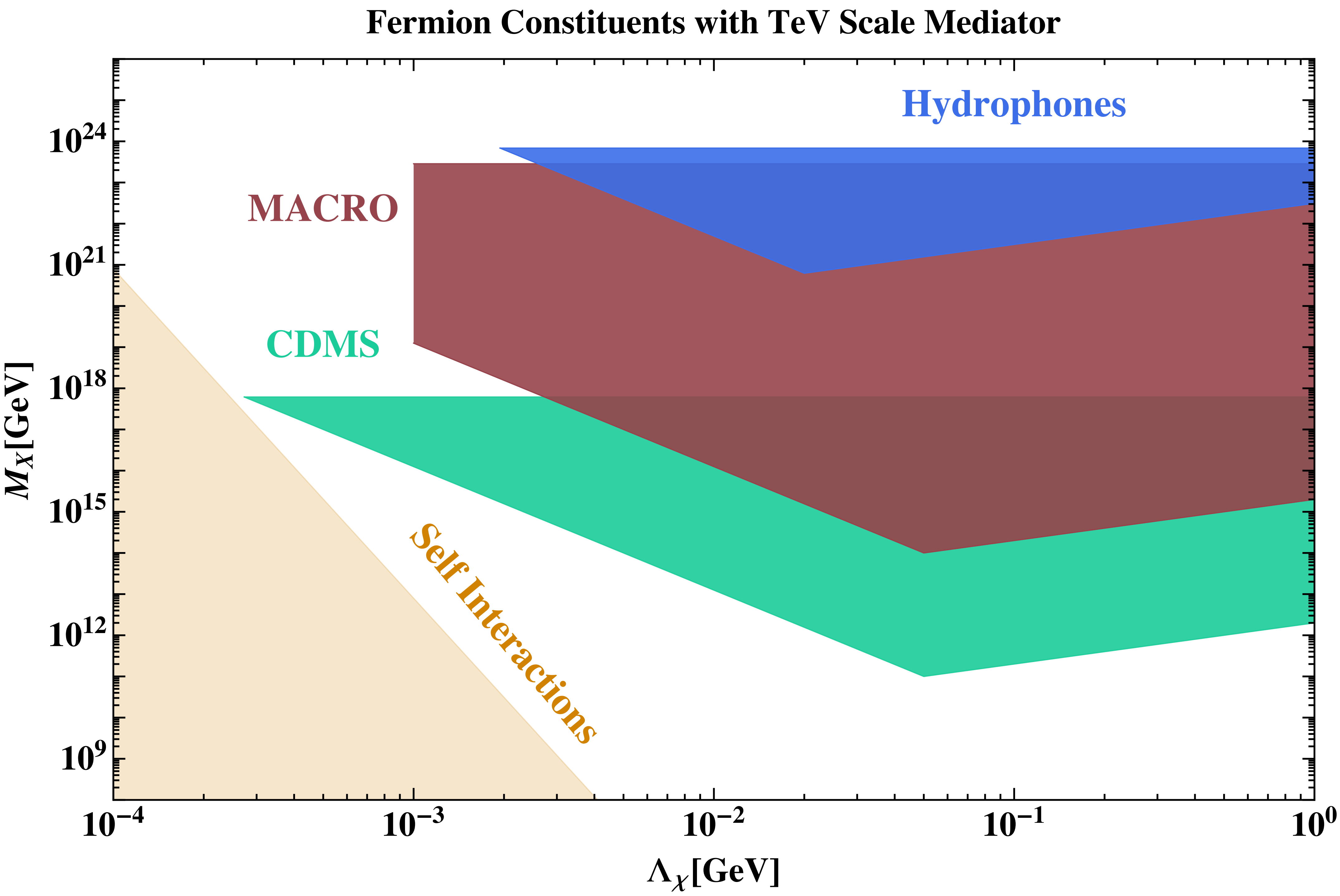
Classical field created by dark matter - correlated excitation of multiple detectors

Same class of effects as light dark matter - excitation of currents, spin precession, acceleration, variation of fundamental constants

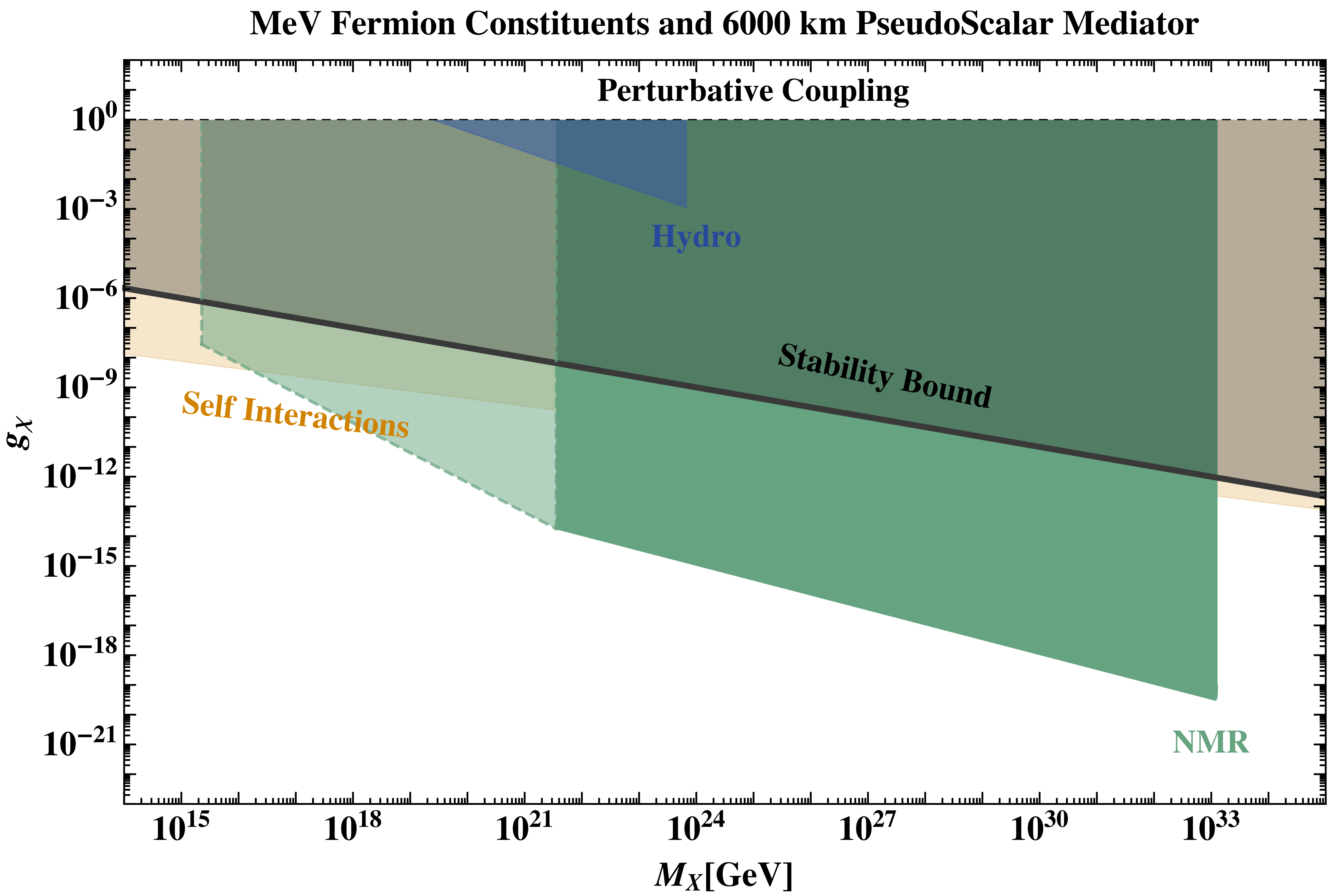
Instead of continuous, coherent a/c effect, look for correlated transients in network

Up to dark matter mass ~ 10^8 gm

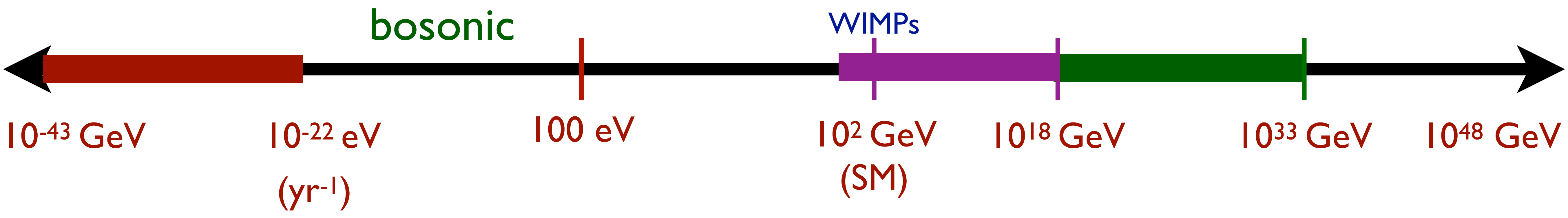
Reach


Fermion Constituents with TeV Scale Mediator
Hydrophones
MACRO
CDMS
Self Interactions
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
M_X[GeV]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Λ_χ[GeV]

Reach


MeV Fermion Constituents and 6000 km PseudoScalar Mediator
Perturbative Coupling
Hydro
Stability Bound
Self Interactions
NMR
g_χ
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{15}
10^{18}
10^{21}
10^{24}
10^{27}
10^{30}
10^{33}
M_X[GeV]

The Dark Matter Landscape



Poor observational constraints on dark matter

Current Experimental Concepts can probe region from 10^{18} GeV - 10^{33} GeV

Possible to probe above 10^{33} GeV using astrophysical systems - particularly white dwarfs