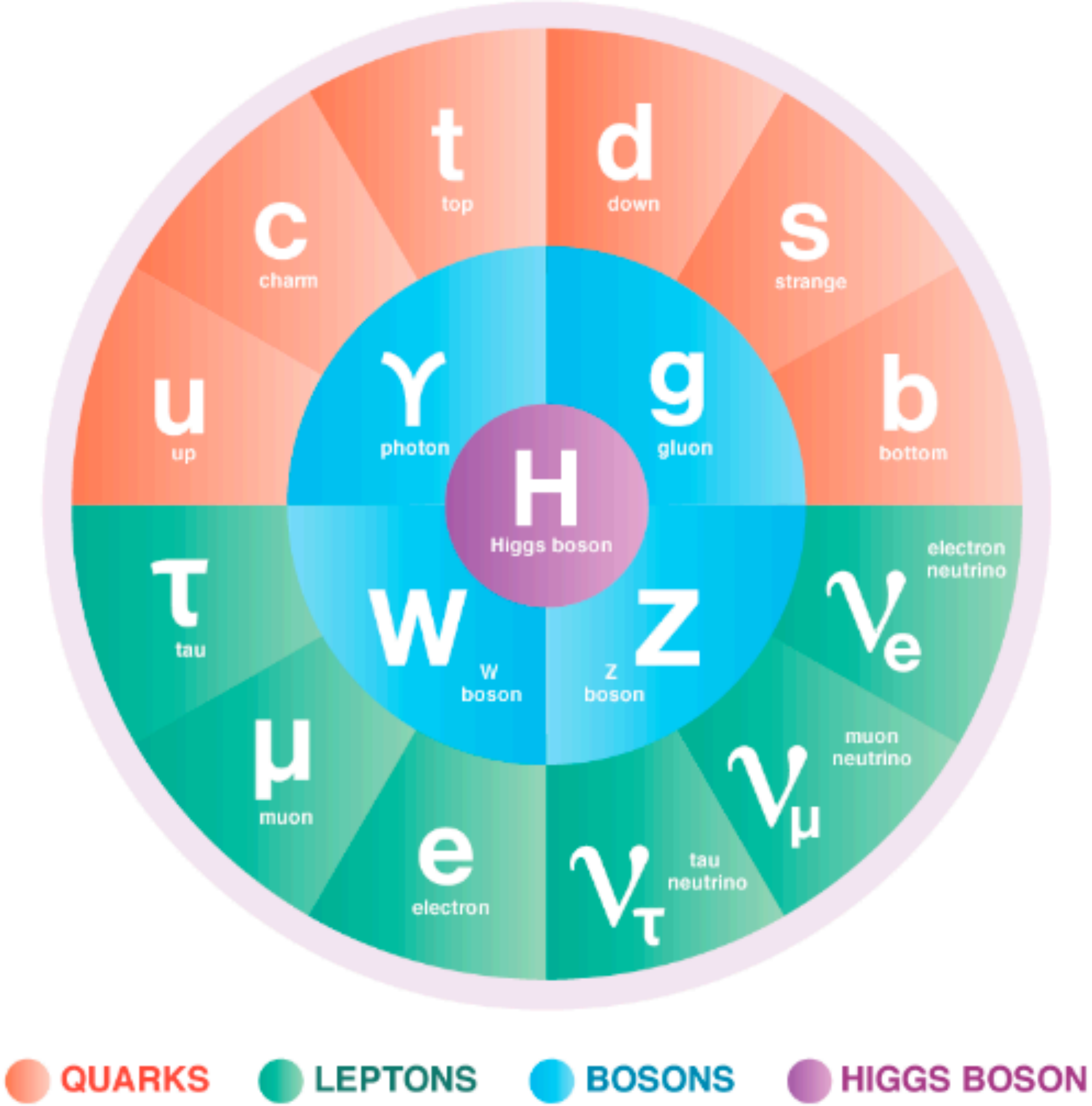
THE UNIVERSITY OF SYDNEY

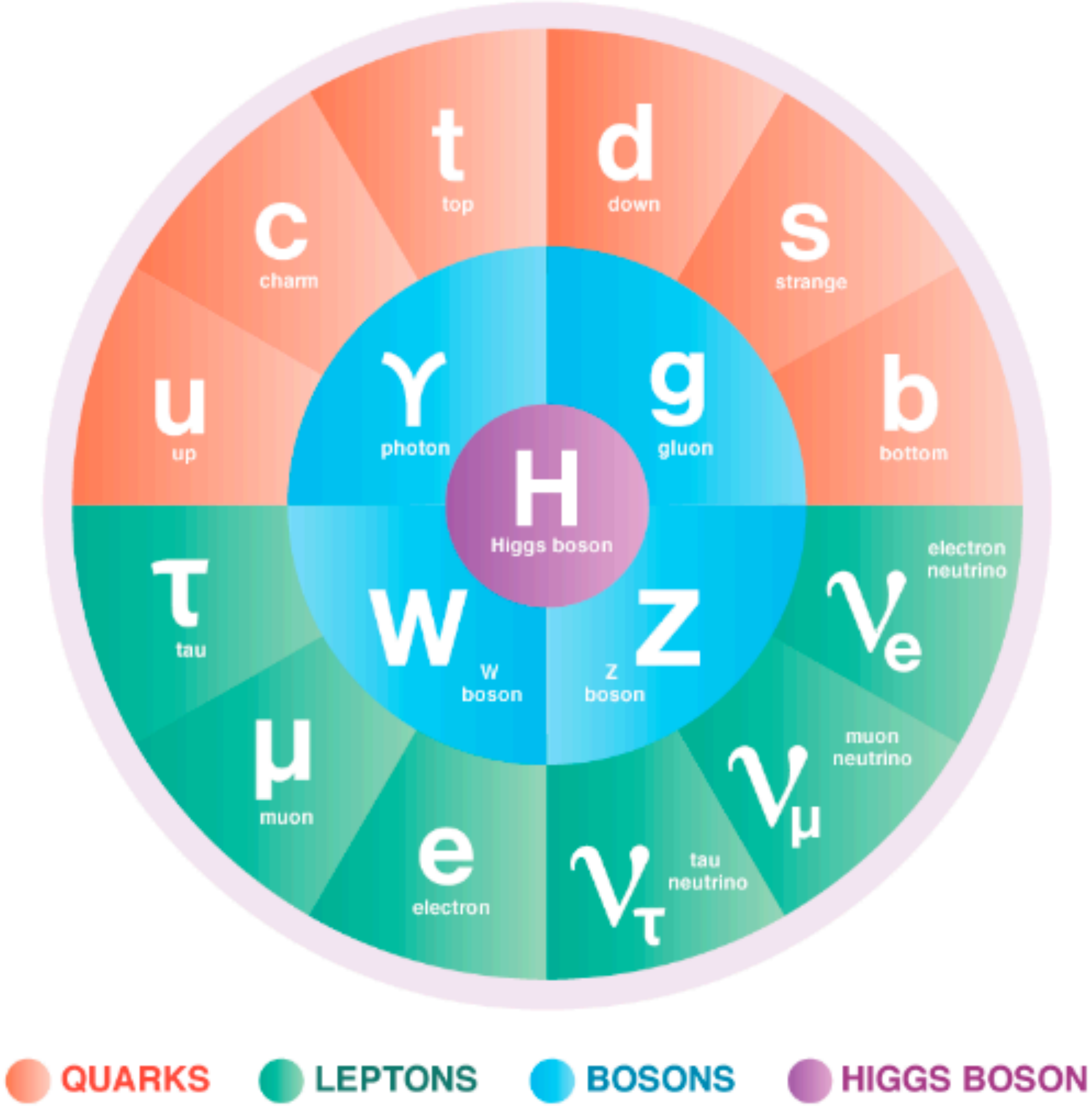
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Searching for dark particles across disciplines

Ciaran O'Hare



Symmetry magazine

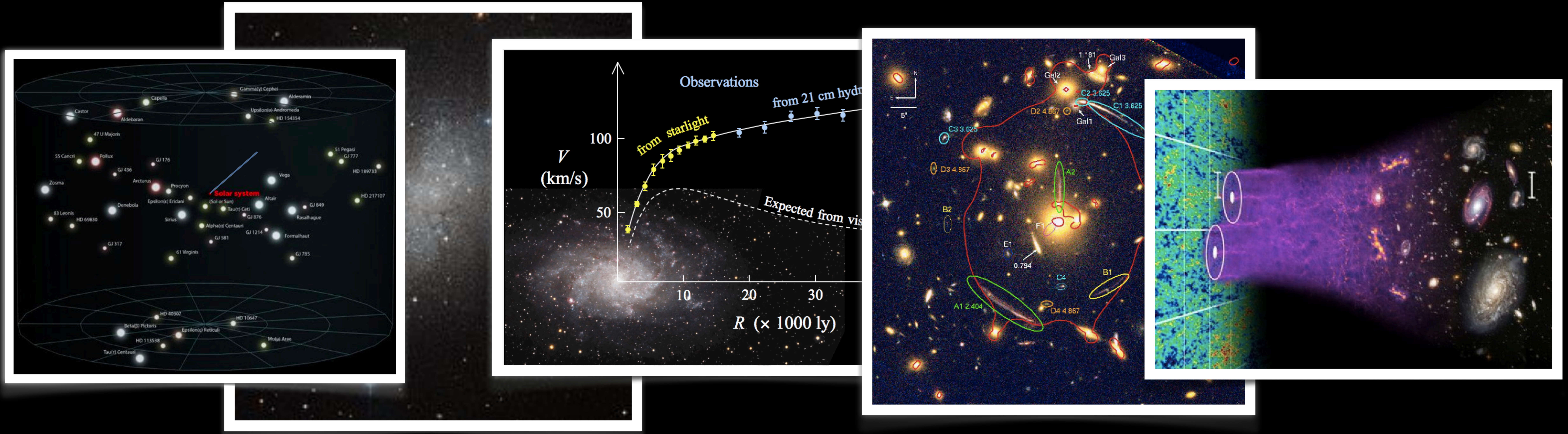


- dark matter?
- dark energy?
- Supersymmetric particles?
- Right-handed neutrinos?
- an inflaton?
- an axion?

Symmetry magazine

Evidence for dark matter across all length scales and across cosmic time

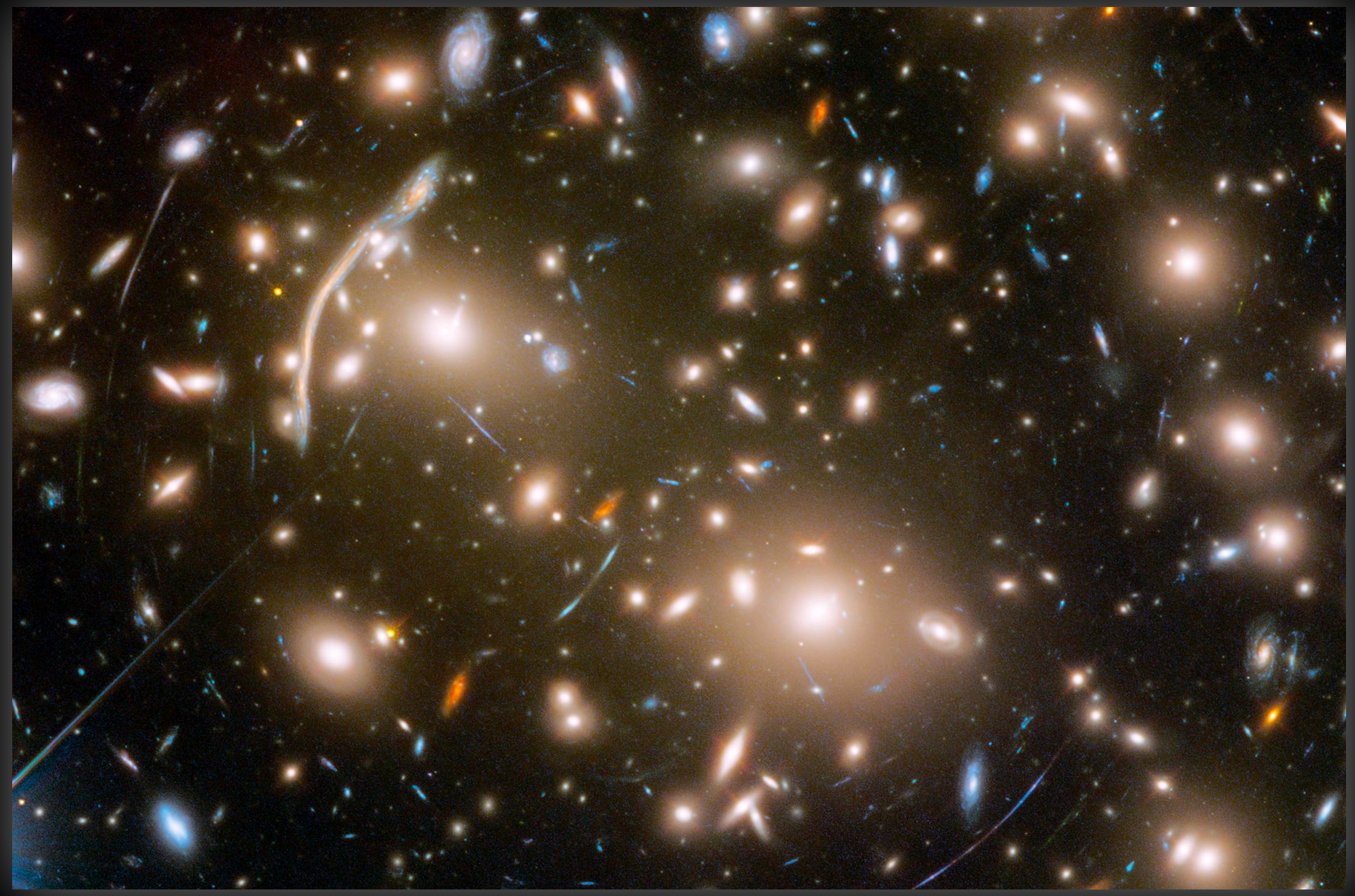
~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	Seeds large scale structure



Why is dark matter a problem for physics?

For describing **astrophysical systems** "dark matter" is just a label given to a set of observations

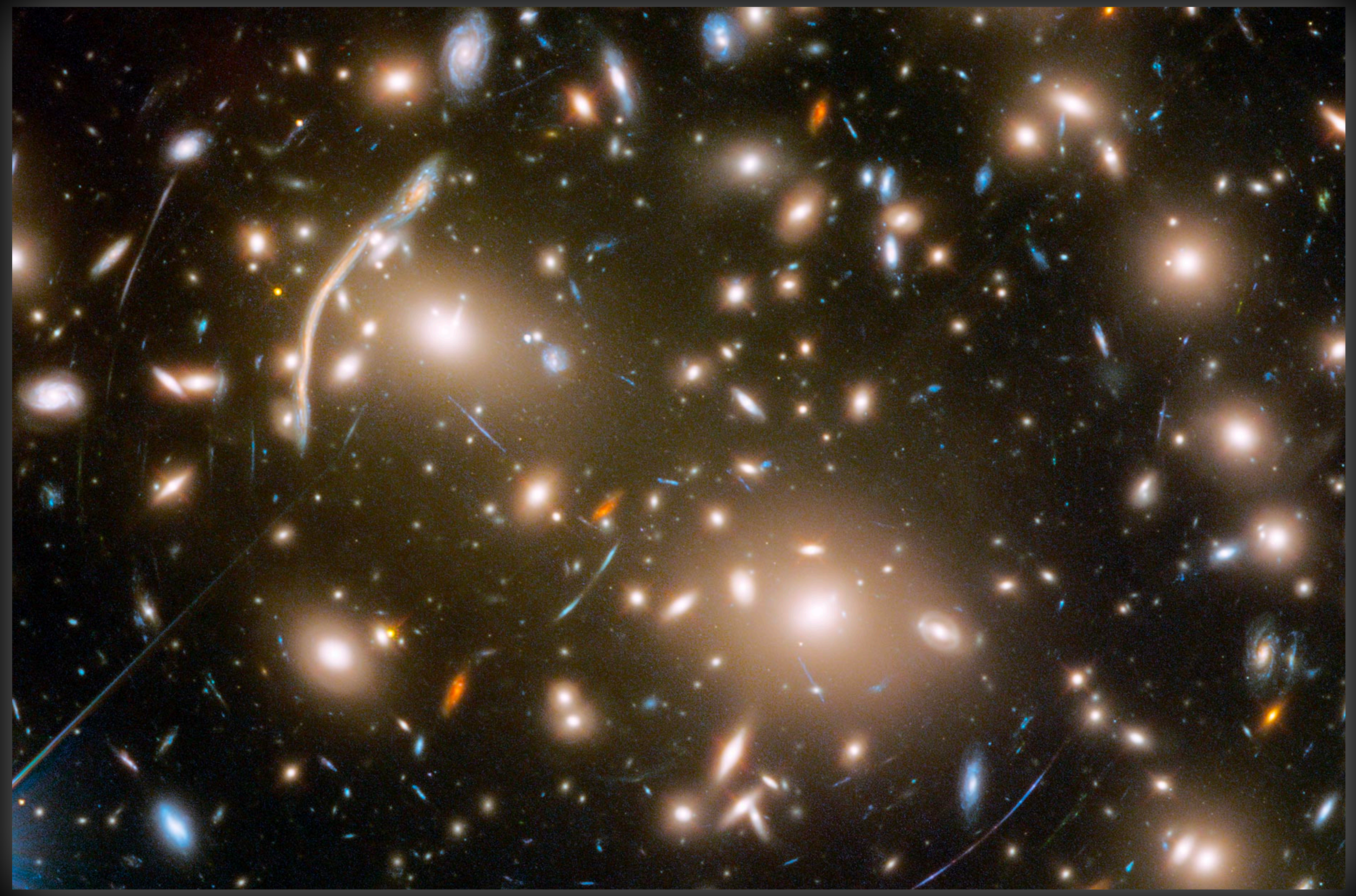
It is actually an incredibly elegant solution → you can explain the dynamics of structures across the Universe if you just make ~85% of all mass invisible



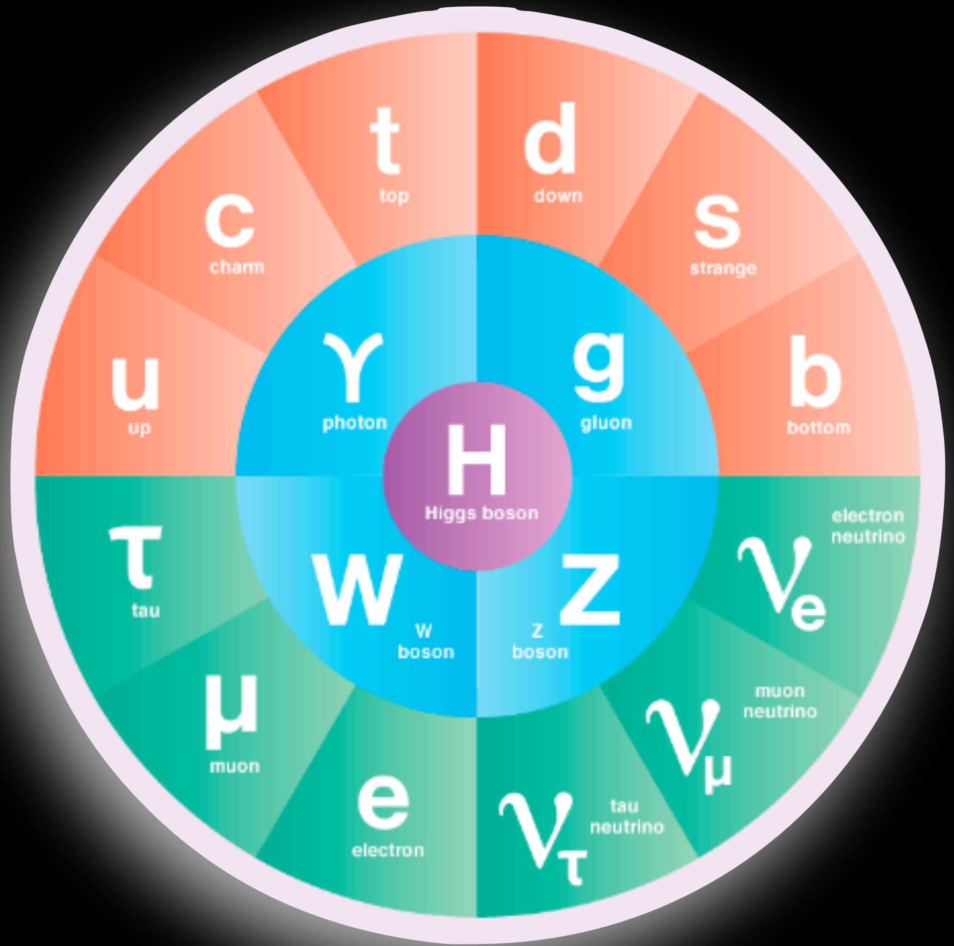
Why is dark matter a problem for physics?

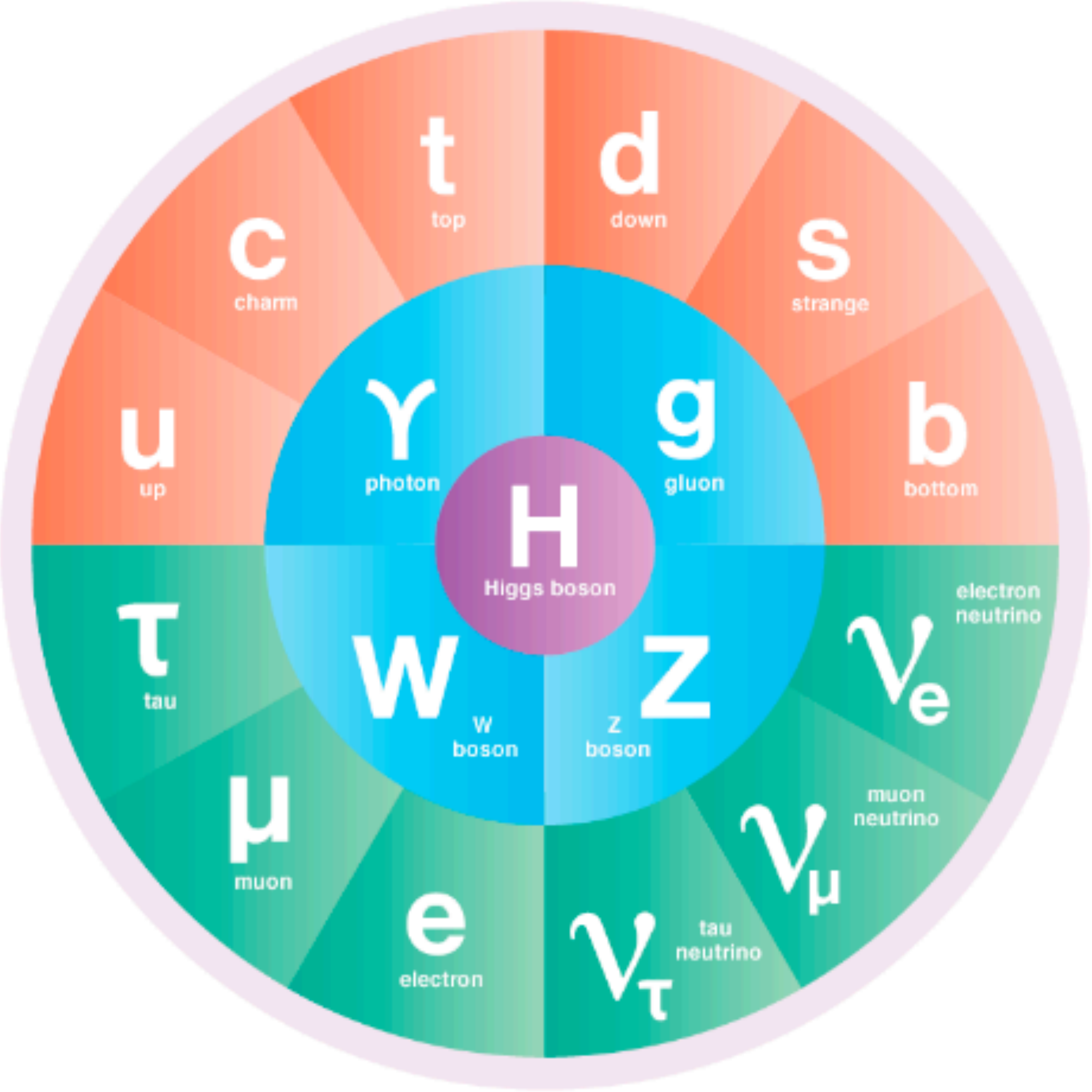
For describing **astrophysical systems** “dark matter” is just a label given to a set of observations

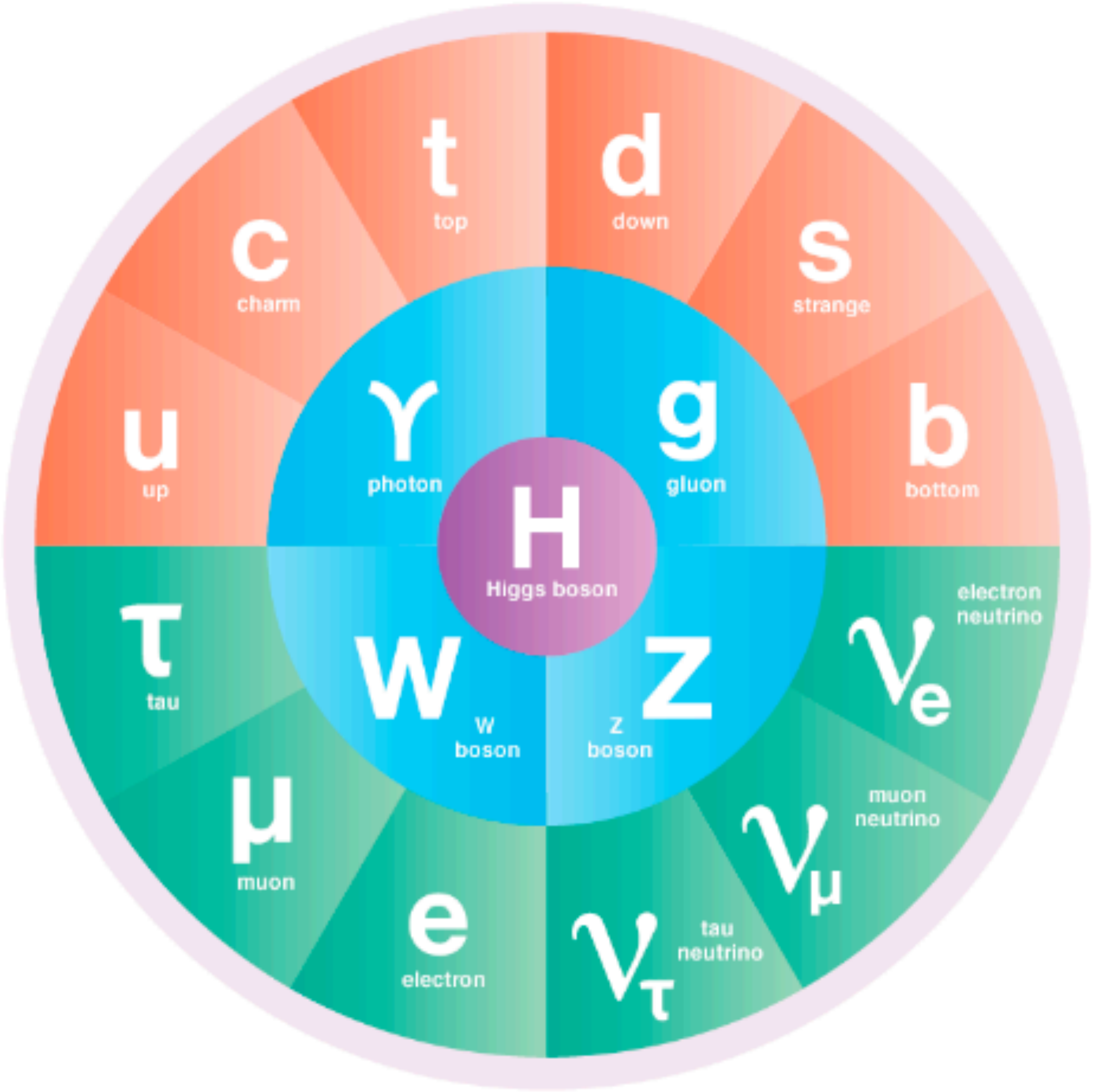
<u>It is actually an incredibly elegant solution</u>
→ you can explain the dynamics of structures across the Universe if you just make ~85% of all mass invisible



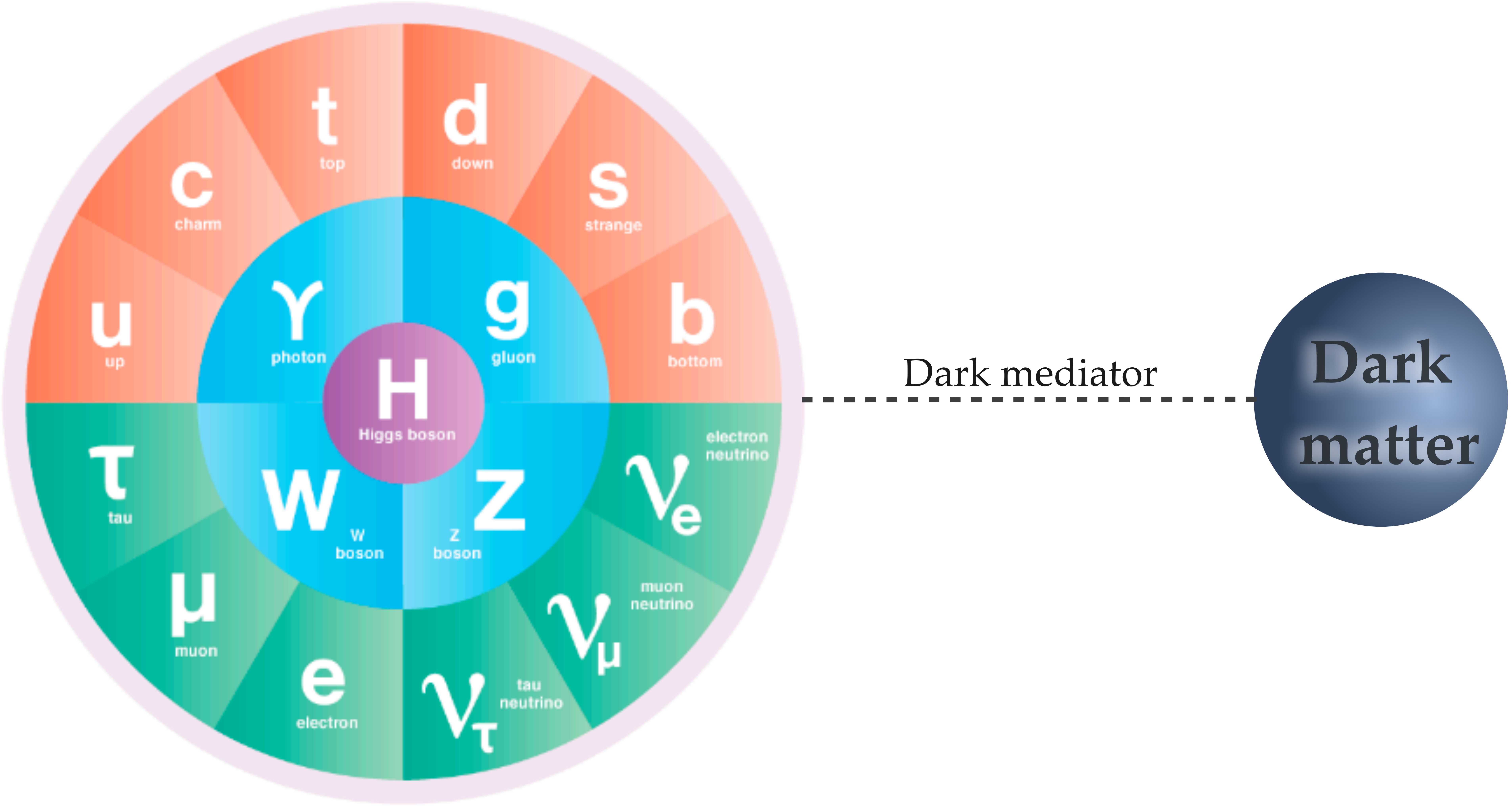
The problem lies with **particle physics** we have no fundamental explanation for what the identity of dark matter is, how it was created, or how it connects to the Standard Model

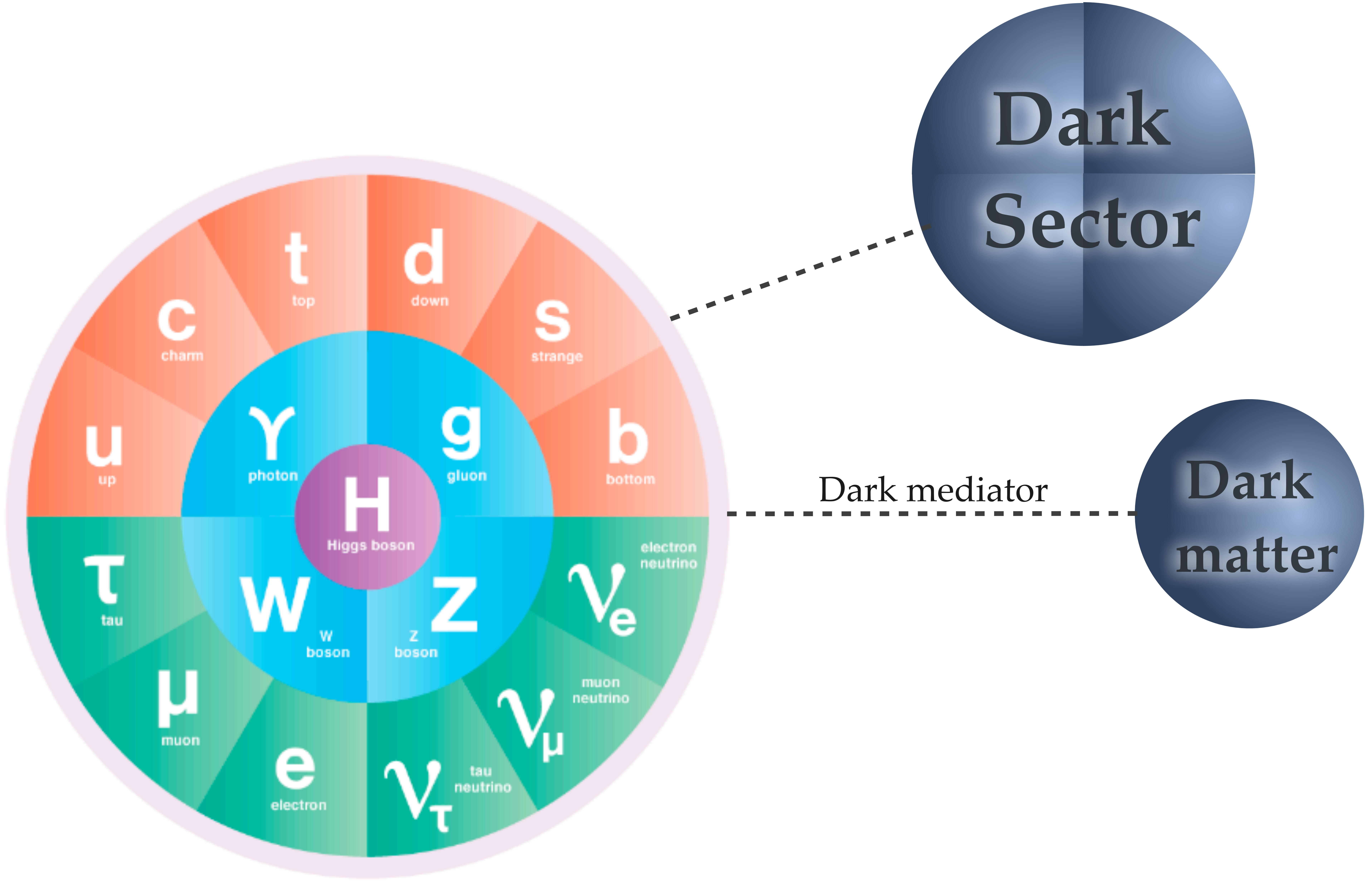


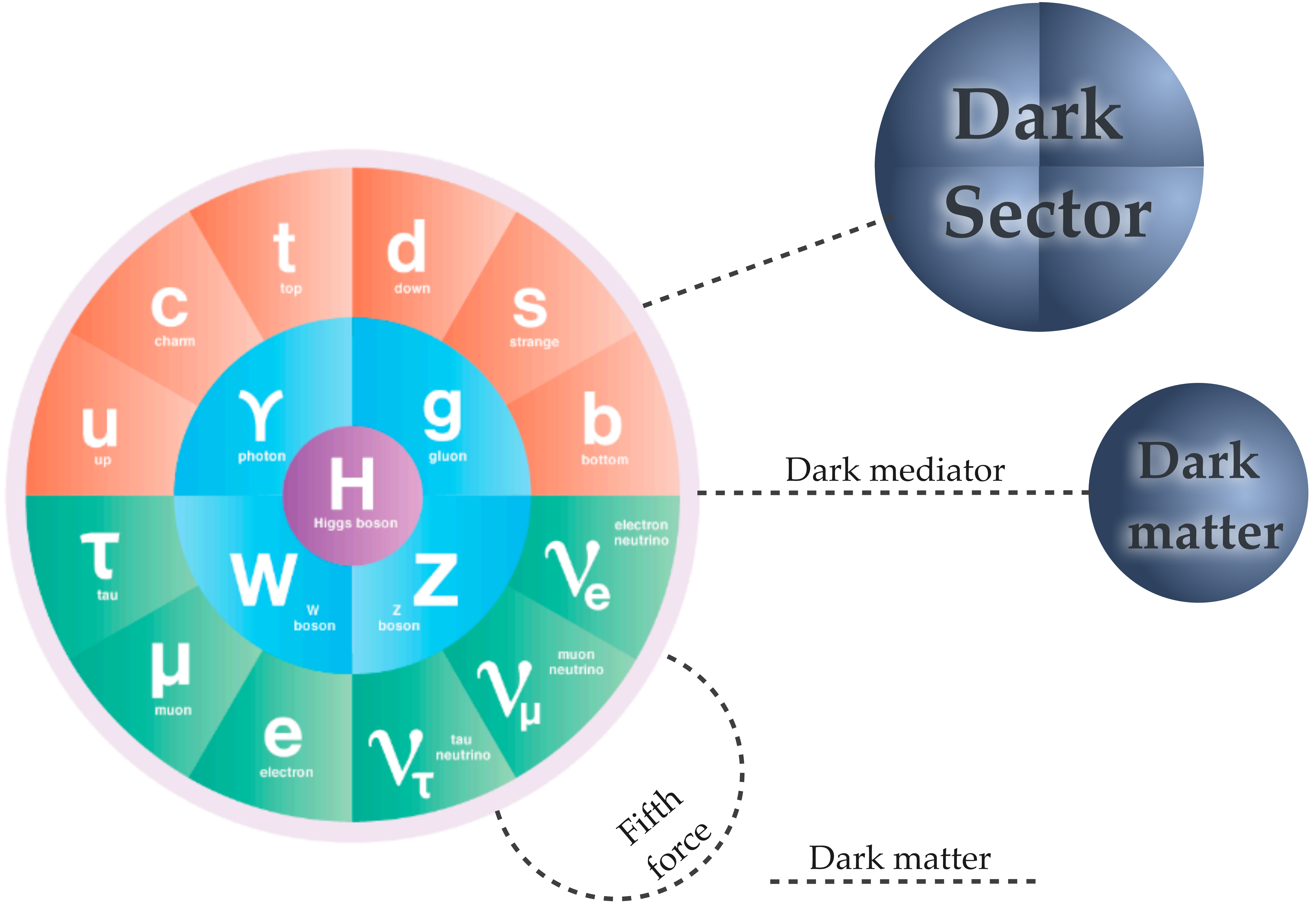

t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W
boson
Z
Z
boson
electron
neutrino
ν_e
μ
muon
muon
neutrino
ν_μ
e
electron
ν_τ
tau
neutrino


t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W
boson
Z
Z
boson
electron
neutrino
μ
muon
muon
neutrino
e
electron
tau
neutrino

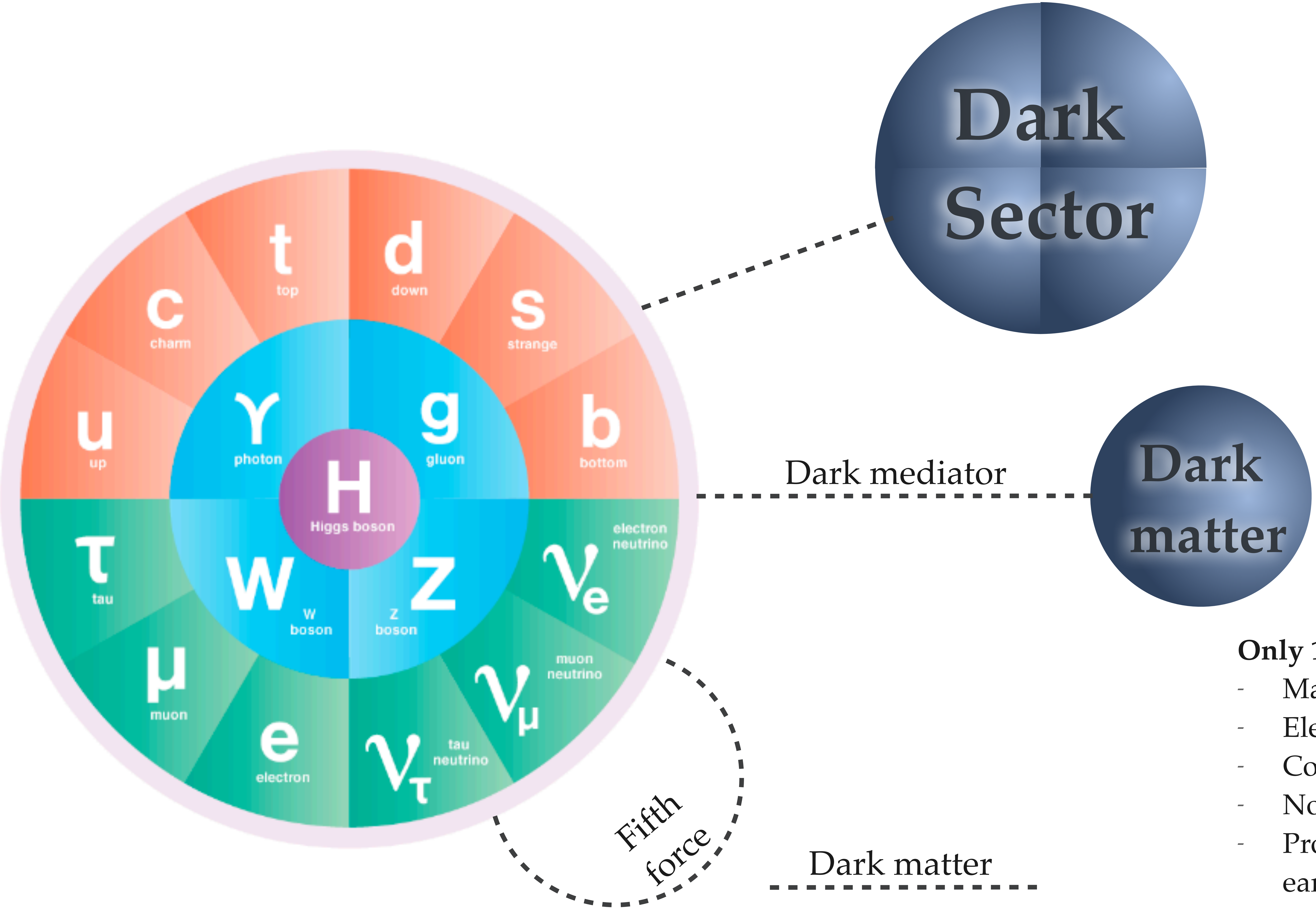
Dark
matter


t
top
d
down
c
charm
s
strange
u
up
γ
photon
g
gluon
b
bottom
H
Higgs boson
τ
tau
W
W
boson
Z
Z
boson
electron
neutrino
ν_e
μ
muon
muon
neutrino
ν_μ
e
electron
ν_τ
tau
neutrino
Dark mediator
Dark
matter


t
top
d
down
c
charm
s
strange
u
up
b
bottom
ϒ
photon
g
gluon
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
ν_e
electron neutrino
μ
muon
ν_μ
muon neutrino
e
electron
ν_τ
tau neutrino
Dark Sector
Dark mediator
Dark matter

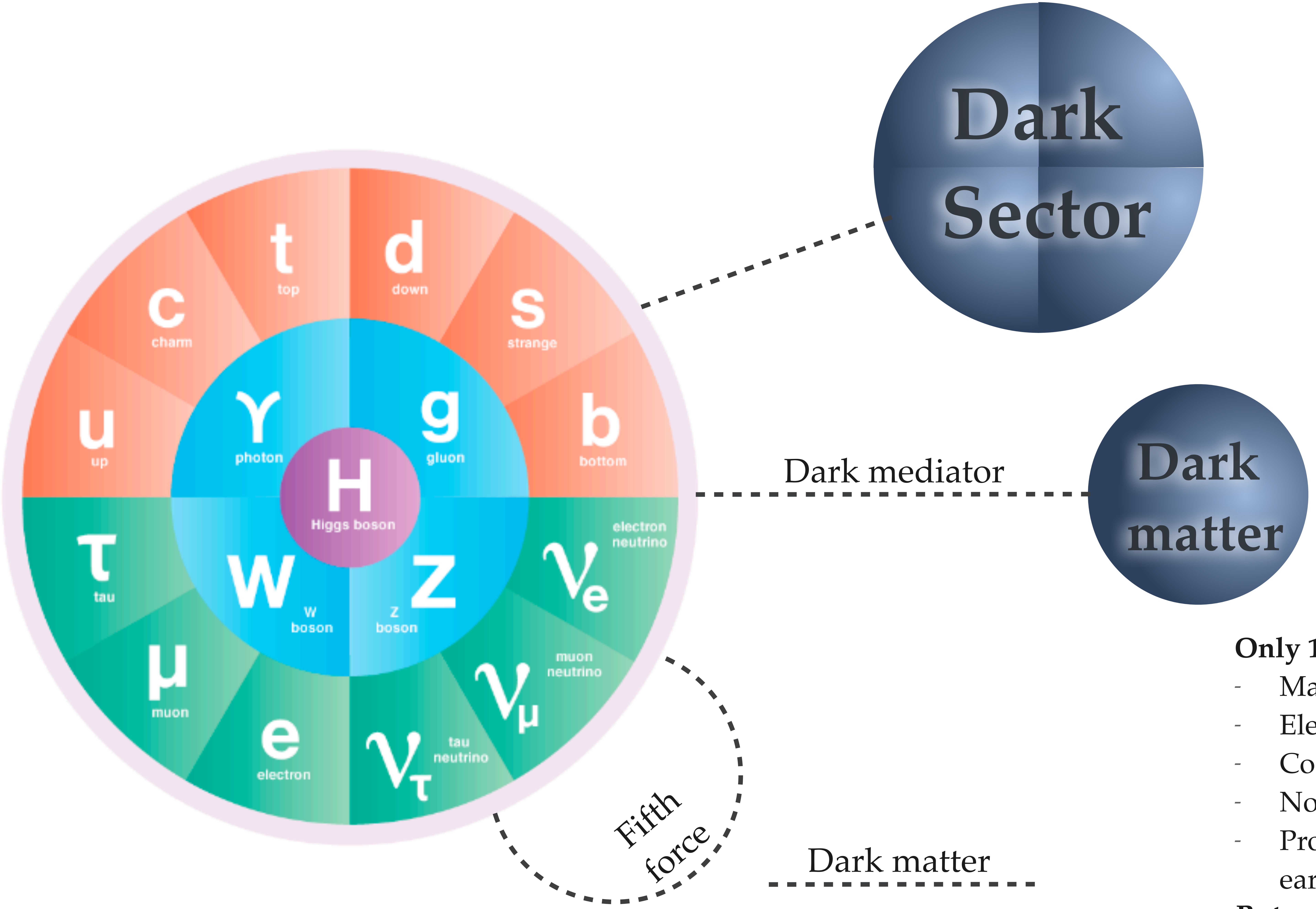


Dark
Sector
Dark mediator
Dark
matter
Fifth
force
Dark matter
t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W
boson
Z
Z
boson
electron
neutrino
μ
muon
muon
neutrino
e
electron
tau
neutrino



Only 1 of these particles needs to be:

- Massive
- Electrically neutral
- Cosmologically stable
- Non-relativistic
- Produced in large quantities in the early universe



Only 1 of these particles needs to be:

- Massive
- Electrically neutral
- Cosmologically stable
- Non-relativistic
- Produced in large quantities in the early universe

But, we know for sure that they cannot interact strongly

No new heavy particles for the time being…

Could there be particles these experiments missed?

Beyond colliders: extremely light, feebly-coupled particles

Many new hypothetical particles associated with some new physics at a very high energy scale Λ, their low-energy couplings to the Standard Model will be suppressed by that energy scale

$$g \sim \frac{1}{\Lambda^n}$$

$\rightarrow$ By testing for very feeble interactions, indirectly we are able to access physics at high energies, potentially well above the collider scale

How to search for particles with tiny couplings

How to search for particles with tiny couplings

Measure numbers very precisely

Sample a lot of particles

How to search for particles with tiny couplings

Measure numbers very precisely

- Precision tests of QED
- Rare processes
- Tiny microscopic forces

Sample a lot of particles

How to search for particles with tiny couplings

Measure numbers very precisely

- Precision tests of QED
- Rare processes
- Tiny microscopic forces

Sample a lot of particles

- Astrophysical environments
- High intensity collider experiments
- Dark matter

The axion

How to search for particles with tiny couplings

Measure numbers very precisely

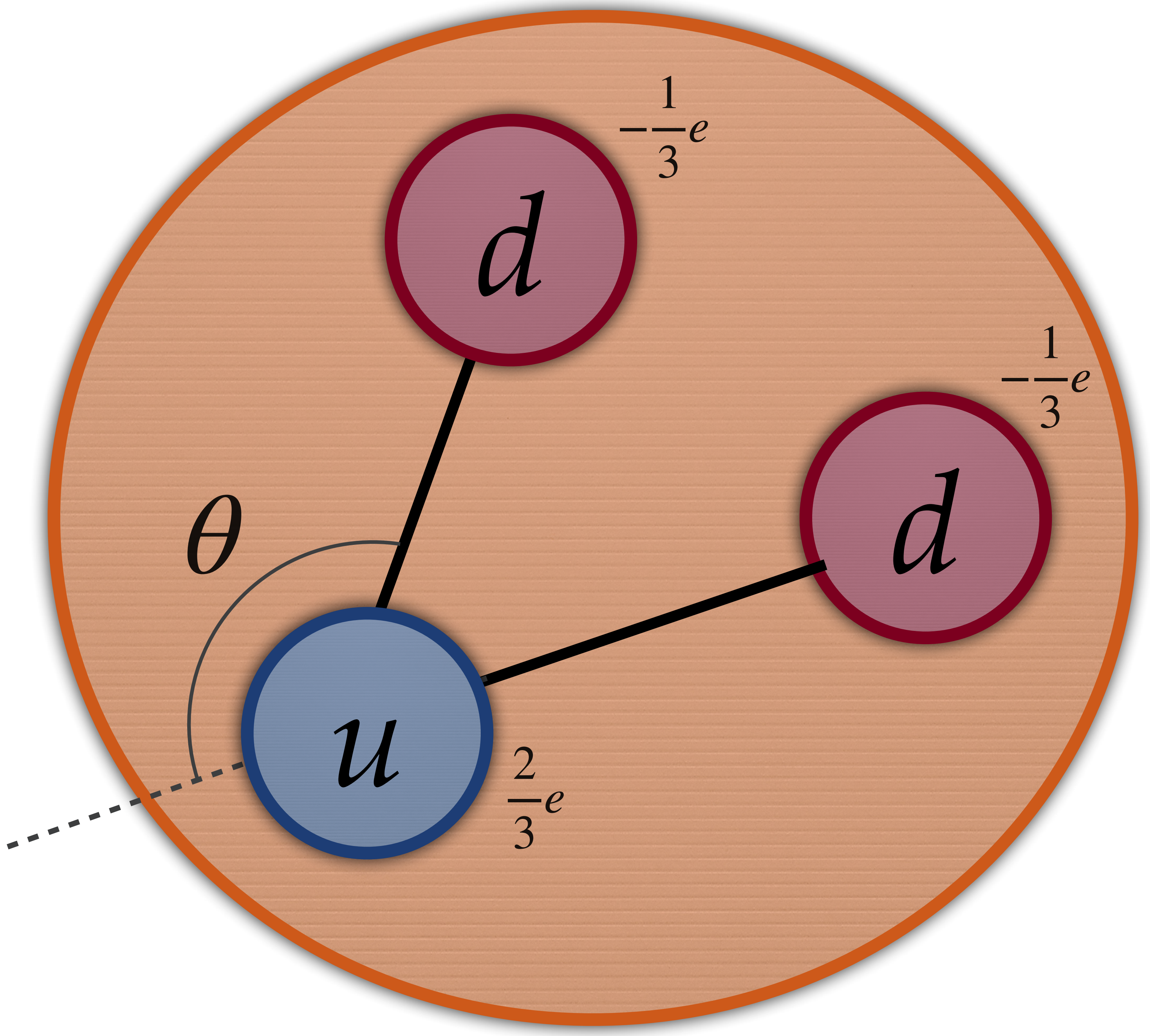
- Precision tests of QED
- Rare processes
- Tiny microscopic forces

Sample a lot of particles

- Astrophysical environments
- High intensity collider experiments
- Dark matter

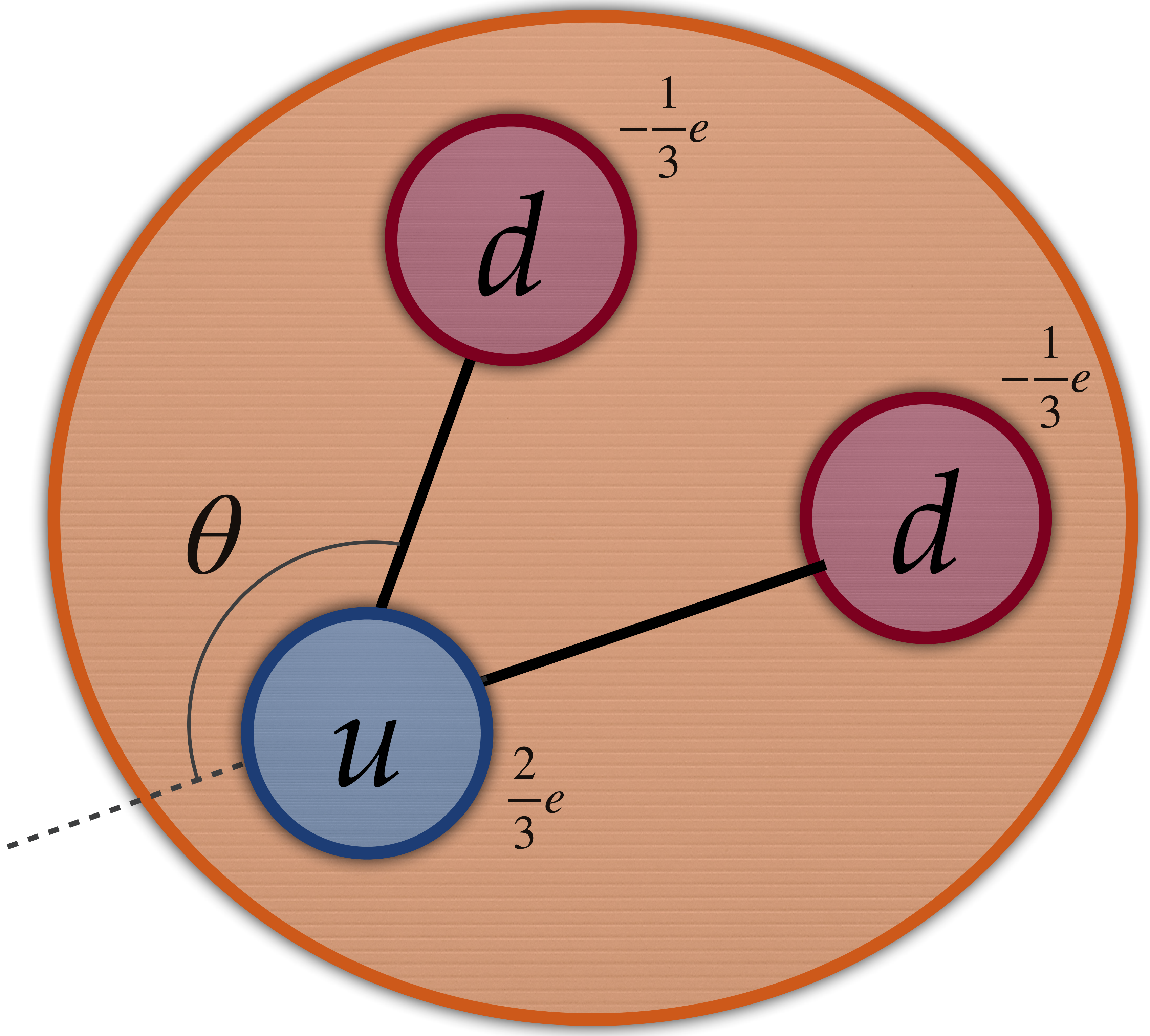
What is the electric dipole moment of the neutron?

$$d_n \sim e\,\mathrm{fm}$$

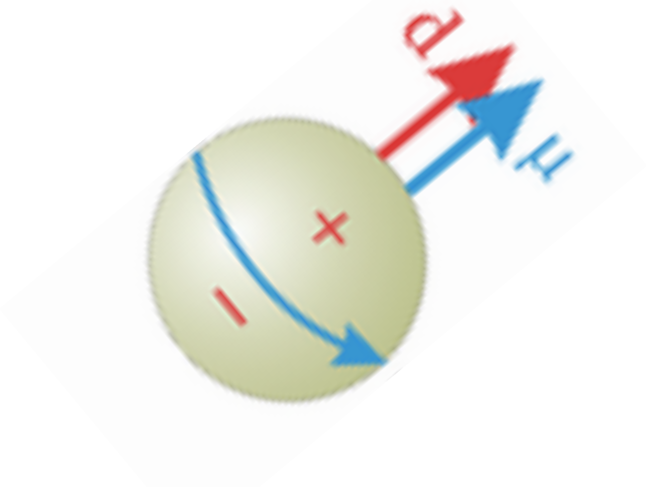


What is the electric dipole moment of the neutron?

$$d_n \sim e\,\mathrm{fm}$$

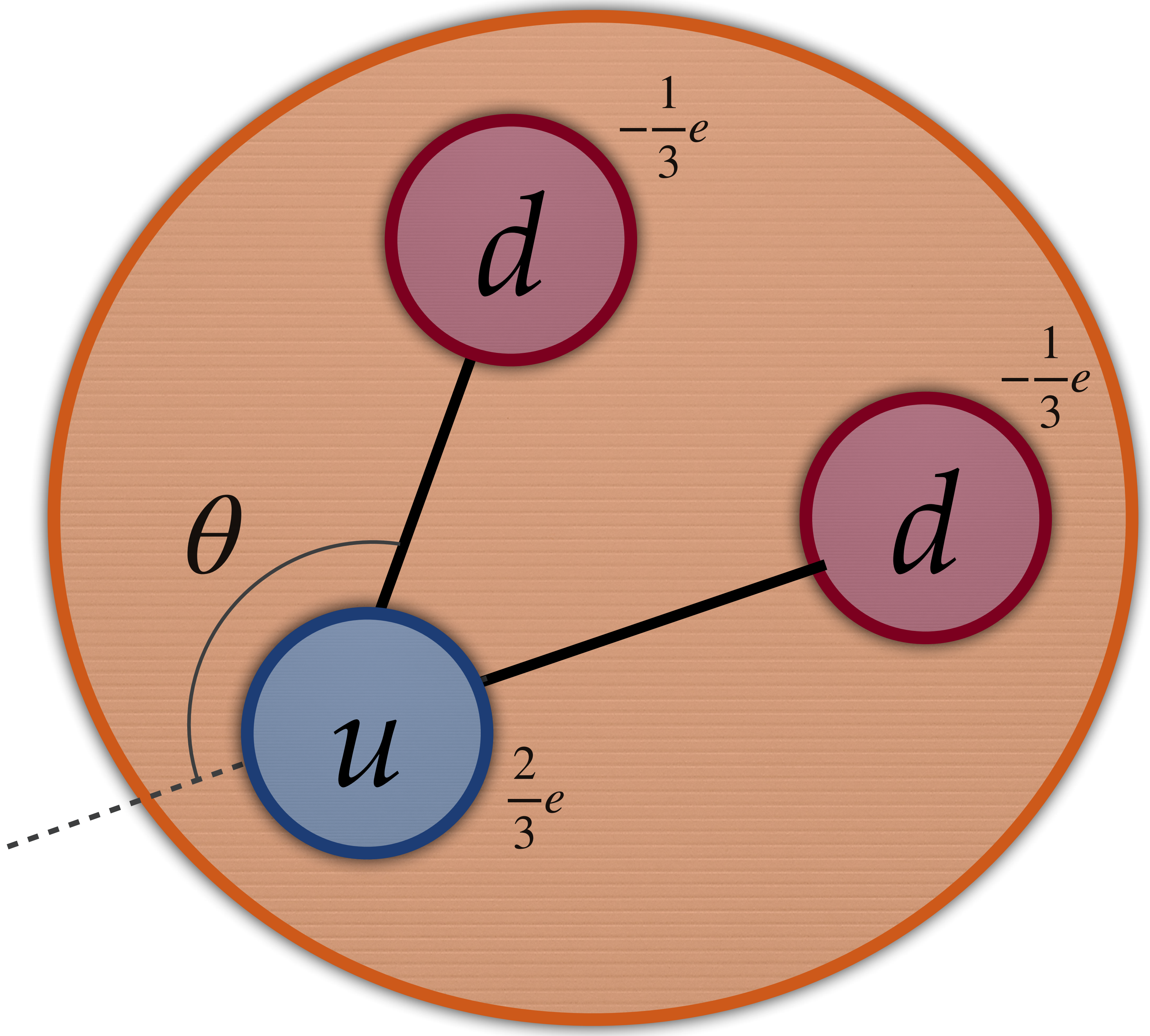


Put some spin-polarised neutrons in E, B fields

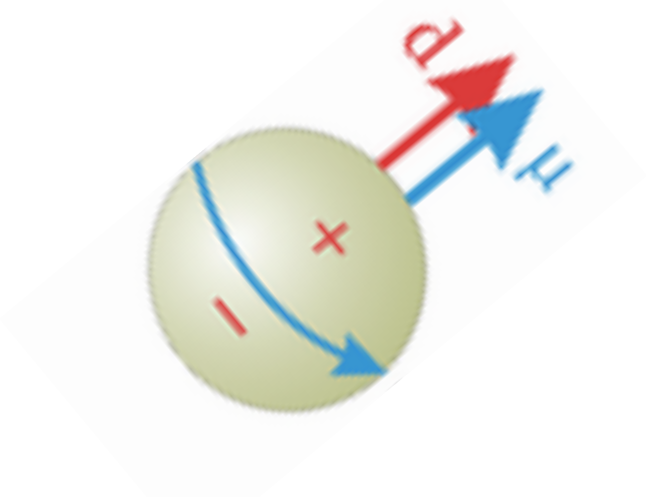


What is the electric dipole moment of the neutron?

$$d_n \sim e\,\mathrm{fm}$$



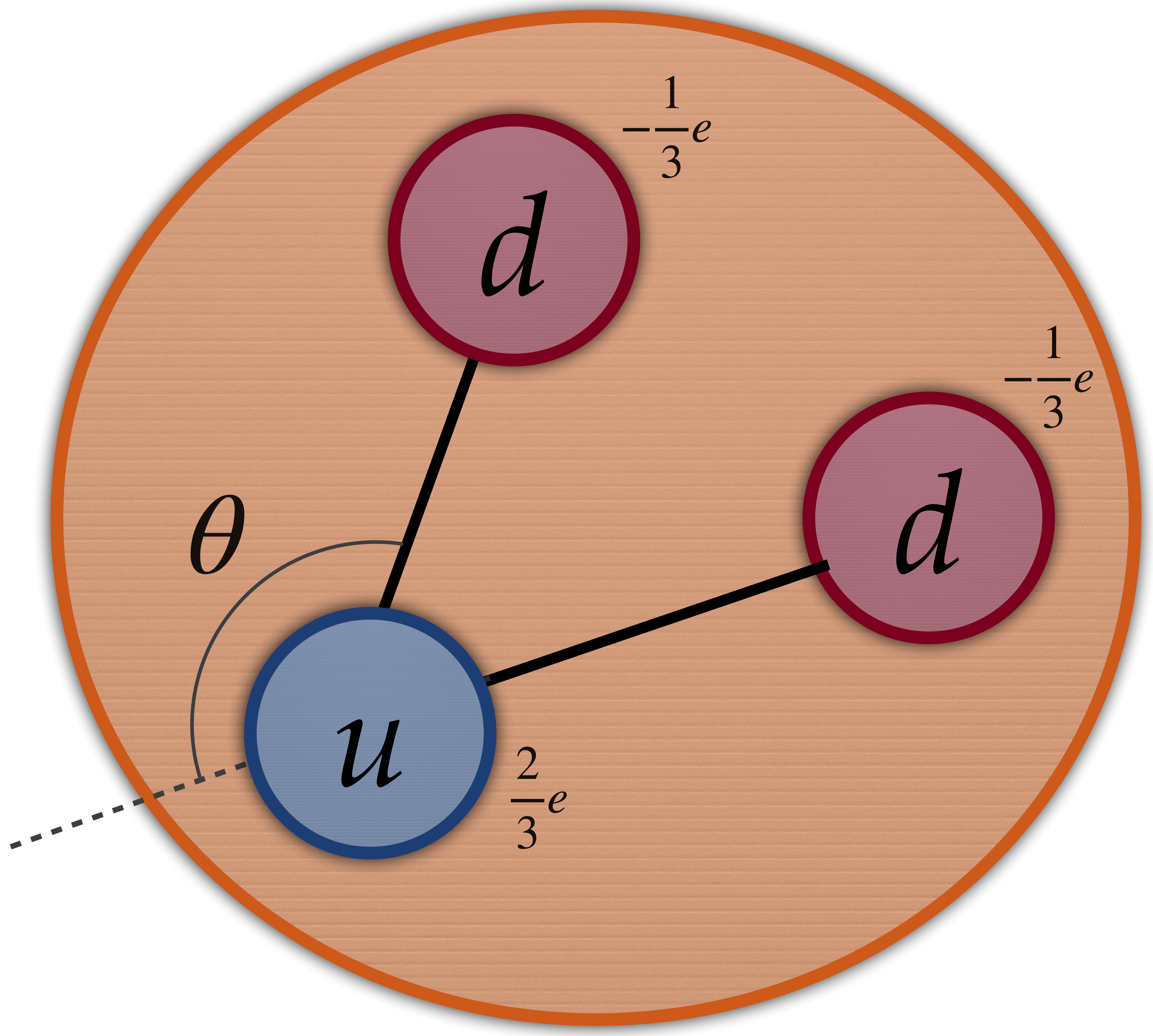
Put some spin-polarised neutrons in E, B fields → Measure spin precession frequencies



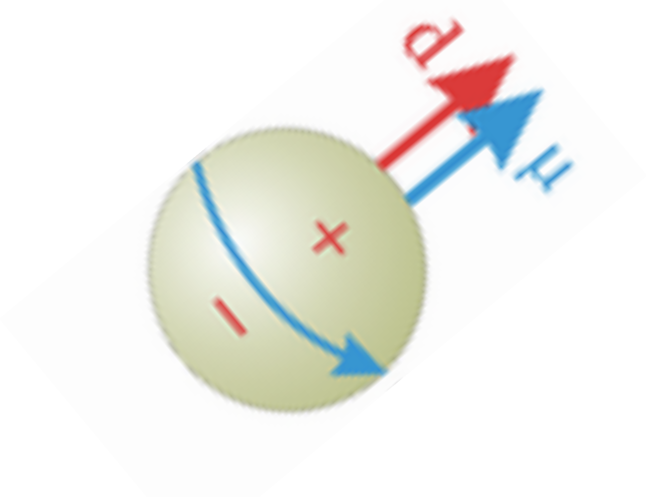
$$\nu_{\pm} = 2|\mu_n B \pm d_n E|$$

What is the electric dipole moment of the neutron?

$$d_n \sim e\,\mathrm{fm}$$



Put some spin-polarised neutrons in E, B fields



→ Measure spin precession frequencies

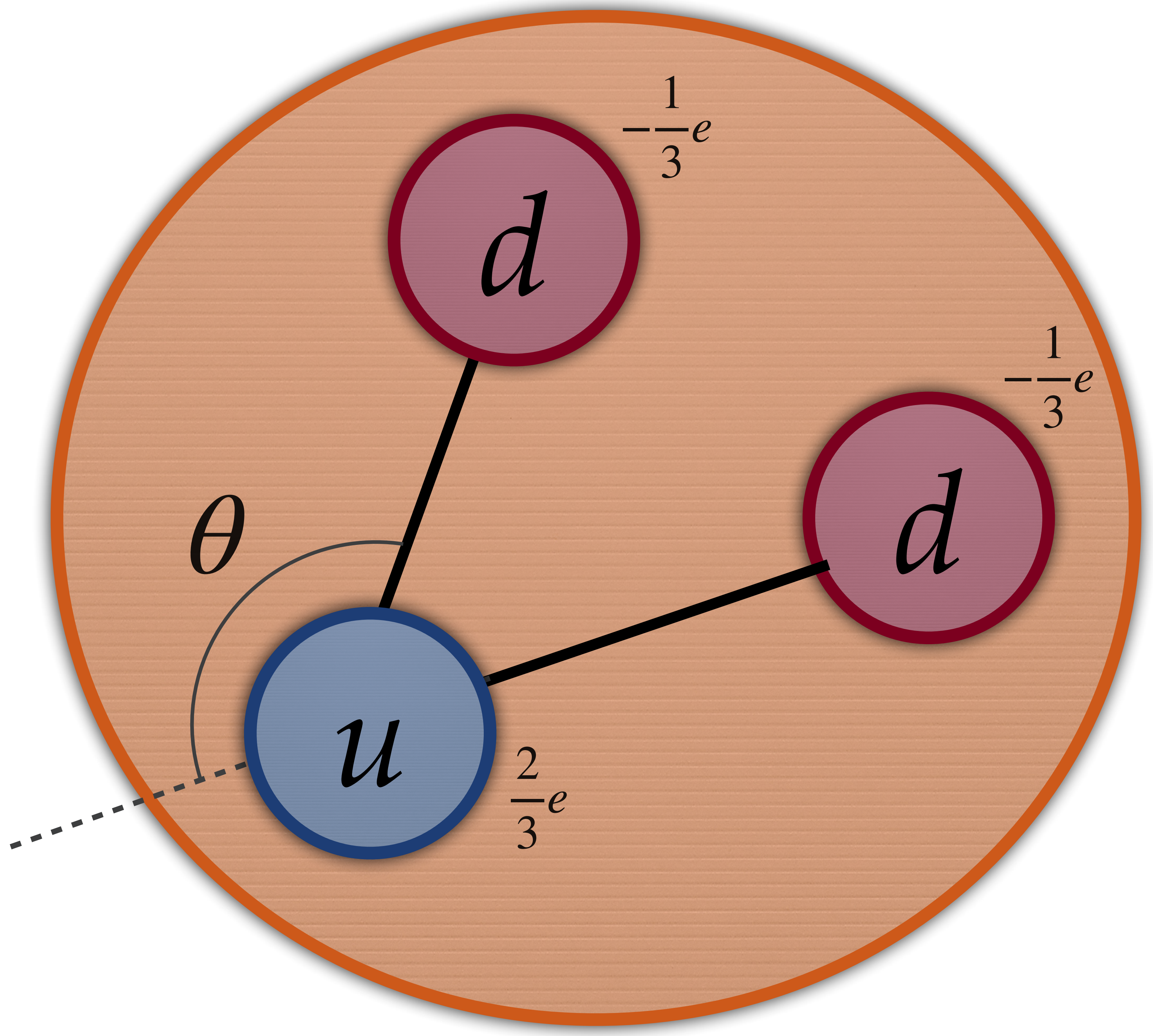
$$\nu_\pm = 2|\mu_n B \pm d_n E|$$

→ Calculate neutron EDM

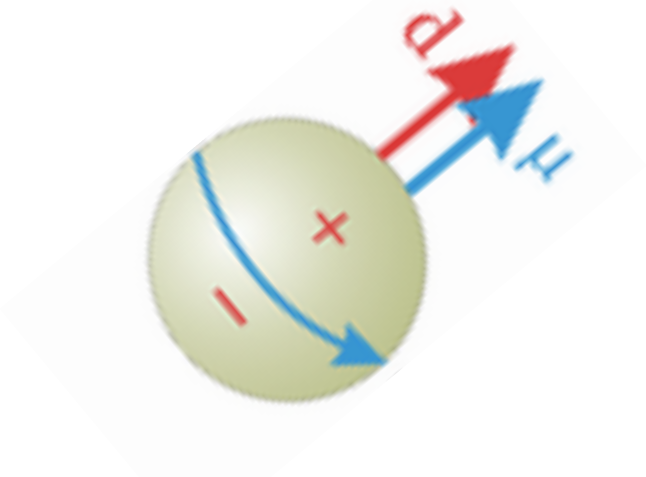
$$d_n$$

What is the electric dipole moment of the neutron?

$$d_n \sim e\,\mathrm{fm}$$



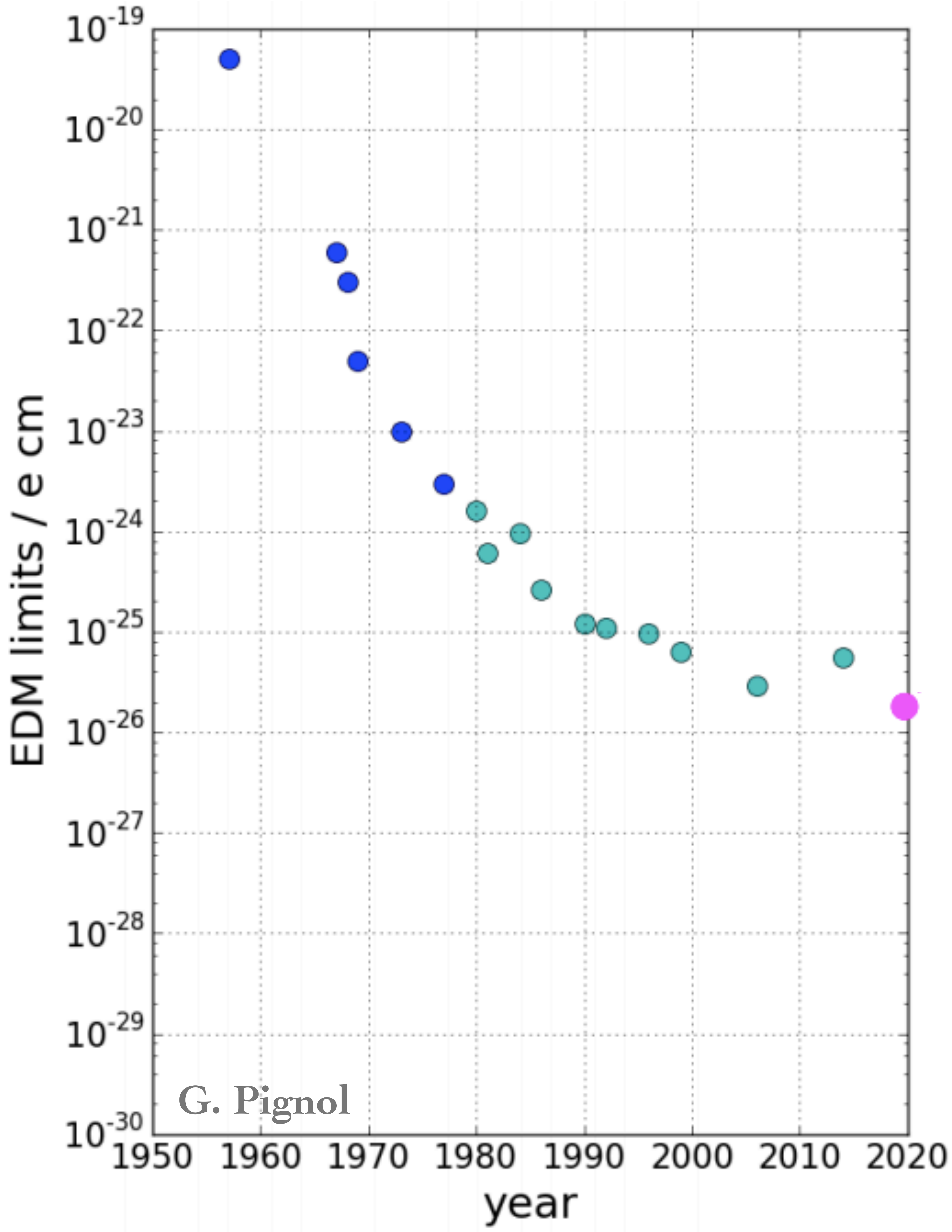
Put some spin-polarised neutrons in E, B fields → Measure spin precession frequencies → Calculate neutron EDM → Measure Fundamental parameter of SM



$$\nu_\pm = 2|\mu_n B \pm d_n E|$$

$$d_n$$

$$\theta$$

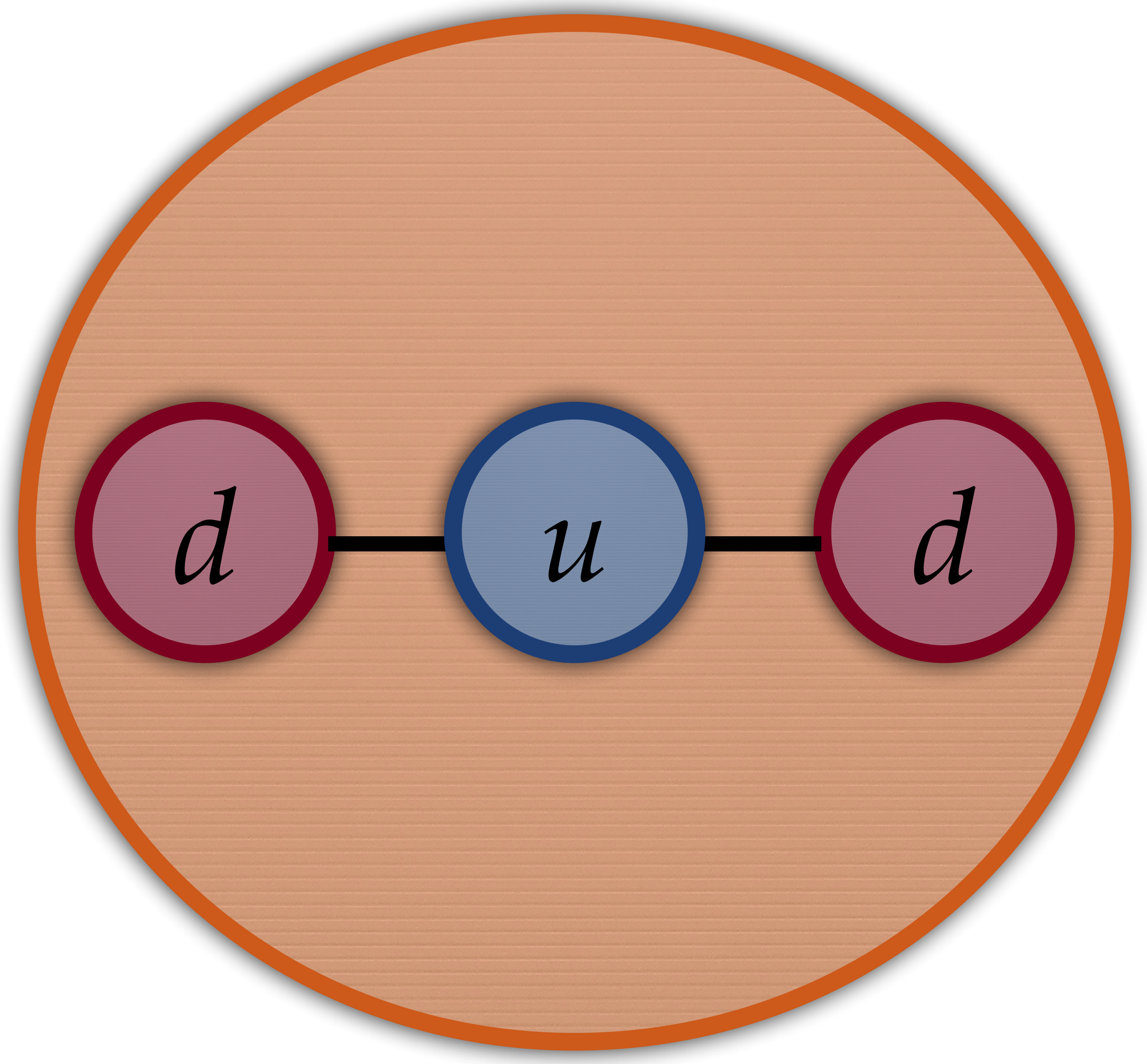


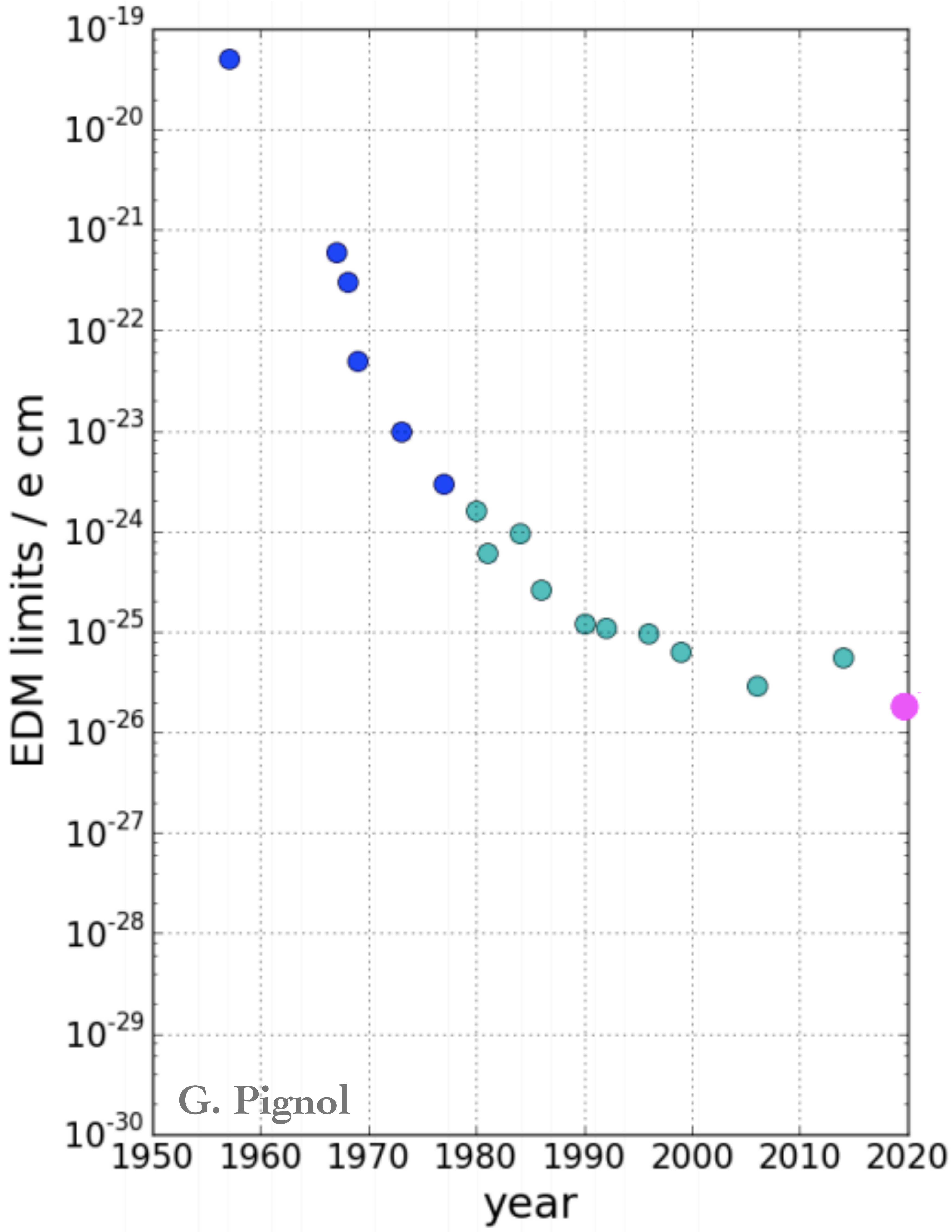
What do they see?

Recent measurement [2001.11966]

$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm} \ \ (90\%\ \mathrm{CL})$$

$$\Rightarrow \theta \lesssim 10^{-10}$$



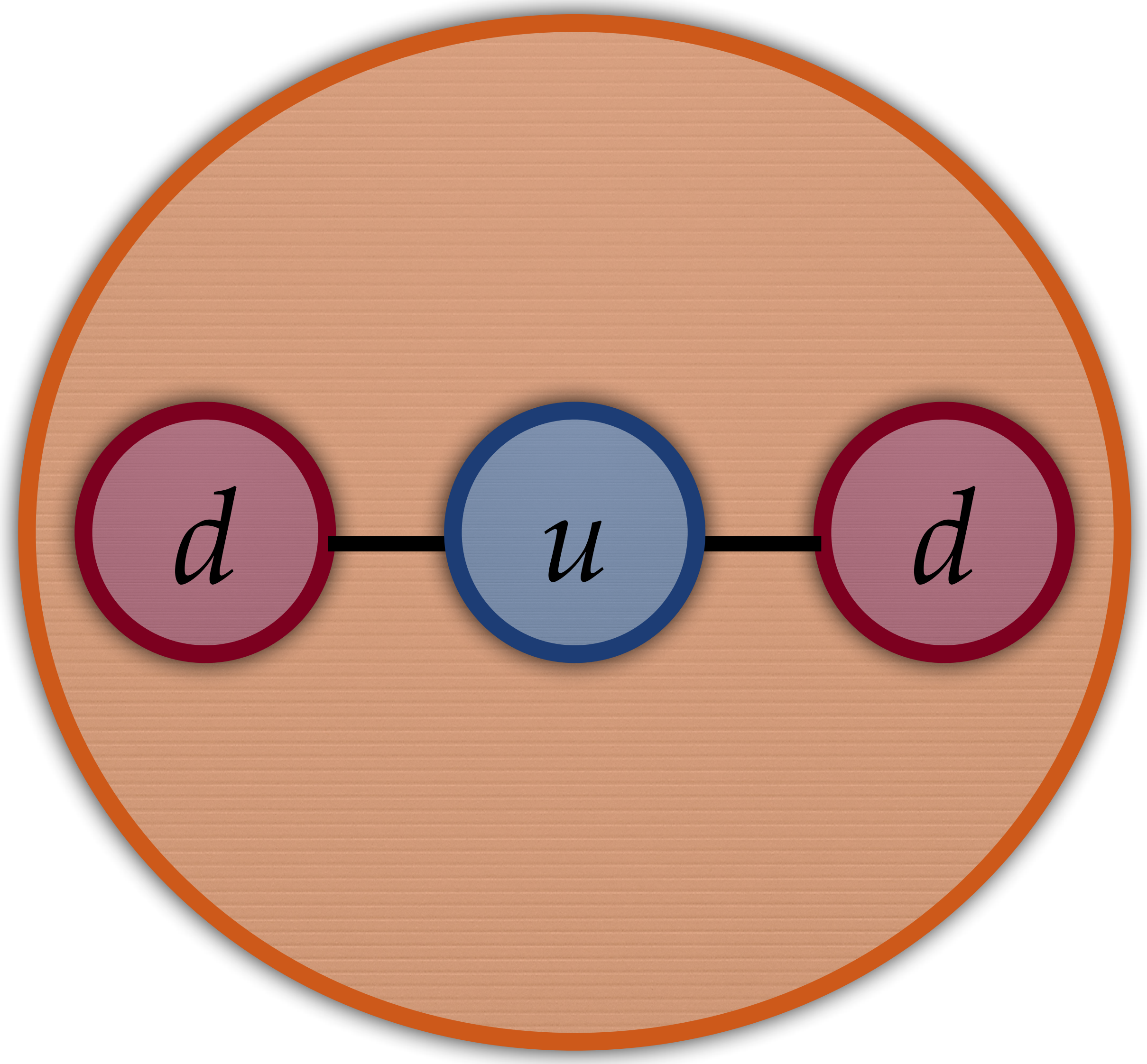


What do they see?

Recent measurement [2001.11966]

$$|d_n| < 1.8 \times 10^{-26}\, e\,\text{cm} \;\; (90\%\ \text{CL})$$

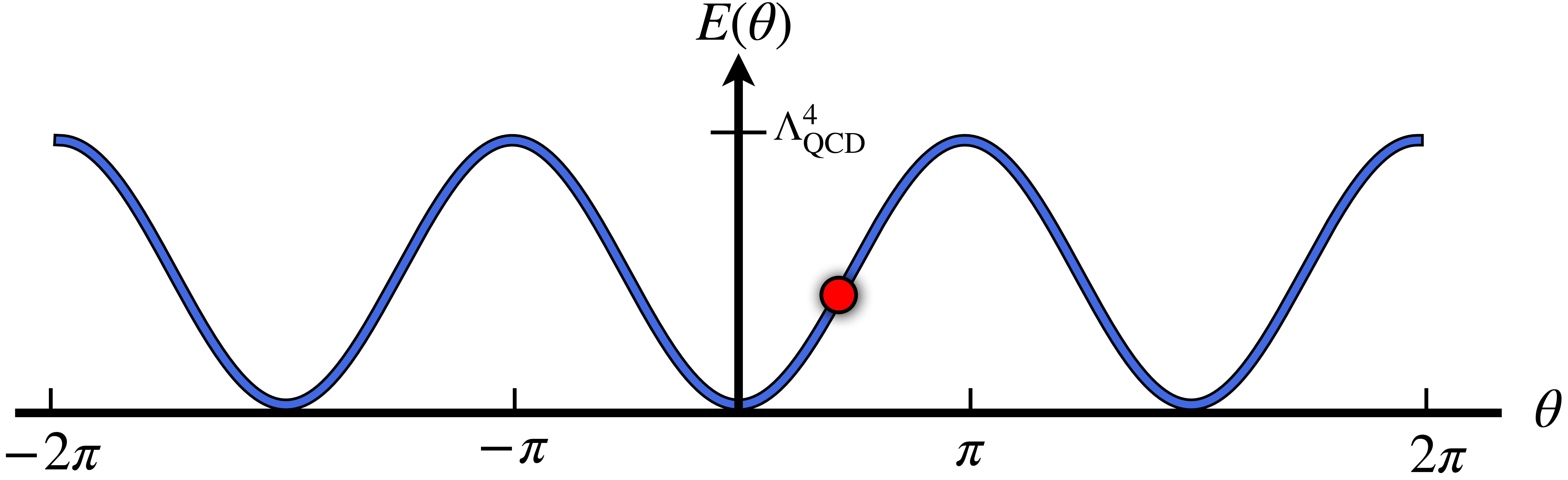
$$\Rightarrow \theta \lesssim 10^{-10}$$



Conclusion: The strong interaction seems to be conserving CP when it generically shouldn't → **The strong CP problem**

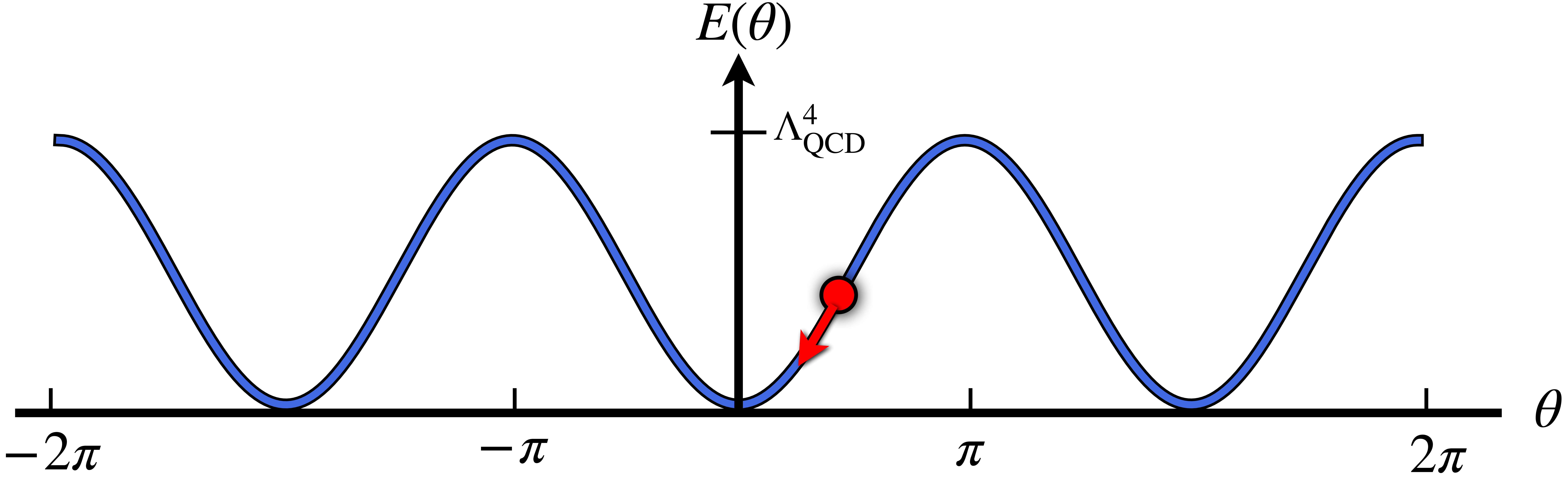
The solution is closer than it seems…

→ The problem is that θ is simply a parameter that we cannot change but if it were dynamical it would be able to relax to its energy minimising configuration



The solution is closer than it seems…

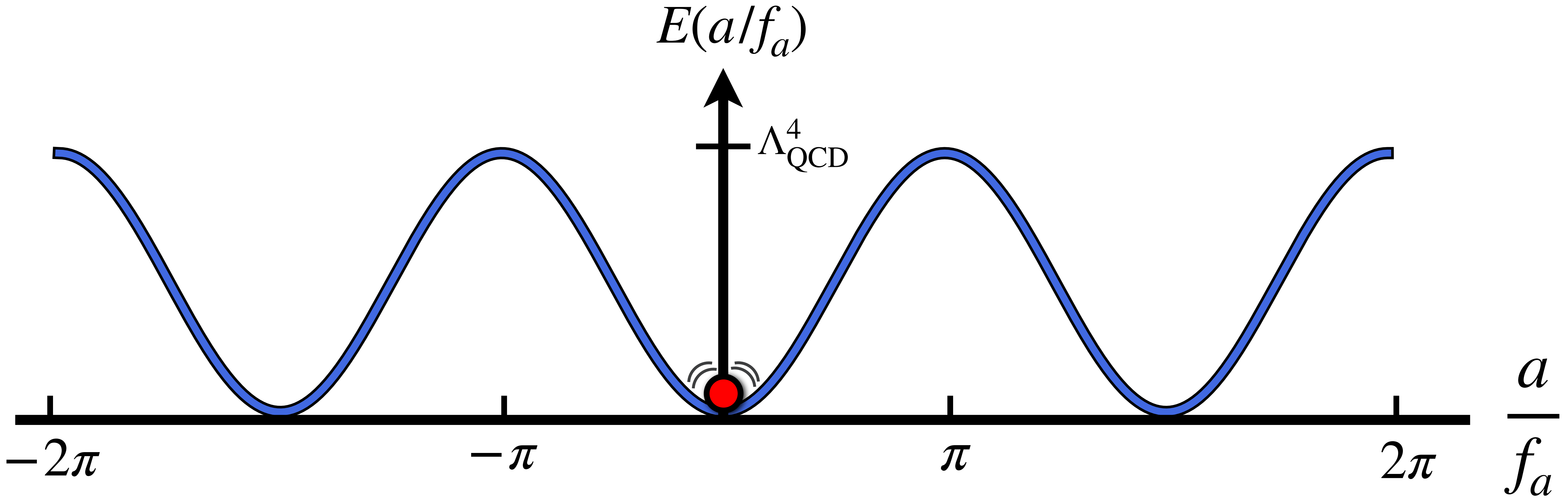
→ The problem is that θ is simply a parameter that we cannot change but if it were dynamical it would be able to relax to its energy minimising configuration



Solution of Peccei & Quinn: what if this could happen?

Interpret this energy as the potential of a new particle: the axion

Created at some very high energy scale, f_a



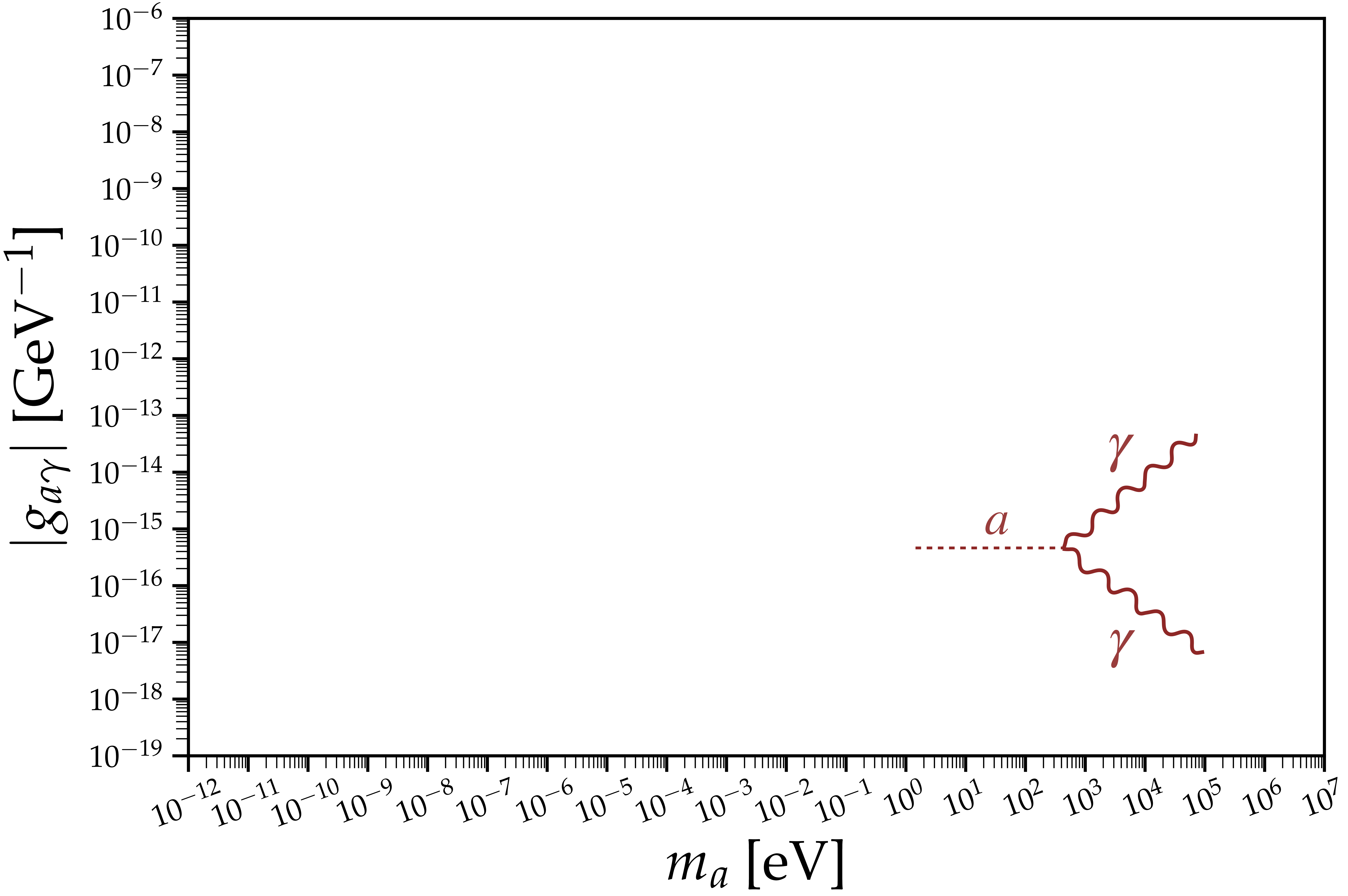
Very light mass

$$m_a \simeq \frac{\Lambda^2_{\mathrm{QCD}}}{f_a} \simeq 6\,\mathrm{meV}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

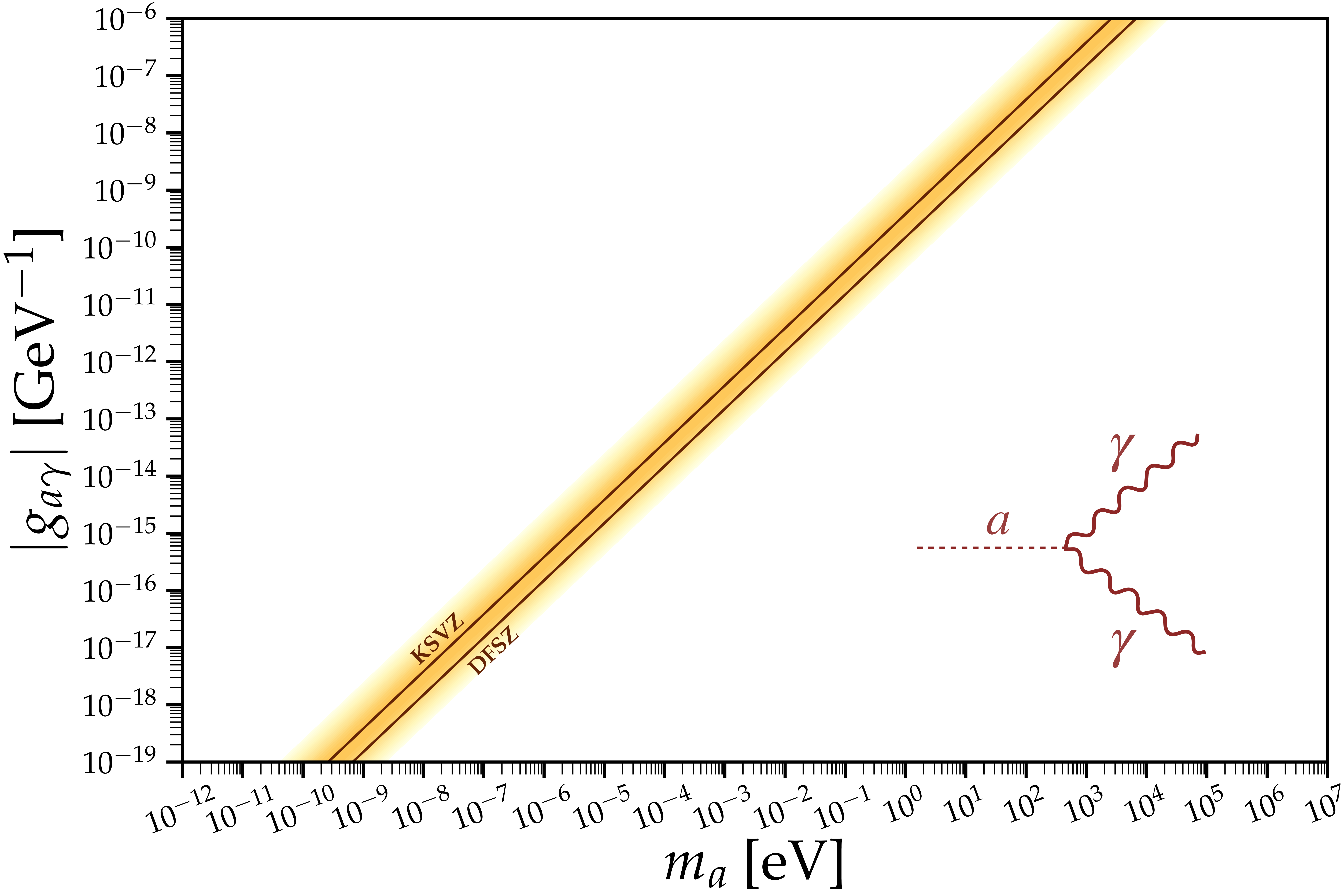
Suppressed couplings (e.g. to the photon)

$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_a}$$

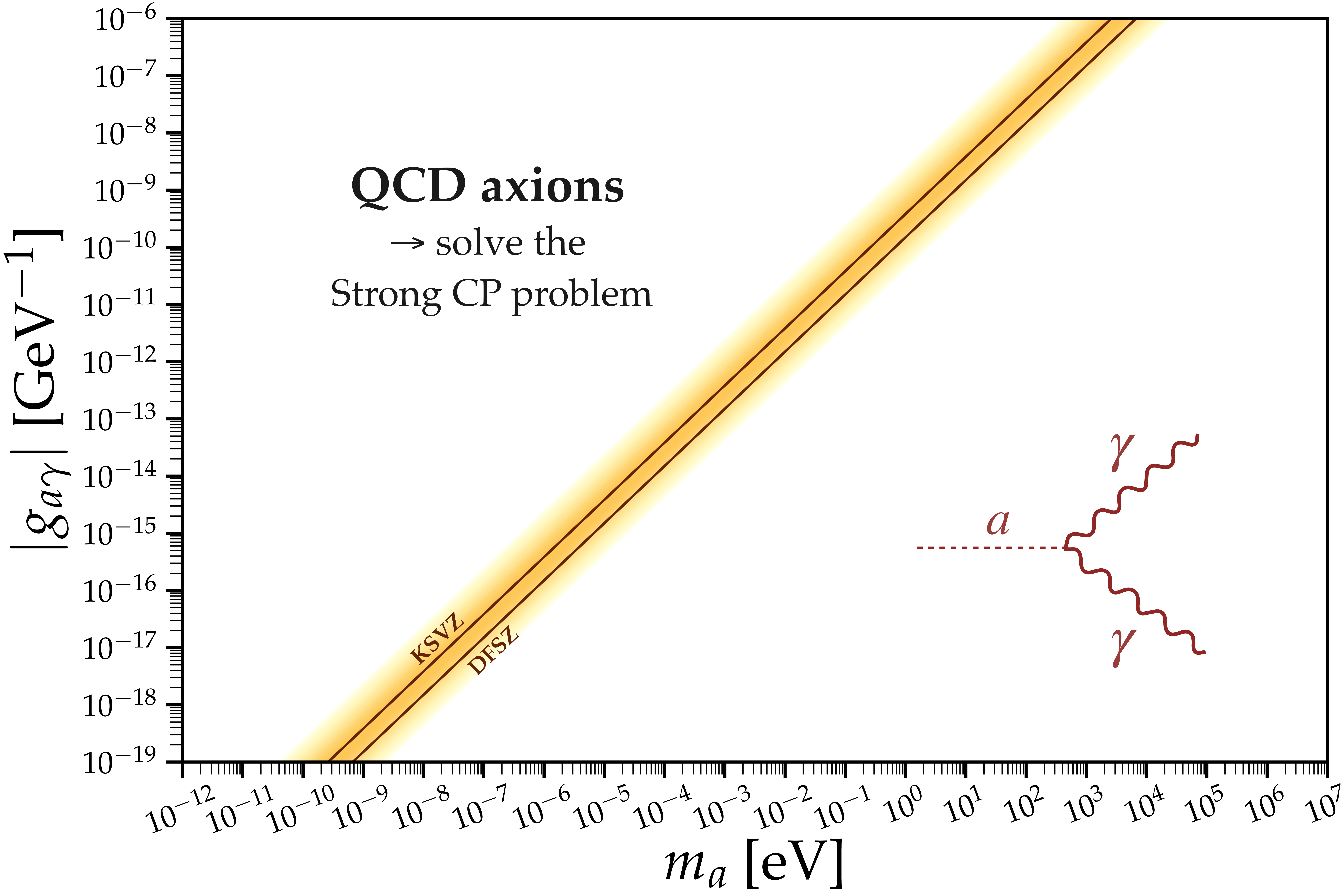
Where is the axion?



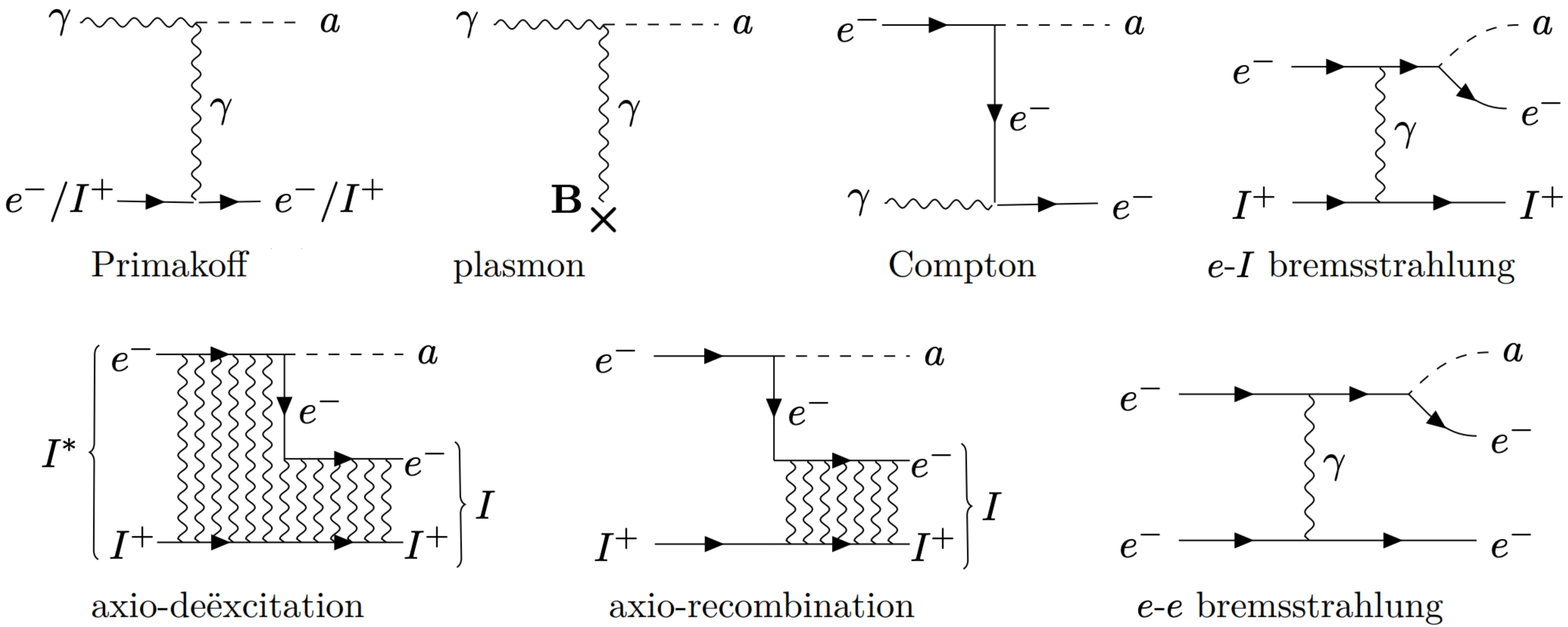
Where is the axion?



Where is the axion?



Axion can couple to photons, electrons, …

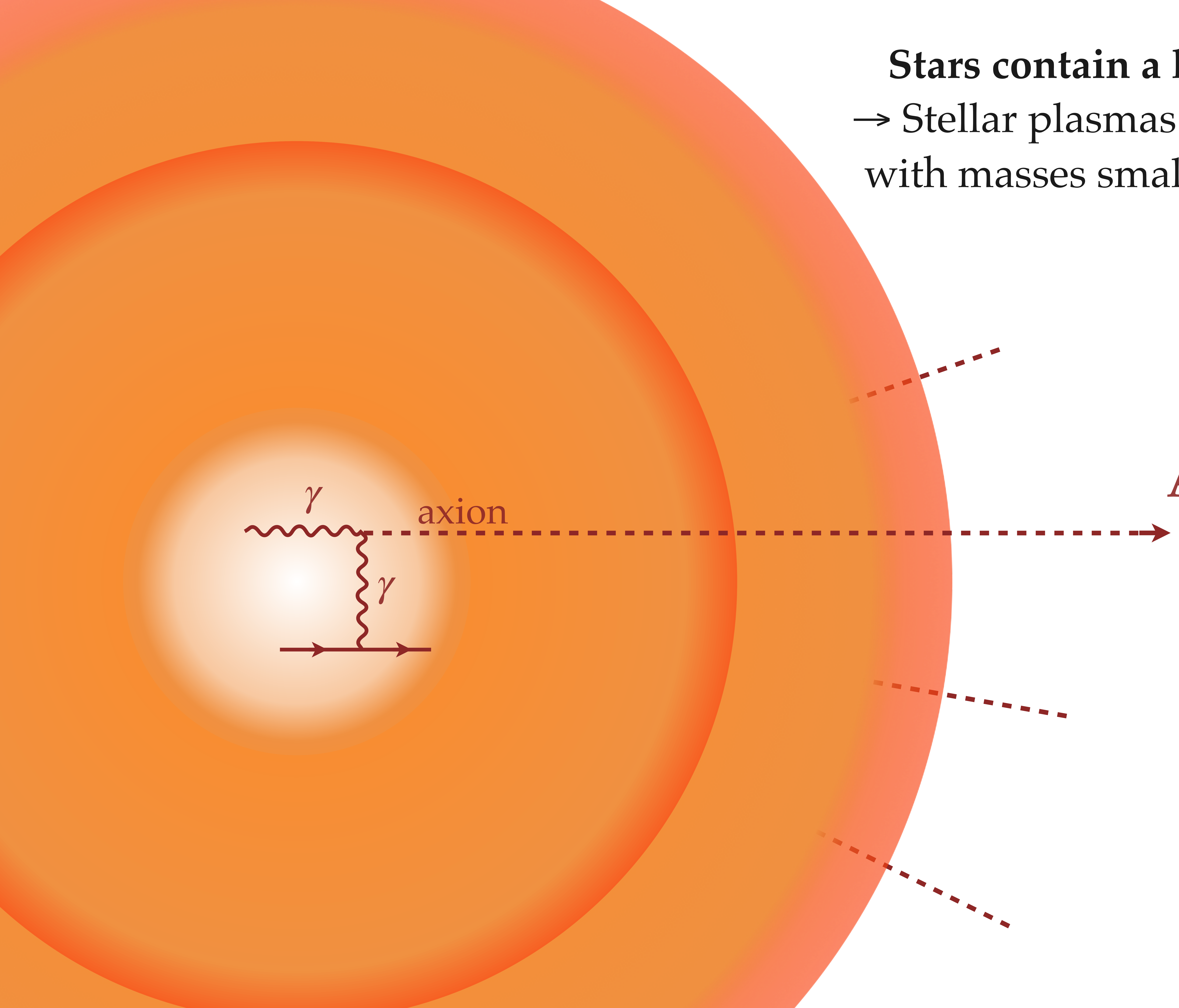


Where could these processes be happening?

Stars contain a lot of ions, and a lot of photons

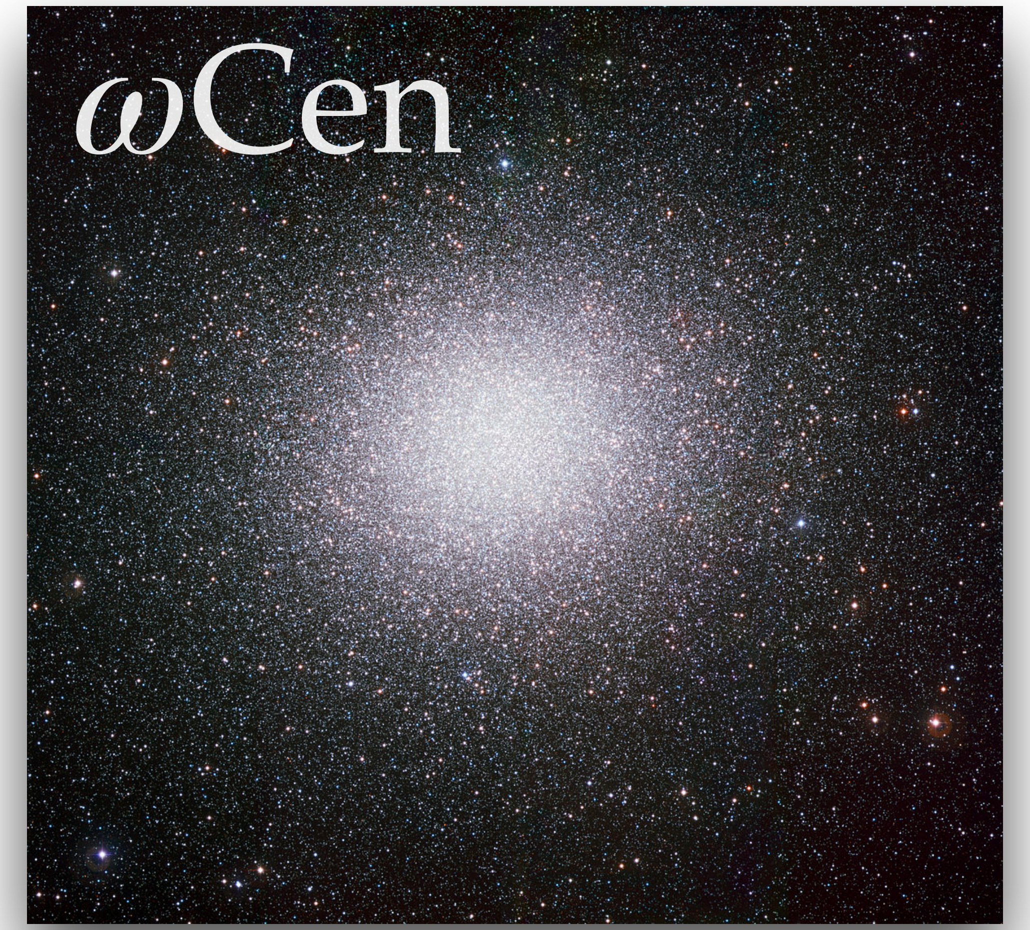
→ Stellar plasmas should be factories for particles with masses smaller than their core temperatures

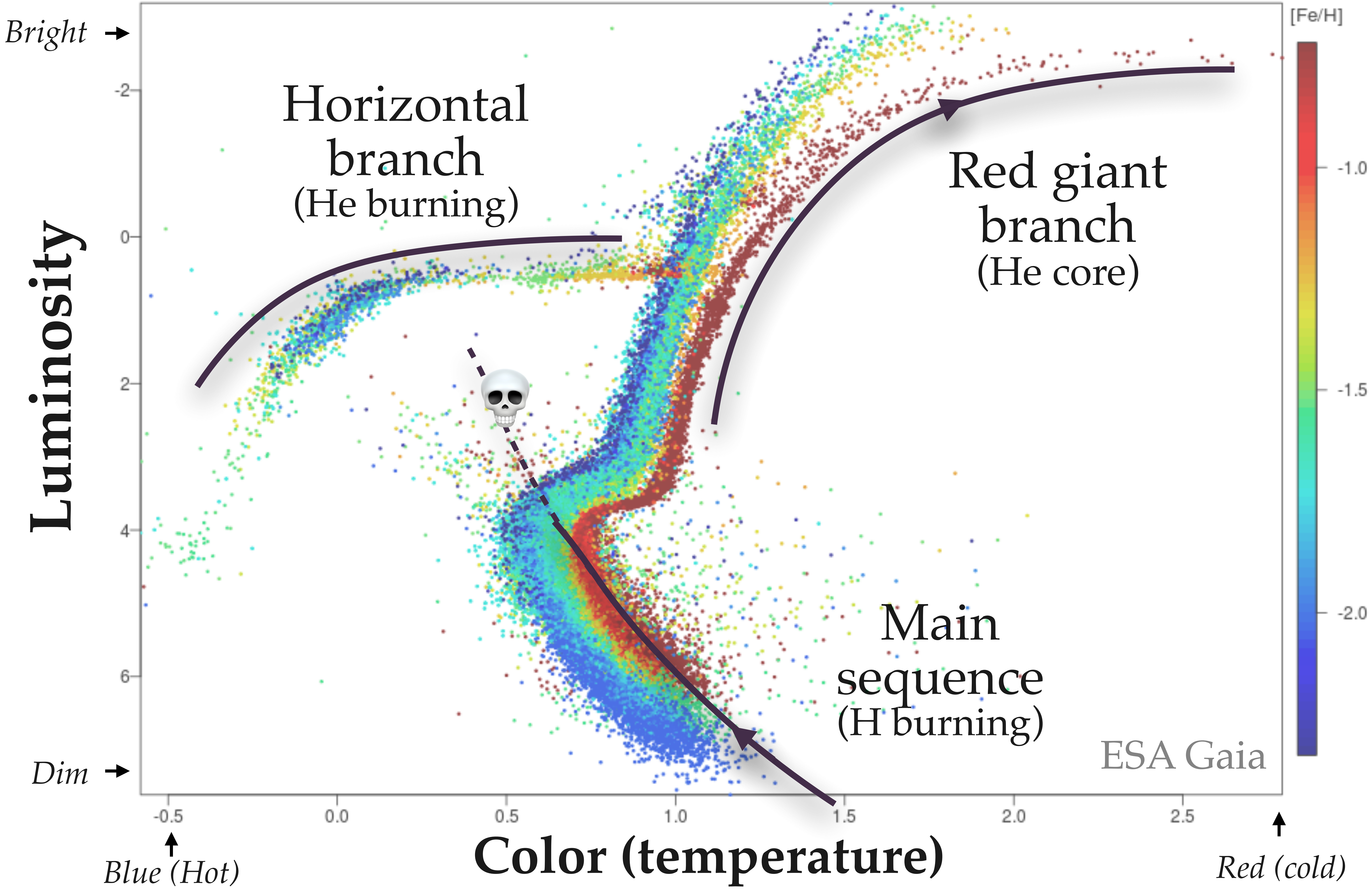
$m_a \lesssim$ 1-100 keV



Axions emitted by stars,
Axions cooling stars

Globular clusters: ideal testing ground for stellar evolution



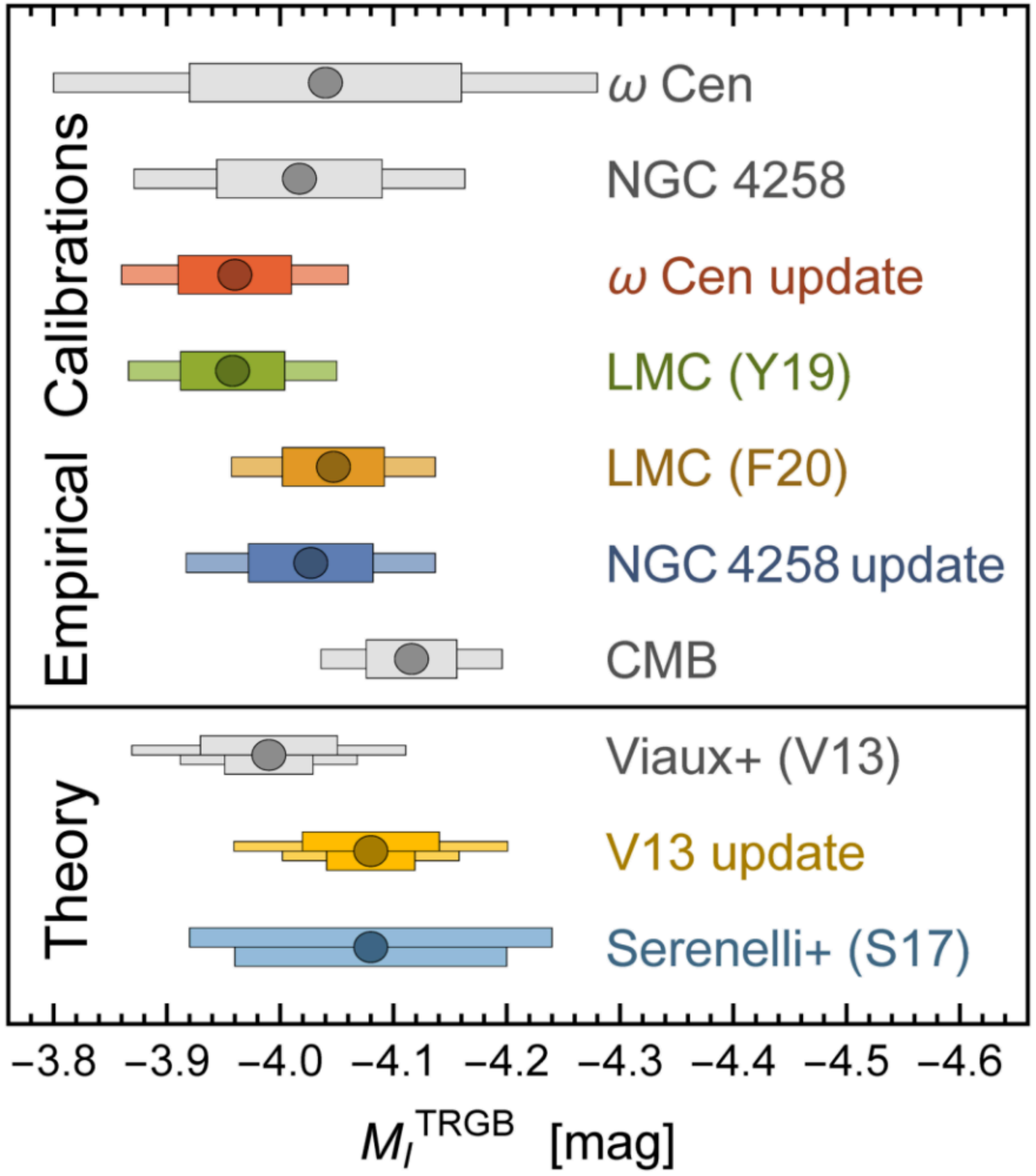


Emission of axions influences stellar evolution

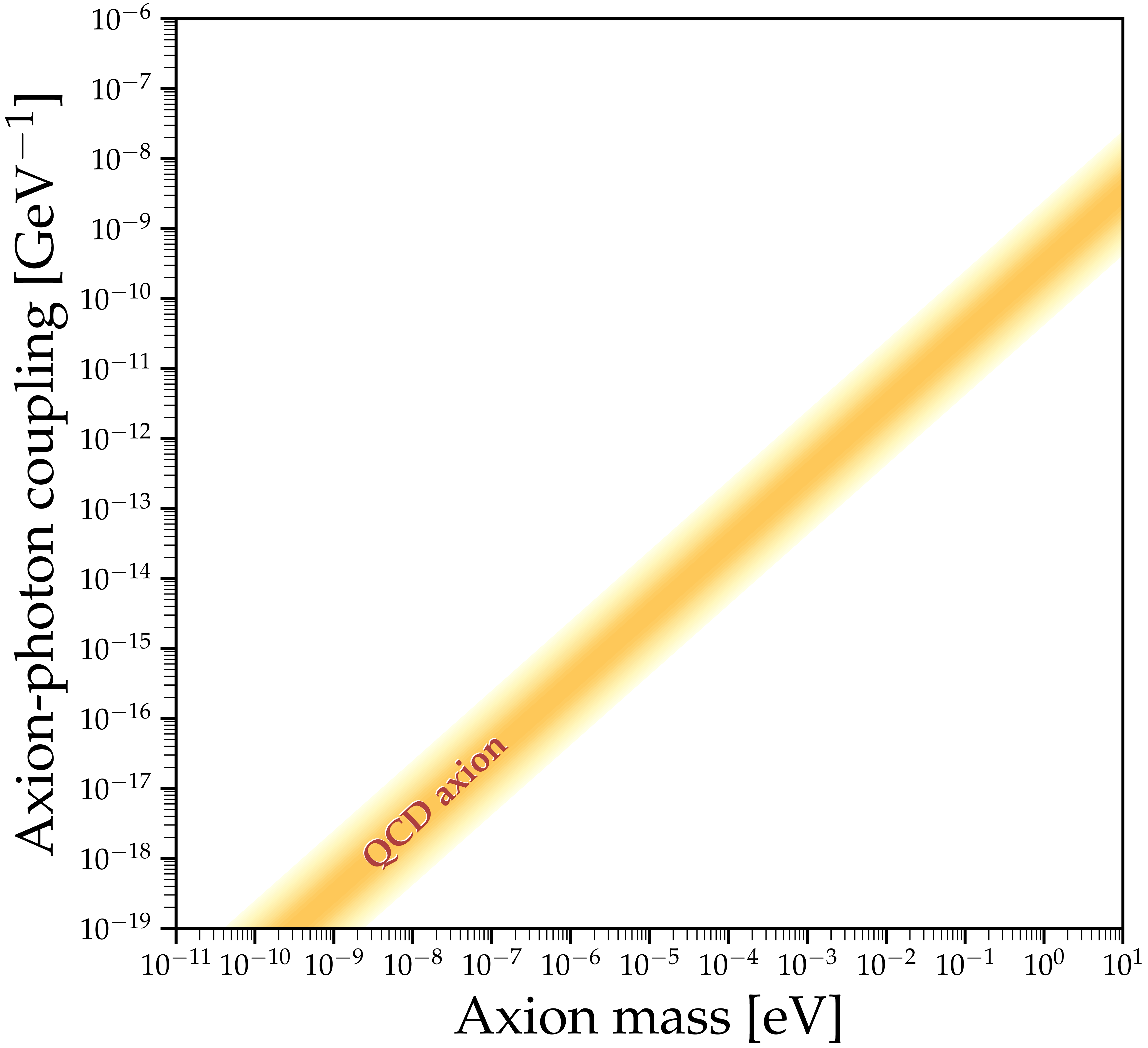
→ Emission of low mass particles provides additional cooling to the helium core, thereby delaying the onset of helium burning and allowing a brighter tip of the red giant branch (TRGB)

→ *Gaia*-based distance determination substantially reduced observational errors, now uncertainty dominated by theoretical uncertainties

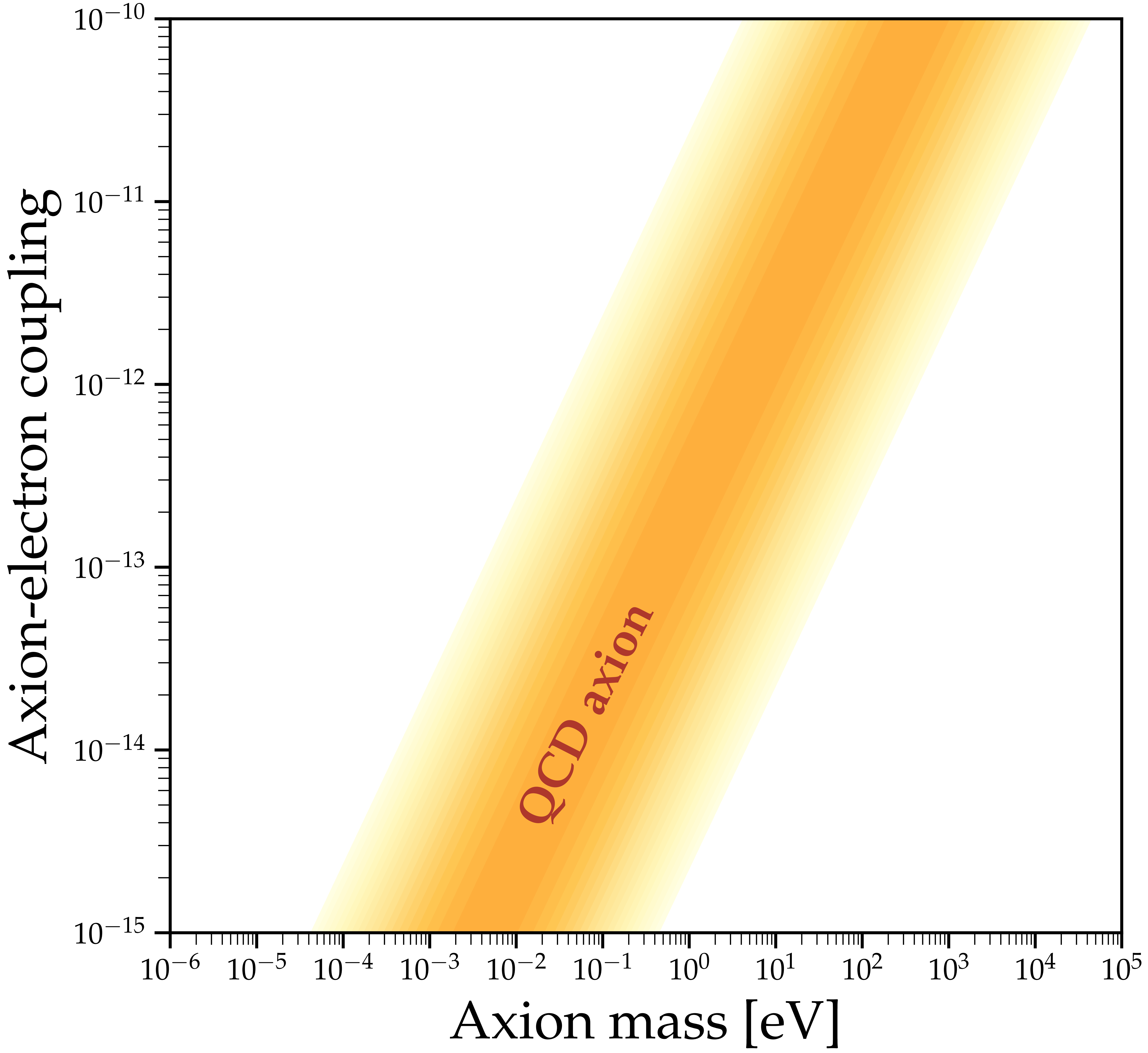
Capozzi & Raffelt [2007.03694]



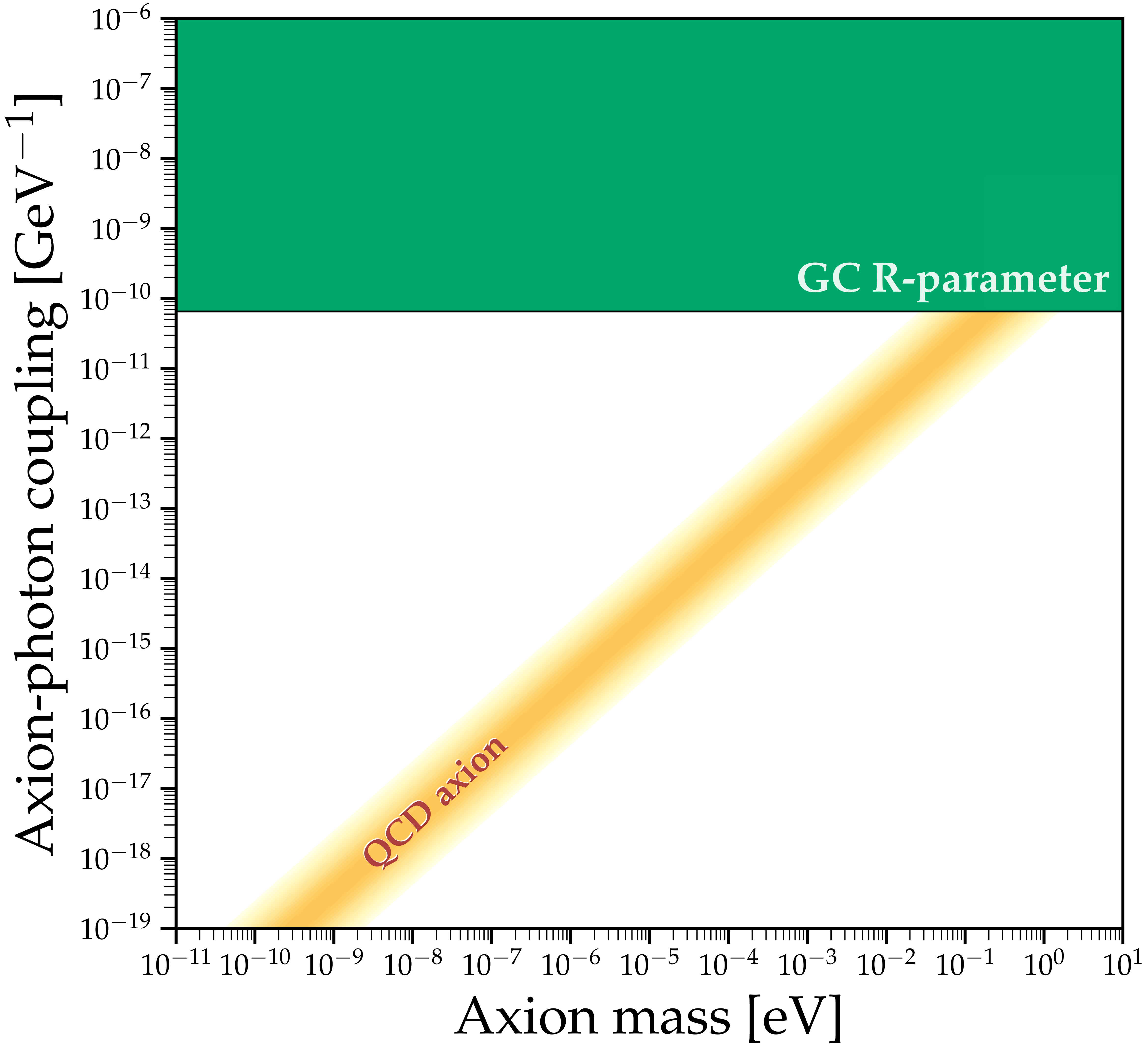
Axion-Photon coupling



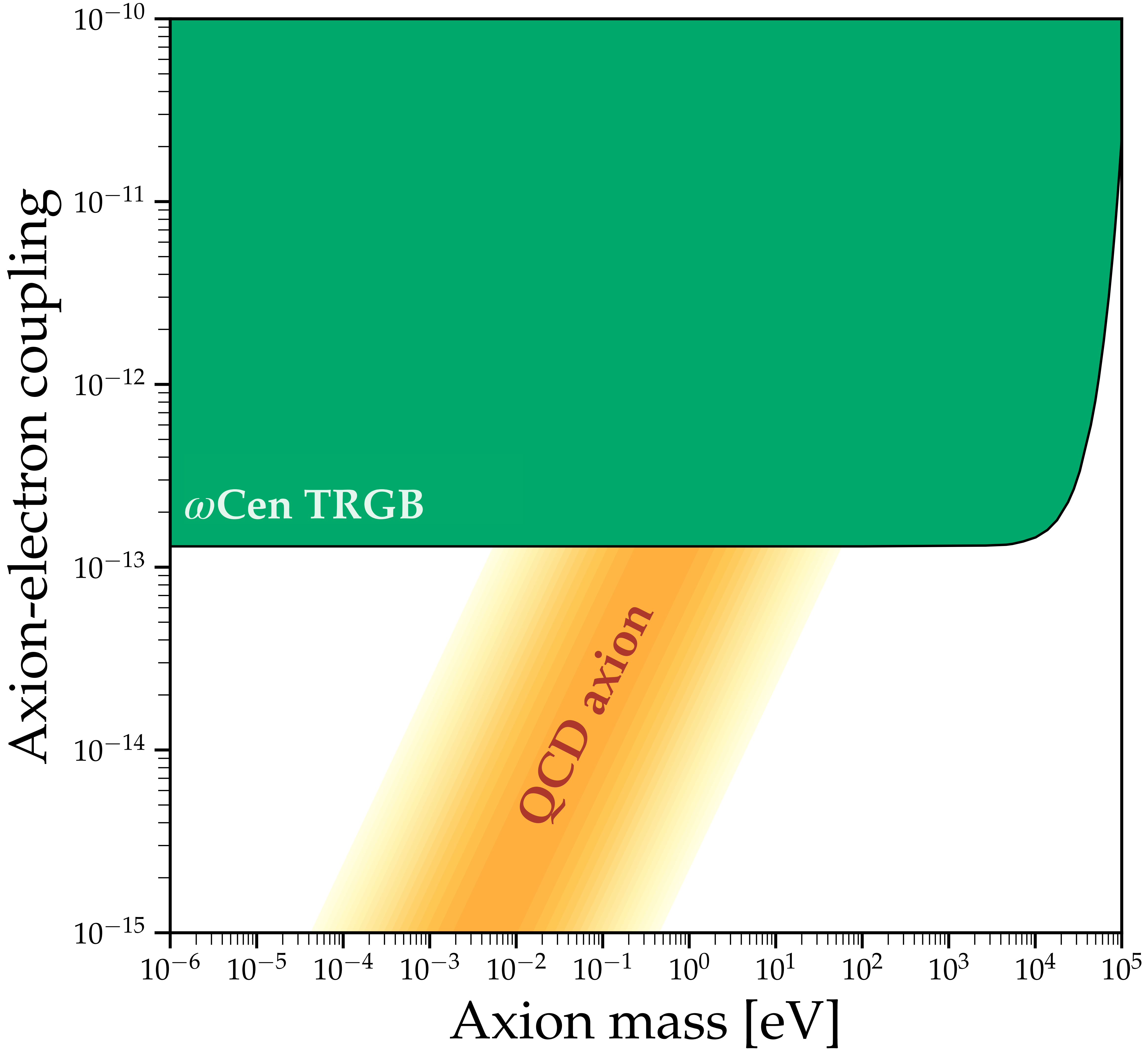
Axion-electron coupling



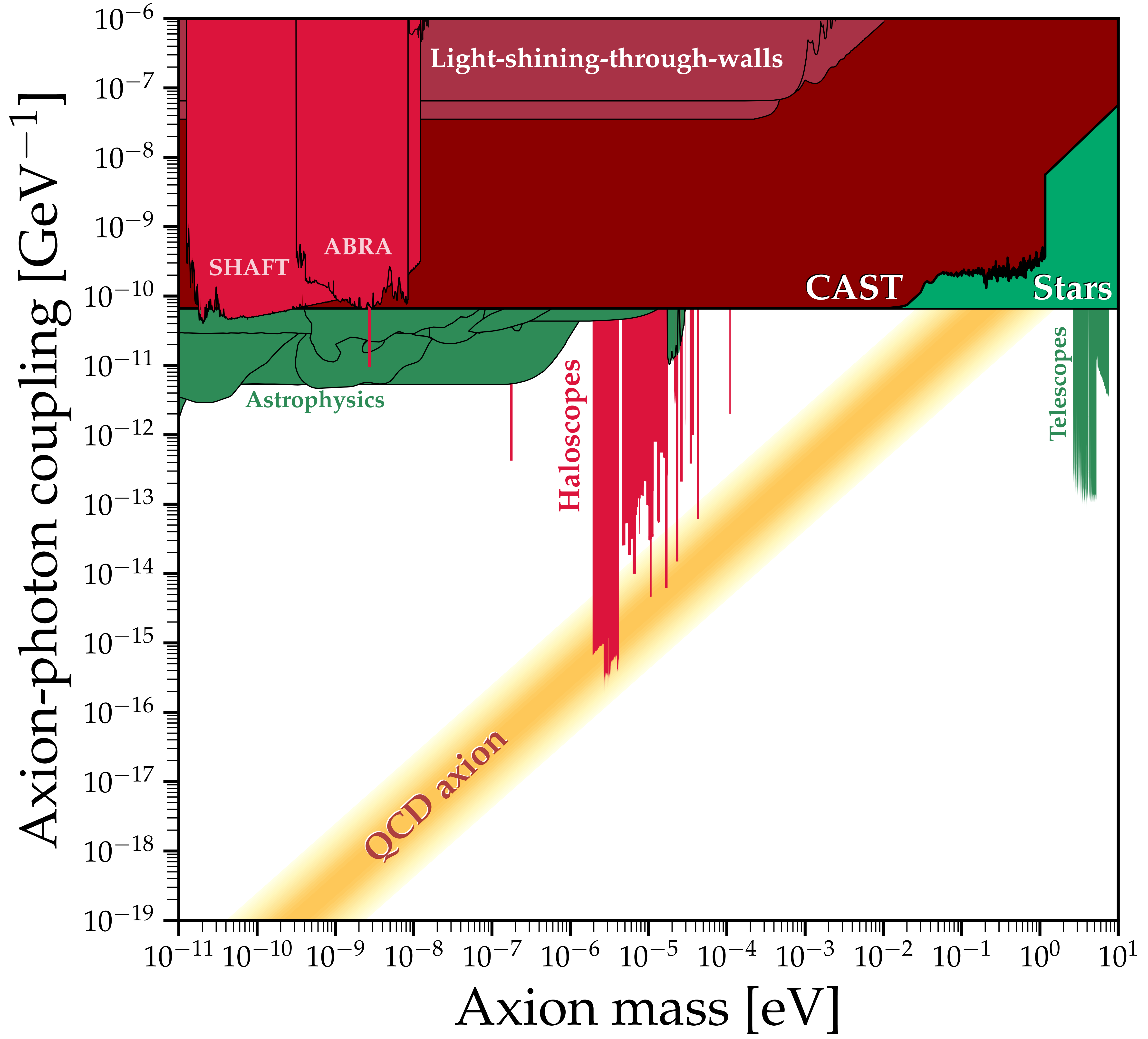
Axion-Photon coupling



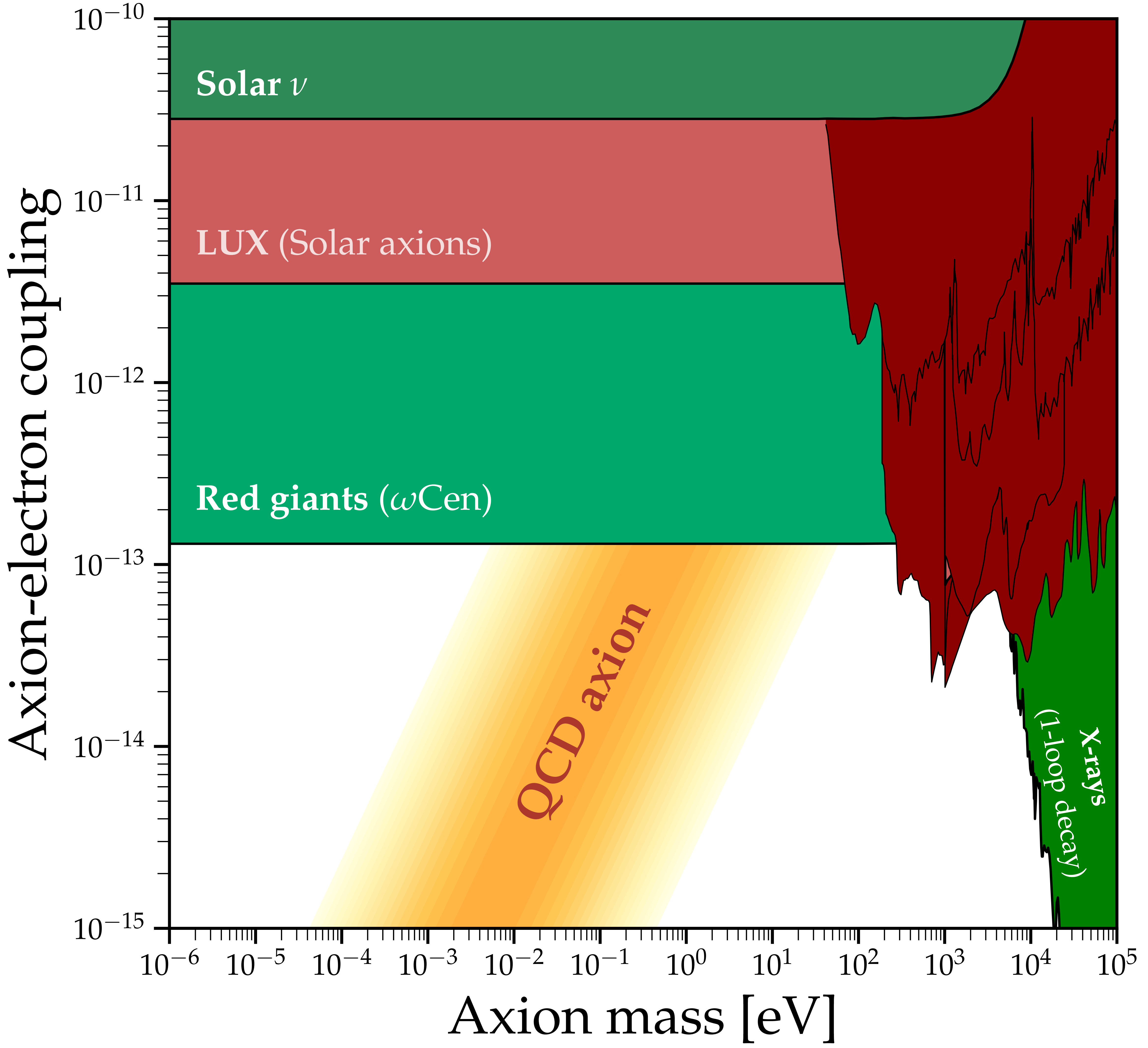
Axion-electron coupling



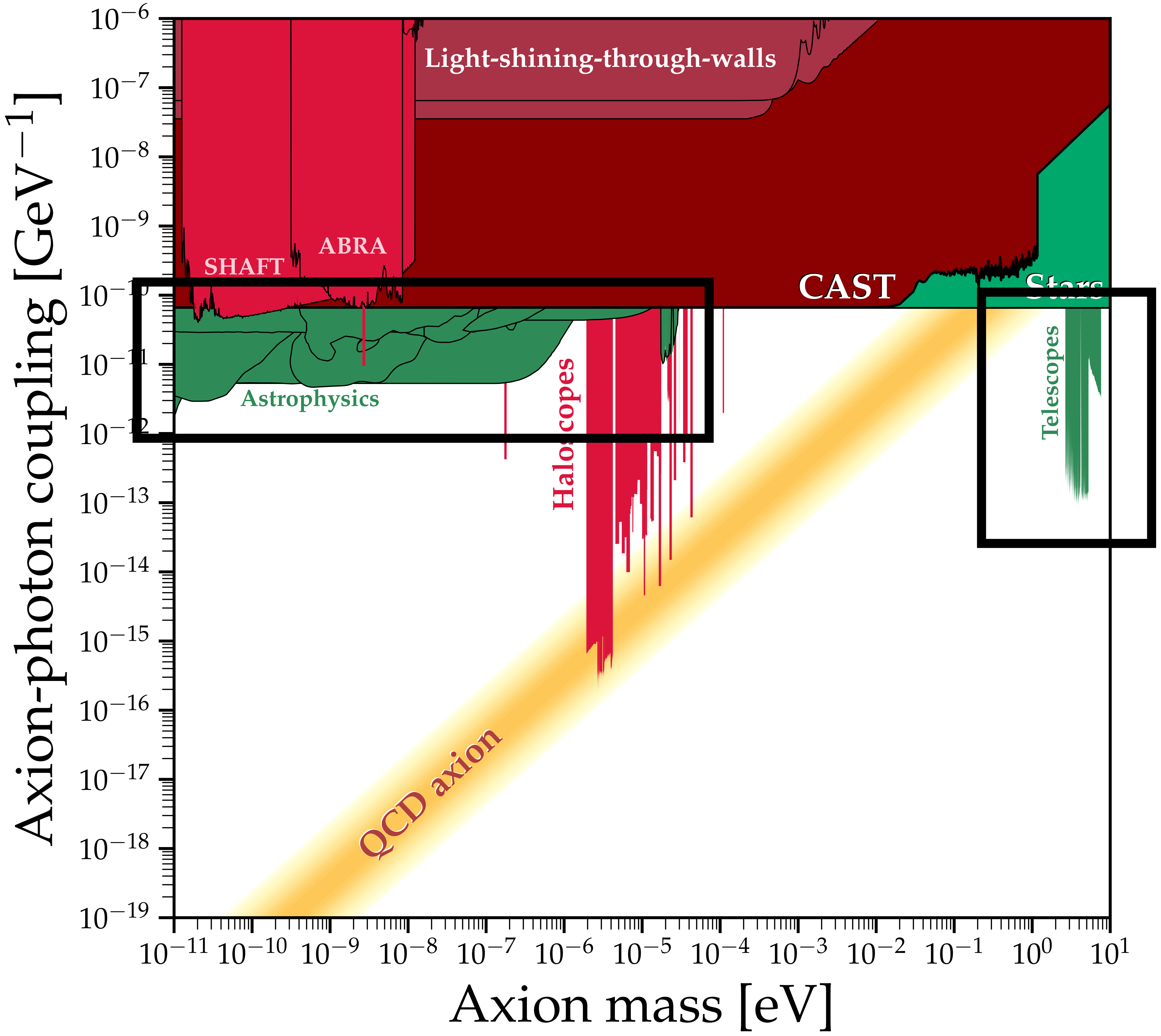
Axion-Photon coupling



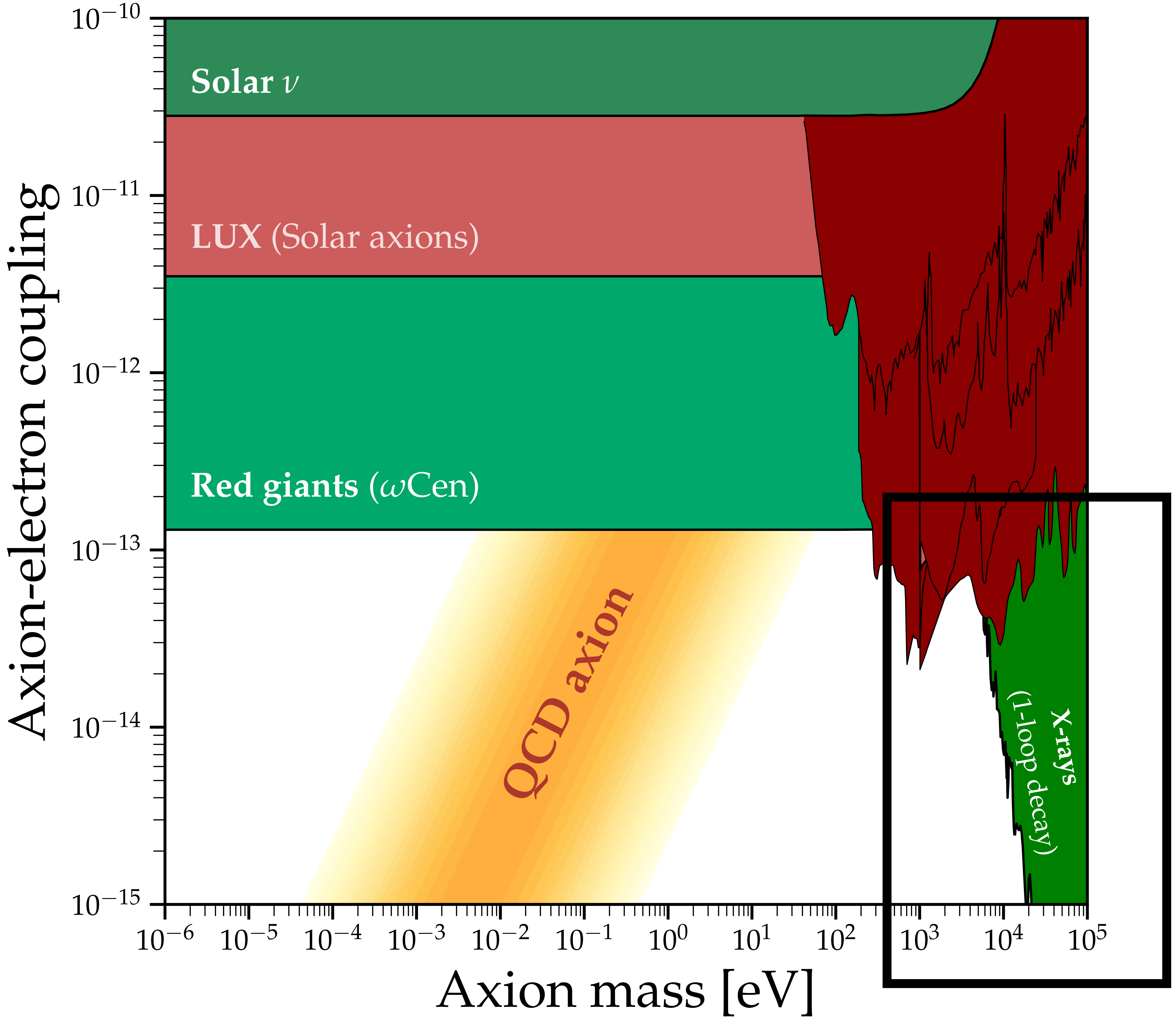
Axion-electron coupling



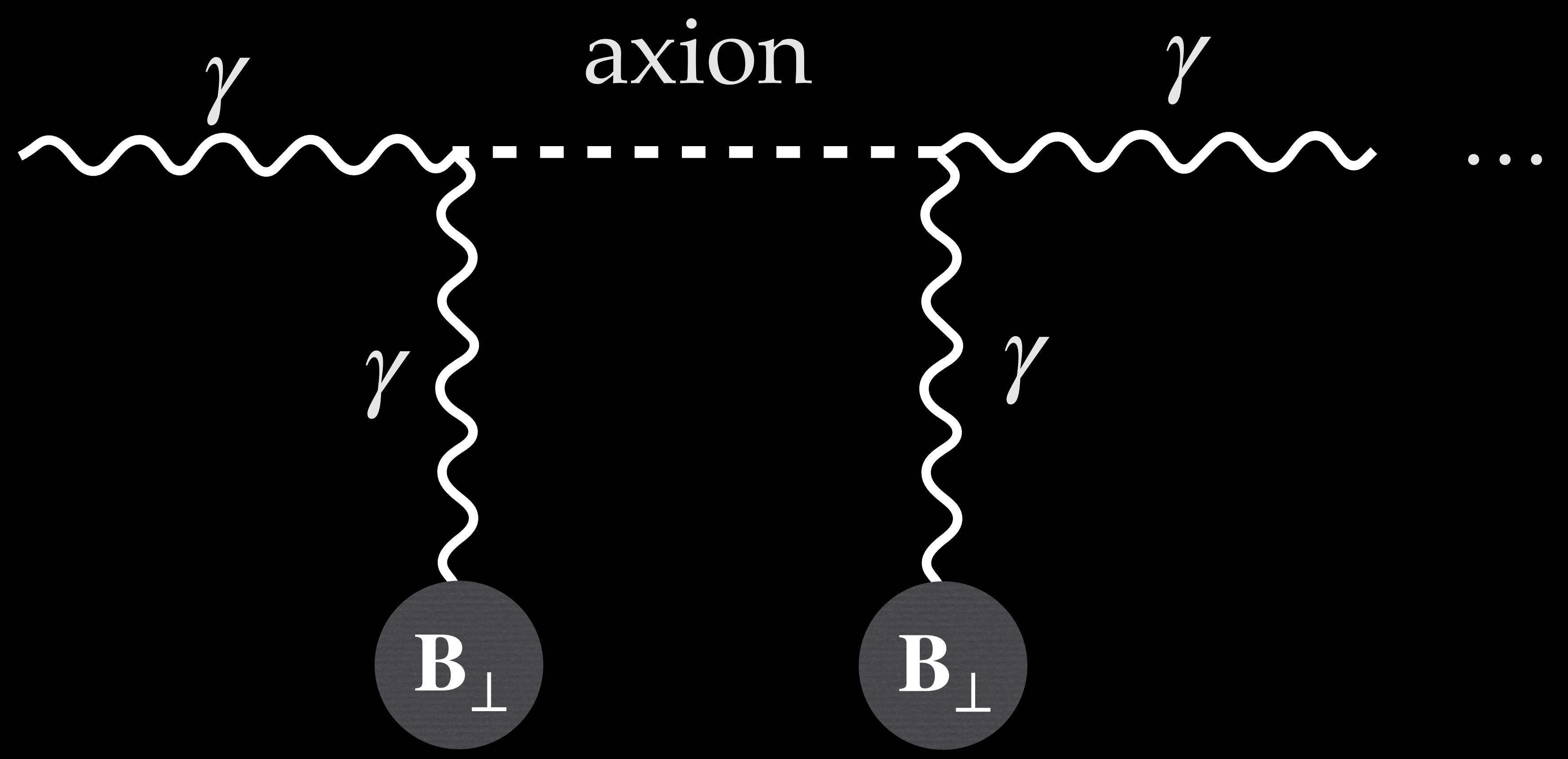
Axion-Photon coupling



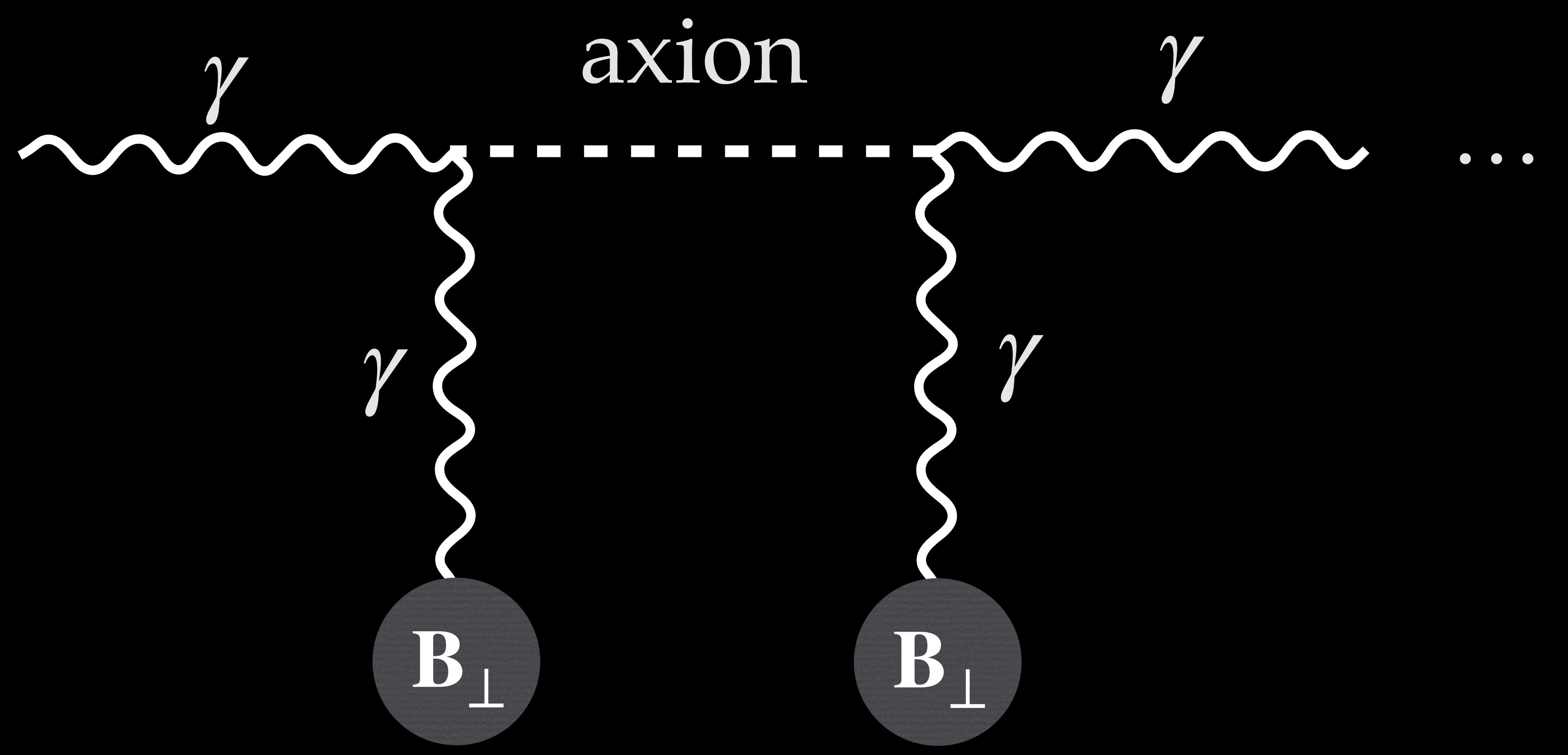
Axion-electron coupling



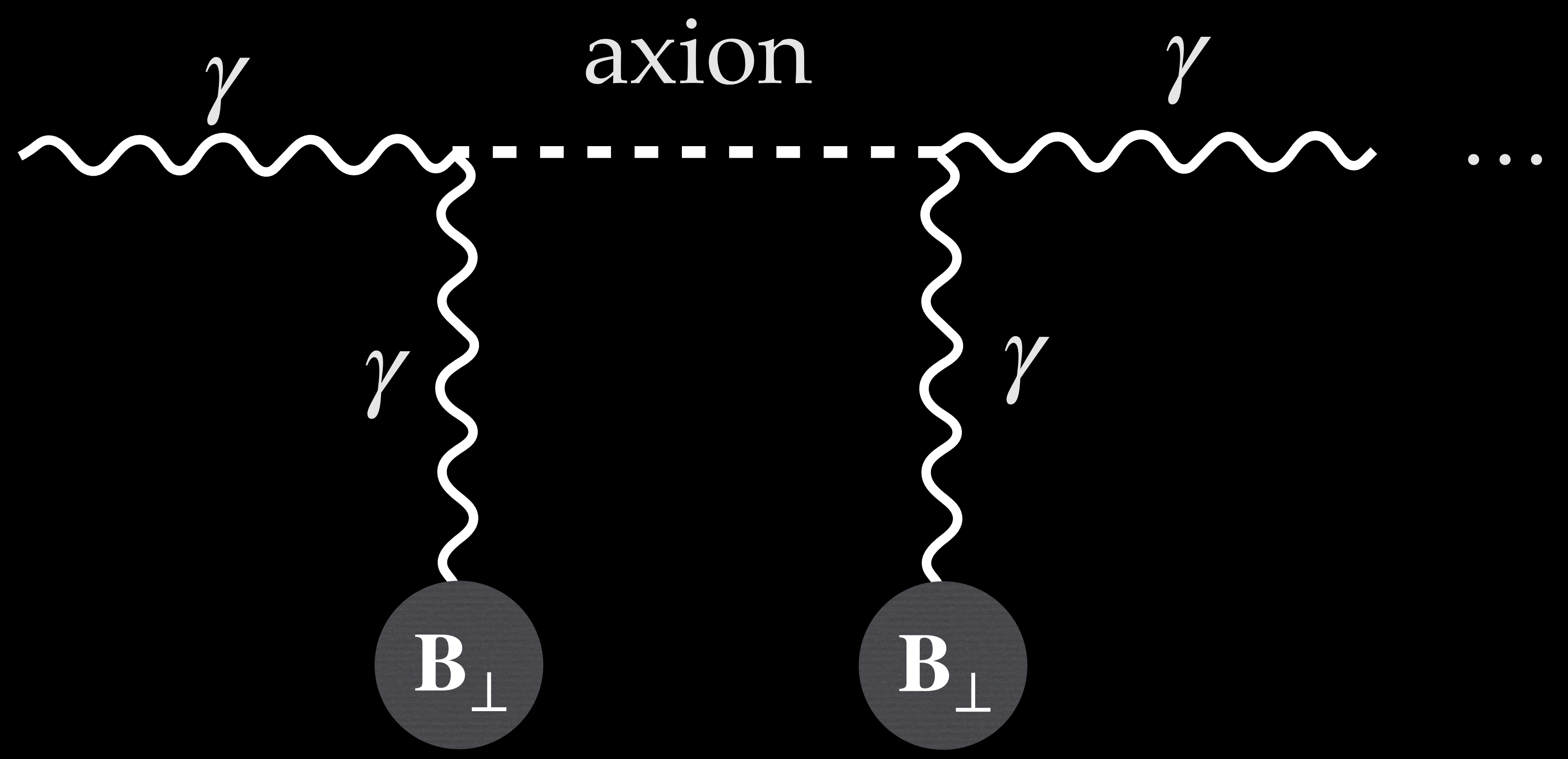
Photon-axion mixing in a B-field



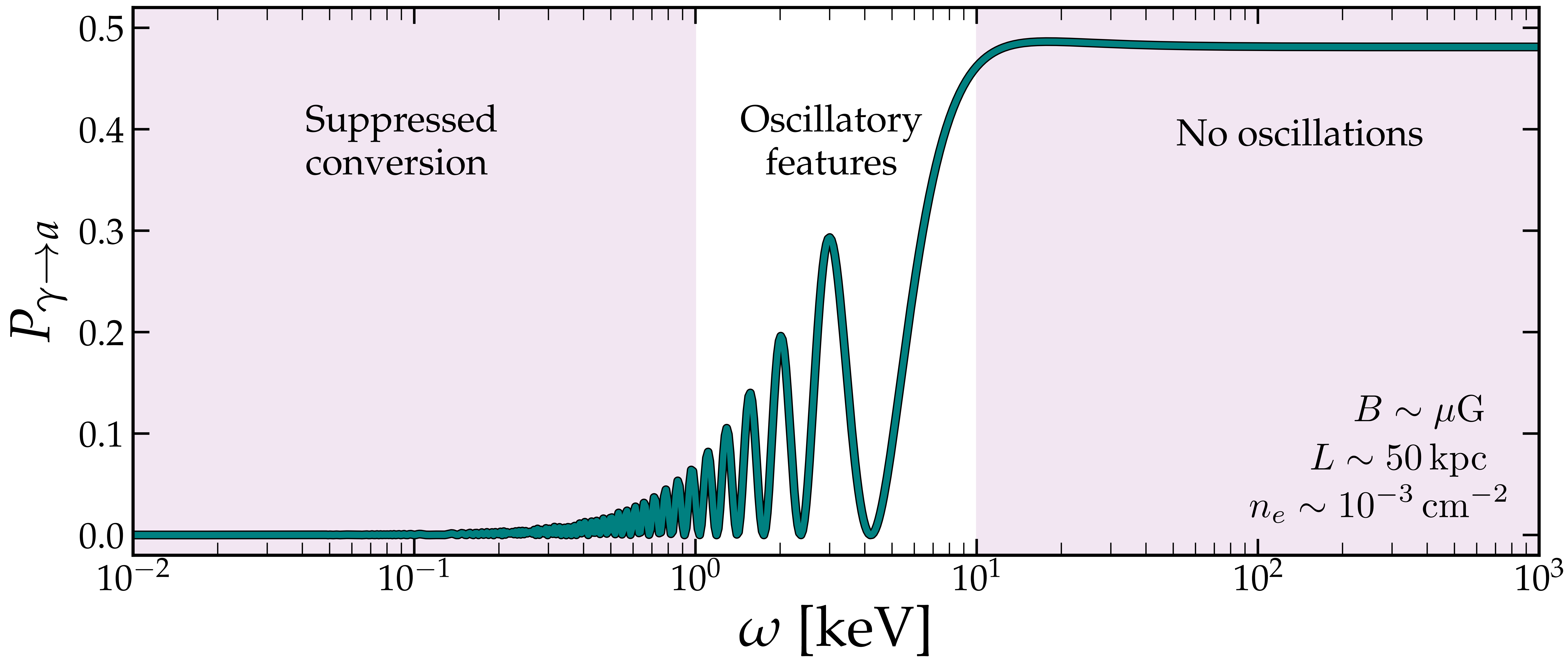
Photon-axion mixing in a B-field

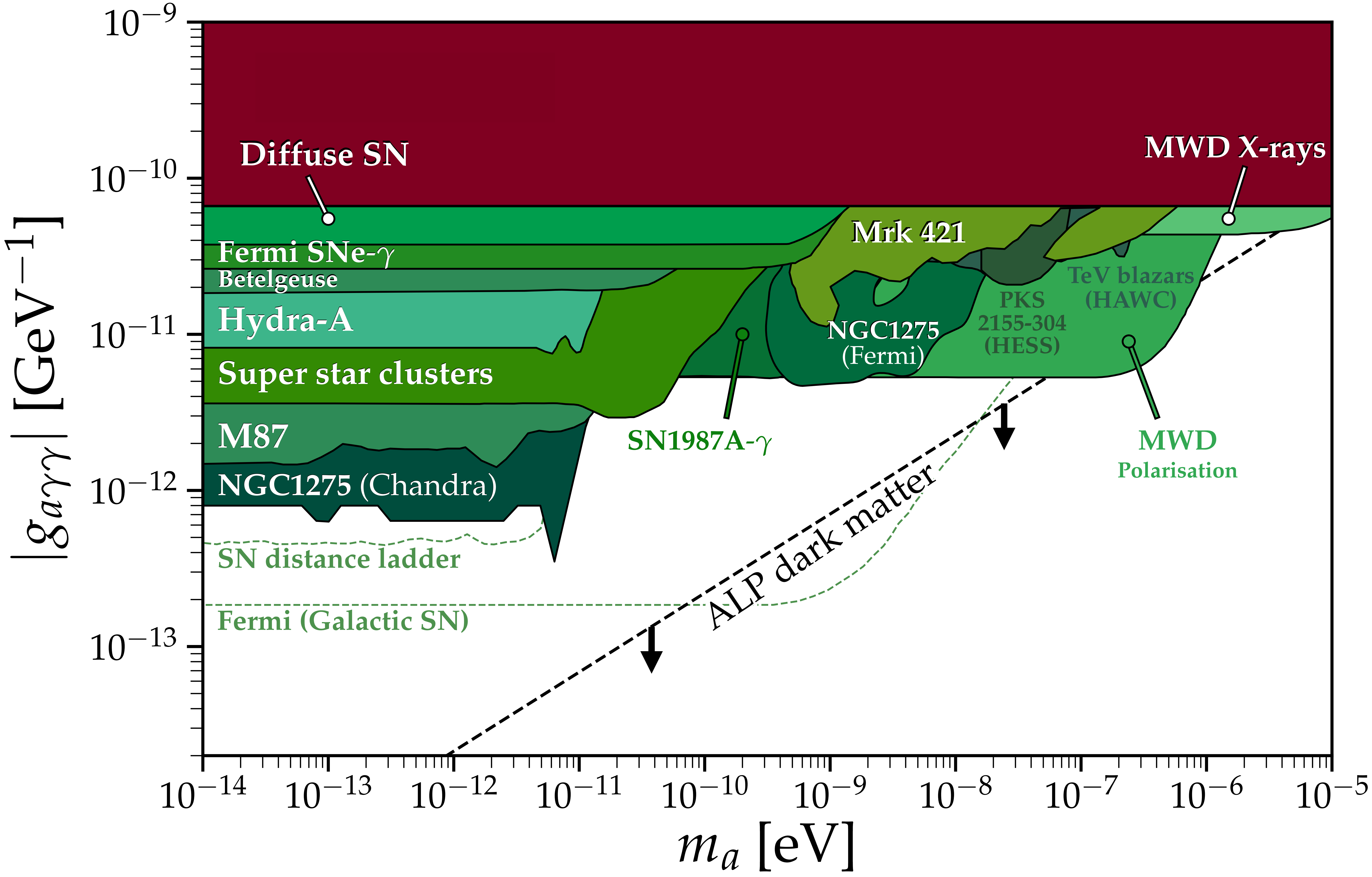


Photon-axion mixing in a B-field

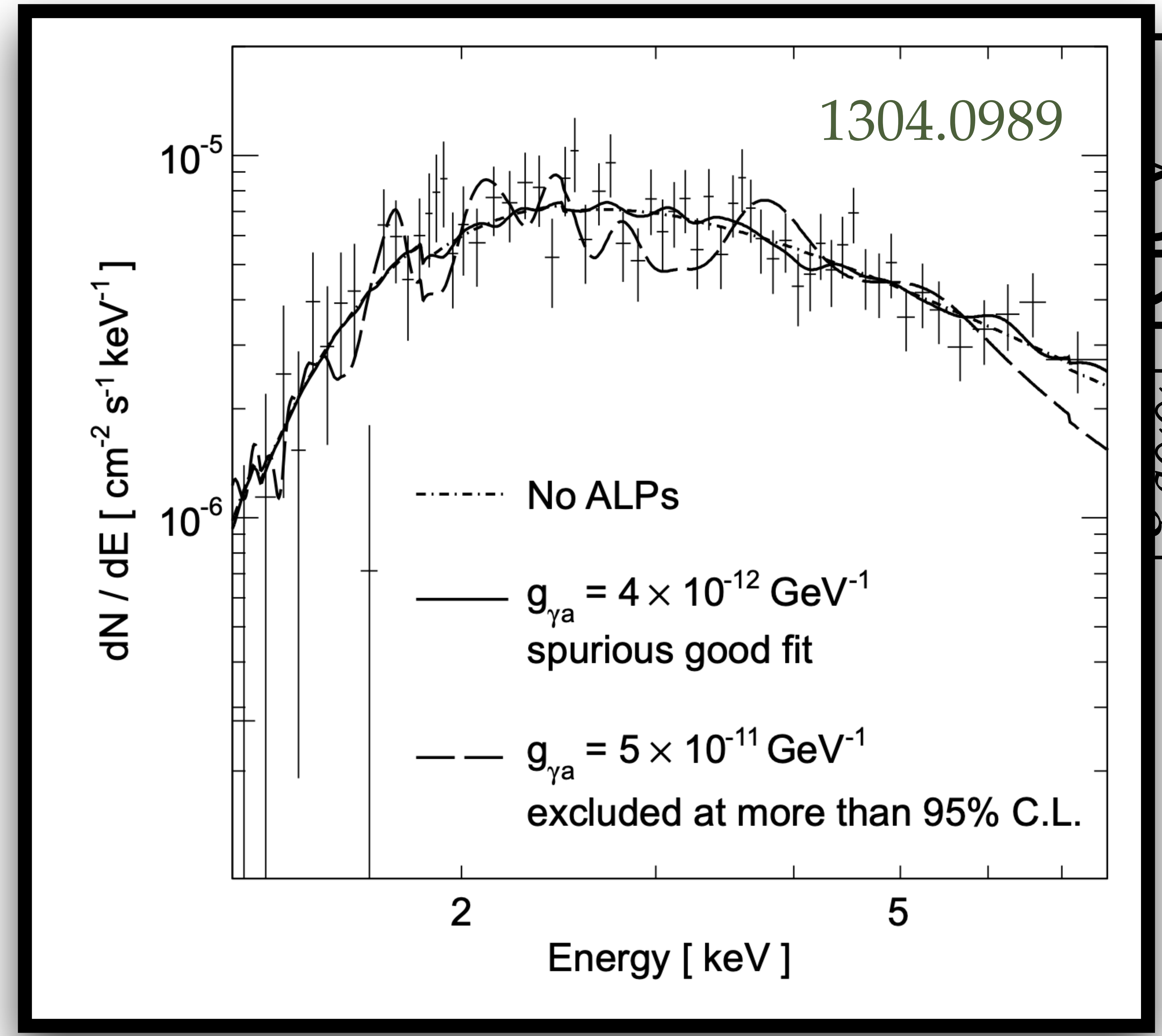


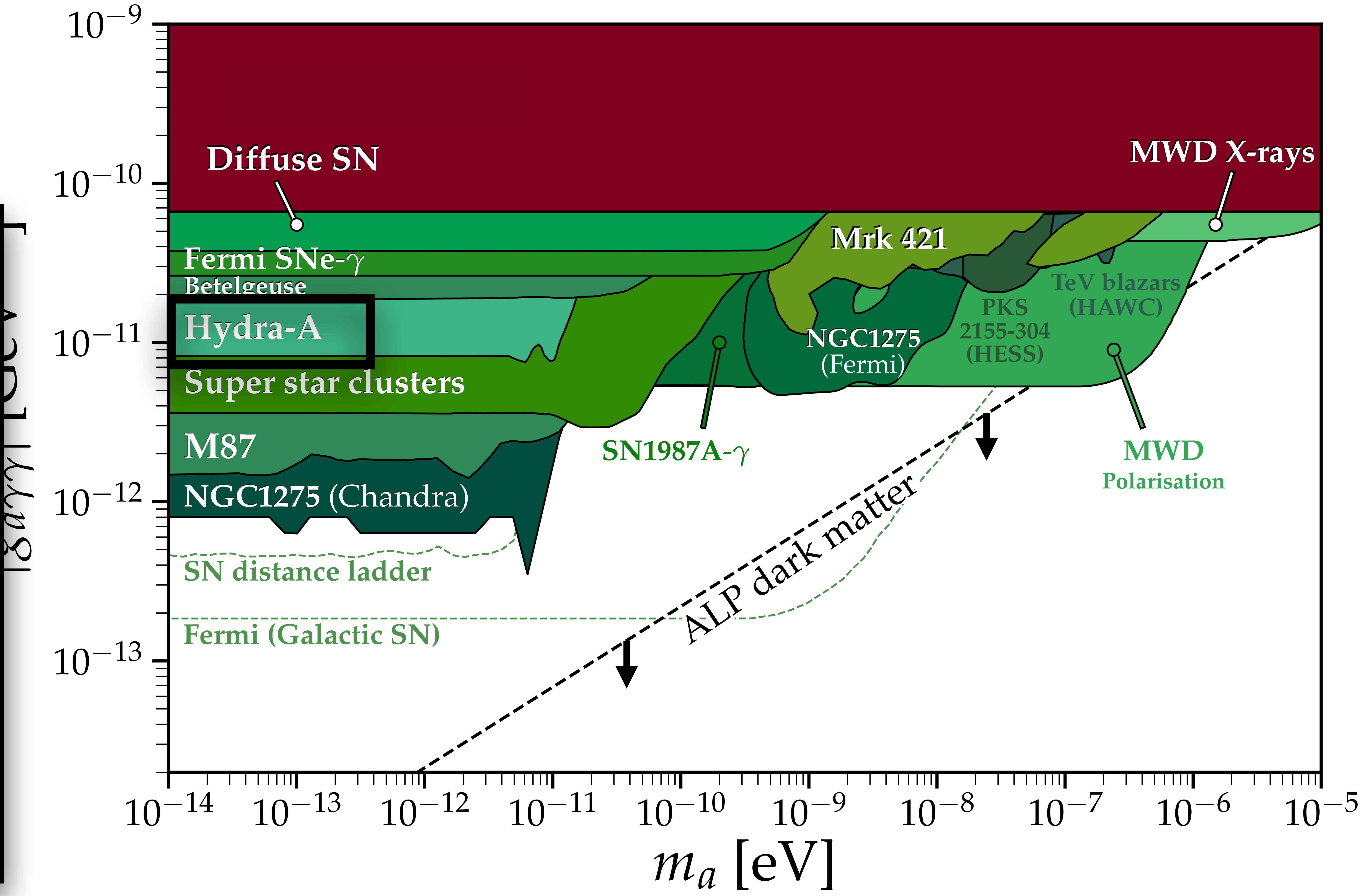
Photon-axion conversion probability

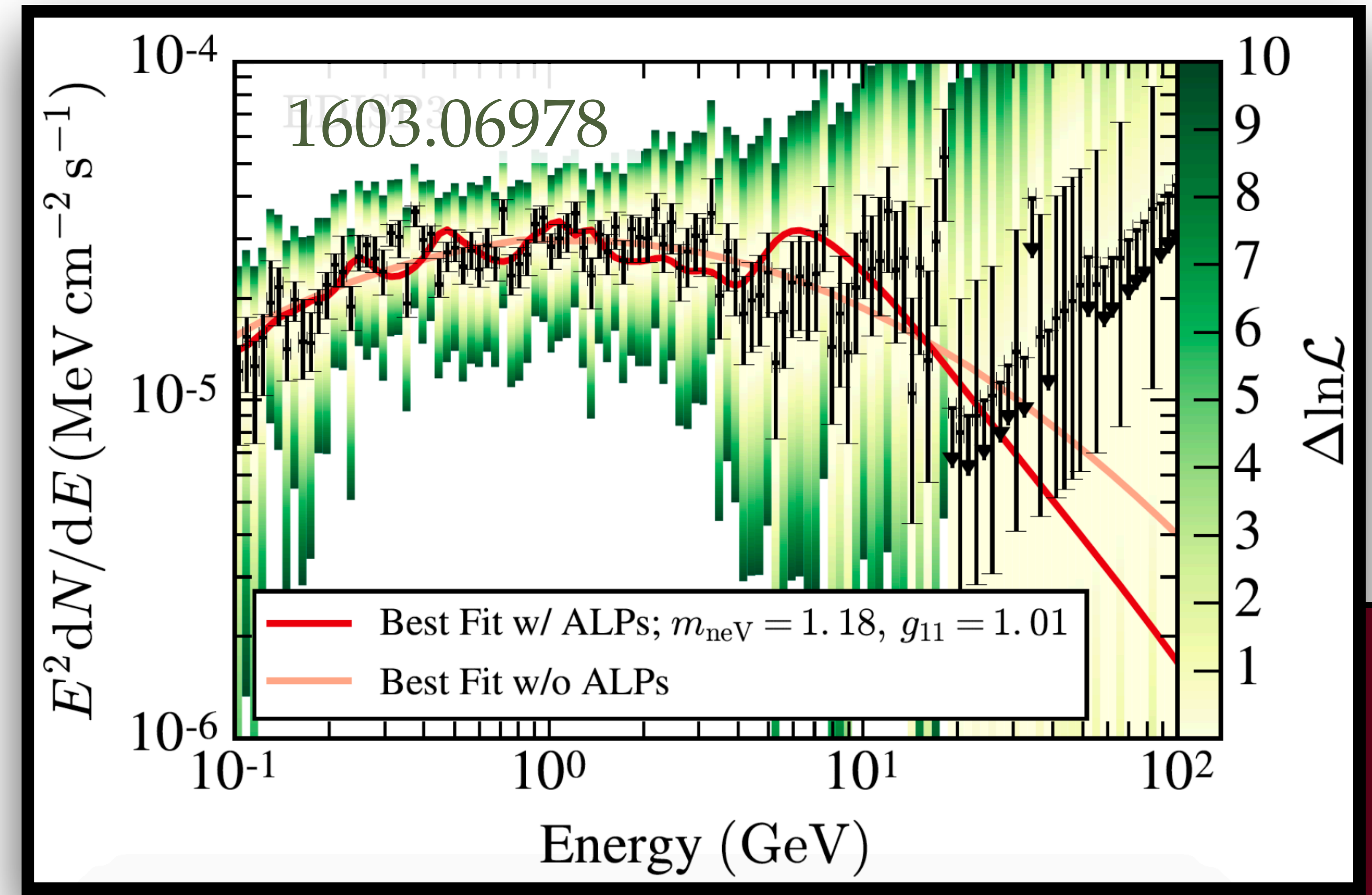


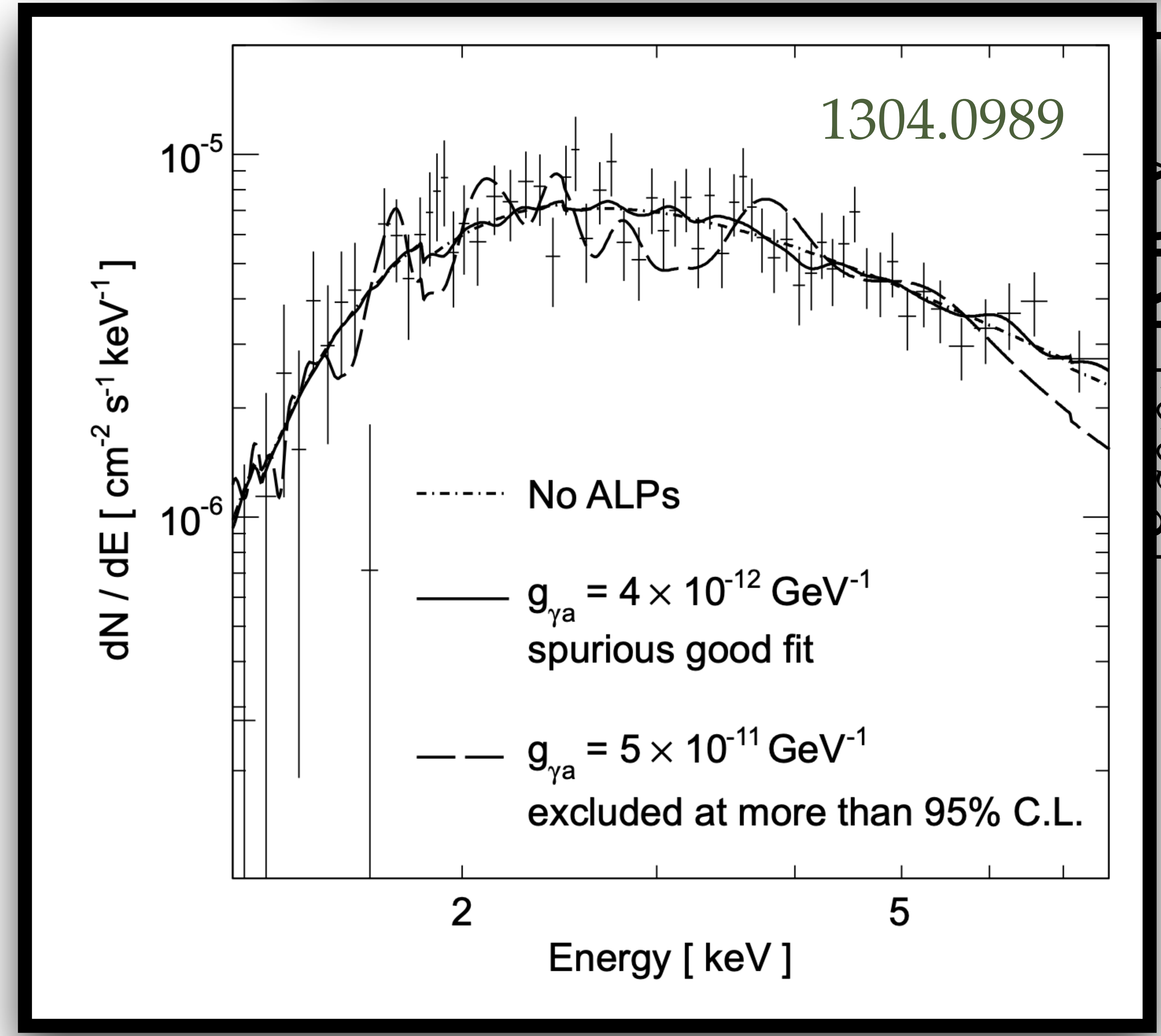


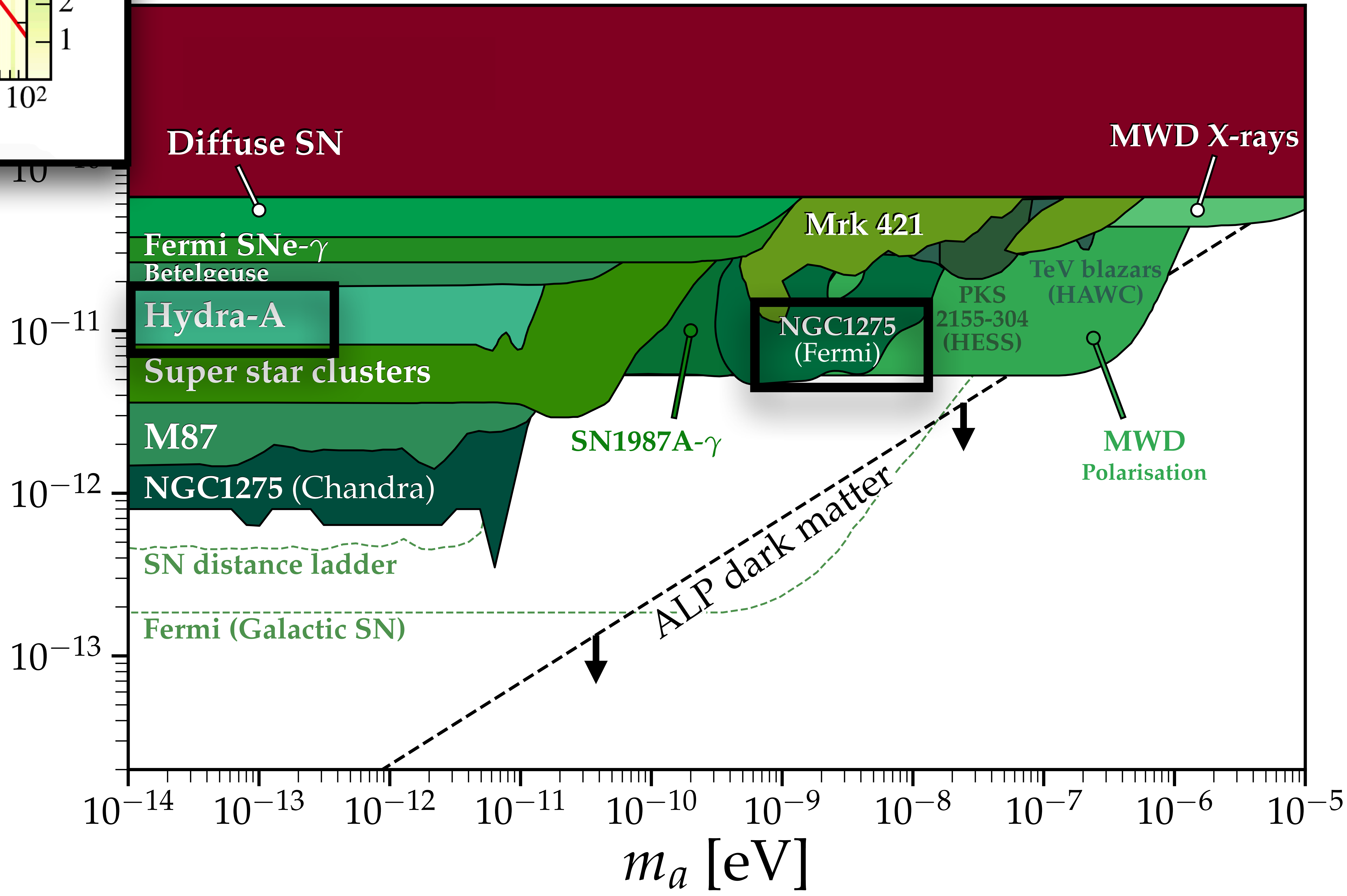
Diffuse SN
MWD X-rays
Mrk 421
Fermi SNe-γ
Betelgeuse
Hydra-A
Super star clusters
M87
NGC1275 (Chandra)
SN distance ladder
Fermi (Galactic SN)
TeV blazars (HAWC)
PKS 2155-304 (HESS)
NGC1275 (Fermi)
SN1987A-γ
MWD Polarisation
ALP dark matter
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-8}
10^{-7}
10^{-6}
10^{-5}

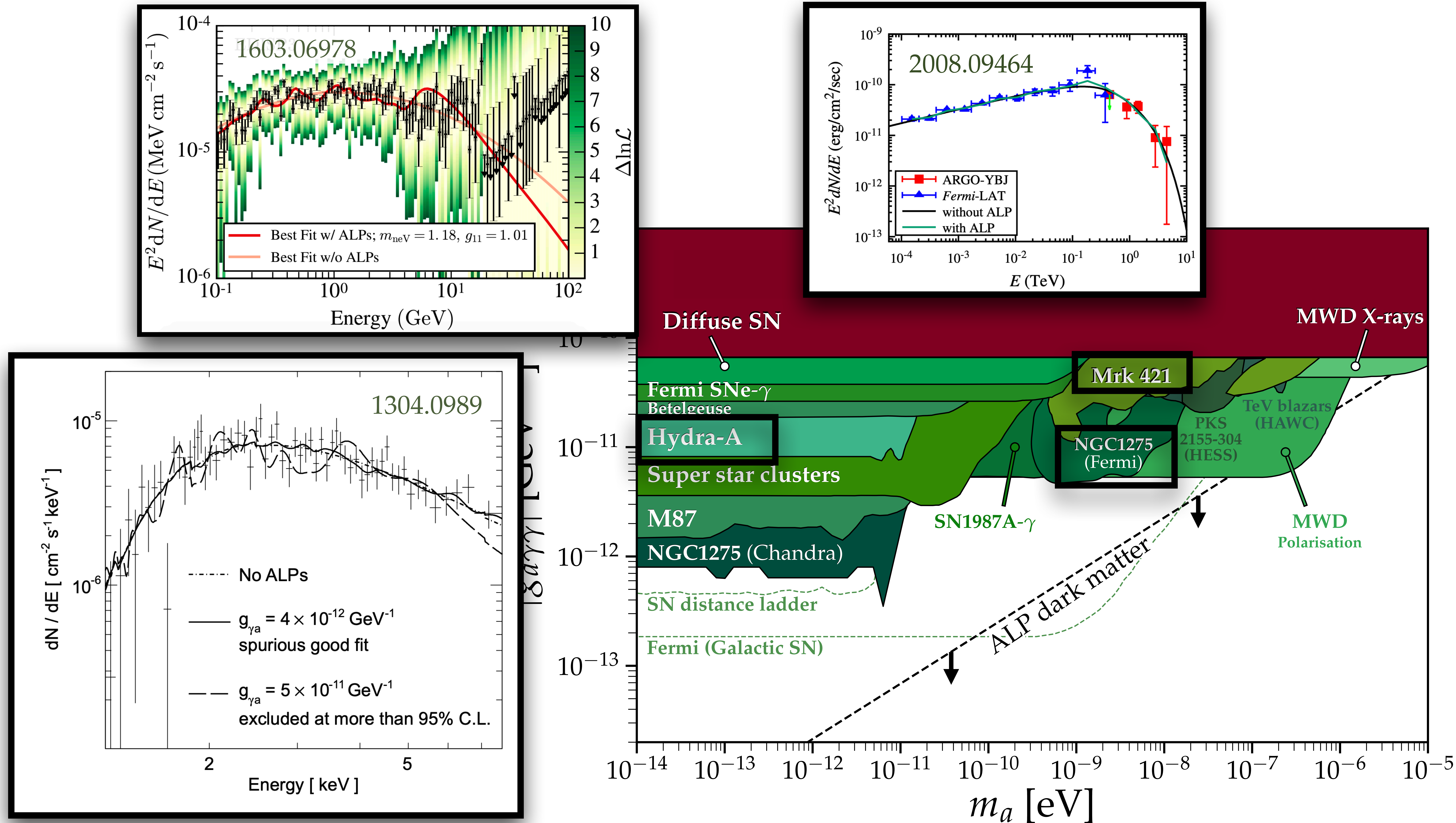

1304.0989
dN / dE [cm^-2 s^-1 keV^-1]
Energy [keV]
No ALPs
g_γa = 4 × 10^-12 GeV^-1
spurious good fit
g_γa = 5 × 10^-11 GeV^-1
excluded at more than 95% C.L.


Diffuse SN
MWD X-rays
Mrk 421
Fermi SNe-γ
Betelgeuse
Hydra-A
TeV blazars
(HAWC)
PKS
2155-304
(HESS)
NGC1275
(Fermi)
Super star clusters
M87
SN1987A-γ
MWD
Polarisation
NGC1275 (Chandra)
SN distance ladder
ALP dark matter
Fermi (Galactic SN)
m_a [eV]


1603.06978
Best Fit w/ ALPs; $m_{\mathrm{neV}} = 1.18$, $g_{11} = 1.01$
Best Fit w/o ALPs
$E^2 dN/dE$ (MeV cm^{-2} s^{-1})
Energy (GeV)
$\Delta \ln \mathcal{L}$


1304.0989
No ALPs
$g_{\gamma a} = 4 \times 10^{-12}$ GeV^{-1}
spurious good fit
$g_{\gamma a} = 5 \times 10^{-11}$ GeV^{-1}
excluded at more than 95% C.L.
dN / dE [cm^{-2} s^{-1} keV^{-1}]
Energy [keV]


Diffuse SN
MWD X-rays
Fermi SNe-γ
Betelgeuse
Mrk 421
Hydra-A
Super star clusters
NGC1275 (Fermi)
PKS 2155-304 (HESS)
TeV blazars (HAWC)
M87
NGC1275 (Chandra)
SN1987A-γ
MWD Polarisation
SN distance ladder
Fermi (Galactic SN)
ALP dark matter
m_a [eV]



1603.06978
Best Fit w/ ALPs; $m_{\rm neV} = 1.18$, $g_{11} = 1.01$
Best Fit w/o ALPs
$E^2 dN/dE$ (MeV cm^{-2} s^{-1})
Energy (GeV)
$\Delta \ln \mathcal{L}$
2008.09464
ARGO-YBJ
Fermi-LAT
without ALP
with ALP
$E^2 dN/dE$ (erg/cm^2/sec)
E (TeV)
1304.0989
No ALPs
$g_{\gamma a} = 4 \times 10^{-12}$ GeV^{-1}
spurious good fit
$g_{\gamma a} = 5 \times 10^{-11}$ GeV^{-1}
excluded at more than 95% C.L.
dN / dE [cm^{-2} s^{-1} keV^{-1}]
Energy [keV]
Diffuse SN
MWD X-rays
Mrk 421
Fermi SNe-γ
Betelgeuse
Hydra-A
TeV blazars (HAWC)
PKS 2155-304 (HESS)
NGC1275 (Fermi)
Super star clusters
M87
NGC1275 (Chandra)
SN1987A-γ
MWD Polarisation
SN distance ladder
Fermi (Galactic SN)
ALP dark matter
m_a [eV]

Astrophysics has a lot to contribute to the search for new particles

In particular improved understanding of environments like stellar interiors, and the magnetic fields of galaxies and clusters, will help greatly in bounding the dauntingly large parameter spaces we have to search over… and potentially find something unexpected

How to search for particles with tiny couplings

Measure numbers very precisely

- Precision tests of QED
- Rare nuclear decays
- Tiny microscopic forces

Sample a lot of particles

- Astrophysical environments
- High intensity collider experiments (beam dump)
- Dark matter

How to search for particles with tiny couplings

Measure numbers very precisely

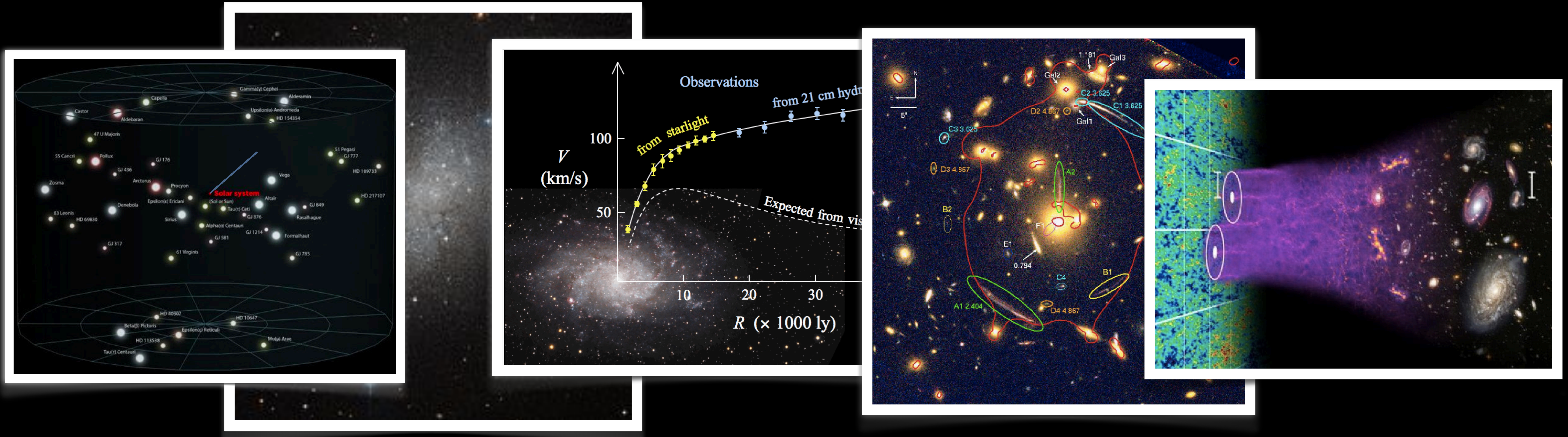
- Precision tests of QED
- Rare nuclear decays
- Tiny microscopic forces

Sample a lot of particles

- Astrophysical environments
- High intensity collider experiments (beam dump)
- Dark matter

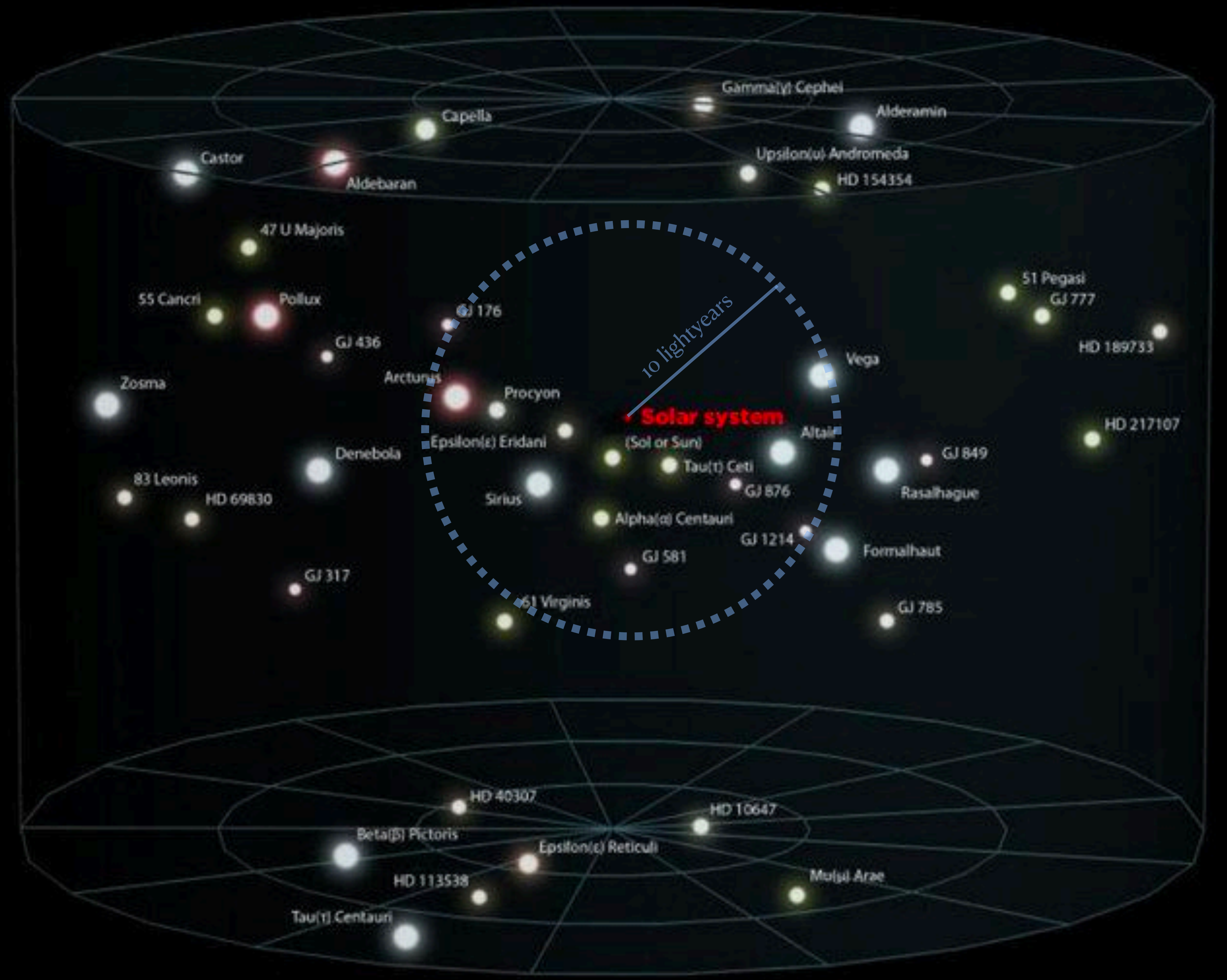
Evidence for dark matter

~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	Seeds large scale structure



How much dark matter is around?

~100 pc ~kpc ~100 kpc ~Mpc >Gpc



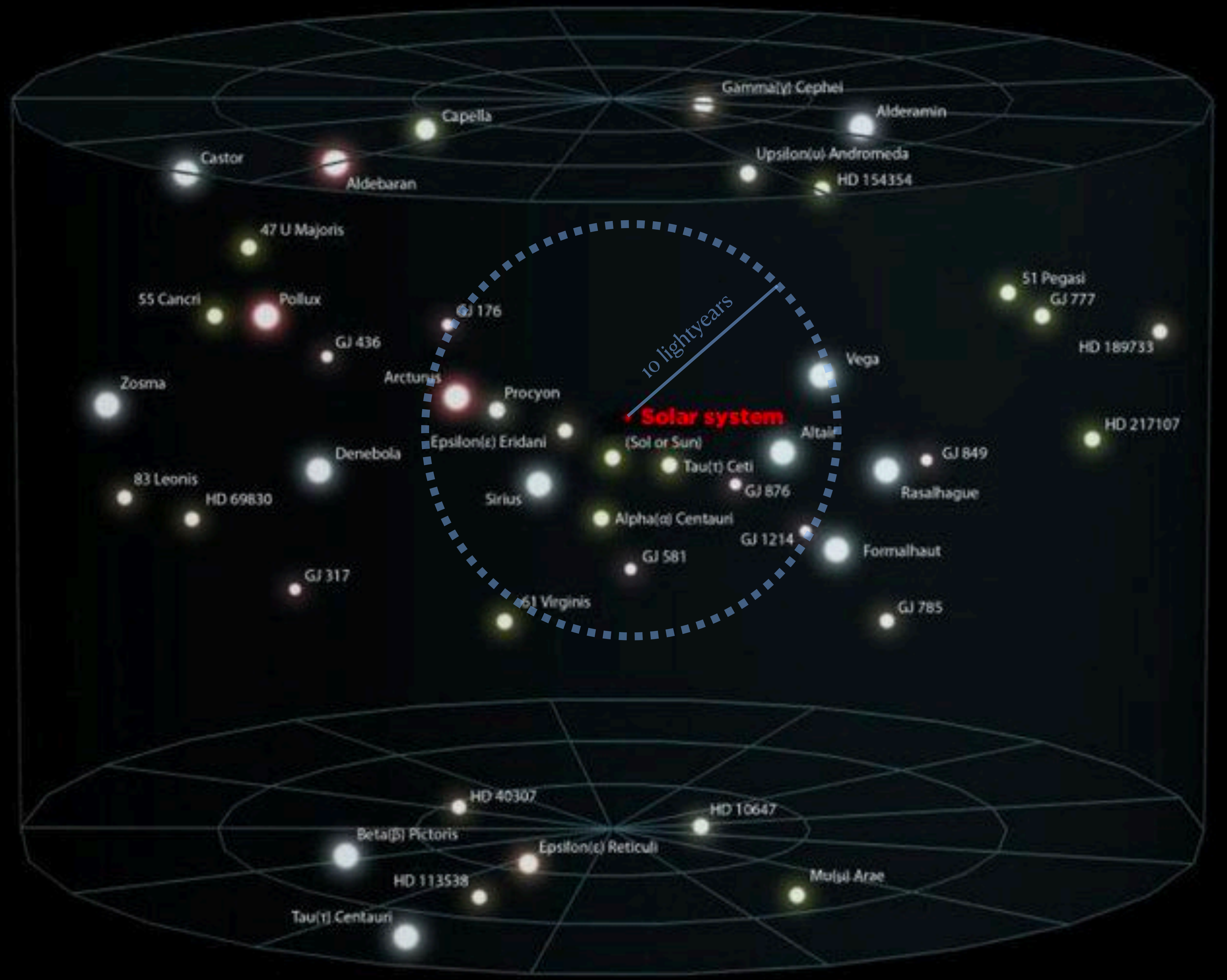
Local density of dark matter (i.e. in this room!)

$$\rho_{\rm dm} \approx 0.4\,{\rm GeV/cm^3} \longleftarrow \textit{Particle physicist's unit}$$

$$\approx 0.01\,{\rm M_\odot/pc^3} \longleftarrow \textit{Astrophysicist's unit}$$

How much dark matter is around?

~100 pc ~kpc ~100 kpc ~Mpc >Gpc



<u>Local density of dark matter</u> (i.e. in this room!)

$$\rho_{\rm dm} \approx 0.4\,{\rm GeV/cm^3} \longleftarrow \textit{Particle physicist's unit}$$

$$\approx 0.01\,{\rm M_\odot/pc^3} \longleftarrow \textit{Astrophysicist's unit}$$

$$\approx 2\,\text{protons/teaspoon}$$

$$\approx 1\,\text{sand grain/Sydney harbour}$$

$$\approx 1\,\text{cockatoo/Earth}$$

$$\approx 1\,\text{asteroid/Solar System}$$

“Wave like dark matter”

Extremely light dark matter particles will behave collectively like an oscillating and undulating classical field

$$a(\mathbf{x}, t) \approx \frac{\sqrt{2\rho_a}}{m_a} \cos\left(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha\right)$$

$$\omega \approx m_a$$

Oscillating at the DM mass

...Still need to overcome the extremely interaction strength

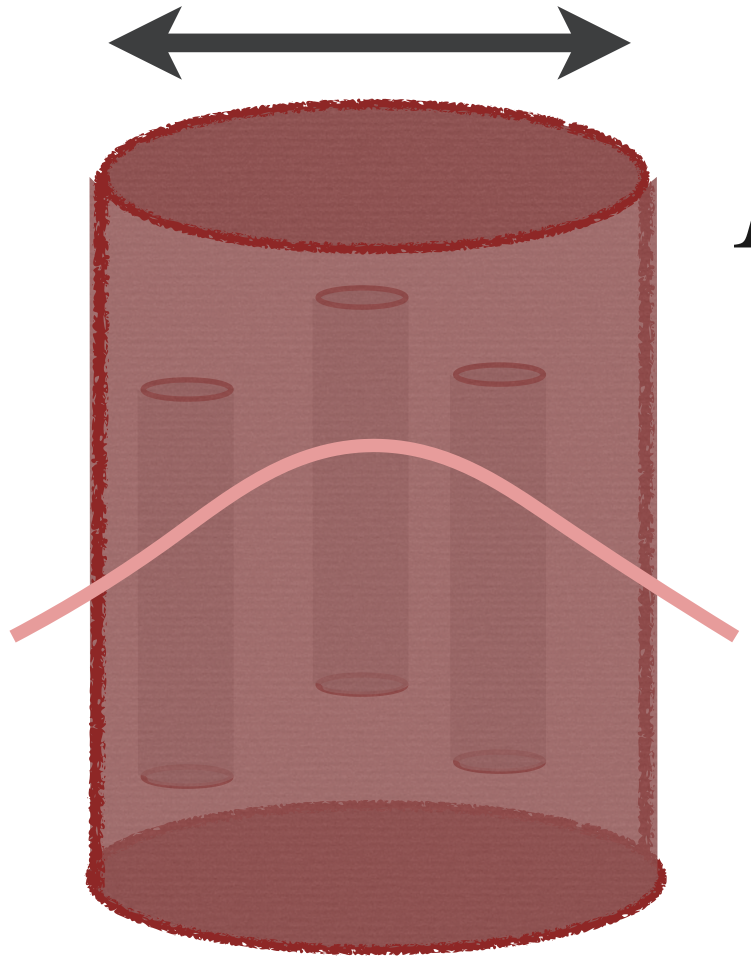
But… If we try to convert the DM oscillations inside a device which has a resonance at the same frequency then we can get resonant amplification of the power output

→ **"Haloscope"**

...Still need to overcome the extremely interaction strength

But… If we try to convert the DM oscillations inside a device which has a resonance at the same frequency then we can get resonant amplification of the power output

→ **"Haloscope"**

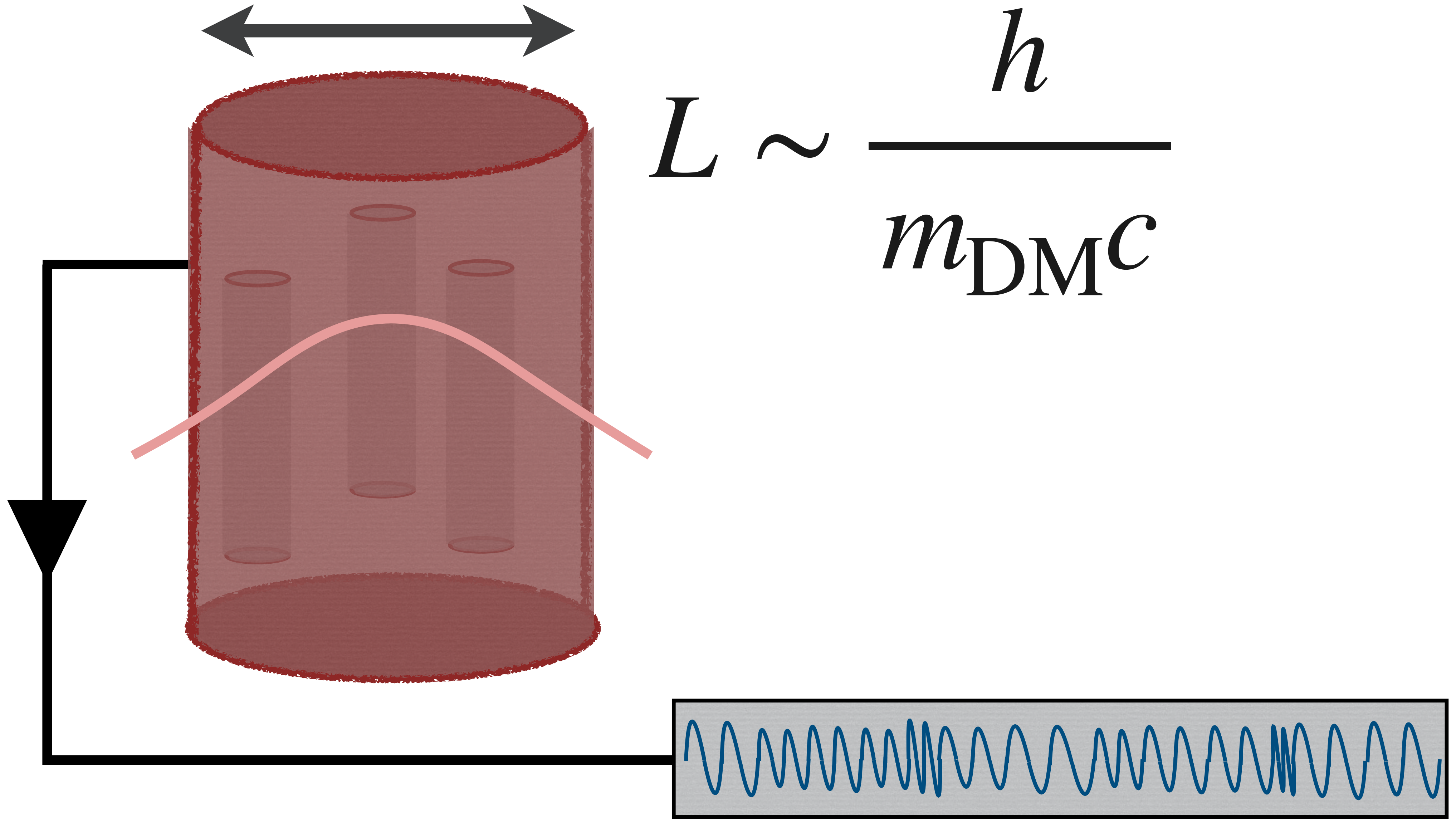


$$L \sim \frac{h}{m_{\rm DM} c}$$

...Still need to overcome the extremely interaction strength

But… If we try to convert the DM oscillations inside a device which has a resonance at the same frequency then we can get resonant amplification of the power output

→ **"Haloscope"**

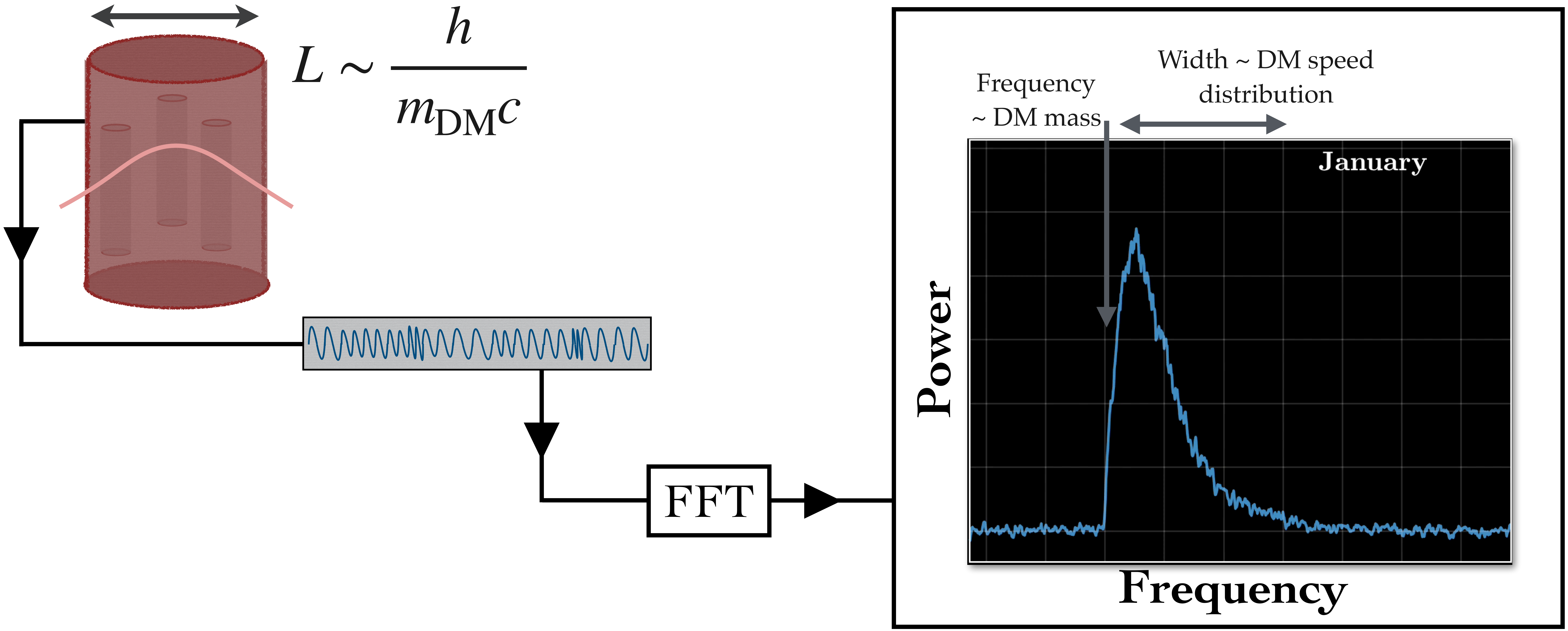


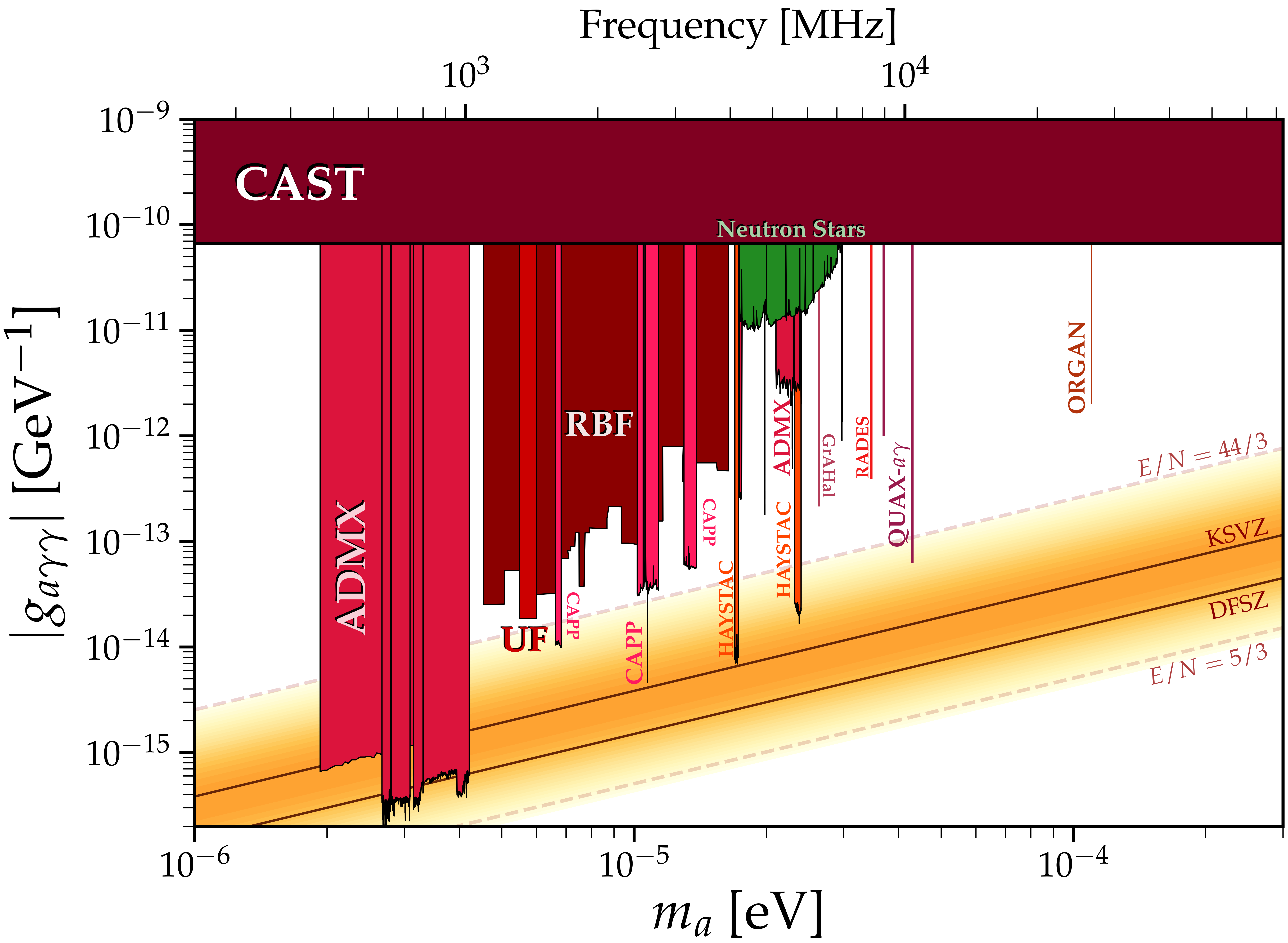
$$L \sim \frac{h}{m_{\mathrm{DM}} c}$$

...Still need to overcome the extremely interaction strength

But… If we try to convert the DM oscillations inside a device which has a resonance at the same frequency then we can get resonant amplification of the power output

→ **"Haloscope"**

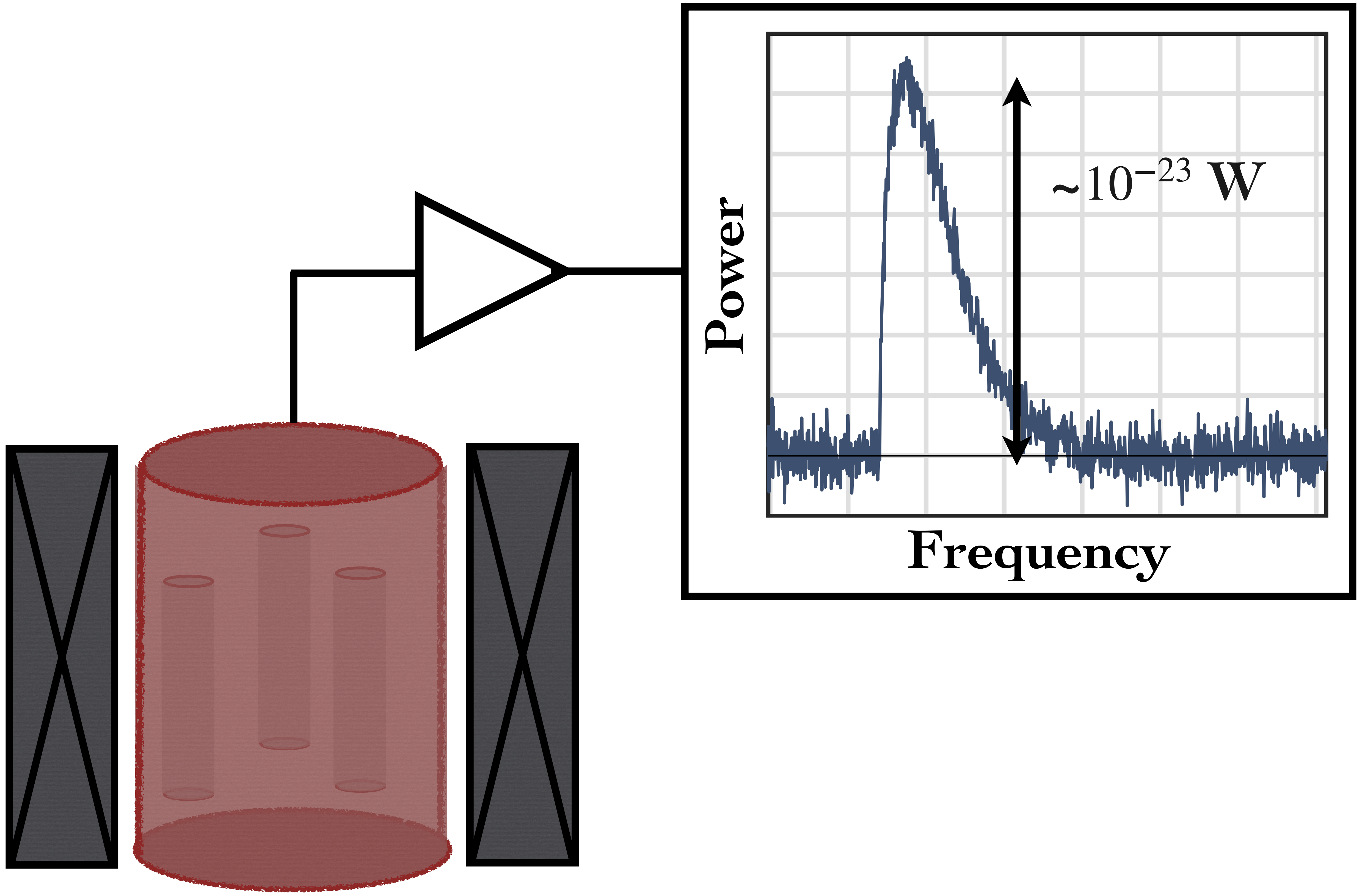




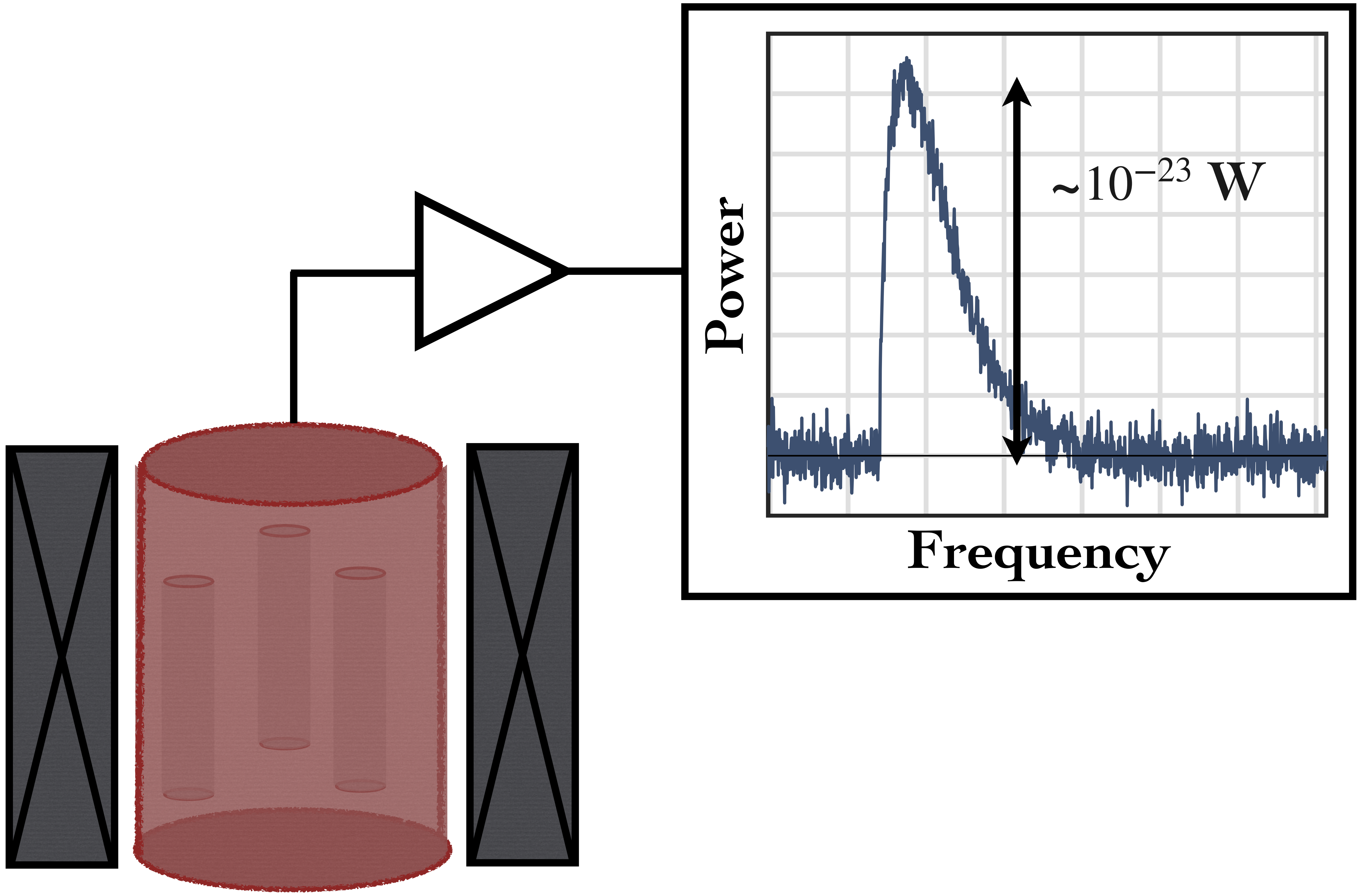
Frequency [MHz]
10^3
10^4
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
CAST
Neutron Stars
ADMX
RBF
UF
CAPP
HAYSTAC
GrAHal
RADES
QUAX-$a\gamma$
ORGAN
E/N = 44/3
KSVZ
DFSZ
E/N = 5/3
10^{-6}
10^{-5}
10^{-4}
m_a [eV]

Frequency [MHz]
10^3
10^4
CAST
Neutron Stars
ADMX
RBF
UF
CAPP
HAYSTAC
GrAHal
RADES
QUAX-$a\gamma$
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
2110.06096
Power [Watt] (offset)
$\times 10^{-21}$
TM_{011}
TM_{010}
DFSZ SNR
Frequency [MHz]
Total Signal Power [Watt]

Looking for a signal above noise…



Looking for a signal above noise…



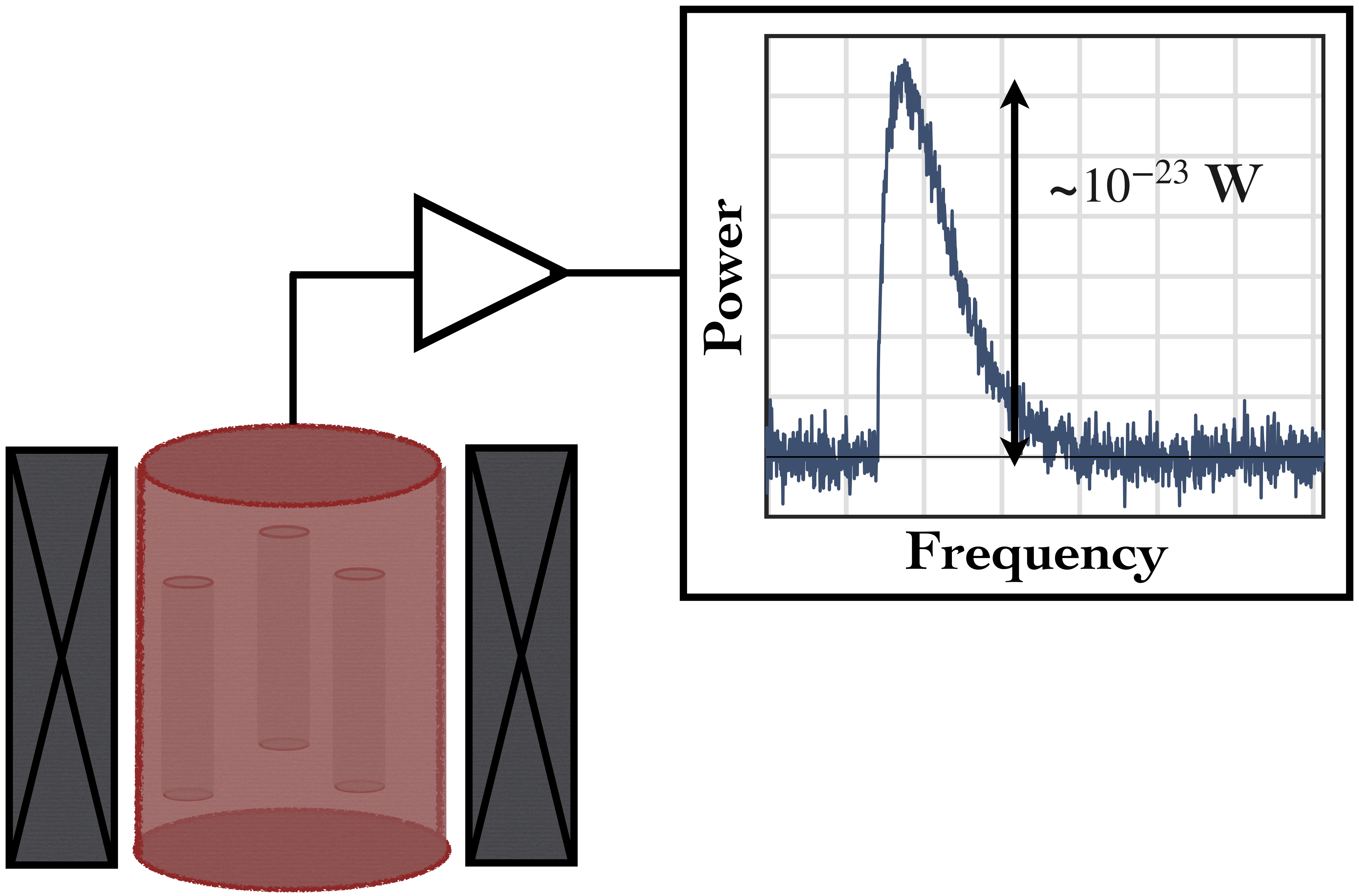
$$\frac{S}{N} = \frac{P_\mathrm{S}}{k_\mathrm{B} T_\mathrm{N}} \sqrt{\frac{t}{\Delta v}}$$

Signal power

Measurement time

Bandwidth

Looking for a signal above noise…



Signal power

Measurement time

Bandwidth

$$\frac{S}{N} = \frac{P_{\mathrm{S}}}{k_{\mathrm{B}} T_{\mathrm{N}}}\sqrt{\frac{t}{\Delta v}}$$

Noise temperature

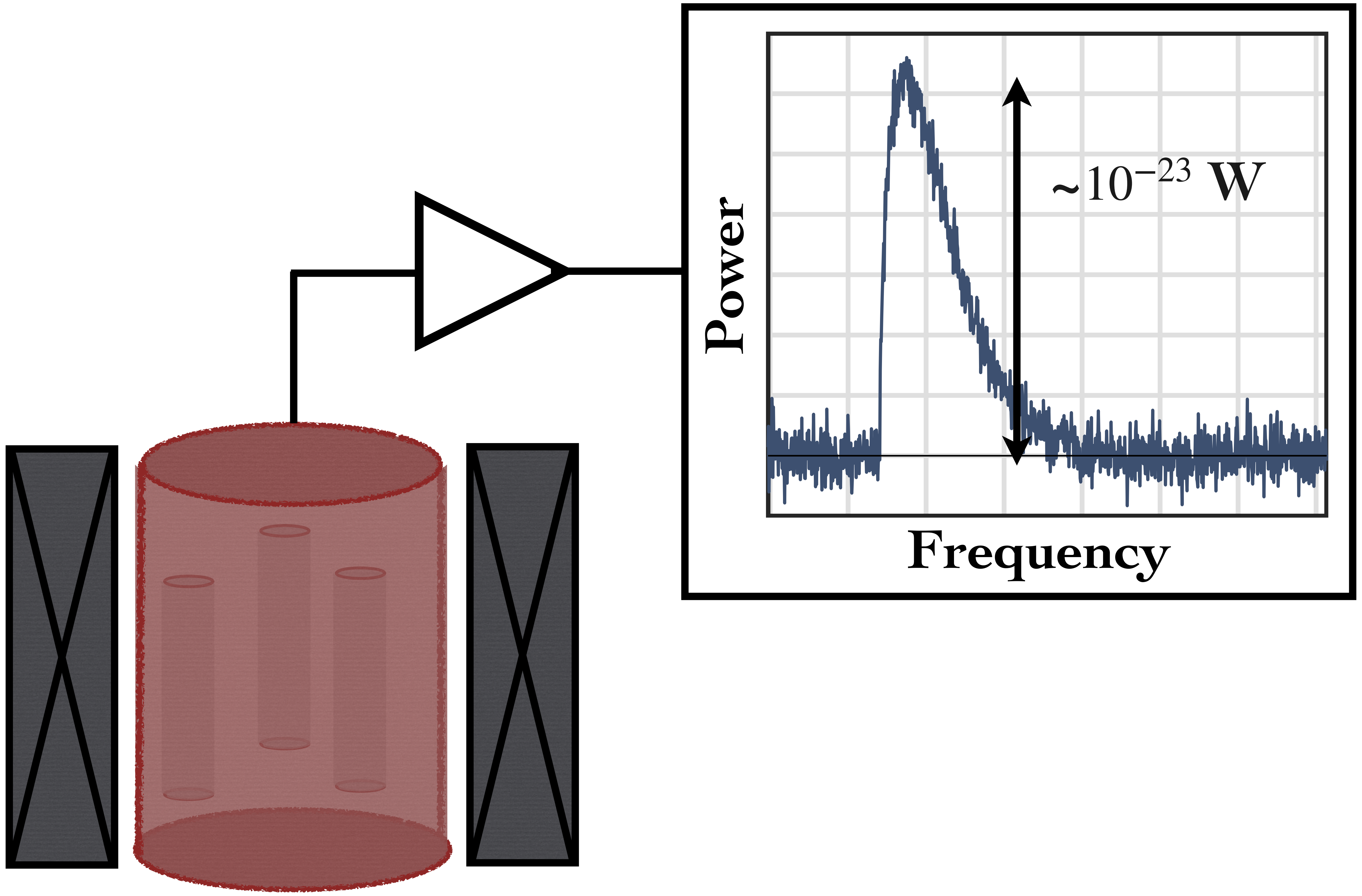
$$k_{\mathrm{B}} T_{\mathrm{N}} = hv\left(\frac{1}{\mathrm{e}^{hv/k_{\mathrm{B}}T}-1}+\frac{1}{2}\right)+k_{\mathrm{B}} T_{\mathrm{A}}$$

Thermal

Quantum

Amplifier

Looking for a signal above noise…



$$\frac{S}{N} = \frac{P_{\mathrm{S}}}{k_{\mathrm{B}} T_{\mathrm{N}}} \sqrt{\frac{t}{\Delta v}}$$

Signal power

Measurement time

Bandwidth

Noise temperature

$$k_{\mathrm{B}} T_{\mathrm{N}} = hv \left(\frac{1}{e^{hv/k_{\mathrm{B}}T} - 1} + \frac{1}{2} \right) + k_{\mathrm{B}} T_{\mathrm{A}}$$

Thermal

Quantum

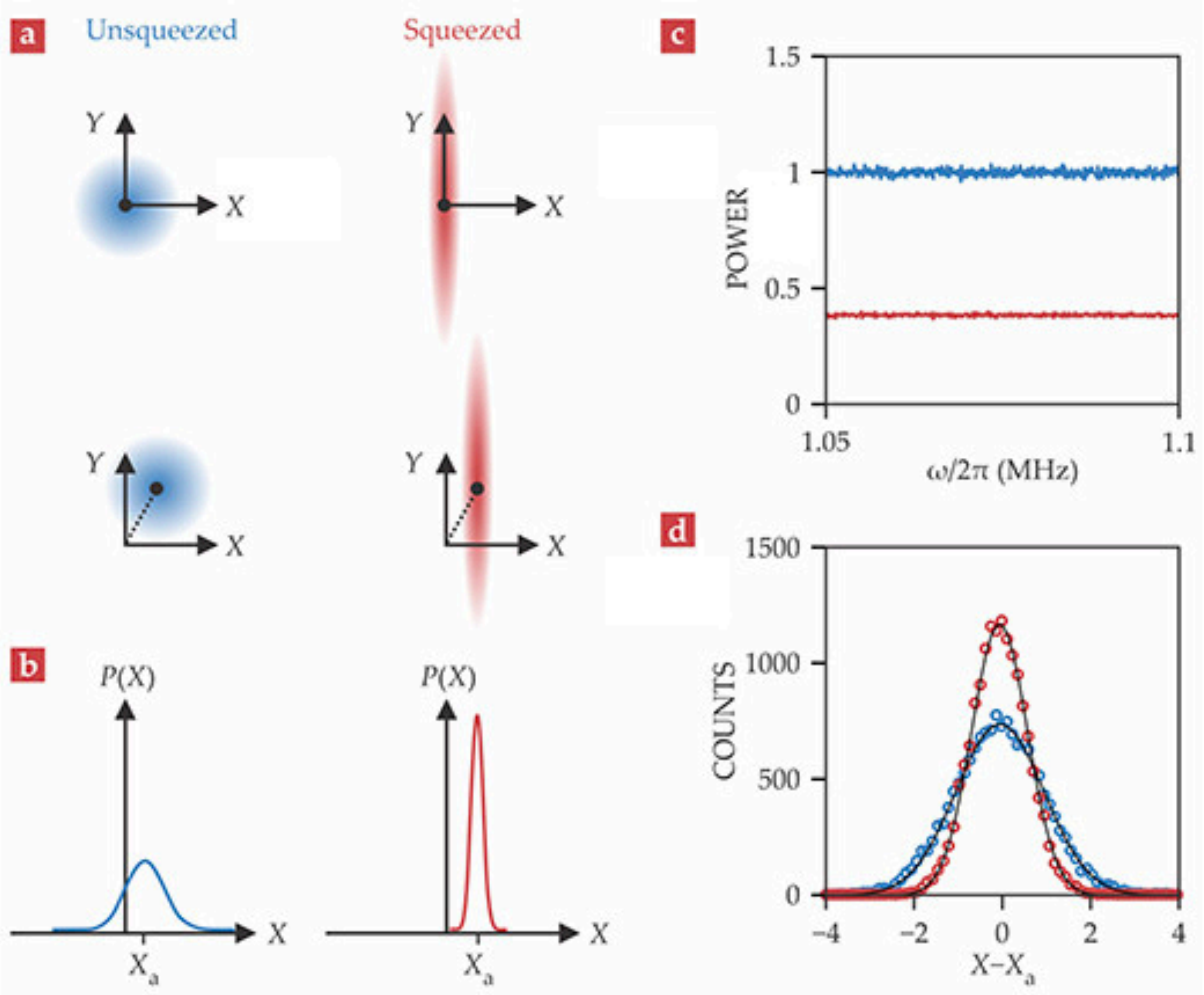
Amplifier

Even in the zero-temperature case there is irreducible quantum noise that is now actually limiting the sensitivity of dark matter searches.

How to beat the Standard Quantum Limit (SQL)

Quantum squeezing

e.g. HAYSTAC [2008.01853]

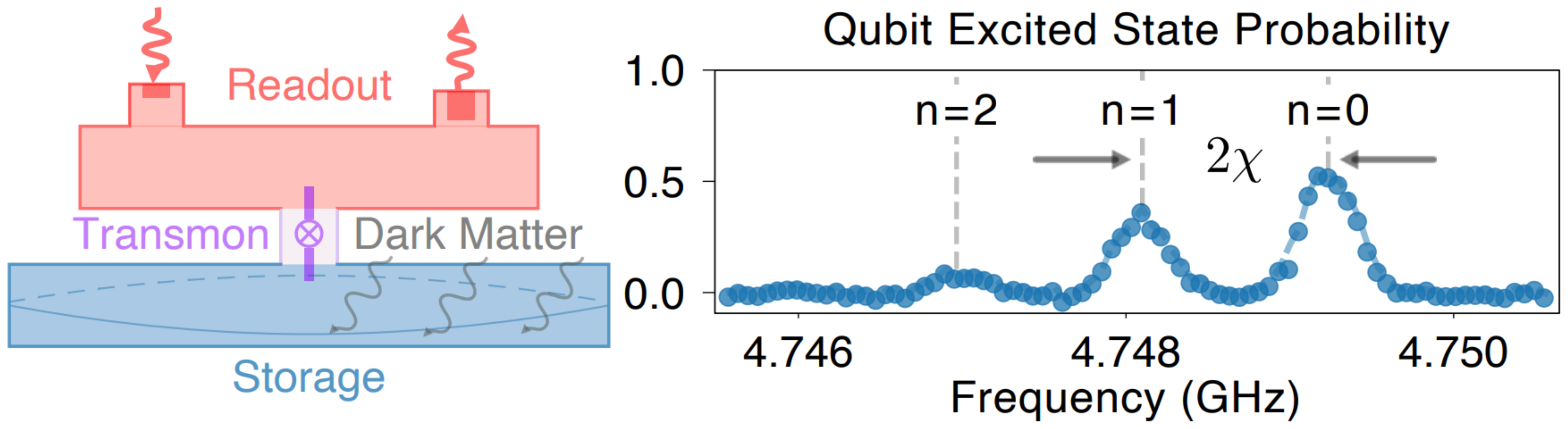


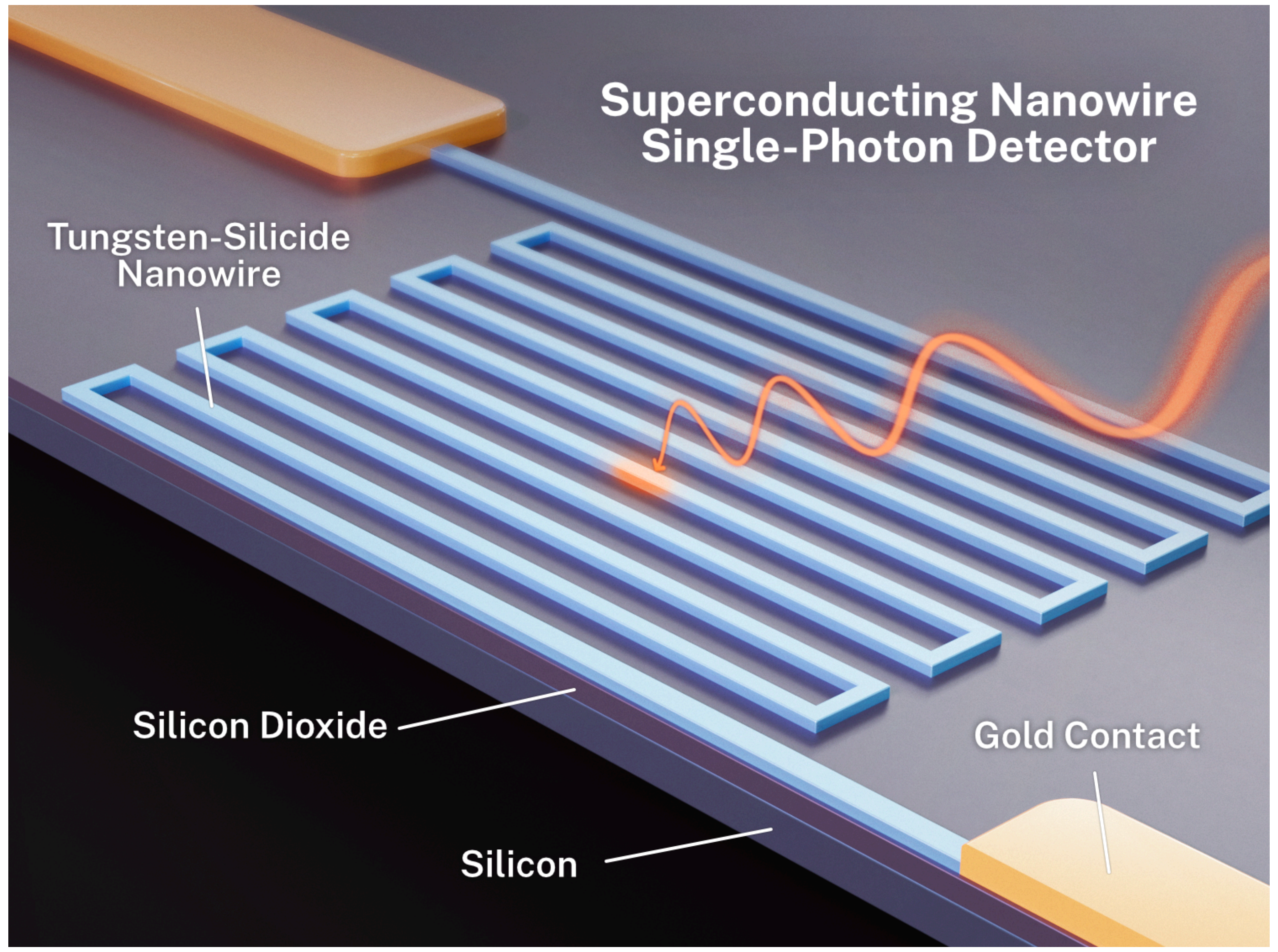
$$\text{Signal} \sim X\sin(\omega t) + Y\cos(\omega t) \quad \Delta X \Delta Y > \frac{1}{2}$$

Single photon sensors

e.g. Qubits [2008.12231]

SNSPDs [2111.12103]

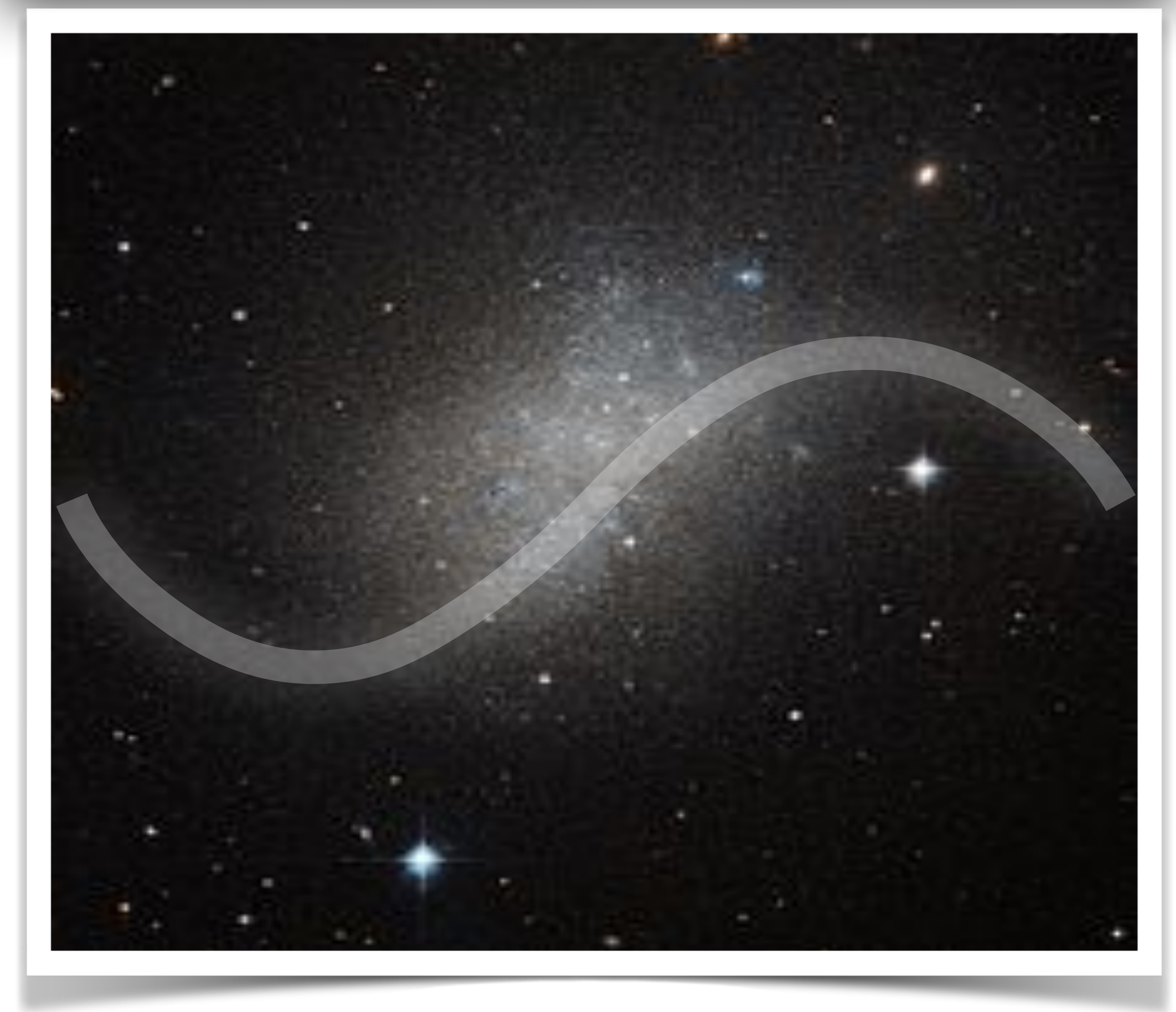




So far only discussed very light feebly interacting particles, what about more massive things?

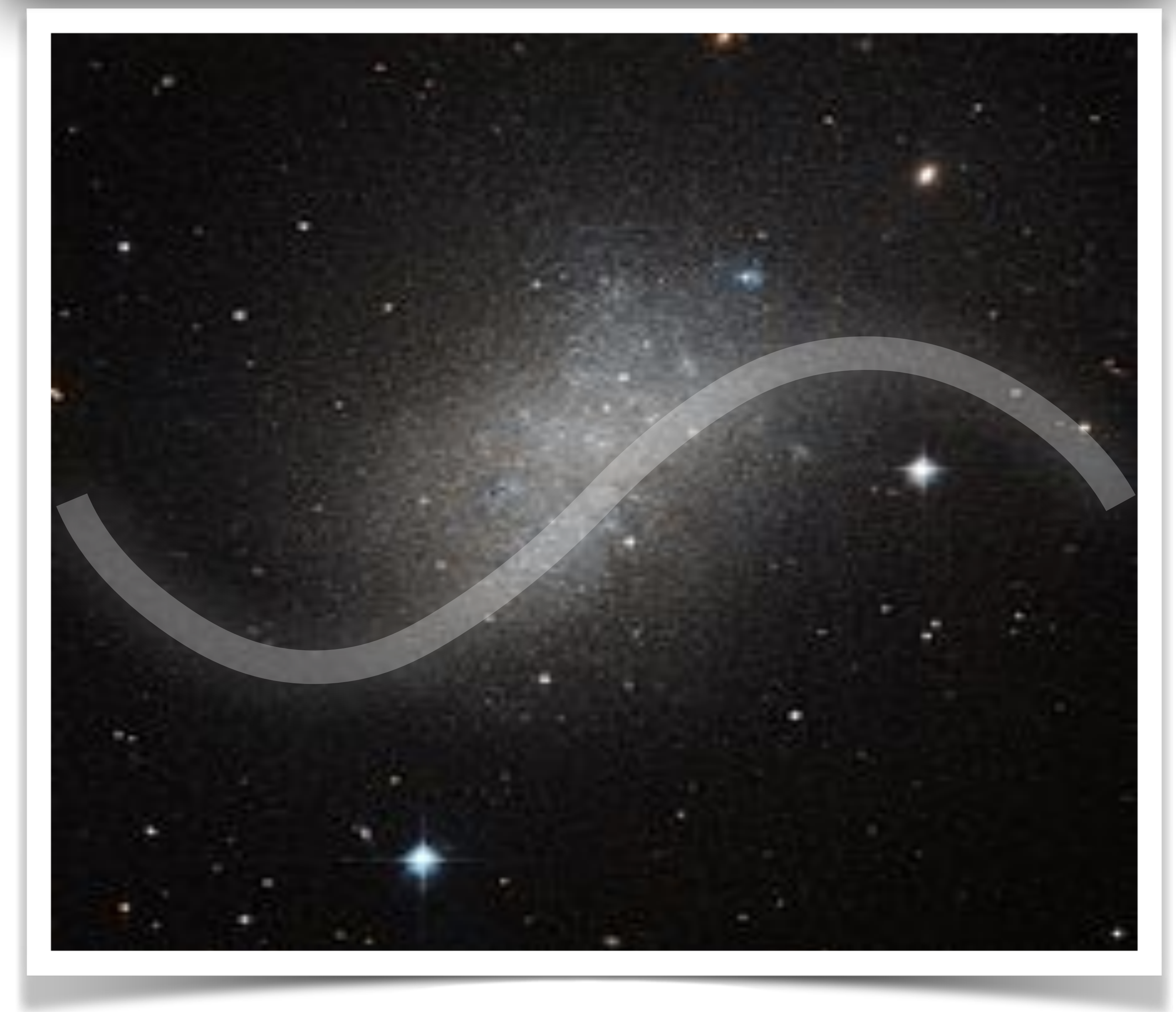

zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
kg
$M_\oplus$
$M_\odot$
$10^6\,M_\odot$

$m \gtrsim 10^{-21}$ eV
de Broglie wavelength must **fit inside** dwarf galaxies ~ 100 pc

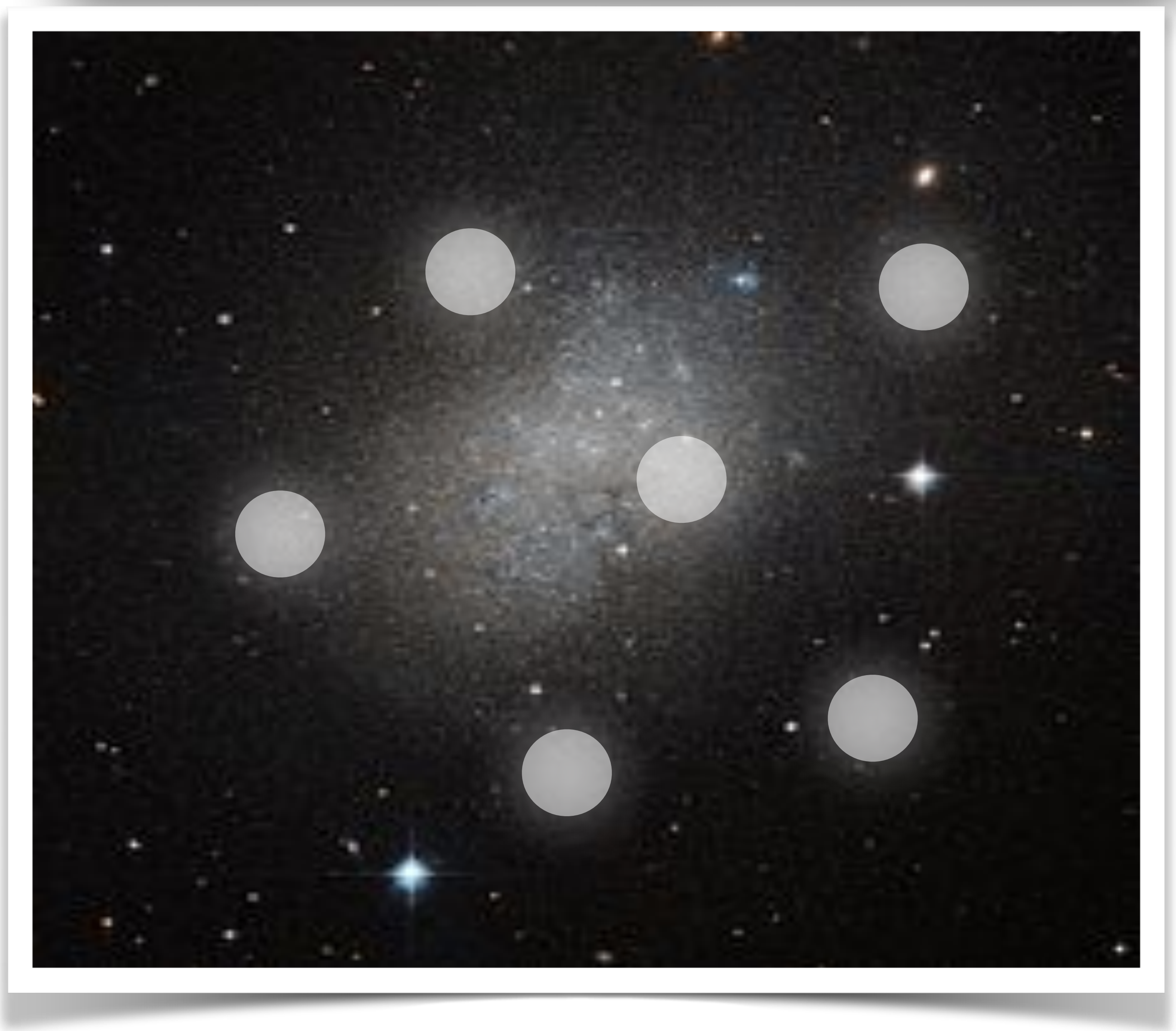



zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
kg
$M_\oplus$
$M_\odot$
$10^6\,M_\odot$
$m \gtrsim 10^{-21}$ eV
de Broglie wavelength must **fit**
inside dwarf galaxies ~ 100 pc
$m \lesssim 10^6 M_\odot$
Must **fill** dwarf galaxies

$m \gtrsim 10^{-21}$ eV
de Broglie wavelength must **fit inside** dwarf galaxies ~ 100 pc



$m \lesssim 10^6 M_\odot$
Must **fill** dwarf galaxies

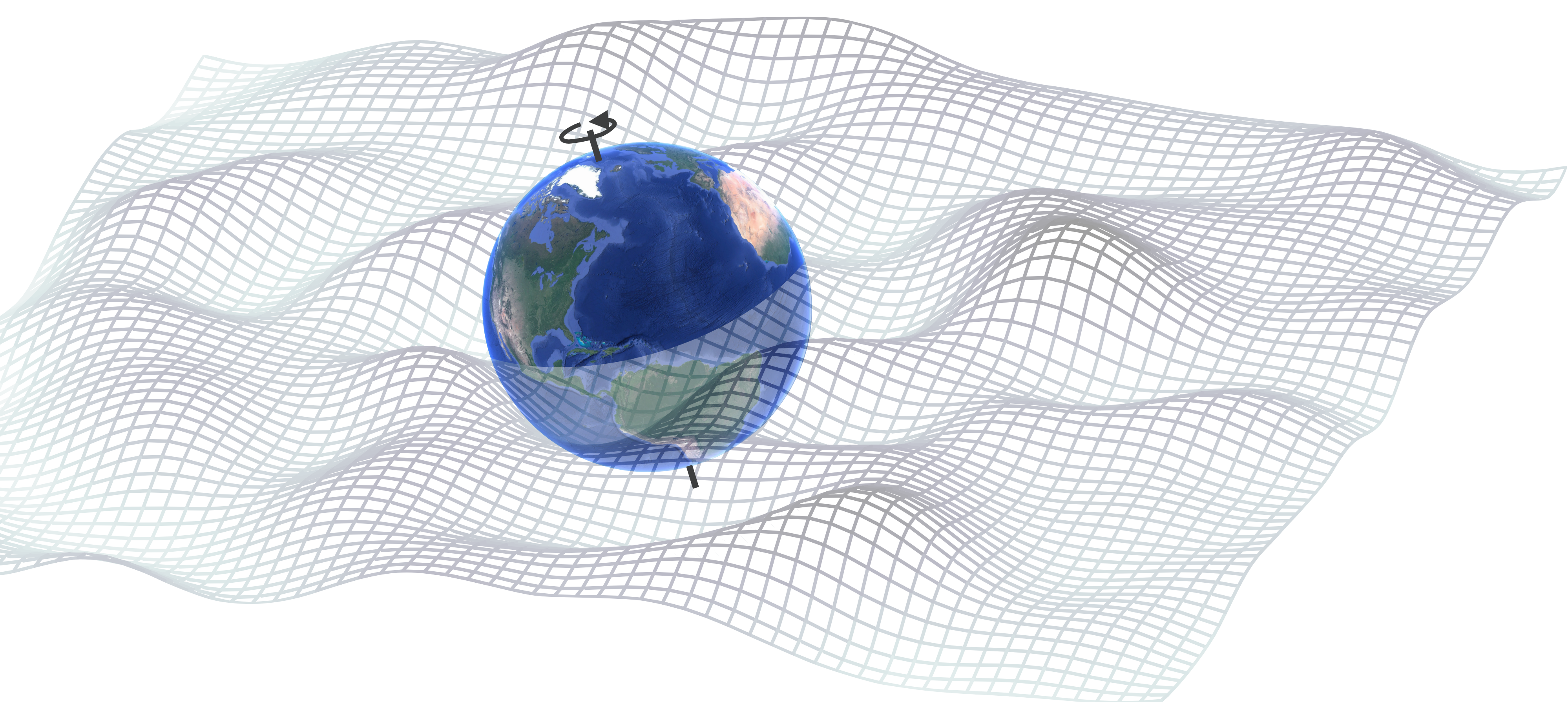


Possible mass range only bounded by ~75 orders of magnitude, but it's a start

Types of dark matter

Mass →

Wave-like (Must be bosonic)

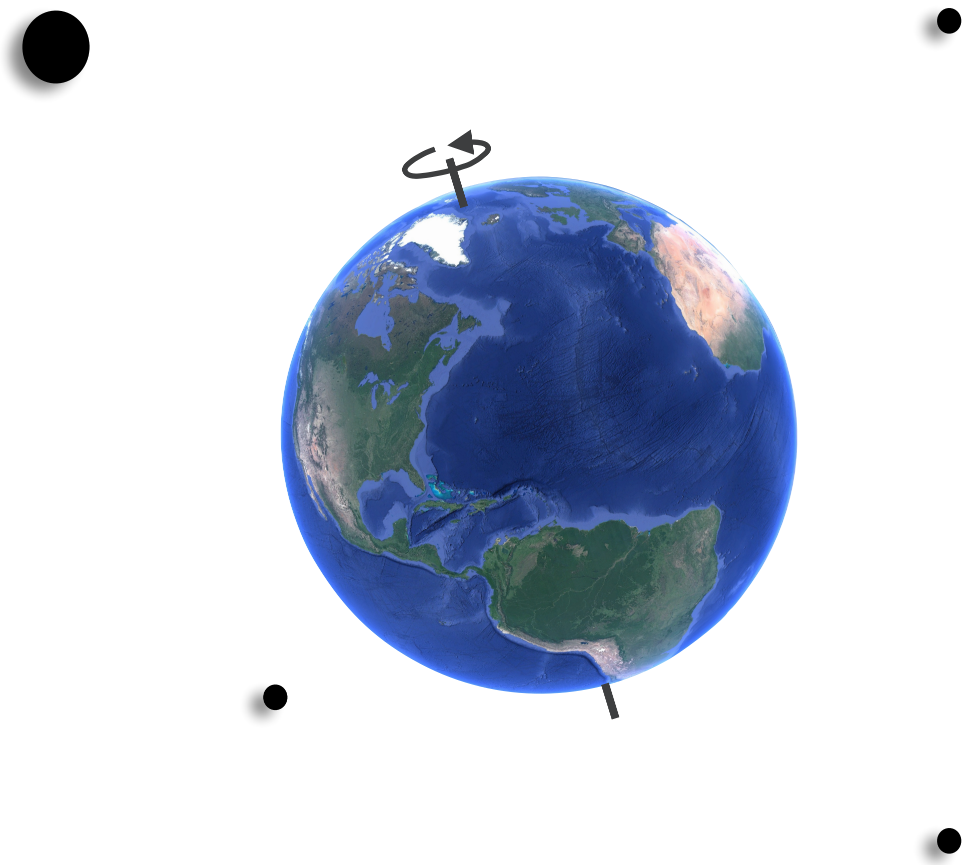


Continuously oscillating and fluctuating field that can couple to other fields (e.g. the electromagnetic one)

Particle-like

Discrete particles occasionally colliding with each other or other stuff

Object-like (e.g. black holes)

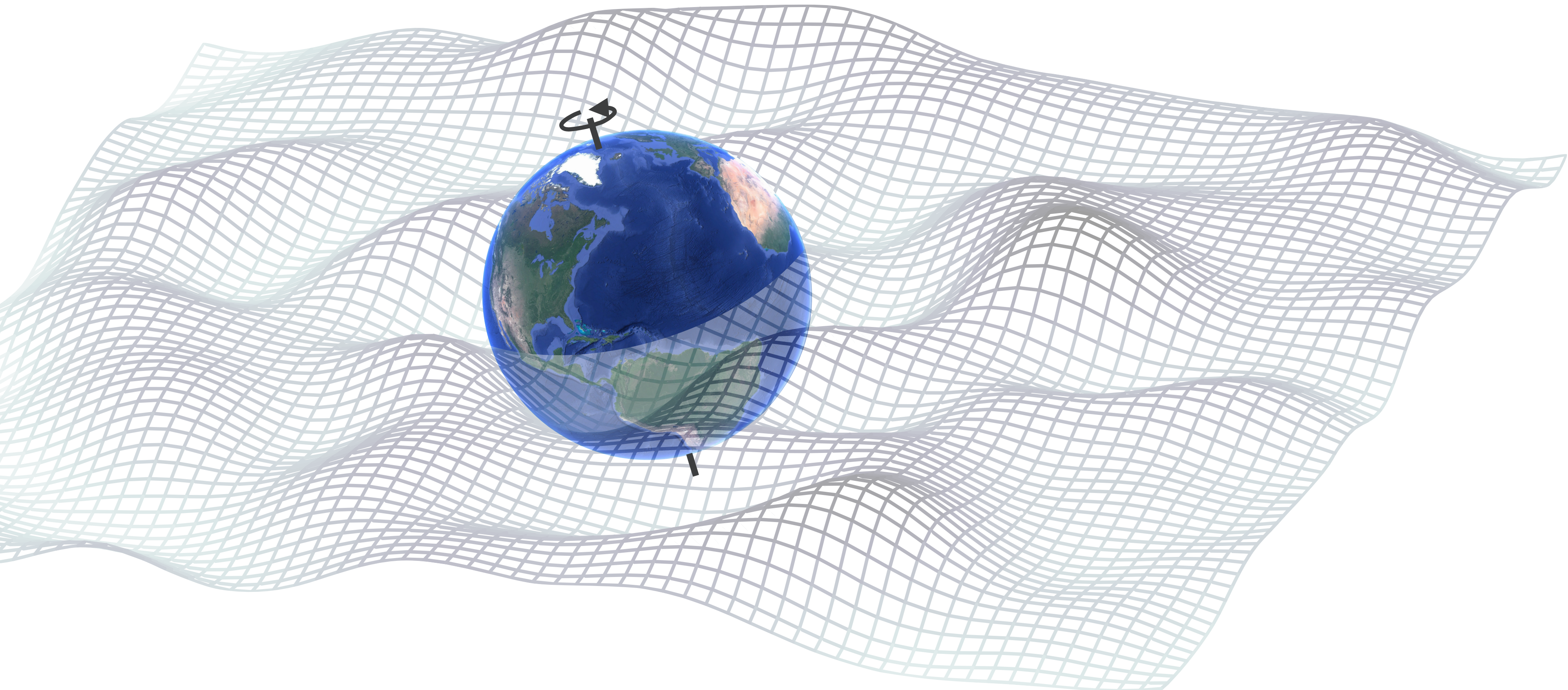


Very sparse population of heavy bodies exerting distant gravitational interactions

Types of dark matter

Mass →

Wave-like
(Must be bosonic)

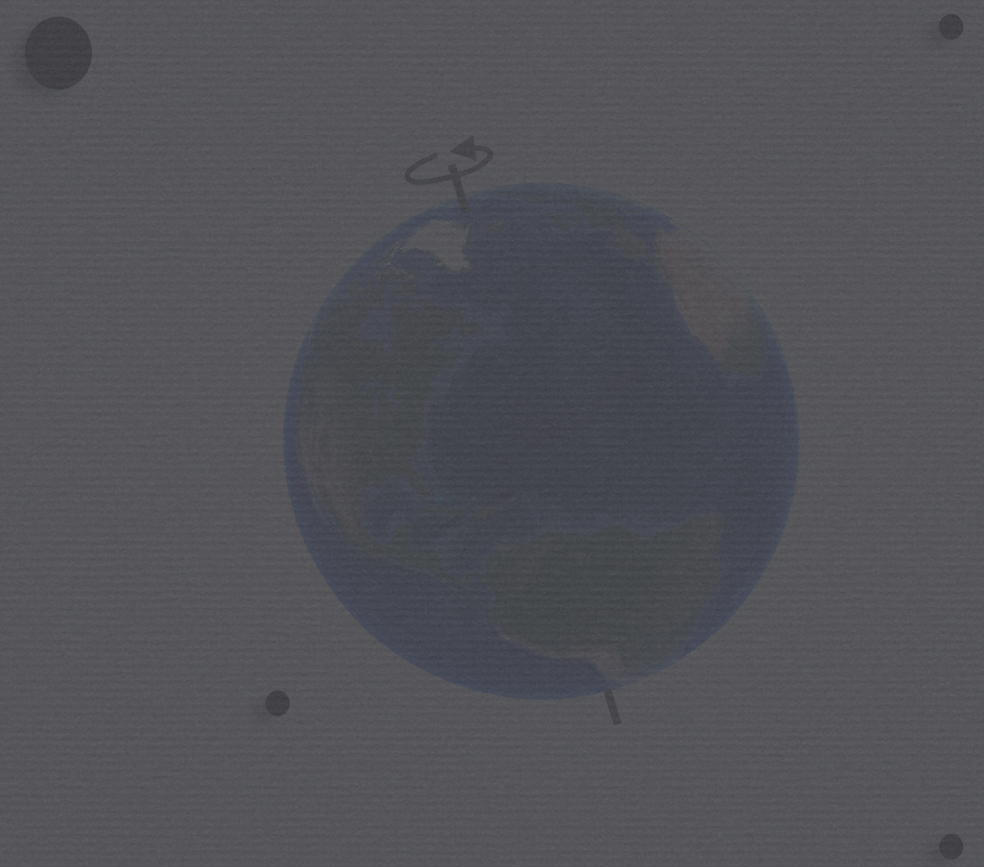


Continuously oscillating and fluctuating field that can couple to other fields (e.g. the electromagnetic one)

Particle-like

Discrete particles occasionally colliding with each other or other stuff

Object-like
(e.g. black holes)

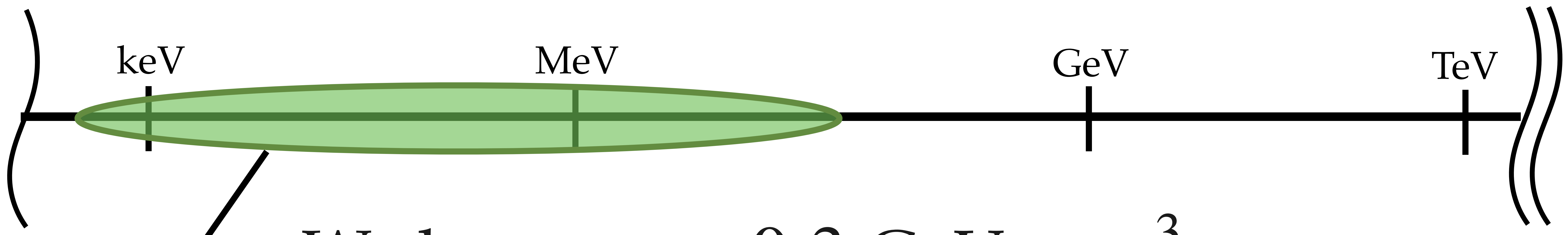


Very sparse population of heavy bodies exerting distant gravitational interactions

Particle-like dark matter

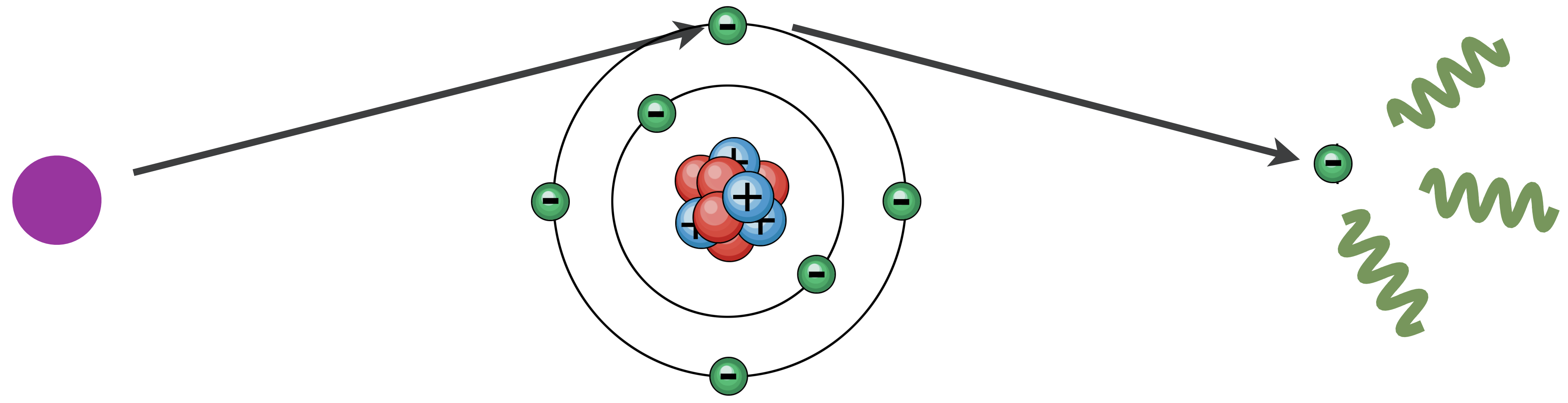
We know $\rho \sim 0.3$ GeV cm^{-3}
and $v \sim 300$ km/s
from astrophysics

Particle-like dark matter

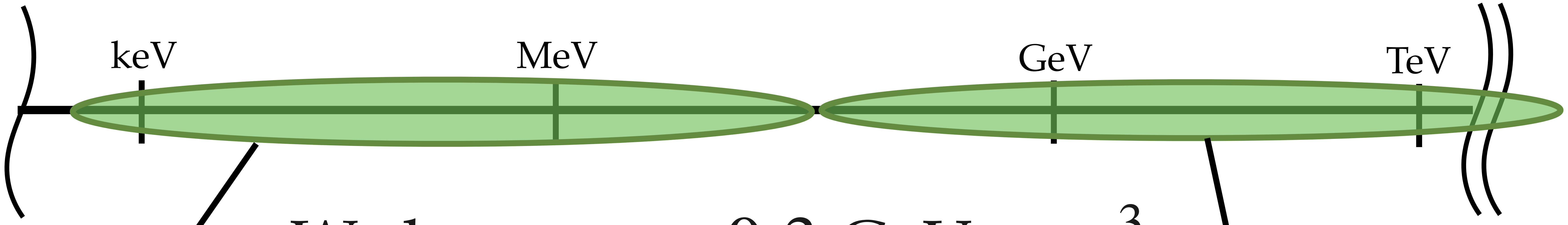


We know $\rho \sim 0.3 \text{ GeV cm}^{-3}$
and $v \sim 300 \text{ km/s}$
from astrophysics

High number density, but low energy deposits
→ **need to be sensitive to low-energy signals**

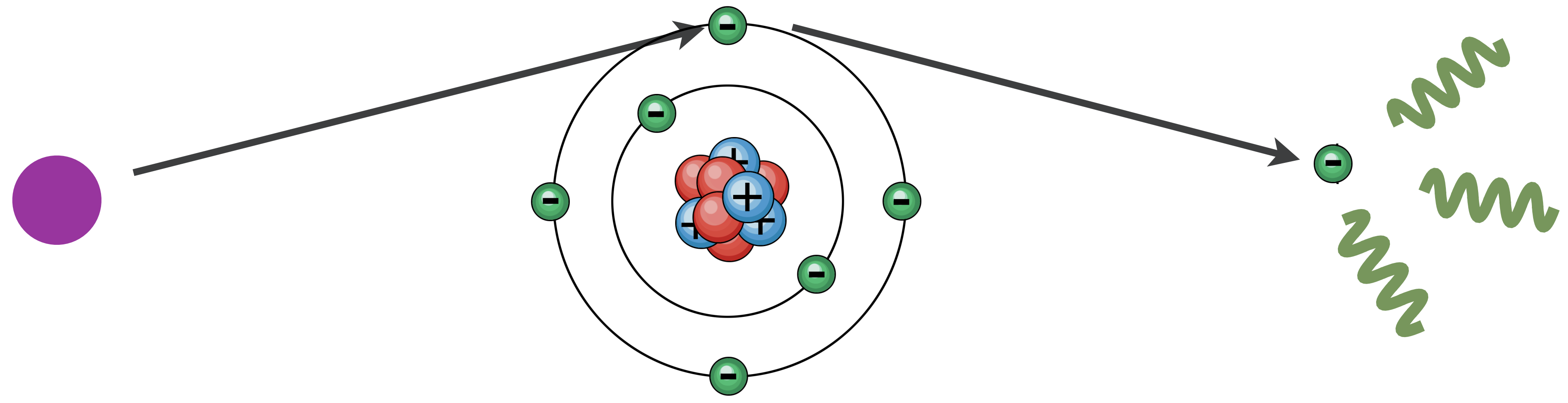


Particle-like dark matter

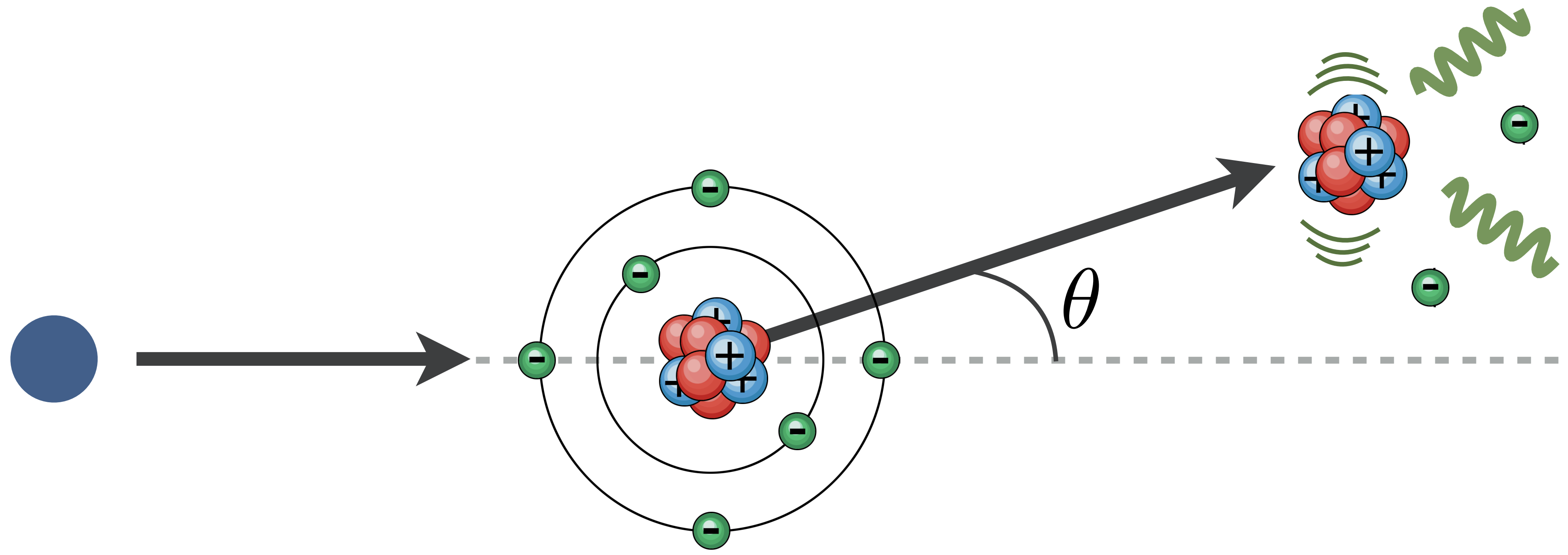


We know $\rho \sim 0.3$ GeV cm^{-3}
and $v \sim 300$ km/s
from astrophysics

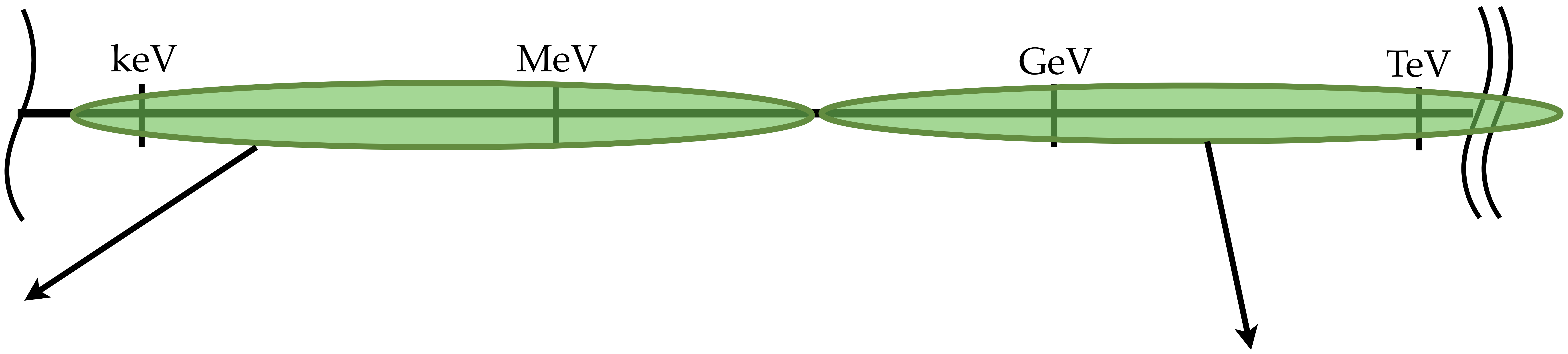
High number density, but low energy deposits
→ **need to be sensitive to low-energy signals**



Energetic recoils (>keV) but very low number density
→ **need to have huge detectors**



Particle-like dark matter



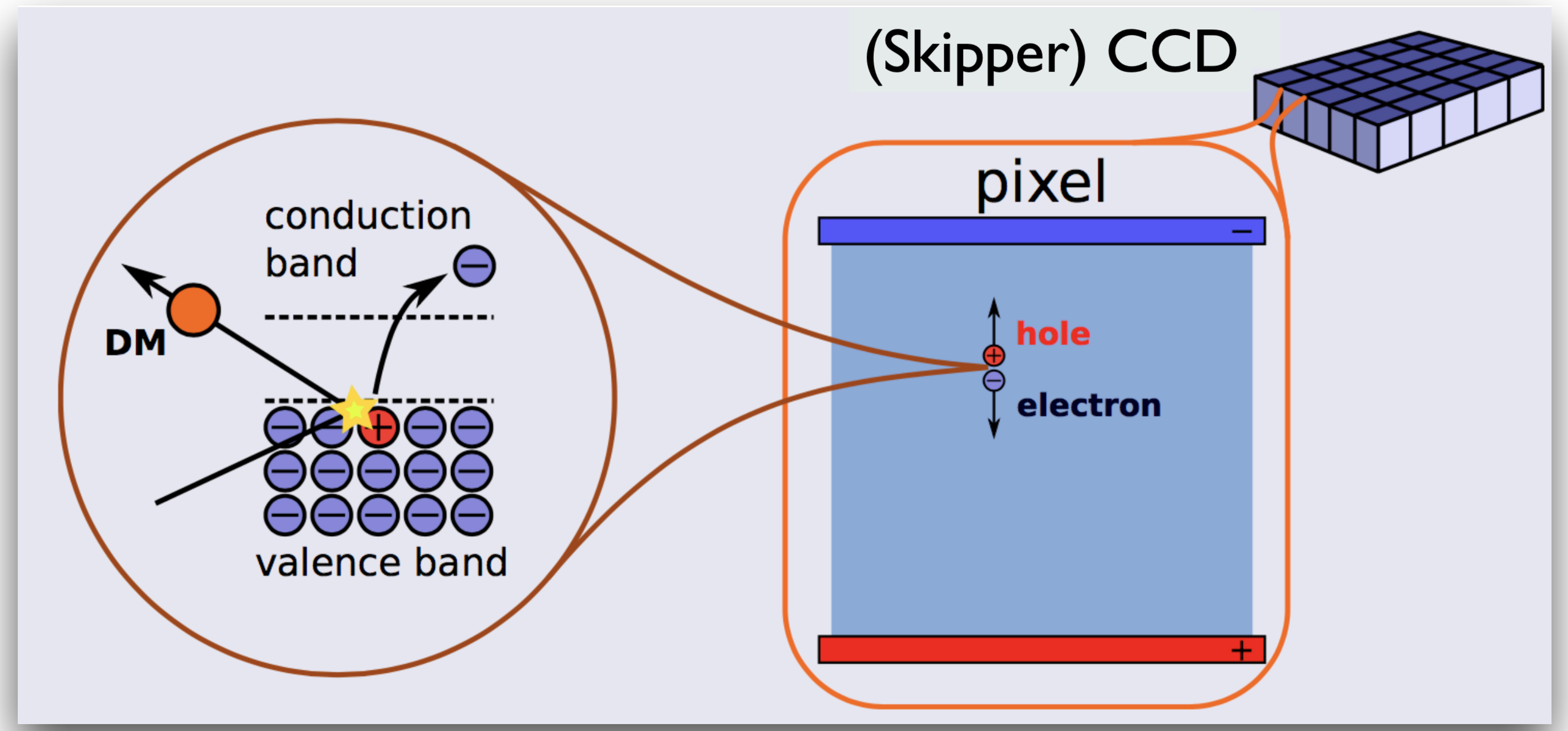
Emphasis on low-energy

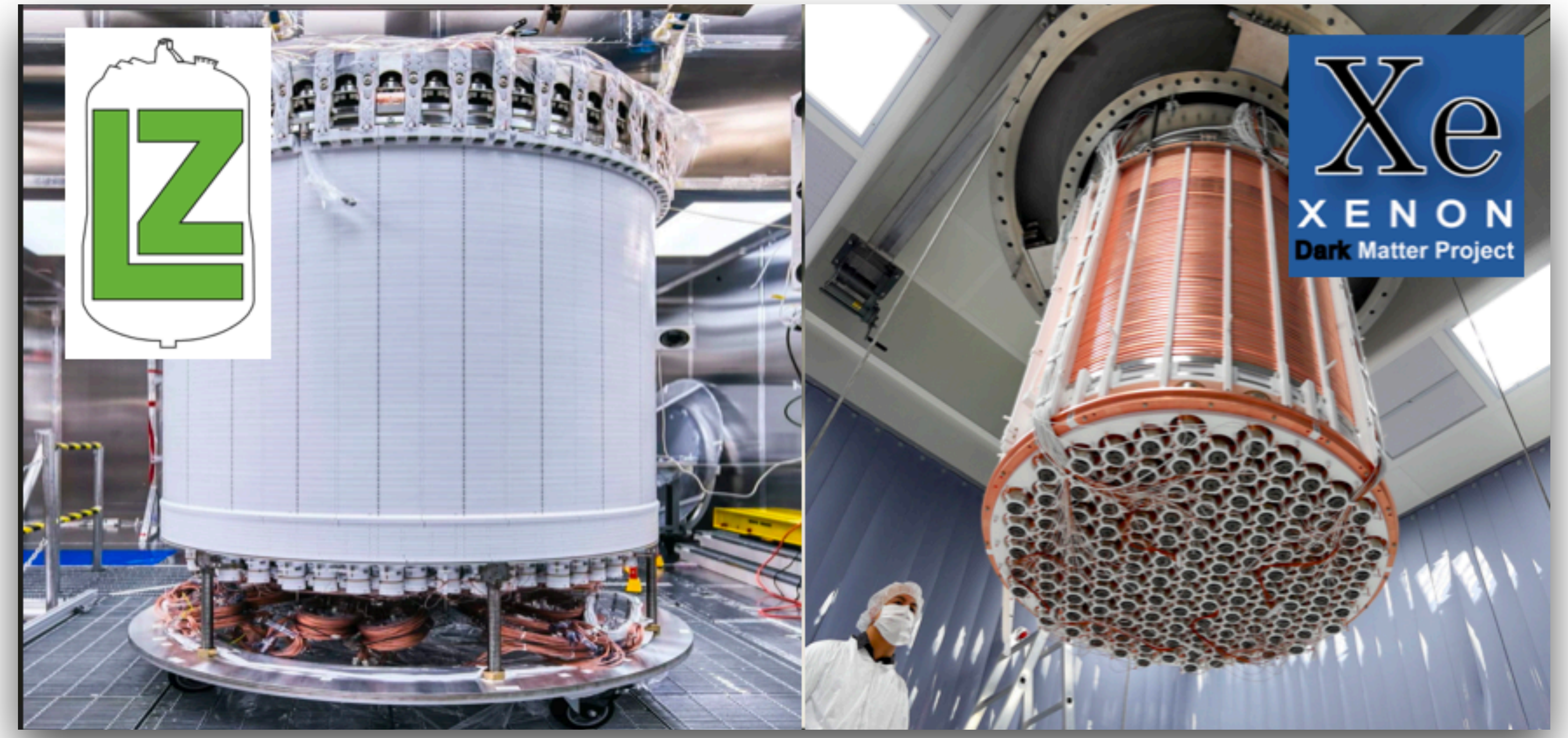
→ electronic recoils

→ collective excitations

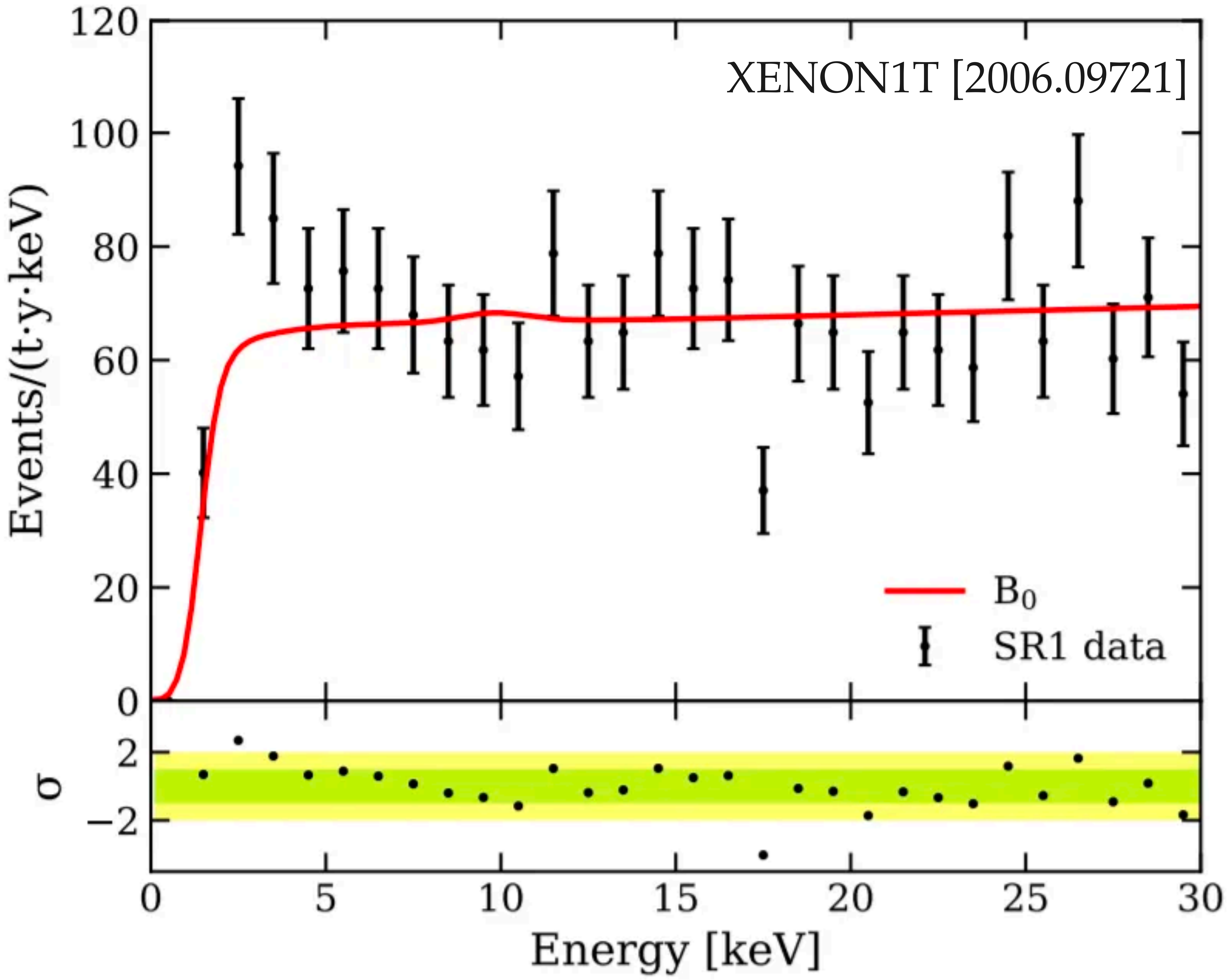
Emphasis on big

→ large detector bulk of heavy material

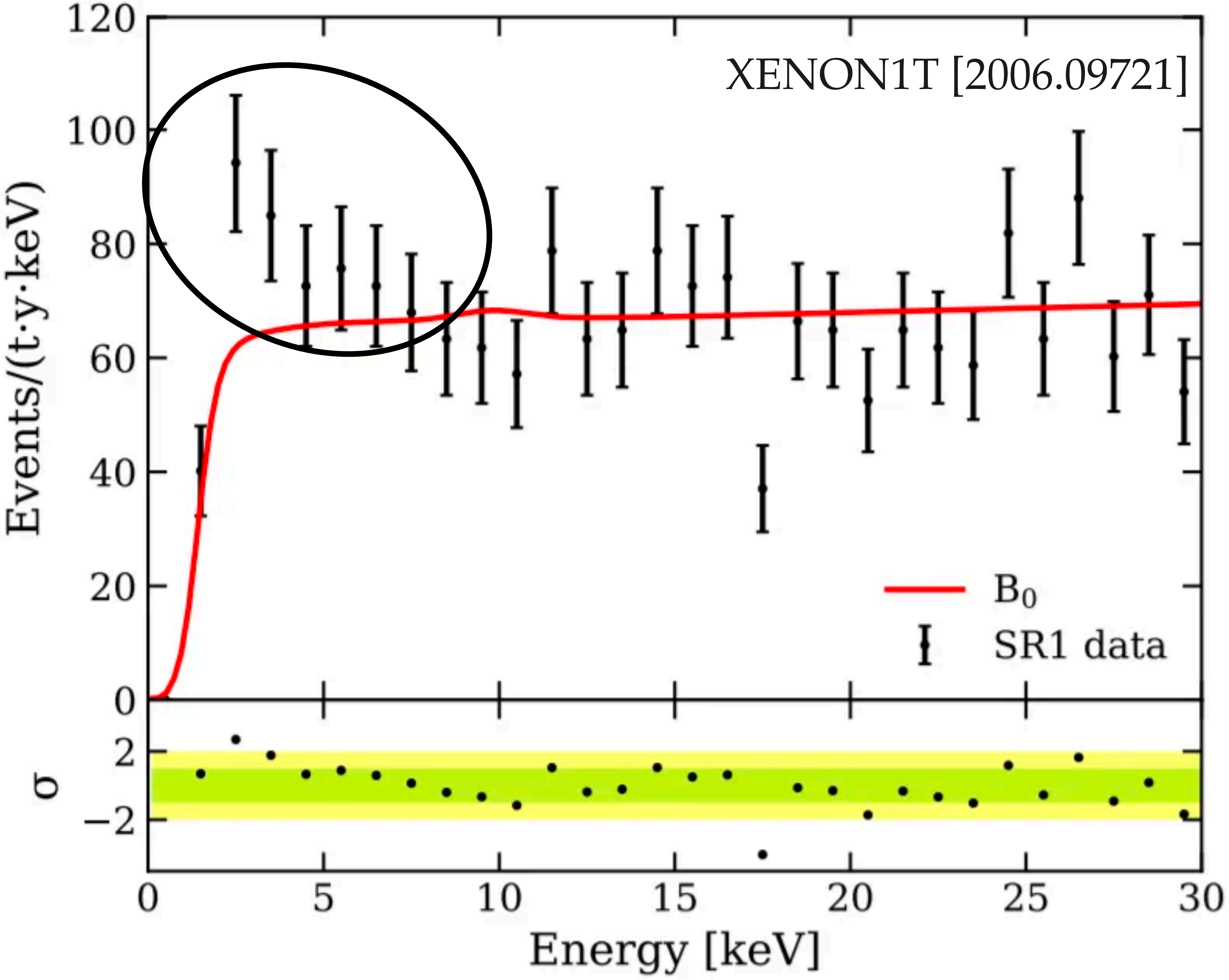




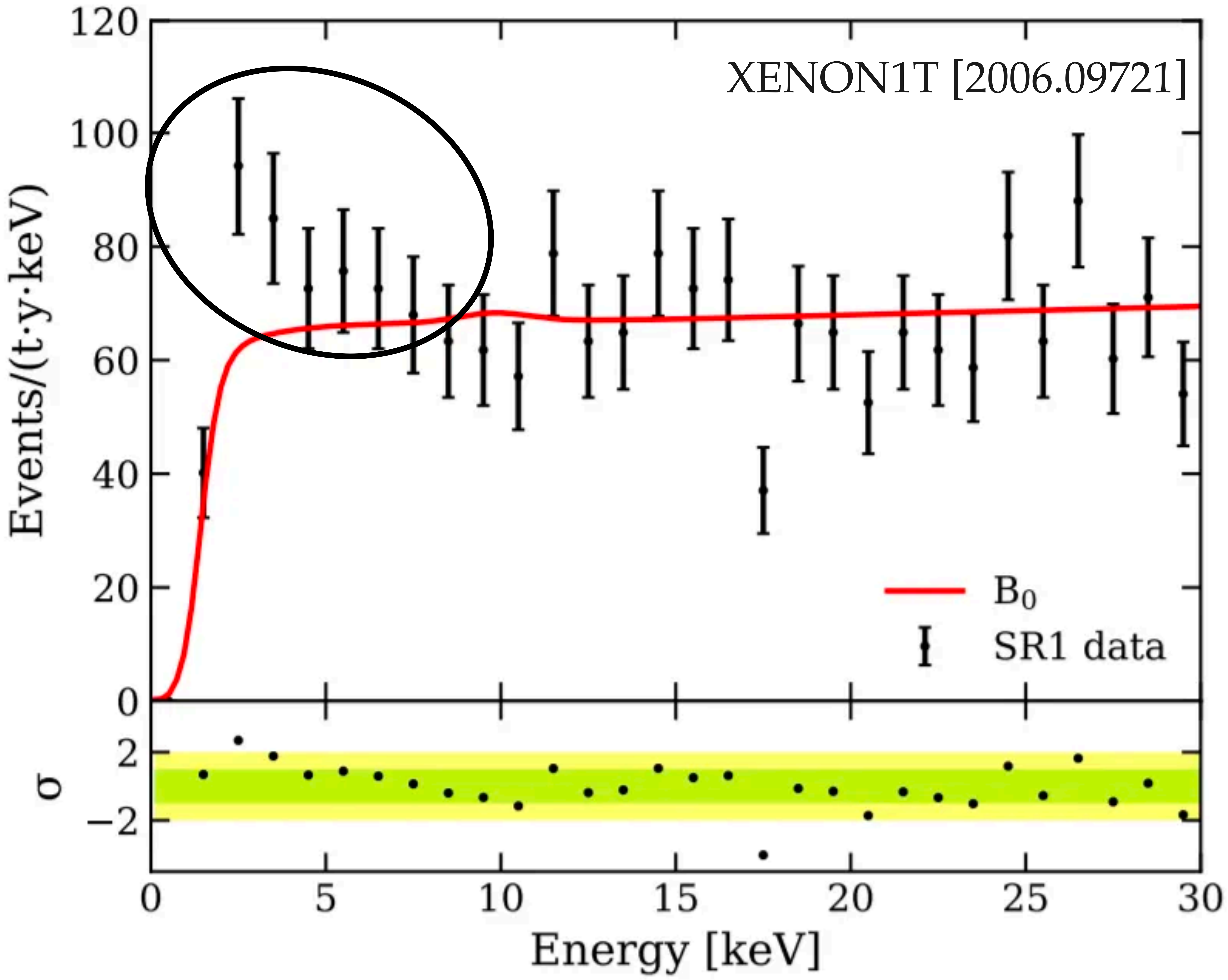
Is this what a "discovery" of dark matter could look like



Is this what a “discovery” of dark matter could look like



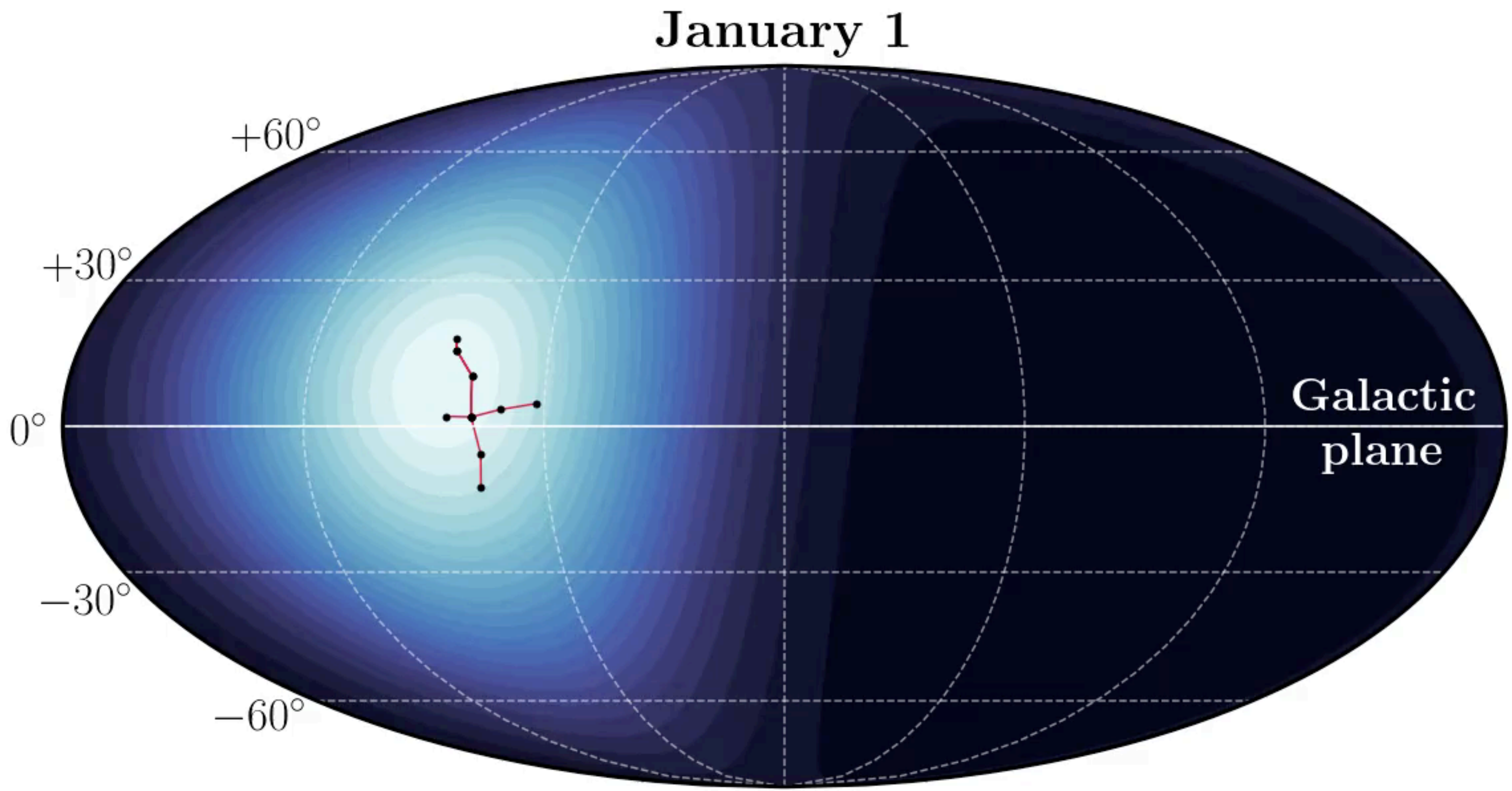
Is this what a “discovery” of dark matter could look like

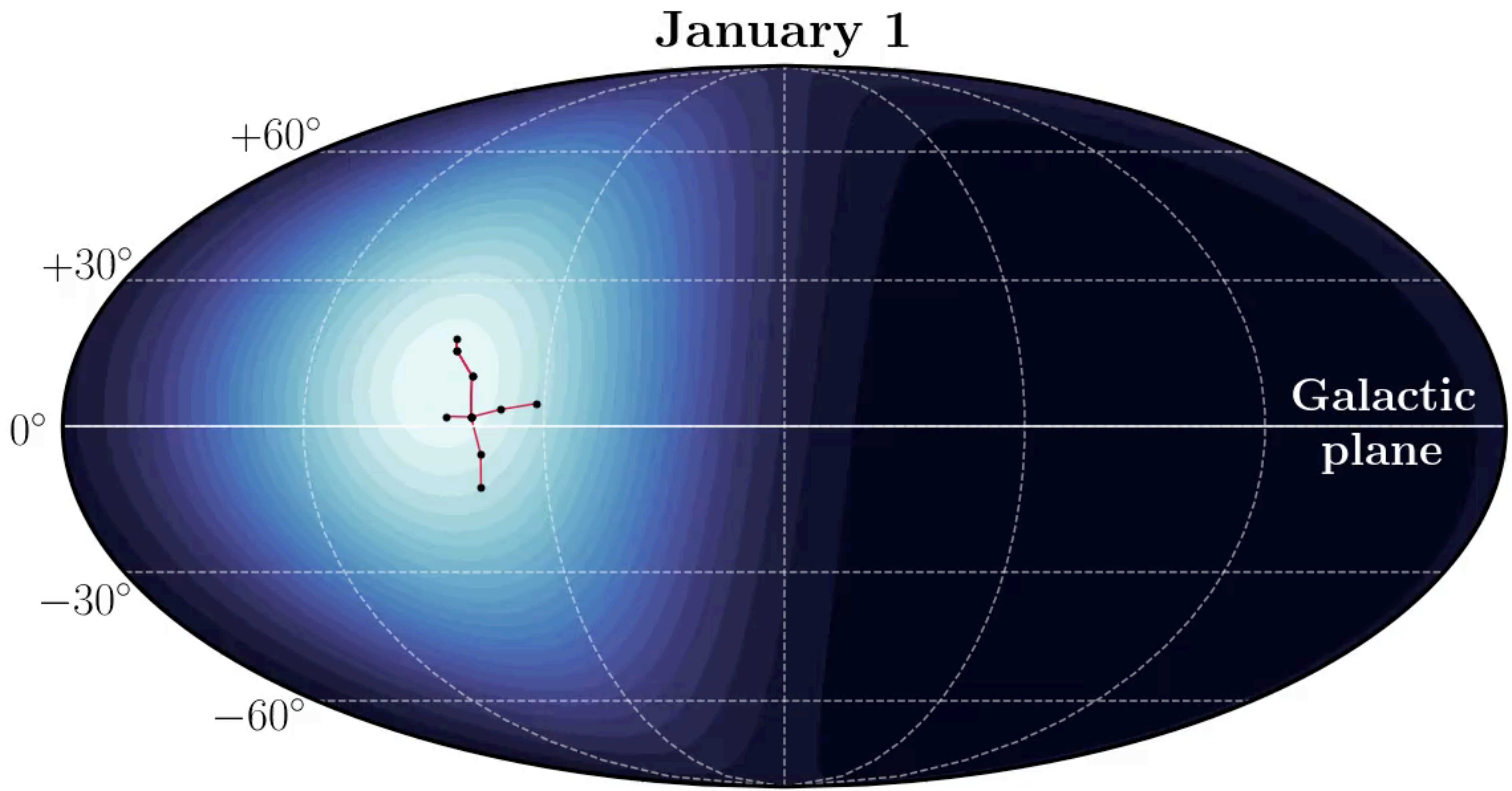


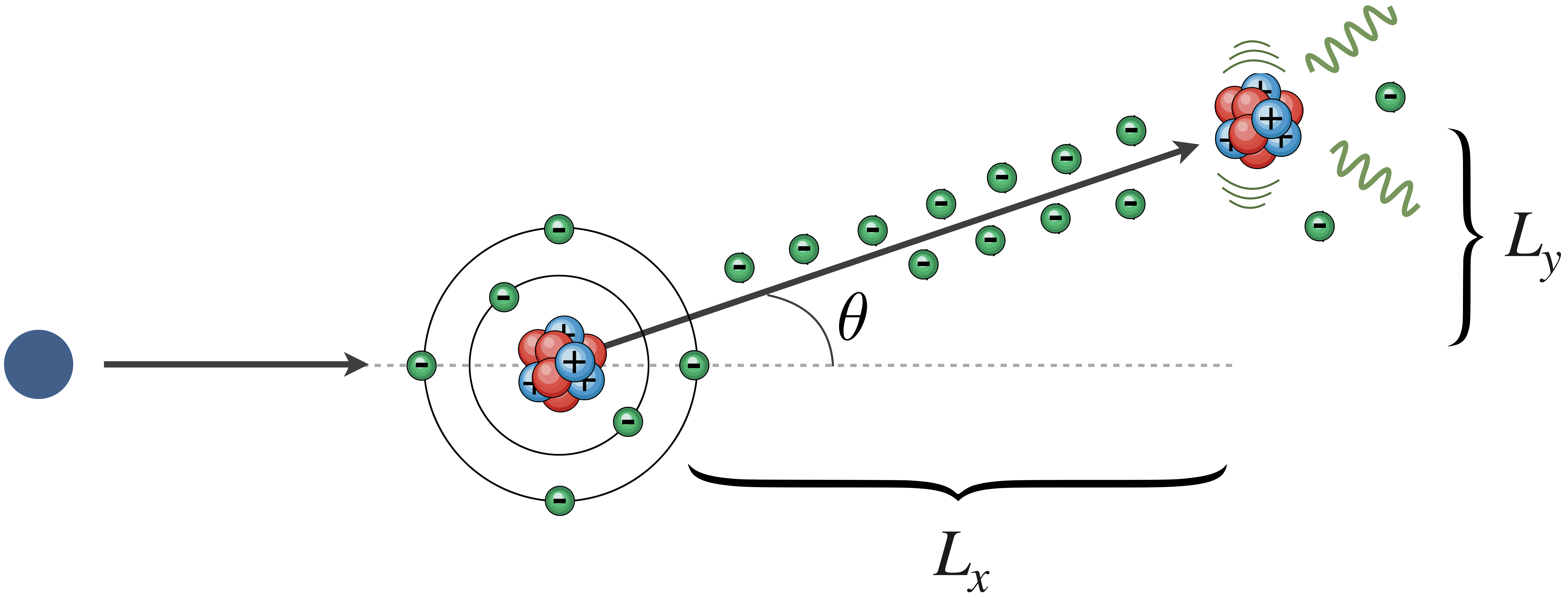
How do we make sure we can really discover DM interactions, and are not just on the road to seeing an anomaly we cannot explain?

Directional detection

Directional detection


January 1
+60°
+30°
0°
−30°
−60°
Galactic
plane


January 1
+60°
+30°
0°
−30°
−60°
Galactic
plane



θ
L_y
L_x

What material do you need to do directional detection of particle interactions?

Liquid → particle tracks typically shorter (~10-100 nm) than the diffusion scale in the detector so are washed out almost straight away

What material do you need to do directional detection of particle interactions?

Liquid → particle tracks typically shorter (~10-100 nm) than the diffusion scale in the detector so are washed out almost straight away

Gas → tracks typically longer than diffusion scale, so this can work as long you can image ionisation at a high-enough resolution

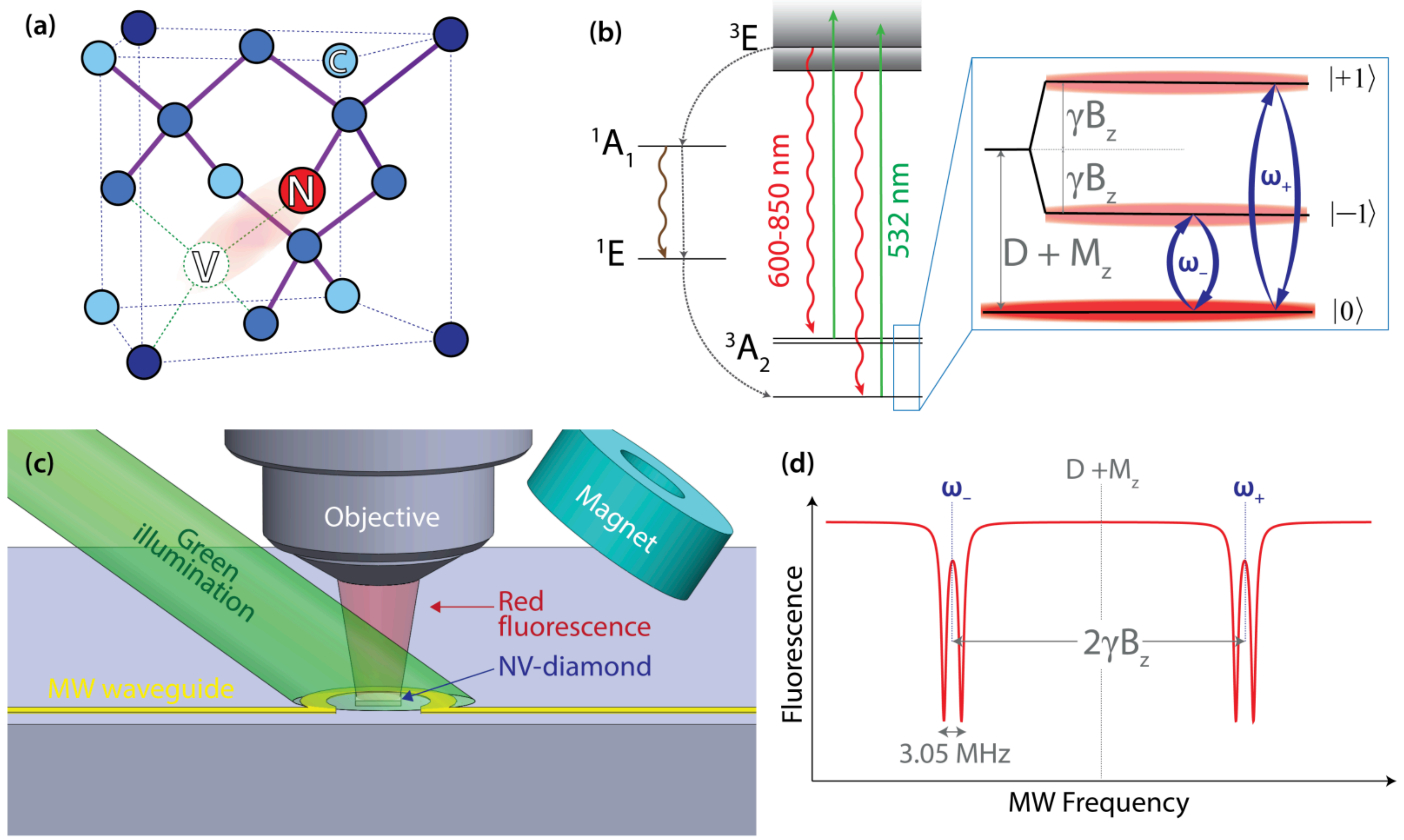
What material do you need to do directional detection of particle interactions?

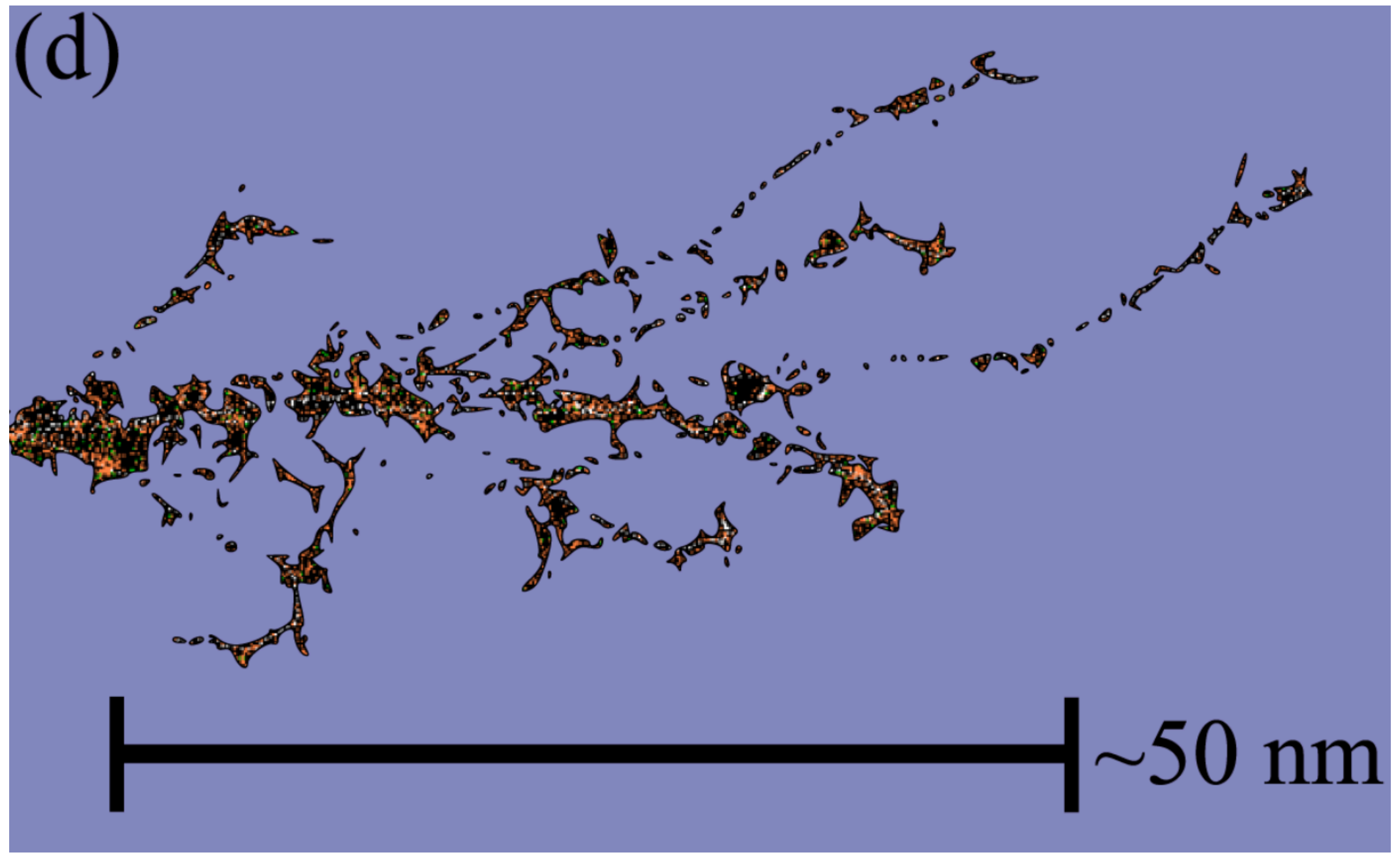
Liquid → particle tracks typically shorter (~10-100 nm) than the diffusion scale in the detector so are washed out almost straight away

Gas → tracks typically longer than diffusion scale, so this can work as long you can image ionisation at a high-enough resolution

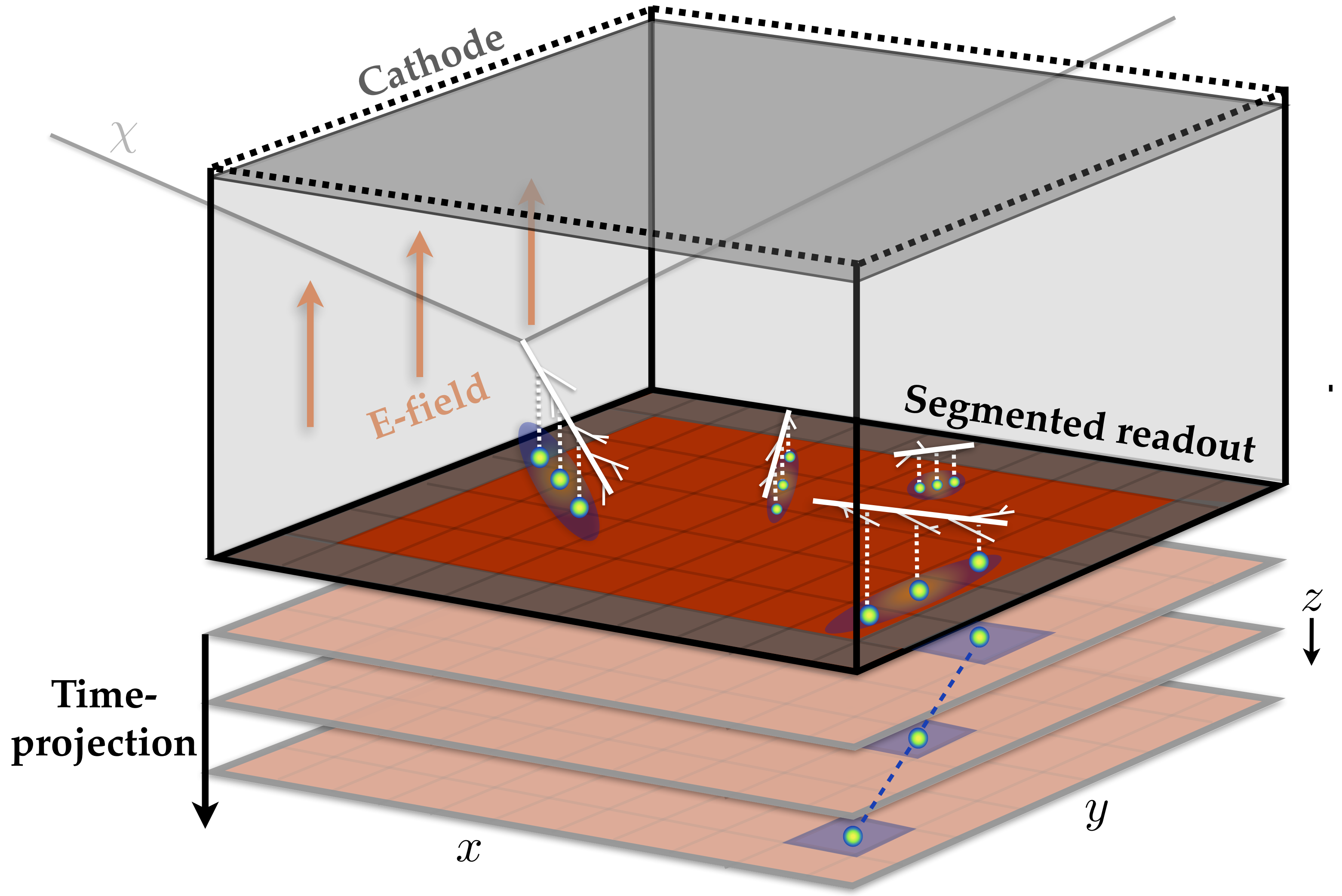
Solid → tracks tiny (~nm) in size but do not diffuse. Can work as long as you can do nanoscale imaging of the interior of a solid material

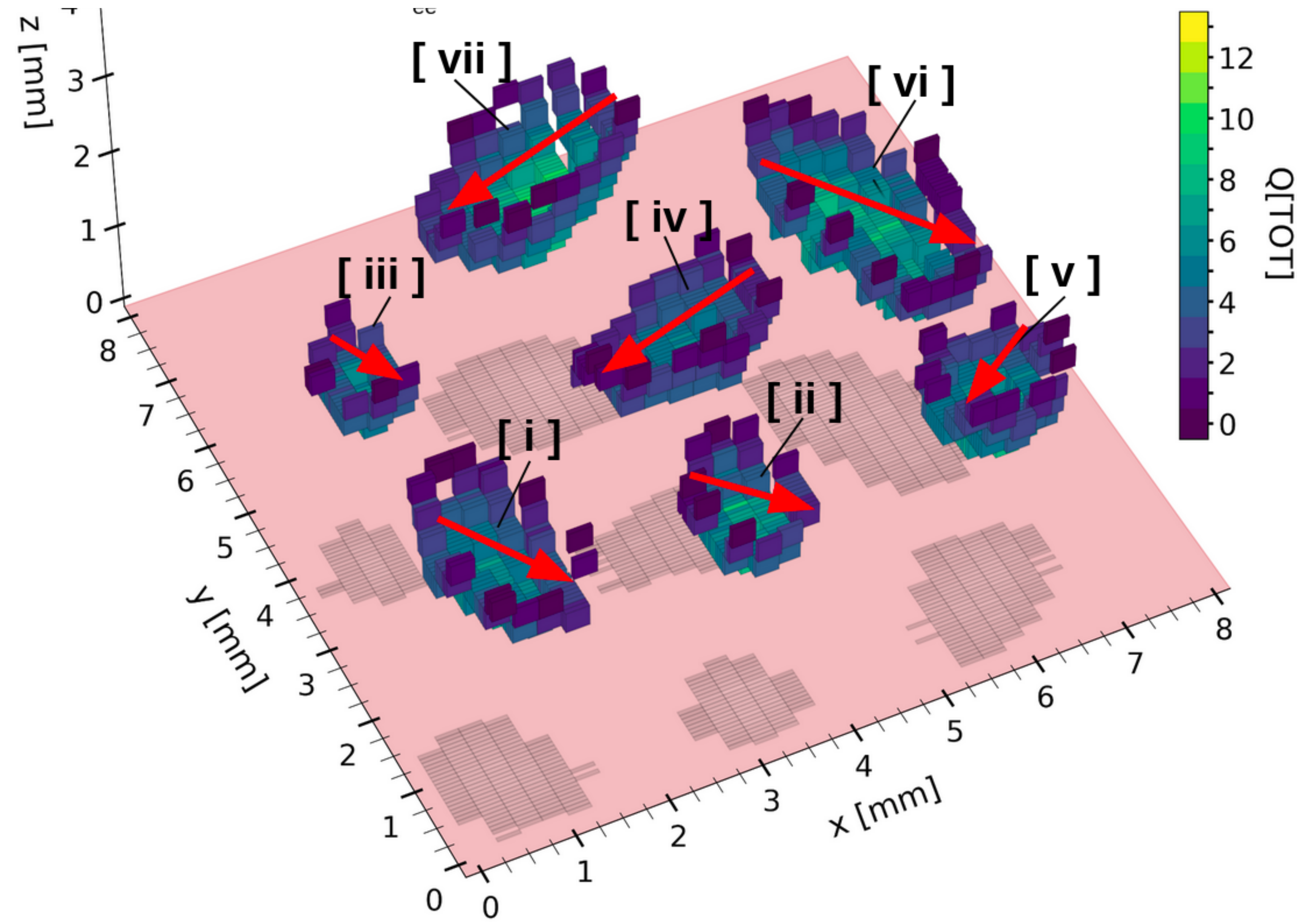
Directionality in solids
2203.06037





Directionality in gases
2102.04596





What material do you need to do directional detection of particle interactions?

Liquid → particle tracks typically shorter (~10 nm) than the diffusion scale in the detector (micron) so are washed out almost straight away

Gas → tracks typically longer than diffusion scale, works as long as you don't allow them to diffuse much and can image ionisation at a high-enough resolution

Solid → tracks ~nm in size but do not diffuse. Can work as long as you can do nanoscale imaging of the interior of a solid material

What material do you need to do directional detection of particle interactions?

Liquid → particle tracks typically shorter (~10 nm) than the diffusion scale in the detector (micron) so are washed out almost straight away

Gas → tracks typically longer than diffusion scale, works as long as you don't allow them to diffuse much and can image ionisation at a high-enough resolution

Solid → tracks ~nm in size but do not diffuse. Can work as long as you can do nanoscale imaging of the interior of a solid material

Nanoscale information storage?

DNA detector?

2105.11949

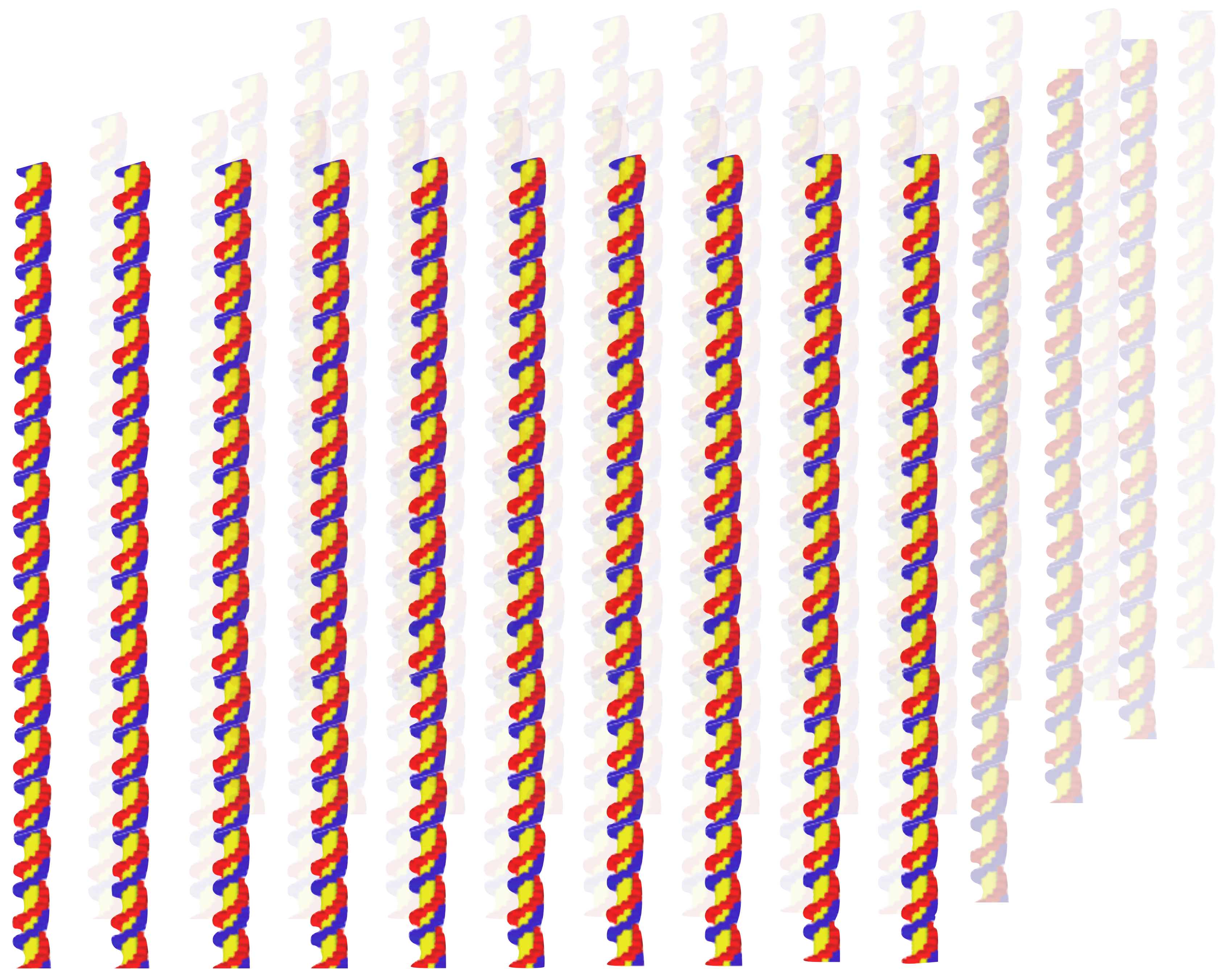
Particle detection and tracking with DNA

Ciaran A. J. O'Hare,[1,2,*] Vassili G. Matsos,[2] Joseph Newton,[2] Karl Smith,[2] Joel Hochstetter,[2] Ravi Jaiswar,[2] Wunna Kyaw,[3] Aimee McNamara,[4] Zdenka Kuncic,[2] Sushma Nagaraja Grellscheid,[5] and Céline Bœhm[1,2]

[1]*ARC Centre of Excellence for Dark Matter Particle Physics, The University of Sydney, NSW, Australia*
[2]*School of Physics, Physics Road, The University of Sydney, NSW 2006 Camperdown, Sydney, Australia*
[3]*Garvan Institute of Medical Research, NSW 2010, Darlinghurst, Australia*
[4]*Department of Radiation Oncology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA*
[5]*Computational Biology Unit, Department of Biological Sciences,*
University of Bergen, Thormohlensgt 55, Bergen N-5008, Norway

DNA-based particle detector?

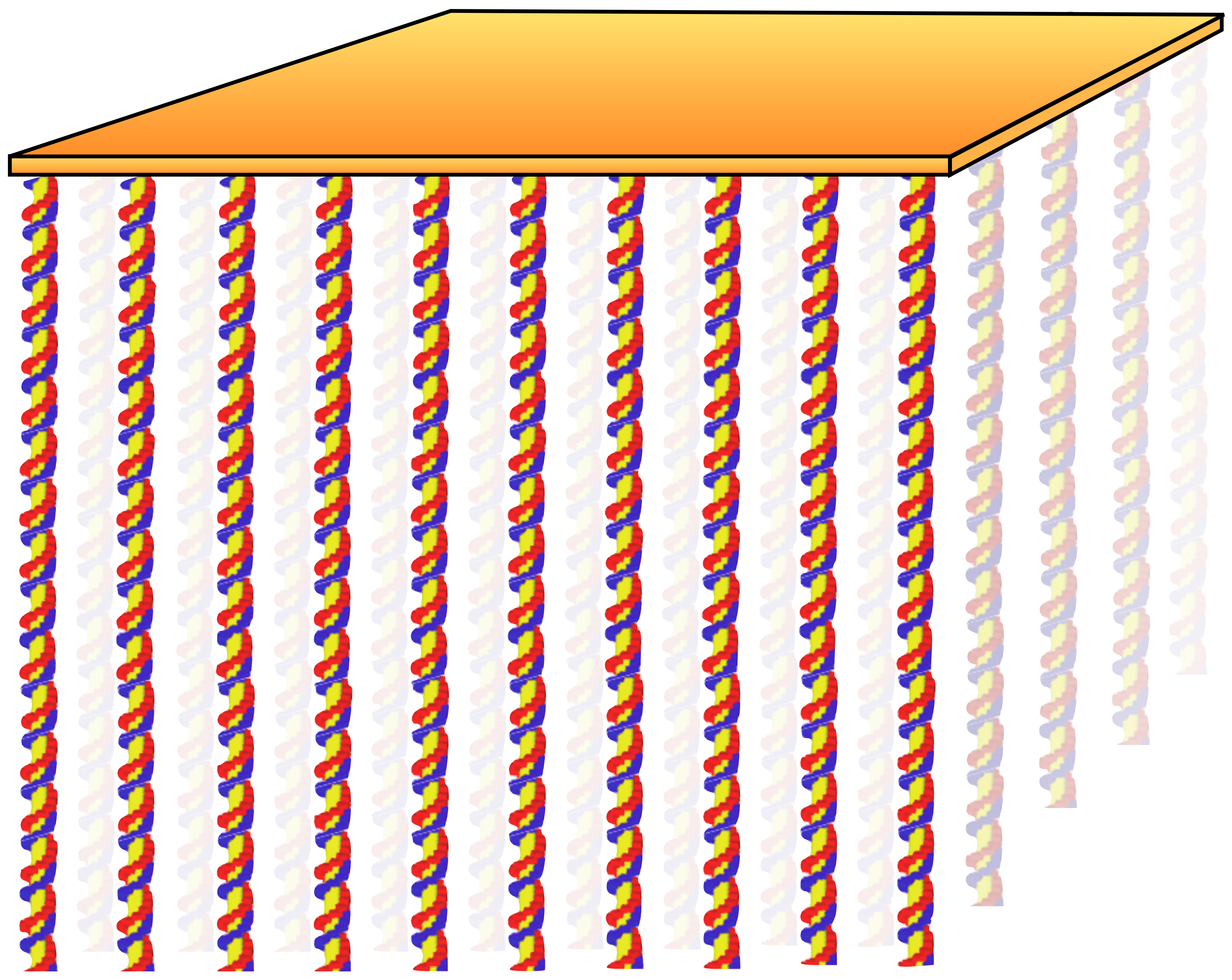
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases



DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

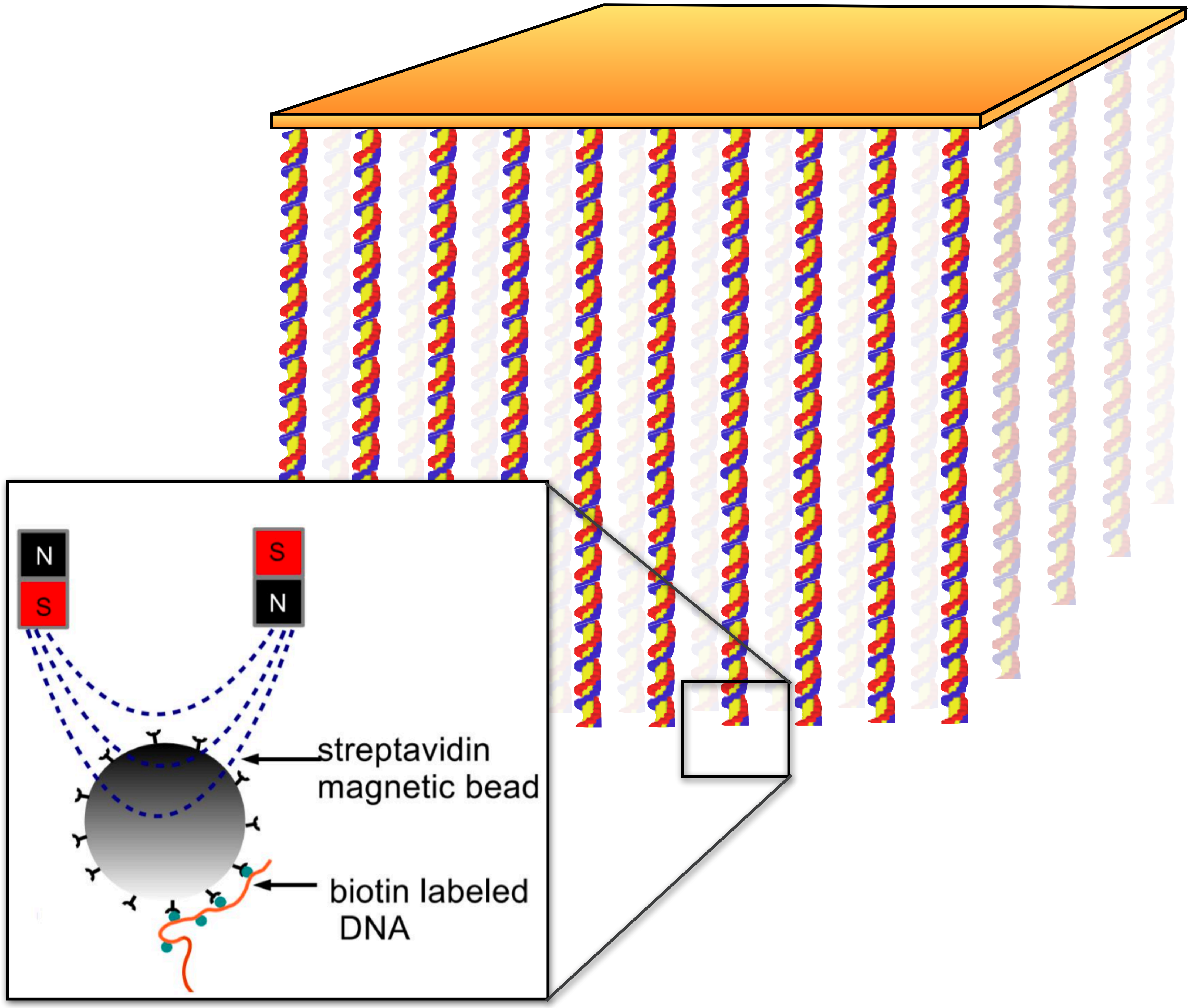


DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand



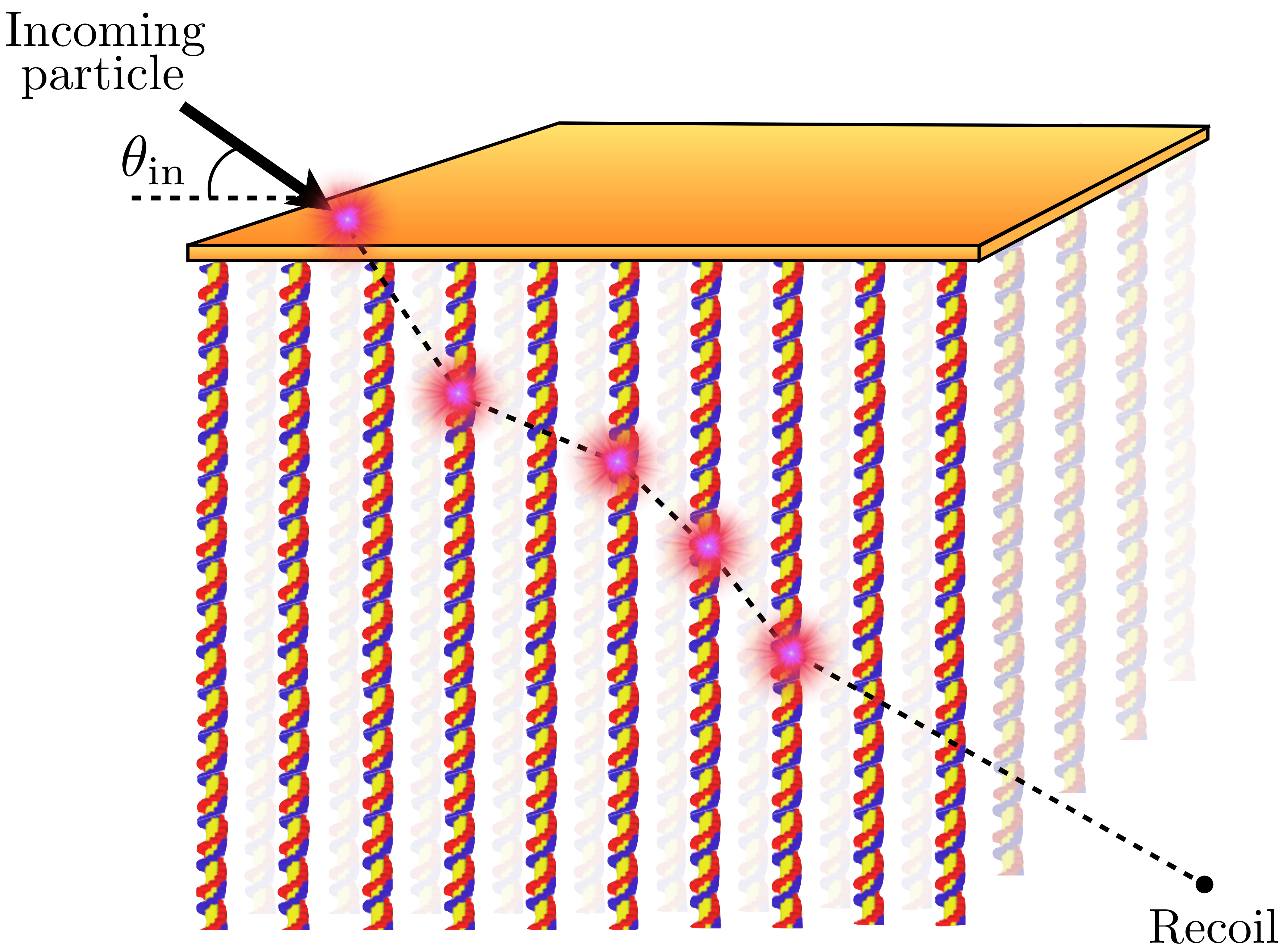
DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand

Step 4: Particles come in and break a sequence of bases



DNA-based particle detector?

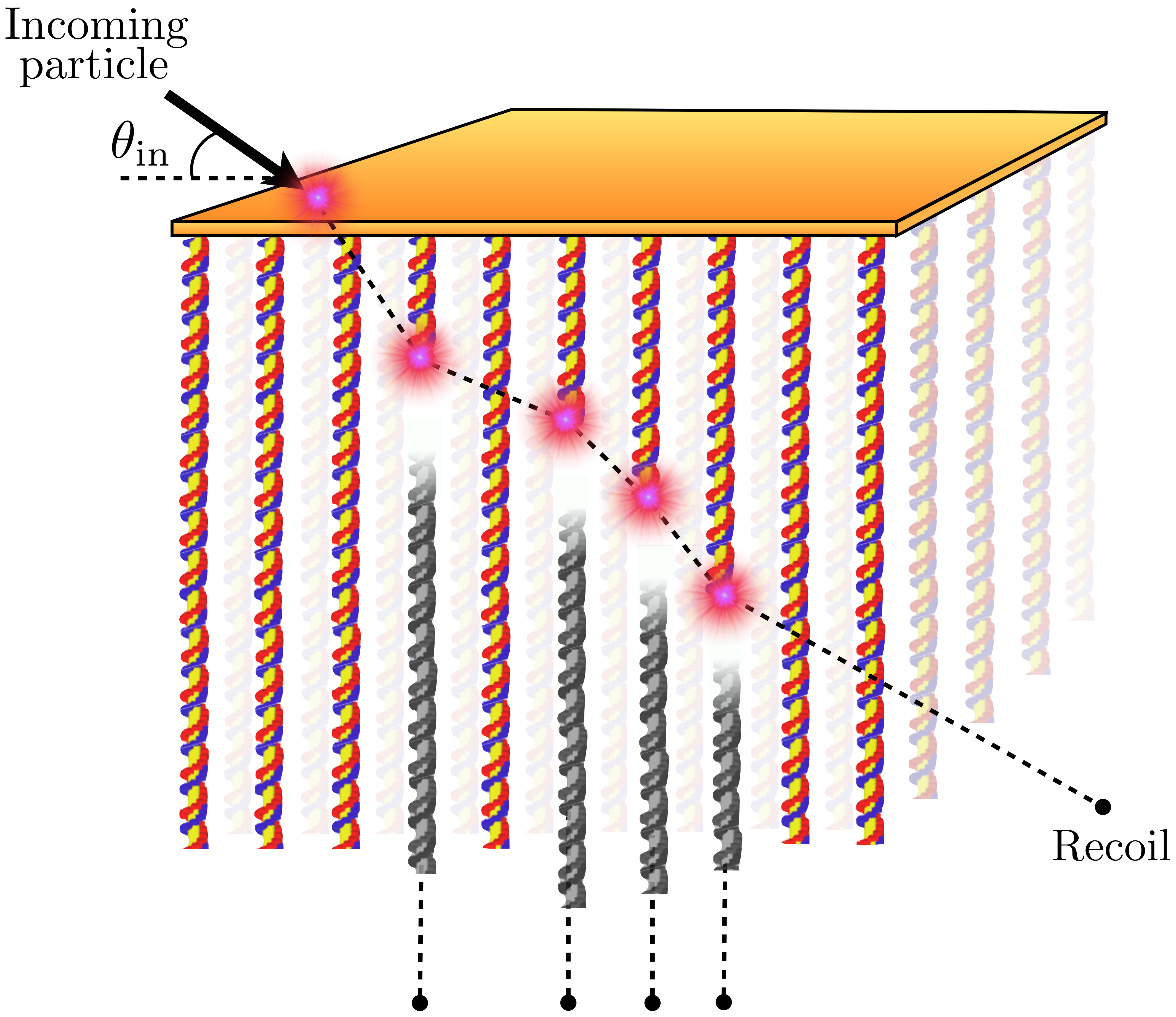
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand

Step 4: Particles come in and break a sequence of bases

Step 5: Broken strand segments fall down



DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

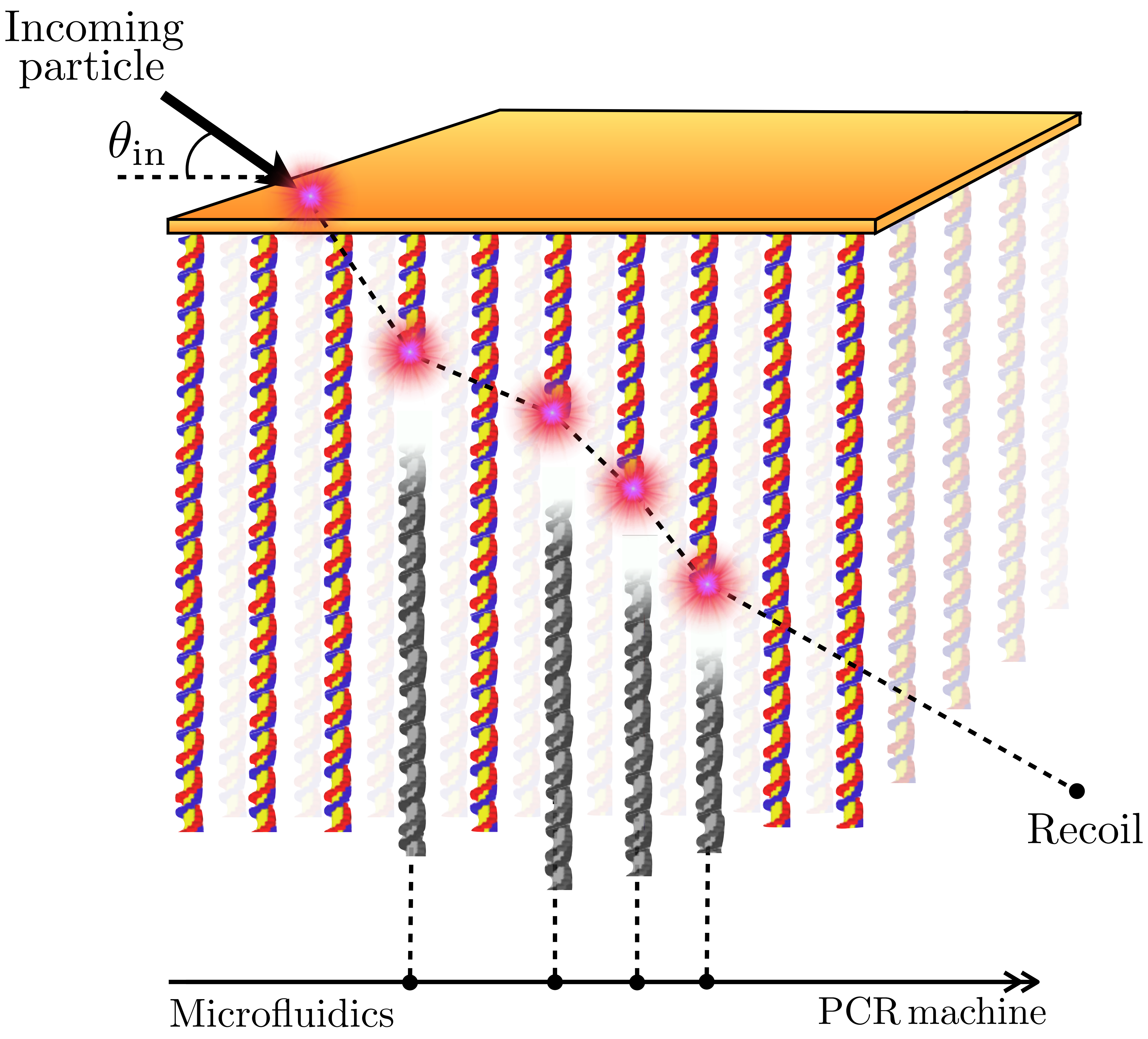
Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand

Step 4: Particles come in and break a sequence of bases

Step 5: Broken strand segments fall down

Step 6: System of microfluidics transports the strand segments to a PCR machine which amplifies them and the original (x,y,z) positions are reconstructed

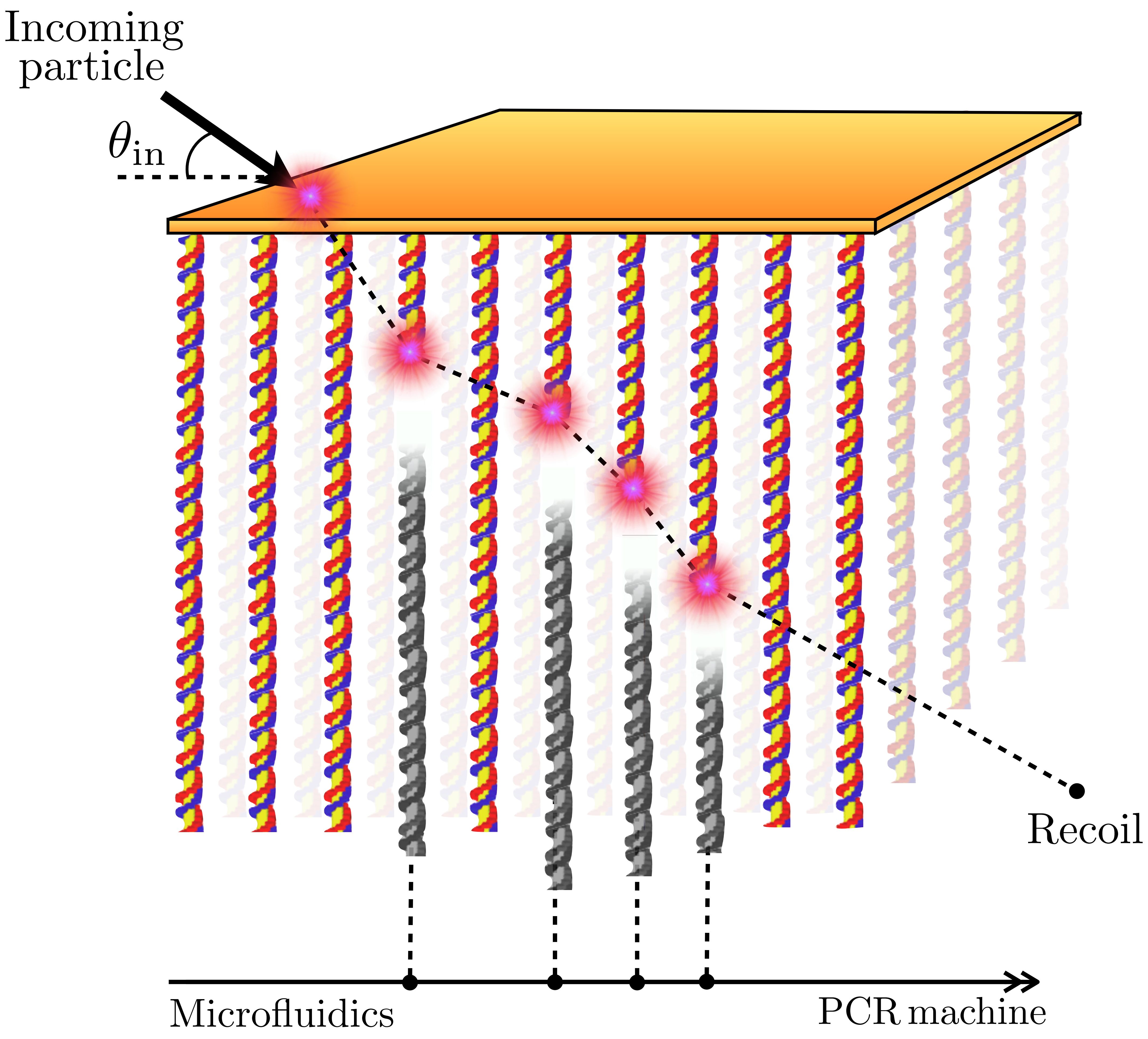


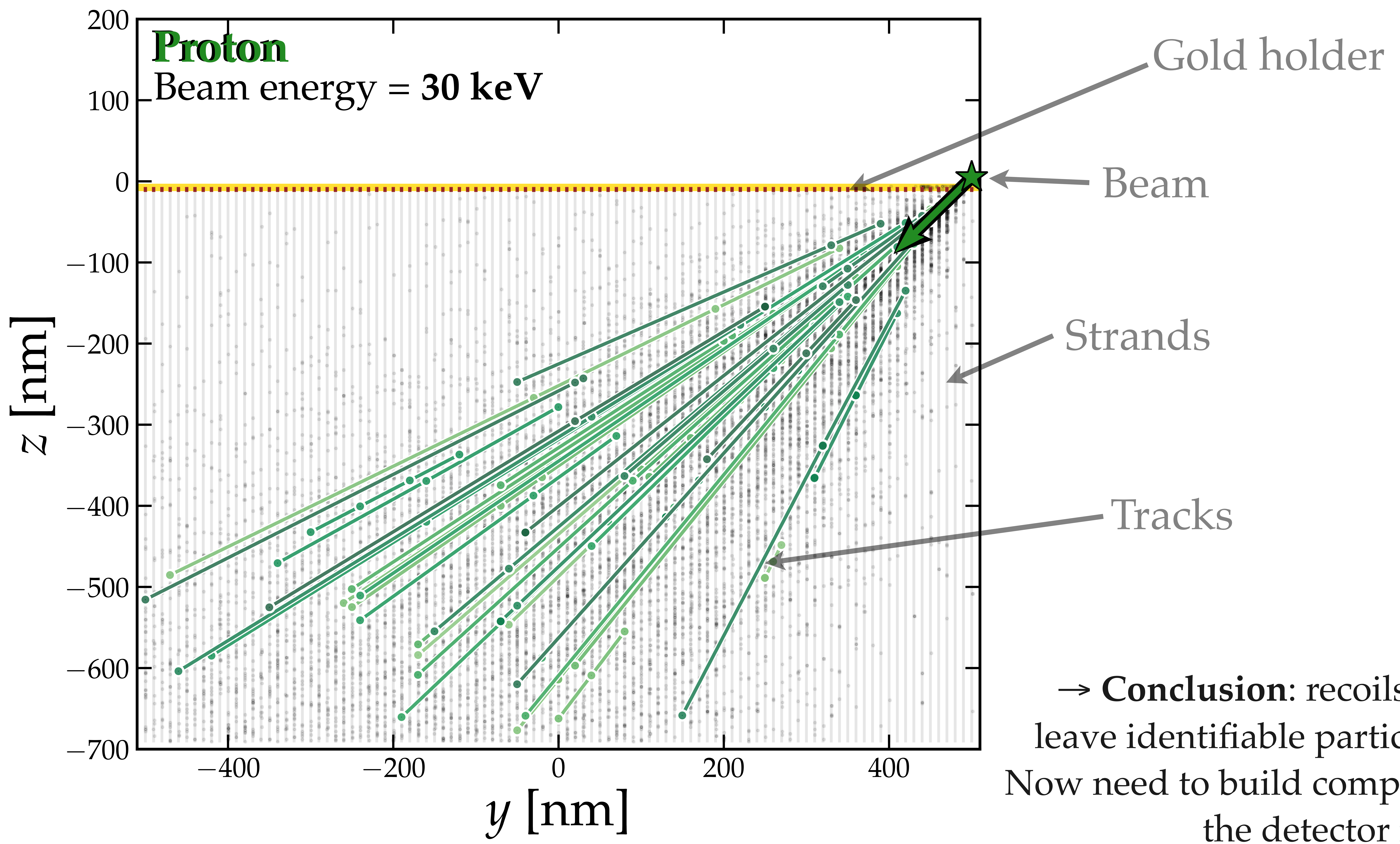
DNA-based particle detector?

How crazy is it?

Putting aside the obvious experimental challenge, there is a clear advantage in the context of directional detection

→ <u>No diffusion and no nanoscale imaging required</u>



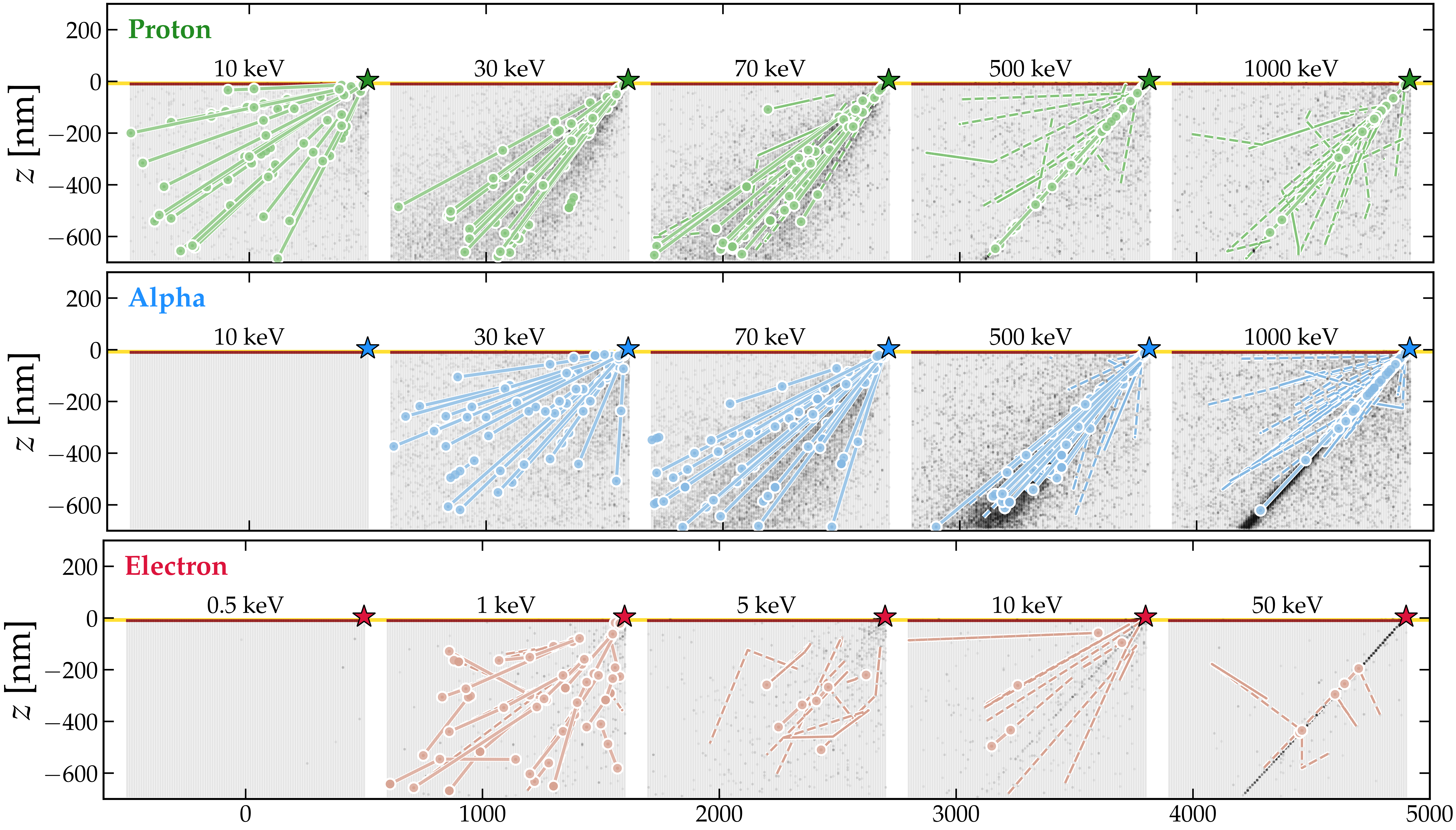


→ **Conclusion**: recoils >10 keV leave identifiable particle tracks,
Now need to build components of the detector in the lab

Summary

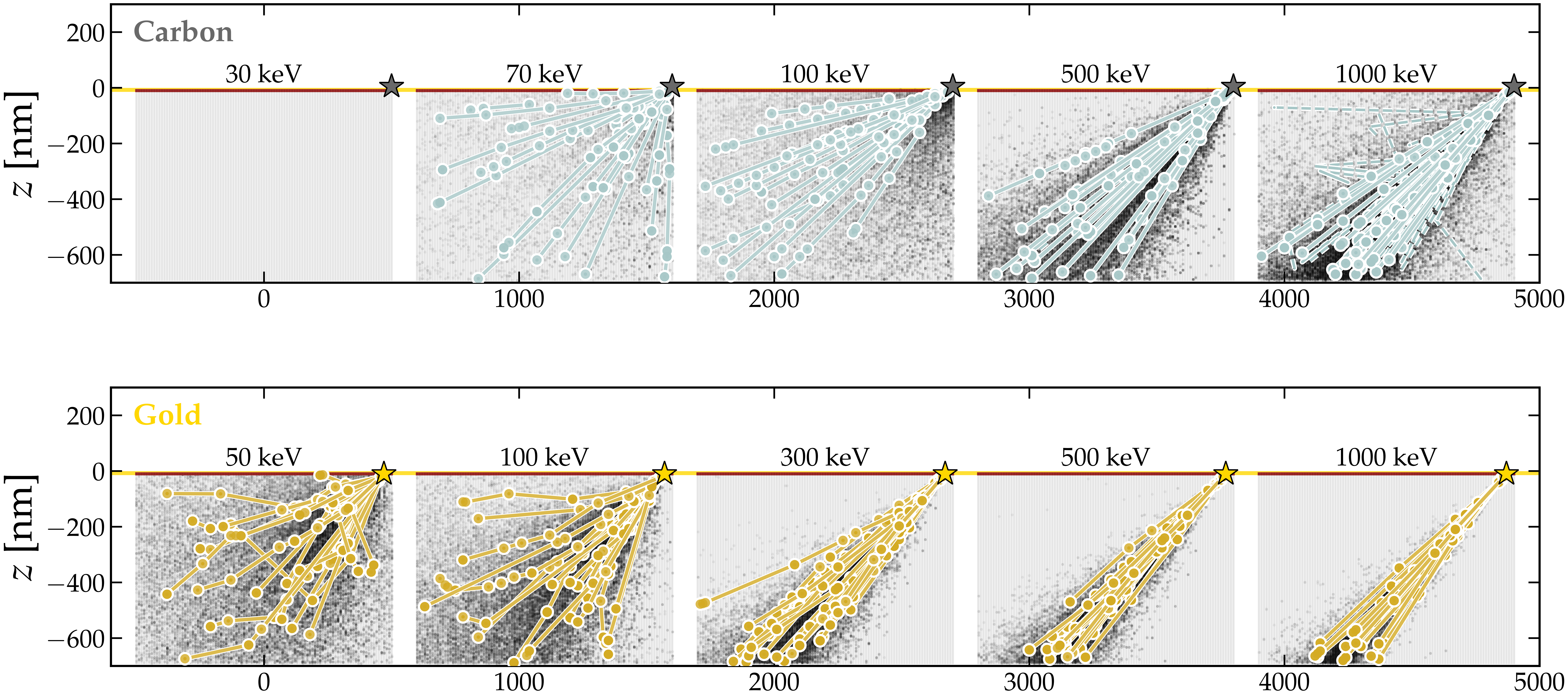
Many exciting for different fields to contribute to fundamental physics

- **Astrophysics**: High energy environments like stellar interiors are potentially factories for new feebly-coupled particles. Astrophysical arguments are essential for bounding the parameter spaces we have to search across
- **Quantum sensors**: new techniques such as single photon counting are needed to improve searches for new light fields by helping us to beat the fundamental quantum noise limit.
- **Solid state physics/nanoscience**: novel materials are needed that can detect extremely low-energy interactions below the band-gaps of semiconductors, e.g. via collective excitations
- **Biophysics**: is there the possibility to use advances in biotechnology to create a new type of particle detector?

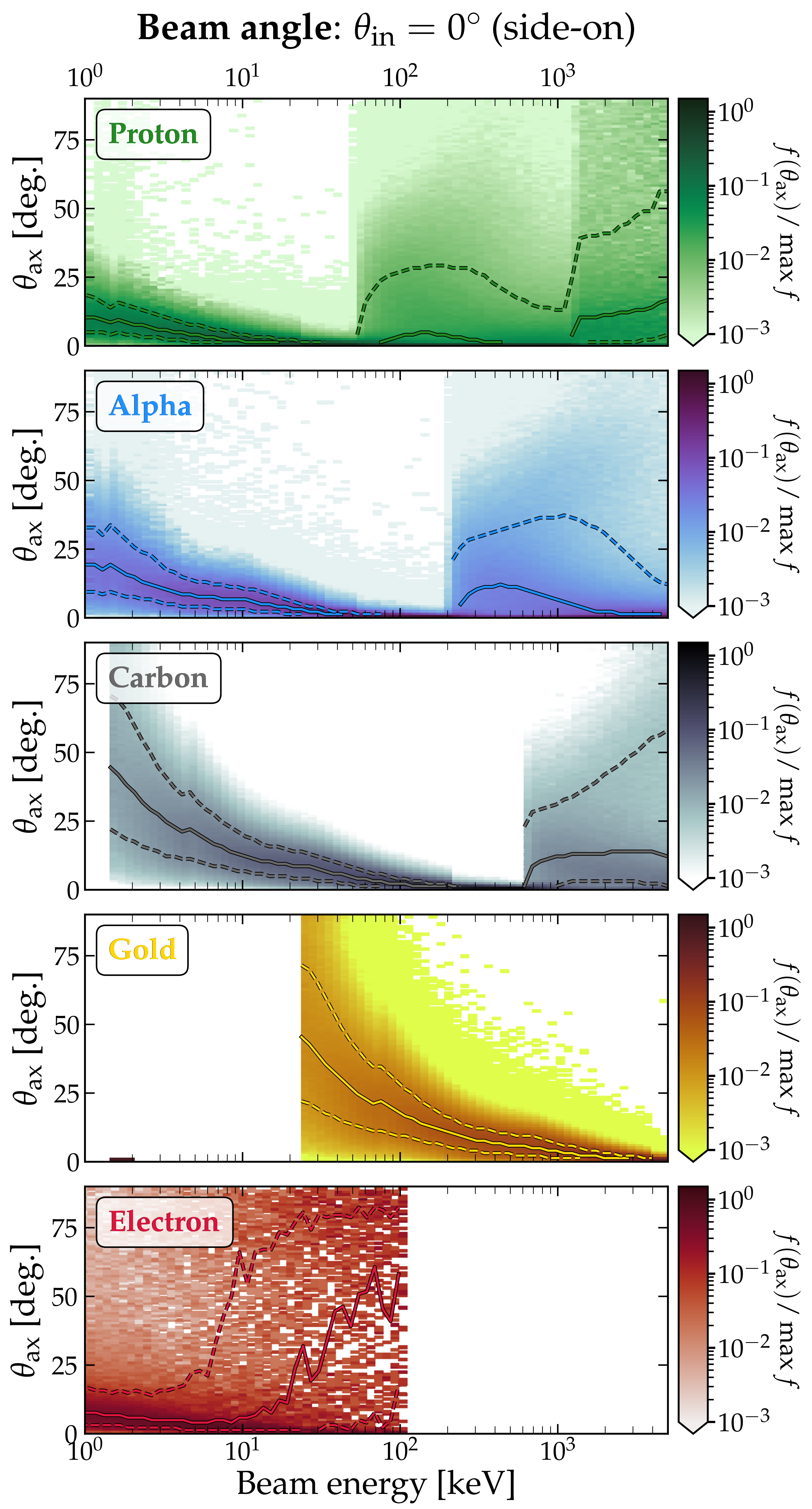


Proton
Alpha
Electron
10 keV
30 keV
70 keV
500 keV
1000 keV
0.5 keV
1 keV
5 keV
10 keV
50 keV
z [nm]
200
0
−200
−400
−600
0
1000
2000
3000
4000
5000

[2105.11949]


Carbon
30 keV
70 keV
100 keV
500 keV
1000 keV
Gold
50 keV
100 keV
300 keV
500 keV
1000 keV
z [nm]
200
0
−200
−400
−600
0
1000
2000
3000
4000
5000

[2105.11949]



Main conclusions from the μm^3 unit simulation

- Track directions well-preserved. Around 25° angular res. for *initial* recoil direction

- Particle ID and energy reconstruction not really possible, need to look at tracks over many units and measure dE/dx

- Need to find a good purpose for the idea…

[2105.11949]

Experimental side

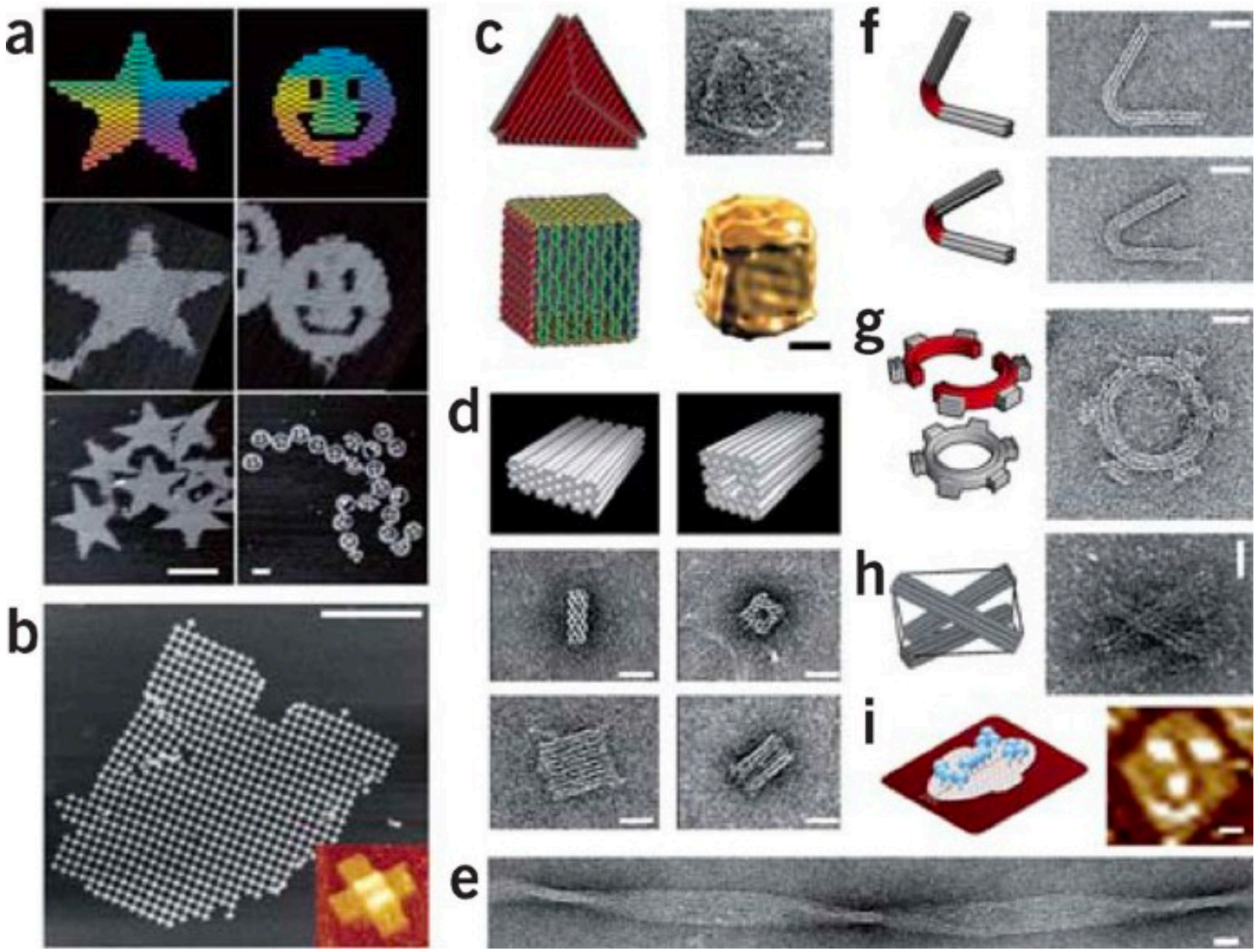
- **Detector construction →**
  DNA-origamists can make practically anything

Primer | Published: 28 January 2021

DNA origami

Swarup Dey, Chunhai Fan, Kurt V. Gothelf, Jiang Li, Chenxiang Lin, Longfei Liu, Na Liu, Minke A. D. Nijenhuis, Barbara Saccà, Friedrich C. Simmel, Hao Yan & Pengfei Zhan

Nature Reviews Methods Primers **1**, Article number: 13 (2021) | Cite this article

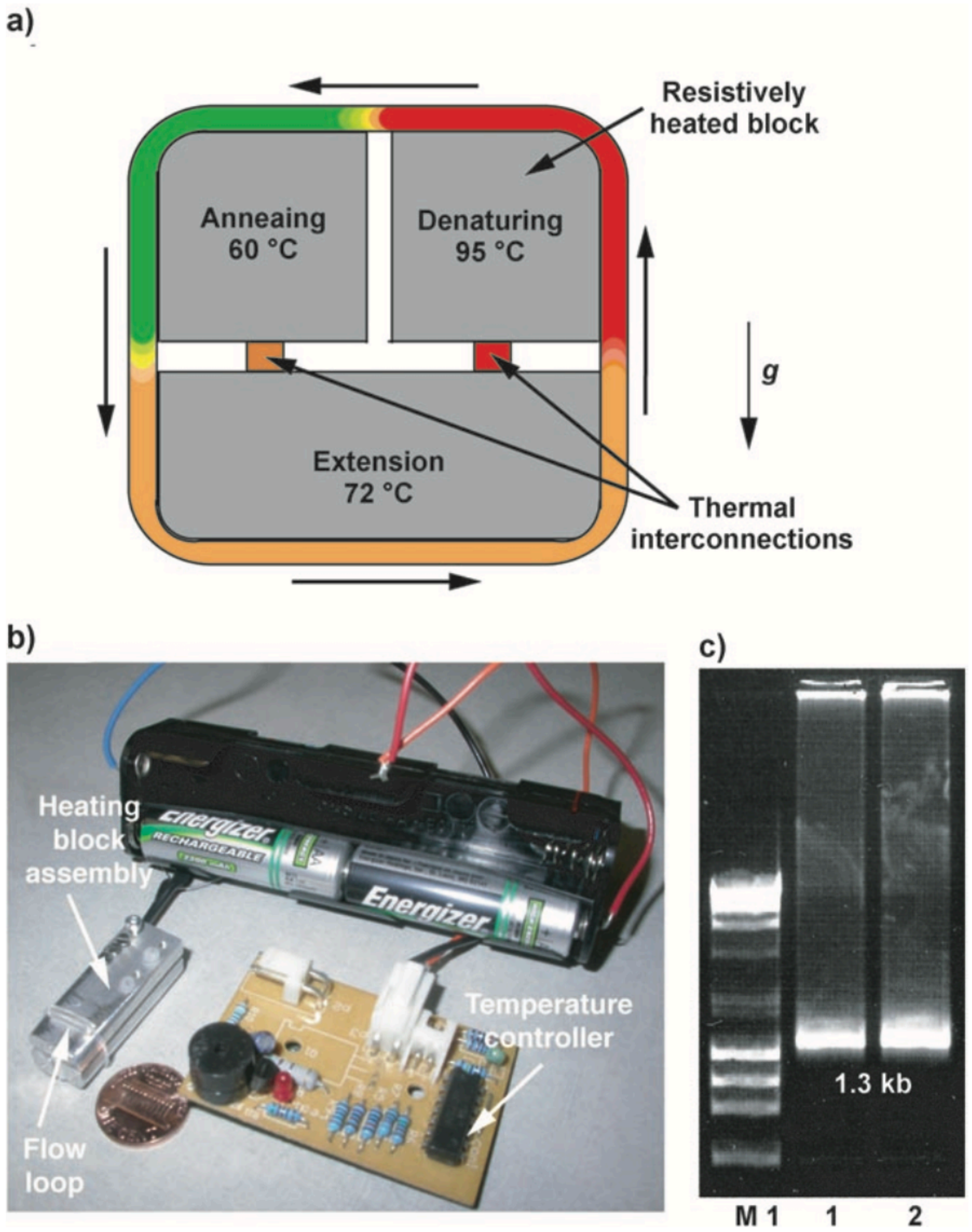


Experimental side

- **Detector construction →** DNA-origamists can make practically anything
- **PCR machines →** cheap, commercially available, portable, and fast.

A Pocket-Sized Convective PCR Thermocycler**

*Nitin Agrawal, Yassin A. Hassan, and Victor M. Ugaz**



https://pubmed.ncbi.nlm.nih.gov/17465434/

Experimental side

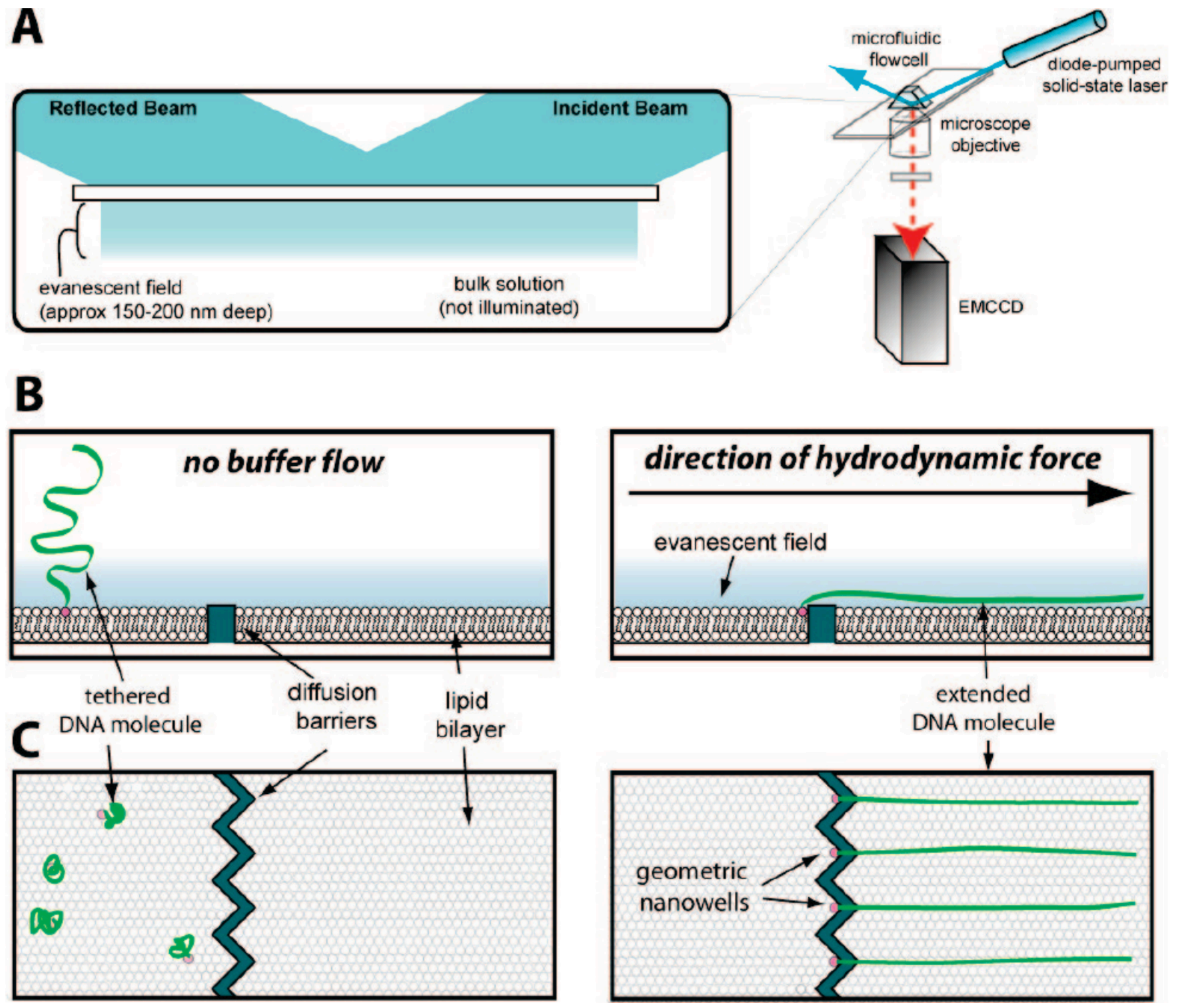
- **Detector construction →** DNA-origamists can make practically anything
- **PCR machines →** cheap, commercially available, portable, and fast.
- **DNA-substrate attachment →** standard protocols (looking at this in the lab right now!)

Parallel Arrays of Geometric Nanowells for Assembling Curtains of DNA with Controlled Lateral Dispersion

Mari-Liis Visnapuu,[‡,§] Teresa Fazio,[†,§] Shalom Wind,[†] and Eric C. Greene*[,‡]

Department of Applied Physics and Applied Mathematics, Center for Electron Transport in Molecular Nanostructures, NanoMedicine Center for Mechanical Biology, Columbia University 1020 Schapiro CEPSR, 530 West 120th Street, New York, New York 10027, and Department of Biochemistry and Molecular Biophysics, Columbia University, 650 West 168th Street, Black Building Room 536, New York, New York 10032

Received June 6, 2008. Revised Manuscript Received August 18, 2008



https://pubmed.ncbi.nlm.nih.gov/17465434/

Experimental side

- **Detector construction →** DNA-origamists can make practically anything
- **PCR machines →** cheap, commercially available, portable, and fast.
- **DNA-substrate attachment →** standard protocols (looking at this in the lab right now!)
- **Main challenge →** stability of detector and ensuring strands are collected, maybe a total rethink of design is in order (DNA-based harddrive?)

https://doi.org/10.1038/s41467-020-15588-z

DNA punch cards for storing data on native DNA sequences via enzymatic nicking

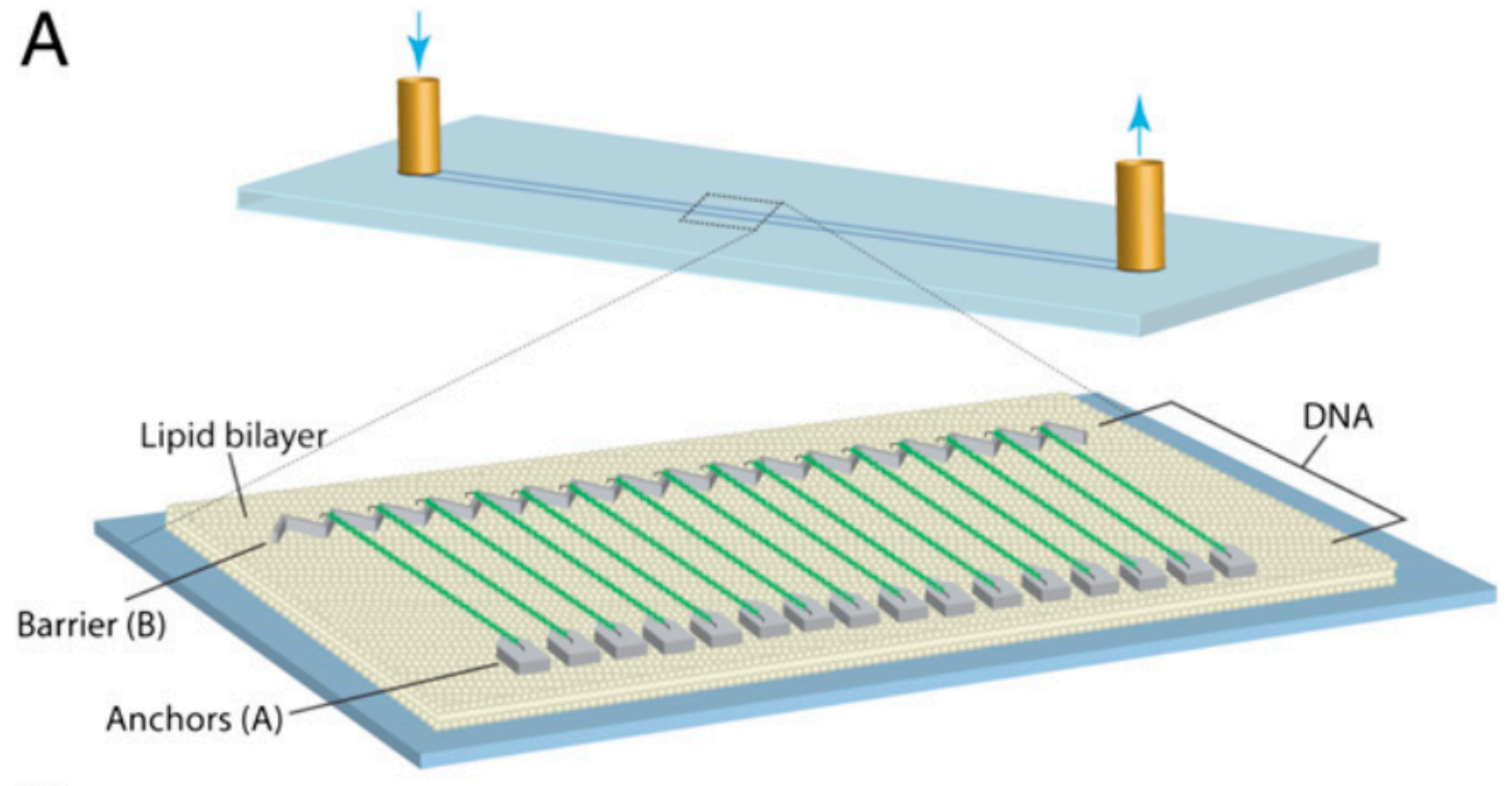
S. Kasra Tabatabaei[1], Boya Wang[2,8], Nagendra Bala Murali Athreya[3,8], Behnam Enghiad[4], Alvaro Gonzalo Hernandez[5], Christopher J. Fields[6], Jean-Pierre Leburton[3], David Soloveichik[2], Huimin Zhao[1,4,7]✉ & Olgica Milenkovic[3]✉

+

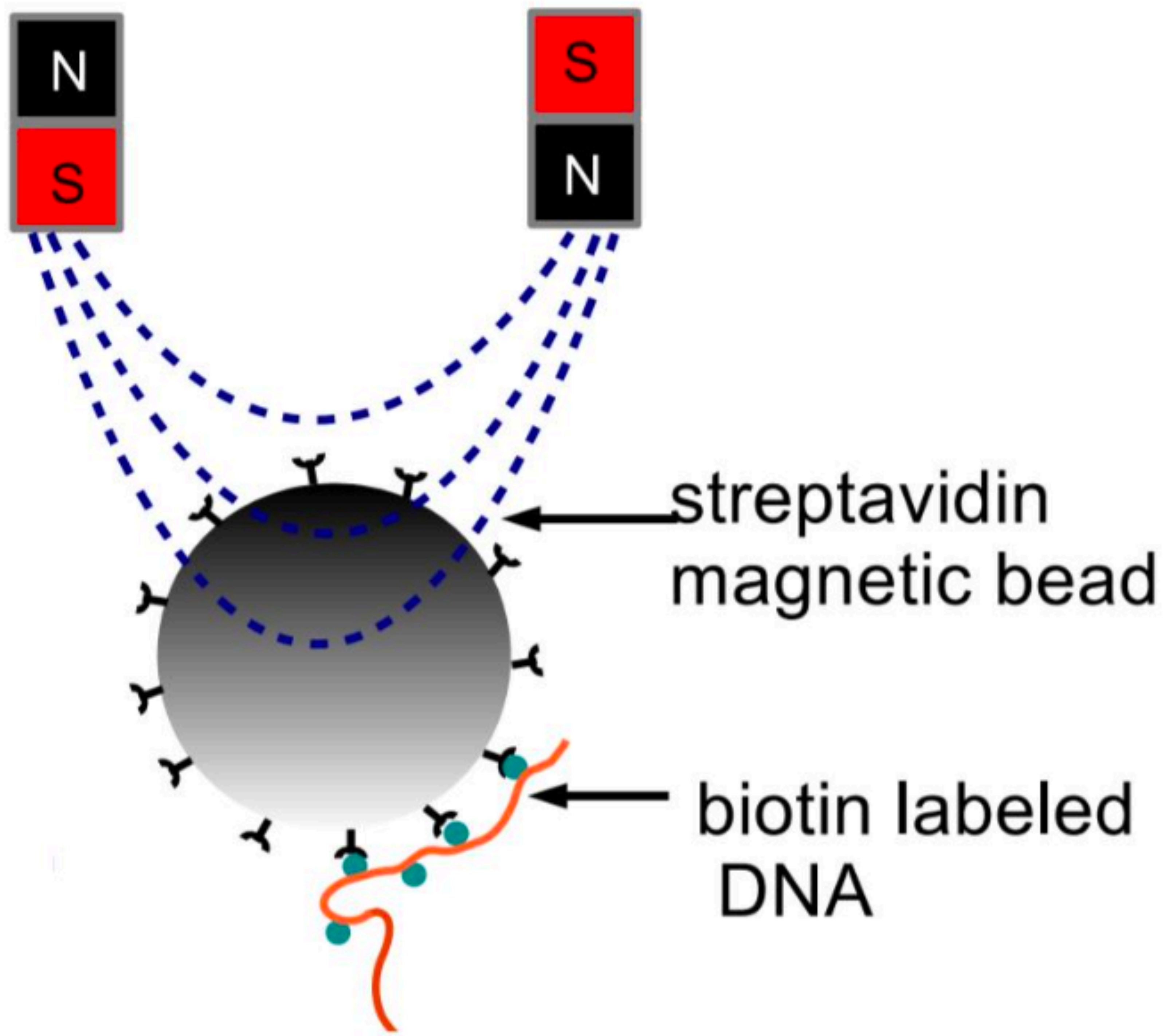
Single-molecule imaging of DNA curtains reveals mechanisms of KOPS sequence targeting by the DNA translocase FtsK

Ja Yil Lee[a,1], Ilya J. Finkelstein[a,1], Estelle Crozat[b,2], David J. Sherratt[b], and Eric C. Greene[a,c,3]

[a]Department of Biochemistry and Molecular Biophysics and [c]Howard Hughes Medical Institute, Columbia University, New York, NY 10032; and [b]Department of Biochemistry, University of Oxford, Oxford OX1 3QU, United Kingdom



Attachment of paramagnetic beads to the DNA strands



[t]

FIG. 3. Diagram from [16] illustrating the DNA to paramagnetic bead attachment and manipulation via an external magnetic field. The connection occurs due to the extreme affinity of Streptavidin (a type of protein) to biotin molecules (vitamin H). Streptavidin is known to form one of the strongest bonds known in nature with biotin.

https://iopscience.iop.org/article/10.1088/1478-3975/12/4/046011

Ampere's law

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

Ampere's law

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

Oscillating
axion field

Ampere's law

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

Axion-induced electric field

Oscillating axion field

Ampere's law

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

Axion-induced magnetic field

Axion-induced electric field

Oscillating axion field

Ampere's law

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

Axion-induced magnetic field

Axion-induced electric field

Oscillating axion field

What kind of experiment do we need to measure this?

→ Depends on size of Compton wavelength ($1/m_a$) relative to the size of some instrument, say $\mathcal{O}$(metres)

Haloscope strategies

<μeV**:** Compton wavelength long relative to experiment. DC magnetic field induces oscillating magnetic field

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

Haloscope strategies

<μeV: Compton wavelength long relative to experiment. DC magnetic field induces oscillating magnetic field

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

~1-100 μeV: Compton wavelength similar scale to experiment. Axion sources oscillating E&M-fields → couple to an EM mode inside a cavity

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Haloscope strategies

<μeV: Compton wavelength long relative to experiment. DC magnetic field induces oscillating magnetic field

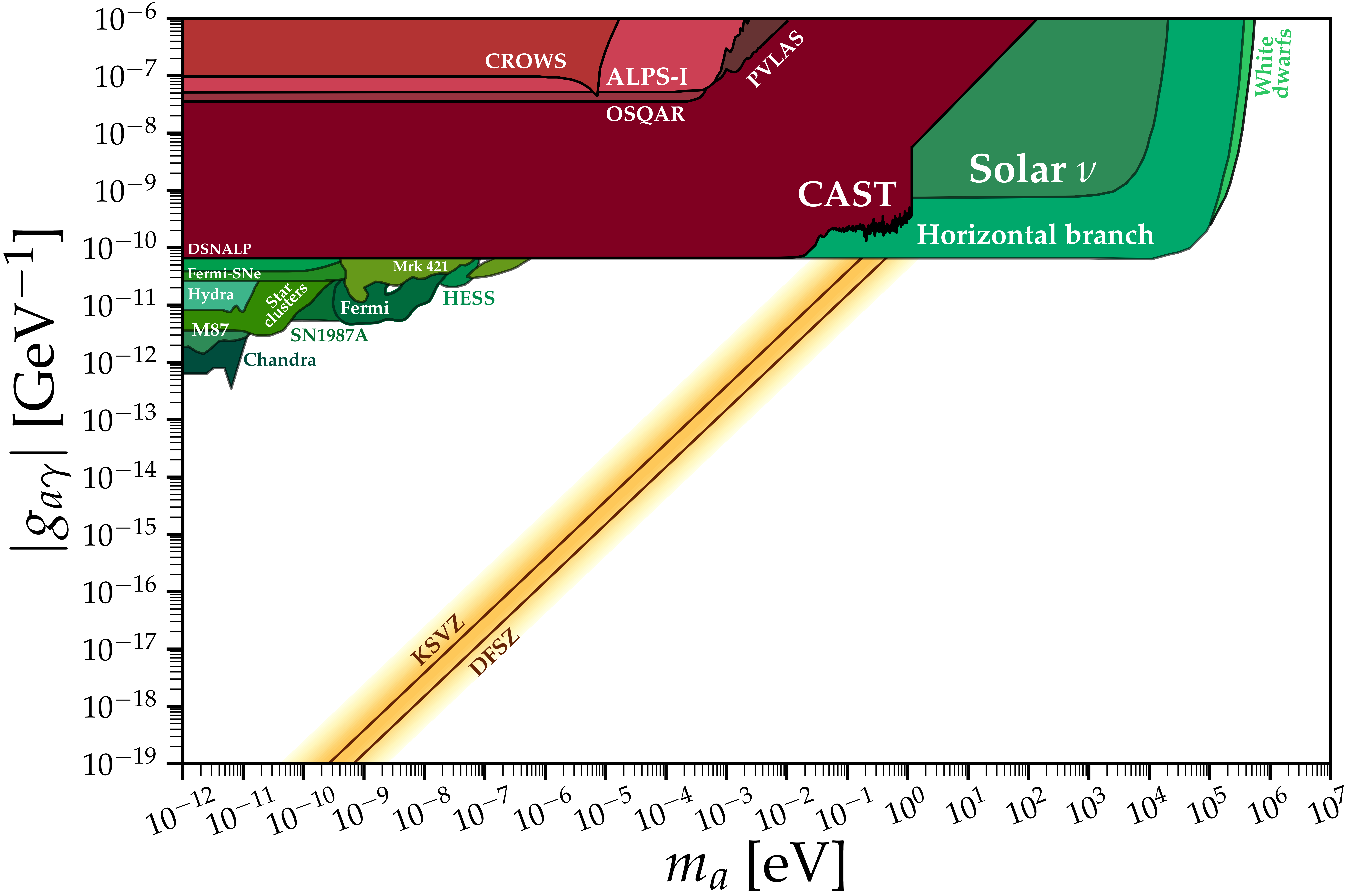
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

~1-100 μeV: Compton wavelength similar scale to experiment. Axion sources oscillating E&M-fields → couple to an EM mode inside a cavity

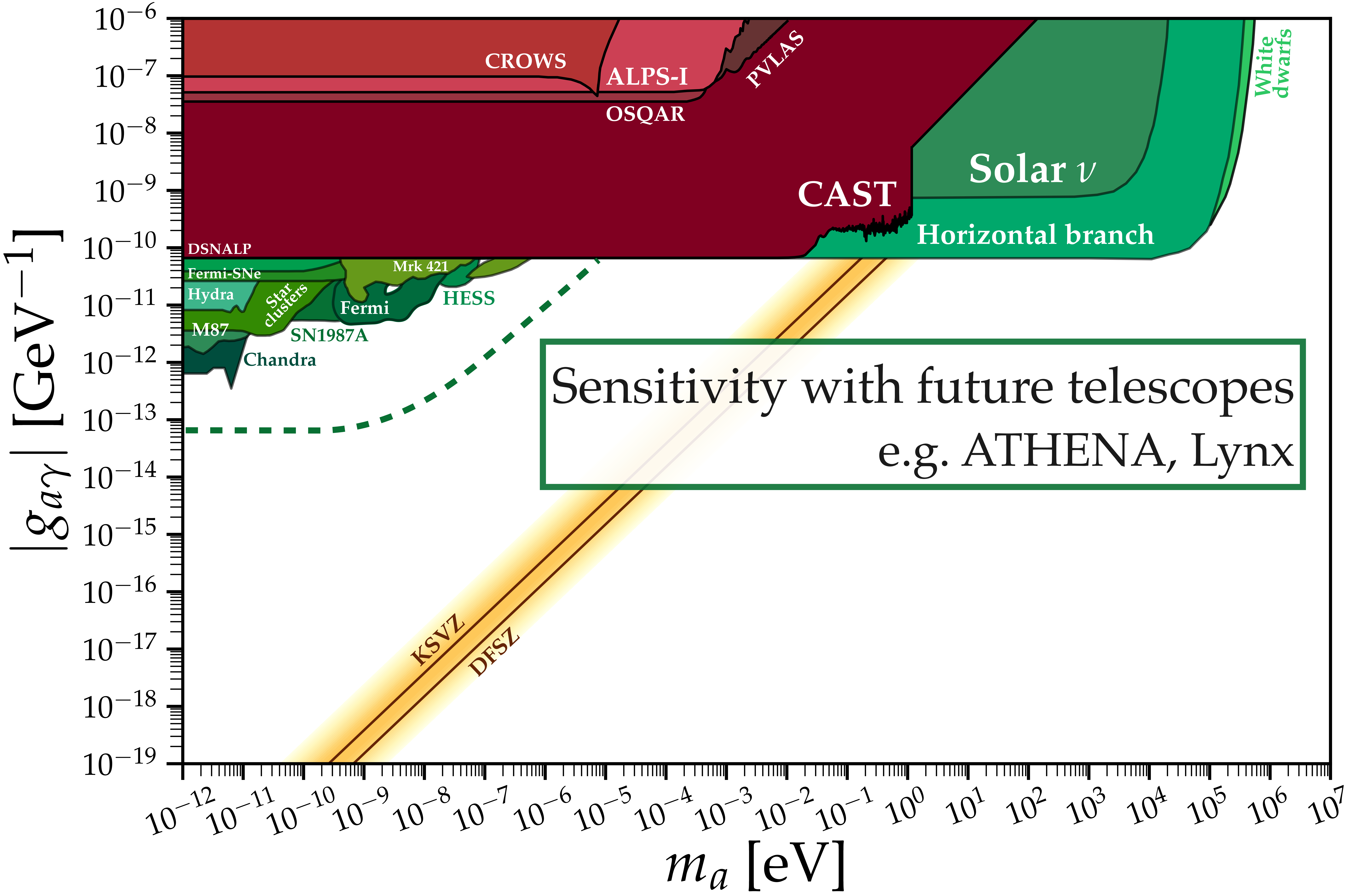
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

$\gtrsim 100\,\mu$eV: Compton wavelength short relative to experiment. Axion generates radiation → arrange experiment to have constructive interference

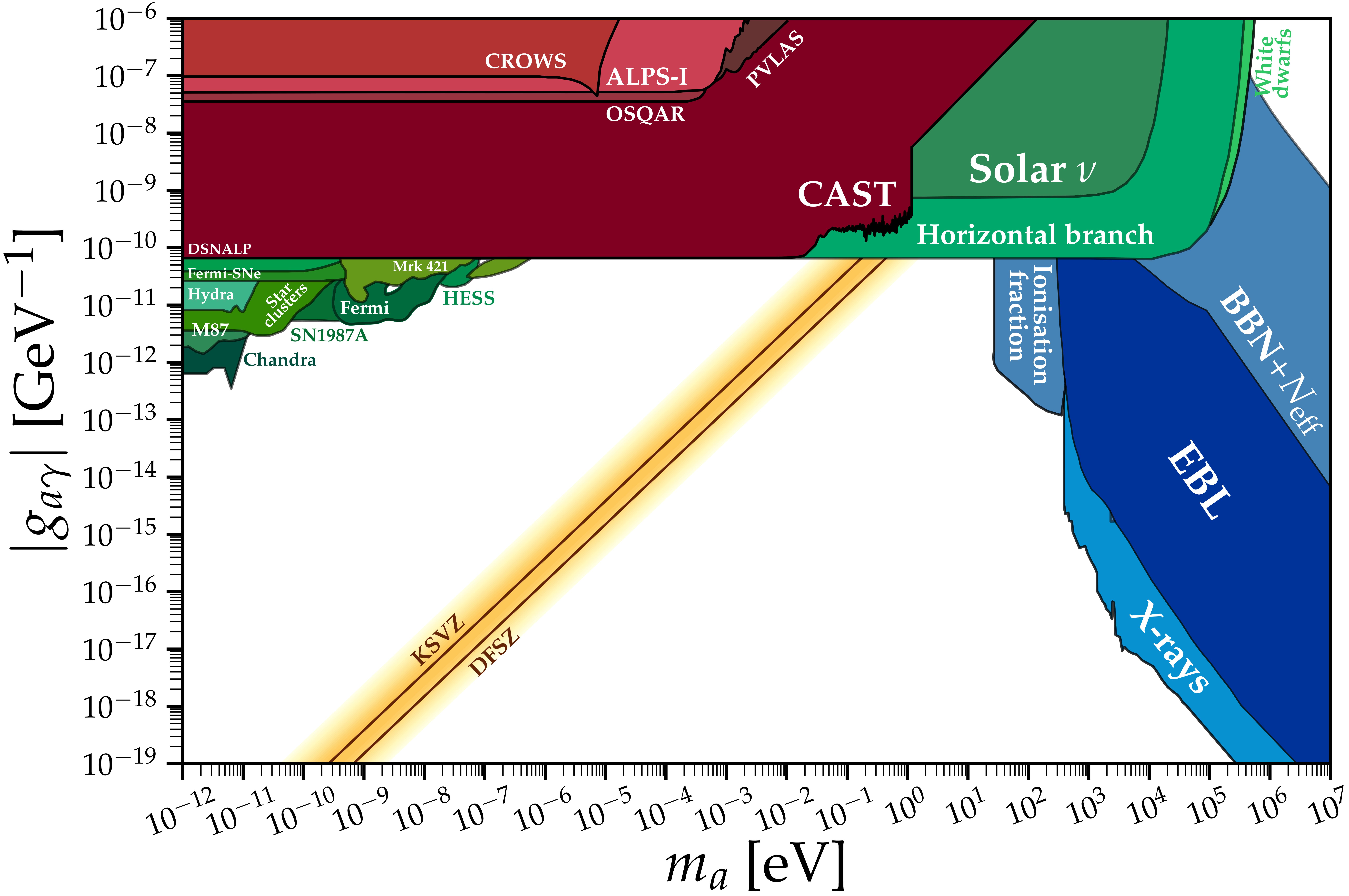
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$



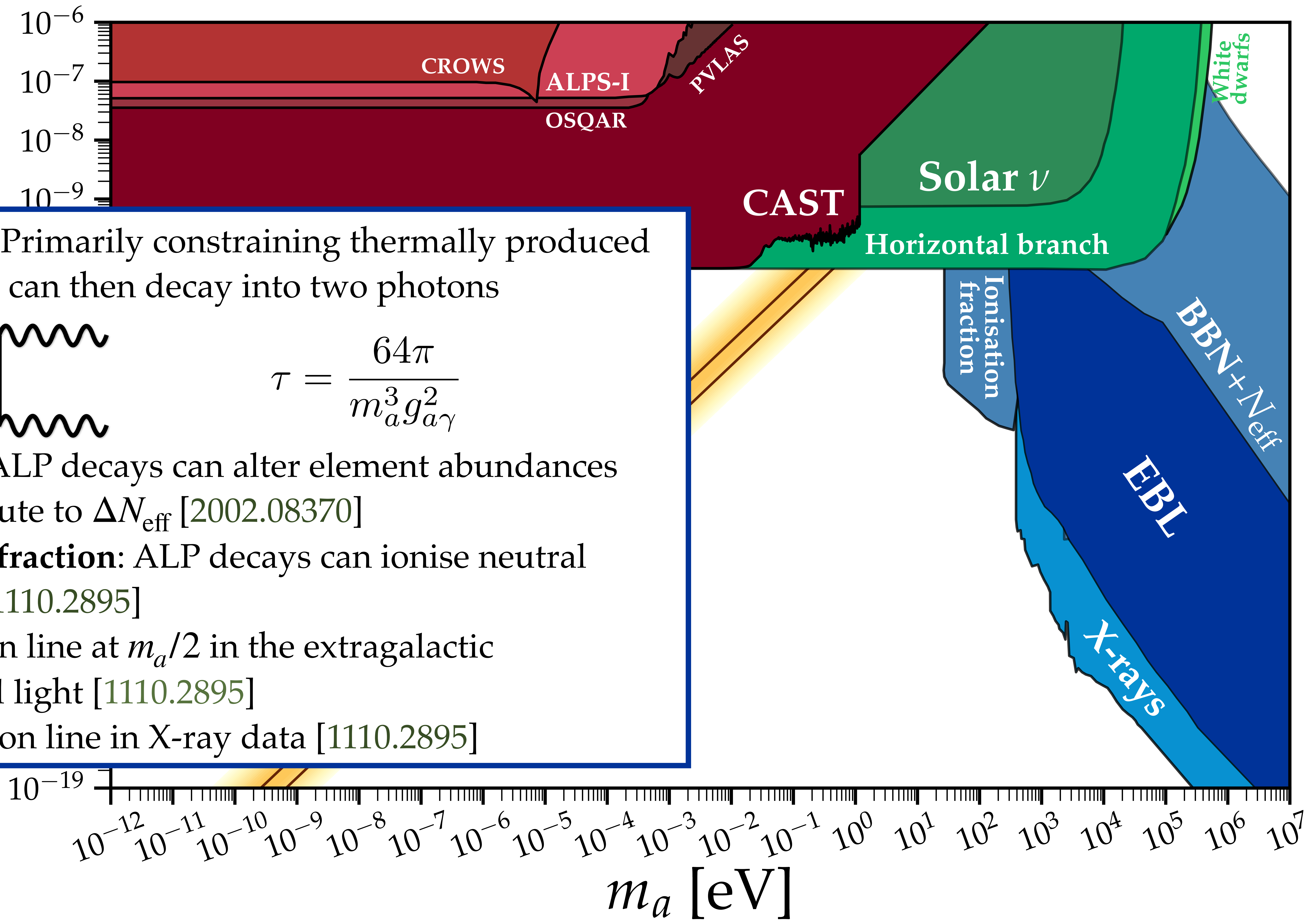
CROWS
ALPS-I
PVLAS
OSQAR
Solar ν
CAST
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



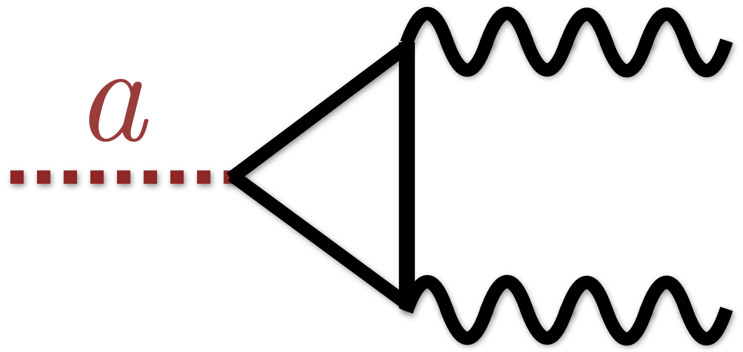
CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Mrk 421
Fermi
HESS
SN1987A
Chandra
KSVZ
DFSZ
Sensitivity with future telescopes
e.g. ATHENA, Lynx
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



CROWS
ALPS-I
PVLAS
OSQAR
CAST
Solar ν
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
Ionisation fraction
BBN+N_eff
EBL
X-rays
|g_aγ| [GeV^−1]
m_a [eV]

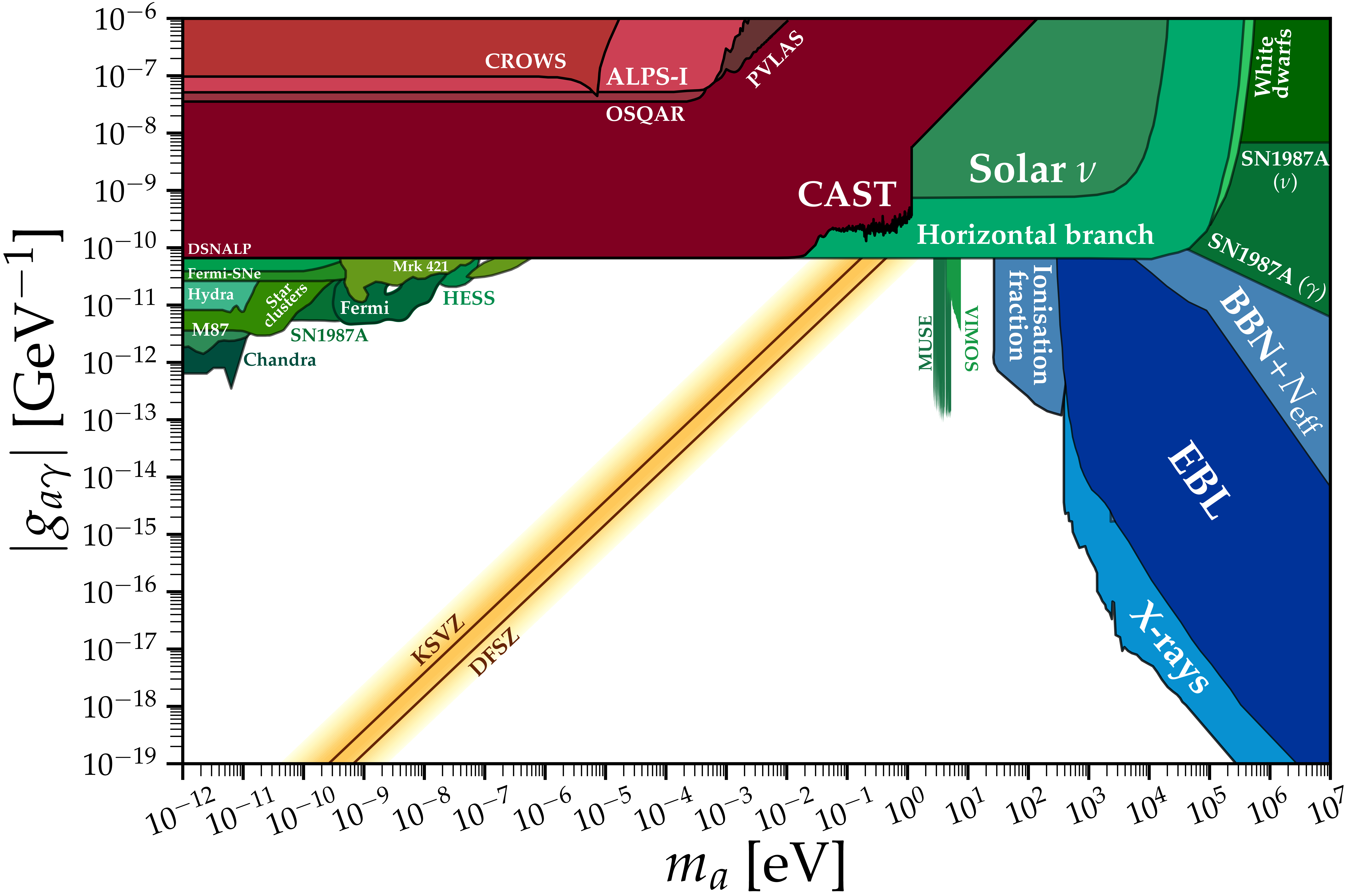


Cosmology: Primarily constraining thermally produced ALPs, which can then decay into two photons

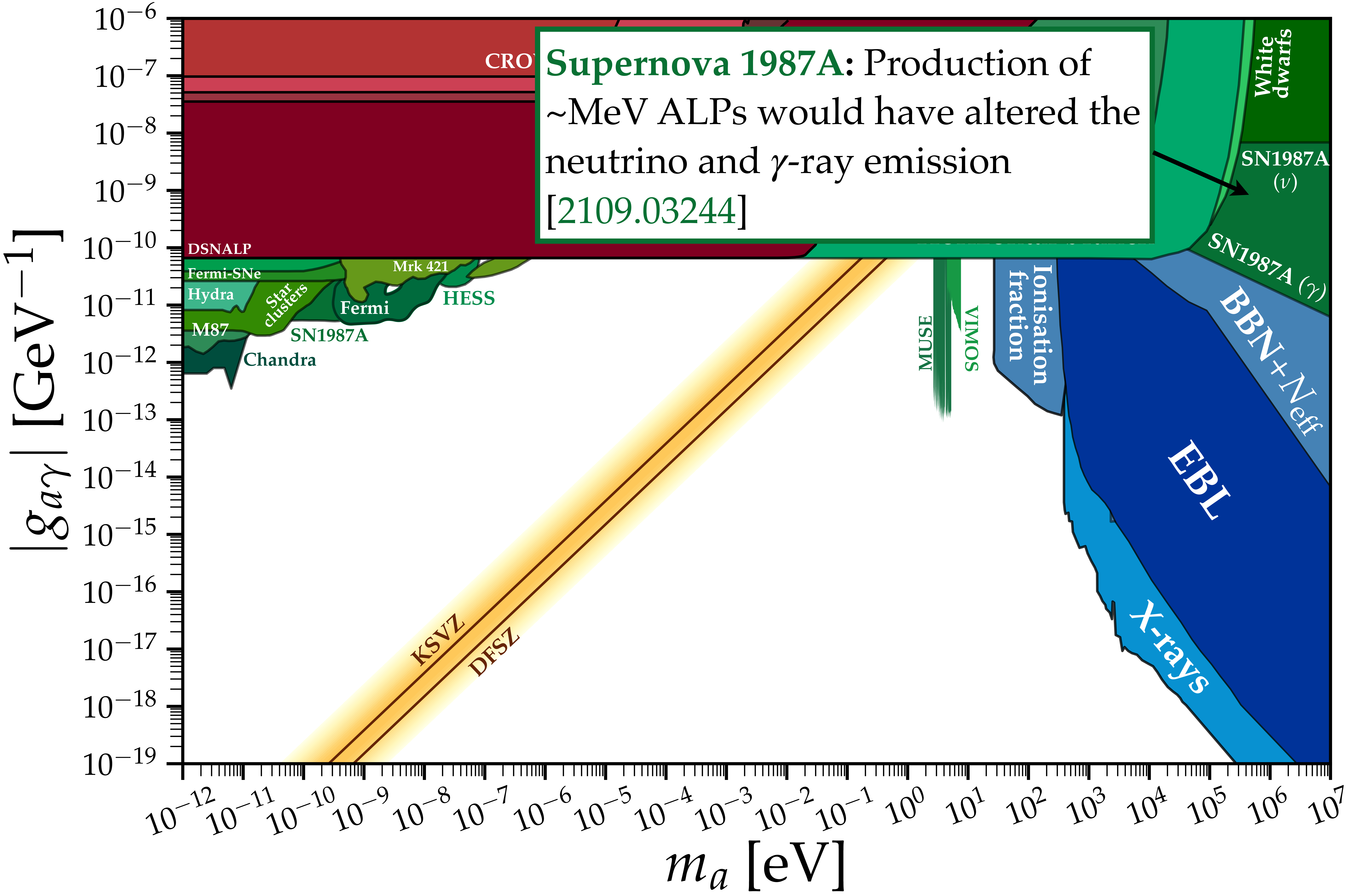


$$\tau = \frac{64\pi}{m_a^3 g_{a\gamma}^2}$$

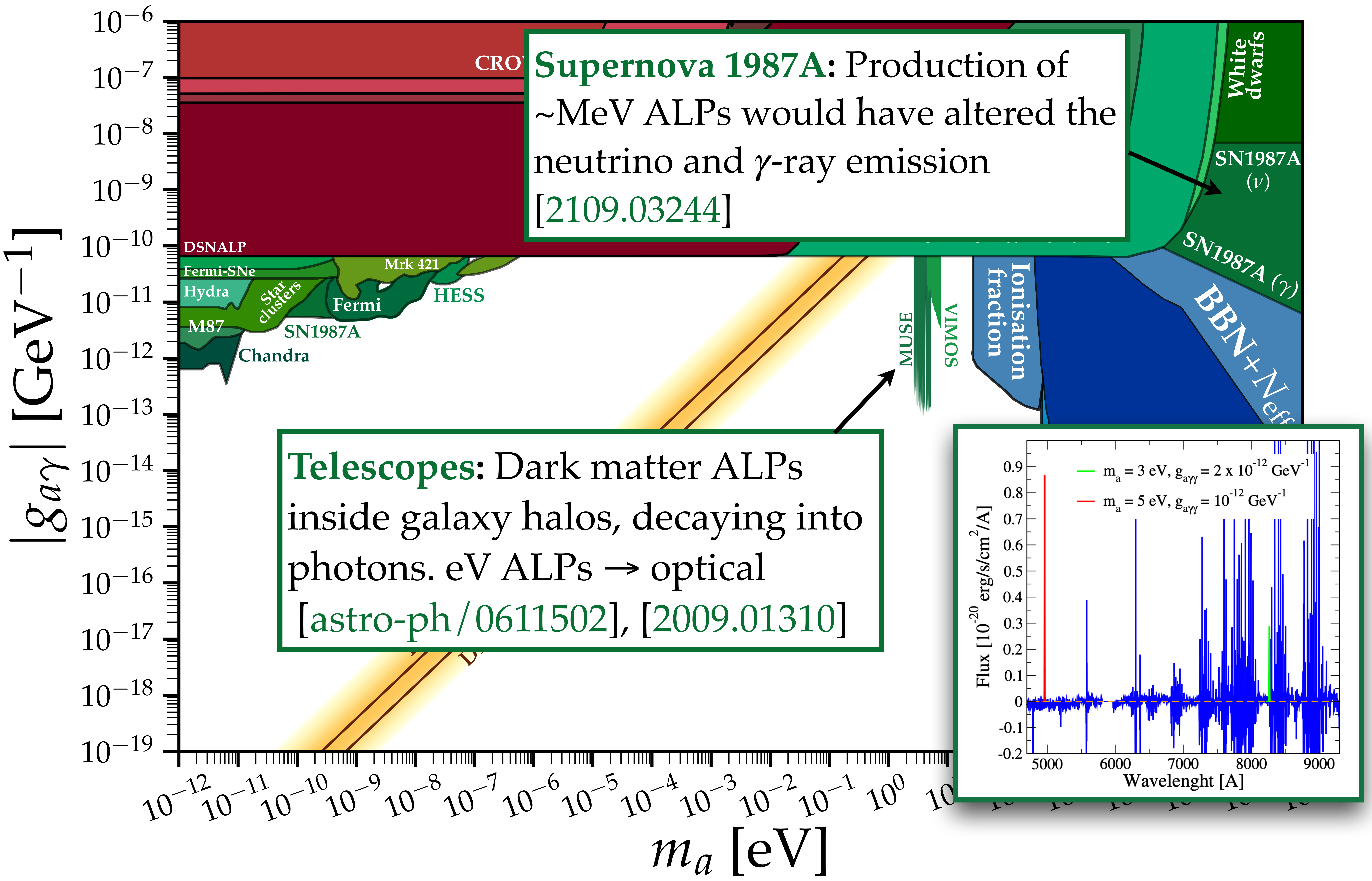
- **BBN/N_{eff}**: ALP decays can alter element abundances and contribute to ΔN_{eff} [2002.08370]
- **Ionisation fraction**: ALP decays can ionise neutral hydrogen [1110.2895]
- **EBL**: photon line at $m_a/2$ in the extragalactic background light [1110.2895]
- **X-ray**: photon line in X-ray data [1110.2895]



CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Chandra
SN1987A
Fermi
Mrk 421
HESS
MUSE
VIMOS
Ionisation fraction
BBN+N_{eff}
EBL
X-rays
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}



Supernova 1987A: Production of ~MeV ALPs would have altered the neutrino and γ-ray emission [2109.03244]
CRO
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Chandra
SN1987A
Fermi
Mrk 421
HESS
KSVZ
DFSZ
MUSE
VIMOS
Ionisation fraction
White dwarfs
SN1987A (ν)
SN1987A (γ)
BBN+N_eff
EBL
X-rays
|g_aγ| [GeV^−1]
m_a [eV]



Supernova 1987A: Production of ~MeV ALPs would have altered the neutrino and γ-ray emission [2109.03244]
Telescopes: Dark matter ALPs inside galaxy halos, decaying into photons. eV ALPs → optical [astro-ph/0611502], [2009.01310]
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Chandra
SN1987A
Fermi
Mrk 421
HESS
MUSE
VIMOS
Ionisation fraction
White dwarfs
SN1987A (ν)
SN1987A (γ)
BBN+N_{eff}
m_a = 3 eV, $g_{a\gamma\gamma}$ = 2 x 10^{-12} GeV^{-1}
m_a = 5 eV, $g_{a\gamma\gamma}$ = 10^{-12} GeV^{-1}
Flux [10^{-20} erg/s/cm^2/A]
Wavelenght [A]