Axions in the sky and on tables

Hyungjin Kim (DESY)

2nd CERN Baltic Conference

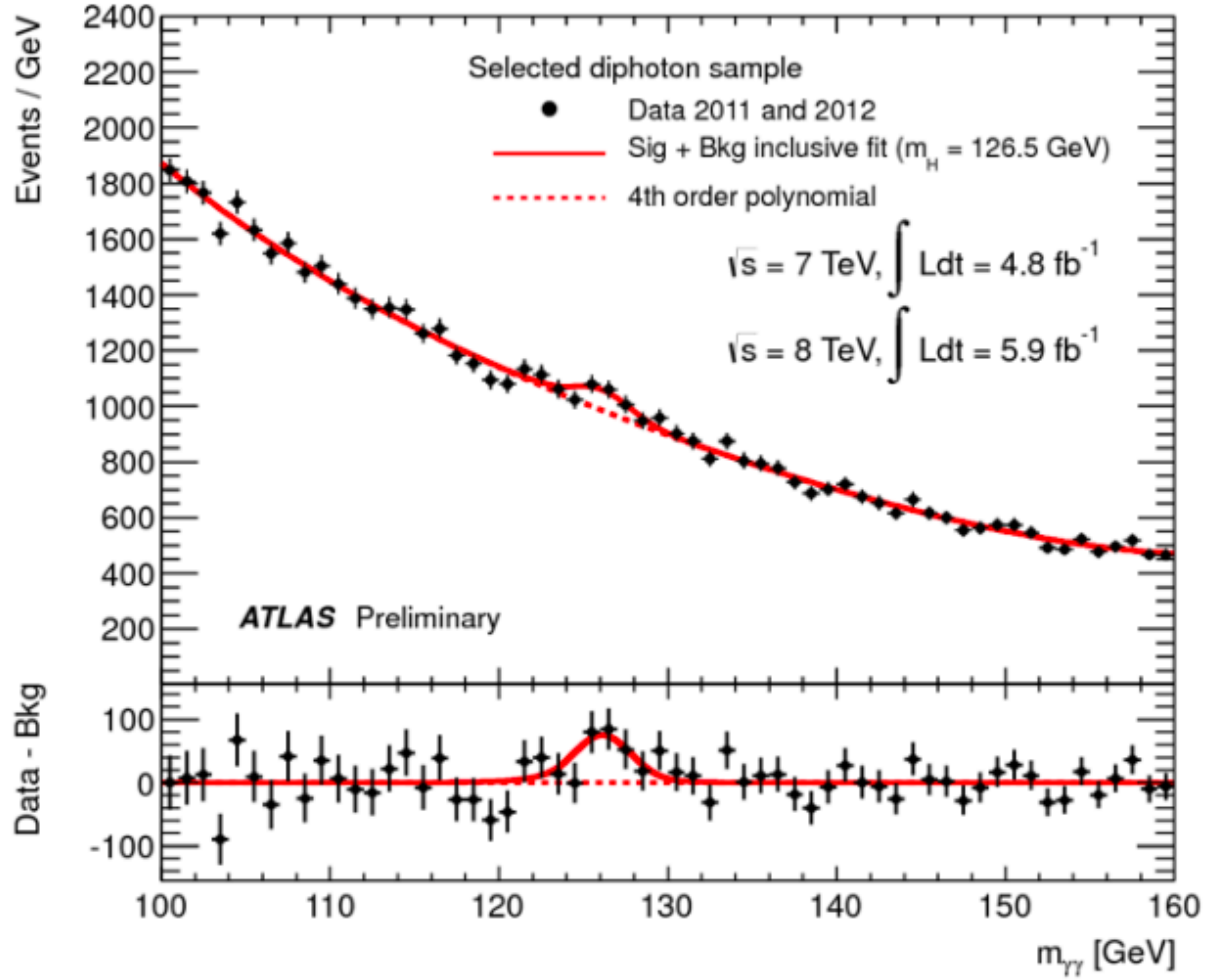
Two milestones

in high energy physics

during past 10 years

The discovery of the Higgs boson

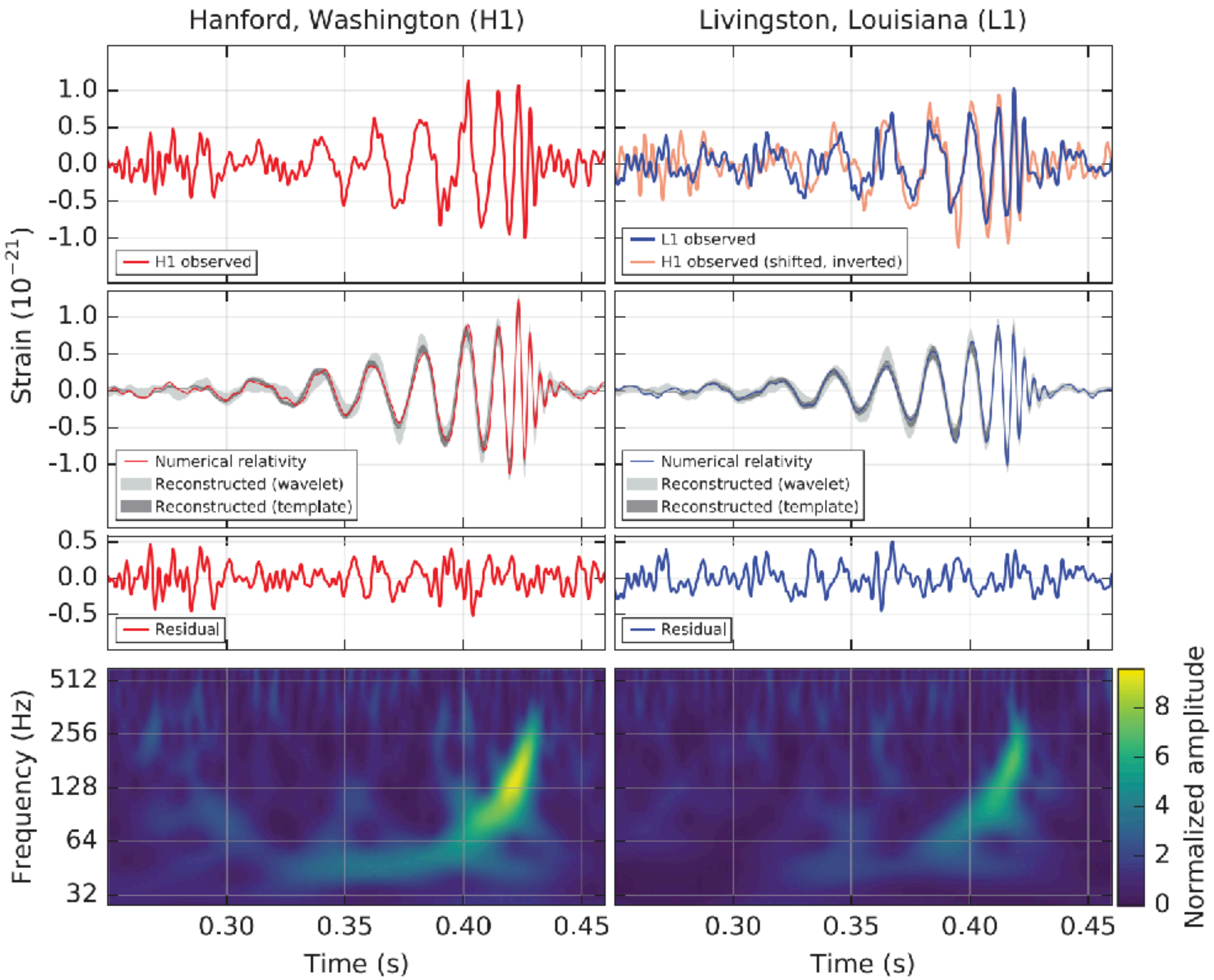
July 2012



(Image: ATLAS Collaboration/CERN)

The first observation of gravitational waves

2015



Abbott et al (16)

Two milestones

in high energy physics

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confirming the standard model (SM) physics

$$S = \int d^4x \sqrt{-g} \left[-\frac{M_P^2}{2} R + \mathcal{L}_{\rm SM} \right]$$

Two milestones

in high energy physics

during past 10 years

confirming the standard model (SM) physics

$$S = \int d^4x \sqrt{-g} \left[-\frac{M_P^2}{2} R + \mathcal{L}_{\rm SM} \right]$$

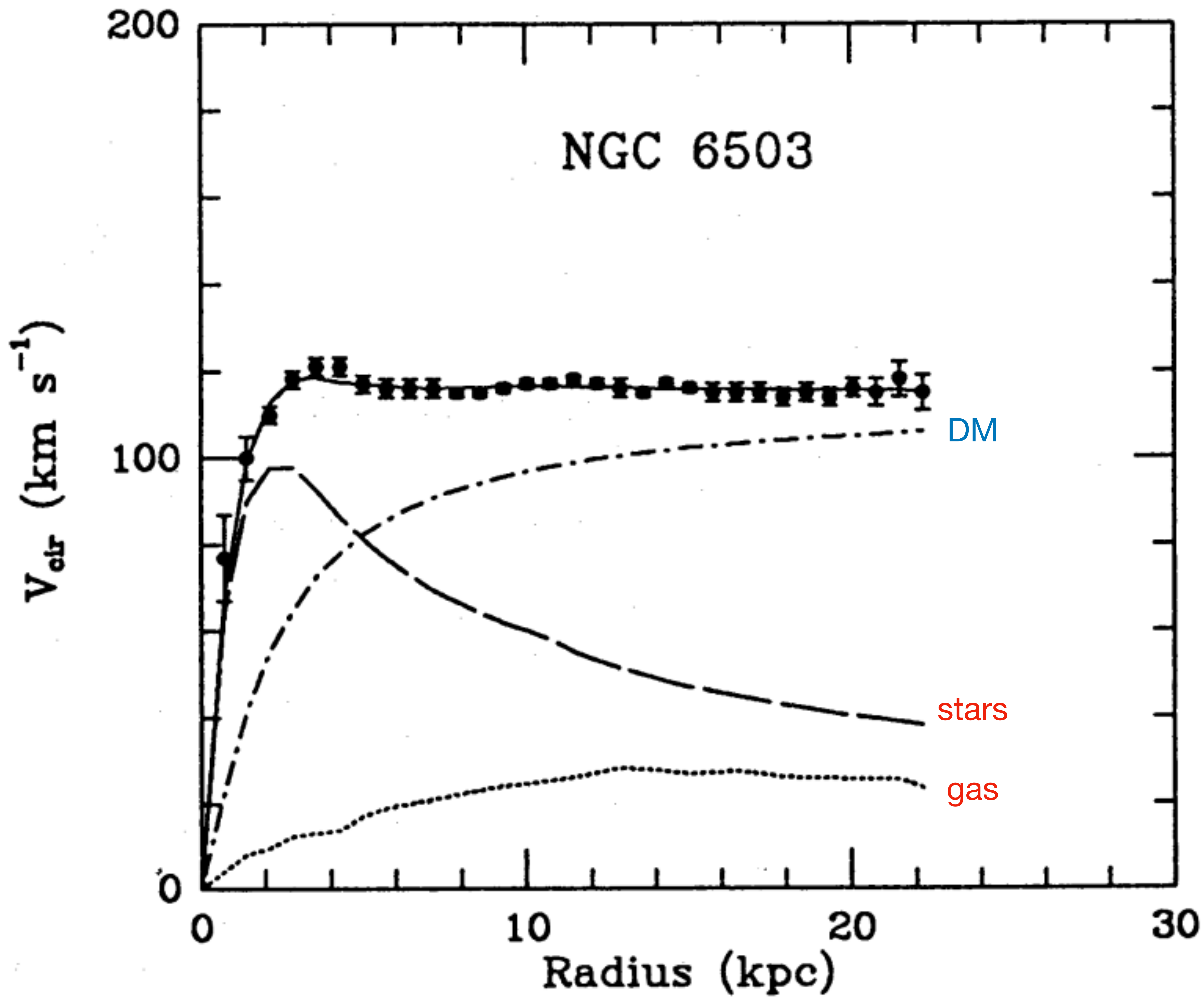
while leaving no clear sign of beyond SM physics …

and yet

we know there are something more than just SM

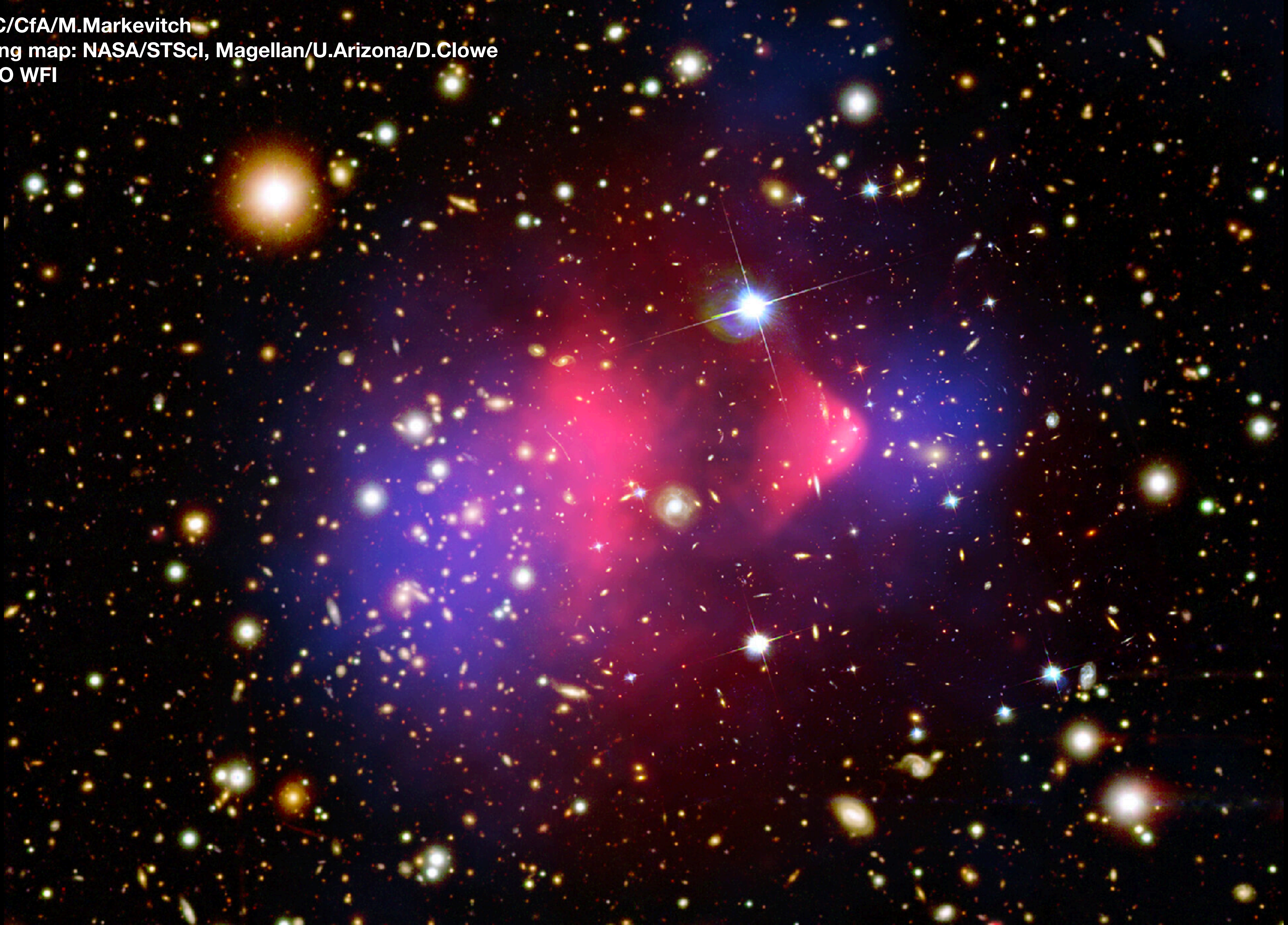
NGC 6503

Credit: NASA/ESA



Begeman et al (91)

X-ray: NASA/CXC/CfA/M.Markevitch
Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe
Lensing map: ESO WFI



certainly

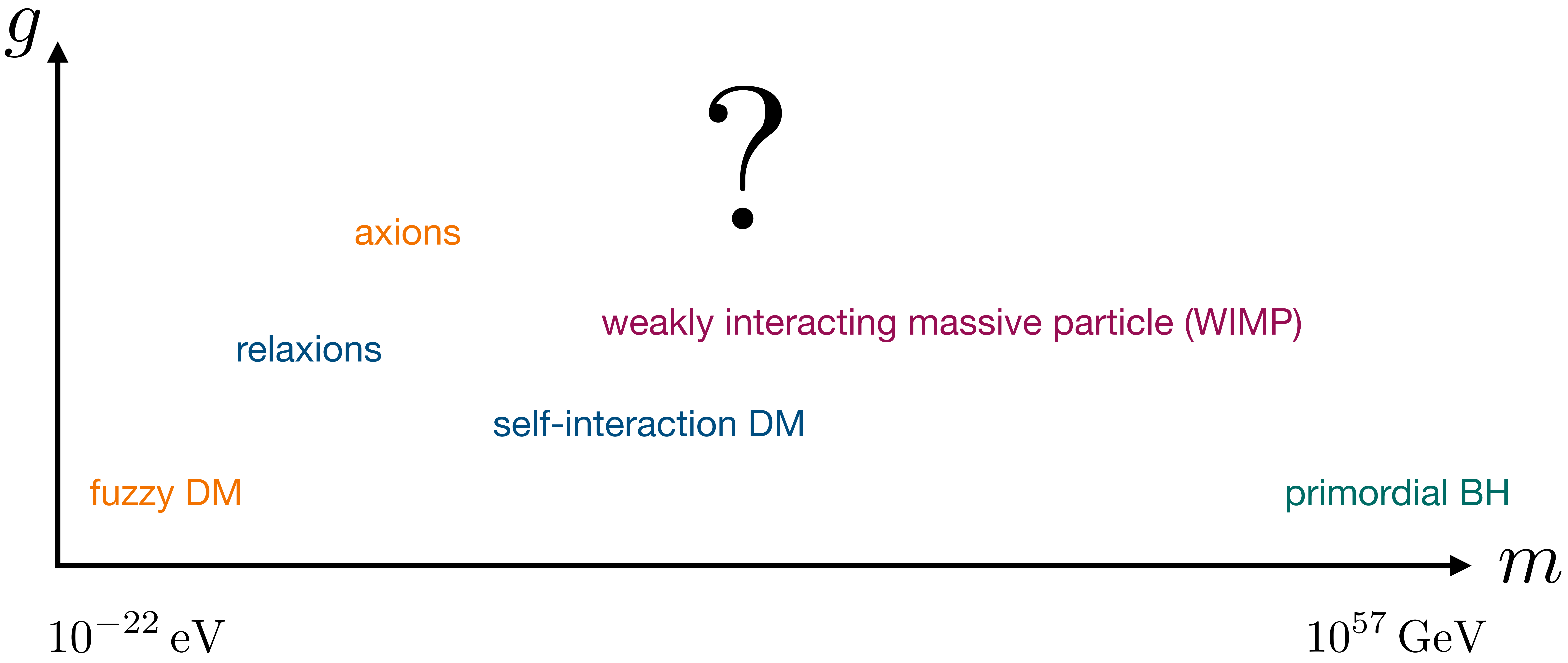
$$S = \int d^4x \sqrt{-g} \left[-\frac{M_P^2}{2} R + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}(m^2, g) \right]$$

where should we look for ?

without any guiding principle

searching for new physics could be challenging

for dark matter



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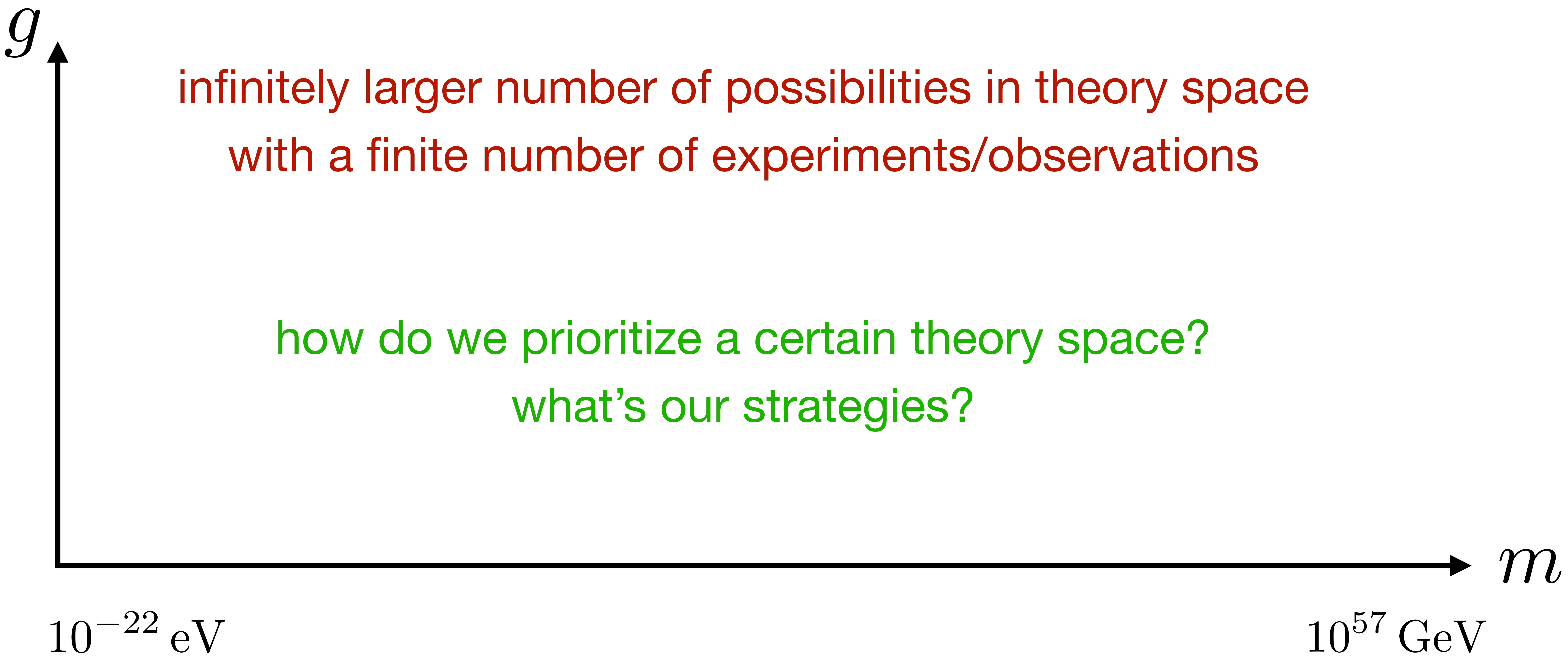
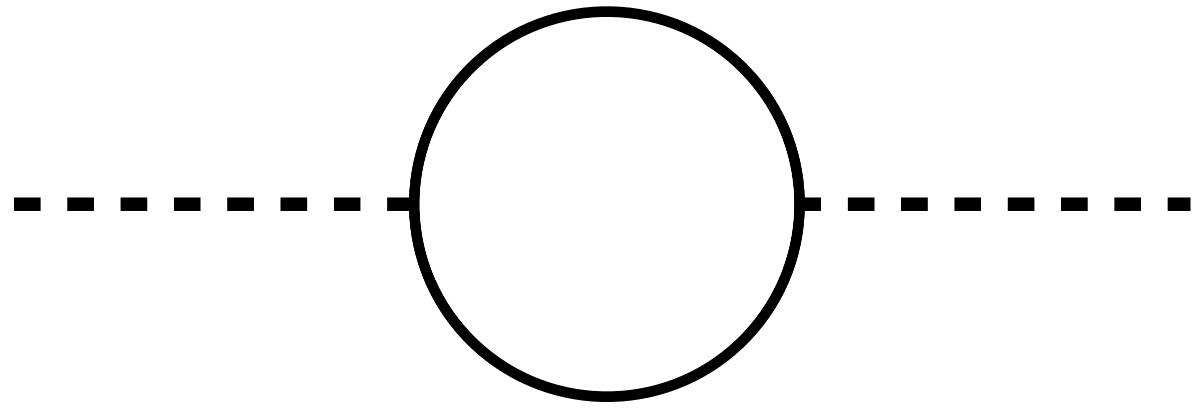


naturalness reasoning

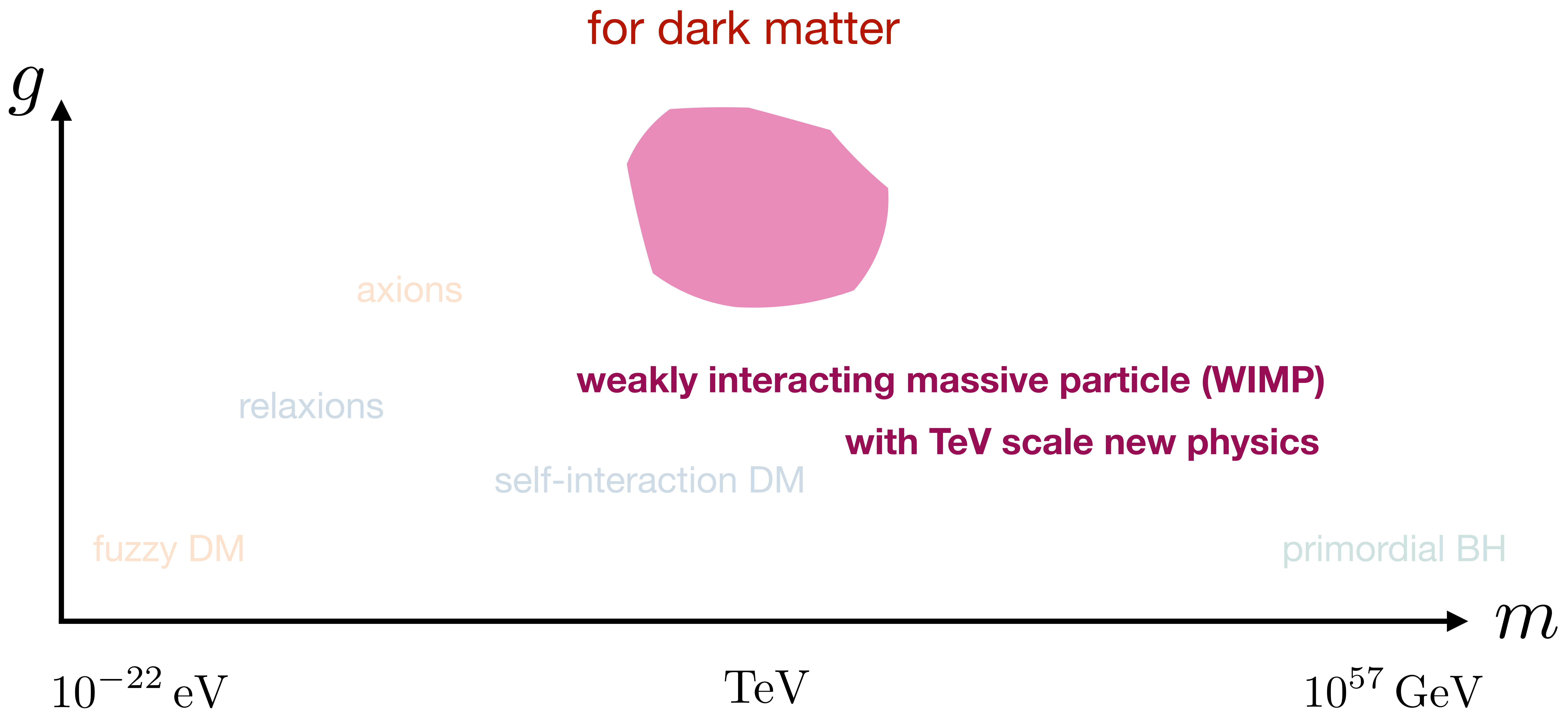


$$\Delta m_H^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

canonical approaches based on symmetry
introduce TeV scale new dynamics
to soften UV sensitivities of the Higgs mass

e.g. supersymmetry, technicolor, compositness, etc.

with naturalness reasoning



with naturalness reasoning

Particle Data Group 2021

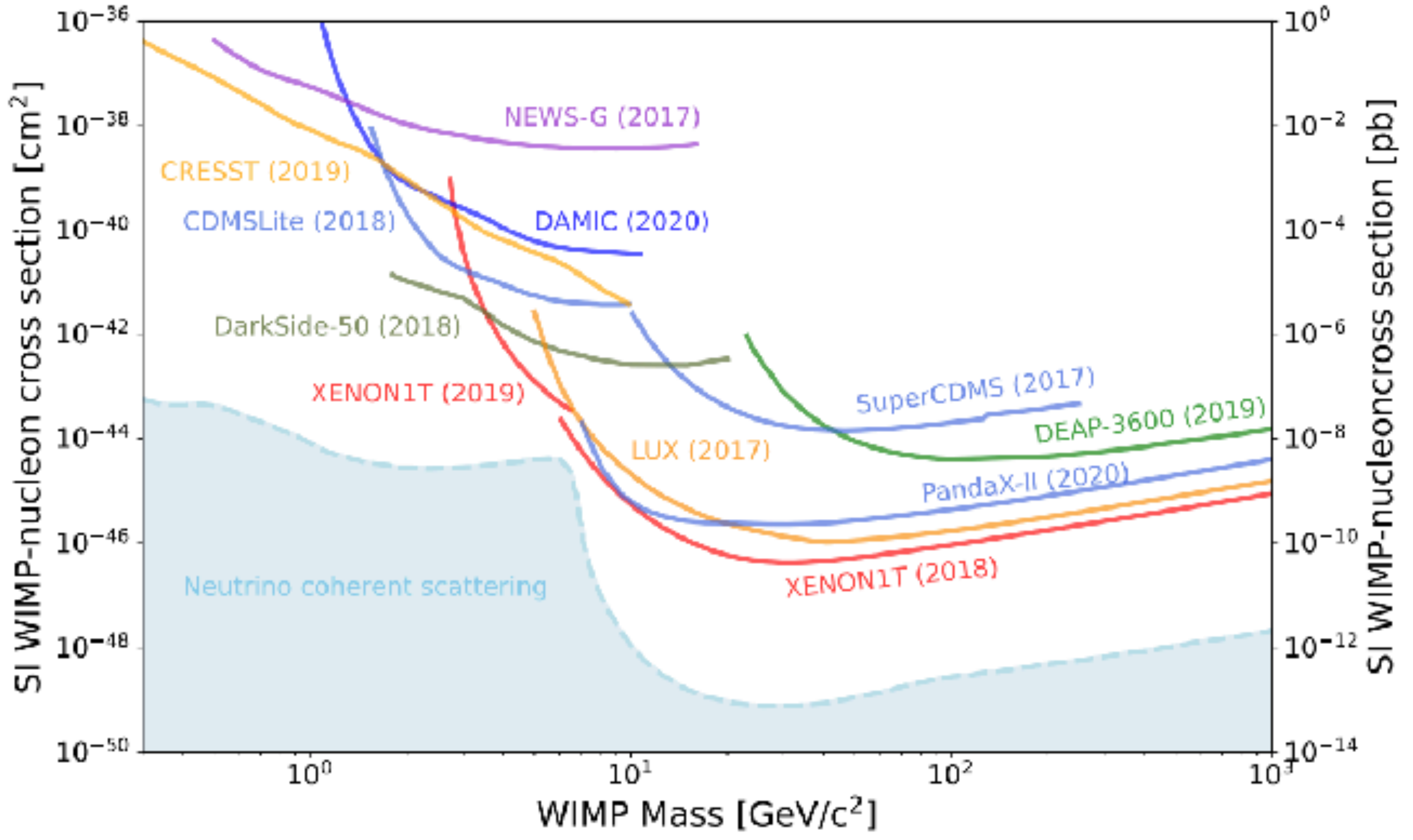
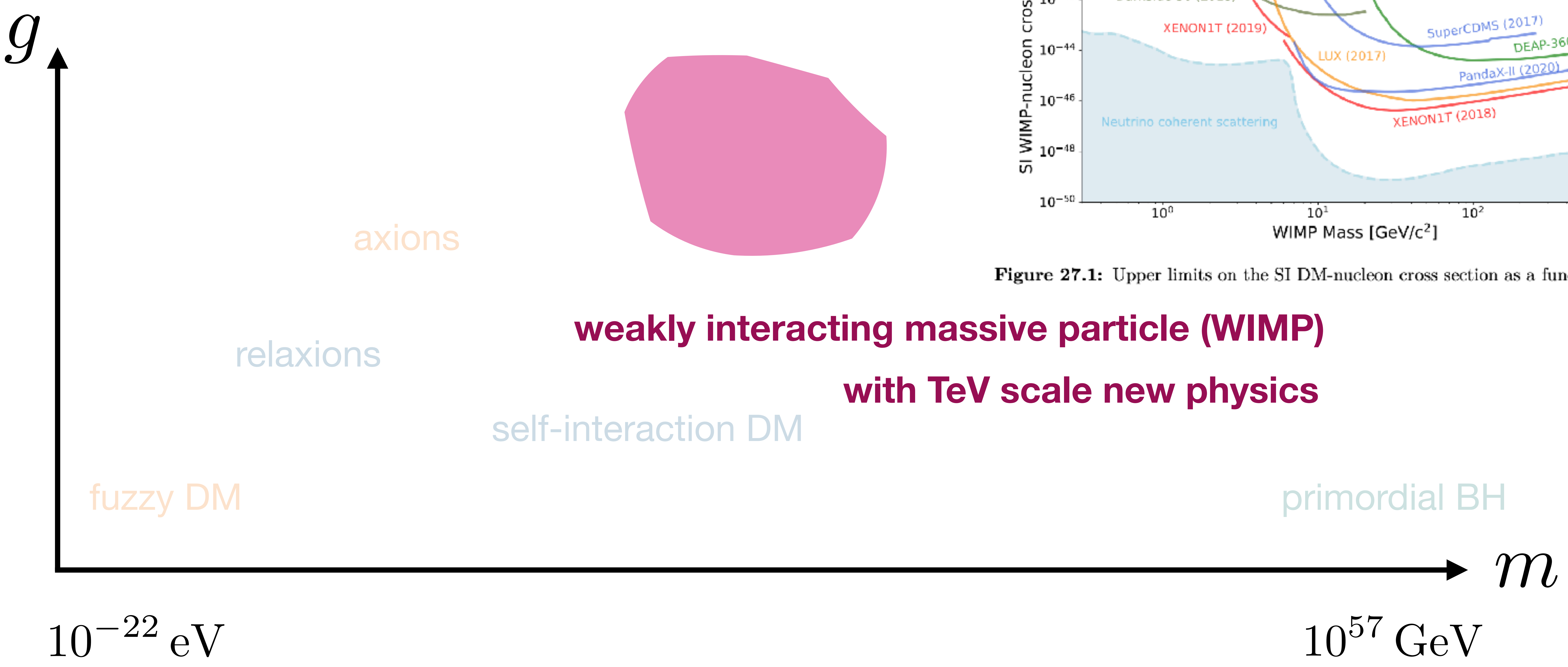


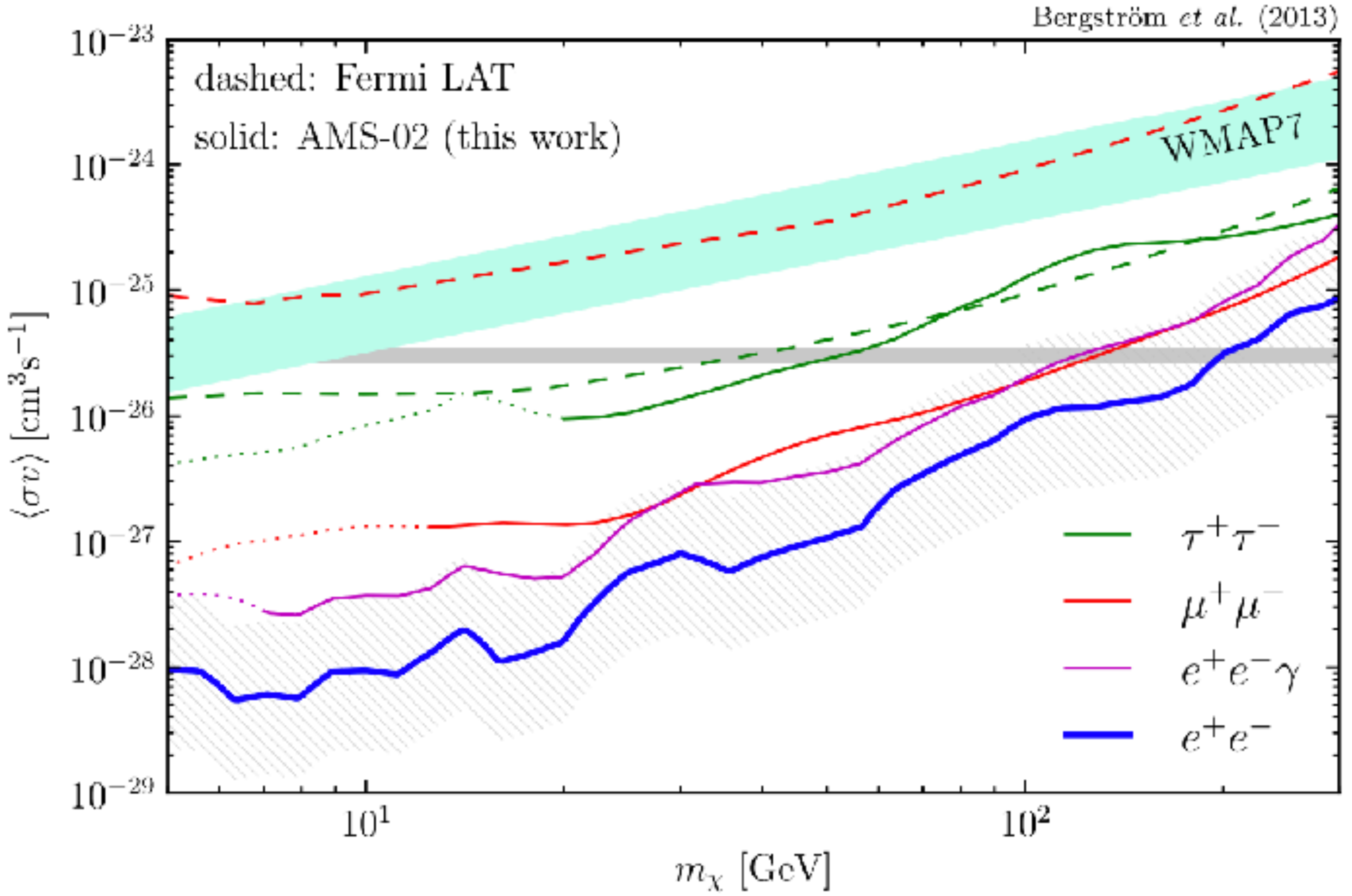
Figure 27.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.

for dark matter



weakly interacting massive particle (WIMP)

with TeV scale new physics



naturalness reasoning

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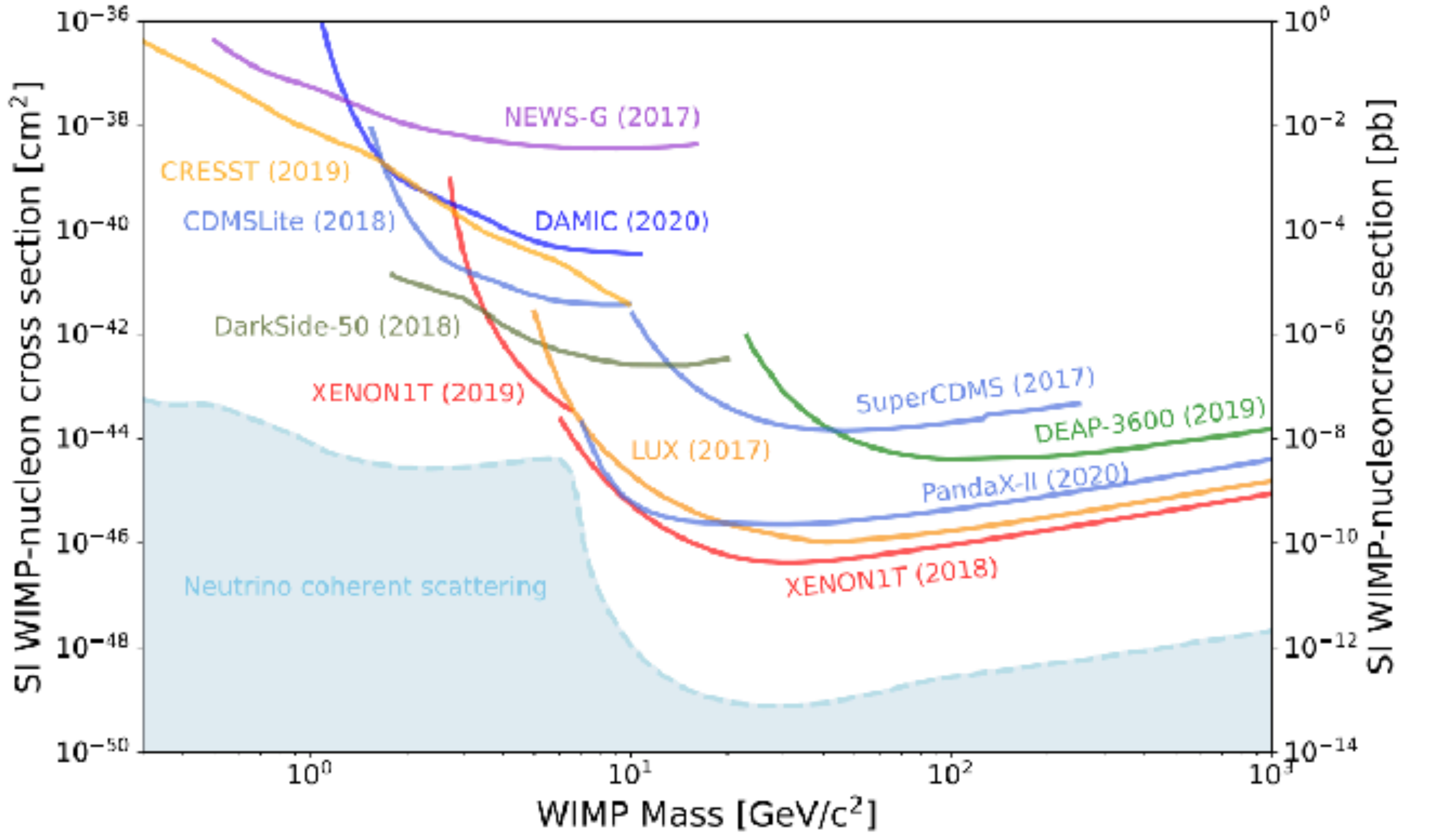

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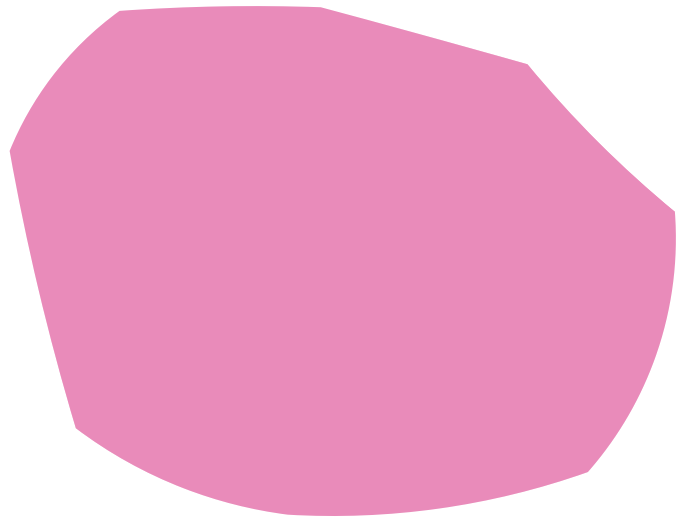


axions

weakly interacting massive particle (WIMP)

relaxions

with TeV scale new physics

self-interaction DM

fuzzy DM

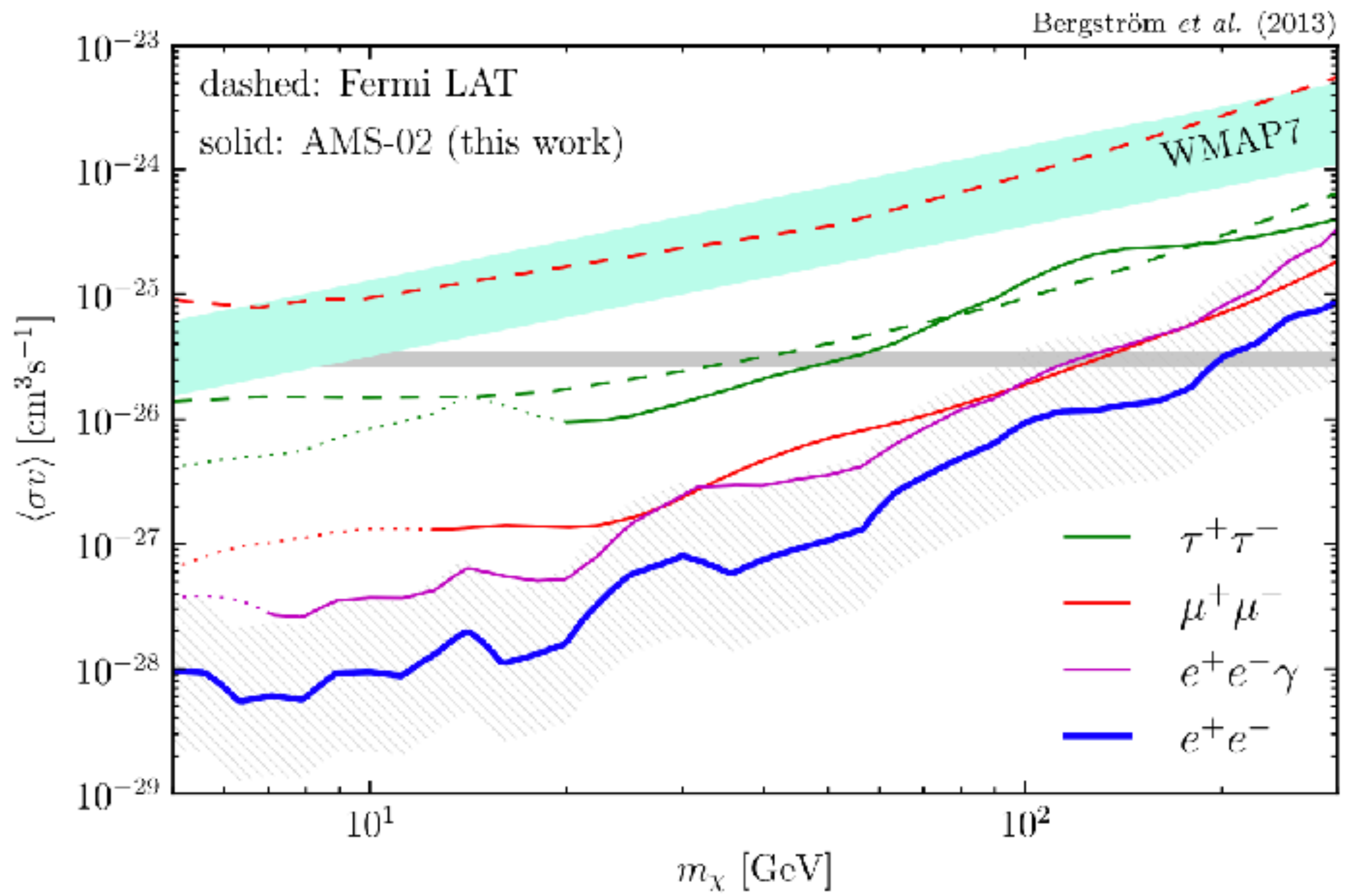
primordial BH

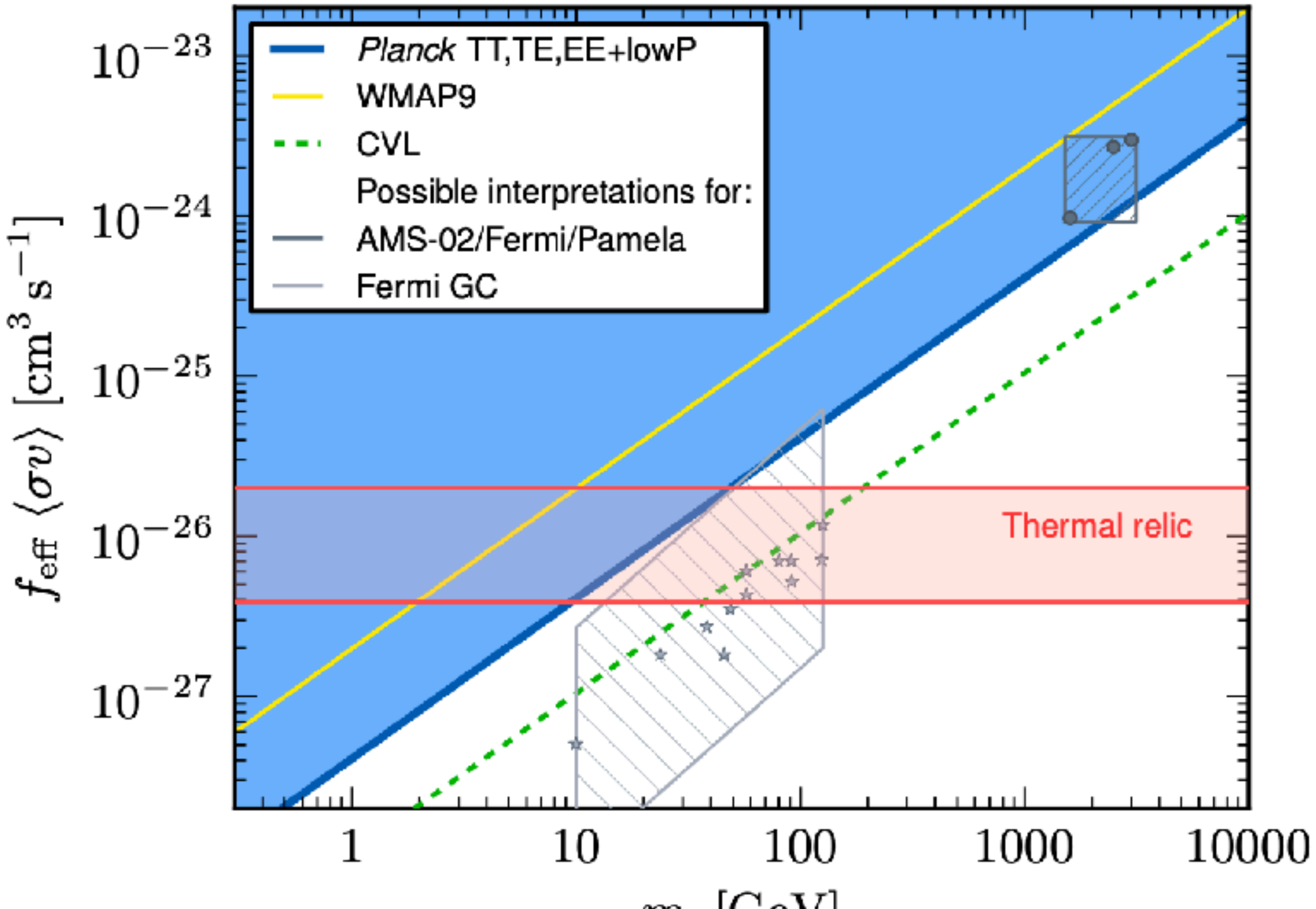
m

10^{-22} eV

10^{57} GeV

naturalness reasoning





Planck collaboration(15)

Particle Data Group 2021

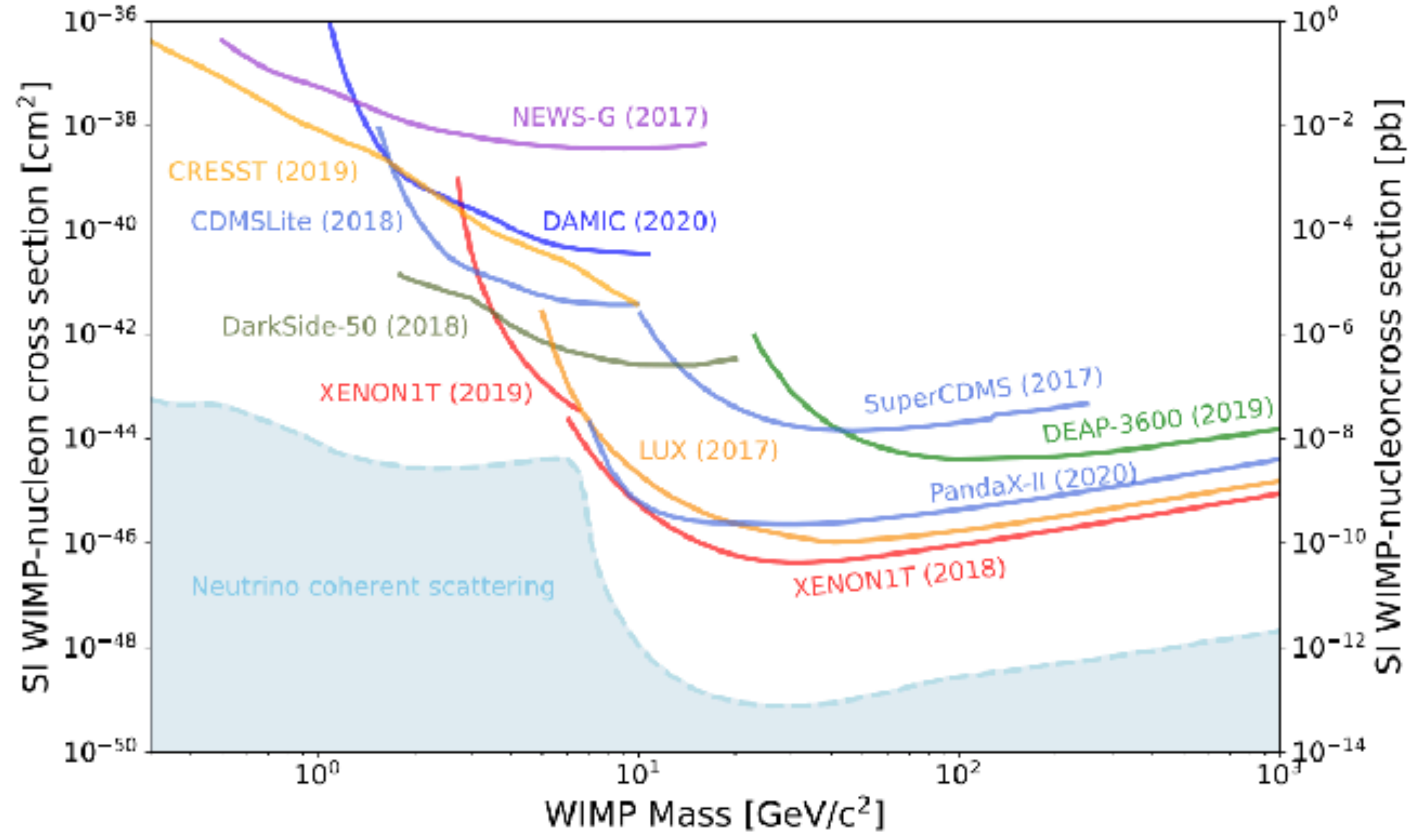


Figure 27.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.

for dark matter

weakly interacting massive particle (WIMP)

with TeV scale new physics

f-interaction DM

primordial BH

m

10^{57} GeV

WIMP and TeV scale new physics
guided by naturalness reasoning
are under intense pressure
from DM (in)direct detection exps. and LHC

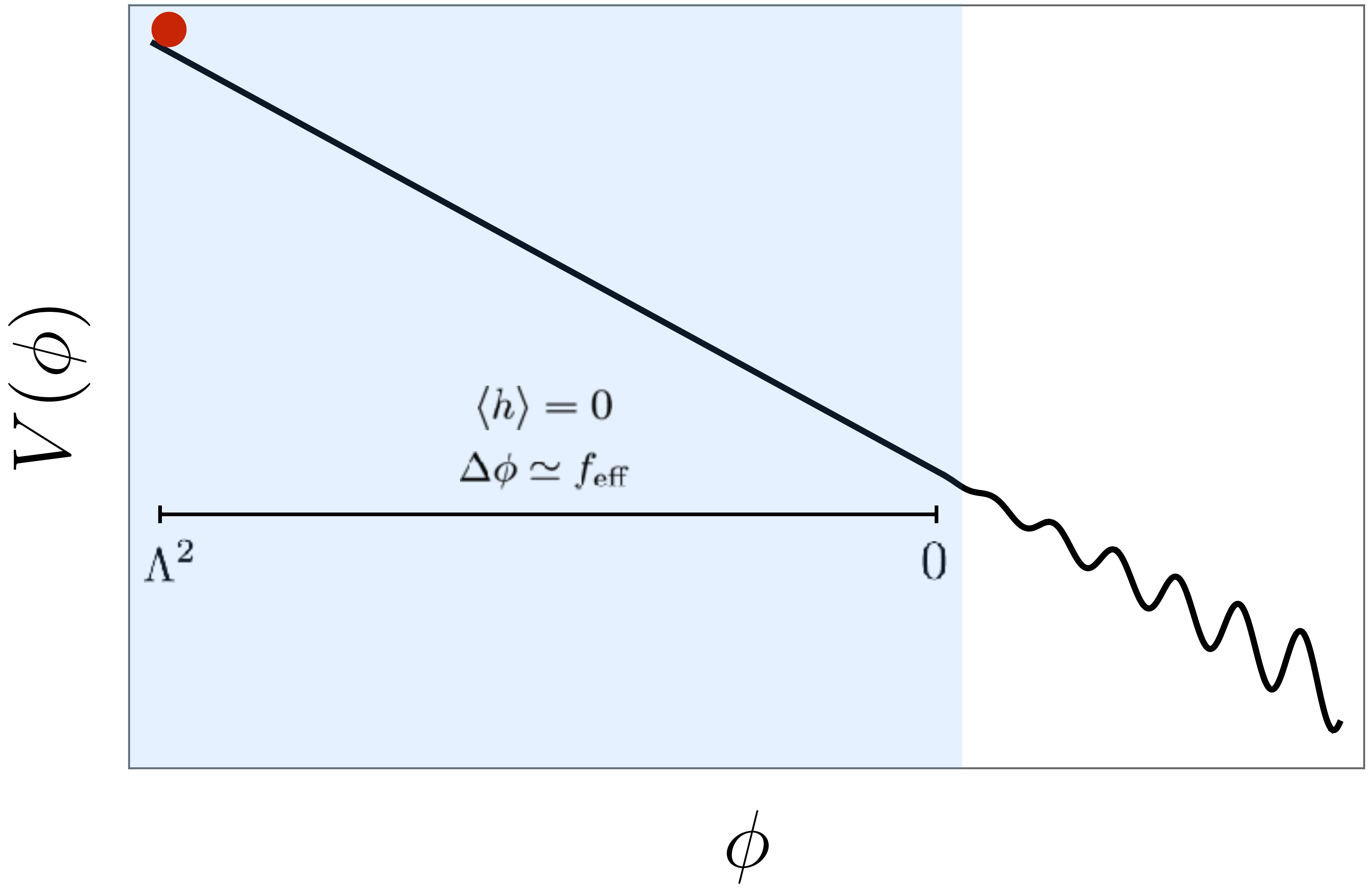
A recent development in naturalness reasoning provide interesting new insights

a particularly interesting proposal is

cosmological relaxation of EW scale

Graham, Kaplan, Rajendran (15)

$$V(\phi) = \left(\Lambda^2 - \Lambda^2 \frac{\phi}{f_{\rm eff}}\right)|h|^2 - \frac{\Lambda^4}{f_{\rm eff}}\phi - \mu_b^2 |h|^2 \cos(\phi/f)$$



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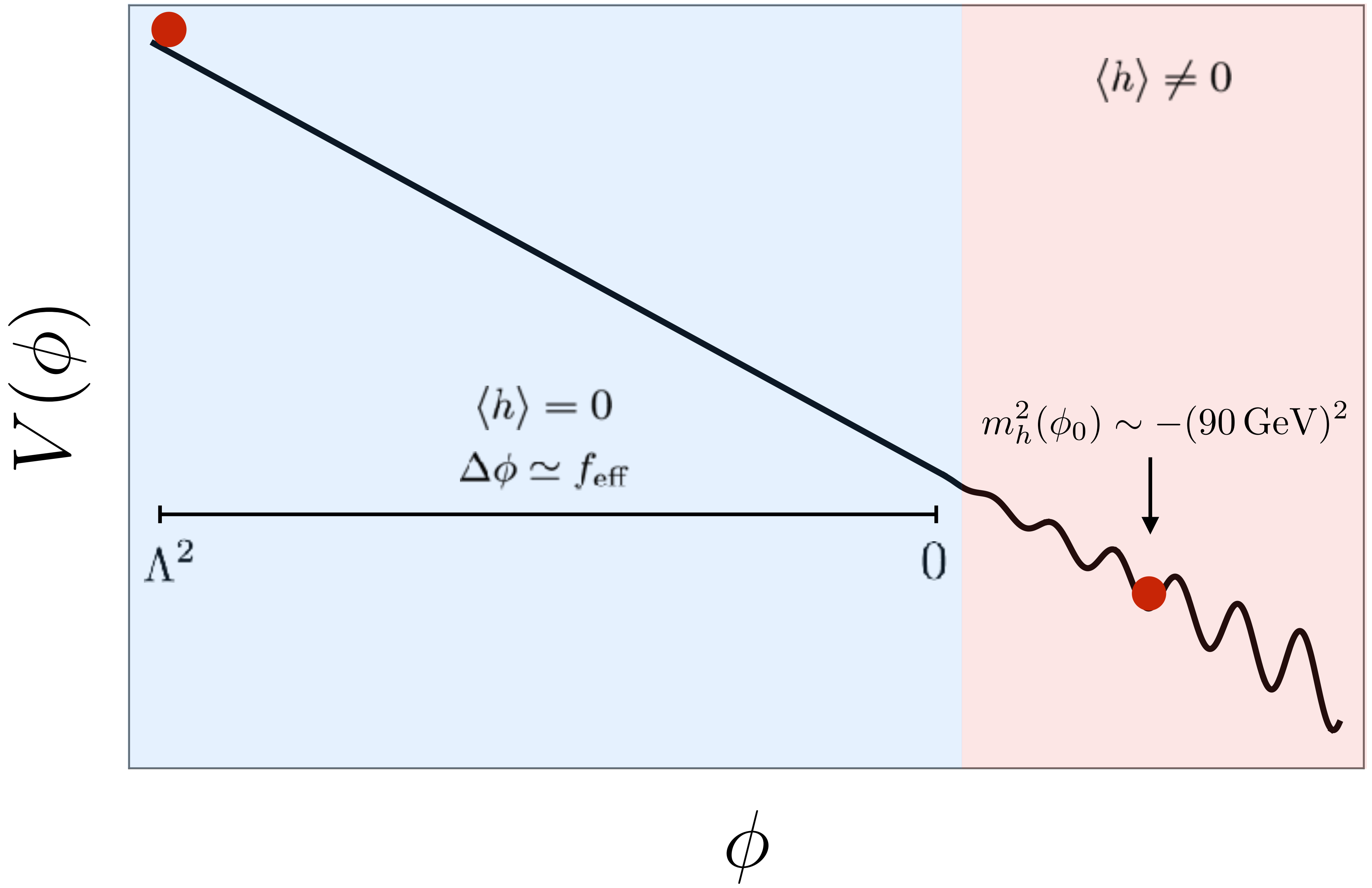


this solution is distinctive to canonical approaches
as it resolves the hierarchy problem in a *dynamical way*

predictions/signatures are also quite different:
unlike symmetry-based approahces predicting TeV scale new physics
this dynamical solution predicts an IR d.o.f — an axion-like particle

not only cosmological relaxation scenario

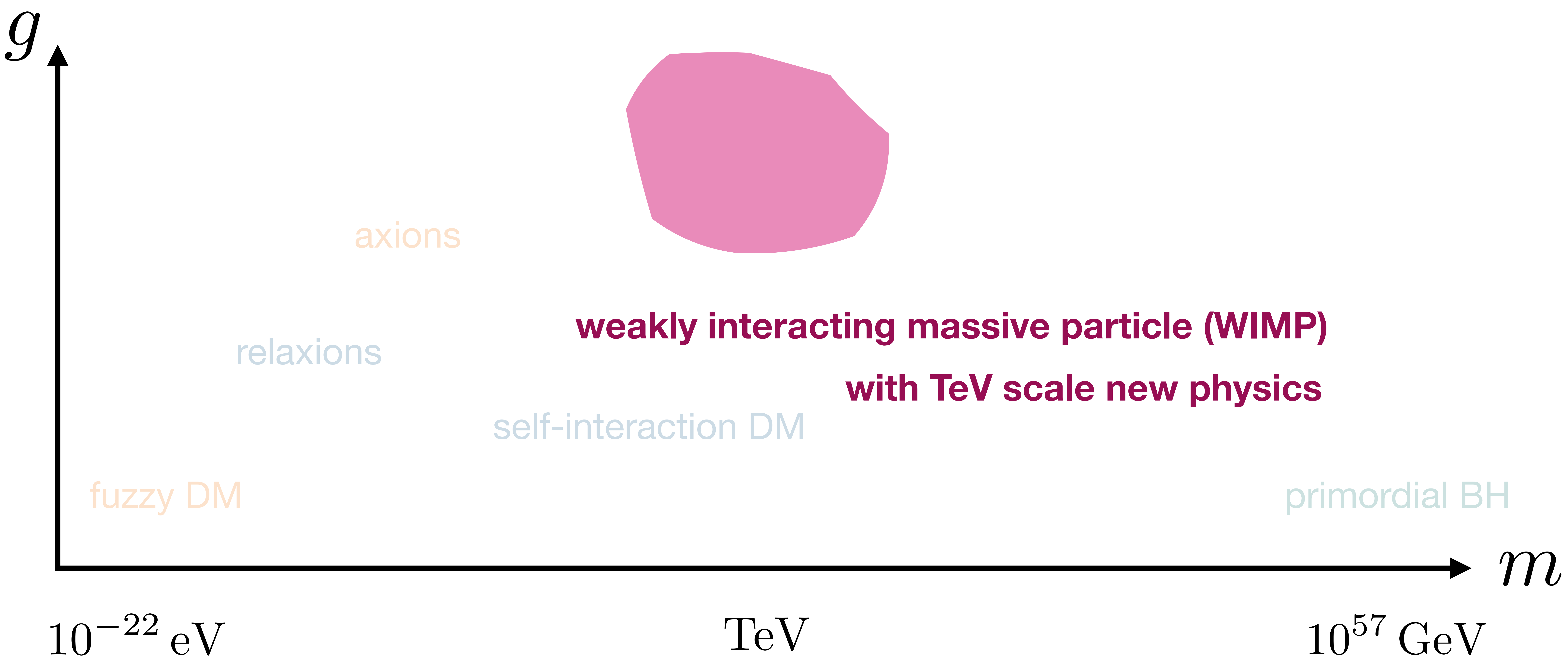
but also *many other dynamical solutions*

predicts axion-like particles

at the same time this axion-like particles

can also be dark matter in the universe!

Svrcek, Witten (08); Arvanitaki et al (09);
Graham, Kaplan, Rajendran (15); Arvanitaki et al (16);
Banerjee, **HK**, Perez (18); Arkani-Hamed et al (20);
Tito D'Agnolo, Teresi (21); Chatrchyan, Servant (22);
many others …



g
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10^{-22} eV
TeV
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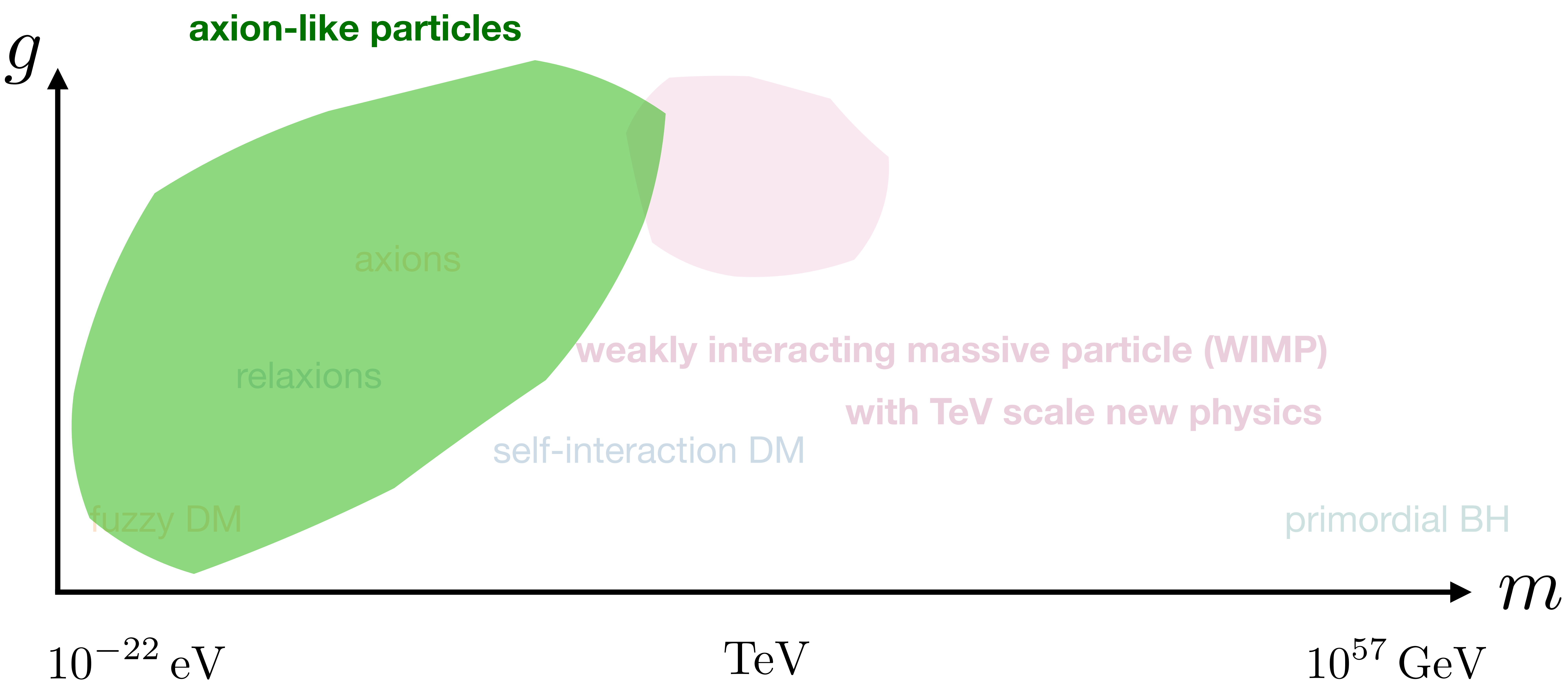
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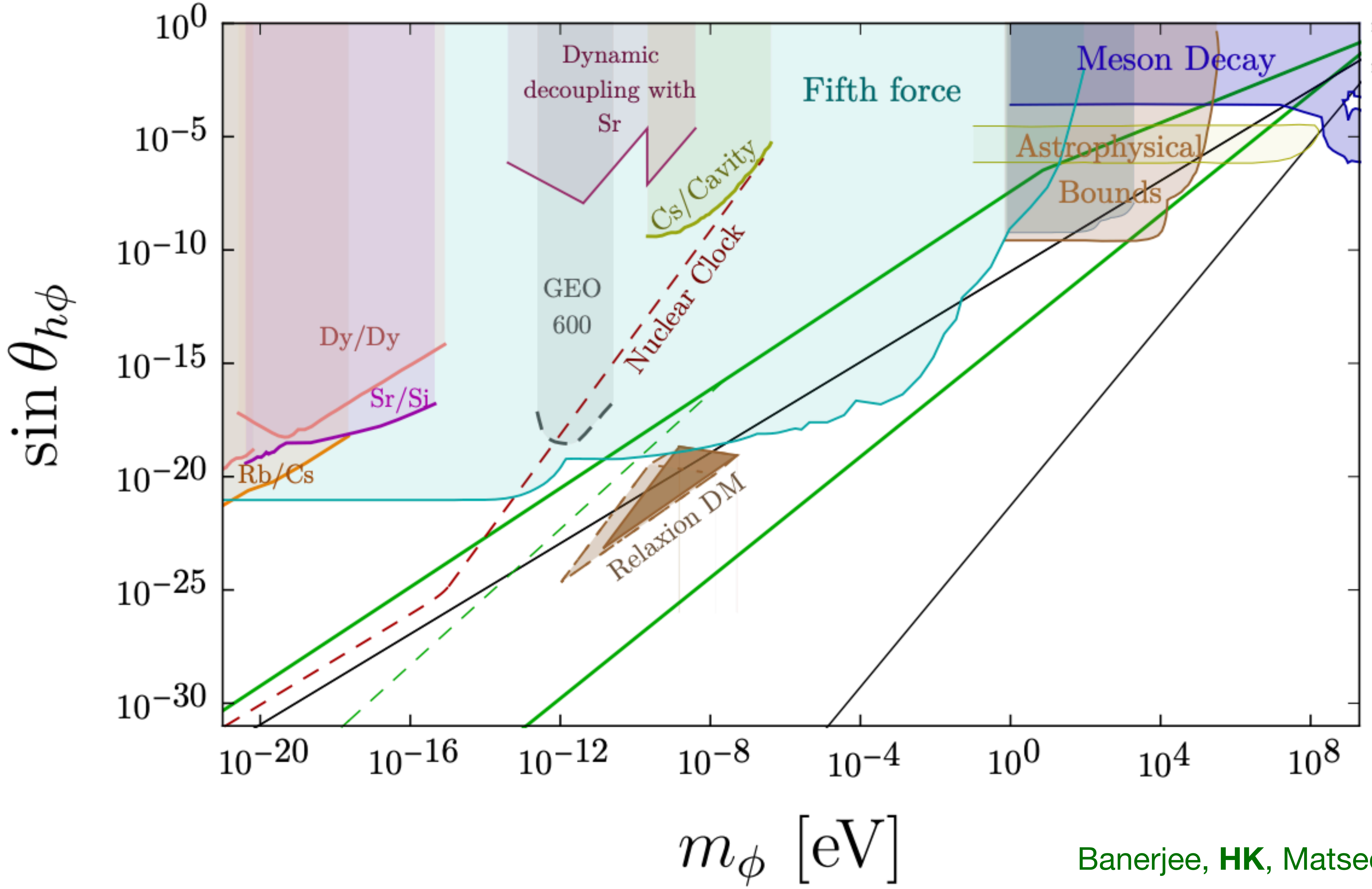
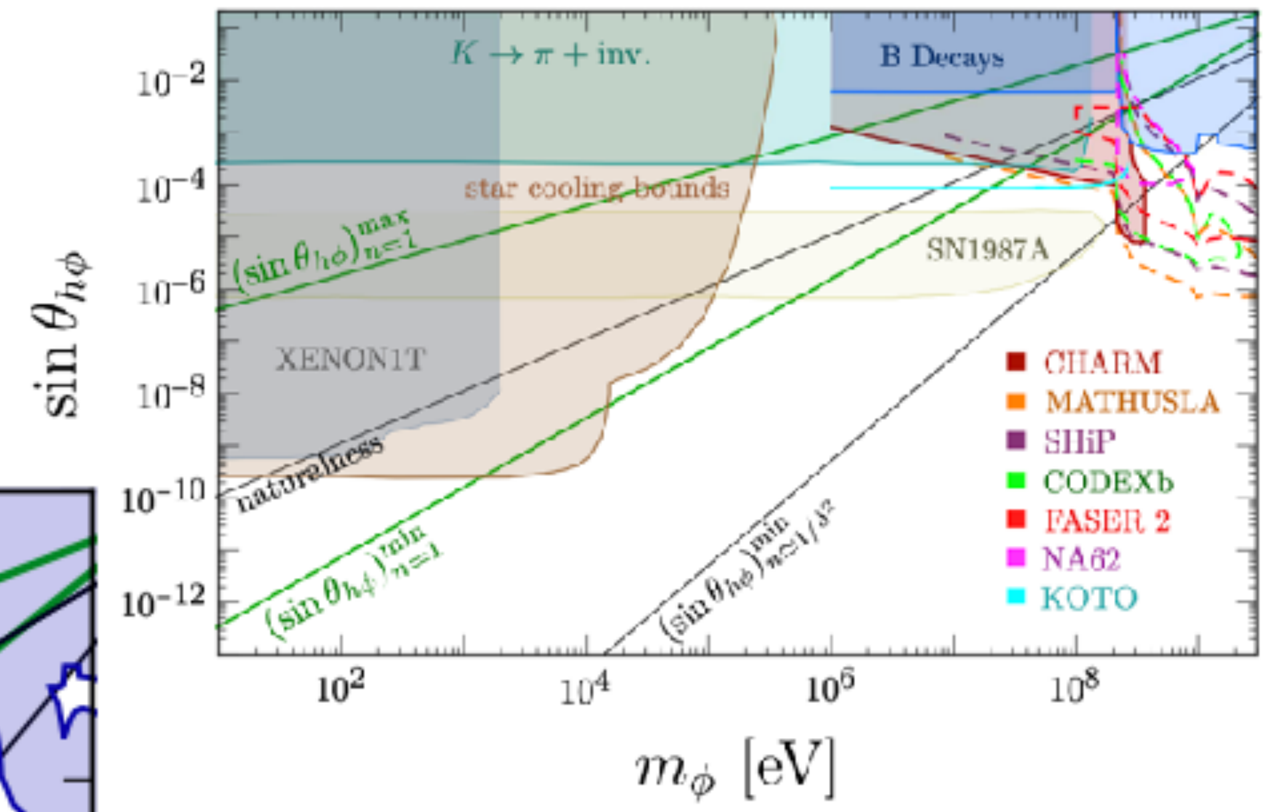
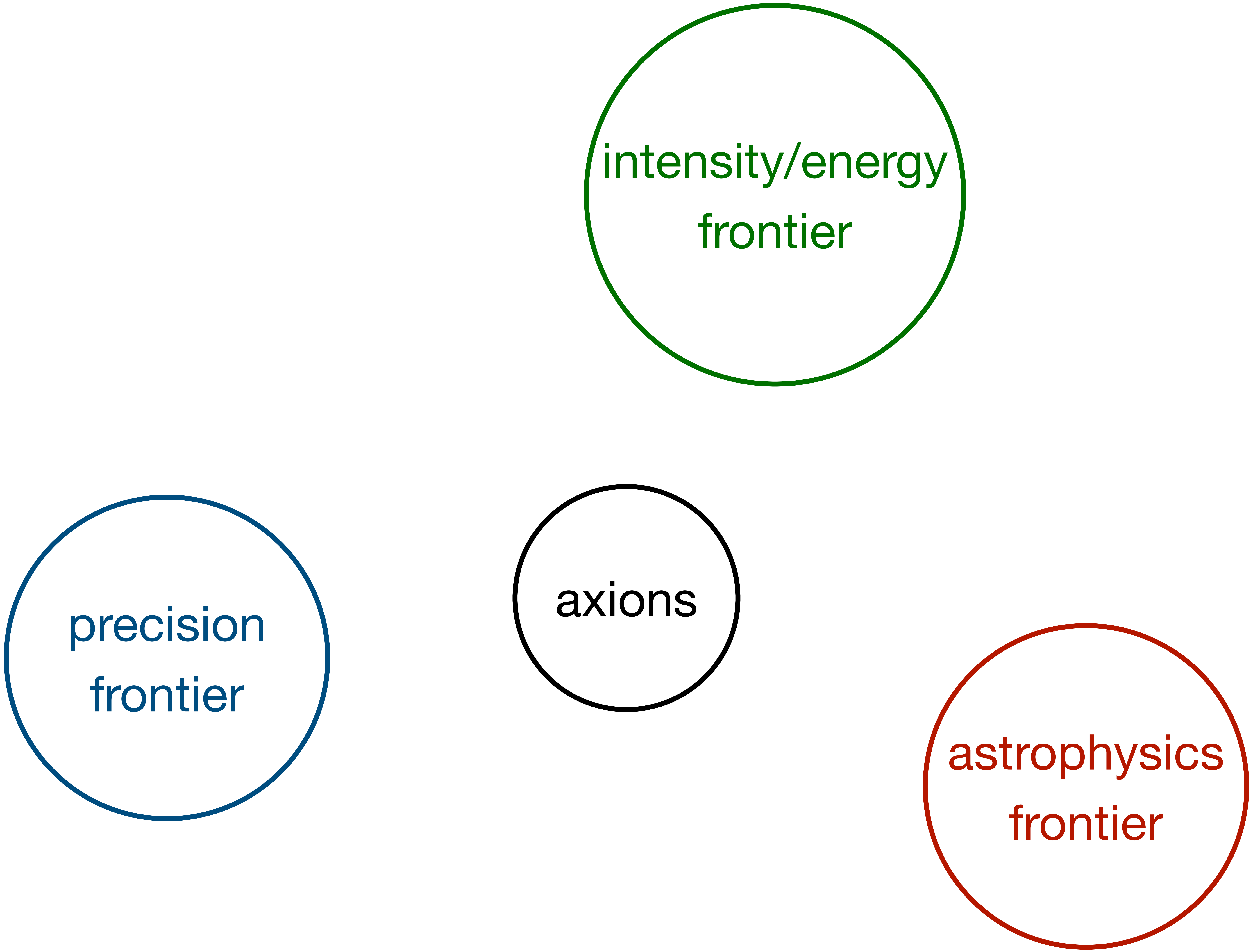




Banerjee, **HK**, Matsedonskyi, Perez, Safronova (20)
see also Chatrchyan and Servant (22)

as this type of solution predicts a light degree of freedom
strategies for new physics search must be adapted accordingly

since the mass of axion-like particle is less restricted
it introduces *new challenges:*
where / how should we search for this new physics?

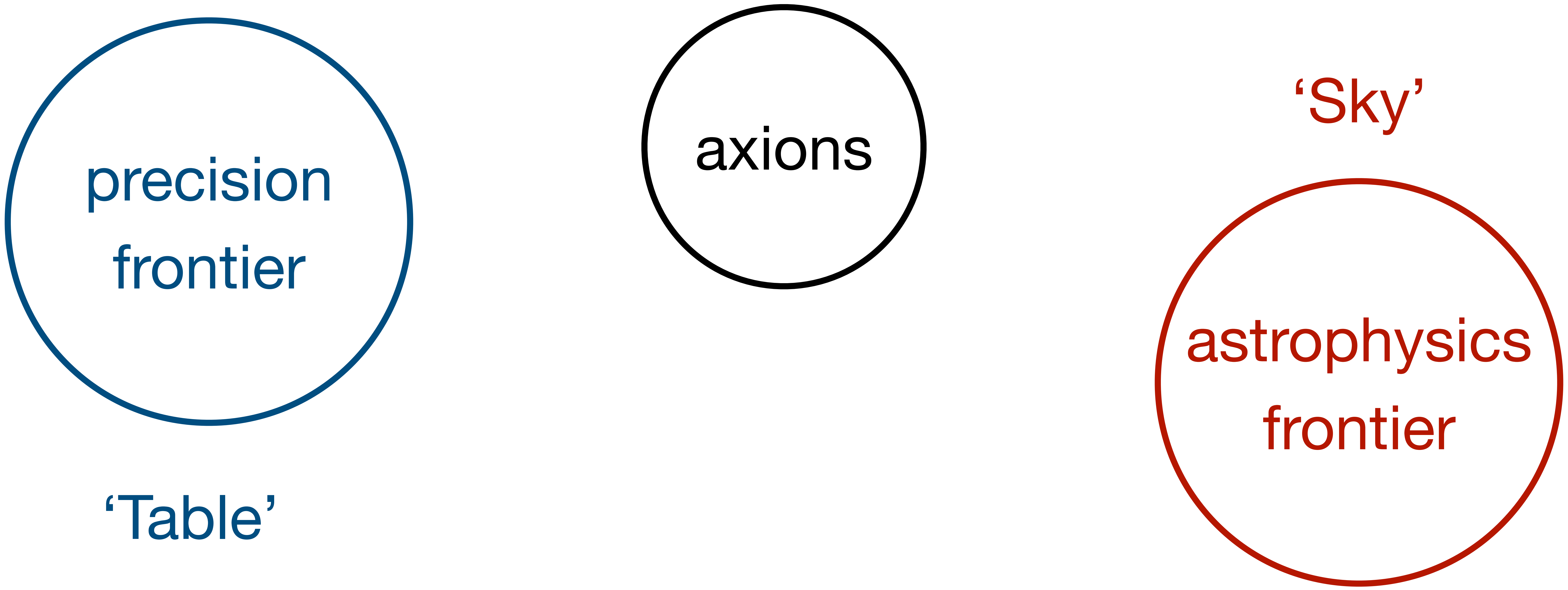

intensity/energy
frontier
axions
precision
frontier
astrophysics
frontier

in past 10 years

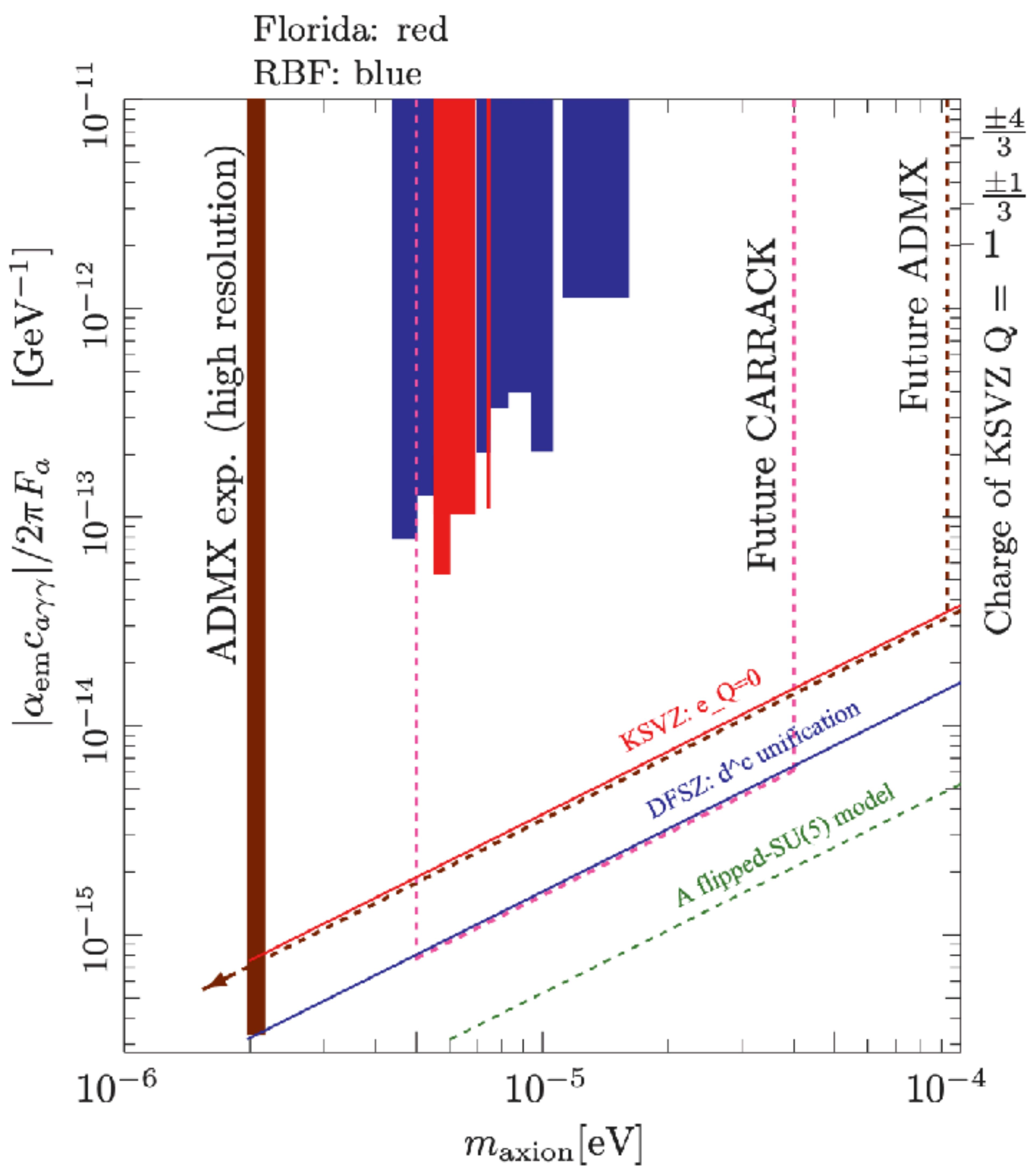
interesting progress has been made

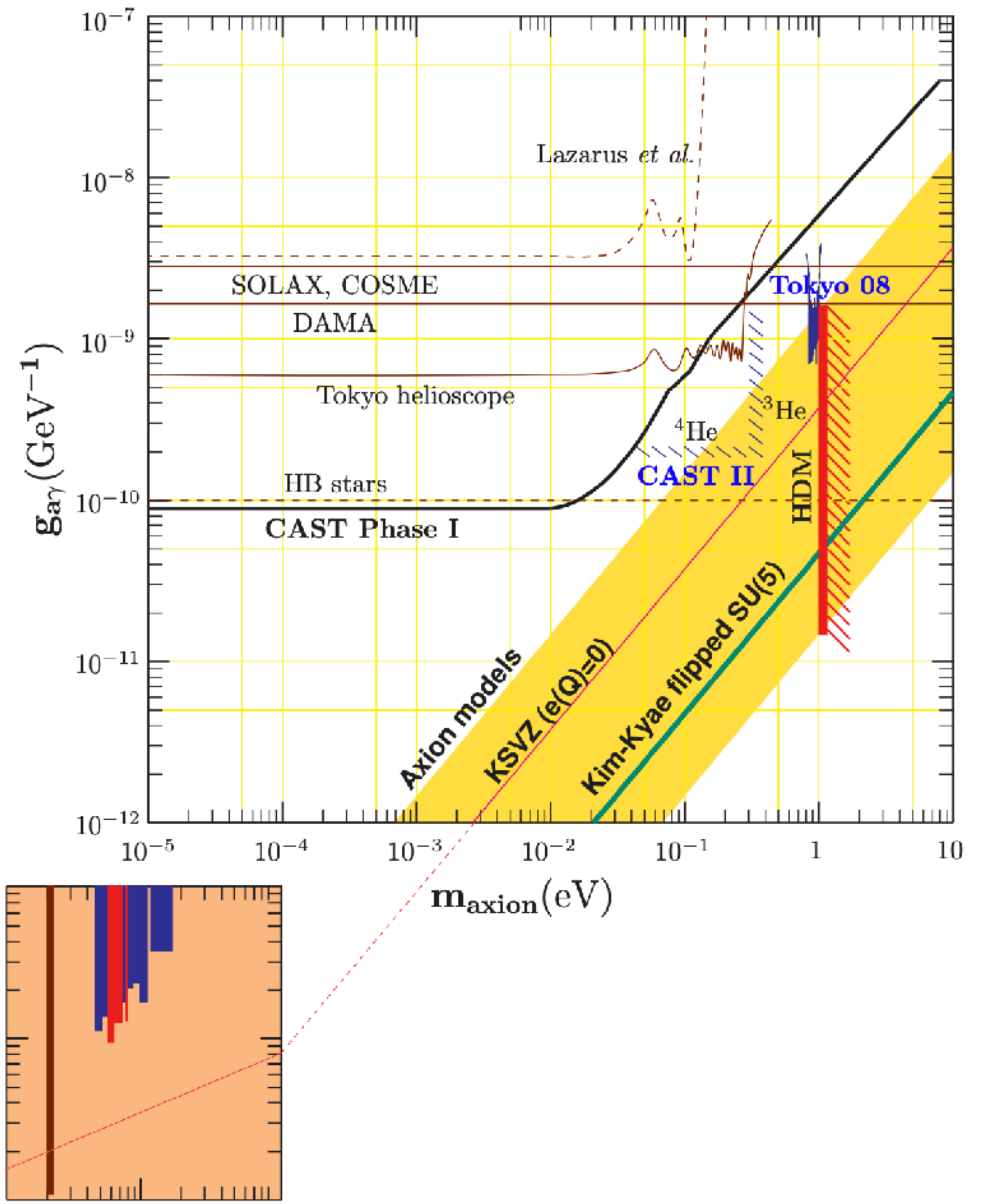
for *searching for axion-like particle (DM)*

in the 'sky' and on 'tables'



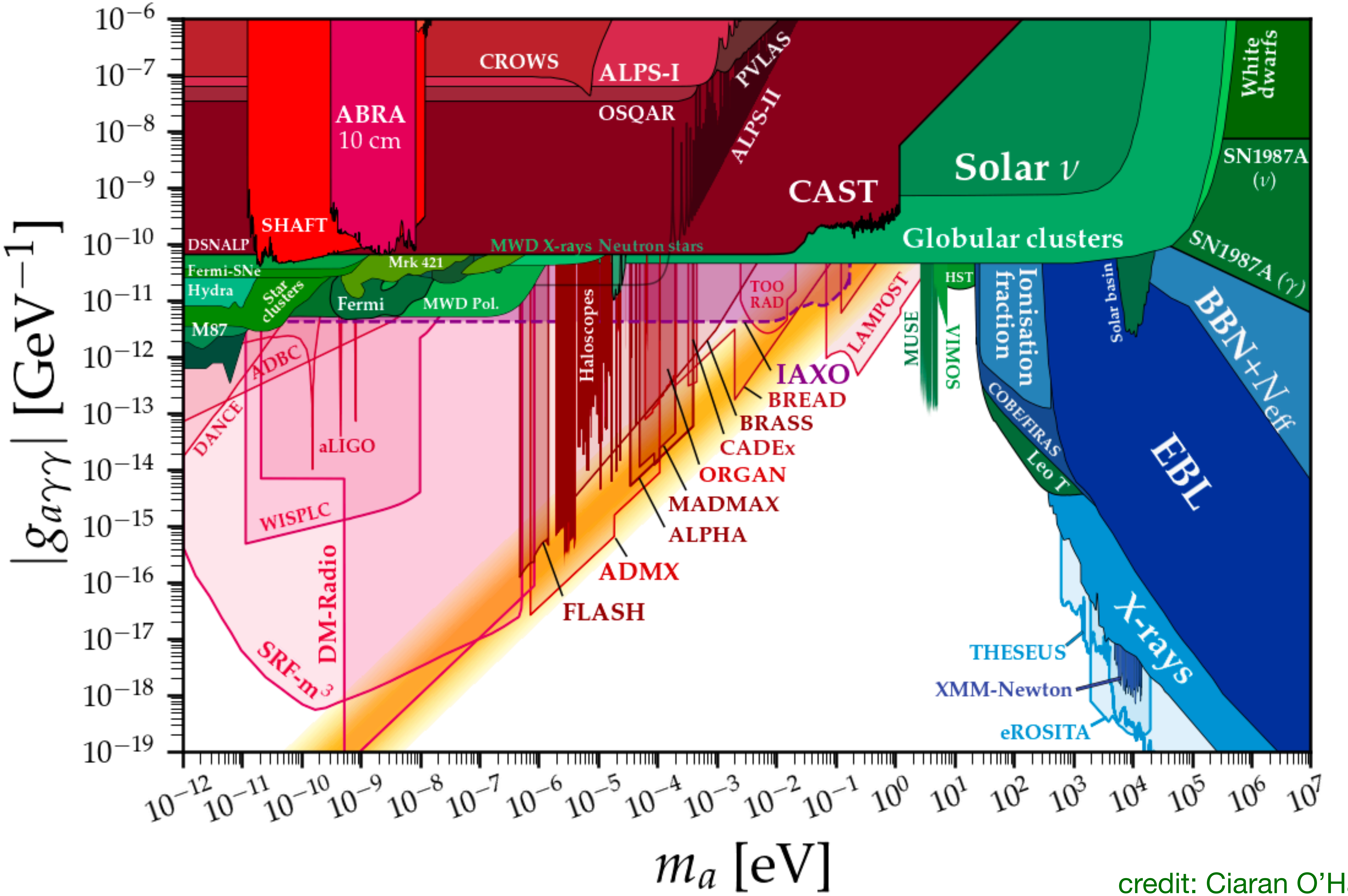
axion searches on ‘tables’ looked like this 14 years ago …



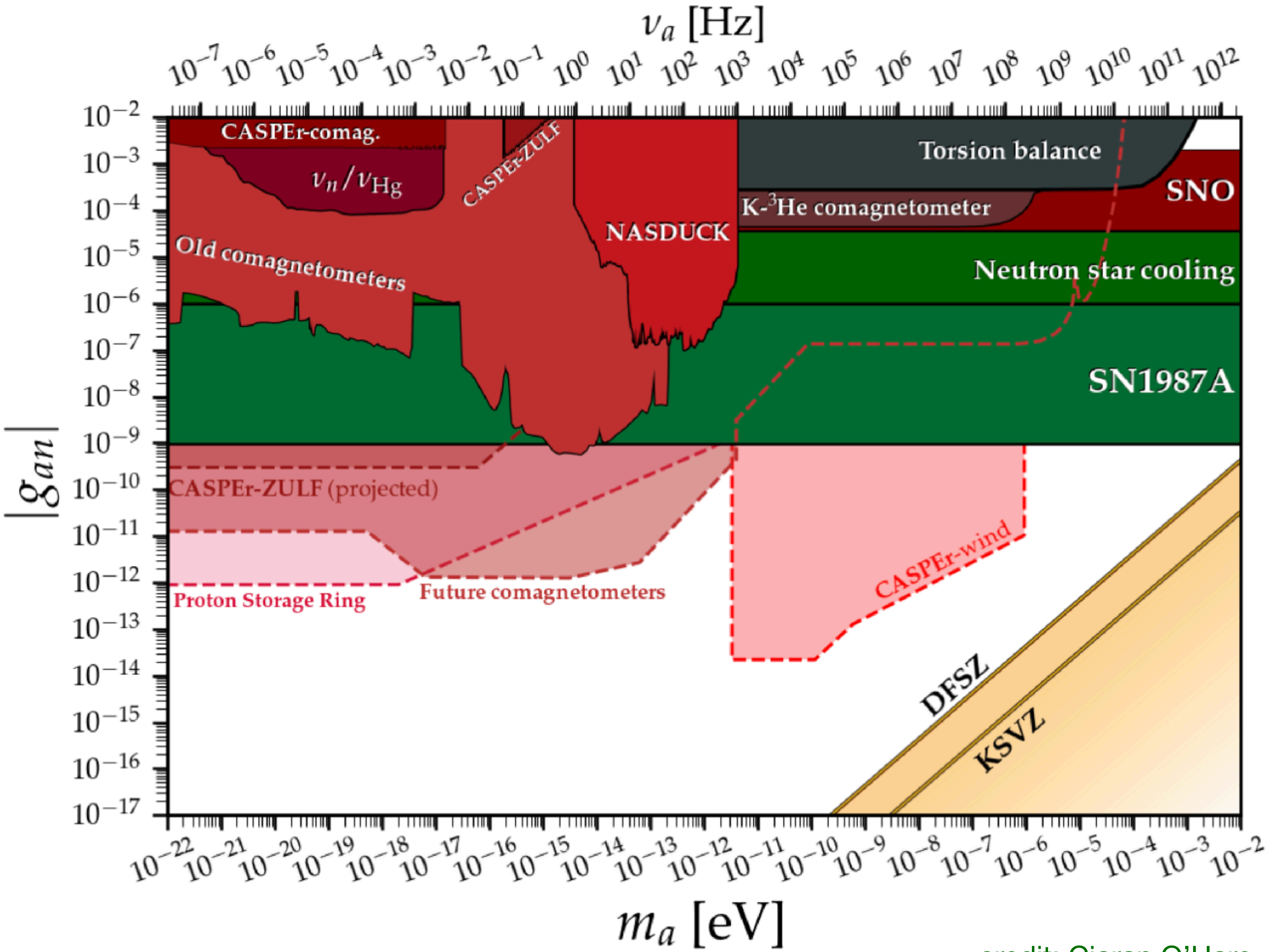


Kim and Carosi (08)

now it looks like …



credit: Ciaran O'Hare



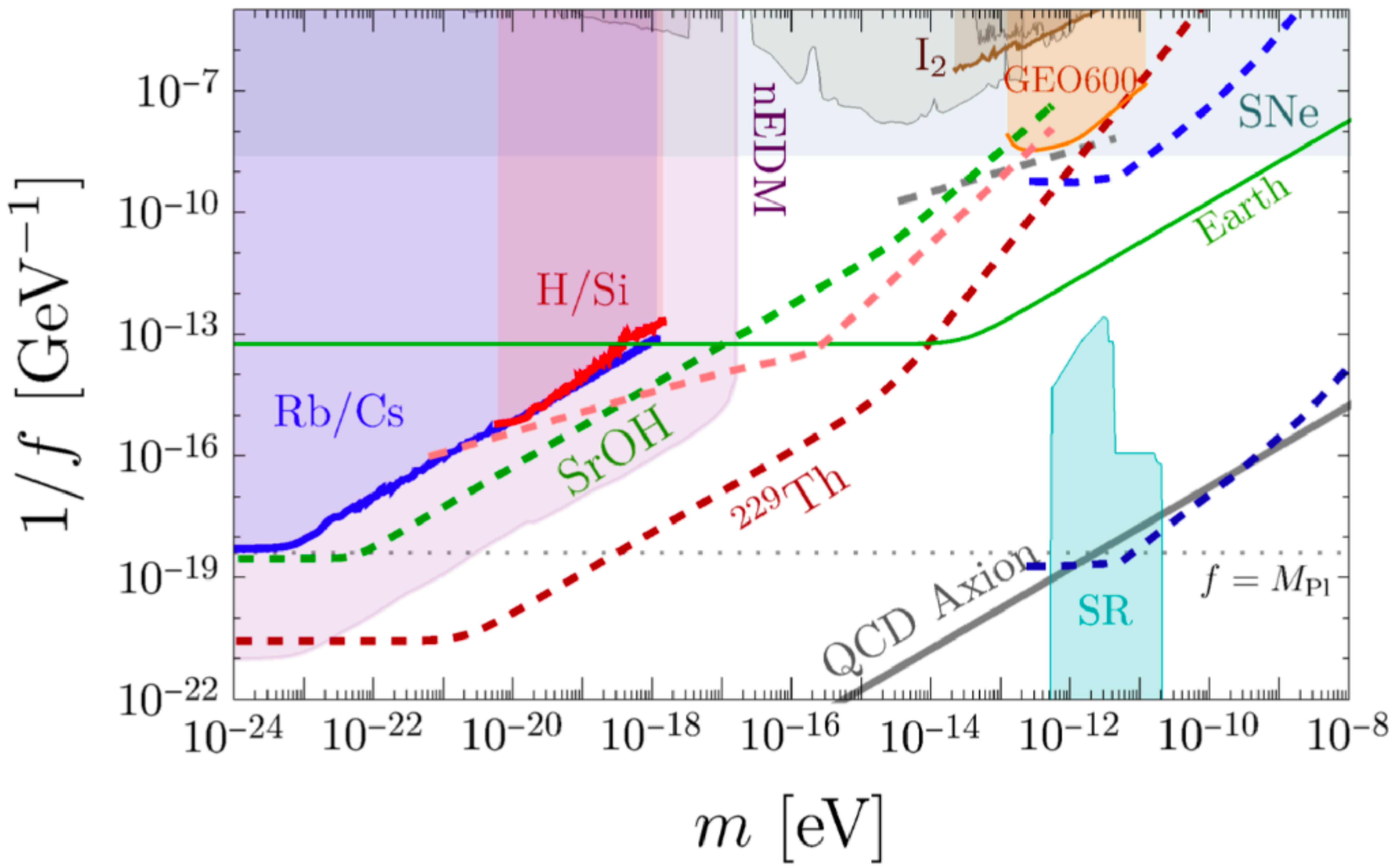
credit: Ciaran O'Hare

in addition to this

axion DM can also be searched

with atomic/molecular spectroscopy, interferometry, and accelerometry

HK, Perez (22)



In the standard model

the following is allowed

$$\mathcal{L} = \theta G \widetilde{G}$$

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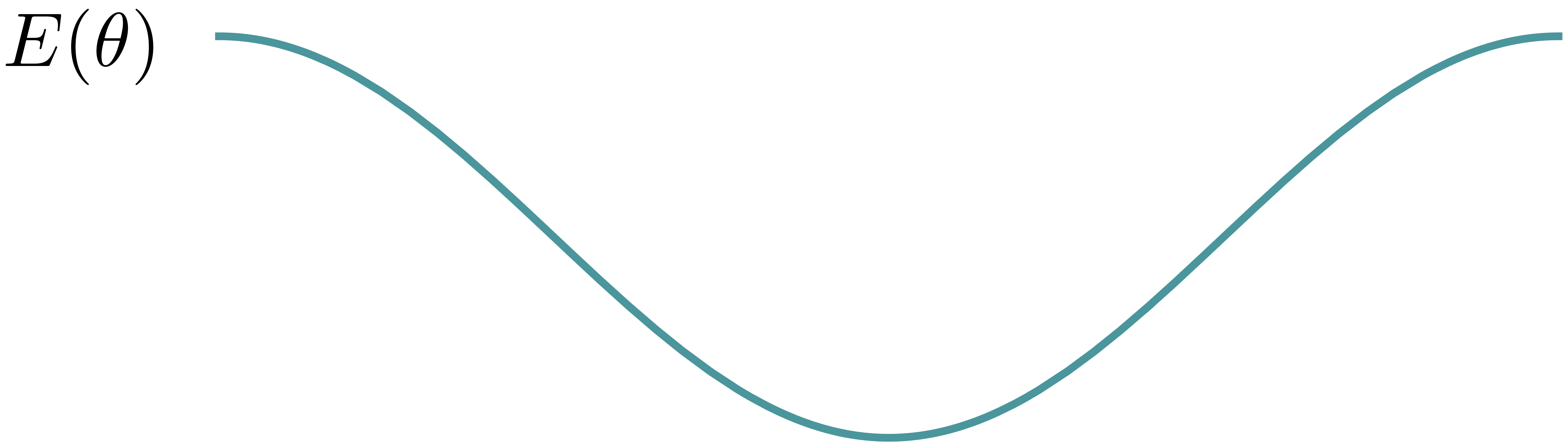
θ is physical

QCD vacuum energy depends on θ



In the standard model

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θ is physical

pion mass also depends on θ

$$m_\pi^2(\theta) = m_\pi^2(0)\sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2}\sin^2(\theta/2)}$$

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$$m_\pi^2(\theta) = m_\pi^2(0)\sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2}\sin^2(\theta/2)}$$

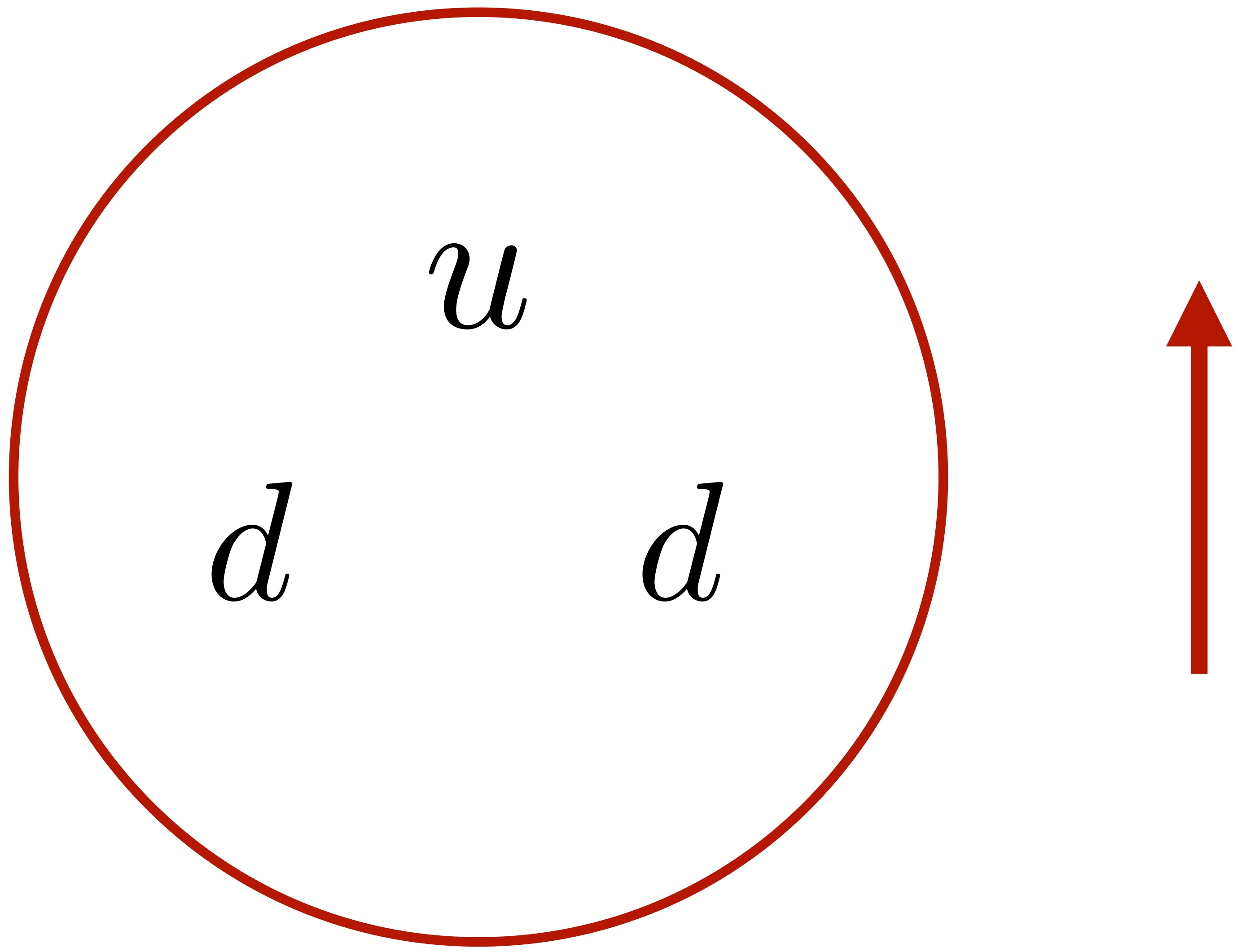
Different choice of θ leads to different spectrum

In the standard model

the following is allowed

$$\mathcal{L} = \theta G\widetilde{G}$$

θ is physical



$$d_n \sim 10^{-16}\theta\, \mathrm{e}\cdot\mathrm{cm}$$

$$|d_n|_{\mathrm{exp}} \lesssim 10^{-26}\, \mathrm{e}\cdot\mathrm{cm}$$

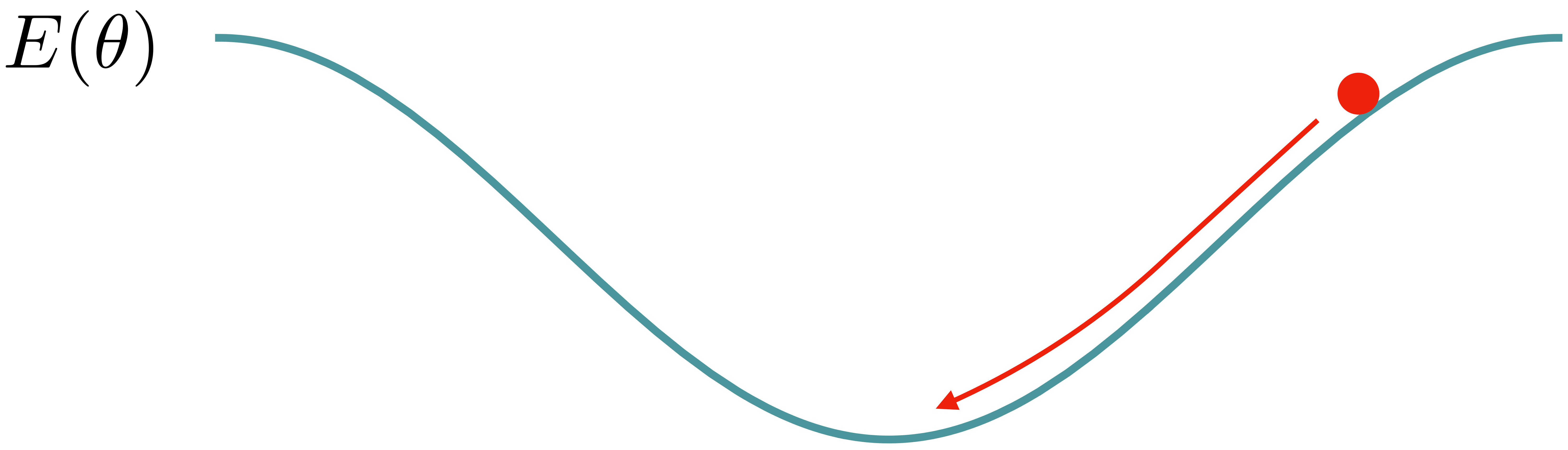
Abel et al (20)

neutron electric dipole moment

Consider

$$\mathcal{L} = \theta G\widetilde{G}$$

Now imagine θ=a/f as dynamical degrees of freedom



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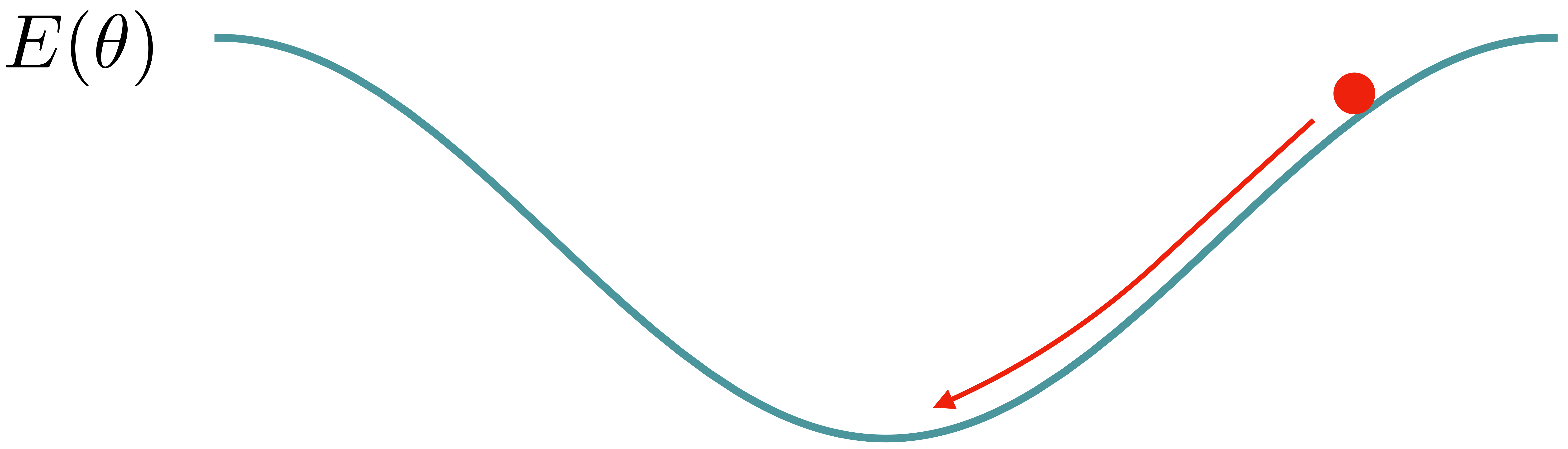
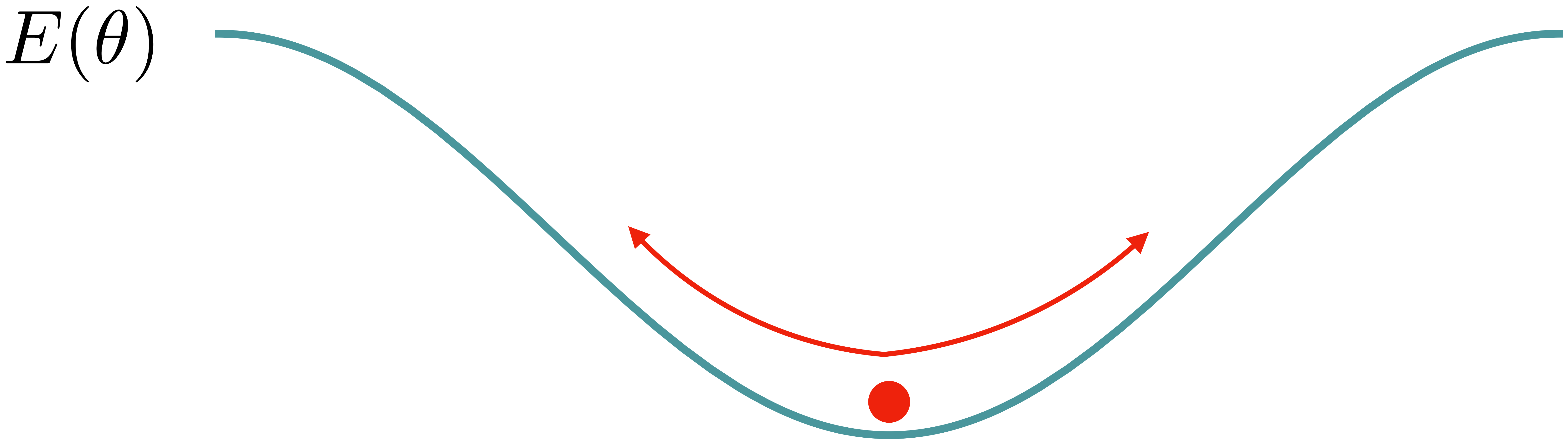


The strong CP angle dynamically relaxes to CP-conserving vacuum

solving the strong CP dynamically

This *axion* could oscillate around minimum



Such a oscillating field behaves like matter

Axion oscillation around its minimum comprises ***DM*** *in the present universe*

What are the implications?

Since QCD spectrum depends on θ

the presence of axion DM naturally imply

oscillations of nuclear quantities

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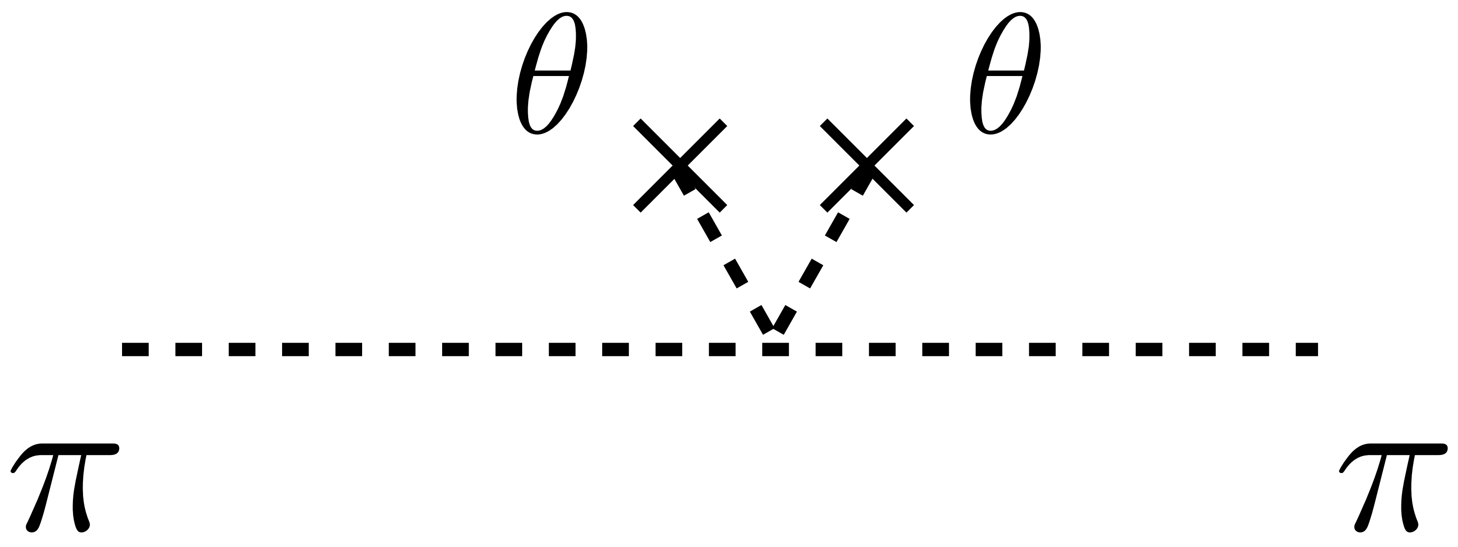
$$m_\pi^2(\theta)$$



$$\frac{\delta m_\pi^2}{m_\pi^2} = -\frac{m_u m_d}{2(m_u + m_d)^2}\theta^2$$

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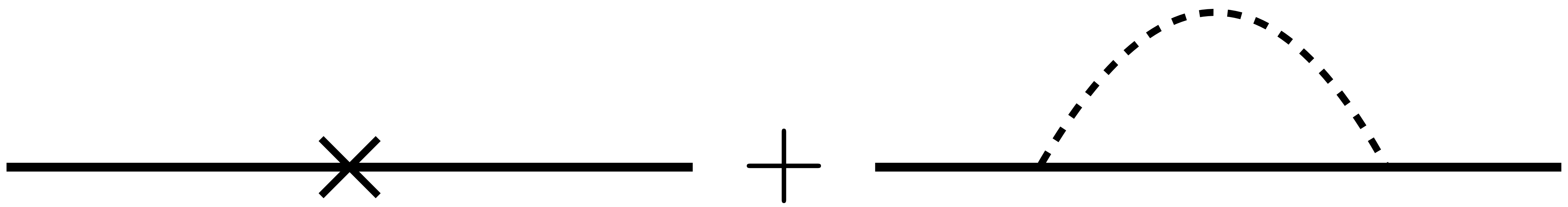
the presence of axion DM naturally imply

oscillations of nuclear quantities

$$m_\pi^2(\theta) \qquad m_N(\theta)$$



$$\Delta m_N \simeq -4c_1 m_\pi^2(\theta) - \frac{3g_A^2 m_\pi^3(\theta)}{32\pi f_\pi^2}$$

What are the implications?

Since QCD spectrum depends on θ

the presence of axion DM naturally imply

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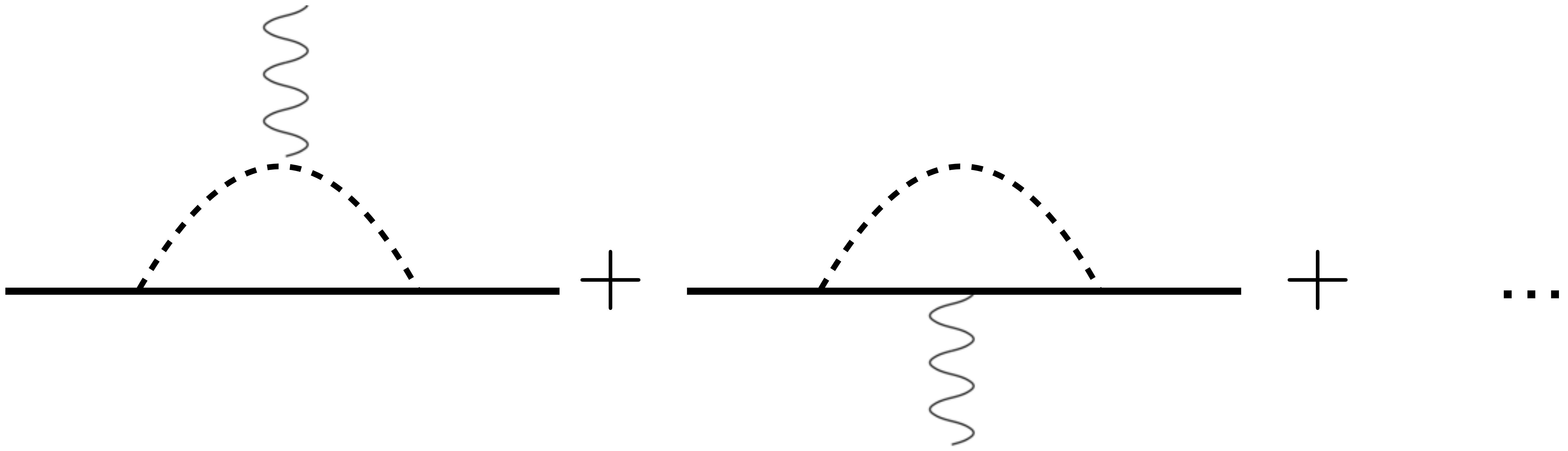
$$m_\pi^2(\theta) \qquad m_N(\theta) \qquad g_{n,p}(\theta)$$



$$\Delta g_{n,p}(\theta) \simeq \pm \frac{g_A^2 m_N m_\pi(\theta)}{4\pi f_\pi^2}$$

Are oscillations of atomic energy level observable in a lab?

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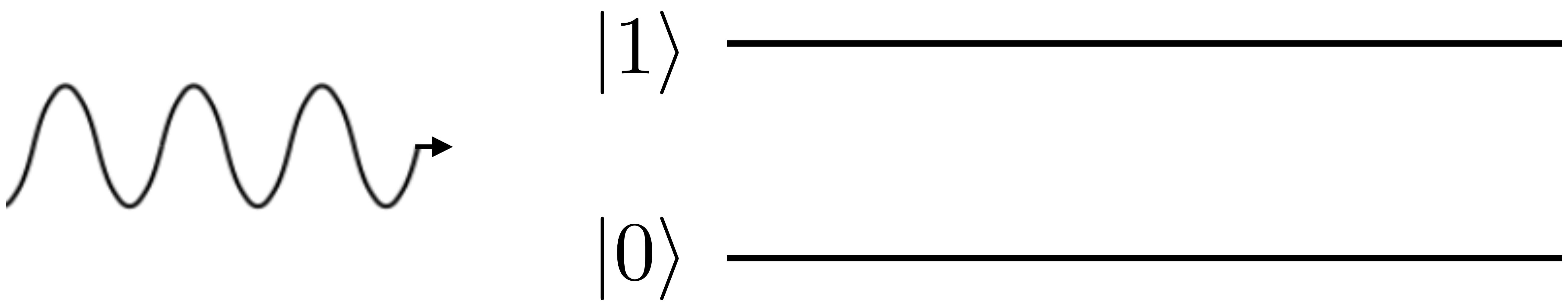
Imagine a situation where we interrogate atoms periodically to measure the transition frequency



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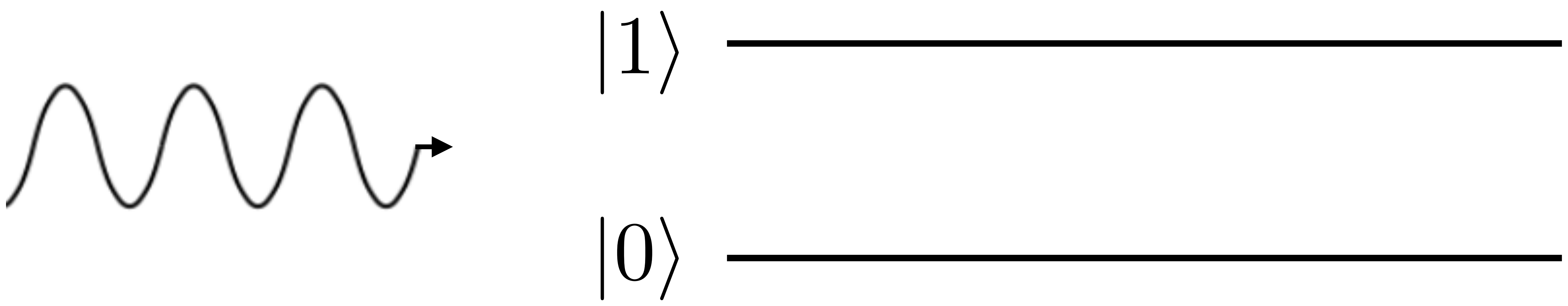
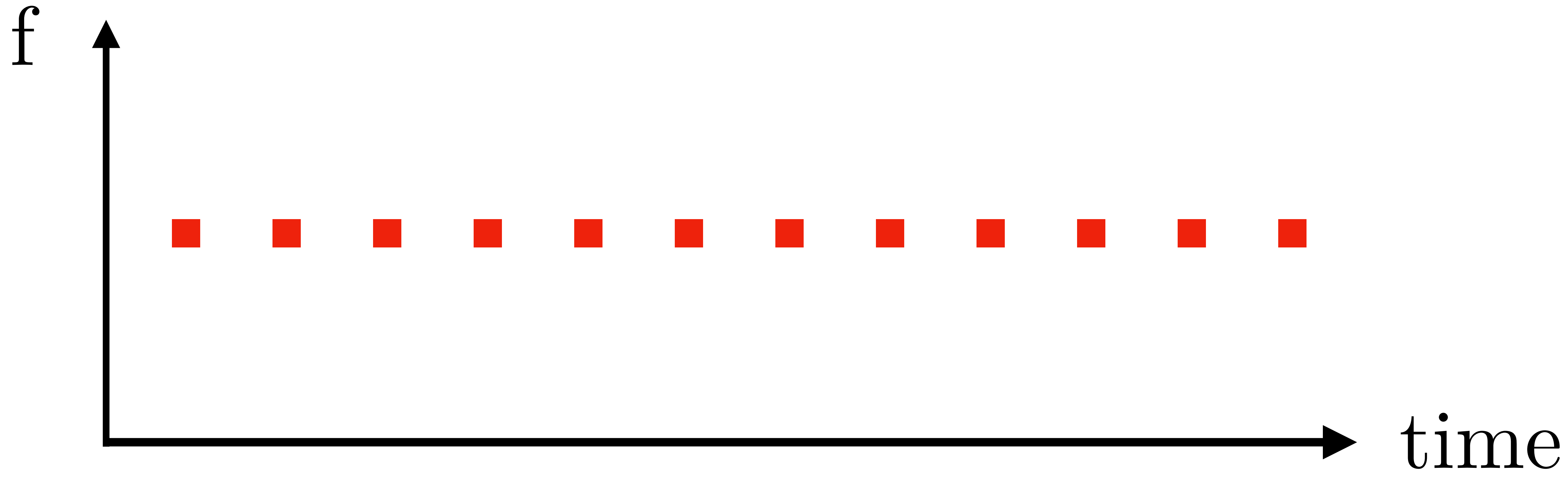
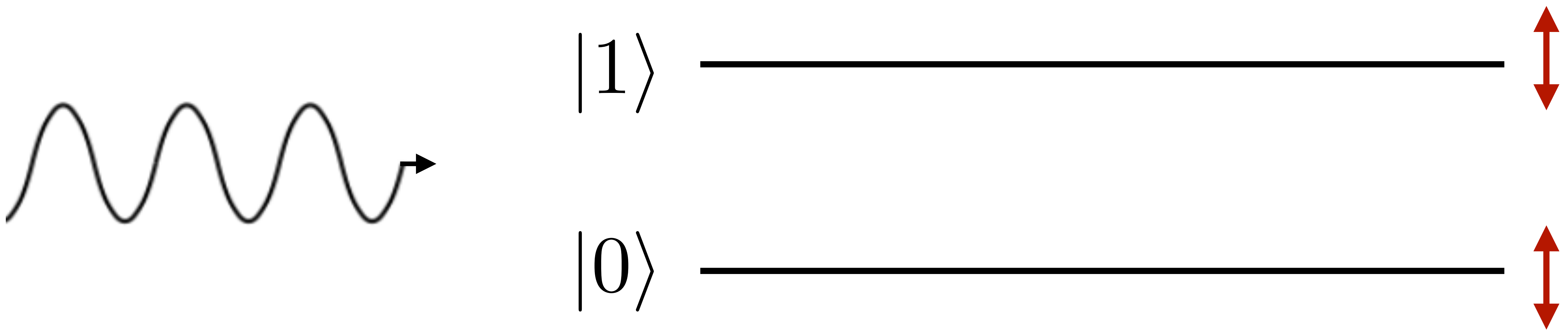


In an *ideal world* without axion, this measurement would give us



Now imagine the same exp. but with axion



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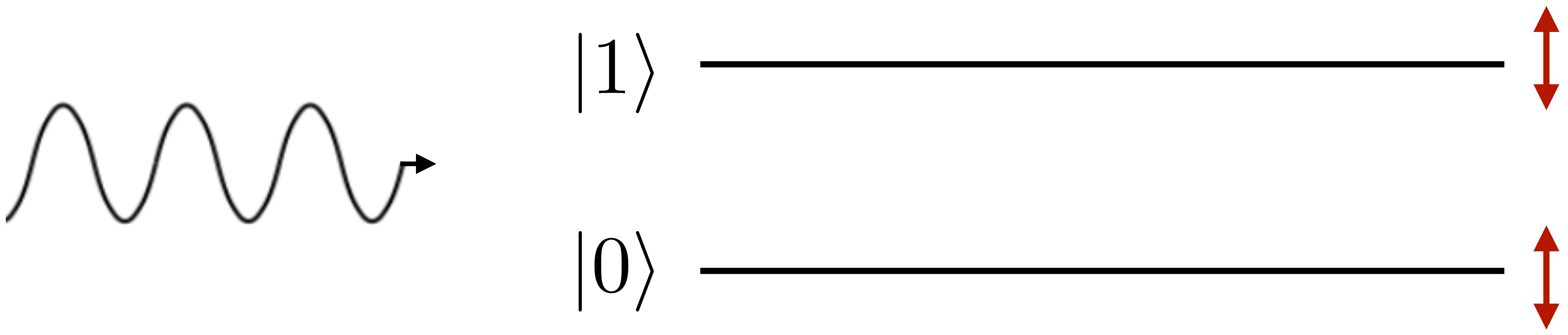

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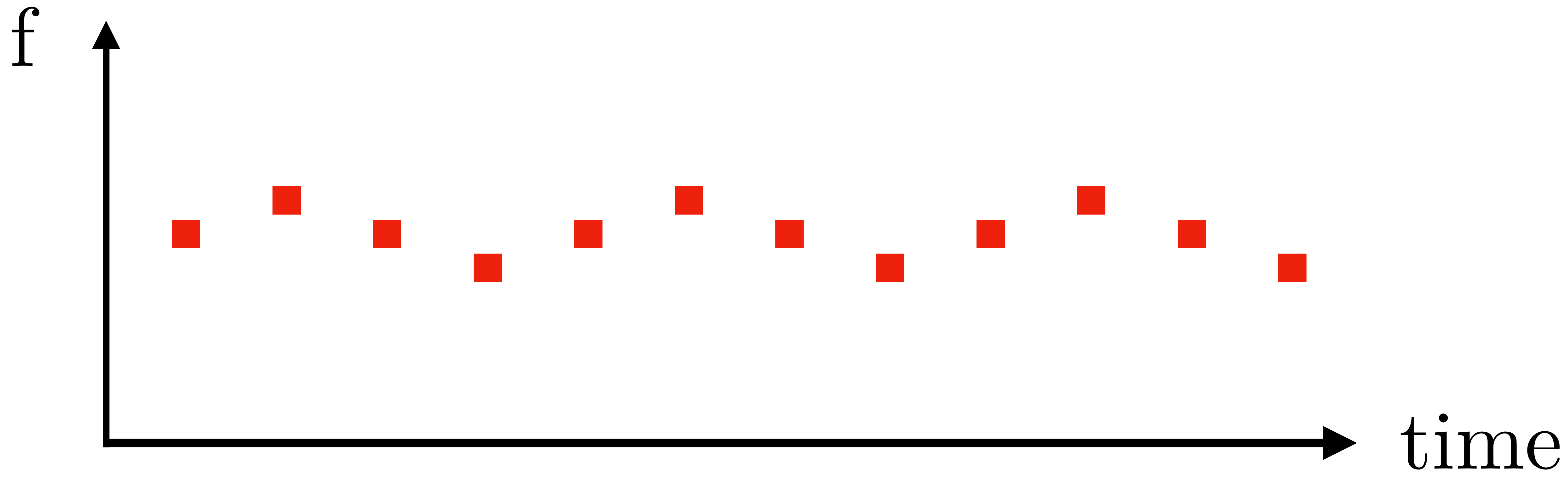

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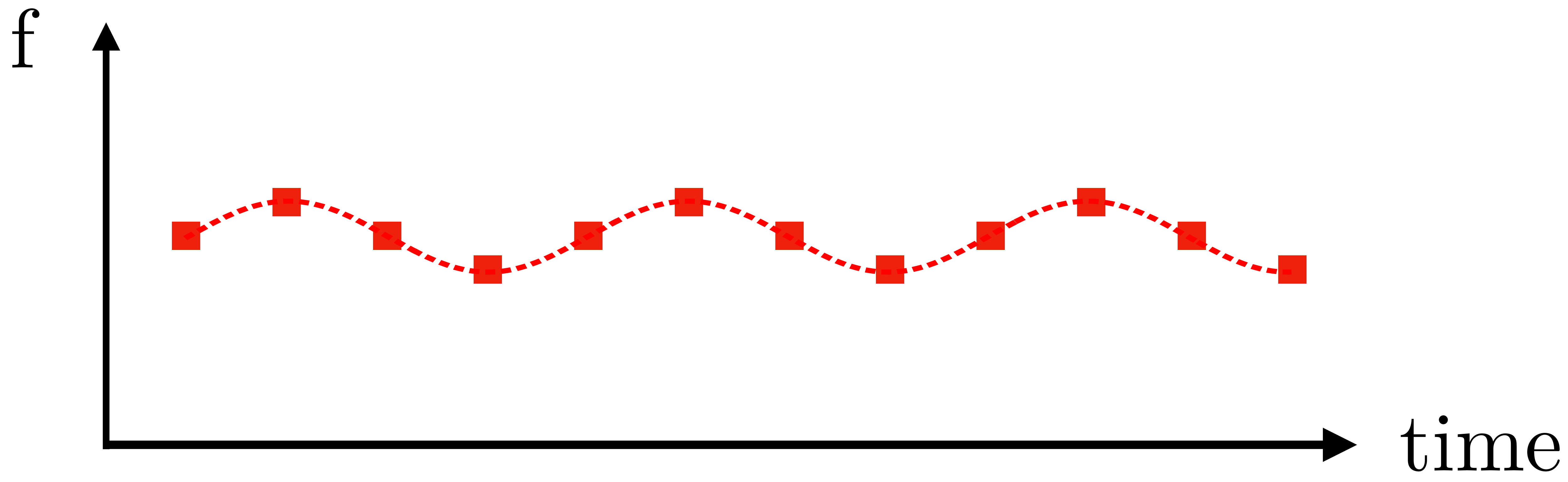
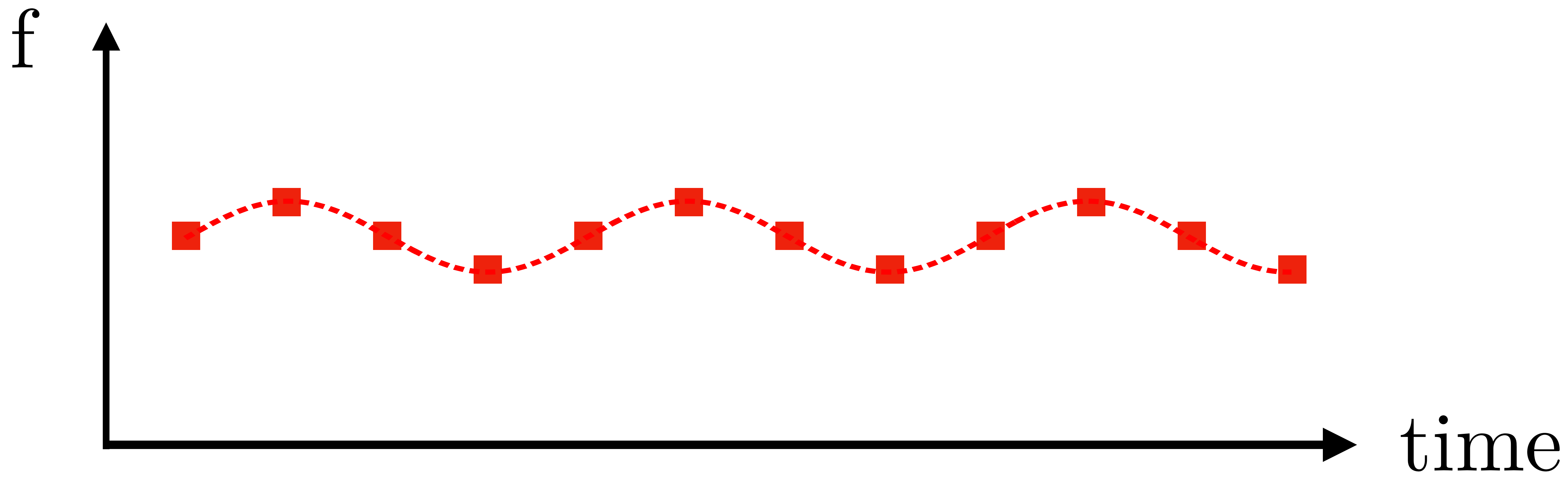


by looking for a harmonic signal
oscillations of energy level can be probed

the same measurement would give us



by looking for a harmonic signal
oscillations of energy level can be probed

for dilaton-like (or scalar) DM searches

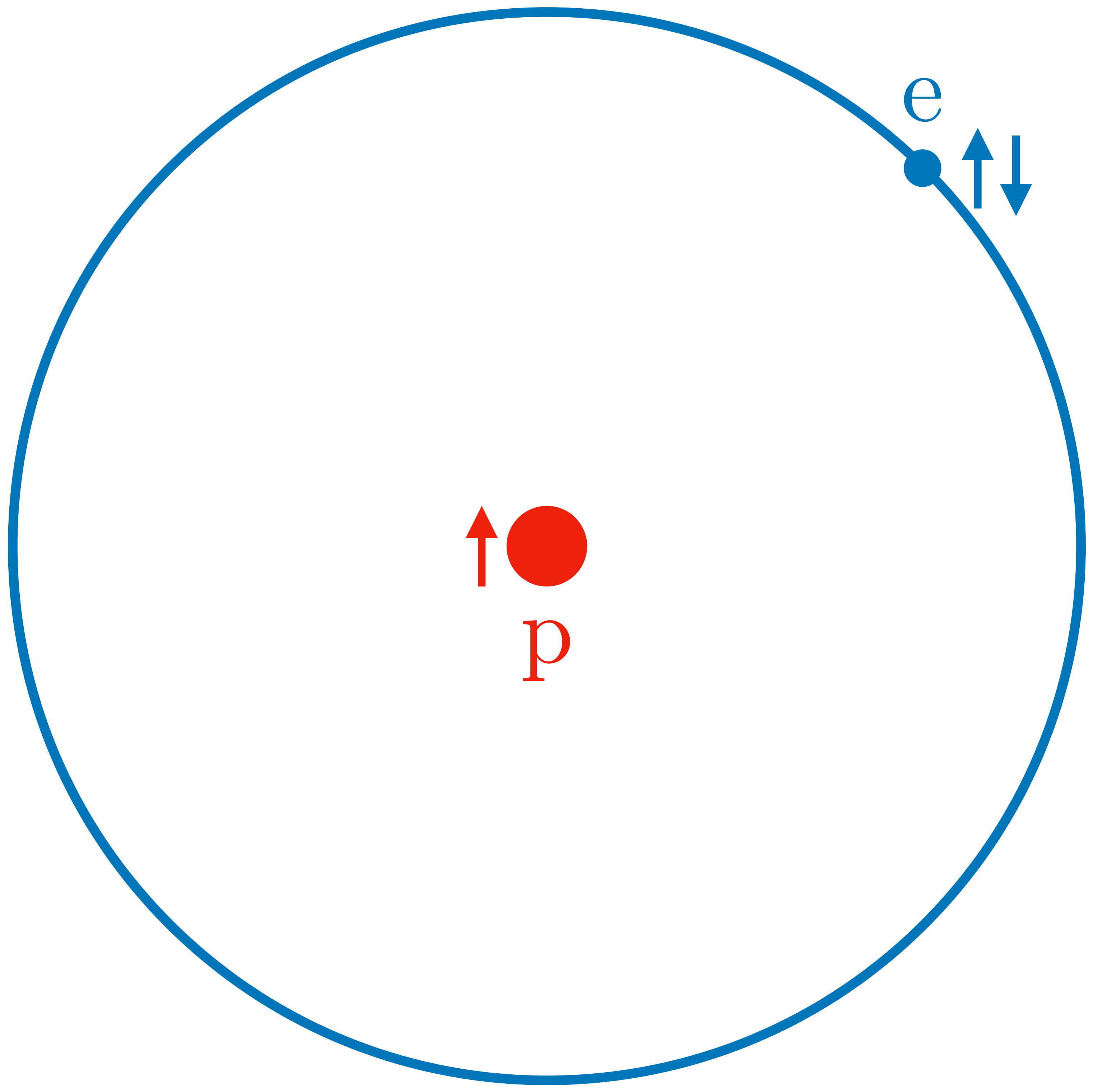
$$\mathcal{L} = \phi\bar{\psi}\psi + \phi FF + \phi GG$$

atomic clocks provide useful tools

[Arvanitaki, van Tilburg, Huang 14]

To see how it works

let us consider *hyperfine splitting in hydrogen atom*



$|1\rangle$

$f = 1420\,\mathrm{MHz}$

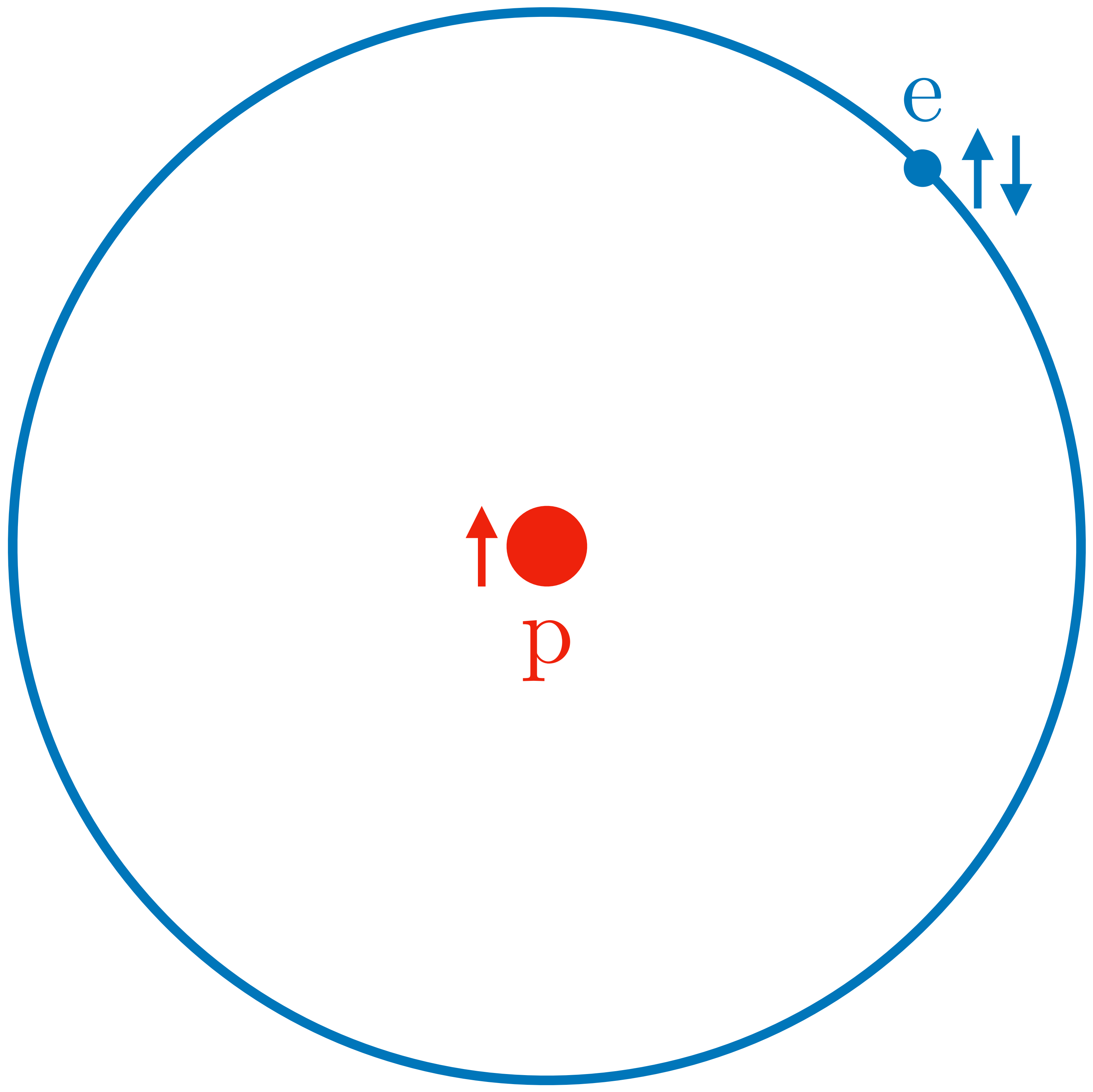
$\lambda = 21\,\mathrm{cm}$

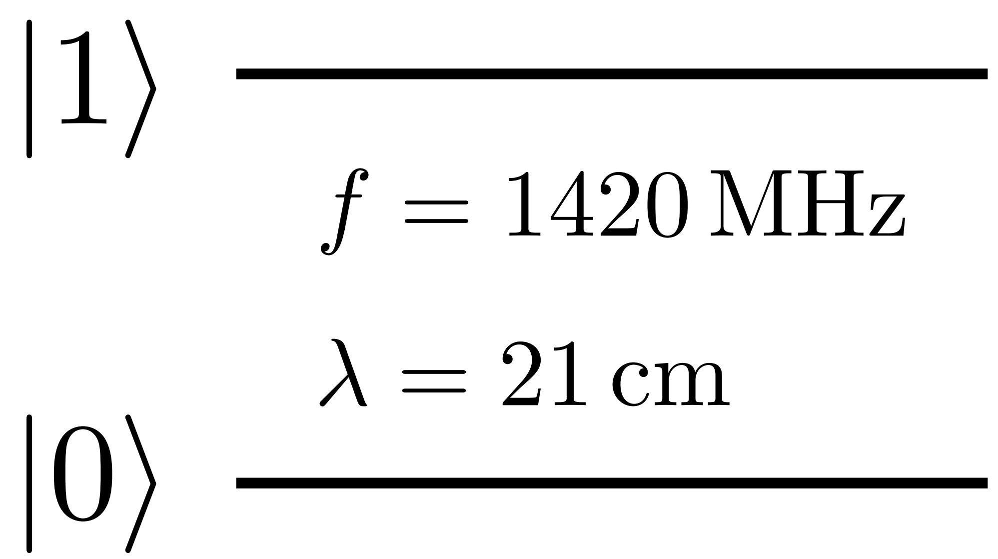
$|0\rangle$

$$H = -\vec{\mu}_e \cdot \vec{B}_p$$

To see how it works

let us consider *hyperfine splitting in hydrogen atom*





$$E = \frac{4}{3}(m_e^2 \alpha^4)\frac{g_p}{m_p}$$

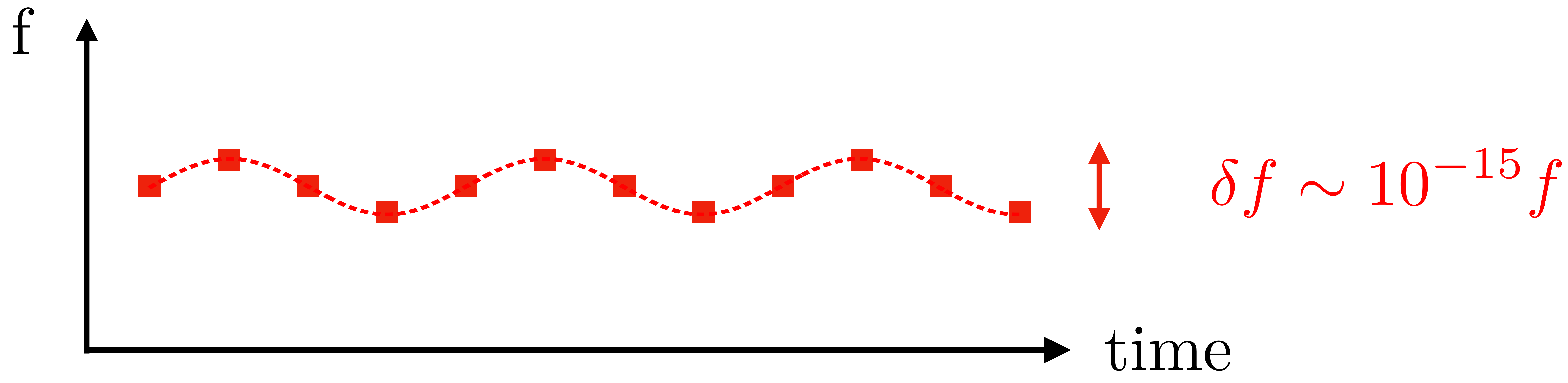
In the presence of axion DM

$$E = \frac{4}{3}(m_e^2\alpha^4)\frac{g_p}{m_p}$$

energy level slightly changes as

$$\frac{\delta E}{E} \sim 10^{-15}\frac{1}{m_{15}^2 f_{10}^2}[1+\cos(2mt)]$$

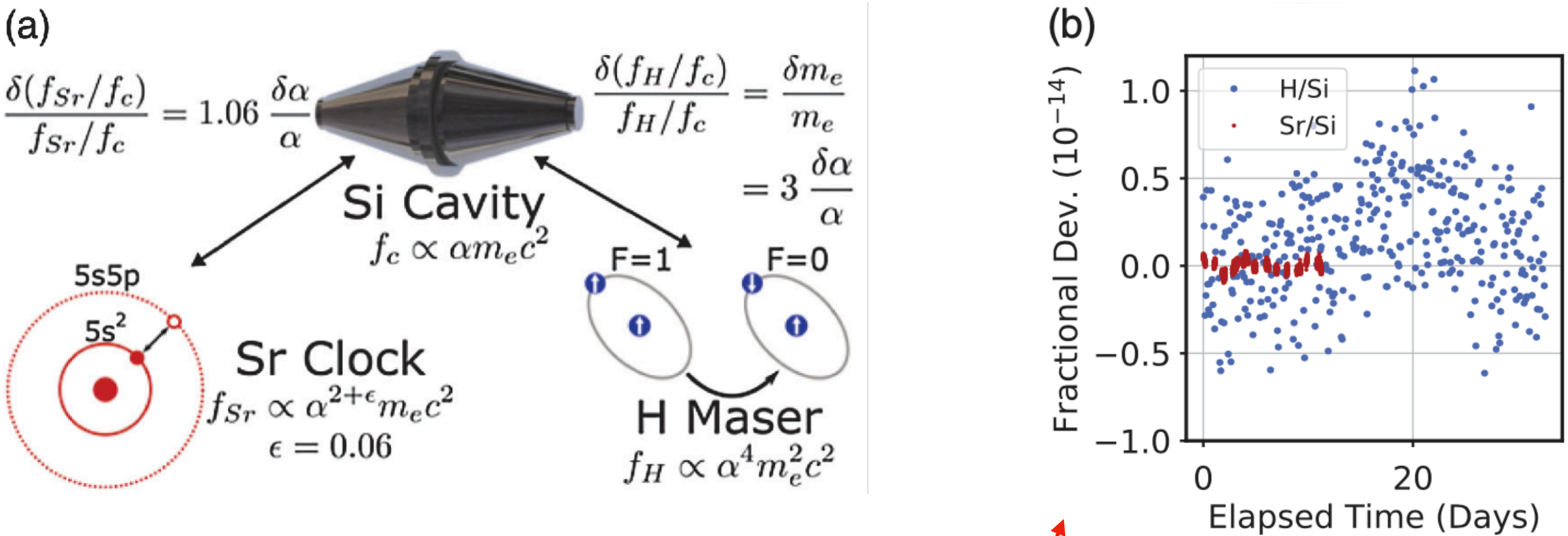
harmonic signal @ $\omega = 2m$



Is it a realistic system or just a toy model?

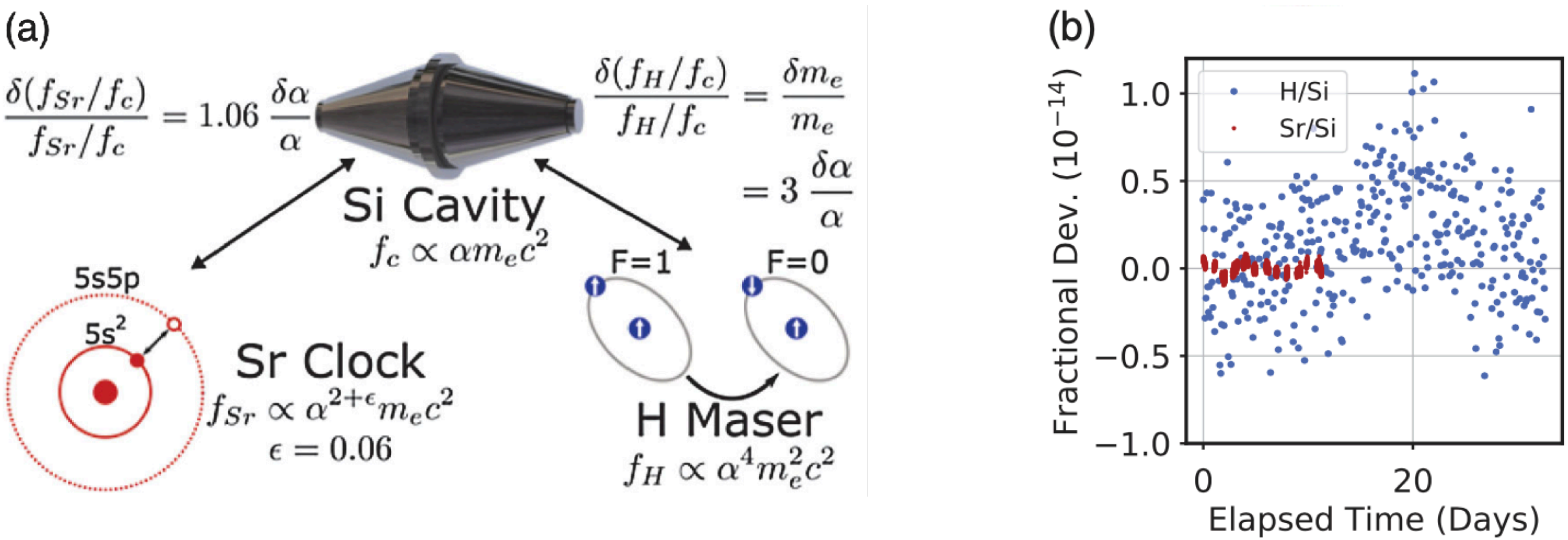
Is this observable?

[Kennedy et al 20]



$$\frac{\delta(f_H/f_{\mathrm{Si}})}{(f_H/f_{\mathrm{Si}})} \approx \frac{\delta f_H}{f_H}$$

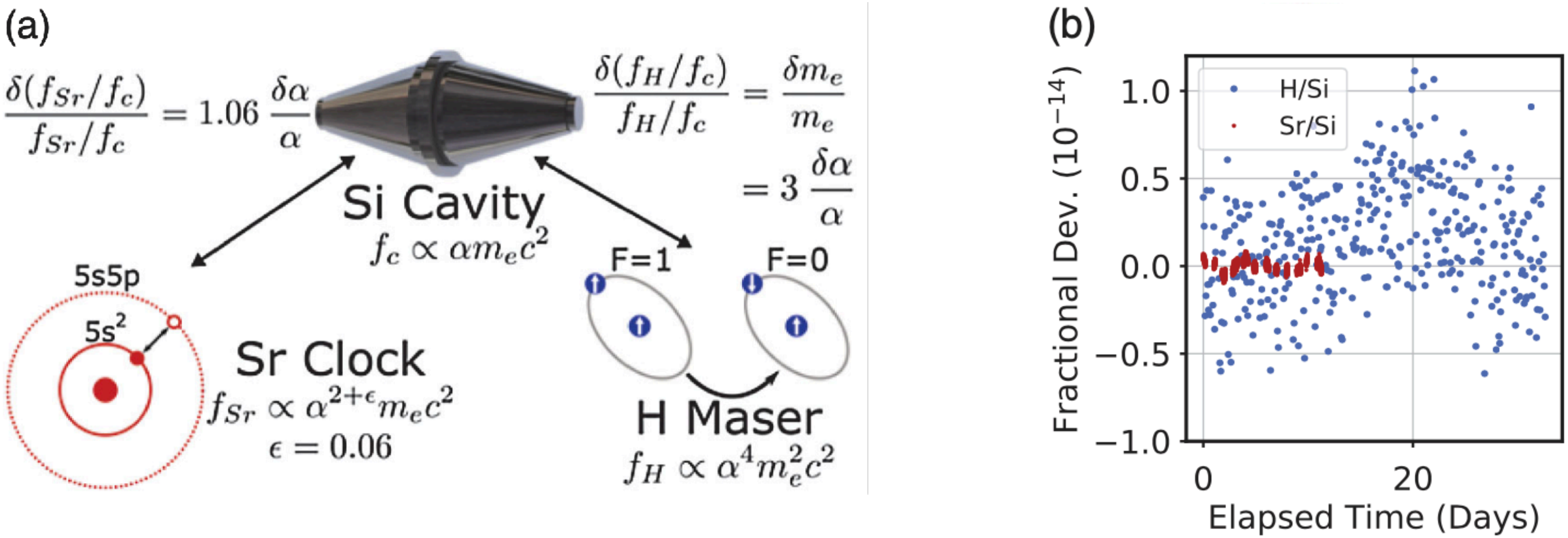
[Kennedy et al 20]



With 33 days of observation

$$\delta f/f \sim 10^{-16}$$

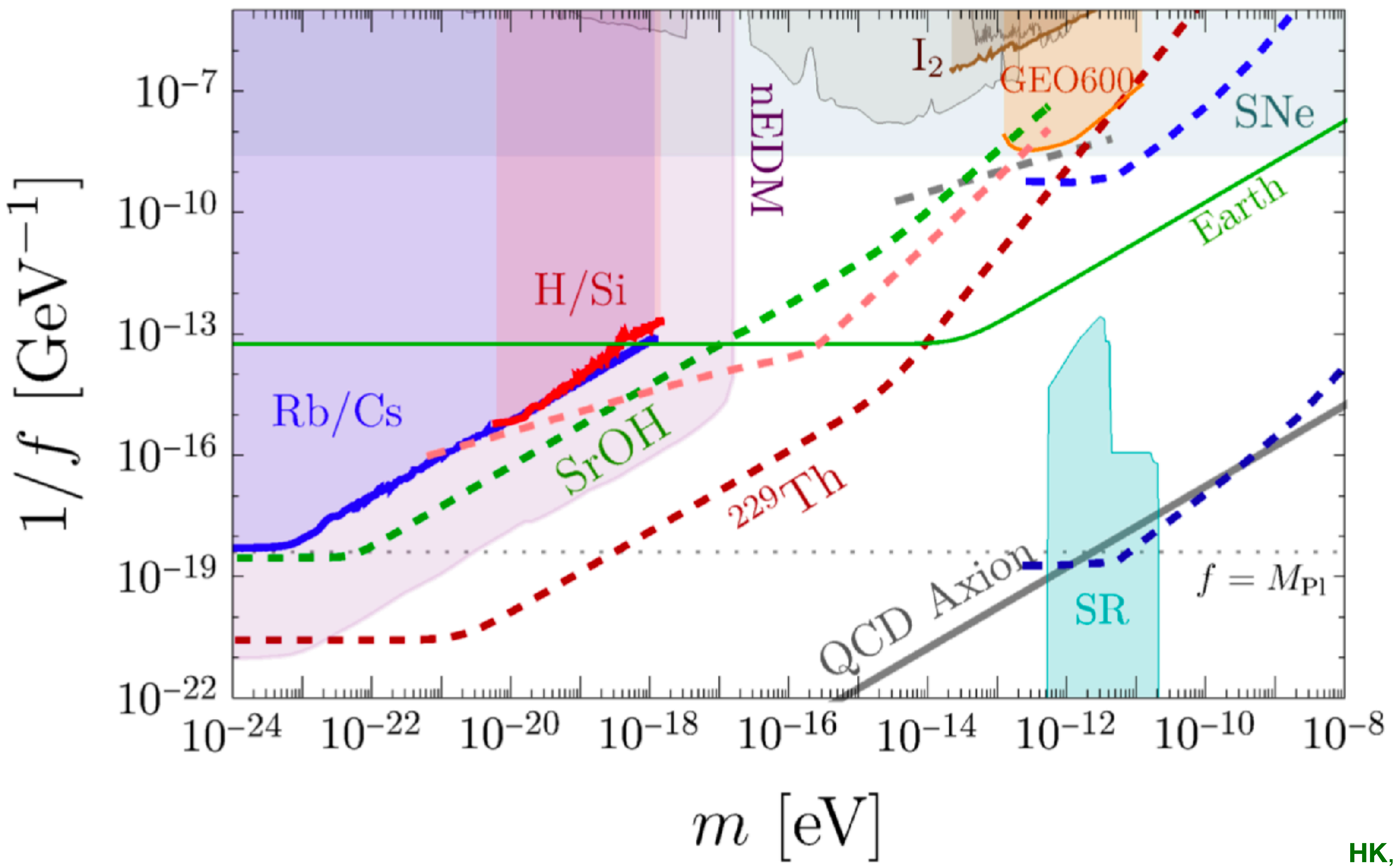
[Kennedy et al 20]



With 33 days of observation

$$\delta f/f \sim 10^{-16}$$

$$(\delta f/f) \sim 10^{-15}\frac{1}{m_{15}^2 f_{10}^2}[1+\cos(2mt)]$$



10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
$1/f$ [GeV^{-1}]
10^{-24} 10^{-22} 10^{-20} 10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8}
m [eV]
I_2
GEO600
SNe
nEDM
Earth
H/Si
Rb/Cs
SrOH
^{229}Th
SR
QCD Axion
$f = M_{Pl}$

HK, Perez (22)

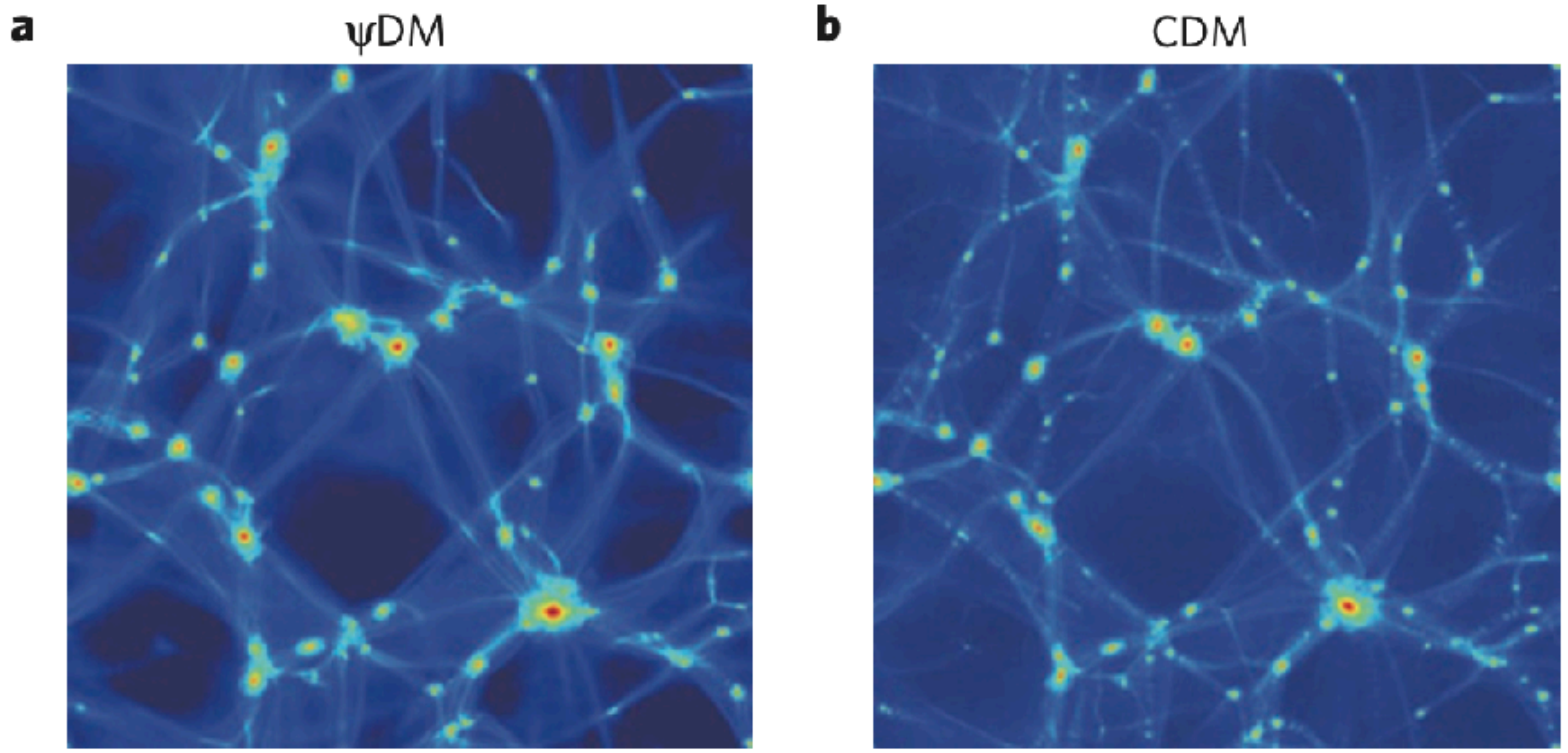
axion DM searches in the ‘sky’
has also observed significant progress
during past 10 years

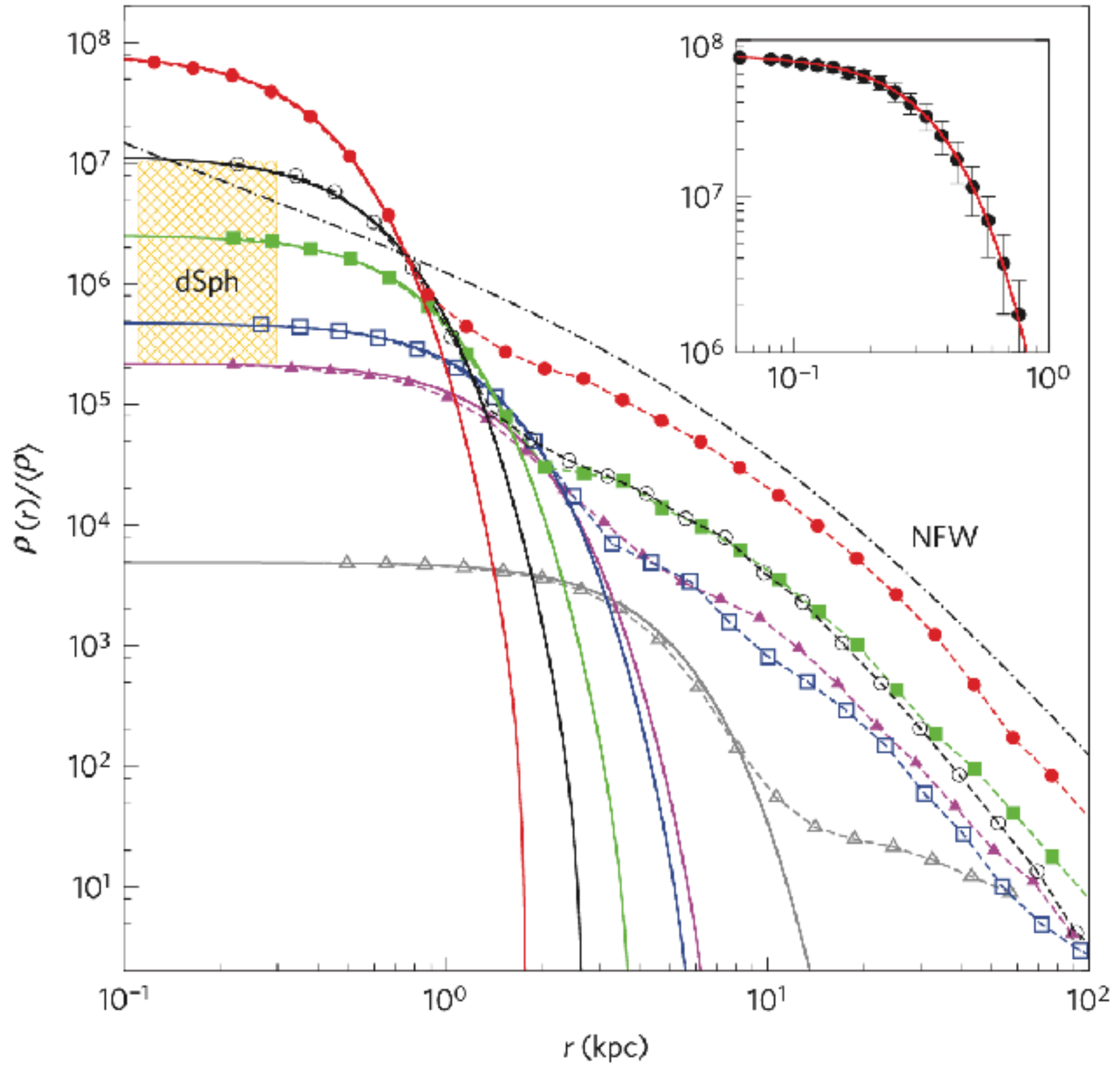
a characteristic feature of axion DM
is its wave nature

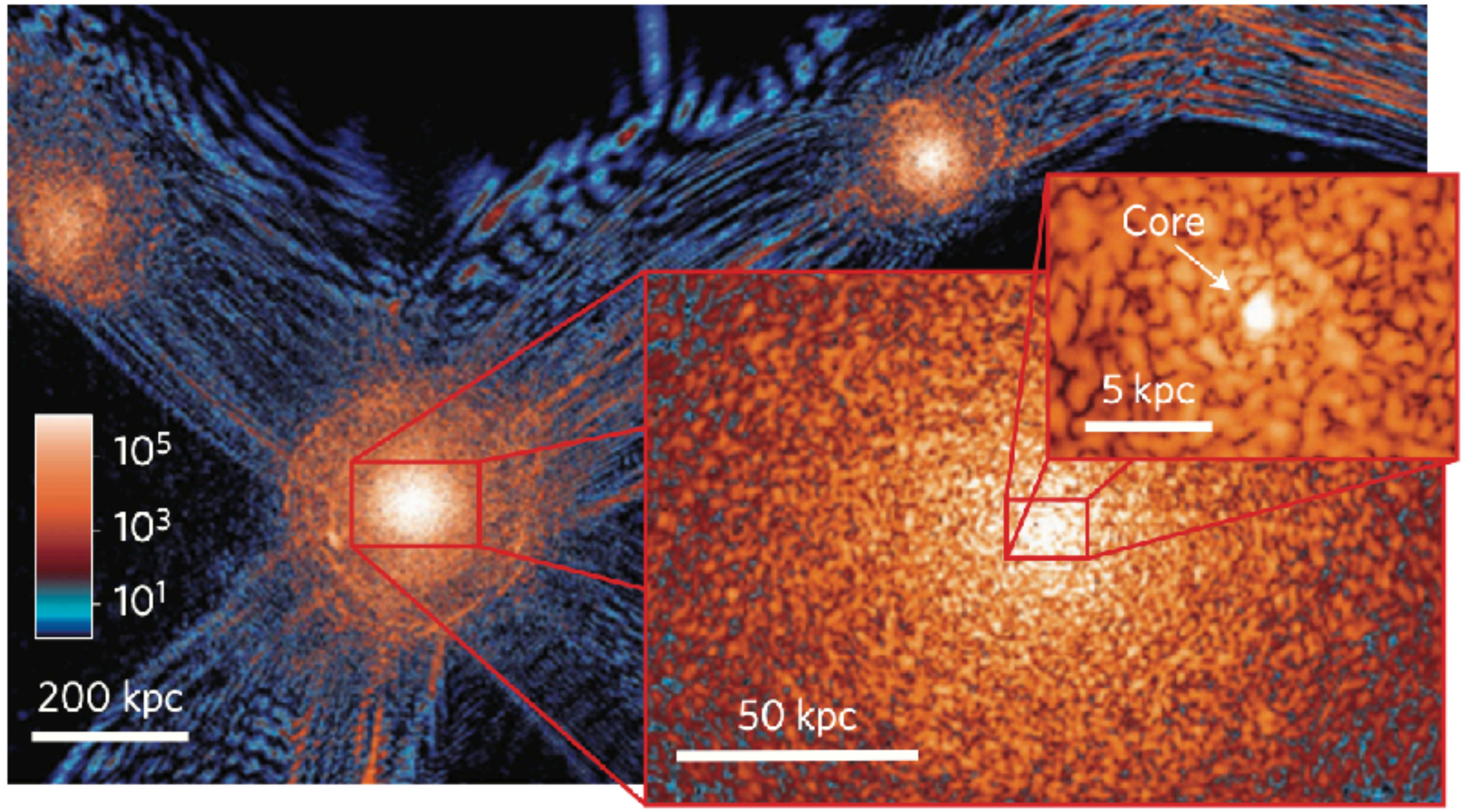
$$\lambda = \frac{2\pi}{mv} \simeq 0.6\,\mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{200\,\mathrm{km/sec}}{v}\right)$$

the size of wavelength could be astronomical !

Schive, Chiueh, Broadhurst (14)

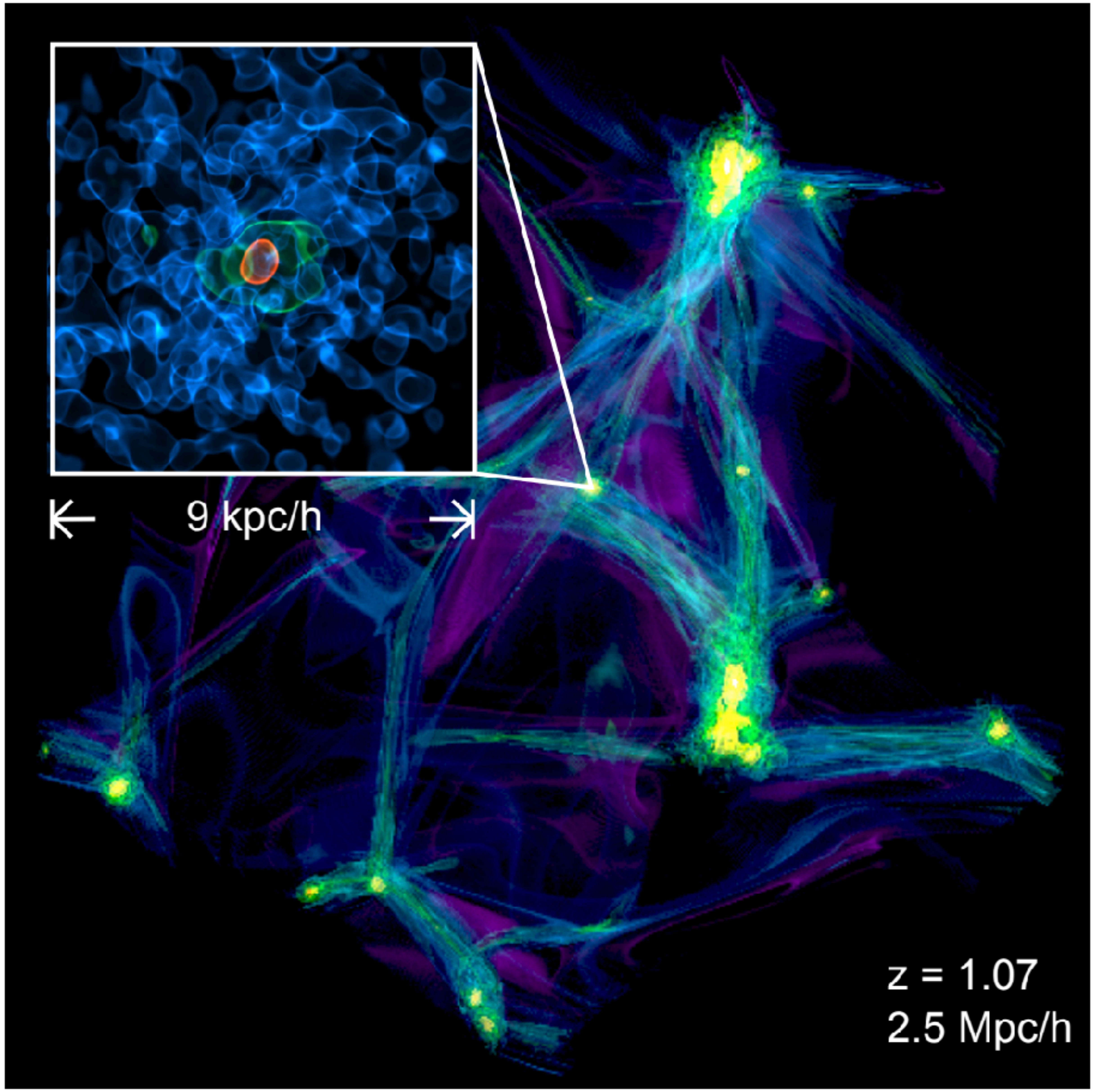






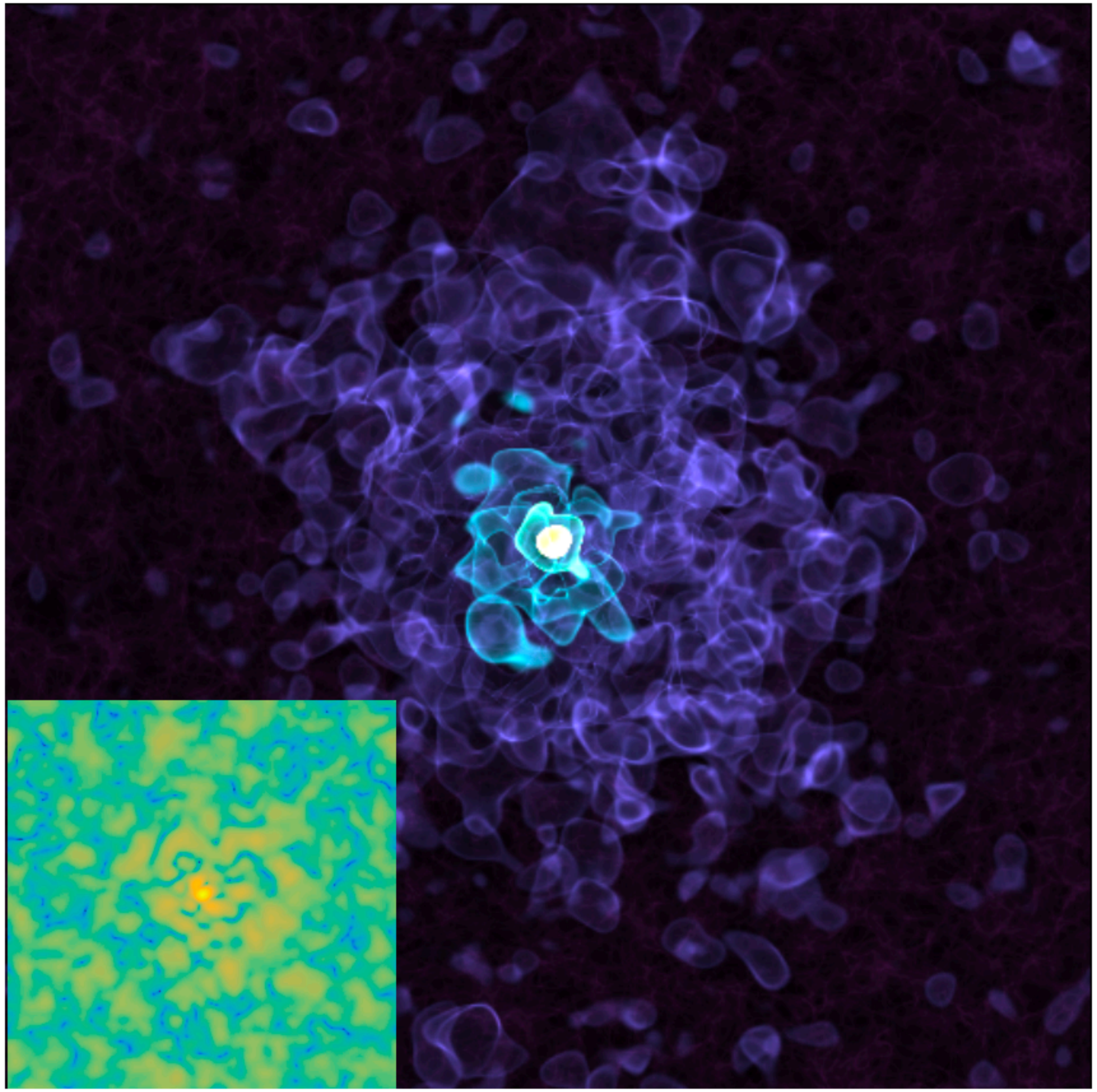
* characteristic *soliton* at the center has been observed

* small scale structures are erased



Veltmaat, Niemeyer, Schwabe (18)

Mocz et al (17)



Many interesting astrophysical phenomena arises from solitons and granule structure of axion DM

- galaxy rotation curve — Bar, Blas, Blum, Sibiryakov (18); Bar, Blum, Eby, Sato (19); Bar, Blum Chen (21)

- interaction between quasiparticle and stars — Amorisco, Loeb (18) ; Church, Mocz, Ostriker (18); Marsh, Niemeyer (19); Dalal et al (20); Dalal, Kravtsov (22)

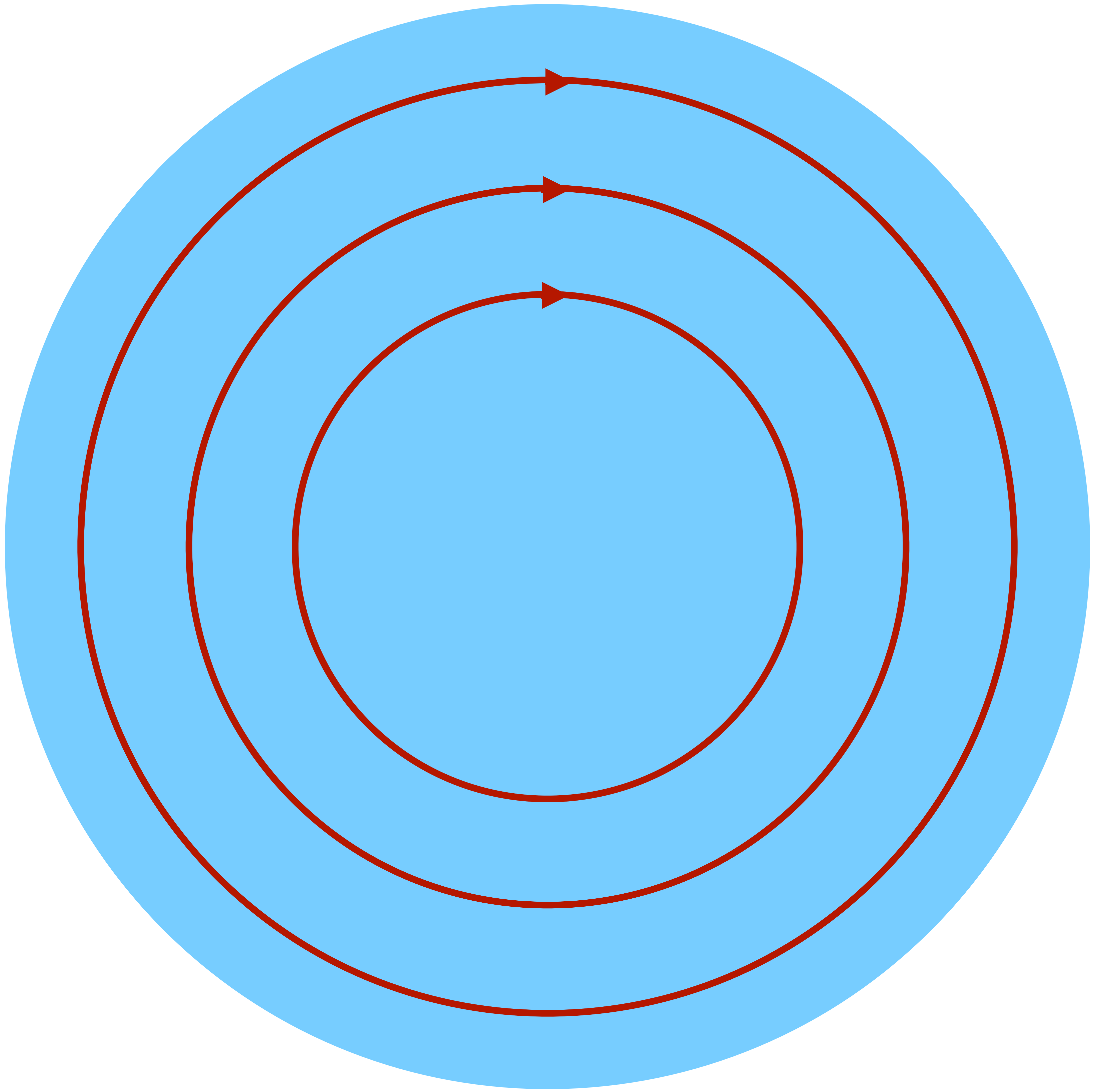
- large scale structures — Iršič et al (17); Hlozek et al (17); Kobayashi et al (17); Nori et al (18); Rogers, Peiris (20); Schutz (20); Laguë et al (21)

See also a recent review by Lam Hui (21)

Axion (wave) dark matter can also be tested by

gravitational waves

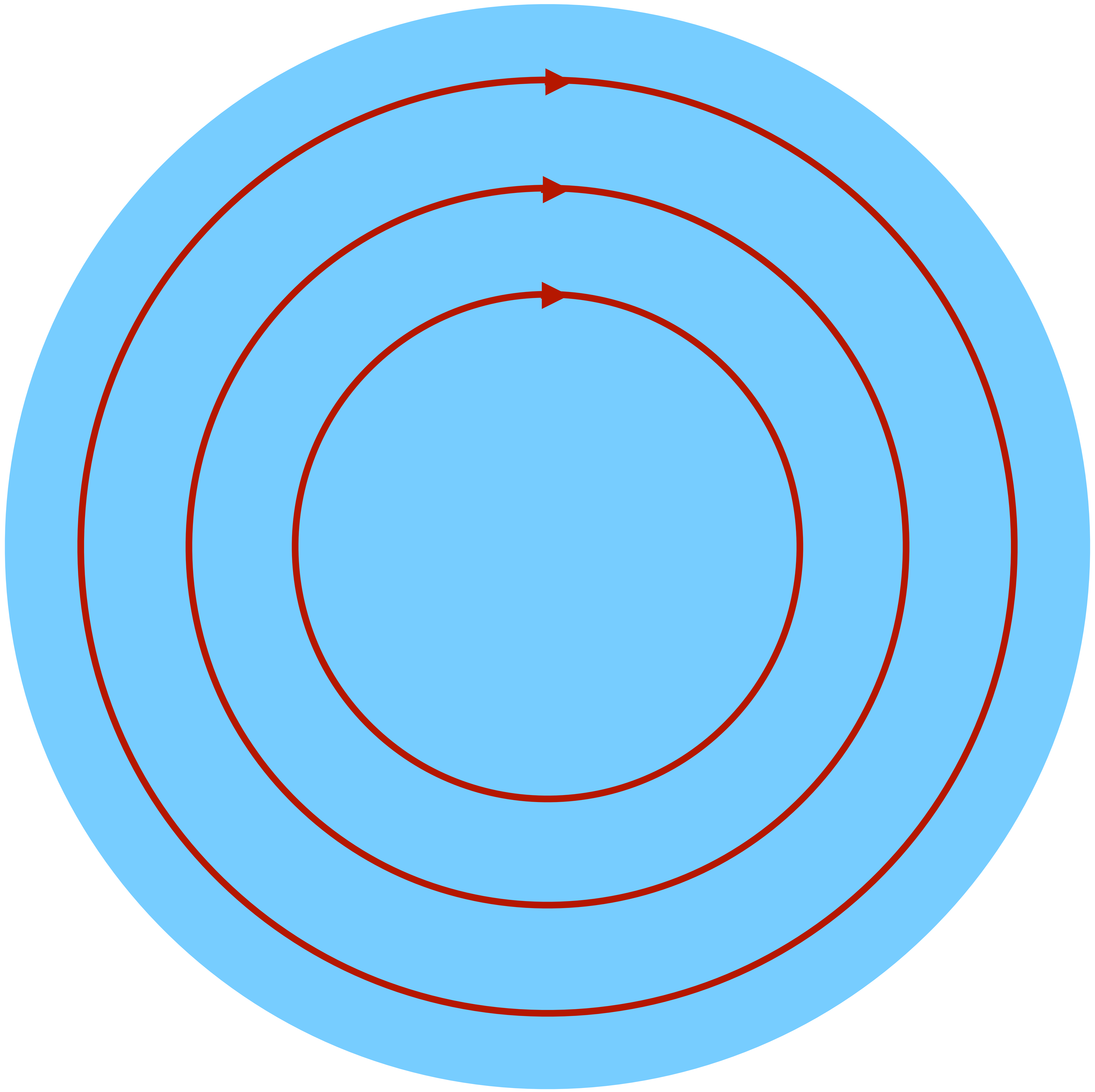
HK, Alessandro Lenoci, Isak Stomberg, Xiao Xue (in preparation) let us consider a gas cloud and stars (DM) in a circular orbit



gas

star (or dark matter)

imagine gas could contracts via dissipation adiabatically

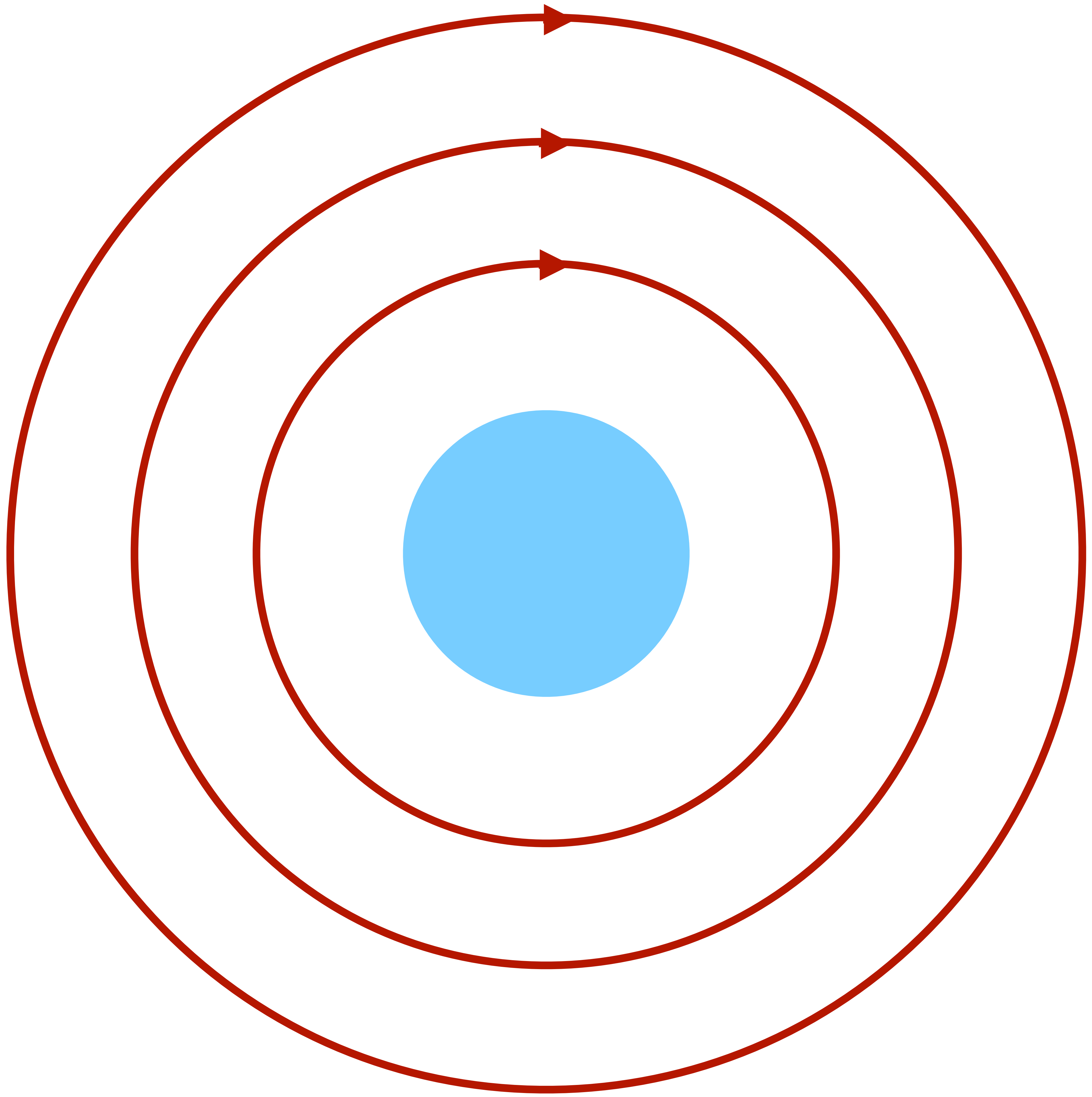


$$L = rv = \sqrt{GM_{\rm enc}(r)r}$$

gas

star (or dark matter)

imagine gas could contracts via dissipation adiabatically

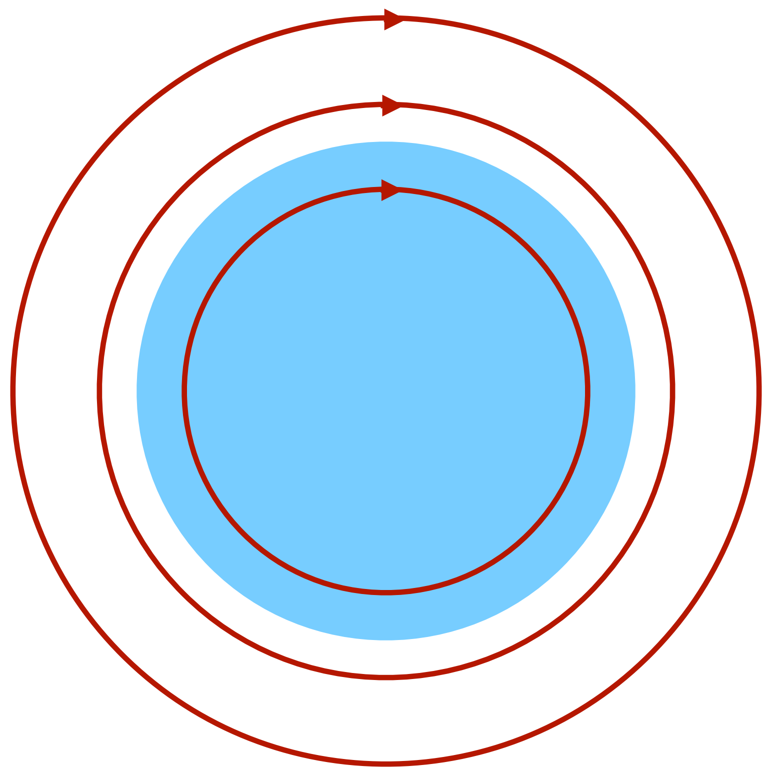


$$L = rv = \sqrt{GM_{\rm enc}(r)r}$$

gas

star (or dark matter)

imagine gas could contracts via dissipation adiabatically

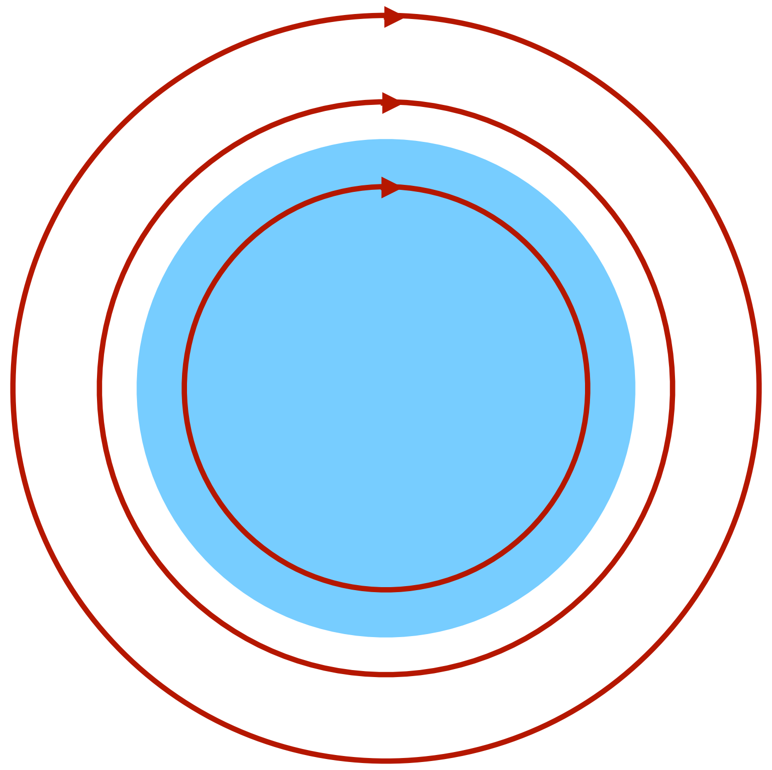


$$L = rv = \sqrt{GM_{\rm enc}(r)r}$$

gas

star (or dark matter)

imagine gas could contracts via dissipation adiabatically



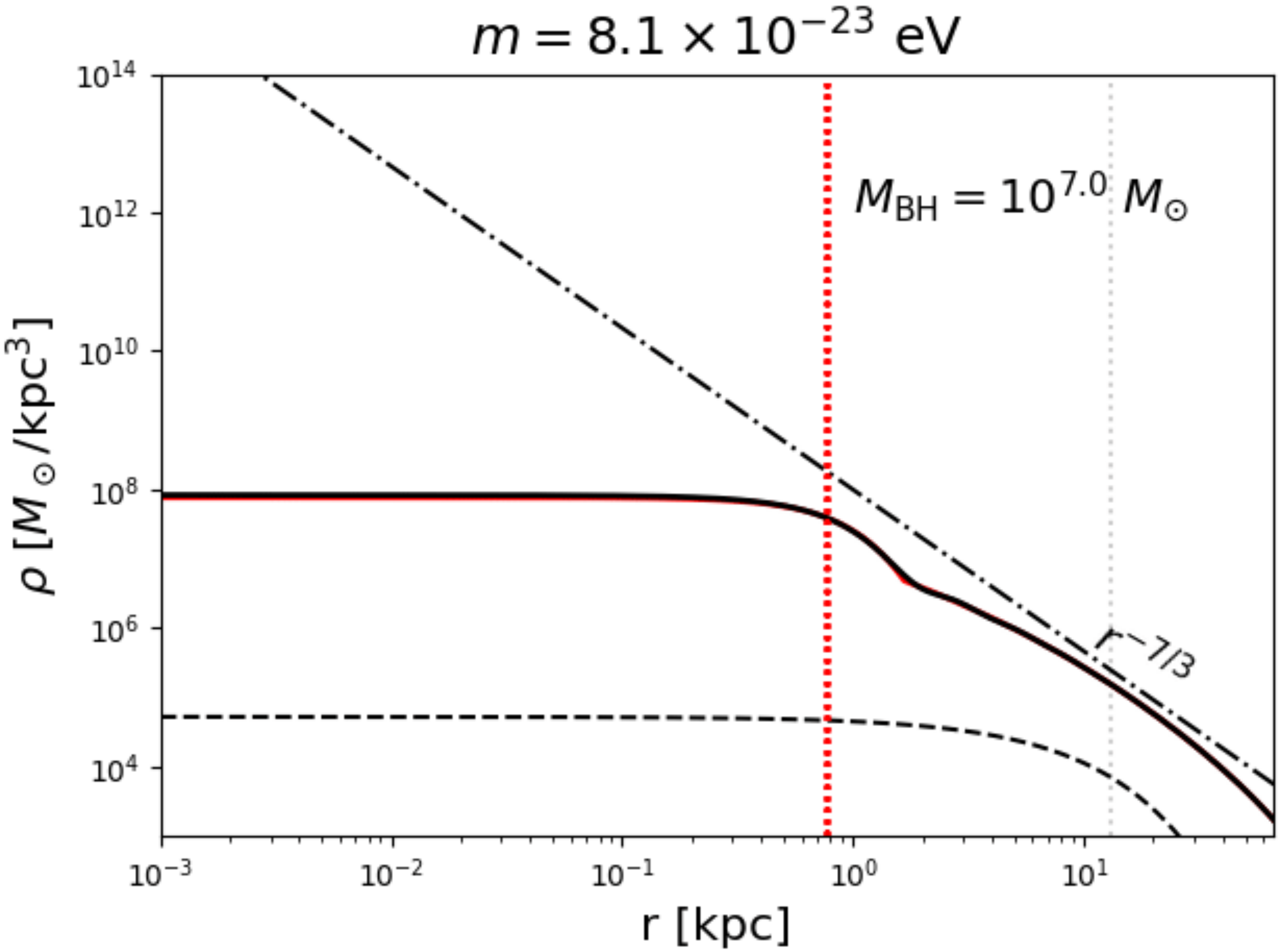
stellar (DM) distribution becomes steeper

near the center of system

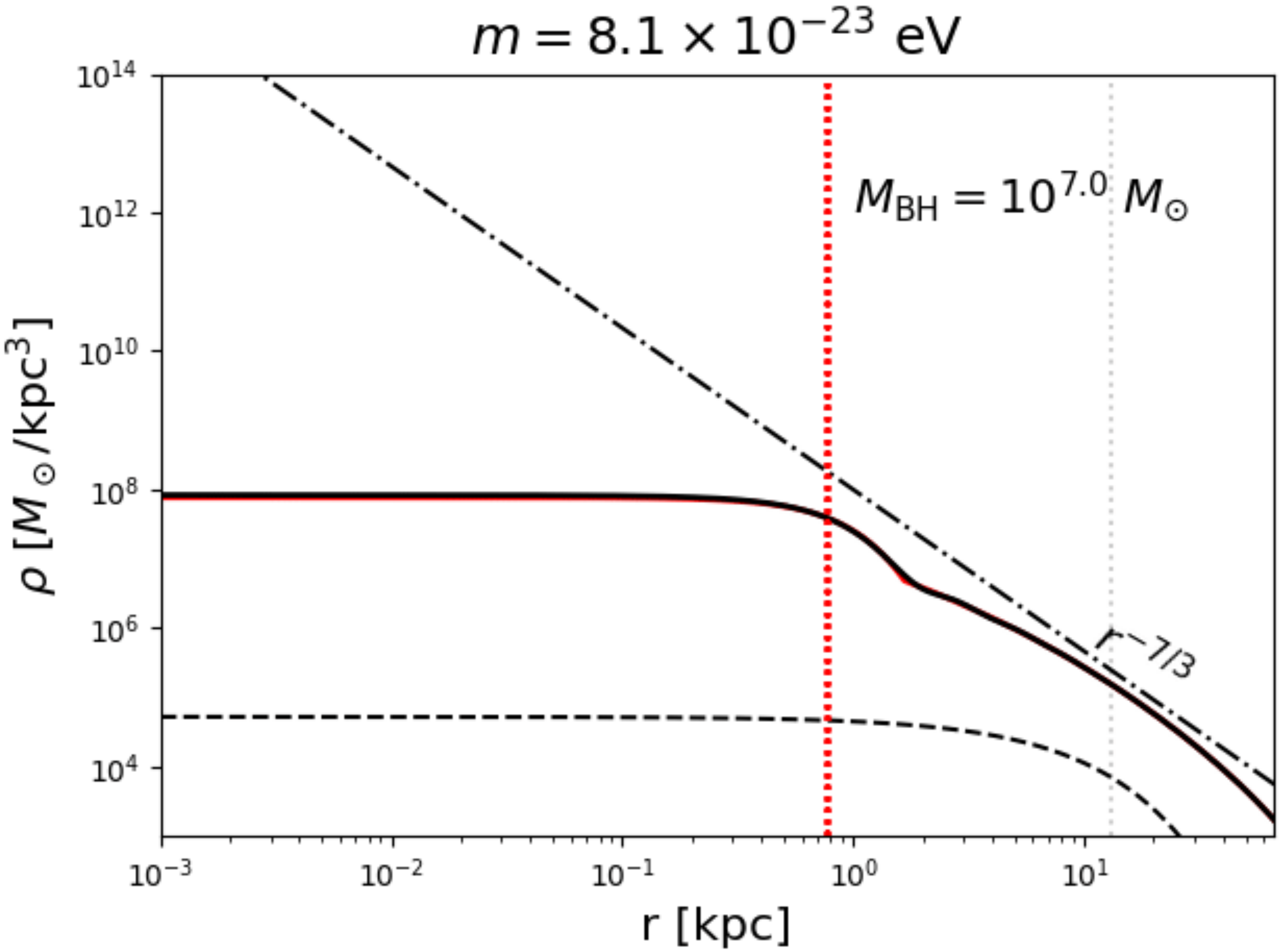
$$L = rv = \sqrt{GM_{\mathrm{enc}}(r)r}$$

gas

star (or dark matter)



$m = 8.1 \times 10^{-23}$ eV
$M_{\rm BH} = 10^{7.0}\, M_\odot$
$r^{-7/3}$
$\rho\ [M_\odot/{\rm kpc}^3]$
r [kpc]
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



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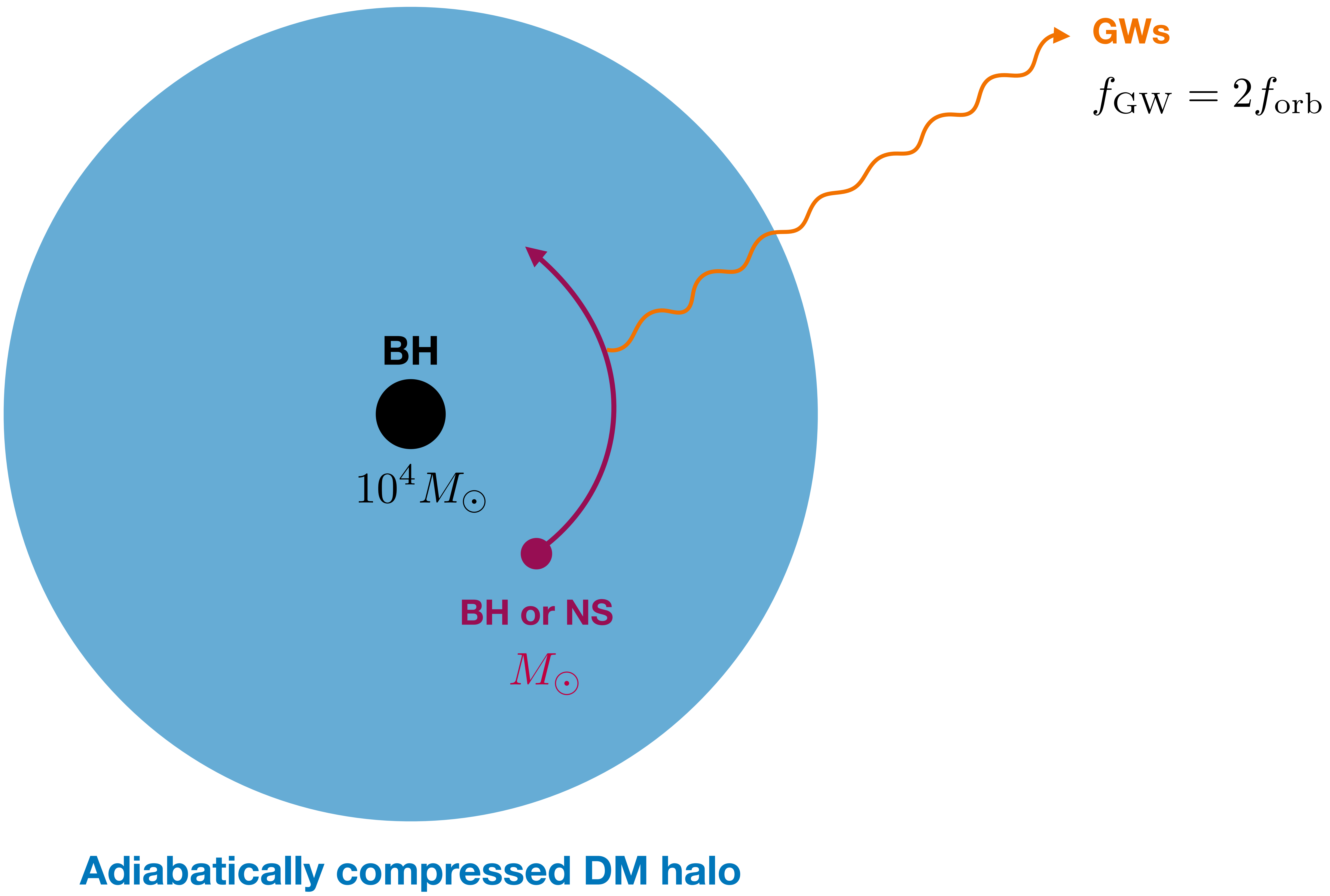
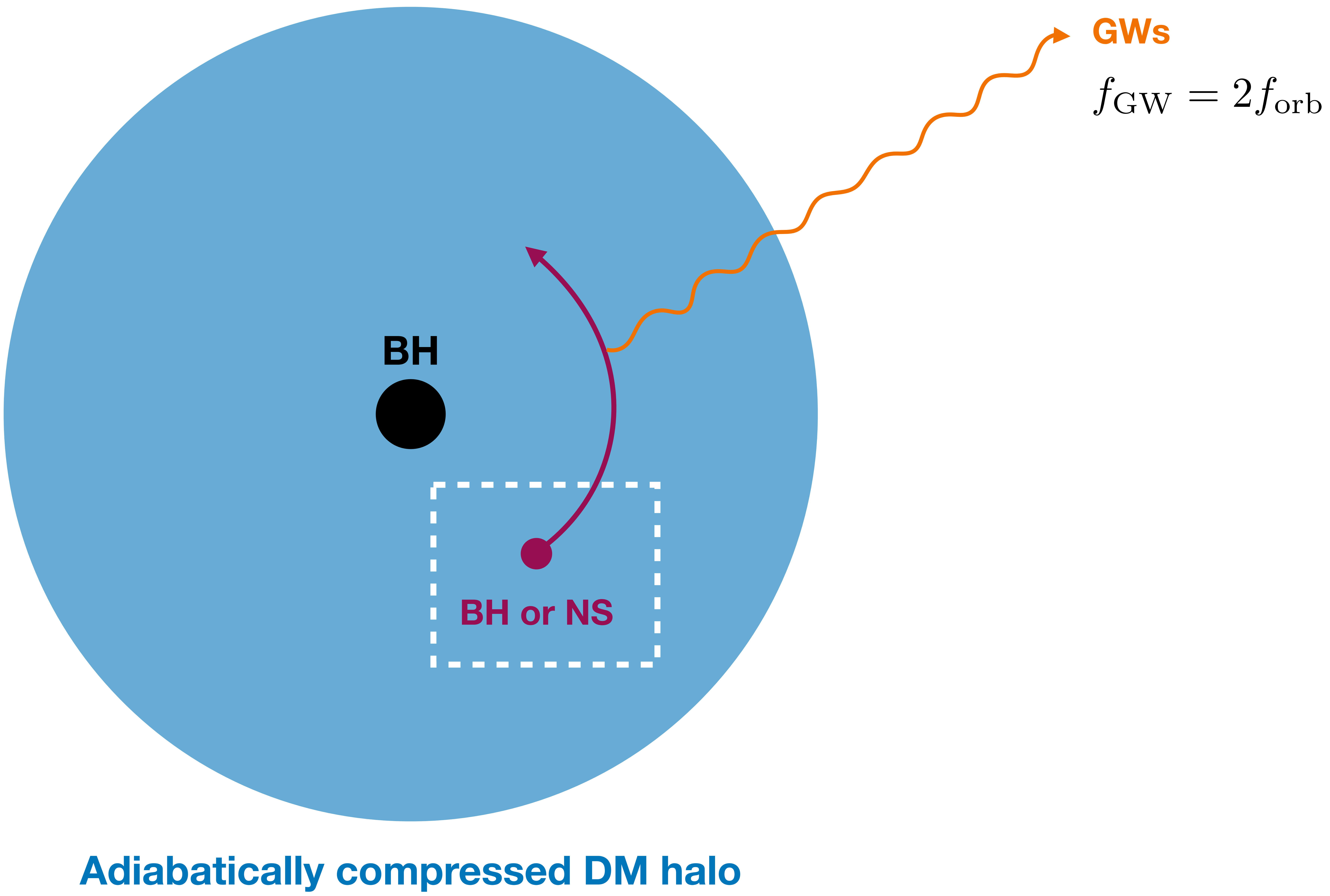
$\rho\ [M_\odot/\mathrm{kpc}^3]$
r [kpc]


GWs
$f_{\rm GW} = 2 f_{\rm orb}$
BH
$10^4 M_\odot$
BH or NS
$M_\odot$
Adiabatically compressed DM halo


GWs
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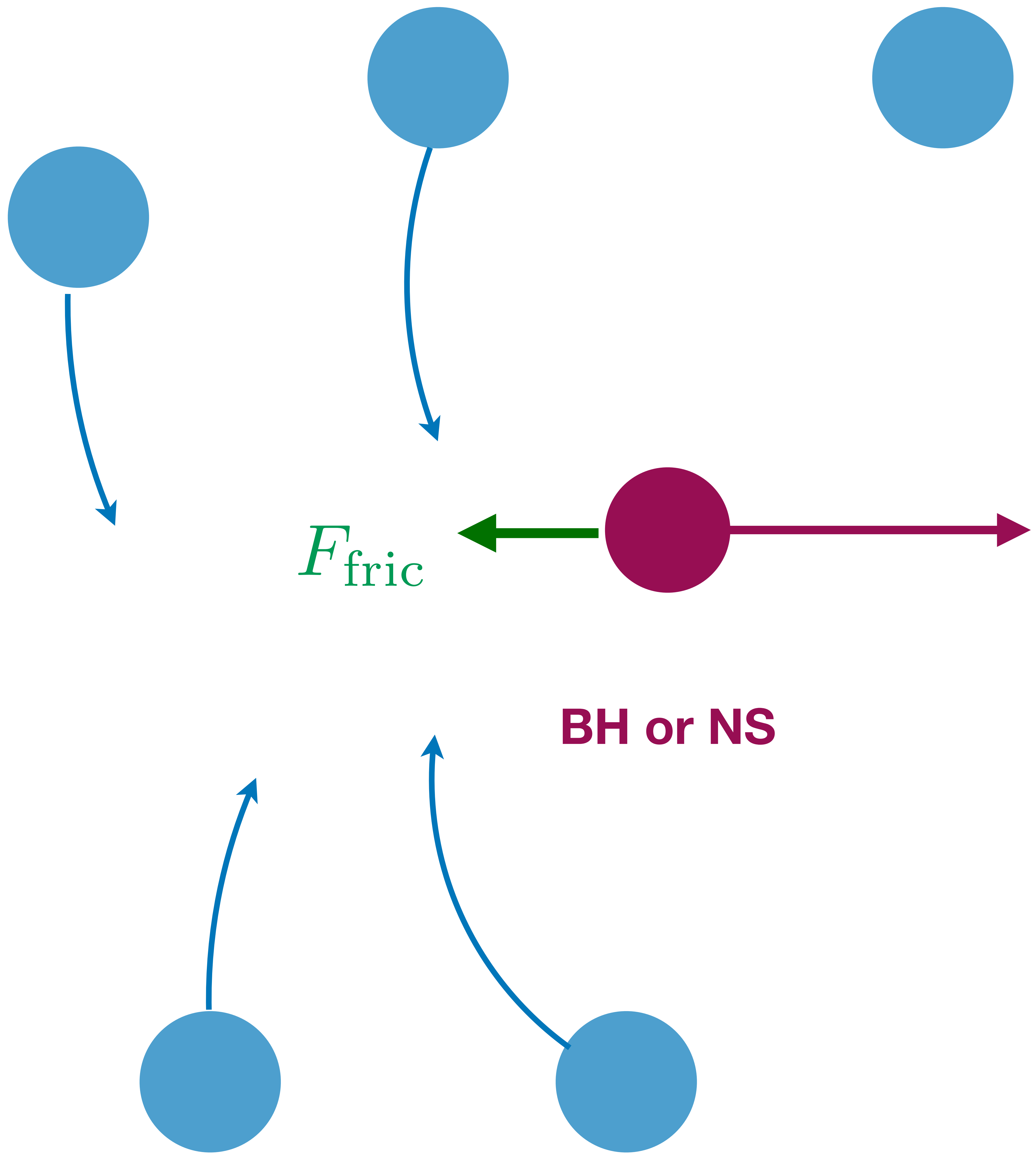
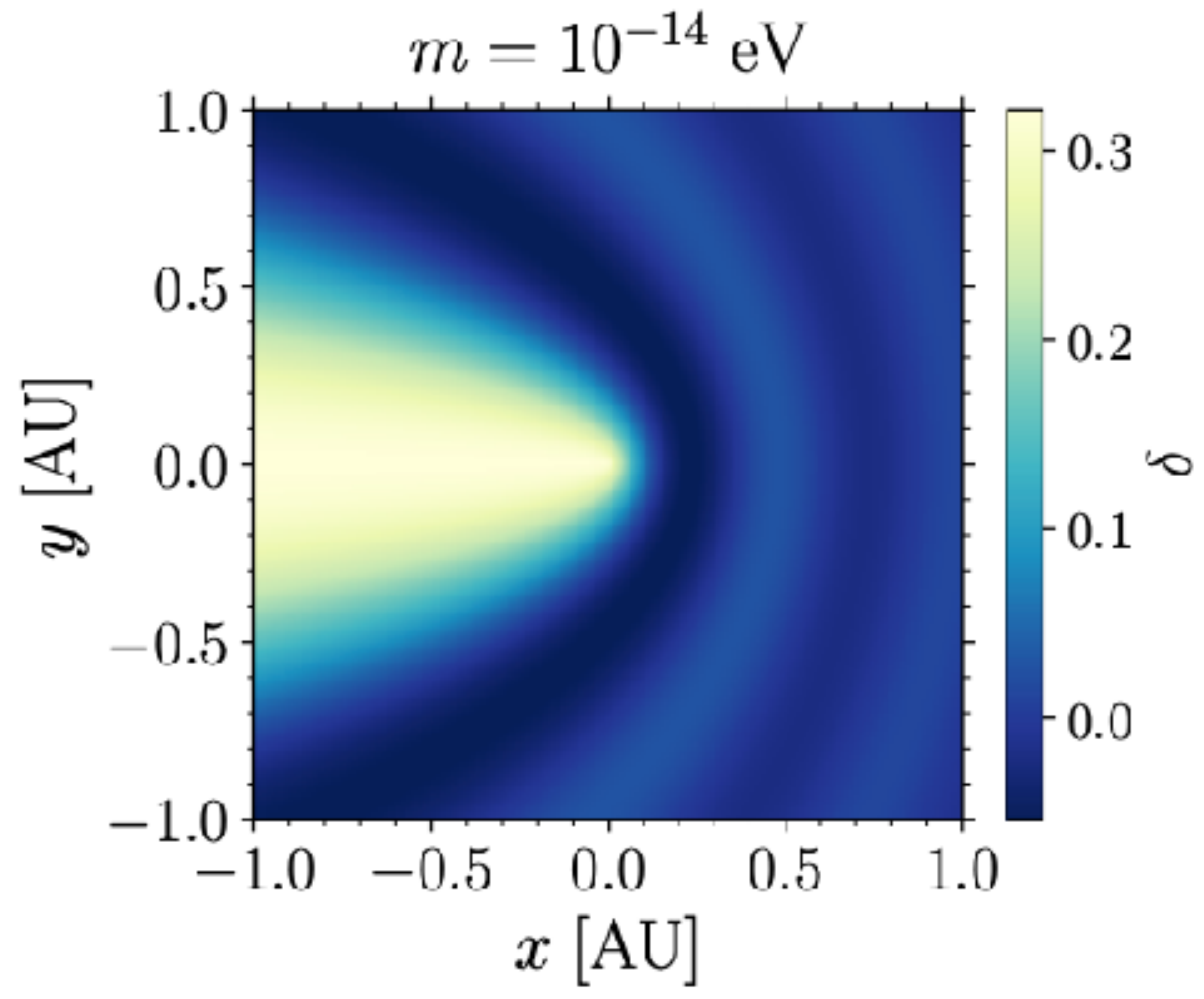
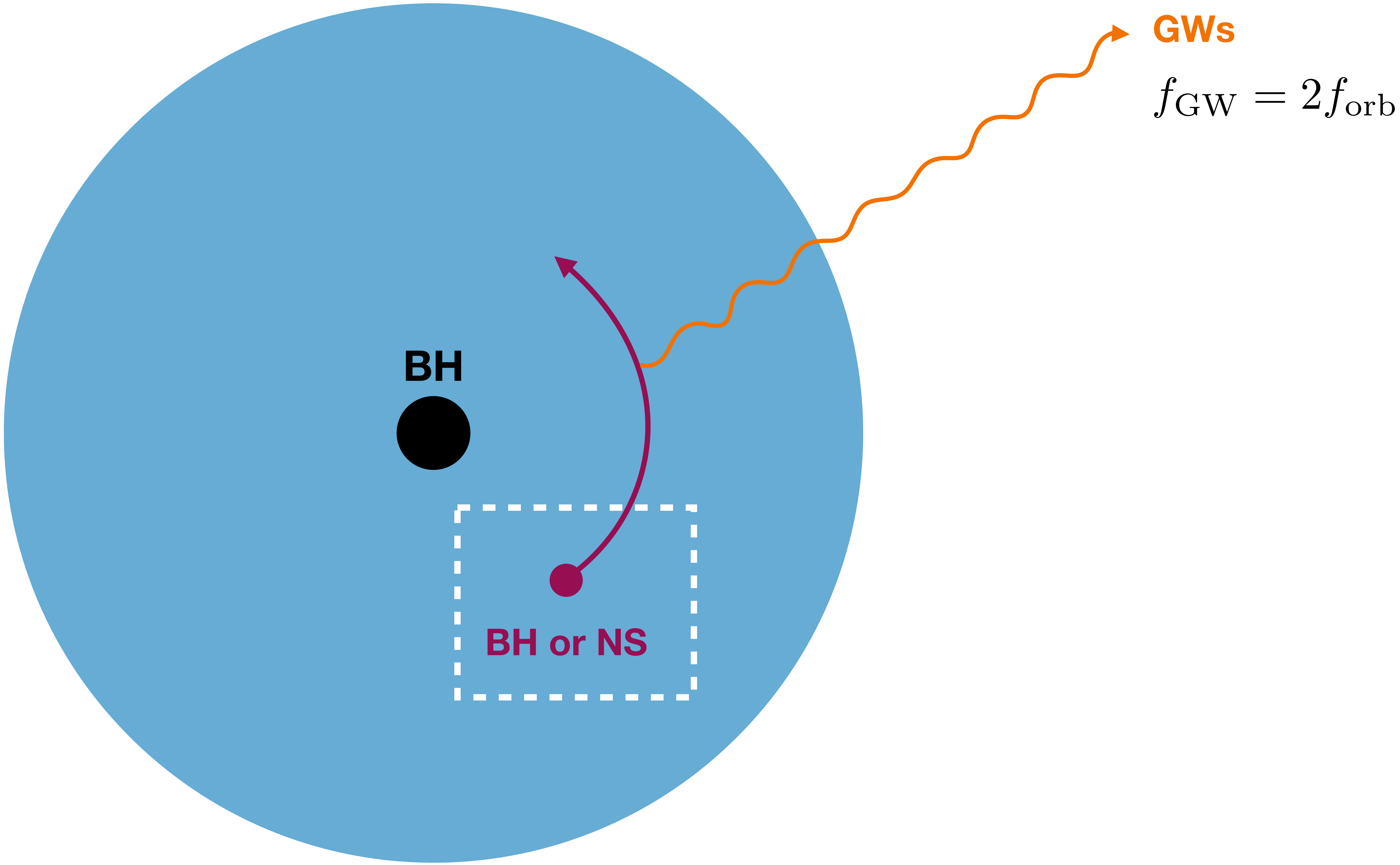
Adiabatically compressed DM halo





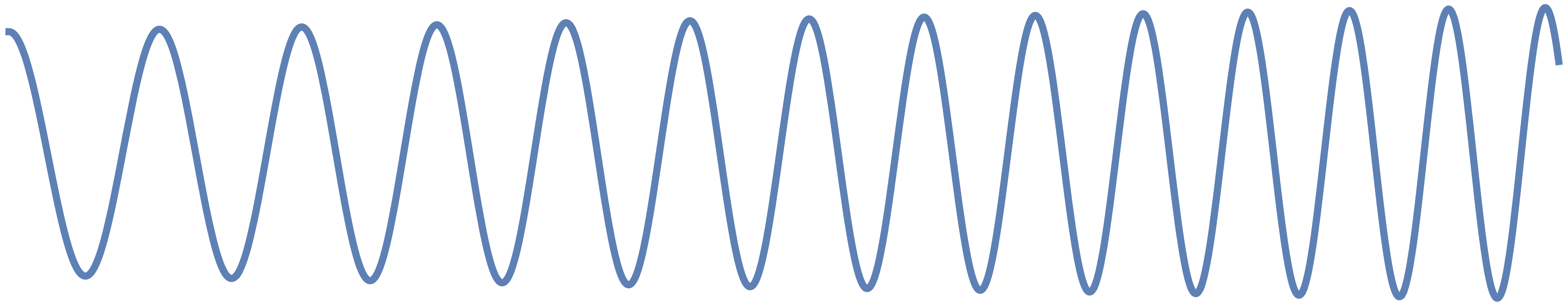
HK, Alessandro Lenoci (21)

DM overdensity forms
behind the BH or NS
exerting additional frictional force

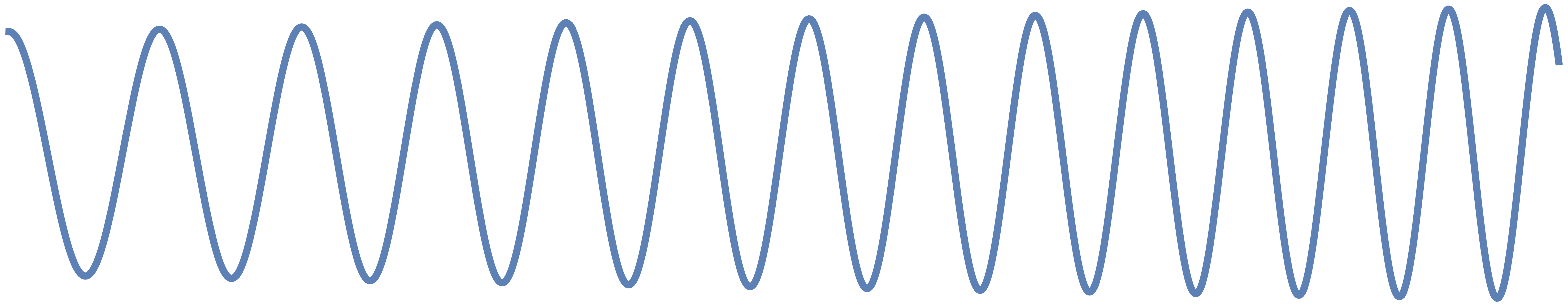


In **adiabatically compressed DM halo**, the orbit of BH (or NS) decay faster

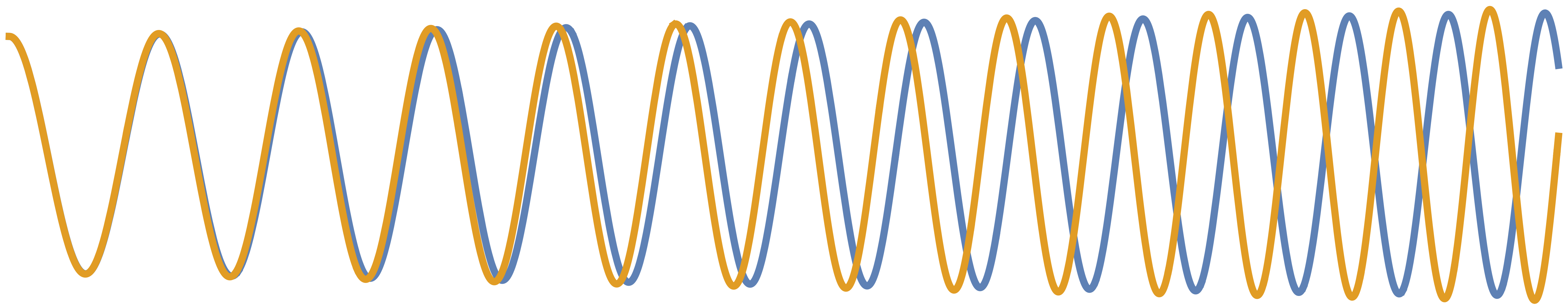
In the absence of compressed halo
gravitaitonal wave would look like



In the absence of compressed halo
gravitaitonal wave would look like



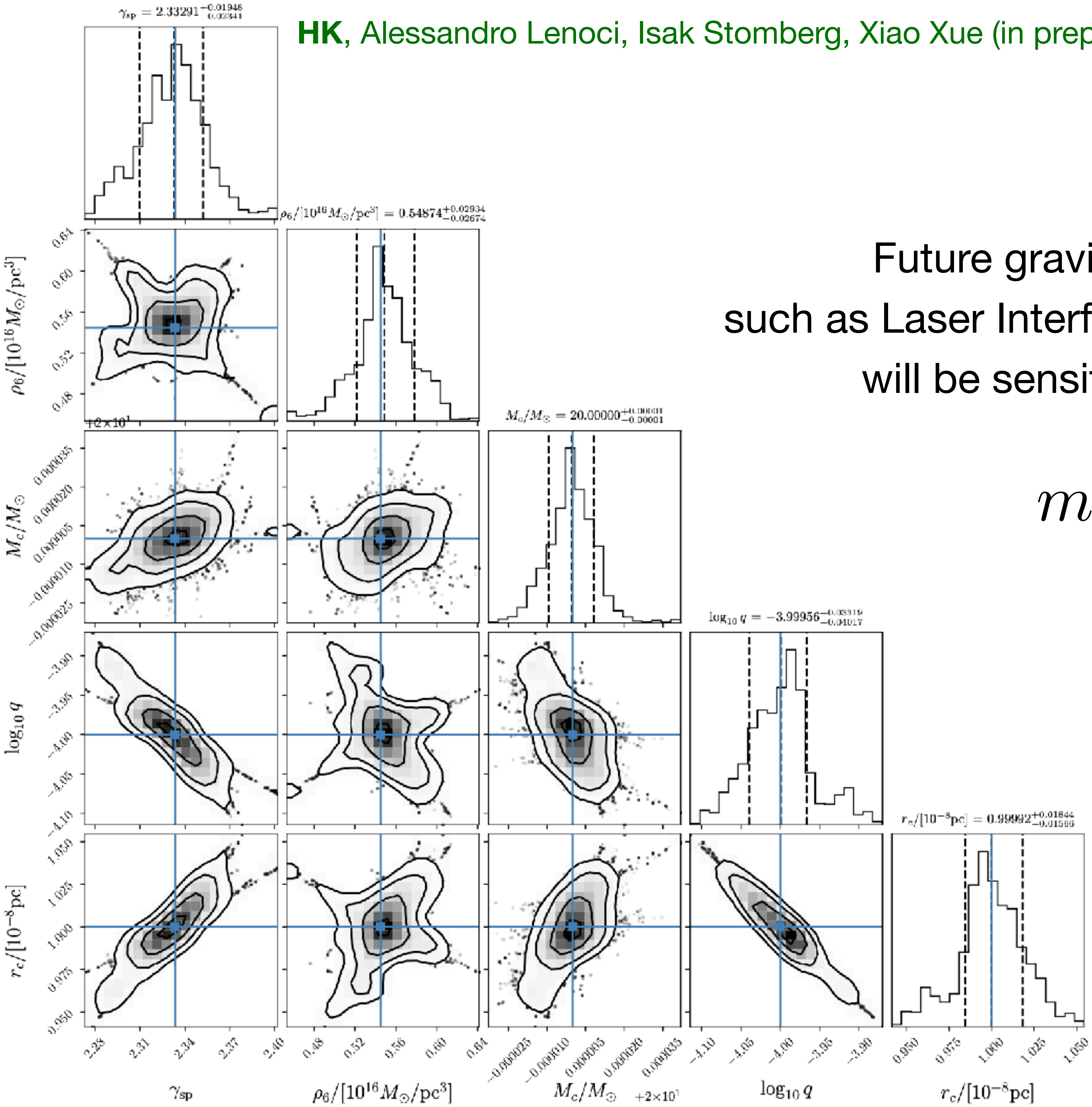
But in the presence of compressed DM halo
it would instead look like



dephasing takes place here

HK, Alessandro Lenoci, Isak Stomberg, Xiao Xue (in preparation)

Preliminary



Future gravitational wave detectors
such as Laser Interferometer Space Antenna (LISA)
will be sensitive to this kind of signal

$$m \sim 10^{-14}\,\mathrm{eV}$$

Summary

- A fresh look at hierarchy problem has revealed an interesting direction for new physics search in the context of axion and axion-like particles
- Axion (DM) search could be challenging as its mass is less restricted
- Over past ~ 10 years, interesting progress has been made in terms of terrestrial axion detection as well as astrophysical probes of axion
- To maximize the discovery potential, probing axions from multiple physics frontier, e.g. precision/astro/intensity, is needed