# Kaleidoscope of Axion Models and Probes

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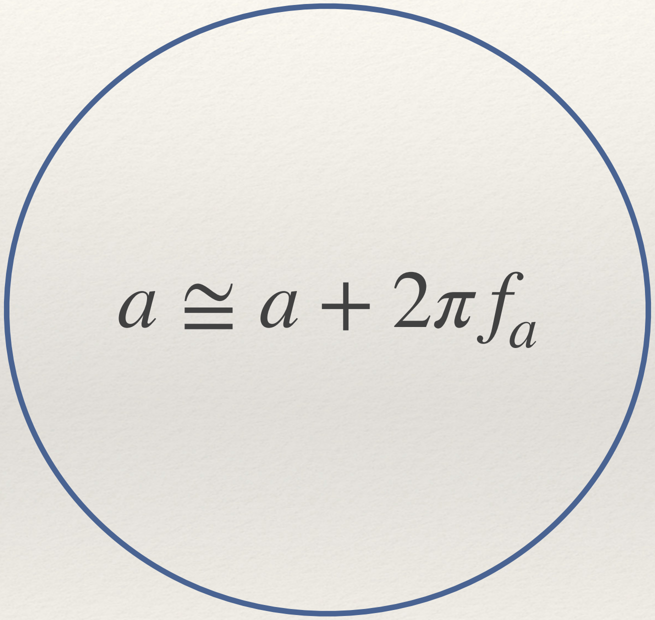
PIKIMO meeting, Dec 4, 2021

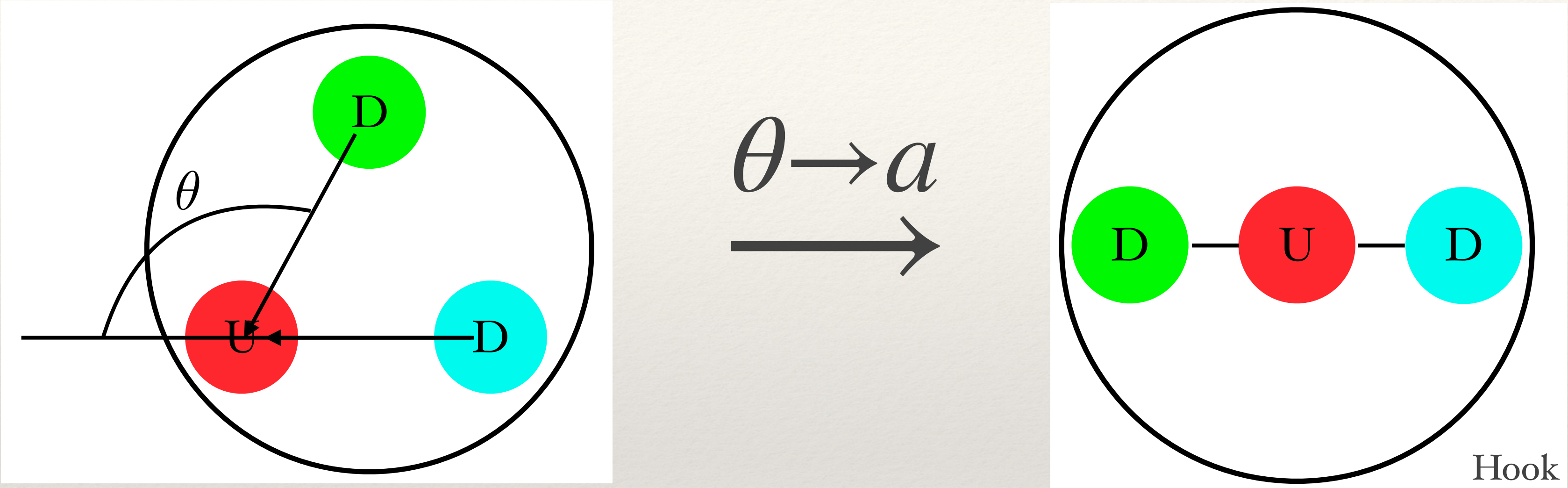
# What is an axion ?

a periodic pseudo-scalar field



$$a \cong a + 2\pi f_a$$

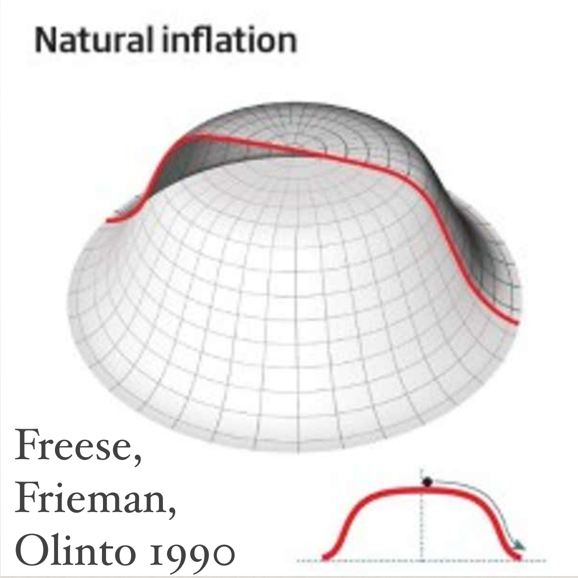
# Strong CP problem: QCD axion



Hook

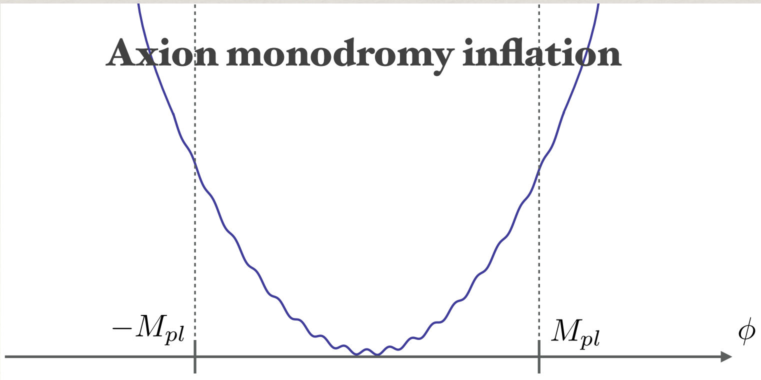
Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki 1977 - 1981

# Other applications



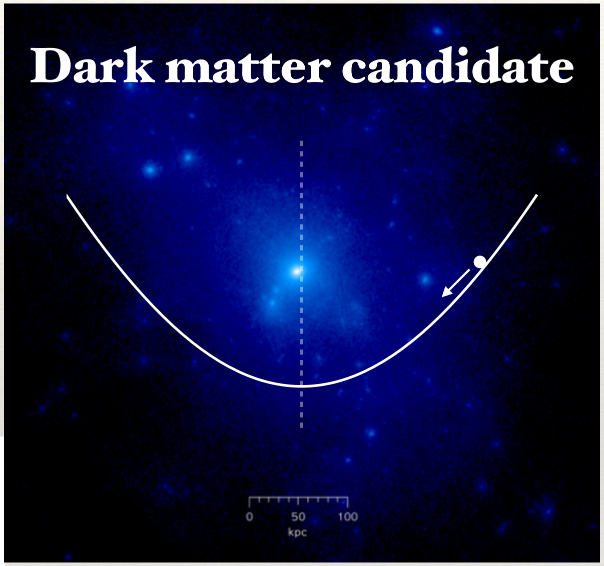
**Natural inflation**

Freese, Frieman, Olinto 1990



**Axion monodromy inflation**

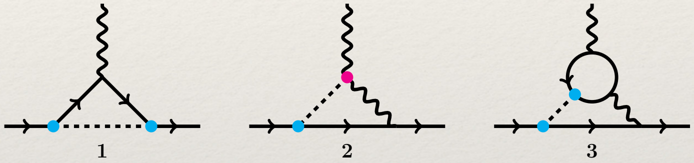
Silverstein, Westphal, McAllister 2008



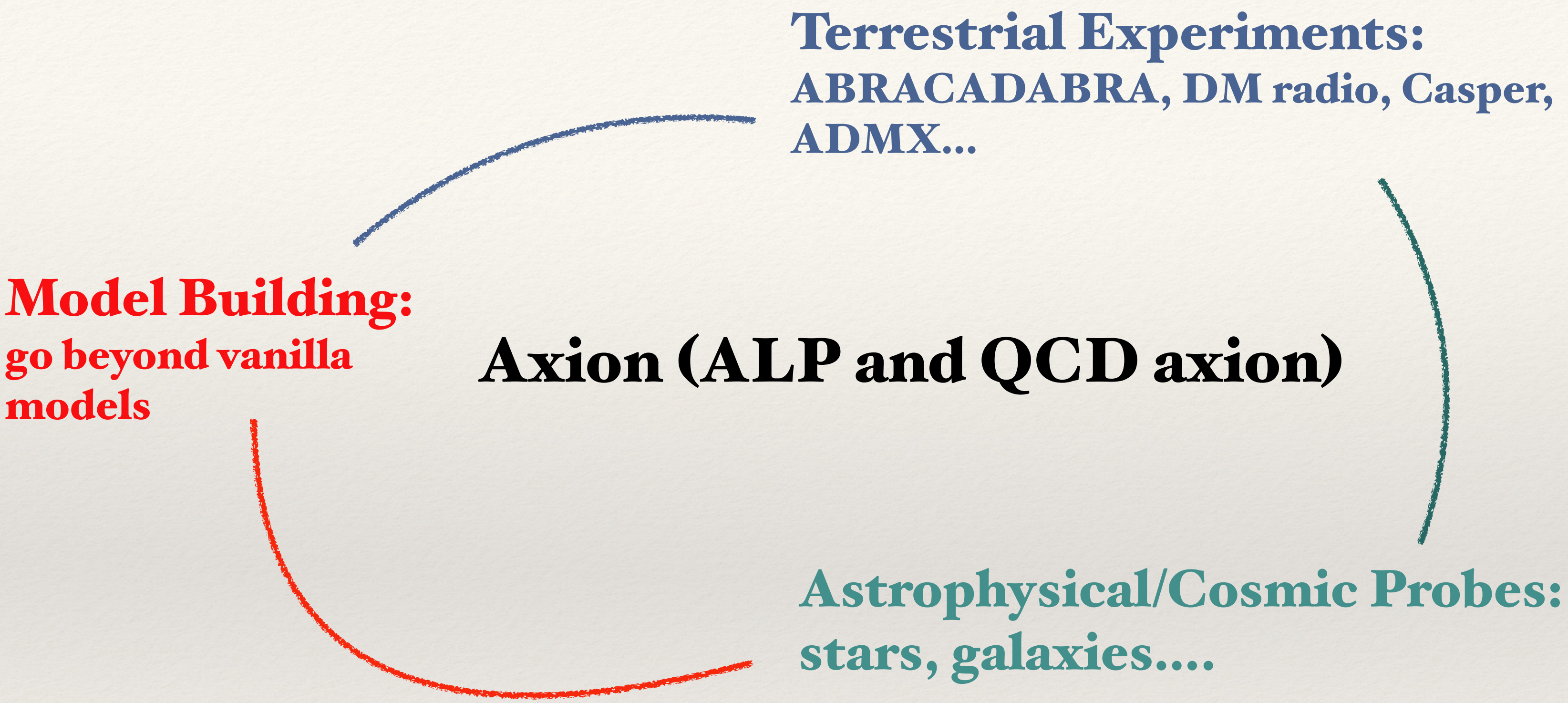
**Dark matter candidate**

Preskill, Wise, Wilczek; Dine, Fischler; Abbott, Sikivie 1983

**Muon g-2**



Marciano, Masiero, Paradisi, Passera 2016; Bauer, Neubert, Thamm 2017; Buen-Abad, Fan, Reece, Sun 2021



**Terrestrial Experiments:**
ABRACADABRA, DM radio, Casper, ADMX...

**Model Building:**
go beyond vanilla models

## Axion (ALP and QCD axion)

**Astrophysical/Cosmic Probes:**
stars, galaxies....

# Plan

- ***New source of axion potential***: axion potential from virtual magnetically charged particles.

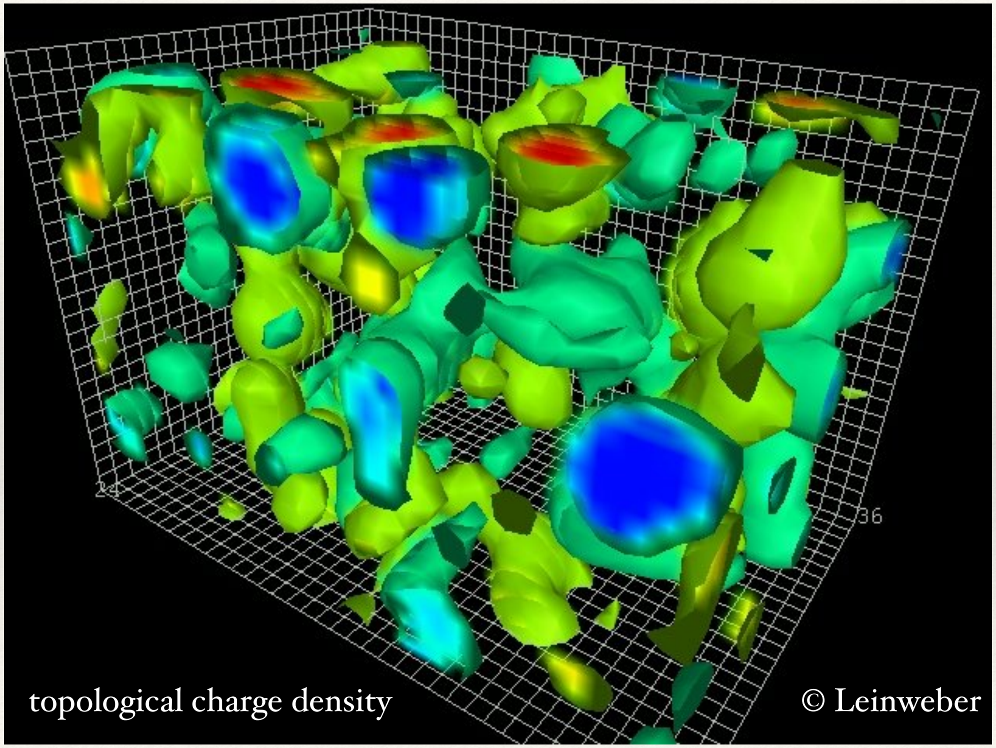
- ***New astrophysical probes of axion couplings***: axion echos from supernovae remnants; cosmological distance ladders.

- ***New cosmological model of QCD axion dark matter***: dynamically relaxed initial misalignment angle to enlarge the mass window of QCD axion dark matter (if time allows).

# New source of axion potential

# New source of axion potential

For axion coupling to non-Abelian gauge group, strong dynamics generates a potential for axion.



topological charge density

© Leinweber

Yet for axion coupling to ***Abelian*** gauge fields, $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$ , axion could still acquire a potential through ***loops of magnetically charged particles*** (magnetic monopoles and dyons).

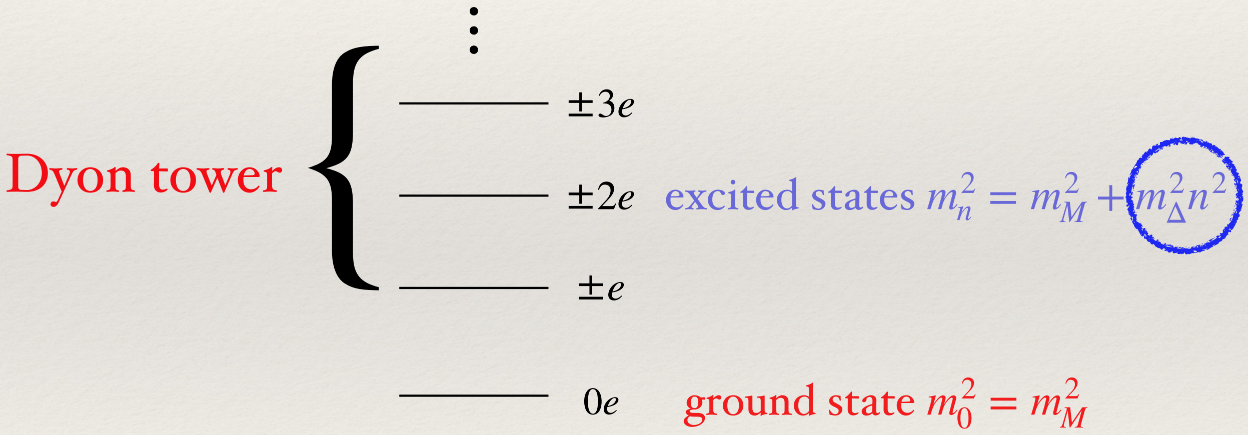
Fan, Fraser, Reece and Stout, PRL, 2021

Existence of magnetic monopoles: “***completeness hypothesis***” Polchinski 2003

Any UV-complete theory of an interacting U(1) gauge field contains magnetic monopoles, e.g., $SU(2) \to U(1)$ ’t Hooft-Polyakov (’t H-P) monopole.

Not only magnetic monopoles, but also ***dyons*** (particles with both magnetic and electric charges).

E.g., in ’t H-P case, a residual unbroken global $U(1)$ rotation could be realized by a compact real scalar. In 4d, this is described by QM of a particle living on a circle, $\sigma \cong \sigma + 2\pi$ (dyonic collective coordinate).



Dyon tower

$\vdots$

$\pm 3e$

$\pm 2e$ excited states $m_n^2 = m_M^2 + \enclose{circle}{m_\Delta^2 n^2}$

$\pm e$

$0e$ ground state $m_0^2 = m_M^2$

Review: Chapter 4 of “Advanced topics in quantum field theory”, Shifman

# Witten effect

Witten, 1979

For a magnetic monopole at the origin,

magnetic Gauss' law: $\nabla \cdot \mathbf{B} = \frac{g_m}{4\pi}\delta(\mathbf{r})$

$e$ : electric charge unit; $g_m$ : magnetic charge unit; $eg_m = 2\pi$ Dirac quantization condition;

electric Gauss' law: $\nabla \cdot \mathbf{E} + \frac{e^2}{4\pi^2}\theta\,(\nabla \cdot \mathbf{B}) = 0 \Rightarrow \frac{Q_E}{e} = -\frac{\theta}{2\pi}$

$$\uparrow$$

$$\frac{e^2}{16\pi^2}\theta F\tilde{F} \text{ with } \theta = \frac{a}{f_a}$$

A monopole obtains an effective electric charge in the presence of an axion field!

In general, the dyon electric charge is shifted to be

$$\frac{Q_E}{e} = n - \frac{\theta}{2\pi}, \quad n = 0, \pm 1, \pm 2, \cdots$$

The corresponding energy spectrum will be modified as well!

The Lagrangian for the dyon: $L = \frac{1}{2}\dot{\sigma}^2 + \frac{\theta}{2\pi}\dot{\sigma}$  $\sigma$: dyonic collective coordinate

Conjugate momentum: $\Pi_\sigma = \dot{\sigma} + \frac{\theta}{2\pi}$

Hamiltonian: $H = \frac{1}{2}\left(\Pi_\sigma - \frac{\theta}{2\pi}\right)^2 \quad \Rightarrow \quad E_n = \frac{1}{2}\left(n - \boxed{\frac{\theta}{2\pi}}\right)^2$

Integrating out these excited dyonic states with masses depending on axion ⇒ potential for the axion $\theta$ !

$e^{-S_{\text{inst}}} \sim e^{-8\pi^2/g^2}$ in 't H-P model

$$V_{\text{eff}}(\theta) = -\sum_{\ell=1}^{\infty} \frac{m_\Delta^2 m_{\mathrm{M}}^2}{32\pi^4\ell^3} e^{-2\pi\ell m_{\mathrm{M}}/m_\Delta} \boxed{\cos(\ell\theta)} \times \left(1+\frac{3m_\Delta}{2\pi\ell m_{\mathrm{M}}}+\frac{3m_\Delta^2}{(2\pi\ell m_{\mathrm{M}})^2}\right),$$

periodic

$\ell$: winding number; $m_M$ : ground state monopole mass; $m_\Delta$ : mass splitting unit

# A pheno application

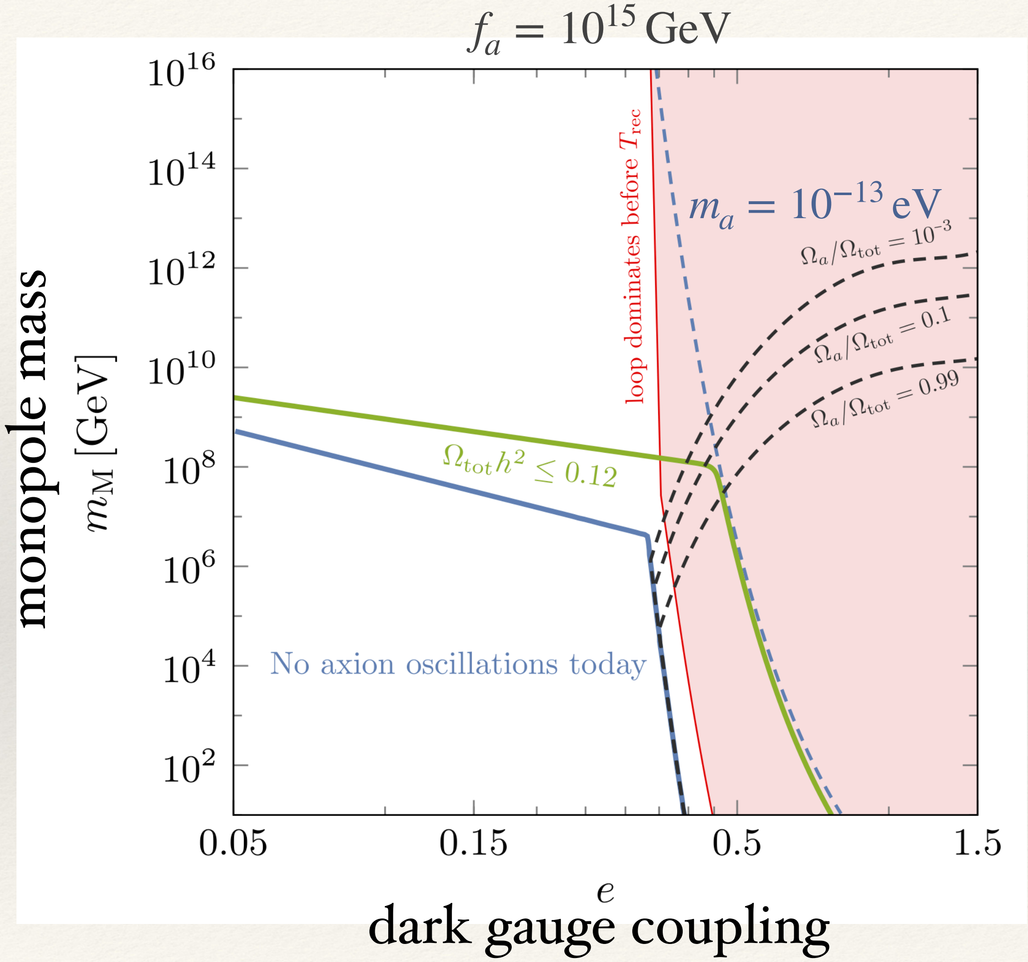
A hidden gauged $U(1)$ sector with an axion (monopole/dyons in the spectrum).

Real monopoles could be produced as topological defects through Kibble-Zurek mechanism in the early Universe. Kibble 1997; Zurek 1985

Axion mass gets two contributions:

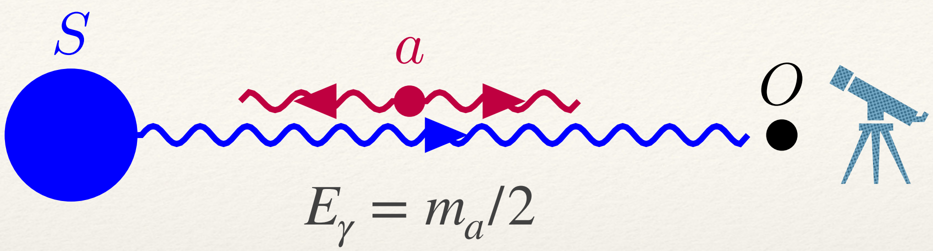
- Virtual magnetic monopole/dyon contributions;
- Real magnetic monopole background Fischler, Preskill 1983

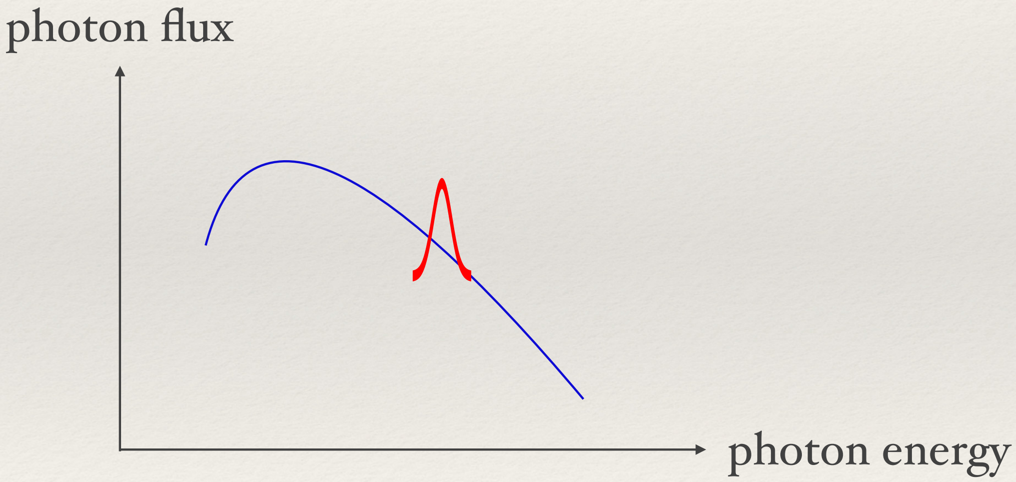
Both axion and monopole (produced in the early Universe) contribute to dark matter.



# New astrophysical probes of axion couplings

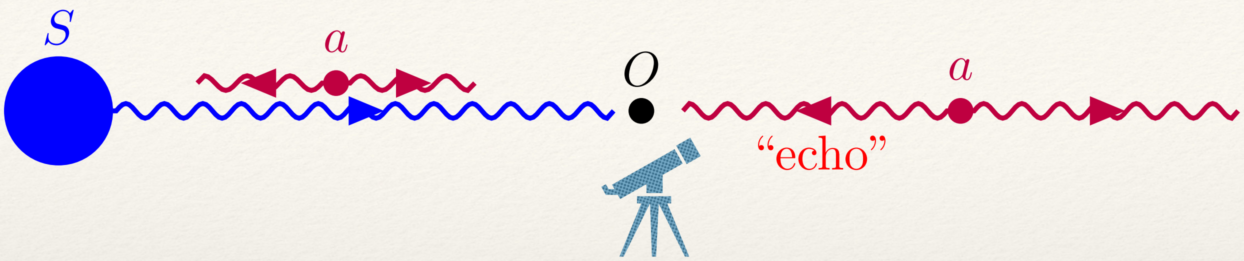
# Stimulated axion decays

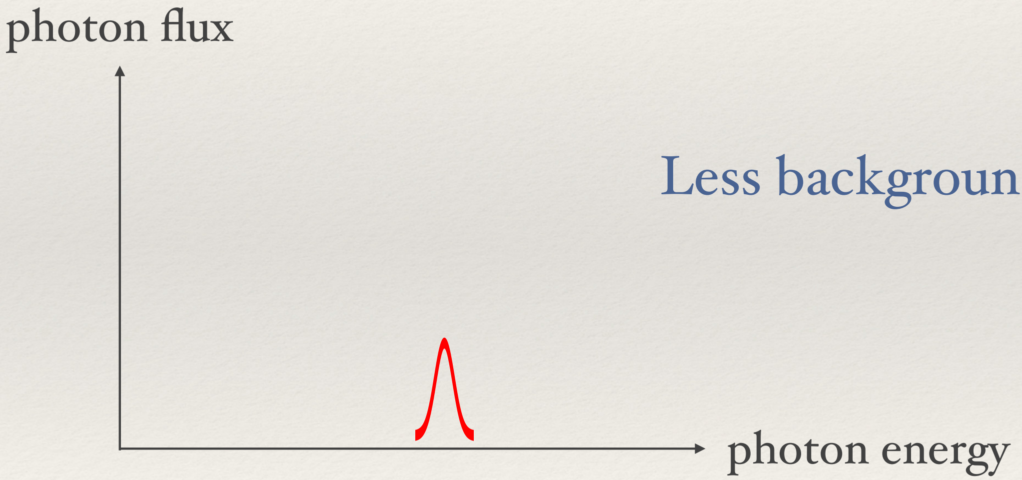




Caputo, Regis, Taoso and Witte 2018

# Axion echos

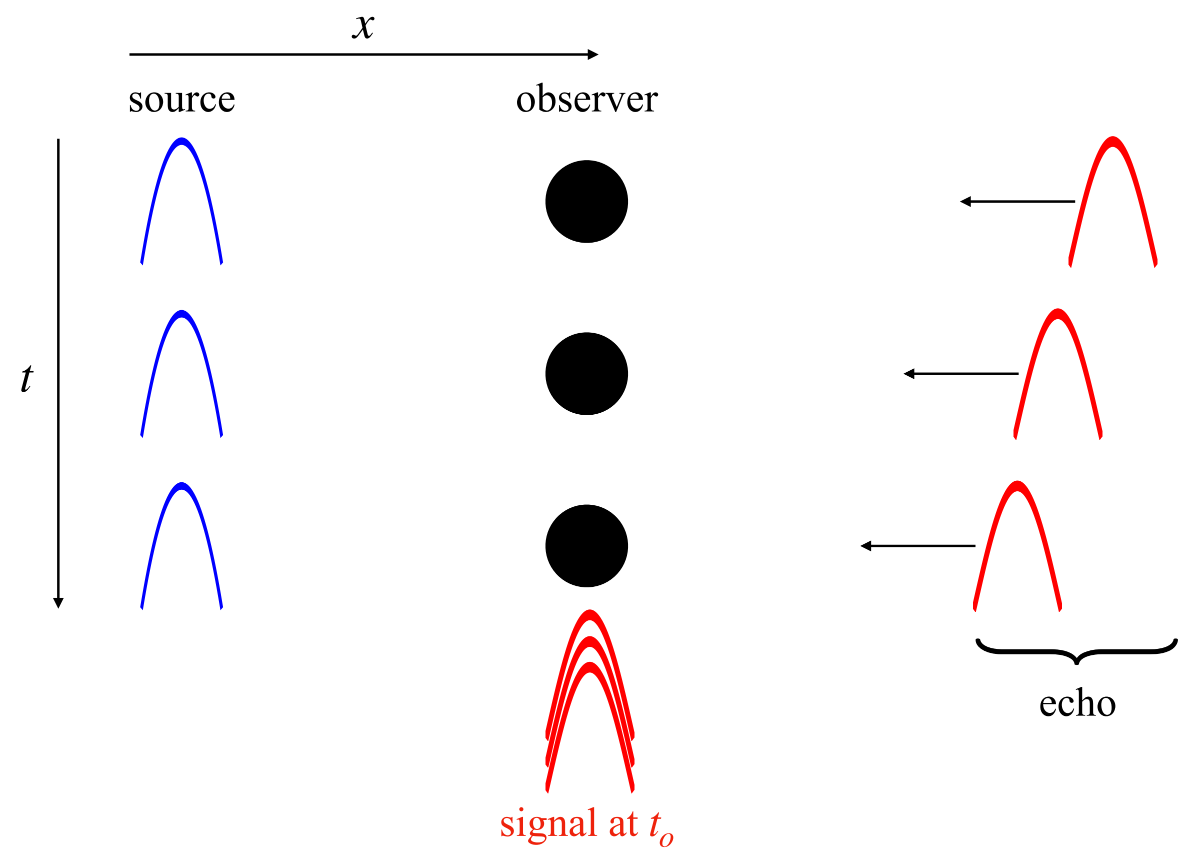




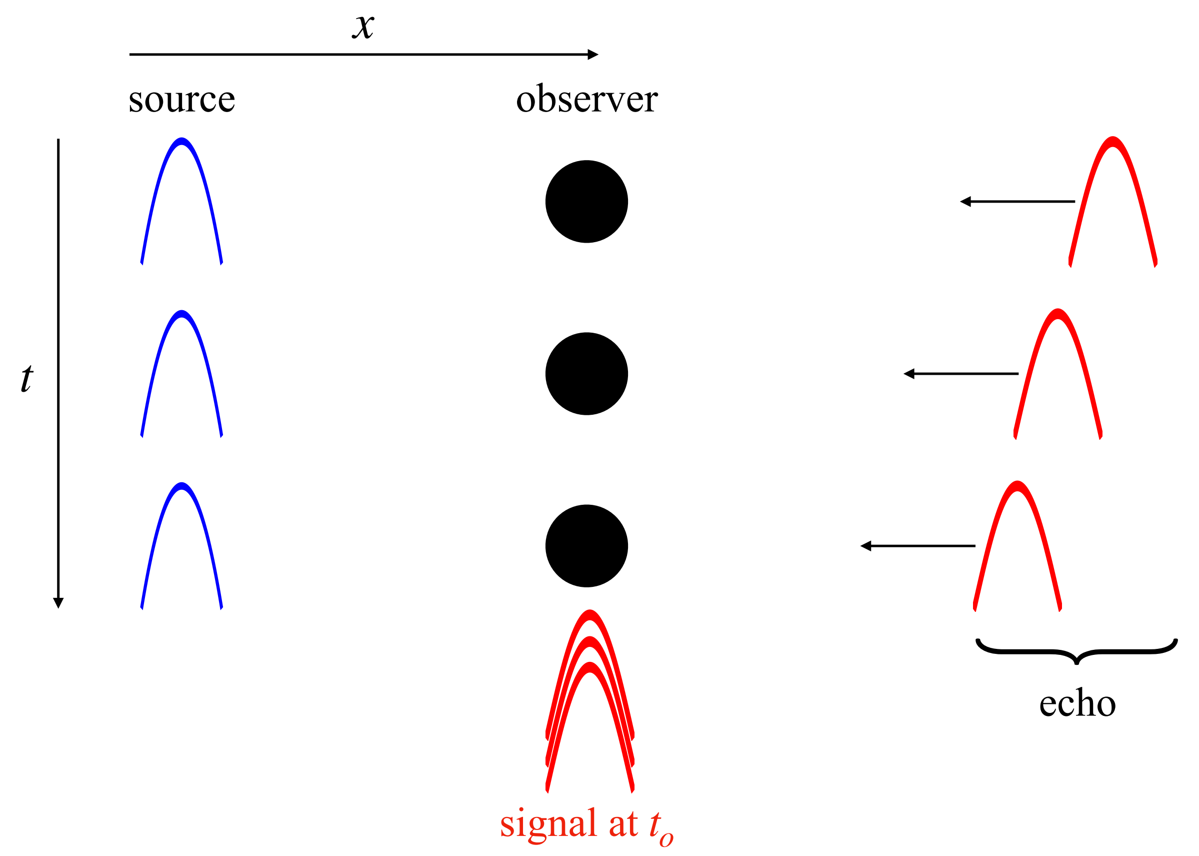
Less background !

Arza, Sikivie 2019; Ghosh, Salvado and Miralda-Escude 2020

# Axion echos from the entire history of the source



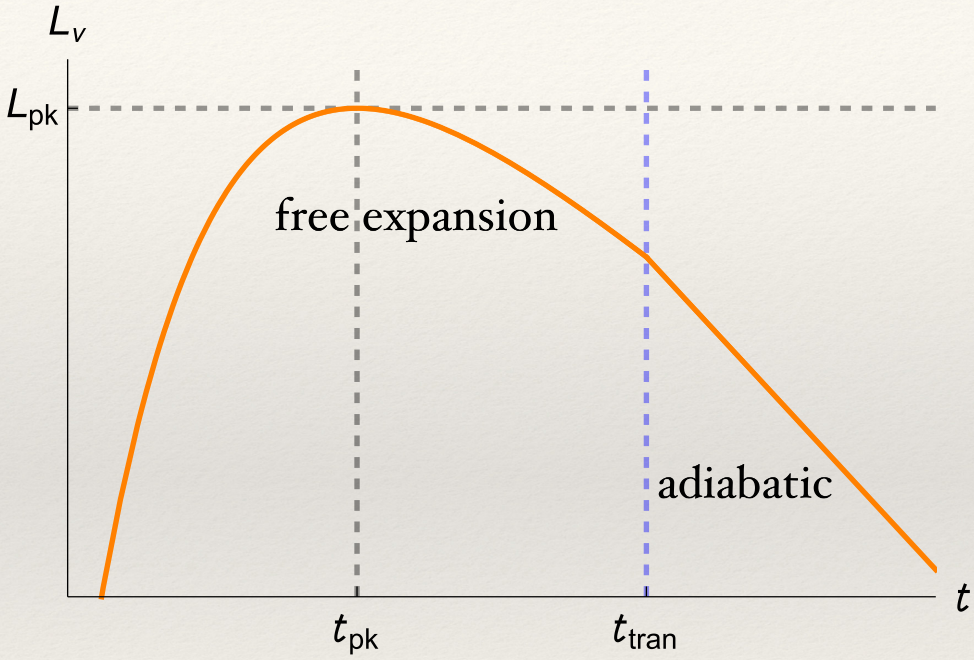
# Axion echos from the entire history of the source



Dim old source which used to be very bright could lead to a strong signal !

Signal is integrated over the entire history of the source

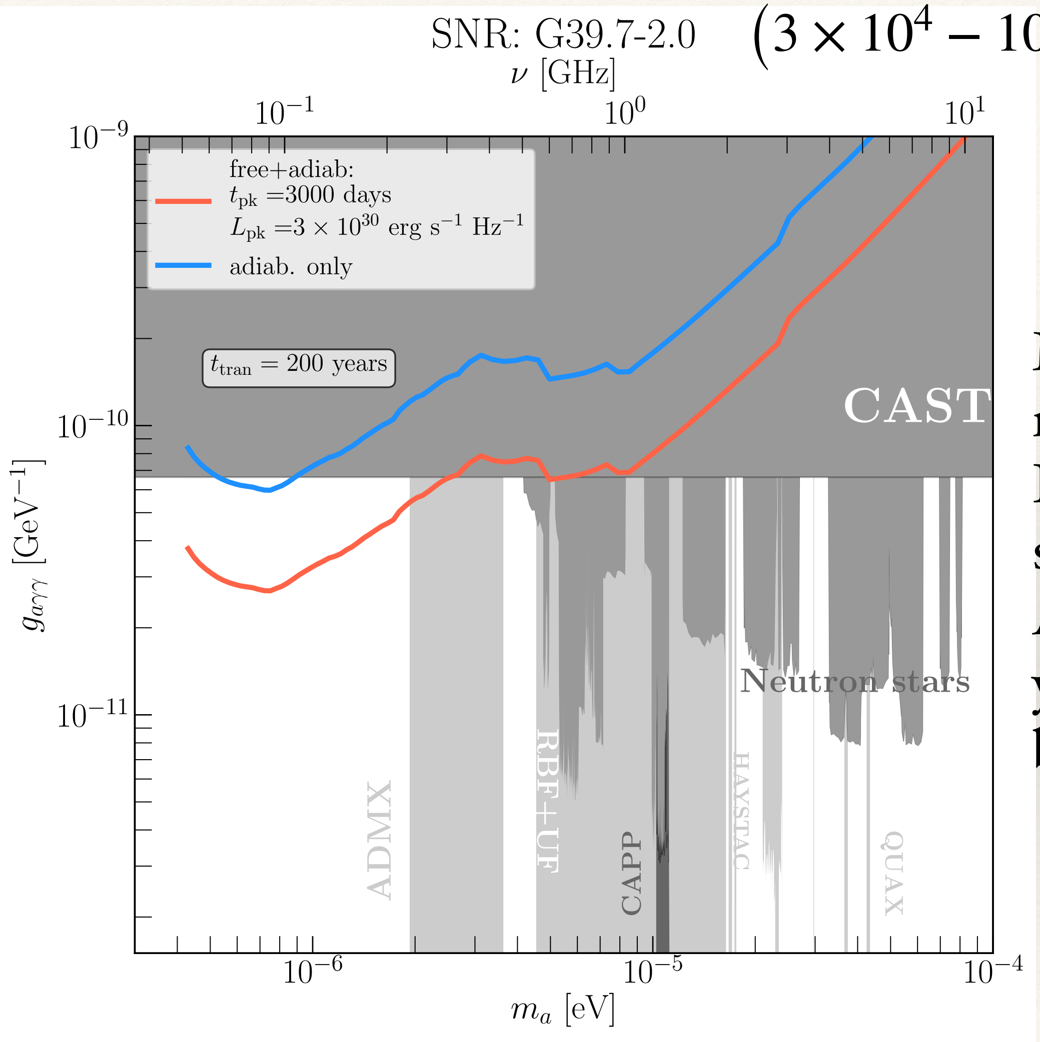
# Axion echos from supernovae remnants



Buen-Abad, Fan, Sun; Sun, Schutz, Nambrath, Leung, Masui 2021

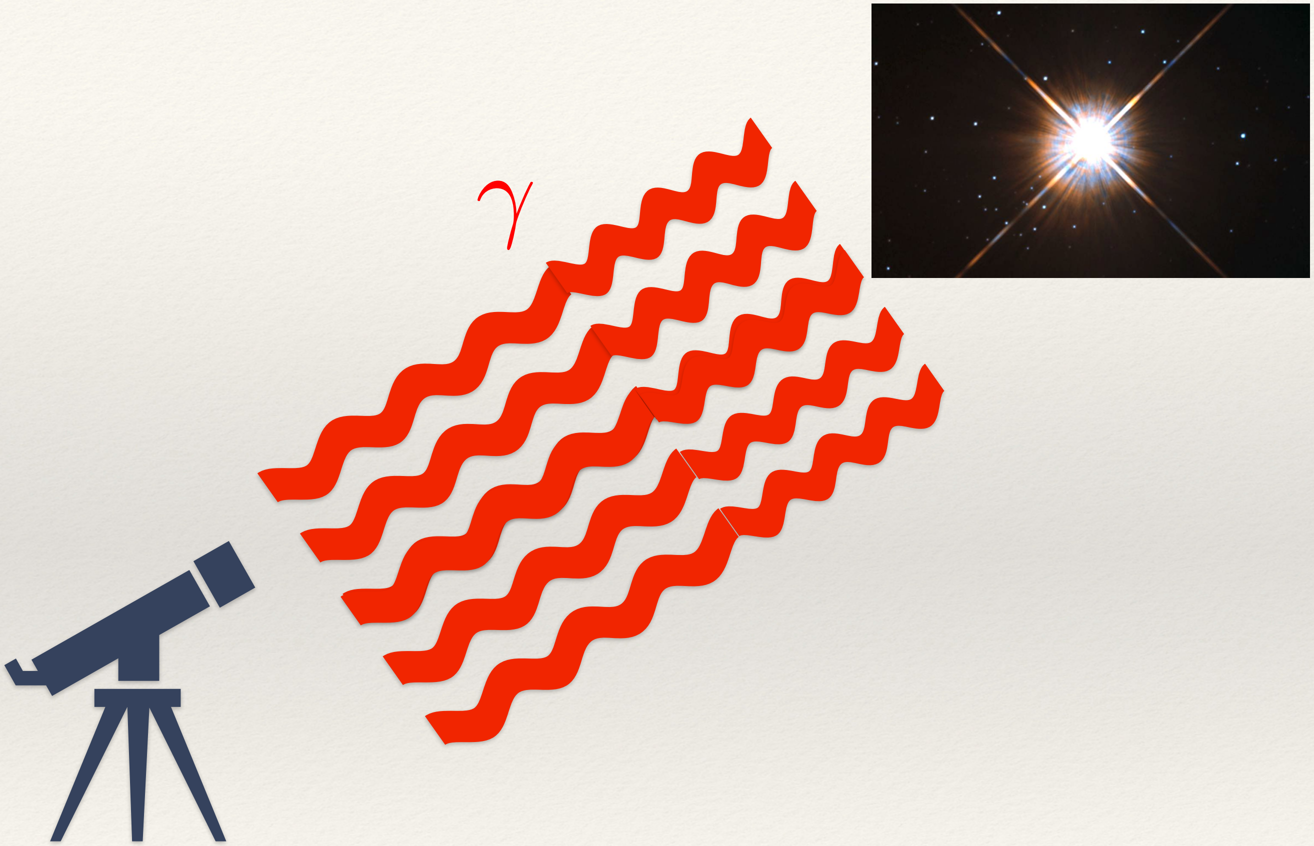
$(3 \times 10^4 - 10^5)$ years old

Radio telescope:
SKA1



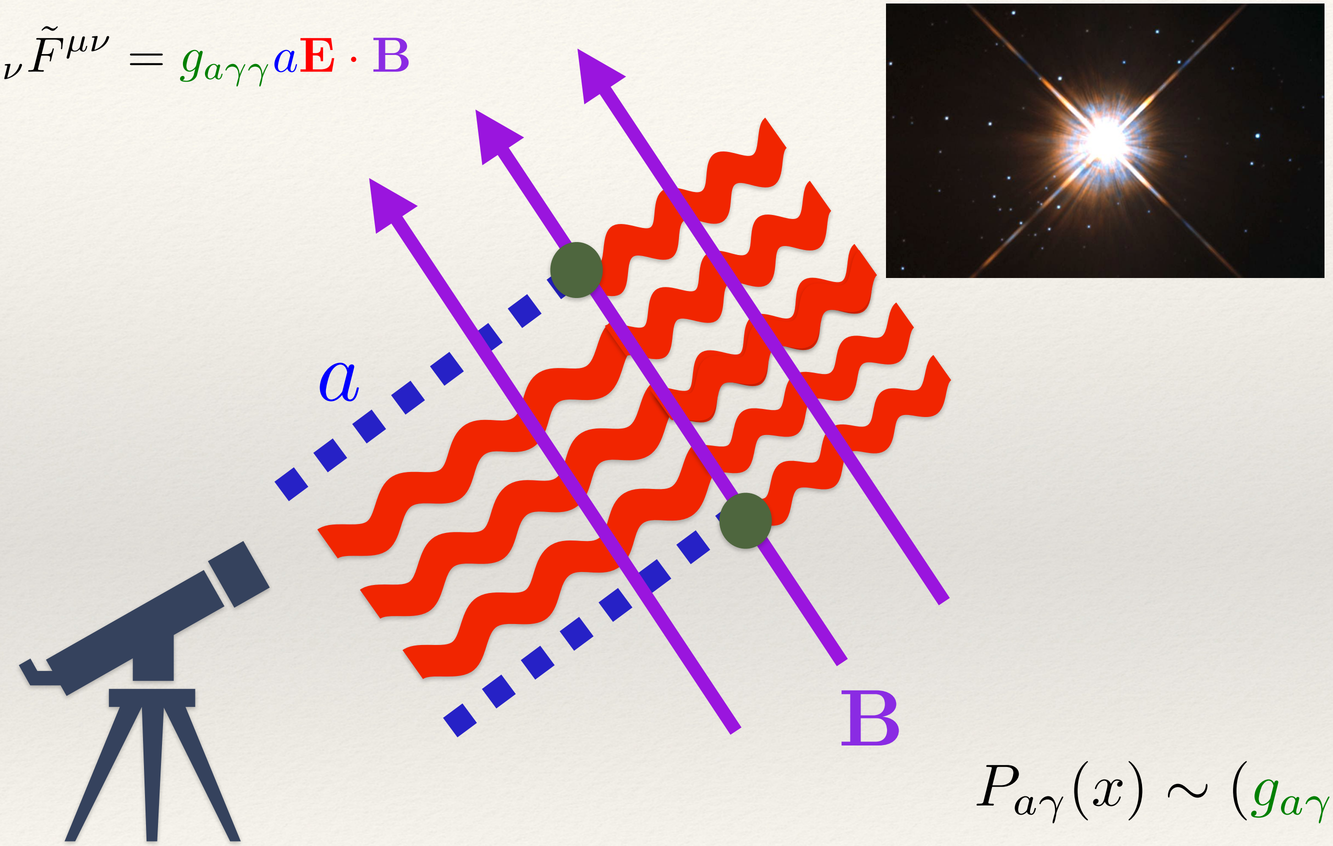
Not among the brightest radio source today !
Brightest extrasolar radio source above 1 GHz, Cas A (also a SNR of 340 years old), is ~ 30 times as bright as this one.

# Dimming of bright sources



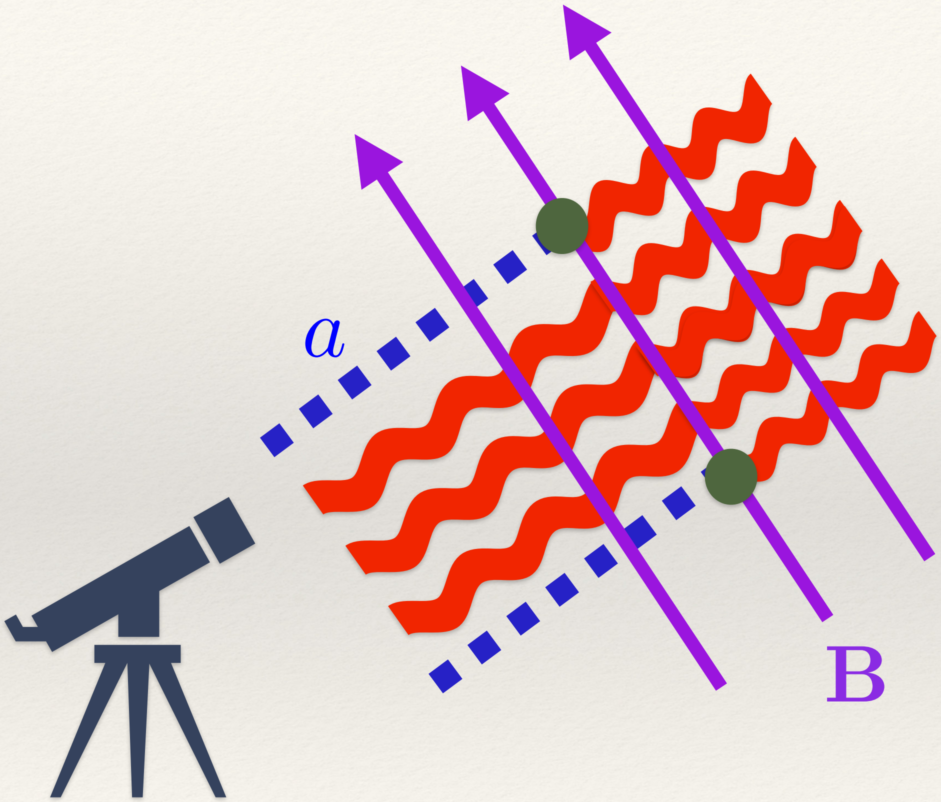
# Dimming of bright sources

$$-\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$



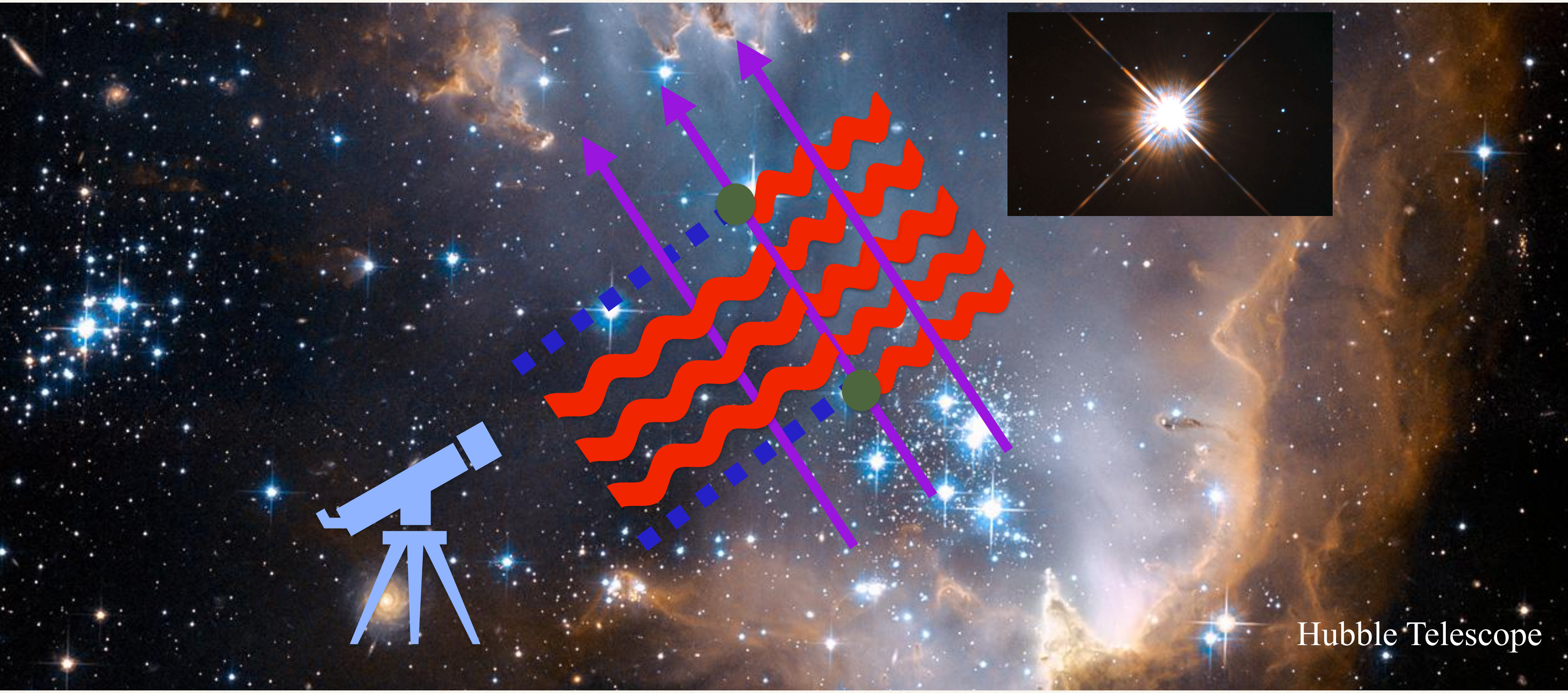
$$P_{a\gamma}(x) \sim \left(g_{a\gamma\gamma} B\right)^2 x^2$$

# Dimming of bright sources



Further

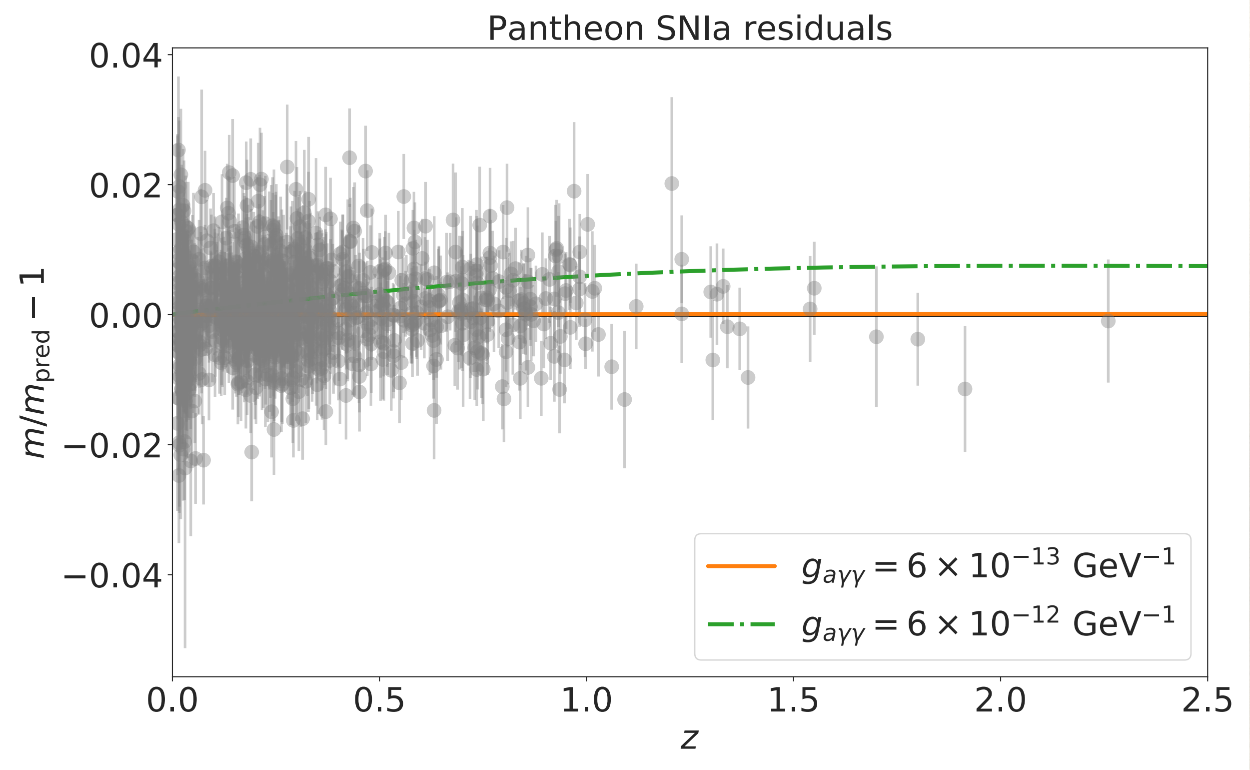
# Cosmic Distance



Hubble Telescope

# Type Ia SN Pantheon data set (1048 SNIa)

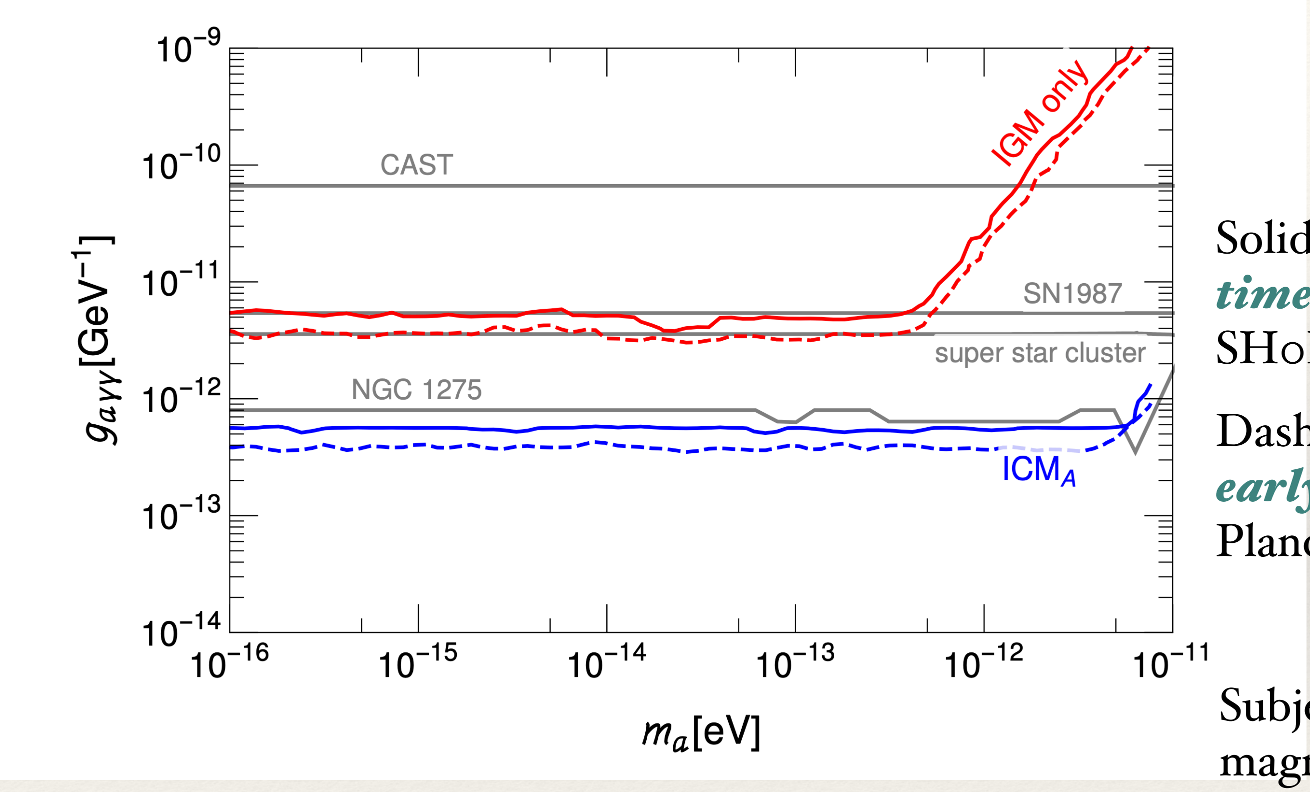
apparent magnitude (proxy of luminosity distance)



redshift

Buen-Abad, Fan, Sun 2020

Red: type Ia SN Pantheon luminosity distance data set



Solid: anchor $H_0$ with ***late time*** measurements, SH0Es;

Dashed: anchor $H_0$ with ***early time*** measurements, Planck.

Subject to uncertainties of magnetic field modeling

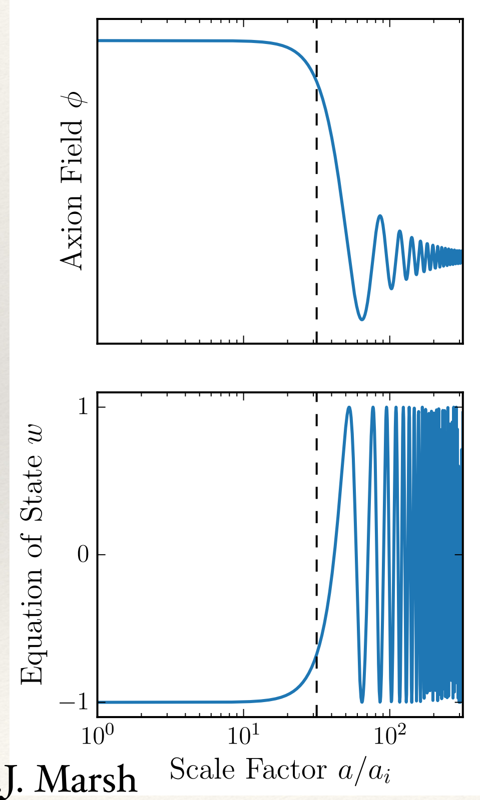
Blue: galaxy cluster angular diameter distance data set

Buen-Abad, Fan, Sun 2020

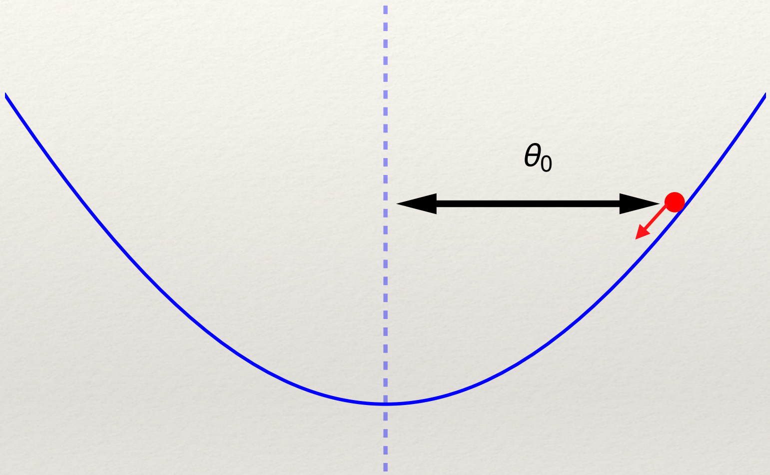
# New cosmological model of QCD axion dark matter

# Enlarging the mass window of QCD axion DM

Vanilla QCD axion DM model: *Misalignment mechanism:* Preskill, Wise, Wilczek; Dine, Fischler; Abbott, Sikivie 1983



D.J. Marsh



QCD axion (PQ breaking during inflation)

$$\theta_0 \sim \mathcal{O}(1), \quad f_a \lesssim \mathcal{O}(10^{12})\,\text{GeV}$$

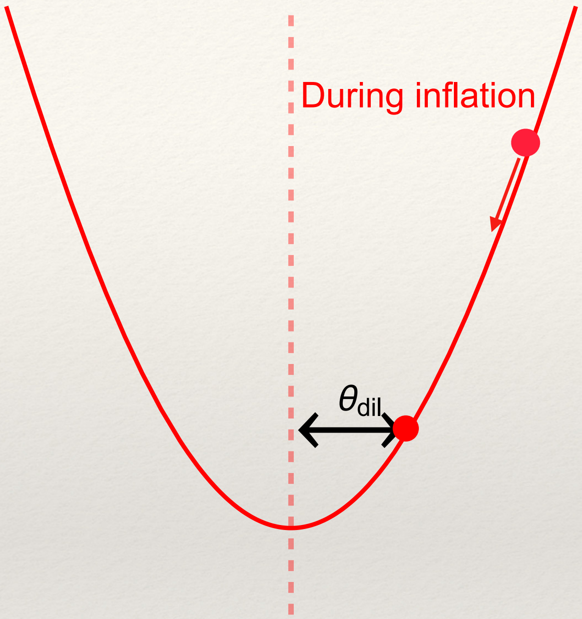
Axion dark matter mass in scenario of PQ breaking after inflation: Buschmann, Foster et.al 2021

# Enlarging the mass window of QCD axion DM

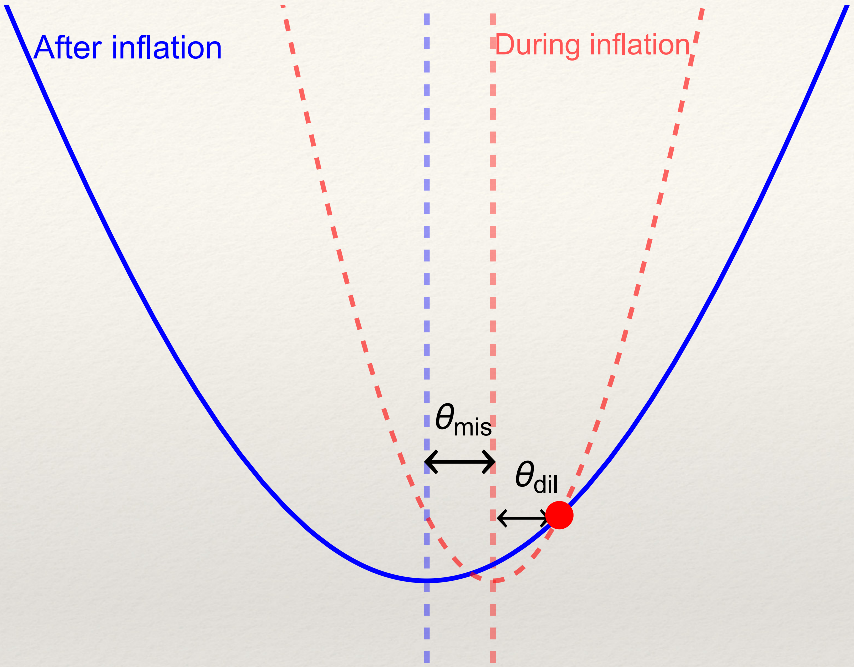
Light QCD axion DM: axion mass $\ll 10^{-5}$ eV and $f_a \gg 10^{12}$ GeV, overproduction from misalignment. Relax the initial misalignment angle to make $\theta_0 \ll 1$.

- Anthropic: Tegmark, Aguirre, Rees, Wilczek 2006;
- Exponentially long inflationary period: Takahashi, Yin, Guth 2018; Graham, Scherlis 2018;
- **Dynamical axion potential during and after inflation**: Dvali 1995; Co, Gonzalez, Harigaya 2018; Buen-Abad, Fan 2019;

# Basic mechanism and requirements

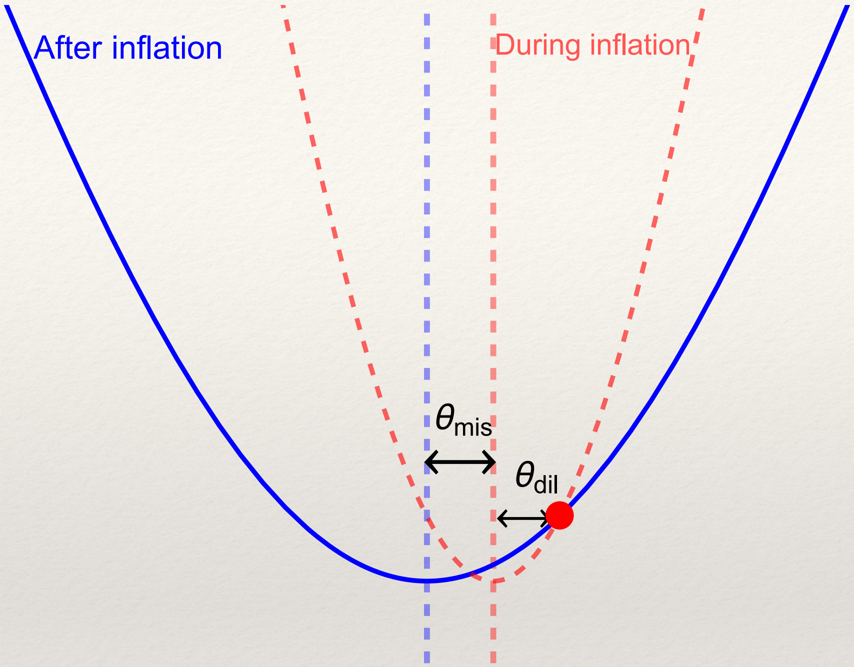


Steeper axion potential during inflation. Axion oscillates during inflation. By the end of inflation, axion misalignment angle $\theta_{\rm dil} \ll 1$.



Relaxed to the usual axion potential after inflation;

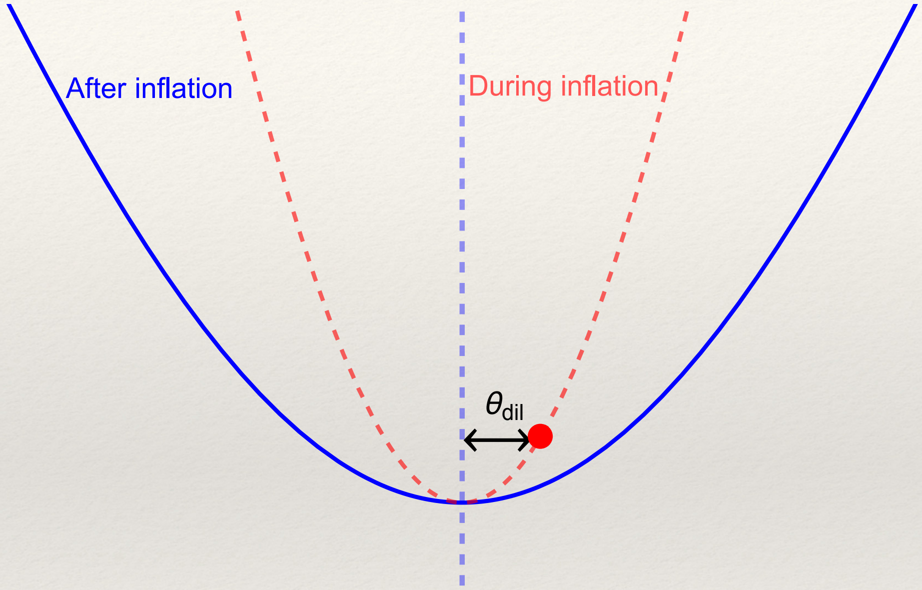
The minima of the two potentials may ***not*** be at the same place, the mismatch characterized by $\theta_{\mathrm{mis}}$ .

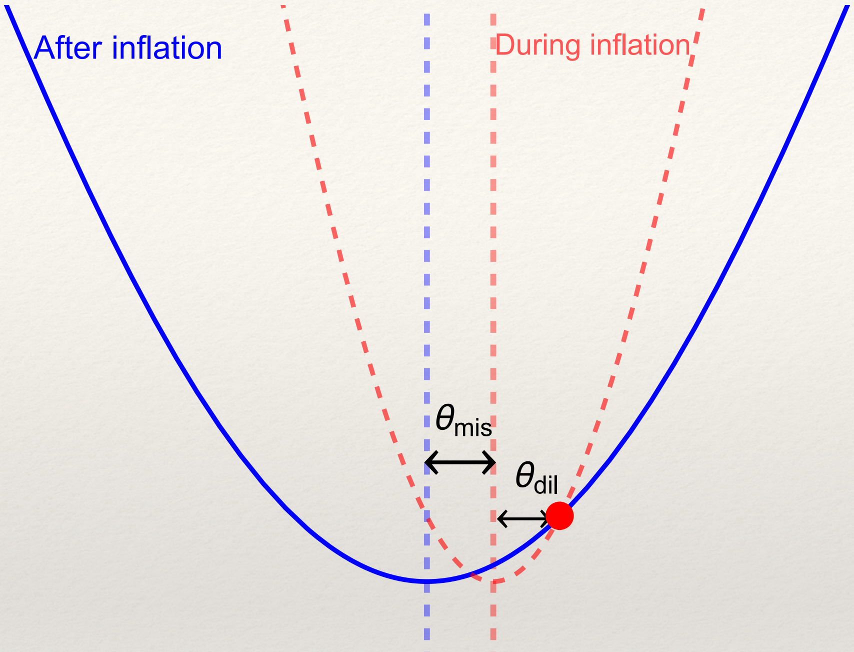


After inflation, axion is frozen until the Hubble rate drops around its mass. Then it starts to oscillate again. The new misalignment angle is of order $\max(\theta_{\mathrm{mis}}, \theta_{\mathrm{dil}})$.

$\theta_{\mathrm{dil}} \ll 1$ due to inflation. Thus if $\theta_{\mathrm{mis}} \ll 1$, the misalignment angle of axion when it starts to oscillate again after inflation is $\ll 1$.

# What we want:





***Approximate alignment*** of the minima of the QCD axion potential during and after inflation: ***negligible*** new CP phases.

In general, new CP phases are unavoidable when one introduces new particles beyond the Standard Model to generate a dynamical axion potential.

# Small UV instantons

Color instanton contribution to the axion potential $\propto \mathrm{e}^{-2\pi/\alpha_s}$ : $\alpha_s \uparrow$ , $\mathrm{e}^{-2\pi/\alpha_s} \uparrow$

Holdom, Peskin 1982; Dine, Seiberg 1986; Flynn, Randall 1987; Choi, Kim, Sze 1988…

A new elegant way to realize this idea: Agrawal, Howe 2017

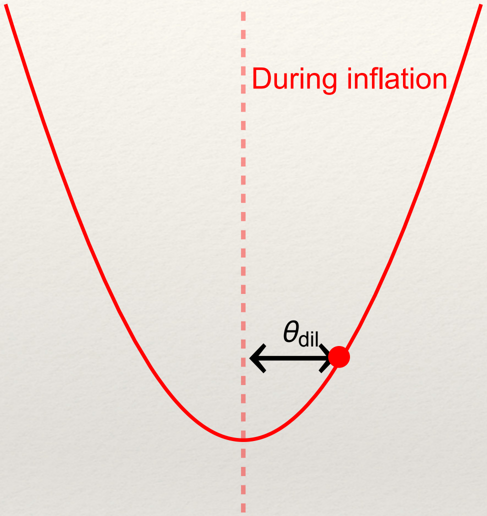
$$SU(3)_1 \times SU(3)_2 \xrightarrow{\langle\Sigma\rangle} SU(3)_c \qquad \Sigma : (3, \bar{3})$$

At symmetry breaking scale $M$,

$$\frac{1}{\alpha_s(M)} = \frac{1}{\alpha_1(M)} + \frac{1}{\alpha_2(M)}, \qquad \Rightarrow \alpha_1(M), \alpha_2(M) > \alpha_s(M)$$

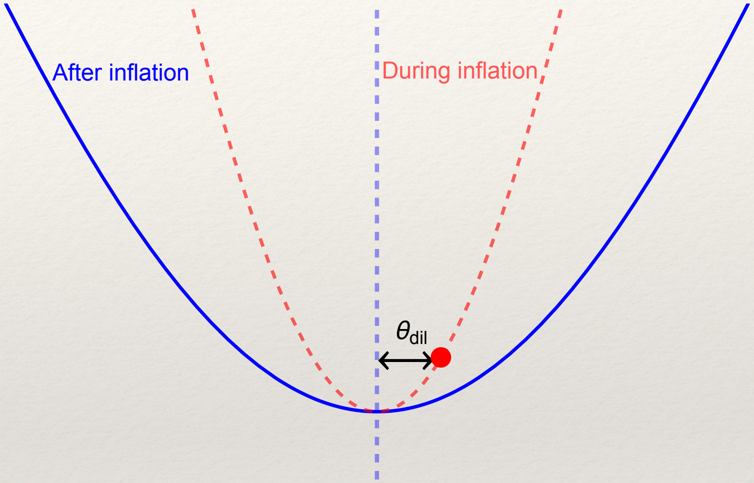
***No*** new fermions beyond the SM need to be introduced. ***No new phases!***

UV instanton dominates



dynamical Yukawa coupling

IR instanton dominates



$$f_a \lesssim 10^{12}\,\text{GeV} \Rightarrow f_a \lesssim 10^{15}\,\text{GeV}$$

Buen-Abad, Fan 2019

# Outlook

Axion physics is an old subject but still a lot of fun things to explore from many different directions.

- Axion potential from virtual magnetically charged particles;

- Different types of astrophysical probes to axion coupling.

- Dynamical axion potential: QCD axion dark matter could have a decay constant as high as the GUT scale; close interplay with inflationary physics;

Clearly there are more out there for the axion hunters!

# Thank you!

# Back up

In general, the energy spectrum of dyons in the presence of an axion:

$$m_n^2 - m_M^2 = m_\Delta^2 \boxed{\left(n - \frac{\theta}{2\pi}\right)^2}$$

periodicity:

$$n \to n + 1, \quad \theta \to \theta + 2\pi$$

Integrating out these excited states with masses depending on axion ⇒ potential for the axion $\theta$ !

Two viewpoints:

1. Integrate out the dyons to get a Coleman-Weinberg potential for axion.
2. Do the path integral over all monopole loops.

Related by Poisson resummation

invariant length

transition amplitude $\langle x | x \rangle_\tau$

$$V_{\text{eff}} = -\int_0^\infty \frac{\mathrm{d}\tau}{2\tau} \frac{1}{2(2\pi\tau)^2} \exp\left(-\frac{m^2\tau}{2}\right).$$

$$m_n^2 = m_{\text{M}}^2 + m_\Delta^2 \left(n - \frac{\theta}{2\pi}\right)^2$$

$$\Bigg\downarrow$$

$$-\sum_{n\in\mathbb{Z}} \int_0^\infty \frac{\mathrm{d}\tau}{4\tau\,(2\pi\tau)^2} \exp\left(-\frac{m_{\text{M}}^2\tau}{2} - \frac{m_\Delta^2\tau}{2}\left(n - \frac{\theta}{2\pi}\right)^2\right).$$

Poisson resum

$$\sum_{n\in\mathbb{Z}} \mathrm{e}^{-\frac{1}{2}m_\Delta^2\tau\left(n-\frac{\theta}{2\pi}\right)^2} = \sum_{\ell\in\mathbb{Z}} \sqrt{\frac{2\pi}{m_\Delta^2\tau}} \exp\left(-\frac{2\pi^2\ell^2}{m_\Delta^2\tau} + i\ell\theta\right).$$