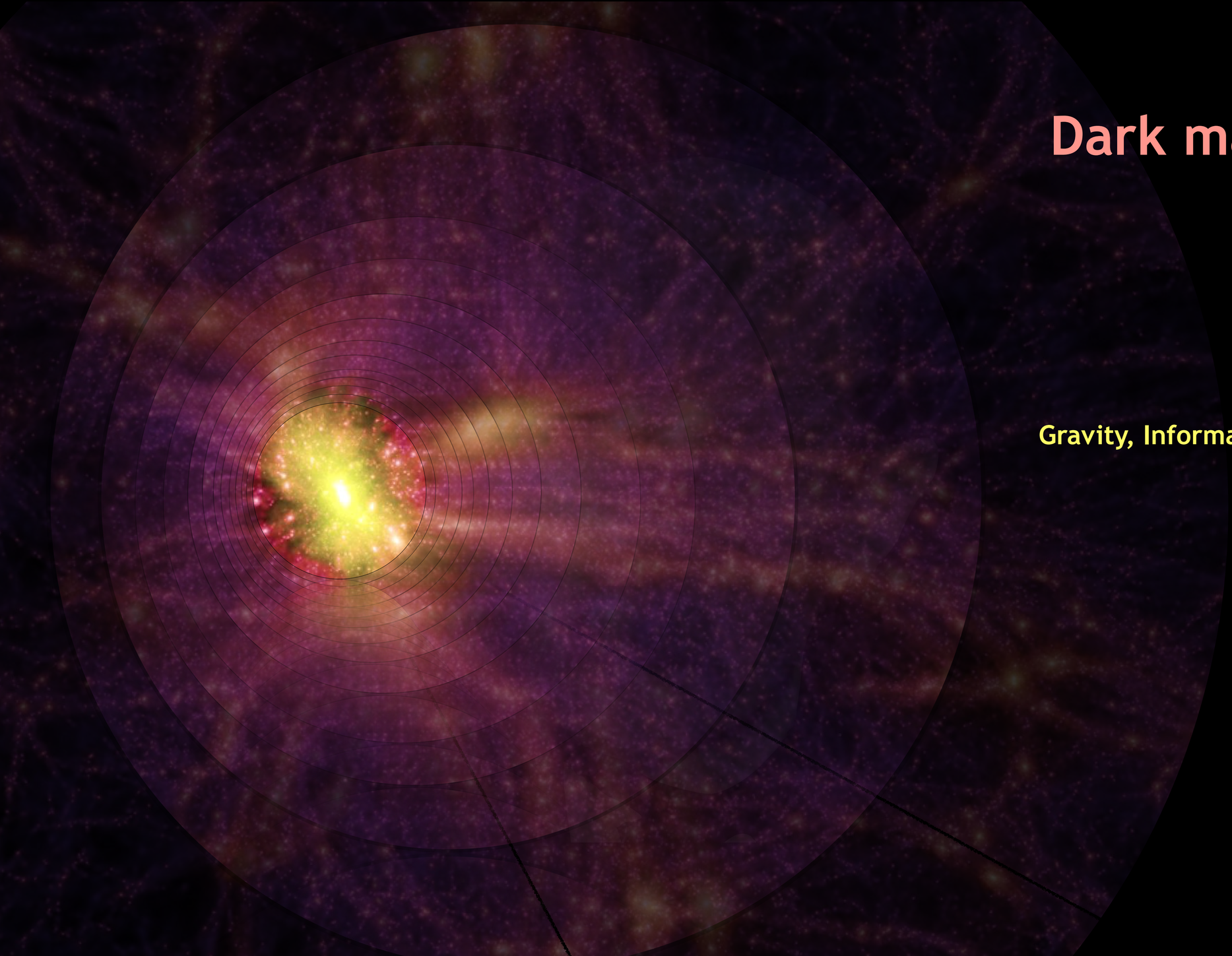


Dark matter and Axions

Javier Redondo
Gravity, Information and Fundamental Systems
5/11/2019

MAX-PLANCK-GESELLSCHAFT

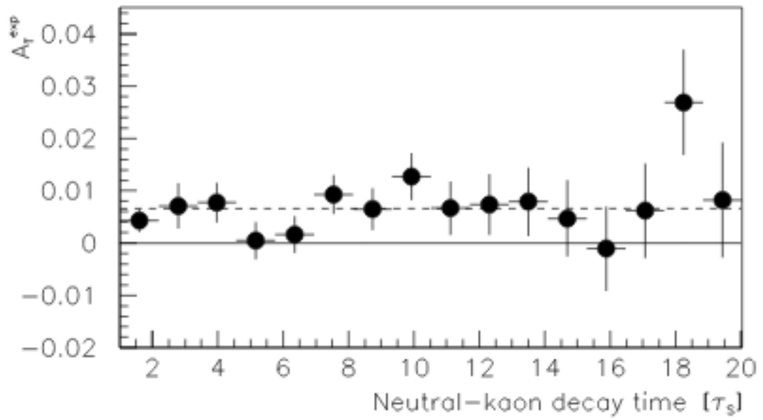
Dep. Theoretical Physics
Universidad de Zaragoza

MPP Munich

CP is violated by electroweak interactions

CP-violation (CPLEAR 90's)

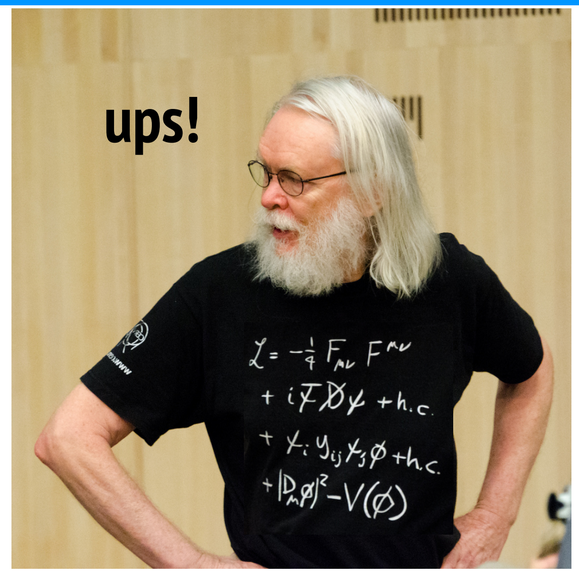
$$\frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$



... but not in the strong interactions

which is shocking! QCDs are P, T violating

$$\mathcal{L}_{\rm QCD} = \underbrace{-\frac{1}{4}G_{\mu\nu a}G_a^{\mu\nu} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq}_{\text{P,T conserving}} + \underbrace{\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\tilde{G}_a^{\mu\nu}}_{\text{P,T violating}}$$



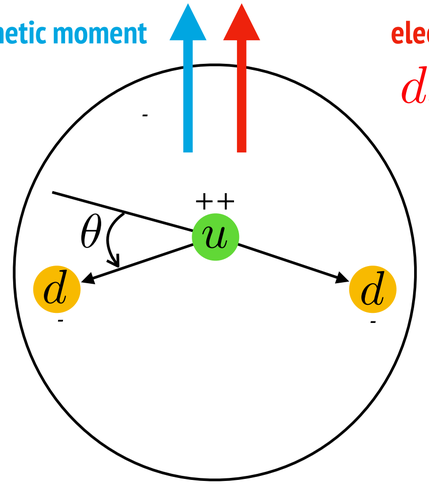
we tend to forget this

In SM, quark phases contribute to θ (and they are responsible for EW CP violation) $\theta = \theta_{\rm QCD} + {\rm argDet}\{M_q\}$

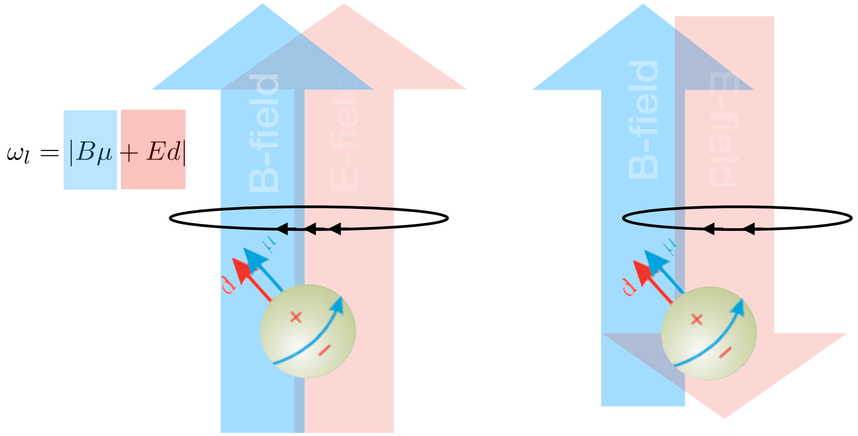
$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$ **induces P and T (CP) violation** $\propto \theta$

Electric Dipole Moment of the neutron?

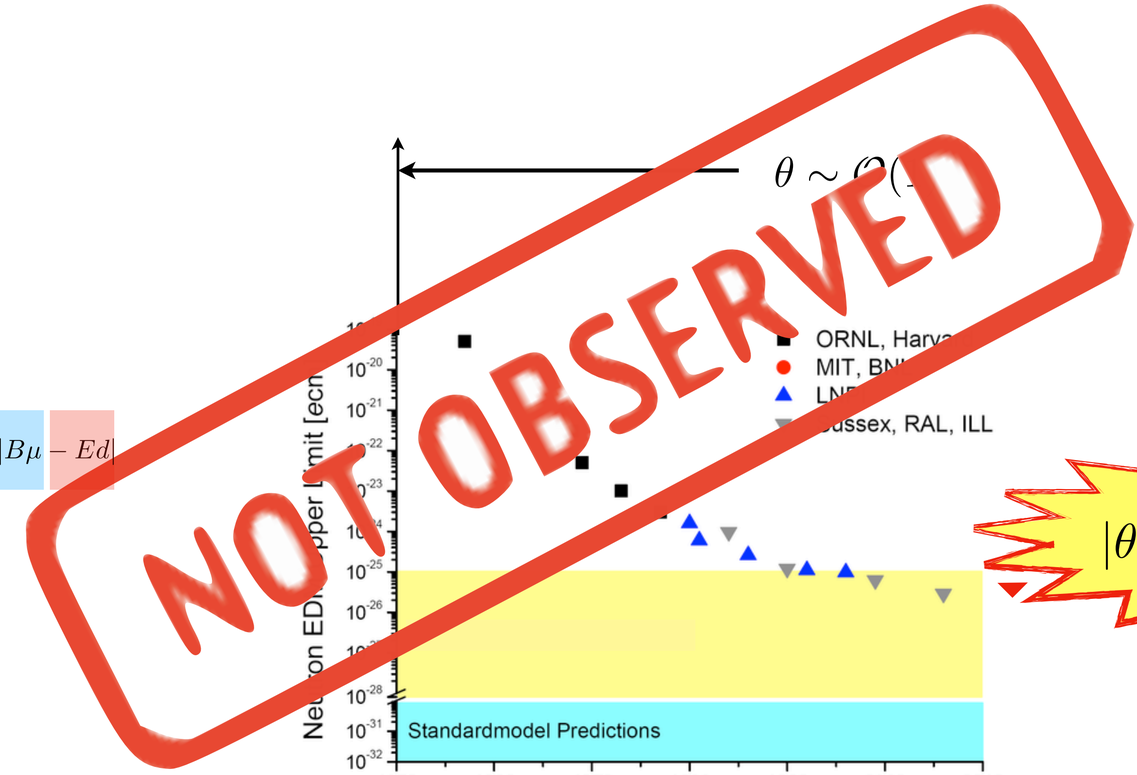
A classical pic of a neutron (~ 2 fm)



Experimental search ...



Mesurable larmor precession difference?



$|\theta| < 1.3 \times 10^{-10}$

Baker '13 Pendlebury '15

QCD vacuum energy minimised at theta = 0 !!

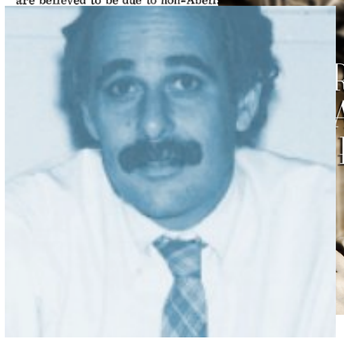
1 -... if $\theta(t, \mathbf{x})$ is a dynamical field, QCD will relax it to its minimum ... strong CP explained! *Peccei & Quinn 77*

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

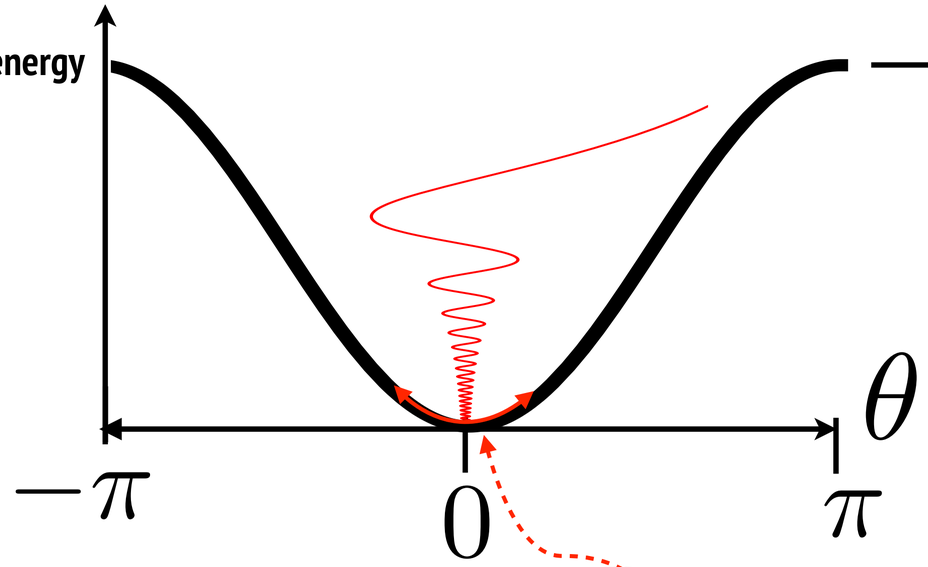
We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that
world where P and CP are good sy
the level of strong interactions. In
quantum chromodynamics the stron
are believed to be due to non-Abeli



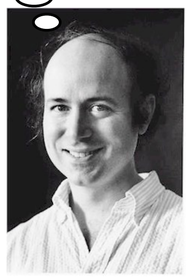
Roberto Peccei

Helen Quinn



2 - PQ Mechanism: Global U(1) axial sym spontaneously broken-> Goldstone boson

S. Weinberg



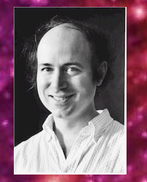
F. Wilczek

COLD DARK MATTER

3 - Relic oscillations of the axion-field ...

J. Preskill

M. Wise



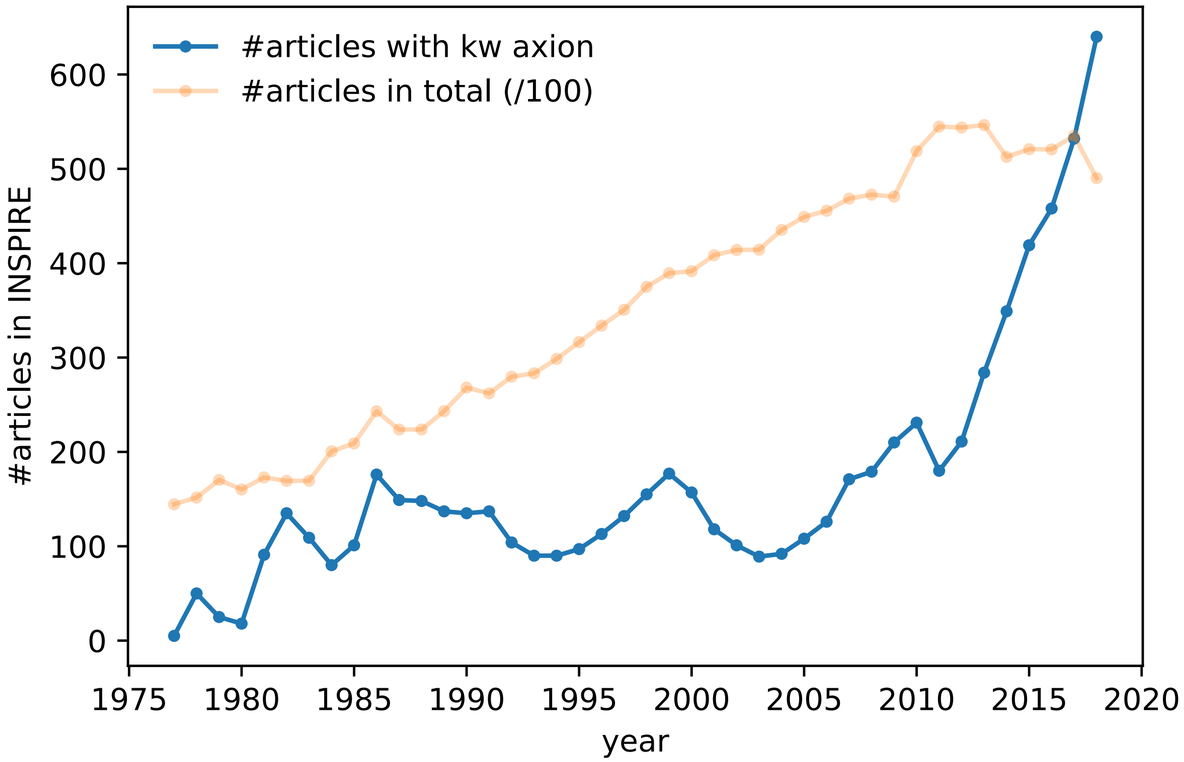
F. Wilczek

W. Fischler

M. Dine

P. Sikivie

The axion "field" is NOT relaxing...

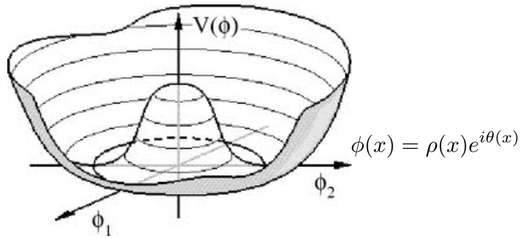


Motivations (hep-th): axions and axion-like particles beyond the SM

- Axions and "axion-like" particles are generic in BSM + compatible with SUSY, GUTs and String Theories

pseudo Goldstone Bosons

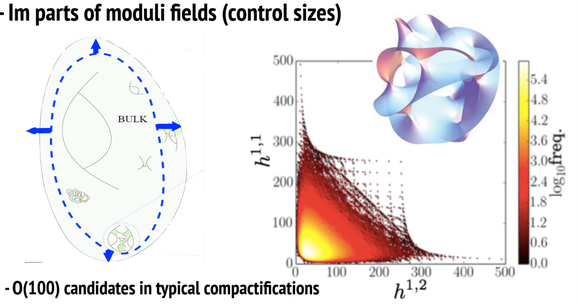
- Global symmetry spontaneously broken



Examples: QCD mesons, ..., QCD axion, Majoron, R-axion, Familon ...

stringy axions

- Im parts of moduli fields (control sizes)



- O(100) candidates in typical compactifications
- masses from non-perturbative effects

- The QCD axion might be a requirement of quantum gravity

A Proof of the Axion?

Gia Dvali[a,b,c], Cesar Gomez[d] and Sebastian Zell[a,b]

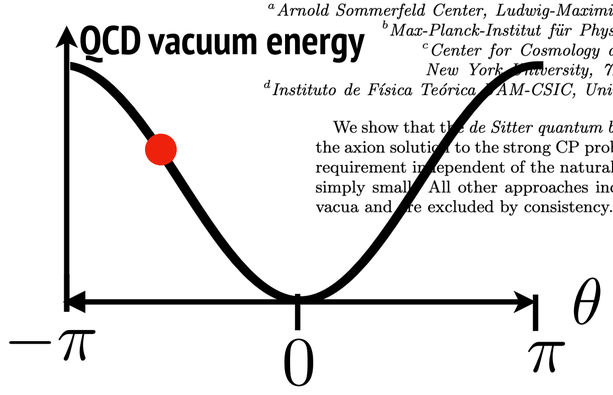
[a] *Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstraße 37, 80333 München, Germany*

[b] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*

[c] *Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA*

[d] *Instituto de Física Teórica, IFT-UAM-CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

We show that the *de Sitter quantum breaking bound* when applied to QCD exposes the necessity of the axion solution to the strong CP problem. The Peccei-Quinn mechanism emerges as a *consistency* requirement independent of the naturalness questions. The ϑ-angle must be unphysical rather than simply small. All other approaches including a fine-tuning of ϑ lead to the existence of de Sitter vacua and are excluded by consistency.



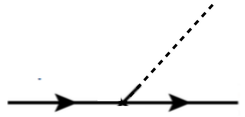
- Axion couplings with SM particles are also generic (shift-symmetry determines leading interactions)

photon coupling

$$-\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

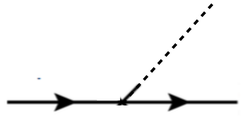
electron coupling

$$g_{ef}[\bar{e}\gamma_5 e]a$$



nucleon coupling

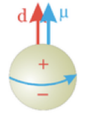
$$g_{Nf}[\bar{N}\gamma_5 N]a$$



~~CP~~ Neutron electric dipole

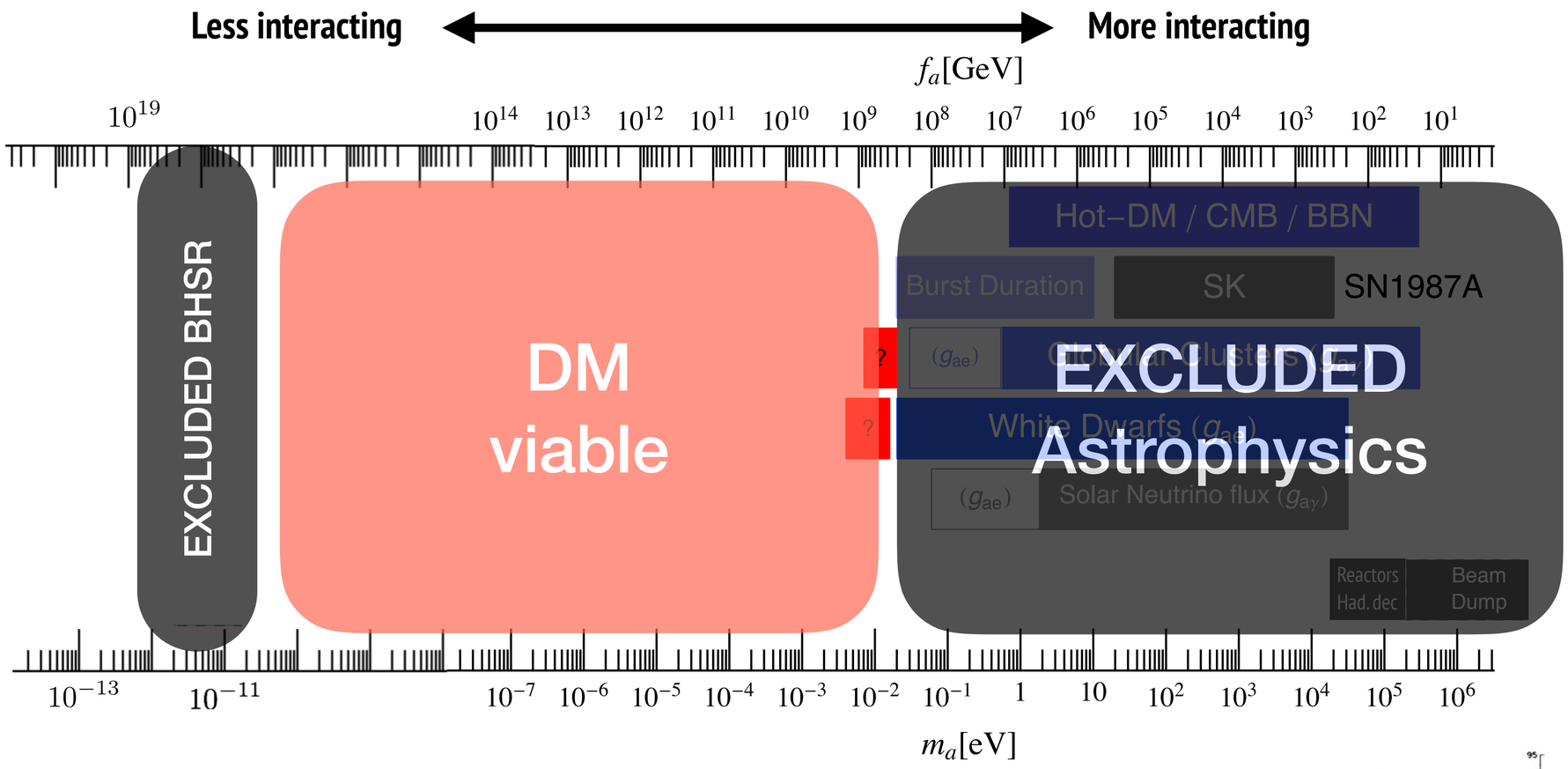
$$\propto \frac{1}{m_n}[F_{\mu\nu}\bar{n}\sigma^{\mu\nu}\gamma_5 n]\frac{A}{f_A}$$

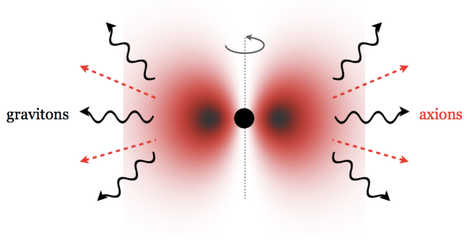
X



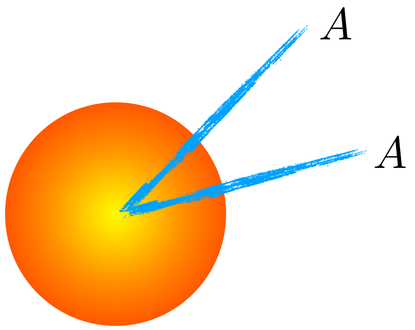
$$\mathcal{L}_{a\gamma} = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{F^{\mu\nu}\widetilde{F}^{\mu\nu}}{4} = -g_{a\gamma}\frac{F^{\mu\nu}\widetilde{F}^{\mu\nu}}{4}a = -g_{a\gamma}\vec{E}\cdot\vec{B}a$$

One parameter theory: decay constant f_A

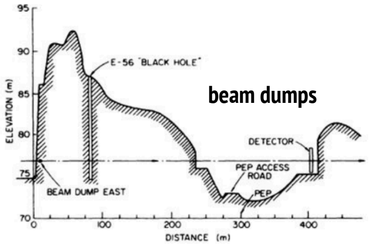




Black hole spin radiated

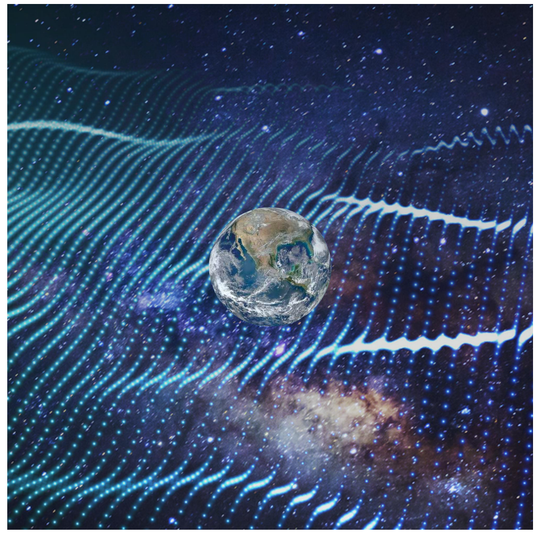


Stellar evolution accelerated*

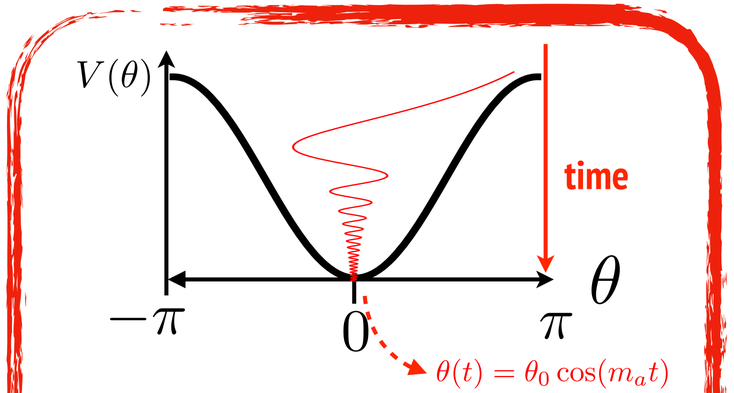


Detecting axion DM

$$\theta = \sum_k \theta_k \cos(\omega t - \vec{k}\cdot\vec{x})$$



$$v_g = \frac{k}{\omega} \sim v_{\rm vir} \sim 200{\rm km/s} < v_{\rm esc}$$



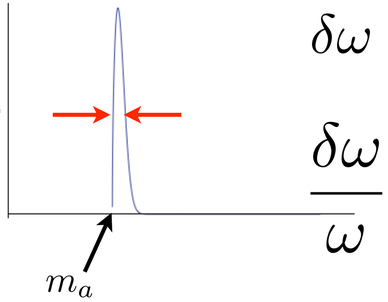
Local Dark Matter density*

$$\rho_{c,0} \simeq \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2 = 0.4\frac{\rm GeV}{\rm cm^3}$$

$$\theta_0 = 3.6 \times 10^{-19}$$

- Axion spectrum is not exactly monochromatic, non-zero velocity of DM in the galaxy -> finite width

frequency $\omega \simeq m_a(1 + v^2/2 + ...)$



$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

coherence time

$$\delta t \sim \frac{1}{\delta\omega} \sim 0.13{\rm ms}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)$$

coherence length

$$\delta L \sim \frac{1}{\delta p} \sim 20{\rm m}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)$$

Axion DM and the cavity concept

- Axion DM, $\theta = \theta_0 \cos(m_a t)$ +B, source in Maxwell'

$$
\begin{aligned}
\nabla \cdot \mathbf{D} &= \rho_f \\
\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J}_f - C_{a\gamma}\frac{\alpha}{2\pi}\mathbf{B}\frac{\partial \theta}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} &= 0
\end{aligned}
$$

In a magnetised medium

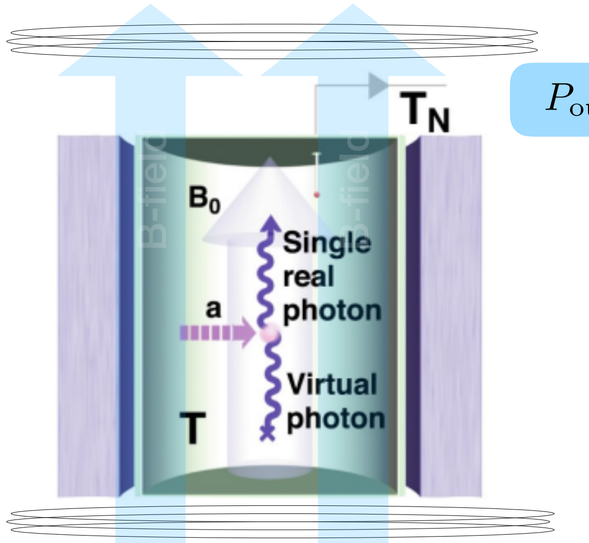
$$\mathbf{E}(t) = \frac{C_{a\gamma}\alpha\theta_0\mathbf{B}}{2\pi\epsilon}\cos(m_a t)$$

$$|\mathbf{E}| \simeq 10^{-12}\frac{V}{m}\frac{C_{a\gamma}}{2}\frac{|\mathbf{B}|}{10\mathrm{T}}$$

- Haloscope (Sikivie 83)

"Amplify resonantly the EM field in a resonant cavity"

P. Sikivie

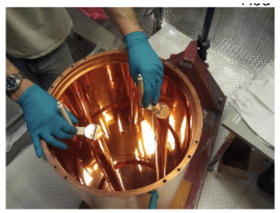


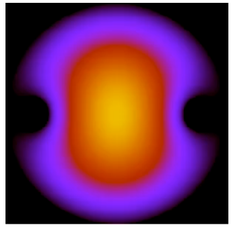
$P_{\mathrm{out}} \sim Q|\mathbf{E}_a|^2 V m_a$ (on resonance)

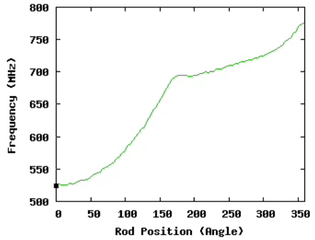
- Cavity quality factor $Q \sim 10^5$
- B-fields $B \sim 10\mathrm{T}$
- Volume $\sim 1/m_a^3$ (typically a few liters)

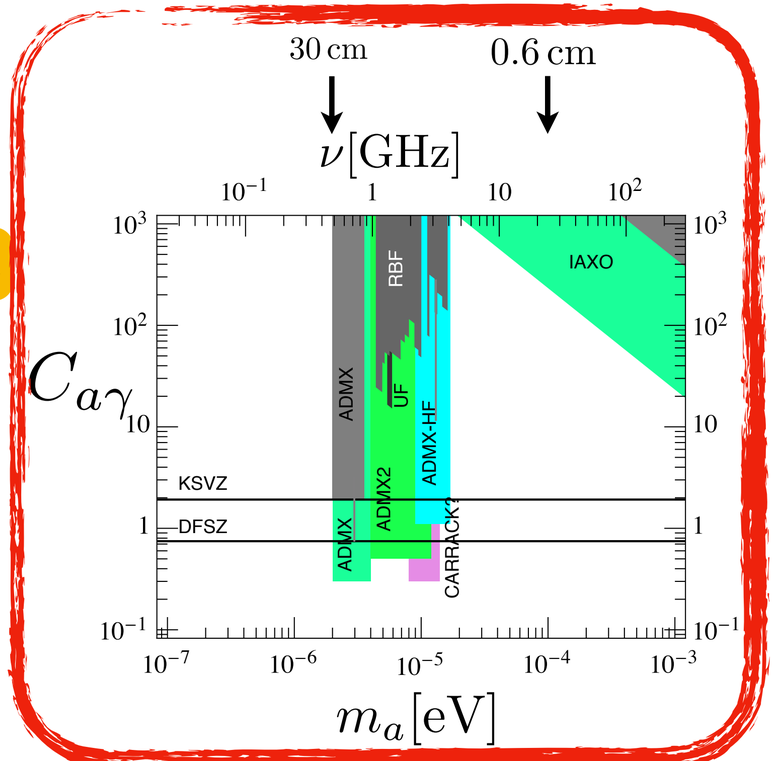
$P_{\mathrm{noise}} = T_{\mathrm{sys}}\Delta\nu_a \sim T_{\mathrm{sys}}10^{-6}m_a$

- Temperature $T \sim 0.2 - 4\,\mathrm{K}$
- System T ~ Quantum limited (SQUID, JPA

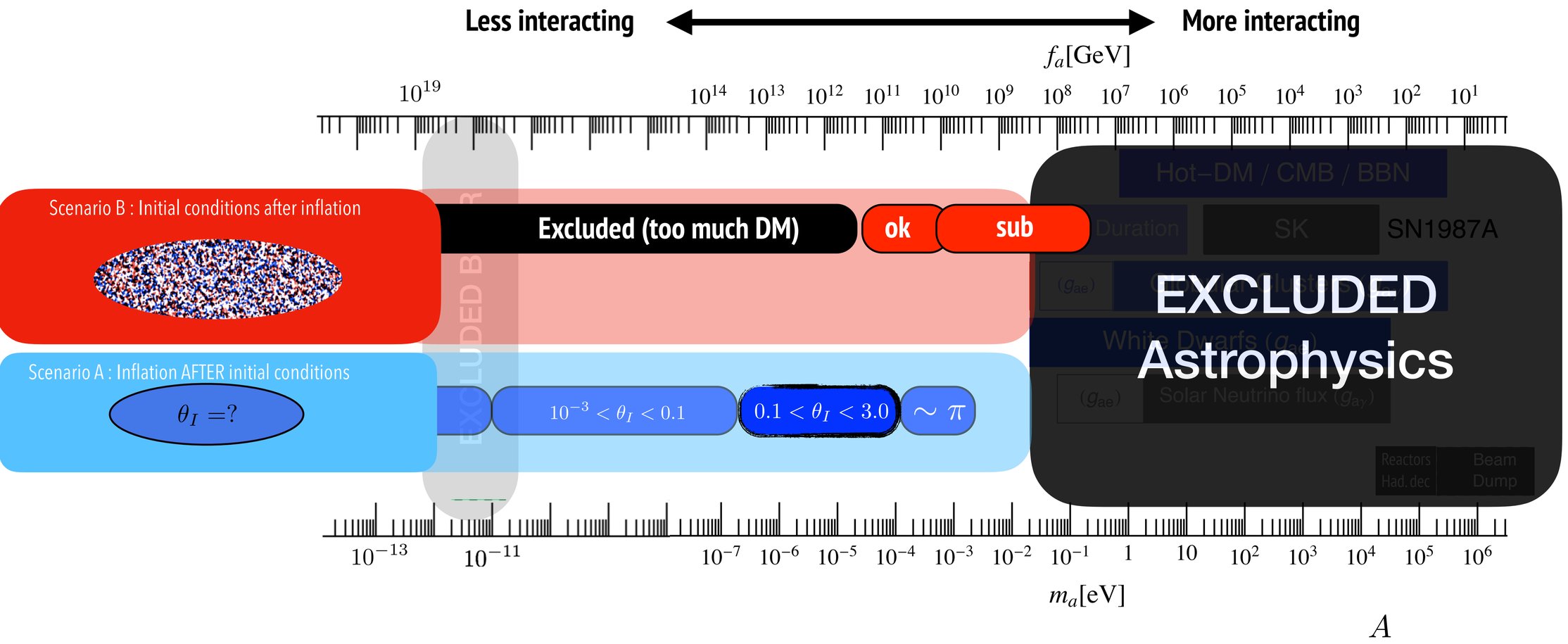








The axion DM mass: two predictions

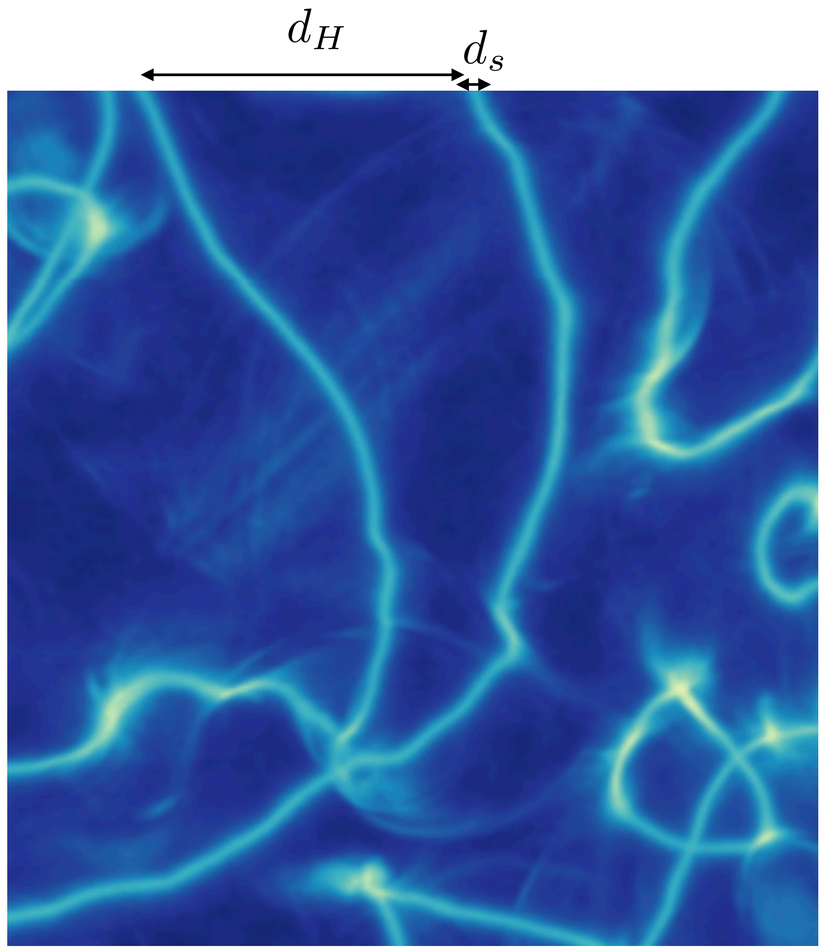


Post-inflation scenario: a prediction is possible (IC conditions are averaged accross the universe)

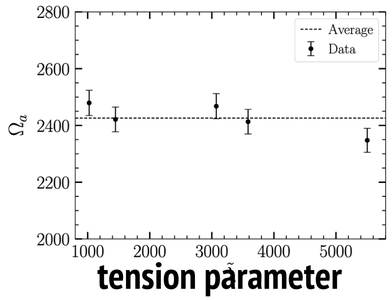
Predictions precision is spoiled by cosmic strings

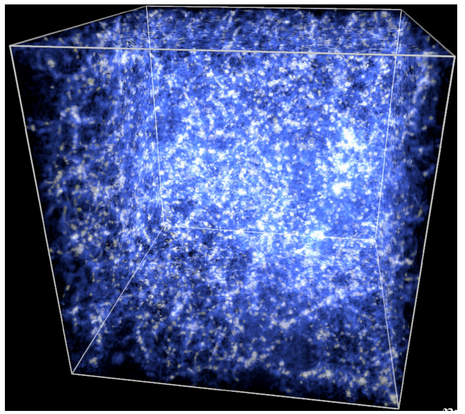
Axionic string simulations

- Axion DM from string network with molecular dynamics simulations (HPC 8192^3)
  - Problem: dynamical range $d_H/d_s \sim 10^{30}, (\log(d_H/d_s) \sim 70)$ but available only $10^3(8)$



- Small Dependence of Omega on $\log(d_H/d_s)$





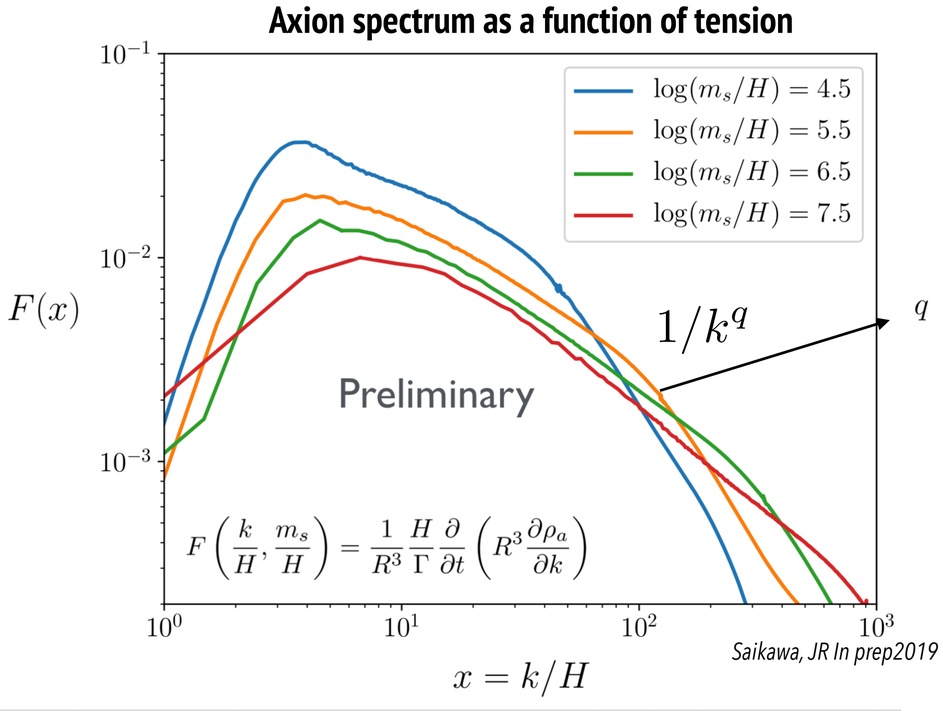
Safdi 2019

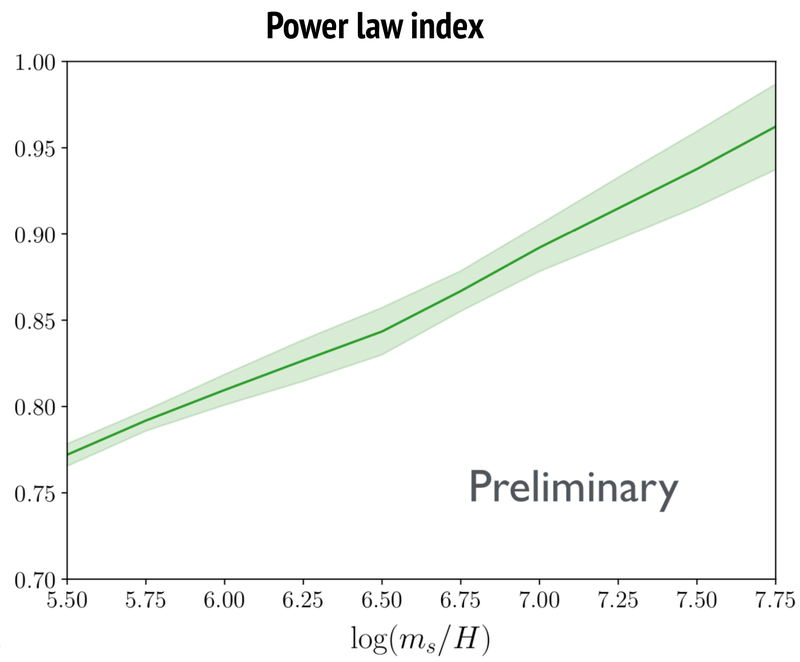
- Large (effective) tension simulations also available
- Results reveal negligible influence of strings

$\sim 15\mu\text{eV}$ (Moore,JR), $\sim 26\mu\text{eV}$ (Moore HT), $\sim 26\mu\text{eV}$ (Safdi LT)

Axion radiated spectrum

- Method 2, understanding radiation (safer extrapolation)





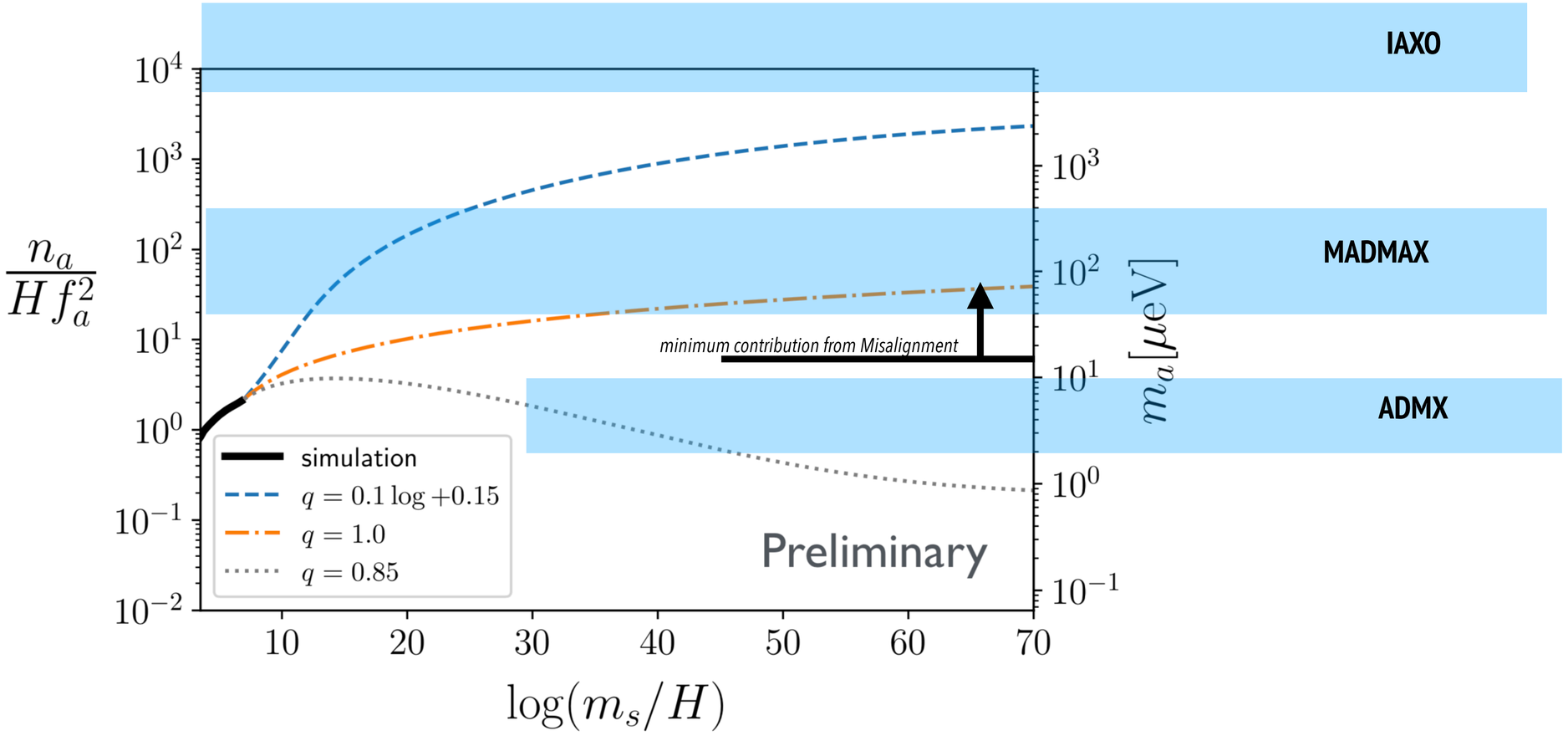
Current simulations are in a tension regime where q<1 (few UV axions take most energy);

Trend towards q>1 is seen -> (many IR axions take most energy -> more DM!)

Extrapolation to physical values

- Extrapolate in q and integrate the axion emission from strings from PQ to QCD epochs

- Very large uncertainties at the moment



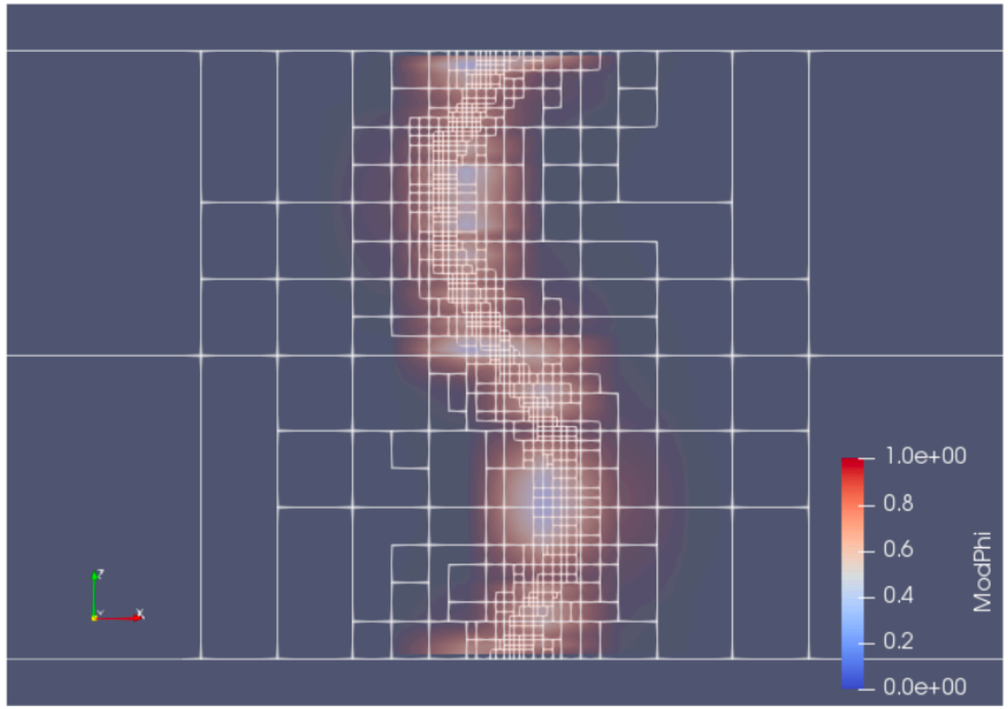
Saikawa, JR In prep2019

The future : AMR?

Perhaps we do not need to be able to extrapolate to log = 70

A factor of 2 in log will be more than sufficient to understand much better dynamics and reduce uncertainty

Dedicated Adaptive Mesh Refinement simulations can cover this gap and see if there is a change of behaviour at q = 1



Shellard 2019

Miniclusters and axion stars

Scaling

Misalignment

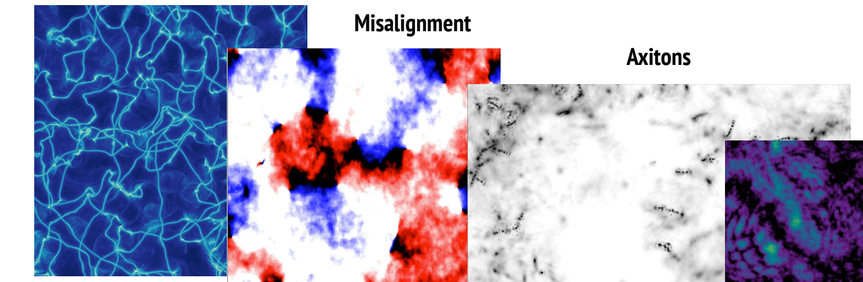
Axitons

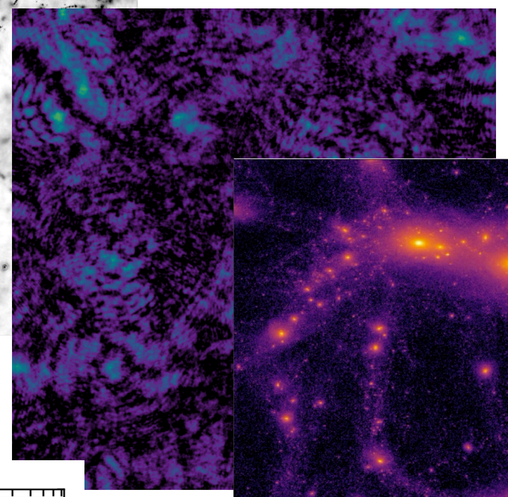
Free-stream (RD)

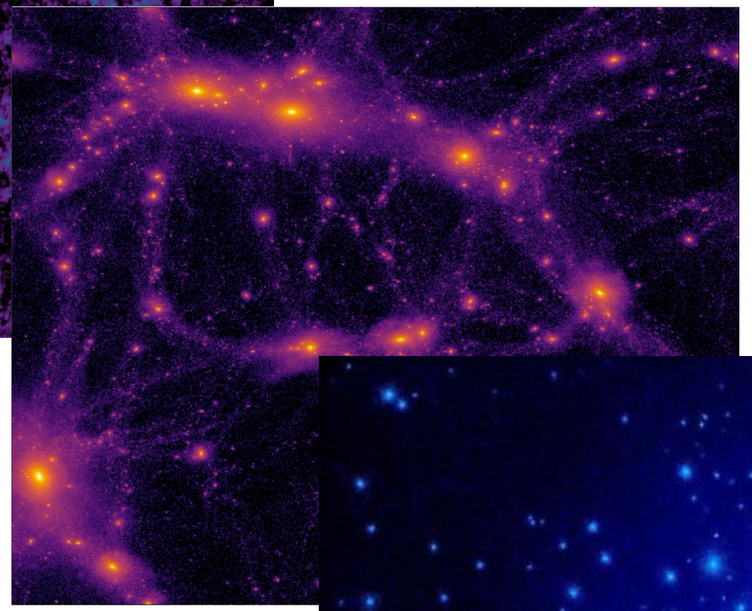
Miniclusters form

hierarchical growth

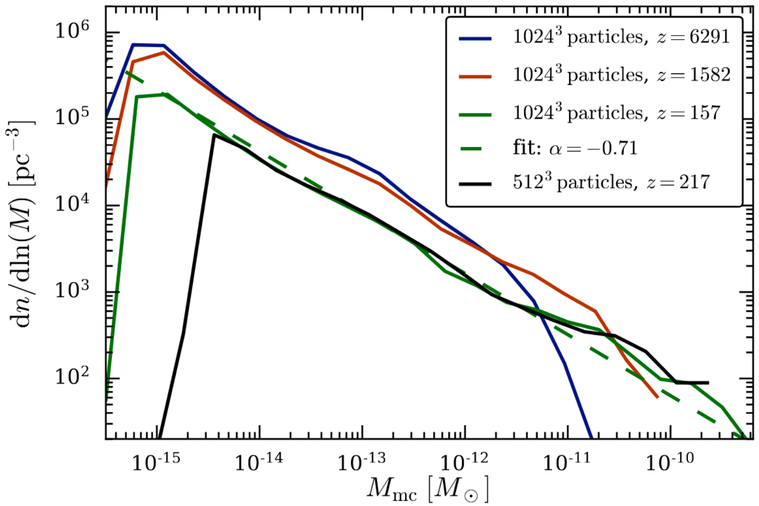
Galaxy forms with MC halo





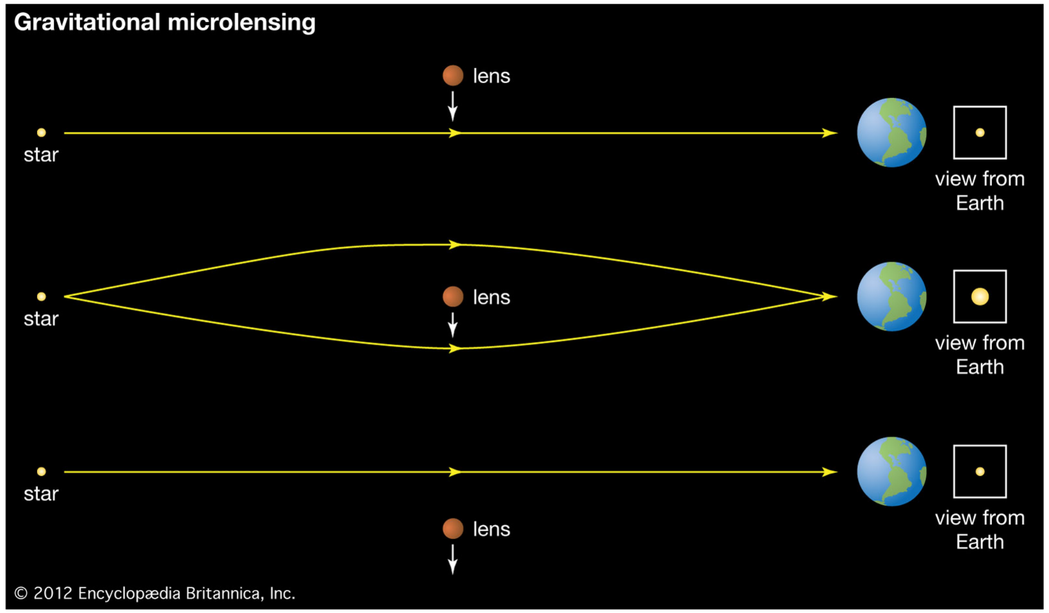


Minicluster mass function from N-body Simulations



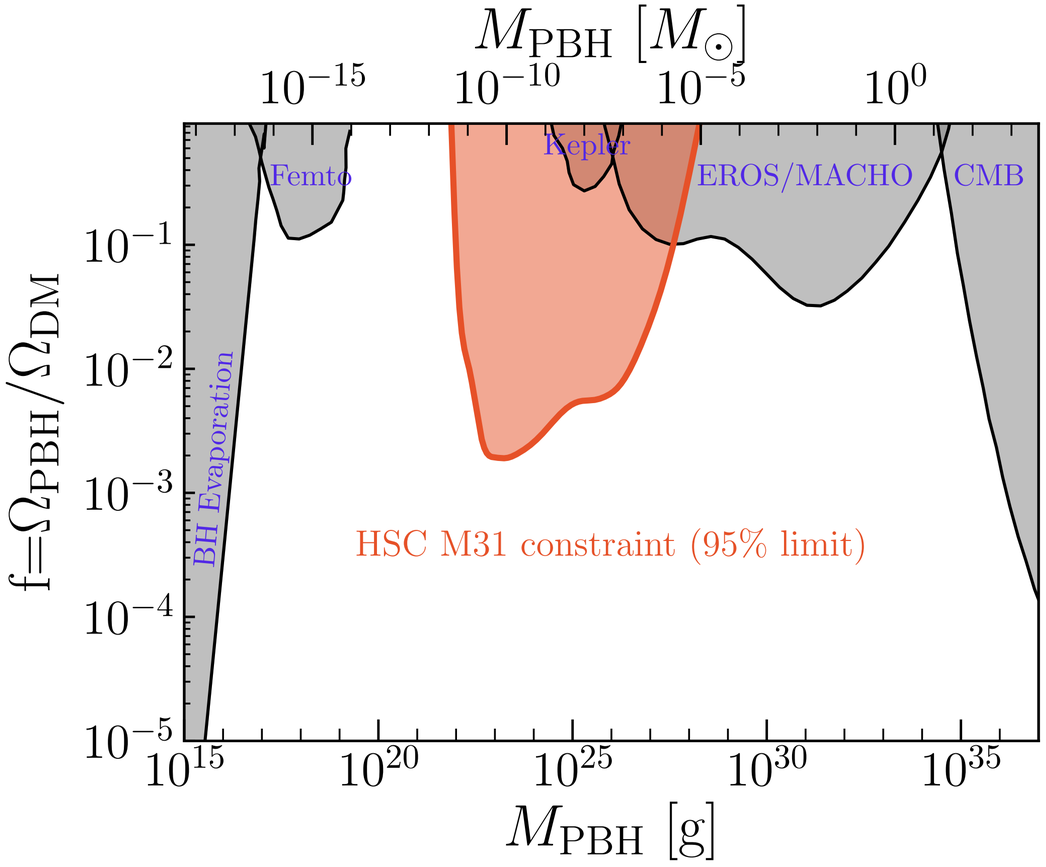
- Uncertainties in early stages propagate until today
- Predictions based on direct simulations

Miniclusters could be detected by femto- pico- and microlensing



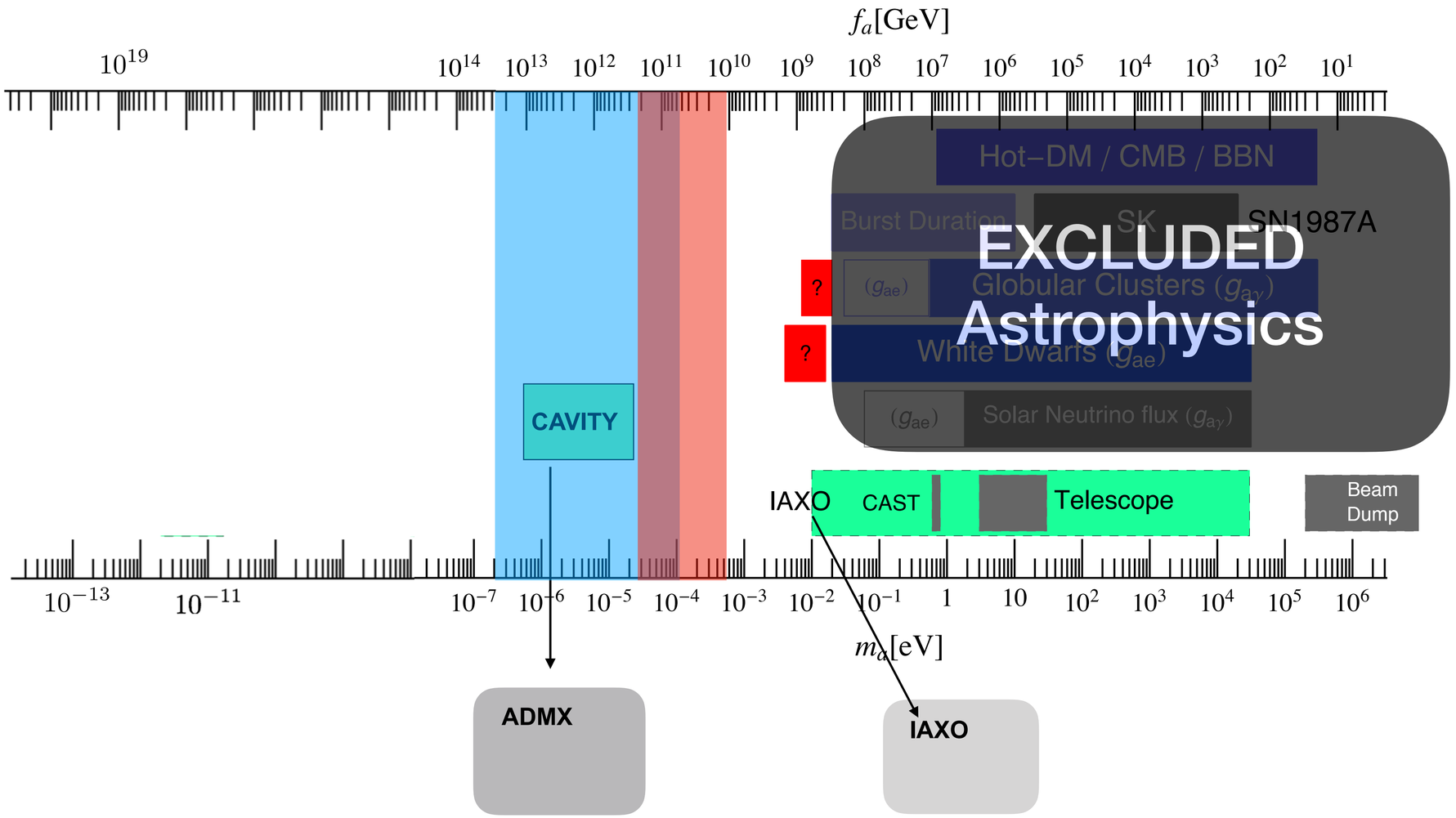
- First studies available
- Distinguishing between DM models

- Constraints on compact objects
- (need to be adapted to MCs)

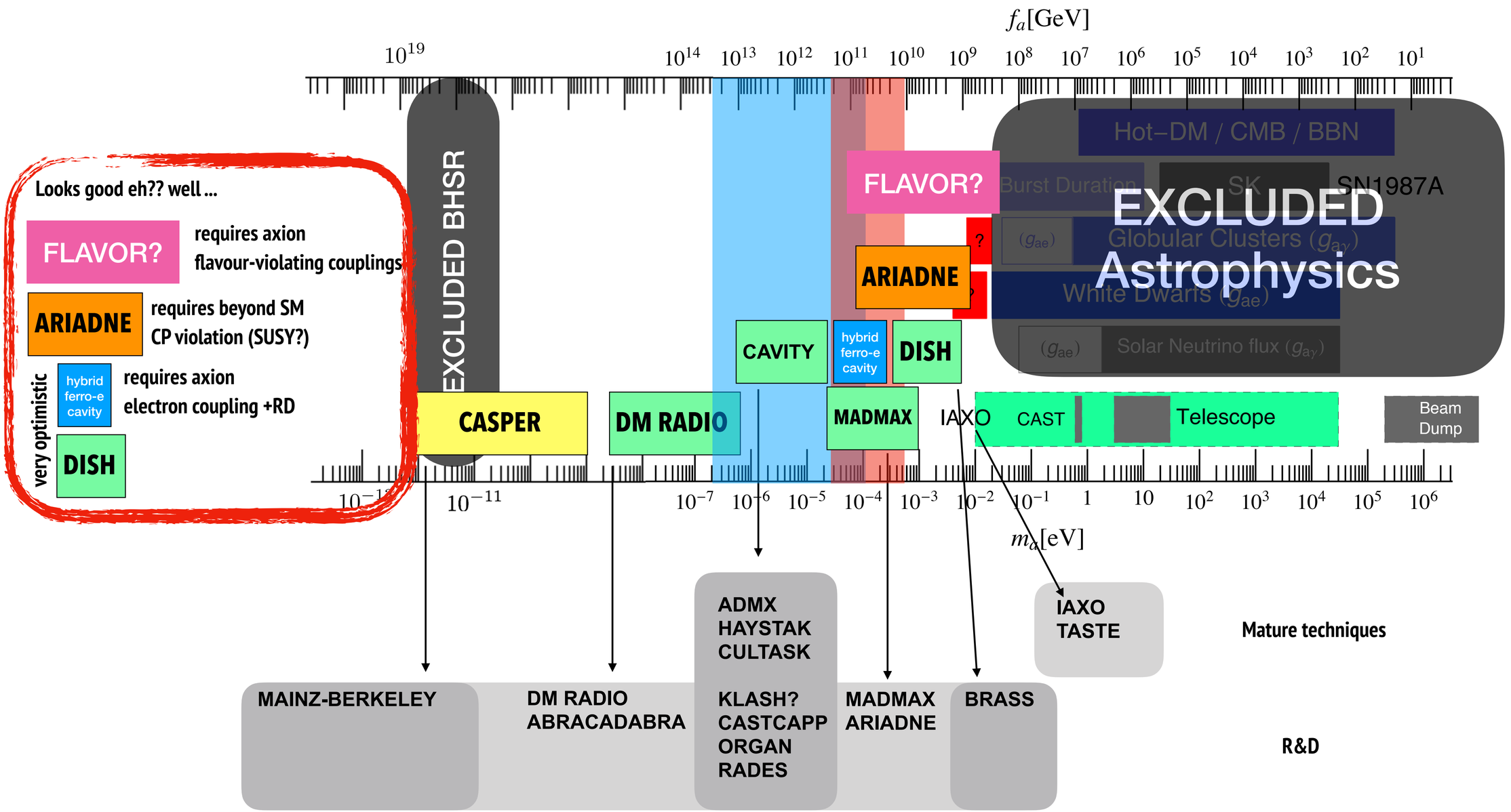


Detecting axion DM

On the search for the axion: 2012



On the search for the axion: 2019

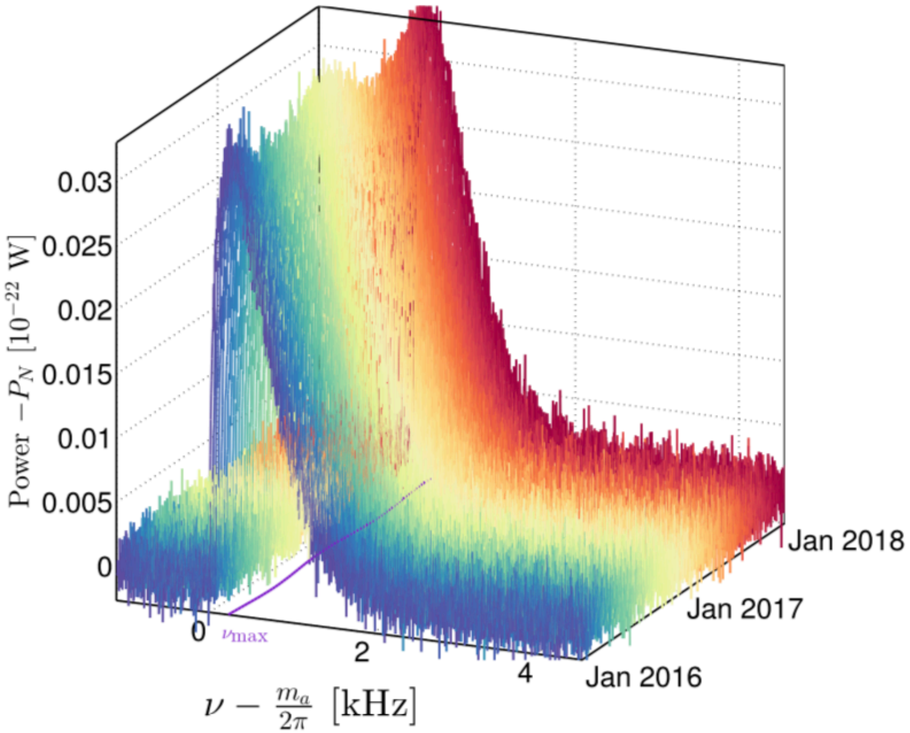


Axtronomy

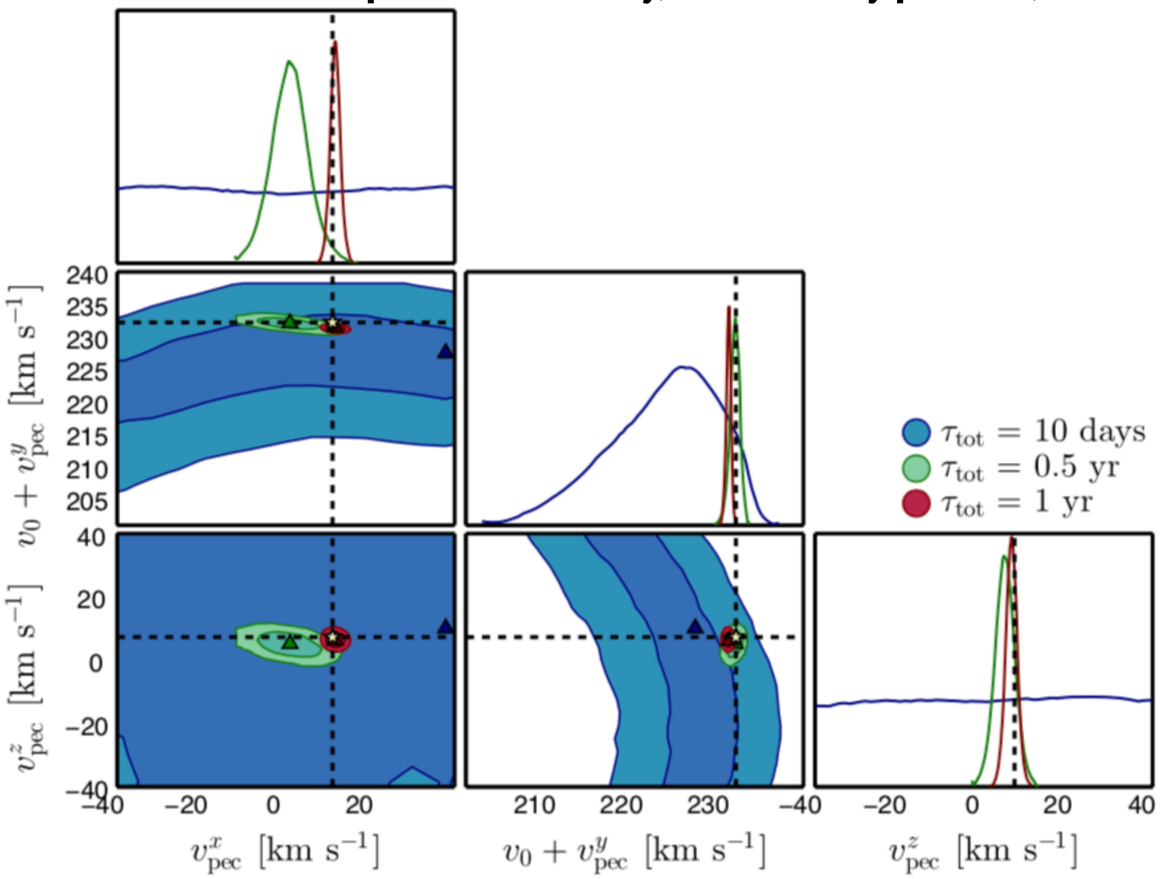
Detection of the axion would allow to study the galactic halo directly:

Velocity of axions has annual & daily modulations $\mathbf{v}_{\rm lab}(t) = \mathbf{v}_0 + \mathbf{v}_{\rm pec} + \mathbf{v}_{\rm rev}(t) + \mathbf{v}_{\rm rot}(t),$

Spectrum modulations



Reconstruc solar peculiar velocity, DM velocity profiles, substructure...

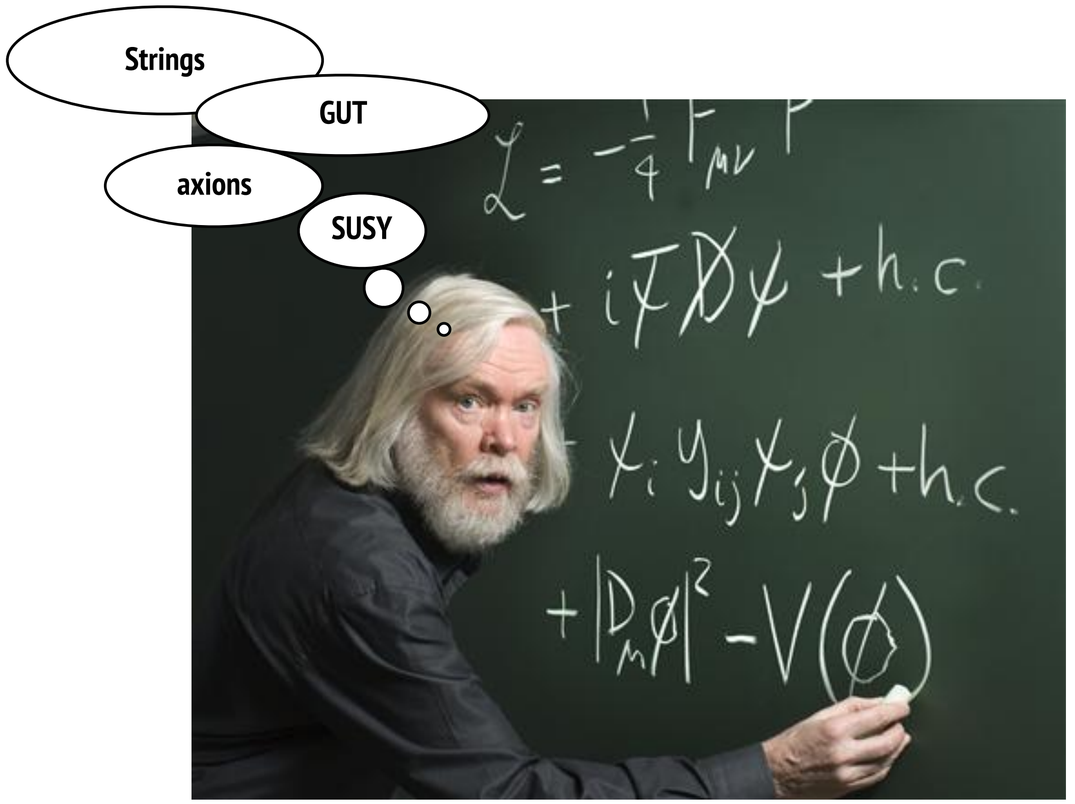


O'Hare et al 17,19

Conclusions

Evidence of DM is compelling

Conclusions

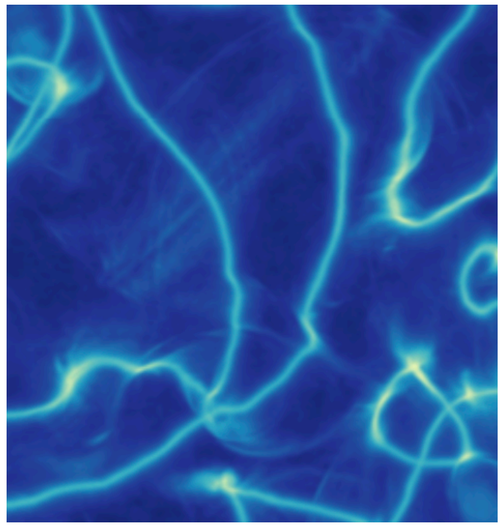


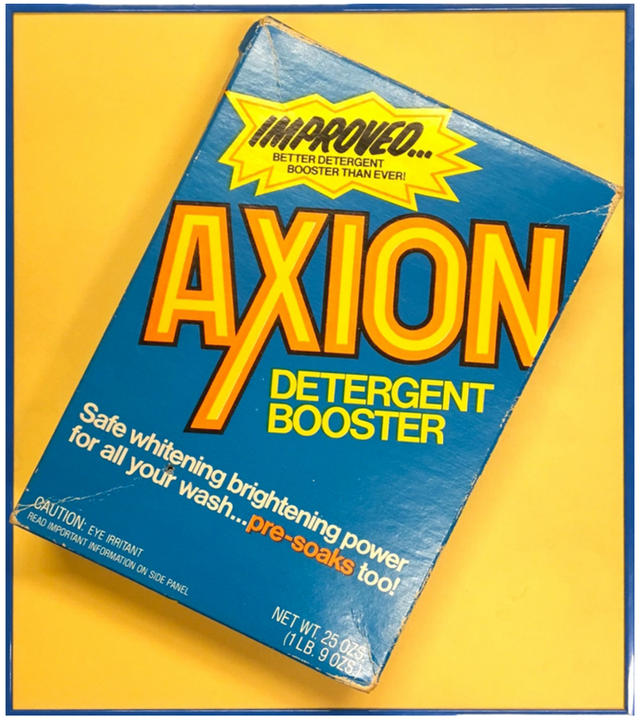
Particle physics offers very well motivated DM candidates

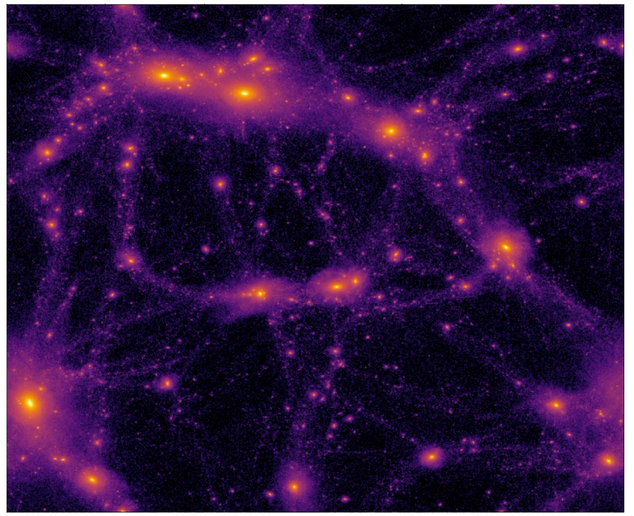
predictions on particle properties inspire experimental tests

and creates links to early Universe cosmology

Axions







The axion would solve the strong CP problem and be an excellent CDM candidate

Has potentially different DM features than WIMPs (miniclusters ...)

Times are becoming very exciting with new experiments to come

A prediction of the axion DM mass is possible in the post-inflationary scenario > guide experimental detection