AXIONS and Dark Matter

Overview

- Dark Matter
- Strong CP problem
- Axions and ALPS
- Axion / Dark Matter experiments

Evidence for Dark Matter

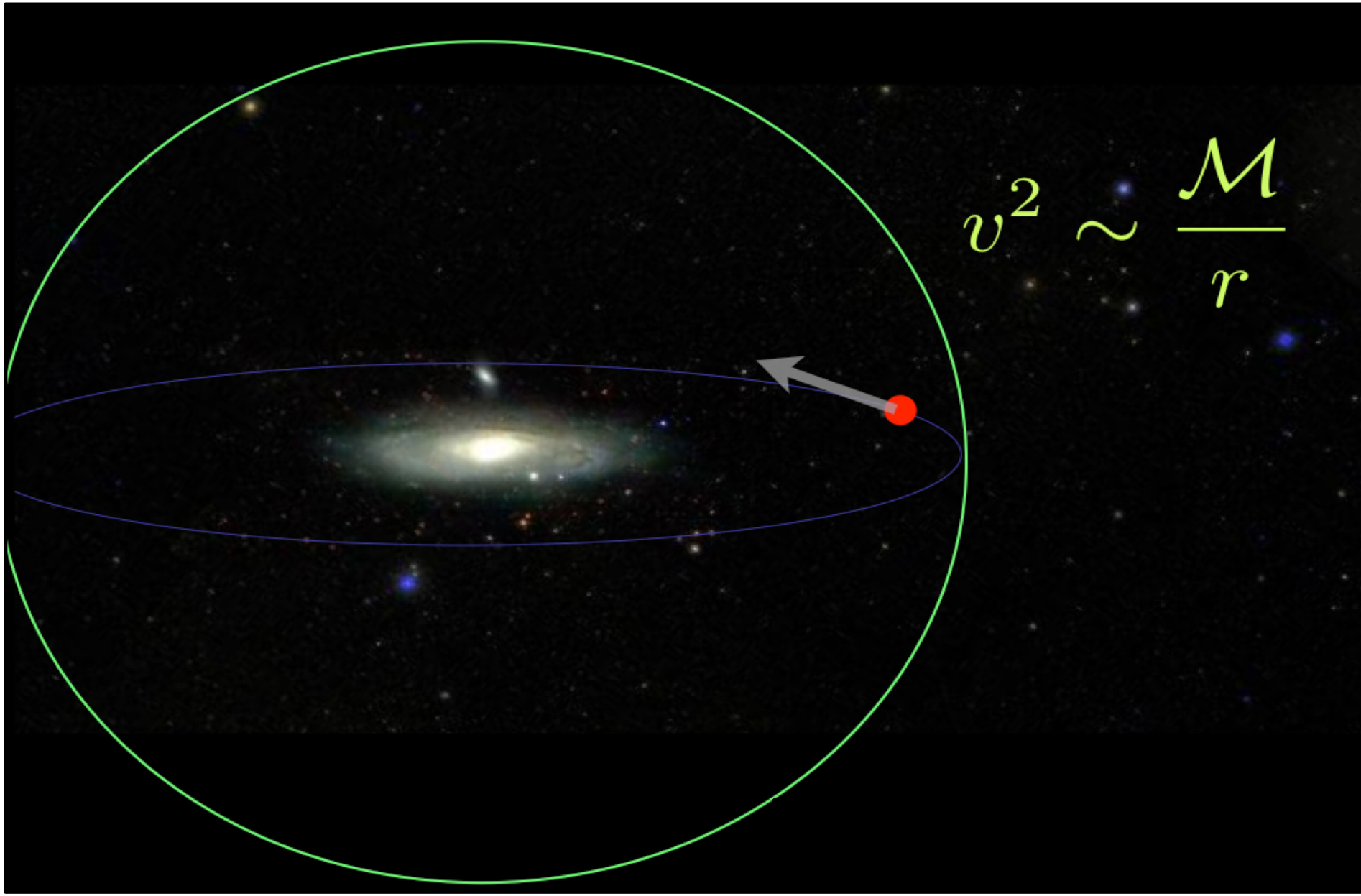
Dark matter: nonluminous matter not yet directly detected by astronomers that is hypothesized to exist to account for various observed gravitational effects.

www.merriam-webster.com

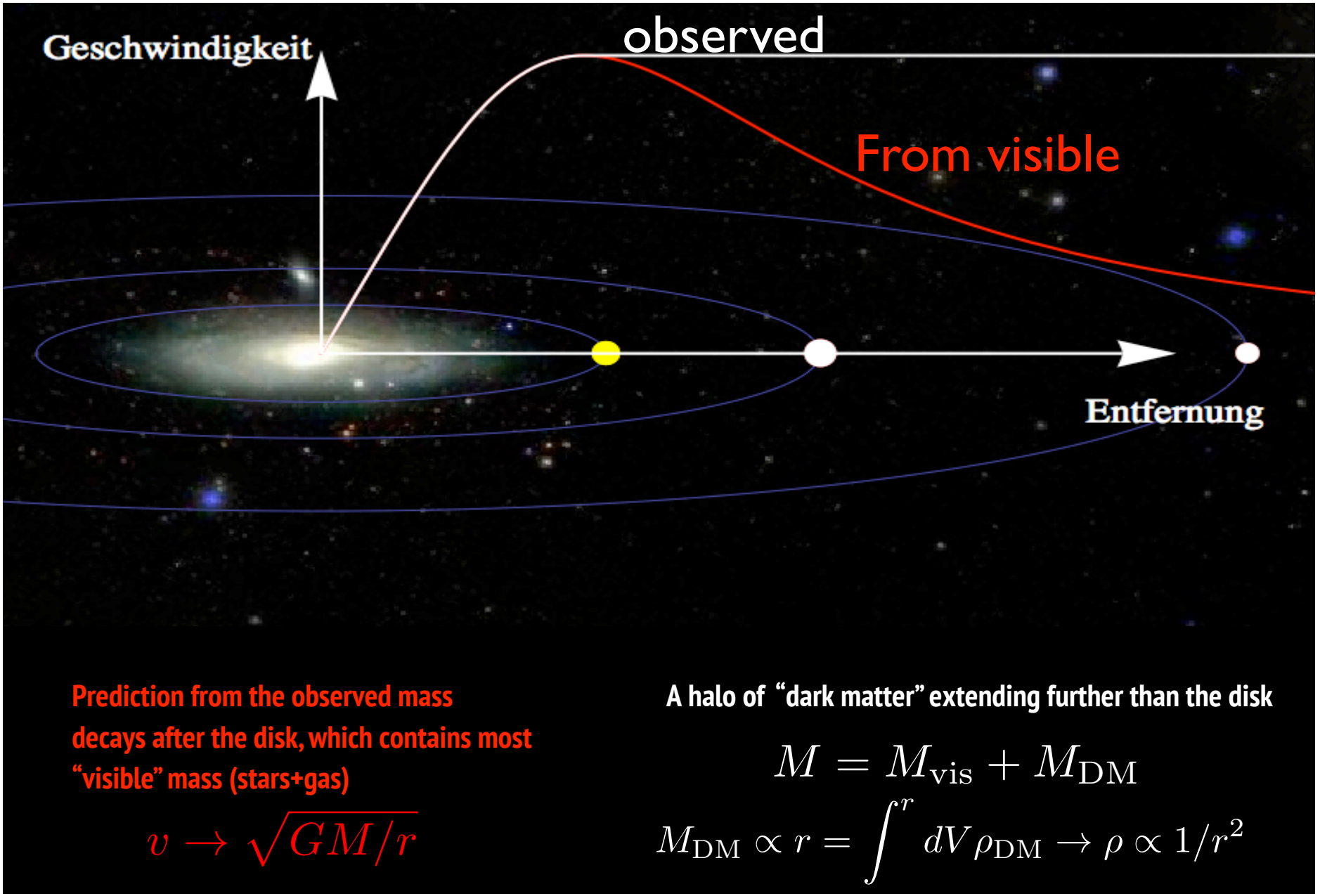
A long history (astronomers miss a lot of matter)

Evidences in a huge range of scales !

Galactic Rotation Velocity



Galactic Rotation Velocity



Prediction from the observed mass decays after the disk, which contains most "visible" mass (stars+gas)

$$v \to \sqrt{GM/r}$$

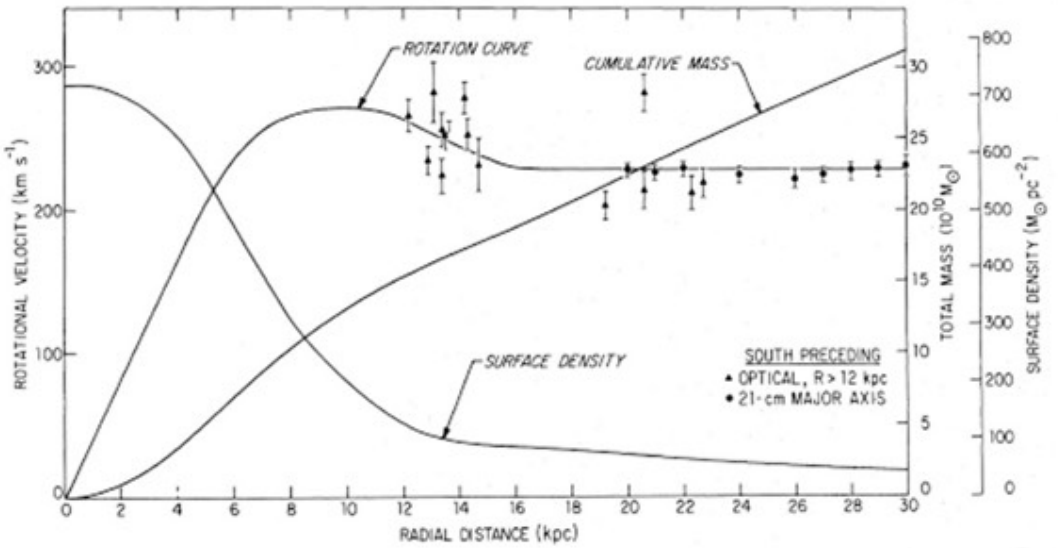
A halo of "dark matter" extending further than the disk

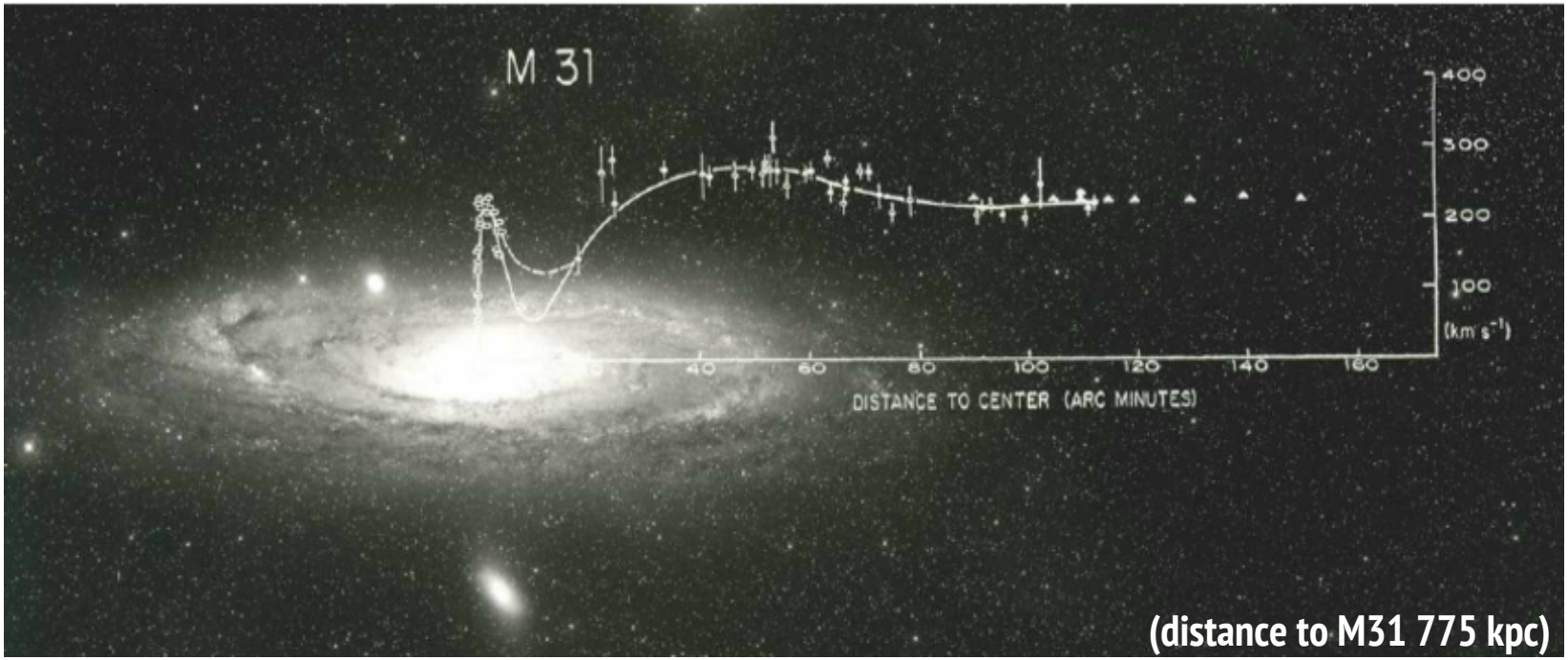
$$M = M_{\rm vis} + M_{\rm DM}$$

$$M_{\rm DM} \propto r = \int^{r} dV\, \rho_{\rm DM} \to \rho \propto 1/r^2$$

M31

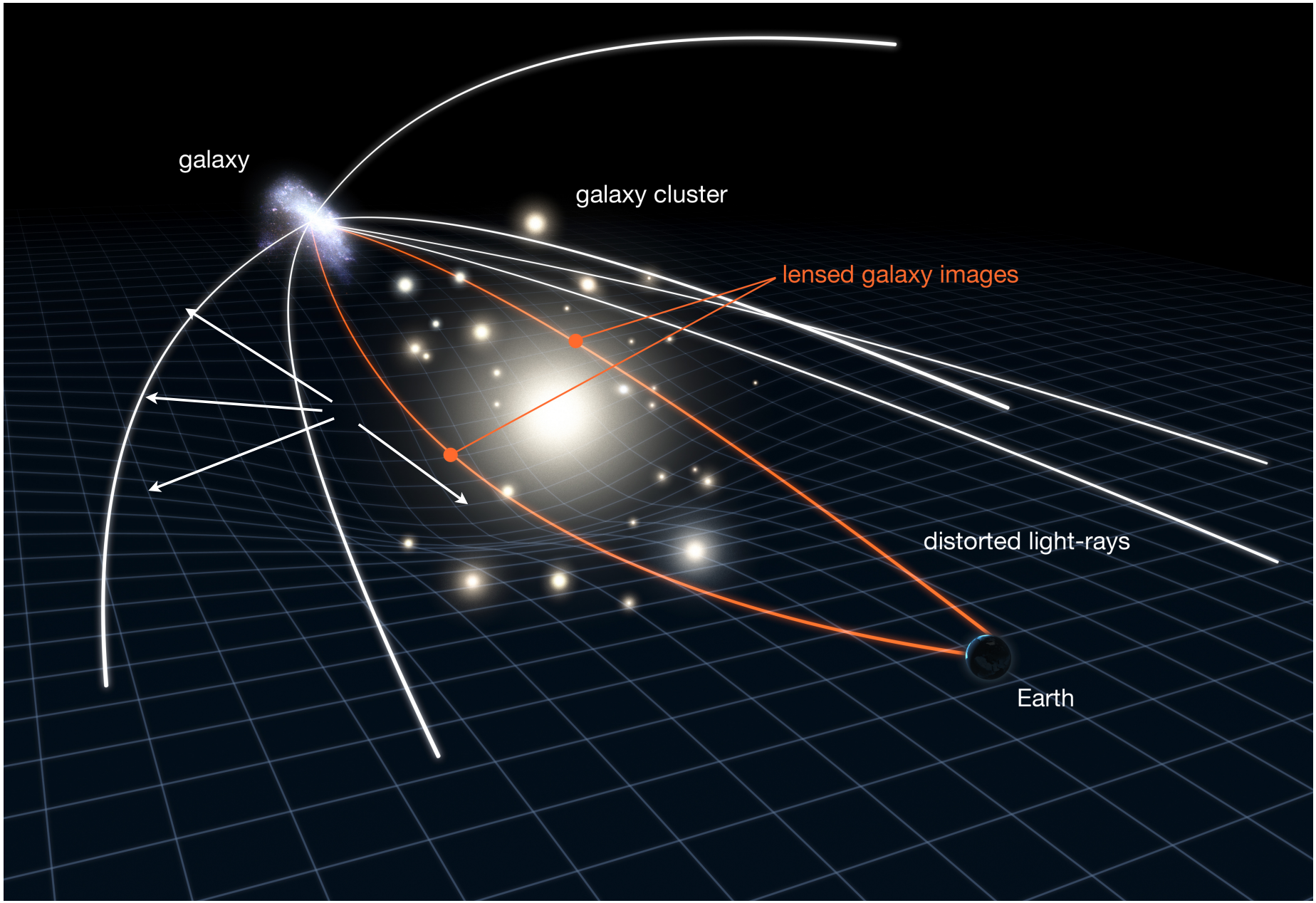
Vera Rubin (1928-2016)
Astrophys Journal. 159: 379–404:
"Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions".



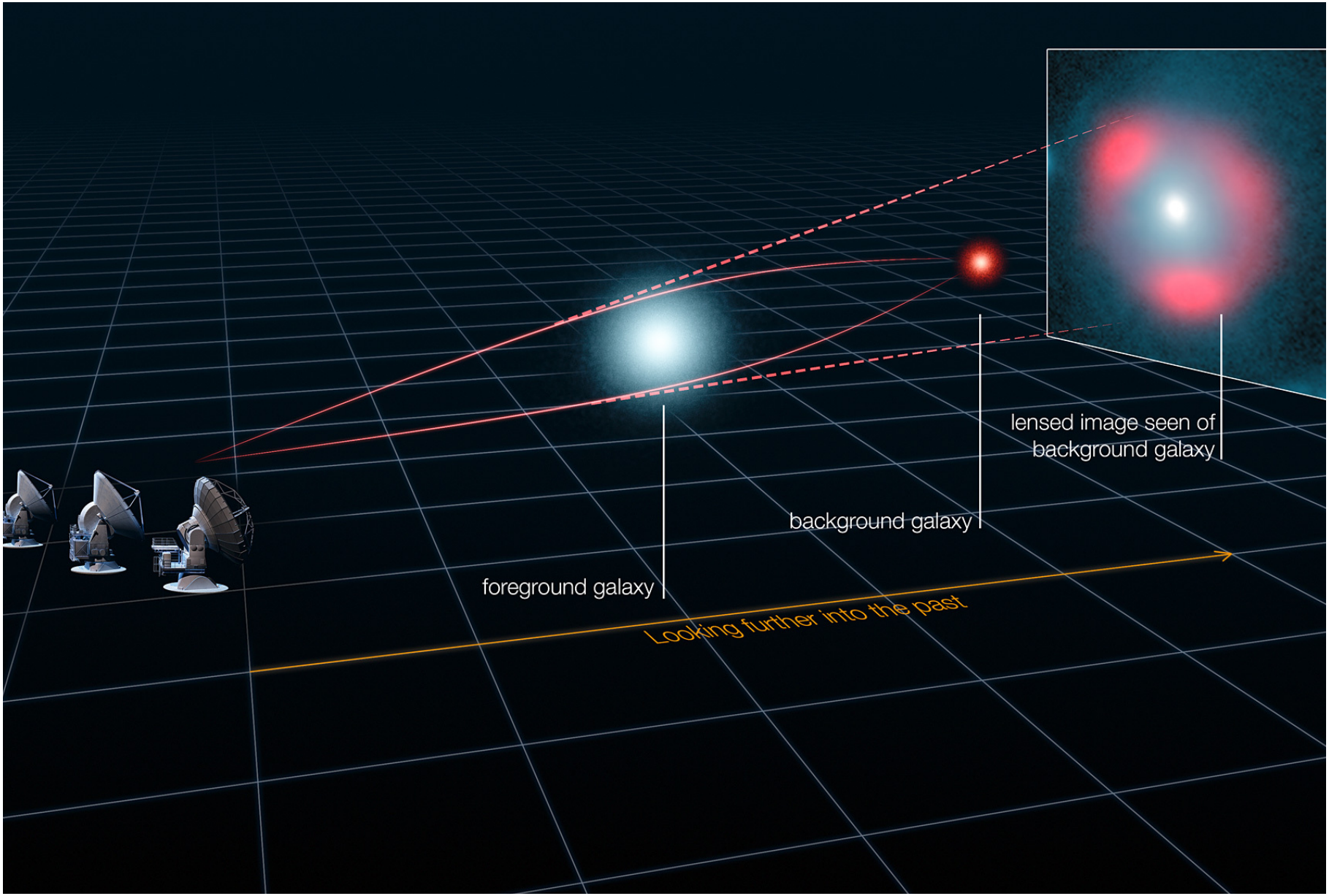


(distance to M31 775 kpc)

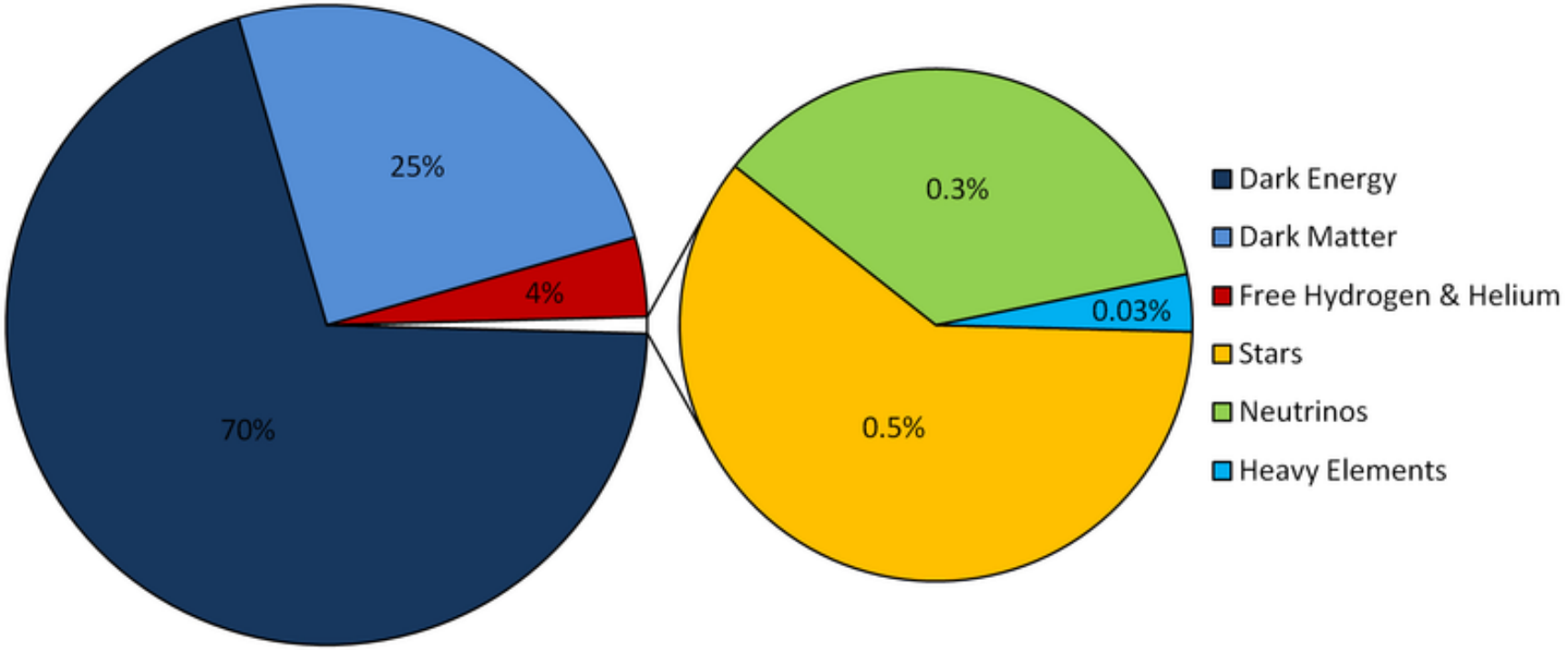
Gravitational Lensing



Gravitational Lensing



The cosmic pie



Finding the right DM particle ...

- Weakly interacting with itself (Bullet, CMB)
- Present galaxies-clusters-universe
- Non baryonic
- what can it be?

> Dark Matter ≈ 30 · luminous matter (stars)
  - Dark baryons (p, n) ≈ 5 · luminous matter
    (indirect observations (gas), big bang nucleosynthesis, CMBR)
  - Unknown "dark" particles ≈ 6 · baryonic matter

    Only gravitational (and weak) interaction
    Should be non-relativistic ("cold")

- Unstable
- Baryonic
- Interacts quite a bit with light
- Photons = massless
  Neutrinos = too light

need something beyond the SM

P, C, CP, T and CPT

CPT Theorem: CPT conserved → CP parity = T parity

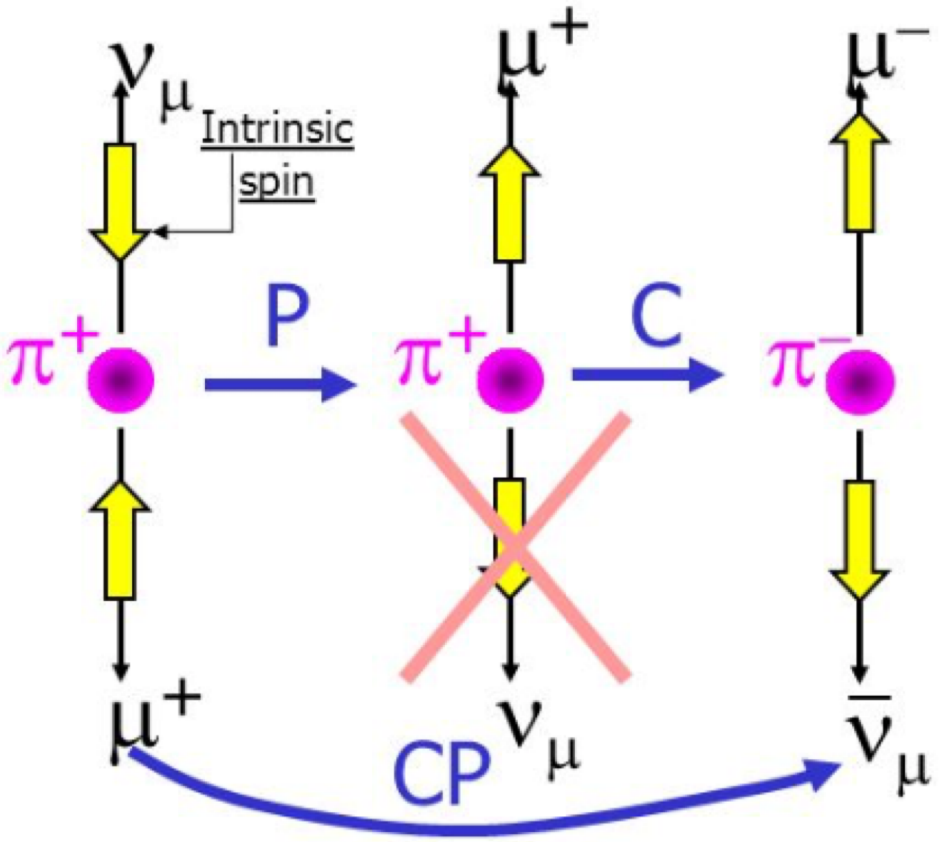
P and T (CP) are separately conserved in electromagnetic interactions

P and T(CP) are NOT conserved in weak interactions

T (CP) is (apparently) conserved in strong interactions QCD

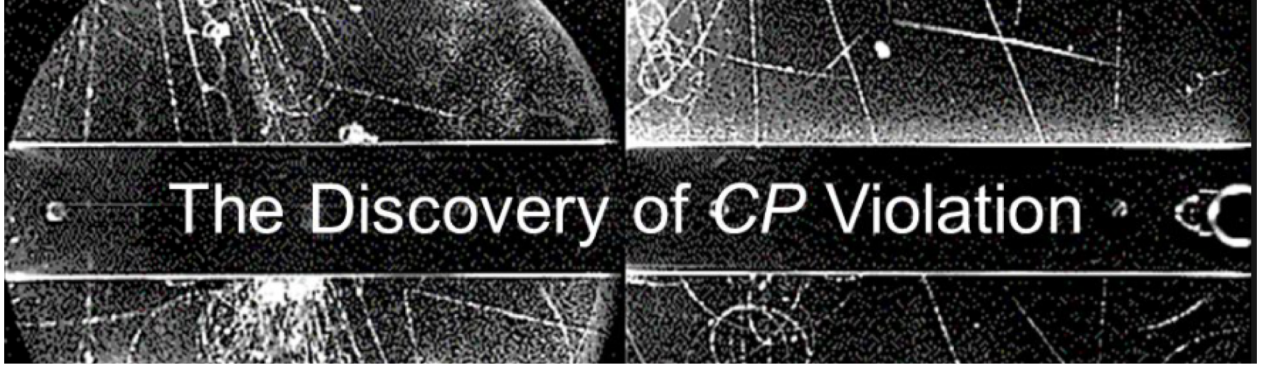
The Weak force and C,P parity violation

- What about C+P ≡ CP symmetry?
  - CP symmetry is parity conjugation (x,y,z → -x,-y,z) followed by charge conjugation (X → $\overline{X}$)



100% P violation:
All ν's are lefthanded
All $\overline{\nu}$'s are righthanded

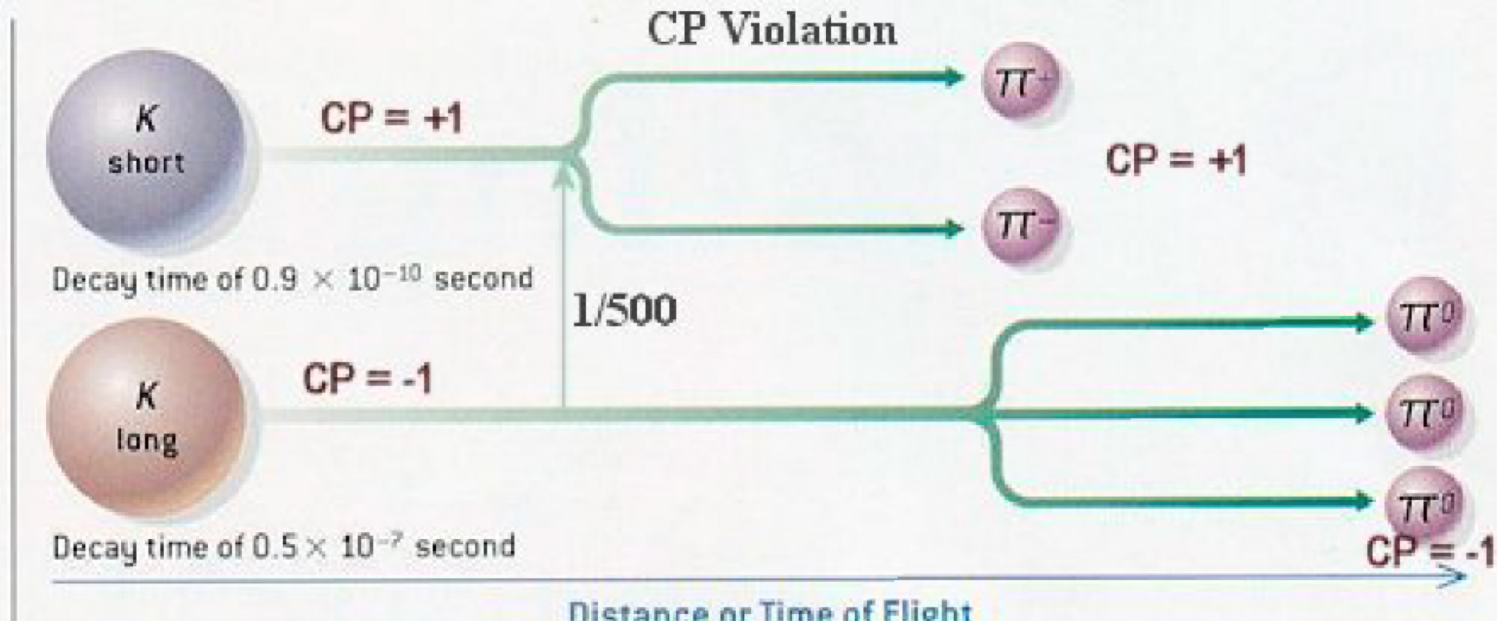
CP appears to be preserved in weak interaction!



VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

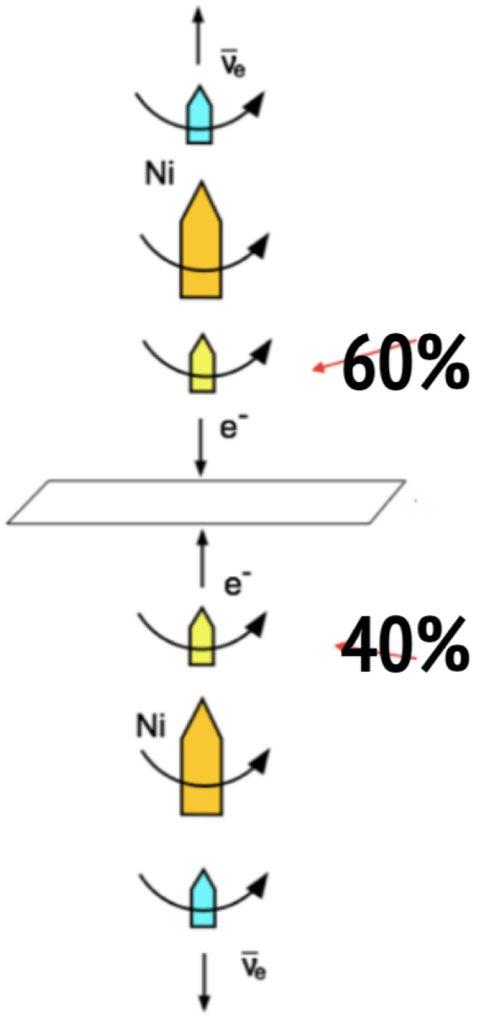
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)



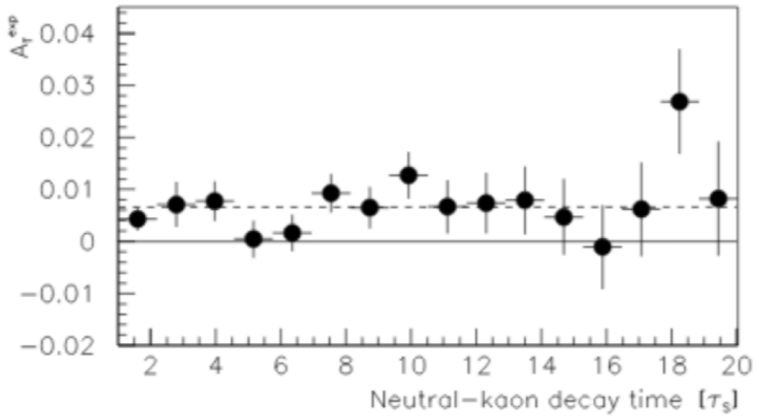
in particle physics (electroweak interactions)

P-violation (Wu 56)



T-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

many theories based on SU(3)c (QCD)

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

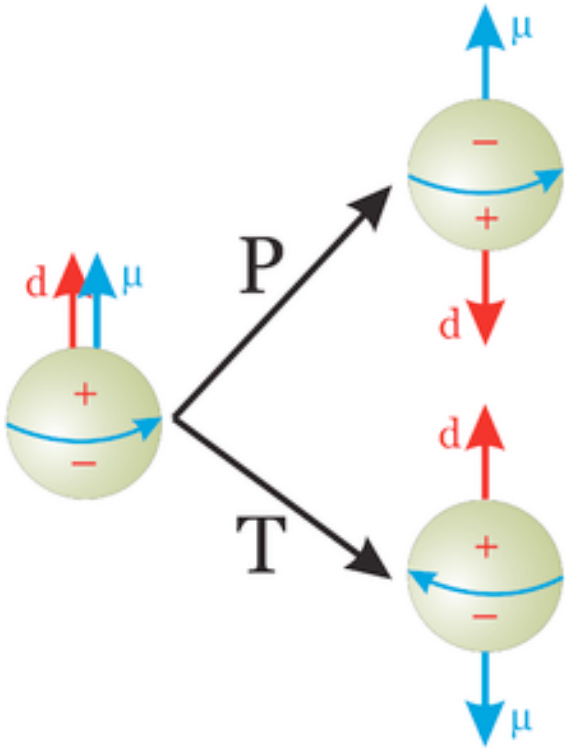
we tend to forget this

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

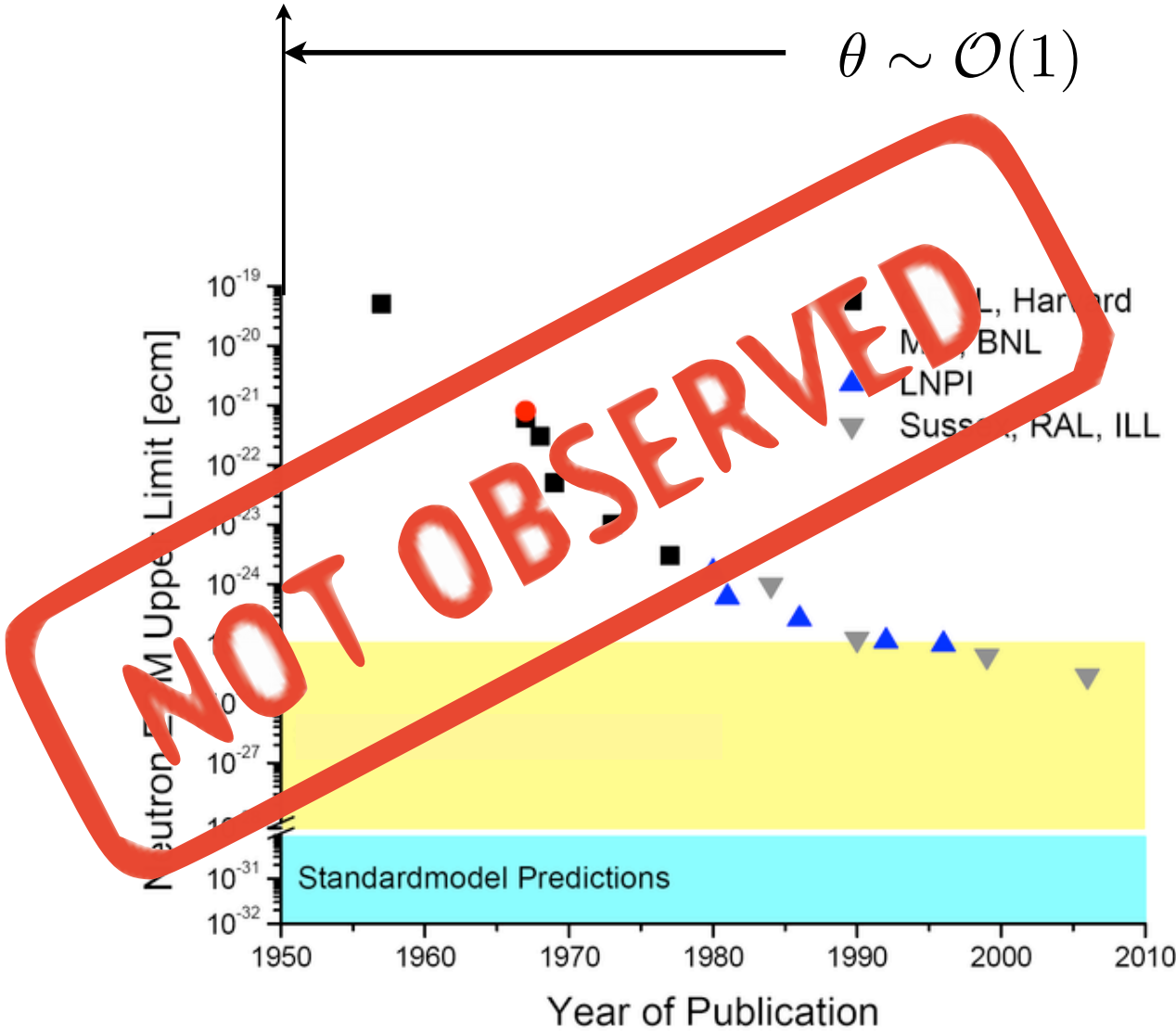
$\theta \in (-\pi, \pi)$ infinitely versions of QCD... all are P,T violating

Neutron EDM

Most important P, T violating observable $d_n \sim \theta \times \mathcal{O}(10^{-15})\,\mathrm{e\,cm}$

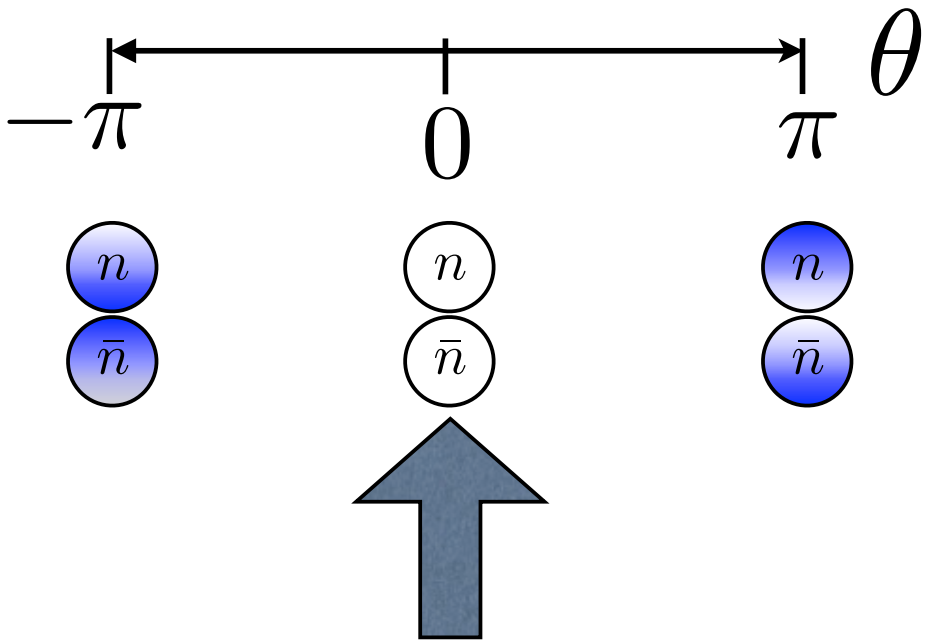


EDM violates P,T



The theta angle of the strong interactions

- The value of θ controls P,T violation in QCD



Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Roberto Peccei and Helen 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 we live in a wor… the … of qua… …ns are …u- ons … …ry, whe… zer… …in- var… …am- eter… anc… …atu- ral … …of qua… …ng to a … …x- pec… pos… …wa cou… T… …gu-

grangian.

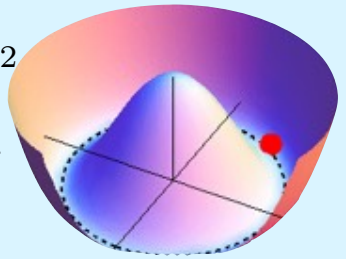
If all fermions which couple to the non-Abelian g… …s θ c… …s most c… …n the e… …ing an e… …Ve de- f… …th sec- t… (1) w… (2) T… …] in- d… …n by (3)

Example: Simple model KSVZ

- Peccei-Quinn global U(1) symmetry, color anomalous + spontaneously broken at f_a

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{Q}DQ + \frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma^*) - (y\bar{Q}_L Q_R \sigma + \text{h.c}) - \lambda|\sigma|^4 + \mu^2|\sigma|^2$$

$$\sigma(x) = \rho(x)e^{i\frac{a(x)}{f_a}} \qquad f_a = \sqrt{\mu^2/2\lambda}$$



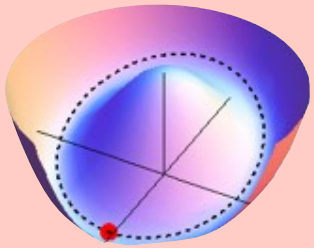
~f_a

- At energies below f_a, (also PQ scale)

$$\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi}G\tilde{G}\frac{a}{f_a}$$

~GeV

- At energies below , $\Lambda_{\rm QCD}$ mixing $a - \eta' - \pi^0 - \eta - \ldots$



axion mass $m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6\text{meV}\frac{10^9\text{GeV}}{f_a}$

couplings $\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}\frac{a}{f_a} + \ldots$

nucleons ... photons ... mesons ...

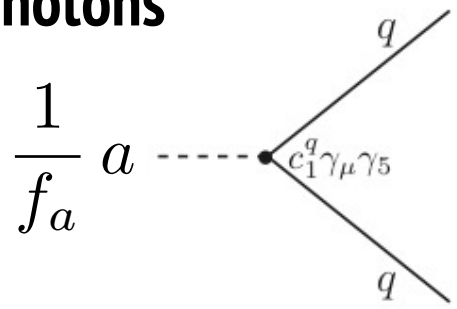
ENERGY

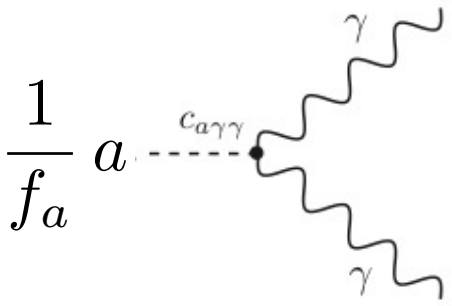
Axion couplings at low energy

Mass

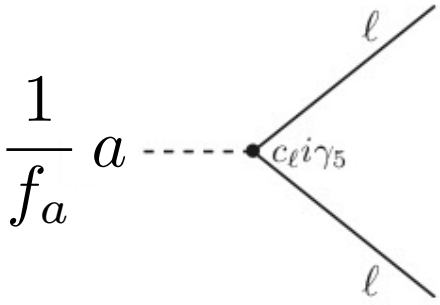
$$m_a = \sqrt{V_{\theta\theta}(\theta)}\frac{1}{f_a} = \sqrt{\chi}\frac{1}{f_a} \simeq 5.7\ \mathrm{meV}\frac{10^9\mathrm{GeV}}{f_a}$$

hadrons, Photons





Leptons (in some models)



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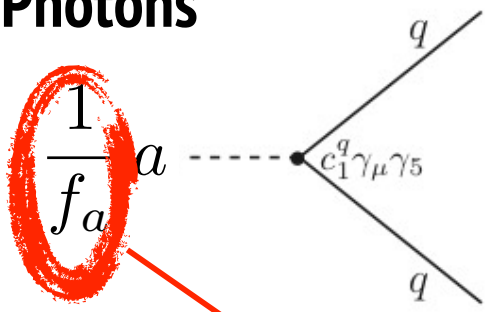
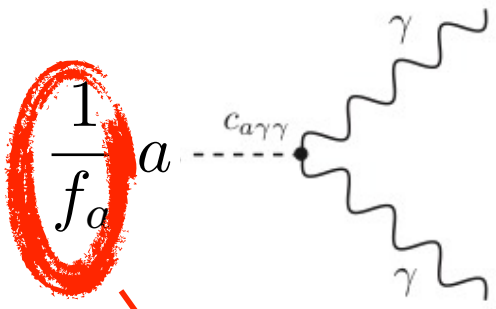
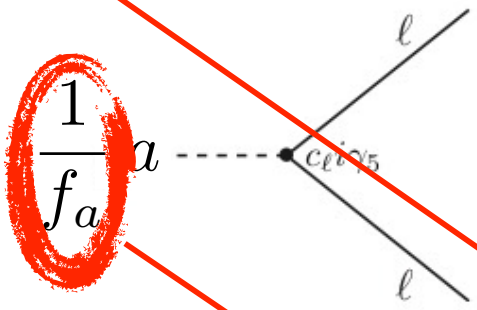
hadrons, Photons



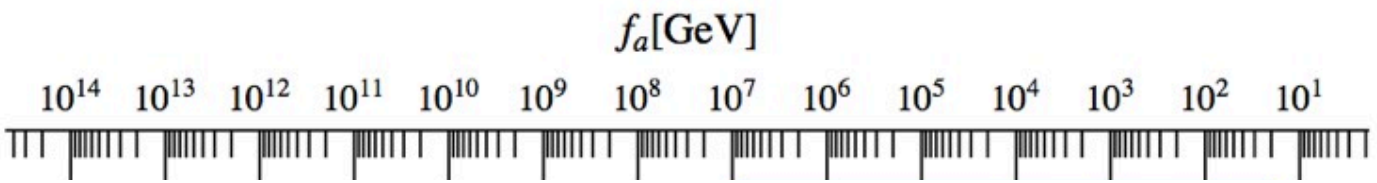


Leptons (in some models)



The lighter the more weakly interacting

Axion Landscape

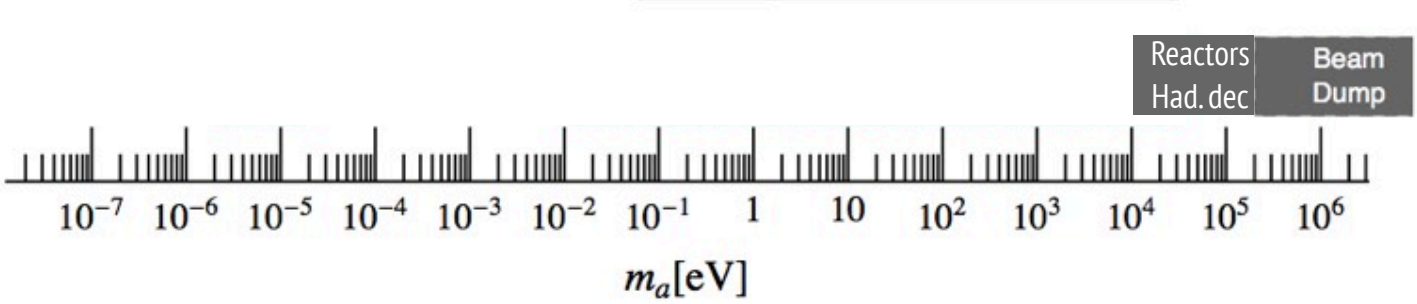


$f_a \gg v_{\rm EW}$

Invisible models

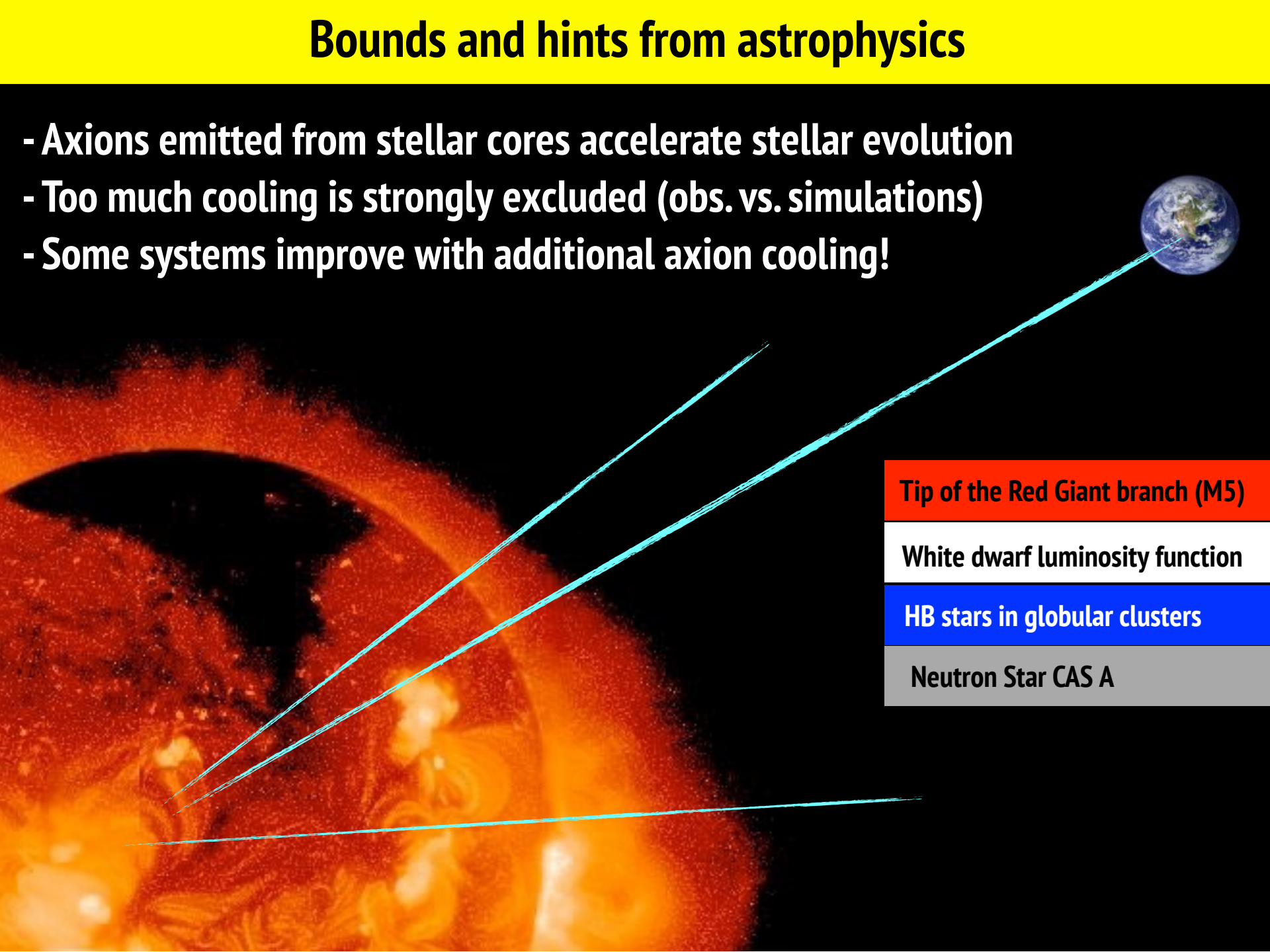
$f_a \sim v_{\rm EW}$

PQWW models



Bounds and hints from astrophysics

- Axions emitted from stellar cores accelerate stellar evolution
- Too much cooling is strongly excluded (obs. vs. simulations)
- Some systems improve with additional axion cooling!



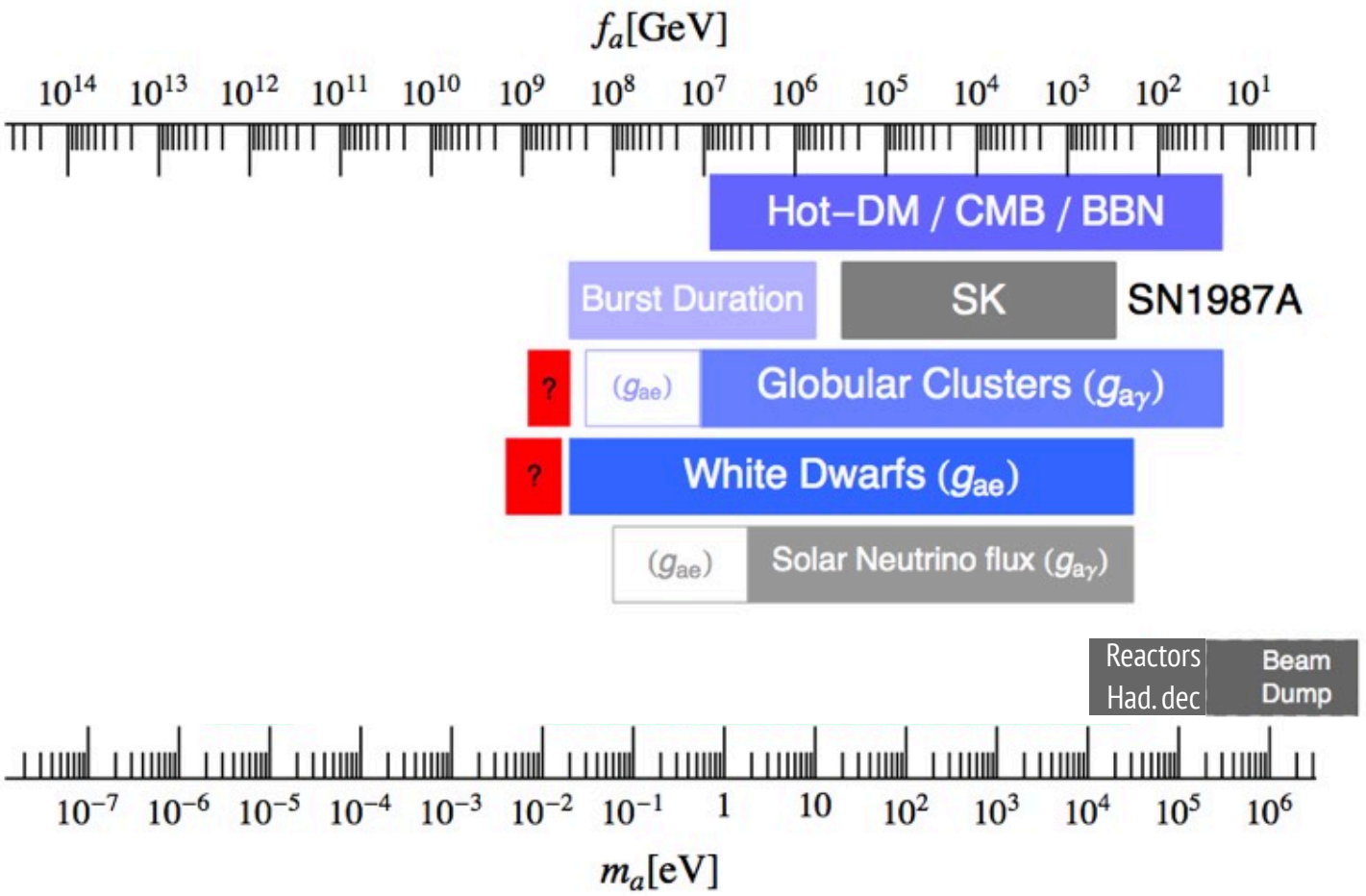
Tip of the Red Giant branch (M5)

White dwarf luminosity function

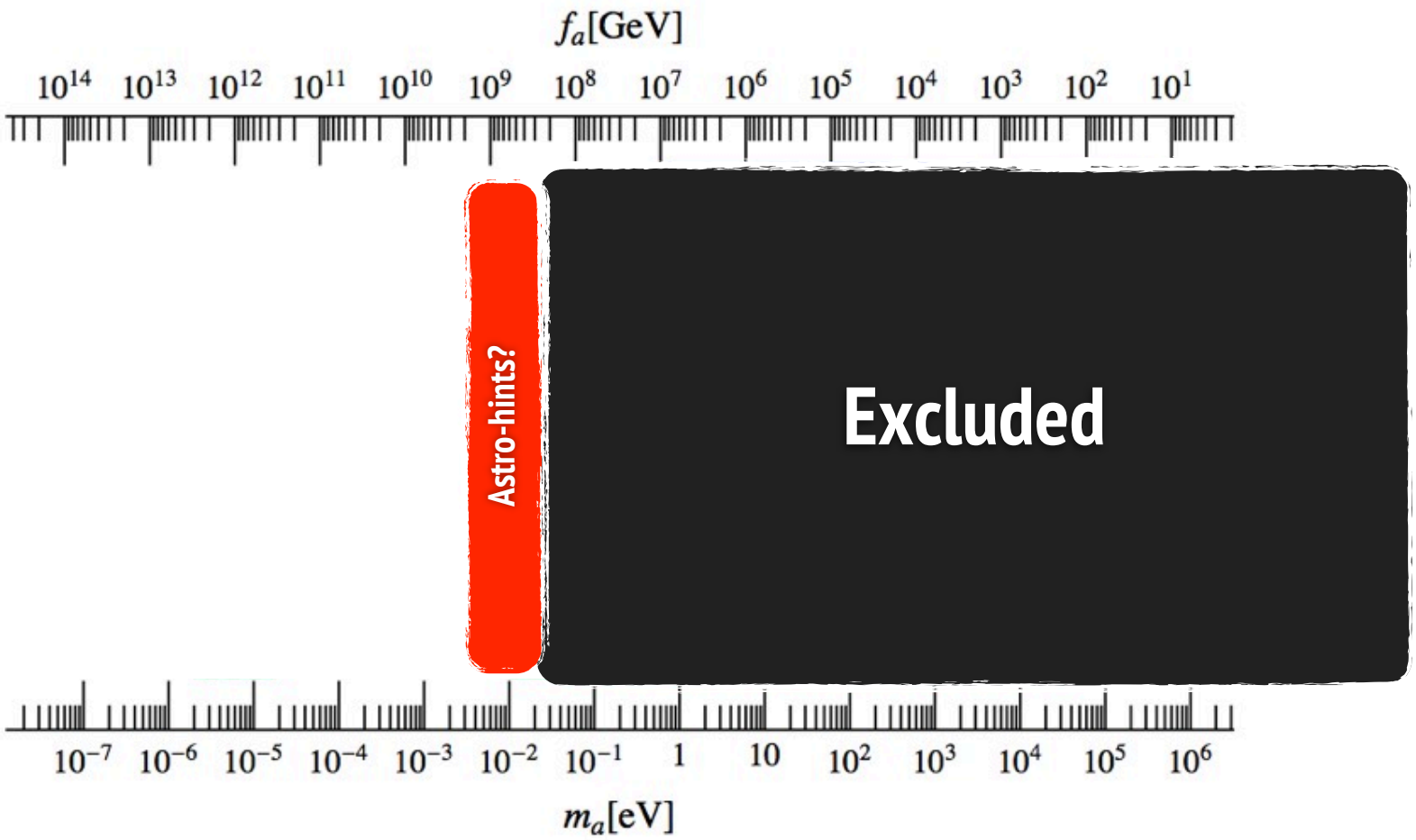
HB stars in globular clusters

Neutron Star CAS A

Axion Landscape



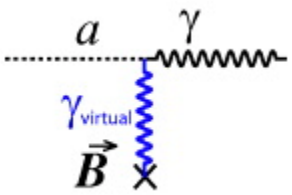
Axion Landscape

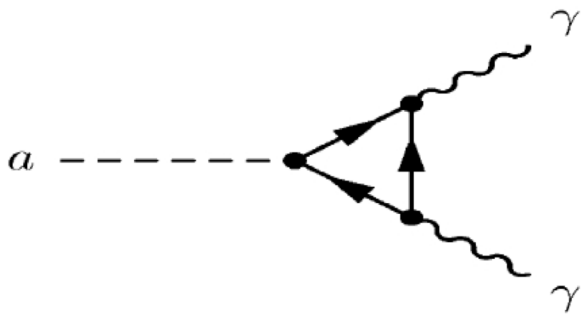


Axion Like Particles ALPs

Extension of the model with particles that are not from QCD but interact weakly with Photons

$$\mathcal{L}_I = \frac{1}{4} G\, a\, F^{\mu\nu} \tilde{F}_{\mu\nu} = G\, a\, \boldsymbol{H} \cdot \partial_0 \boldsymbol{A}.$$





The ALP mass is no longer linked to the coupling
They solve the Dark Matter Issue but not the QCD puzzle