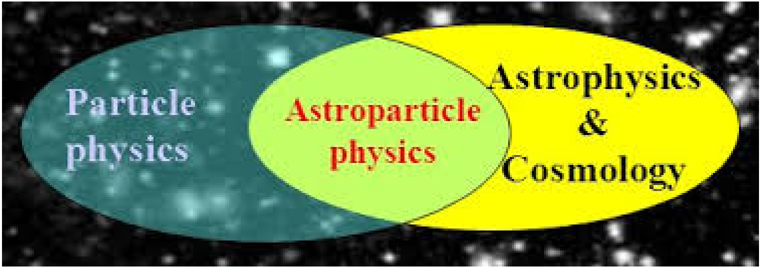
Axions and neutrinos in astrophysics and cosmology

Pierluca Carenza

Dipartimento Interateneo di Fisica "Michelangelo Merlin"
INFN Bari

November 27, 2018

Astroparticle Physics



Astroparticle Physics: Main Questions

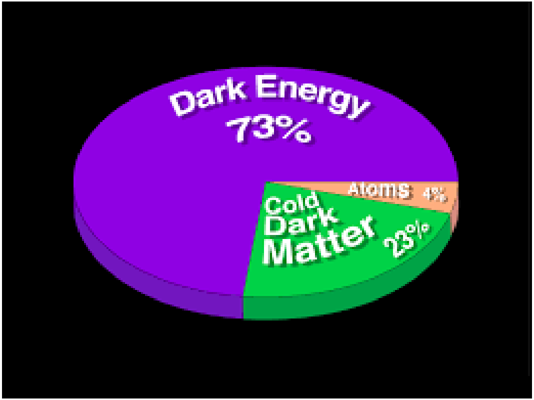
Astroparticle physics aims to gain insights into longstanding enigmas at the heart of our understanding of the Universe, such as:

- *The Extreme Universe*: What can we learn about the cataclysmic events in our Universe by combining all of the messengers that we have at our disposal?
- *The Dark Universe*: What is the nature of Dark Matter and Dark Energy?
- *Mysterious Neutrinos*: What are their intricate properties and what can they tell us?
- *The Early Universe*: What else can we learn about the Big Bang – for instance, from the CMB?

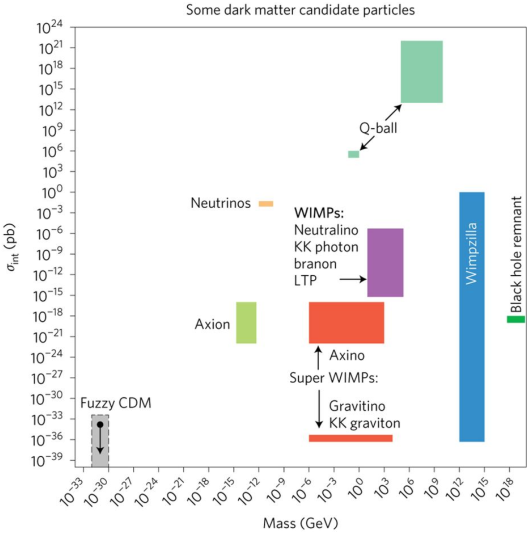
Dark Matter

The $\sim$ 30% of matter is non-baryonic Cold Dark Matter

- Cold: otherwise structure formation is suppressed
- Dark: weak or no interactions with photons



Dark Matter candidates



A well motivated candidate is the **axion**

The strong CP problem

The QCD Lagrangian includes a CP-odd term

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \bar{\theta}_{\rm QCD} \frac{g^2}{32\pi^2} \,\mathrm{tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

where $\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta}$ and $\bar{\theta}_{\rm QCD} = \theta_{\rm QCD} + \arg\det M_{\rm quark}$

QCD predicts a neutron electric dipole moment
$d_n \approx |\bar{\theta}_{\rm QCD}| \times 10^{-15} e\,\mathrm{cm}$
Experimental bound: $|\bar{\theta}_{\rm QCD}| < 10^{-10}$
Naturalness problem, why $\bar{\theta}_{\rm QCD}$ *is so small?*

The Peccei-Quinn mechanism

Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978

PQ symmetry

$U(1)_{PQ}$ is a chiral global symmetry that drives dynamically $\bar{\theta}_{QCD} \to 0$

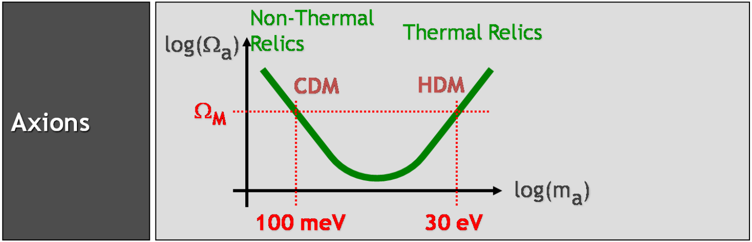
$$\mathcal{L}_{\rm ax} = \frac{1}{2}\partial_\mu a \partial^\mu a - \xi \frac{a}{f_a}\frac{g^2}{32\pi^2}\tilde{G}^a_{\mu\nu}G^{\mu\nu a}$$

The minimum condition removes the CP-odd term: $\bar{\theta}_{\rm QCD} = 0$

$U(1)_{PQ}$ is broken at a scale f_a, the **Peccei-Quinn scale**, and the Goldstone boson is the **axion**

Axion as DM

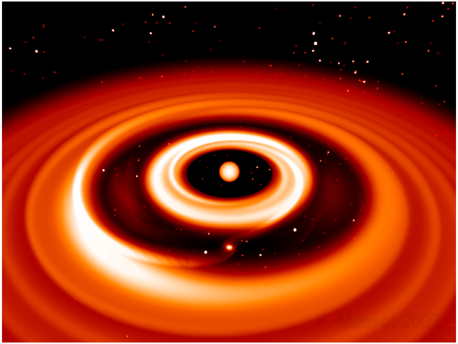
Axions could constitute hot or cold dark matter



Axions as CDM: non-thermally produced as a condensate and very light

CDM signatures: Axion Stars, Clumps and Miniclusters

Axion CDM creates stars, clumps and miniclusters



Intricate interactions between axions, photons and background electrons

Axion Laser

Kolb and Tkachev 1993, Sawyer 2018, Hertzberg and Schiappacasse 2018

Axion-Photon interactions as parametric down-conversion in quantum optics

Axion, photon-pair mixing in models of axion dark matter

R. F. Sawyer[1]

Dark Matter Axion Clump Resonance of Photons

Mark P. Hertzberg,* Enrico D. Schiappacasse[†]

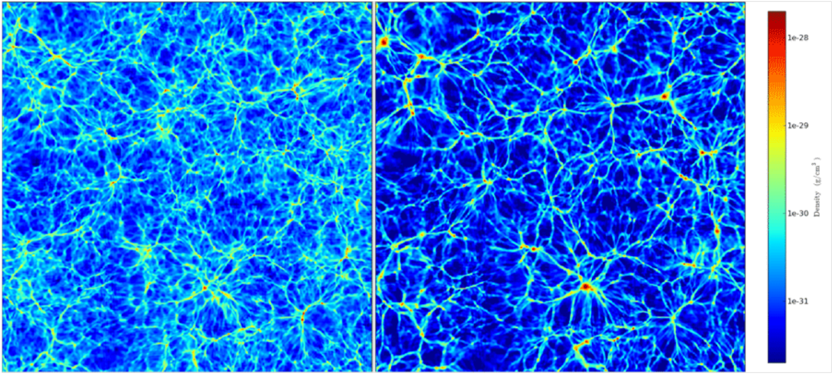
Axion Miniclusters and Bose Stars

Edward W. Kolb[(1),(2)] and Igor I. Tkachev[(1),(3)]

I am interested in studying non-linear effects in axion stars, clumps and miniclusters

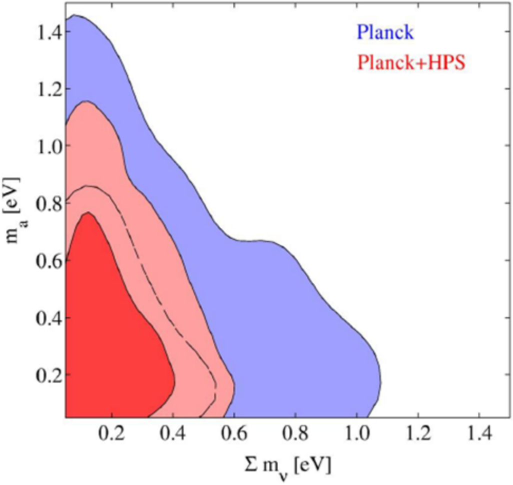
HDM signatures: Large Scale Structures

Neutrinos, as HDM, erase the structure formation at scale smaller than their free-streaming length. Thermally produced axions (with $m_a \sim$ eV) would behave in a similar way



Standard cosmology bound on axions

Axion masses $m_a > 0.6\,\text{eV}$ are excluded by standard cosmology: too much HDM

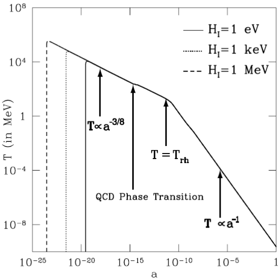


Axion and neutrinos bounds.

Low-Temperature Reheating Scenario

Grin, Smith and Kamionkowski 2008

No evidence for radiation-domination before 1 MeV. Long period of reheating driven by inflaton decay. If axions freeze-out during reheating, their abundance is suppressed with respect to standard cosmology

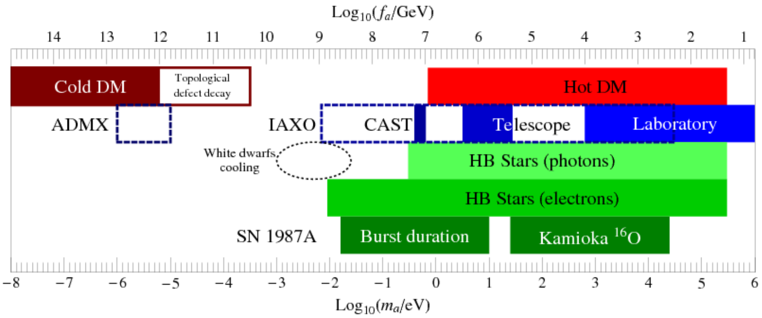


I plan to study the axion thermalization in non-standard cosmology to obtain a new axion mass bound using cosmological codes

Axions in astrophysics

Axions are produced in stars

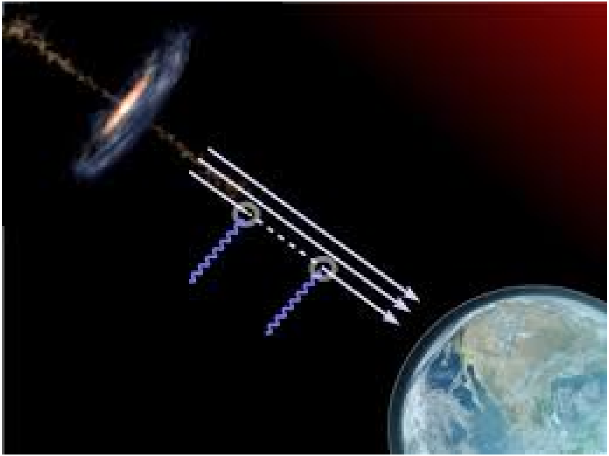
- Detection of SN axions
- Lifetime of stars



I plan to update astrophysical bounds by means of recent astrophysical simulations

$a - \gamma$ Oscillations

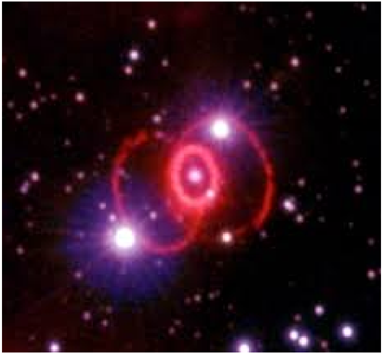
Photons from cosmic sources can mix with axions/ALPs in the large scale cosmic magnetic fields



I will study signatures of $a - \gamma$ oscillations in gamma-ray experiments as Fermi-LAT and CTA

Supernovae as laboratories for axions and neutrinos

SN explosions produce a lot of neutrinos (and axions)



Supernovae can be used as an important laboratory to probe exotic particles (like axions) and neutrino oscillations in extremely dense environments

I intend to perform dedicated studies on these topics

Thanks for your attention