A signal from stimulated decays of axion dark matter in the Milky Way

Takuya Okawa, Francesc Ferrer, Bhupal Dev

APS April Meeting 2023

Axions - motivation

- solve the strong CP problem

$$\mathscr{L}_{\mathrm{QCD}} \supset -\left(\bar{\mathbf{q}}_L m_q e^{i\theta_Y}\mathbf{q}_R + \text{ h.c. }\right) - \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \theta_{\mathrm{QCD}} = -\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \theta$$

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

J. M. Pendlebury et al. 1509.04411

- possible candidates for dark matter

L. F. Abbott & P. Sikivie (1983), M. Dine & W. Fischler (1983), J. Preskill et al. (1983)

- explain astrophysical anomalies:
  - Stellar cooling
  - TeV gamma-ray transparency
  - Hard X-ray from neutron stars

G. G. Raffelt et al. 1110.6397
M. Giannotti et al. 1512.08108
K. Kohri & H. Kodama 1704.05189
G. Galanti et al. 2210.05659
Malte Buschmann et al. 1910.0416
...

- naturally arise in string theory E. Witten (1984)

Axion searches

haloscopes & helioscopes

CAST
IAXO
ADMX
ALPS
MADMAX
…

Image: CAST collaboration

beam dump experiments & coliders

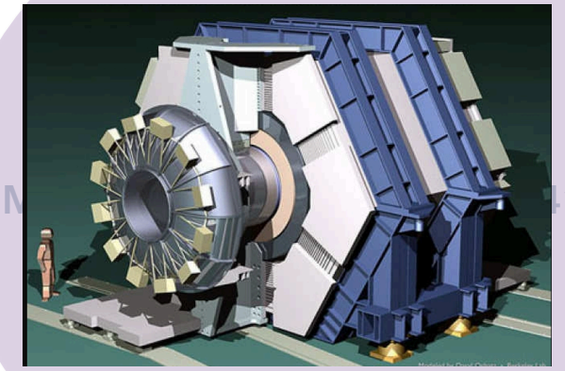


Image: BaBar collaboration

BaBar
E137
E141
CHARM
LEP
…

GRB
Sun
Globular Cluster
NS, WD, SN
Polarizations
…

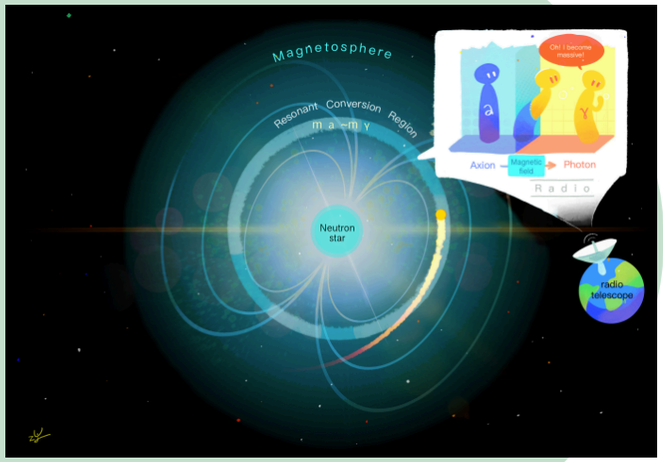


Image: J.H. Buckley et al. 2004.06486

astrophysics

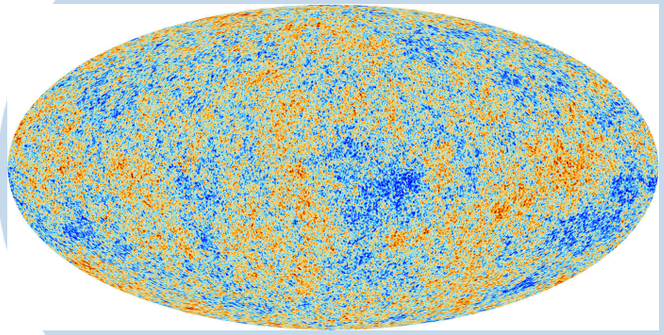


Image: Planck collaboration

CMB spectra
birefringence
D & He abundance
extragalactic BG
…

cosmology

Stimulated decay of axion

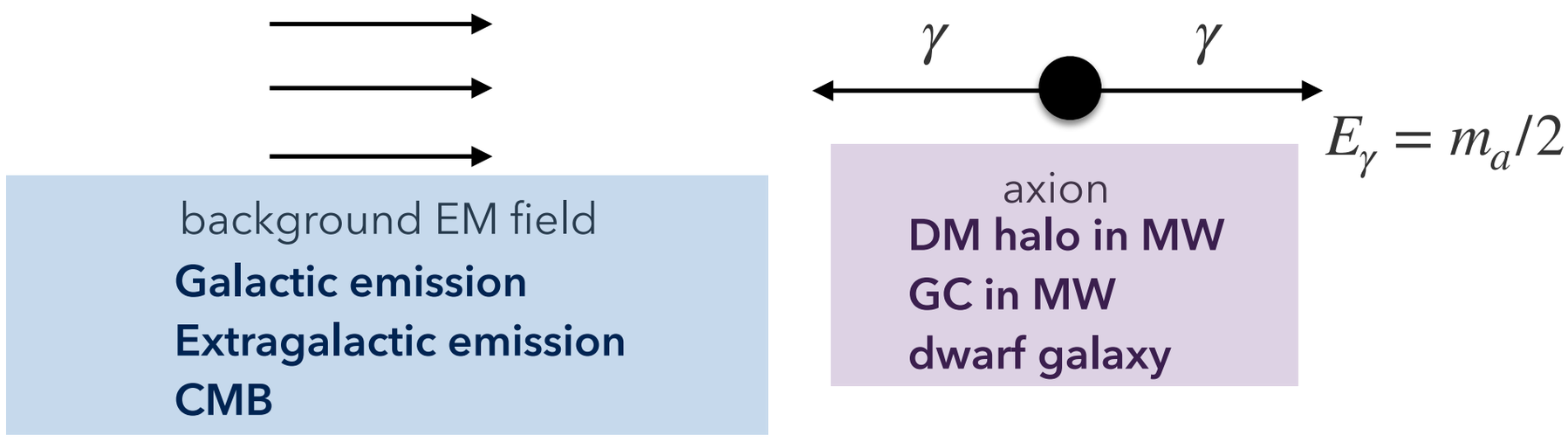
Boltzmann equation $a\left(\mathbf{p_a}\right) \to \gamma\left(\mathbf{p}_1\right) + \gamma\left(\mathbf{p}_2\right)$

$$\frac{\mathrm{d}}{\mathrm{d}t} f_1 = \frac{1}{2E_1} \int \frac{\mathrm{d}^3 p_a}{(2\pi)^3 2E_a} \int \frac{\mathrm{d}^3 p_2}{(2\pi)^3 2E_2} \left|\mathscr{M}\right|^2 \left(f_a\left(1 + f_1 + f_2\right) - f_1 f_2\right) (2\pi)^4 \delta^4\left(p_a - p_1 - p_2\right)$$

stimulated decay of axion (Bose enhancement)

axion production from two photons

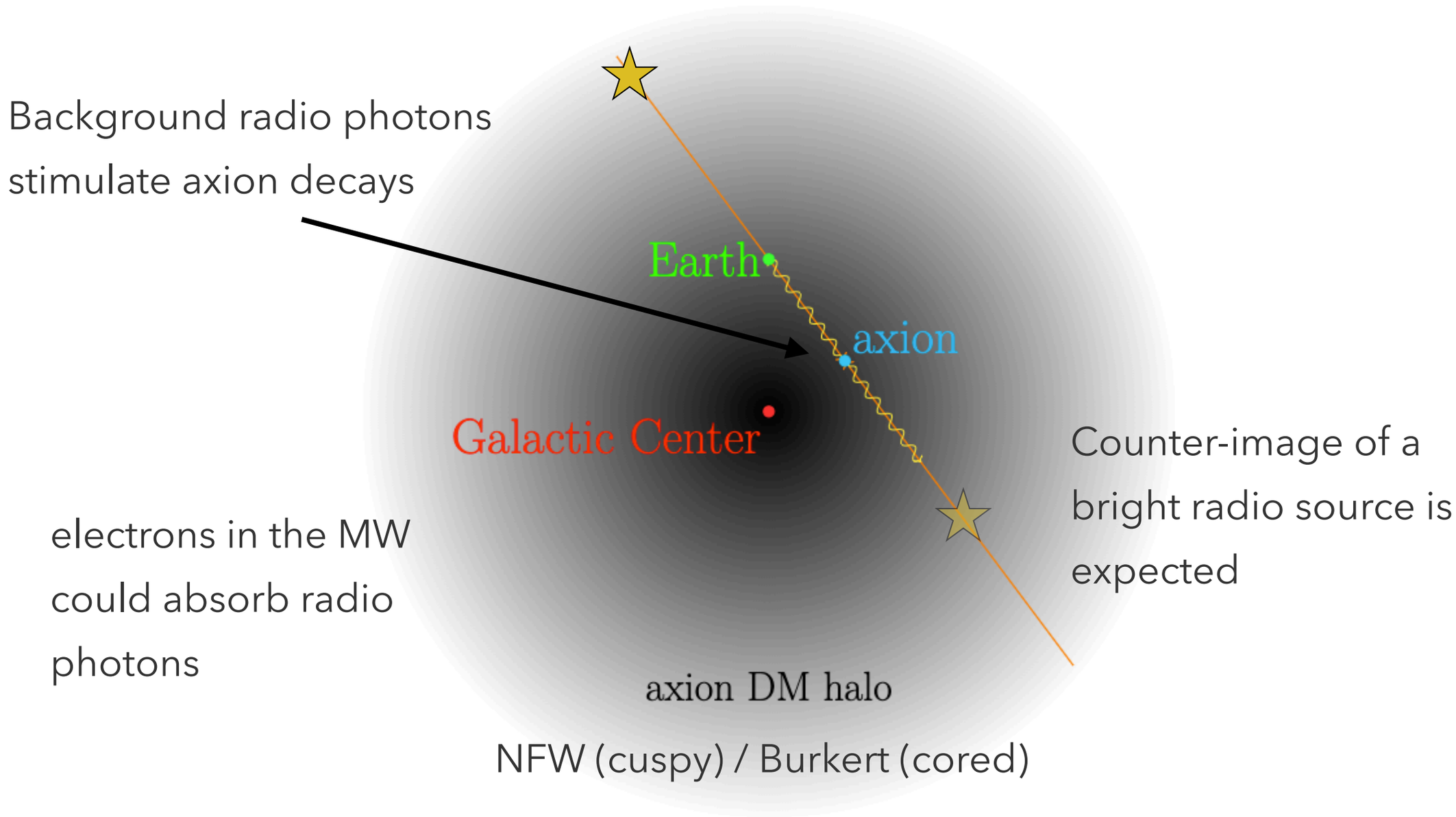
In the rest frame of axion,



generated flux could be observed by telescopes (SKA, FAST, CHORD…)

A. Caputo et al. 1811.08436, O. Ghosh et al. 2008.02729, Y. Sun et al. 2110.13920, M. A. Buen-Abad et al. 2110.13916, G. Wang et al. 2303.14117 …

Stimulated decay of axion in the Milky Way



Signal

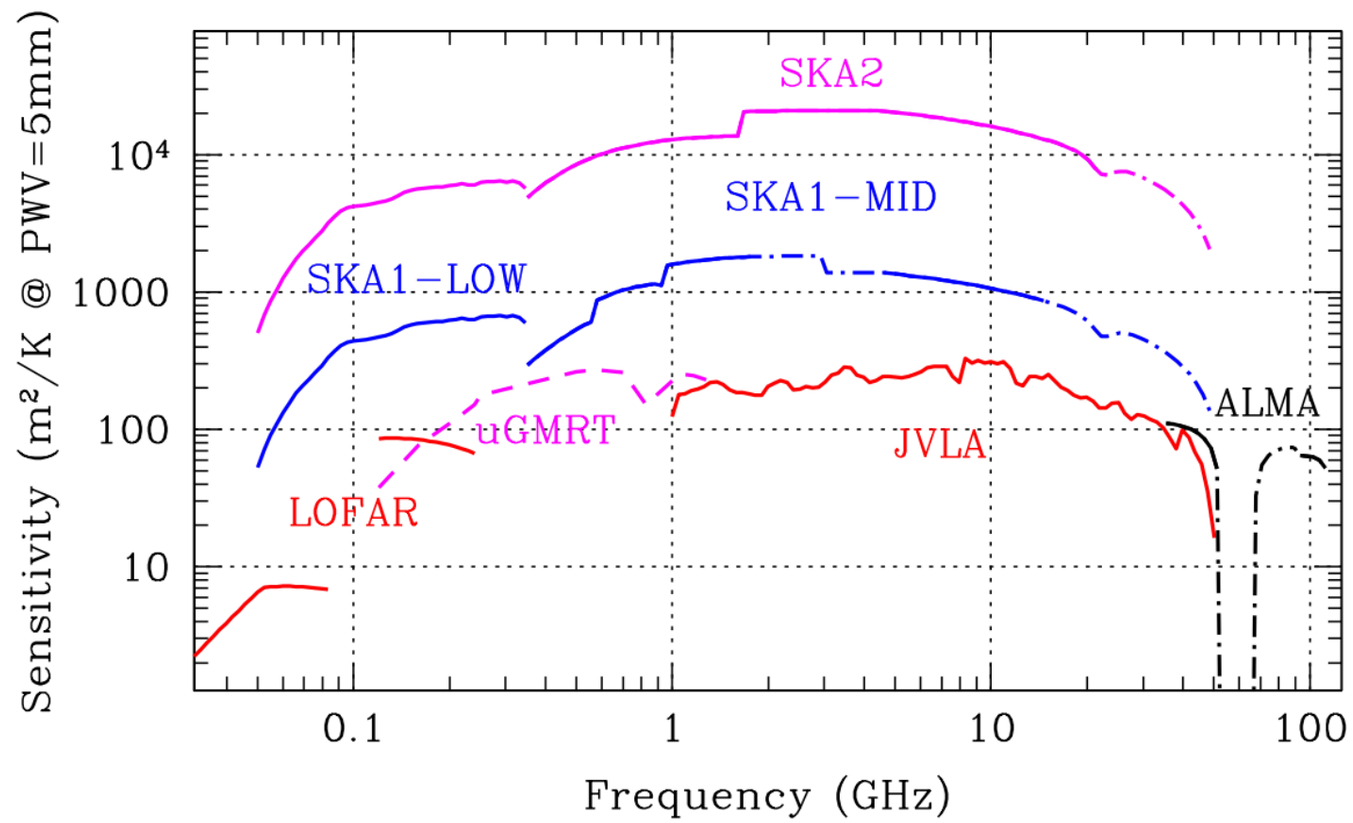
$$S(\nu) = \frac{m_a^3 g_{a\gamma}^2}{64\pi} \frac{1}{4\pi\Delta\nu} \int \mathrm{d}x \int \mathrm{d}\Omega \; \rho_a(x,\Omega) e^{-\tau(\nu,x,\Omega)} \left(f_\gamma(x,\Omega,t) + \tilde{f}_\gamma(x,\Omega,t) \right)$$

Telescopes

SKA Observatory

Image: SKAO

	SKA-low	SKA-mid
Frequency [MHz]	50-350	350-1540
$N_{\rm tele}$	512	197
D [m]	35	13.5, 15
$\theta_{\rm res}$ [deg]	12-1.7	4-1
$T_{\rm r}$ [K]	40	20



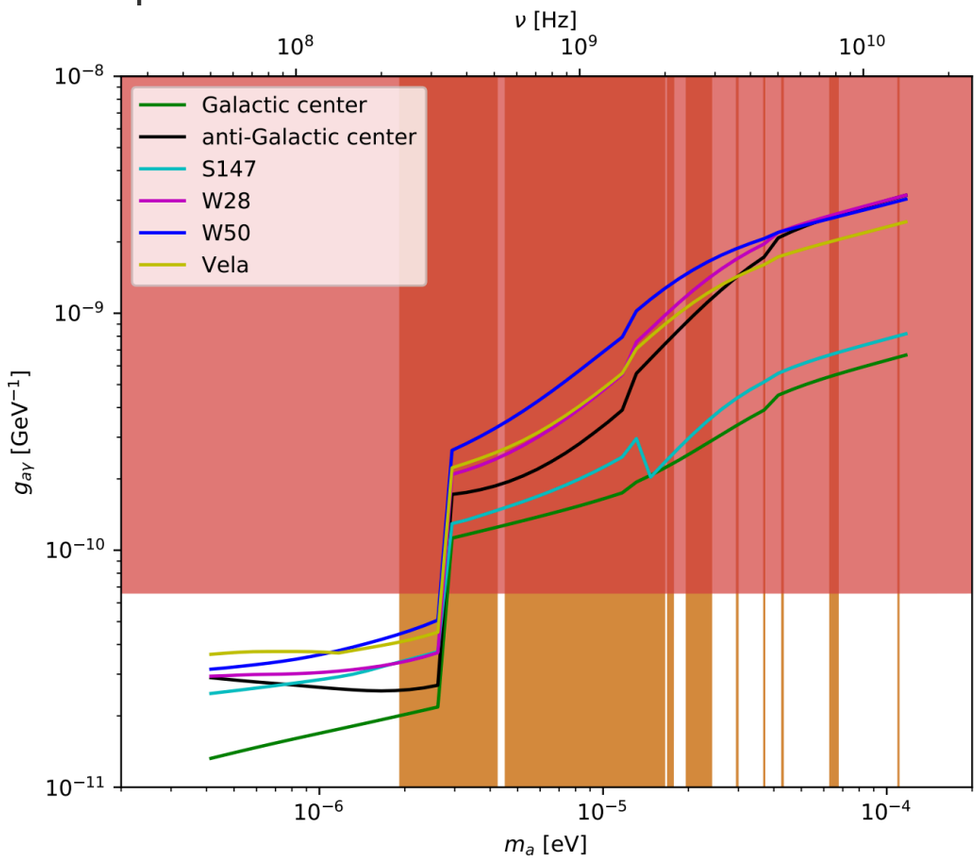
R. Braun et al. 1912.12699

Signal-to-noise ratio of a single antenna

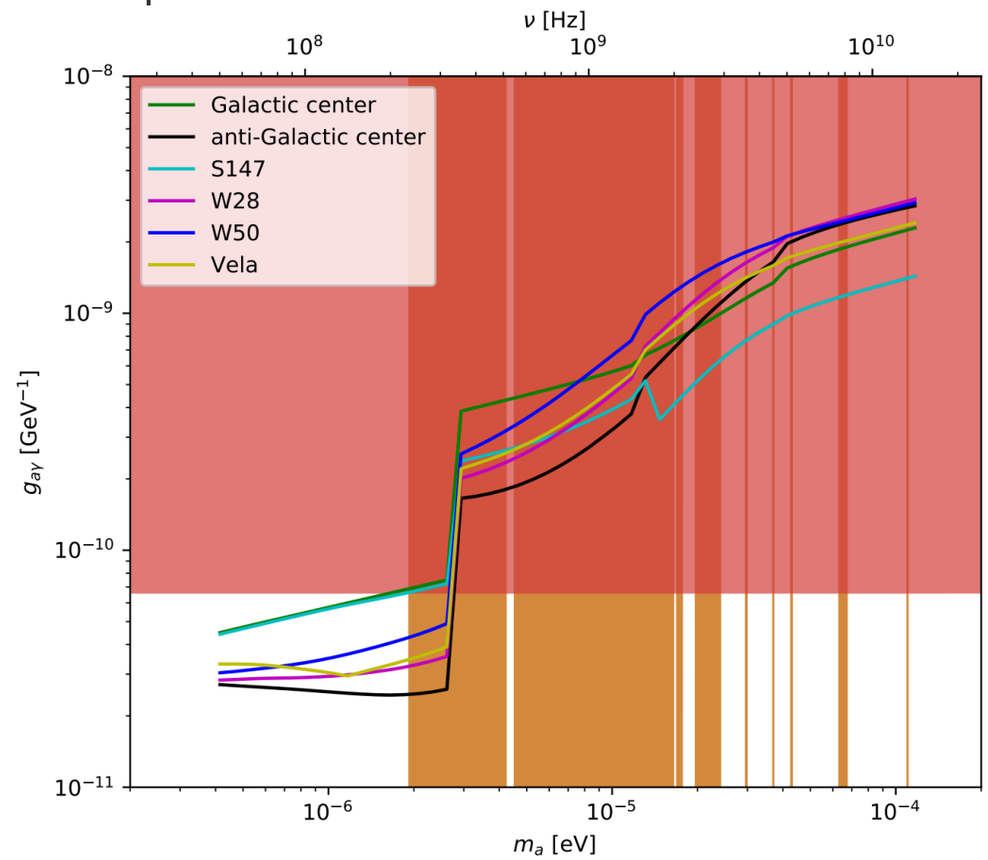
$$\frac{S}{N} = \frac{m_a^3 g_{a\gamma}^2}{512\pi^2} \frac{\eta A f_\Delta}{k_B T} \sqrt{\frac{t_{\rm obs}}{\Delta\nu}} \int {\rm d}x \int {\rm d}\Omega \rho_a(x,\Omega) e^{-\tau(\nu,x.\Omega)} \left(f_\gamma + \tilde{f}_\gamma\right)$$

Flux from stimulated axion decays

NFW profile



Burkert profile



- $g_{a\gamma} \gtrsim 2 \times 10^{-11}$ GeV^{-1} ($m_a \simeq 10^{-6}$ eV) or $g_{a\gamma} \gtrsim 10^{-10}$ GeV^{-1} ($m_a \gtrsim 10^{-5}$ eV) produce the radio photon flux detectable at the SKA Observatory
- Strongest constraints by Galactic Center and S147 (NFW profile) or anti-Galactic Center and S147 (Burkert profile)

Dilute axion stars

- Clumps of axions bounded by quantum pressure

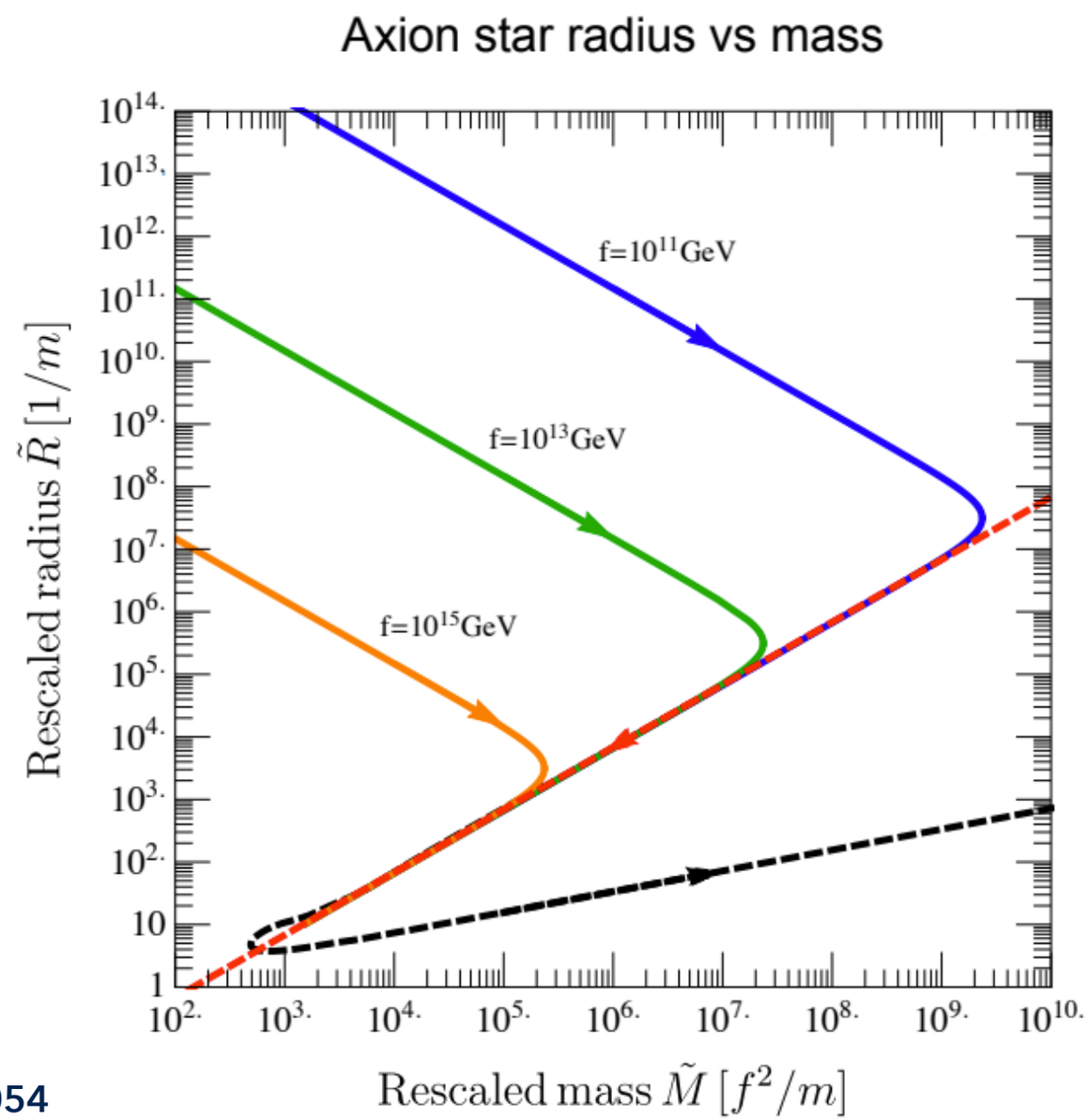
- Solution to the Gross-Pitaevskii-Poisson equations:

$$i\dot{\psi} = -\frac{1}{2m_a}\nabla^2\psi + \left[V'_{\text{eff}}\left(\psi^*\psi\right) + m_a\Phi\right]\psi$$

$$\nabla^2\Phi = 4\pi G m_a \psi^*\psi$$

- $$R_a \sim (270\ \text{km})\left(\frac{10\mu\text{eV}}{m_a}\right)^2\left(\frac{10^{-12}M_\odot}{M_a}\right)$$

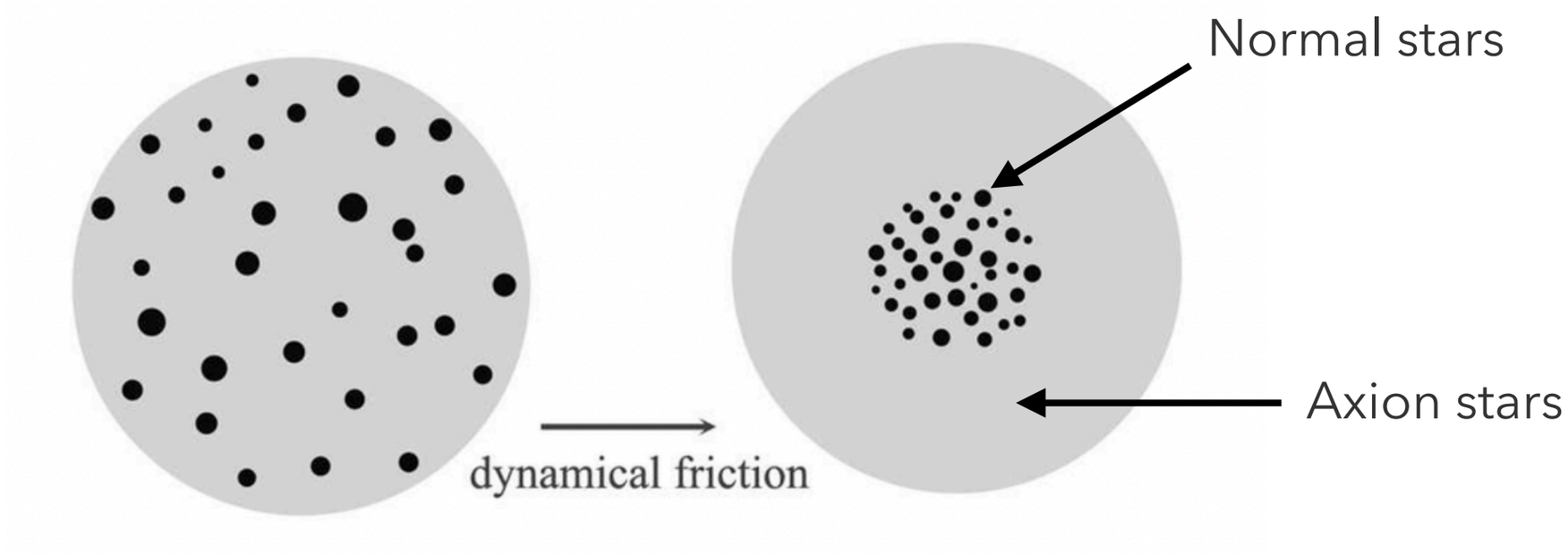
P. H. Chavanis & L. Delfini 1103.2054



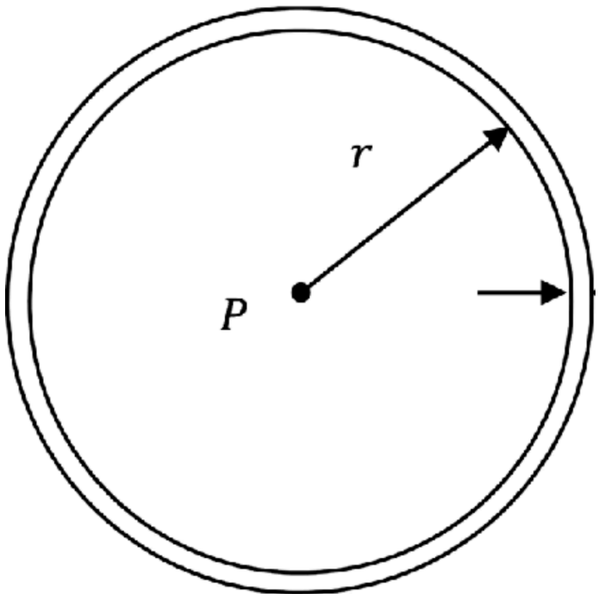
L. Visinelli et al. 1710.08910

Dynamical friction

More massive component tends to be distributed closer to the center as a consequence of gravitational interactions



Assume the effect of mass segregation is spherically symmetric and the virial theorem holds.

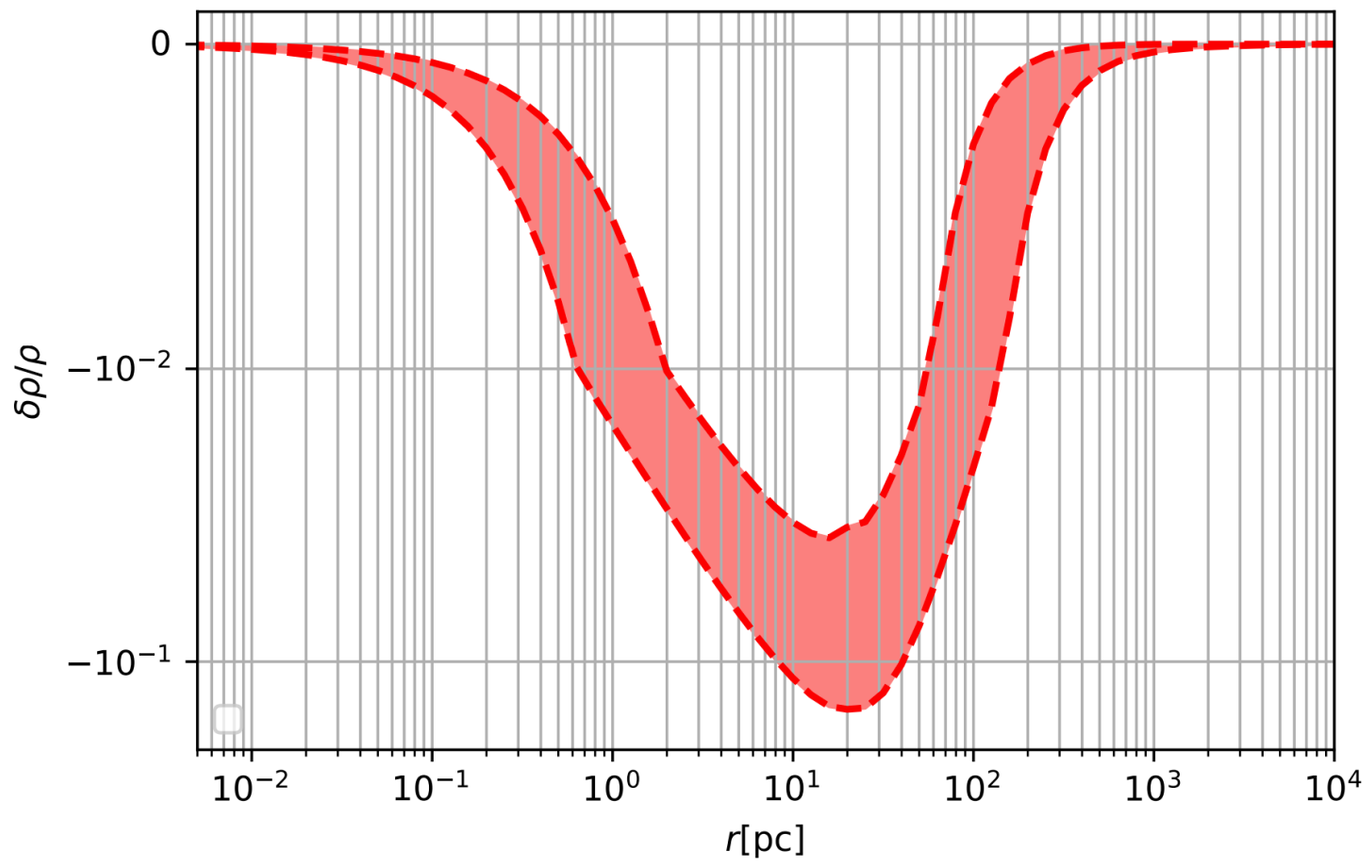


The evolution of a radial shell is given by:

$$\frac{dr}{dt} = \frac{4\sqrt{2}\pi G^2 \rho_s m_s}{\sigma} \ln \Lambda \left(\frac{\mathrm{d}\Psi(r)}{\mathrm{d}r} \right)^{-1}$$

Expected axion density profile

Mass deficit $\delta\rho/\rho$



- The mass density of axions drops by $\lesssim 10\,\%$ at around $r = 10^{1\sim2}$ pc
- Mass segregation results in $\lesssim 1\,\%$ of difference in constraints on $g_{a\gamma}$

Summary

Stimulated decays of axions

- Decays of axions stimulated by background radio waves (Galactic+Extragalactic+CMB) could produce the flux detectable at SKA Observatory

- Galactic Center, anti-Galactic Center, and S147 give the strongest constraints of the axion-photon coupling $g_{a\gamma} \gtrsim 2 \times 10^{-11}$ GeV^{-1}

Axion stars & mass segregation

- Formation of axion stars and their interaction with normal stars result in the mass density deficit of $\lesssim 10\,\%$

- In terms of constraints on $g_{a\gamma'}$ only $\lesssim 1\,\%$ of difference

Backup slides

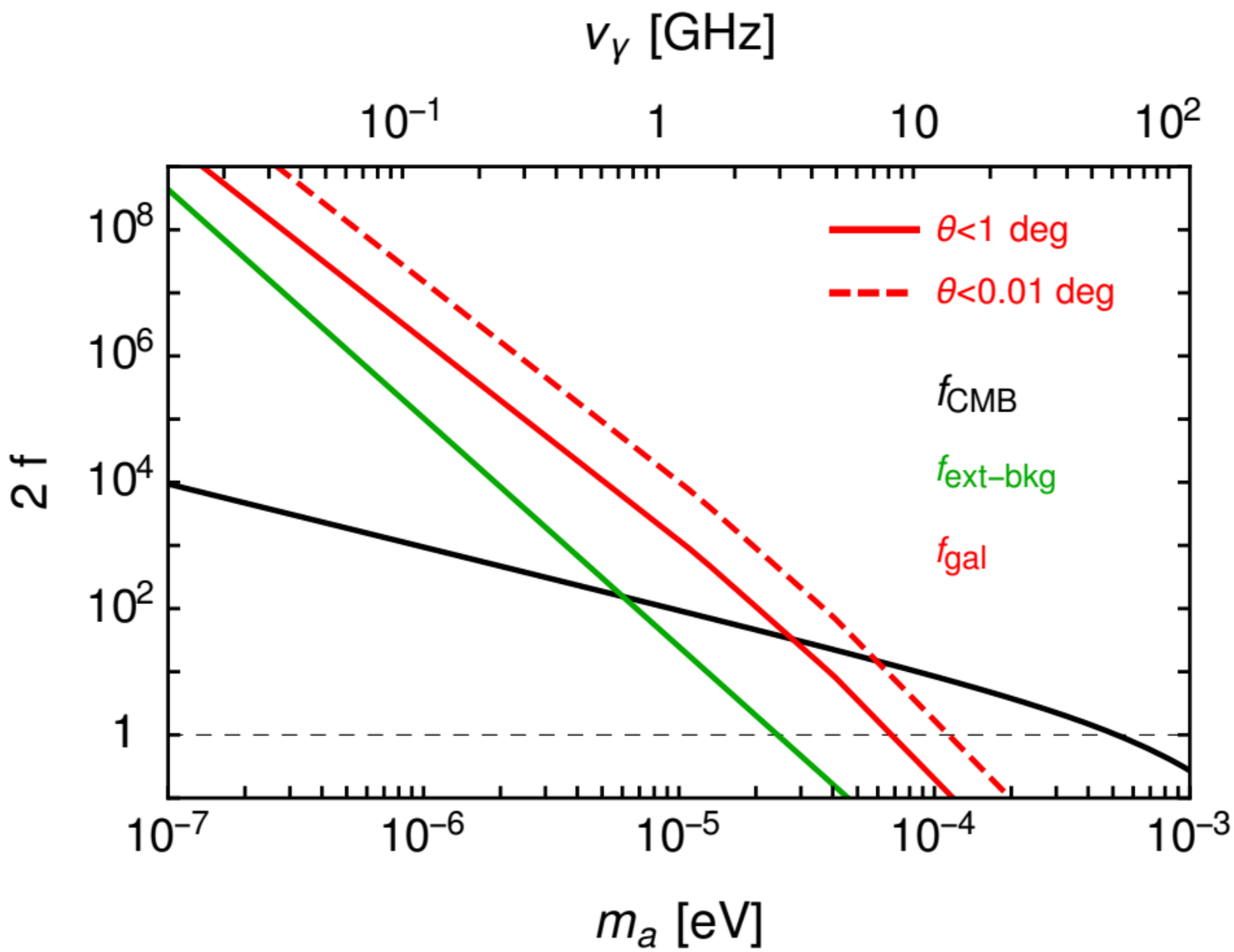
Stimulated decays of axions

- a

Axion stars & mass segregation

- a

Occupation numbers of photons



A. Caputo et al. 1811.08436

Distribution of ALP

The NFW profile:

$$\rho_a(r) = \frac{\delta_c \rho_c}{(r/r_s)\,(1 + r/r_s)^2} \qquad \delta_c = \frac{\Delta_{\rm vir}}{3} \frac{r_c^3}{\ln(1 + r_c) - r_c/(1 + r_c)}$$

$r_s \simeq 20$ kpc : the scale radius

$\Delta_{vir} = 200$

$R_{vir} \simeq 221$ kpc : the virial radius

$r_c \equiv R_{vir}/r_s$

The Burkert profile:

$$\rho(r) = \frac{\rho_s}{\left(1 + \frac{r}{r_{sb}}\right)\left(1 + \frac{r}{r_{sb}}\right)^2}$$

$r_{sb} = 12.67$ kpc

Noise

Four contributions to the noise temperature T

- atmospheric radio wave $T \sim 3\ \mathrm{K}$
- CMB $T \sim 2.725\ \mathrm{K}$
- noise of receiver $T \sim 20{,}40\ \mathrm{K}$
- Synchrotron radiation from the Galactic or extragalactic system

$$T_{\mathrm{bg}} = 60 \left(\frac{300\mathrm{MHz}}{\nu} \right)^{2.55} \mathrm{K}$$

Axion stars

Physics of a scalar field coupled to gravity is described by the action

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{16\pi G} R \right]$$

Trick to solve a resulting EoM:

Assuming axion is non-relativistic

$$\phi(\boldsymbol{r}, t) \approx \frac{1}{\sqrt{2m_a}} \left(\psi(\boldsymbol{r}, t) e^{-im_a t} + \psi^*(\boldsymbol{r}, t) e^{+im_a t} \right)$$

and taking an average over scales larger than m_a

Gross-Pitaevskii-Poisson equations are obtained

$$i\dot{\psi} = -\frac{1}{2m_a} \nabla^2 \psi + \left[V'_{\text{eff}} \left(\psi^* \psi \right) + m_a \Phi \right] \psi$$

$$\nabla^2 \Phi = 4\pi G m_a \psi^* \psi$$