An argument that the dark matter is axions

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Cosmic Frontier Workshop
SLAC, March 6-8, 2013

Collaborators: Ozgur Erken, Heywood Tam, Qiaoli Yang

Outline

1. Cold dark matter axions thermalize and form a Bose-Einstein condensate.

2. The axion BEC rethermalizes sufficiently fast that axions about to fall onto a galactic halo almost all go to the lowest energy state for given total angular momentum.

3. As a result the axions produce
   - caustic rings of dark matter
   - in the galactic plane
   - with radii $a_n \propto 1/n \qquad n = 1, 2, 3, ...$

4. There is observational evidence for the existence of caustic rings of dark matter
   - in the galactic plane
   - with radii $a_n \propto 1/n \qquad n = 1, 2, 3, ...$
   - with overall size consistent with tidal torque theory $(\lambda \simeq 0.05)$

5. The evidence for caustic rings is not explained by other forms of dark matter. Ordinary cold dark matter (WIMPs, sterile neutrinos, non-rethermalizing BEC, …) forms tent-like inner caustics.

The Strong CP Problem

$$L_{\mathrm{QCD}} = \ \ldots + \theta \frac{g^2}{32\pi^2} G^a_{\ \mu\nu} \tilde{G}^{a\mu\nu}$$

Because the strong interactions conserve P and CP, $\theta \le 10^{-10}$.

The Standard Model does not provide a reason for θ to be so tiny,

but a relatively small modification of the model does provide a reason …

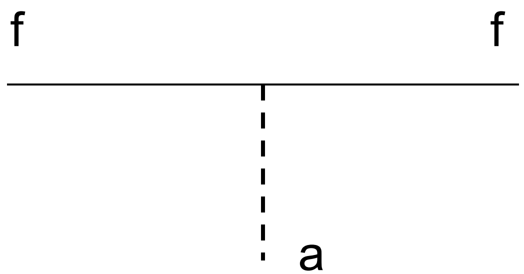
If a $U_{PQ}(1)$ symmetry is assumed,

$$L = \ldots + \frac{a}{f_a}\frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2}\partial_\mu a\, \partial^\mu a + \ldots$$

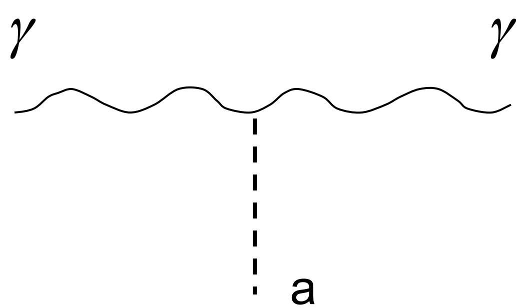
$\theta = \dfrac{a}{f_a}$ relaxes to zero,

and a light neutral pseudoscalar particle is predicted: the axion.

$$m_a \simeq 6\ \text{eV}\ \frac{10^6\ \text{GeV}}{f_a}$$



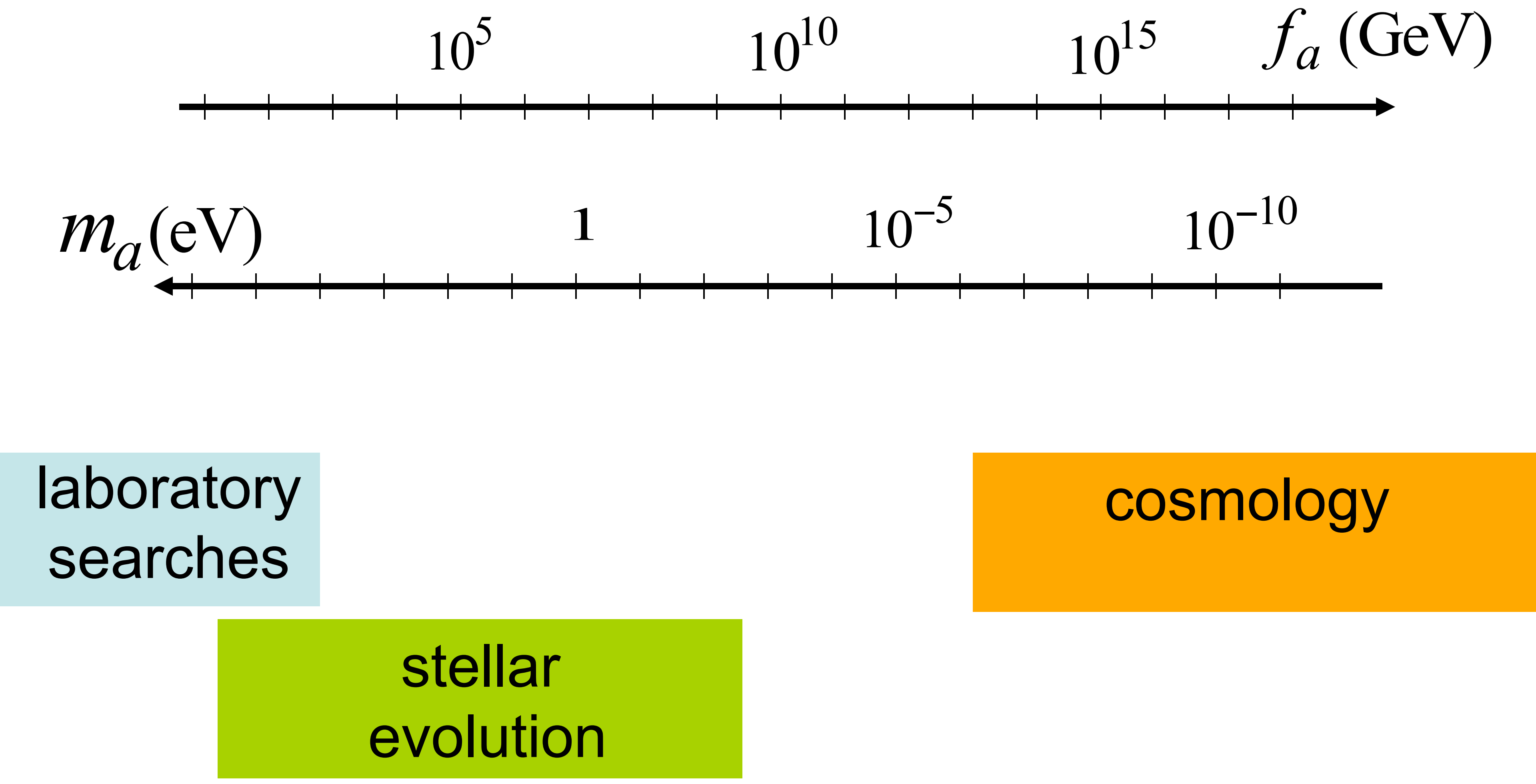
$$L_{a\bar{f}f} = i\, g_f \frac{a}{f_a}\, \bar{f}\, \gamma_5\, f$$



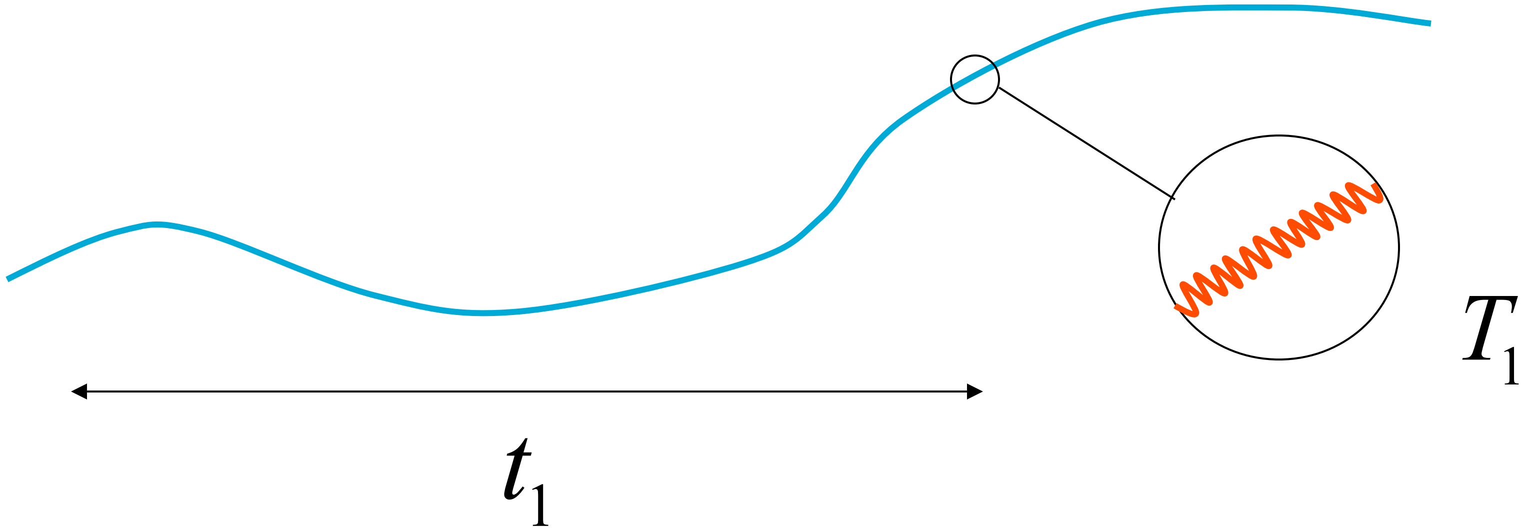
$$L_{a\gamma\gamma} = g_\gamma\, \frac{\alpha}{\pi}\, \frac{a}{f_a}\, \vec{E}\cdot\vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

The remaining axion window



There are two cosmic axion populations: hot and cold.



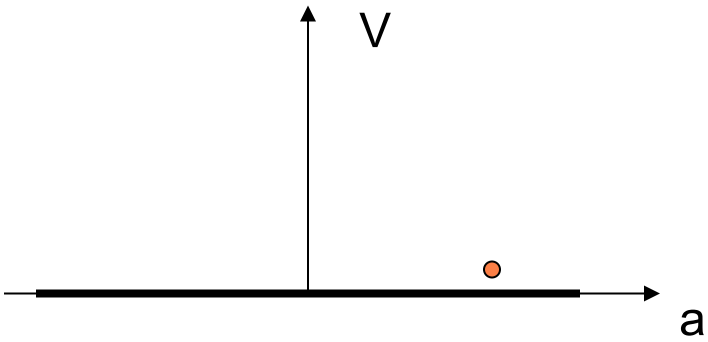
When the axion mass turns on, at QCD time,

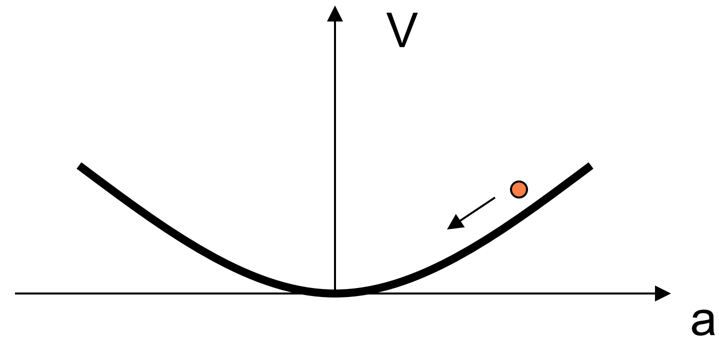
$T_1 \simeq 1 \text{ GeV}$

$t_1 \simeq 2 \cdot 10^{-7} \text{ sec}$

$$p_a(t_1) = \frac{1}{t_1} \simeq 3 \cdot 10^{-9} \text{ eV}$$

Axion production by vacuum realignment





$$T \geq 1\,\mathrm{GeV} \qquad\qquad T \leq 1\,\mathrm{GeV}$$

$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1)\, a(t_1)^2 \simeq \frac{1}{2t_1} f_a^{\,2}\, \alpha(t_1)^2$$

initial
misalignment
angle

$$\rho_a(t_0) \simeq m_a\, n_a(t_1) \left(\frac{R_1}{R_0}\right)^3 \propto m_a^{-\frac{7}{6}}$$

Cold axion properties

- number density

$$n(t) \sim \frac{4\cdot 10^{47}}{\mathrm{cm}^3}\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\frac{5}{3}}\left(\frac{a(t_1)}{a(t)}\right)^3$$

- velocity dispersion

$$\delta \mathrm{v}(t) \sim \frac{1}{m_a\, t_1}\,\frac{a(t_1)}{a(t)}$$

if decoupled

- phase space density

$$\mathcal{N} \sim n(t)\,\frac{(2\pi)^3}{\frac{4\pi}{3}(m_a\,\delta\mathrm{v})^3} \sim 10^{61}\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\frac{8}{3}}$$

Bose-Einstein Condensation

if identical bosonic particles
are highly condensed in phase space
and their total number is conserved
and they thermalize

then most of them go to the lowest energy
available state

why do they do that?

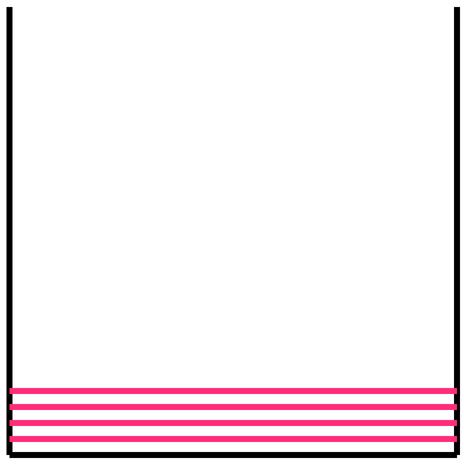
by yielding their energy to the non-condensed particles, the total entropy is increased.

preBEC

BEC

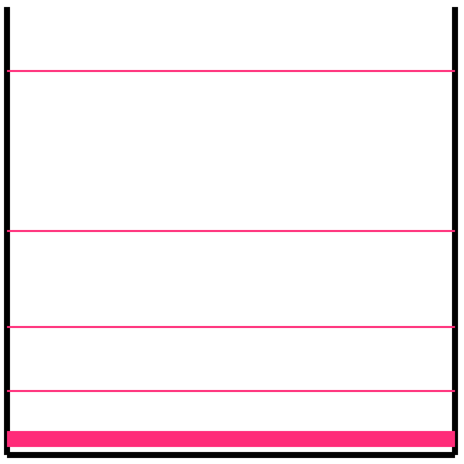
the axions thermalize and form a BEC after a time τ

$t < \tau$



the axion fluid obeys classical field equations, behaves like CDM

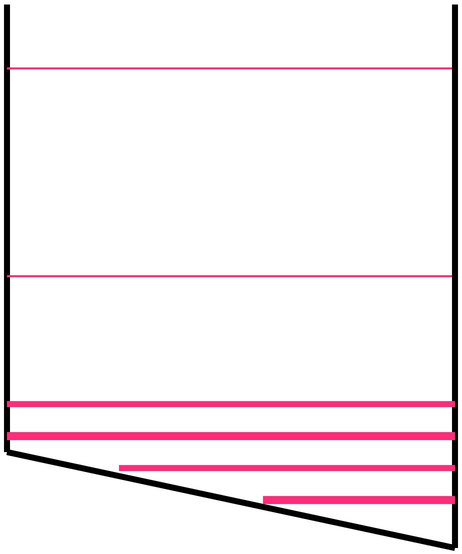
$t > \tau$



the axion fluid does not obey classical field equations, does not behave like CDM

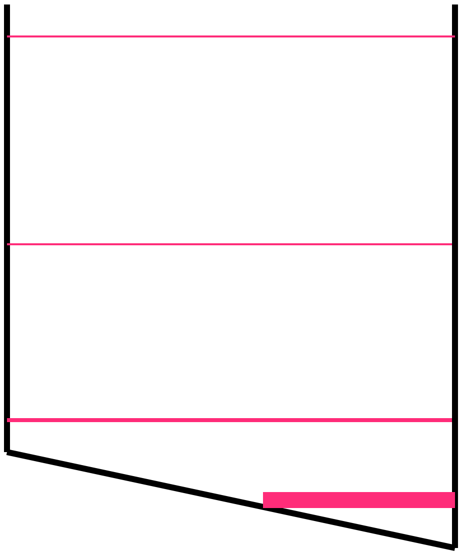
the axion BEC rethermalizes

$t < \tau$



the axion fluid obeys classical field equations, behaves like CDM

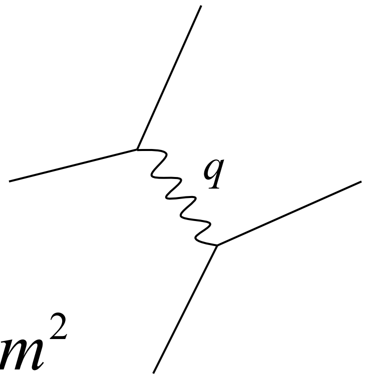
$t > \tau$



the axion fluid does not obey classical field equations, does not behave like CDM

Thermalization occurs due to gravitational interactions

PS + Q. Yang, PRL 103 (2009) 111301



$$\frac{Gm^2}{q^2}$$

$$\Gamma_g \sim 4\pi G n m^2 l^2 \quad \text{with } l = (m\,\delta\mathrm{v})^{-1}$$

$$\sim 5 \cdot 10^{-7} H(t_1) \left(\frac{f}{10^{12}\ \mathrm{GeV}}\right)^{\frac{2}{3}}$$

at time t_1

$$\Gamma_g(t)/H(t) \propto t\,a(t)^{-1} \propto a(t)$$

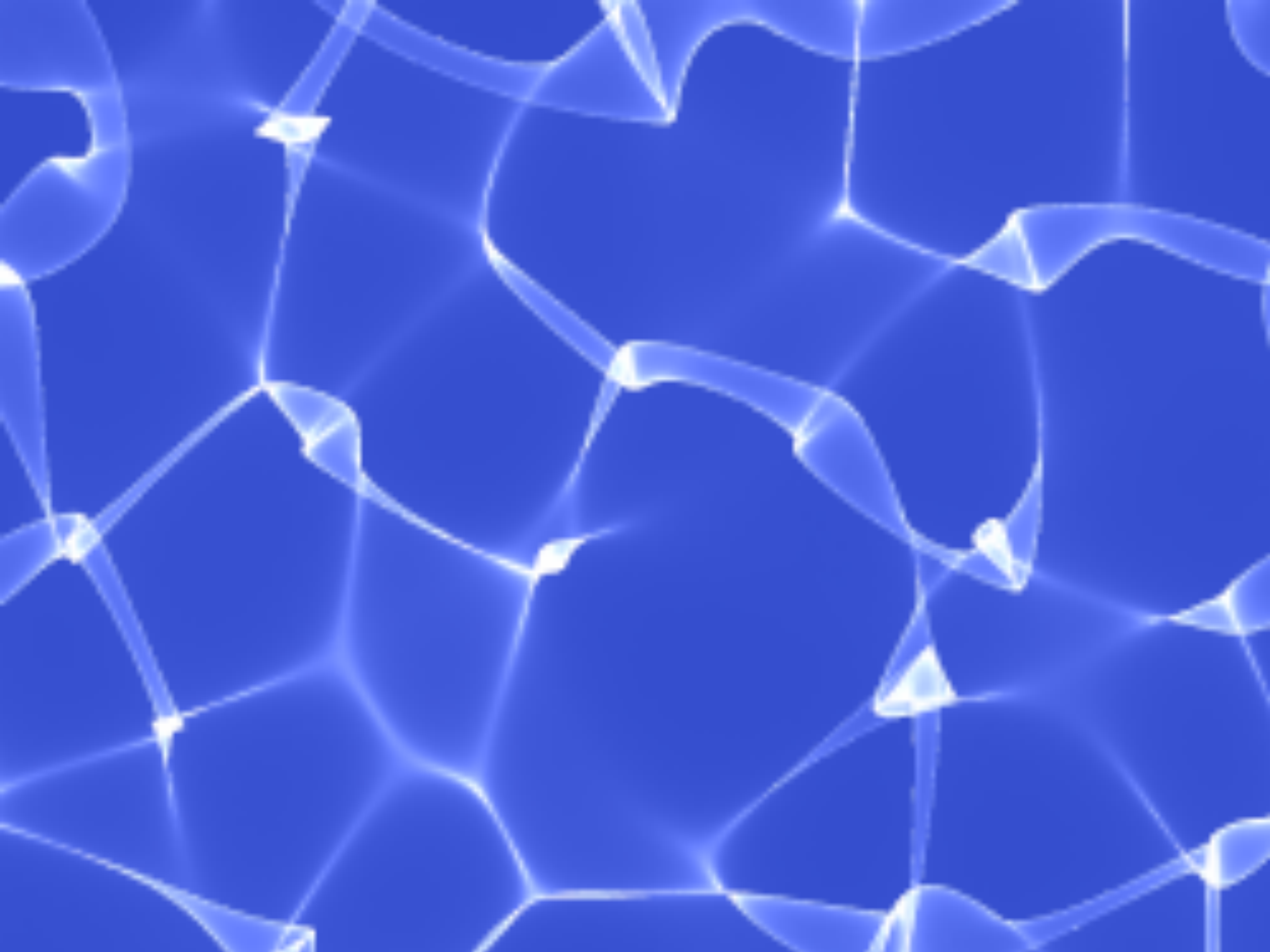
Gravitational interactions thermalize the axions and cause them to form a BEC when the photon temperature

$$T_\gamma \sim 500\ \mathrm{eV} \left(\frac{f}{10^{12}\ \mathrm{GeV}} \right)^{\frac{1}{2}}$$

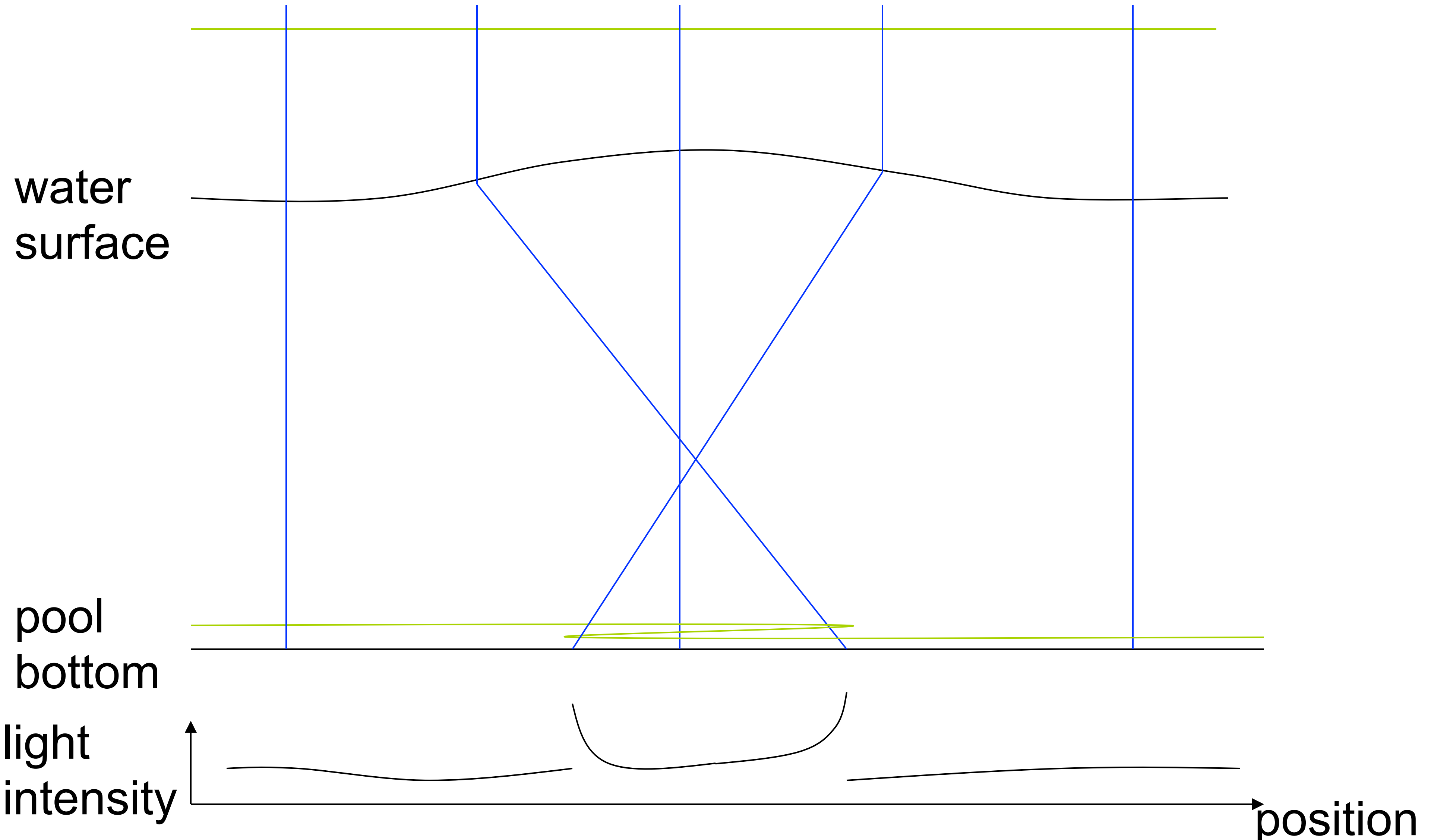
After that

$$\delta \mathrm{v} : \frac{1}{m\,t}$$

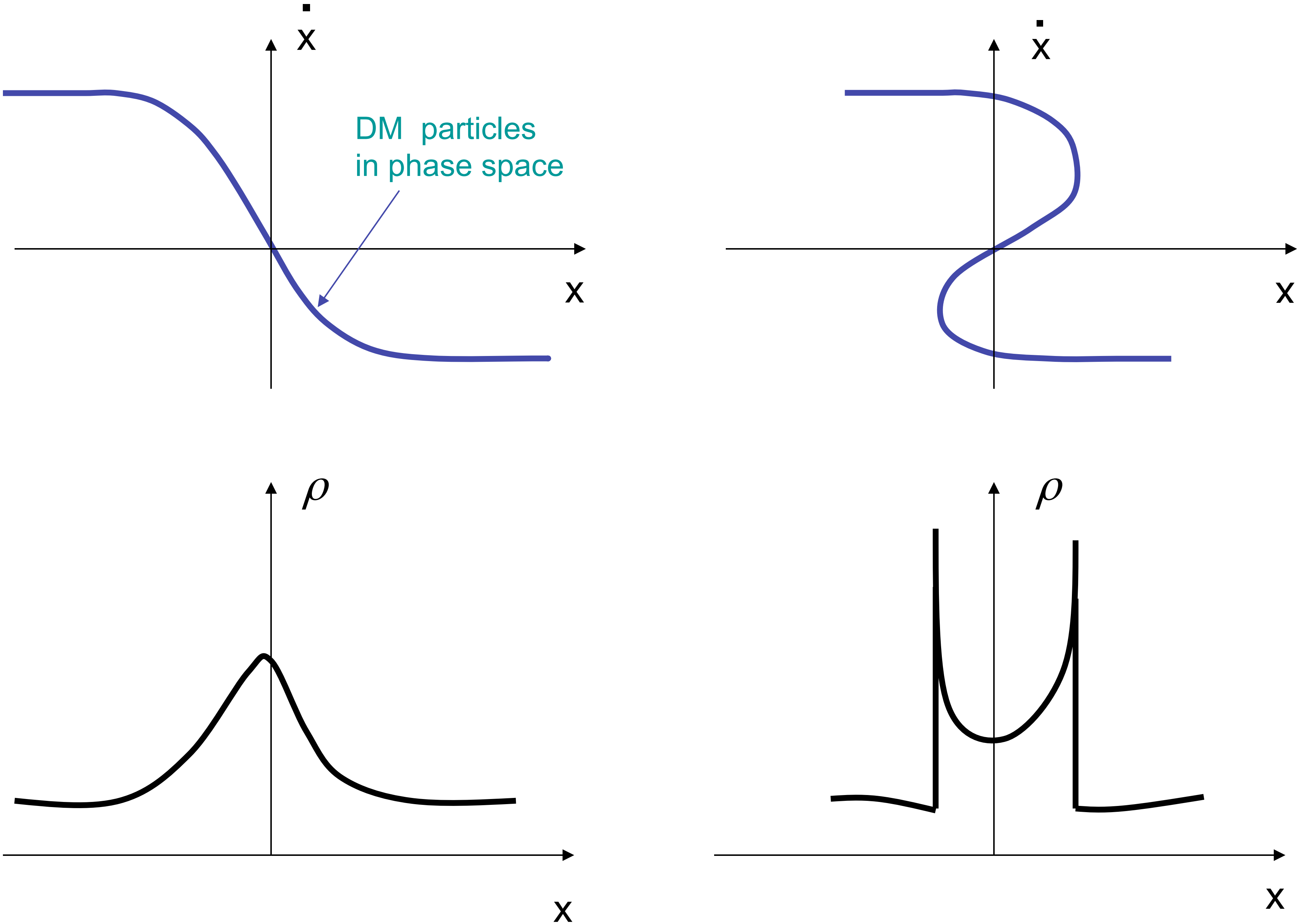
$$\Gamma_g(t) / H(t) \propto t^3\, a(t)^{-3}$$



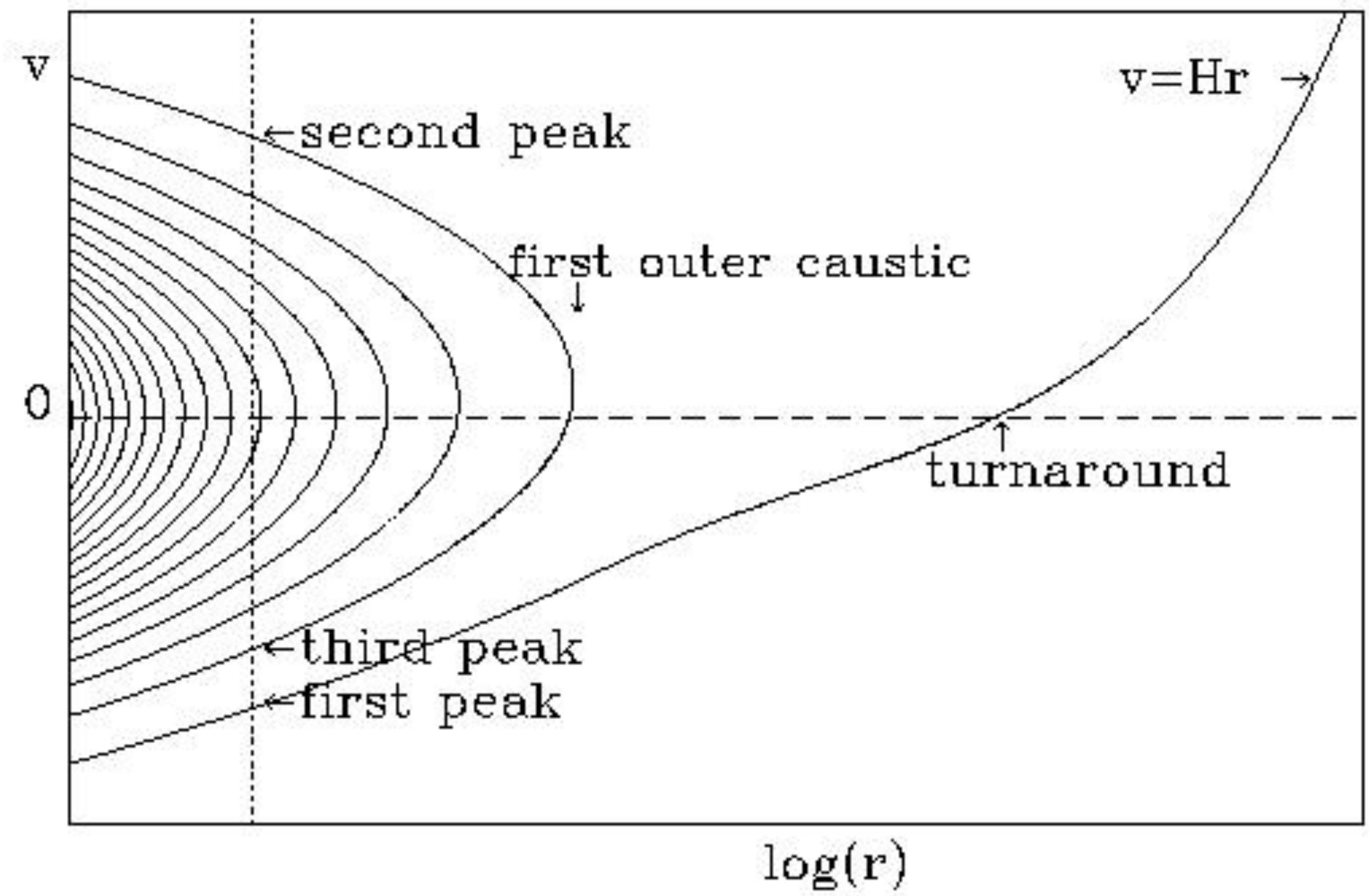
Caustics of light at the bottom of a swimming pool on a sunny breezy day



DM forms caustics in the non-linear regime



Phase space structure of spherically symmetric halos



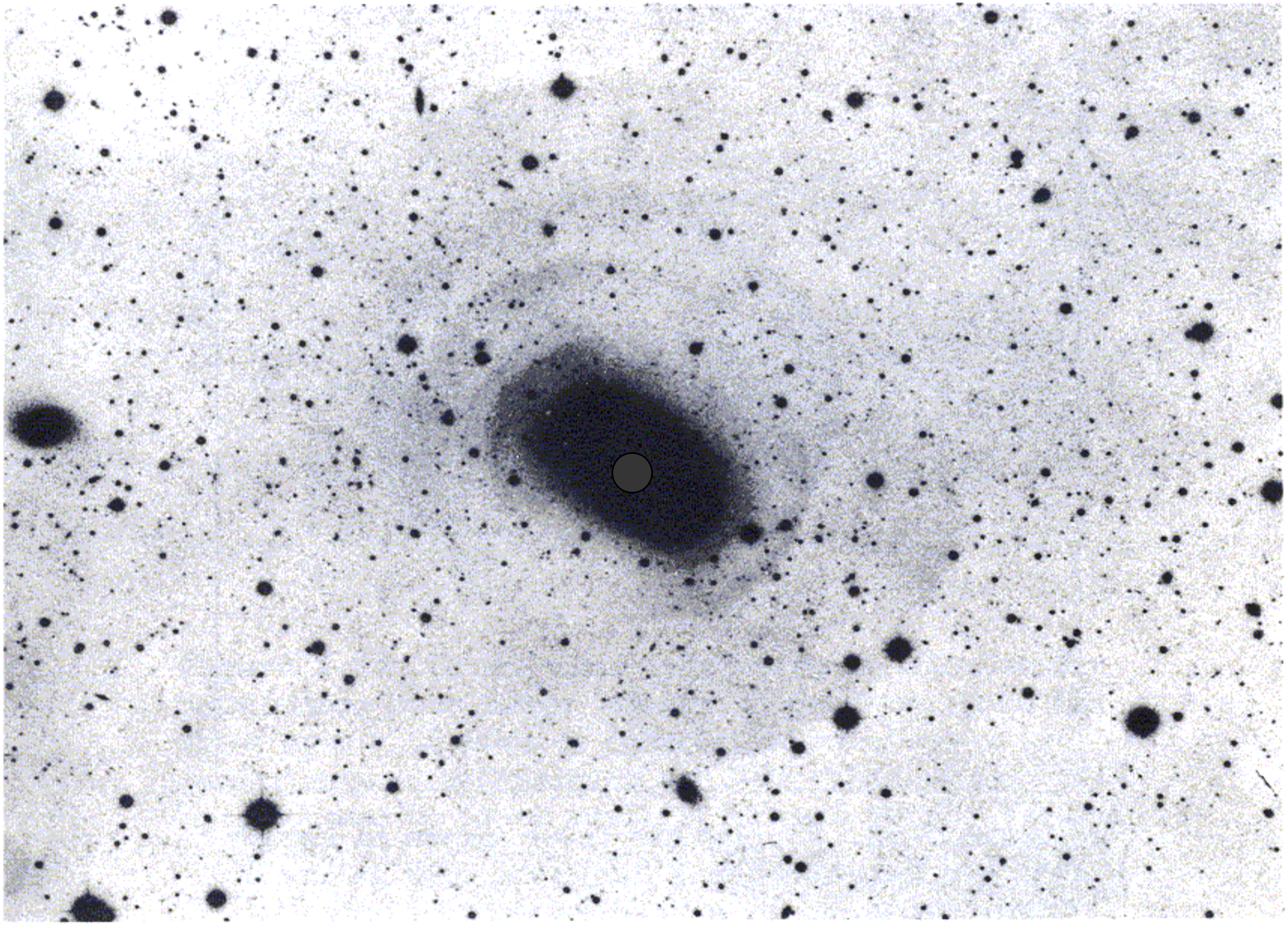


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

(from Binney and Tremaine's book)

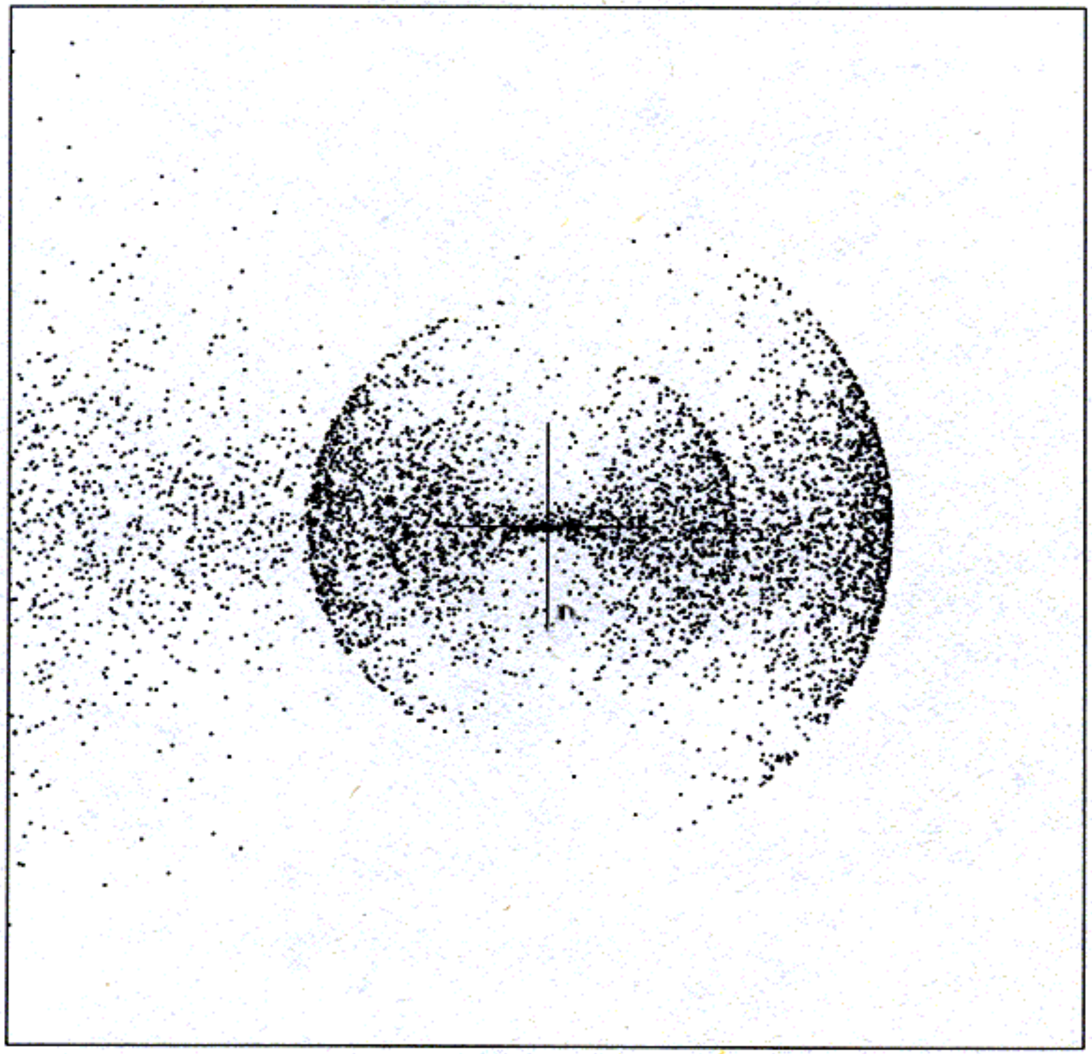
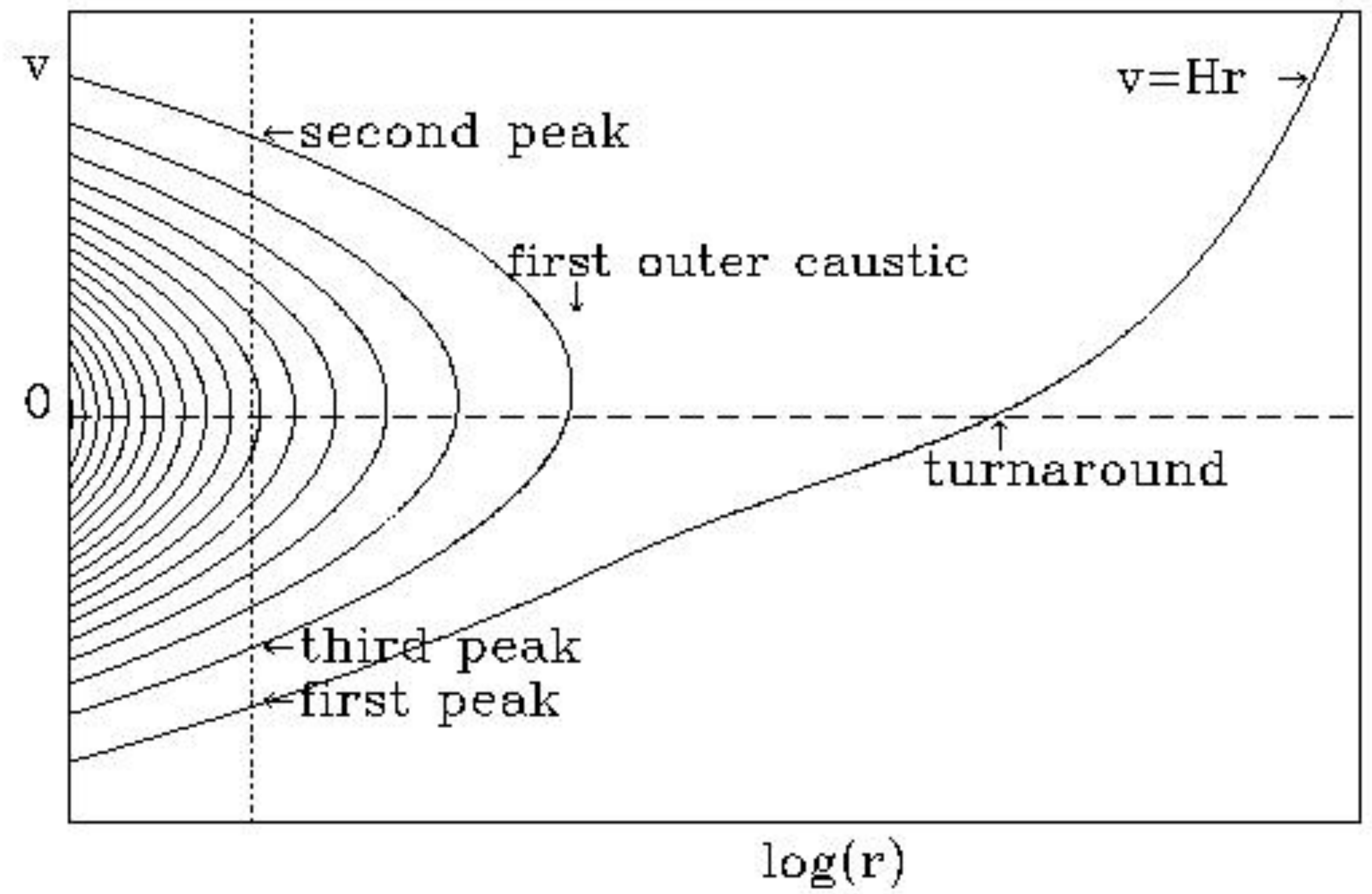


Figure 7-23. Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

Phase space structure of spherically symmetric halos



Galactic halos have inner caustics as well as outer caustics.

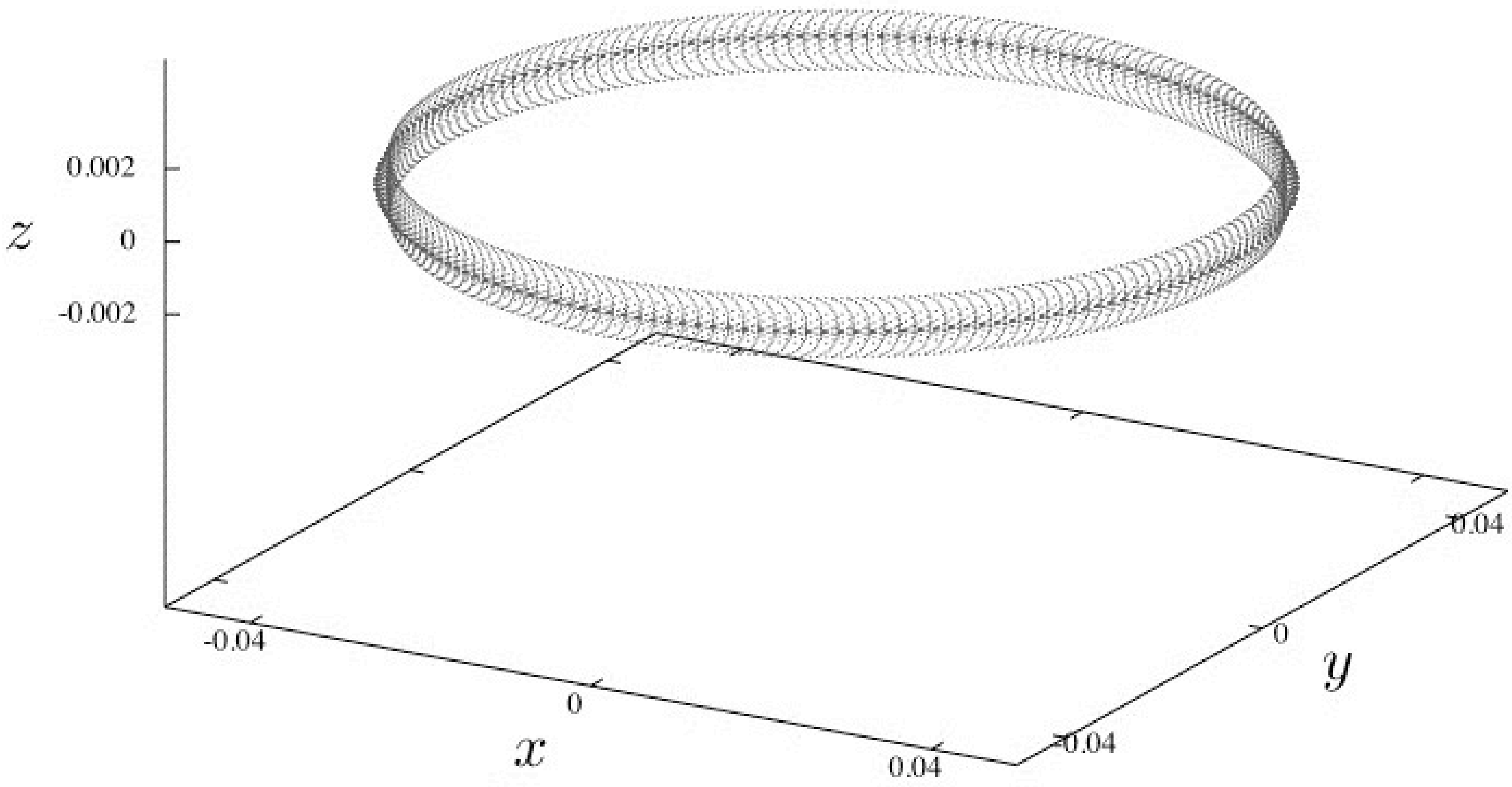
If the initial velocity field is dominated by net overall rotation, the inner caustic is a ‘tricusp ring’.

If the initial velocity field is irrotational, the inner caustic has a ‘tent-like’ structure.

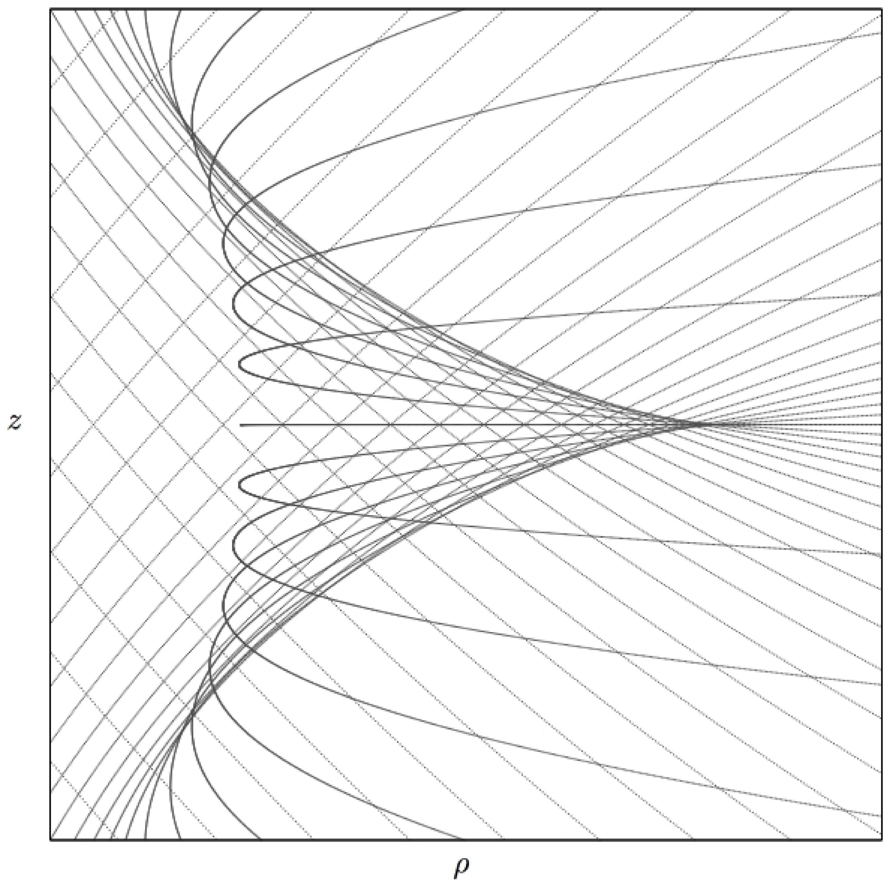
(Arvind Natarajan and PS, 2005).

simulations by Arvind Natarajan

in case of net overall rotation



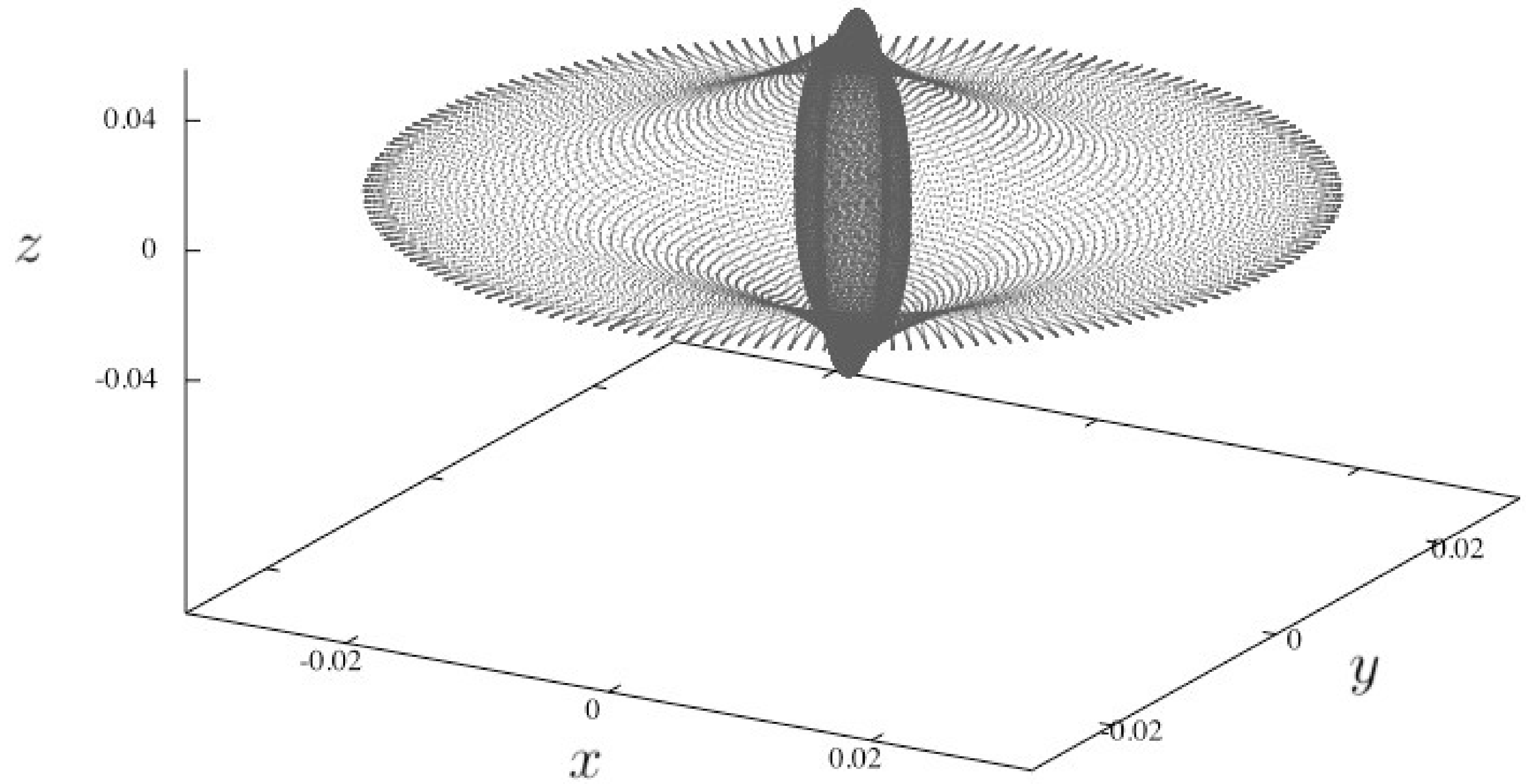
The caustic ring cross-section



D_{-4}

an elliptic umbilic catastrophe

in case of irrotational flow



On the basis of the self-similar infall model (Filmore and Goldreich, Bertschinger) with angular momentum (Tkachev, Wang + PS), the caustic rings were predicted to be

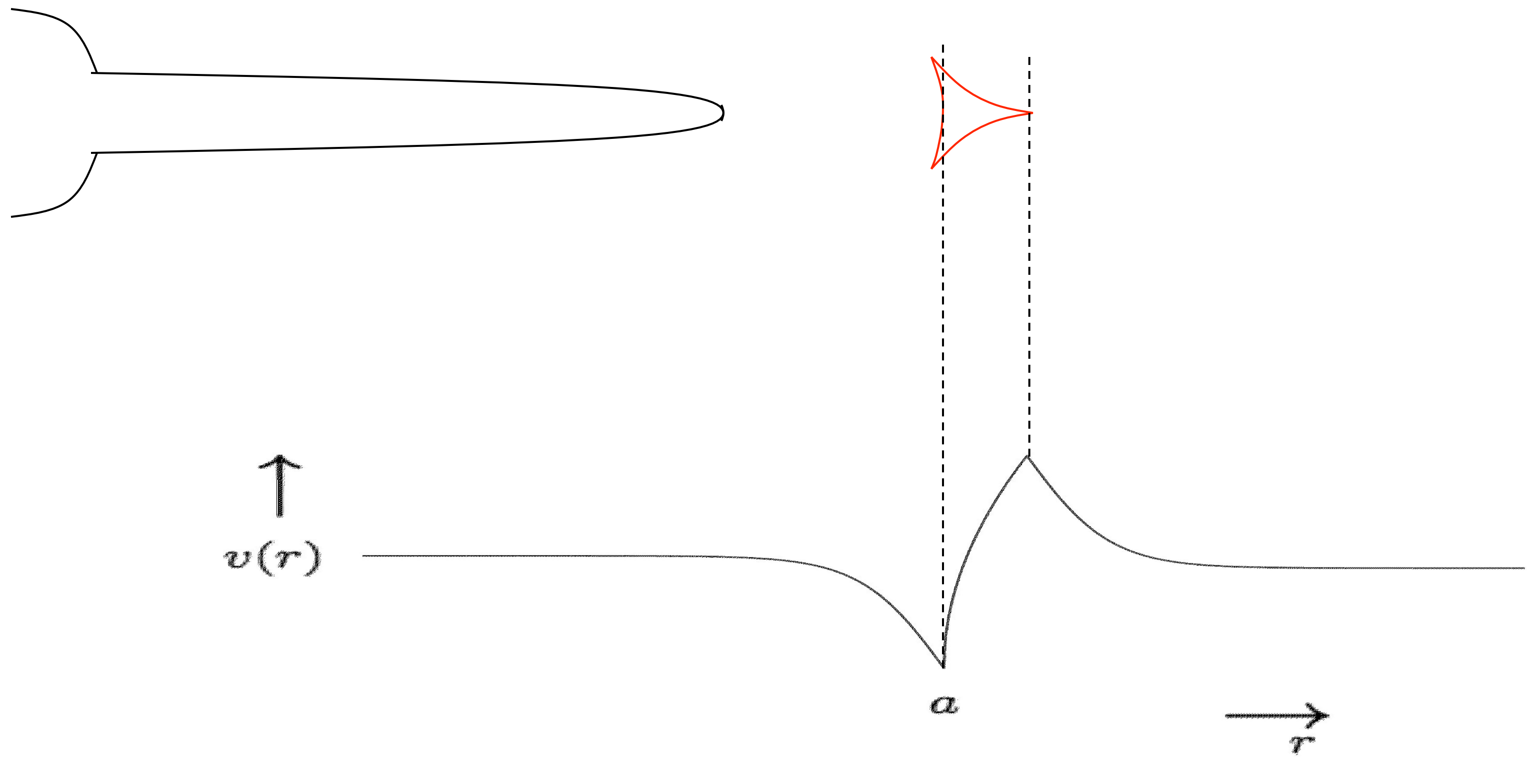
in the galactic plane

with radii $(n = 1, 2, 3 \ldots)$

$$a_n = \frac{40\text{kpc}}{n}\left(\frac{v_{rot}}{220\text{km/s}}\right)\left(\frac{j_{max}}{0.18}\right)$$

$j_{max} \cong 0.18$ was expected for the Milky Way halo from the effect of angular momentum on the inner rotation curve.

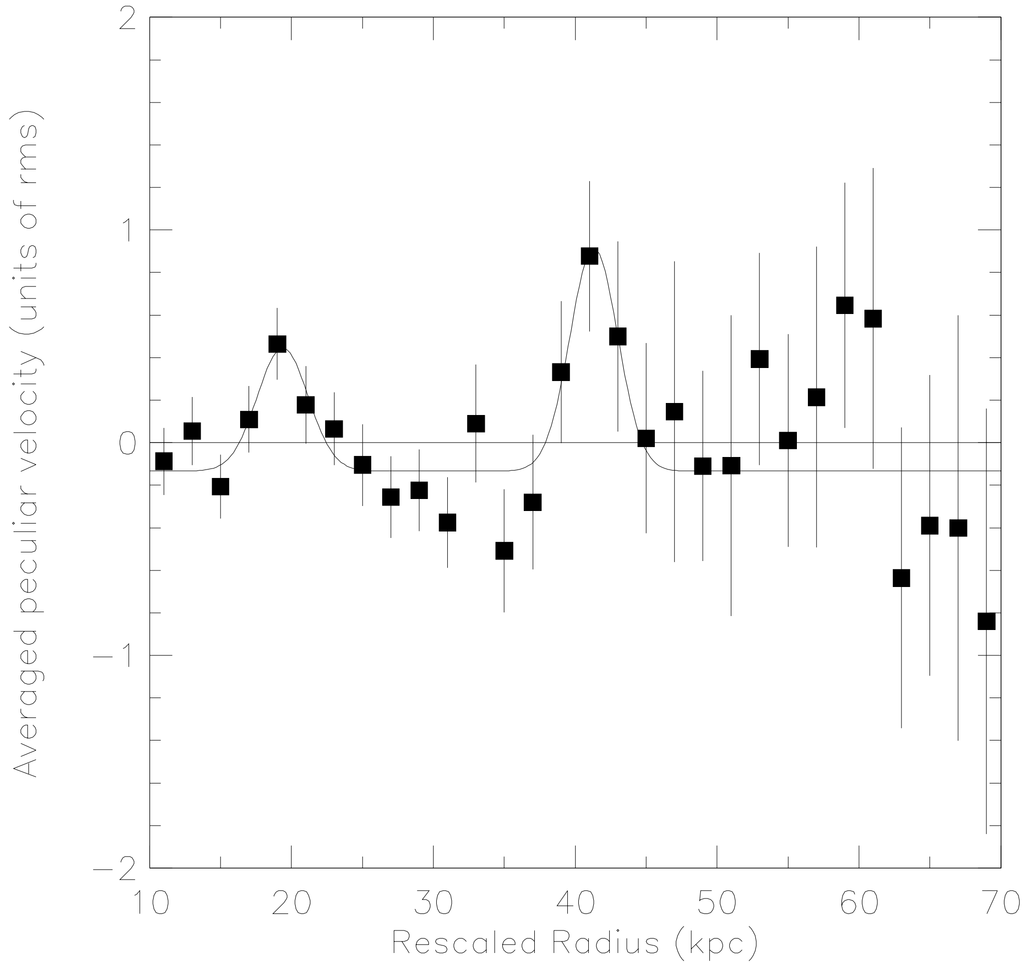
Effect of a caustic ring of dark matter upon the galactic rotation curve



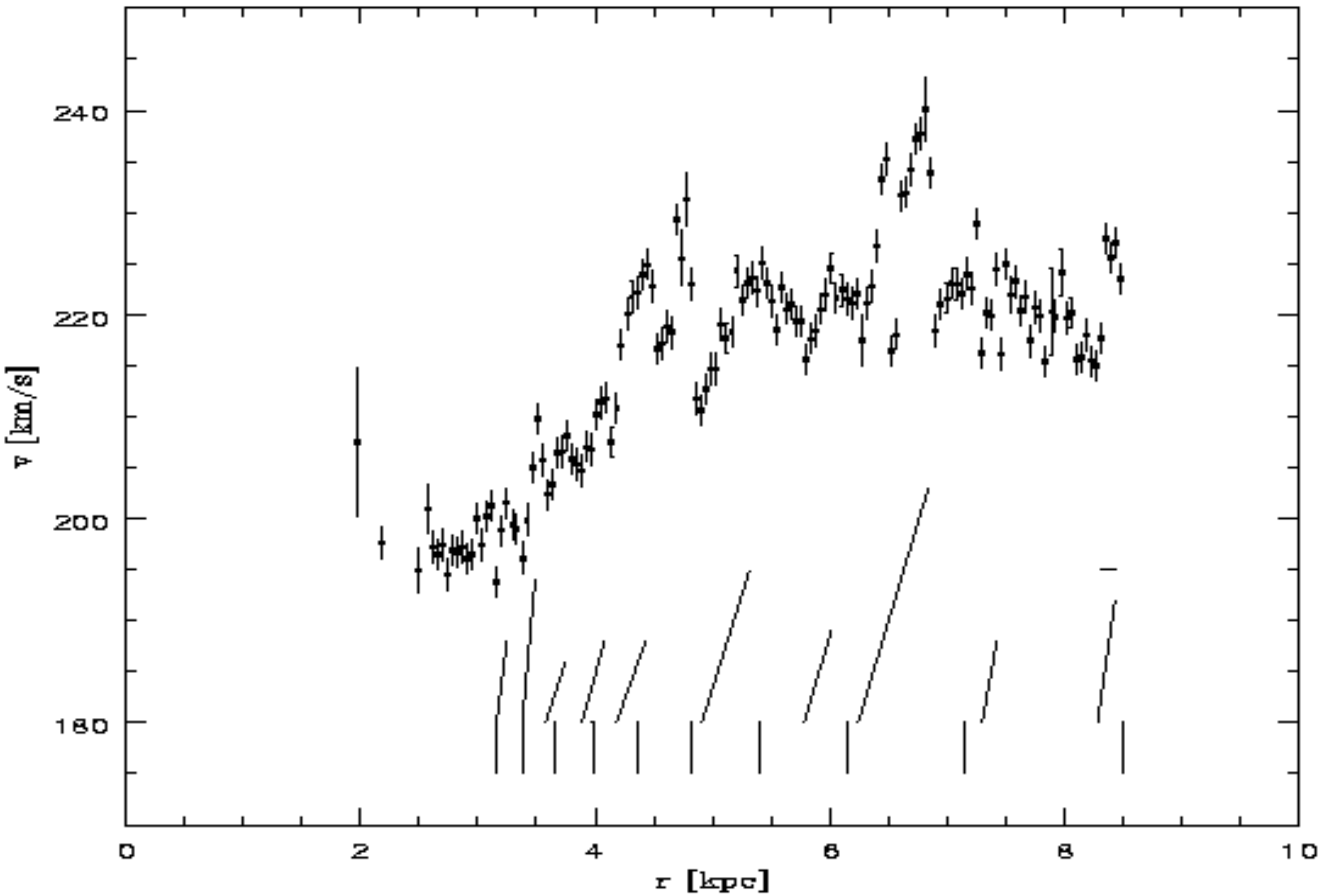
Composite rotation curve
(W. Kinney and PS, astro-ph/9906049)

- combining data on 32 well measured extended external rotation curves

- scaled to our own galaxy

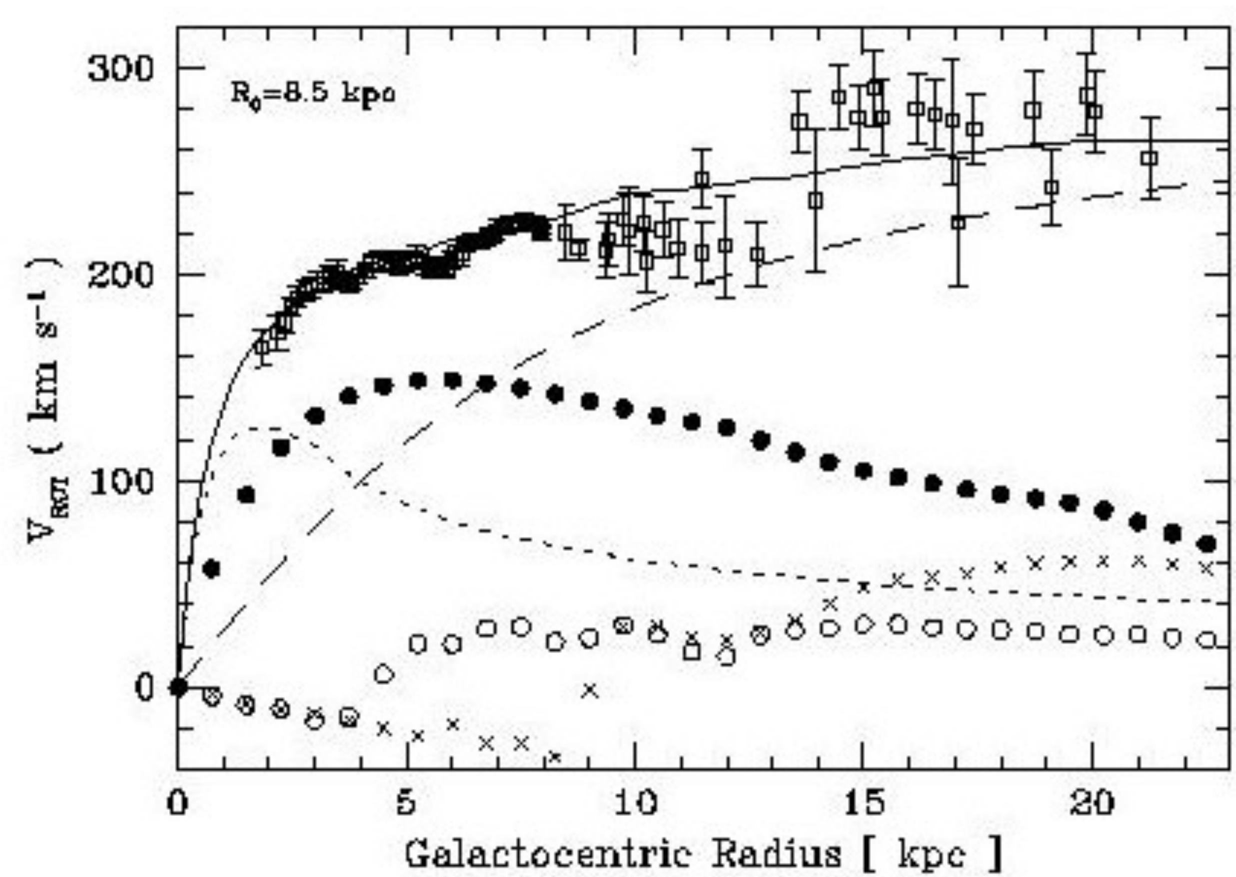


Inner Galactic rotation curve



from Massachusetts-Stony Brook North Galactic Pane CO Survey (Clemens, 1985)

Outer Galactic rotation curve



R.P. Olling and M.R. Merrifield, MNRAS 311 (2000) 361

Monoceros Ring of stars

H. Newberg et al. 2002; B. Yanny et al., 2003; R.A. Ibata et al., 2003;
H.J. Rocha-Pinto et al, 2003; J.D. Crane et al., 2003; N.F. Martin et al., 2005

in the Galactic plane

at galactocentric distance $r\ ;\ 20\,\mathrm{kpc}$

appears circular, actually seen for $100^0 < l < 270^0$

scale height of order 1 kpc

velocity dispersion of order 20 km/s

may be caused by the n = 2 caustic ring of dark matter (A. Natarajan and P.S. ’07)

Rotation curve of Andromeda Galaxy

from L. Chemin, C. Carignan & T. Foster, arXiv: 0909.3846

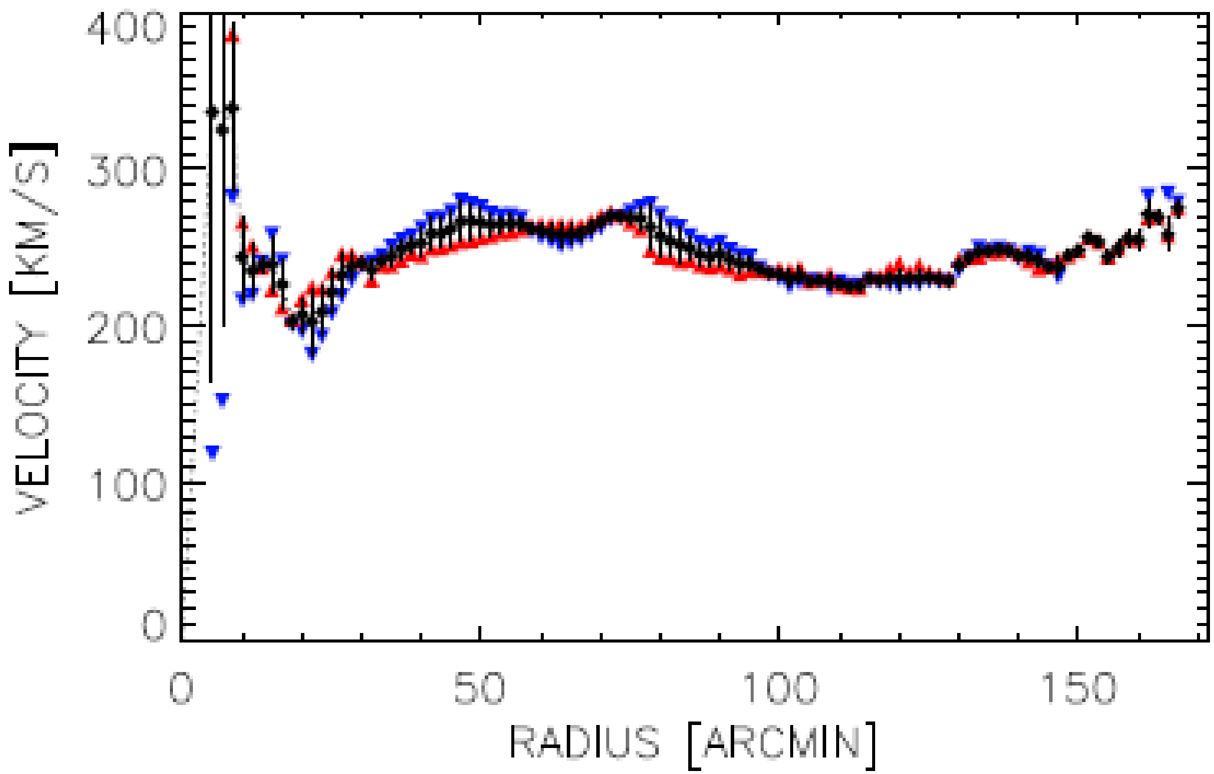
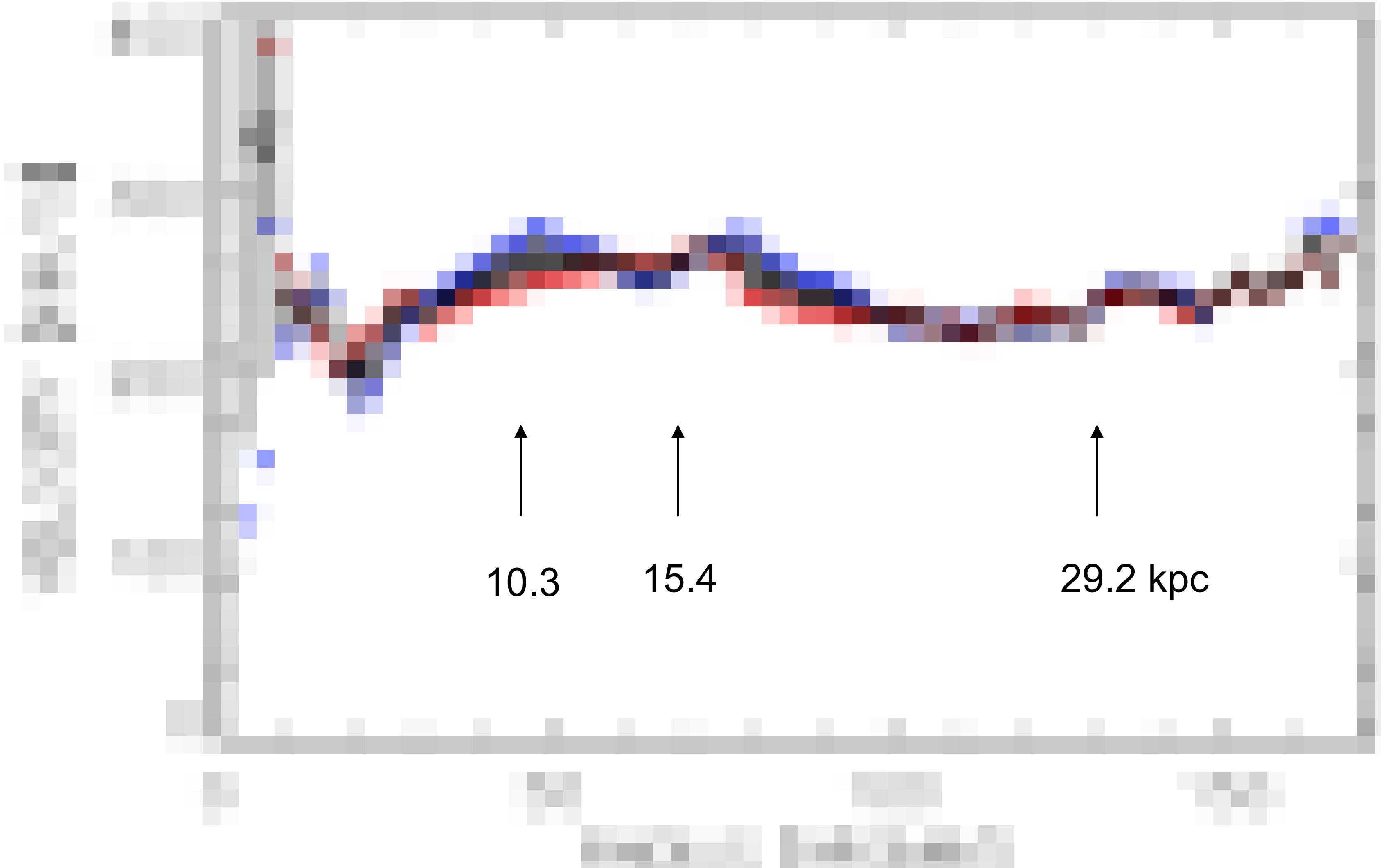


FIG. 10.— HI rotation curve of Messier 31. Filled diamonds are for both halves of the disc fitted simultaneously while blue downward/red upward triangles are for the approaching/receding sides fitted separately (respectively).



10 arcmin = 2.2 kpc

The caustic ring halo model assumes

L. Duffy & PS
PRD78 (2008) 063508

- net overall rotation
- axial symmetry
- self-similarity

The specific angular momentum distribution on the turnaround sphere

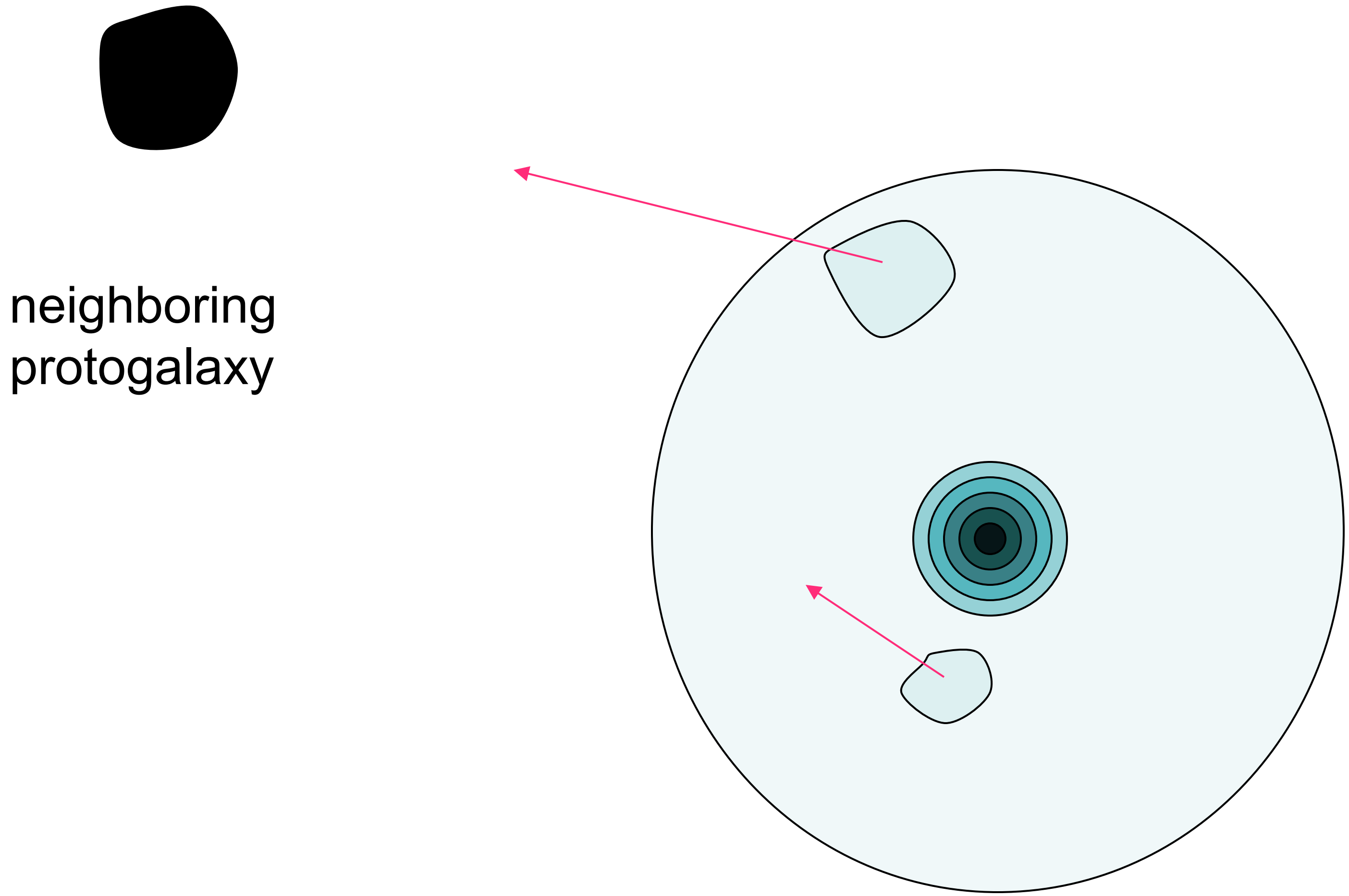
$$\vec{l}(\hat{n},t) = j_{\max}\ \hat{n}\times(\hat{z}\times\hat{n})\ \frac{R(t)^2}{t}$$

$$R(t) \propto t^{\frac{2}{3}+\frac{2}{9\varepsilon}}$$

$$0.25 < \varepsilon < 0.35$$

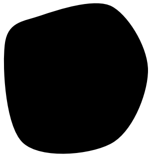
Is it plausible in the context of tidal torque theory?

Tidal torque theory

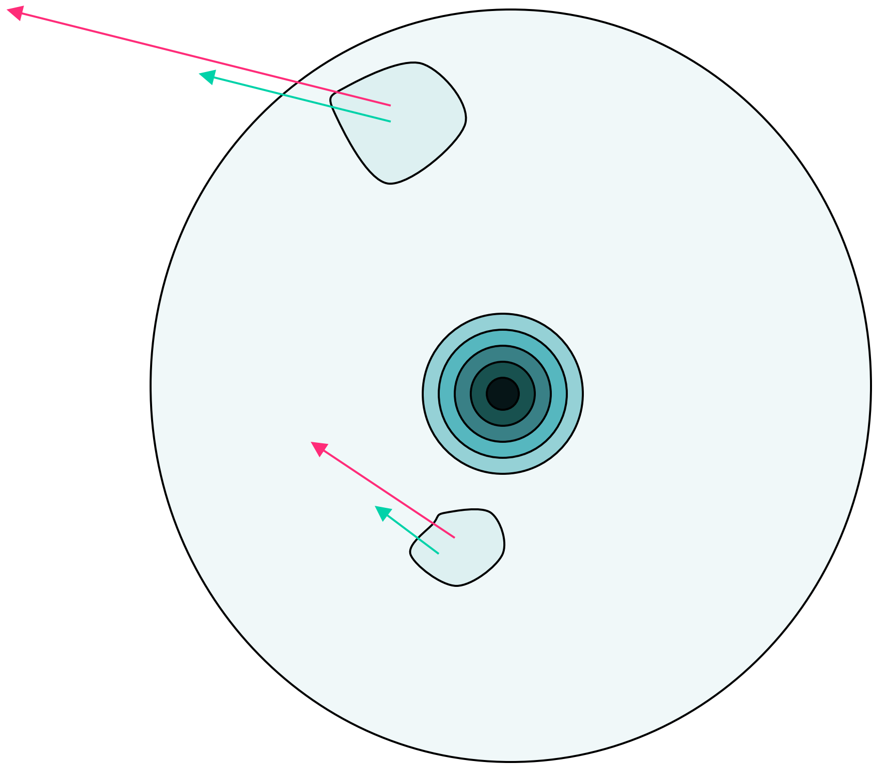


Stromberg 1934; Hoyle 1947; Peebles 1969, 1971

Tidal torque theory with ordinary CDM



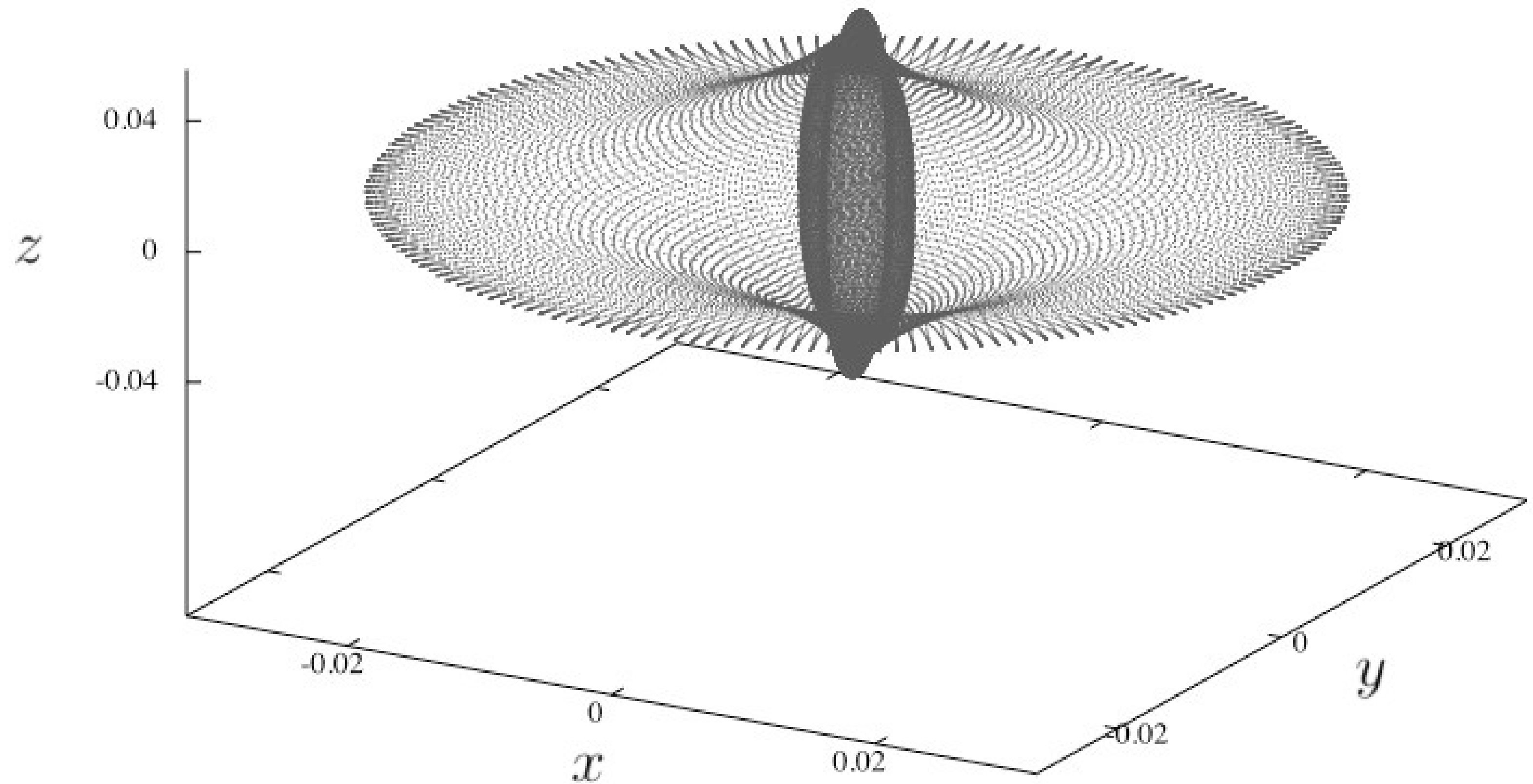
neighboring protogalaxy



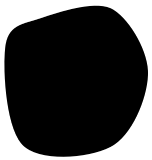
$$\vec{\nabla} \times \vec{v} = 0$$

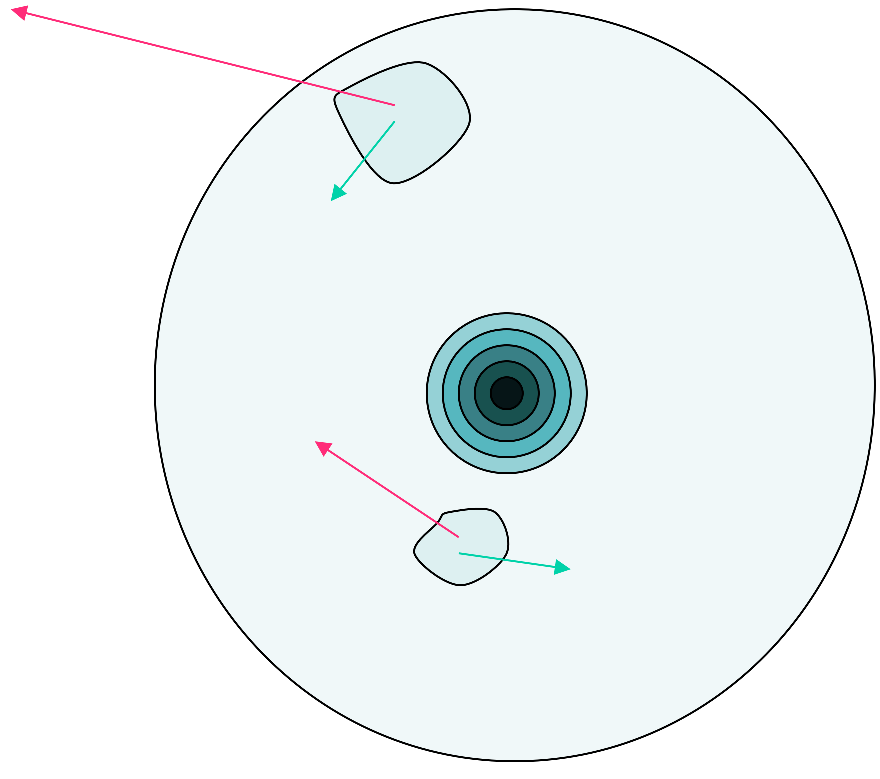
the velocity field remains irrotational

in case of irrotational flow



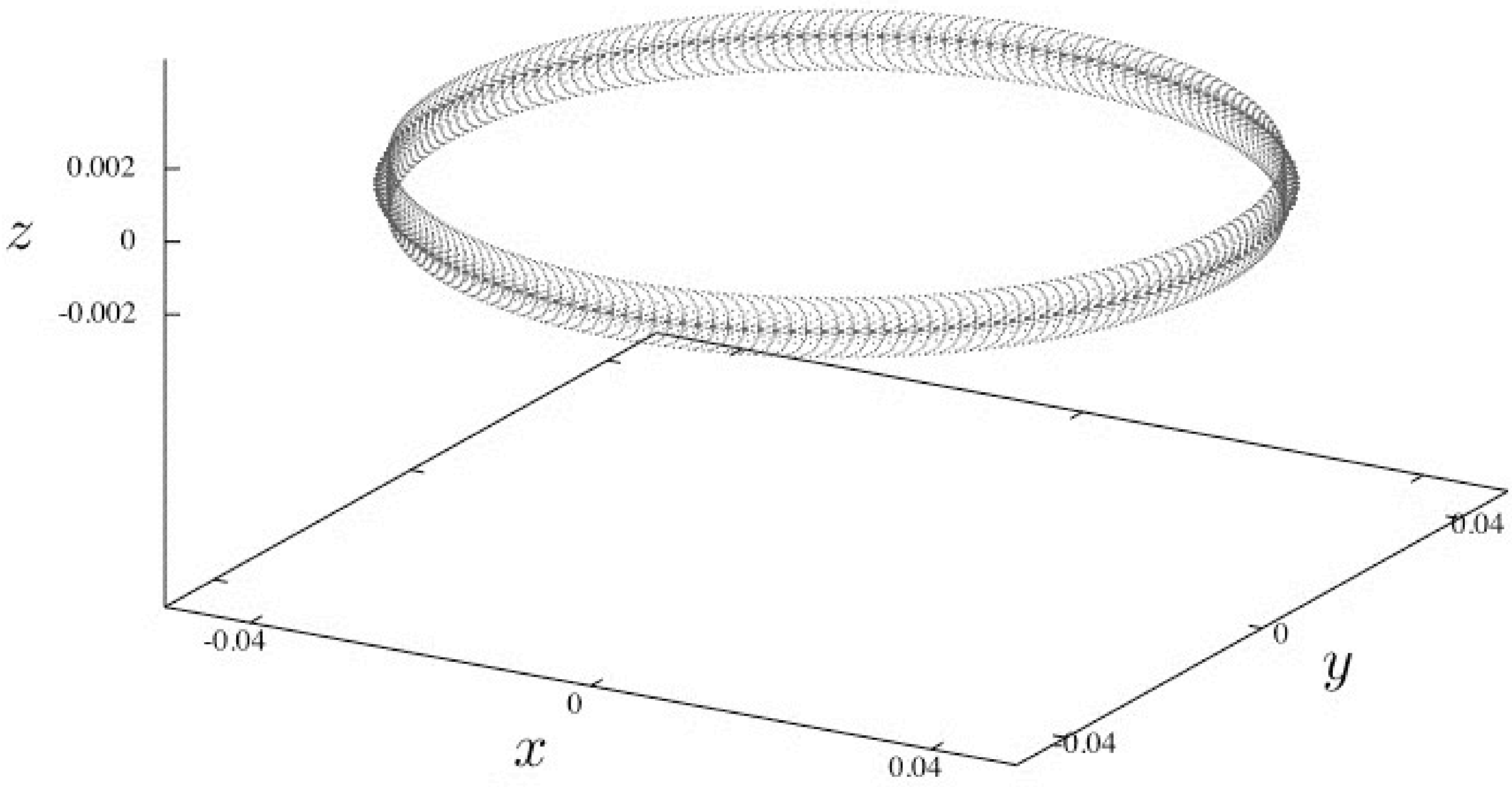
Tidal torque theory with axion BEC





$$\vec{\nabla} \times \vec{v} \neq 0$$

net overall rotation is obtained because, in the lowest energy state, all axions fall with the same angular momentum in case of net overall rotation



The specific angular momentum distribution on the turnaround sphere

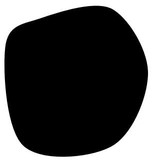
$$\vec{l}(\hat{n},t) = j_{\max}\ \hat{n}\times(\hat{z}\times\hat{n})\ \frac{R(t)^2}{t}$$

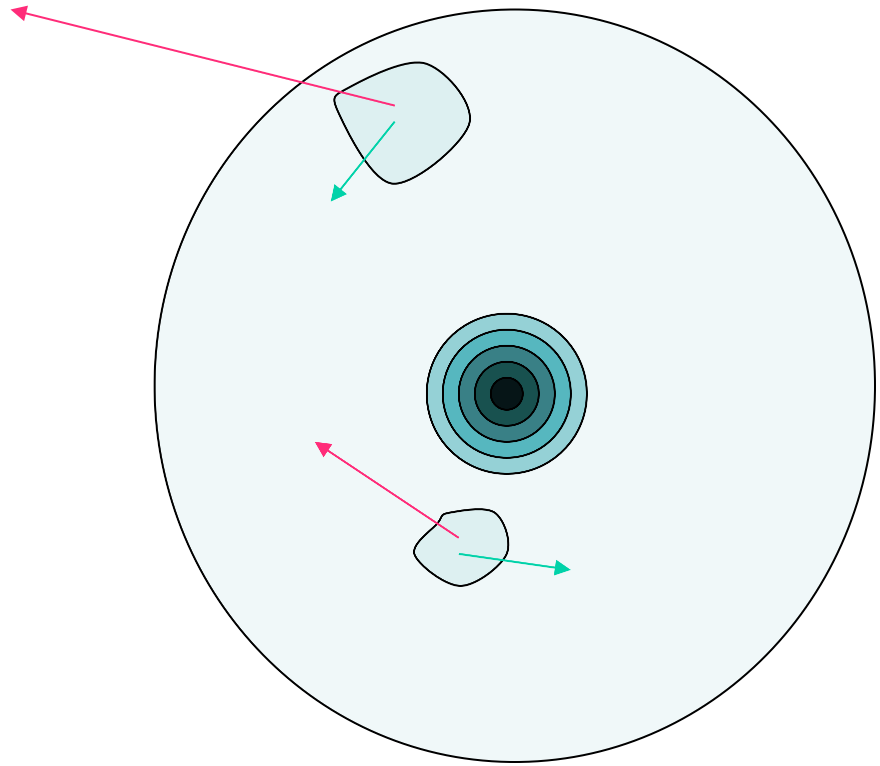
$$R(t) \propto t^{\frac{2}{3}+\frac{2}{9\varepsilon}}$$

$$0.25 < \varepsilon < 0.35$$

Is it plausible in the context of tidal torque theory?

Tidal torque theory with axion BEC





$$\vec{\nabla} \times \vec{v} \neq 0$$

net overall rotation is obtained because, in the lowest energy state, all axions fall with the same angular momentum

Magnitude of angular momentum

$$\lambda = \frac{L\,|E|^{\frac{1}{2}}}{G\,M^{\frac{5}{2}}} = \sqrt{\frac{6}{5-3\varepsilon}}\;\frac{8}{10+3\varepsilon}\;\frac{1}{\pi}\;j_{\max}$$

$\lambda \approx 0.05$

$j_{\max} \simeq 0.18$

G. Efstathiou et al. 1979, 1987

from caustic rings

fits perfectly ($0.25 < \varepsilon < 0.35$)

The specific angular momentum distribution on the turnaround sphere

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$$R(t) \propto t^{\frac{2}{3}+\frac{2}{9\varepsilon}}$$

$$0.25 < \varepsilon < 0.35$$

Is it plausible in the context of tidal torque theory?

Self-Similarity

$$\vec{\tau}(t) = \int_{V(t)} d^3 r \;\; \delta\rho(\vec{r},t) \;\; \vec{r} \times (-\vec{\nabla}\phi(\vec{r},t))$$

a comoving volume

$$\vec{r} = a(t)\,\vec{x}$$

$$\phi(\vec{r} = a(t)\,\vec{x},\; t) = \phi(\vec{x})$$

$$\delta(\vec{r},t) \equiv \frac{\delta\rho(\vec{r},t)}{\rho_0(t)}$$

$$\delta(\vec{r} = a(t)\,\vec{x},\; t) = a(t)\,\delta(\vec{x})$$

$$\vec{\tau}(t) = \rho_0(t)\,a(t)^4 \int_V d^3x \;\; \delta(\vec{x}) \;\; \vec{x} \times (-\vec{\nabla}_x\,\phi(\vec{x}))$$

Self-Similarity (yes!)

$$\vec{\tau}(t) \propto \hat{z}\, a(t) \propto \hat{z}\; t^{\frac{2}{3}}$$

$$\vec{L}(t) \propto \hat{z}\; t^{\frac{5}{3}}$$

time-independent axis of rotation

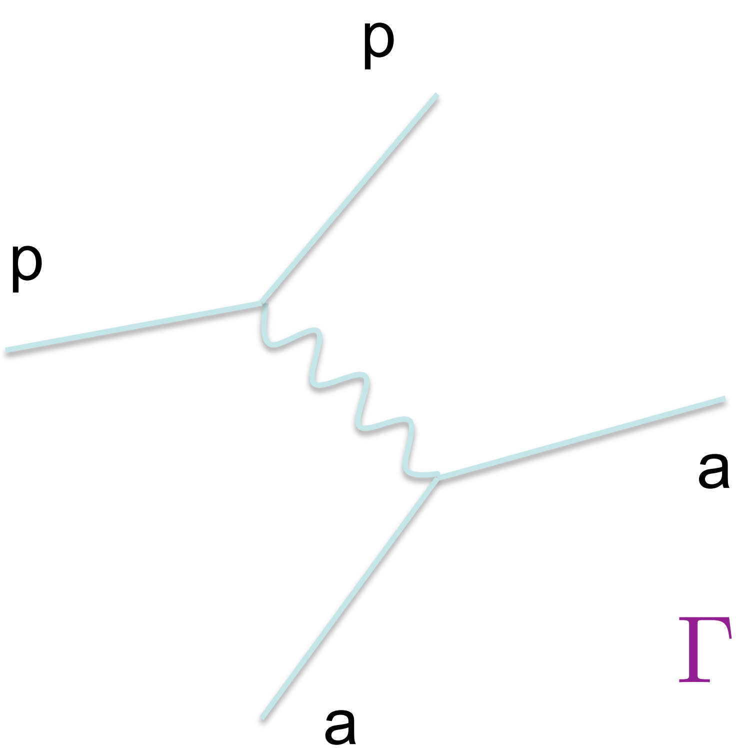
$$\vec{l}(\hat{n},t) \propto \frac{R(t)^2}{t} \propto t^{\frac{1}{3}+\frac{4}{9\varepsilon}} = t^{\frac{5}{3}}$$

provided $\varepsilon = 0.33$

Conclusion:

The dark matter looks like axions

Baryons and photons may enter into thermal contact with the axions by gravitational interactions as well



p may be any species of particle

$$\Gamma \sim 4\pi G\, n\, m\, \ell\, \frac{\omega}{\Delta p}$$

O. Erken, PS, H.Tam and Q. Yang, PRL 108 (2012) 061304

Relativistic axion modes and photons reach thermal contact with the cold axions if the cold axion correlation length reaches horizon size by the time of equality

$$\frac{\Gamma_{r,\gamma}}{H(t)} \sim 8\pi G\; n\; m\; \ell(t)\; t$$

$$\propto \quad a(t) \qquad \text{for} \quad t < t_{eq}$$

$$\sim \quad \frac{\ell(t_{eq})}{t_{eq}} \qquad \text{at} \quad t = t_{eq}$$

$$= \quad \text{constant} \qquad \text{for} \qquad t > t_{eq}$$

If photons, baryons and axions all reach the same temperature before decoupling

photons cool

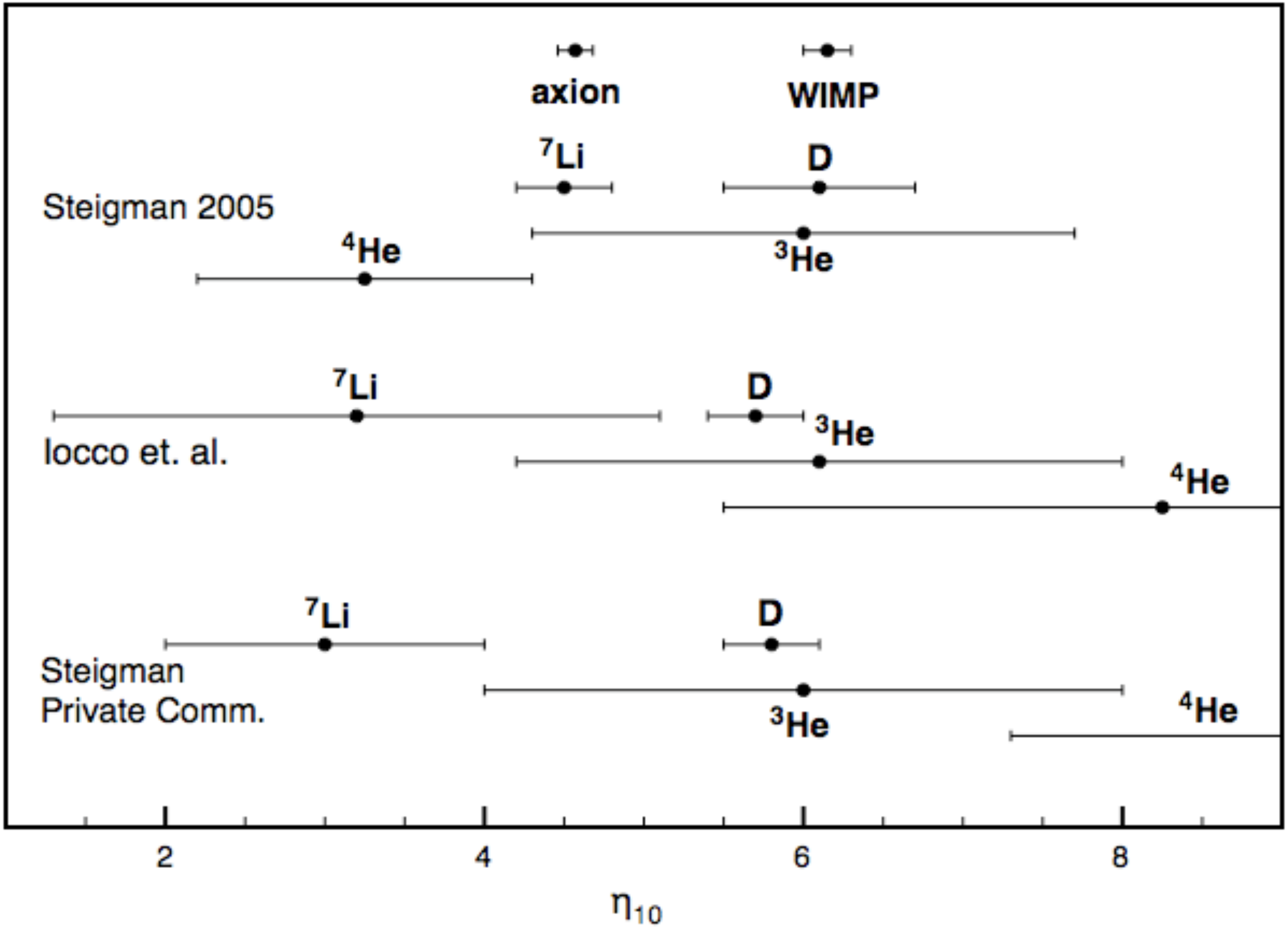
$$T_{\gamma,\mathrm{f}} \;=\; 0.904\, T_{\gamma,\mathrm{i}}$$

baryon to photon ratio

$$\eta_{\mathrm{BBN}} \;=\; 0.738\, \eta_{\mathrm{WMAP}}$$

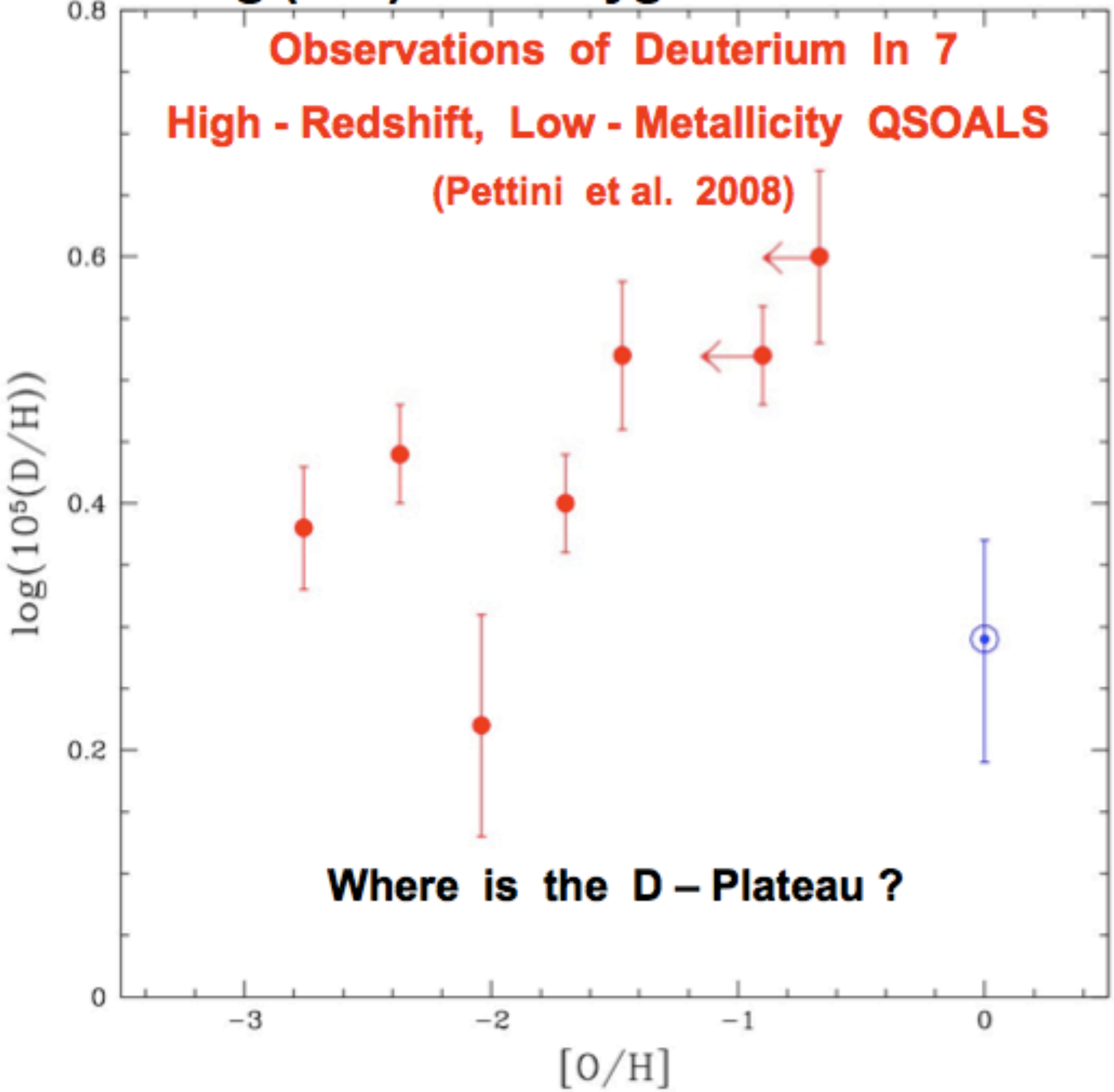
effective number of neutrinos

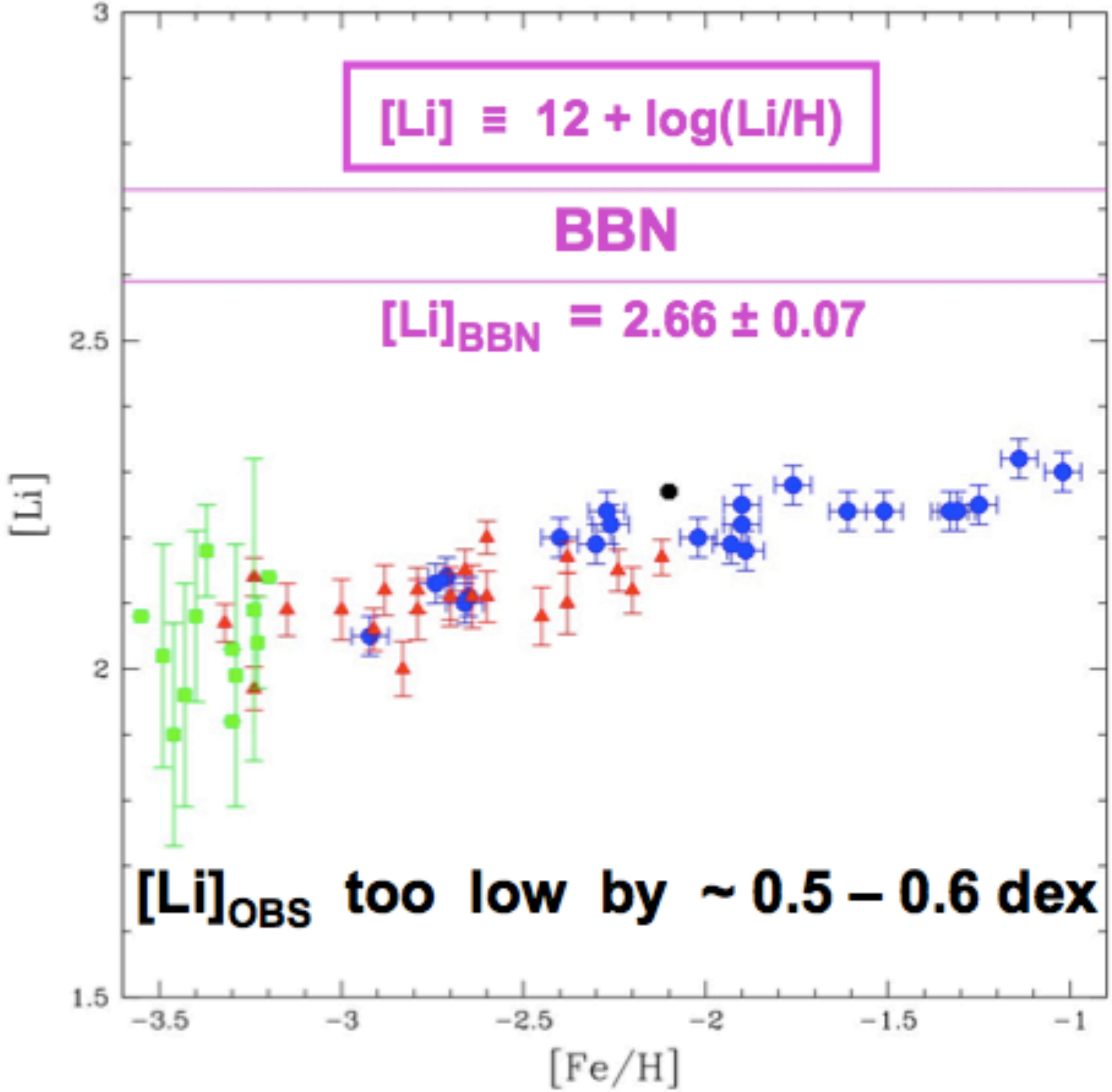
$$N_{\nu,\mathrm{eff}} \;=\; 6.7$$



axion
WIMP
Steigman 2005
7Li
D
4He
3He
Iocco et. al.
7Li
D
3He
4He
Steigman
Private Comm.
7Li
D
3He
4He
2
4
6
8
η10

log (D/H) vs. Oxygen Abundance





[Li] ≡ 12 + log(Li/H)
BBN
[Li]BBN = 2.66 ± 0.07
[Li]OBS too low by ~ 0.5 – 0.6 dex
[Li]
[Fe/H]
3
2.5
2
1.5
−3.5
−3
−2.5
−2
−1.5
−1

Effective number of neutrinos

$$\rho_{\rm rad} = \rho_\gamma + \rho_a + \rho_\nu$$
$$= \rho_\gamma \left[1 + N_{\rm eff} \frac{7}{8} \left(\frac{4}{11}\right)^{\frac{4}{3}}\right]$$

$$N_{\rm eff} = 6.7$$

WMAP 7 year: 4.34 ± 0.87 (68% CL)

J. Hamann et al. (SDSS): 4.8 ± 2.0 (95% CL)

Atacama Cosmology Telescope: 5.3 ± 1.3 (68% CL) we will see …