Axions explain the formation of supermassive black holes at cosmic dawn

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COSMIC WISPers Meeting

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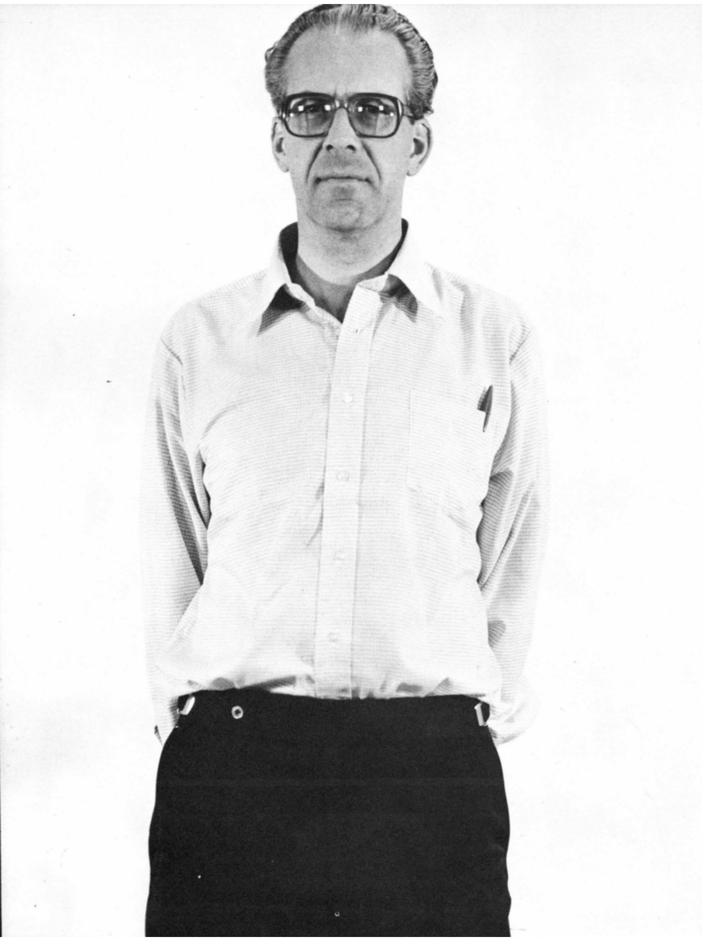
Maarten Schmidt (1929 – 2022)



in 1963, discovered 3C273

the first known quasar
(quasi-stellar object)

at redshift $z = 0.158$

Active Galactic Nuclei (AGN)

including Quasrs, Blazars, ...

are powerful emitters, with luminosities $\sim 10^{13} L_\odot$

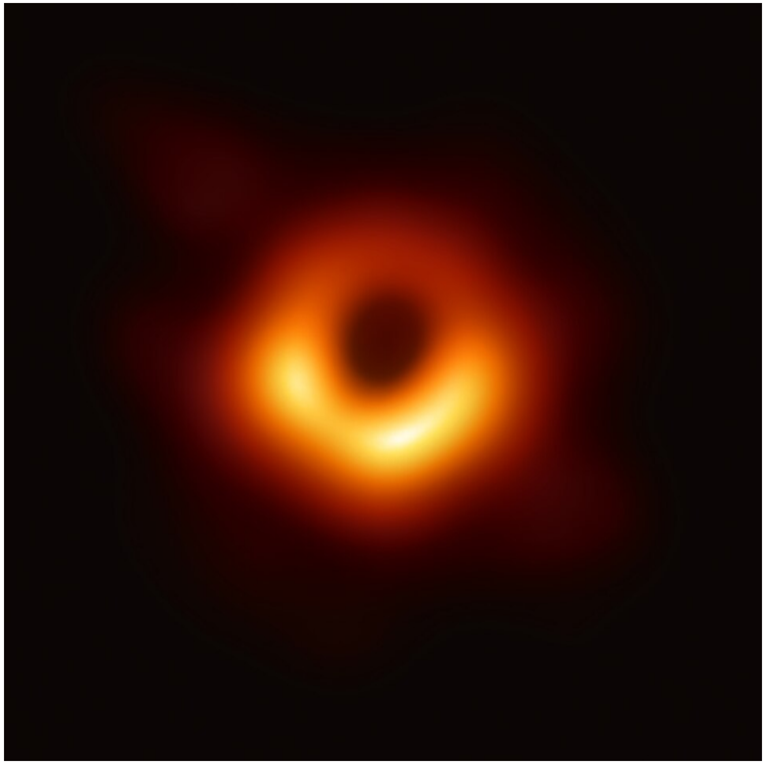
yet variable on short time sclaes (as short as a few hours) and therefore of relatively small spatial extent

They are powered by accretion onto supermassive black holes

Wikipedia's list of supermassive black holes has

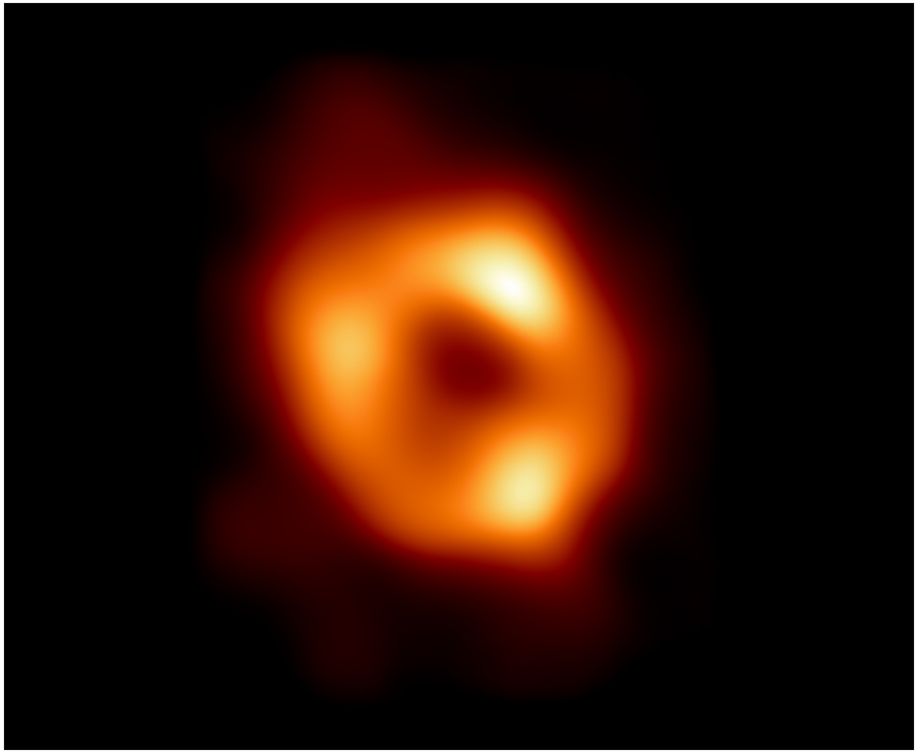
in the mass range	number of black holes
$10^{10} - 10^{11}\ M_\odot$	37
$10^{9} - 10^{10}\ M_\odot$	52
$10^{8} - 10^{9}\ M_\odot$	35
$10^{7} - 10^{8}\ M_\odot$	27
$10^{6} - 10^{7}\ M_\odot$	5

Event Horizon Telescope images of supermassive black holes



in the galaxy M87

$7 \cdot 10^9 \ M_\odot$



in the Milky Way

$4 \cdot 10^6 \ M_\odot$

The James Webb Space Telescope has revealed the existence of powerful AGN near cosmic dawn, i.e.

$$z \sim 10$$

R. Larson et al. 2023, A. Bogdan et al. 2024, R. Maiolino et al. 2023, L.J. Furtak et al. 2024.

There is too little time to grow supermassive black holes before $z = 10$

To form a black hole of mass $M_{\rm b.h.} = 10^8\ M_\odot$ from material in a region of density 10^{-25} gr/cc the region must shrink in all three space dimensions by a factor 10^9

(like squeezing all of Bulgaria into a 1 mm cube volume)

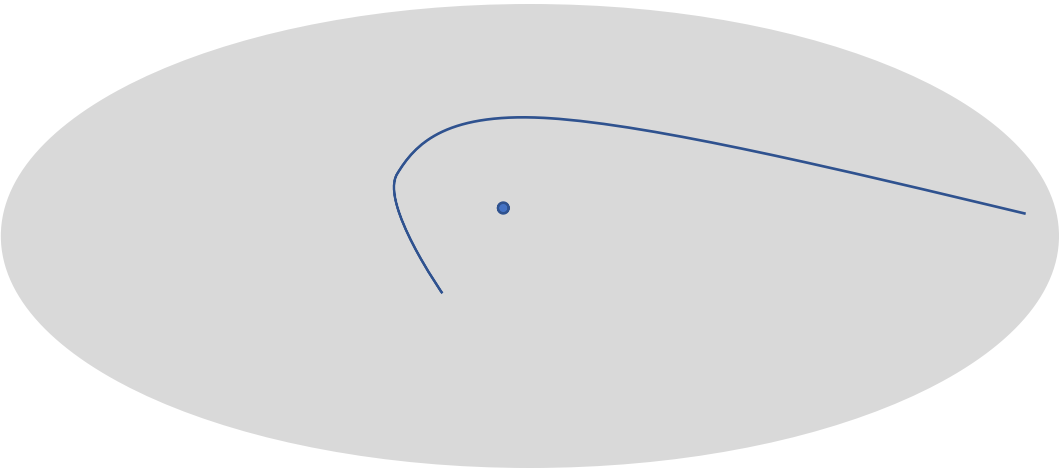
Is this possible?

Apparently so, since it happens!

Angular momentum introduces a distance of closest approach to the center of the overdensity

$$r_{\min} = \frac{L^2}{2GM} + \mathcal{O}(L^4)$$

$L = r v_\perp$ is angular momentum per unit mass



Galactic spin parameter

$$\lambda = \frac{LE^{\frac{1}{2}}}{GM^{\frac{3}{2}}}$$

Peebles 1969

$$0.01 \lesssim \lambda \lesssim 0.18$$

Efstathiou & Jones, 1979

Barnes & Efstathiou, 1987

$$r_{\mathrm{min}} \sim \lambda^2 R >> 10^{-9} R$$

- Angular momentum can be transported outward in case the material forming the black hole has friction, e..g.

gas review by Inayoshi, Visbal & Haiman, 2020

dark matter with strong self-interactions $>> \mathrm{cm}^2/\mathrm{gr}$

Balberg & Shapiro, 2002

Steinhardt & Spergel, 2015, Feng, Yu & Zhong, 2021

- The friction heats up the material and causes it to acquire pressure opposing its compression

Supermassive black hole formation in the initial collapse of axion dark matter

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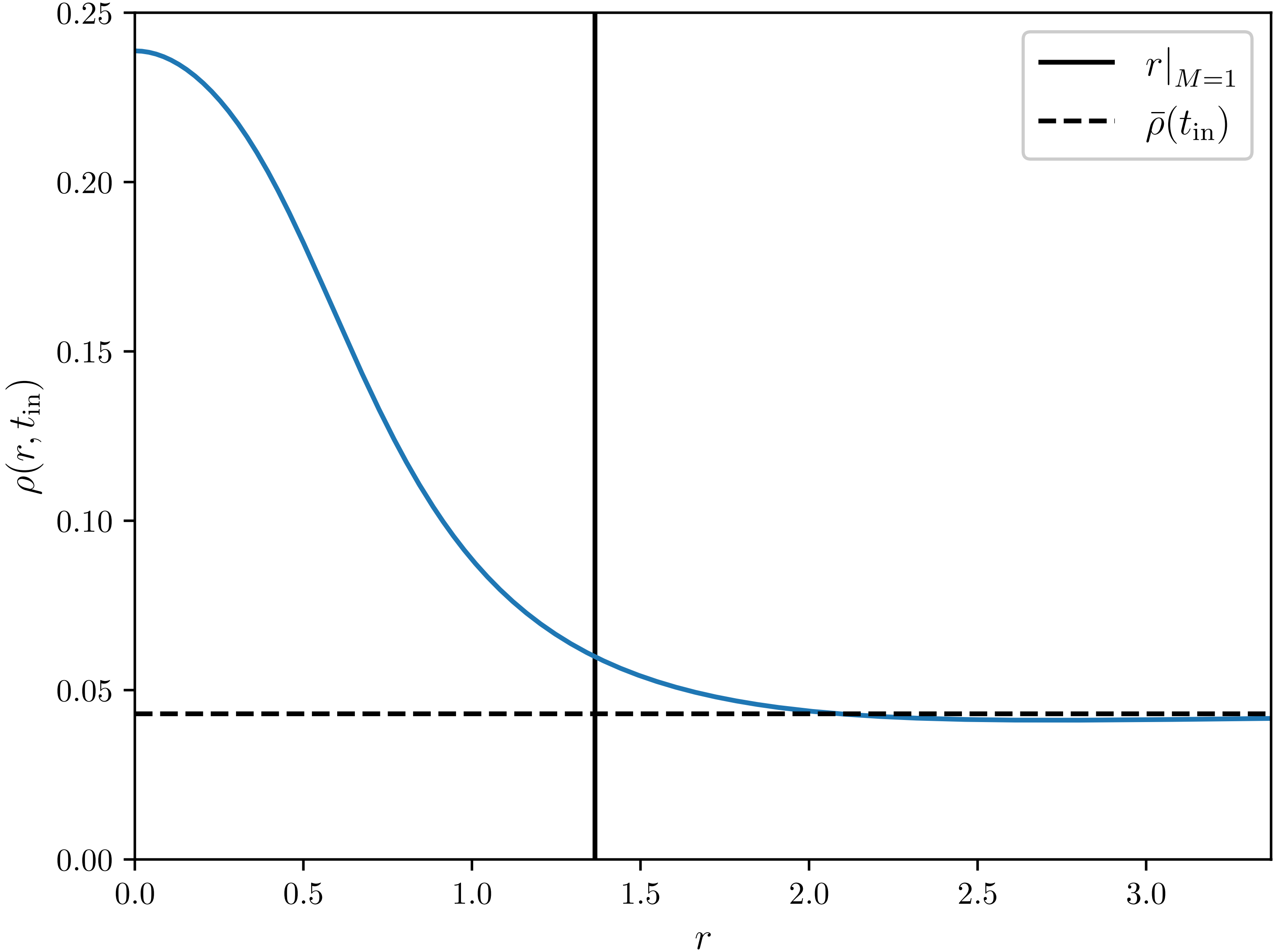
(Dated: July 14, 2024)

Abstract

Axion dark matter thermalizes by gravitational self-interactions and forms a Bose-Einstein condensate. We show that the rethermalization of the axion fluid during the initial collapse of large scale overdensities near cosmic dawn transports angular momentum outward sufficientlly fast that black holes form with masses ranging from approximately 10^5 to a few times 10^{10} $M_\odot$.

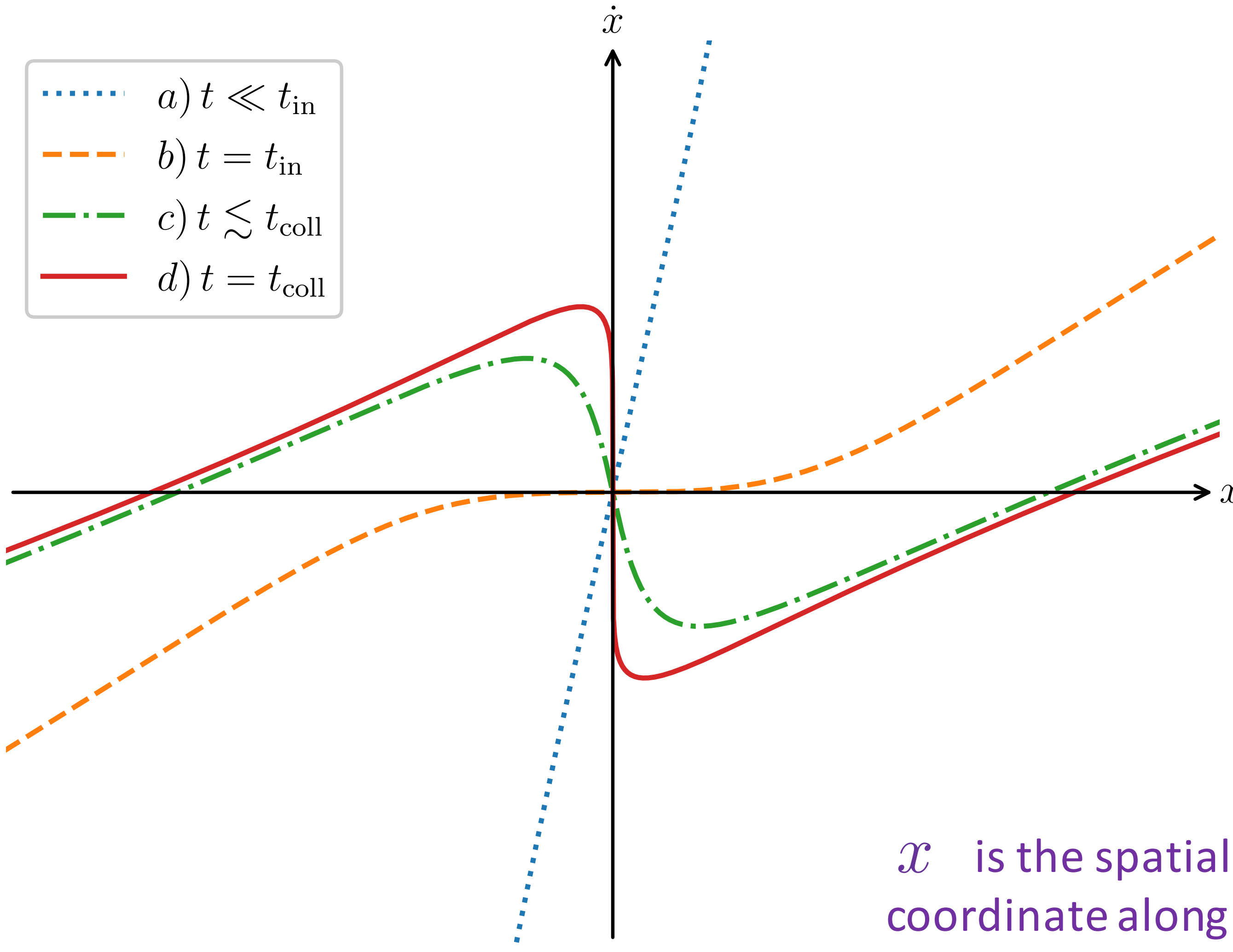
PACS numbers: 95.33.+d

arXiv: 2407.11169



$r|_{M=1}$
$\bar{\rho}(t_{\rm in})$
0.25
0.20
0.15
0.10
0.05
0.00
$\rho(r, t_{\rm in})$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
r

Phase space evolution



x is the spatial coordinate along an arbitrary direction through the overdensitty

The dark matter axion fluid is a highly degenerate Bose system

The fluctuations in such systems are generically large

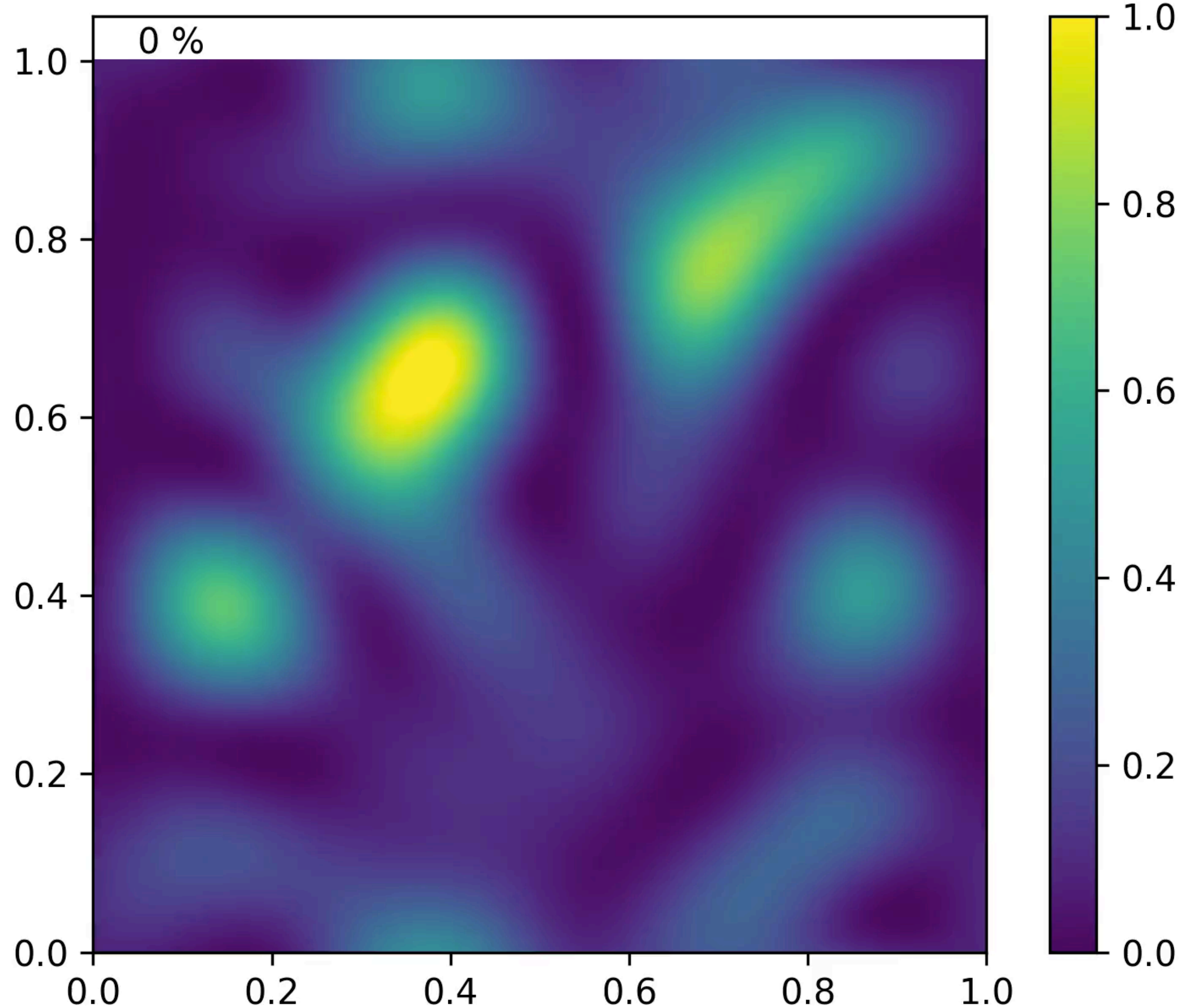
$$\delta\rho \simeq \rho$$

A. Einstein, 1909
......
R. Dicke, 1954
E. Purcell, 1956
.....

and correlated over distances of order

$$\ell \simeq \frac{\hbar}{m\,\delta v}$$

simulation by Yuxin Zhao



Cold Dark Matter (ordinary CDM)

In the linear regime of structure formation, before multi-streaming begins

$$\rho(\vec{x},t) = m\; n(\vec{x},t) \qquad\qquad \vec{v}(\vec{x},t)$$

$$\partial_t n + \vec{\nabla}\cdot(n\;\vec{v}) = 0$$

$$\partial_t \vec{v} + \vec{v}\cdot\vec{\nabla}\;\vec{v} = -\vec{\nabla}\Phi(\vec{x},t)$$

gravitational potential

neglects the CDM velocity dispersion δv .

Wave Dark Matter

$$\Psi(\vec{x},t) = \sqrt{\frac{n(\vec{x},t)}{N}}\, e^{i\beta(\vec{x},t)} \qquad \vec{v} = \frac{\hbar}{m}\vec{\nabla}\beta$$

number of particles

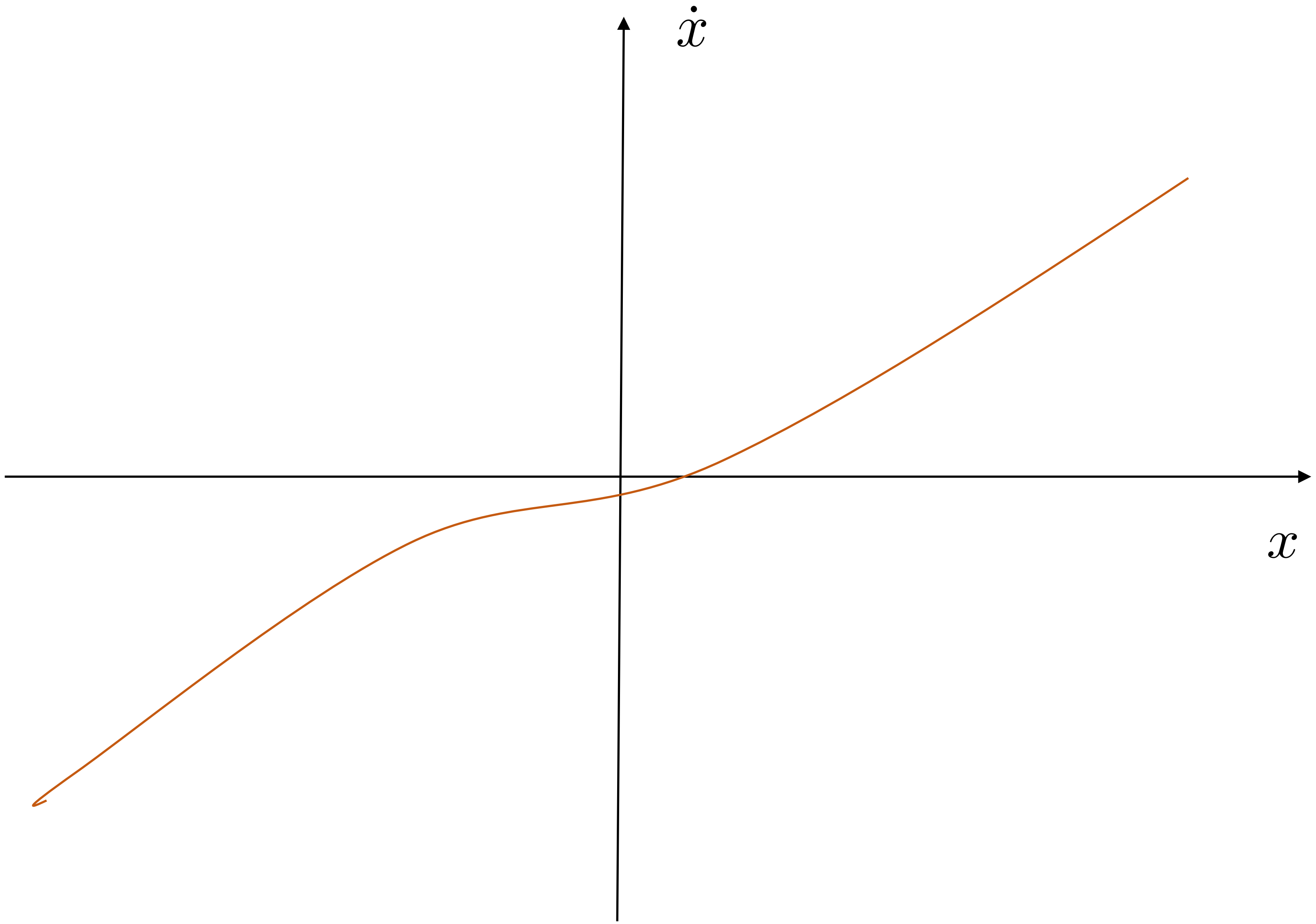
$$\partial_t \vec{v} + \vec{v}\cdot\vec{\nabla}\ \vec{v} = -\vec{\nabla}\Phi + \frac{\hbar^2}{2m^2}\vec{\nabla}\frac{\nabla^2\sqrt{n}}{\sqrt{n}}$$

negligible unless
m is very small

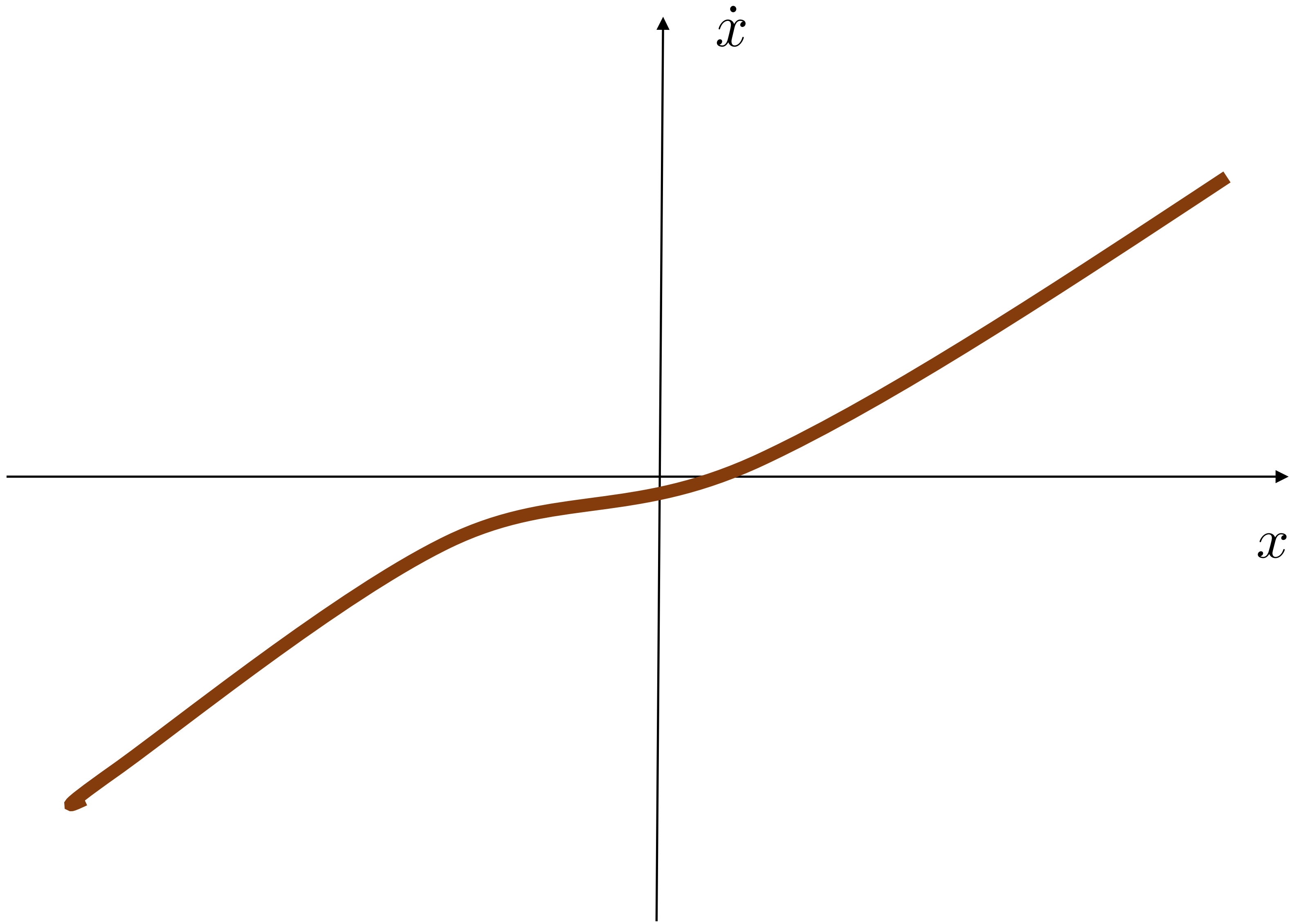
neglects the dark matter velocity dispersion δv .

Velocity dispersion, coherence length and quantum degeneracy

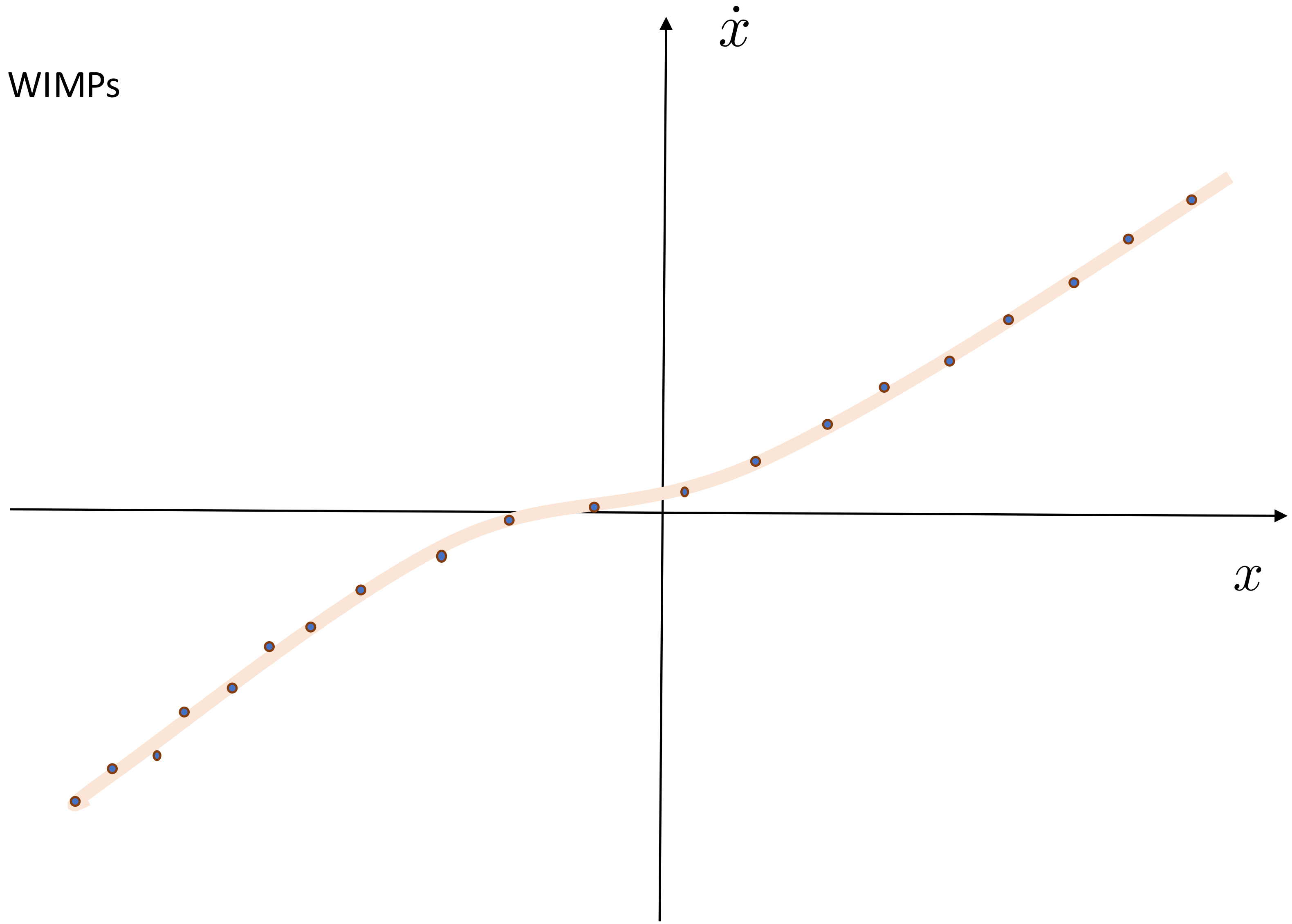
	δv	$\ell = \dfrac{\hbar}{m\,\delta v}$	$\mathcal{N} = (2\pi\ell)^3 n$
100 GeV WIMP	$10^{-12}\ c$	μm	10^{-17}
3 keV neutrino	$10^{-8}\ c$	cm	10^{-2}
micro eV axion	$10^{-17}\ c$	$10^{18}\ \text{cm}$	10^{64}



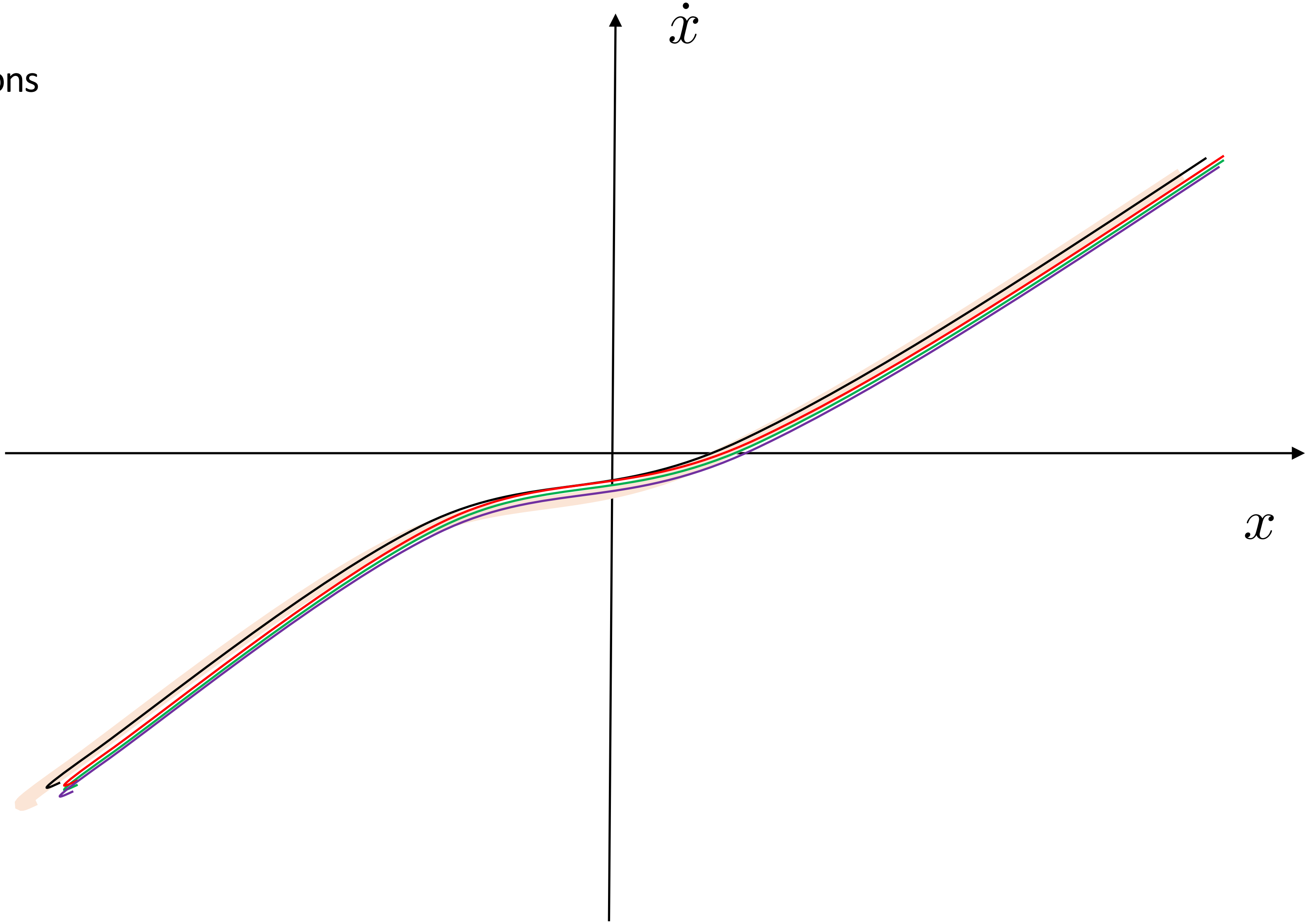
$\dot{x}$
x



$\dot{x}$
x


WIMPs
$\dot{x}$
x

Axions



$$\vec{g}(\vec{x},t) = -\vec{\nabla}\Phi(\vec{x},t)$$

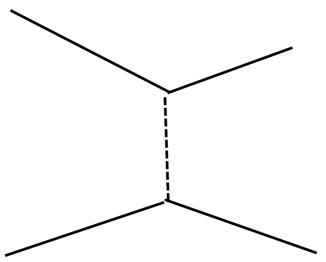
$$\vec{\nabla}\cdot\vec{g}(\vec{x},t) = -4\pi G\ m\ n(\vec{x},t) + \ldots.$$

$$\vec{\nabla}\cdot\delta\vec{g}(\vec{x},t) = -4\pi G\ m\ \delta n(\vec{x},t)$$

$$\delta g \sim 4\pi G\ m\ n\ \ell$$

The axion dark matter thermalizes through its gravitational self-interations

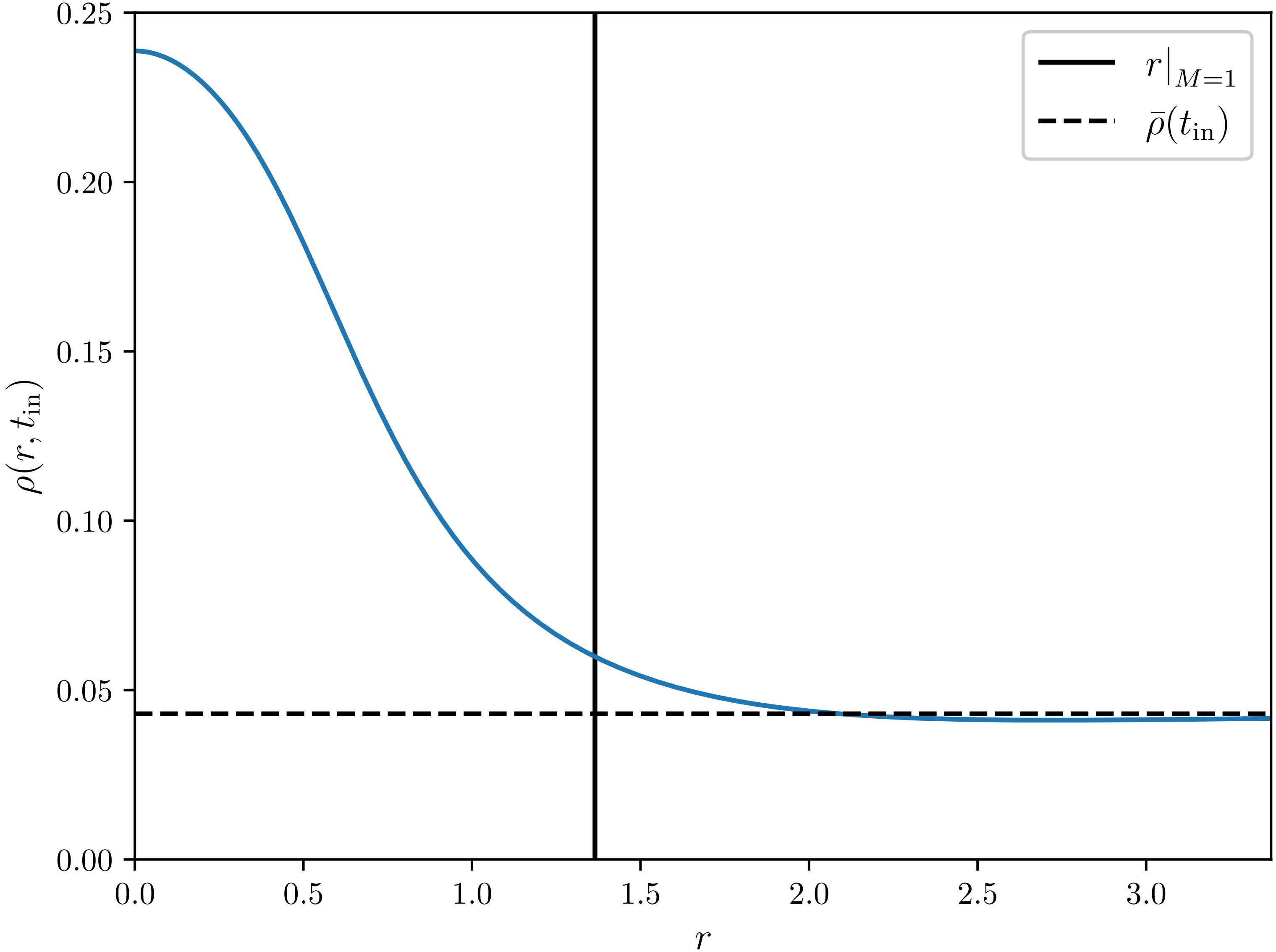
$$\delta g \simeq 4\pi G\ \delta\rho\ \ell \simeq 4\pi G\ \rho\ \ell$$



$$\Gamma \sim \frac{\delta g}{\delta v} \sim 4\pi G\ \rho\ m\ \ell^2/\hbar$$

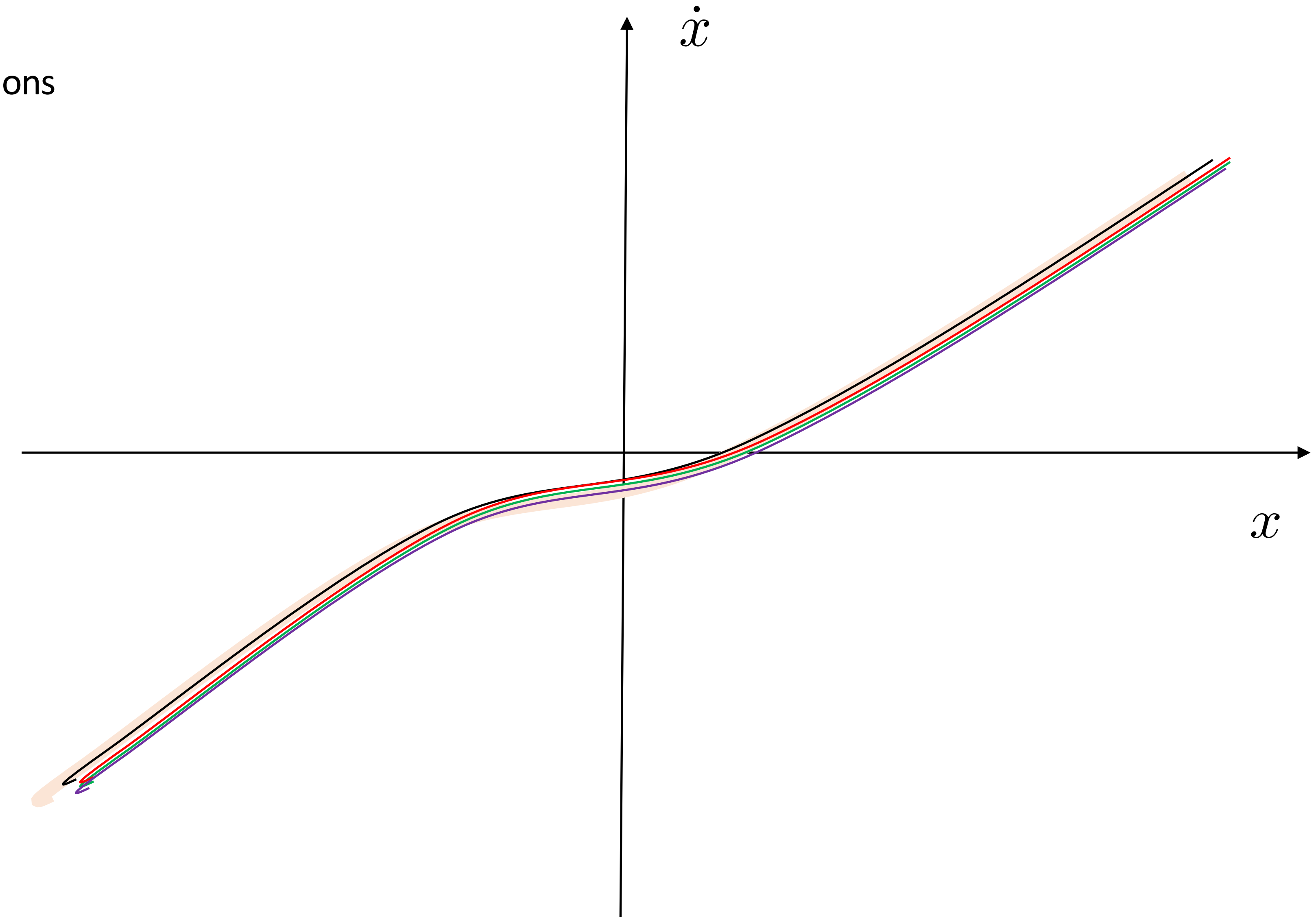
Q. Yang & PS, 2009
O. Erken et al., 2012

The axion fluid thermalizes and forms a Bose-Einstein condensate when $\Gamma > H$, long beofre equality between matter and radiation.



$r|_{M=1}$
$\bar{\rho}(t_{\rm in})$
$\rho(r, t_{\rm in})$
r
0.00
0.05
0.10
0.15
0.20
0.25
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Axions



During the collapse of an axion overdensity at cosmic dawn

$$\Gamma \sim 4\pi G \; \rho \; m \; \ell^2/\hbar$$ with $$\ell \; \sim \; r$$

$$\Gamma(r,t) \sim 10^{17} \; H(t) \; \left(\frac{m}{\mu\text{eV}}\right)\left(\frac{r}{10^{22}\text{ cm}}\right)^2 \left(\frac{220\text{ Myr}}{t}\right)$$

$$\dot{L}_{\max}(r,t) \sim r \; \delta v \; \Gamma \sim 4\pi G\rho(r,t) \; r^2$$

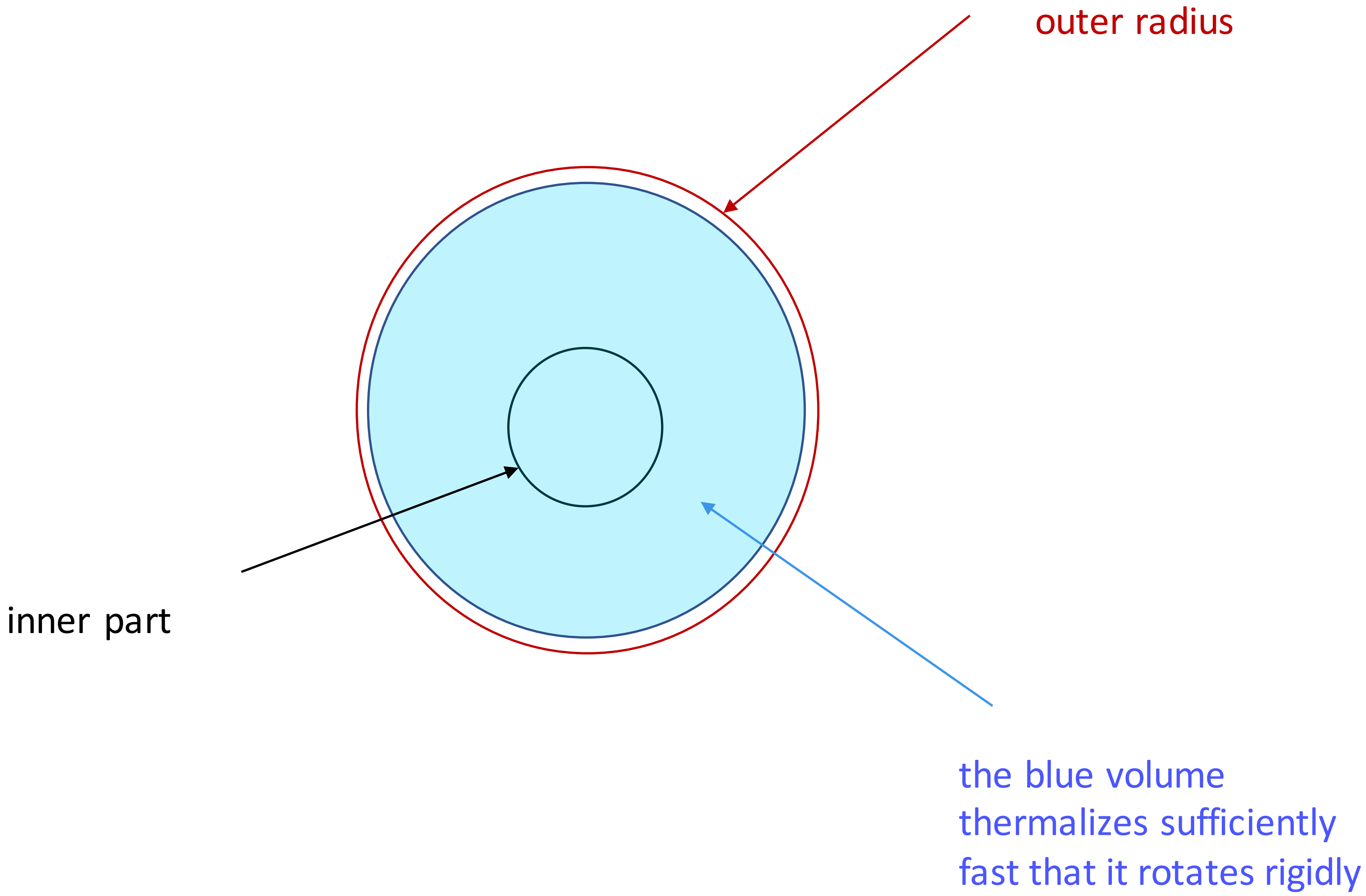
If we use (we should not)

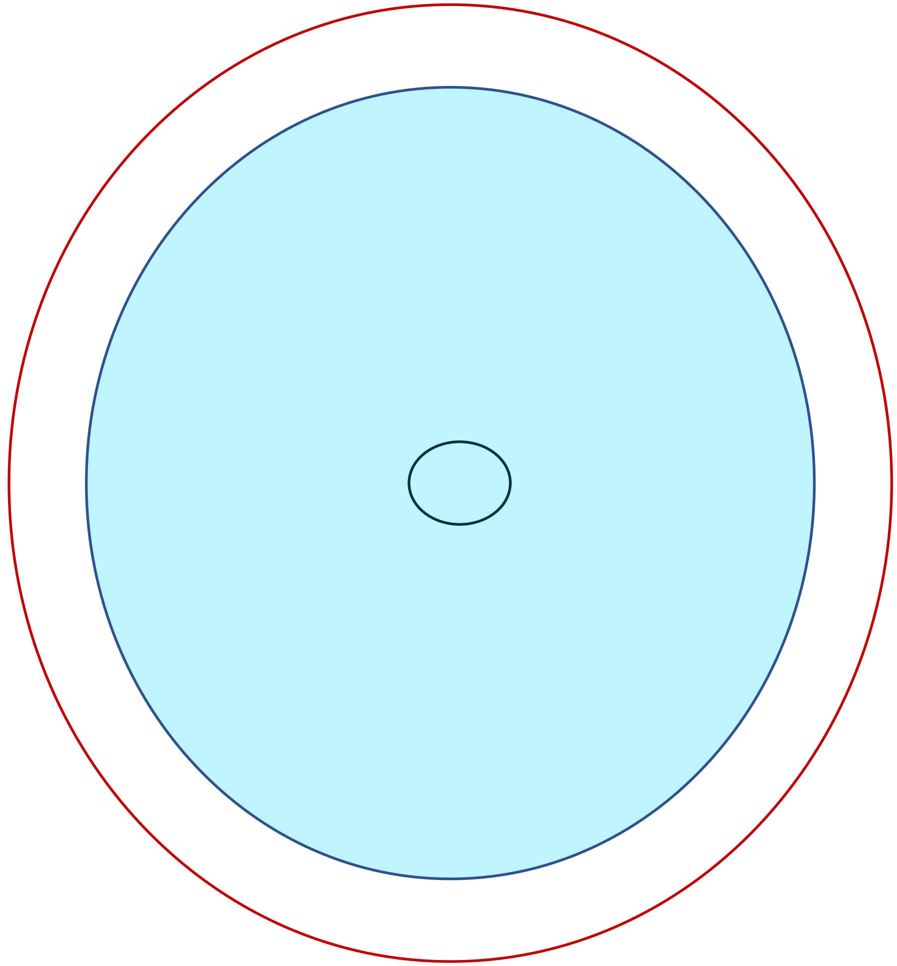
$$\Gamma_k \sim n\ \sigma_g\ \delta v\ \mathcal{N} \quad \text{with} \quad \sigma_g \sim \frac{4G^2m^2}{(\delta v)^4}$$

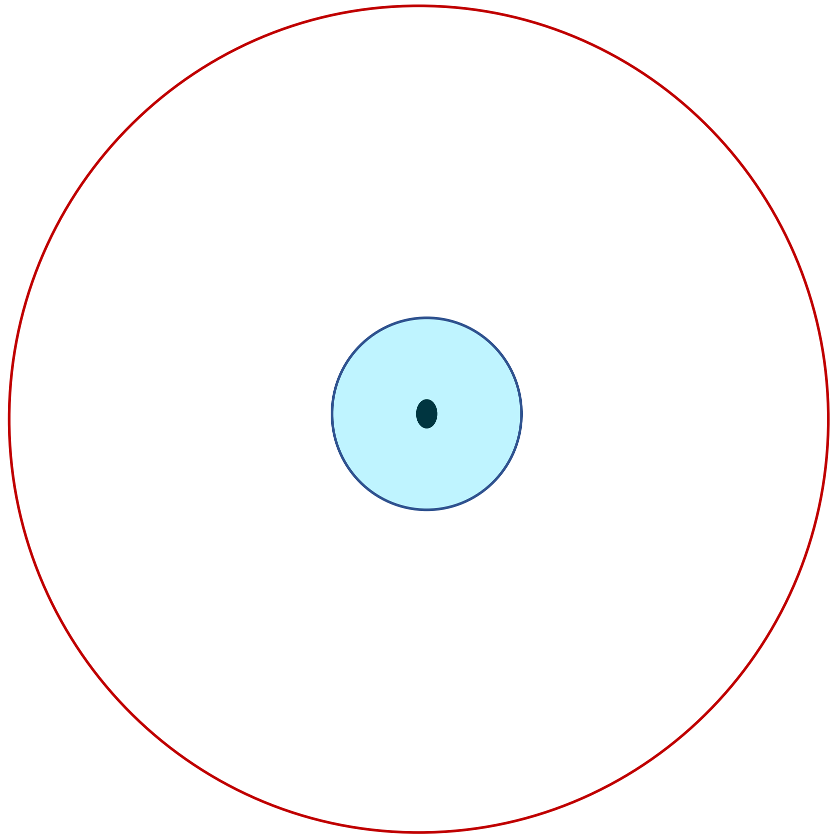
$$\sim \frac{10^{13}}{\mathrm{cm}^3}\ 10^{-21}\frac{\mathrm{cm}}{\mathrm{s}}\ 10^{-50}\mathrm{cm}^2\ 10^{81}$$

$$\sim \frac{10^{33}}{\mathrm{sec}} \sim 10^9\ \mathrm{GeV}$$

angular momentum transport would be far more efficient and supermassive black holes would form far more readily

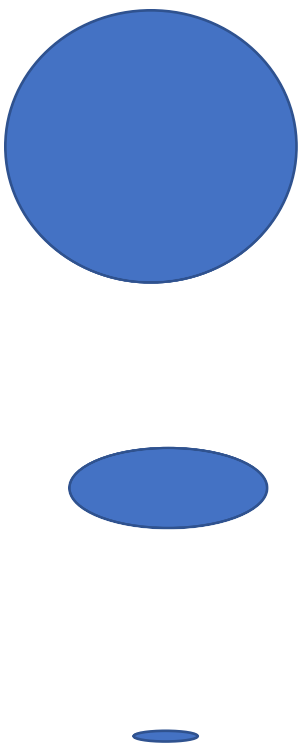

outer radius
inner part
the blue volume
thermalizes sufficiently
fast that it rotates rigidly





The infall is highly anisotropic

C.C. Lin, L. Meistel and F.H. Shu 1965, Y. Zel'dovich 1970, J. Binney 1977



The initial overdensity is not spherically symmetric. Any small anisotropy is amplified during the collapse.

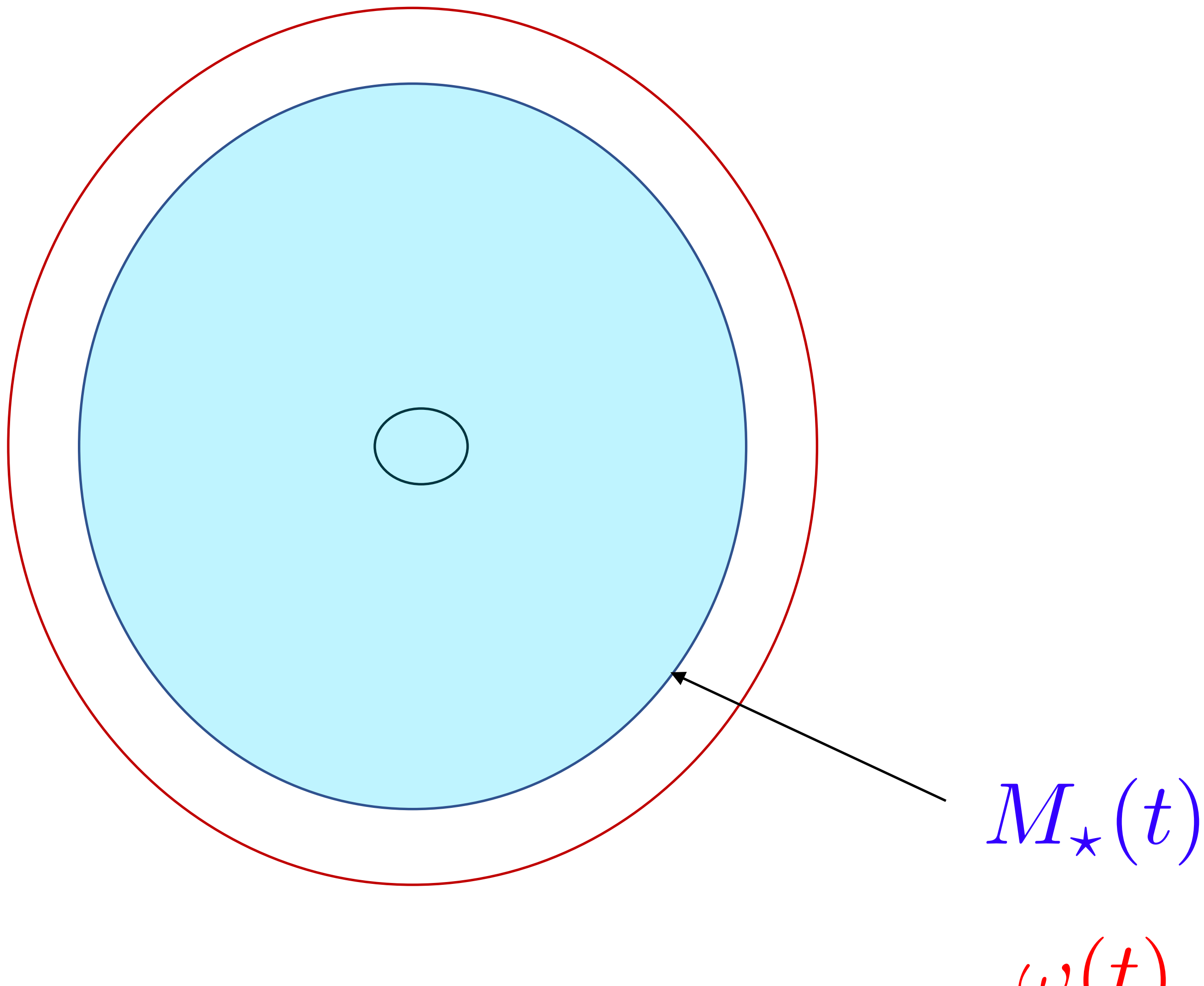
We ignore this in our calculation, arguing that

$$v_\perp \sim \sqrt{\frac{G\rho}{r}} << c$$

Additional approximations

- axions only (ignore baryons, photons, neutrinos, dark energy ...)
- Newtonian gravity and equations of motion
- ignore wave nature of the flow (assumes $m_a > 10^{-16}\ \mathrm{eV}$)

We keep track of $r(M,t)$ and $L(M,t)$



$M_\star(t)$
$\omega(t)$

$$L(M,t) = \omega(t)\; r(M,t)^2$$

$$\dot{L}(M,t) < \dot{L}_{\mathrm{max}}(M,t) = 4\pi G\; \rho(r(M,t),t)\; r(M,t)^2$$

$$\omega(t) < \omega_{\mathrm{max}}(M,t) \simeq 4\pi G\rho(M,t) r(M,t) \frac{1}{\dot{r}(M,t)}$$

$M_\star(t)$ is such that the above condition is satisfied for all $M < M_\star(t)$

As time goes on

$\omega(t)$ ↗ $M_\star(t)$ ↘

$$\frac{d\omega}{dt} = -\omega(t)\frac{\dot{I}(t)}{I(t)} + \left.\frac{d\omega}{dt}\right|_{TT}$$

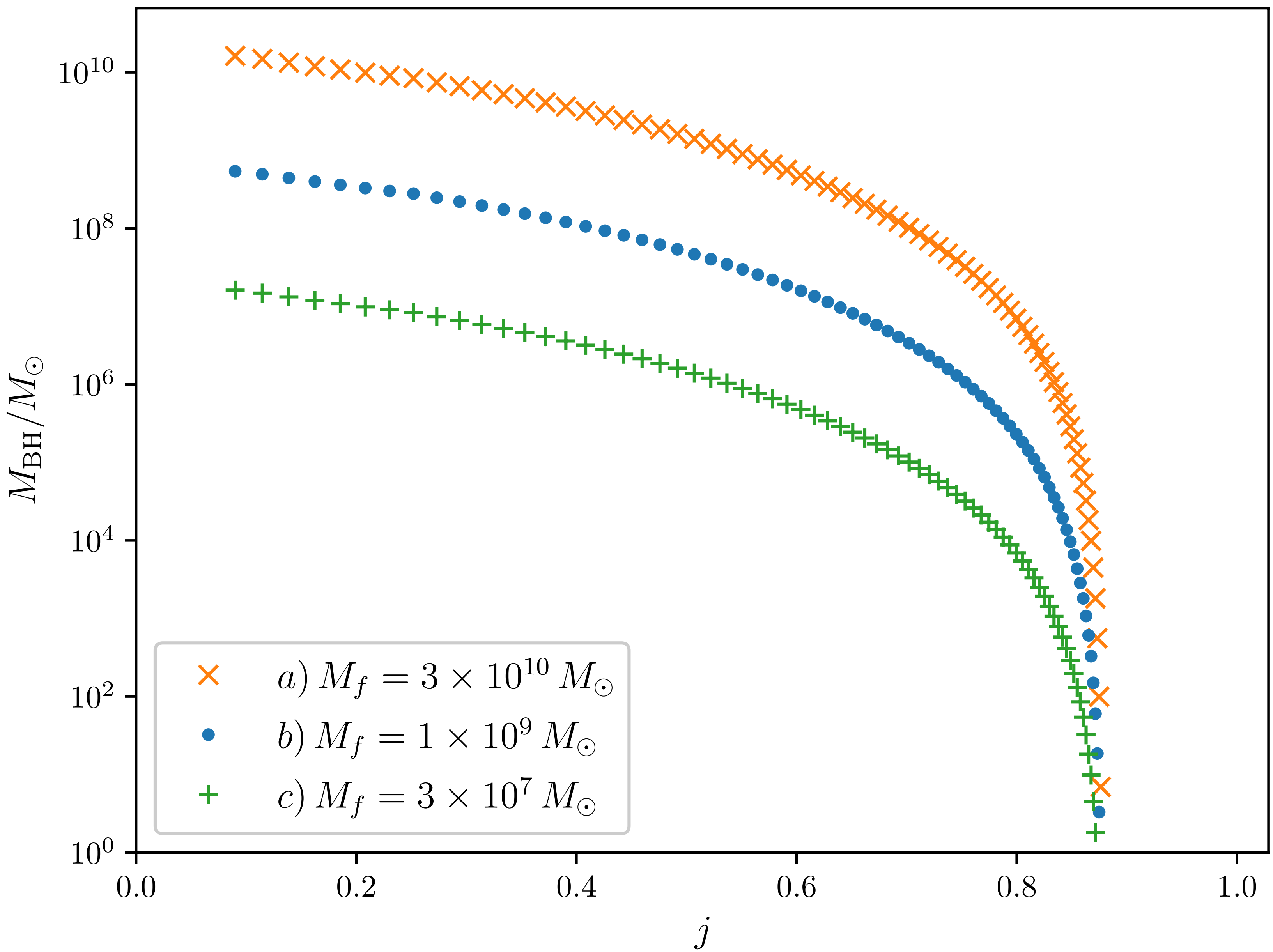
contribution from tidal torquing during collapse; cfr 2407.11169

$$\omega(t_{\rm in}) = \frac{j}{t_{\rm in}}$$

$$t_{\rm in} = \frac{1}{2}\, t_{\rm collapse}$$

$$\lambda = \frac{4}{5\pi}\sqrt{\frac{6}{5}}\, j + \mathcal{O}(j^2)$$

$$0.01 \lesssim \lambda \lesssim 0.18 \longrightarrow 0.04 \lesssim j \lesssim 0.8$$



10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
$M_{\rm BH}/M_\odot$
0.0
0.2
0.4
0.6
0.8
1.0
j
$a)\ M_f = 3 \times 10^{10}\ M_\odot$
$b)\ M_f = 1 \times 10^{9}\ M_\odot$
$c)\ M_f = 3 \times 10^{7}\ M_\odot$

- Black holes form with masses $10^5\ M_\odot$ to $10^{10} M_\odot$

- They form at cosmic dawn

- Black hole mass is proportional to the mass of the initial overdensity

- The cutoff in j implies that some galaxies have no supermassive black hole, e.g. M33

Axions

- solve the “strong CP problem”

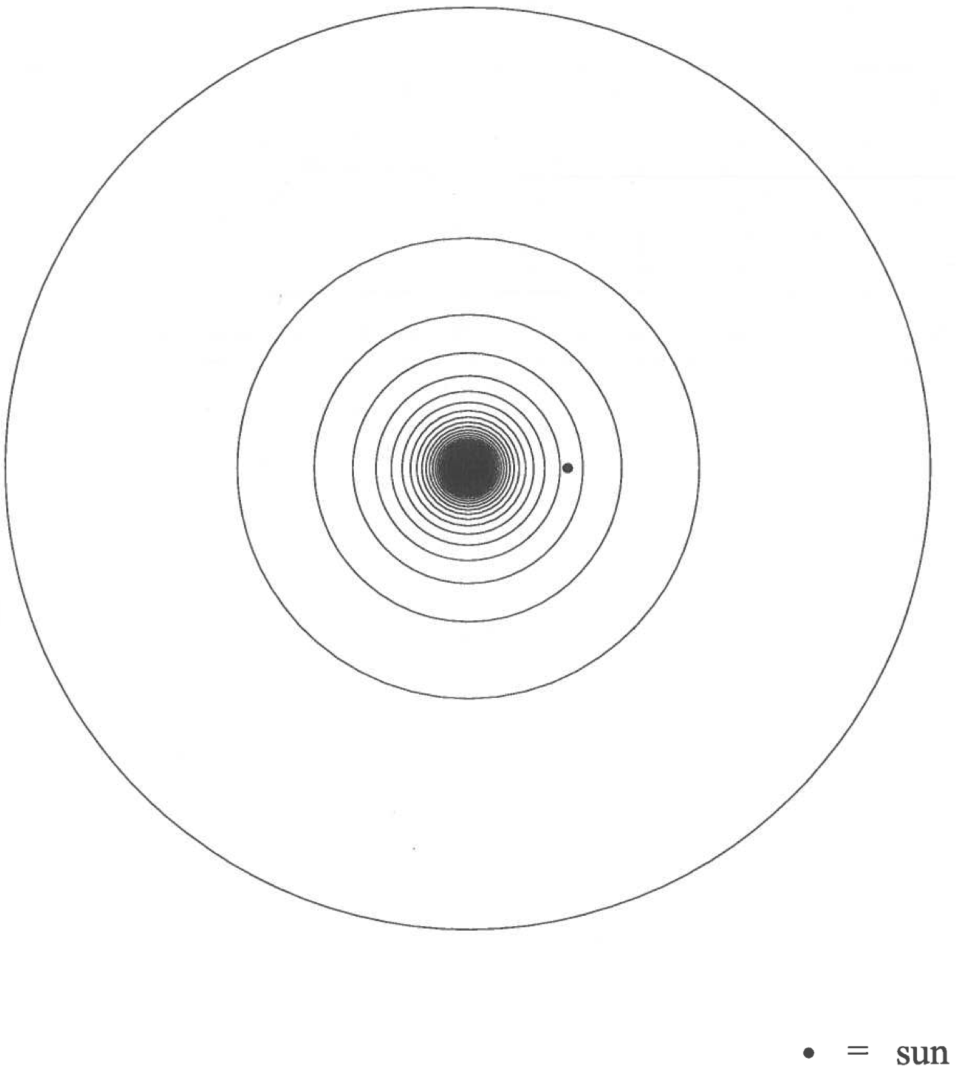
but other solutions have been proposed (spontaneaous CP violation, ...)

- are a natural cold dark matter candidate

but there are other candidates (WIMPS, sterile neutronos, ...)

- explain how and why supermassive black holes form at cosmic dawn

Caustic Rings in the Milky Way



In short

$$\delta\rho = \rho$$

$$\ell = 1/\delta p$$

$$\delta g \sim 4\pi G\rho\ell$$

$$\delta p = m\delta g \ \tau$$

$$\Gamma \equiv \frac{1}{\tau} = \frac{m\delta g}{\delta p} \sim 4\pi G\rho m\ell^2$$