Title: Dark Photon Stars

Speakers: Edward Hardy

Series: Particle Physics

Date: September 13, 2022 - 1:00 PM

URL: https://pirsa.org/22090083

Abstract: I will argue that many theories in which dark matter is light (with a mass < eV) lead to theoretically and observationally interesting dark matter substructure. As a particular, calculable, example I will show that this is the case for a new vector boson with non-zero mass (a `dark photon') that is present during inflation, at which time a relic abundance is automatically produced from vacuum fluctuations. Due to a remarkable coincidence between the size of the primordial density perturbations and the scale at which quantum pressure is relevant, a substantial fraction of the dark matter inevitably collapses into gravitationally bound solitons, which are fully quantum coherent objects. The central densities of these `dark photon star', or `Proca star', solitons are typically a factor 10^6 larger than the local background dark matter density today. I will also mention how similar substructure might occur in theories of post-inflationary axion-like-particles.

Zoom Link: https://pitp.zoom.us/j/94995778057?pwd=T2w4WWU0ZGtwWEIzTHFSZ3J6dGovUT09

Dark photon (and axion) stars

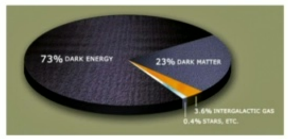
Ed Hardy

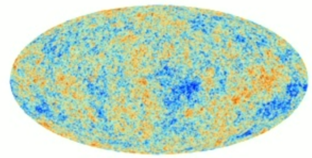
UNIVERSITY OF LIVERPOOL

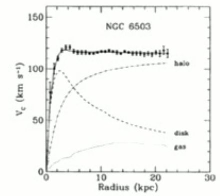
With M. Gorghetto, J. March-Russell, N. Song, S. West

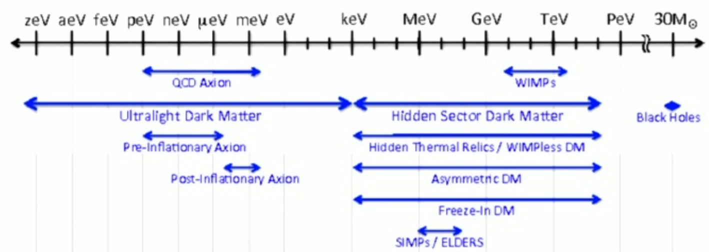
2203.10100 JCAP + ongoing

Dark Matter


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.




NGC 6503
halo
disk
gas
Vc (km s⁻¹)
Radius (kpc)
150
100
50
0
10
20
30

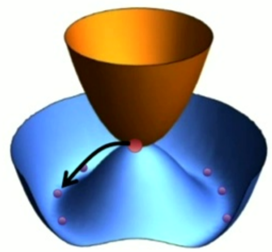

zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS


Dark Matter

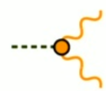
Sub-eV dark matter candidates

Axion, a

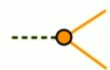
- Spin 0 pseudo-scalar
- Shift symmetry $a \to a + c$



$\frac{1}{4} a \, g^0_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$



$c^0_q \bar{q} \gamma^\mu \gamma_5 q \frac{\partial_\mu a}{2 f_a}$

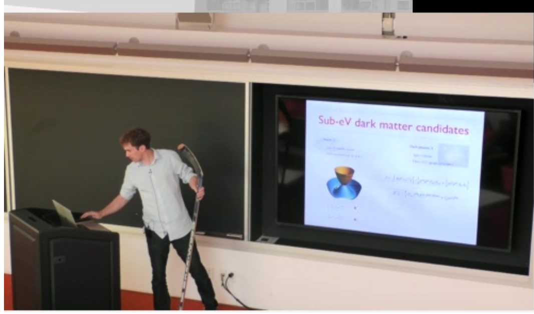


Dark photon, A

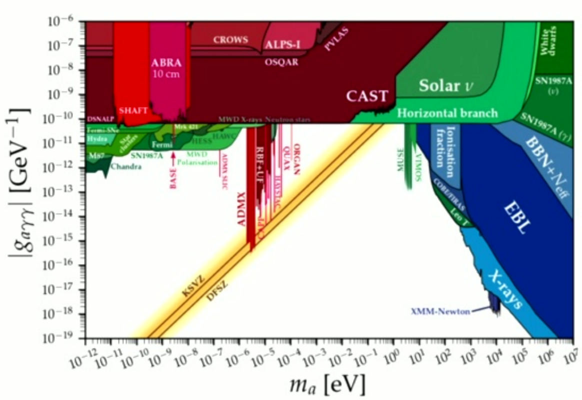
- Spin 1 vector
- New U(1) gauge symmetry

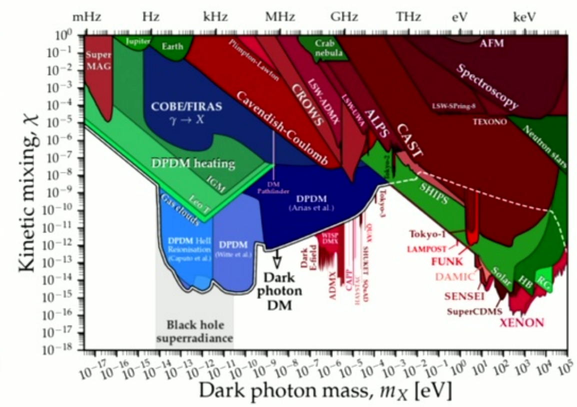
$$S = \int dt d^3x \sqrt{-g} \left[-\frac{1}{4} g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} + \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu \right]$$

$$\mathscr{L} \supset -\frac{\chi}{2} (F_{\mu\nu})^{\rm SM} (F^{\mu\nu})^{\rm dark\ photon} + J_\mu (A^\mu)^{\rm SM}$$



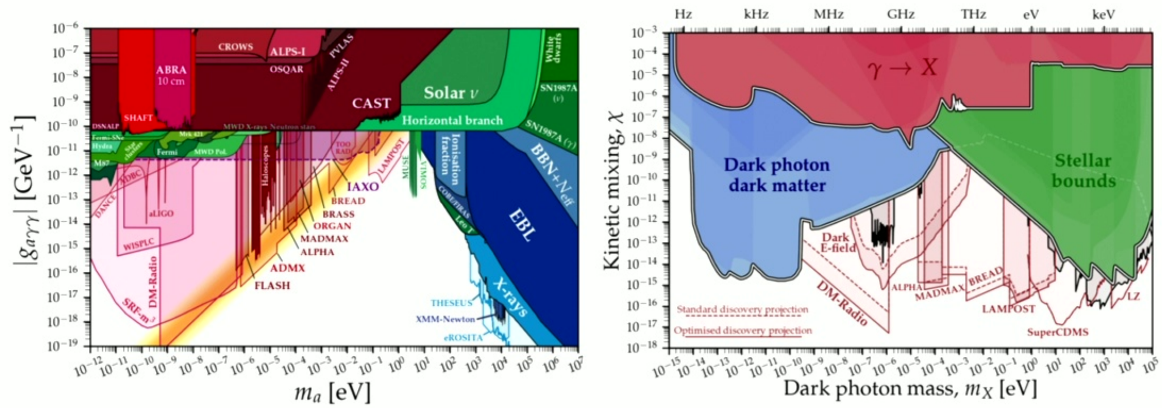
Experimental Searches



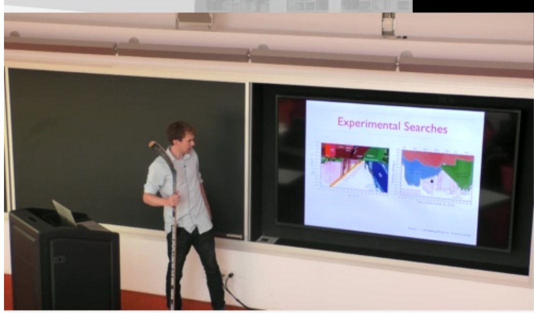


https://cajohare.github.io/AxionLimits

Experimental Searches



https://cajohare.github.io/AxionLimits



Basic definitions

Dark matter over-density field $\delta(x) \equiv \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$

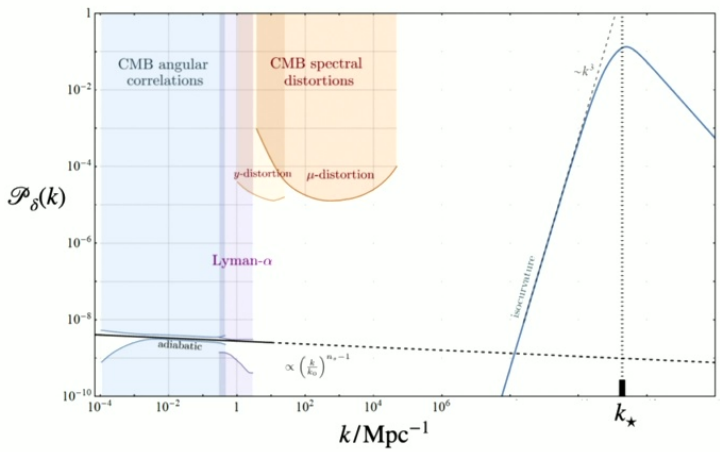
$\rho(x)$ → Dark matter density

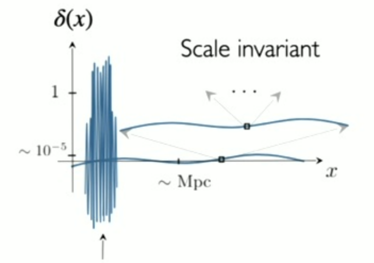
$$\langle \tilde{\delta}^*(\vec{k})\tilde{\delta}(\vec{k}')\rangle \equiv \frac{2\pi^2}{k^3}\delta^3(\vec{k}-\vec{k}')\mathcal{P}_\delta(|\vec{k}|)$$

$\mathcal{P}_\delta(|\vec{k}|)$ → Density power spectrum

$\delta^3(\vec{k}-\vec{k}')$ → Statistical homogeneity + isotropy

Initial spatial distribution



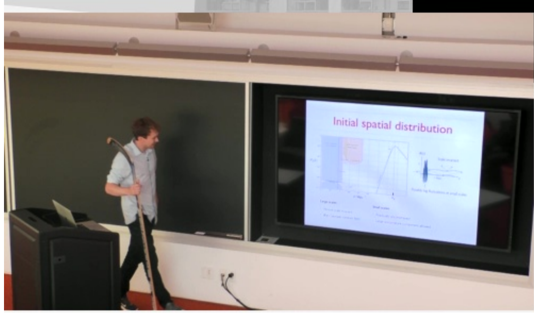


Large scales:

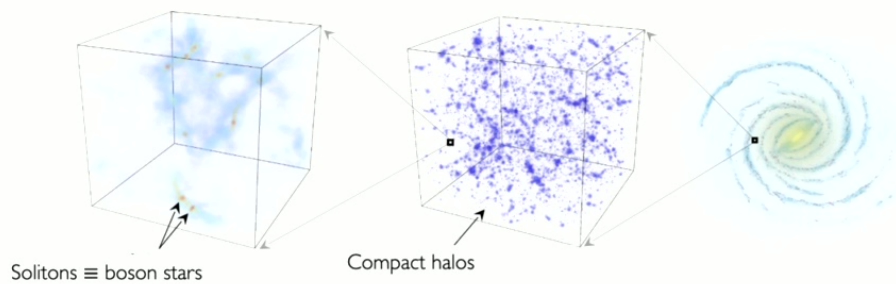
- Almost scale invariant
- $\delta(x)$ Gaussian random field

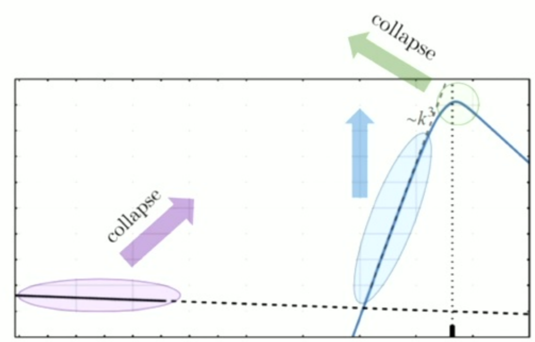
Small scales:

- Practically unconstrained
- Large isocurvature component allowed



Resulting dynamics





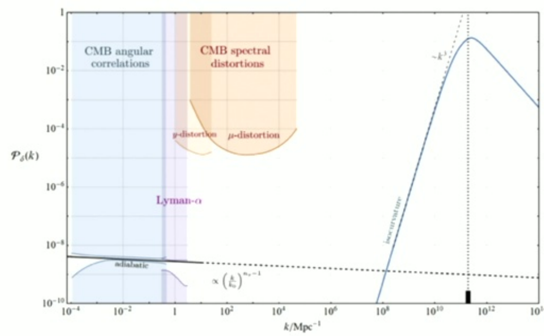
Production mechanisms

Dark photon

- Inflationary fluctuations
- From local strings
- Parametric resonance

Axion

- Post-inflationary ALP
- Axion coupled to dark photon



This talk

Dark photon

- Inflationary fluctuations
- From local strings
- Parametric resonance

Axion

- Post-inflationary ALP
- Axion coupled to dark photon

This talk

Dark photon

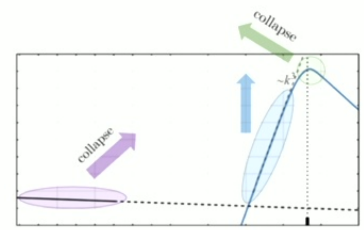
- Inflationary fluctuations
- From local strings
- Parametric resonance

Axion

- Post-inflationary ALP
- Axion coupled to dark photon

Outline

- Vector dark matter from inflationary fluctuations *[Graham, Mardon, and Rajendran]*
- Collapse of the density fluctuations to solitons (`dark photon' stars)
- Subsequent structure formation and survival
- Signals
- Similar dynamics in ALPs



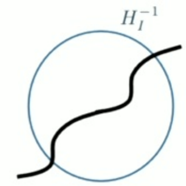
Vector dark matter from inflation

→ Massive vector field during inflation

$$S = \int dt d^3x \sqrt{-g} \left[-\frac{1}{4} g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} + \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu \right]$$

$m \ll H_I$

$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2$$



Generic mode: $k_{\rm phys} \equiv \frac{k}{a} > H_I \gg m$

Subhorizon during inflation $\Longrightarrow$ relativistic

$\tilde{A} = \{A_T, A_L\}$

Transverse $\vec{k} \cdot \vec{A}_T = 0$

Longitudinal $\vec{k} \cdot \vec{A} = k A_L$

Vector dark matter from inflation

$S = S_T + S_L$ (Transverse and longitudinal decoupled)

Transverse

$$S_T = \int \frac{a^3 d^3k\, dt}{(2\pi)^3} \frac{1}{2a^2} \left[|\partial_t \vec{A}_T|^2 - \left(\frac{k^2}{a^2} + m^2 \right) |\vec{A}_T|^2 \right] \xrightarrow{d\eta = \frac{dt}{a}} (2\pi)^{-3} \int d^3k d\eta \frac{1}{2} \left(|\partial_\eta \vec{A}_T|^2 - (k^2 + \cancelto{0}{a^2 m^2}) |\vec{A}_T|^2 \right)$$

(relativistic)

Time translation invariant → modes not produced

Longitudinal

$$S_L = \int \frac{a^3 d^3k\, dt}{(2\pi)^3} \frac{1}{2a^2} \left[\frac{a^2 m^2}{k^2 + a^2 m^2} |\partial_t A_L|^2 - m^2 |A_L|^2 \right] \xrightarrow{\frac{k}{a} \gg m \quad \varphi \equiv \frac{A_L}{k}} \int a^3 d^3x dt \frac{1}{2} [(\partial_t \varphi)^2 - |\nabla \varphi|^2 / a^2]$$

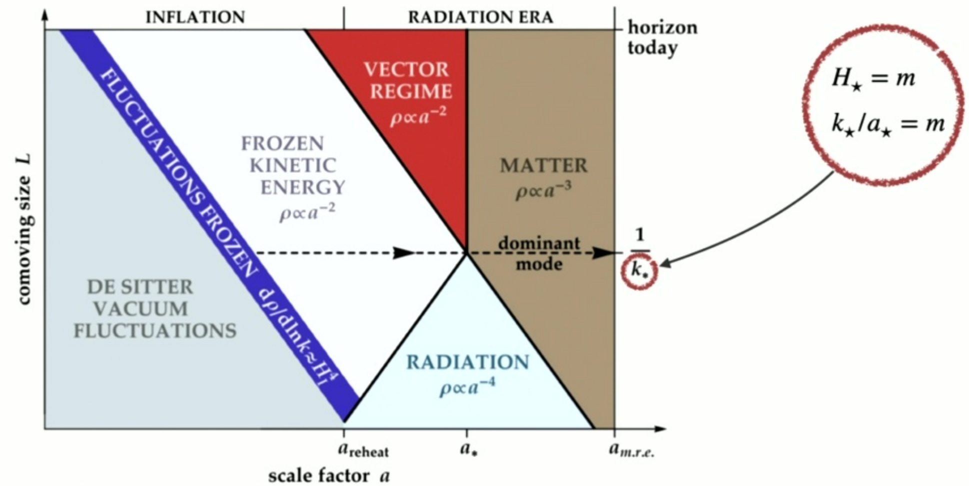
Relativistic scalar field → produced with scale-invariant energy density at horizon exit

Energy density: $\rho_{A_L} \equiv \int dk \frac{\partial \rho_{A_L}}{\partial k}$

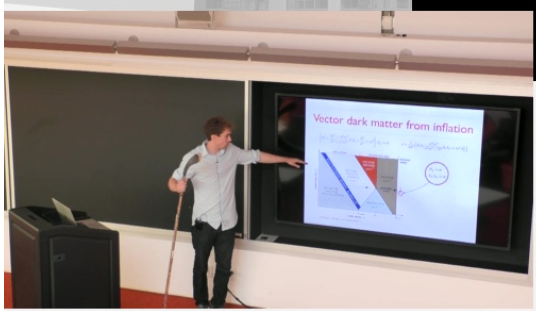
$$\left. \frac{\partial \rho_{A_L}}{\partial \log k} \right|_{a=a_e} \approx \frac{H_I^4}{(2\pi)^2} \qquad \left. \vec{A}_T \right|_{a=a_e} \approx 0$$

Vector dark matter from inflation

$$\left[\partial_t^2 + \frac{3k^2 + a^2m^2}{k^2 + a^2m^2} H\partial_t + \frac{k^2}{a^2} + m^2\right] A_L = 0 \qquad \rho = \frac{1}{2a^2}\left(\partial_t A_L \frac{a^2m^2}{a^2m^2 - \nabla^2}\partial_t A_L + m^2 A_L^2\right)$$

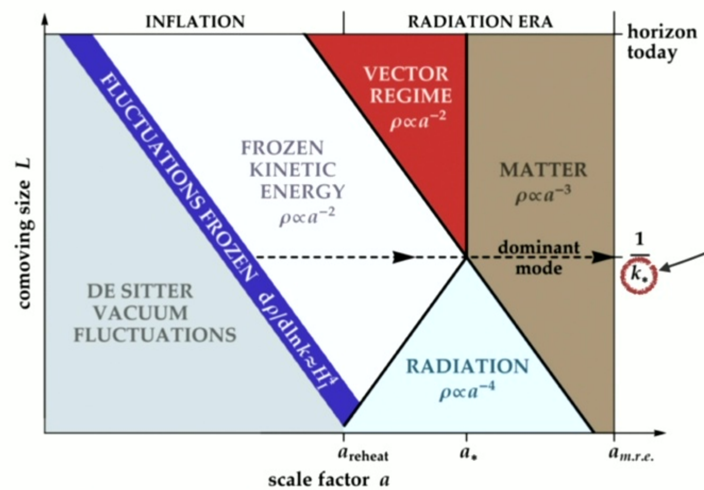


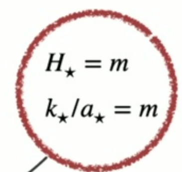
[Graham, Mardon, and Rajendran]



Vector dark matter from inflation

$$\left[\partial_t^2 + \frac{3k^2+a^2m^2}{k^2+a^2m^2} H\partial_t + \frac{k^2}{a^2} + m^2\right] A_L = 0 \qquad \rho = \frac{1}{2a^2}\left(\partial_t A_L \frac{a^2m^2}{a^2m^2-\nabla^2}\partial_t A_L + m^2 A_L^2\right)$$





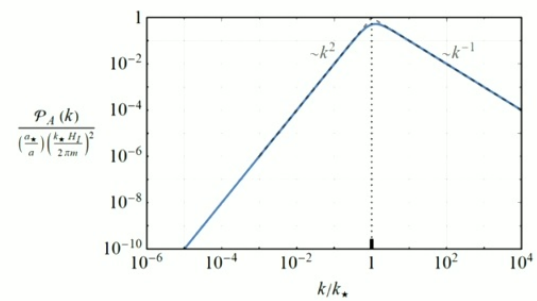
$$\rho(a_0) \simeq \frac{H_I^4}{(2\pi)^2}\left(\frac{k_\star/H_I}{a_\star}\right)^2\left(\frac{a_\star}{a_0}\right)^3$$
$$= \rho_{\rm DM}\sqrt{\frac{m}{6\cdot 10^{-6}\,{\rm eV}}}\left(\frac{H_I}{10^{14}\,{\rm GeV}}\right)^2$$

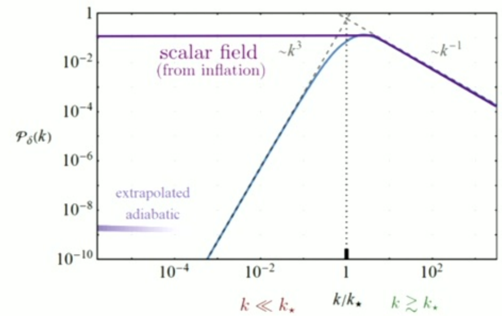
$H_I \lesssim 10^{13}\,{\rm GeV}$ (tensor perturbations)

→ Can comprise the DM for $m \gtrsim 10^{-5}\,{\rm eV}$

[Graham, Mardon, and Rajendran]

Vector dark matter from inflation

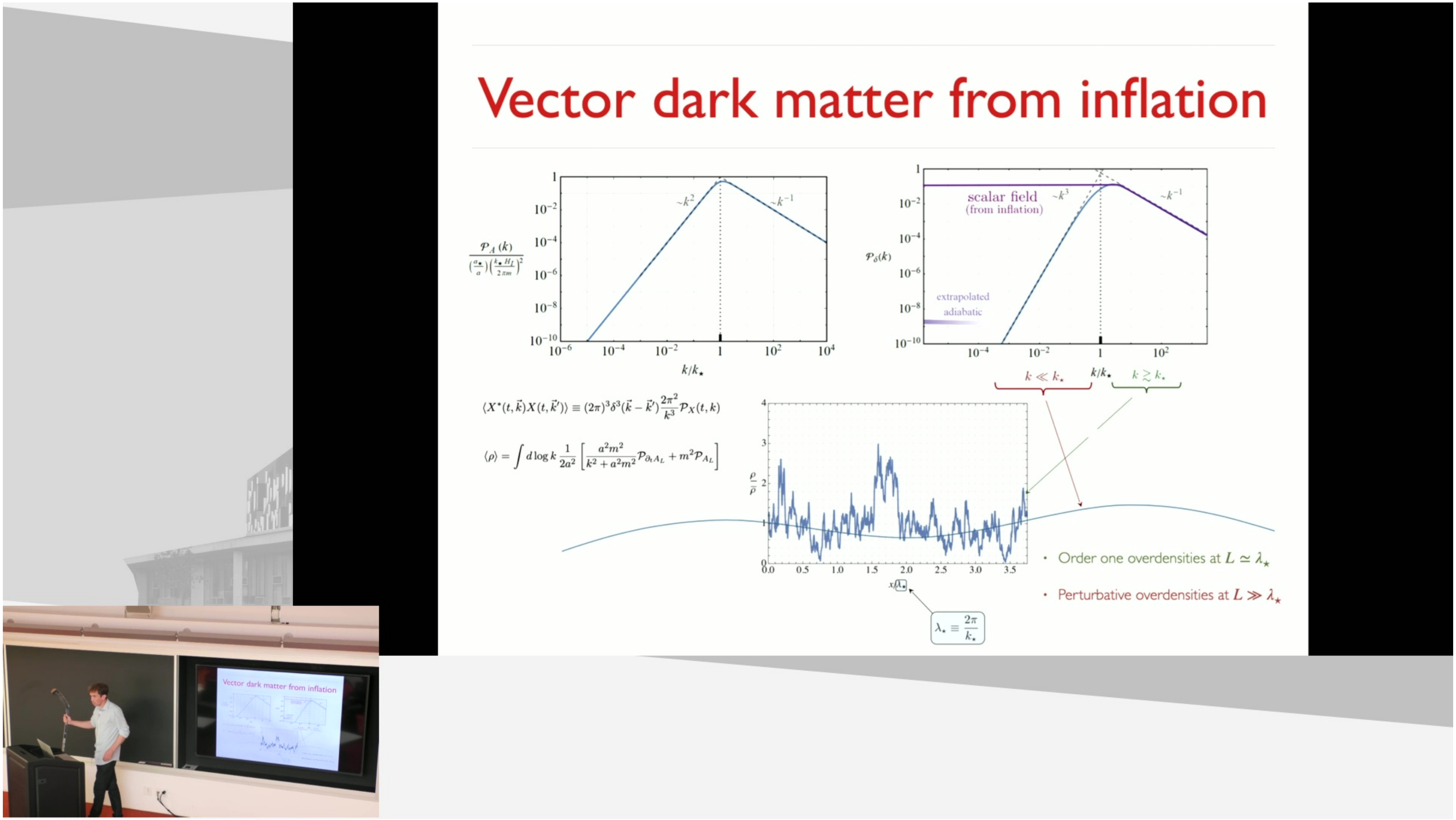




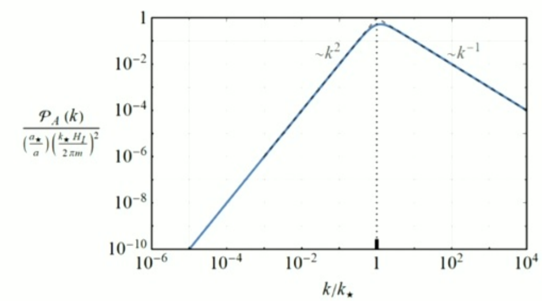
$$\langle X^*(t,\vec{k})X(t,\vec{k}')\rangle \equiv (2\pi)^3\delta^3(\vec{k}-\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_X(t,k)$$

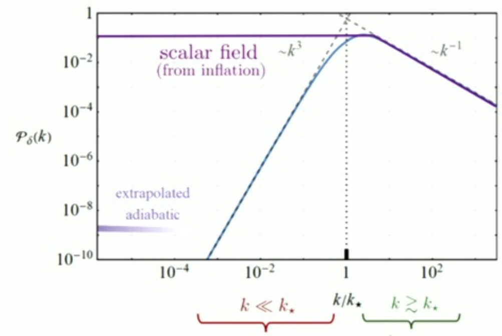
$$\langle\rho\rangle = \int d\log k\,\frac{1}{2a^2}\left[\frac{a^2m^2}{k^2+a^2m^2}\mathcal{P}_{\partial_t A_L} + m^2\mathcal{P}_{A_L}\right]$$

$$\mathcal{P}_\delta(t,k) = \frac{k^2}{8\langle A_L^2\rangle^2}\int_0^\infty dq\int_{|q-k|}^{q+k} dp\,\frac{(k^2-q^2-p^2)^2}{q^4p^4}\mathcal{P}_{A_L}(t,p)\mathcal{P}_{A_L}(t,q)$$


Vector dark matter from inflation
$\frac{\mathcal{P}_A(k)}{\left(\frac{a_\star}{a}\right)\left(\frac{k_\star H_I}{2\pi m}\right)^2}$
$\sim k^2$
$\sim k^{-1}$
$k/k_\star$
$\mathcal{P}_\delta(k)$
scalar field
(from inflation)
$\sim k^3$
$\sim k^{-1}$
extrapolated
adiabatic
$k \ll k_\star$
$k/k_\star$
$k \gtrsim k_\star$
$\langle X^*(t,\vec{k})X(t,\vec{k}')\rangle \equiv (2\pi)^3\delta^3(\vec{k}-\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_X(t,k)$
$\langle\rho\rangle = \int d\log k\, \frac{1}{2a^2}\left[\frac{a^2m^2}{k^2+a^2m^2}\mathcal{P}_{\partial_t A_L} + m^2\mathcal{P}_{A_L}\right]$
$\frac{\rho}{\bar{\rho}}$
$x/\lambda_\star$
$\lambda_\star \equiv \frac{2\pi}{k_\star}$
• Order one overdensities at $L \simeq \lambda_\star$
• Perturbative overdensities at $L \gg \lambda_\star$

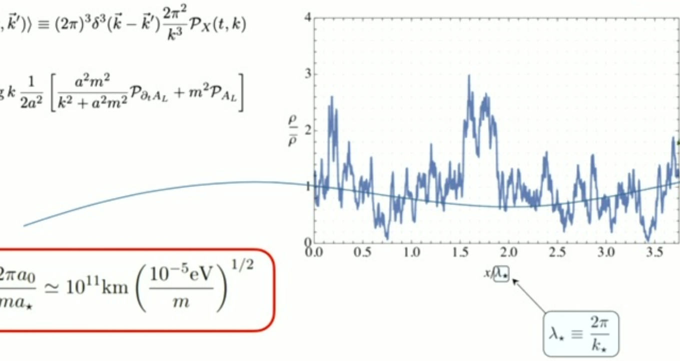
Vector dark matter from inflation





$$\langle X^*(t,\vec{k})X(t,\vec{k}')\rangle \equiv (2\pi)^3\delta^3(\vec{k}-\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_X(t,k)$$

$$\langle\rho\rangle = \int d\log k\,\frac{1}{2a^2}\left[\frac{a^2m^2}{k^2+a^2m^2}\mathcal{P}_{\partial_t A_L} + m^2\mathcal{P}_{A_L}\right]$$



$$a_0\lambda_\star = \frac{2\pi a_0}{m a_\star} \simeq 10^{11}\text{km}\left(\frac{10^{-5}\text{eV}}{m}\right)^{1/2}$$

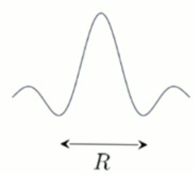
- Order one overdensities at $L \simeq \lambda_\star$
- Perturbative overdensities at $L \gg \lambda_\star$

Gravitational collapse and wave effects

An order one over-density $\delta = \delta\rho/\bar{\rho}$ becomes nonlinear around matter radiation equality

at $a_{\rm collapse} = a_{\rm eq}/\delta$

Density $\rho \simeq \bar{\rho}(a_{\rm collapse})$



de Broglie wavelength of a particle in the resulting clump

$$\lambda_{\rm dB} = \frac{1}{mv} = \frac{1}{m(GM/R)^{1/2}} = \frac{1}{R(4\pi G\rho m^2)^{1/2}}$$

$$R_{\rm crit} \simeq \lambda_J \simeq (16\pi G\rho m^2)^{-1/4}$$

$$\frac{k_J}{a} = (16\pi G\rho m^2)^{1/4}$$

The remarkable coincidence

$$\left.\frac{k_J(\bar{\rho})}{k_\star}\right|_{a=a_{\rm eq}} = \frac{(16\pi G\,\bar{\rho}(a_{\rm eq})\,m^2)^{1/4}}{m(a_\star/a_{\rm eq})} \simeq \left(\frac{\bar{\rho}(a_{\rm eq})}{\bar{\rho}_{\rm M}(a_{\rm eq})})\right)^{\frac{1}{4}} \simeq \left(\frac{\Omega_A}{\Omega_{\rm M}}\right)^{1/4} \quad (\approx 1.9)$$

$$= \frac{T_{\rm eq}}{T_\star} \simeq \left(\frac{G}{m^2}\,\bar{\rho}_{\rm M}(a_{\rm eq})\right)^{1/4}$$

$$H_\star^2 = m^2 \simeq G T_\star^4$$

$$2\bar{\rho}_{\rm M}(a_{\rm eq}) \simeq T_{\rm eq}^4$$

Quantum pressure affects the evolution of the order one over-densities

More rigorously

- From the equations of motion of the vector field $D_\mu F^{\mu\nu} = m^2 A^\nu$

$$A_i \equiv \frac{1}{\sqrt{2m^2a^3}}(\psi_i e^{-imt} + \text{c.c.})$$

Non-relativistic limit $\dot{\psi}_i \ll m\psi_i$ and $\ddot{\psi}_i \ll m^2\psi_i$

$$\begin{cases} \text{Schroedinger:} & \left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi\right)\psi_i = 0\,, & \leftarrow D_\mu F^{\mu\nu} = m^2 A^\nu \\ \text{Poisson:} & \nabla^2\Phi = \frac{4\pi G}{a}\sum_i \left(|\psi_i|^2 - \langle|\psi_i|^2\rangle\right) & \leftarrow G^{00} = 8\pi G\, T^{00} \text{ Einstein eq.} \end{cases}$$

Nonlinear, $\boldsymbol{A_L}$ and $\boldsymbol{A_T}$ now coupled together

More rigorously

$$\left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi\right)\psi_i = 0\,,$$
$$\nabla^2\Phi = \frac{4\pi G}{a}\sum_i \left(|\psi_i|^2 - \langle|\psi_i|^2\rangle\right)$$

Magdelung transformation

$\psi_i = \sqrt{\rho_i}e^{i\theta_i}$

$\vec{v}_i = \frac{1}{m}\nabla\theta_i$

$\longleftrightarrow$

Continuity: $\partial_t\rho_i + 3H\rho_i + a^{-1}\nabla\cdot(\rho_i\vec{v}_i) = 0$

Euler: $\partial_t\vec{v}_i + H\vec{v}_i + a^{-1}(\vec{v}_i\cdot\nabla)\vec{v}_i = -a^{-1}(\nabla\Phi + \nabla\Phi_{Qi})$

$\nabla^2\Phi = 4\pi G a^2(\rho - \bar{\rho})$

(3-component) perfect fluid with 'quantum pressure' term:

$$\Phi_{Qi} \equiv -\frac{\hbar^2}{2a^2m^2}\frac{\nabla^2\sqrt{\rho_i}}{\sqrt{\rho_i}}$$

- Quantum pressure negligible if $\nabla\Phi \gg \nabla\Phi_Q$

$\nabla\cdot$: $4\pi G a^2\rho \gg \frac{1}{2a^2m^2}\nabla^2\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}} \simeq \frac{1}{2a^2m^2}\frac{k^4}{2}$

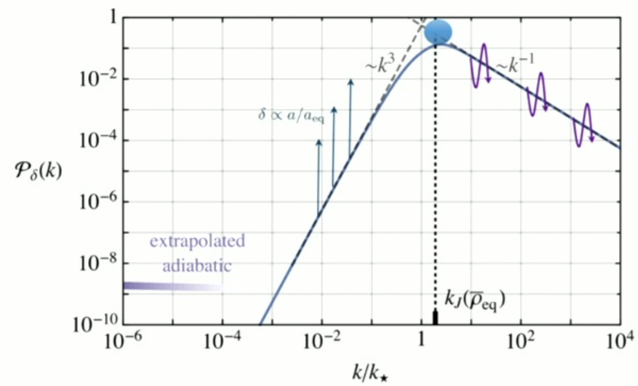
$\downarrow$

$$\left(\,k_J^{\rm phys} =\,\right)\quad \frac{k_J}{a} = (16\pi G\rho m^2)^{1/4}$$

$k \ll k_J$ Overdensities dominated by Φ $\rightarrow$ Grow and collapse

$k \gg k_J$ Overdensities dominated by Φ_Q $\rightarrow$ Prevented from collapsing and oscillate

Evolution of different modes



at $a = a_{eq}$

$k \ll k_J$

Quantum pressure negligible

- Perturbative ($\delta < 1$)
- Initially grow linearly $\delta \propto a/a_{eq}$
- Collapse once $\delta \simeq 1$

$k \simeq k_J$

At the edge of being affected by quantum pressure at MRE

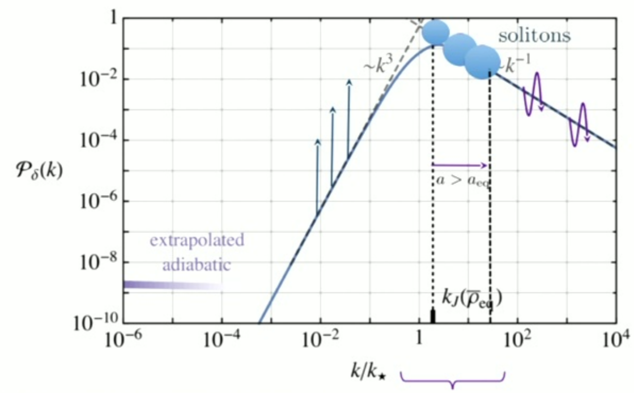
- Already non-perturbative ($\delta \simeq 1$)
- Collapse at around MRE

$k \gg k_J$

Quantum pressure dominated

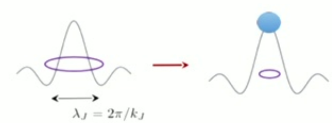
- Prevented from collapsing and oscillate (whether perturbative or not)

Solitons



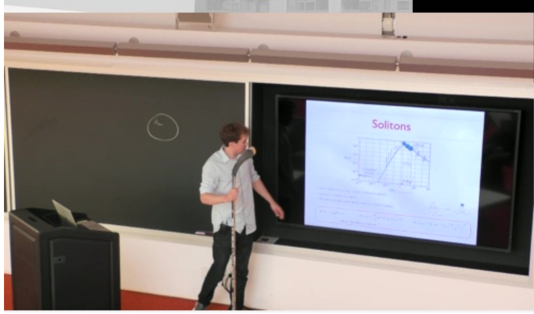
Collapse happened at $a \gtrsim a_{\rm eq}$, quantum pressure is relevant

- Expected to collapse into solitons
- Mass set by the dark matter density inside λ_J^3 at time of collapse



$$M(a) = c_M M_J(a) \qquad M_J(a) \equiv \frac{4\pi}{3}\bar{\rho}a^3\lambda_J^3(a) \propto a^{-3/4} \qquad M_J(a_{\rm eq}) = 1.6\cdot 10^{-15} M_\odot \left(\frac{10^{-5}\ {\rm eV}}{m}\right)^{\frac{3}{2}}$$

Coefficient expected to be order-one



Halos vs Solitons

- Collapsed object = stationary solution of Schrodinger-Poisson equation (with a=1)

$$\begin{cases} \left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi\right)\psi_i = 0 \,, \\ \nabla^2\Phi = \frac{4\pi G}{a}\sum_i \left(|\psi_i|^2 - \langle|\psi_i|^2\rangle\right) \end{cases}$$

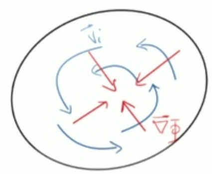
$$\psi_i = \sqrt{\rho_i}e^{i\theta_i}, \quad \vec{v}_i = \tfrac{1}{m}\nabla\theta_i \qquad \longleftrightarrow$$

$$\begin{cases} \partial_t\rho_i + 3H\rho_i + a^{-1}\nabla\cdot(\rho_i\vec{v}_i) = 0 \\ \partial_t\vec{v}_i + H\vec{v}_i + a^{-1}(\vec{v}_i\cdot\nabla)\vec{v}_i = -a^{-1}(\nabla\Phi + \nabla\Phi_{Qi}) \\ \nabla^2\Phi = 4\pi G a^2(\rho - \bar{\rho}) \,, \end{cases}$$

Halos

$\Phi_Q = 0$

→ Gravitational potential balanced by velocity

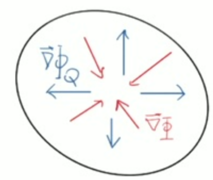


'Supported' by angular momentum

Solitons

$\Phi_Q = -\Phi \quad \longleftrightarrow \quad \vec{v}_i = 0$

→ Gravitational potential balanced by quantum pressure



'Supported' by quantum pressure

Vector solitons

≡ solution that minimises the energy E for fixed value of total mass M

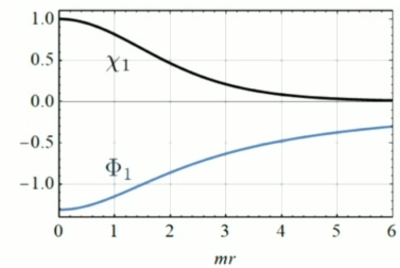
$$M \equiv \int d^3x\, \rho = \int d^3x \sum_i |\psi_i|^2$$

$$E = M + \int d^3x \sum_i \left(\frac{1}{2m^2} |\nabla \psi_i|^2 + \frac{1}{2} \Phi |\psi_i|^2 \right)$$

- Constructed by rescaling the ansatz:

$$\psi_i = \frac{m}{\sqrt{4\pi G}} e^{-i\gamma m t} \chi_1(mr) u_i, \qquad \Phi = \Phi_1(mr) \qquad \gamma \simeq -0.65$$

u_i: Unit vector



Vector solitons

$$M \equiv \int d^3x\, \rho = \int d^3x \sum_i |\psi_i|^2$$

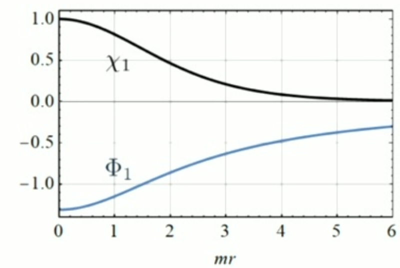
$$E = M + \int d^3x \sum_i \left(\frac{1}{2m^2} |\nabla \psi_i|^2 + \frac{1}{2} \Phi |\psi_i|^2 \right)$$

≡ solution that minimises the energy E for fixed value of total mass M

- Constructed by rescaling the ansatz:

$$\psi_i = \frac{m}{\sqrt{4\pi G}} e^{-i\gamma m t} \chi_1(mr) \boxed{u_i}, \qquad \Phi = \Phi_1(mr) \qquad \gamma \simeq -0.65$$

Unit vector



- $\rho(x) = \sum_i |\psi_i|^2 = \frac{m^2}{4\pi G} \chi_1^2(x)$: Energy density localised at centre

- Other solutions

$\chi_1(x) \to \alpha^2 \chi_1(\alpha x)$, $\Phi_1(x) \to \alpha^2 \Phi_1(\alpha x)$ and $\gamma \to \alpha^2 \gamma$, for any $\alpha > 0$

$$M \simeq \frac{2\alpha}{Gm}, \qquad R \simeq \frac{1.9}{\alpha m} \qquad \boxed{MR \simeq \frac{3.9}{Gm^2}}$$

- For fixed M, infinite set labelled by $\boldsymbol{u}_i$

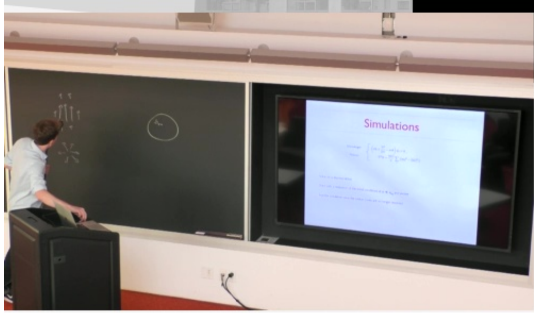
Simulations

$$\begin{cases} \text{Schrodinger:} & \left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi\right)\psi_i = 0\ , \\ \text{Poisson:} & \nabla^2\Phi = \frac{4\pi G}{a}\sum_i \left(|\psi_i|^2 - \langle|\psi_i|^2\rangle\right) \end{cases}$$

Solve on a discrete lattice

Start with a realisation of the initial conditions at $a \ll a_{\rm eq}$ and evolve

End the simulation once the soliton cores are no longer resolved



Simulations

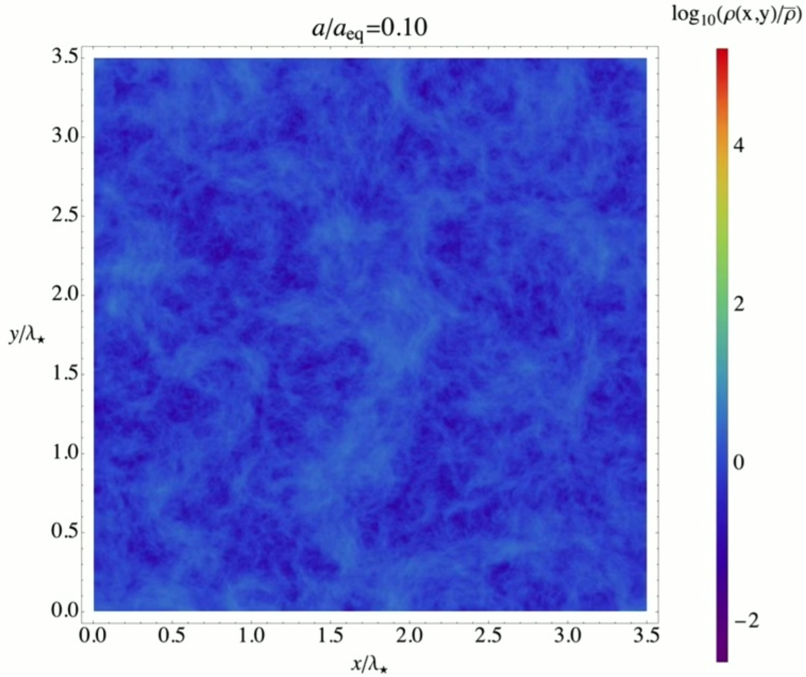
$$\text{Schrodinger:} \quad \left(i\partial_t + \frac{\nabla^2}{2m} - m\Phi\right)\psi_i = 0 \; ,$$

$$\text{Poisson:} \quad \nabla^2\Phi = \frac{4\pi G}{a}\sum_i \left(|\psi_i|^2 - \langle|\psi_i|^2\rangle\right)$$

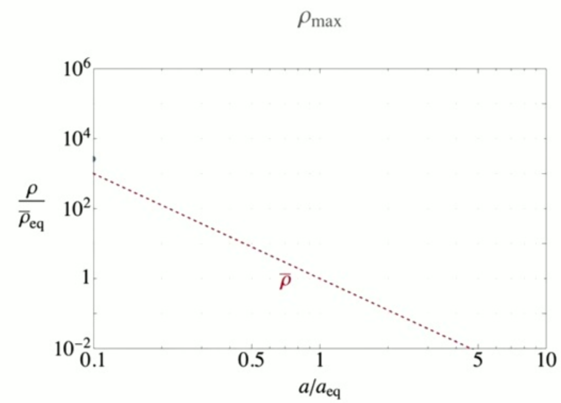
Solve on a discrete lattice

Start with a realisation of the initial conditions at $a \ll a_{\rm eq}$ and evolve

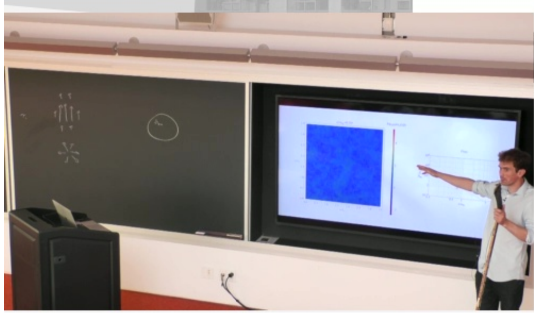
End the simulation once the soliton cores are no longer resolved

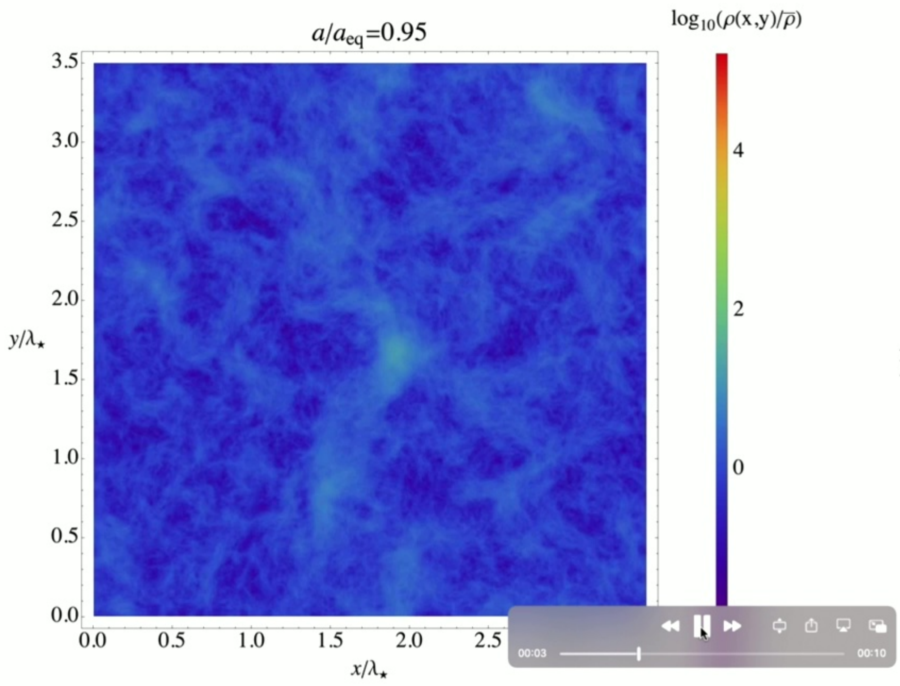


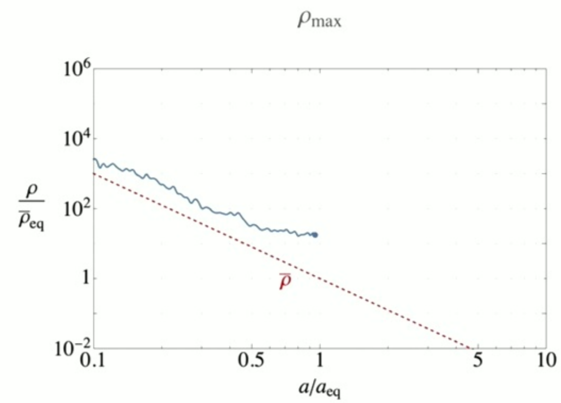
a/a_{eq}=0.10
$\log_{10}(\rho(x,y)/\bar{\rho})$
$y/\lambda_\star$
$x/\lambda_\star$
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
4
2
0
−2

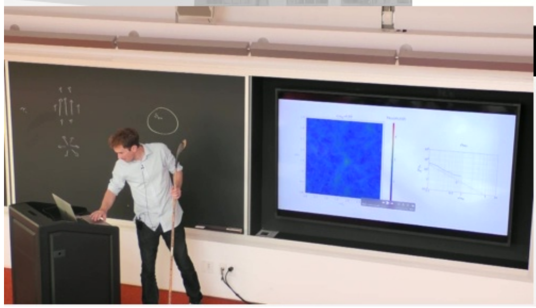


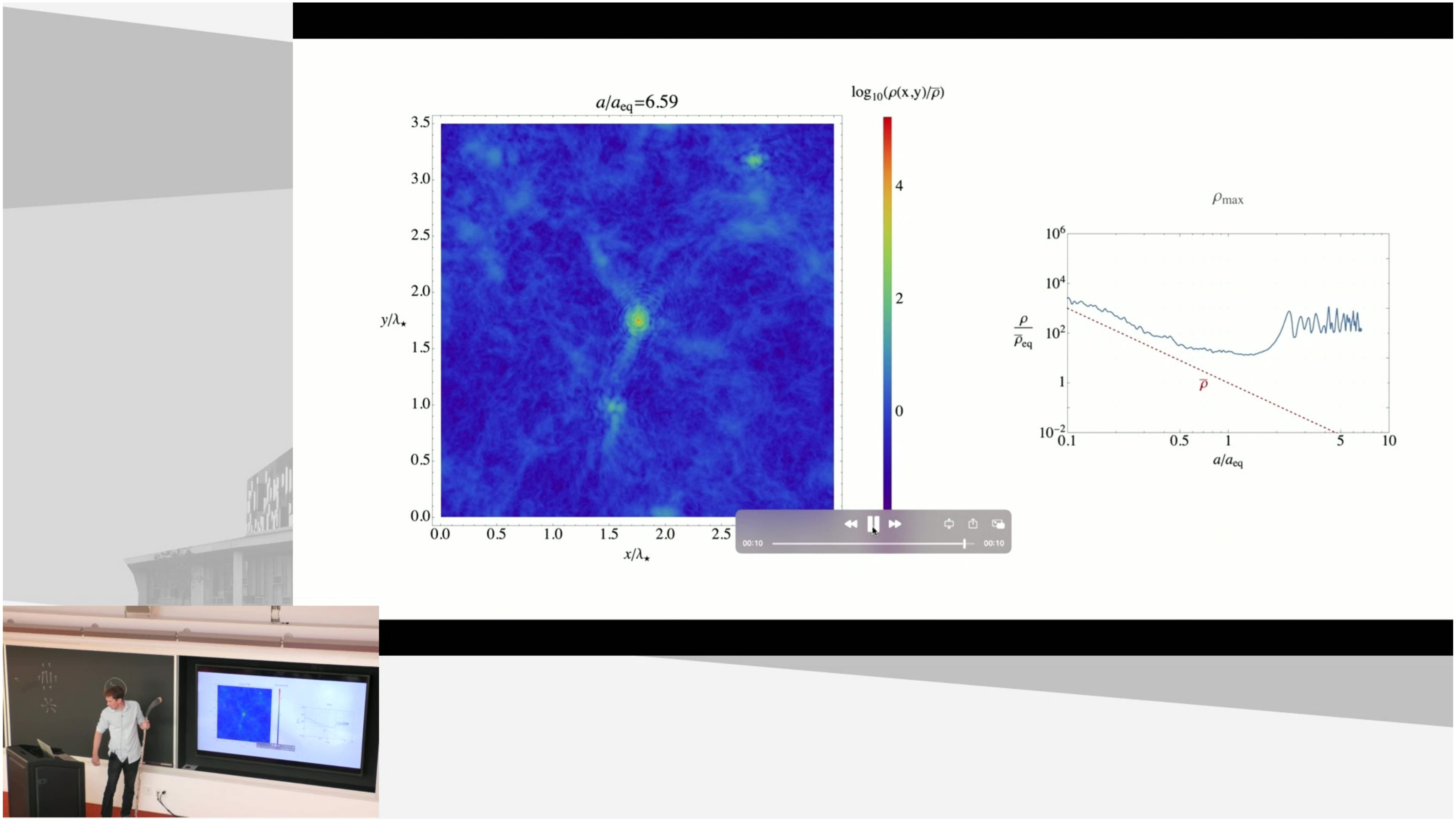
ρ_{max}
$\frac{\rho}{\bar{\rho}_{eq}}$
10^6
10^4
10^2
1
10^{-2}
$\bar{\rho}$
0.1 0.5 1 5 10
a/a_{eq}



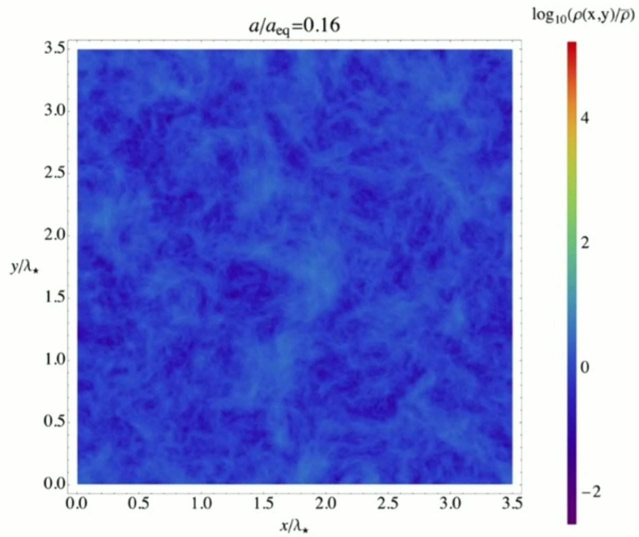

a/a_{eq}=0.95
$\log_{10}(\rho(x,y)/\bar{\rho})$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$y/\lambda_\star$
0.0
0.5
1.0
1.5
2.0
2.5
$x/\lambda_\star$
4
2
0
00:03
00:10

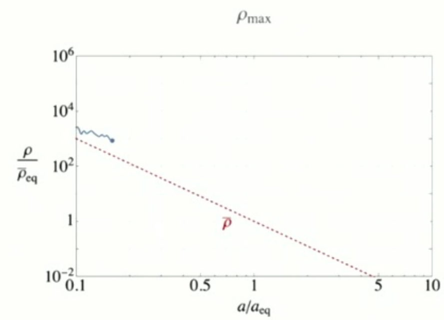

ρ_{max}
10^6
10^4
10^2
1
10^{-2}
$\frac{\rho}{\bar{\rho}_{eq}}$
$\bar{\rho}$
0.1
0.5
1
5
10
a/a_{eq}



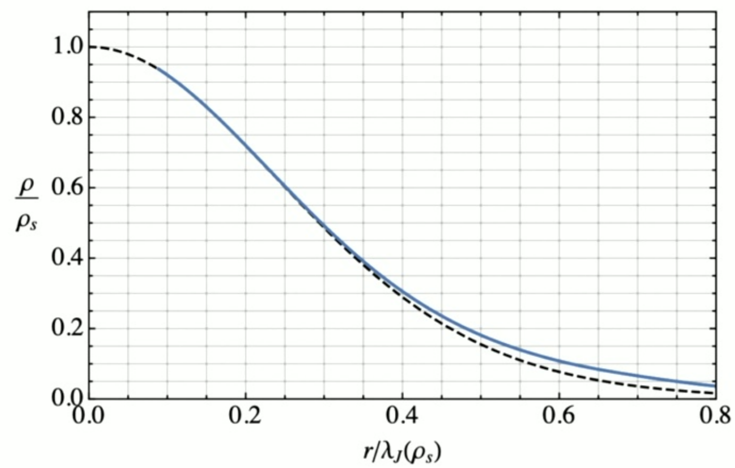

a/a_{eq}=6.59
$\log_{10}(\rho(x,y)/\bar{\rho})$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$y/\lambda_\star$
0.0
0.5
1.0
1.5
2.0
2.5
$x/\lambda_\star$
4
2
0
00:10
00:10
ρ_{max}
10^6
10^4
10^2
1
10^{-2}
$\frac{\rho}{\bar{\rho}_{eq}}$
$\bar{\rho}$
0.1
0.5
1
5
10
a/a_{eq}

Simulations

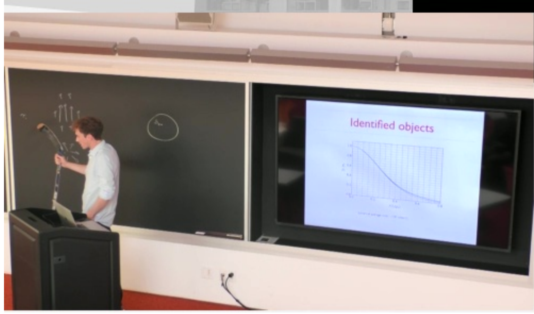




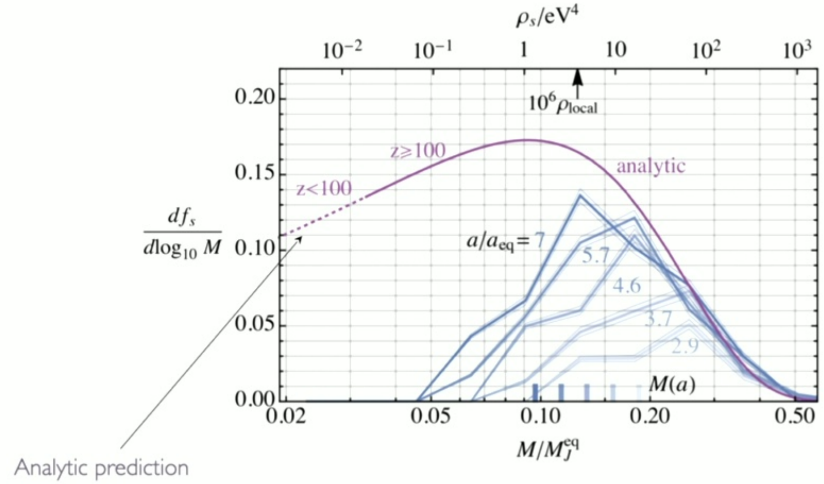
Identified objects



Spherical average over ~100 objects

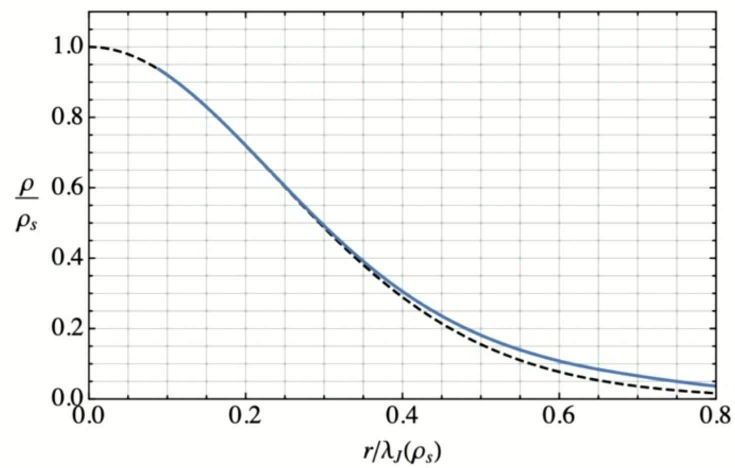


Mass distribution

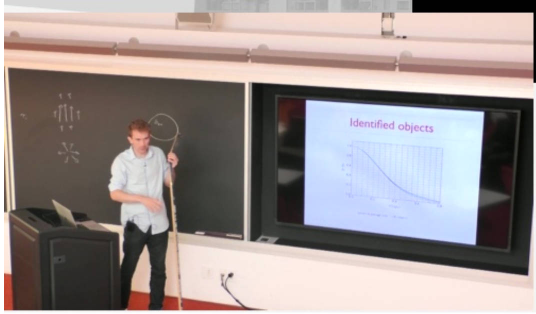


$$M_J(a_{\text{eq}}) \simeq 1.6 \cdot 10^{-15} M_\odot \left(\frac{10^{-5}\ \text{eV}}{m}\right)^{\frac{3}{2}} \qquad \lambda_J(\bar{\rho}(a_{\text{eq}})) \simeq 10^6\ \text{km} \left(\frac{10^{-5}\ \text{eV}}{m}\right)^{\frac{1}{2}}$$

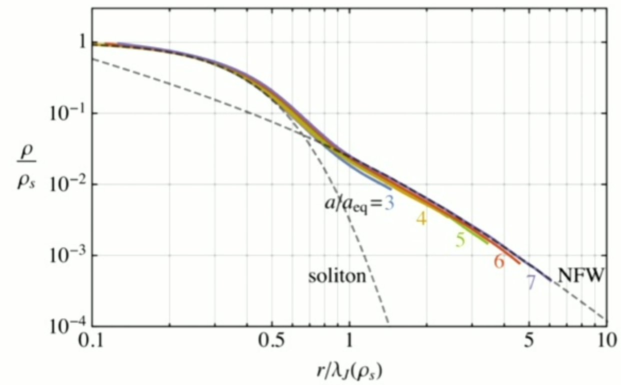
Identified objects



Spherical average over ~100 objects



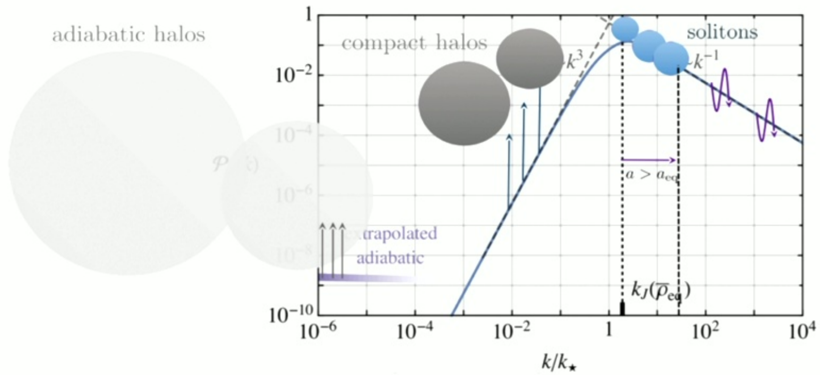
Fuzzy halos



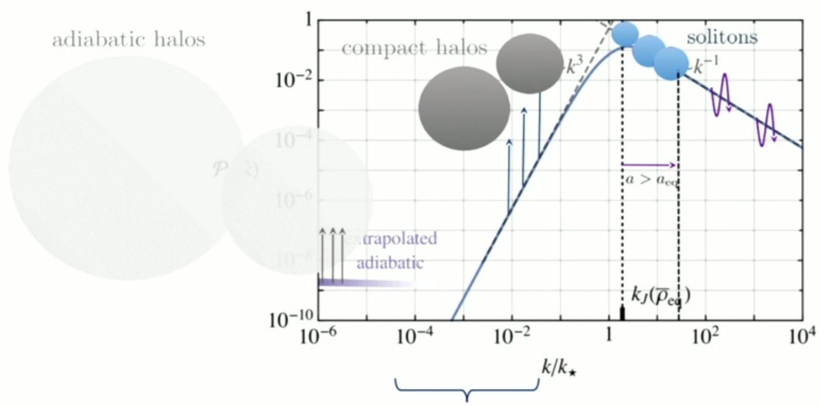
$\lambda_J(a_{eq}) \simeq 10^6\,\text{km}\left(\frac{10^{-5}\,\text{eV}}{m}\right)^{\frac{1}{2}}$

- Soliton exact solution only in vacuum
- 'Fuzzy' halo follows an NFW profile

Compact Halos vs Solitons



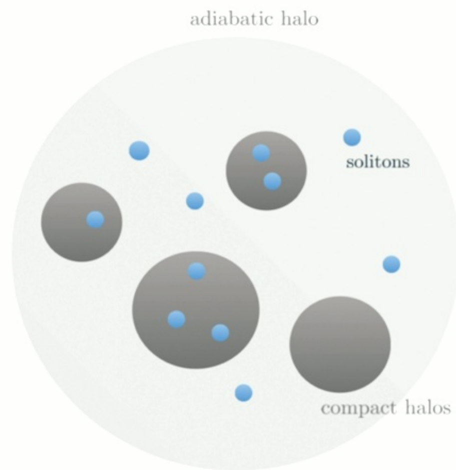
Compact Halos vs Solitons



Collapse at $a \gg a_{eq}$ and quantum pressure is not relevant

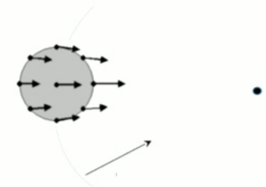
- Into compact halos
- Contain some of the solitons
- At $z \simeq 20$ adiabatic modes become non-perturbative $\equiv$ normal structure formation

Compact Halos vs Solitons

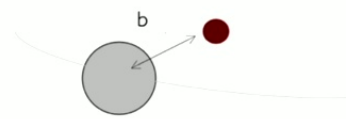


Survival of the substructure

- Tidal forces by a central potential
- Dynamical friction $\Longrightarrow$ orbit decay



- Collisions with stars



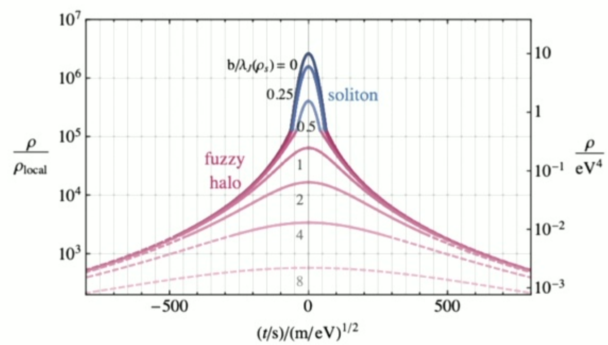
- Tidal shocks by galactic disk
- Tidal shocks during formation of halos/ merging

Encounter rate with the Earth

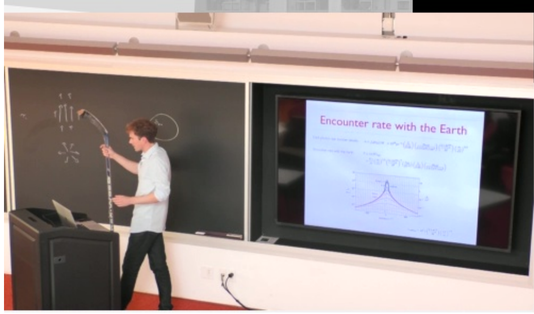
Dark photon star number density $\quad n = f_s \bar{\rho}(t_0)/M \simeq 10^{20}\mathrm{pc}^{-3}\left(\frac{f_s}{0.05}\right)\left(\frac{\rho_{\rm local}}{0.5\,\mathrm{GeV/cm^3}}\right)\left(\frac{0.1 M_J^{\rm eq}}{M}\right)\left(\frac{m}{\mathrm{eV}}\right)^{3/2}$

Encounter rate with the Earth $\quad \Gamma \simeq n\pi R^2 v_{\rm rel}$

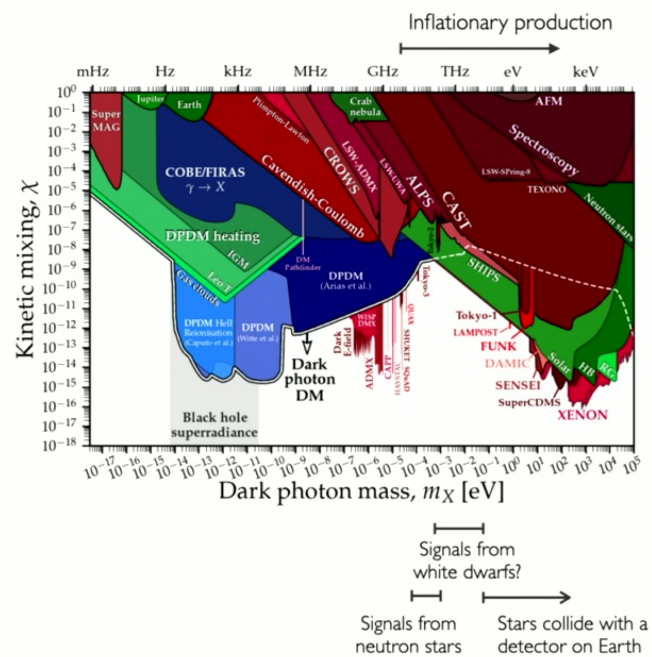
$$\simeq \frac{0.1}{\mathrm{yr}}\left(\frac{m}{\mathrm{eV}}\right)^{1/2}\left(\frac{0.1M_J^{\rm eq}}{M}\right)^3\left(\frac{v_{\rm rel}}{10^{-3}}\right)\left(\frac{f_s}{0.05}\right)\left(\frac{\rho_{\rm local}}{0.5\,\mathrm{GeV/cm^3}}\right)$$



$$t_{\rm collision} \simeq 10^2\ \mathrm{s}\left(\frac{0.1M_J^{\rm eq}}{M}\right)\left(\frac{\mathrm{eV}}{m}\right)^{1/2}$$



Signals


Inflationary production
mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing, χ
Dark photon mass, m_X [eV]
Super MAG
Jupiter
Earth
Crab nebula
AFM
Spectroscopy
COBE/FIRAS
$\gamma \to X$
Cavendish-Coulomb
CROWS
ALPS
CAST
DPDM heating
IGM
Leo T
Gas clouds
DPDM HeII Reionisation
DPDM
DPDM
Dark photon DM
Black hole superradiance
SHIPS
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
XENON
Solar
HB
RG
Neutron stars
TEXONO
ADMX
Signals from white dwarfs?
Signals from neutron stars
Stars collide with a detector on Earth


Signals

Other production mechanisms

Dark photon

- Inflationary fluctuations
- From local strings
- Parametric resonance

Axion

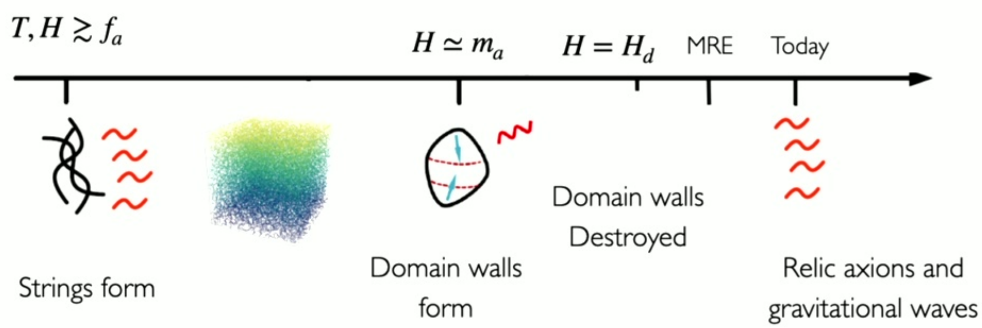
- Post-inflationary ALP
- Axion coupled to dark photon

The time when $H = m$ plays a key role in all of these

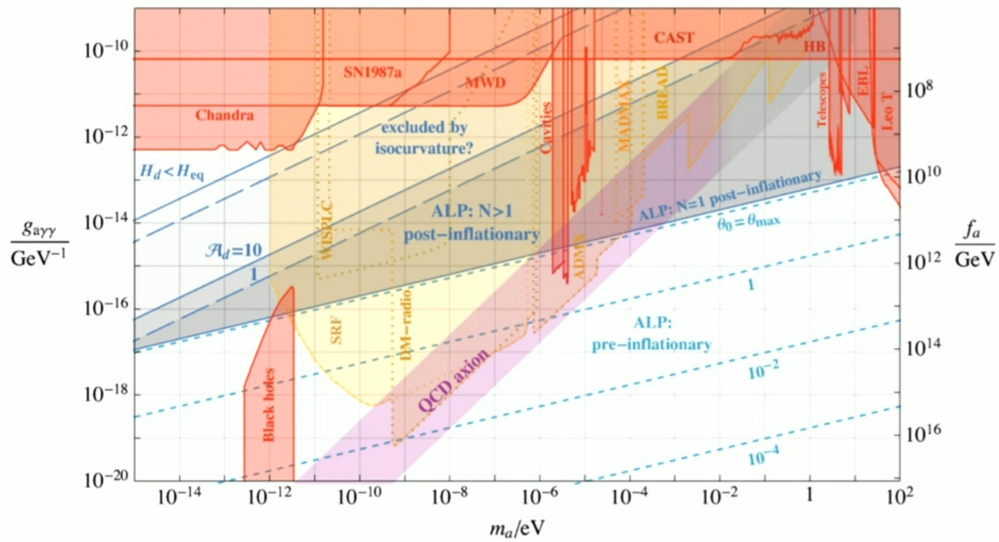
Post-inflationary ALPs

$$V_\phi(\phi) = \frac{m_r^2}{2v^2}\left(|\phi|^2 - v^2\right)^2 + \dots$$

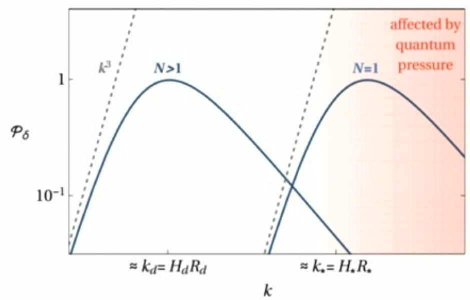
$$V(a) = m_a^2 f_a^2 \left(1 - \cos(a/f_a)\right) + \delta V_{PQ}(a)$$



Relic abundance



Density power spectrum

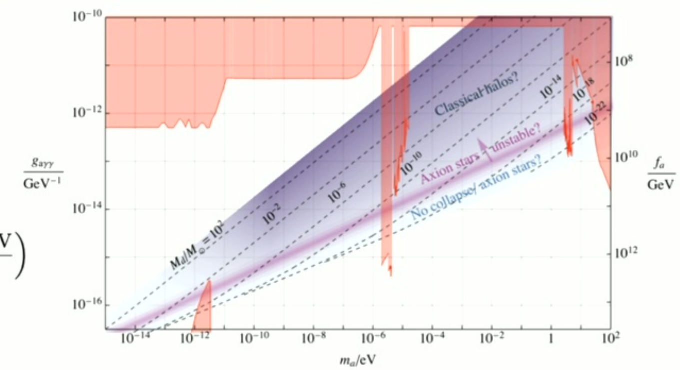


$$\frac{k_{\rm peak}}{k_J^{\rm eq}} \simeq \left(\frac{H_d}{m_a}\right)^{1/2}$$

$$M_d \simeq \;\; 3.5 \cdot 10^{-10} M_\odot A_d^{-3} \left(\frac{10^{12}\;\;\mathrm{GeV}}{f_a}\right)^6 \left(\frac{10^{-6}\;\;\mathrm{eV}}{m_a}\right)^3$$

$$V \supset g_4^2 m_a^2 a^4/(4! f_a^2)$$

$$M_{\rm crit} \simeq 50 \frac{f_a M_P}{m_a g_4} \simeq \frac{10^{-10} M_\odot}{g_4} \left(\frac{f_a}{10^{12}\;\;\mathrm{GeV}}\right) \left(\frac{10^{-6}\;\;\mathrm{eV}}{m_a}\right)$$



Conclusions

- Wave-like dark matter can have interesting substructure
- Dark photon produced by inflationary fluctuations provides a minimal, easily calculable, theory
- Solitonic `dark photon stars' automatically form at matter radiation equality
- Contain roughly 5 to 10% of the dark matter abundance and likely to survive to the present day

Future:

- Possible observational signals
- Similar dynamics for other dark photon production mechanisms, also for axions/ axion-like-particles

Conclusions

- Wave-like dark matter can have interesting substructure
- Dark photon produced by inflationary fluctuations provides a minimal, easily calculable, theory
- Solitonic `dark photon stars' automatically form at matter radiation equality
- Contain roughly 5 to 10% of the dark matter abundance and likely to survive to the present day

Future:

- Possible observational signals
- Similar dynamics for other dark photon production mechanisms, also for axions/ axion-like-particles

Thanks