

Darkest Before Dawn: Between Inflation and Thermalisation

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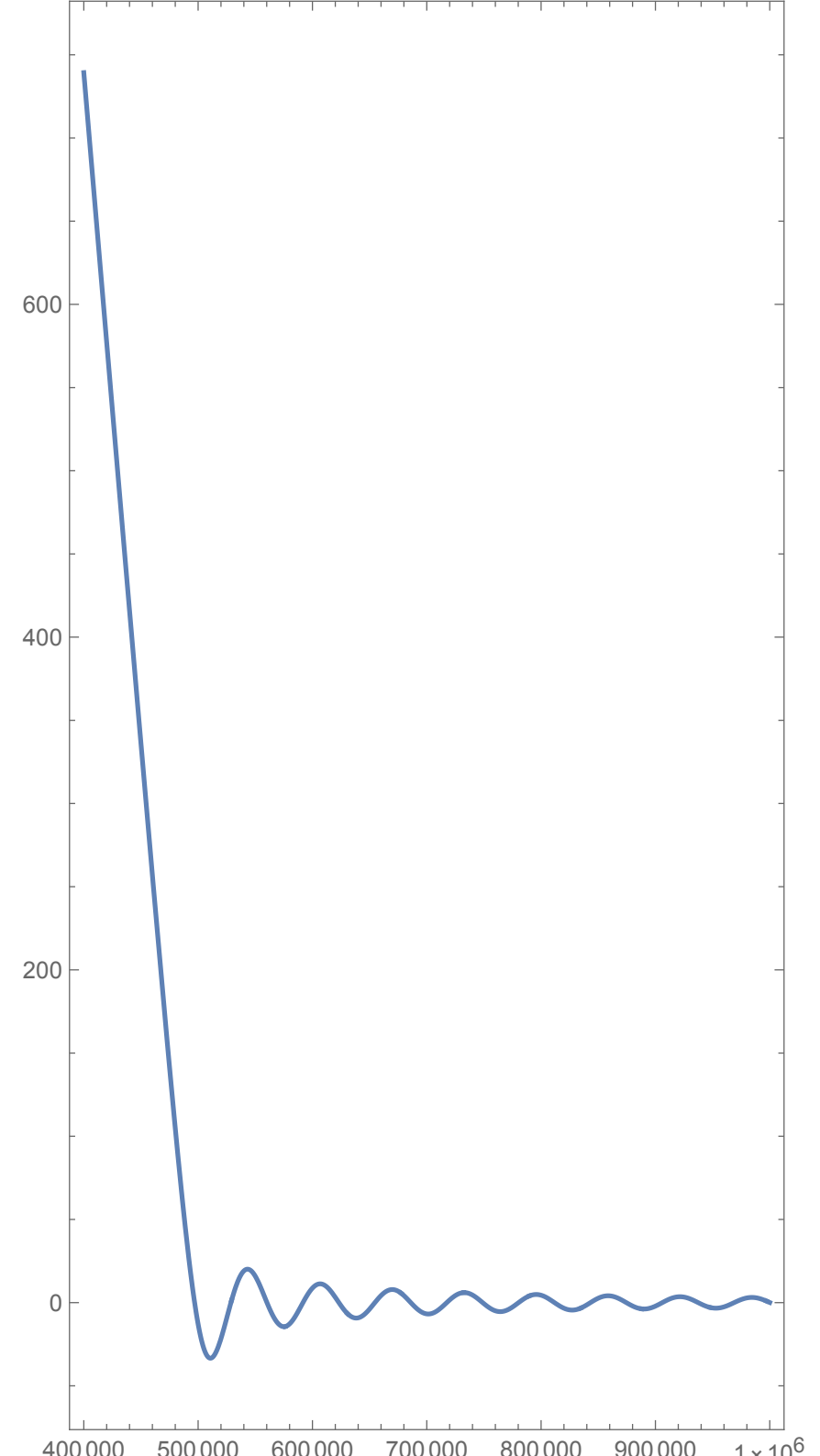
Post-inflationary Dynamics

- ▶ Inflation needs roughly 10^{-30} seconds
 - ▶ During the next 10^{-12} seconds universe may grow 10^{15} times larger
 - ▶ At the end of this 10^{-12} seconds, interaction energies $\sim$ LHC scales
 - ▶ Very large growth, in a very short time, obeying “unknown physics”
- ▶ Given a simple inflationary model, we do (roughly) know how it ends...
 - ▶ Almost homogeneous inflaton condensate
 - ▶ Quadratic minimum: condensate naively behaves like pressureless matter
- ▶ Will assume no quick reheating into standard model particles
 - ▶ Plus dark matter and baryogenesis

Field couplings / Gravity	No inflaton interactions	Inflaton interactions
No local gravitational potentials	Damped Oscillator 1982 physics Slow thermalisation	Klein-Gordon Resonance Oscillons High frequency GW
Local gravitational potentials	Schrodinger-Poisson “Large scale” structure formation Low frequency GW	?

Post Inflation

- ▶ After inflation, universe *reheats*
 - ▶ Originally assumed to be driven by inefficient quantum processes...
- ▶ H small but not zero
 - ▶ Field oscillates about origin
 - ▶ Lightly damped oscillator
 - ▶ Can show: $a(t) \propto t^{2/3}$
- ▶ Inhomogeneities, nonlinearities and local gravity ignored
 - ▶ Circa 1982



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Nonlinearity in the field

▶ Klein-Gordon equation: $-\Box\phi + \frac{dV(\phi)}{d\phi} = 0$

▶ $\frac{\partial^2}{\partial t^2}\phi - \frac{1}{a^2}\nabla^2\phi + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0$

▶ Driven by inflaton self-couplings or couplings to other fields...

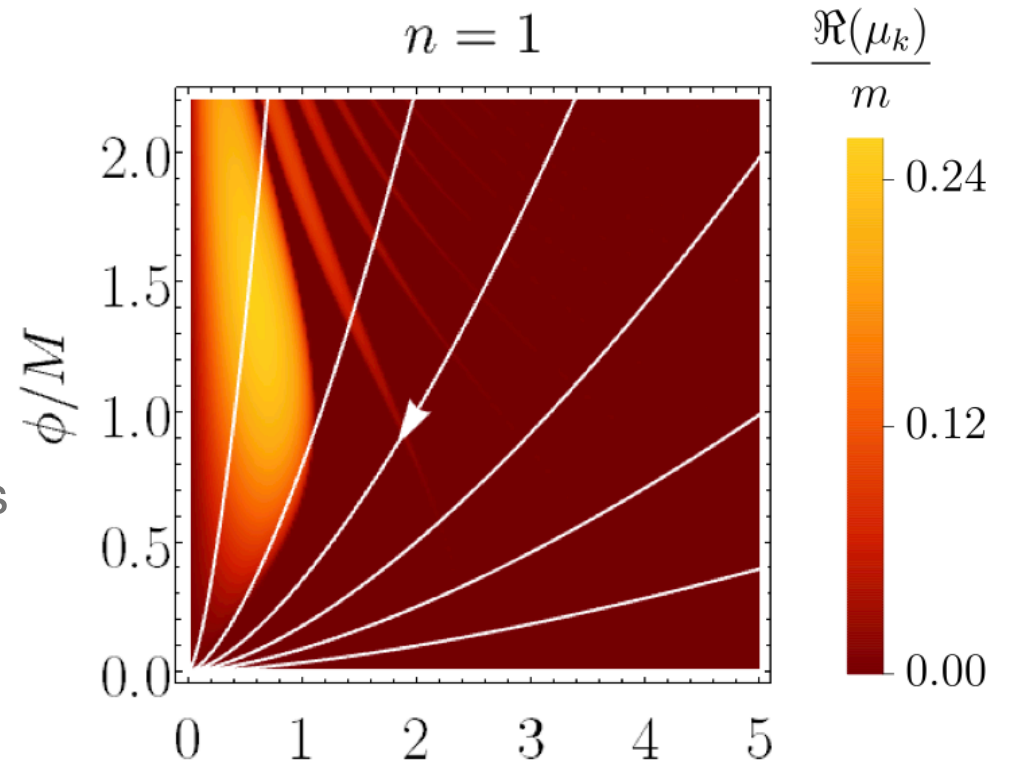
▶ “Parametric Resonance” or “Preheating”

▶ $\frac{\partial^2}{\partial t^2}(\phi_0 + \delta\phi_k) + \frac{k^2}{a^2}\delta\phi_k + 3H(\dot{\phi}_0 + \delta\dot{\phi}_k) + V_{,\phi}(\phi_0 + \delta\phi_k) = 0$

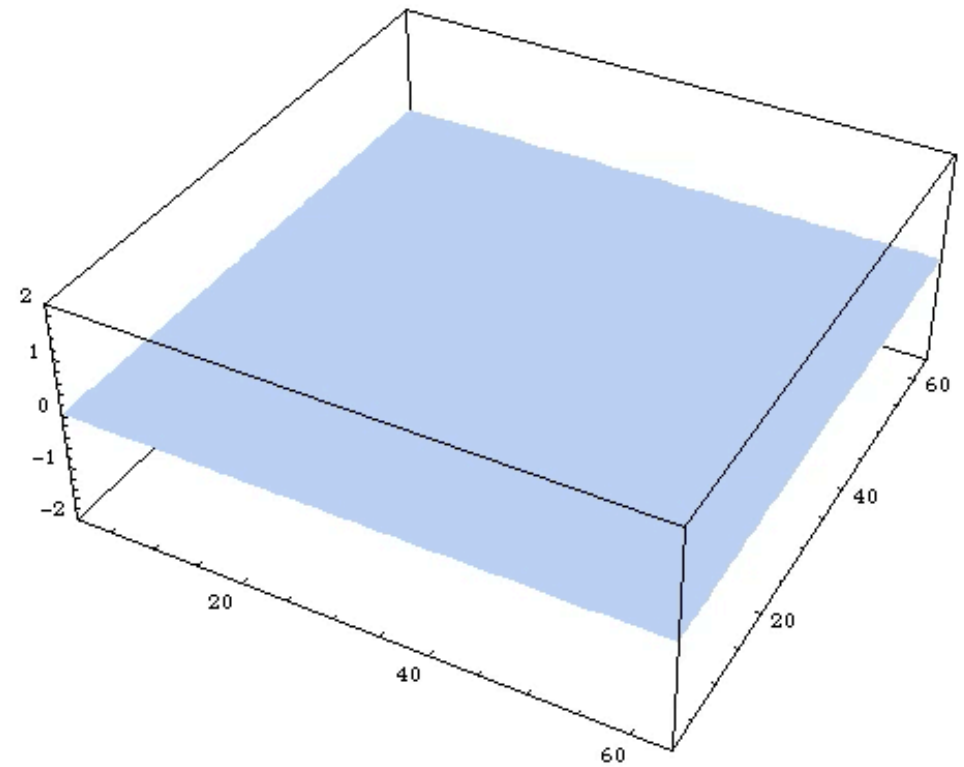
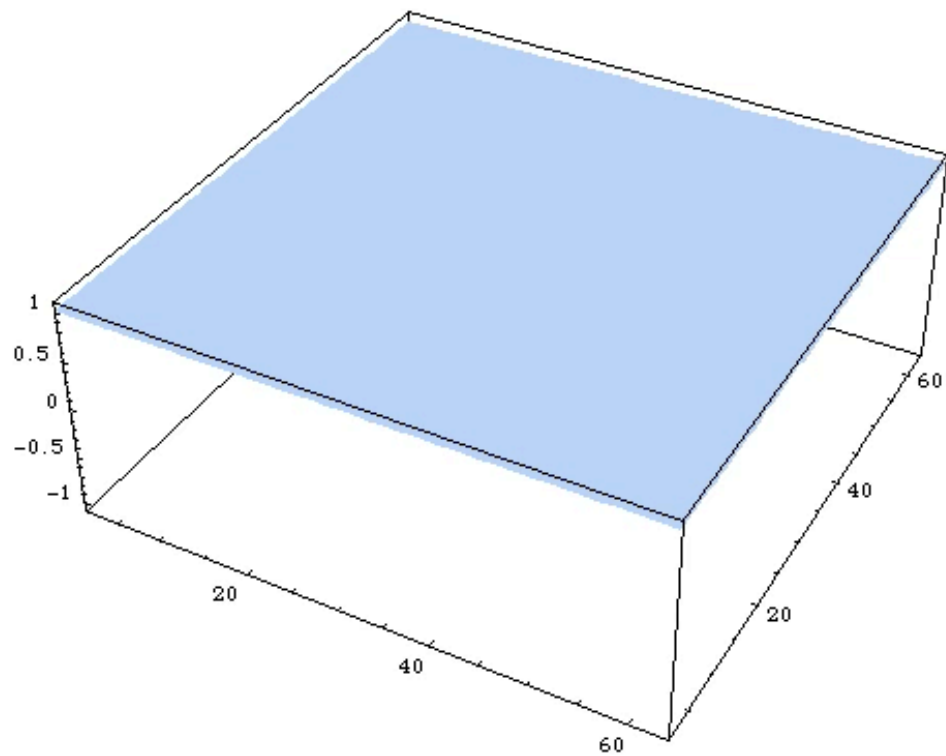
▶ $\frac{\partial^2}{\partial t^2}\delta\phi_k + \frac{k^2}{a^2}\delta\phi_k + V_{,\phi\phi}(\phi_0)\delta\phi_k = 0$

Explosive particle production

- ▶ $\delta\phi_k$ is effectively occupation number for corresponding momentum state
 - ▶ Modes in resonance grow exponentially
 - ▶ Akin to stimulated emission
- ▶ Modes move through resonance bands
 - ▶ And ϕ slowly decreases
- ▶ Condensate fragmented by resonance
- ▶ Dates back to early 90s
 - ▶ Inflaton and fields coupled to it...
- ▶ Sources gravitational waves



Amin and Losanov



Two field model: $\phi^2 \chi^2$

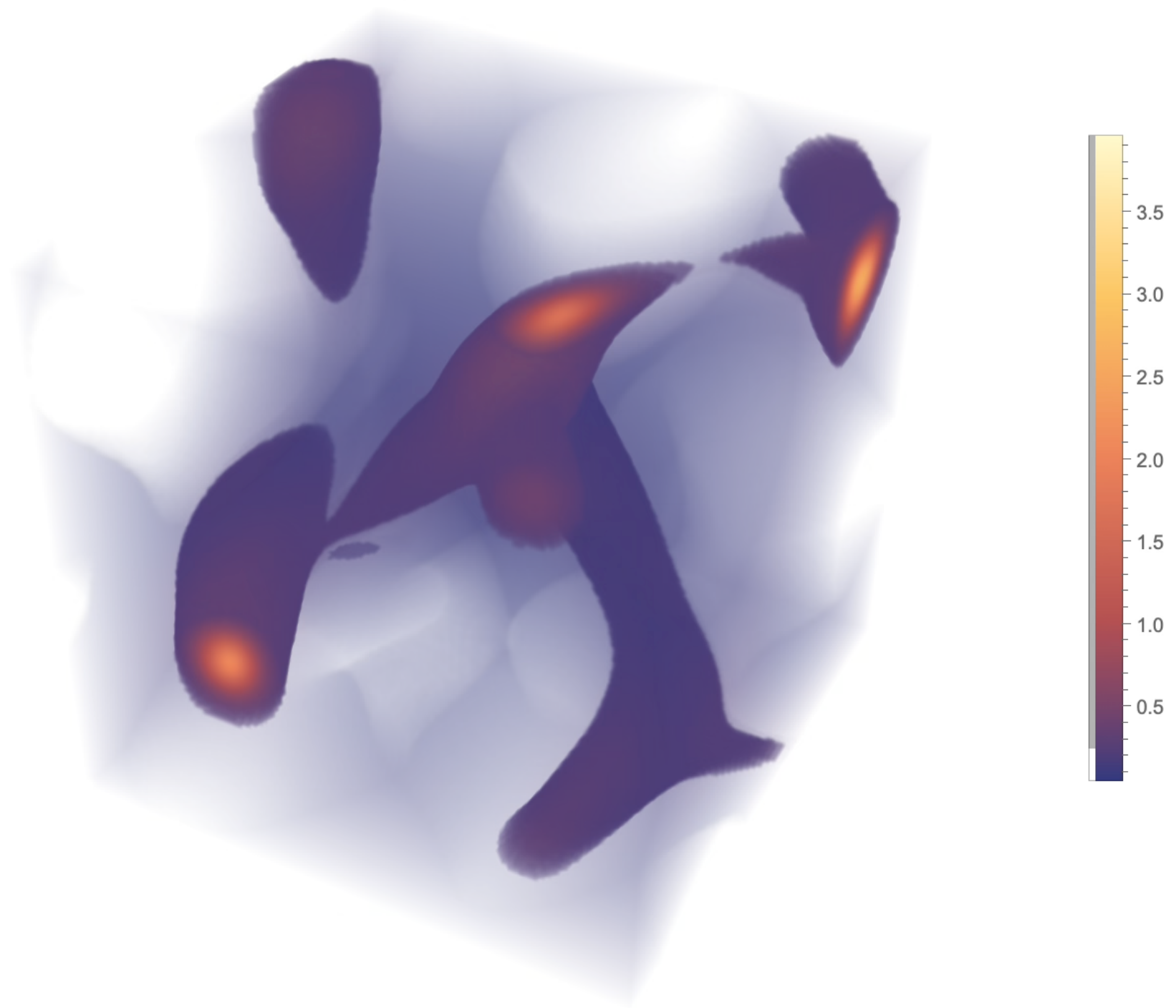
Oscillons

- ▶ “Breathers” in nonlinear field theories - nontopological (no conserved charge)
- ▶ Akin to classical “kink” solitons (e.g. the propagating tanh profile)
 - ▶ But effectively “jogging on the spot” $\phi \sim \Phi(r)\cos(\omega t)$
 - ▶ Or, more often $\phi \sim \Phi(r, t)\cos(\omega t)$ - period of Φ much bigger than $1/\omega$
- ▶ Key condition for existence of oscillons: potential sub-quadratic near origin
 - ▶ Studied since the 1970s
 - ▶ Bogolyubsky and Makhankov, Pisma Zh. Eksp. Teor. Fiz. 24, 15 (1976).
 - ▶ + Kolb, Gleiser, Copeland and others
- ▶ But just because solutions exist, will they actually be populated?

Monodromy Inflation

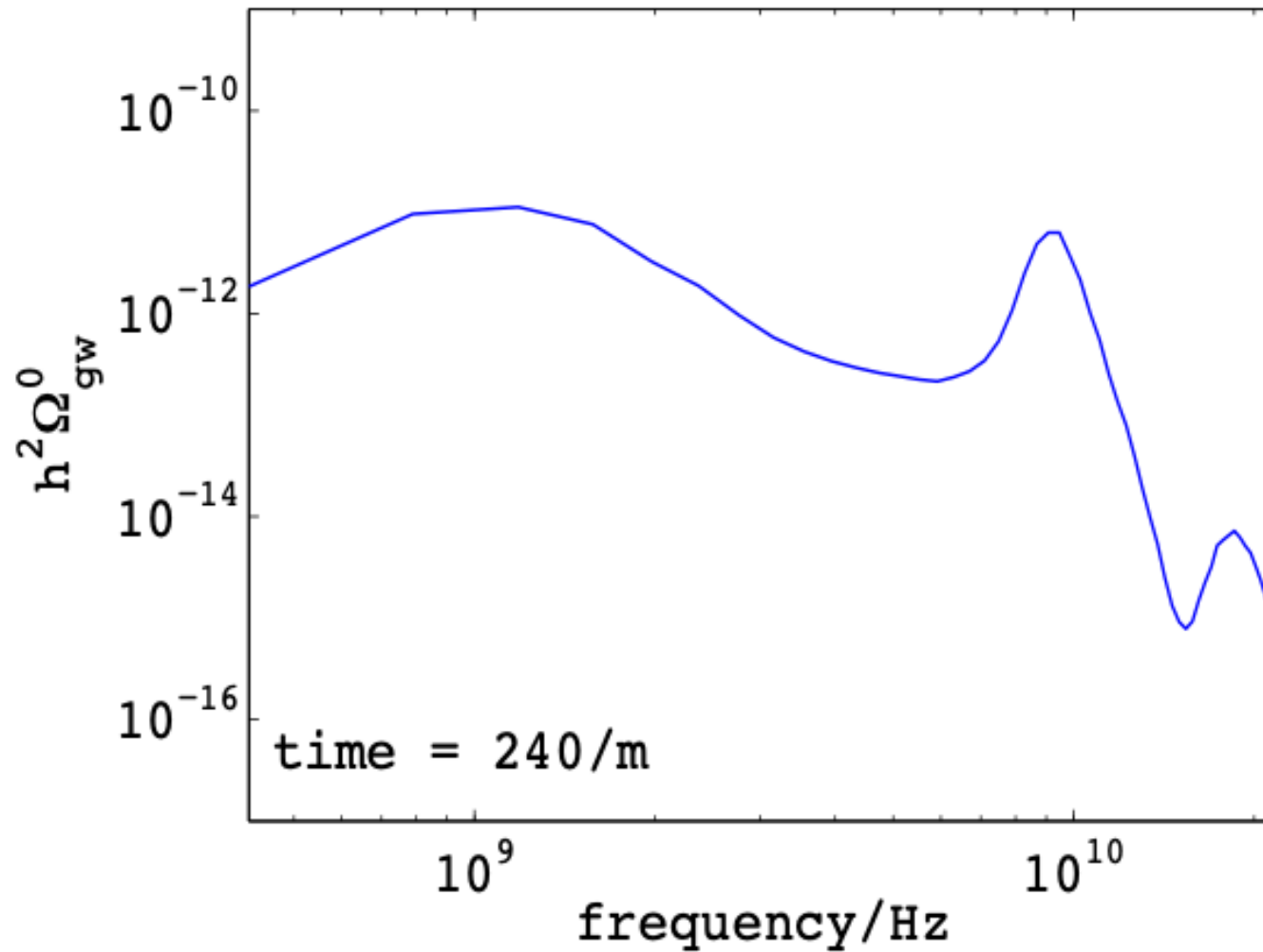
► Potential:
$$\frac{m^2 M^2}{2\alpha} \left[\left(1 + \frac{\phi^2}{M^2} \right)^{2\alpha} - 1 \right]$$

- Amin, Easter, Finkel, Flauger and Hertzberg arXiv:1106.3335
- Decent resonance, but also a relatively small gravitational wave background
 - Not small enough in 2026, but looked better in 2011...
- Well motivated model (as these things go, derived from stringy arguments)
 - *Naturally* produces oscillons for sub-Planckian M
 - Also vigorous gravitational wave production on GHz scales
- Suggests oscillons generic in models with strong resonance and low r



Resonance and Gravitational Waves

- ▶ Known since mid-90s that resonance can produce gravitational waves
 - ▶ Makes the contents of the universe lumpy and quickly changing
- ▶ Produces “classical” gravitational waves
 - ▶ As opposed to an inflationary background, which only exists if $\hbar \neq 0$
- ▶ See: Khlebnikov and Tkachev hep-ph/9701423 and
 - ▶ Easter, Giblin and Lim astro-ph/0601617, astro-ph/0612294
 - ▶ Garcia-Bellido and Figueroa astro-ph/0701014
 - ▶ Defaux, Bergman, Felder, Kofman and Uzan arXiv:0707.0875



Zhou, Copeland, Easter, Finkel, Mou and Saffin

Gravitational Waves
(In an oscillon model)

arXiv:1304.6094

Gravitational Waves from the Early Universe

- ▶ A great place to do a “blind” search...
 - ▶ Most things above roughly 10 kHz are “new physics”
 - ▶ So a great place to just go and look
- ▶ LIGO et al. are tuned to the most promising sources
 - ▶ If you have have never seen a gravitational wave it makes sense to look where they are most likely to be found
- ▶ But now maybe high frequency searches are worth doing?
 - ▶ But also technically challenging...
- ▶ See, e.g. Roshan and White arXiv:2401.04388
 - ▶ High Frequency Gravitational Waves Working Group arXiv:2501.11723

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Gravitational Collapse...

Back to quadratic inflation...

- ▶ Pressureless matter corresponds to the era of galaxy formation
 - ▶ Well understood (if we ignore questions about what dark matter actually is)
- ▶ 2010: people looked at the detailed dynamics (26 years late?)
 - ▶ Jedamzik, Lemoine and Martin arXiv:1002.3278
 - ▶ Easter, Flauger and Gilmore arXiv:1003.3011
- ▶ Showed that gravitational collapse will happen before reheating
- ▶ Hard to simulate: the “fast” timescale does not change as universe expands
- ▶ New phenomenology in a very, very simple model
 - ▶ Oddly, it took a long time to see this...

Schrodinger-Poisson Limit

- ▶ Write the metric + perturbations in Newtonian gauge

- ▶ $ds^2 = -(1 + 2\Phi)dt^2 + a^2(t)(1 - 2\Phi)\delta_{ab}dx^a dx^b$

- ▶ Write the inflaton as

- ▶ $\phi = \frac{1}{ma^{3/2}} (\psi e^{-imt} + \psi^* e^{imt})$

- ▶ And make a series of WKB-like approximations to get

- ▶ Schrodinger: $i\dot{\psi} = -\frac{1}{2ma^2} \nabla^2 \psi + m\psi\Phi$

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

Gravitational Collapse in Early Universe

- ▶ Auckland and Gottingen groups
 - ▶ Musoke, Easter and Hotchkiss
- ▶ Leads to the formation of *solitons*
 - ▶ Gravity + “quantum pressure”
- ▶ Possible primordial black holes?
- ▶ Maps to “ultralight dark matter”
 - ▶ Very low mass particles
 - ▶ We had codes for this already
- ▶ Gravitational wave signals...
- ▶ + Amin and Mocz arXiv:1902.07261

PHYSICAL REVIEW LETTERS

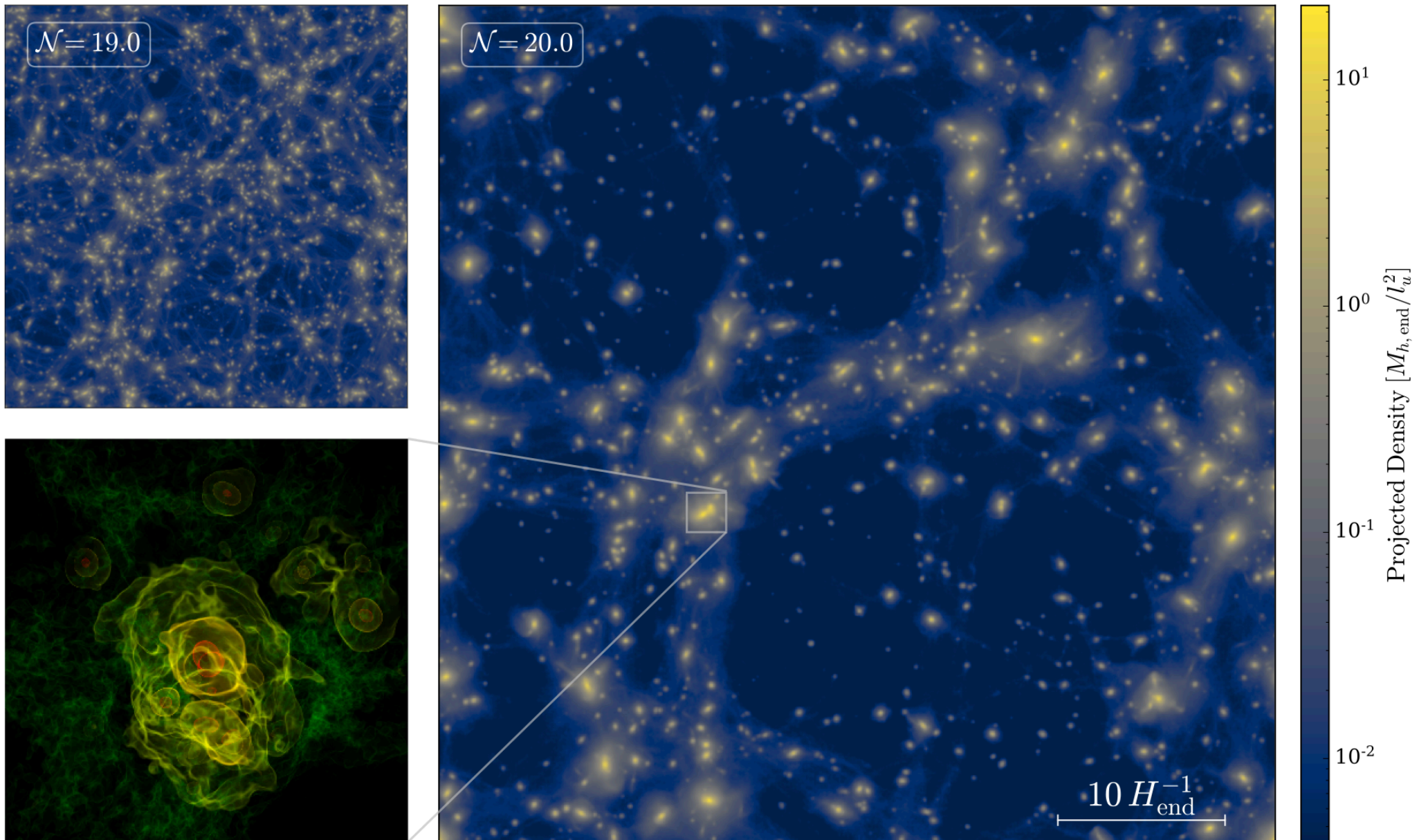
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arXiv:2011.13333

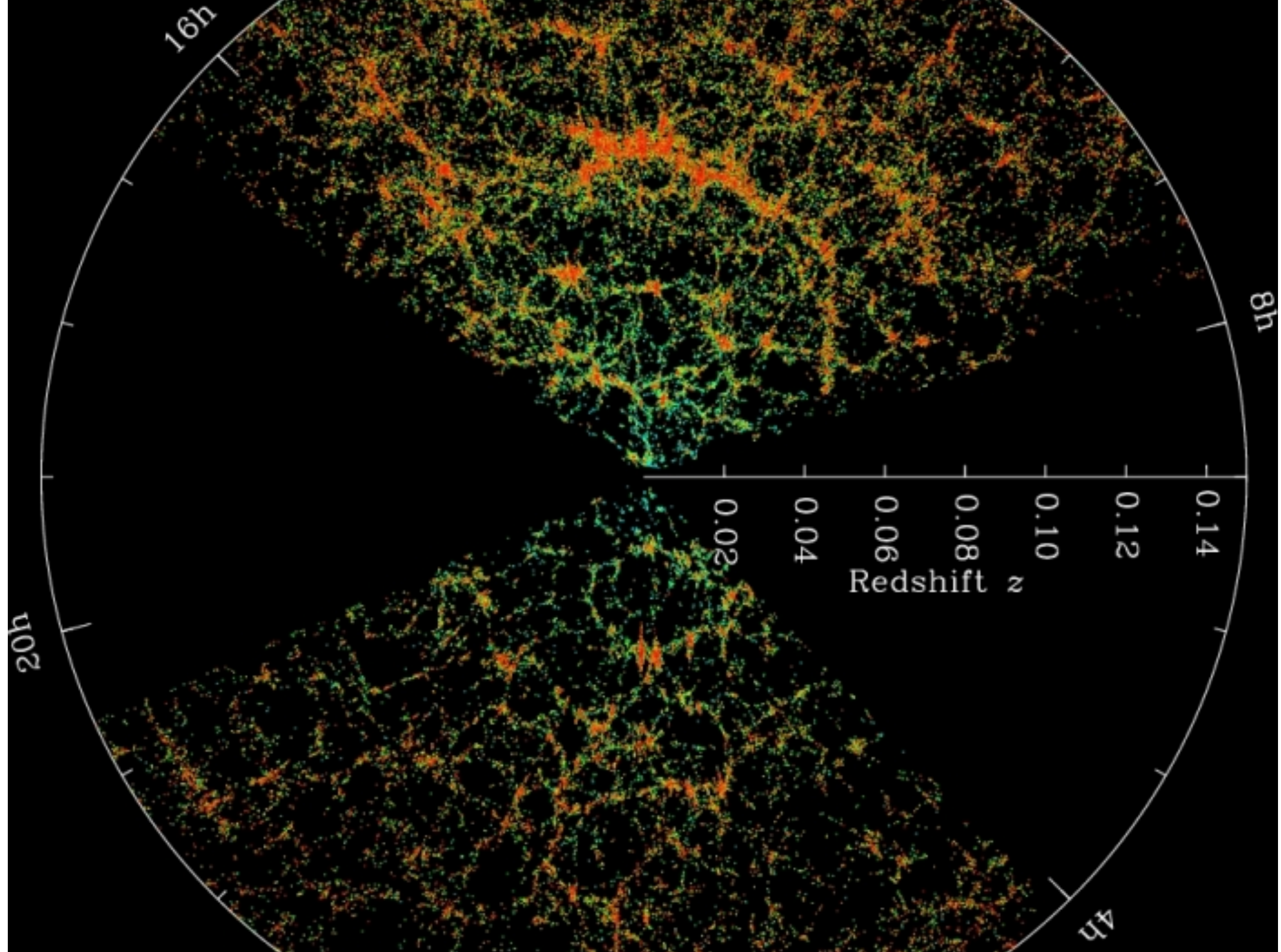
20 kg...

Early Structure Formation

- ▶ Universe can grow 10^{15} times larger between end of inflation and reheating
 - ▶ Present-day matter dominated phase has $\sim 10^4$ in growth
- ▶ In simple models $\delta\rho/\rho \sim 10^{-6}$ at end of inflation
 - ▶ But $\delta\rho/\rho \propto a(t)$ so after 10^6 worth of growth expect nonlinearity
 - ▶ And we still have another 10^9 up our sleeve
 - ▶ This nonlinear phase potentially much “longer” than present one
- ▶ Universe *can* reheat quickly if coupling permit/require it
 - ▶ And must thermalise at some point
 - ▶ But does thermalisation happen from an inhomogeneous state?

Next steps...

- ▶ Auckland - Göttingen collaboration (Jens Niemeyer)
- ▶ Inflaton halos and inflaton stars arXiv:1911.01661
 - ▶ Draws on parallel with fuzzy/ultralight dark matter
 - ▶ Used Press-Schechter formalism to predict growth of overdensities
- ▶ Get both halos (NFW-like) and “stars” — gravitational solitons
- ▶ Verified in Eggemeier, Niemeyer and Easter arXiv:2011.13333
 - ▶ Used AxioNyx — AMR-based Schrodinger-Poisson code
 - ▶ Simulated structure formation in the early universe
- ▶ Use tools from structure formation...



Gravitational solitons

- ▶ Ground state, stationary solution to the Schrodinger-Poisson equation

- ▶ Schrodinger: $0 = -\frac{1}{2m} \nabla^2 \psi + m\psi\Phi$

- ▶ Poisson: $\nabla^2 \Phi = 4\pi G |\psi^2|$

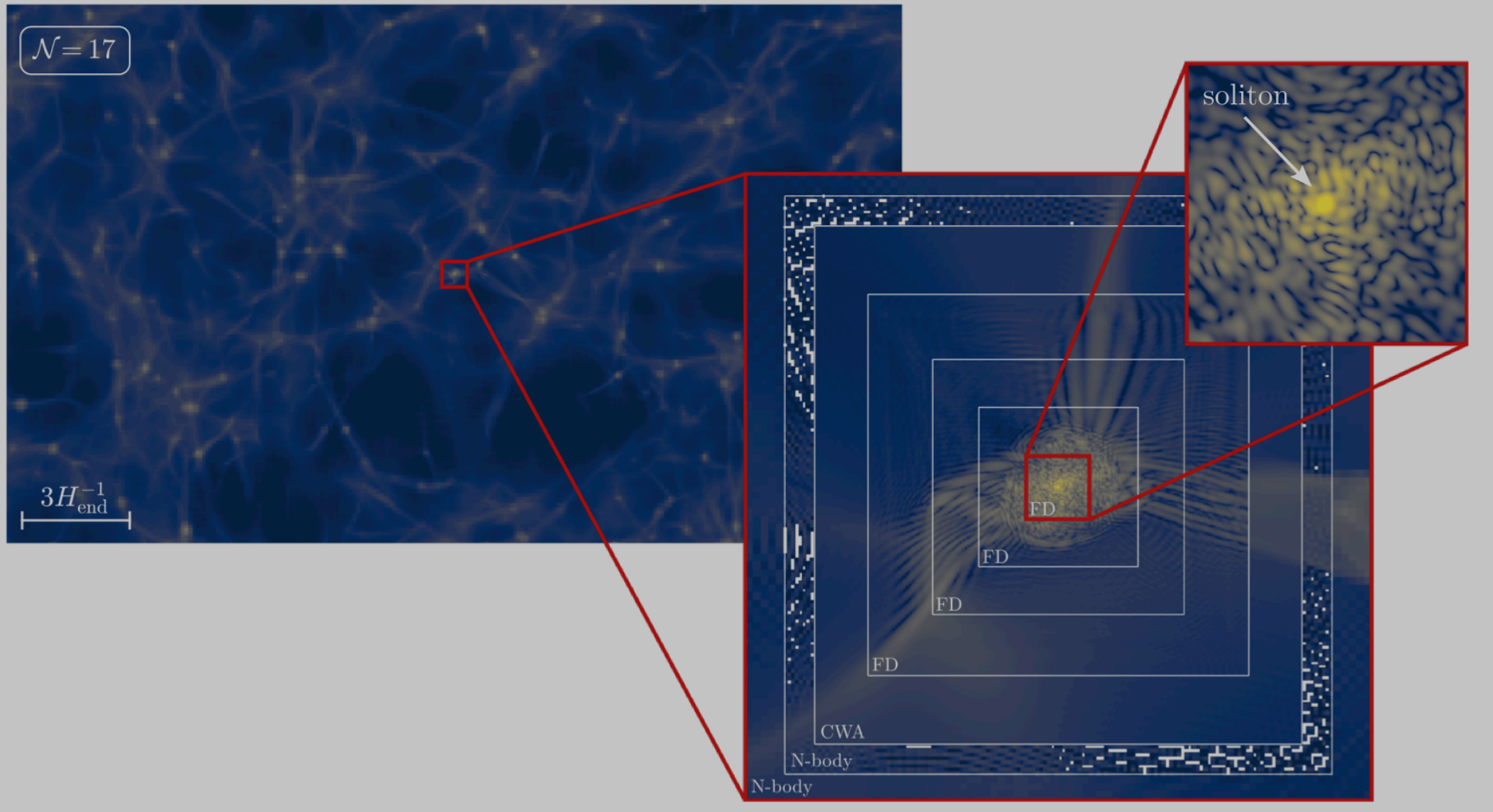
- ▶ No analytic solution

- ▶ But “generic” profile scales out total soliton mass and particle mass

- ▶ More massive solutions have a smaller radius

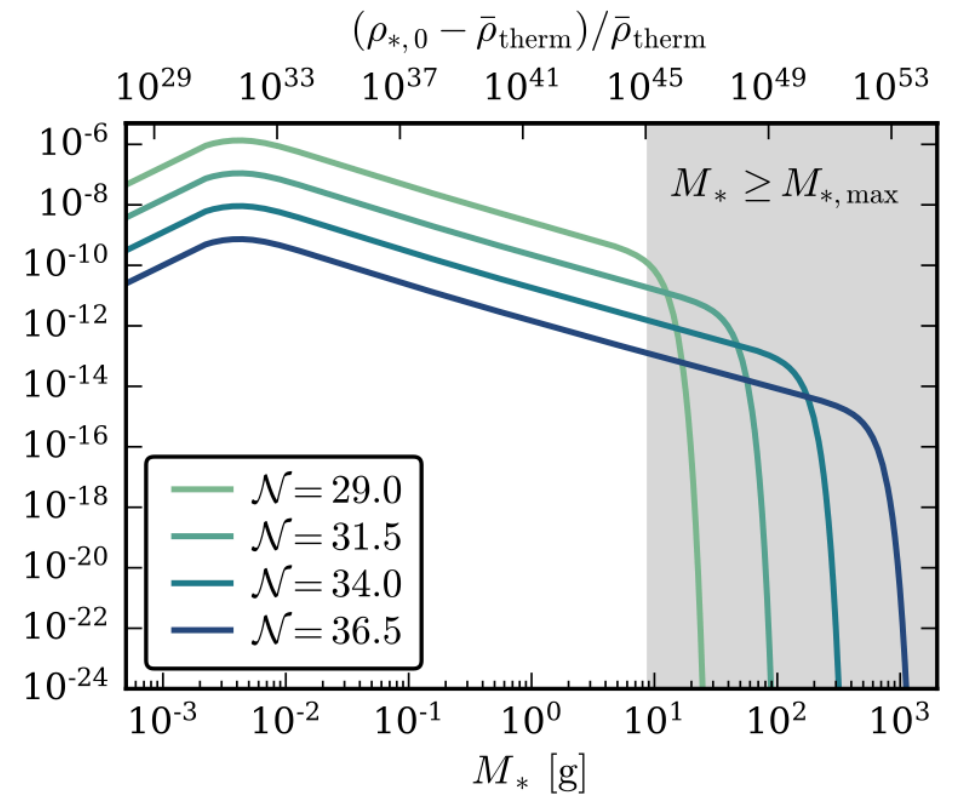
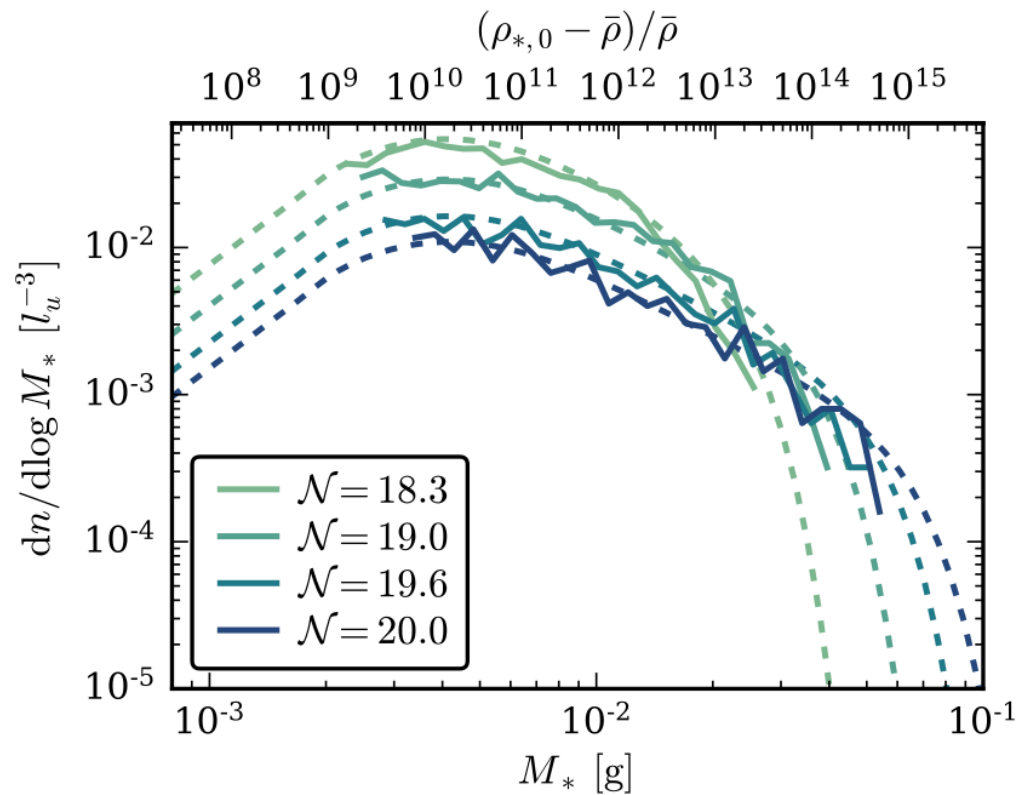
- ▶ Literature spread from mathematics to astrophysics

- ▶ Interested in their perturbations, normal modes

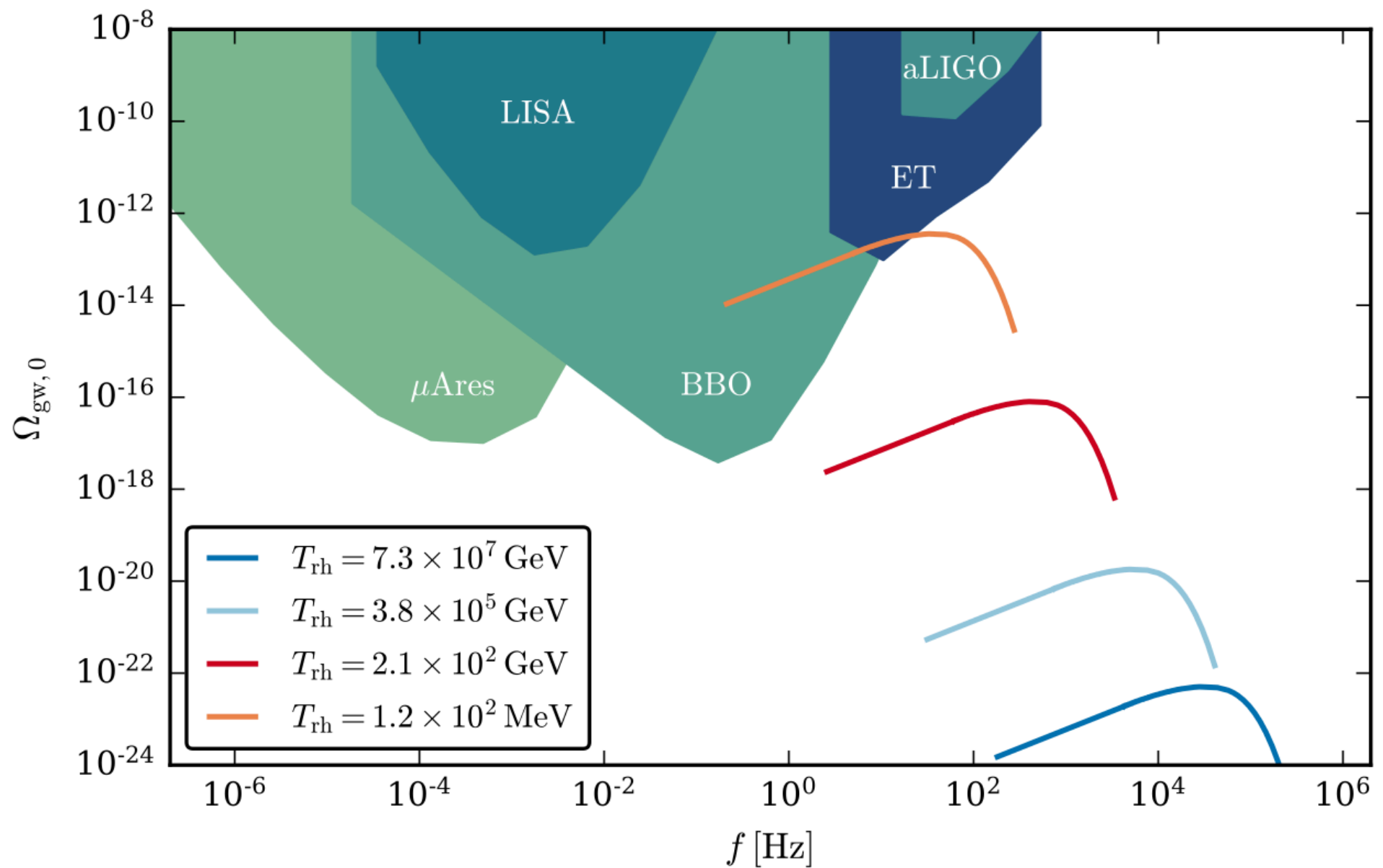


Eggemeier, Schwabe, Niemeyer and Easter....

arXiv:2110.15109



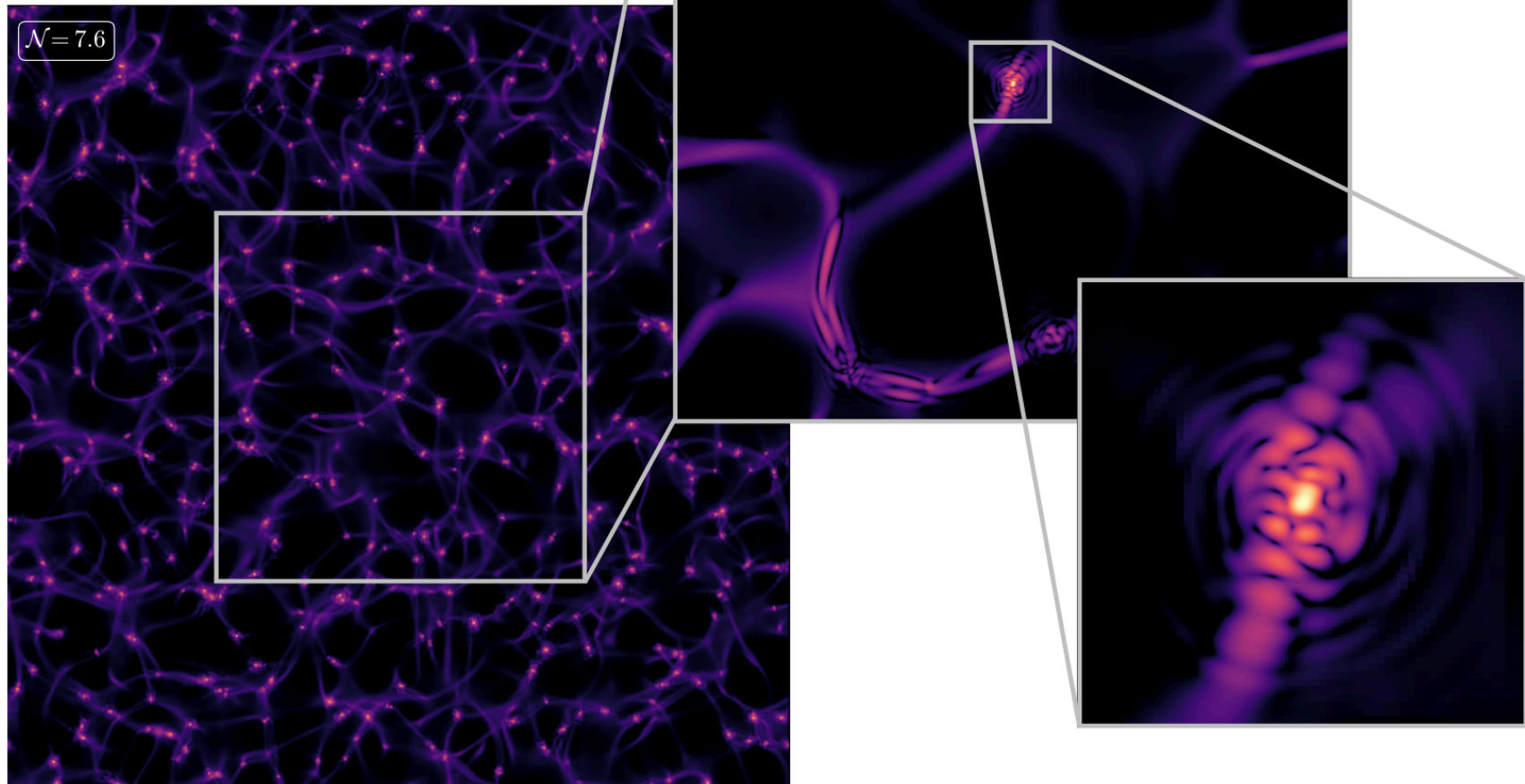
Press-Schechter in early
universe



Eggemeier, Niemeyer, Jedamzik and Easter....

arXiv:2311.08780

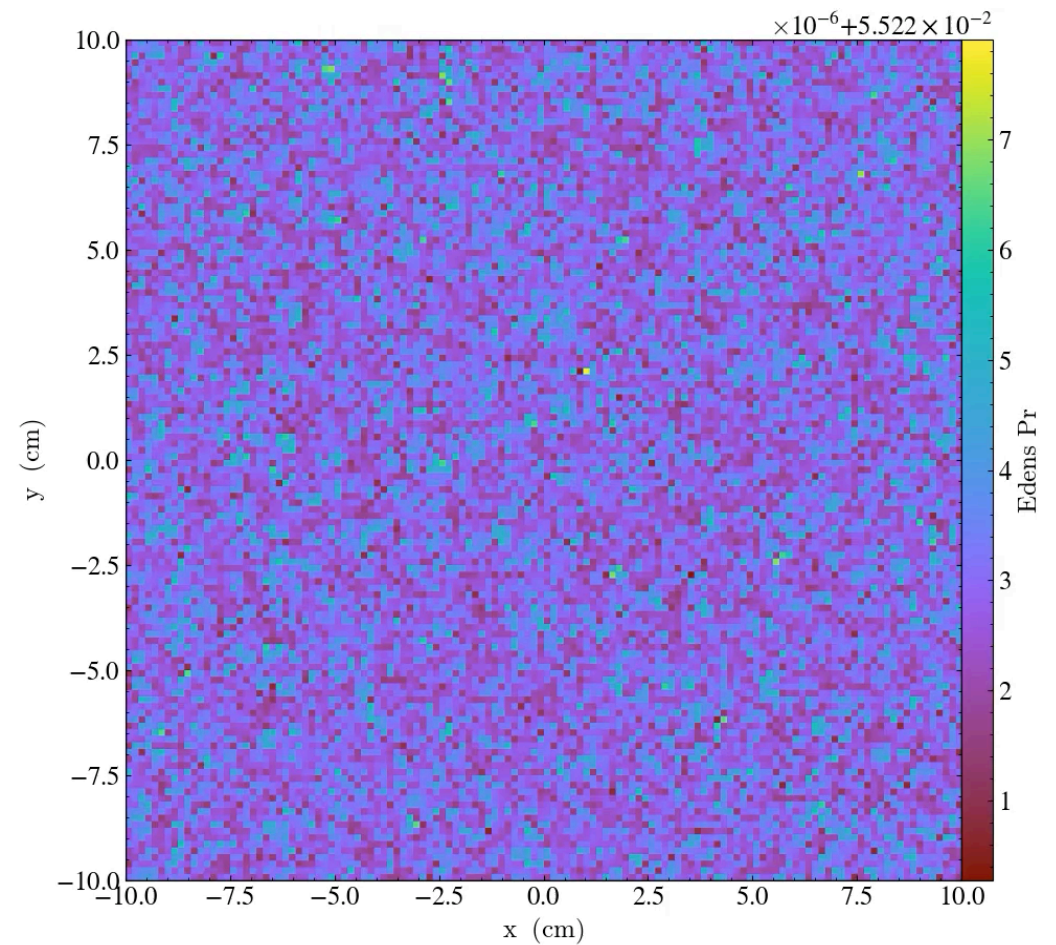
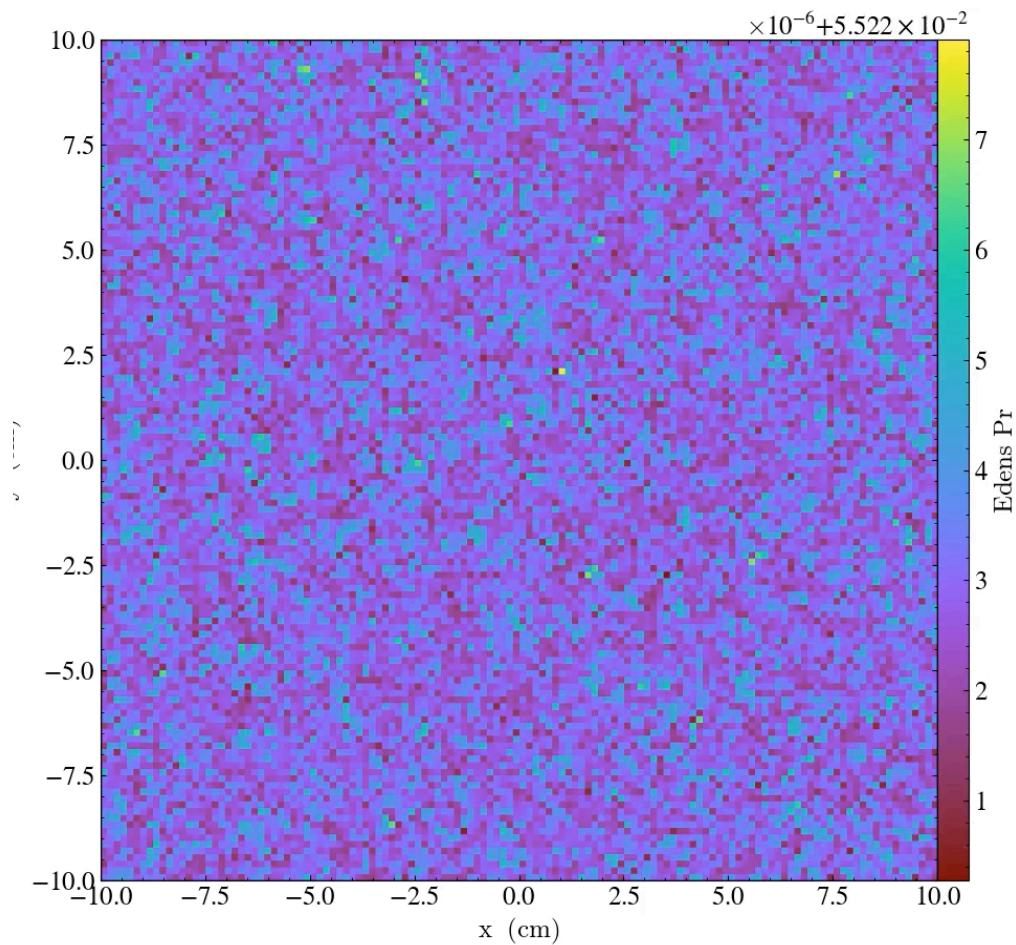
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Post Resonance Collapse

Accelerated gravitational collapse

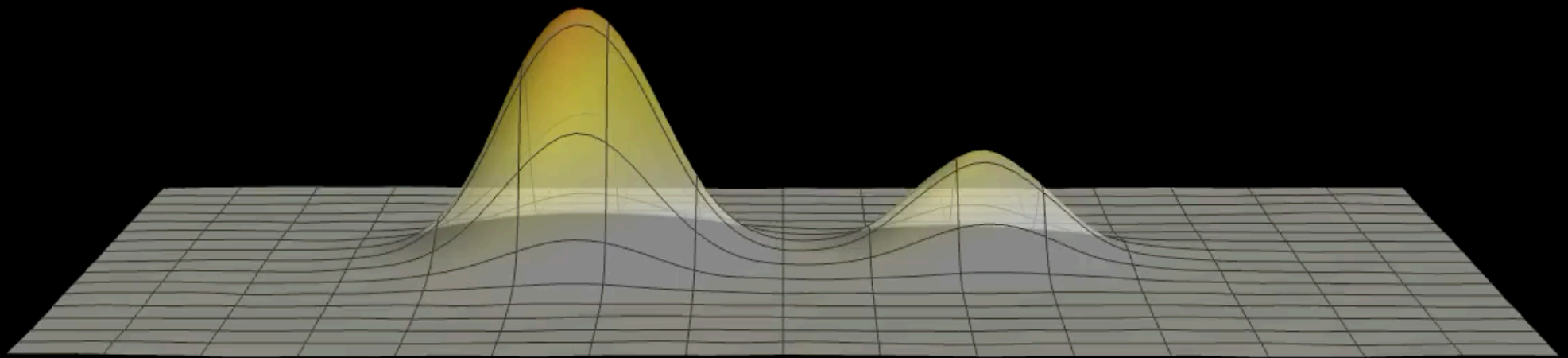
Eggemeier, Hayman, Niemeyer
and Easter arXiv:2311.08780



Preliminary!!

Oscillon Dynamics with
Local Gravity

L Southey-Ray



“Artificial” oscillon collision

Xue, Chen, Verzyde, Hayman, Easter

2510.01597

Consequences...

- ▶ Studying oscillon formation / resonance with local gravity
 - ▶ Working in the perturbative limit...
 - ▶ Done in full GR but too expensive for large scale / long term simulations
- ▶ Changes structure of resonance / oscillon population
 - ▶ Can potentially lead to oscillon collisions
- ▶ Interacting oscillons likely generate gravitational waves
 - ▶ Gravitational wave background from oscillon generated diluted by subsequent matter dominated expansion
 - ▶ Long oscillon-dominated phase rebuilds gravitational wave background

Soliton Structure

- ▶ Solitons appear in ultralight dark matter structure formation simulations
 - ▶ Purely gravitational couplings
- ▶ We see analogous structures in the early universe
 - ▶ But realistic inflationary models have self couplings
 - ▶ Solitons grow with time (both mass and central amplitude)
 - ▶ Interactions become more important
- ▶ Solving the Gross–Pitaevskii equation
 - ▶ Summed interaction terms can have either sign
 - ▶ Different viable inflationary models have very different solitons

Lots of questions to answer

- ▶ Oscillons + gravity + long structure formation phase
- ▶ Interacting “wild” oscillons
- ▶ Gravitational wave generation late in the early matter dominated phase
 - ▶ From oscillon interactions or transient structure formation
- ▶ PBH formation – possible with long term structure formation
 - ▶ Like small and fast to evaporate
- ▶ Reheating — couplings to other fields
- ▶ Dark matter production (has to happen somehow)