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ANGEL DUST: DUST WITH PRESSURE

with
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The Gist: New Class Models

- ***One scalar*** degree of freedom
- Speed of sound is ***exactly zero*** for all backgrounds, equation of state is ***arbitrary***
- There is no wave-like propagating degree of freedom which would communicate between geodesics
- ***Single d.o.f.*** can describe ***all*** of the ***dark sector***

Heuristics

- Pressure is the Lagrangian for a perfect fluid

$$S = \int \mathrm{d}^4x \sqrt{-g}\,\mathcal{P}$$

- For a canonical scalar

$$\mathcal{P} = X - V(\phi)$$

$$X \equiv (\partial\phi)/2$$

- Introduce a Lagrange multiplier

$$S = \int \mathrm{d}^4x \sqrt{-g}\,\lambda(X - V(\phi))$$

In Reality

- We have an action for ***two*** fields

$$S = \int \mathrm{d}^4x\sqrt{-g}\, K(\phi, X) + \lambda\left(X - \frac{\mu^2(\phi)}{2}\right)$$

- λ enforces a non-holonomic constraint

$$(\partial_\alpha\phi)^2 = \mu^2(\phi)$$

- But: we also get an EoM for λ

$$\nabla_\alpha(\lambda\nabla^\alpha\phi) + \cdots$$

A Perfect Fluid *with* Pressure

$$T_{\alpha\beta} = (\mathcal{E} + \mathcal{P})u_\alpha u_\alpha - \mathcal{P}g_{\alpha\beta}$$

Energy $\mathcal{E}(\phi, \lambda) = \mu^2(K_X + \lambda) - K$

Pressure $\mathcal{P}(\phi) = K\left(\phi, \frac{\mu^2}{2}\right)$

4-velocity $u^\alpha = \frac{\nabla^\alpha \phi}{\sqrt{2X}} = \mu^{-1}\nabla^\alpha \phi$

Acceleration vanishes $a^\alpha = u^\beta \nabla_\beta u^\alpha = 0$

Energy always follows geodesics

Equations of Motion

$$\theta = \nabla_\alpha u^\alpha$$

$$\dot{\phi} = u^\alpha \nabla_\alpha \phi = \mu(\phi)$$
$$\dot{\lambda} = u^\alpha \nabla_\alpha \lambda = -\mu^{-2}\big(\mu \mathcal{E}_\phi + \theta(\mathcal{E} + \mathcal{P})\big)$$

- Along geodesics, two ***ordinary*** differential equations
  - a ***single*** degree of freedom
  - But: ***no*** wave-like mode communicating between geodesics

Linear Perturbations

- We can solve for the for Newtonian potential at ***all scales***

$$\Phi = C_1(\boldsymbol{x}) + \frac{H}{a} C_2(\boldsymbol{x}) - C_1(\boldsymbol{x}) \frac{H}{a} \int \frac{\mathrm{d}a}{H}$$

- Density perturbations

$$\delta\mathcal{P} = \mathcal{P}_\phi \delta\phi$$

$$\dot{\delta} - 3Hw\delta + 3H \frac{\delta\mathcal{P}}{\mathcal{E}} = (1+w)\left(3\dot{\Phi} + \frac{\nabla^2}{a^2}\left(\frac{\delta\phi}{\mu}\right)\right)$$

- When $w = \text{const}$, subhorizon $\delta \propto a^{1+3w}$

- ***No ghosts*** when $w > -1$

An example: Dusty Dark Energy

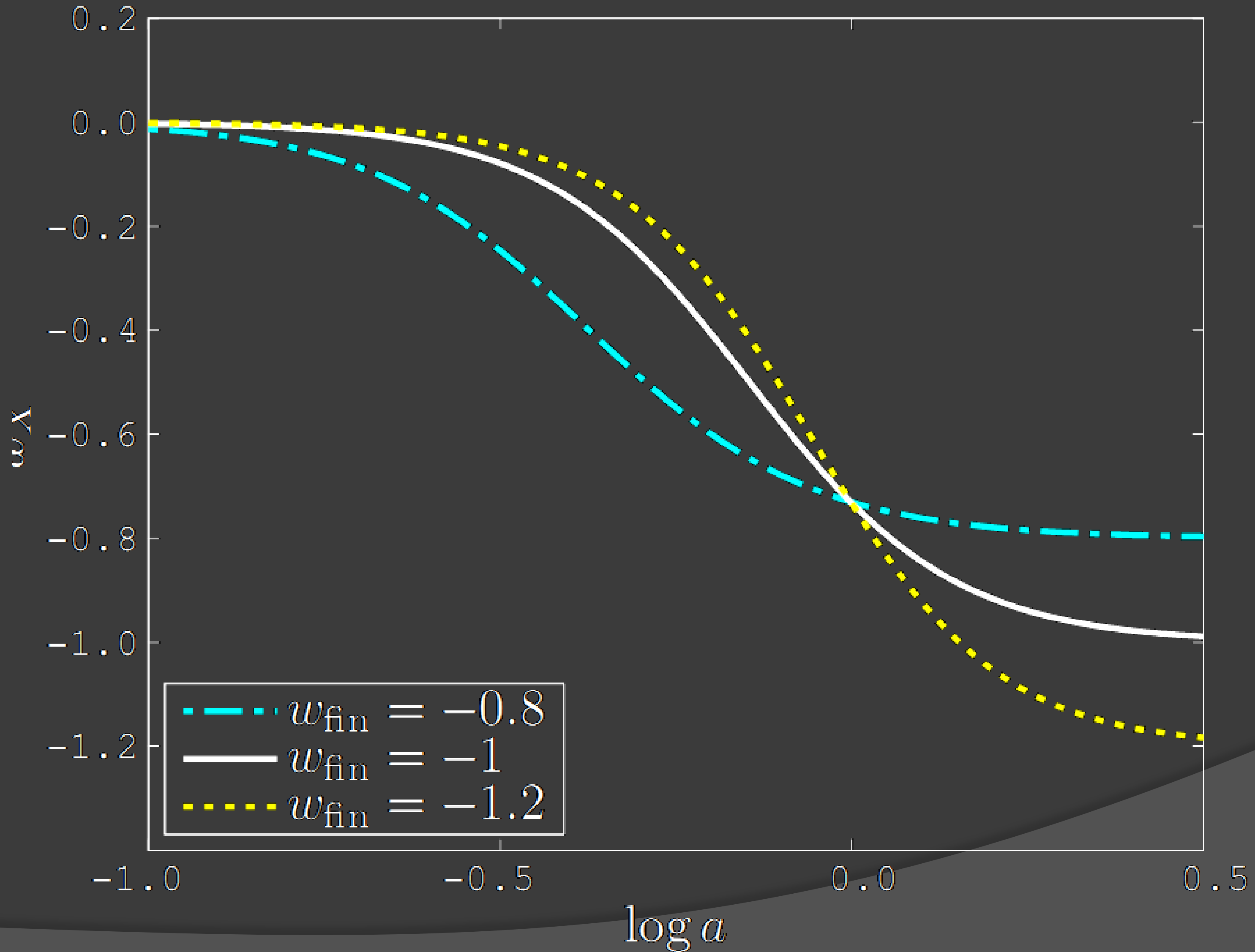
$$K = -X \qquad \mu = \mu_0 \exp\left(-\frac{\phi}{m}\right)$$

$$m = \sqrt{\frac{8}{3}\frac{\sqrt{-w_{\rm fin}}}{1+w_{\rm fin}}} M_{\rm Pl}$$

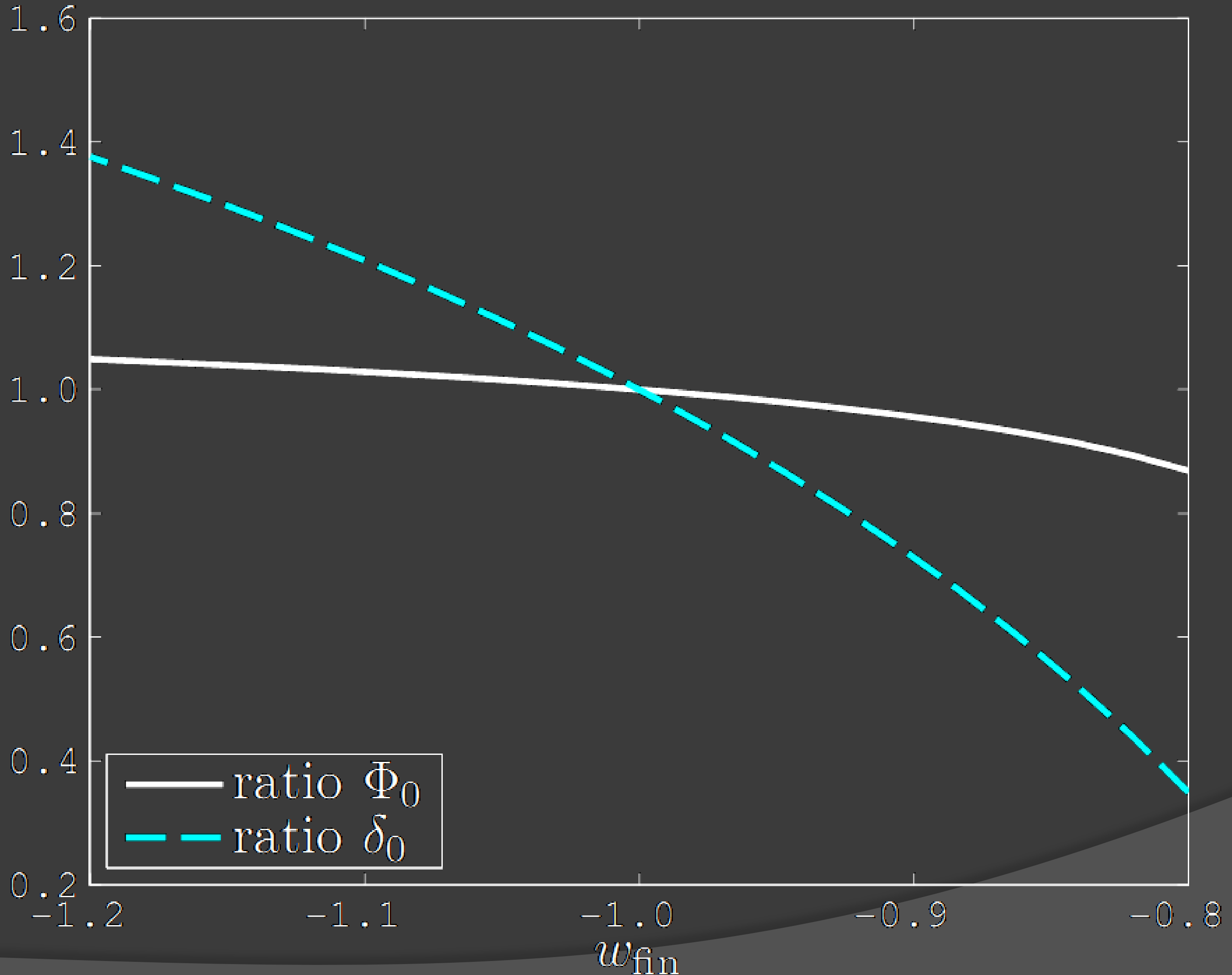
- Final attractor: $w = w_{\rm fin}$

$$w' = 3w\left(1 + w - \sqrt{\frac{w}{w_{\rm fin}}}(1 + w_{\rm fin})\right)$$

Expansion History Approximately ΛCDM



Perturbations Approximately ΛCDM



The Take Away

- A new class of scalar-field theories
  - Sound speed vanishes on any background
  - No wave-like mode
- Minimal model for coincidence problem
  - Single d.o.f. for both dark matter and dark energy
  - Arbitrary w
  - Perturbations collapse like dust

THANKS FOR LISTENING!

HOT TIP:

Alex Vikman's talk on KGB, here at 15^{15}