

Cosmic Tsunamis in Modified Gravity

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Modified Gravity and Screening

- Start with General Relativity
- Add some small terms (not *too* small)

Modified Gravity and Screening

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- Add some small terms (not *too* small)
- Example: **Scalar-Tensor Theories**
 - Symmetron, $f(R)$, Brans-Dicke, Disformal ...

Scalar-Tensor Theories

- A scalar field ϕ in the EH action

$$S = \int \left[\sqrt{-g} \left(\frac{R}{16\pi G} - \frac{1}{2} \phi'^{\mu} \phi_{,\mu} - V(\phi) \right) + \sqrt{-\bar{g}} \bar{\mathcal{L}}_m \right] d^4x$$

- A **coupling** to matter

$$\bar{g}_{\mu\nu} = A(\phi) g_{\mu\nu}$$

Scalar-Tensor Theories

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- A **coupling** to matter (disformal)

$$\bar{g}_{\mu\nu} = A(\phi) g_{\mu\nu} + B(\phi) \phi_{,\mu} \phi_{,\nu}$$

Quasi-Static Scalar Fields

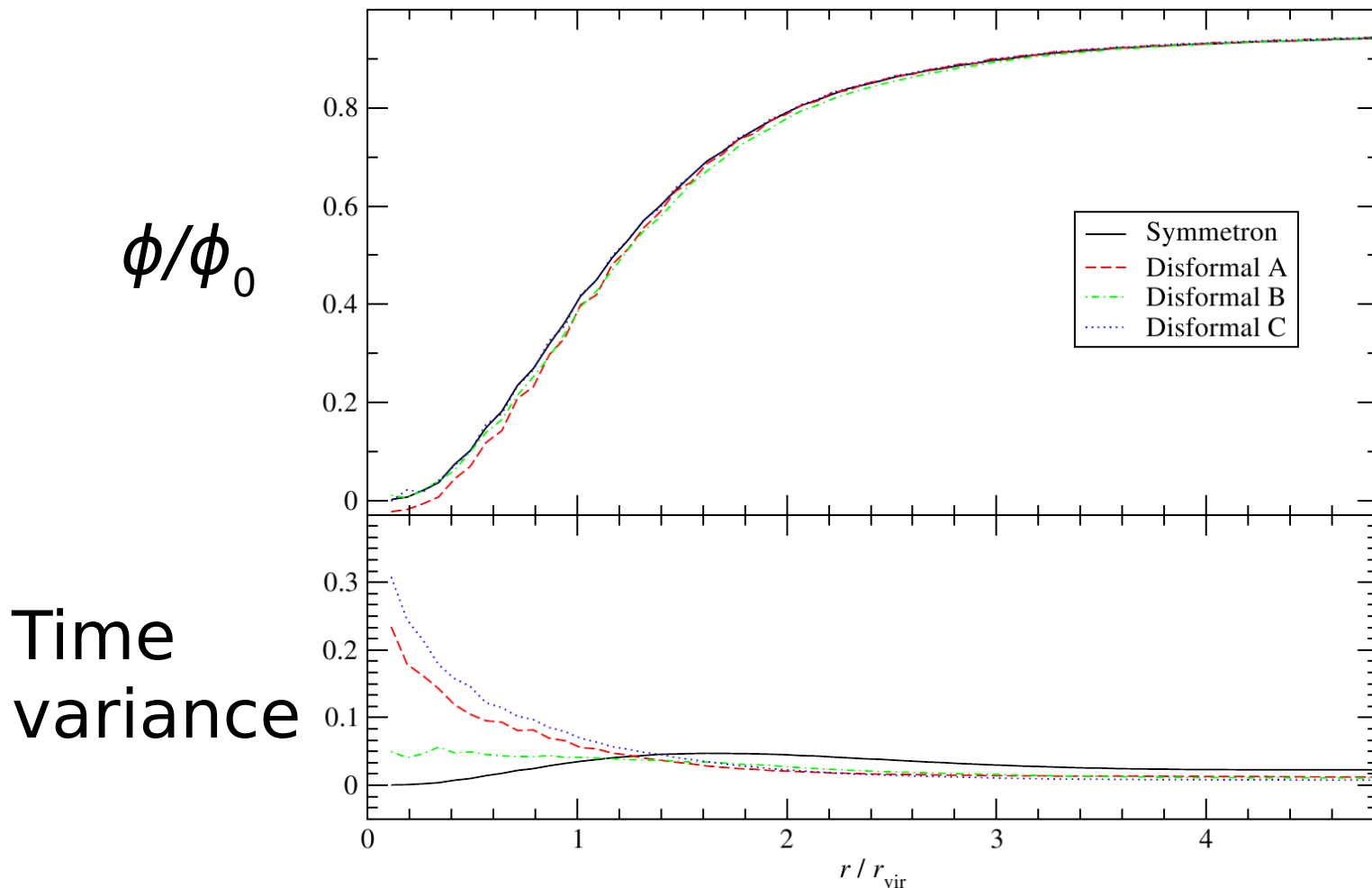
- Scalar field equation of motion (KG)

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi = -V_{\text{eff},\phi}(\rho, \phi)$$

- A damped **wave equation**

Motivation

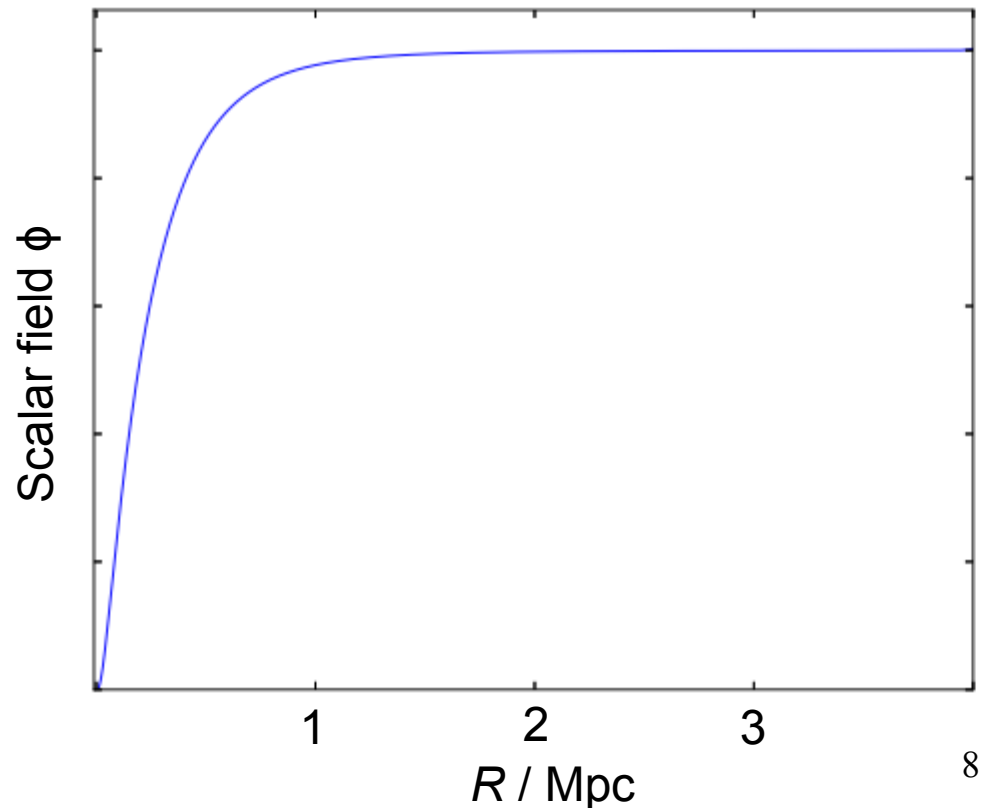
- Scalar field, disformal symmetron N -body



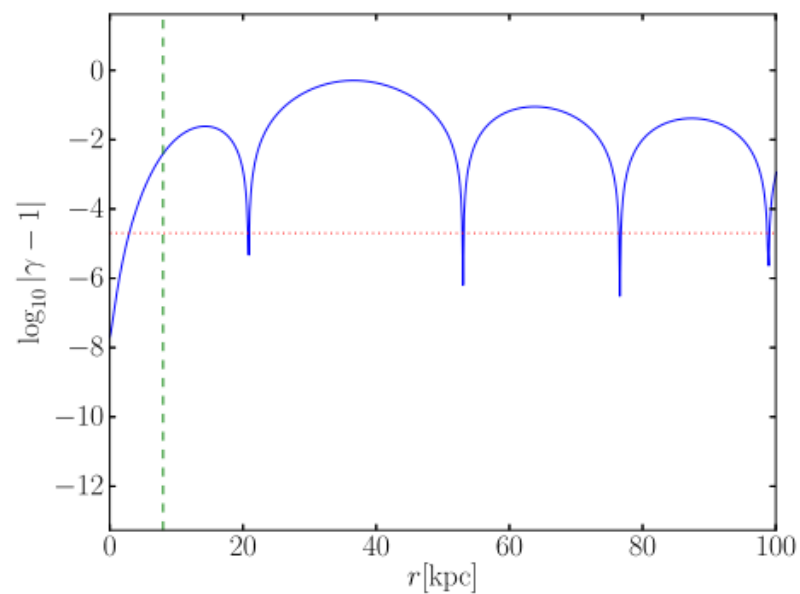
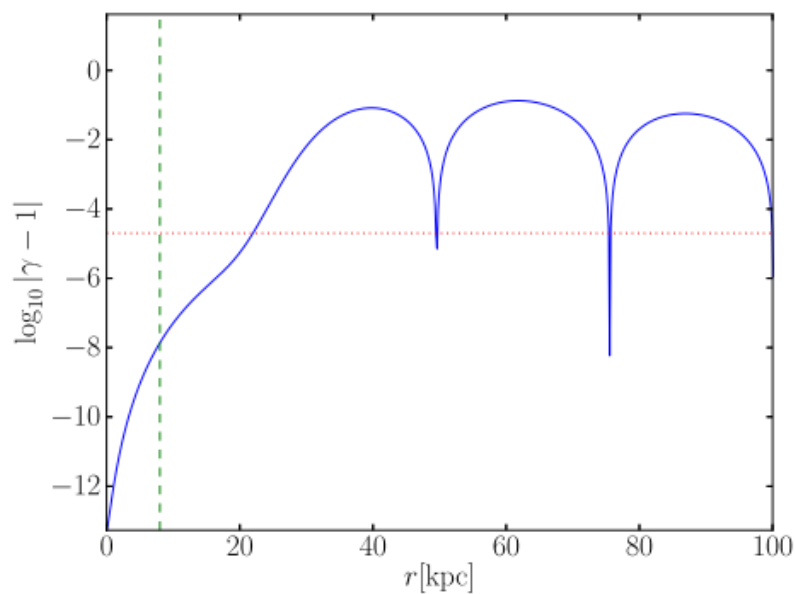
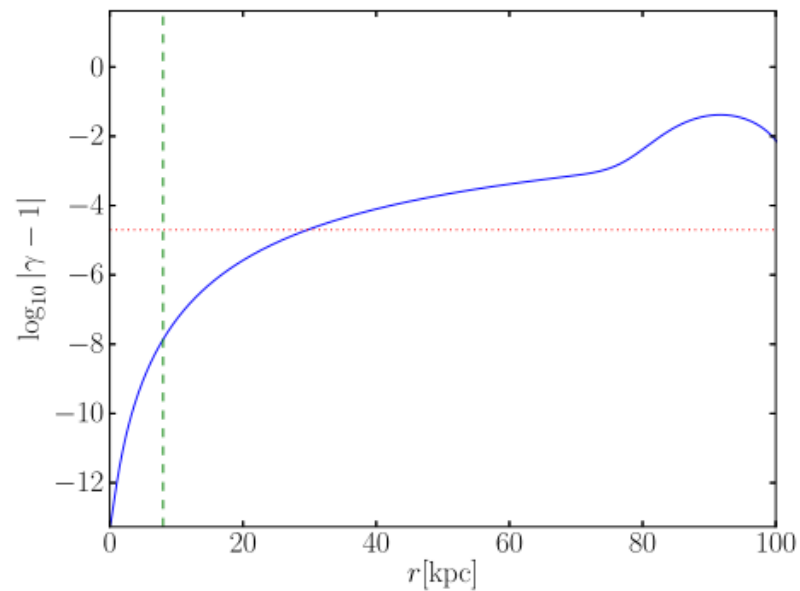
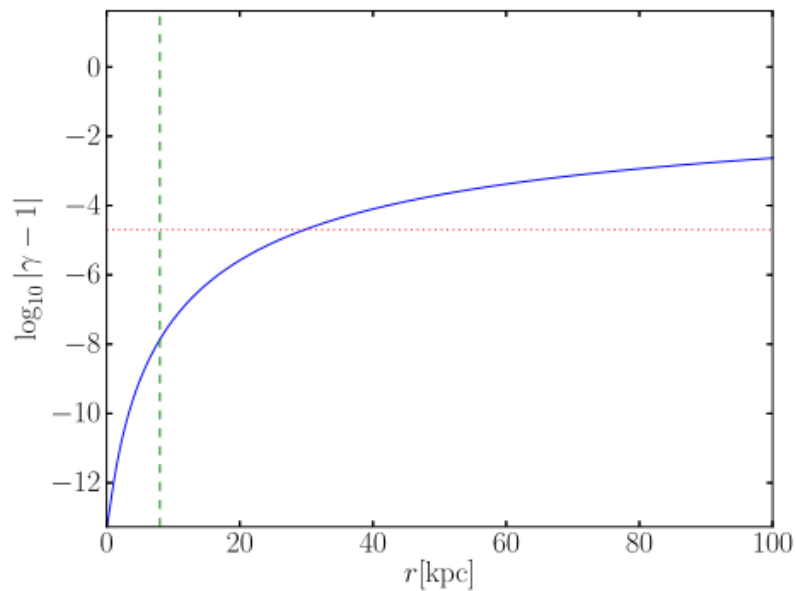
Hagala *et al.*
A&A 2016

Spherical Wave Model

- Spherically symmetric, static density
 - NFW fitted to the Milky Way
- Waves applied at boundary, travelling in radial direction
- Very high resolution, fast execution



Spherical Wave Model



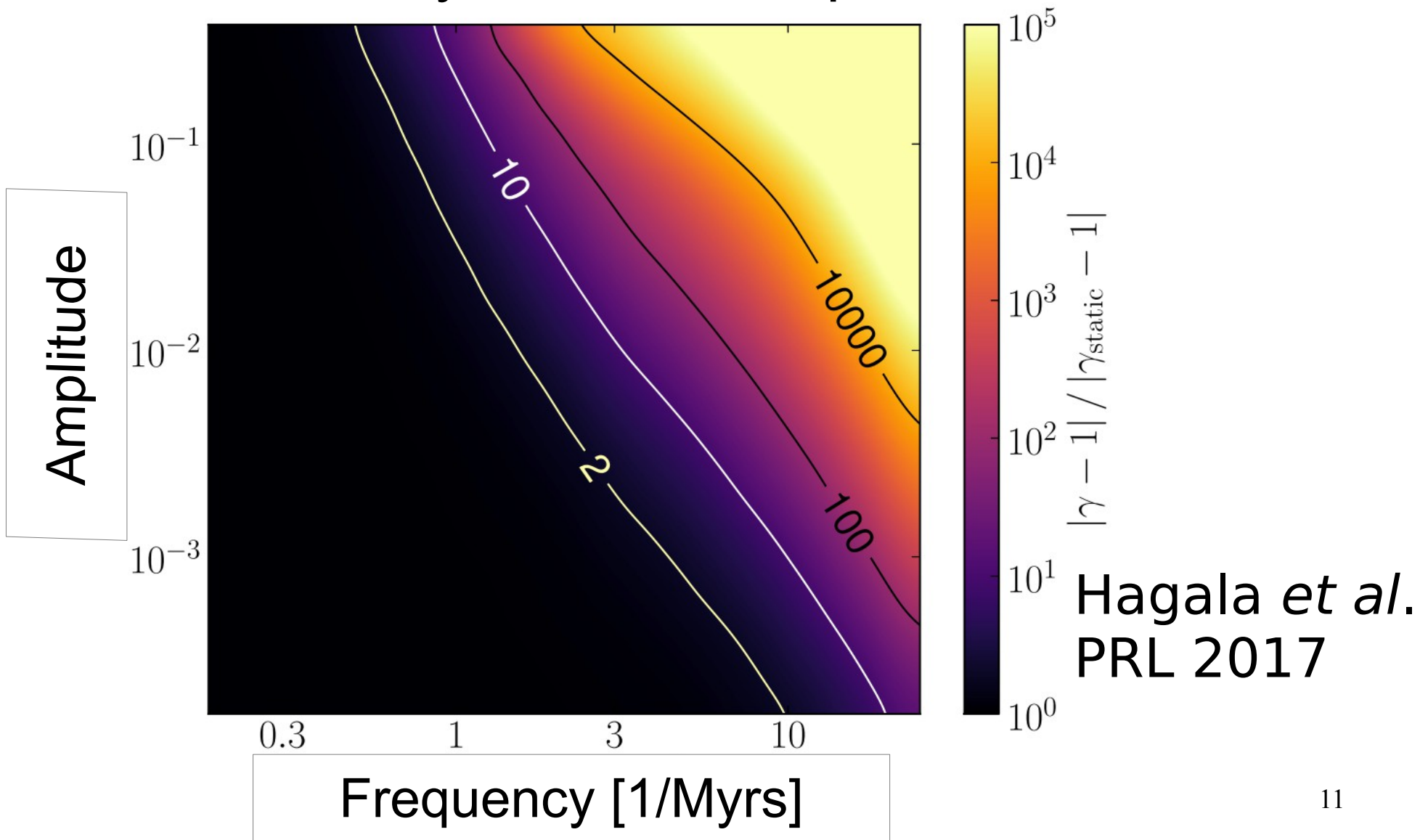
(Symmetron)

Results

- The field perturbed close to center
- Frequency and amplitude dependent

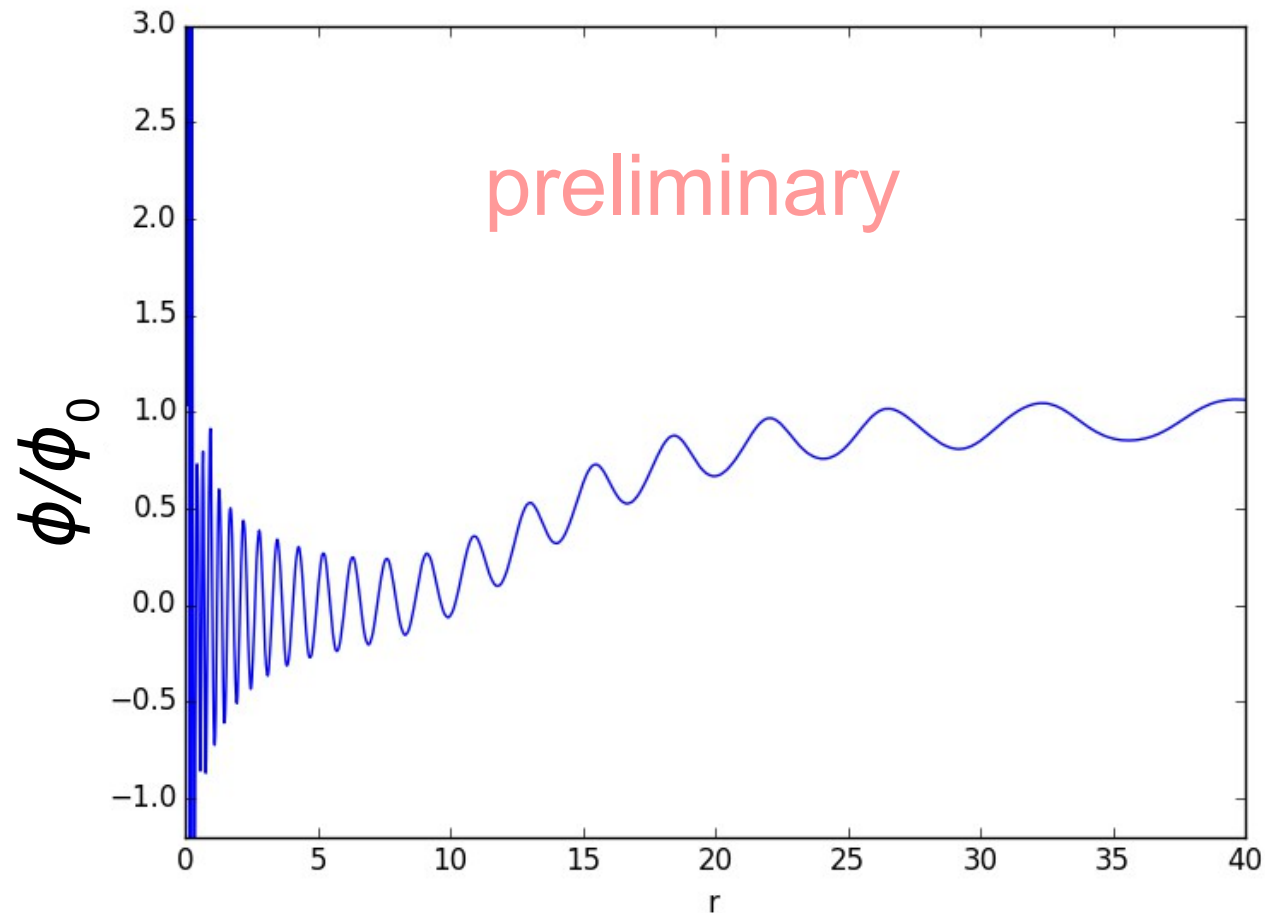
Results

Symmnetron, 8 kpc



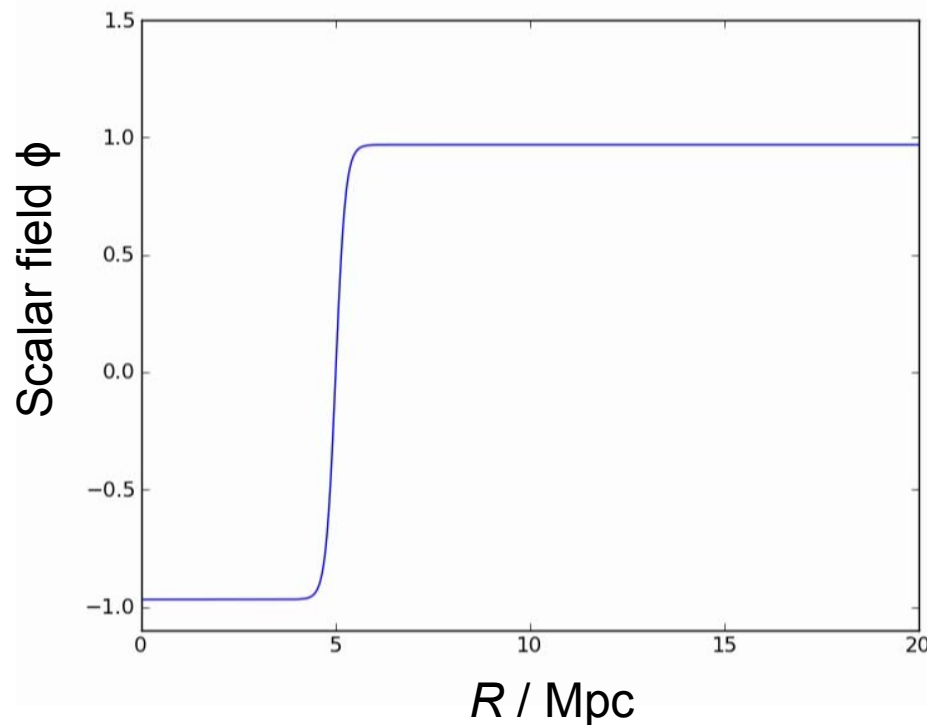
Results

- Disformal effect: wave speed slows down



How to Create Waves?

- In the Symmetron:
 - Spontaneous Symmetry Breaking (SSB)
 - Collapsing topological defects (domain walls)

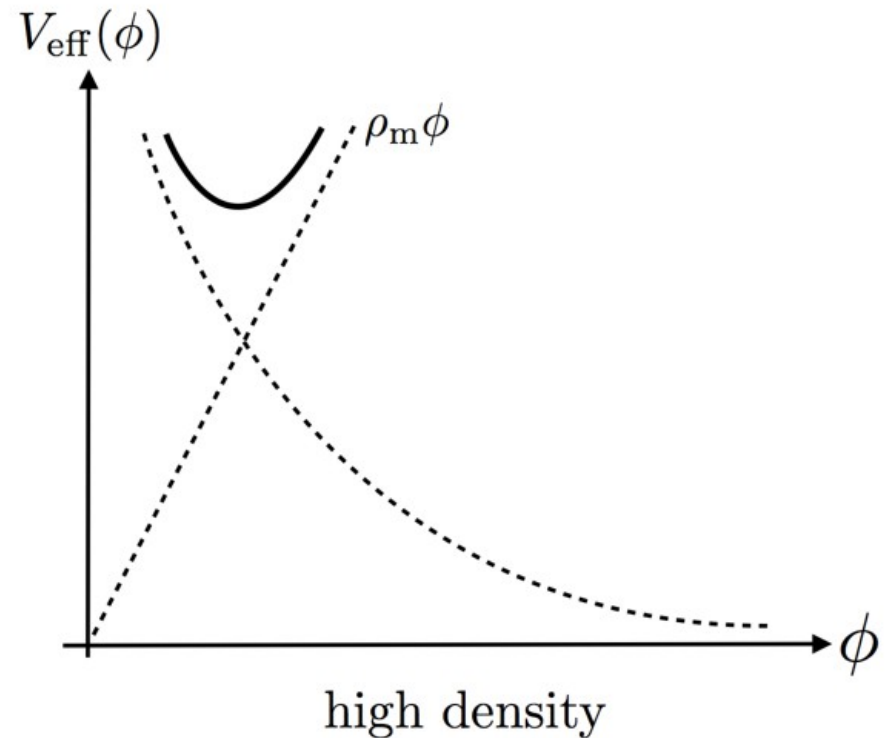
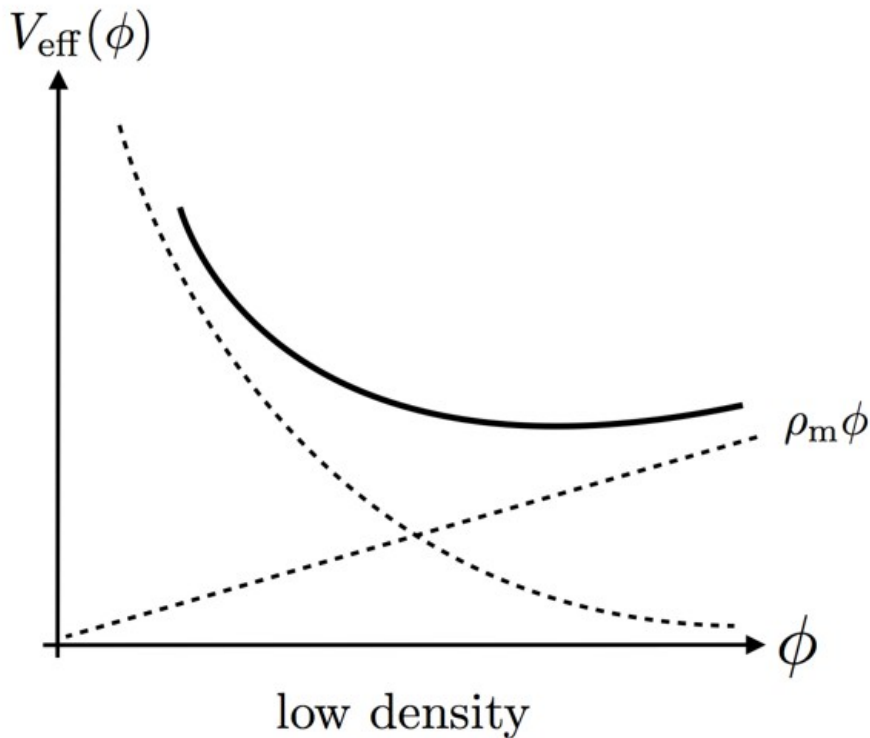


How to Create Waves?

- In the Symmetron:
 - Spontaneous Symmetry Breaking (SSB)
 - Collapsing topological defects (domain walls)
- Other Scalar-Tensor theories:
 - Neutron star collisions
 - Massive binaries
 - Super-massive black holes
 - Supernova explosions

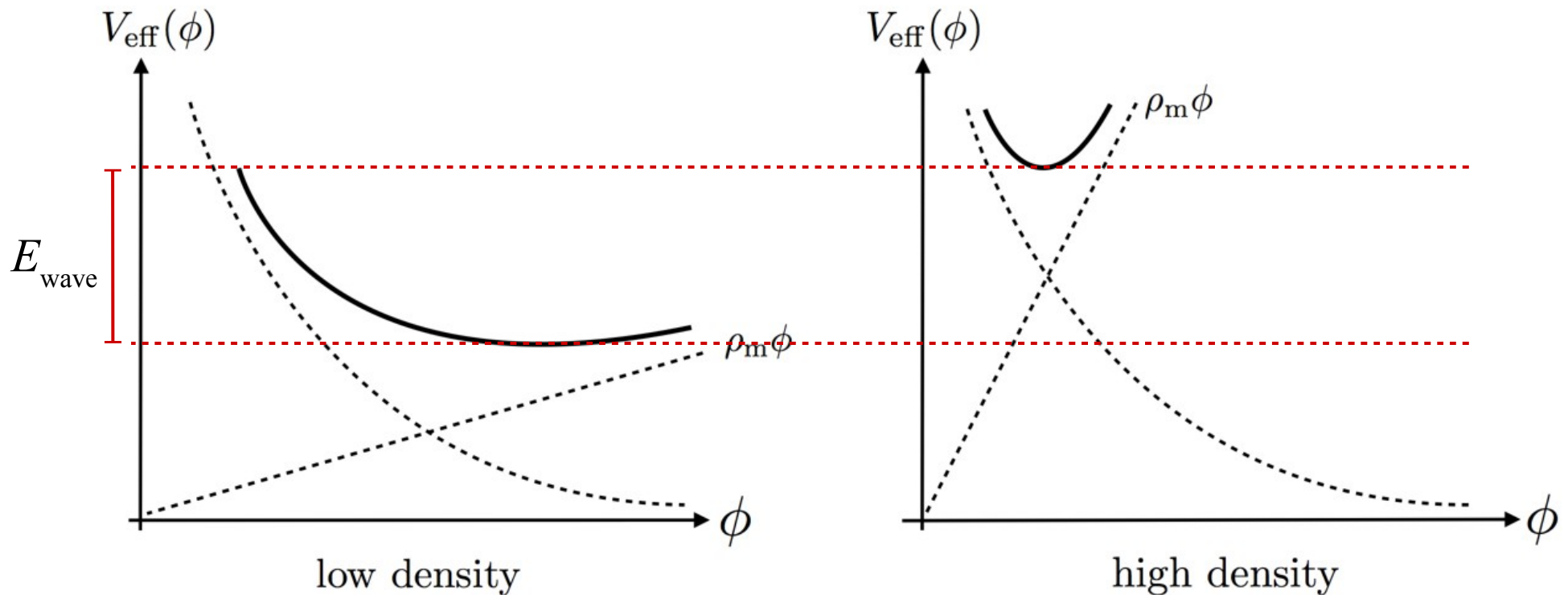
How to Create Waves?

- The Chameleon model:
 - Supernova explosions



How to Create Waves?

- The Chameleon model:
 - Supernova explosions could increase gamma by a factor of 10 even at 10 Mpc



Conclusions

- Scalar-Tensor theories need **screening**
- Waves can disrupt screening

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- Waves can disrupt screening
- **Any theory**: check if waves are important!
 - Valid screening?
 - Solar system constraints?

Conclusions

- Scalar-Tensor theories need **screening**
- Waves can disrupt screening
- **Any theory**: check if waves are important!
 - Valid screening?
 - Solar system constraints?
- Can lead to new models and probes

Extra Slides...

Overview

- Screening & Scalar-Tensor Theories
- The Quasi-Static Approximation
- The Spherical Wave Model
- Results when Applying Waves
- How are Waves Made?

Modified Gravity and Screening

- Start with General Relativity
- Add some small terms
- GR is well tested in the solar system, $\gamma \approx 1$ ($\pm 10^{-5}$)
- **Screening**: Equations reduce to GR, $\gamma \rightarrow 1$, in the solar system

Quasi-Static Scalar Fields

- Scalar field equation of motion

$$\frac{1}{a^2} \nabla^2 \phi = V_{\text{eff},\phi}(\rho, \phi)$$

- **Quasi-static** approximation:
Poisson eq.
- No waves!

Further work

- Other theories than Disformal/Symmetron
- Simulate supernova explosions
- Explore other observables, dG/dt ?

The Disformal Model

- The **equation of motion** for the field

$$(1 + \gamma^2 \rho) \ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2} \nabla^2 \phi =$$
$$\gamma^2 \rho \left(\frac{2\phi}{M^2 + \phi^2} - \frac{\beta}{2\phi_0} \right) \dot{\phi}^2 - \frac{\rho\phi}{M^2} \left(\frac{\gamma^2}{B_0 \exp\left(\beta \frac{\phi}{\phi_0}\right)} \right) + \mu^2 \phi - \lambda \phi^3$$

$$A(\phi) = 1 + \left(\frac{\phi}{M} \right)^2 \quad B(\phi) = B_0 \exp\left(\beta \frac{\phi}{\phi_0} \right)$$

The Disformal Model

- Fifth forces acting on matter

$$\begin{aligned}
 & \ddot{x}^i + \frac{\Psi_{,i}}{a^2} - \frac{2}{AM^2 a^2} \gamma^2 \phi \phi_{,i} \dot{\phi}^2 + 2 \left(H + \frac{\phi \dot{\phi}}{AM^2} \right) \dot{x}^i \\
 & + \frac{1}{a^2} \gamma^2 \left(\ddot{\phi} - \frac{1}{a^2} \sum_{k=1,2,3} \Psi_{,k} \phi_{,k} + \frac{1}{2} \frac{\beta}{\phi_0} \dot{\phi}^2 \right) \phi_{,i} \\
 & + 2 \frac{1}{a^2} \gamma^2 \left(\dot{\phi}_{,j} - H \phi_{,j} - \Psi_{,j} \dot{\phi} + \frac{\beta}{2\phi_0} \dot{\phi} \phi_{,j} \right) \phi_{,i} \dot{x}^j \\
 & + \frac{1}{M^2 a^2} \frac{1}{A - 2BX} \phi \phi_{,i} - 4 \gamma^2 \frac{\phi}{a^2 AM^2} \phi_{,i} \phi_{,j} \dot{\phi} \dot{x}^j = 0
 \end{aligned}$$

GR

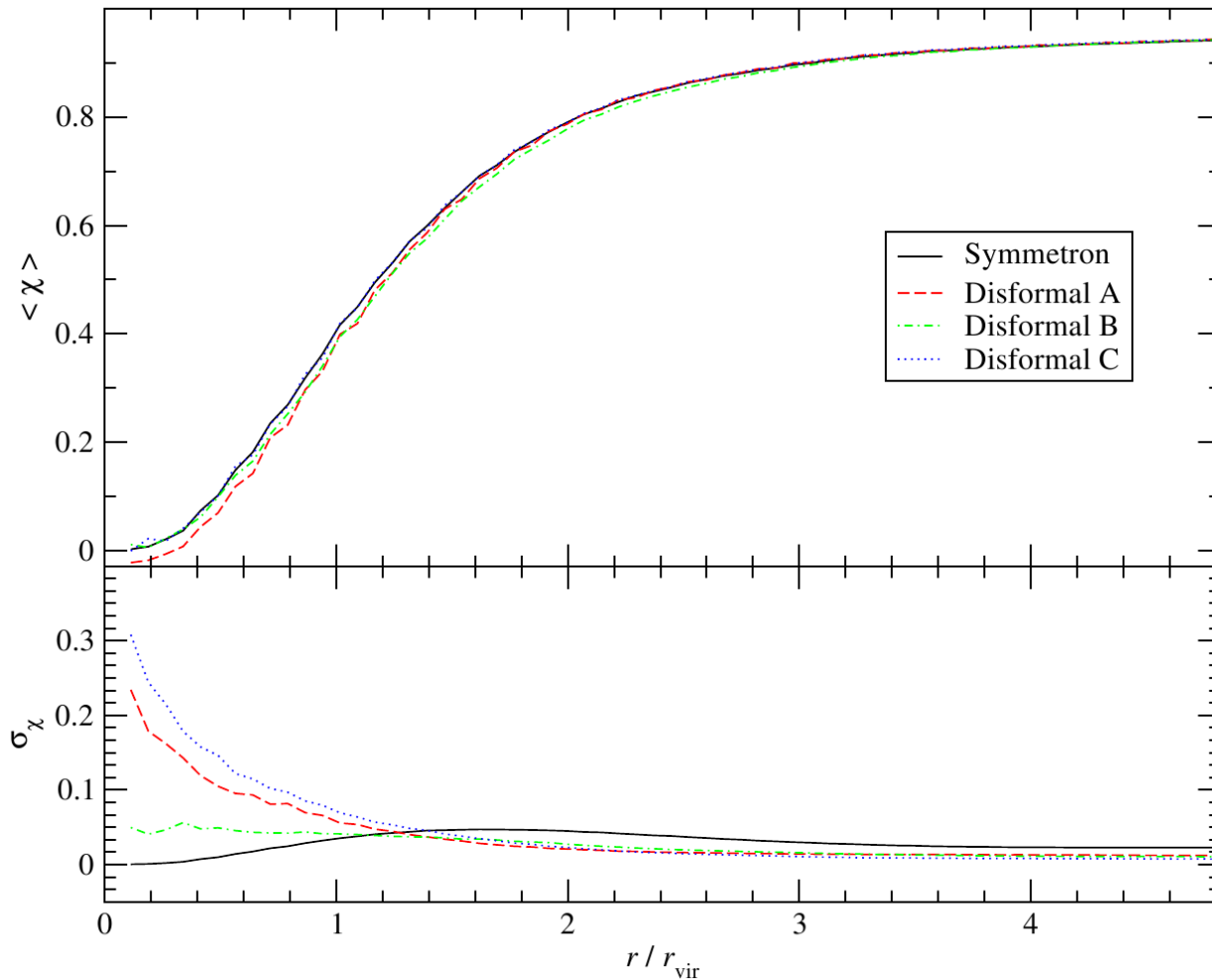
Hubble friction

Disformal

Symmetron

Results

- Time averaged field profiles, disformal N -body



$$\chi = \pm\phi/\phi_0$$