

Title: Cosmic Acceleration: Dark Energy vs Modified Gravity

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Abstract: I will discuss distinctions between dark energy and modified gravity explanations of cosmic acceleration from the horizon scale to the deeply non-linear regime using the modified action $f(R)$ and braneworld DGP models as worked toy examples.

Cosmic Acceleration

Dark Energy
v.
Modified Gravity

Wayne Hu
Perimeter Institute
April 2010

No Signal

VGA-1

No Signal

VGA-1

No Signal

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Cosmic Acceleration

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Outline

- Dark Energy vs Modified Gravity
- Three Regimes of Modified Gravity
- Worked (Toy) Models: $f(R)$ and DGP Braneworld
- Collaborators

Wenjuan Fang

Marcos Lima

Michael Mortonson

Fabian Schmidt

Iggy Sawicki

Uros Seljak

Anze Slosar

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Dragan Huterer

Lucas Lombriser

Hiro Oyaizu

Hiranya Peiris

Sanjeev Seehra

Yong-Seon Song

Amol Upadhye

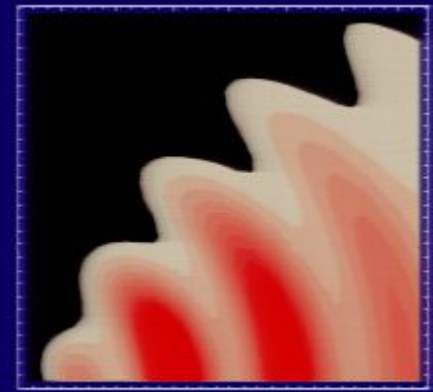
Alexey Vikhlinin

Charting Out the Expansion

- **Standard candle:** apparent **brightness** of objects with a fixed luminosity to judge distance
- **Standard ruler:** apparent (angular) **separation** of objects with a fixed physical separation to judge distance



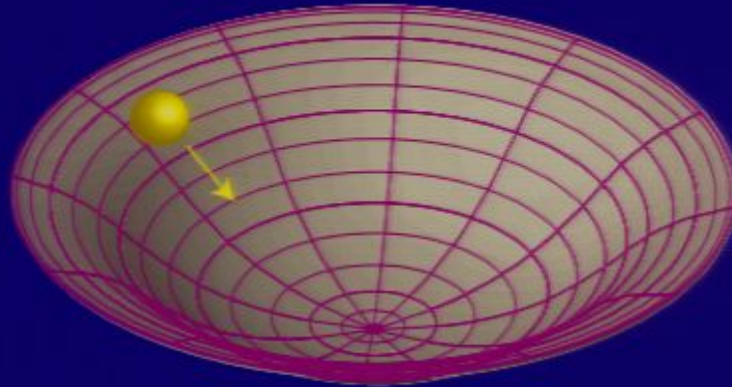
Supernovae
1998 Discovery



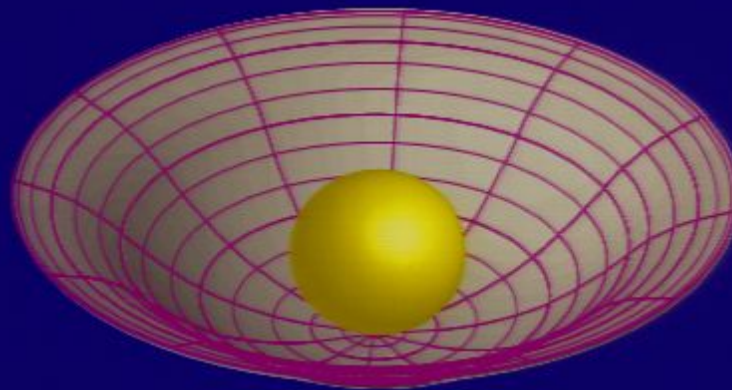
Sound waves
CMB+Galaxies

Mercury or Pluto?

- General relativity says **Gravity = Geometry**



- And **Geometry = Matter-Energy**



- Could the **missing energy** required by **acceleration** be an **incomplete** description of how **matter determines geometry**?

Modified Gravity = Dark Energy?

- Solar system tests of gravity are informed by our knowledge of the local stress energy content
- With **no other constraint** on the stress energy of dark energy other than **conservation**, modified gravity is **formally equivalent** to dark energy

$$F(g_{\mu\nu}) + G_{\mu\nu} = 8\pi G T_{\mu\nu}^{\text{M}} \quad \boxed{-F(g_{\mu\nu}) = 8\pi G T_{\mu\nu}^{\text{DE}}}$$
$$G_{\mu\nu} = 8\pi G [T_{\mu\nu}^{\text{M}} + T_{\mu\nu}^{\text{DE}}]$$

and the **Bianchi identity** guarantees $\nabla^{\mu} T_{\mu\nu}^{\text{DE}} = 0$

- **Distinguishing** between **dark energy** and **modified gravity** requires closure relations that relate components of stress energy tensor
- For **matter components**, closure relations take the form of equations of state relating **density**, **pressure** and **anisotropic stress**

Modified Gravity \neq “Smooth DE”

- **Scalar field** dark energy has $\delta p = \delta \rho$ (in constant field gauge) – relativistic sound speed, **no anisotropic stress**
- **Jeans stability** implies that its energy density is **spatially smooth** compared with the **matter** below the **sound horizon**

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^2$$

$$\nabla^2(\Phi - \Psi) \propto \text{matter density fluctuation}$$

- **Anisotropic stress** changes the amount of **space curvature** per unit dynamical mass

$$\nabla^2(\Phi + \Psi) \propto \text{anisotropic stress}$$

but its absence in a **smooth dark energy** model makes

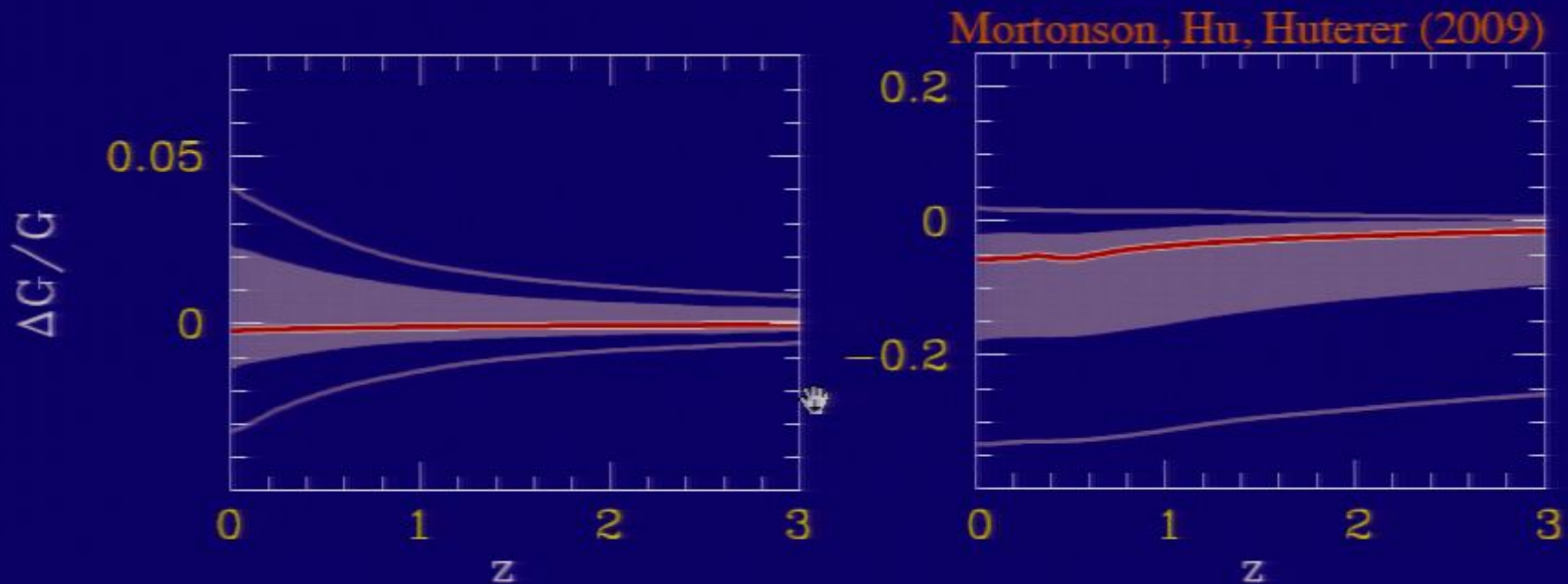
$$g = (\Phi + \Psi)/(\Phi - \Psi) = 0 \text{ for non-relativistic matter}$$

Falsifiability of Smooth Dark Energy

- With the **smoothness assumption**, dark energy only affects **gravitational growth of structure** through changing the **expansion rate**
- Hence **geometric** measurements of the expansion rate **predict** the **growth** of structure
 - Hubble Constant
 - Supernovae
 - Baryon Acoustic Oscillations
- **Growth of structure** measurements can therefore **falsify** the whole smooth dark energy paradigm
 - Cluster Abundance
 - Weak Lensing
 - Velocity Field (Redshift Space Distortion)

Falsifying Quintessence

- Dark energy slows growth of structure in highly predictive way



Cosmological Constant

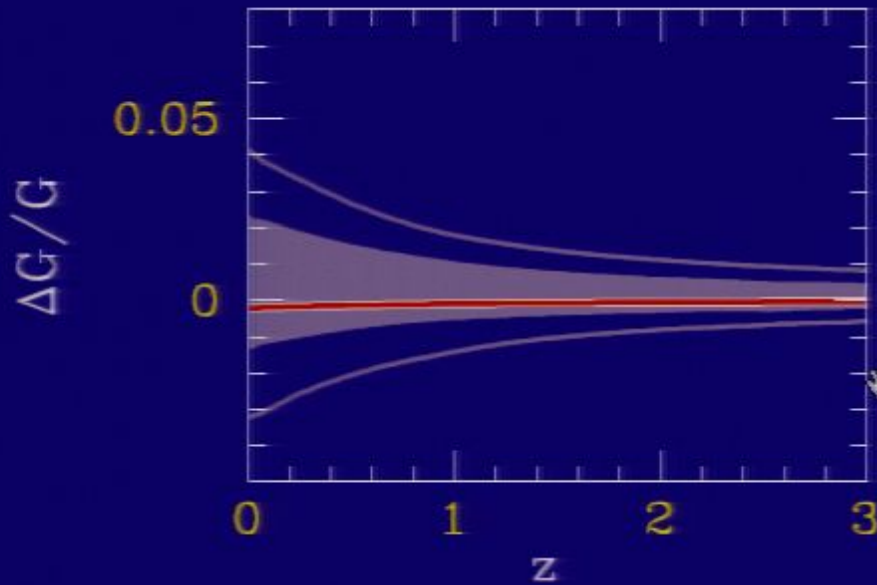
Quintessence

- Deviation significantly $>2\%$ rules out Λ with or without curvature
- Excess $>2\%$ rules out quintessence with or without curvature and early dark energy [as does $>2\%$ excess in H_0]

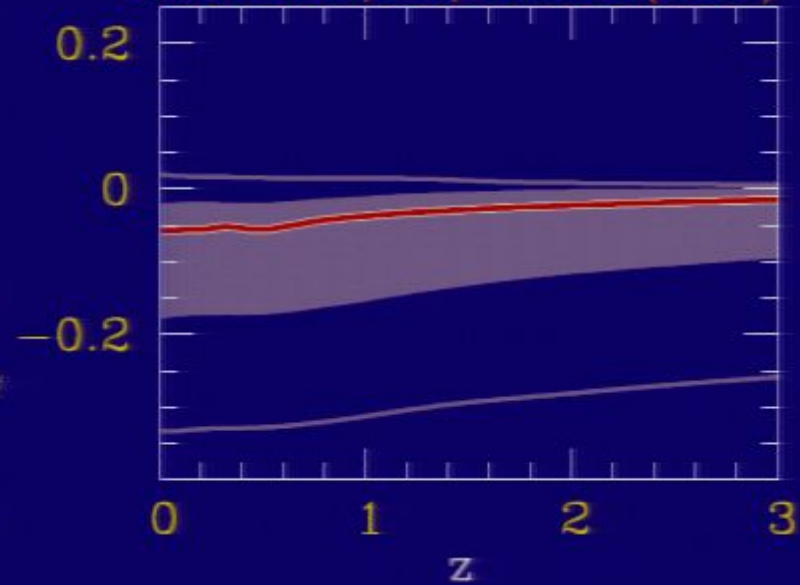
Dynamical Tests of Acceleration

- Dark energy slows growth of structure in highly predictive way

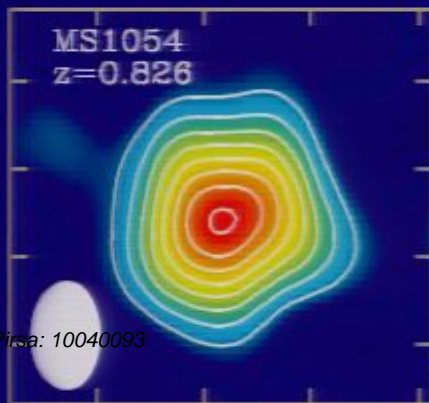
Mortonson, Hu, Huterer (2009)



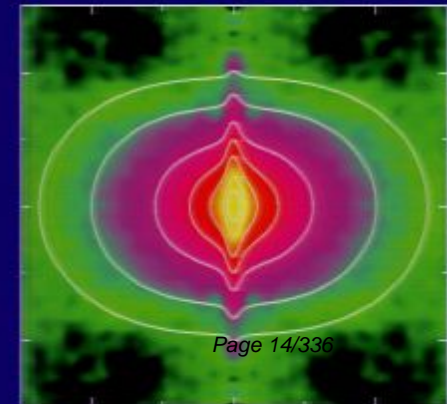
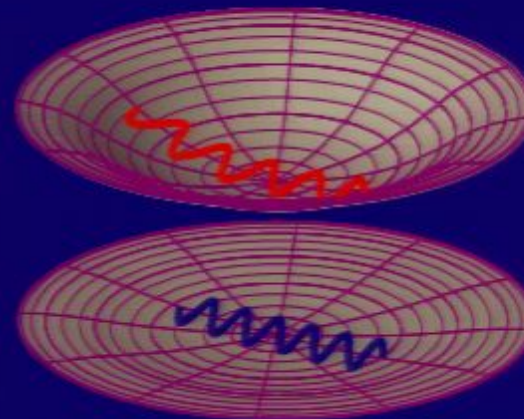
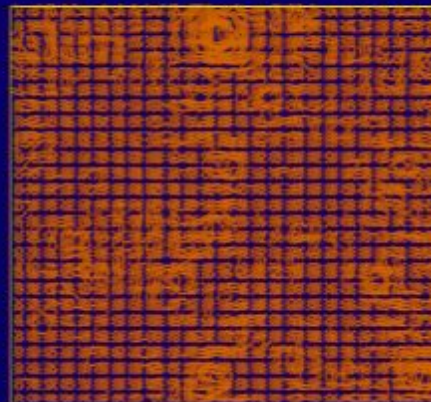
Cosmological Constant



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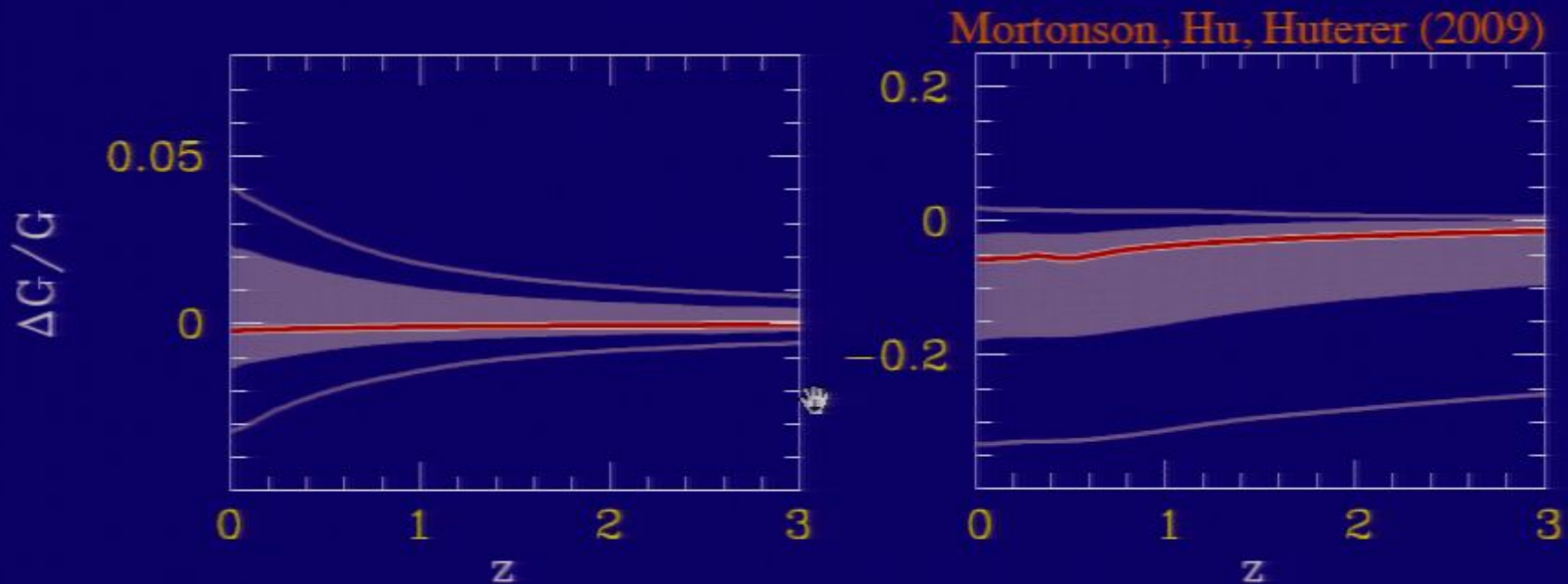
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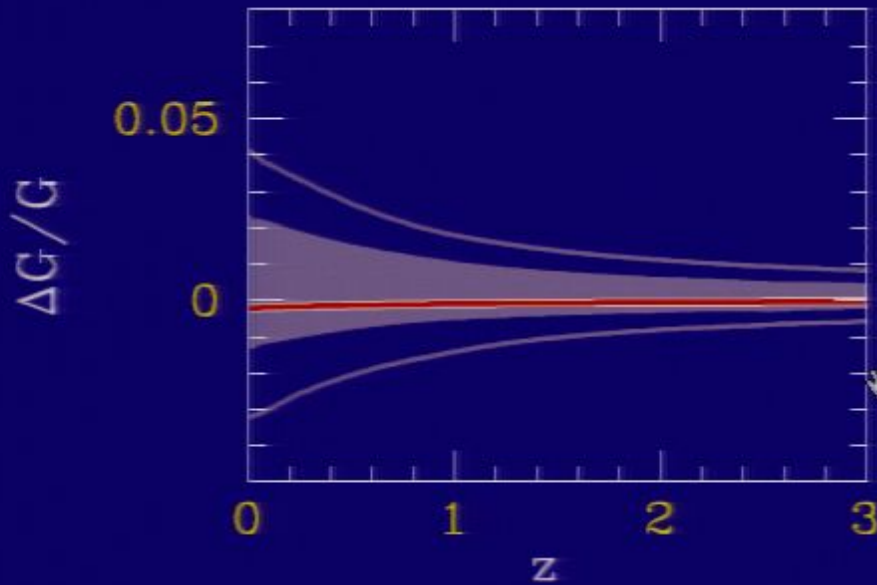
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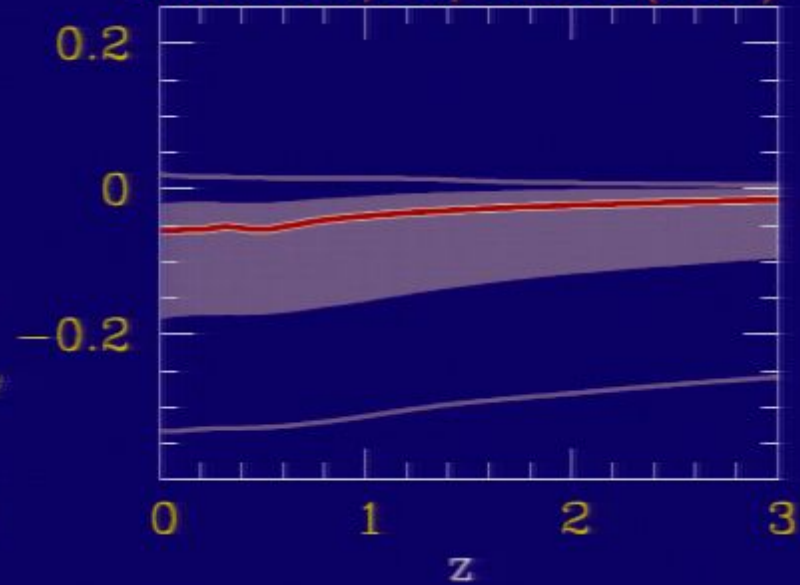
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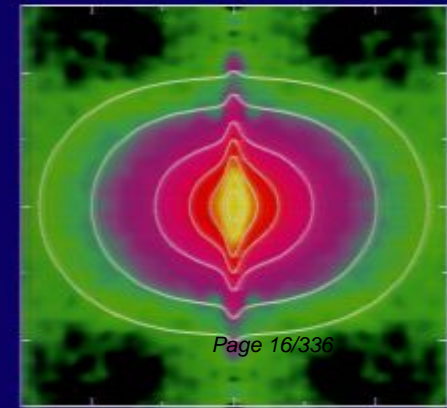
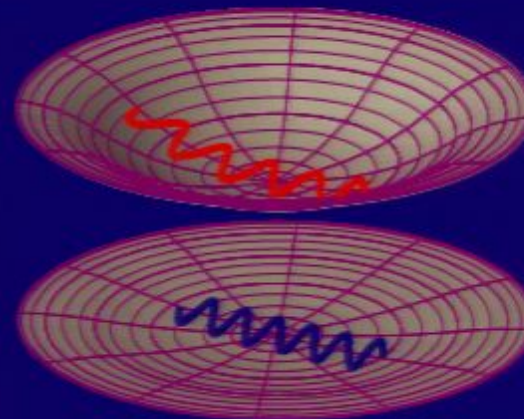
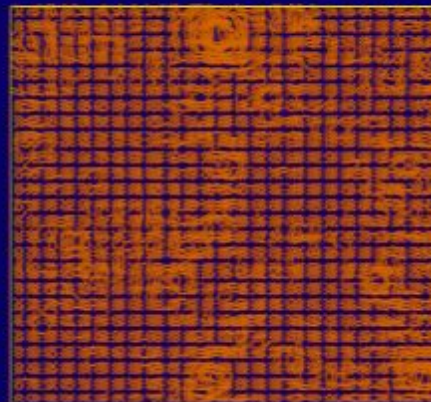
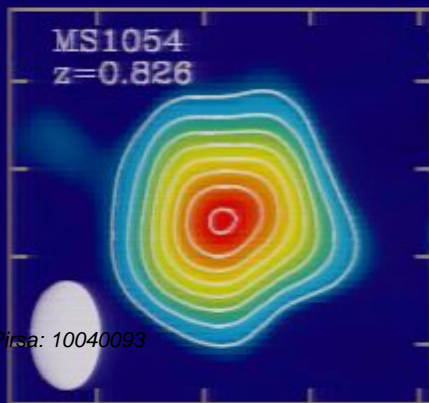
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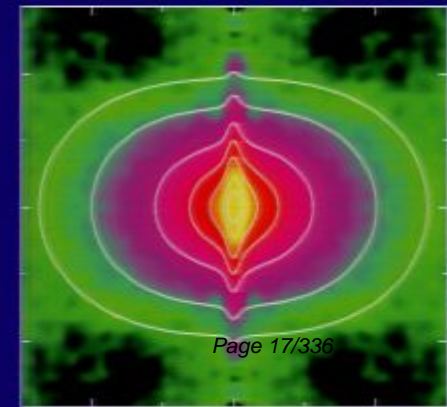
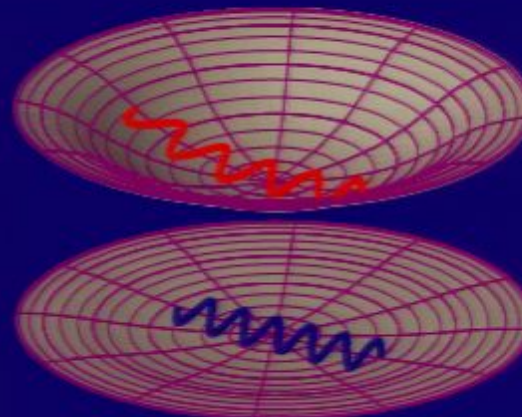
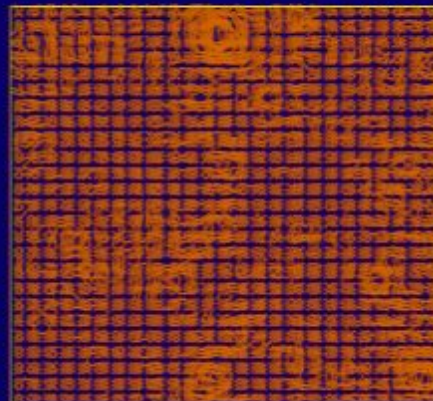
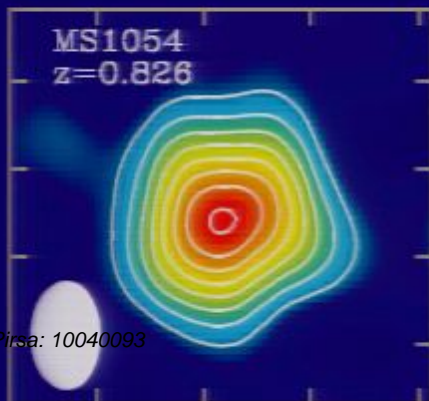


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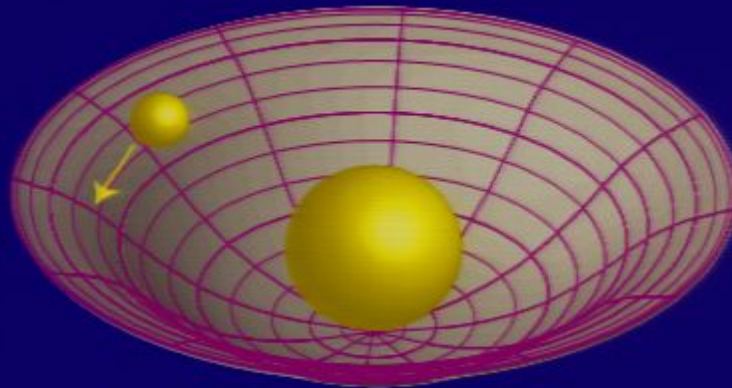
Quintessence Falsified?

- No **excess** numbers of massive $z > 1$ X-ray or SZ clusters with Gaussian initial conditions (Jee et al 2009, Brodwin et al 2010)
- No **excess** power in gravitational lensing at high z relative to low z (Bean 0909.3853)
- But would such violations favor modified gravity?
- Given **astrophysical systematics**, expect purported 2σ violations of smooth dark energy predictions will be **common** in coming years!

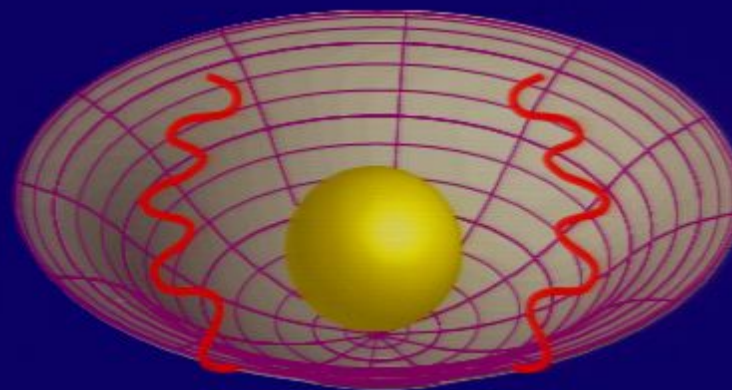


Dynamical vs Lensing Mass

- Newtonian potential: $\Psi = \delta g_{00} / 2g_{00}$ which non-relativistic particles feel



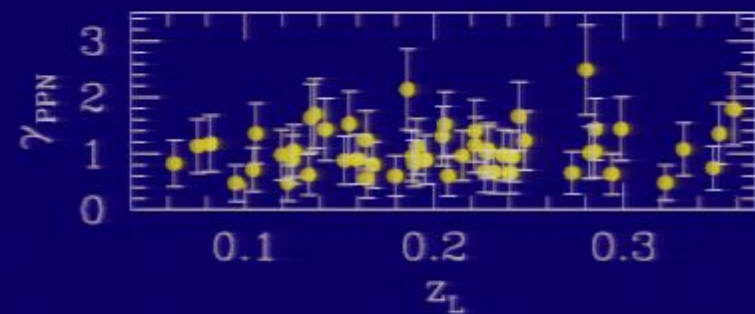
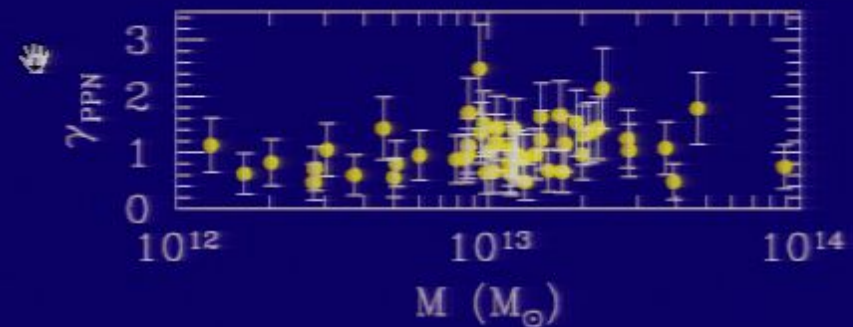
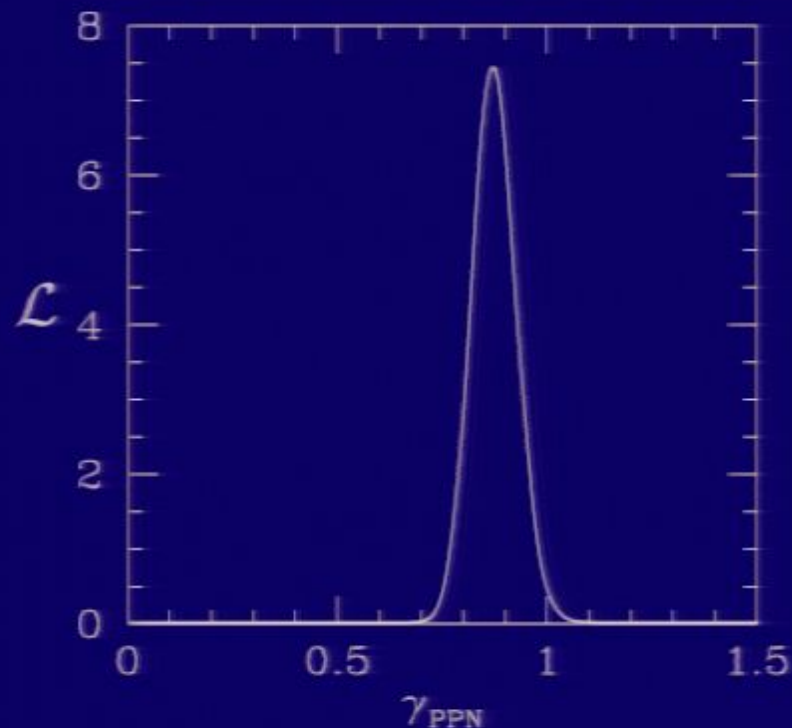
- Space curvature: $\Phi = \delta g_{ii} / 2g_{ii}$ which also deflects photons



- Most of the incisive tests of gravity reduce to testing the space curvature per unit dynamical mass

Dynamical v Strong Lensing

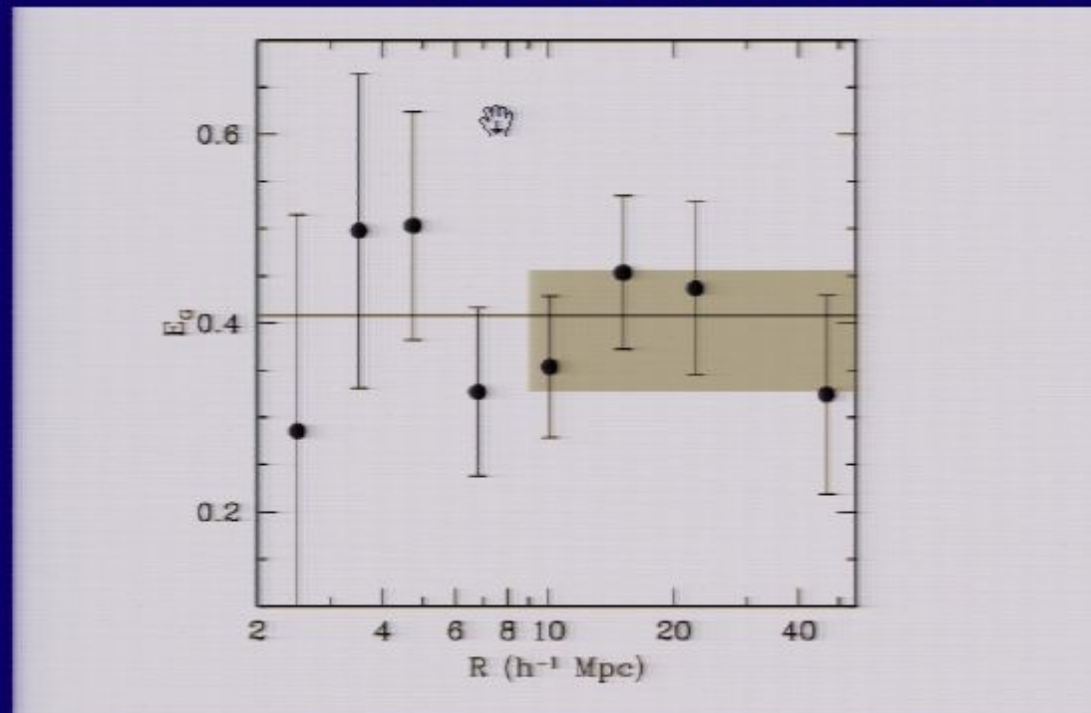
- Comparison of strong lensing and dynamical mass assuming a density profile and velocity dispersion data
- Mean exhibits a bias from GR expectation with statistical errors only
- No mass trend detectable



Lensing v Dynamical Comparison

- Gravitational lensing around galaxies vs. linear velocity field (through redshift space distortions and galaxy autocorrelation)
- Consistent with GR + smooth dark energy beginning to test interesting models

Reyes et al (2010); Lombriser et al (2010)



Falsify in Favor of What?

- Modified gravity models change **space curvature** per unit **dynamical mass** - enhanced or reduced forces on matter
- Requires **two closure relations** - 1st an an effective **anisotropic stress** that distinguishes lensing from dynamical mass
- Viable induced modifications exhibit **three separate regimes**
 - Horizon Scale
 - Scalar-Tensor
 - General Relativistic
- Choice of **lensing mass** contribution as 2nd parameter in scalar-tensor regime favored by conformal invariance of E&M (Hu & Sawicki 2007; see also Caldwell et al 2007; Amendola et al 2007)

CAMB Package for Linearized PPF: <http://camb.info/ppf>

Other uses: phantom crossing dark energy (Fang, Hu, Lewis 2009), dark energy PCs (Mortonson, Hu, Huterer 2009) cascading gravity (Afshordi, Geshnizjani, Khoury 2008)

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No Signal

VGA-1

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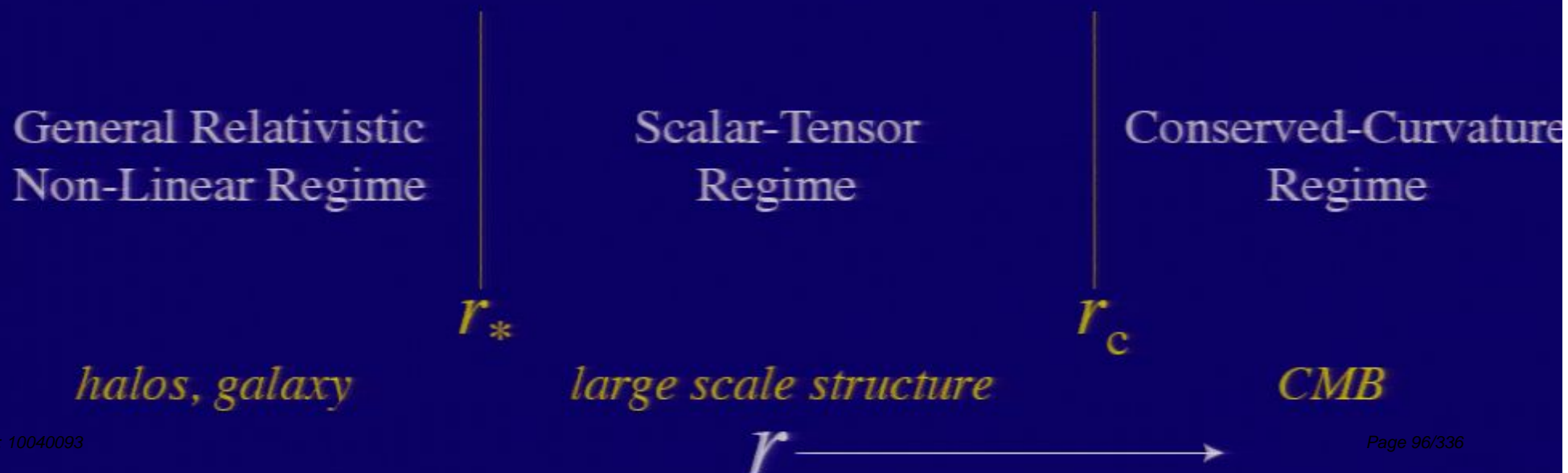
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Three Regimes

- Three regimes with different dynamics
- Examples $f(R)$ and DGP braneworld acceleration
- Parameterized Post-Friedmann description
- Non-linear regime return to General Relativity / Newtonian dynamics



Worked Examples

Modified Action $f(R)$ Model

- R : Ricci scalar or “curvature”
- $f(R)$: modified action (Starobinsky 1980; Carroll et al 2004)

$$S = \int d^4x \sqrt{-g} \left[\frac{R + f(R)}{16\pi G} + \mathcal{L}_m \right]$$

- $f_R \equiv df/dR$: additional propagating **scalar** degree of freedom (metric variation)
- $f_{RR} \equiv d^2f/dR^2$: **Compton wavelength** of f_R squared, inverse mass squared
- B : Compton wavelength of f_R squared in units of the Hubble length

$$B \equiv \frac{f_{RR}}{1 + f_R} R' \frac{H}{H'}$$

- $' \equiv d/d \ln a$: scale factor as time coordinate

Modified Einstein Equation

- In the **Jordan frame**, gravity becomes 4th order but matter remains **minimally coupled** and separately **conserved**

$$G_{\alpha\beta} + f_R R_{\alpha\beta} - \left(\frac{f}{2} - \square f_R \right) g_{\alpha\beta} - \nabla_\alpha \nabla_\beta f_R = 8\pi G T_{\alpha\beta}$$

- **Trace** can be interpreted as a **scalar field equation** for f_R with a **density-dependent effective potential** ($p = 0$)

$$3\square f_R + f_R R - 2f = R - 8\pi G \rho$$

- For small deviations, $|f_R| \ll 1$ and $|f/R| \ll 1$,

$$\square f_R \approx \frac{1}{3} (R - 8\pi G \rho)$$

the field is **sourced** by the deviation from GR relation between **curvature** and **density** and has a mass

$$m_{f_R}^2 \approx \frac{1}{3} \frac{\partial R}{\partial f_R} = \frac{1}{3 f_{RR}}$$

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- Braneworld acceleration (Dvali, Gabadadze & Porrati 2000)

$$S = \int d^5x \sqrt{-g} \left[\frac{{}^{(5)}R}{2\kappa^2} + \delta(\chi) \left(\frac{{}^{(4)}R}{2\mu^2} + \mathcal{L}_m \right) \right]$$

with crossover scale $r_c = \kappa^2/2\mu^2$

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$$S = \int d^5x \sqrt{-g} \left[\frac{{}^{(5)}R}{2\kappa^2} + \delta(\chi) \left(\frac{{}^{(4)}R}{2\mu^2} + \mathcal{L}_m \right) \right]$$

with crossover scale $r_c = \kappa^2/2\mu^2$

- Influence of bulk through **Weyl tensor anisotropy** - solve **master equation** in bulk (Deffayet 2001)
- Matter still **minimally coupled** and conserved
- Exhibits the 3 regimes of modified gravity
- **Weyl tensor anisotropy** dominated conserved curvature regime $r > r_c$ (Sawicki, Song, Hu 2006; Cardoso et al 2007)
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DGP Field Equations

- DGP field equations

$$G_{\mu\nu} = 4r_c^2 f_{\mu\nu} - E_{\mu\nu}$$

where $f_{\mu\nu}$ is a tensor **quadratic** in the 4-dimensional Einstein and energy-momentum tensors

$$f_{\mu\nu} \equiv \frac{1}{12} A A_{\mu\nu} - \frac{1}{4} A_{\mu}^{\alpha} A_{\nu\alpha} + \frac{1}{8} g_{\mu\nu} \left(A_{\alpha\beta} A^{\alpha\beta} - \frac{A^2}{3} \right)$$

$$A_{\mu\nu} \equiv G_{\mu\nu} - \mu^2 T_{\mu\nu}$$

and $E_{\mu\nu}$ is the bulk **Weyl tensor**

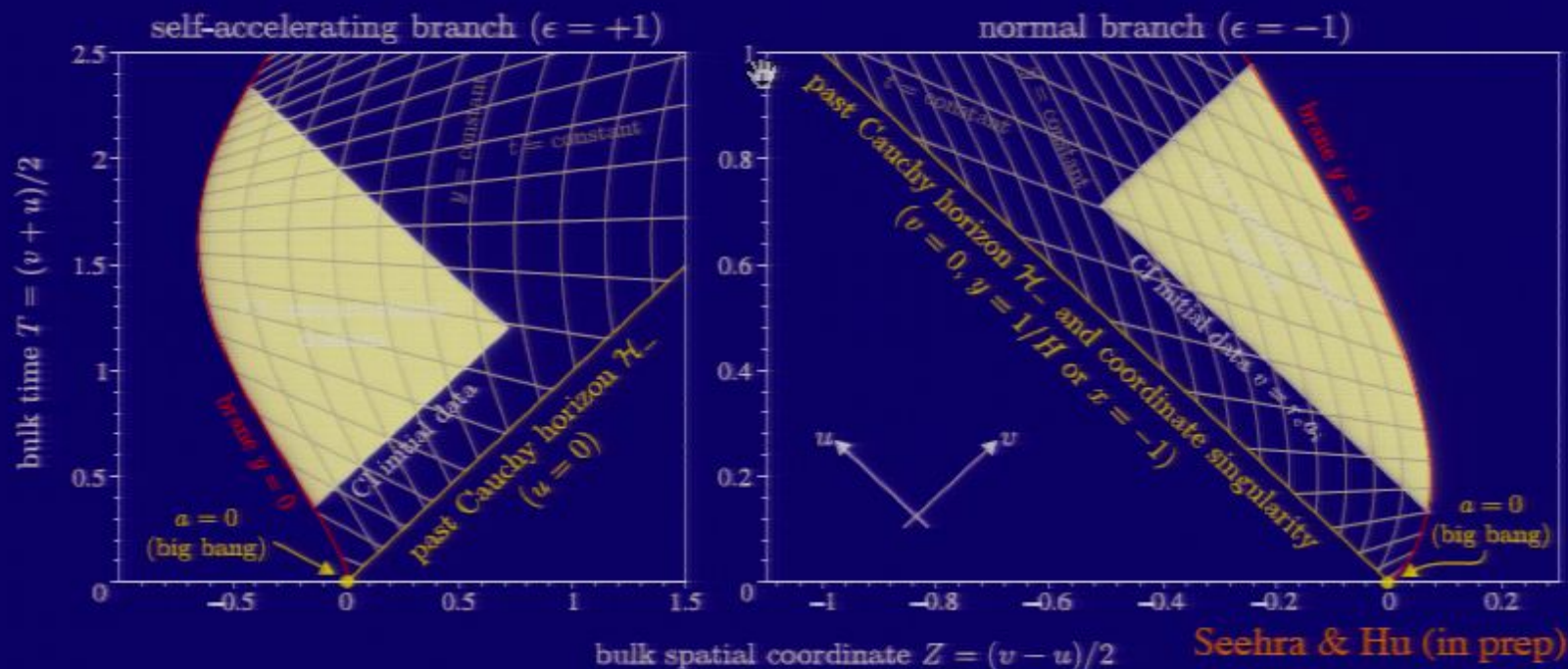
- Background metric yields the **modified Friedmann equation**

$$H^2 \mp \frac{H}{r_c} = \frac{\mu^2 \rho}{3}$$

- For perturbations, involves solving **metric perturbations** in the **bulk** through the “**master equation**”

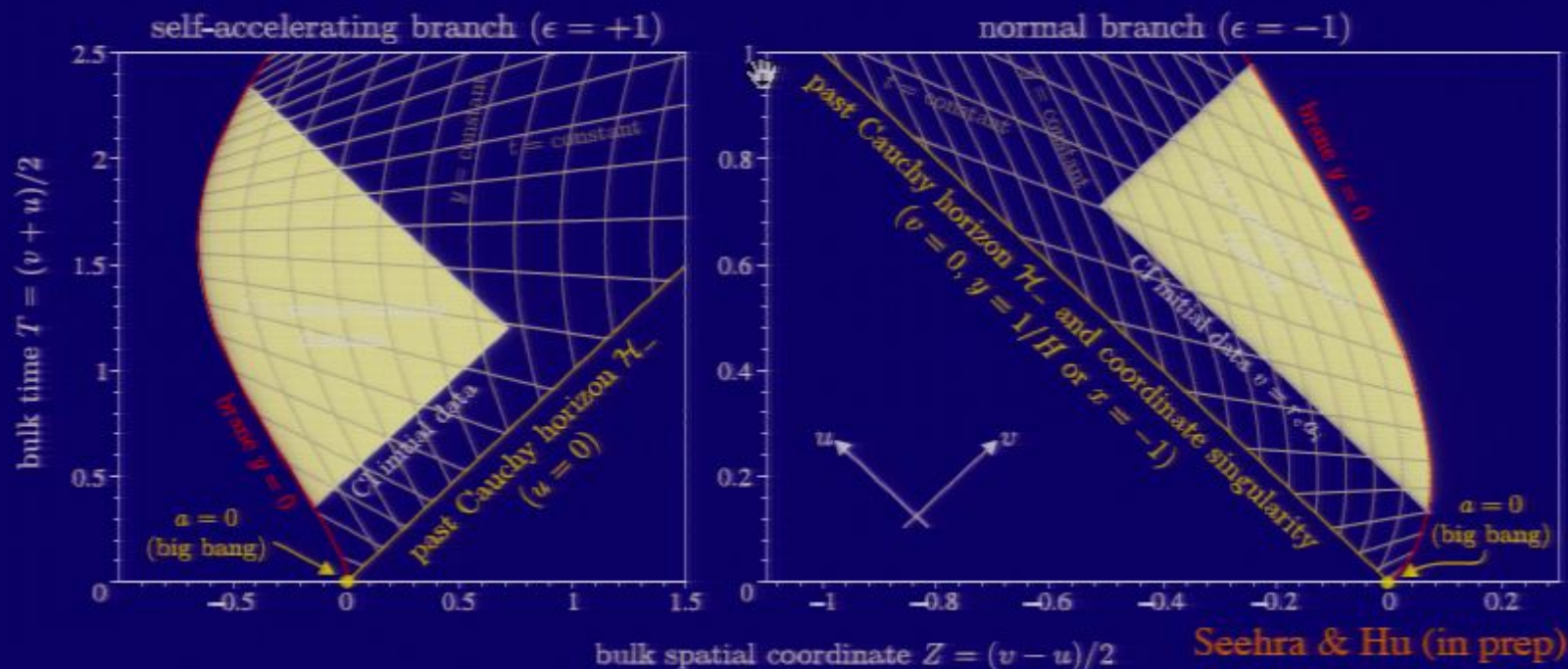
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- Calculation of the metric ratio $g = \Phi + \Psi / \Phi - \Psi$ requires solving for the propagation of **metric fluctuations** into the **bulk**
- Encapsulated in the **off brane gradient** which **closes** the system (e.g. normal branch $g = -1/(2Hr_c + 1)$) until deep in **de Sitter**)



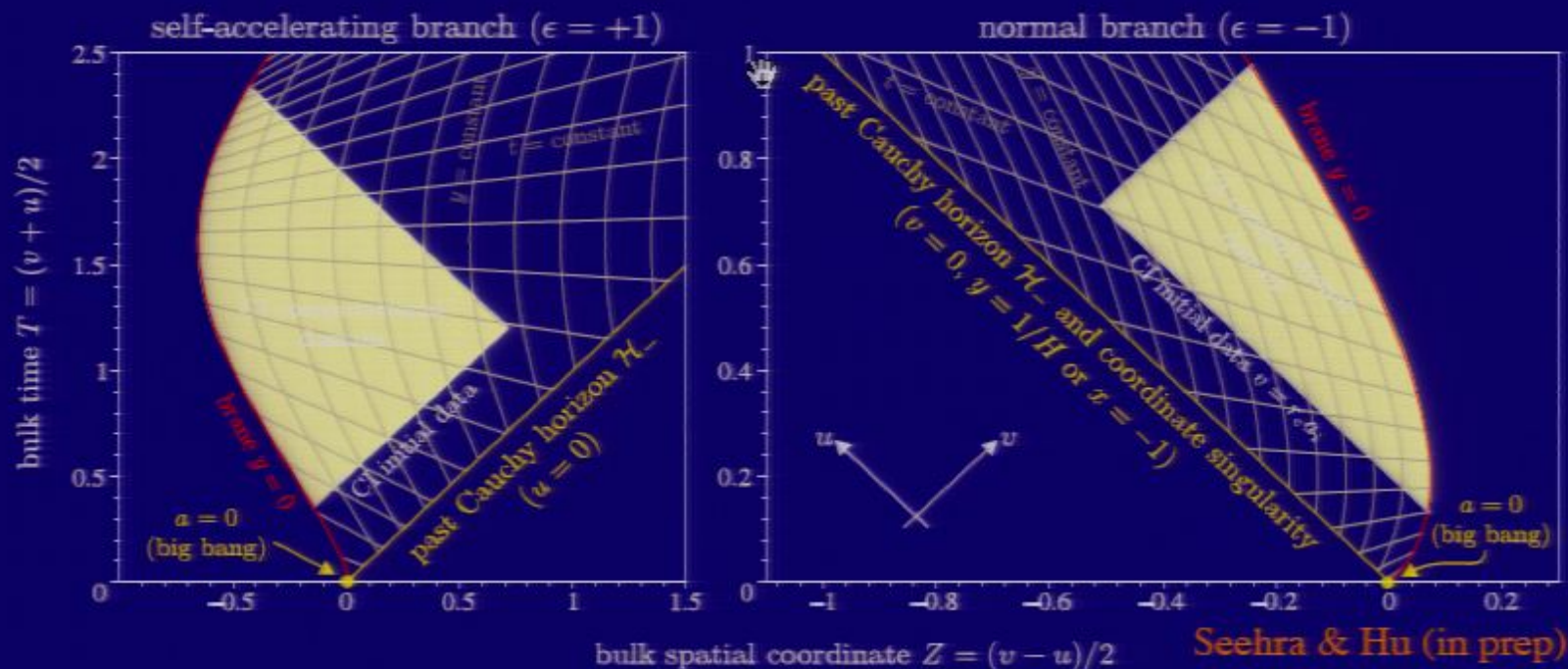
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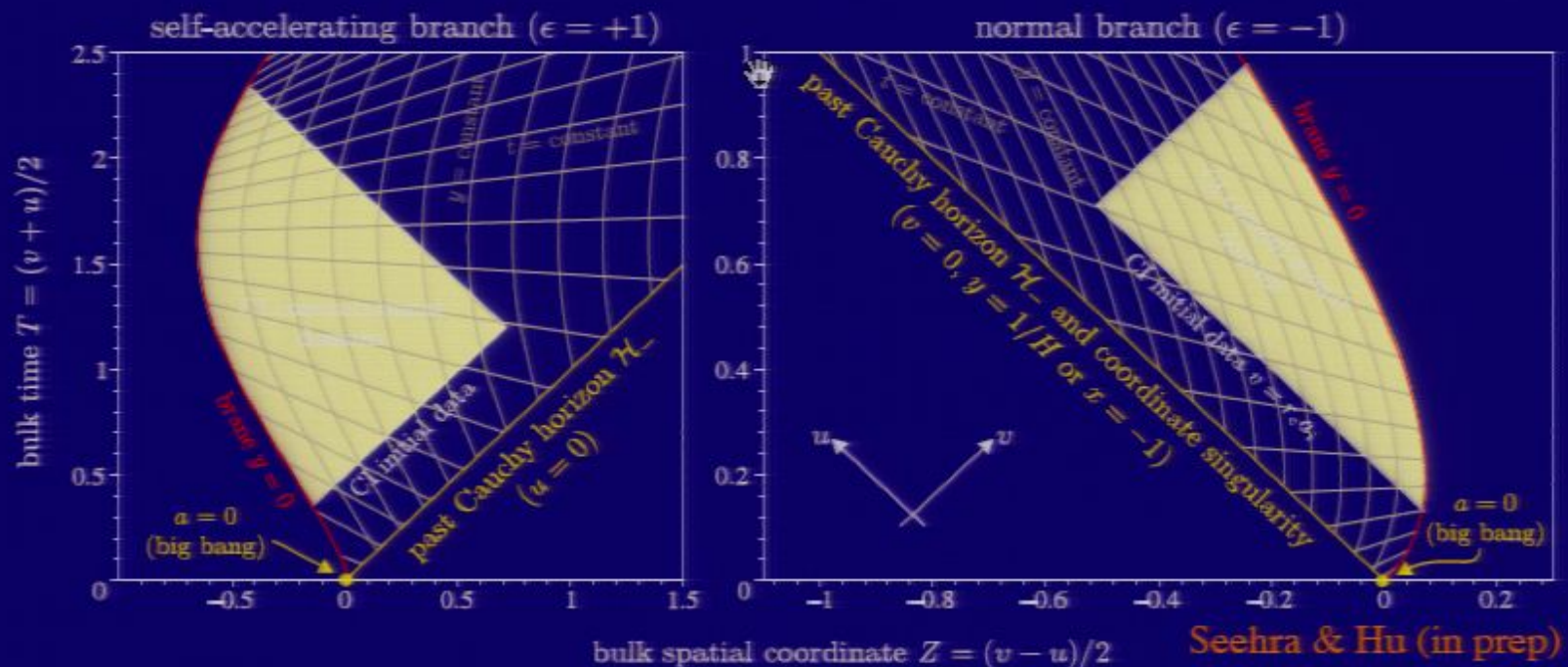
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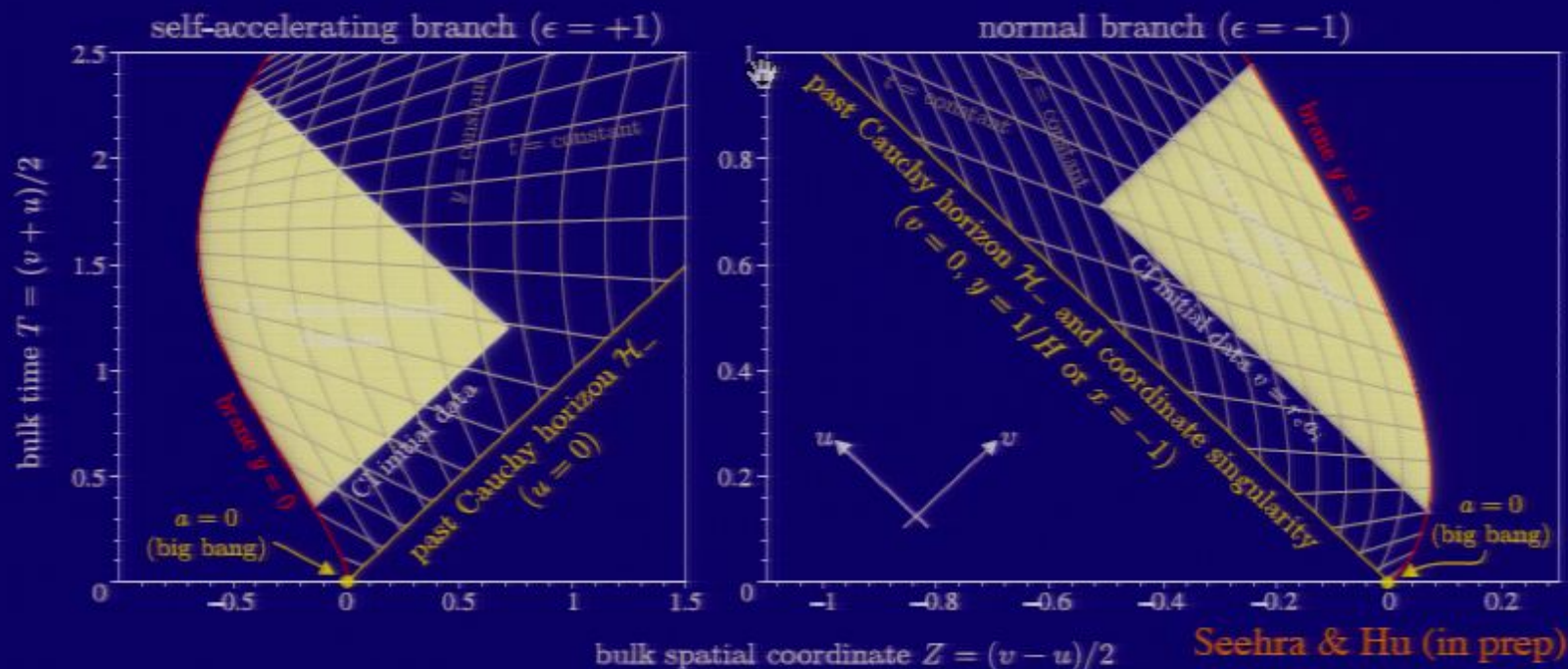
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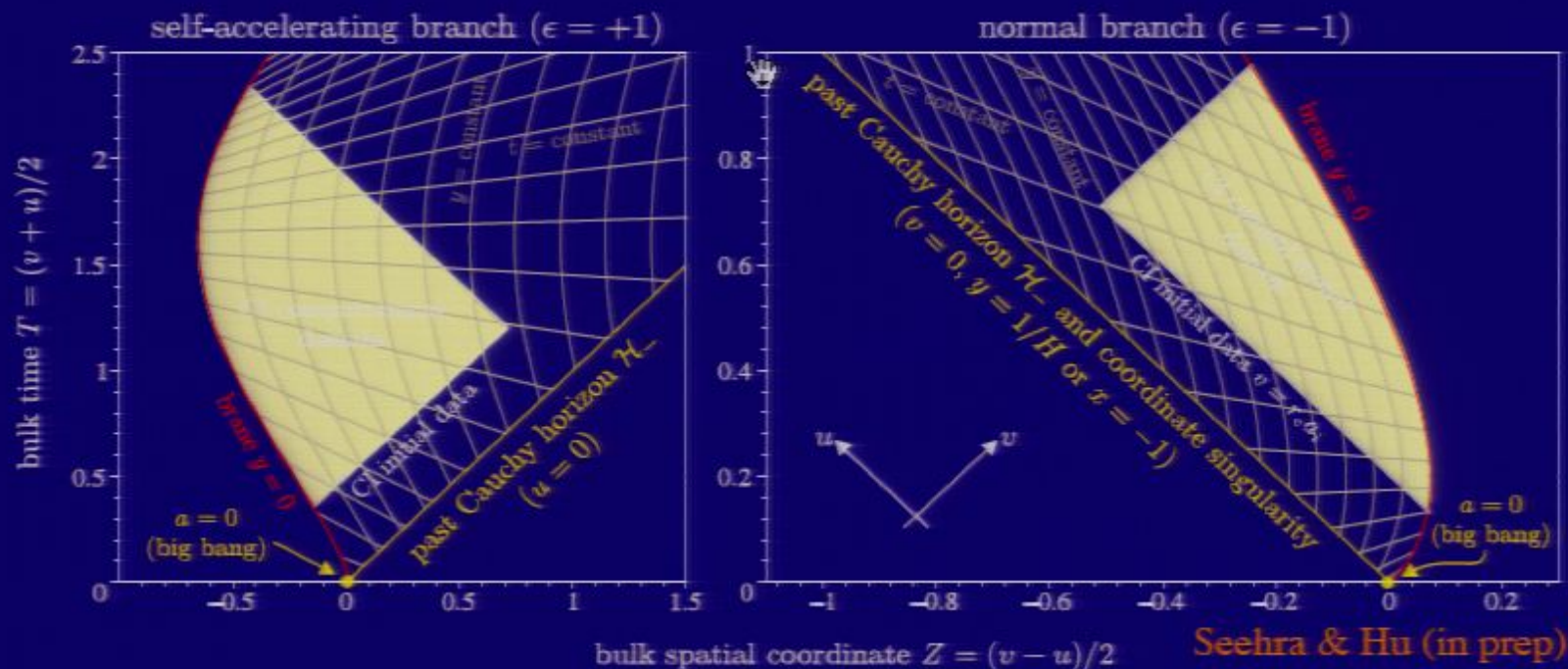
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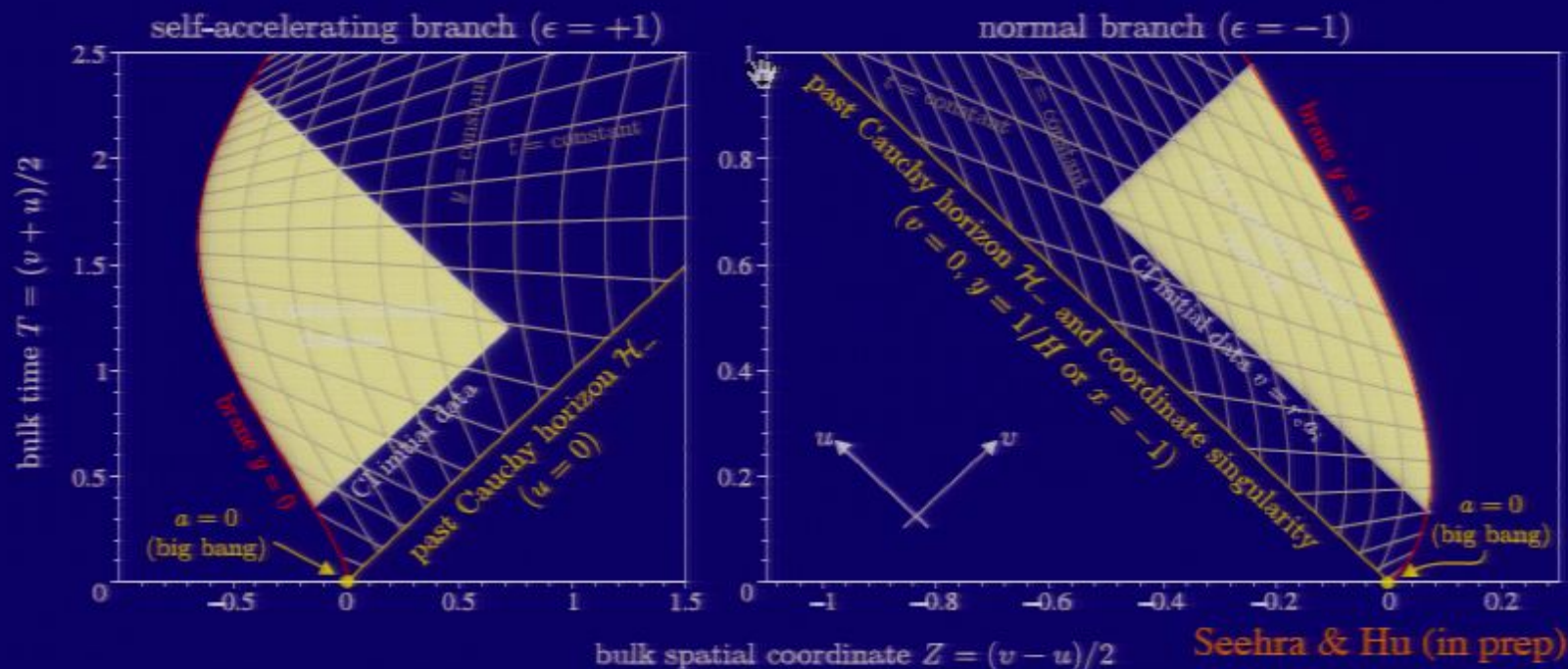
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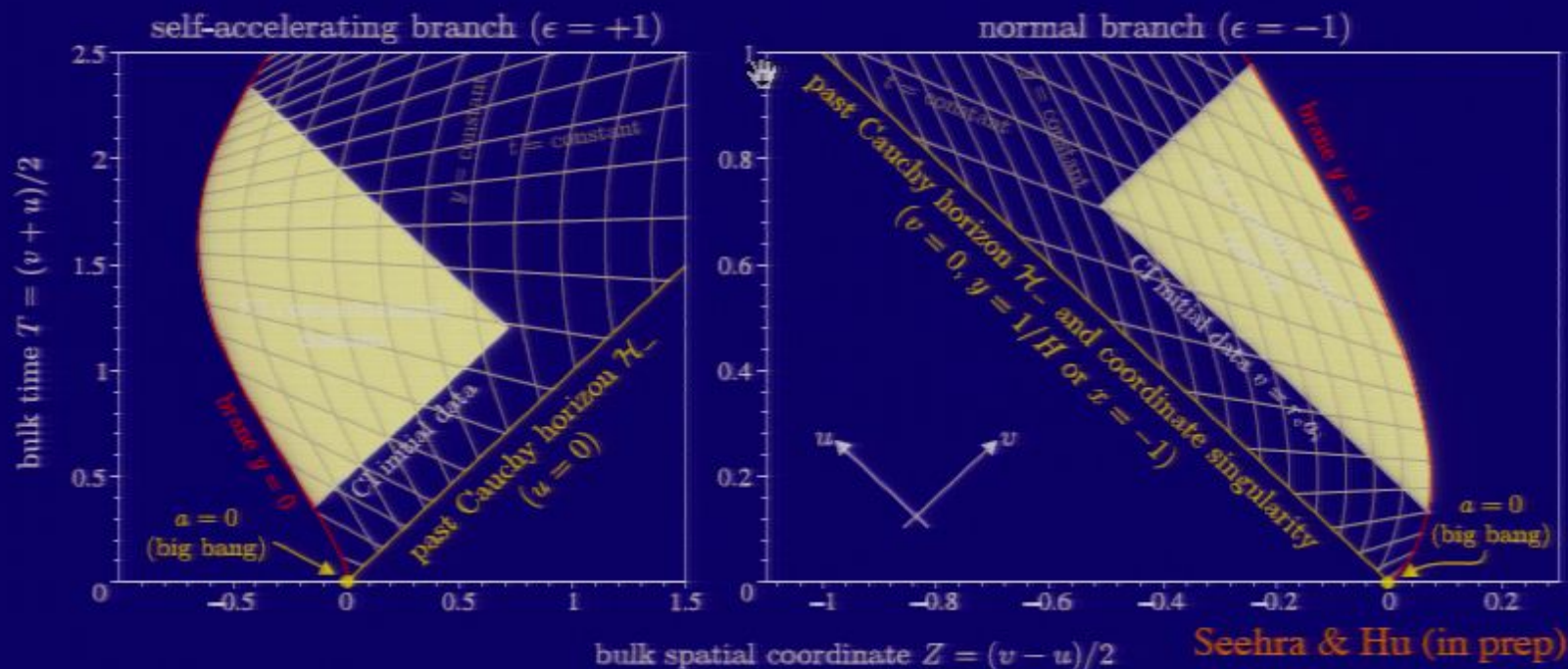
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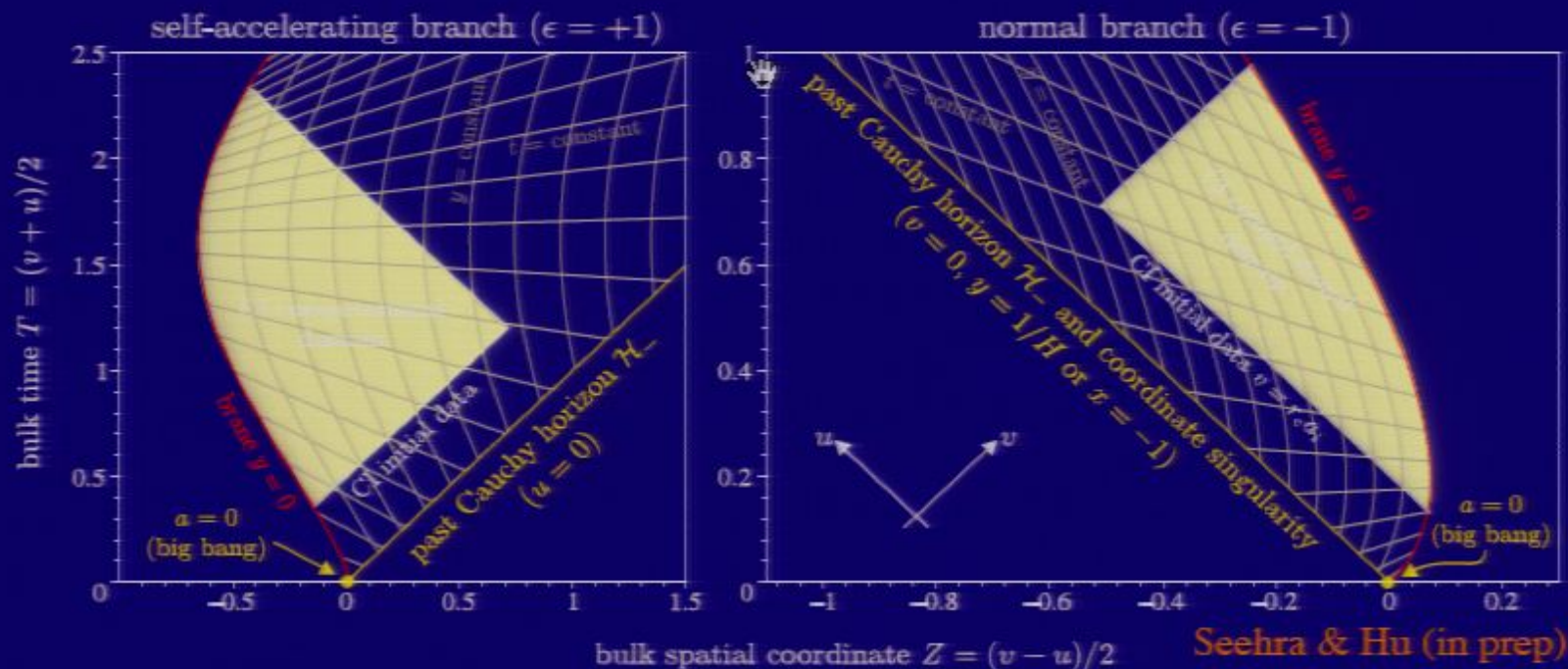
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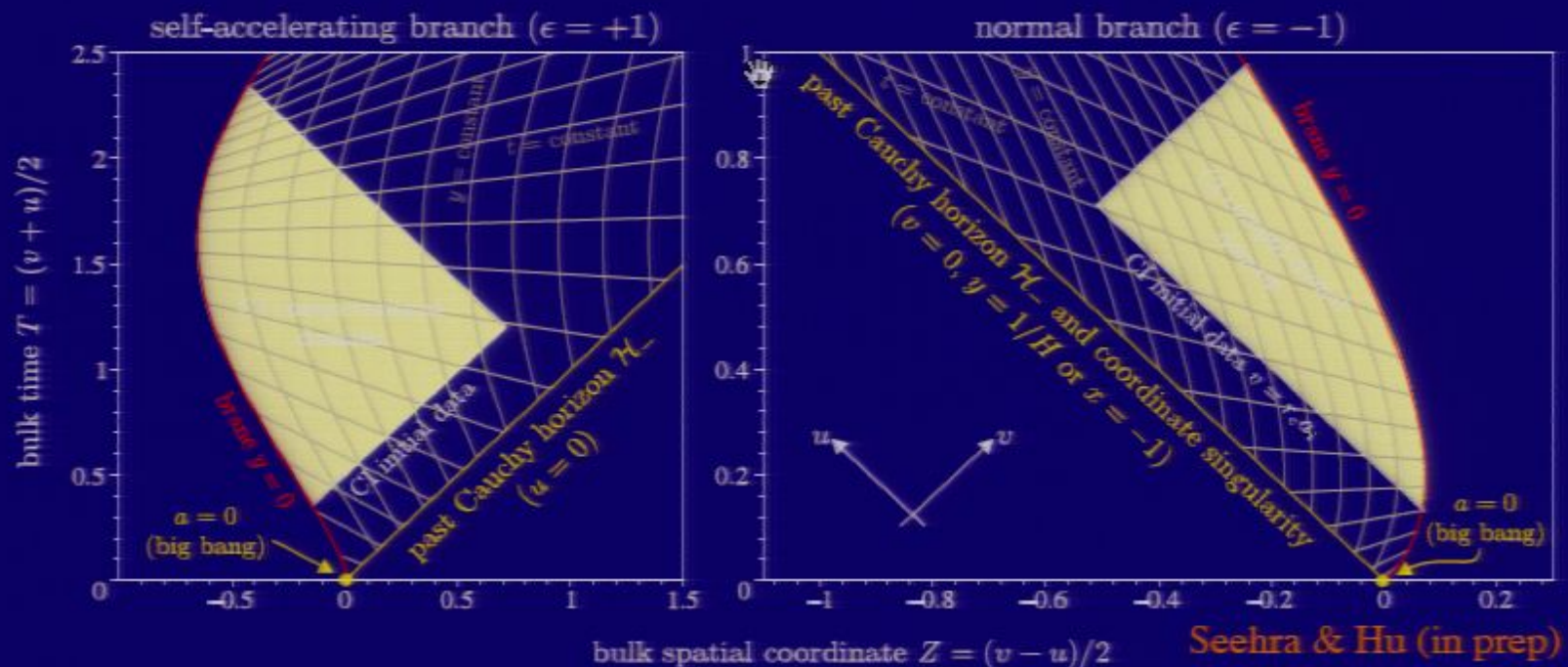
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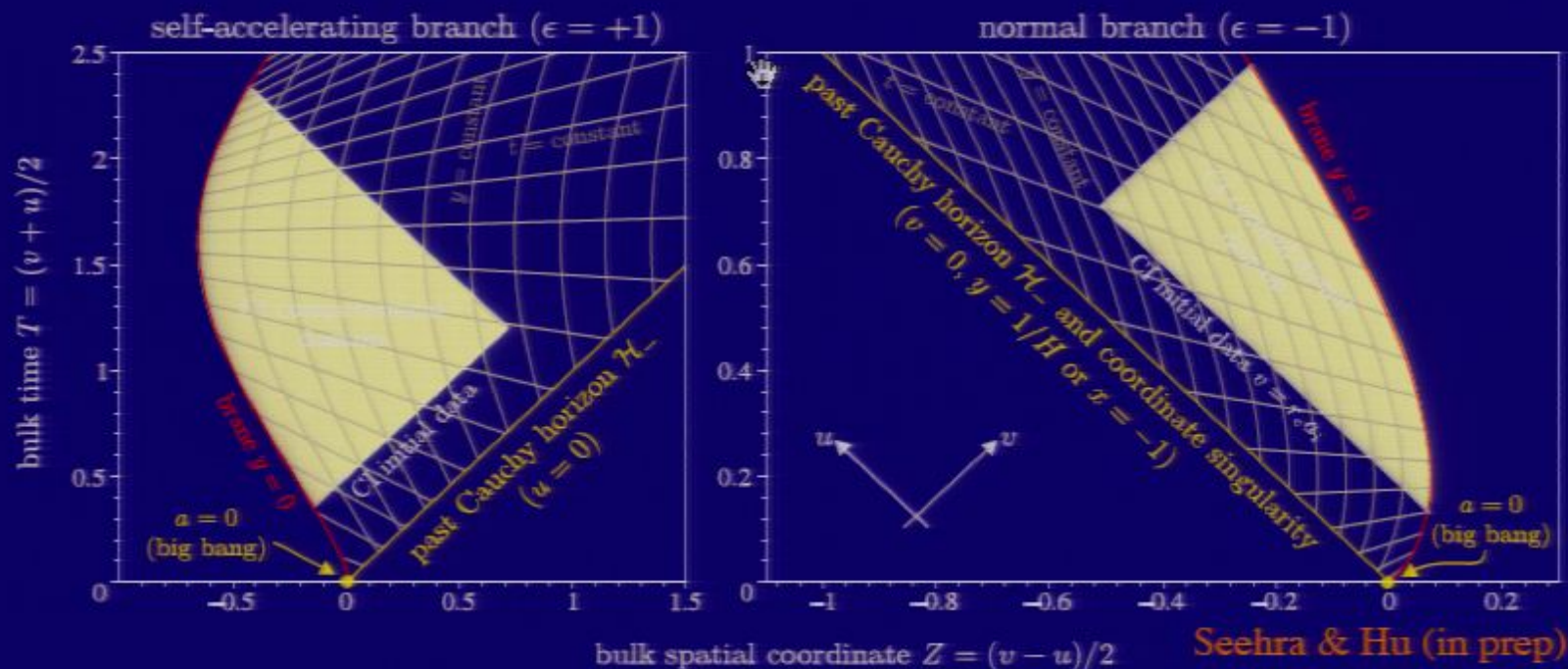
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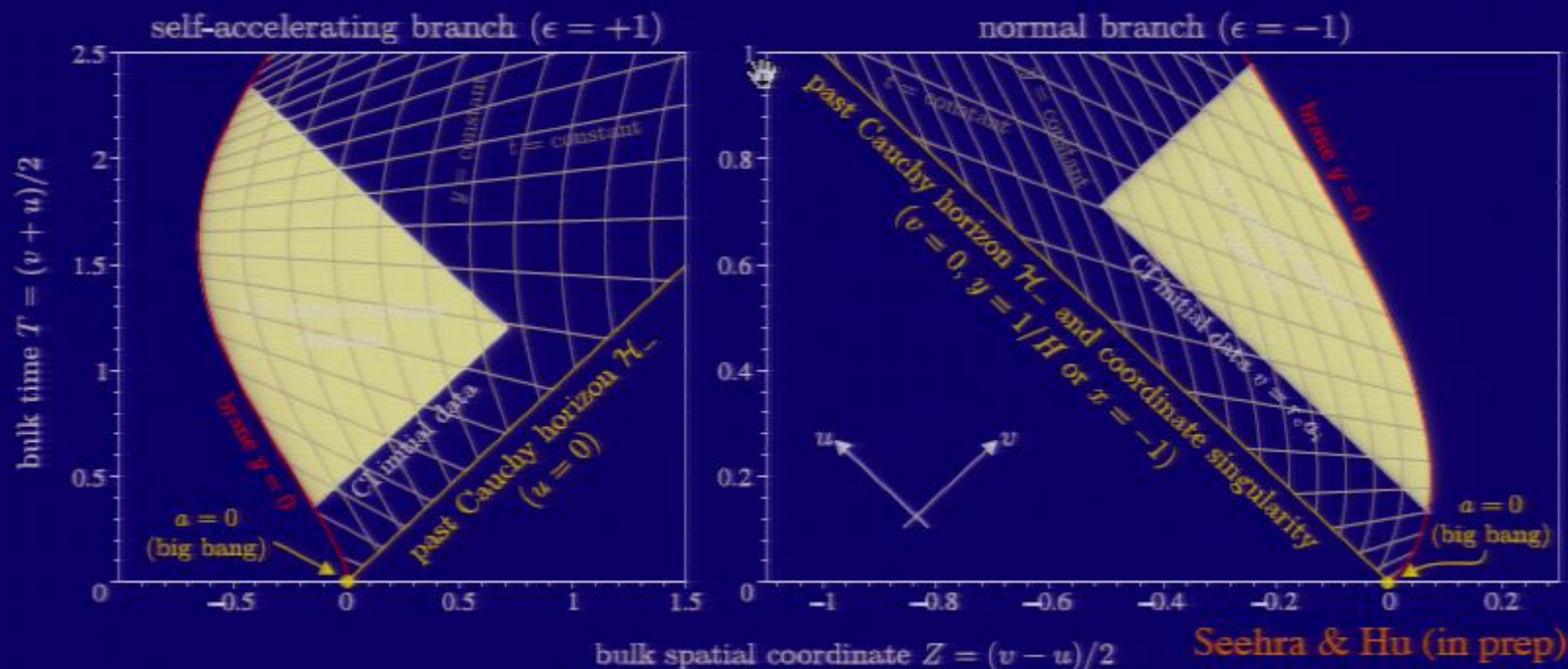
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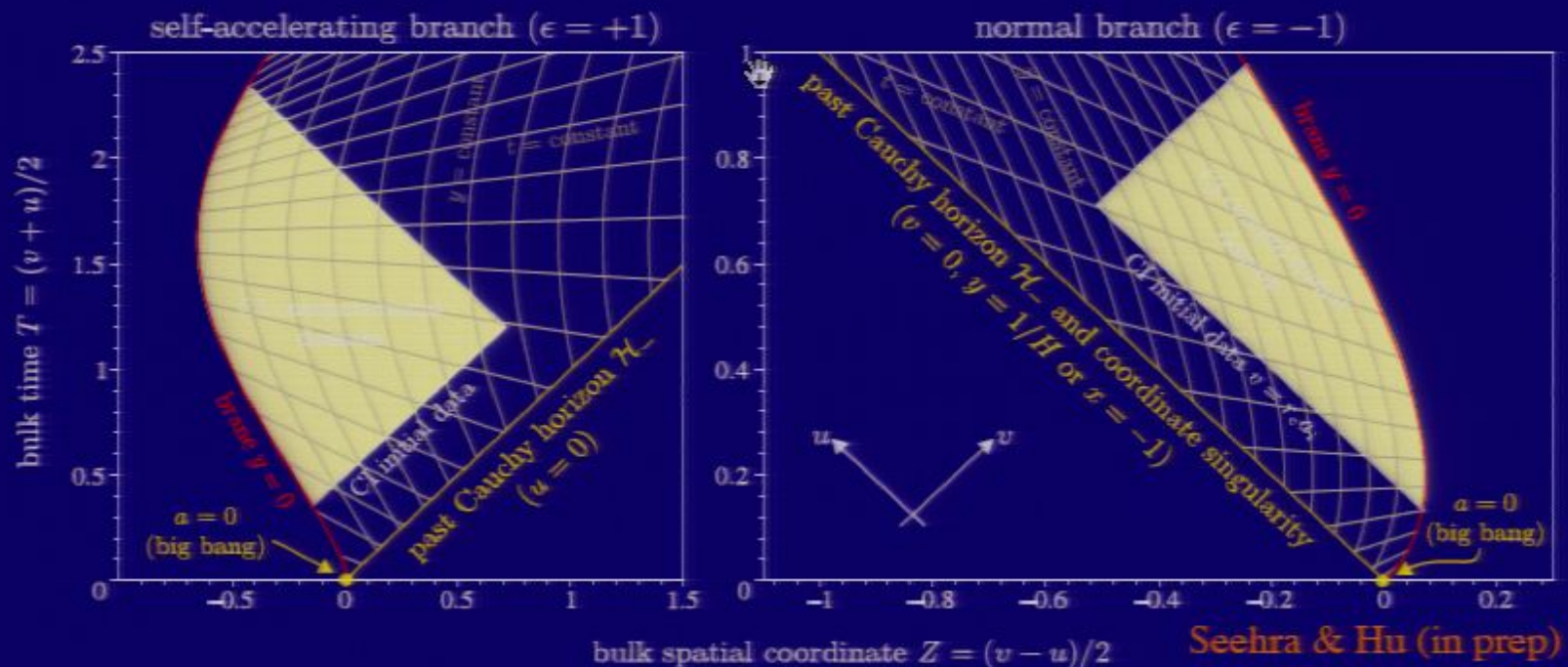
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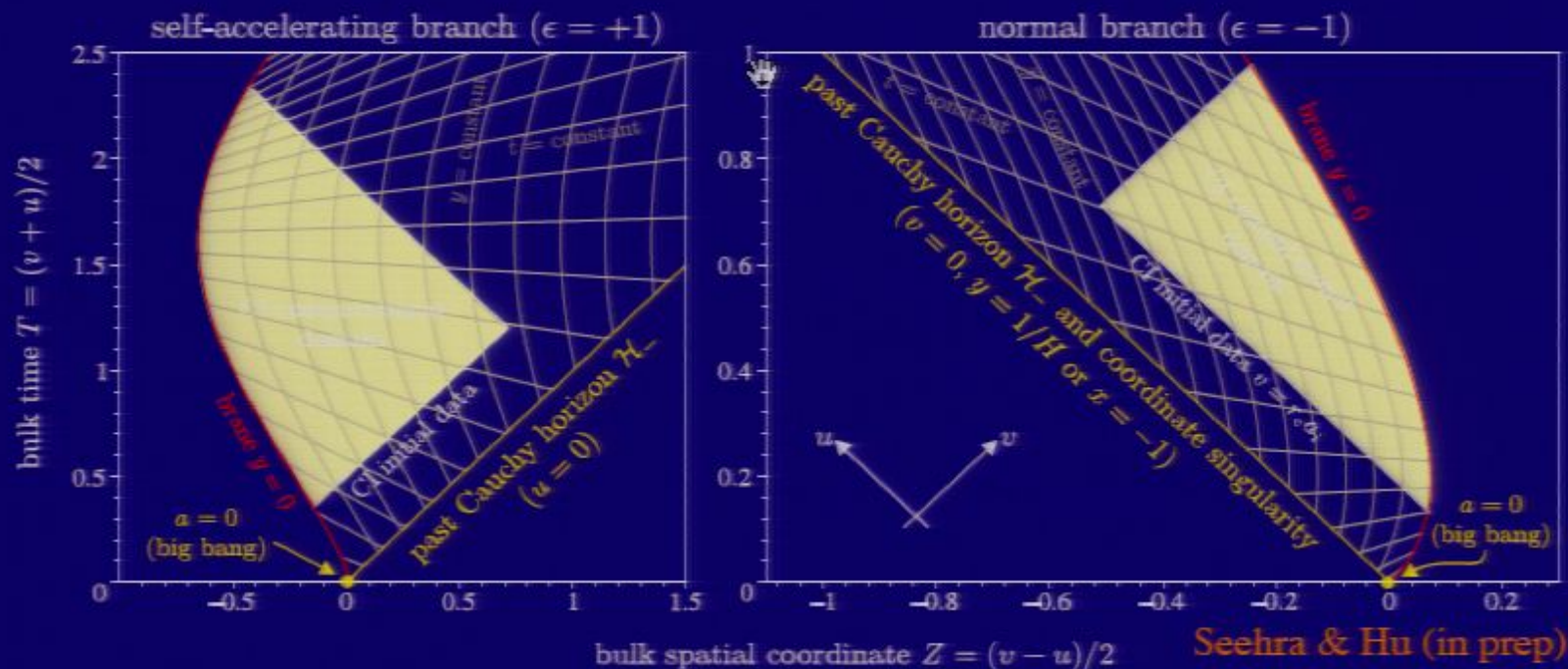
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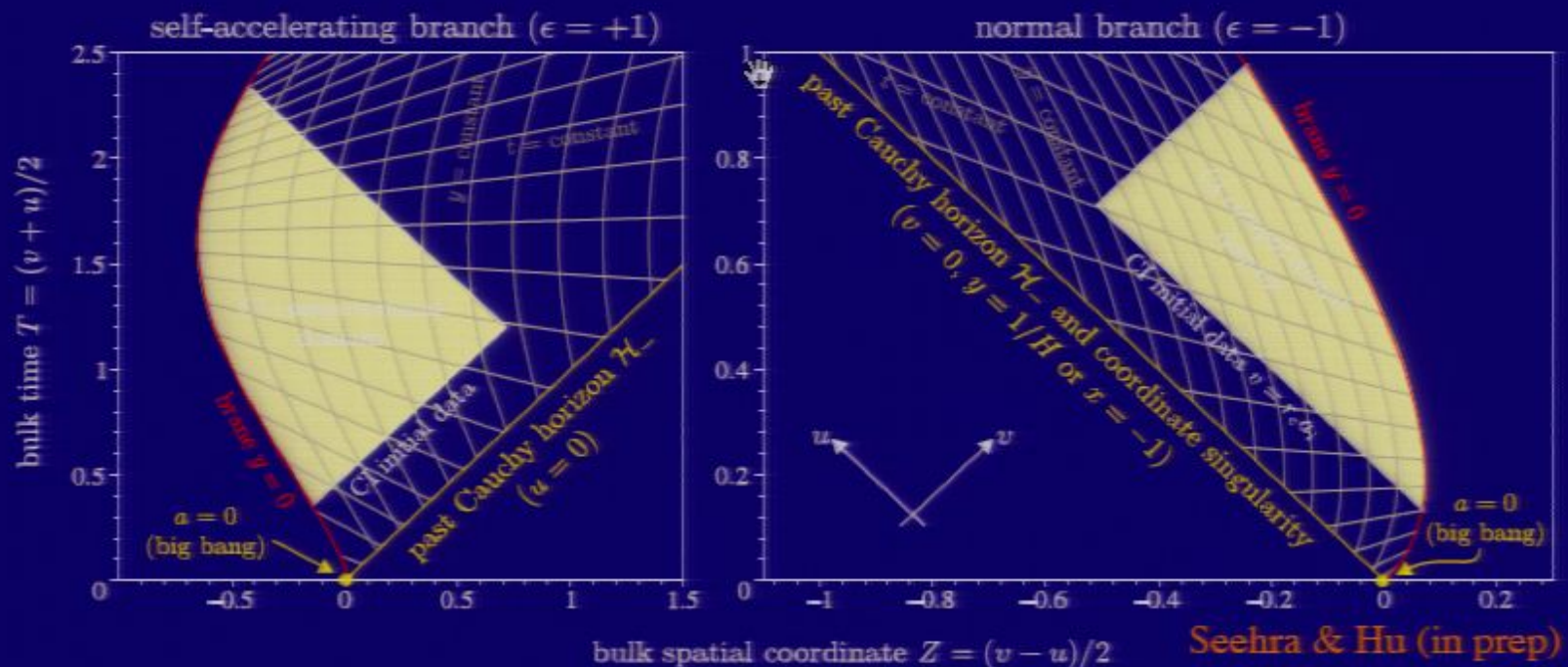
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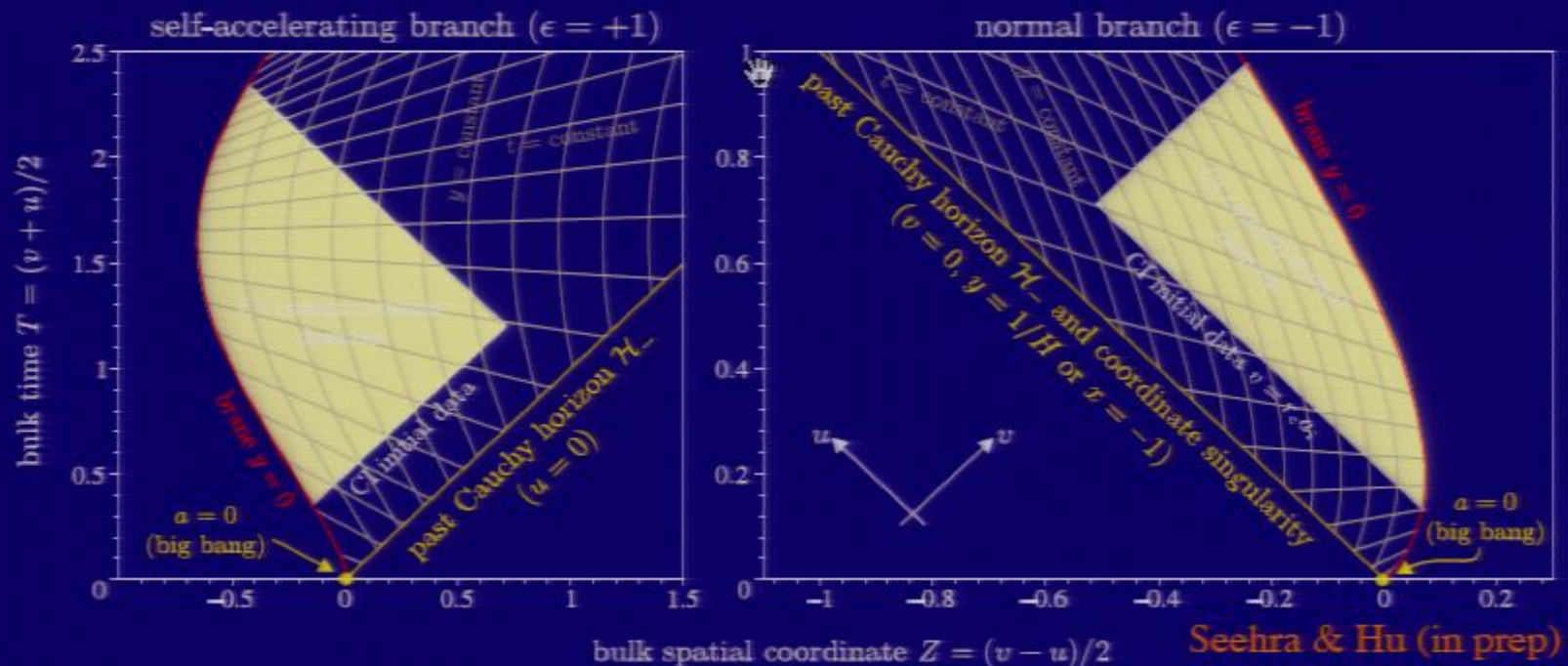
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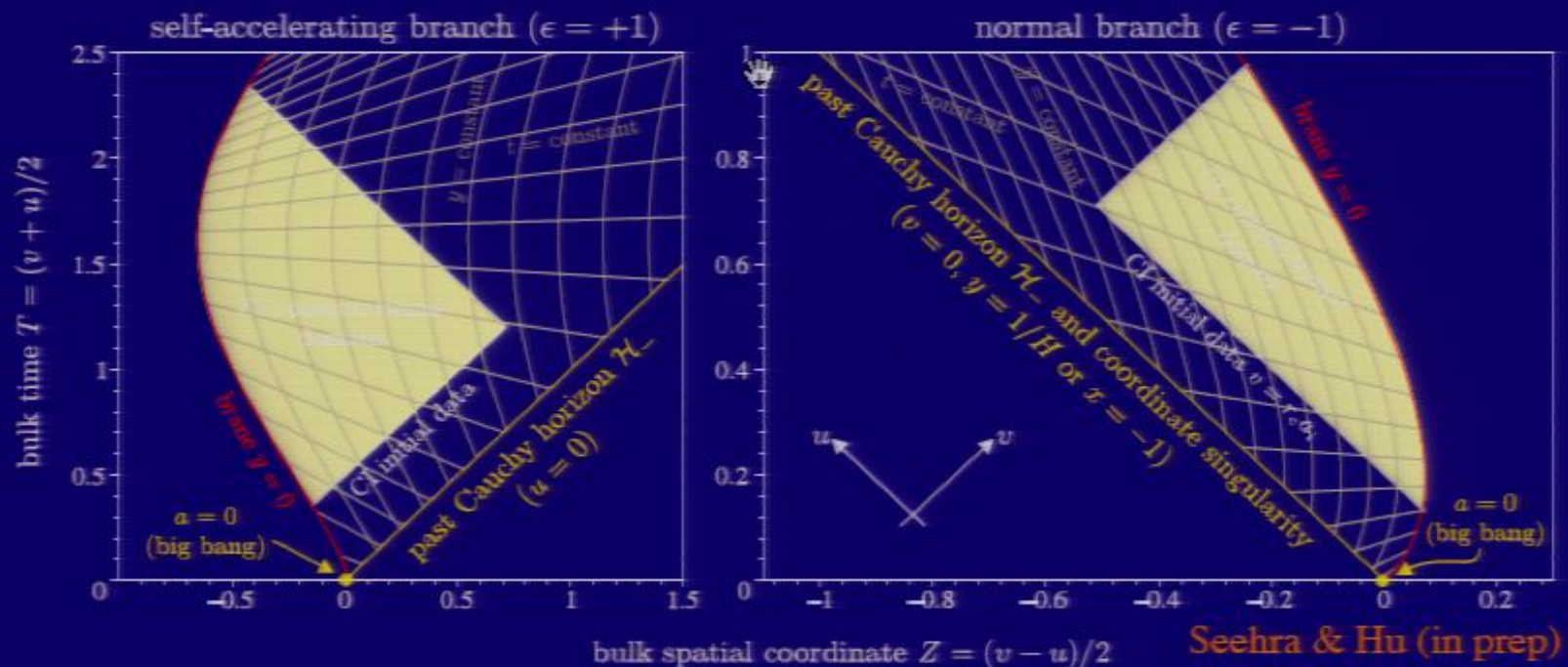
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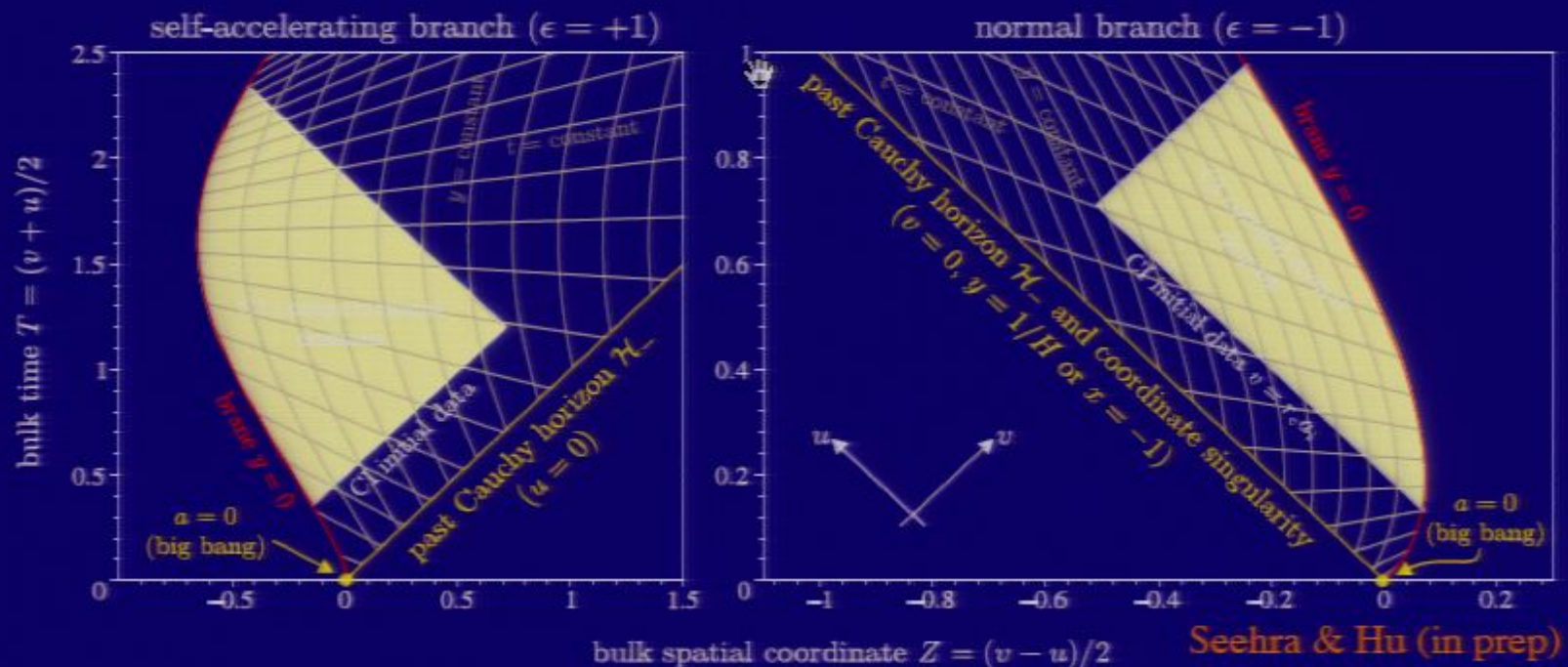
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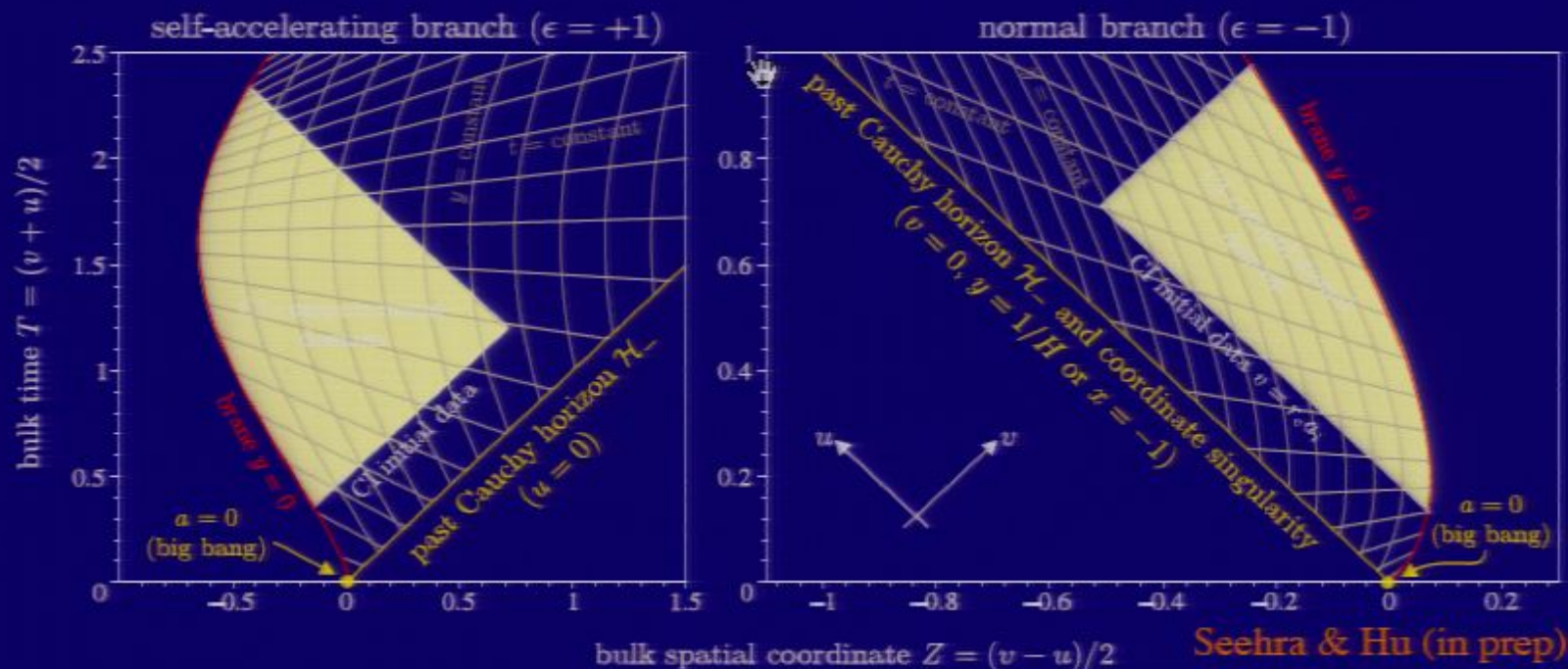
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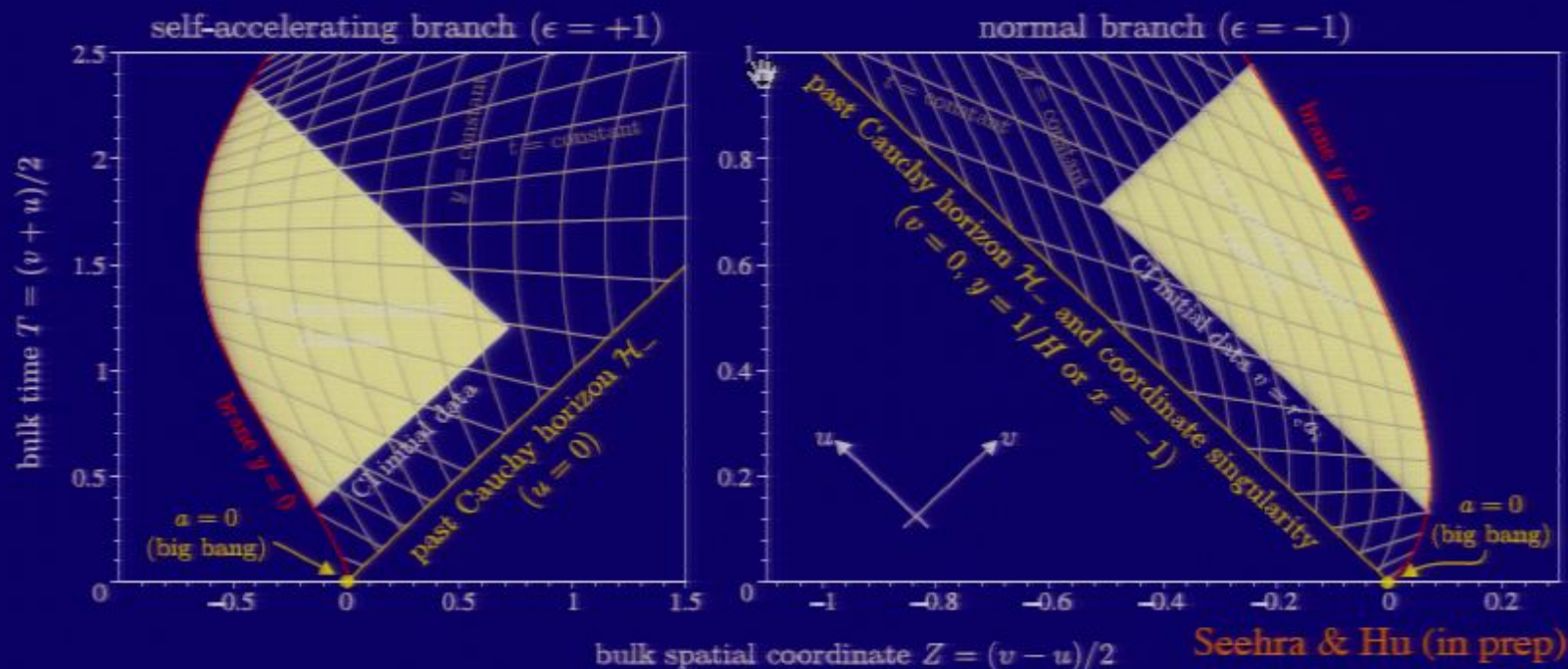
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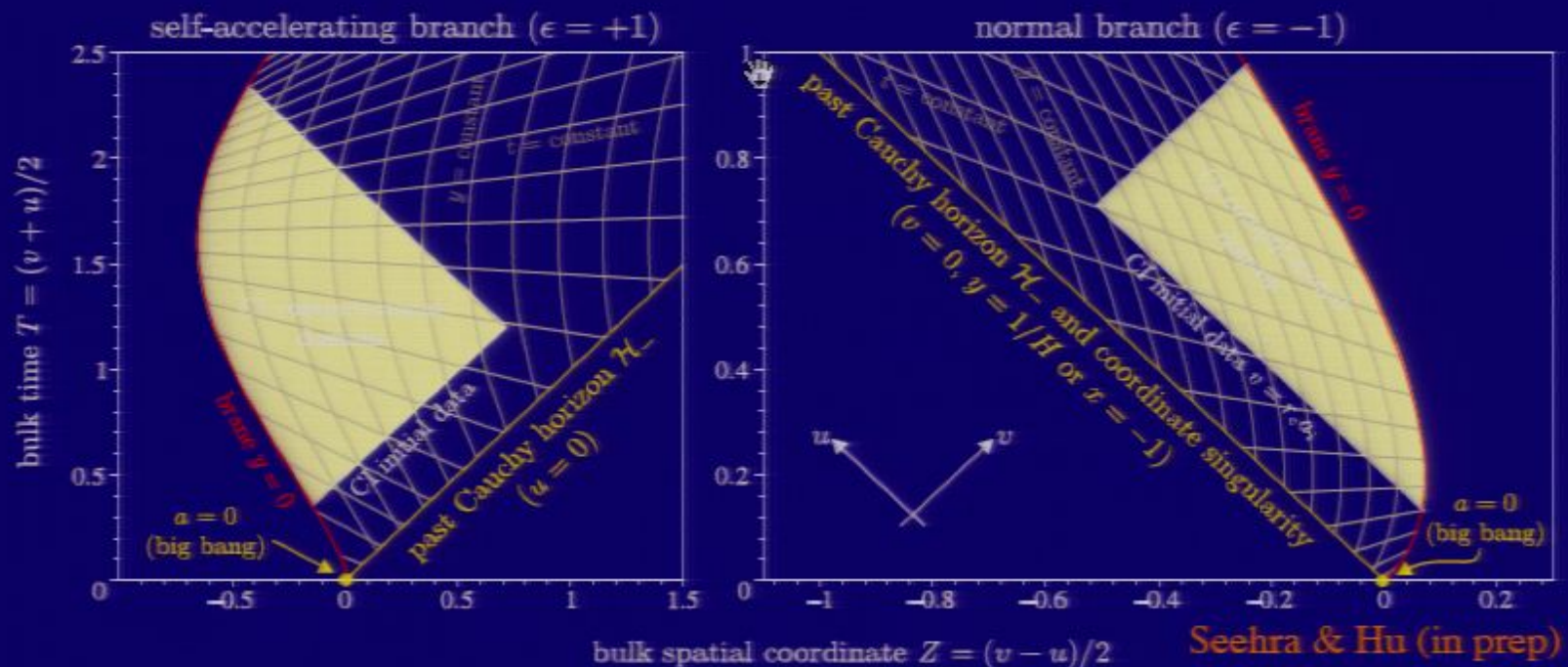
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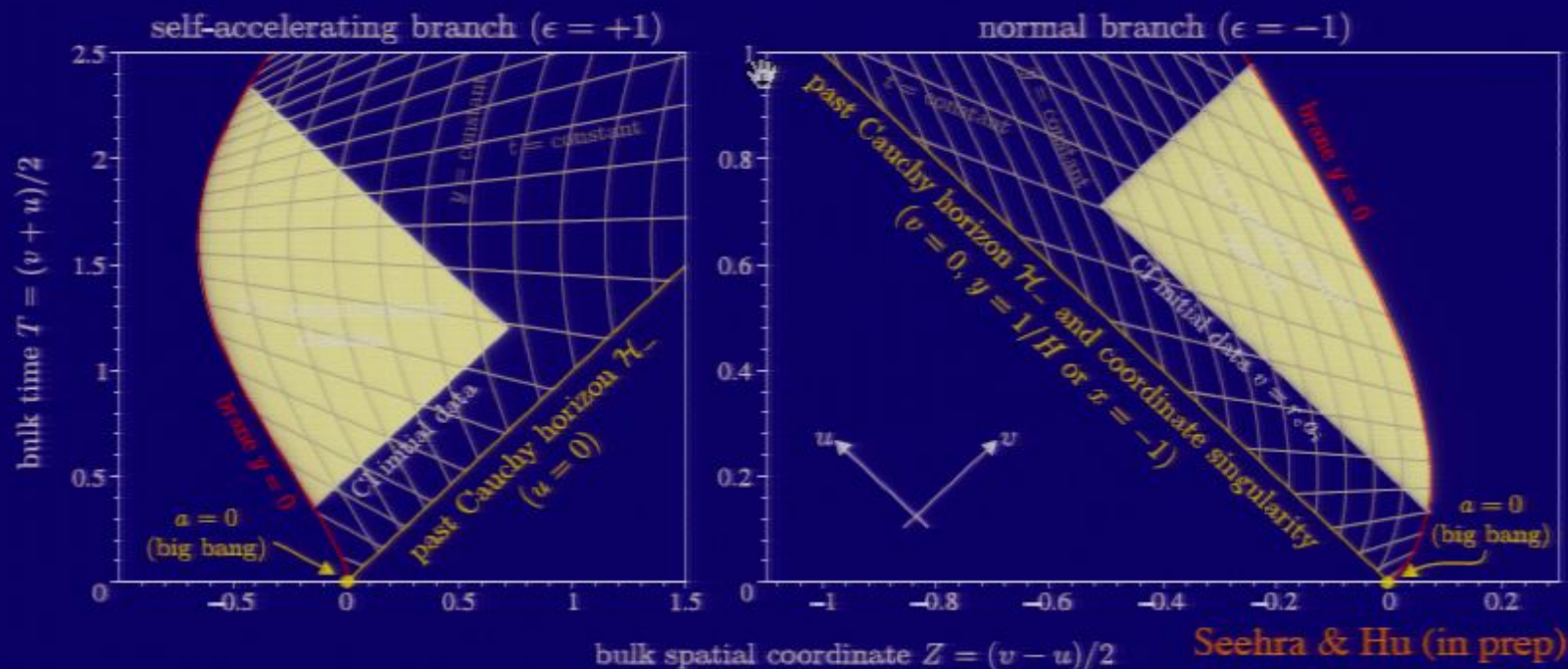
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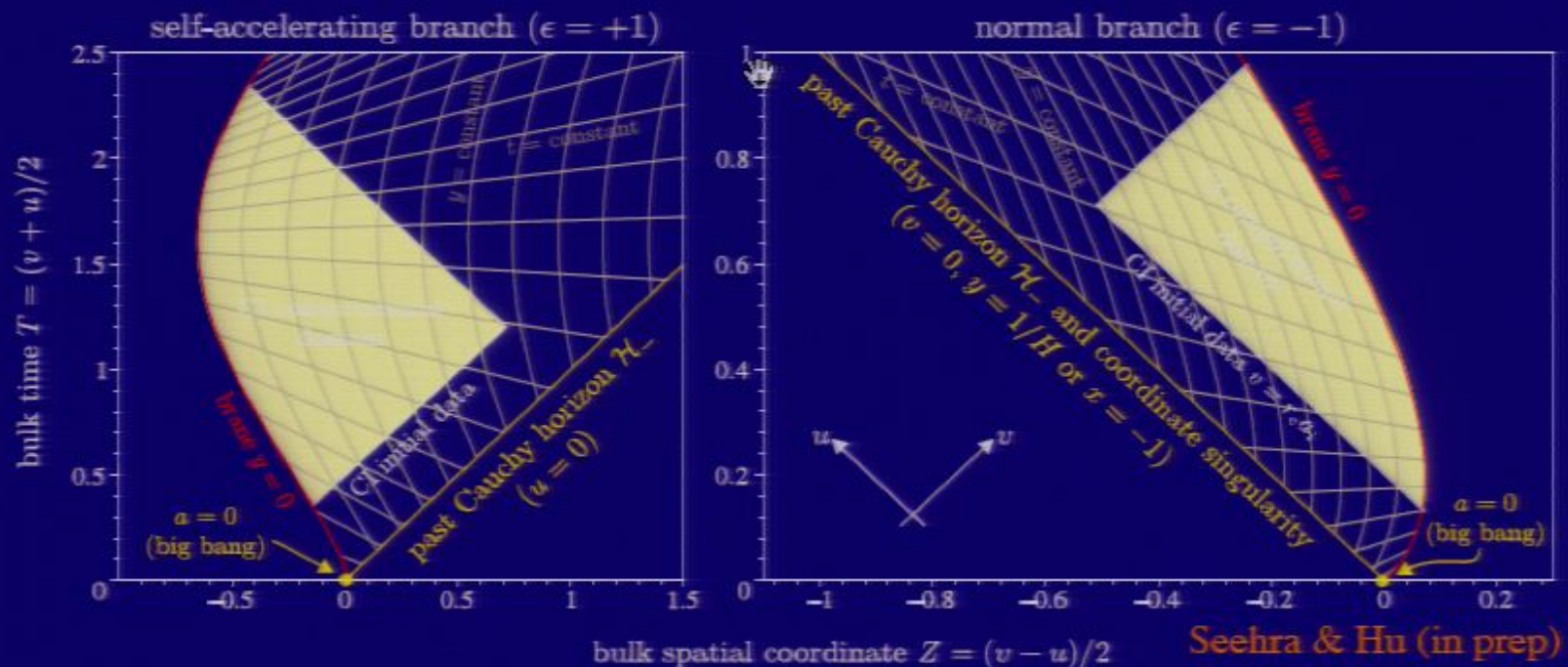
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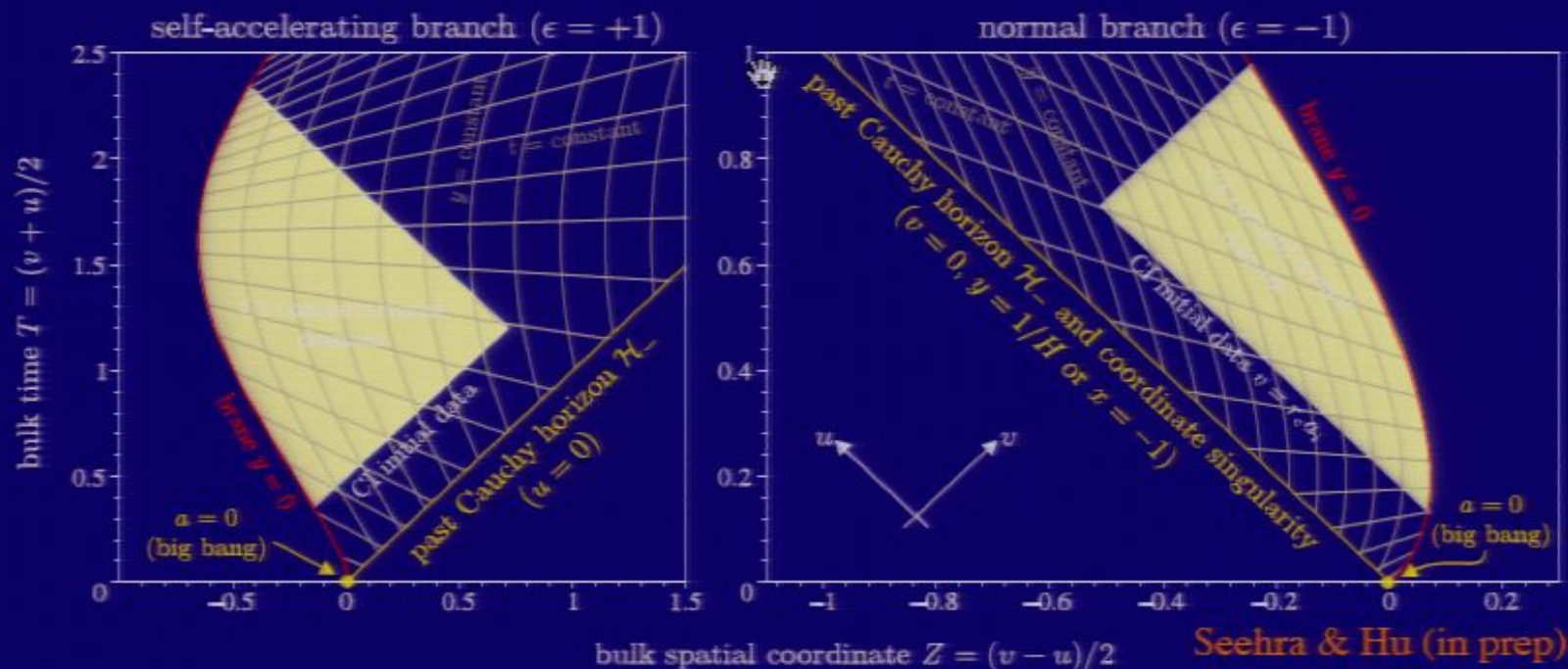
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Seehra & Hu (in prep)

$f(R)$ Expansion History

Engineering $f(R)$ Models

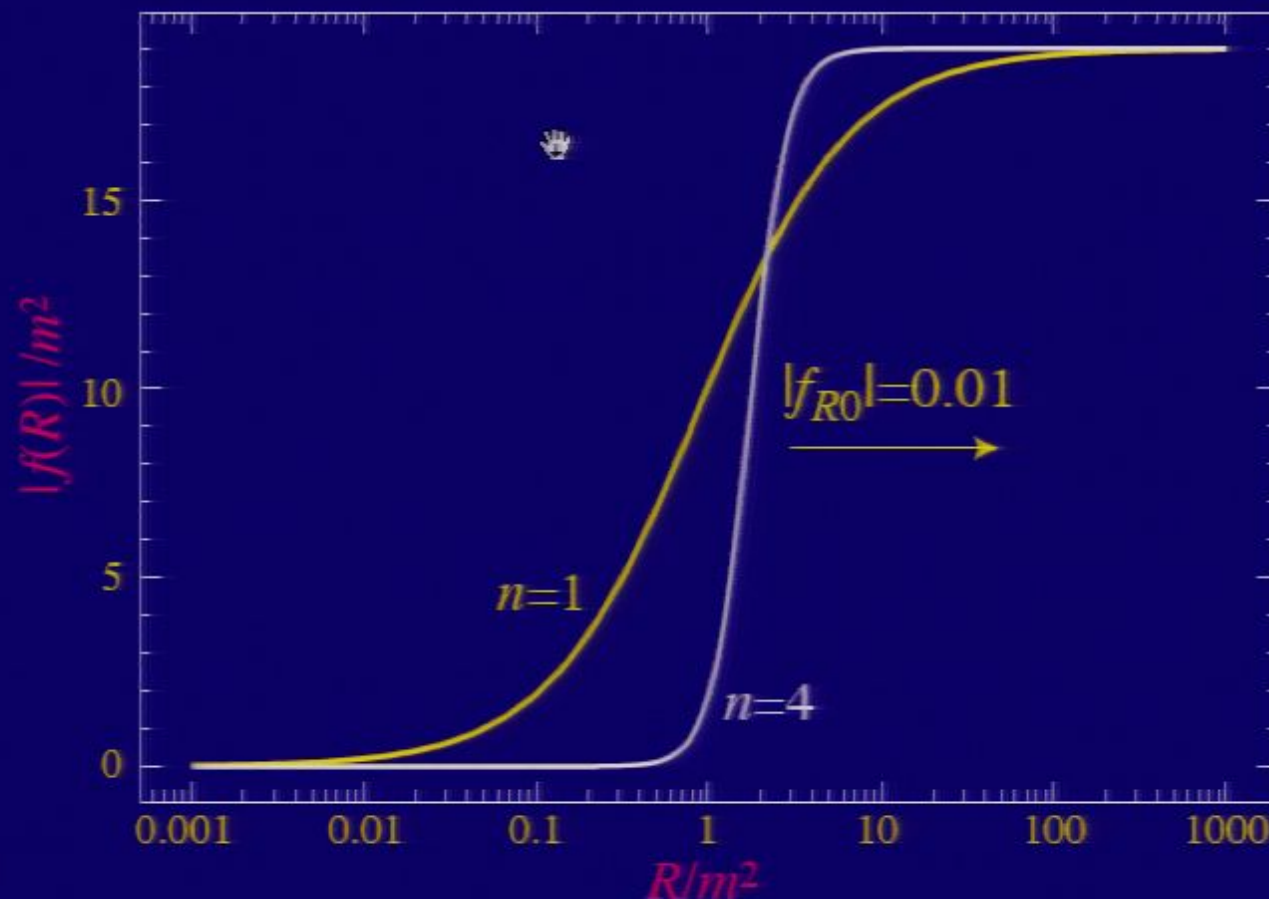
- Mimic Λ CDM at high redshift
- **Accelerate** the expansion at **low redshift** without a cosmological constant
- Sufficient **freedom** to vary **expansion history** within observationally allowed range
- **Contain** the phenomenology of Λ CDM in both cosmology and solar system tests as a **limiting case** for the purposes of constraining **small deviations**
- Suggests

$$f(R) \propto \frac{R^n}{R^n + \text{const.}}$$

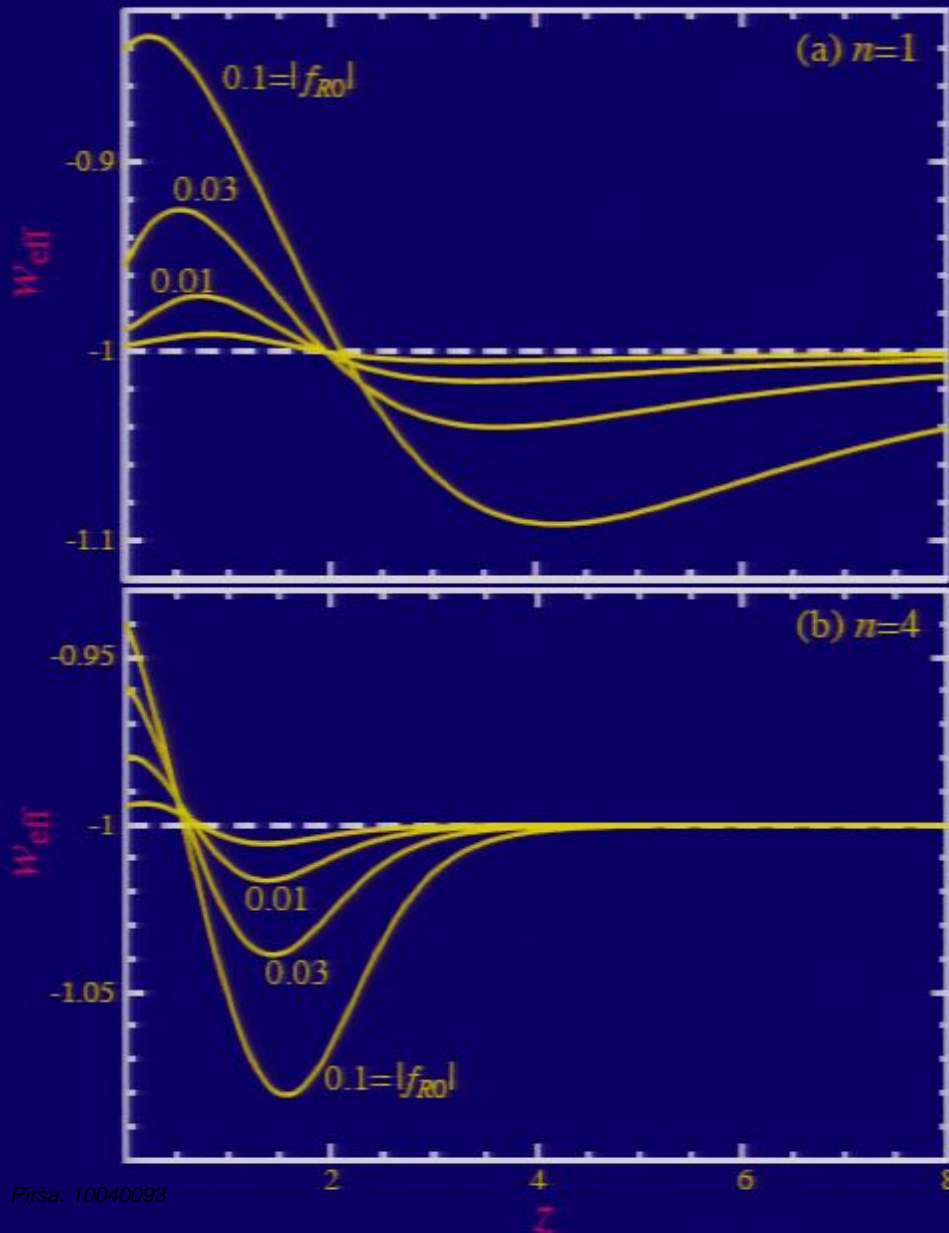
such that modifications **vanish** as $R \rightarrow 0$ and go to a **constant** as $R \rightarrow \infty$

Form of $f(R)$ Models

- Transition from **zero** to **constant** across an adjustable curvature scale
- Slope n controls the **rapidity** of transition, field amplitude f_{R0} **position**
- Background **curvature** stops declining during acceleration epoch and thereafter behaves like **cosmological constant**



Expansion History

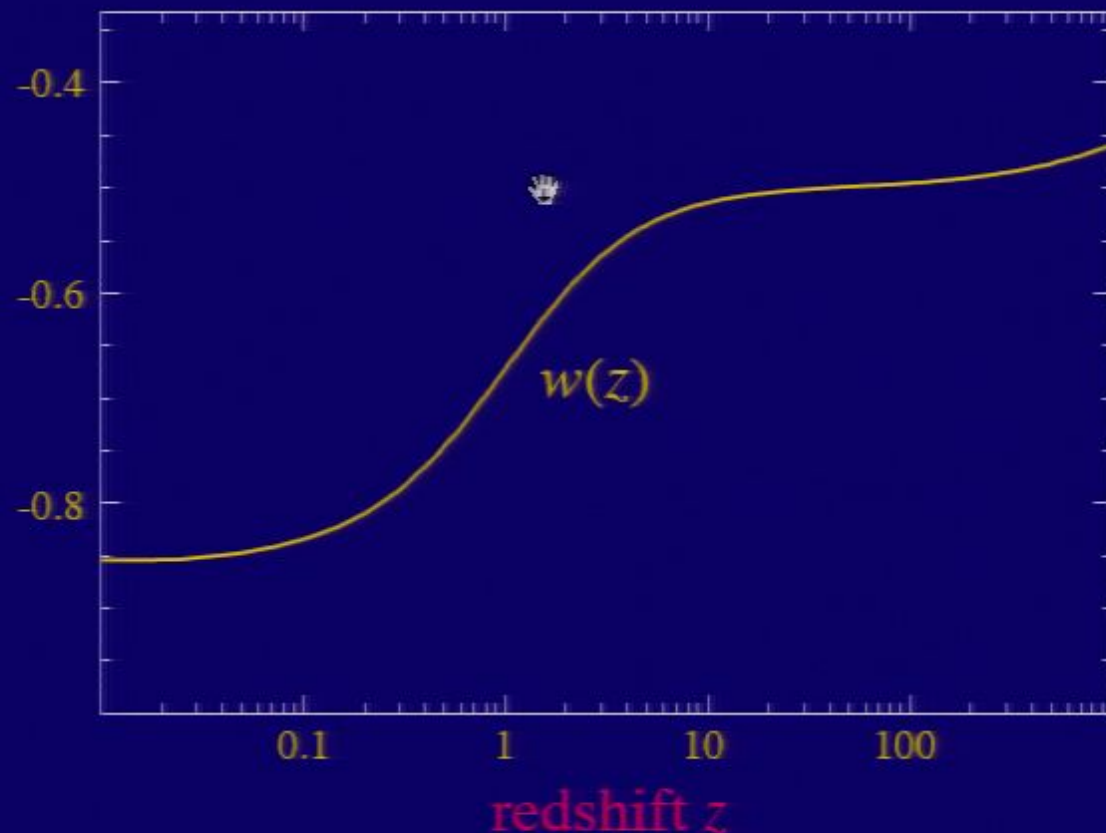


- Effective equation of state w_{eff} scales with field amplitude f_R
- Crosses the **phantom divide** at a redshift that decreases with n
- Signature of **degrees of freedom in dark energy beyond standard kinetic and potential energy of k-essence or quintessence or modified gravity**

DGP Expansion History

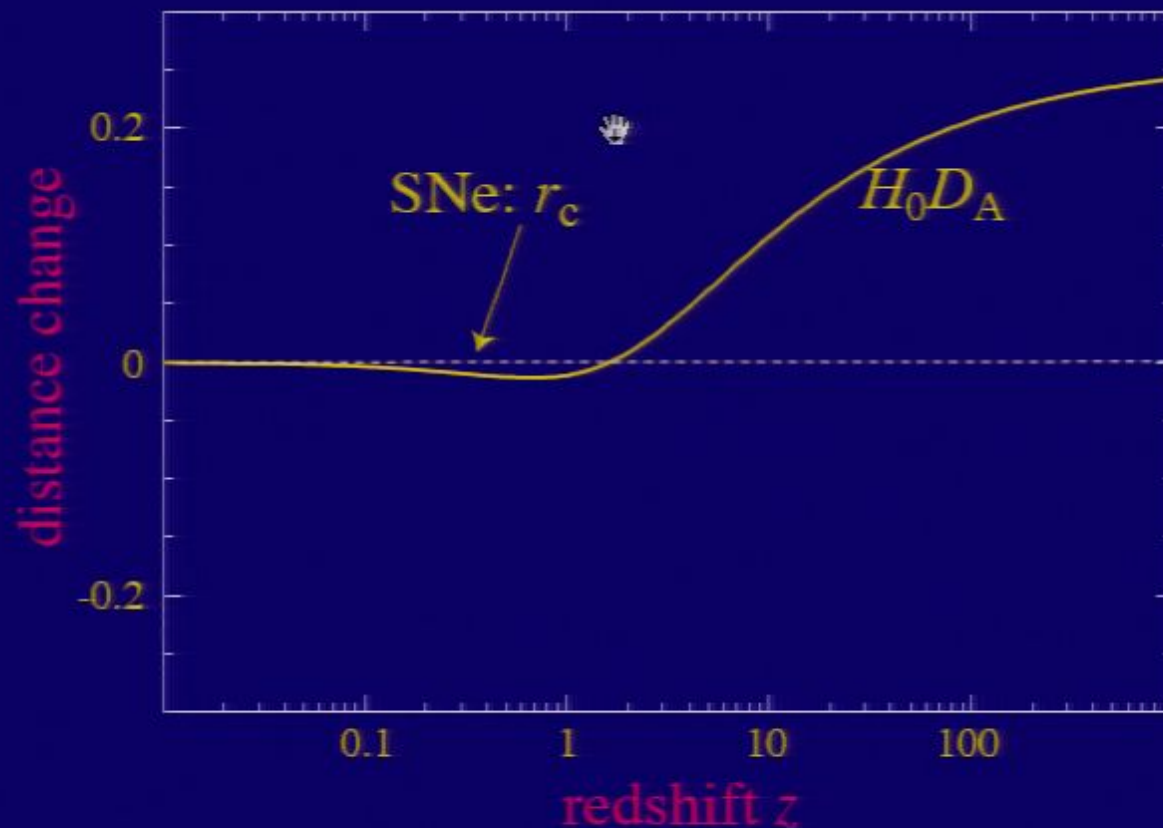
DGP Expansion History

- Matching the DGP expansion history to a dark energy model with the same expansion history
- Effective equation of state $w(z)$ [$w_0 \sim -0.85$, $w_a \sim 0.35$]



DGP Expansion History


- Crossover scale r_c fit to SN relative distance from $z=0$: $H_0 D_A$



DGP Normal Branch

- On the **normal branch**, expansion does not self-accelerate and **dark energy** in the form of a brane tension or scalar field **necessary**

$$H^2 + \frac{H}{r_c} = \frac{\mu^2}{3}(\rho_m + \rho_{\text{DE}})$$

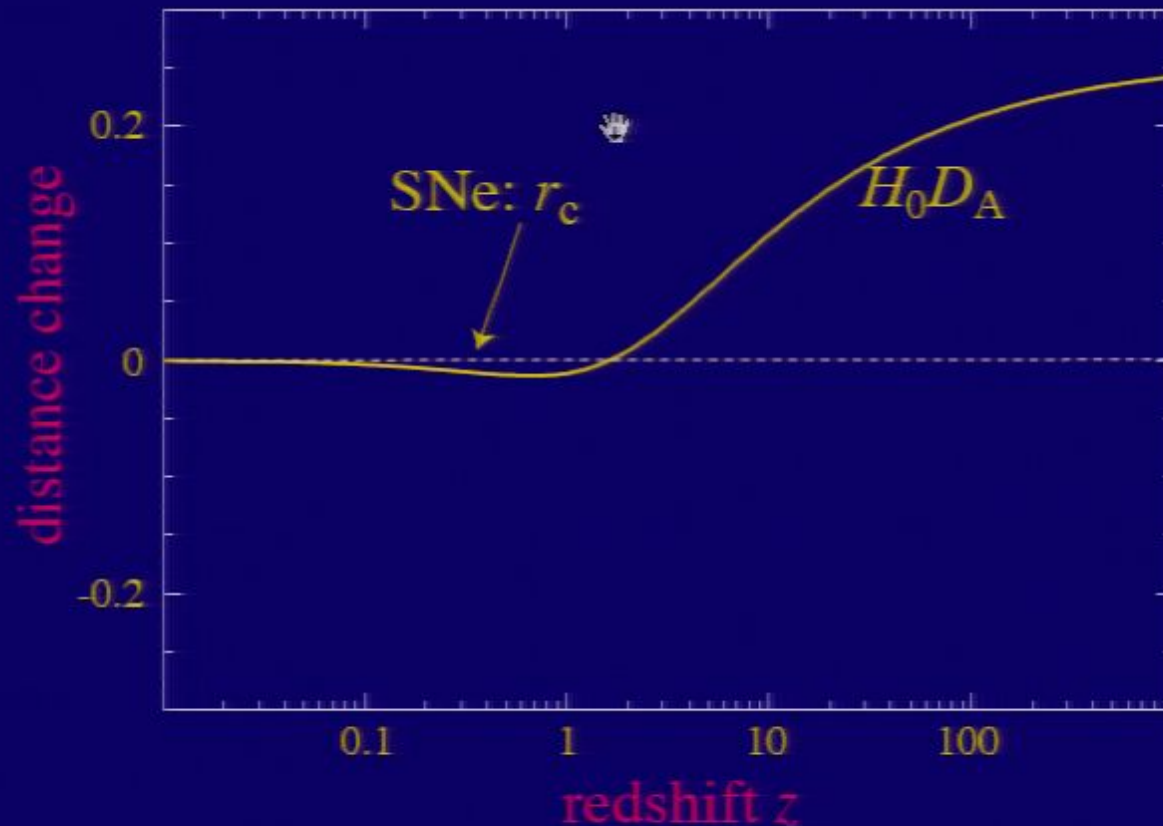
- **Gravity** is still **modified** as in the self-accelerated branch (but with attractive forces) 
- **Ghost free** in the quantum theory
- Can choose ρ_{DE} to match **any desired expansion history** including flat Λ CDM

$$H^2 \equiv \frac{\mu^2}{3}(\rho_m + \rho_\Lambda) \rightarrow \rho_{\text{DE}}$$

- Separate out **geometrical** and **dynamical** tests of acceleration

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Conserved Curvature Regime

Curvature Conservation

- On **superhorizon** scales, **energy momentum conservation** and **expansion history** constrain the evolution of metric fluctuations (Bertschinger 2006)
- For **adiabatic perturbations** in a **flat universe**, conservation of comoving curvature applies $\zeta' = 0$ where $' \equiv d/d \ln a$ (Bardeen 1980)
- Gauge transformation to **Newtonian gauge**

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^2$$

yields (Hu & Eisenstein 1999)

$$\Phi'' - \Psi' - \frac{H''}{H'}\Phi' - \left(\frac{H'}{H} - \frac{H''}{H'}\right)\Psi = 0$$

- Modified gravity theory supplies the **closure relationship** $\Phi = -\gamma(\ln a)\Psi$ between and **expansion history** $H = \dot{a}/a$ supplies rest.

Linear Theory for $f(R)$

- In $f(R)$ model, “superhorizon” behavior persists until **Compton wavelength** smaller than fluctuation wavelength $B^{1/2}(k/aH) < 1$
- Once **Compton wavelength** becomes **larger** than fluctuation

$$B^{1/2}(k/aH) > 1$$

perturbations are in **scalar-tensor regime** described by $\gamma = 1/2$.

- Small scale **density growth enhanced** and

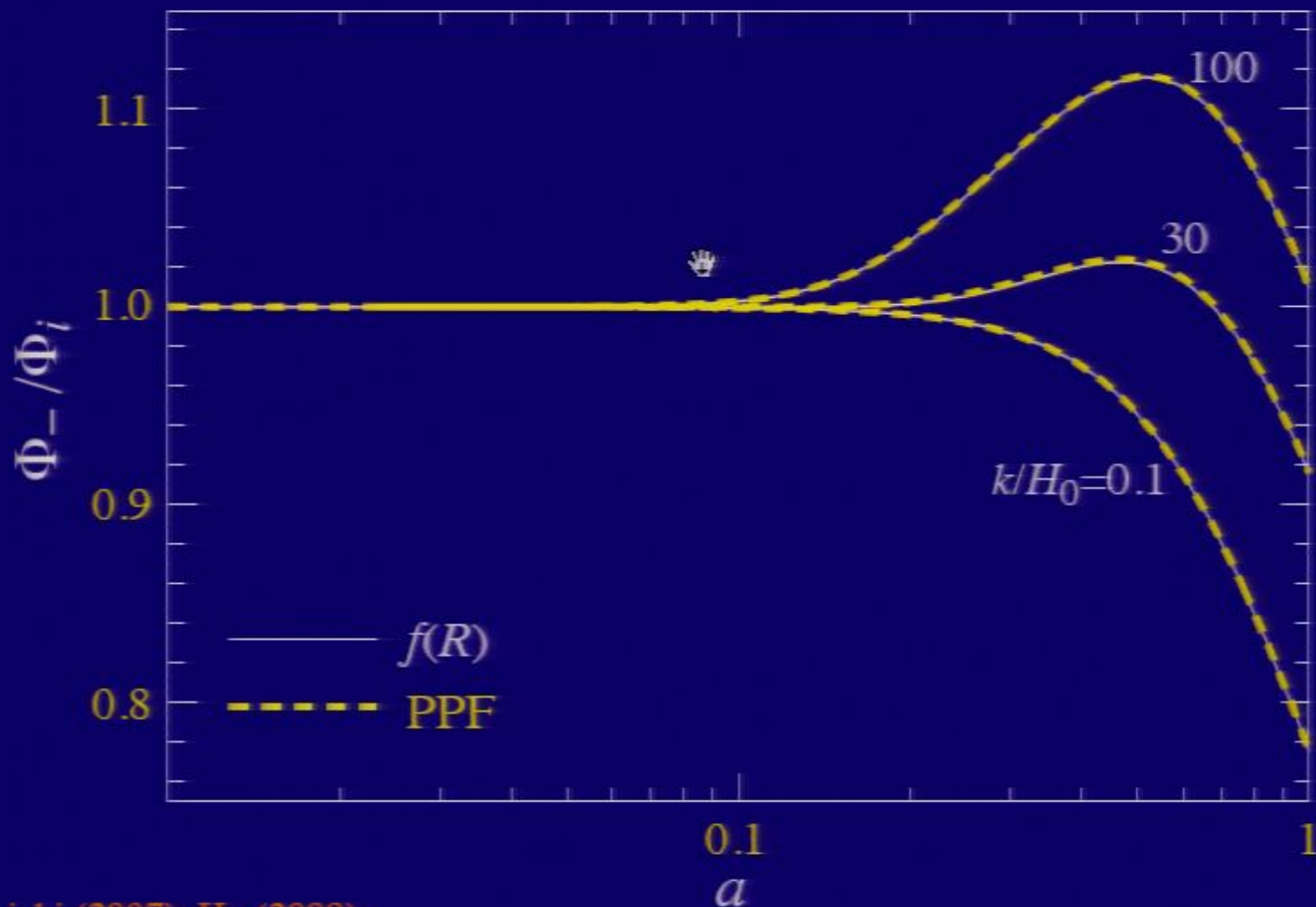
$$8\pi G\rho > R$$

low curvature regime with order unity **deviations from GR**

- Transitions in the **non-linear regime** where the Compton wavelength can shrink via **chameleon mechanism**
- Given $k_{\text{NL}}/aH \gg 1$, even **very small f_R** have scalar-tensor regime

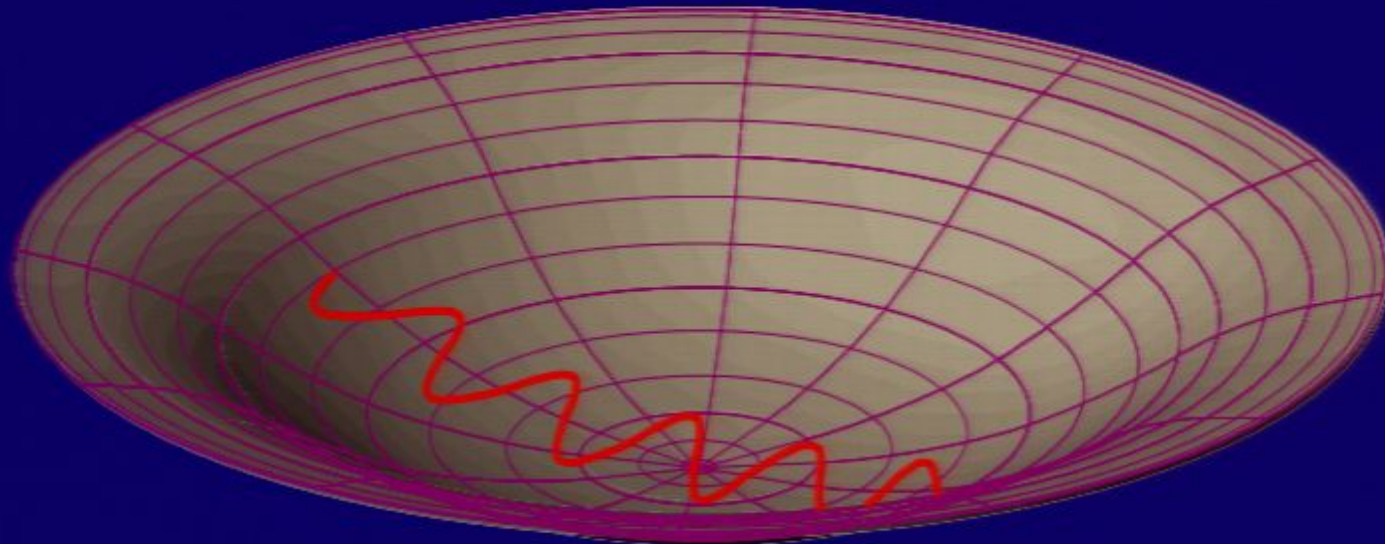
PPF $f(R)$ Description

- Metric and matter evolution well-matched by PPF description
- Standard GR tools apply (CAMB), self-consistent, gauge invar.



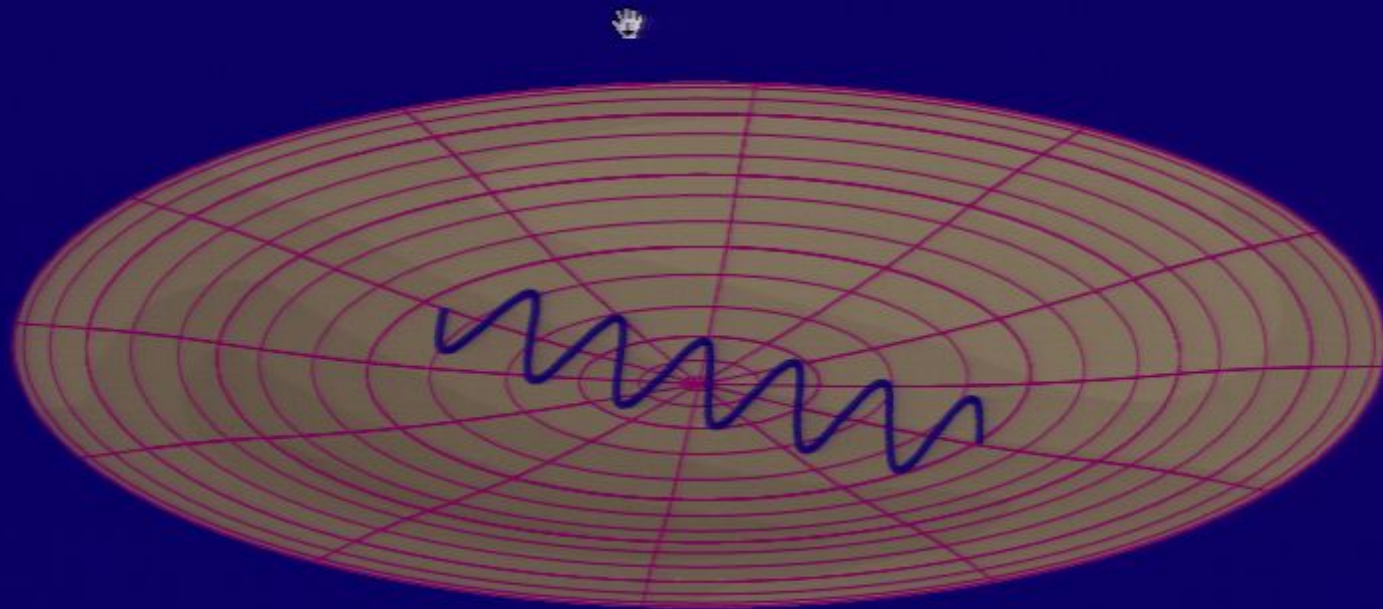
Integrated Sachs-Wolfe Effect

- CMB photons transit gravitational potentials of large-scale structure
- If potential decays during transit, gravitational blueshift of infall not cancelled by gravitational redshift of exit
- Spatial curvature of gravitational potential leads to additional effect $\Delta T/T = -\Delta(\Phi - \Psi)$



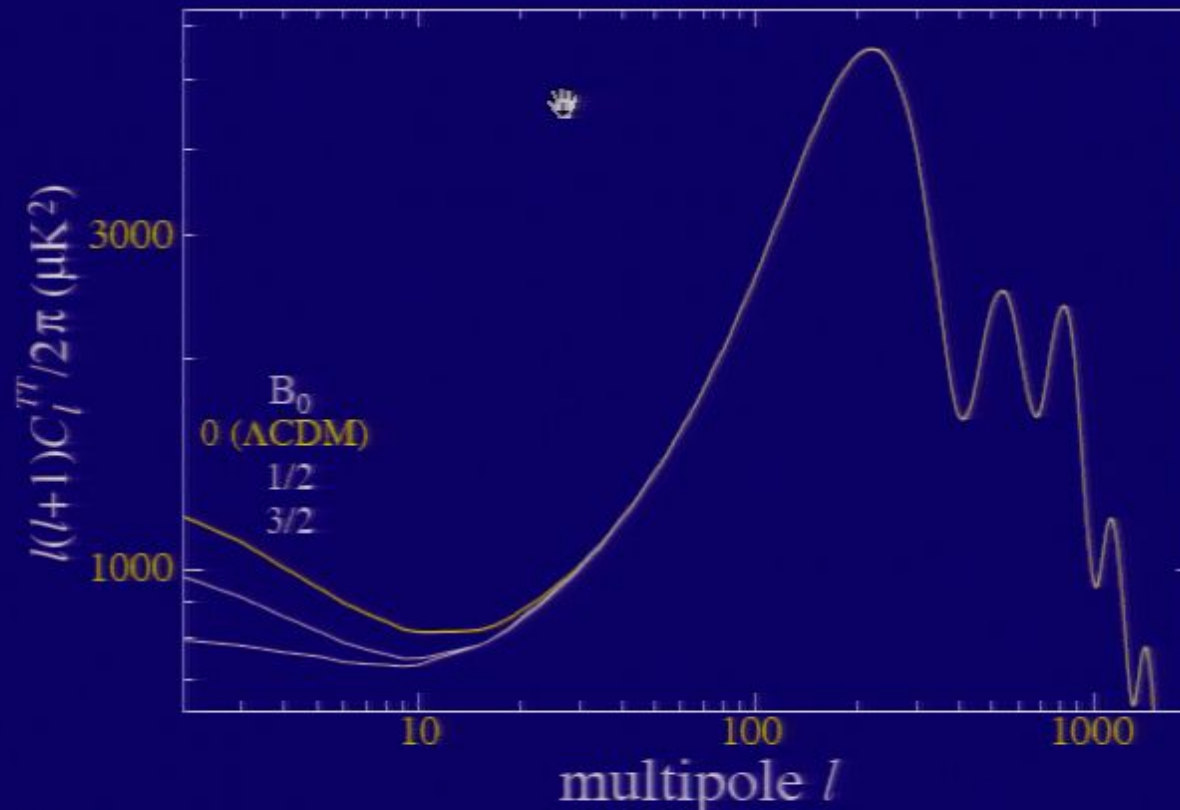
Integrated Sachs-Wolfe Effect

- CMB photons transit gravitational potentials of large-scale structure
- If potential decays during transit, gravitational blueshift of infall not cancelled by gravitational redshift of exit
- Spatial curvature of gravitational potential leads to additional effect $\Delta T/T = -\Delta(\Phi - \Psi)$



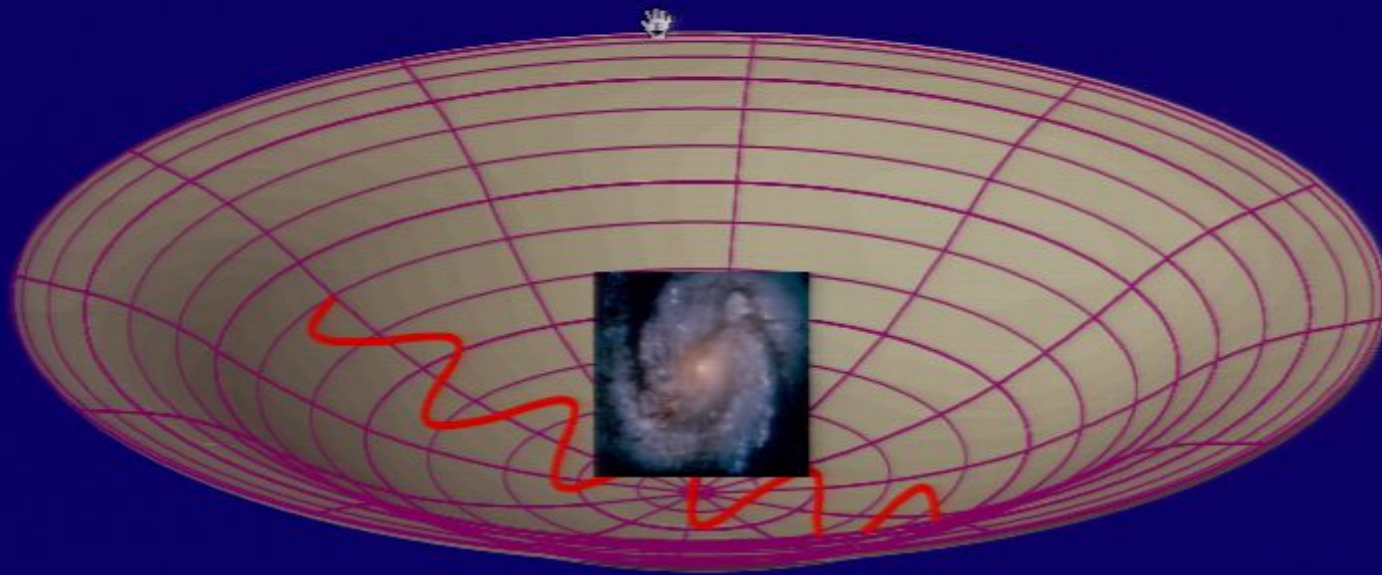
ISW Quadrupole

- Reduction of large angle anisotropy for $B_0 \sim 1$ for same expansion history and distances as Λ CDM
- Well-tested small scale anisotropy unchanged



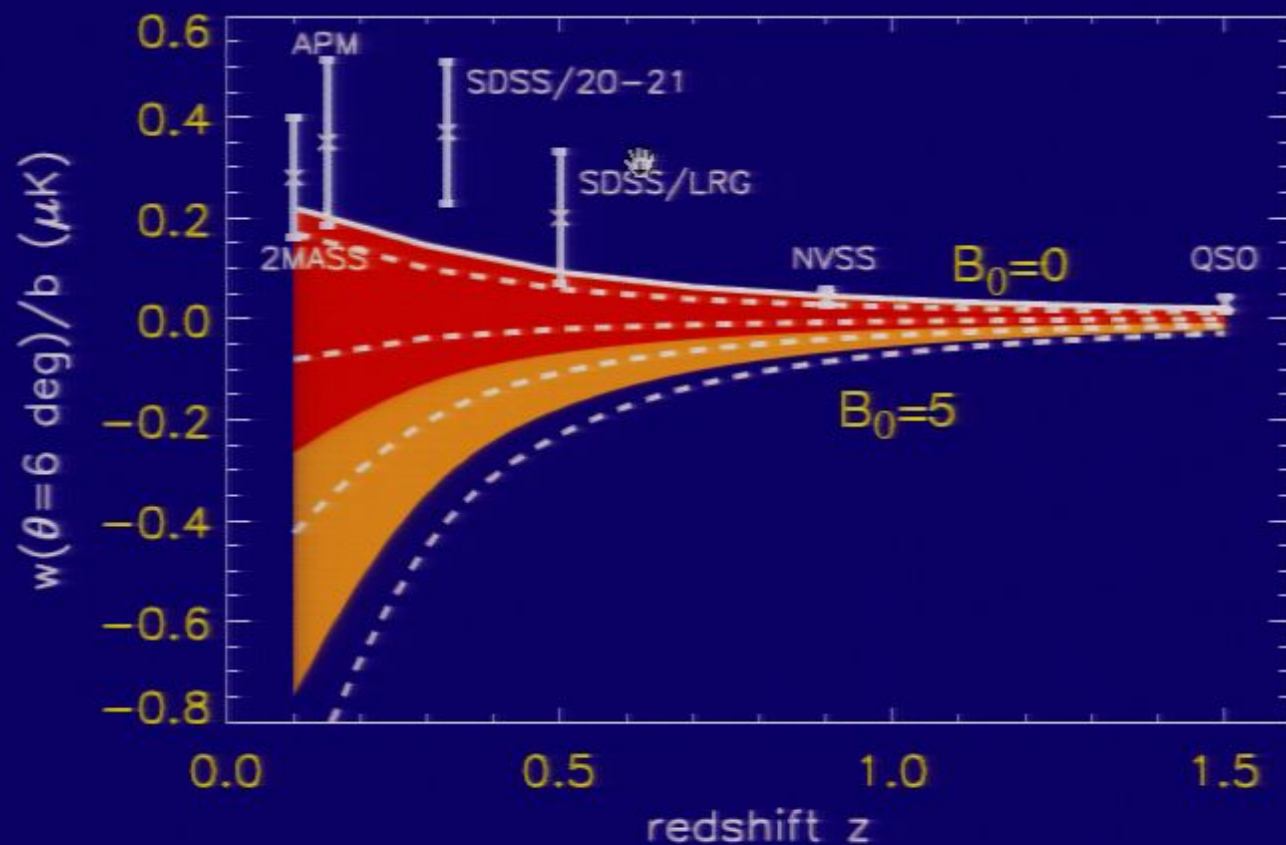
ISW-Galaxy Correlation

- Decaying potential: galaxy positions correlated with CMB
- Growing potential: galaxy positions anticorrelated with CMB
- Observations indicate correlation



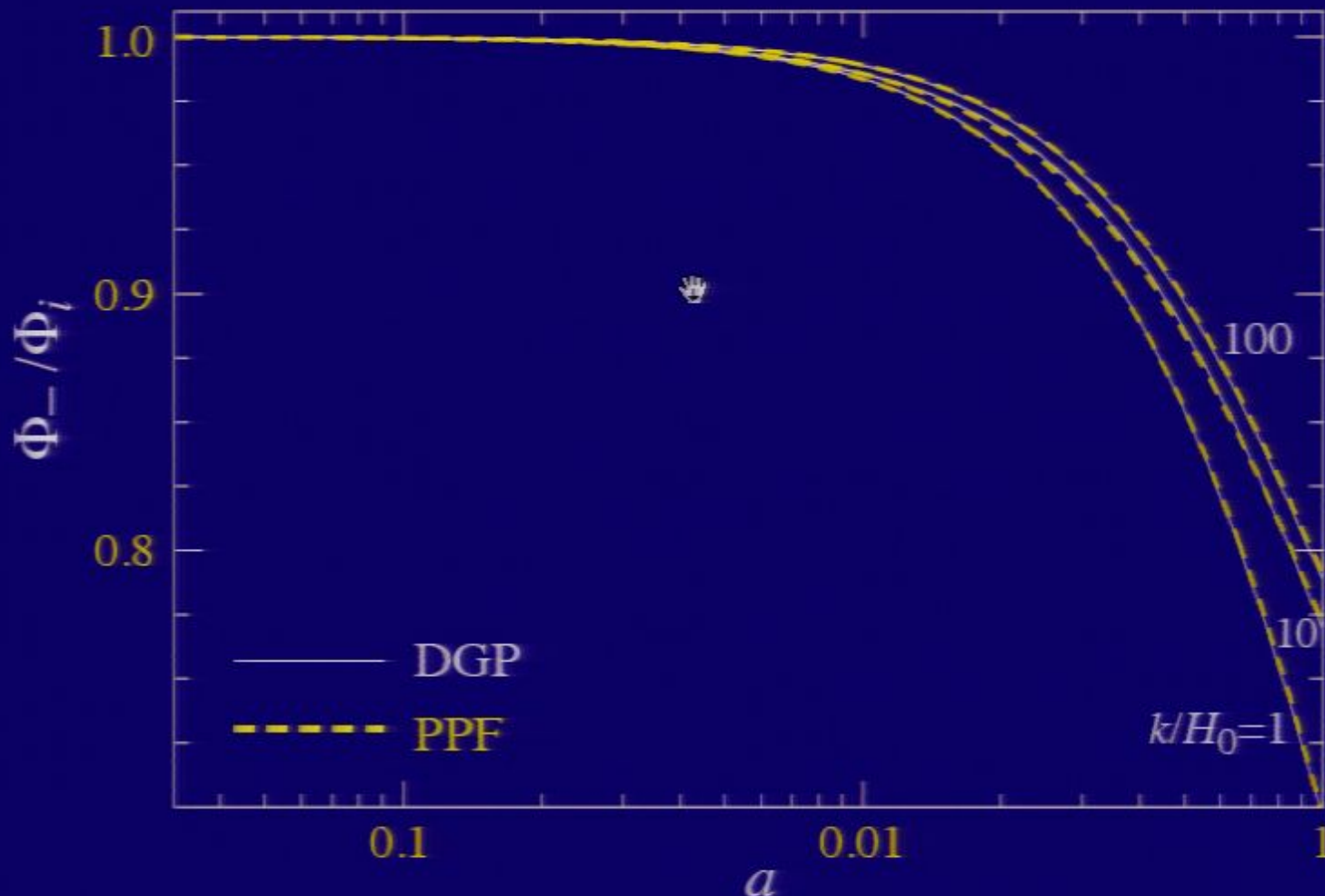
Galaxy-ISW Anti-Correlation

- Large Compton wavelength $B^{1/2}$ creates potential growth which can anti-correlate galaxies and the CMB
- In tension with detections of **positive correlations** across a range of redshifts



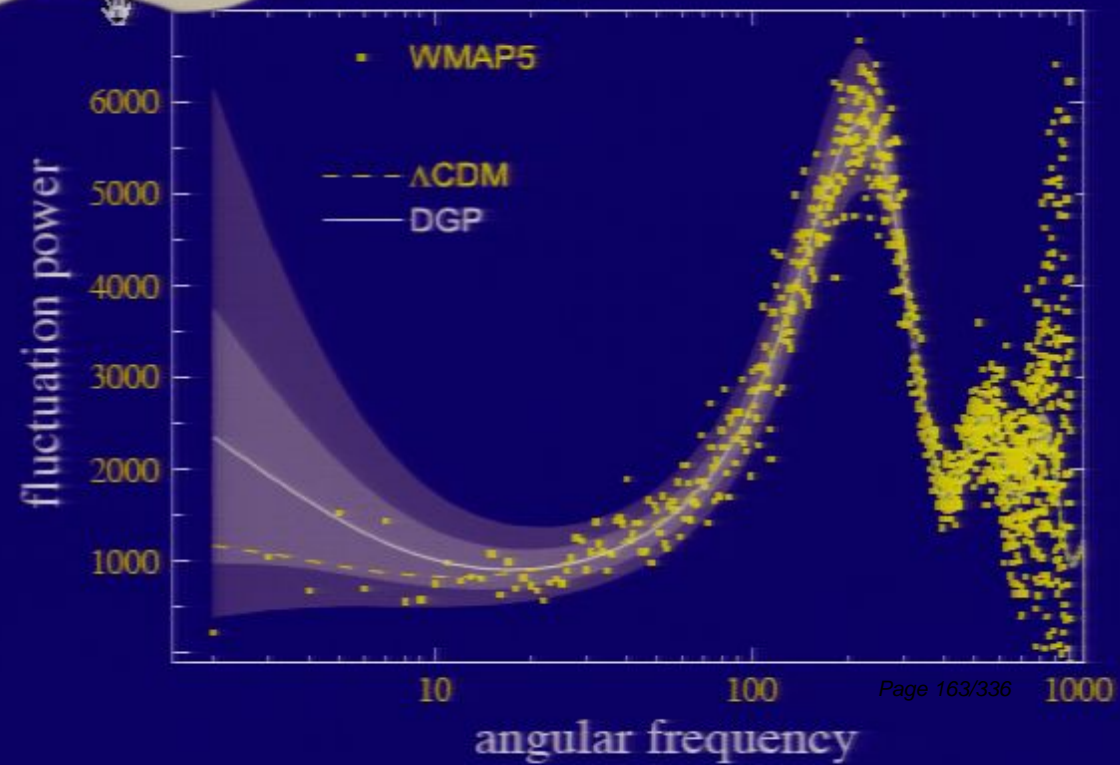
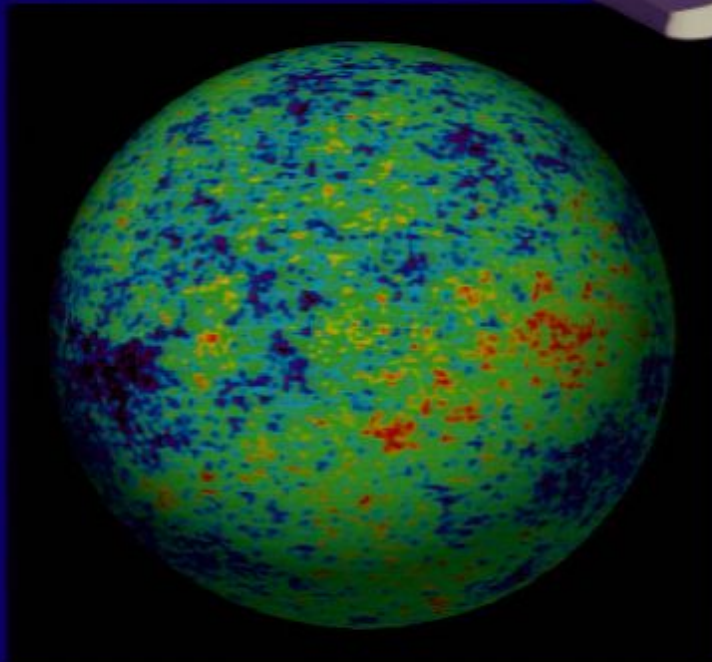
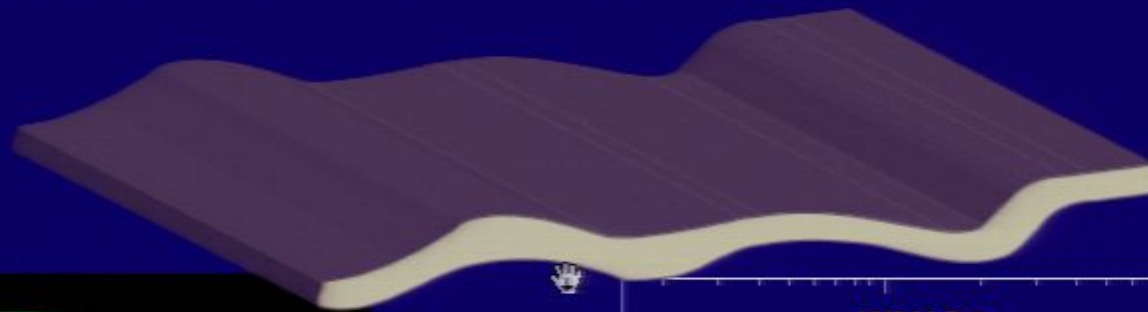
DGP Horizon Scales

- Metric and matter evolution well-matched by PPF description
- Standard GR tools apply (CAMB), self-consistent, gauge invar.



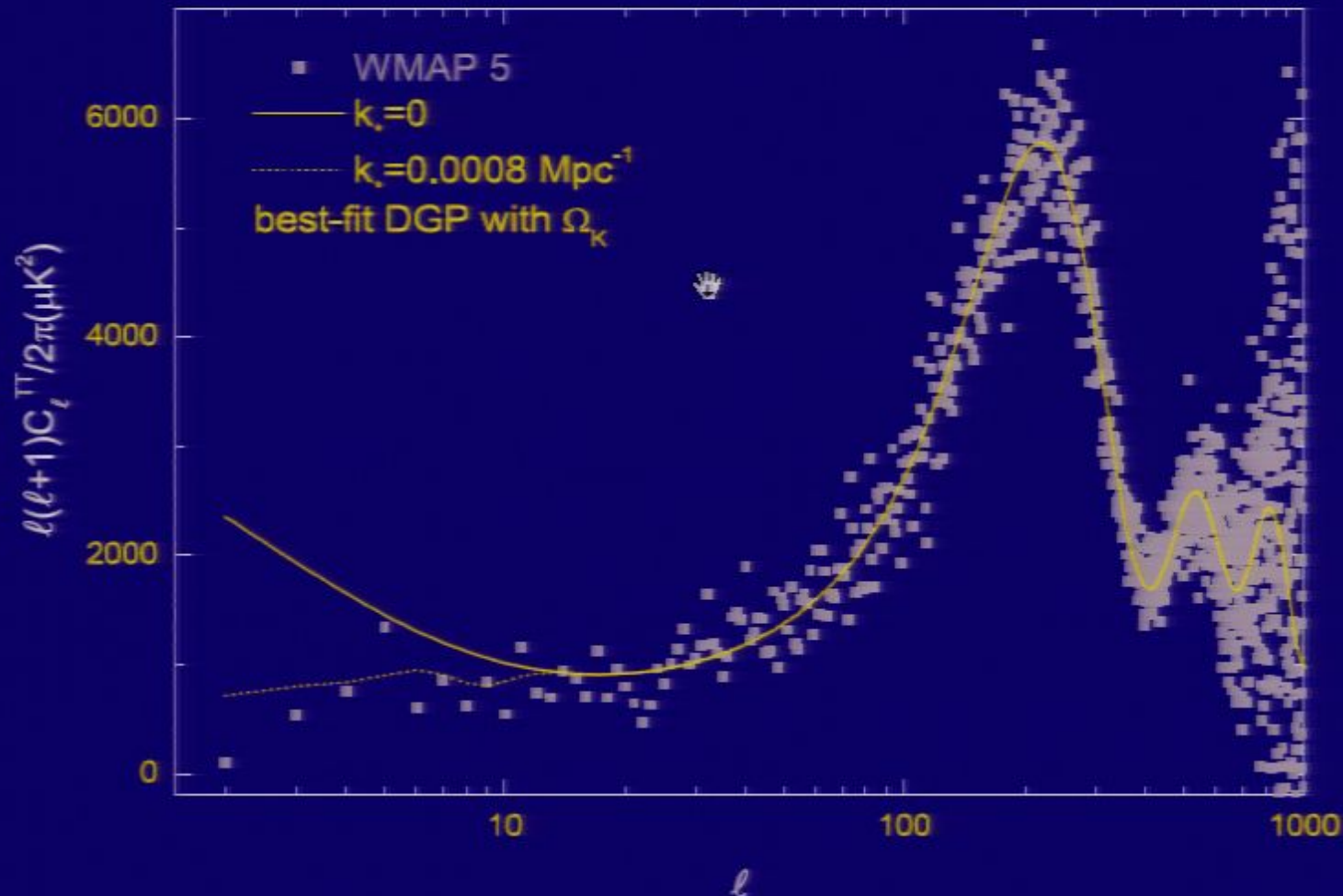
DGP CMB Large-Angle Excess

- Extra dimension **modify gravity** on large scales
- 4D universe **bending into extra dimension** alters gravitational redshifts in cosmic microwave background



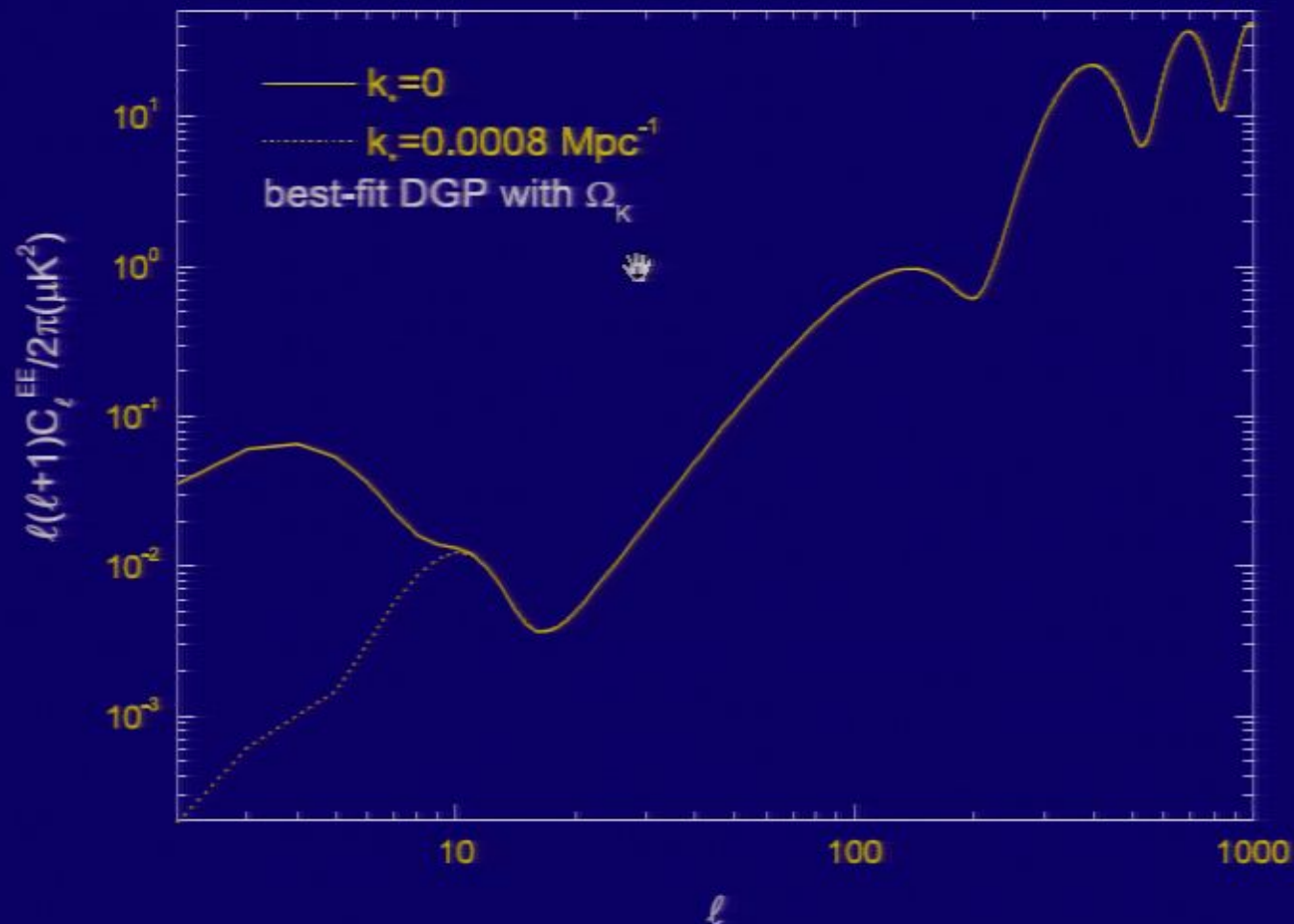
CMB in DGP

- Adding cut off as an epicycle can fix distances, ISW problem
- Suppresses polarization in violation of EE data - cannot save DGP!



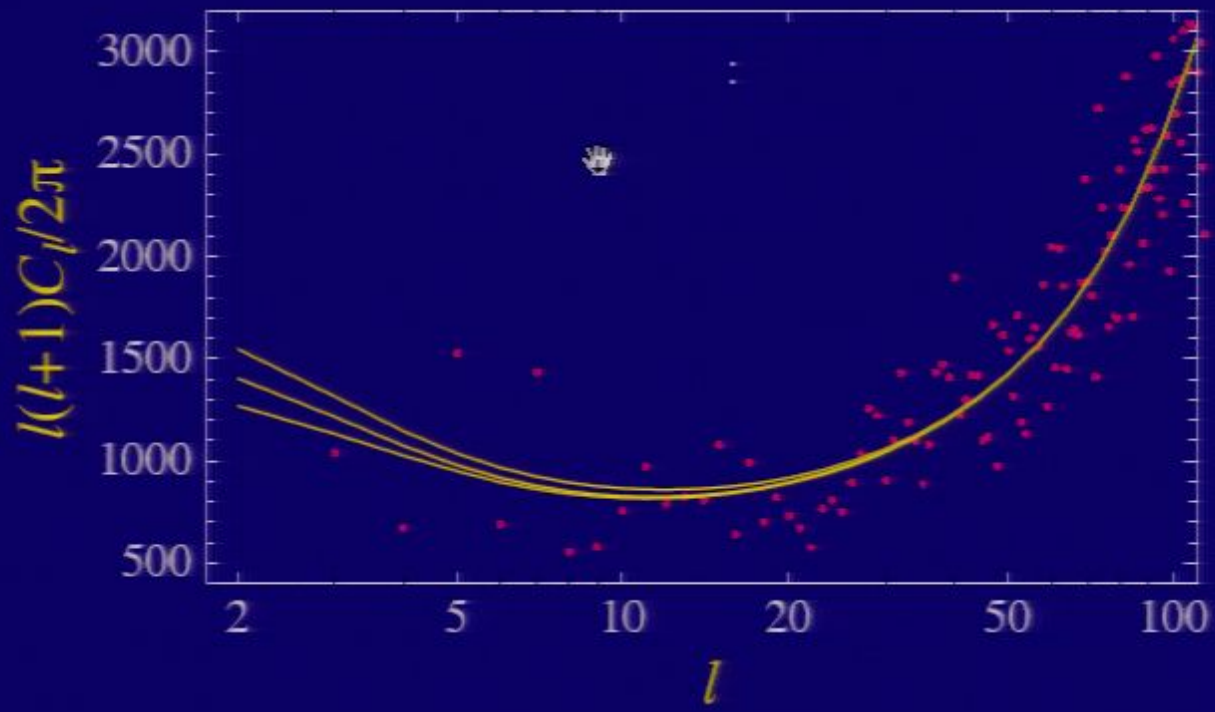
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DGP Normal Branch

- Brane tension (cosmological constant) on normal branch allows models to pass ISW test
- Joint expansion history constraints require $Hr_c > 3$ at 95% CL



Linear Scalar Tensor Regime

Three Regimes

- **Metric:** $ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^2$
- **Superhorizon regime:** $\zeta = \text{const.}, g(a) = (\Phi + \Psi)/(\Phi - \Psi)$
- **Linear regime - closure** \leftrightarrow “smooth” dark energy density:

$$\nabla^2(\Phi - \Psi)/2 = -4\pi G a^2 \Delta\rho$$

G can be promoted to $G(a), G(a, k)$ but for scalar degrees of freedom conformal invariance requires $G = G_N$ and

- **Non-linear regime:**

$$\nabla^2(\Phi - \Psi)/2 = -4\pi G a^2 \Delta\rho$$

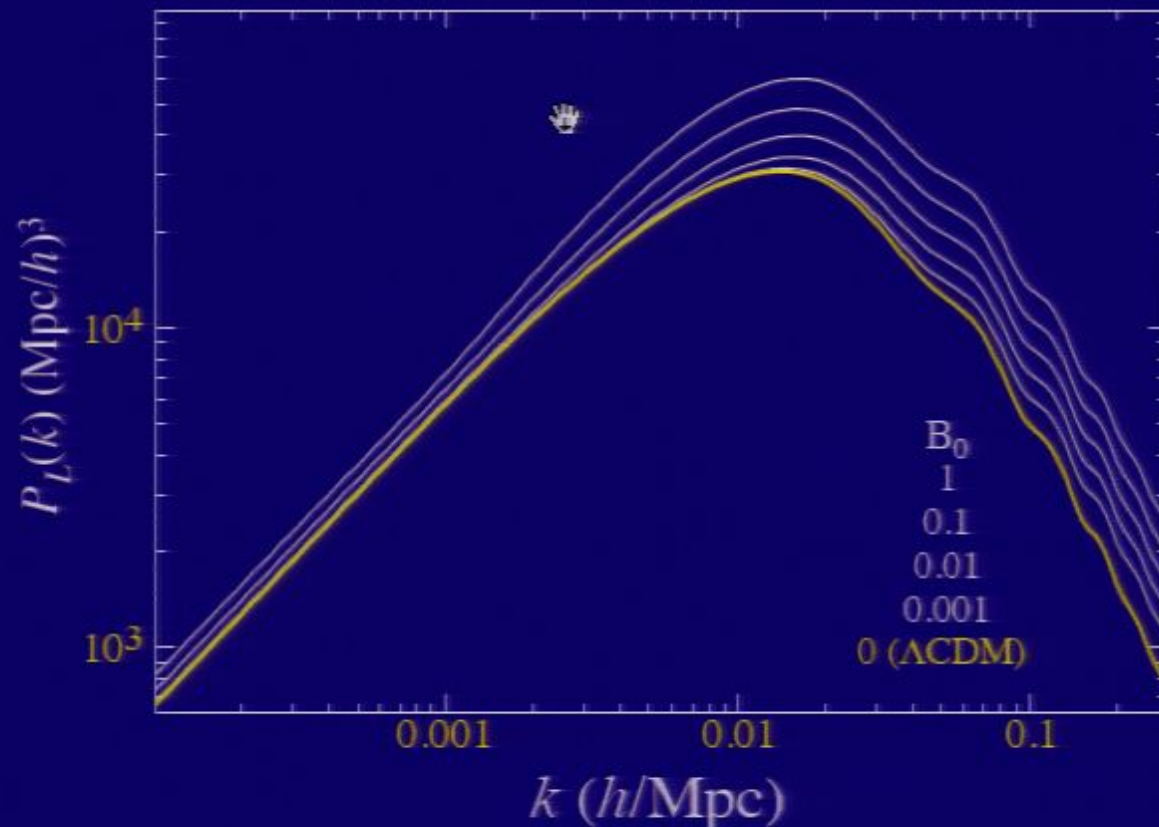
$$\nabla^2\Psi = 4\pi G a^2 \Delta\rho + \frac{1}{2}\nabla^2\phi$$

with non-linearity in the **field equation**

$$\nabla^2\phi = g_{\text{lin}}(a)a^2(8\pi G\Delta\rho - N[\phi])$$

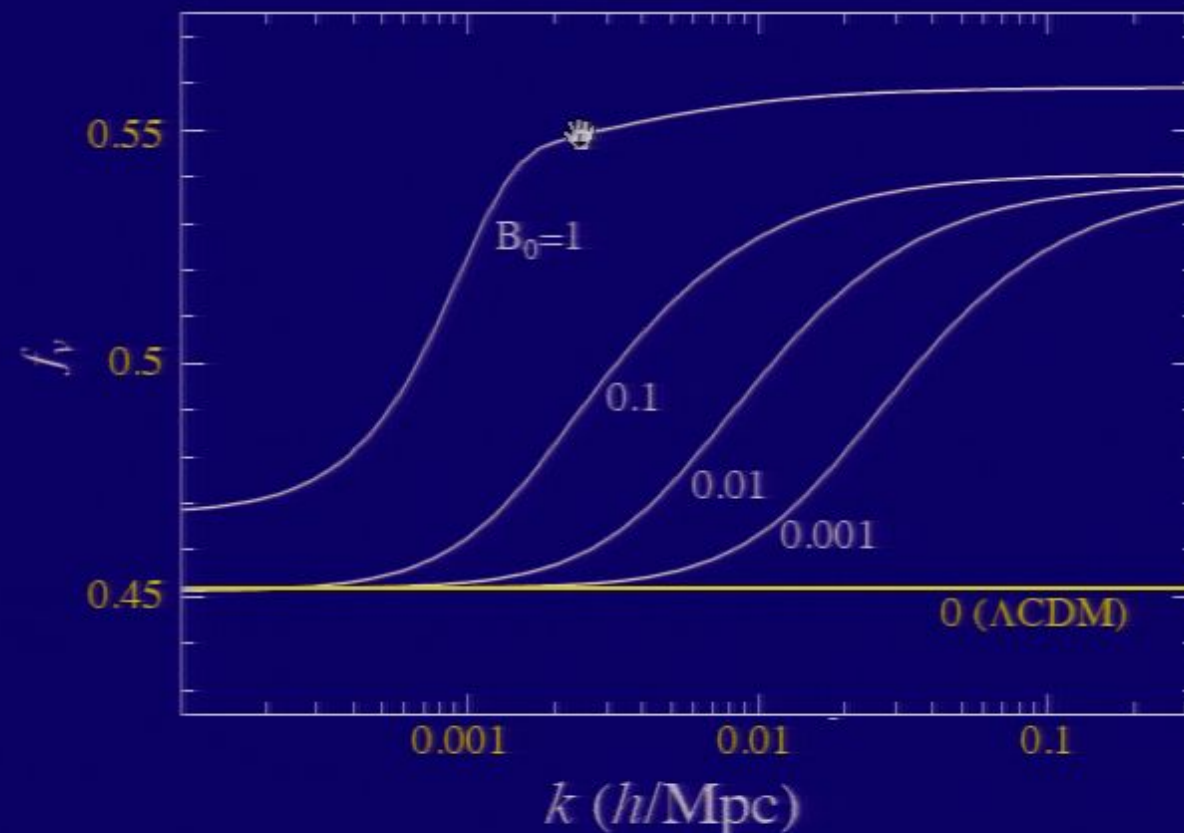
Linear Power Spectrum

- Linear real space power spectrum enhanced on small scales
- Degeneracy with galaxy bias and lack of non-linear predictions leave constraints from shape of power spectrum



Redshift Space Distortion

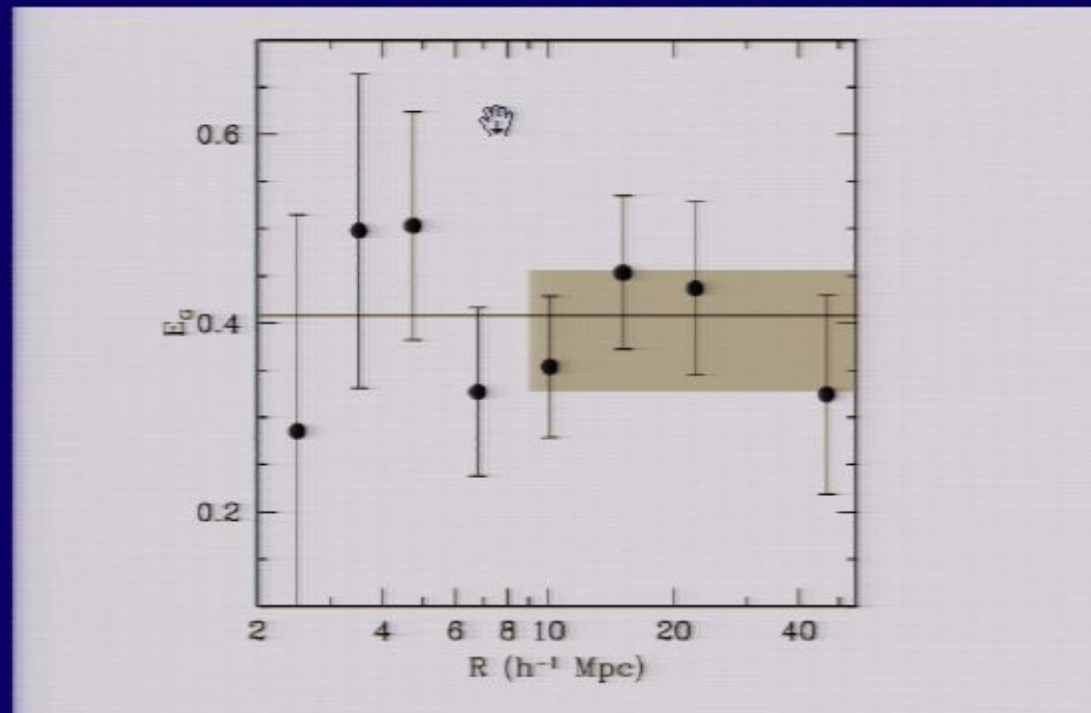
- Relationship between **velocity** and **density** field given by **continuity** with modified **growth rate** ($f_v = d\ln D/d\ln a$)
- **Redshift space power spectrum** further distorted by **Kaiser effect**



Lensing v Dynamical Comparison

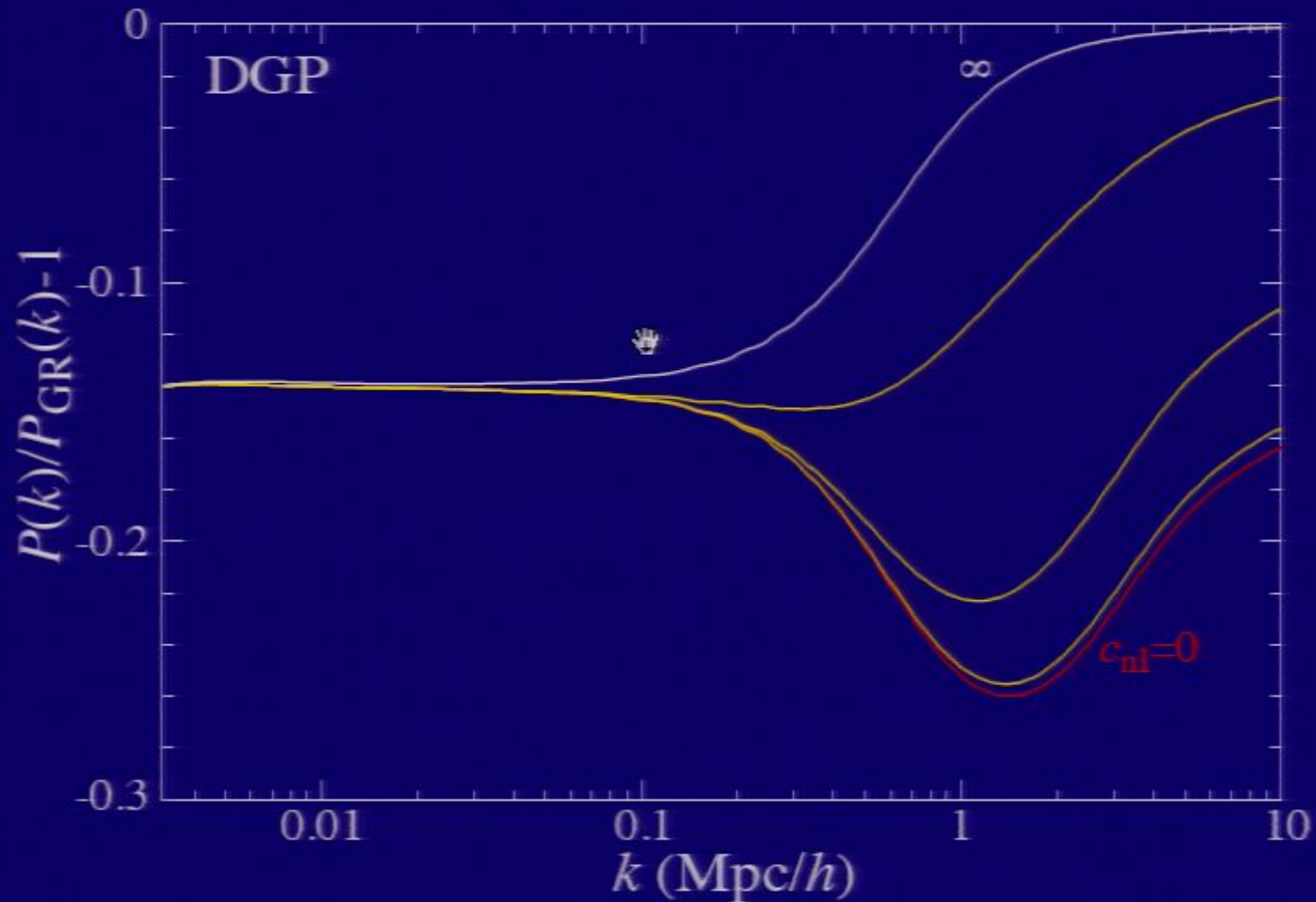
- Gravitational lensing around galaxies vs. linear velocity field (through redshift space distortions and galaxy autocorrelation)
- Consistent with GR + smooth dark energy beginning to test interesting models

Reyes et al (2010); Lombriser et al (2010)



DGP Power Spectrum

- Constant suppression in the linear regime for self-acceleration



Non-Linear GR Regime

Three Regimes

- Fully worked $f(R)$ and DGP examples show 3 regimes
- **Superhorizon** regime: $\zeta = \text{const.}$, $g(a)$
- **Linear** regime - closure condition - analogue of “smooth” dark energy density:

$$\nabla^2(\Phi - \Psi)/2 = -4\pi G a^2 \Delta\rho$$

$$g(a, \mathbf{x}) \leftrightarrow g(a, k)$$

G can be promoted to $G(a)$ but conformal invariance relates fluctuations to field fluctuation that is small

- **Non-linear** regime:

$$\nabla^2(\Phi - \Psi)/2 = -4\pi G a^2 \Delta\rho$$

$$\nabla^2\Psi = 4\pi G a^2 \Delta\rho - \frac{1}{2}\nabla^2\phi$$

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Non-linearity in the field equation

$$\nabla^2 \phi = g_{\text{lin}}(a) a^2 (8\pi G \Delta \rho - N[\phi])$$

recovers linear theory if $N[\phi] \rightarrow 0$

- For $f(R)$, $\phi = f_R$ and

$$N[\phi] = \delta R(\phi)$$

a non-linear function of the field

Linked to **gravitational potential**

- For **DGP**, ϕ is the brane-bending mode and

$$N[\phi] = \frac{r_c^2}{\alpha^4} [(\nabla^2 \phi)^2 - (\nabla_i \nabla_j \phi)^2]$$

a non-linear function of second derivatives of the field

Linked to **density fluctuation**

Non-Linear Chameleon

- For $f(R)$ the field equation

$$\nabla^2 f_R \approx \frac{1}{3}(\delta R(f_R) - 8\pi G\delta\rho)$$

is the **non-linear** equation that returns **general relativity**

- **High curvature** implies short Compton wavelength and **suppressed deviations** but requires a **change** in the **field** from the background value $\delta R(f_R)$

- Change in field is generated by **density perturbations** just like **gravitational potential** so that the chameleon appears only if

$$\Delta f_R \leq \frac{2}{3}\Phi,$$

else required **field** gradients **too large** despite $\delta R = 8\pi G\delta\rho$ being the **local minimum** of effective potential

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Non-Linear Dynamics

- Supplement that with the **modified Poisson equation**

$$\nabla^2 \Psi = \frac{16\pi G}{3} \delta\rho - \frac{1}{6} \delta R(f_R)$$

- Matter evolution given metric unchanged: usual **motion of matter** in a gravitational potential Ψ
- Prescription for ***N*-body code**
- **Particle Mesh (PM)** for the Poisson equation
- Field equation is a non-linear Poisson equation: **relaxation** method for f_R
- **Initial conditions** set to GR at high redshift

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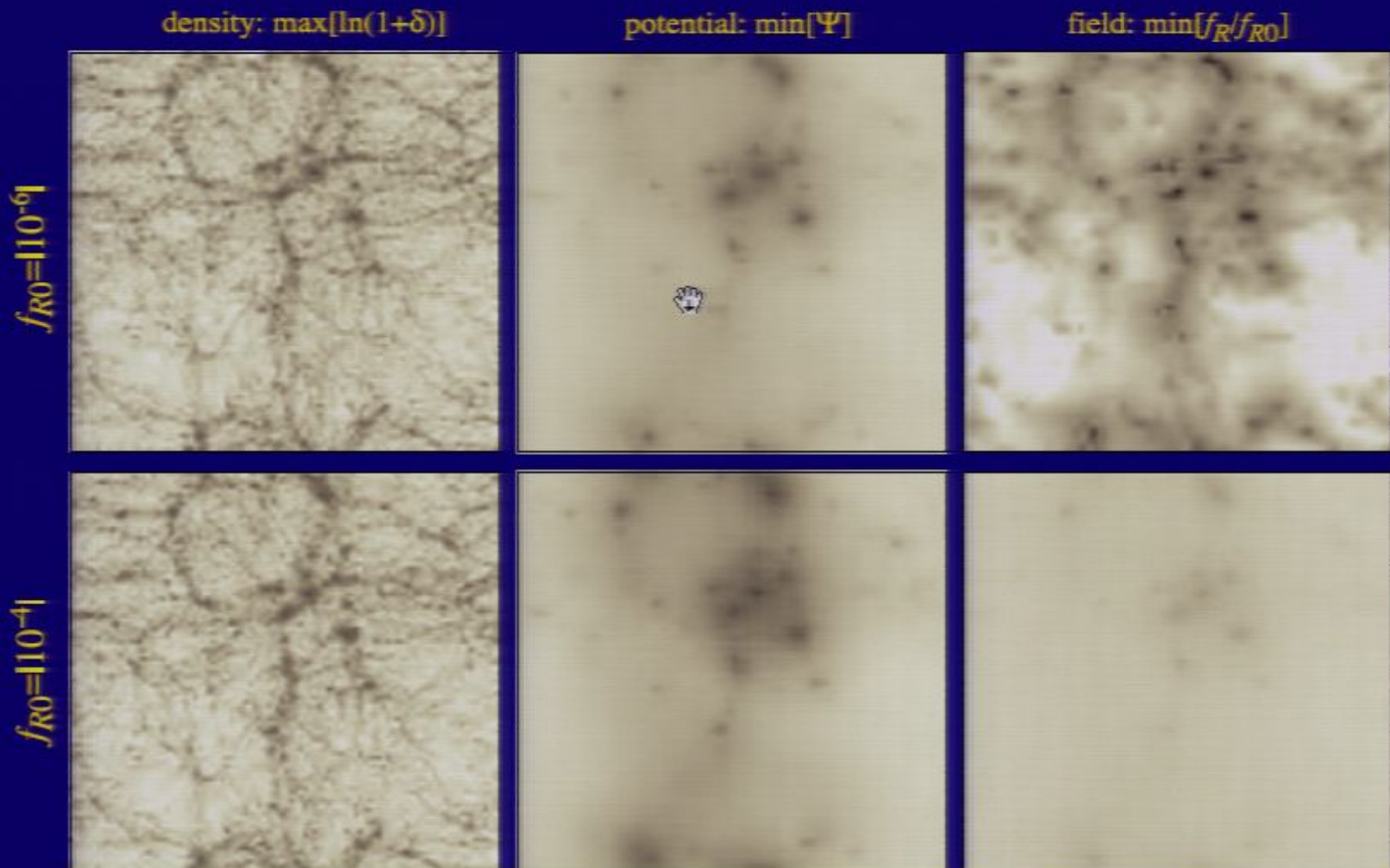
Environment Dependent Force

- Chameleon suppresses extra force (scalar field) in high density, deep potential regions



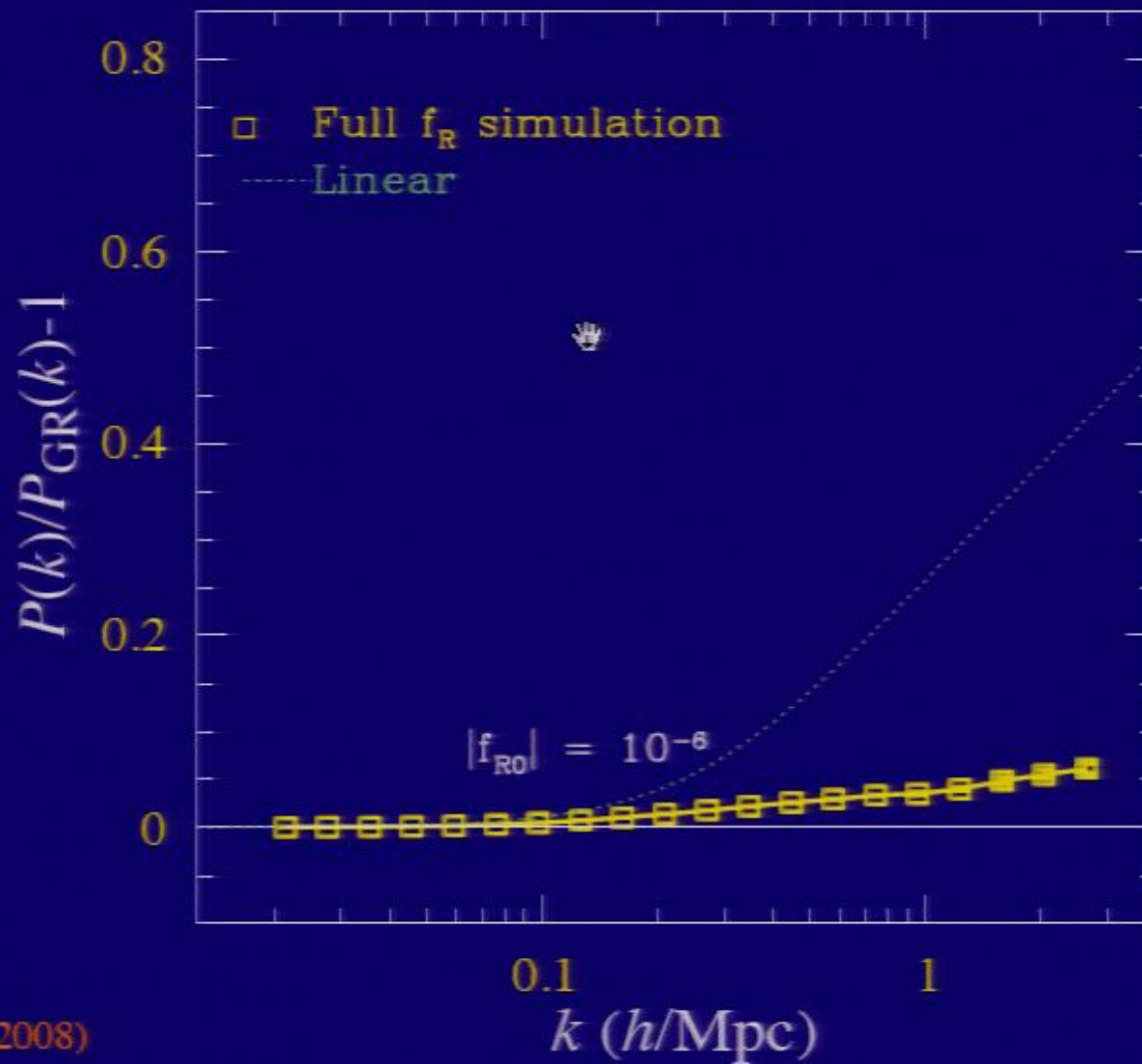
Environment Dependent Force

- For large background field, gradients in the scalar prevent the chameleon from appearing



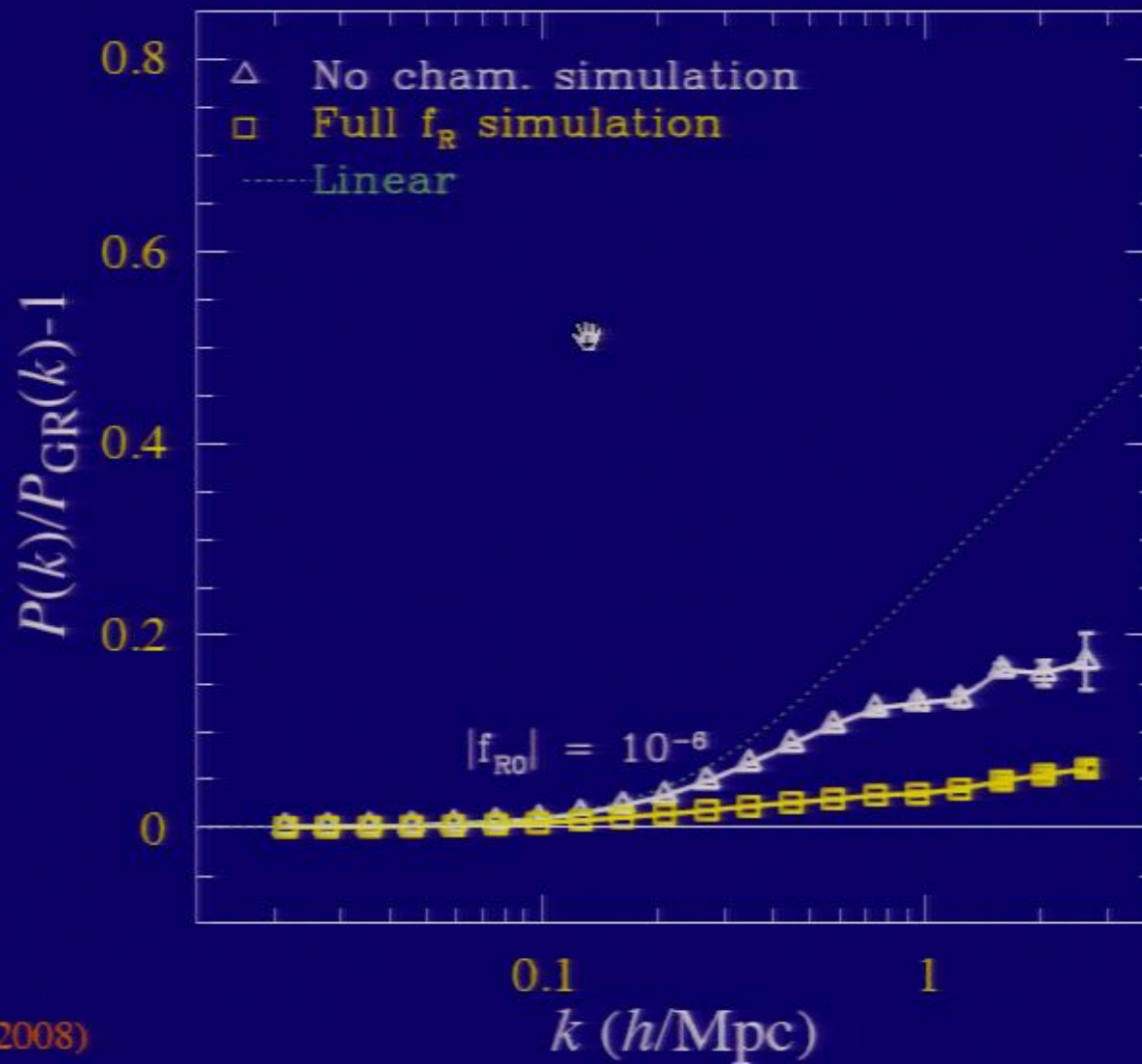
N-body Power Spectrum

- 512³ PM-relaxation code resolves the chameleon transition to GR: greatly reduced non-linear effect



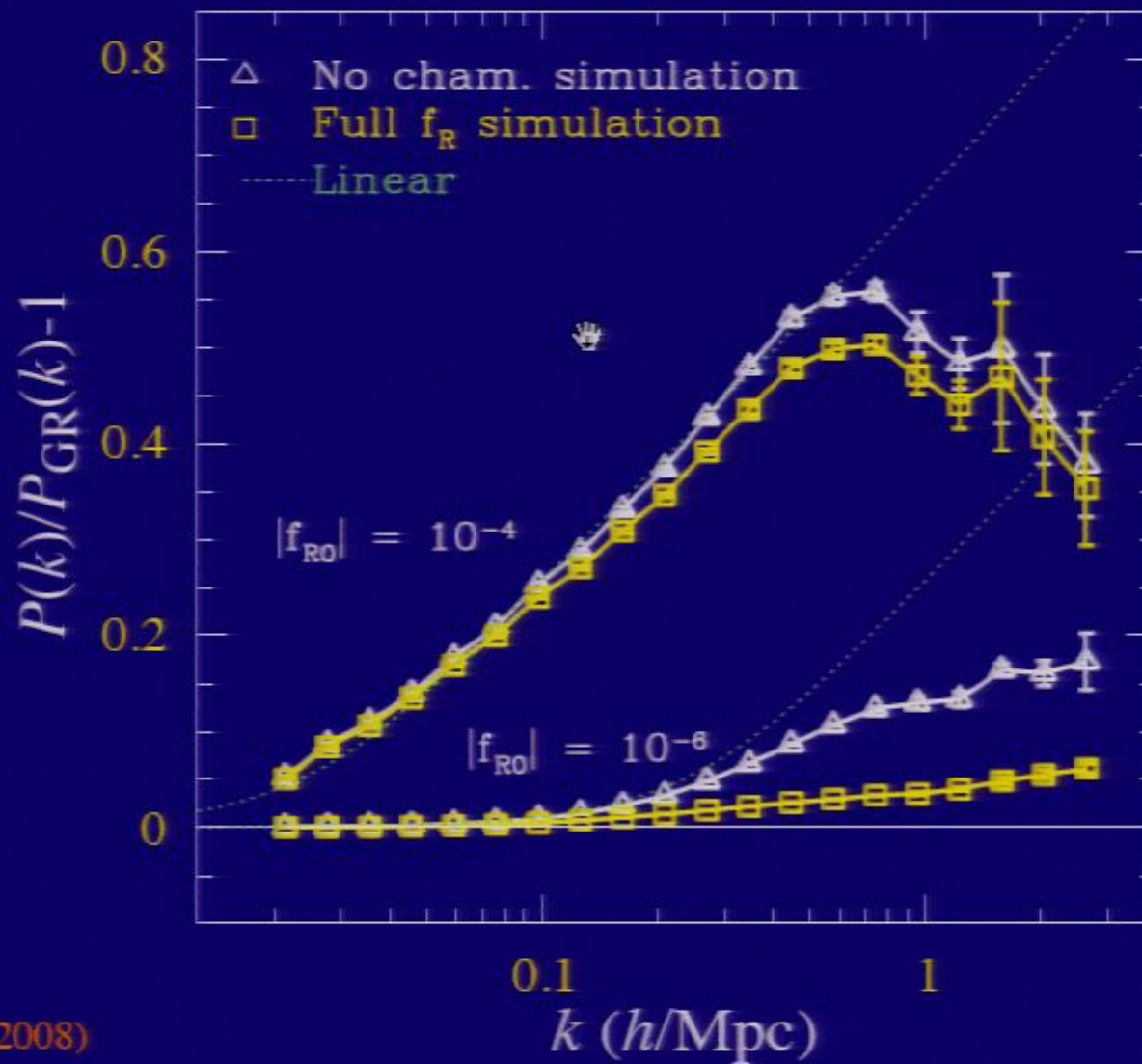
N-body Power Spectrum

- Artificially turning off the chameleon mechanism restores much of enhancement



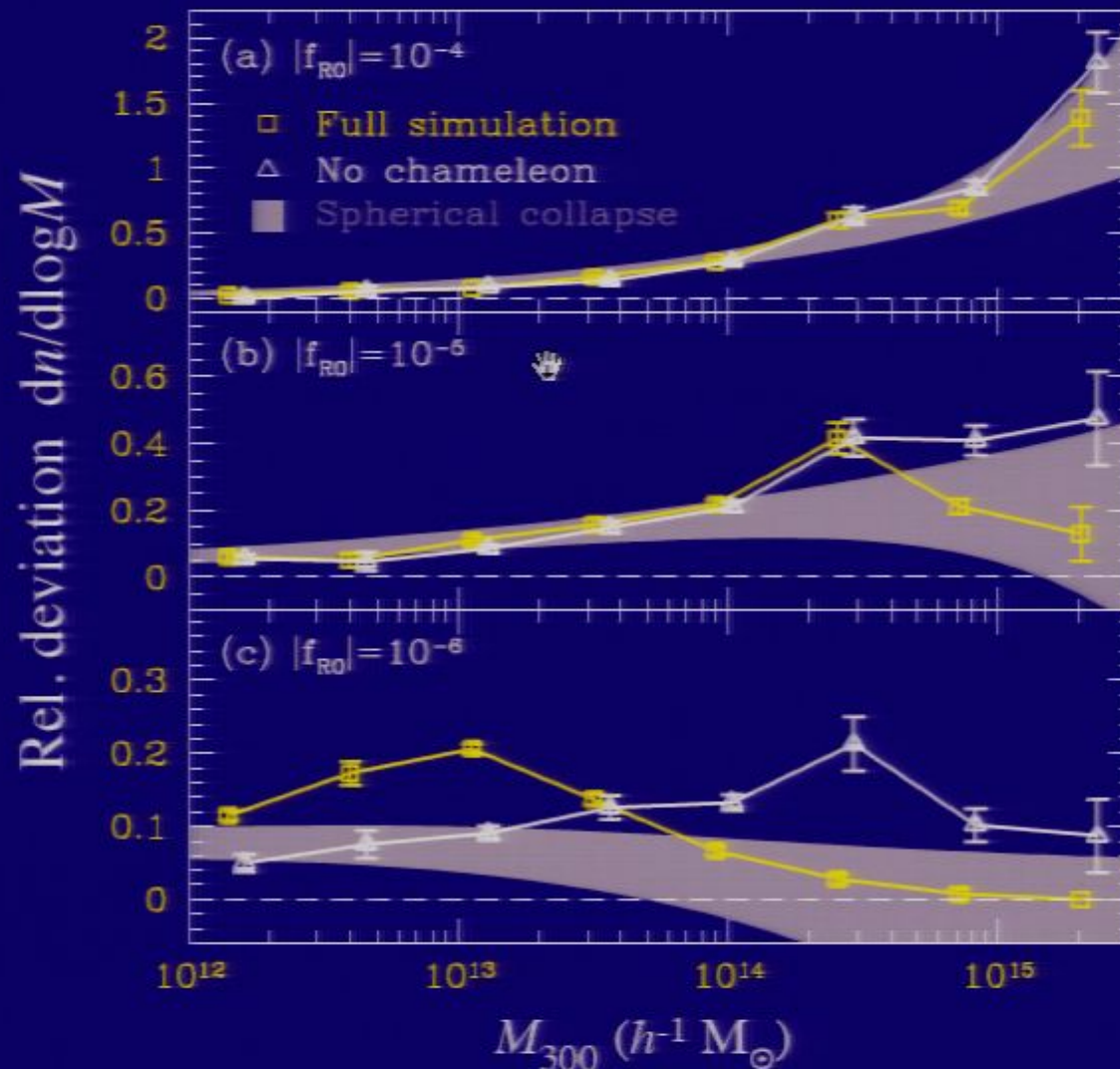
N-body Power Spectrum

- Models where the chameleon is absent today (large field models) show residual effects from a high redshift chameleon



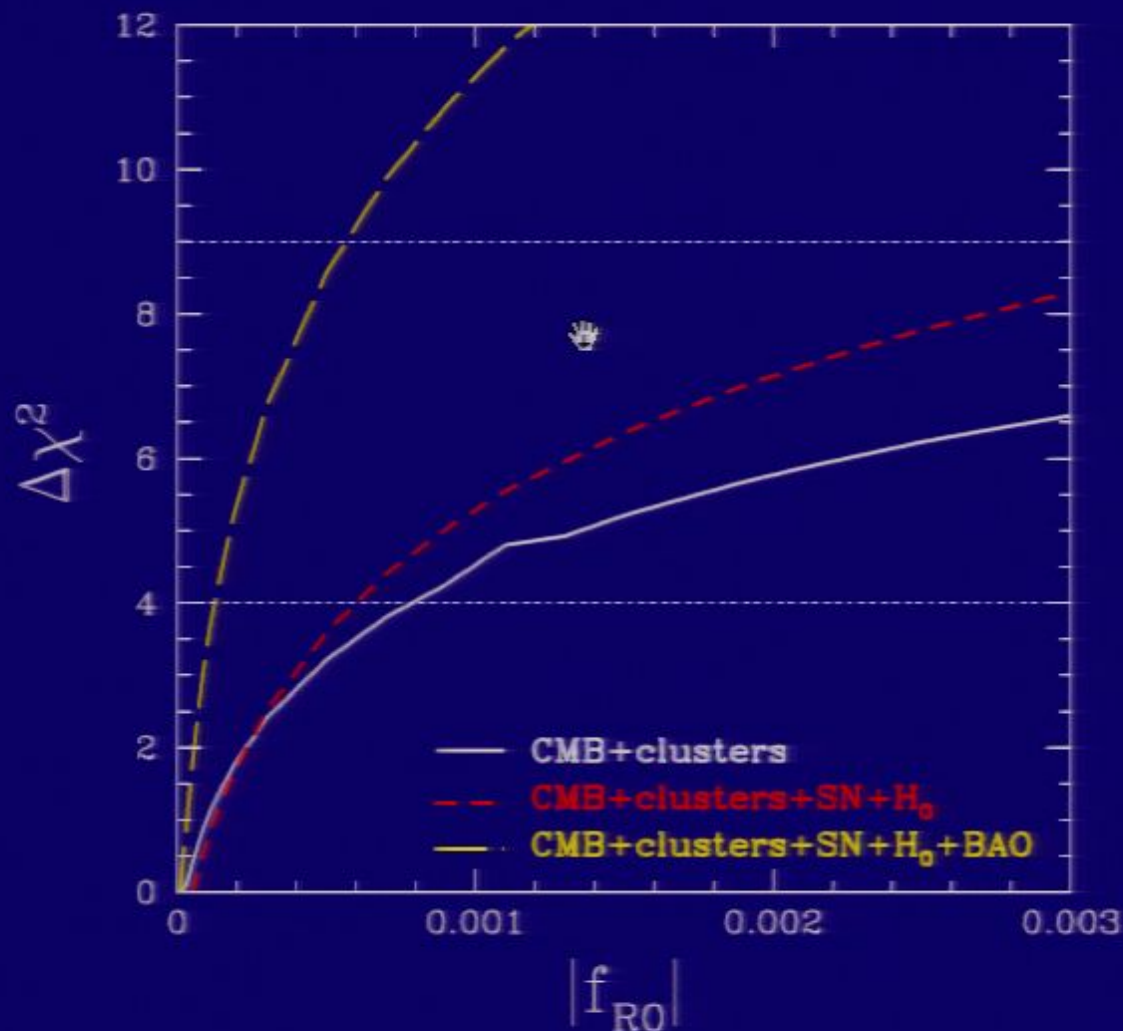
Mass Function

- Enhanced abundance of rare dark matter halos (clusters) with extra force



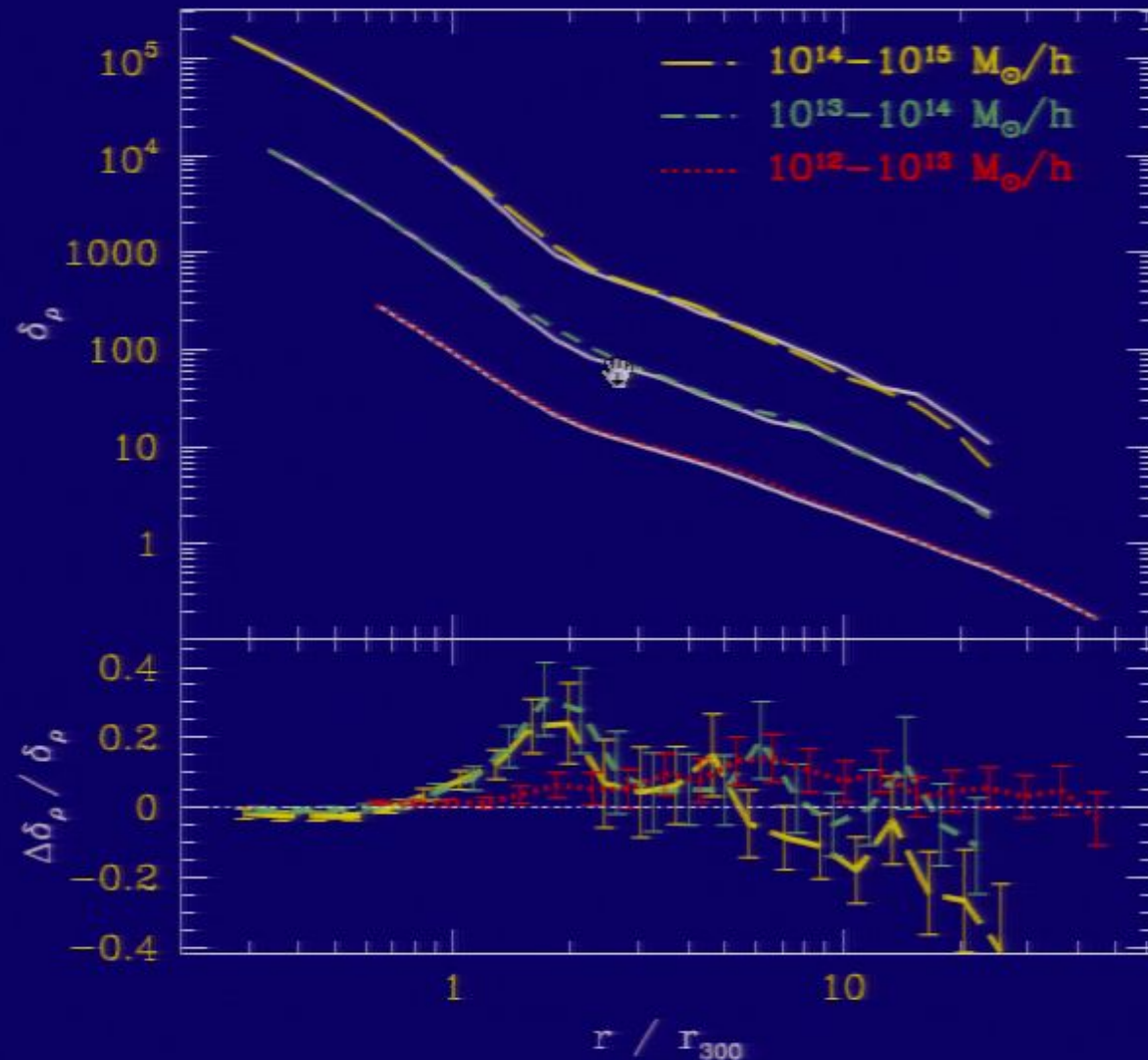
Mass Function

- Local cluster abundance (Chandra sample) current **best** cosmological constraint (~ 4 orders of magnitude better than ISW)



Halo Mass Correlation

- Enhanced forces vs lower bias



Nonlinear Interaction

Non-linearity in the field equation

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recovers linear theory if $N[\phi] \rightarrow 0$

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a non-linear function of the field

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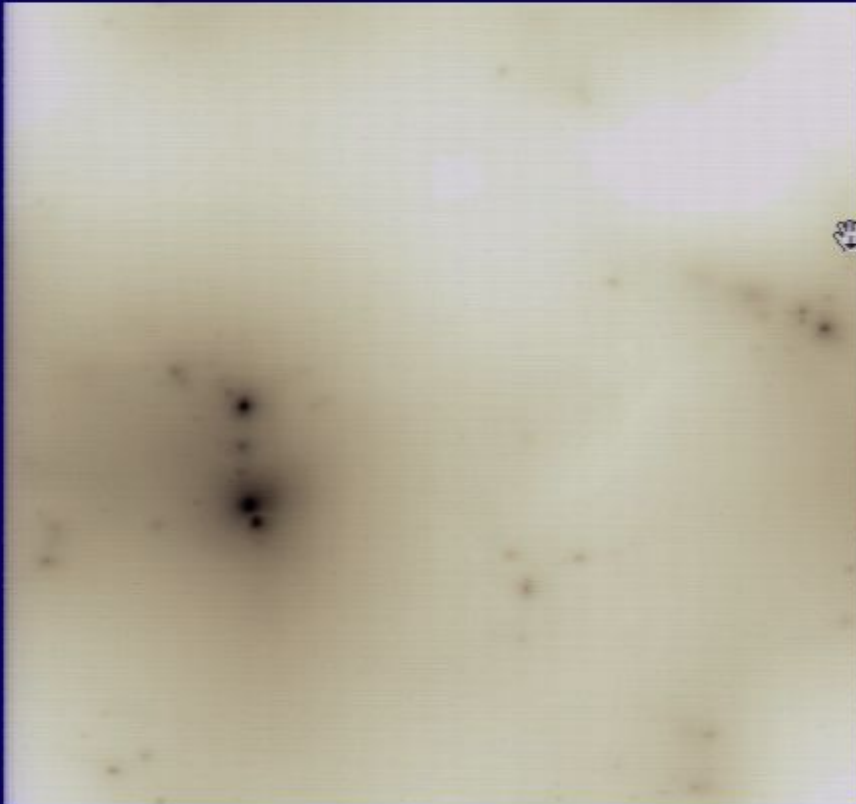
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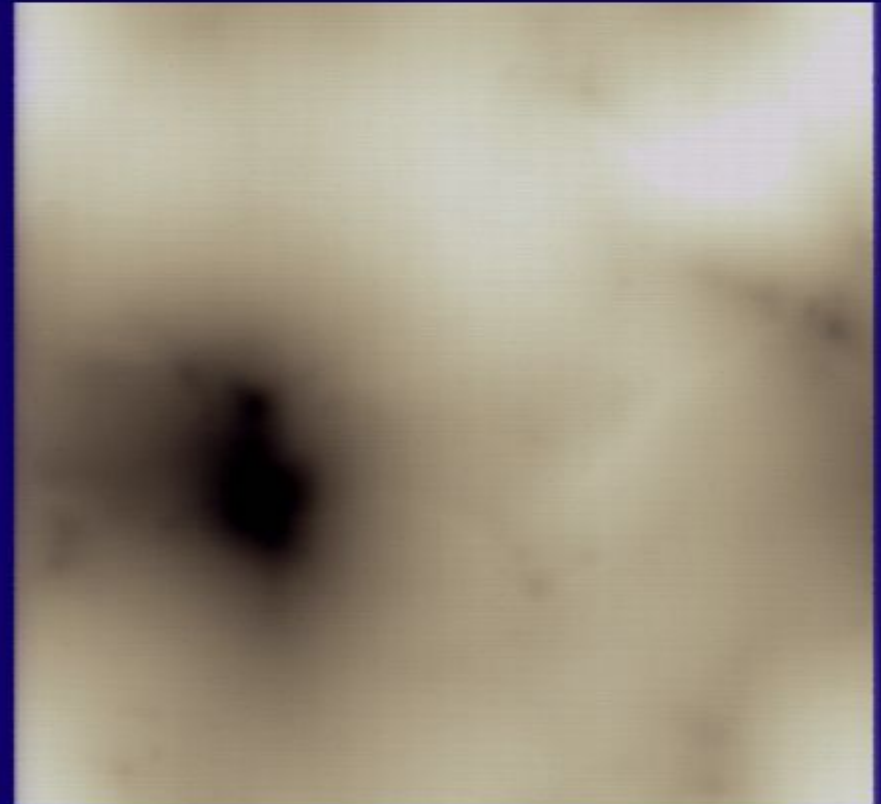
DGP N-Body

- DGP nonlinear derivative interaction solved by **relaxation** revealing the **Vainshtein mechanism**

Newtonian Potential

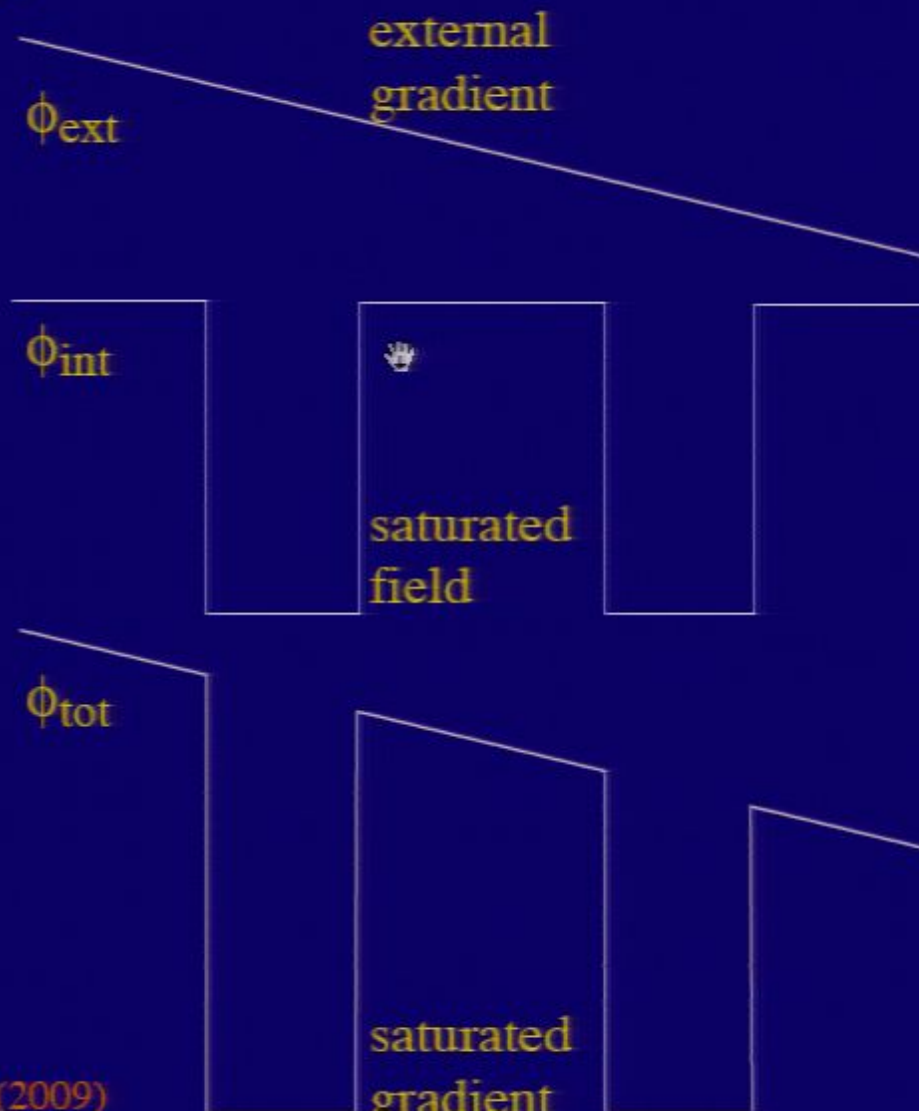


Brane Bending Mode



Apparent Equivalence Principle Violation

- Self-field of a “test mass” can saturate an external field (for $f(R)$ in the gradient, for DGP in the second derivatives)



Summary

- Lessons from the $f(R)$ and DGP worked examples – 3 regimes:
 - large scales: conservation determined
 - intermediate scales: scalar-tensor
 - small scales: GR in high density regions, modified in low
- Large scales: expansion history and metric ratio
 $g = (\Phi + \Psi)/(\Phi - \Psi)$ through curvature conservation
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No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1