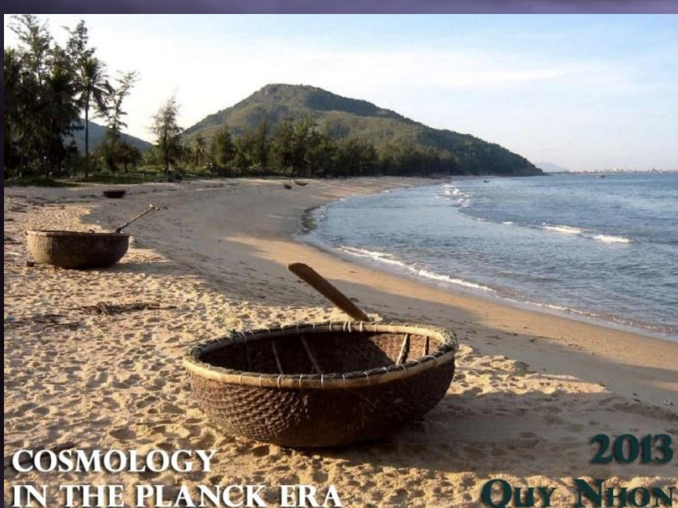
Pulsar Tests of Modified Gravity

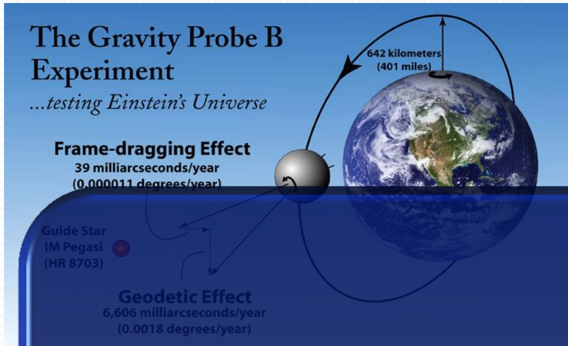


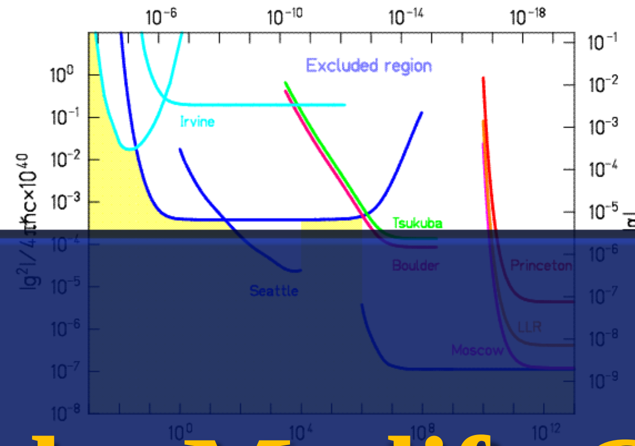
Claudia de Rham

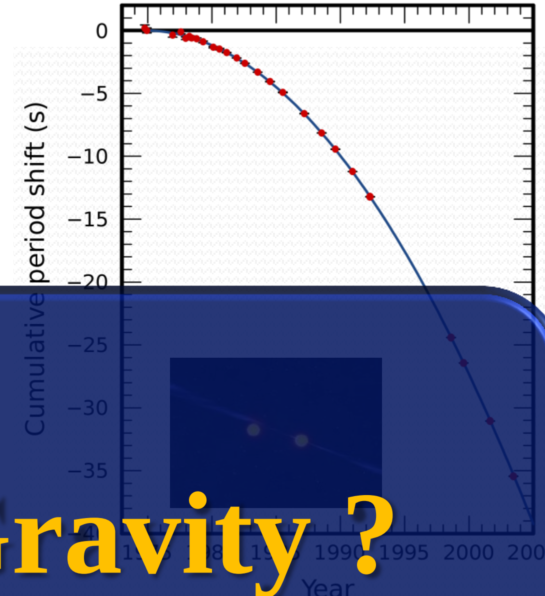
CASE WESTERN RESERVE UNIVERSITY EST. 1826

July 30th 2013

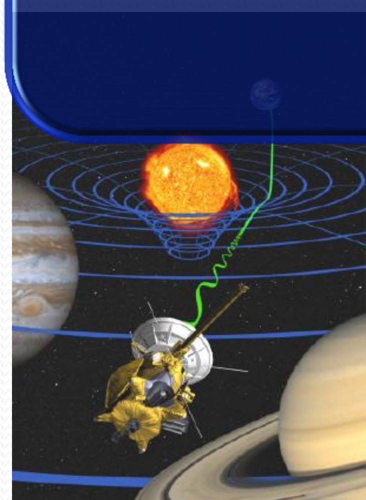
GR has been a successful theory from mm length scales to Cosmological scales

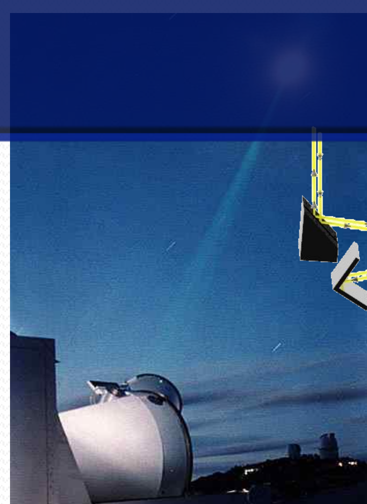


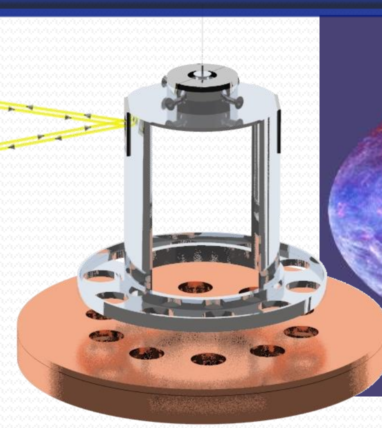


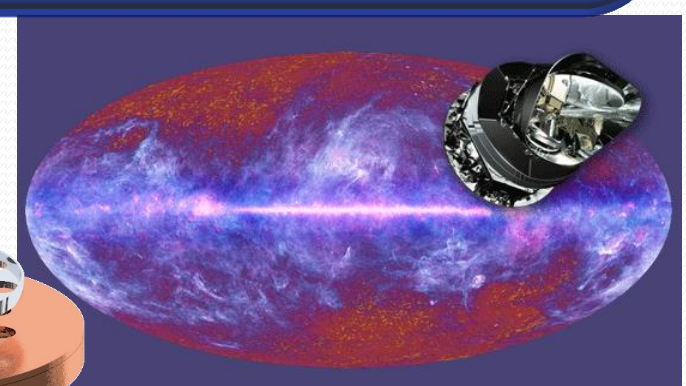


Then why Modify Gravity ?









Why Modify Gravity in the IR ?

Late time acceleration
&
CC problem

↔

First signs of the
breakdown of GR
on cosmological scales

An accelerating Universe

DE vs Λ

New dof in the matter sector

New dof in the gravity sector (self-acceleration)

An accelerating Universe

DE vs Λ

New dof in the matter sector

New dof in the gravity sector (self-acceleration)

Old Cosmological constant problem

An accelerating Universe

DE vs Λ

New dof in the matter sector

New dof in the gravity sector (self-acceleration)

Old Cosmological constant problem

$$m^2_{\rm de} \sim 10^{-120} M^2_{\rm Pl}$$

$$\rho_\Lambda \sim 10^{-120} M^4_{\rm Pl}$$

An accelerating Universe

DE vs Λ

New dof in the matter sector

New dof in the gravity sector (self-acceleration)

Old Cosmological constant problem

mGR

$$\delta m^2 \sim m^2 \frac{M^2}{M_{\rm Pl}^2}$$

GR

$$\delta\Lambda \sim M^4$$

An accelerating Universe

DE

vs

Λ

New dof in the matter sector

New dof in the gravity sector (self-acceleration)

Old Cosmological constant problem

In addition modified gravity (and especially massive gravity) comes hand in hand with a mechanism that can screen the effect of a cosmological field on short distances

Massive Gravity

$$S = \int \sqrt{-g}\frac{M_{\rm Pl}^2}{2}\left(R - \text{Mass Term}\right)$$

- The notion of mass requires a ***reference*** !
- Having the flat Metric as a Reference breaks Covariance !!! (Coordinate transformation invariance)
- The loss in symmetry generates new dof

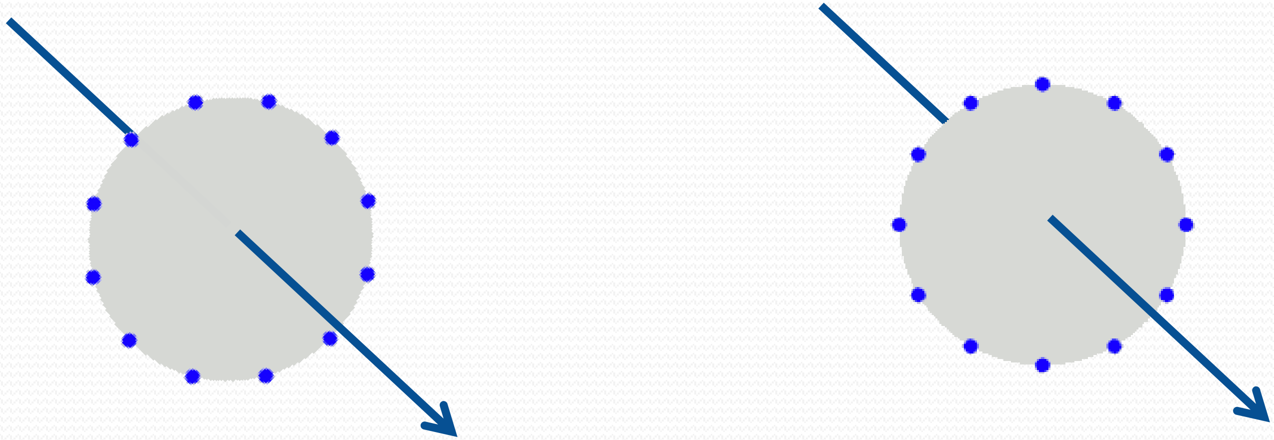
$$2 + 4 = 6$$

GR

Loss of 4 sym

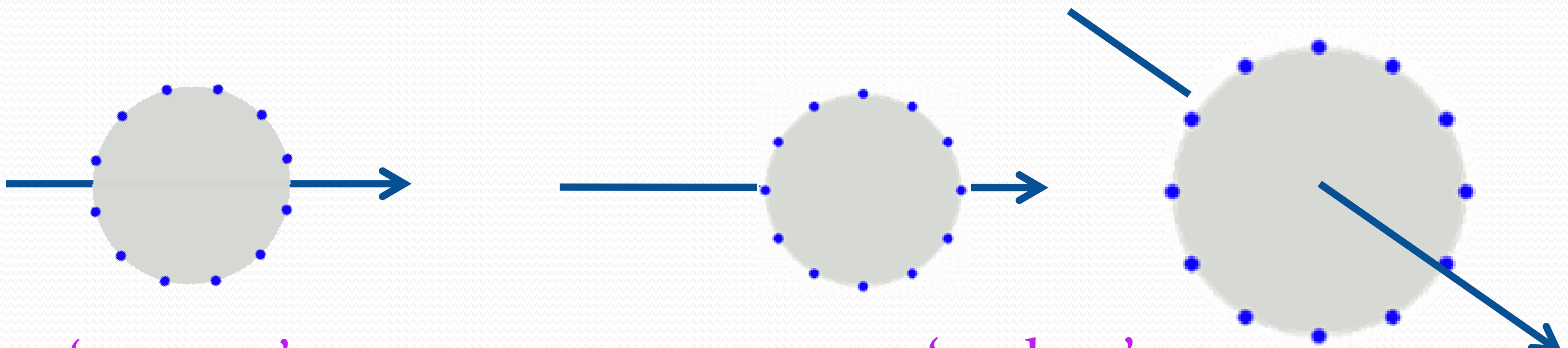
Gravitational Waves

- **GR: 2** polarizations



Gravitational Waves

- **GR: 2** polarizations
- In principle GW could have 4 other polarizations



2 'vectors' 2 'scalars'

Potential `new degrees of freedom'

Massive Gravity

$$S = \int \sqrt{-g}\,\frac{M_{\rm Pl}^2}{2}\left(R - \text{Mass Term}\right)$$

- The notion of mass requires a ***reference*** !
- Having the flat Metric as a Reference breaks Covariance !!! (Coordinate transformation inva
- The loss in symmetry generates new dof

$$2 + 4 = 6 = 5 + 1$$

Boulware & Deser, PRD6, 3368 (1972)

Fierz-Pauli Massive Gravity

$$\mathcal{U}_{\rm FP} = h_{\mu\nu}^2 - h^2$$

- Mass term for the fluctuations around flat space-time

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Transforms under a change of coordinate

$$x^\mu \;\to\; x^\mu + \partial^\mu \xi$$

$$h_{\mu\nu} \;\to\; h_{\mu\nu} + 2\partial_\mu\partial_\nu\xi + \partial_\mu\partial_\alpha\xi\partial_\nu\partial^\alpha\xi$$

Fierz-Pauli Massive Gravity

$$\mathcal{U}_{\rm FP} = H_{\mu\nu}^2 - H^2$$

- Mass term for the 'covariant fluctuations'

$$H_{\mu\nu} = h_{\mu\nu} + 2\partial_\mu\partial_\nu\pi - \partial_\mu\partial_\alpha\pi\partial_\nu\partial^\alpha\pi$$

- Does not transform under that change of coordinate

$$x^\mu \;\to\; x^\mu + \partial^\mu\xi$$

$$h_{\mu\nu} \;\to\; h_{\mu\nu} + 2\partial_\mu\partial_\nu\xi + \partial_\mu\partial_\alpha\xi\partial_\nu\partial^\alpha\xi$$

$$\pi \;\to\; \pi - \xi$$

Fierz-Pauli Massive Gravity

$$\mathcal{U}_{\rm FP} = H_{\mu\nu}^2 - H^2$$

- Mass term for the 'covariant fluctuations'

$$H_{\mu\nu} = h_{\mu\nu} + 2\partial_\mu\partial_\nu\pi - \partial_\mu\partial_\alpha\pi\partial_\nu\partial^\alpha\pi$$

- The potential has higher derivatives…

$$\mathcal{U}_{\rm FP} = \underbrace{(\partial_\mu\partial_\nu\pi)^2 - (\Box\pi)^2}_{\text{Total derivative}} + \left(\partial^2\pi\right)^3 + \cdots$$

Ghost reappears at the non-linear level

Deffayet & Rombouts, gr-qc/0505134

Ghost-free Massive Gravity

$$\mathcal{U}_{\rm GF} = \mathcal{K}^2_{\mu\nu} - \mathcal{K}^2$$

- With the tensor

$$\mathcal{K}^\mu_\nu = \delta^\mu_\nu - \sqrt{\delta^\mu_\nu - H^\mu_\nu} = \partial^\mu \partial_\nu \pi + h\partial\partial\pi + h^2\partial\partial\pi + \cdots$$

- The potential has NO higher derivatives…

$$\mathcal{U}_{\rm GF} = (\partial_\mu \partial_\nu \pi)^2 - (\Box \pi)^2 + \cancel{(\partial^2 \pi)^3} + \cdots$$

Ghost DOES NOT reappear

CdR, Gabadadze, Tolley, 1011.1232

Ghost-free Massive Gravity

$$\mathcal{U}_{\rm GF} = \mathcal{K}^2_{\mu\nu} - \mathcal{K}^2$$

- With the tensor

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- The potential has NO higher derivatives…

$$\mathcal{U}_{\rm GF} = h\partial\partial\pi + h(\partial\partial\pi)^2 + \cdots$$

Galileon in disguise after diagonalization

CdR, Gabadadze, 1007.0443

Galileons

$$\begin{aligned}\mathcal{L}_2 &= (\partial\pi)^2 \\ \mathcal{L}_3 &= (\partial\pi)^2\Box\pi \\ \mathcal{L}_4 &= (\partial\pi)^2((\Box\pi)^2 - (\partial_\mu\partial_\nu\pi)^2) \\ \mathcal{L}_5 &= (\partial\pi)^2((\Box\pi)^3 + \cdots)\end{aligned}$$

- Finite Class of Interactions

- That enjoy a shift and Galileon symmetry

$$\pi \to \pi + v_\mu x^\mu + c$$

- Have no ghost (2nd order eom)

- Enjoy a non-renormalization theorem

Nicolis, Rattazzi, Trincherini, 0811.2197

Ghost-free Massive Gravity

One can construct a consistent theory of massive gravity around any reference metric which

- propagates 5 dof in the graviton (free of the BD ghost)

- one of which is a **helicity-0** mode
  which behaves as a scalar field (a Galileon)
  couples to matter $\pi\ T$

- "hides" itself via a **Vainshtein mechanism**

Vainshtein, PLB**39**, 393 (1972)

Vainshtein Mechanism

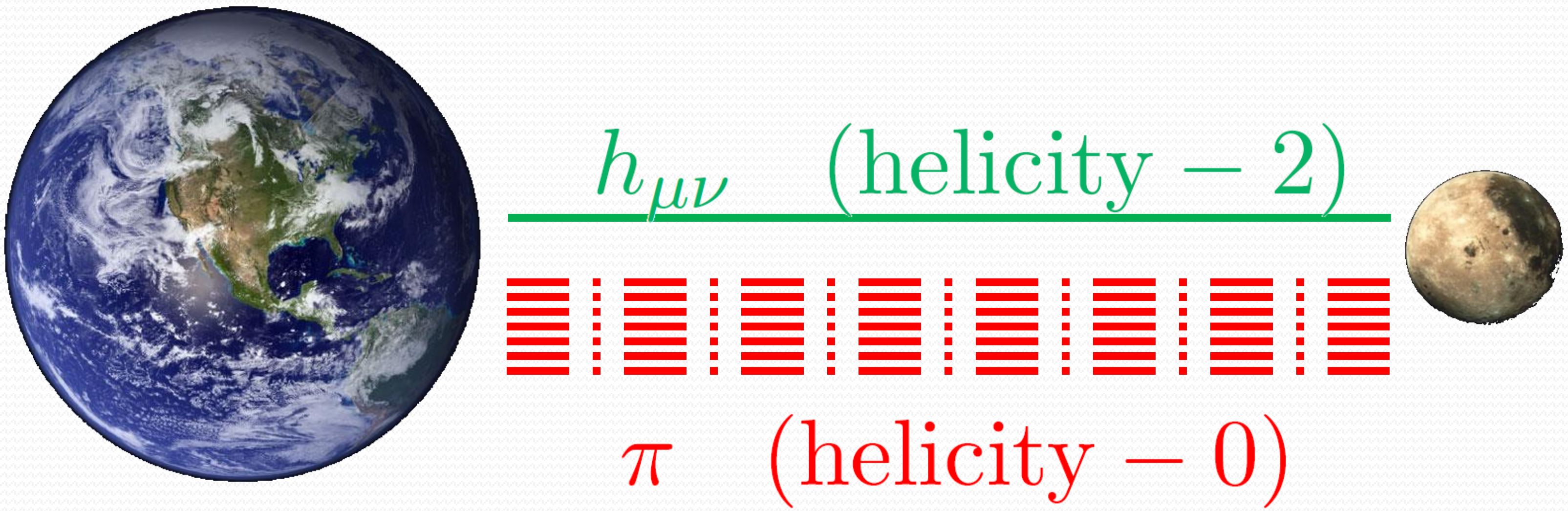
$$h_{\mu\nu} \quad (\text{helicity} - 2)$$

$$\pi \quad (\text{helicity} - 0)$$

Origin of the vDVZ discontinuity

van Dam & Veltman, Nucl.Phys.B 22, 397 (1970)
Zakharov, JETP Lett.12 (1970) 312

Vainshtein Mechanism

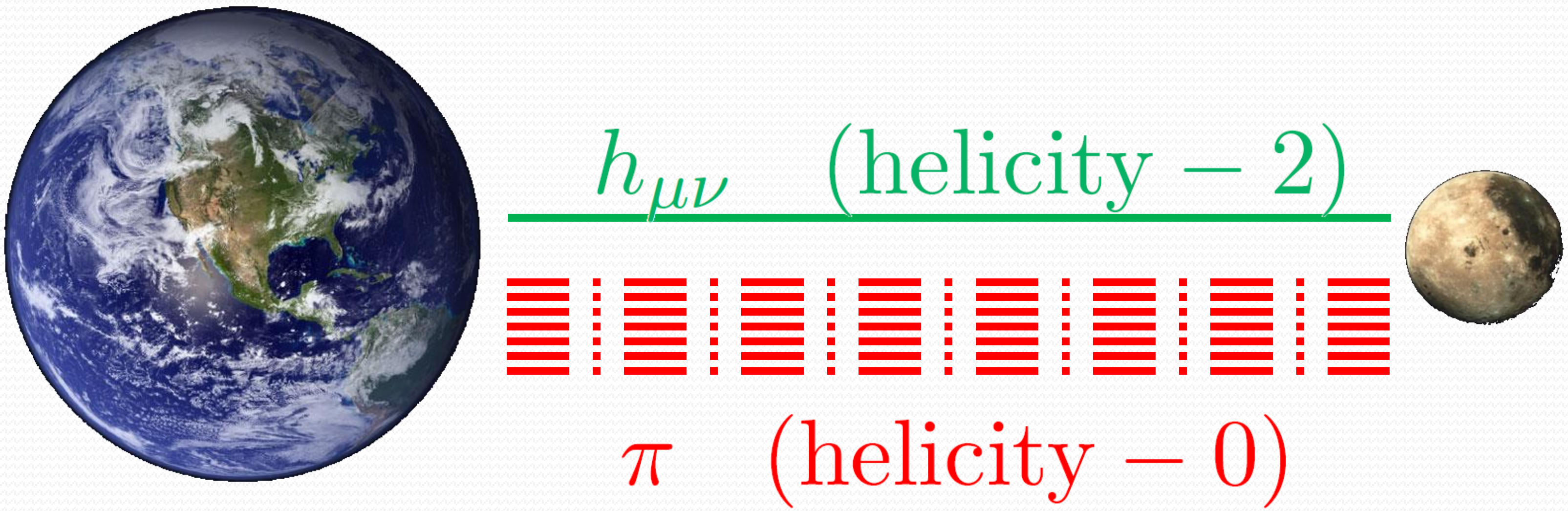


The non-linearities are essential in screening the helicity-0 mode

Vainshtein, PLB**39**, 393 (1972)

Babichev & Deffayet, 1304.7240

Vainshtein Mechanism



The interactions for the helicity-0 mode are important at a very low energy scale, $\Lambda \ll M_{\rm Pl}$

Vainshtein mechanism

- Close to a source the interactions are important

$$\Box\pi + \frac{1}{\Lambda^3}\left((\Box\pi)^2 + \cdots\right) = -T$$

- Perturbations end up being weakly coupled to matter,

$$\pi = \pi_0 + \delta\pi$$

$$\underbrace{\left(1 + \frac{\Box\pi_0}{\Lambda^3} + \cdots\right)}_{Z\left(\partial^2\pi_0\right) \gg 1}\Box\delta\pi = -\frac{1}{M_{\rm Pl}}\delta T$$

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$$\boxed{Z = 1 + \frac{\partial^2\pi_0}{\Lambda^3} + \cdots \gg 1}$$

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$$\Box\widehat{\delta\pi} = -\frac{1}{Z M_{\rm Pl}}\delta T$$

$$\boxed{Z = 1 + \frac{\partial^2\pi_0}{\Lambda^3} + \cdots \gg 1}$$

Vainshtein mechanism

- Well understood for Static & Spherically Symmetric configurations $e.g. \quad T_0 = -M_\odot \delta^{(3)}(r)$
- Background is analytic for $\pi_0'(r)$

$$\frac{\pi_0'}{r} + \frac{1}{\Lambda^3}\left(\frac{\pi_0'}{r}\right)^2 = \frac{M_\odot}{4\pi M_{\rm Pl} r^3}$$

Vainshtein radius:

$$r_\star = \frac{1}{\Lambda}\left(\frac{M_\odot}{M_{\rm Pl}}\right)^{1/3}$$

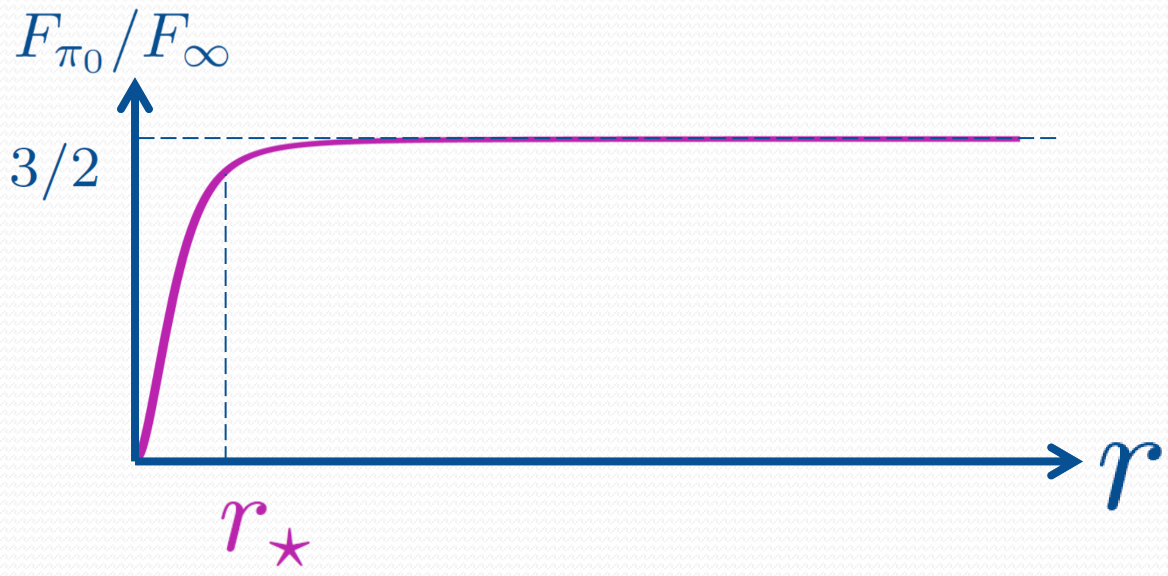
$$\text{for} \quad r \gg r_\star\,, \quad \pi_0'(r) \sim \frac{M_\odot}{M_{\rm Pl}}\frac{1}{r^2}$$

$$\text{for} \quad r \ll r_\star\,, \quad \pi_0'(r) \sim \frac{M_\odot}{M_{\rm Pl}}\frac{1}{r_\star^{3/2}\sqrt{r}}$$

Vainshtein mechanism

- Well understood for Static & Spherically Symmetric configurations $e.g. \quad T_0 = -M_\odot \delta^{(3)}(r)$

$$\frac{F_{r \ll r_\star}}{F_{r \gg r_\star}} = \left(\frac{r}{r_\star}\right)^{3/2}$$



$$r_\star = \frac{1}{\Lambda}\left(\frac{M_\odot}{M_{\rm Pl}}\right)^{1/3} \qquad \Lambda = (m^2 M_{\rm Pl})^{1/3}$$

Vainshtein mechanism

- Well understood for Static & Spherically Symmetric configurations $e.g. \quad T_0 = -M_\odot \delta^{(3)}(r)$

$$\frac{F_{r \ll r_\star}}{F_{r \gg r_\star}} = \left(\frac{r}{r_\star}\right)^{3/2} \sim 10^{-12}$$

For Sun-Earth System

$$\text{for} \quad \begin{cases} r \sim 1UA \\ M = M_\odot \\ \Lambda \sim (1000\text{km})^{-1} \quad \text{or} \quad m \sim H_0 \sim 10^{-33}\text{eV} \end{cases}$$

$$r_\star = \frac{1}{\Lambda}\left(\frac{M_\odot}{M_{\rm Pl}}\right)^{1/3} \qquad \Lambda = (m^2 M_{\rm Pl})^{1/3}$$

Vainshtein mechanism

- Well understood for Static & Spherically Symmetric configurations *e.g.* $T_0 = -M_{\odot}\delta^{(3)}(r)$

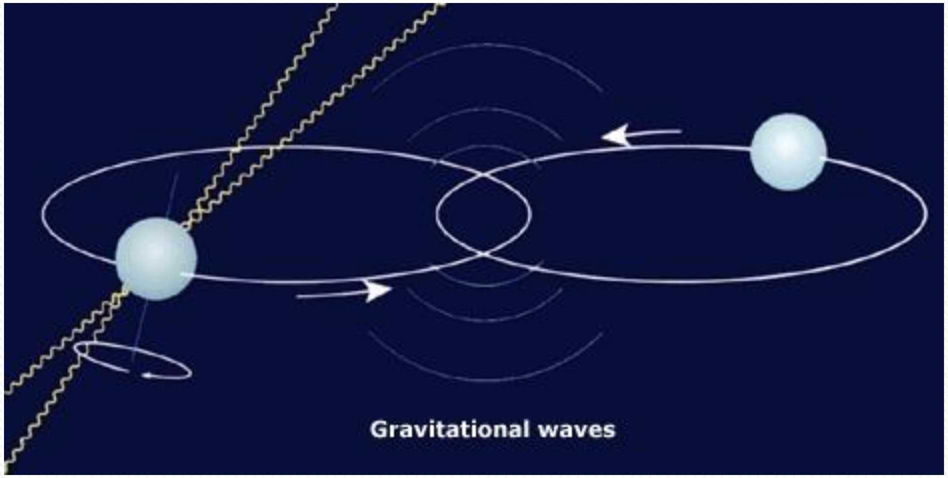
$$\frac{F_{r \ll r_\star}}{F_{r \gg r_\star}} = \left(\frac{r}{r_\star}\right)^{3/2}$$

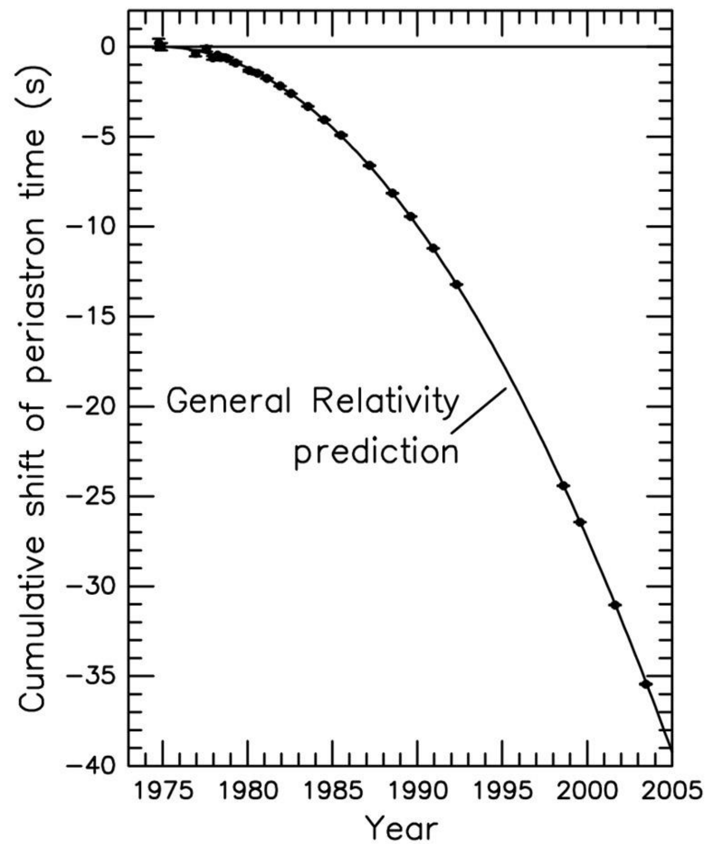
$\sim 10^{-12}$ For Sun-Earth System

$\sim 10^{-13}$ For Earth-Moon System

$\sim 10^{-15}$ For Hulse-Taylor Pulsar

Vainshtein mechanism in a Binary System





Vainshtein mechanism in a Binary System

1. Method

   Effective Action Approach

   described by Goldberger & Rothstein

   hep-th/0409156 & subsequent literature

Vainshtein mechanism in a Binary System

1. Method
   Effective Action Approach

2. Monopole & Quadrupole Radiation

$$\text{Vainshtein Suppression in the Monopole} \sim \frac{1}{(\Omega_p r_\star)^{3/2}}$$

$$\text{Vainshtein Suppression in the Quadrupole} \sim \frac{1}{(\Omega_p r_\star)^{3/2}} \frac{1}{\Omega_p \bar{r}}$$

Vainshtein mechanism in a Binary System

1. Method
   Effective Action Approach

2. Monopole & Quadrupole Radiation
   in Simplest Galileon

3. Subtleties in General Galileon Model…

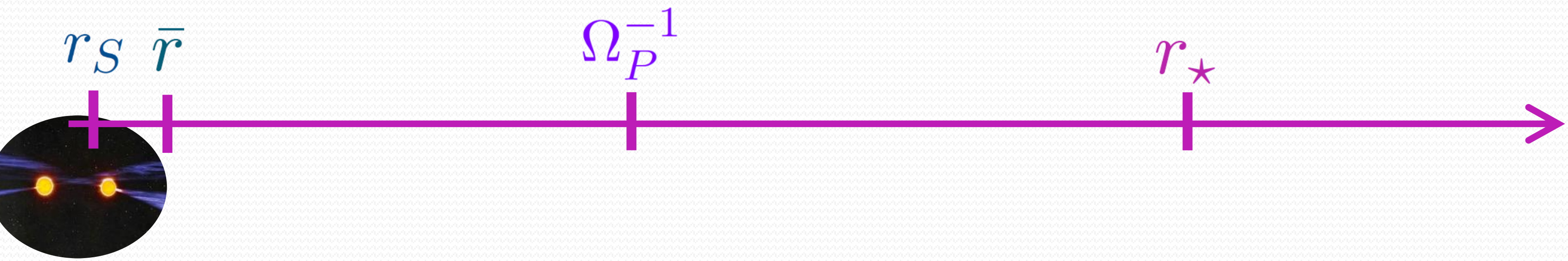
What is an EFT ?

- A Clever way to parameterize our "ignorance"

- Instead of trying to solve the *full theory*, we only include the most important contributions in the Effective description

- This makes sense when there is Hierarchy of scales.

Hierarchy of Scales



$$r_S \sim 10 \text{ km}$$

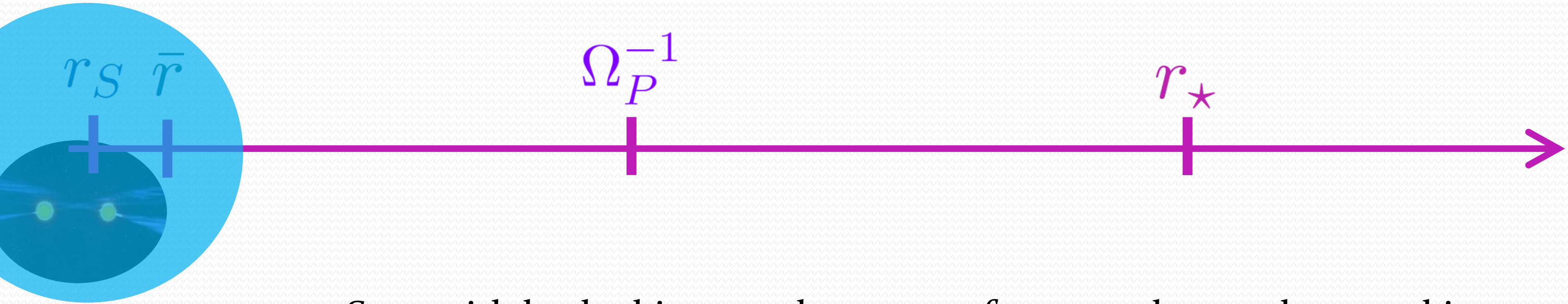
$$\bar{r} \sim 10^6 \text{ km}$$

$$\Omega_P^{-1} \sim 10^9 \text{ km}$$

$$r_\star \sim 10^{15} \text{ km}$$

$$r_S \ll \bar{r} \ll \Omega_P^{-1} \ll r_\star \ll m^{-1}$$

Hierarchy of Scales



Start with both objects at the center of mass and perturb around it

$$T = T_0 + \delta T$$

Total mass at center of mass

$$\pi = \pi_0(r) + \phi$$

Radiation emitted by that scalar

Effective Action

- Start with the Cubic Galileon

$$S_{\mathrm{Gal}} = \int \mathrm{d}^4 x \left(-\frac{1}{2}(\partial\pi)^2 + \frac{1}{\Lambda^3}(\partial\pi)^2 \Box\pi + \frac{1}{M_{\mathrm{Pl}}}\pi T \right)$$

$$T = T_0 + \delta T$$

Total mass at center of mass

$$\pi = \pi_0(r) + \phi$$

Radiation emitted by that scalar

Effective Action

- Start with the Cubic Galileon

$$S_{\mathrm{Gal}} = \int \mathrm{d}^4x \left(-\frac{1}{2}(\partial\pi)^2 + \frac{1}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{1}{M_{\mathrm{Pl}}}\pi T \right)$$

$$T = T_0 + \delta T$$

Total mass at center of mass

$$\pi = \pi_0(r) + \phi$$

Radiation emitted by that scalar

Effective Action

- Start with the Cubic Galileon

$$S_{\rm Gal} = \int \mathrm{d}^4x \left(-\frac{1}{2} Z(\pi_0)(\partial\phi)^2 + \frac{1}{M_{\rm Pl}} \phi \delta T \right)$$

$$T = T_0 + \delta T$$

Total mass at center of mass

$$\pi = \pi_0(r) + \phi$$

Radiation emitted by that scalar

Effective Action

- Start with the Cubic Galileon

$$S_{\mathrm{Gal}} = \int \mathrm{d}^4x \left(-\frac{1}{2} Z(\pi_0)(\partial\phi)^2 + \frac{1}{M_{\mathrm{Pl}}} \phi \delta T \right)$$

- Integrate out the scalar field

$$\phi(x) = \frac{i}{M_{\mathrm{Pl}}} \int \mathrm{d}^4x' G_F(x, x') \delta T(x')$$

$$Z(\partial^2 \pi_0(r))\, \partial_x^2 G_F(x, x') = i\delta^4(x - x')$$

Effective Action

- Start with the Cubic Galileon

$$S_{\mathrm{Gal}} = \int \mathrm{d}^4x \left(-\frac{1}{2} Z(\pi_0)(\partial\phi)^2 + \frac{1}{M_{\mathrm{Pl}}}\phi\delta T \right)$$

- Integrate out the scalar field

$$S_{\mathrm{eff}} = \frac{i}{2M_{\mathrm{Pl}}^2} \int \mathrm{d}^4x \, d^4x' \;\; \delta T(x) G_F(x, x') \delta T(x')$$

$$Z(\partial^2\pi_0(r))\, \partial_x^2 G_F(x, x') = i\delta^4(x - x')$$

Effective Action

- The average power emitted can then be computed out of the Im part of the effective action

$$P = -\left\langle \frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} \right\rangle = \int_0^\infty \mathrm{d}\omega\, \omega f(\omega) \quad \text{with} \quad \frac{2}{T_P}\mathrm{Im}S_{\text{eff}} = \int \mathrm{d}\omega\, f(\omega)$$

Effective Action

- The average power emitted can then be computed out of the Im part of the effective action

$$P = -\left\langle \frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} \right\rangle = \int_0^\infty \mathrm{d}\omega\, \omega f(\omega) \quad \text{with} \quad \frac{2}{T_P} \mathrm{Im} S_{\rm eff} = \int \mathrm{d}\omega f(\omega)$$

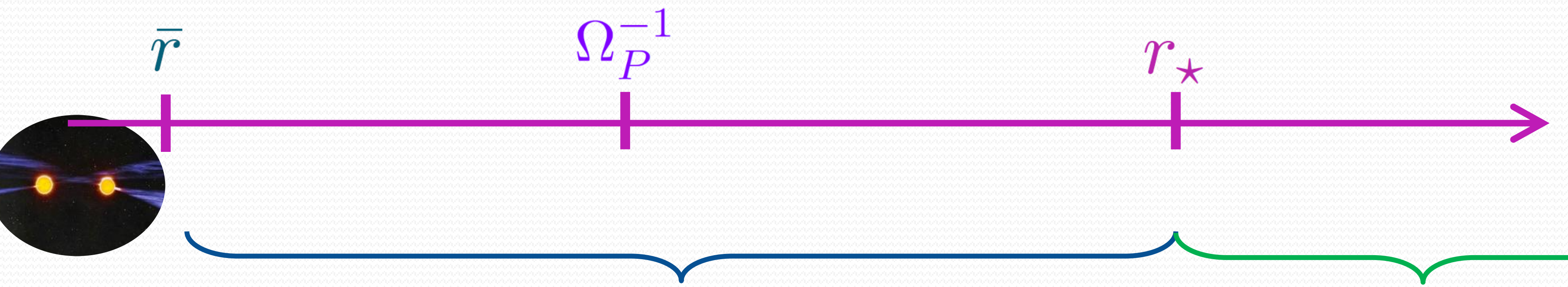
- In terms of the modes spherical harmonic space

$$Z \partial_x^2 \left[u_\ell(r) Y_{\ell m}(\Omega) e^{-i\omega t} \right] = 0$$

$$\boxed{P \sim \sum_{n=0}^{\infty} \sum_{\ell,m} (n\Omega_P) \left| \frac{1}{M_{\rm Pl} T_P} \int_0^{T_P} \mathrm{d}t \mathrm{d}^3x \; u_\ell(r) Y_{\ell,m} e^{-in\Omega_p t} \delta T \right|^2}$$

Normalization

- We choose the normalization by matching to the correct modes at infinity



Strong Coupling region

$$u_\ell = \bar{u} \left(\frac{r}{r_\star}\right)^{1/4} J_\nu \left(\frac{\sqrt{3}}{2}\omega r\right)$$

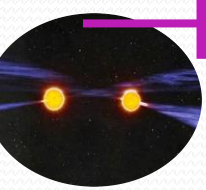
Free Field
in Minkowski

$$u_\ell = \frac{1}{\sqrt{\pi \omega r}} \cos\left(\omega r\right)$$

$$\nu = \begin{cases} (2\ell+1)/4 & \text{for} \quad \ell > 0 \\ -1/4 & \text{for} \quad \ell = 0 \end{cases}$$

Normalization

- We choose the normalization by matching to the correct modes at infinity



$\bar{r}$ Ω_P^{-1} $r_\star$

Strong Coupling region

Free Field
in Minkowski

$$u_\ell = \bar{u} \left(\frac{r}{r_\star}\right)^{1/4} J_\nu \left(\frac{\sqrt{3}}{2}\omega r\right)$$

$$u_\ell = \frac{1}{\sqrt{\pi \omega r}} \cos\left(\omega r\right)$$

Fixed by matching in the WKB region

$$\bar{u} \sim r_\star^{-1/2}$$

Monopole

- The leading order contribution to the monopole vanishes by conservation of energy…
- The first relativistic correction gives

$$\delta T = -\left[\sum_{i=1,2} M_i \left(1 - \frac{1}{2}(\omega r_i(t))^2 + \ldots\right) \delta^{(3)}(\vec{x} - \vec{x}_i(t)) - M\delta^{(3)}(\vec{x})\right]$$

$$u_0(r) \sim \frac{1}{(\omega r_\star^3)^{1/4}} \left(1 - \frac{1}{4}(\omega r)^2 + \cdots\right)$$

With $r_i(t) = \dfrac{\bar{r}(1-e^2)}{1 + e\cos\Omega_P t}\dfrac{M_{2,1}}{M}$

Monopole

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$$u_0(r) \sim \frac{1}{(\omega r_\star^3)^{1/4}}\left(1 - \frac{1}{4}(\omega r)^2 + \cdots\right)$$

With $r_i(t) = \frac{\bar{r}(1-e^2)}{1 + e\cos\Omega_P t}\frac{M_{2,1}}{M}$

Monopole

- The leading order contribution to the monopole vanishes by conservation of energy…
- The first relativistic correction gives

$$P_{\rm Monopole} \sim \frac{(\Omega_P \bar{r})^4}{(\Omega_P r_\star)^{3/2}} \frac{\mathcal{M}^2}{M_{\rm Pl}^2} \Omega_P^2$$

$$\text{Vainshtein Suppression in the Monopole} \quad \sim \quad \frac{1}{(\Omega_p r_\star)^{3/2}}$$

For the Hulse-Taylor Pulsar $\quad \sim 10^{-10}$

Quadrupole

- A priori the quadrupole is suppressed by a few powers of velocity compared to the monopole…
- But does not need to include to relativistic corrections

$$u_2(r) \sim \frac{(\omega r)^{3/2}}{(\omega r_\star^3)^{1/4}} + \cdots$$

Quadrupole

- A priori the quadrupole is suppressed by a few powers of velocity compared to the monopole…
- But does not need to include to relativistic corrections

$$P_{\text{Quadrupole}} \sim \frac{(\Omega_P \bar{r})^3}{(\Omega_P r_\star)^{3/2}} \frac{\mathcal{M}^2}{M_{\text{Pl}}^2} \Omega_P^2$$

$$\text{Vainshtein Suppression in the Quadrupole} \quad \sim \quad \frac{1}{(\Omega_p r_\star)^{3/2}} \frac{1}{\Omega_p \bar{r}}$$

For the Hulse-Taylor Pulsar $\sim 10^{-8}$

Quartic Galileon

- In the Quartic Galileon, the angular direction is *not screened as much* as along the others

- The quadrupole is screened compared to GR

$$\frac{P^{\text{Quadrupole}}_{\text{Quartic Galileon}}}{P^{\text{Quadrupole}}_{\text{GR}}} \sim \frac{1}{(\Omega_P r_\star)^2} \sim 10^{-12} \ !!!$$

- But many multipoles contribute to the power with the same magnitude…

$\longrightarrow$ Multipole expansion breaks down

Effective metric

- In the Cubic Galileon, the Effective metric for perturbations had of the same behavior along all directions

$$S_{\rm Gal} = \int {\rm d}^4x \left(-\frac{1}{2}(\partial\pi)^2 + \frac{1}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{1}{M_{\rm Pl}}\pi T \right)$$

$$\pi \;=\; \pi_0(r) + \phi$$

With $Z_{\mu\nu} \sim \left(\frac{\pi_0'}{\Lambda^3 r}\right)\eta_{\mu\nu}$

$$\Big\downarrow$$

$$S_{\rm Gal} = \int {\rm d}^4x \left(-\frac{1}{2} Z^{\mu\nu}(\pi_0)\partial_\mu\phi\partial_\nu\phi + \frac{1}{M_{\rm Pl}}\phi\delta T \right)$$

Effective metric

- In the Quartic Galileon, the Effective metric for perturbations is *different* along different directions

$$Z_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \sim \left(\frac{\pi_0'}{\Lambda^3 r}\right)^2 \left(-\mathrm{d}t^2 + \mathrm{d}r^2 + r_\star^2 \mathrm{d}\Omega^2\right)$$

Effective metric

- In the Quartic Galileon, the Effective metric for perturbations is *different* along different directions

$$Z_{\mu\nu}\mathrm{d}x^{\mu}\mathrm{d}x^{\nu} \sim \left(\frac{\pi_0'}{\Lambda^3 r}\right)^2 \left(-\mathrm{d}t^2 + \mathrm{d}r^2 + r_\star^2 \mathrm{d}\Omega^2\right)$$

Multipoles are no longer suppressed by more power of velocity

Quartic Galileon

- Perturbations are under control when there is another Hierarchy of scales

eg. hierarchy of mass between the two objects
Solar System

- For a generic binary pulsar system, one needs to do perturbations about a different background…

Outlook

- Massive Gravity is a specific framework to study IR modifications of Gravity

- It could play a role for
  - the late-time acceleration of the Universe
  - the cosmological constant problem

- We now have the theoretical formalism to describe a stable theory of massive gravity

- It behaves a scalar-tensor Galileon theory in some limit, hand in hand with a Vainshtein mechanism

Outlook

- The scalar field opens new channels of radiations which would have been observable in binary pulsar systems if they were not Vainshtein screened.
- The monopole is suppressed by a factor of $\dfrac{1}{(\Omega_p r_\star)^{3/2}}$
- The quadrupole is suppressed by $\dfrac{1}{(\Omega_p r_\star)^{3/2}} \dfrac{1}{\Omega_p \bar{r}}$
- While this suppression makes these effects unobservable in binary pulsar, it shows that the Vainshtein mechanism is much more subtle in time-dependent configurations.