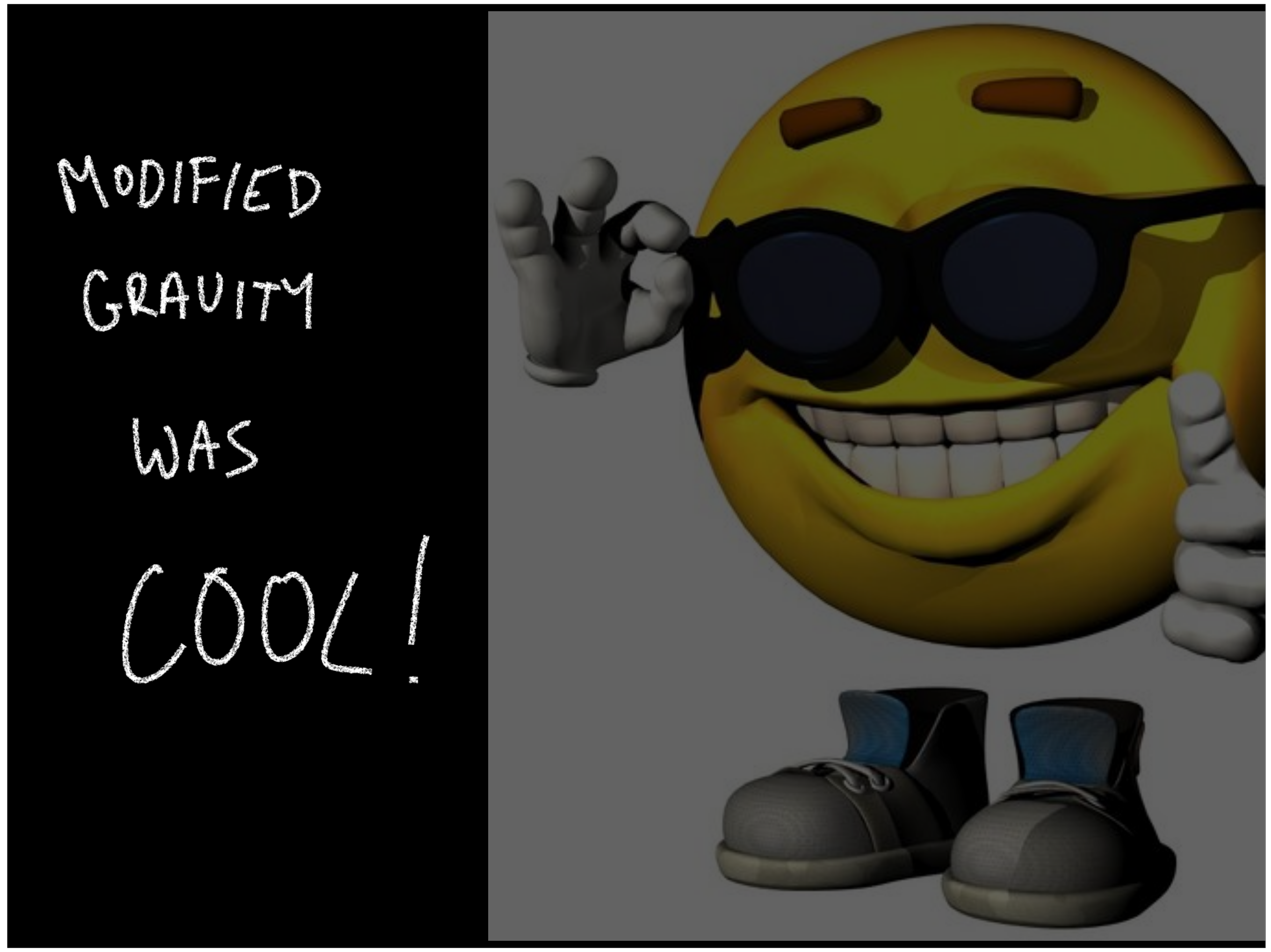
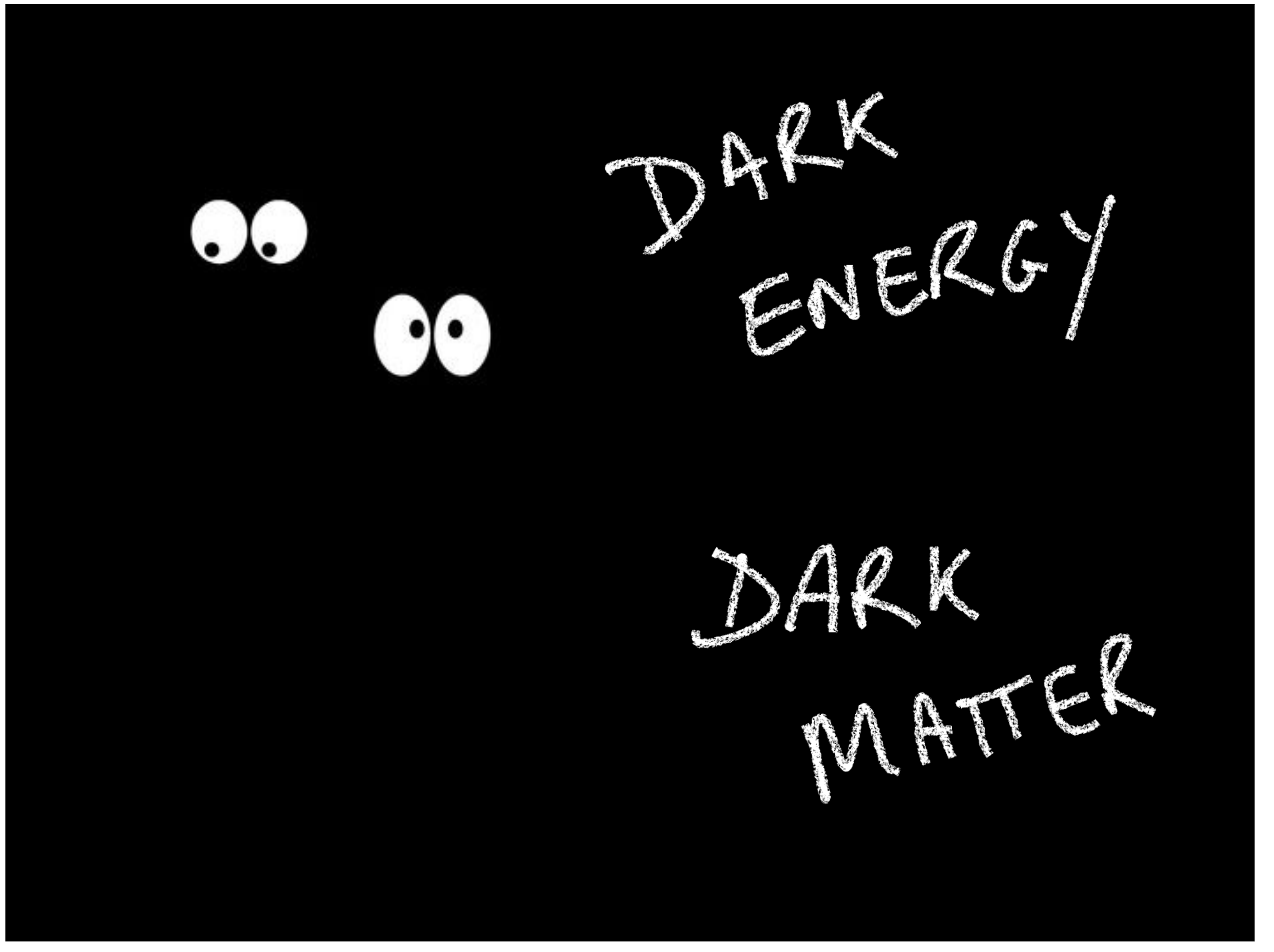
DARK ENERGY SOME TIME AFTER GW170817

Prof. Tony Padilla

LET'S RETURN TO A TIME BEFORE ANYONE HAD EVER 'SEEN' A GRAVITATIONAL WAVE...


MODIFIED
GRAVITY
WAS
COOL!


DARK ENERGY
DARK MATTER

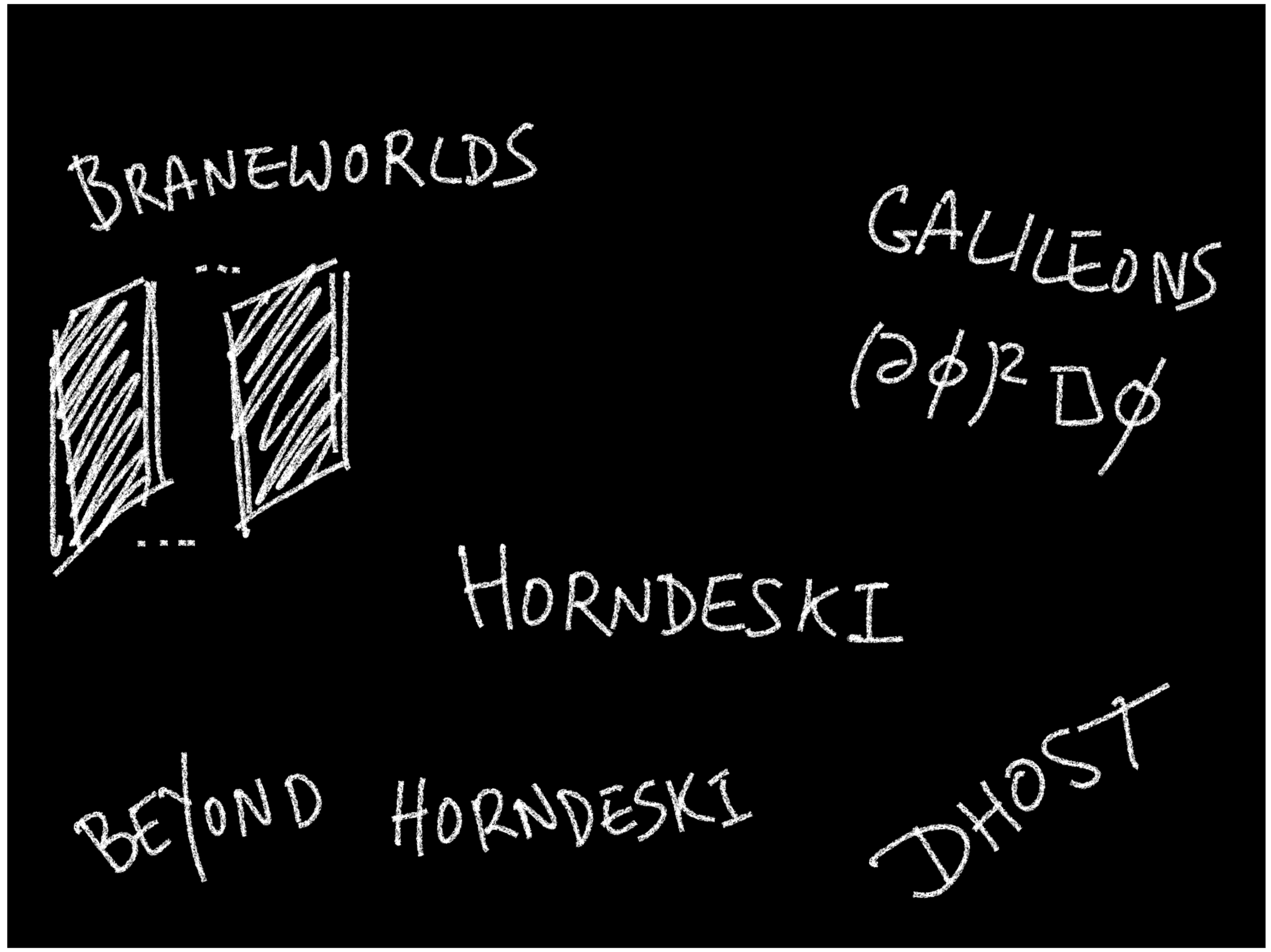
Isn't just Λ?


OTTO, MY FRIEND,
THE UNIVERSE
WOULD NOT EVEN
REACH TO THE
MOON!

PEOPLE BEGAN TO COOK UP FANCY NEW PHYSICS AT $r > H_0^{-1}$

FINE, AS LONG AS YOU COULD SATISY

- SOLAR SYSTEM CONSTRAINTS
- CONSISTENCY OF YOUR EFT


BRANEWORLDS
GALILEONS
$(\partial\phi)^2 \Box\phi$
HORNDESKI
BEYOND HORNDESKI
DHOST


HORNDESKI
FRAME TO THE SERIAL STORY OF MY ARTISTIC LIFE ENTITLED "HOW I BECAME A MEDIOCRE (=M) ARTIST (=A)." RECALL THAT IN THE LAST EPISODE, WHICH APPEARED ON "WORKING IN THE PARK" ©2009, I BE-
GAN DISCUSSING MY DEALINGS WITH Gs (=GALLERYs). HOPEFULLY I'LL BE ABLE TO COMPLETE THAT HERE SO THAT ON THE NEXT FRAME I CAN DESCRIBE HOW TO COOK NOURISHING + ECONOMI-
CAL MEALS + TREATS. AS USUAL I BEGIN BY RECALLING MY DEFINITION OF A MA. MAs ARE As WHO CAN WORK FULL-TIME ON THEIR ARTWORK + DON'T NEED TO DO ANY OTHER TYPE OF WORK TO PAY
THE BILLS. SO IF YOU'RE AN A + YOU'RE TEACHING OR PAINTING HOUSES TO GET BY THEN YOU'RE NOT A MA. NOW YOU MAY THINK I'VE SET THE BAR FOR MEDIOCRITY QUITE HIGH FOR As. I
DON'T THINK SO. FOR SUPPOSE JOE IS SOME GUY WHO WORKS FOR THE CITY OR AT A FACTORY OR SOMEWHERE, + HE MAKES ENOUGH FROM HIS JOB TO PAY HIS BILLS. ARE WE GOING TO
ING THEIR DUPLICITY. I LEFT THAT G SHORTLY AFTER THAT INCIDENT. MANY Gs + EVEN ART CONSULTANTS LET THEMSELVES GET BEHIND IN PAYING THEIR As. IT'S TOUGH FOR AN A TO DETERMINE
WHAT'S GOING + WHEN TO PULL OUT. I HAVE HAD TO USE LAWYERS 3 TIMES TO GET MY MONEY FROM Gs. BINDER WAS THE 1st THEN THERE WAS THE VIRGINIA MILLER G IN MIAMI + THE LIZ BLACKMAN G in
L.A. LIZ MADE THE MISTAKE OF LEAVING A MESSAGE ON MY ANSWERING MACHINE SAYING THAT SHE SOLD 1 OF MY PXs AT THE OUTSIDER ART FAIR IN NY, + THAT SHE'D SEND ME MONEY SOON. WHEN SOON NEVER ARRIV-
ED, I CALLED HER ABOUT IT + SHE TRIED BACK PEDALING, SAYING SHE NEVER SOLD THE PX + ASKING WHAT MADE ME THINK OTHERWISE? WELL, FORTUNATELY I SAVED THE TAPE ON MY ANSWERING MACHINE SO I COU-

THE MOST GENERAL SCALAR TENSOR THEORY

(rediscovered by Deffayet et al 2011)

$$\mathcal{L}_{\text{Horndeski}} = \sqrt{-g}\Big\{ G_2(\phi,X) + G_3(\phi,X)\Box\phi$$

$$+ G_4(\phi,X)R - 2G_{4,X}\,\mathcal{E}_2$$

$$+ G_5(\phi,X)G_{\mu\nu}\nabla^\mu\phi\nabla^\nu\phi + \frac{G_{5,X}}{3}\,\mathcal{E}_3 \Big\}$$

$$X = -\tfrac{1}{2}(\nabla\phi)^2\,, \quad \mathcal{E}_n = \nabla_{[\mu_1}\nabla^{\mu_1}\phi \ldots \nabla_{\mu_n]}\nabla^{\mu_n}\phi$$

BEYOND HORNDESKI (Gleyzes et al 2015)

$$\mathcal{L}_{BH} = \mathcal{L}_{Horndeski}$$

$$+ \sqrt{-g}\,\Big\{ F_4(\phi, X)\, \nabla_{[\mu_1}\phi\, \nabla^{\mu_1}\phi\, \nabla_{\mu_2}\nabla^{\mu_2}\phi\, \nabla_{\mu_3]}\nabla^{\mu_3}\phi$$

$$+ F_5(\phi, X)\, \nabla_{[\mu_1}\phi\, \nabla^{\mu_1}\phi\, \nabla_{\mu_2}\nabla^{\mu_2}\phi \ldots \nabla_{\mu_3]}\nabla^{\mu_3}\phi \Big\}$$

Higher derivative field eqns

Degeneracy conditions $\Rightarrow$ no ostrogradski

WRITE $\mathcal{L}_{Horndeski} = \sqrt{-g}\ \frac{M_{pl}^2}{2}\left(R - \frac{1}{2}(\partial\phi)^2 + \mathcal{L}_{int}\right)$

WITH HORNDESKI INTERACTIONS

$$\text{eg } \mathcal{L}_{int} \supset +\lambda \frac{X\Box\phi}{M^3}$$

$$+ \mu \frac{XR}{M^4} + \frac{\nu}{M^6}\left(X^2 R - 4X(\partial\partial\phi)^2\right) + \ldots$$

Assume matter couples minimally to $g_{\mu\nu}$

For Horndeski interactions relevant on cosmo scales we require $M \lesssim H_0$

HUGE FAMILY

OF

DARK ENERGY MODELS

(and some relevant to CC problem

eg Fab 4)

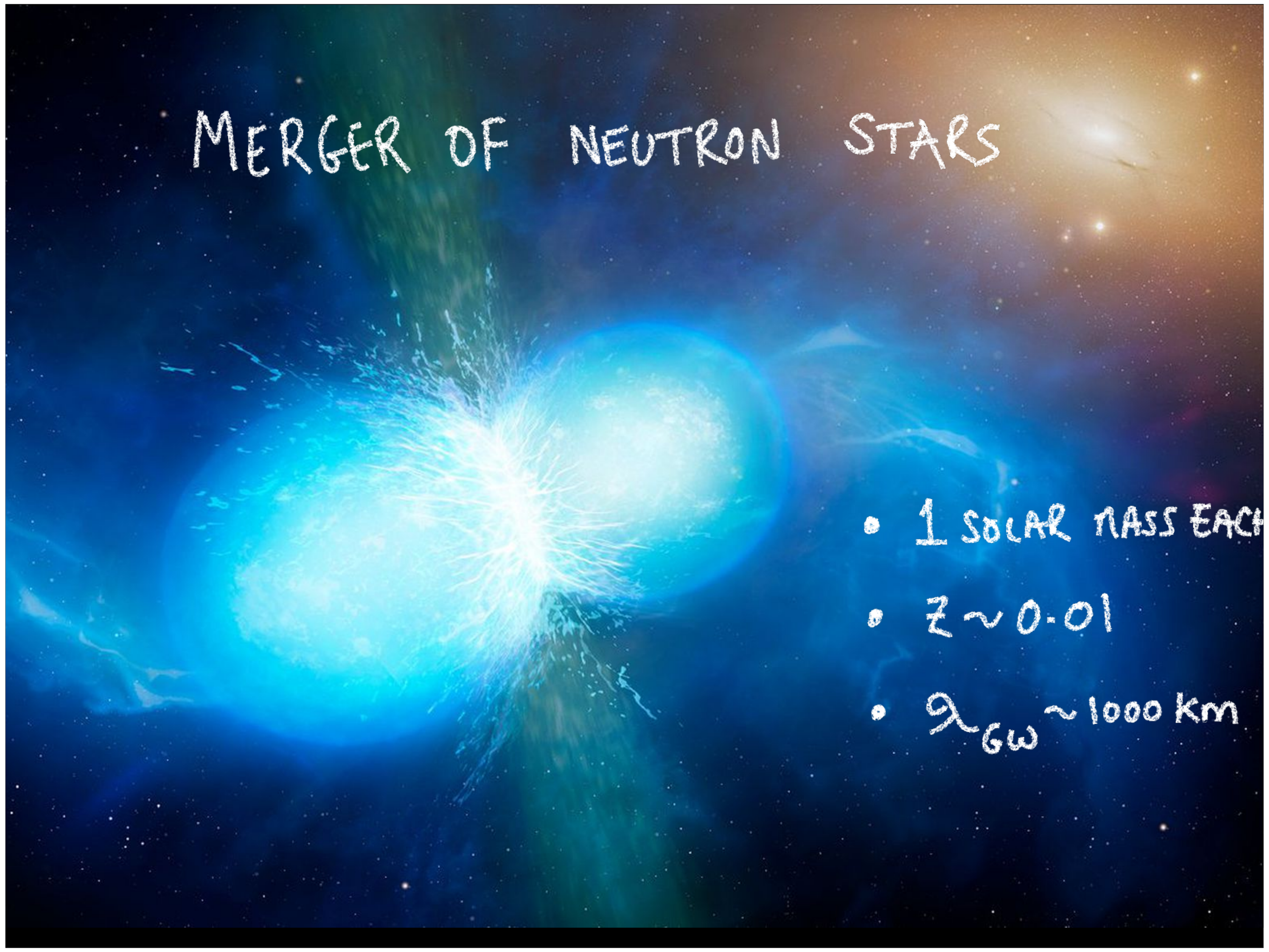
FINE, AS LONG AS YOU COULD SATISY

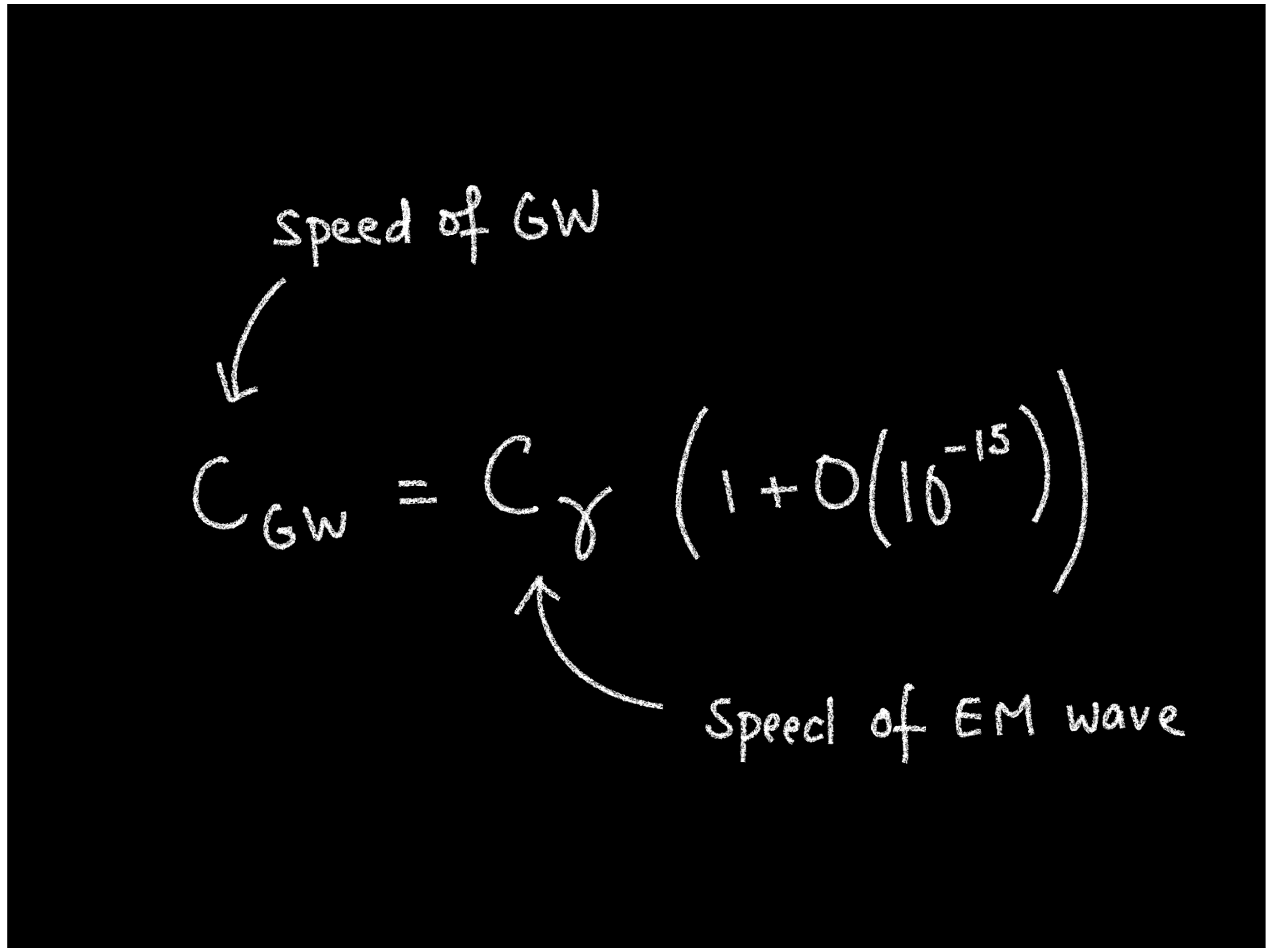
- SOLAR SYSTEM CONSTRAINTS
- CONSISTENCY OF YOUR EFT

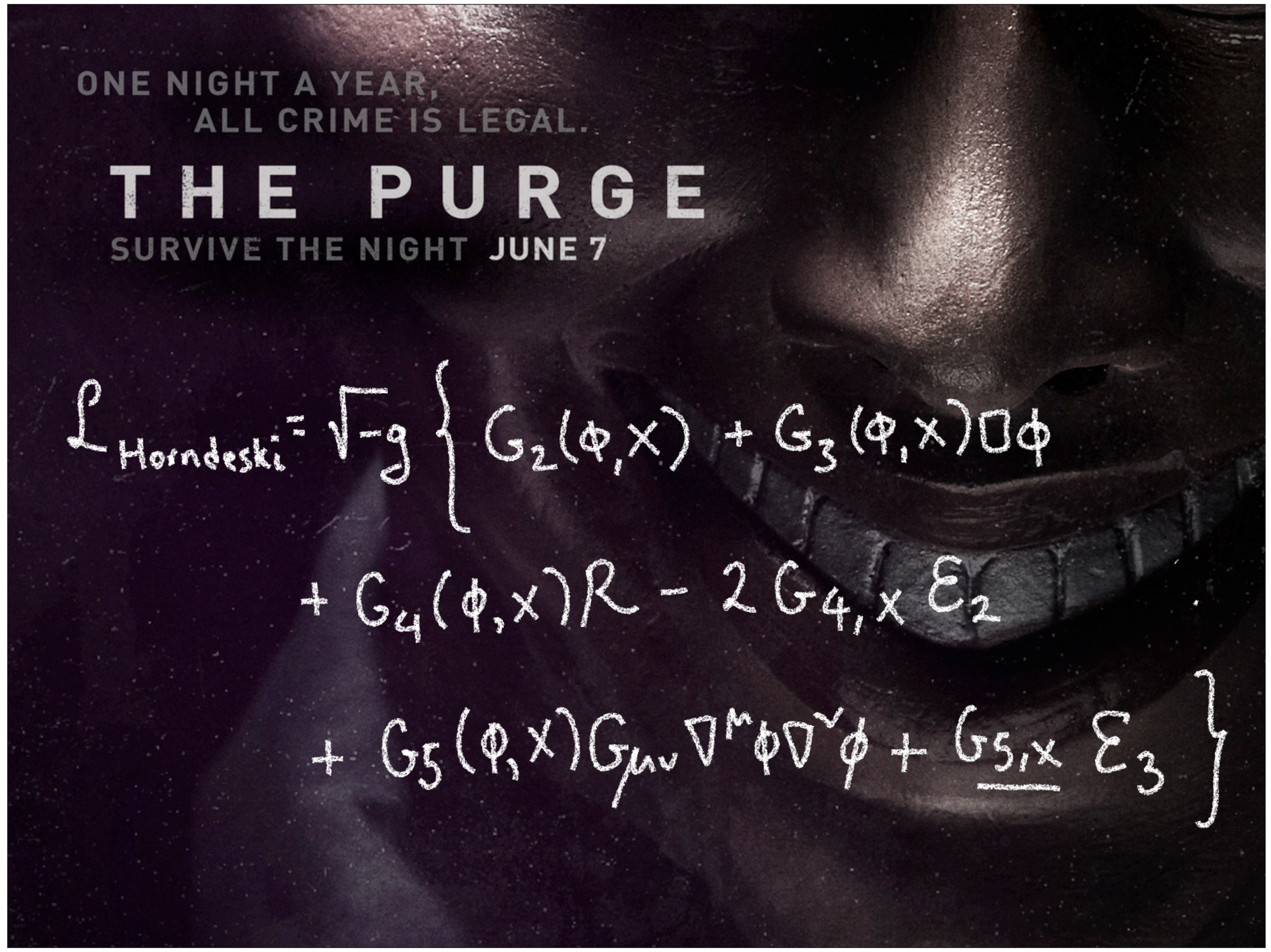
BEFORE GWs BIGGEST ISSUE WAS NEED TO "SCREEN".

AND THEN CAME

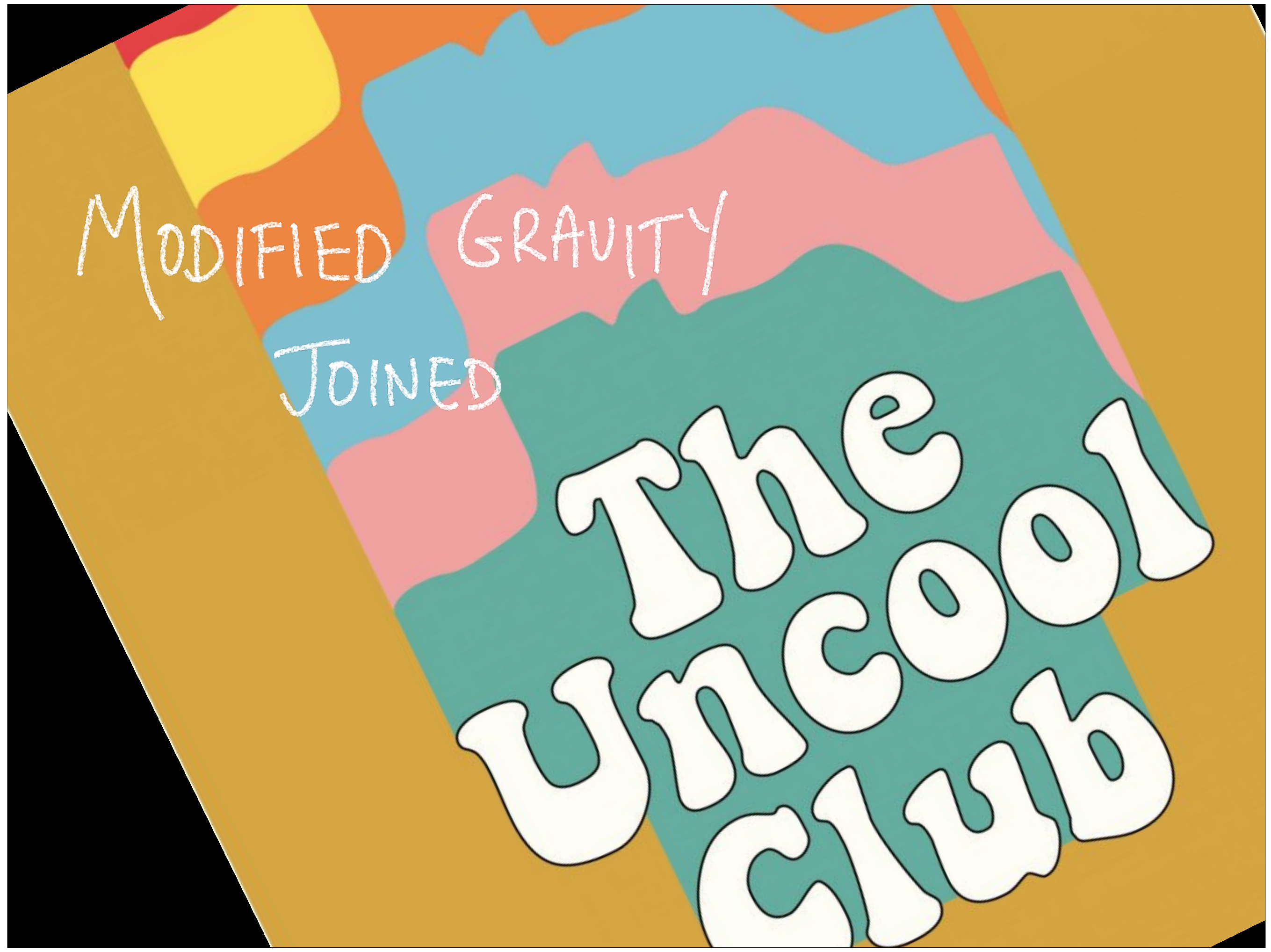
GW170817.

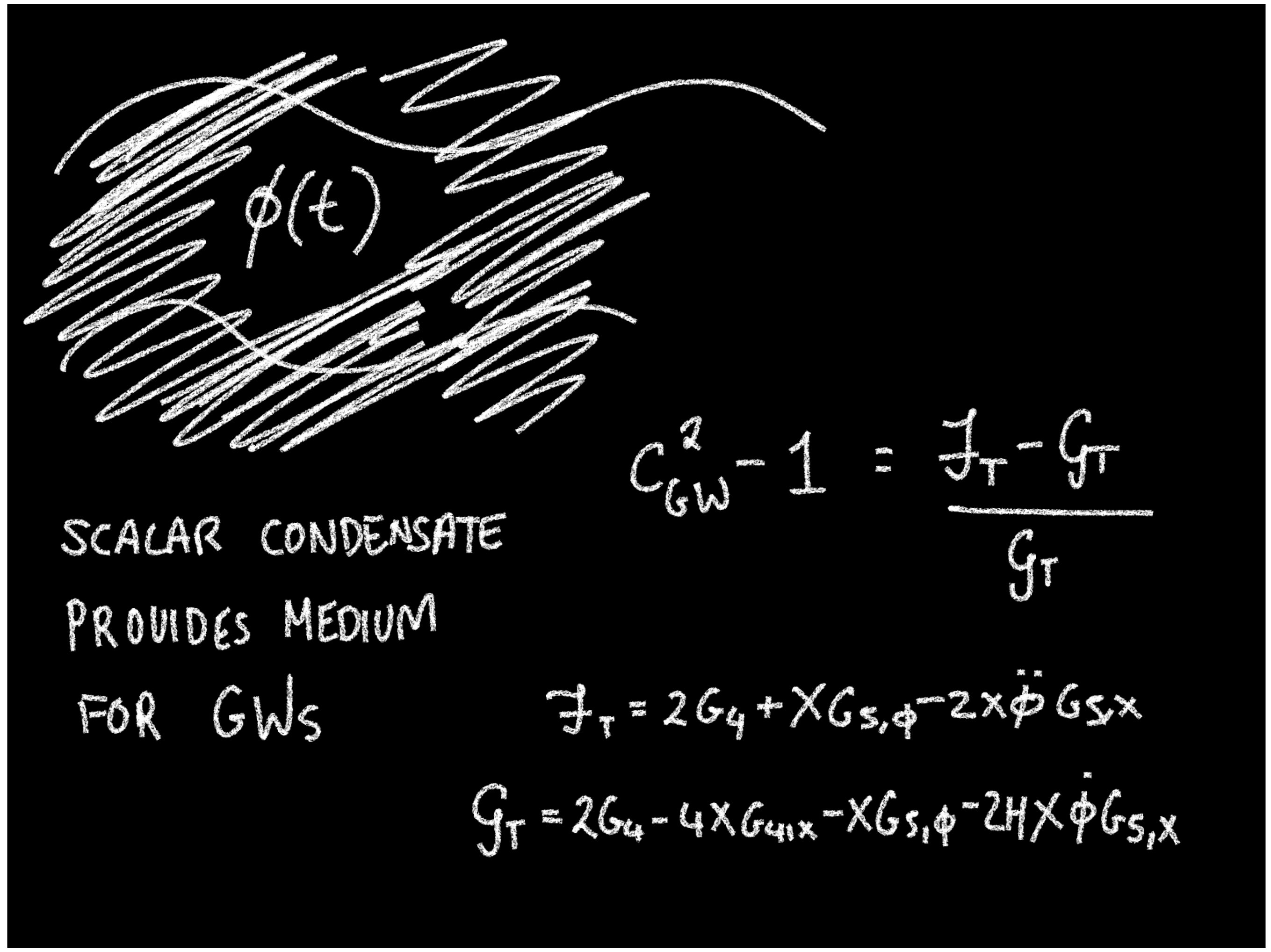

MERGER OF NEUTRON STARS
• 1 SOLAR MASS EACH
• Z ~ 0.01
• λ_GW ~ 1000 km


speed of GW
$c_{GW} = c_\gamma \left(1 + O\left(10^{-15}\right)\right)$
Speed of EM wave



ONE NIGHT A YEAR,
ALL CRIME IS LEGAL.
THE PURGE
SURVIVE THE NIGHT JUNE 7
$\mathcal{L}_{\text{Horndeski}} = \sqrt{-g}\,\{ G_2(\phi, X) + G_3(\phi, X)\Box\phi$
$+ G_4(\phi, X) R - 2 G_{4,X} \mathcal{E}_2$
$+ G_5(\phi, X) G_{\mu\nu} \nabla^\mu\phi \nabla^\nu\phi + \underline{G_{5,X}}\, \mathcal{E}_3 \}$


MODIFIED GRAVITY
JOINED
The Uncool Club


$\phi(t)$
SCALAR CONDENSATE
PROVIDES MEDIUM
FOR GWs
$c_{GW}^2 - 1 = \frac{\mathcal{F}_T - \mathcal{G}_T}{\mathcal{G}_T}$
$\mathcal{F}_T = 2G_4 + XG_{5,\phi} - 2X\ddot{\phi}G_{5,X}$
$\mathcal{G}_T = 2G_4 - 4XG_{4,X} - XG_{5,\phi} - 2HX\dot{\phi}G_{5,X}$

Creminelli & Vernizzi, Baker et al,
Ezquiaga & Zumalacárregui, Sakstein & Jain (2017)

$$c_{GW}^2 - 1 = \frac{\mathcal{F}_T - \mathcal{G}_T}{\mathcal{G}_T} \qquad \begin{aligned} \mathcal{F}_T &= 2G_4 + XG_{5,\phi} - 2X\ddot{\phi}G_{5,X} \\ \mathcal{G}_T &= 2G_4 - 4XG_{4,X} - XG_{5,\phi} - 2HX\dot{\phi}G_{5,X} \end{aligned}$$

REQUIRE $c_{GW}^2 - 1 = 0 \quad \forall\ \phi, \dot{\phi}, \ddot{\phi}, H, \dot{H}$

$$\Rightarrow \quad 4XG_{4,X} + 2XG_{5,\phi} + 2X(H\dot{\phi} - \ddot{\phi})G_{5,X} = 0$$

$$4XG_{4,X} + 2XG_{5,\phi} + 2X(H\dot{\phi} - \ddot{\phi})G_{5,X} = 0$$

$$G_{5,X} = 0 \qquad 4XG_{4,X} + 2XG_{5,\phi} = 0$$

$$\Rightarrow \quad G_5 = V_5(\phi) \, , \quad G_4 = V_4(\phi) - \frac{1}{2} X V_5(\phi)$$

From Ezquiga & Zumalacarregui (2017)

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

WRITE $\mathcal{L}_{Horndeski} = \sqrt{-g}\;\frac{M_p^2}{2}\left(R - \frac{1}{2}(\partial\phi)^2 + \mathcal{L}_{int}\right)$

WITH HORNDESKI INTERACTIONS

$$\text{eg } \mathcal{L}_{int} \supset +\lambda \frac{X\Box\phi}{M^3} + \mu\frac{XR}{M^4} + \frac{\nu}{M^6}\left(X^2R - 4X(\partial\partial\phi)^2\right) + \dots$$

COULD TAKE $M \gg H_0 \Rightarrow$ **NOT** DARK ENERGY

ANY QUESTIONS?

CAN WE ESCAPE
THE PURGE?

DE RHAM & MELVILLE (2018)

$$\mathcal{L}_{\text{Horndeski}} = \sqrt{-g}\,\frac{M_P^2}{2}\left(R - \frac{1}{2}(\partial\phi)^2 + \mathcal{L}_{int}\right)$$

WITH HORNDESKI INTERACTIONS

$$\text{eg } \mathcal{L}_{int} \supset +\lambda\,\frac{X\Box\phi}{H_0^3}$$

$$+\mu\frac{XR}{H_0^4} + \frac{\nu}{H_0^6}\left(X^2R - 4X(\partial\partial\phi)^2\right) + \ldots$$

$$\phi \to \phi / M_p$$

$$\mathcal{L}_{\text{Horndeski}} = \sqrt{-g}\ \frac{M_p^2}{2} R - \frac{1}{2}(\partial\phi)^2 + \mathcal{L}_{int}$$

WITH HORNDESKI INTERACTIONS

$$\text{eg } \mathcal{L}_{int} \supset + \lambda \frac{X \Box \phi}{M_p H_0^3}$$

$$+ \mu \frac{X R}{M_p^2 H_0^4} + \frac{\nu}{M_p^2 H_0^6}\left(X^2 R - 4X(\partial\partial\phi)^2 \right) + \ldots$$

$$\frac{1}{\left(M_p H_0^2\right)^{1/3}} \sim 1000\,\text{km} \sim \lambda_{GW}$$

DYNAMICAL LOOPHOLES

A.P WITH COPELAND, KOPP, SAFFIN & SKORDIS (2018)

SCALAR E.O.M. VANISHES IDENTICALLY $\mathcal{E}_\phi = \frac{\delta S}{\delta \phi} = 0$

FIND THEORIES SUCH THAT $\mathcal{E}_\phi = 0 \Rightarrow c_{GW} = 1$

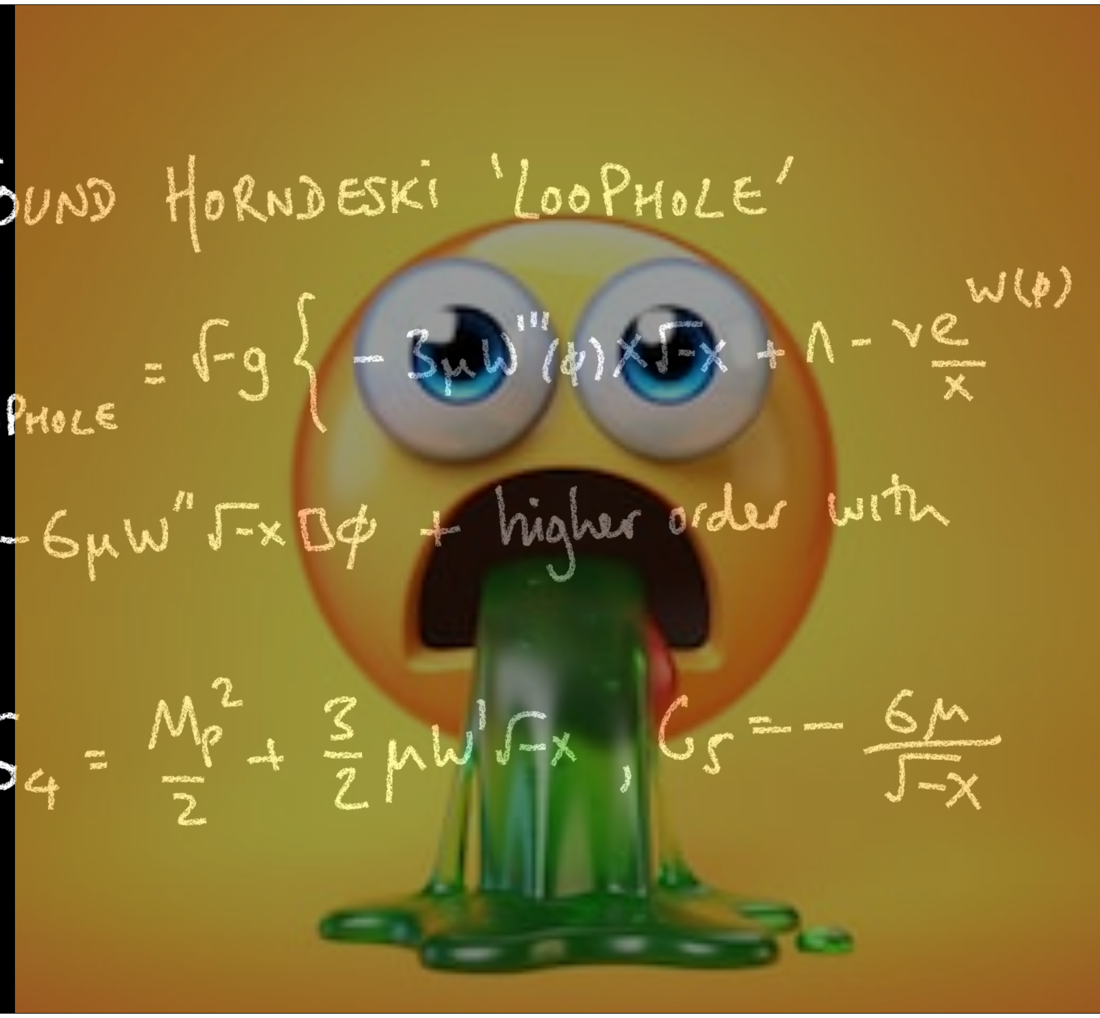
eg $\quad c_{GW}^2 - 1 \propto \mathcal{E}_\phi$

$$4XG_{4,X} + 2XG_{5,\phi} + 2X(H\dot{\phi} - \ddot{\phi})G_{5,X} = 0$$

Now $\mathcal{E}_\phi = A(\phi, \dot{\phi}, H, \dot{H})\,\ddot{\phi} + B(\phi, \dot{\phi}, H, \dot{H})$

USE $\mathcal{E}_\phi = 0$ TO ELIMINATE $\ddot{\phi}$

FOUND HORNDESKI 'LOOPHOLE'



$$\mathcal{L}_{LOOPHOLE} = \sqrt{-g}\Big\{ -3\mu W'''(\phi) X\sqrt{-X} + \Lambda - v\frac{e^{W(\phi)}}{X}$$

$$-6\mu W''\sqrt{-X}\,\Box\phi + \text{higher order with}$$

$$G_4 = \frac{M_p^2}{2} + \frac{3}{2}\mu W'\sqrt{-X}\,, \quad G_5 = -\frac{6\mu}{\sqrt{-X}}$$

$$c_{GW}^2 - 1 \propto \varepsilon_\phi$$

ANY QUESTIONS?

CLOSING THE

LOOPHOLE.

A.P WITH BORDIN & COPELAND (2020)

- EXTEND ANALYSIS TO INCLUDE BEYOND HORNDESKI & DHOST
- INCLUDE LINEAR PERTURBATIONS
- USE $\mathcal{E}_\phi = 0$ AND $\delta\phi = 0$

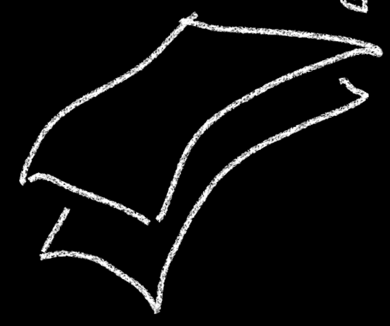
EFFECTIVE THEORY OF DARK ENERGY

Cheung et al (2007) Gubitosi et al (2013)

THEORY OF PERTURBATIONS ABOUT

$$\phi = \phi(t) \qquad ds^2 = -dt^2 + a^2(t)\, d\underline{x}^2$$

In general we have $\phi = \phi(x,t)$, $g_{\mu\nu}$



← constant ϕ slices define a preferred foliation of spacetime

Let $\phi = t$

most general action to preserve this foliation is built from $h_{\mu\nu}$, $K_{\mu\nu}$, g^{00}, D_μ

$$S_{EFT} = \int d^4x \sqrt{-g} \Big\{ \frac{M^2}{2} f(t) R(g) - \Lambda(t) - c(t) g^{00}$$

$$+ m_2^2(t) (\delta g^{00})^2 - \frac{m_3^2(t)}{2} \delta K \, \delta g^{00} - m_4^2(t) \delta K_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R(h)$$

$$- \frac{m_5^2(t)}{2} (\delta g^{00})^2 \delta K_2 - \frac{m_6(t)}{3} \delta K_3 - \tilde{m}_6 \delta g^{00} \delta G_2$$

$$+ \cdots$$

$$g^{00} = -1 + \delta g^{00}, \quad \delta K^\mu_\nu = K^\mu_\nu - H h^\mu_\nu$$

$$\delta K_2 \sim (\delta K)^2, \quad \delta K_3 \sim (\delta K)^3, \quad \delta G_2 \sim R(h) \delta K$$

$$S_{EFT} = \int d^4x \sqrt{-g} \left\{ \frac{M^2}{2} f(t) R(g) - \Lambda(t) - c(t) g^{00} + \dots \right\}$$

background field eqns

$$3H^2 M^2 f - \Lambda - c = \rho_m \qquad g^{00} \text{ variation}$$

$$6Hc + \dot{c} + \dot{\Lambda} - 3M^2 \dot{f} \left(2H^2 + \dot{H}\right) = 0 \quad \text{Bianchi}$$

$$S_{EFT} = \int d^4x \sqrt{-g} \Big\{ \frac{M^2}{2} f(t) R(g) - \Lambda(t) - c(t) g^{00}$$

$$+ m_2^2(t)(\delta g^{00})^2 - \frac{m_3^2(t)}{2} \delta K \delta g^{00} - m_4^2(t) \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R(h)$$

$$- \frac{m_5^2(t)}{2} (\delta g^{00})^2 \delta K_2 - \frac{m_6(t)}{3} \delta \mathcal{K}_3 - \tilde{m}_6 \delta g^{00} \delta \mathcal{G}_2$$

$$+ \cdots$$

$O(2)$ $O(3)$

[but only those that affect GWs]

Stuckelberg ...

$$t \to t + \pi(x,t)$$

$$f \to f + \dot{f}\pi + \frac{\ddot{f}}{2}\pi^2 + \cdots$$

... Then use Newtonian gauge

$$ds^2 = -(1-2\Phi) + a^2\left[(1-2\Psi)\delta_{ij} + \gamma_{ij}\right]dx^i dx^j$$

GW ↗

$$S_{EFT} \sim S_2[\pi, \Phi, \Psi] \leftarrow \text{quadratic in scalars } \pi, \Phi, \Psi$$

$$+ S_2^{GW}[\gamma] \leftarrow \text{quadratic in tensor } \gamma_{ij}$$

$$+ S_2^{GW}[\text{scalars}, \gamma] \leftarrow \text{quadratic in tensor, linear in scalars}$$

$$+ \ldots$$

From this we obtain

GW propagation eqn

$$\mathcal{O}\,\gamma_{ij} = 0$$

Operator $\mathcal{O}$ depends linearly on Scalars

Field eqns up to linear order

$$\mathcal{E}_\pi : \frac{\delta S}{\delta \pi} = 0\,, \quad \mathcal{E}_\psi = \frac{\delta S}{\delta \psi} = 0\,, \quad \mathcal{E}_\phi = \frac{\delta S}{\delta \phi} = \delta \rho$$

(↑ $\delta p = 0$)

Compare propagation of γ_{ij} in general to GR

Require

$$\bigcirc = \bigcirc_{GR} + \text{terms that go like } \varepsilon_\pi \text{ or } \varepsilon_\psi$$

HOMOGENEOUS PERTS

→ RECOVER LOOPHOLE + GENERALISATIONS

INHOMOGENEOUS PERTS $\left(\lambda_{GW} \ll r_{gal} \ll \frac{1}{H_0} \right)$

→

From Ezquiga & Zumalacarregui (2017)

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	Viable after GW170817	Non-viable after GW170817

ANY QUESTIONS?

What now for Dark Energy?

WHAT'S LEFT AFTER THE PURGE?

- CHAMELEONS → NOT DARK ENERGY
- KGB
- BORING QUINTESSENCE
- Λ


BORING
QUINTESSENCE
Λ

THE FUTURE.

OBSERVATIONS → GWS NARROWING PARAMETER SPACE OF NEW THEORIES

THEORY → ESTABLISH CONSISTENCY OF DARK ENERGY IN SUGRA AND STRINGS

THANKS

ありがとう