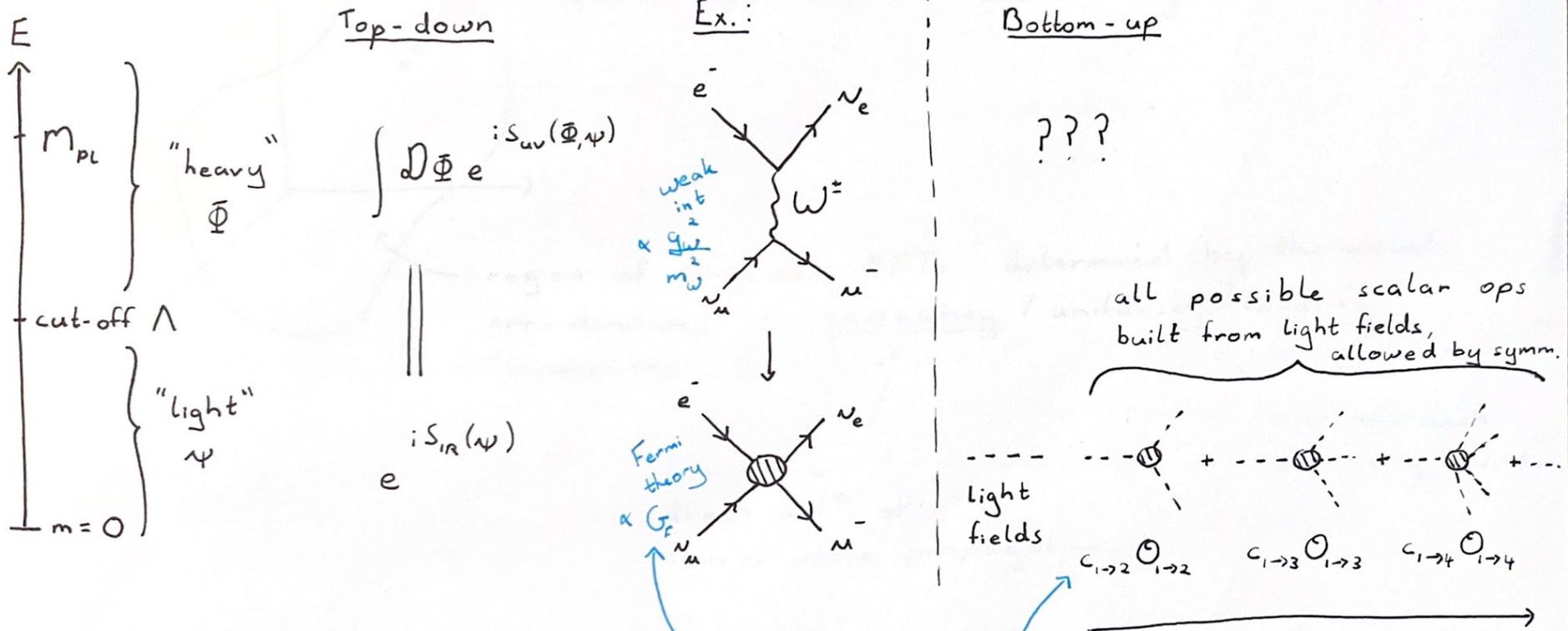


# Causality in the effective field theory of gravity

Based on arXiv:2112.05031 w/ Claudia deRham, Andrew Tolley + Calvin Chen.

① What is EFT?



Ex.: EFT of gravity

$$\mathcal{L}_{IR}(g) = R + \Lambda^2 \sum_{\substack{m \geq 0 \\ n \geq 2}} c_{mn} \left( \frac{\nabla}{\Lambda} \right)^m \left( \frac{R; e}{\Lambda^2} \right)^n$$

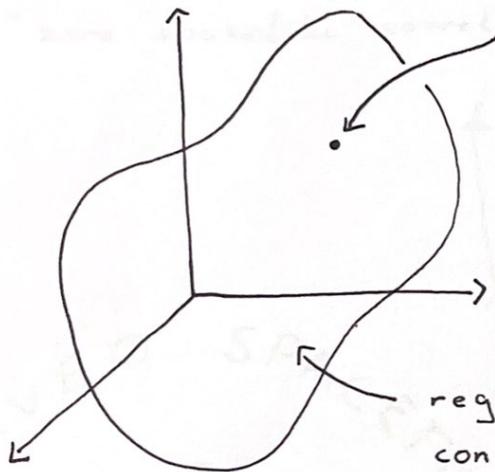
unknown "Wilson" coeffs. characterise EFT

suppressed by higher powers of  $\left( \frac{\text{field energy}}{\text{cut-off}} \right)$

→ first few terms most important when expansion is under control

Q: what are the Wilson coeffs  $c_{mn}$ ?

$c_{mn}$



exact values can only be fixed by knowing the precise UV-completion and/or by experiment

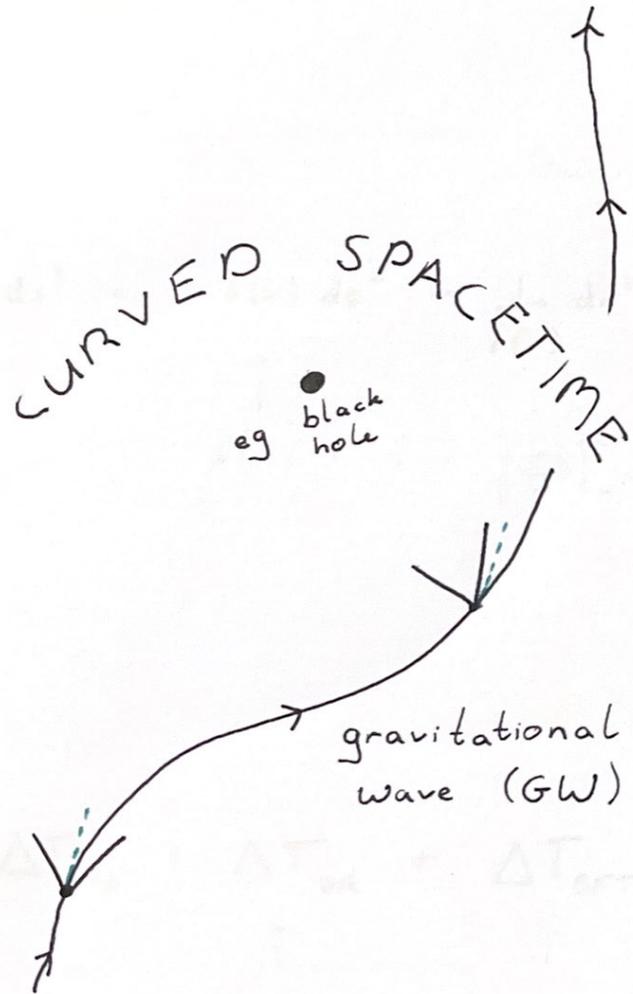
region of physical EFTs determined by theoretical considerations - causality / unitarity / locality / assumptions

this work:  
direct def<sup>n</sup> of  
causal wave propagation

one approach:  
positivity bounds

## ② Causality

= no propagation outside lightcone? ✓  
"zero spacelike correlator"?



In GR speed of GW = speed of light  
= speed of any (minimally coupled)  
massless particle  
= 1

In EFT speed of GW is local  
can be different to other  
massless particles  
+ metric is subject to field  
redefinitions

⇒ need def<sup>n</sup> based on observable  
time delay (on asymptotically flat spacetimes).

$\Delta T$  = diff in travel time from Mink.  
> 0 → delay  
< 0 → advance

Ex.: black hole D=5 - dim

$$\text{Vacuum} \Rightarrow \mathcal{L}_{IR} = R + \frac{c_{GB}}{\Lambda^2} R_{GB}^2 + \mathcal{O}\left(\frac{R^3}{\Lambda^4}\right)$$

↑

$$\text{Gauss-Bonnet } R_{GB}^2 = R_{\text{maxp}}^2 - 4R_{\text{GB}}^2 + R^2$$

$$ds^2 = -f(r) dt^2 + \frac{1}{f(r)} dr^2 + r^2 d\Omega_{0-2}^2$$

↑

$$f(r) = 1 - \left(\frac{r_g}{r}\right)^2 + 4c_{GB} M \left(\frac{r_g}{r}\right)^6 + \mathcal{O}(M^2)$$

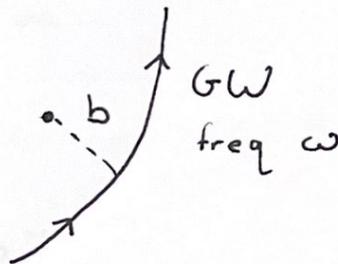
↑

$$M = \frac{1}{r_g^2 \Lambda^2} \sim \frac{R}{\Lambda^2} \quad \text{parameter controlling expansion of } \mathcal{L}_{IR}$$

$$\Delta T_{\text{net}} = \Delta T_{\text{GR}} + \Delta T_{\text{EFT}}$$

↑  
due to  
geometry

↑  
 $\propto c_{GB}$



$$\Delta T_{\text{net}} = \Delta T_{\text{GR}} \left( 1 \overset{+}{\underset{-}{\circlearrowleft}} \# c_{\text{GB}} M \left( \frac{r_g}{b} \right)^2 \right)$$

↗ 3 modes  
↘ 2 modes

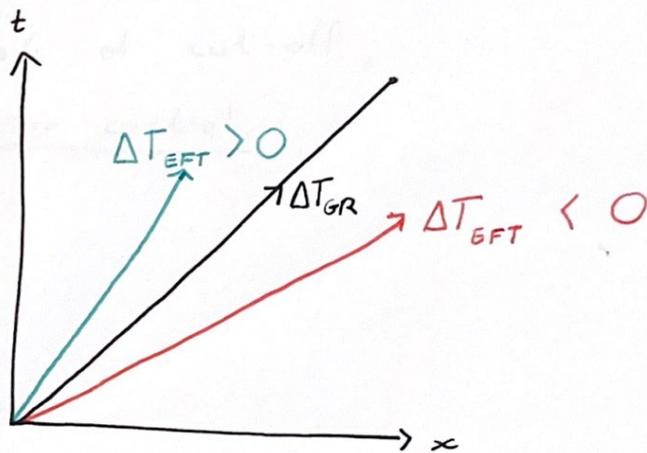
Asymptotic causality:

$$\Delta T_{\text{net}} \gg -\omega^{-1}$$

IR causality:

$$\Delta T_{\text{EFT}} \gg -\omega^{-1}$$

- def<sup>n</sup> of causality relative to background spacetime
- all massless particles experience  $\Delta T_{\text{GR}}$



Uncertainty principle:  $|\omega| |\Delta T| \gg 1$

$\Rightarrow \Delta T$  is unresolvable if  $|\Delta T| < \omega^{-1}$

### ③ Regime of validity

Sufficient condition for causality:  $|\Delta T_{\text{EFT}}| \ll \omega^{-1}$

Why should  $\Delta T_{\text{EFT}} \sim c_{\text{GB}} M \left(\frac{r_g}{b}\right)^4 b$  be bounded?

Can't probe EFT "too closely" b/c of cut-off, need EFT expansion to be under control:

$$\frac{R_{\text{GB}}^2}{\Lambda^2} \gg \frac{R^3}{\Lambda^4}, \frac{R^4}{\Lambda^6}, \dots$$

In general:

$$\nabla^m R_{ie}^n \ll \Lambda^{m+2n}$$

and

$$\delta(\nabla^m R_{ie}^n) \ll \Lambda^{m+2n}$$

↓  
curvature not too large

$$r_g \ll \Lambda b^2$$

↓  
GW freq not too large

$$\omega \ll \Lambda^2 b.$$

$$\boxed{\omega |\Delta T_{\text{EFT}}| \ll 1}$$

## Conclusions

Causality means : within the EFT regime of validity

$$\Delta T^{\text{EFT}} \gtrsim -\omega^{-1}$$

and can be used to constrain Wilson coefficients.