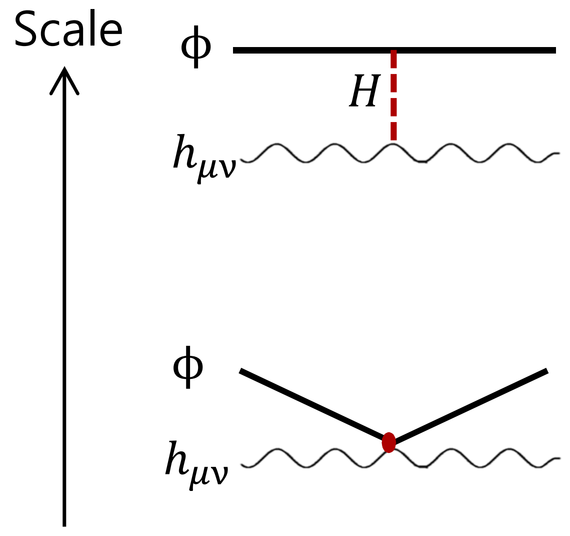
PASCOS 06 Jun 2018

Speed Limits from Gravitational Waves

Scott Melville



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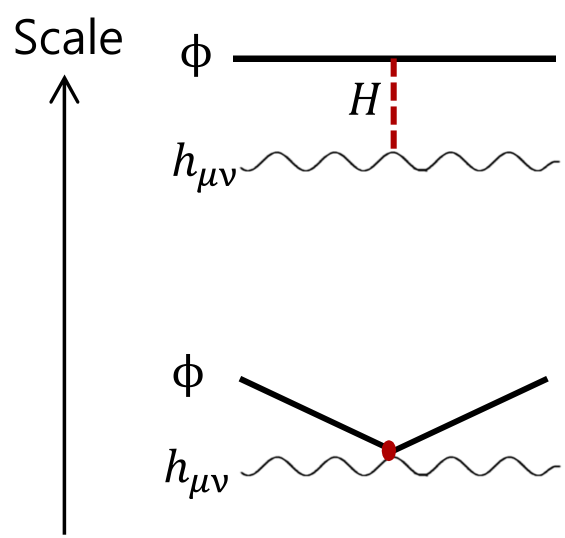

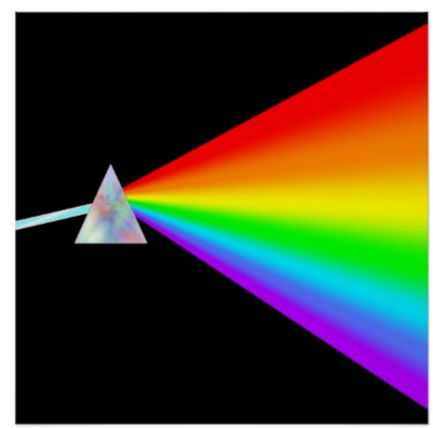

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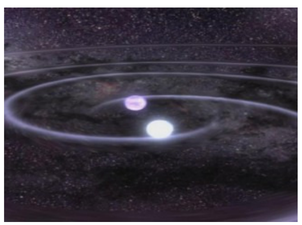

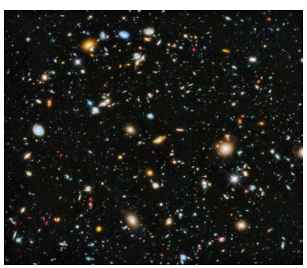

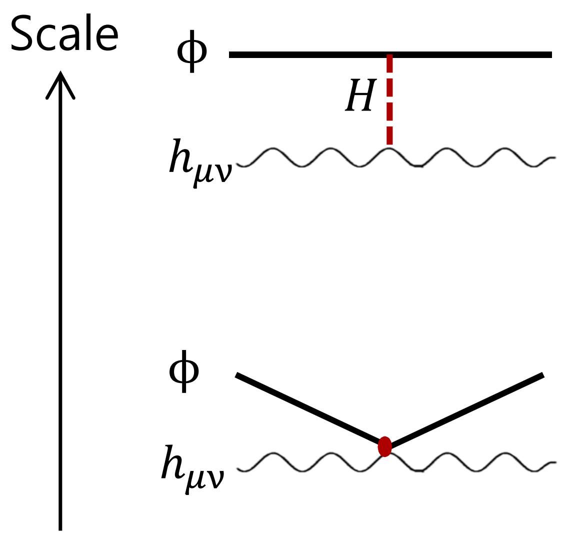

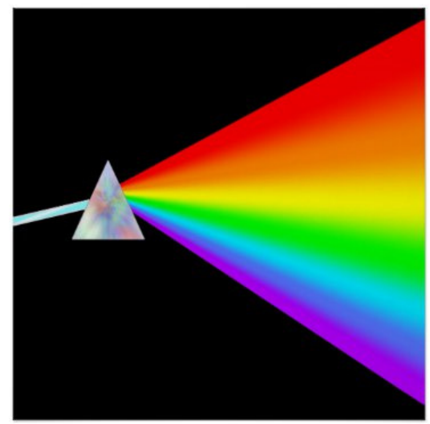

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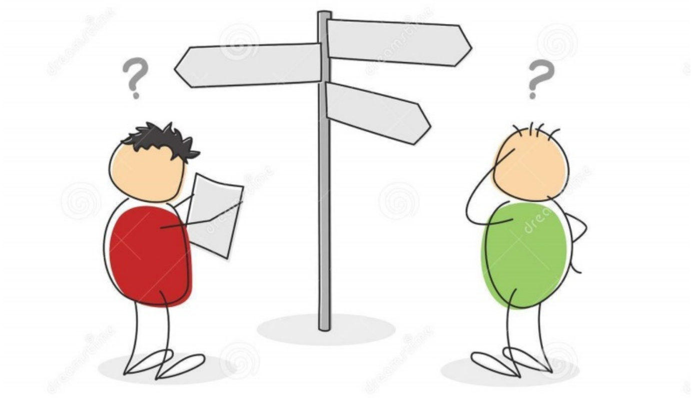
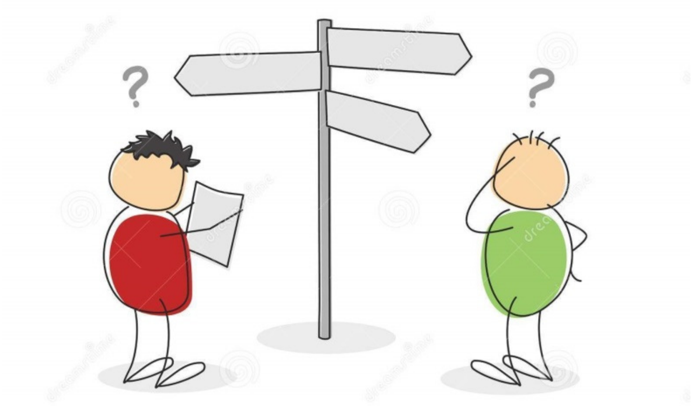
- Scale Dependence
- GW170817 Constraints
- The Future



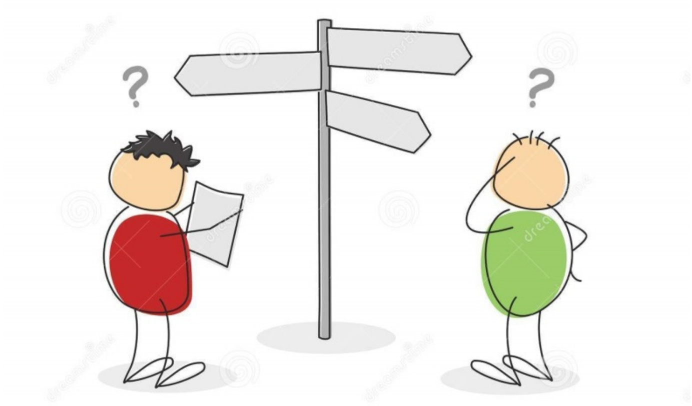
- Scale Dependence UV physics causes IR running
- GW170817 Constraints
- The Future



- Scale Dependence
- GW170817 Constraints
- The Future

UV physics causes IR running

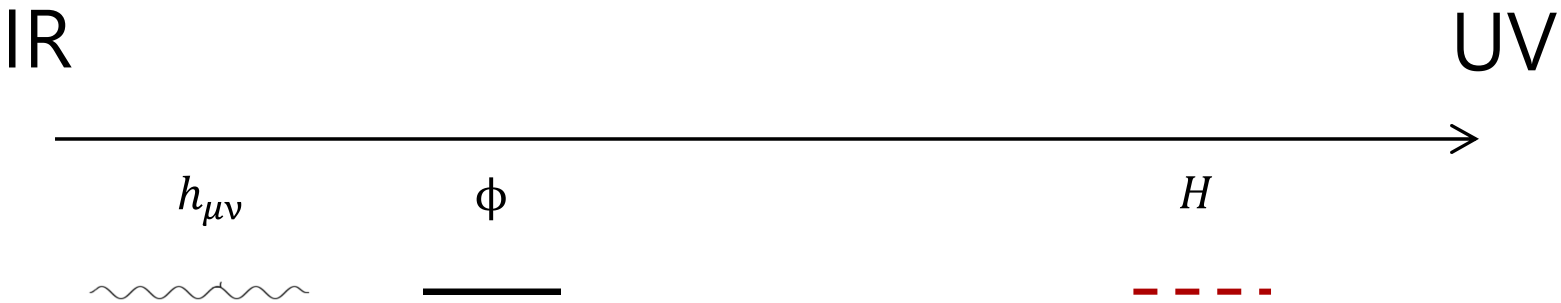
$1 - c_T^2$ depends on scale!

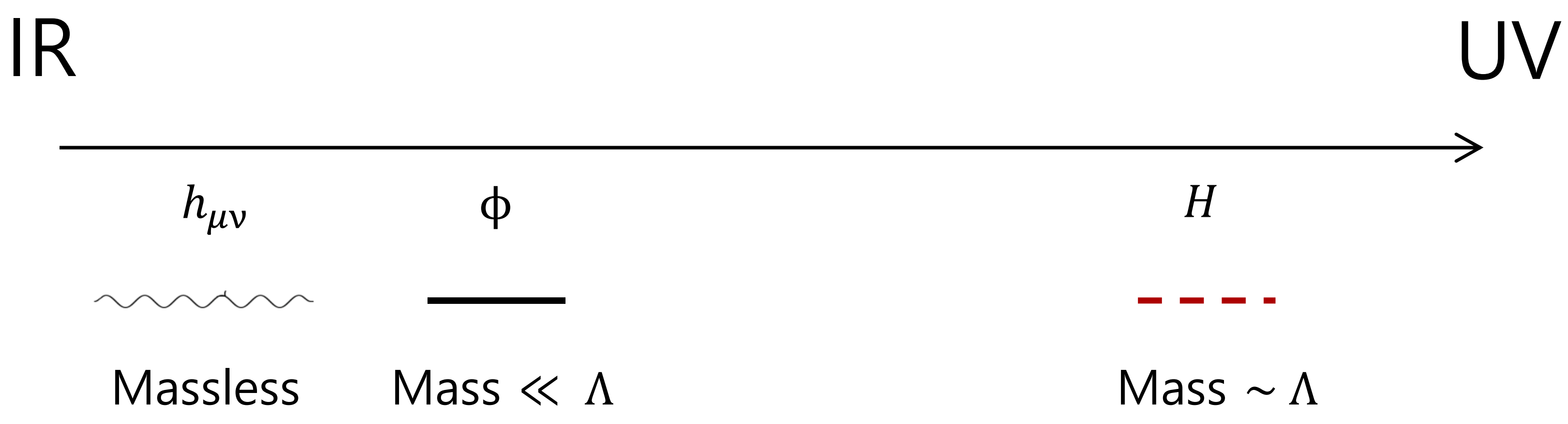


- Scale Dependence — UV physics causes IR running
- GW170817 Constraints — $1 - c_T^2$ depends on scale!
- The Future — Dark energy after GW170817

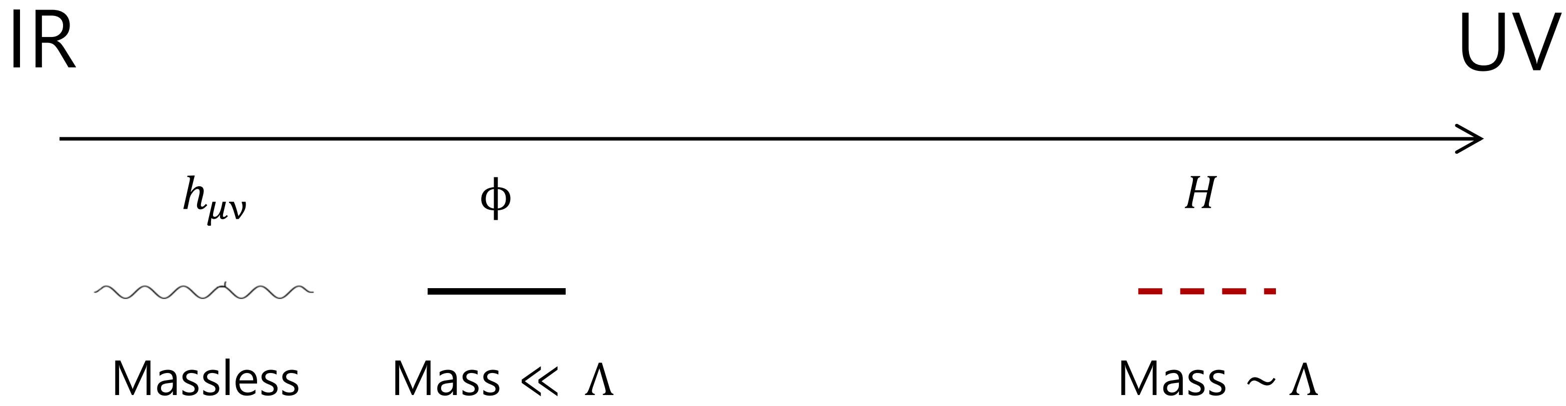
SCALE

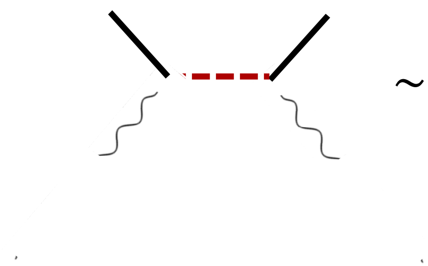
Dependence


IR
UV
$h_{\mu\nu}$
ϕ
H



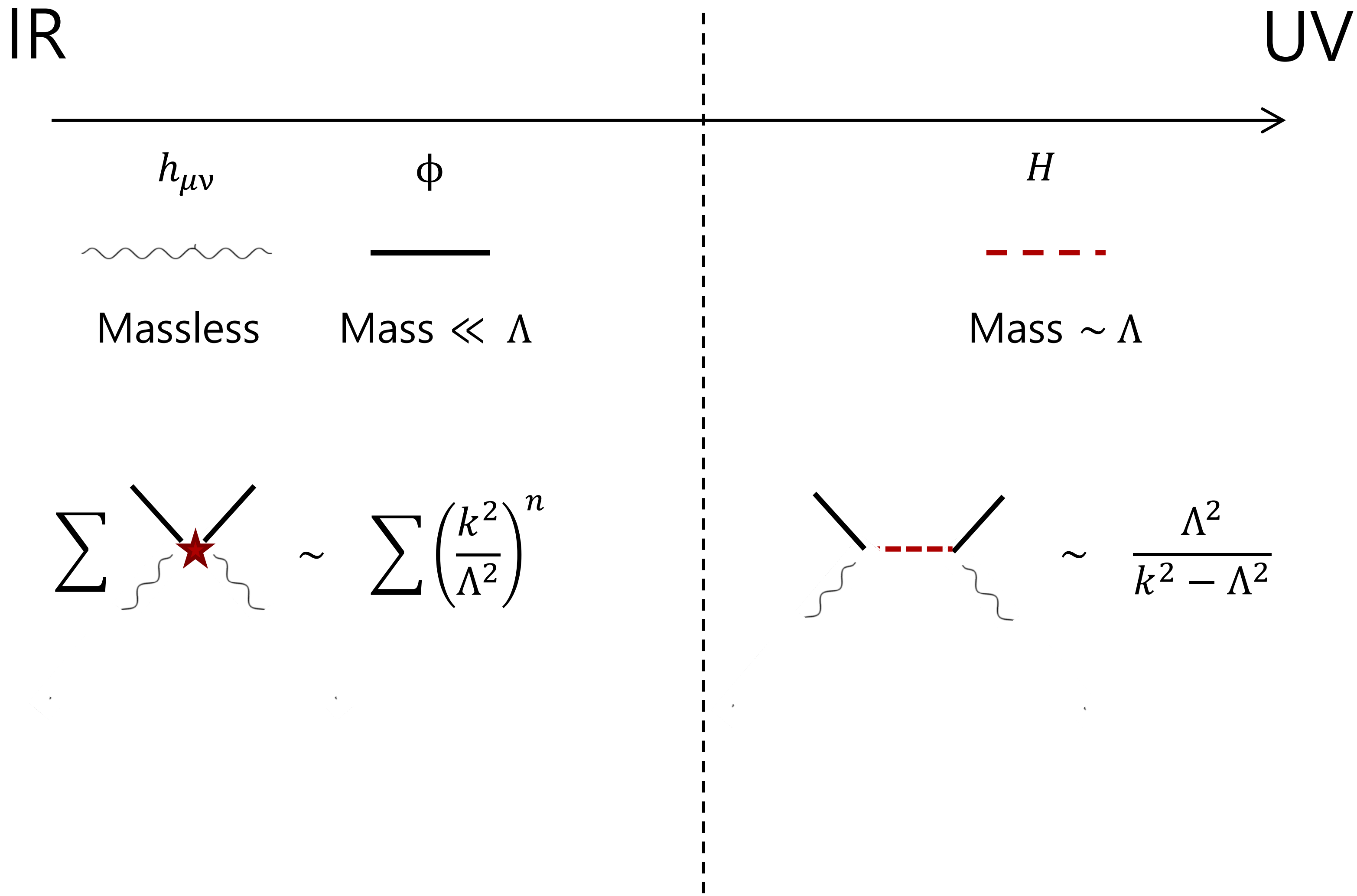
Scale Dependence

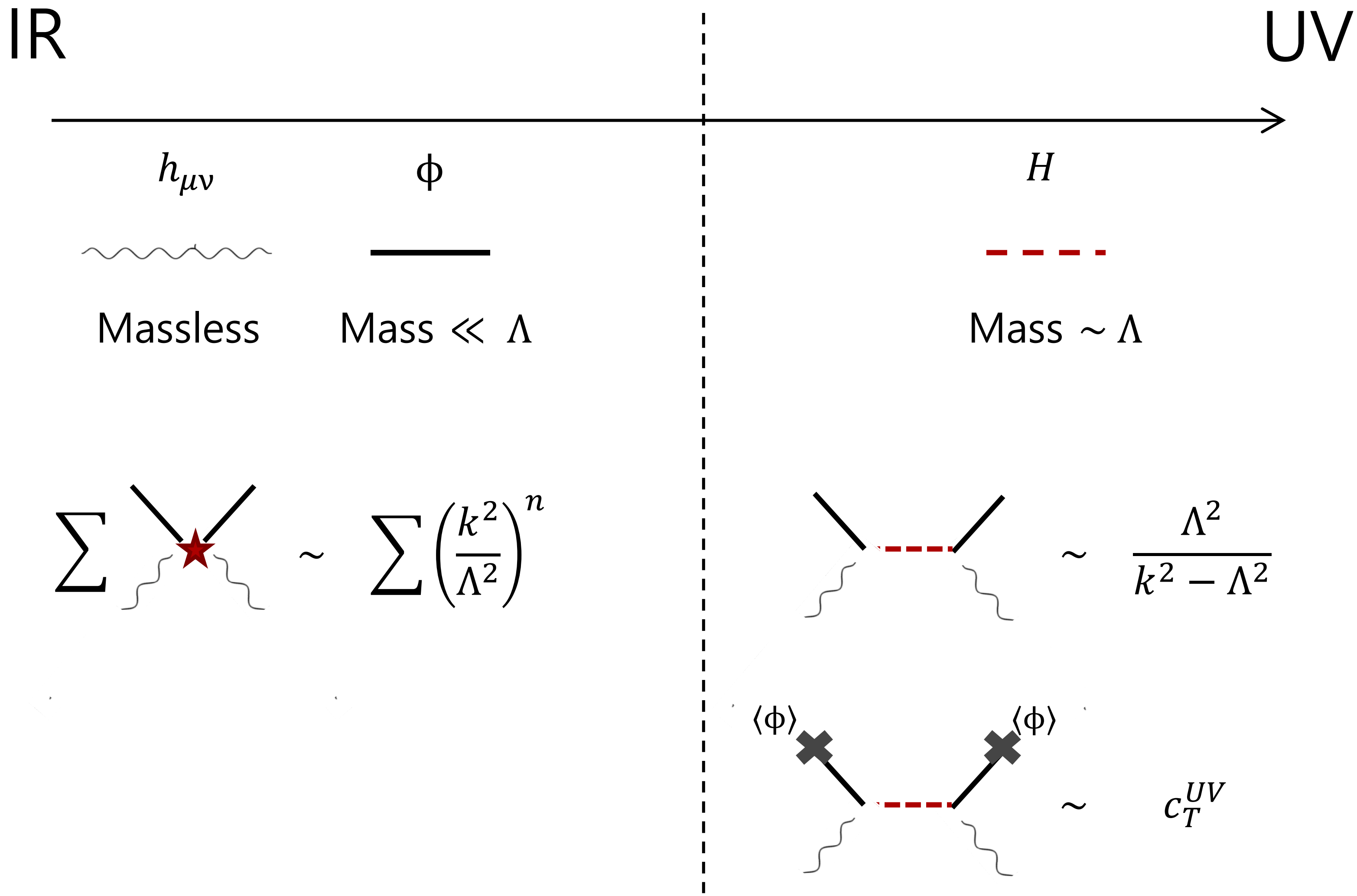




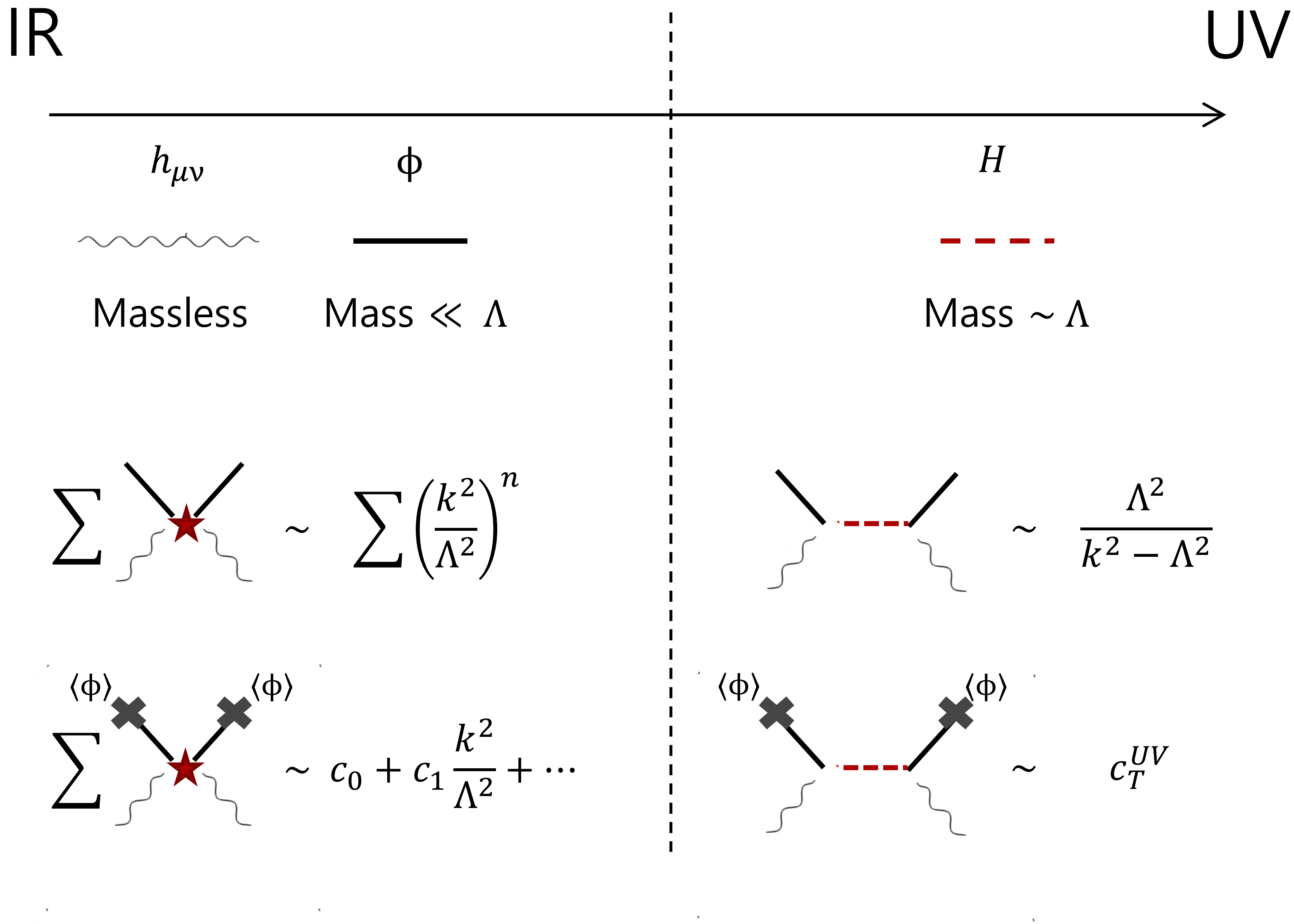
$$\sim \frac{\Lambda^2}{k^2 - \Lambda^2}$$

Scale Dependence

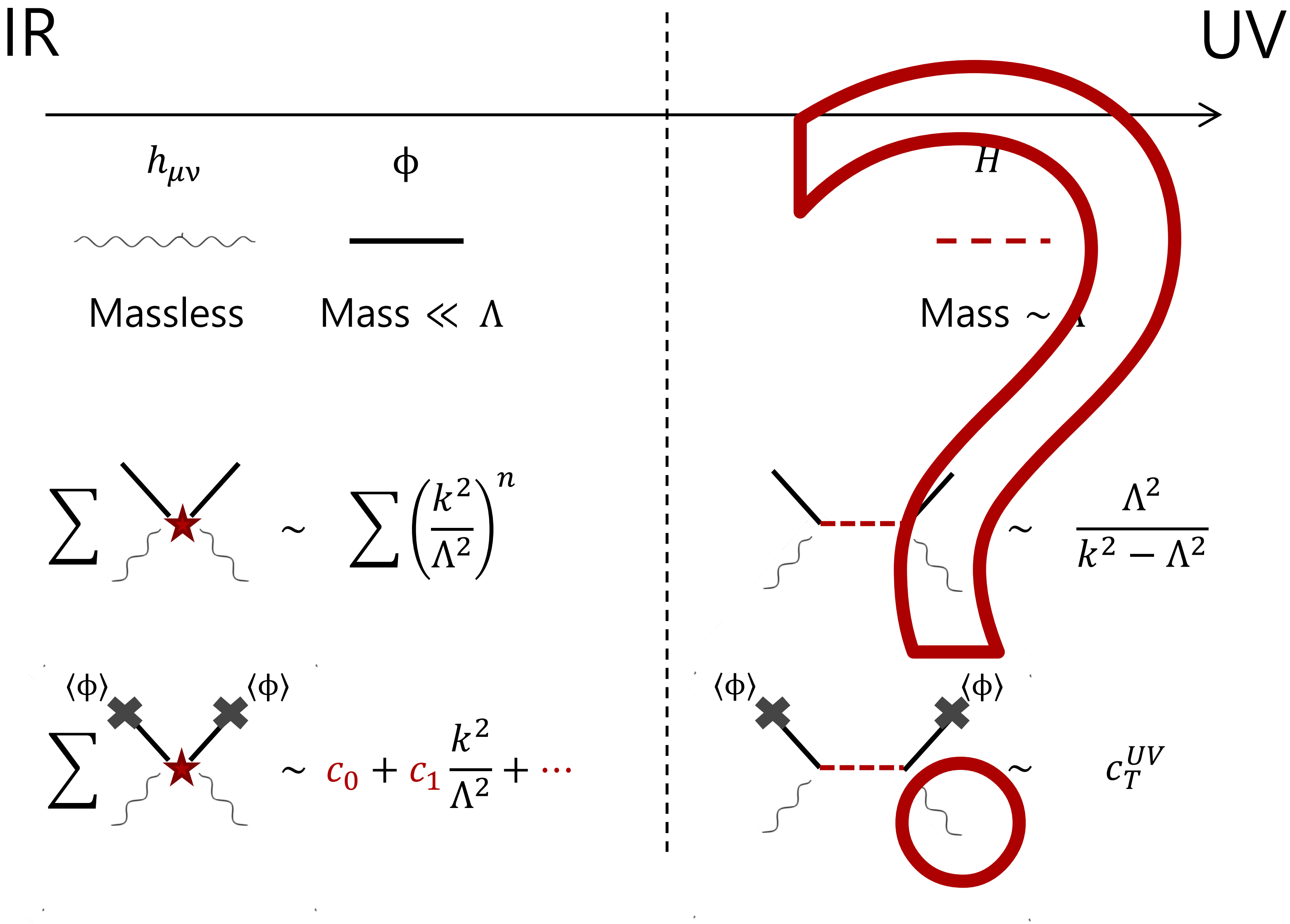

IR
UV
$h_{\mu\nu}$
ϕ
H
Massless
Mass $\ll \Lambda$
Mass $\sim \Lambda$
$\sim \sum \left(\frac{k^2}{\Lambda^2}\right)^n$
$\sim \frac{\Lambda^2}{k^2 - \Lambda^2}$



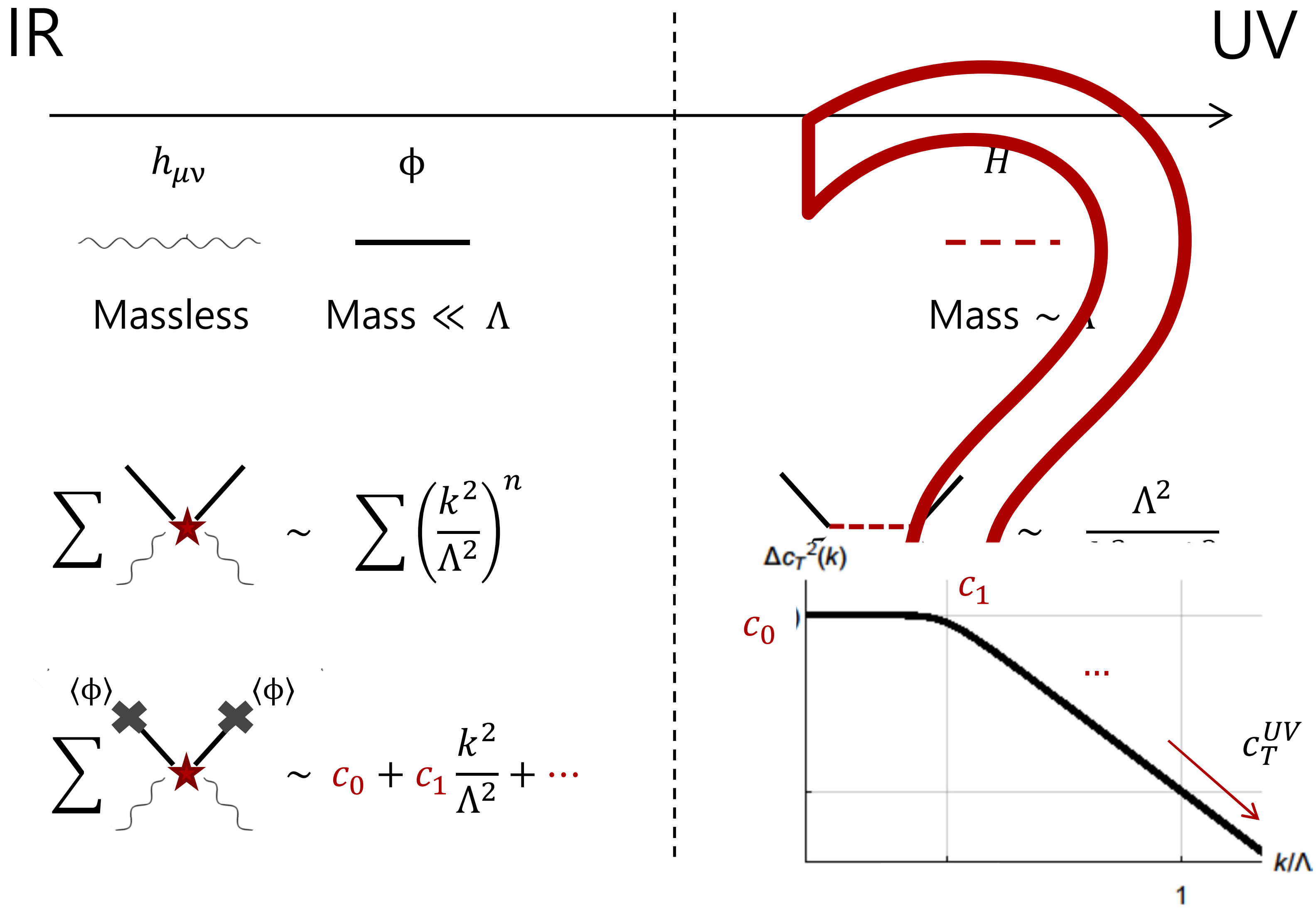
Scale Dependence



IR
UV
$h_{\mu\nu}$
ϕ
H
Massless
Mass $\ll \Lambda$
Mass $\sim \Lambda$
$\sum$ $\sim \sum\left(\frac{k^2}{\Lambda^2}\right)^n$
$\sim \frac{\Lambda^2}{k^2-\Lambda^2}$
$\langle\phi\rangle$
$\langle\phi\rangle$
$\sum$ $\sim c_0 + c_1\frac{k^2}{\Lambda^2}+\cdots$
$\langle\phi\rangle$
$\langle\phi\rangle$
$\sim c_T^{UV}$



Scale Dependence


IR
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$h_{\mu\nu}$
ϕ
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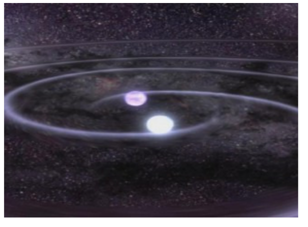
Massless
Mass $\ll \Lambda$
Mass $\sim \Lambda$
$\sum \sim \sum \left(\frac{k^2}{\Lambda^2}\right)^n$
Λ^2
$\langle\phi\rangle$
$\langle\phi\rangle$
$\sum \sim c_0 + c_1 \frac{k^2}{\Lambda^2} + \cdots$
$\Delta c_T^2(k)$
c_1
c_0
...
c_T^{UV}
k/Λ
1

GW170817

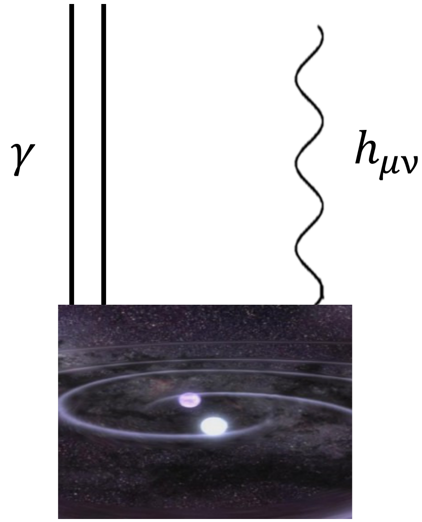
Multi-messenger Signal

Merger



Multi-messenger Signal

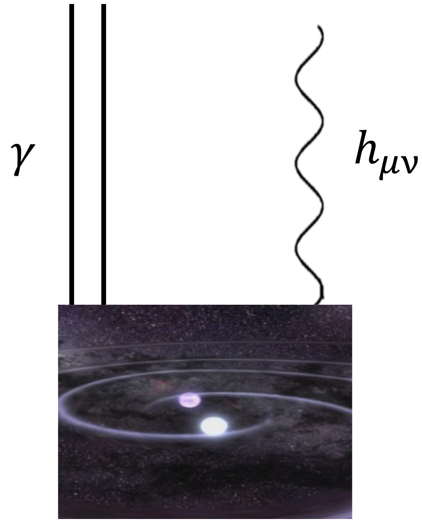
$$|1 - c_T^2|$$



Merger

Multi-messenger Signal

$$\Delta c_T^2 \quad = \; |1 \; - \; c_T^2| \qquad < 10^{-15}$$



Merger

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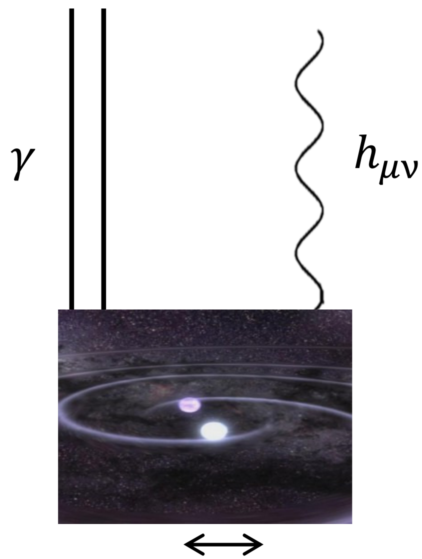
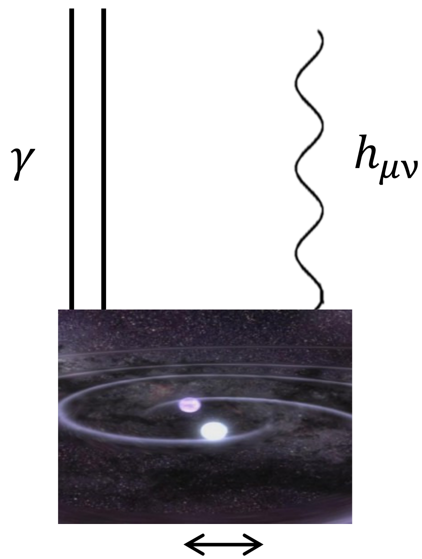


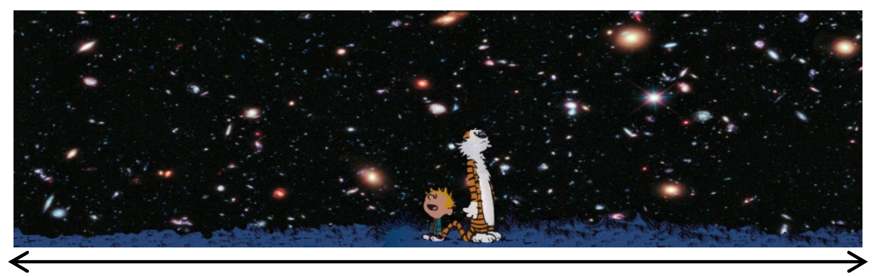
Merger $\approx$ 50Hz

Multi-messenger Signal

$$\Delta c_T^2 = |1 - c_T^2| < 10^{-15}$$



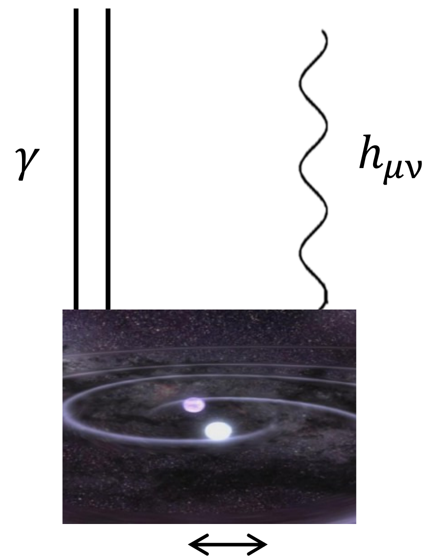
Merger $\approx 50\text{Hz}$



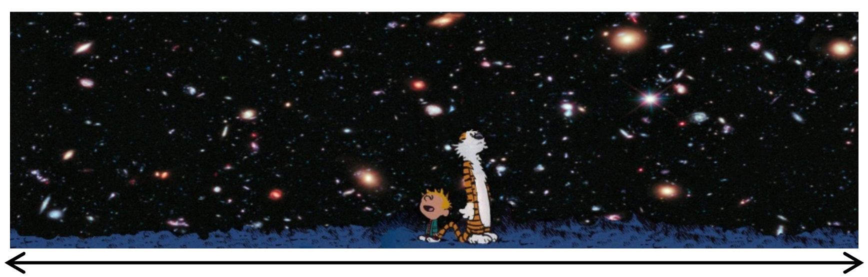
Cosmology 10^{-18} Hz

Multi-messenger Signal

$$\Delta c_T^2(50\text{Hz}) = |1 - c_T^2(50\text{Hz})| < 10^{-15}$$



Merger ≈ 50Hz



Cosmology 10^{-18} Hz

Dark Energy

Scales

10^{41} Hz	M_P	Graviton Sector	$M_P^2 R$
10^{-18} Hz	H_0	Scale of interest	$\langle R \rangle \approx 6H_0^2$

Dark Energy

Scales

10^{41} Hz	M_P	Graviton Sector	$M_P^2 R$
	$(M_P H_0^2)^{1/3} = \Lambda_3$	New Physics	$O_{Gal} = \dfrac{\nabla^2\phi(\nabla\phi)^2}{\Lambda_3^3}$
10^{-18} Hz	H_0	Scale of interest	$\langle R \rangle \approx 6H_0^2$

Dark Energy

Scales

10^{41} Hz	M_P	Graviton Sector	$M_P^2 R$
	$(M_P H_0)^{1/2} = \Lambda_2$	Graviton Loops	$X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$
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Dark Energy

Scales

Frequency	Scale	Sector	Operator
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10^{11} Hz	$(M_P H_0)^{1/2} = \Lambda_2$	Graviton Loops	$X_{ab} = \dfrac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$
10^{1} Hz	$(M_P H_0^2)^{1/3} = \Lambda_3$	New Physics	$O_{Gal} = \dfrac{\nabla^2 \phi (\nabla \phi)^2}{\Lambda_3^3}$
10^{-18} Hz	H_0	Scale of interest	$\langle R \rangle \approx 6 H_0^2$

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Dark Energy

$M_P^2 R \qquad X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4} \qquad \frac{\nabla_a}{\Lambda_3}$

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Dark Energy

$$M_P^2 R \qquad X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4} \qquad \frac{\nabla_a}{\Lambda_3}$$

Horndeski EFT

$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

Dark Energy

$M_P^2 R$ $X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$ $\frac{\nabla_a}{\Lambda_3}$

Horndeski EFT

$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

$$\Delta c_T^2 (k^2) \approx 2\, c_0$$

Dark Energy

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$$\Delta c_T^2(50\text{Hz}) \;=\; 2 c_0$$

Dark Energy

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Dark Energy

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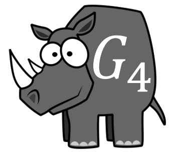
Horndeski EFT



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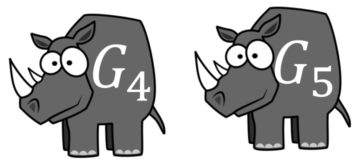
Horndeski EFT



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Dark Energy

$M_P^2 R$ $\quad X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$ $\quad \frac{\nabla_a}{\Lambda_3}$

Horndeski EFT

$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

$$+O\left(\frac{\nabla^2}{\Lambda_3^2}\right)$$

$$\Delta c_T^2(k^2) \approx 2\, c_0$$

$$+O\left(\frac{k^2}{\Lambda_3^2}\right)$$

$$\Delta c_T^2(50\text{Hz}) \;=\; 2c_0 + O(1) \qquad < \; 10^{-15}$$

Dark Energy

$M_P^2 R$ $X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$ $\frac{\nabla_a}{\Lambda_3}$

Horndeski EFT

$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

$$+ \mathcal{O}\left(\frac{\nabla^2}{\Lambda_3^2}\right)$$

$$\Delta c_T^2(k^2) \approx 2\, c_0$$

$$+ \mathcal{O}\left(\frac{k^2}{\Lambda_3^2}\right)$$

$$\Delta c_T^2(50\text{Hz}) \;=\; 2 c_0 + \mathcal{O}(1) \qquad < \; 10^{-15}$$

Dark Energy

$M_P^2 R$ $\quad X_{ab} = \dfrac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$ $\quad \dfrac{\nabla_a}{\Lambda_3}$

Horndeski EFT

$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

$$+ M_P^2 \left[c_2 \frac{\nabla_b \nabla_d}{\Lambda_3^2} R^{abcd} X_{ac} \right]$$

$$\Delta c_T^2(k^2) \approx 2\, c_0$$

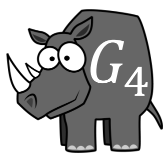
$$+4\, c_0 c_2 \, \frac{k^2}{\Lambda_3^2}$$

$$\Delta c_T^2(50\text{Hz}) \;=\; 2c_0 + 4c_0 c_2 \qquad < \; 10^{-15}$$

Dark Energy

$$M_P^2 R \qquad X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4} \qquad \frac{\nabla_a}{\Lambda_3}$$

Horndeski EFT



$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

$$+ M_P^2 \left[c_2 \frac{\nabla_b \nabla_d}{\Lambda_3^2} R^{abcd} X_{ac} \right]$$

$$+ O\left(\frac{\nabla^4}{\Lambda_3^4} \right)$$

$$\Delta c_T^2(k^2) \approx 2\, c_0$$

$$+4\, c_0 c_2 \,\frac{k^2}{\Lambda_3^2}$$

$$+ O\left(\frac{k^4}{\Lambda_3^4} \right)$$

$$\Delta c_T^2(50\text{Hz}) \;=\; 2c_0 + 4c_0 c_2 + O(1) \qquad < \;\; 10^{-15}$$

Dark Energy

$M_P^2 R \qquad X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4} \qquad \frac{\nabla_a}{\Lambda_3}$

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$$+ \quad \ldots$$

$$\Delta c_T^2(k^2) \approx 2\, c_0$$

$$+4\, c_0 c_2 \frac{k^2}{\Lambda_3^2}$$

$$+ \sum c_n \left(\frac{k^2}{\Lambda_3^2} \right)^n$$

$$\Delta c_T^2(50\text{Hz}) \approx 2 c_0 + 4 c_0 c_2 + \sum^{\infty} c_n < 10^{-15}$$

Dark Energy

$M_P^2 R$ $\qquad X_{ab} = \frac{\nabla_a \phi \nabla_b \phi}{\Lambda_2^4}$ $\qquad \frac{\nabla_a}{\Lambda_3}$

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$$+ \quad \dots$$

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Dark Energy

$$M_P^2 R \qquad X_{ab} = \frac{\nabla_a\phi\nabla_b\phi}{\Lambda_2^4} \qquad \frac{\nabla_a}{\Lambda_3}$$

Horndeski EFT

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$$+ \quad \ldots$$

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Dark Energy

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$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} X_{ab}]$$

$$+ M_P^2 \left[c_2 \frac{\nabla_b \nabla_d}{\Lambda_3^2} R \right.$$

$$+ \quad \dots$$

$$\Delta c_T^2(k^2) \approx 2\, c_0$$

$$c_0 c_2 \frac{k^2}{\Lambda_3^2}$$

$$c_n \left(\frac{k^2}{\Lambda_3^2}\right)^n$$

$$\Delta c_T^2(50\text{Hz}) \approx 2c_0 + 4c_0c_2 + \sum^{\infty} c_n \quad < \quad 10^{-15}$$

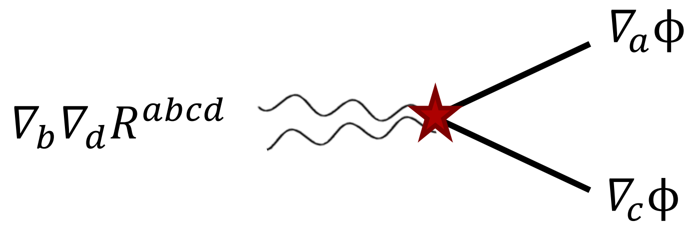
Dark Energy

Partial UV Completion

Dark Energy

Partial UV Completion

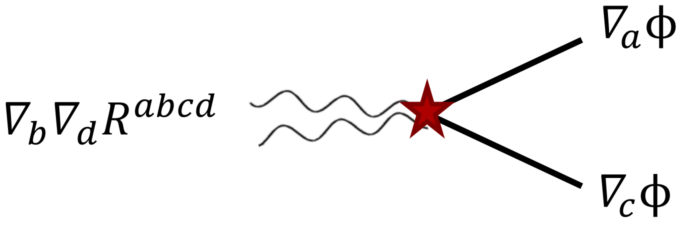
$$c_2 \frac{\nabla_b \nabla_d}{\Lambda_3^2} R^{abcd} X_{ac}$$



Dark Energy

Partial UV Completion

$$c_2 \frac{\nabla_b \nabla_d}{\Lambda_3^2} R^{abcd} X_{ac}$$



$$(\nabla_c H_{ab})^2 - \Lambda_3^2 \, H^{ab} H_{ab}$$

Dark Energy

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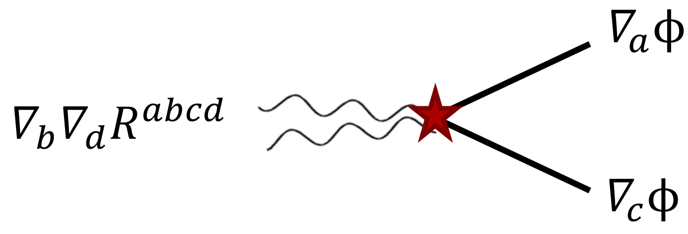

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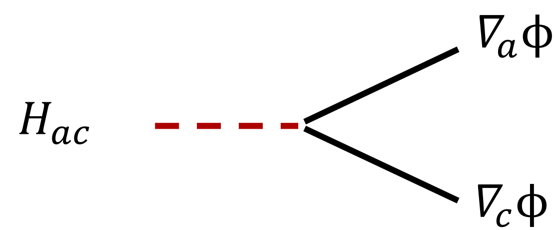

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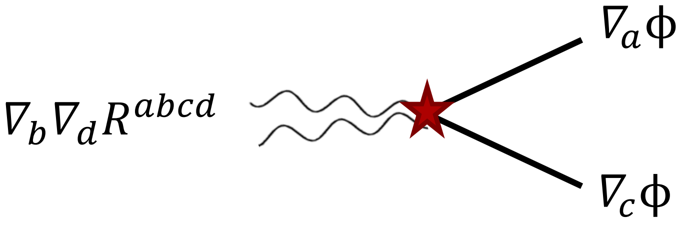

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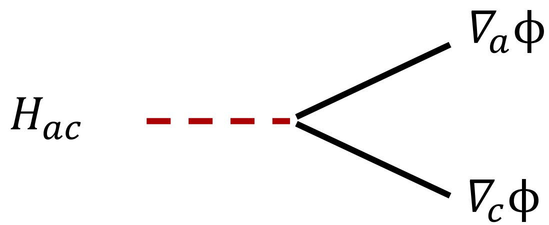

$$\frac{a_R M_P^2}{\Lambda_*^3} \nabla_b \nabla_d R^{abcd} H_{ac}$$

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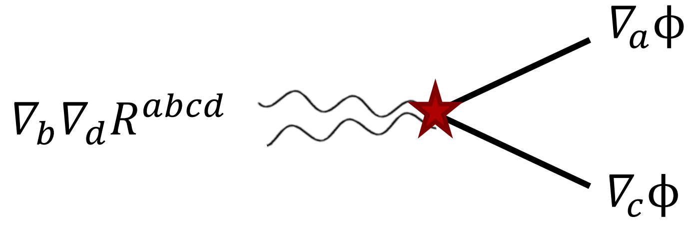

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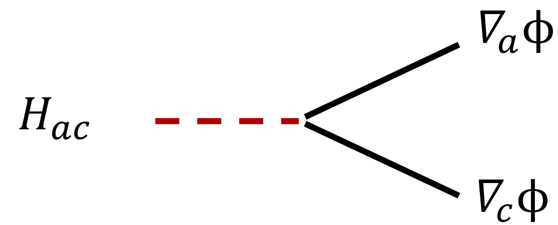

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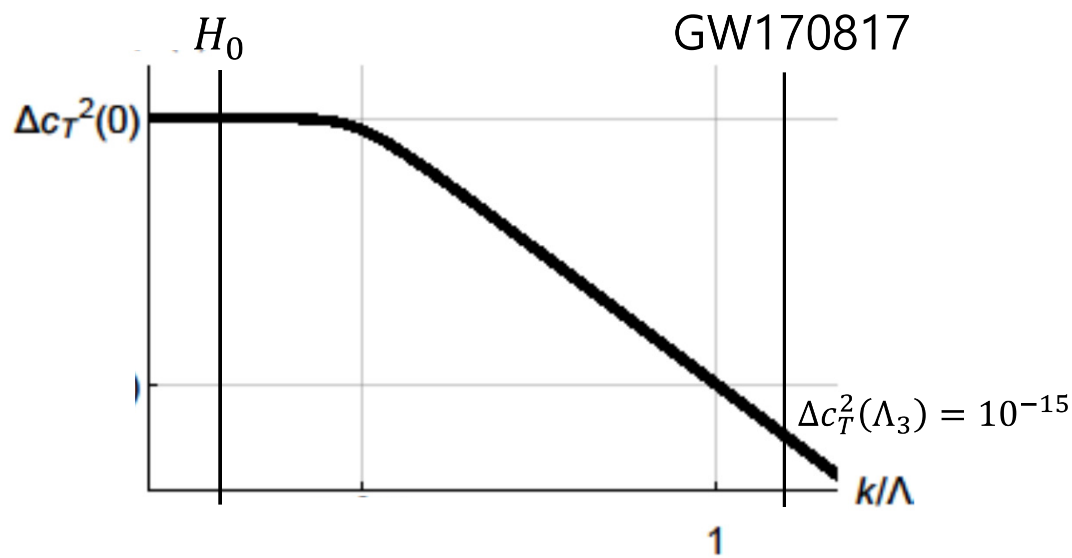

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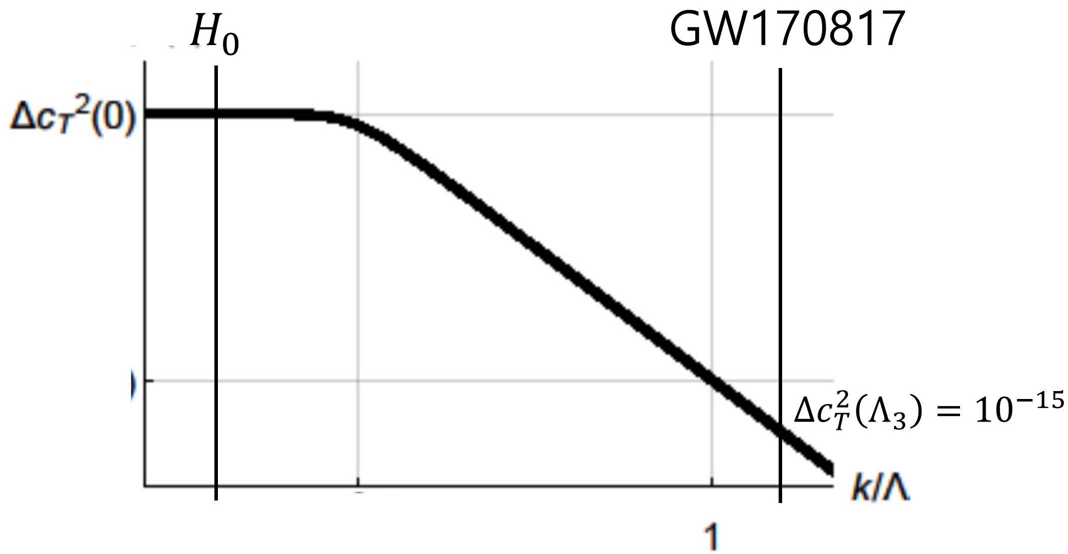

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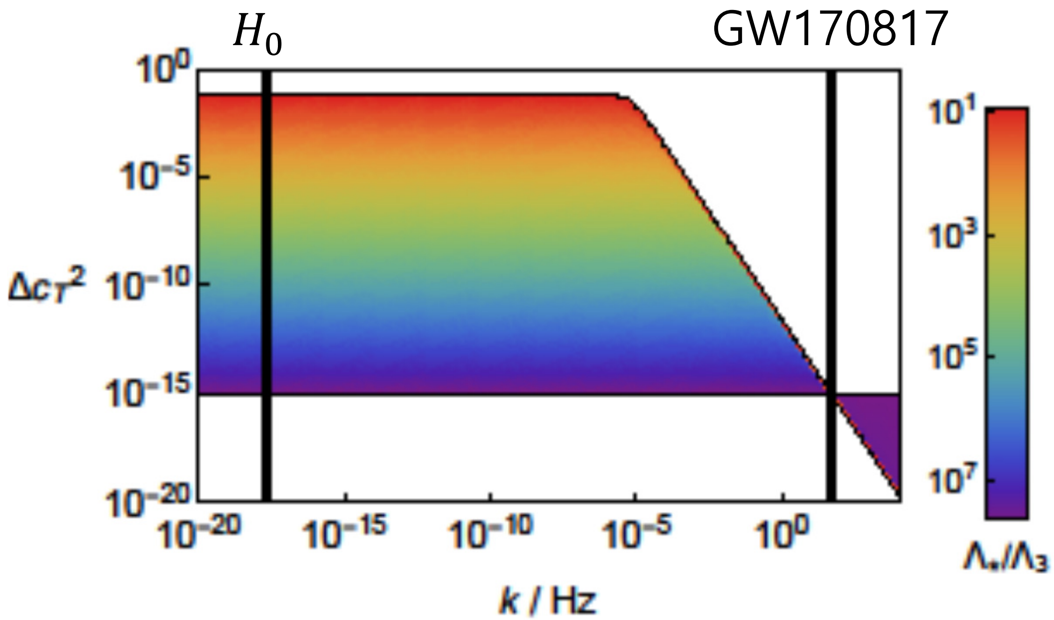

The Future

Theory

Experiment

Theory

$$\mathcal{L}_{EFT} = \mathcal{L}_{LO} + \mathcal{L}_{NLO} + \cdots$$

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e.g. Horndeski Higher Derivatives

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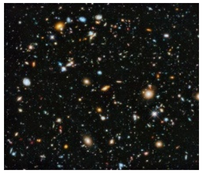
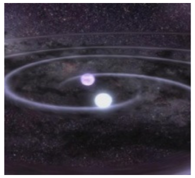
 Cosmology Mergers 

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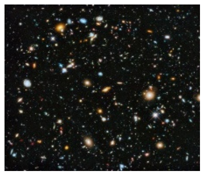
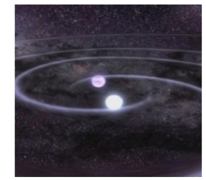


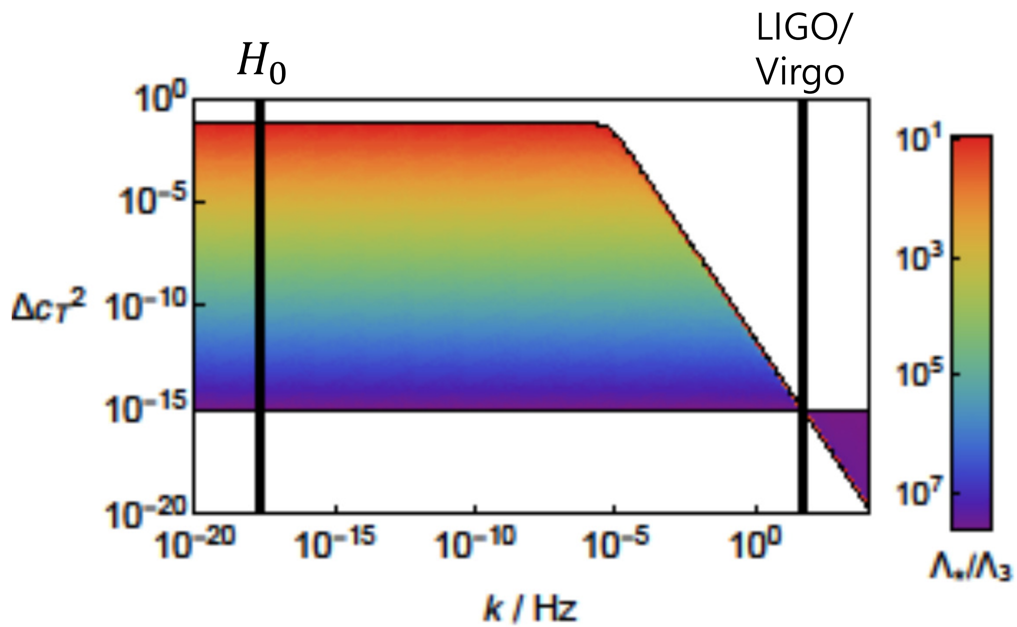
Cosmology

Mergers



Experiment

Lower energy measurements



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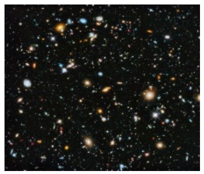
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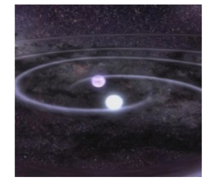

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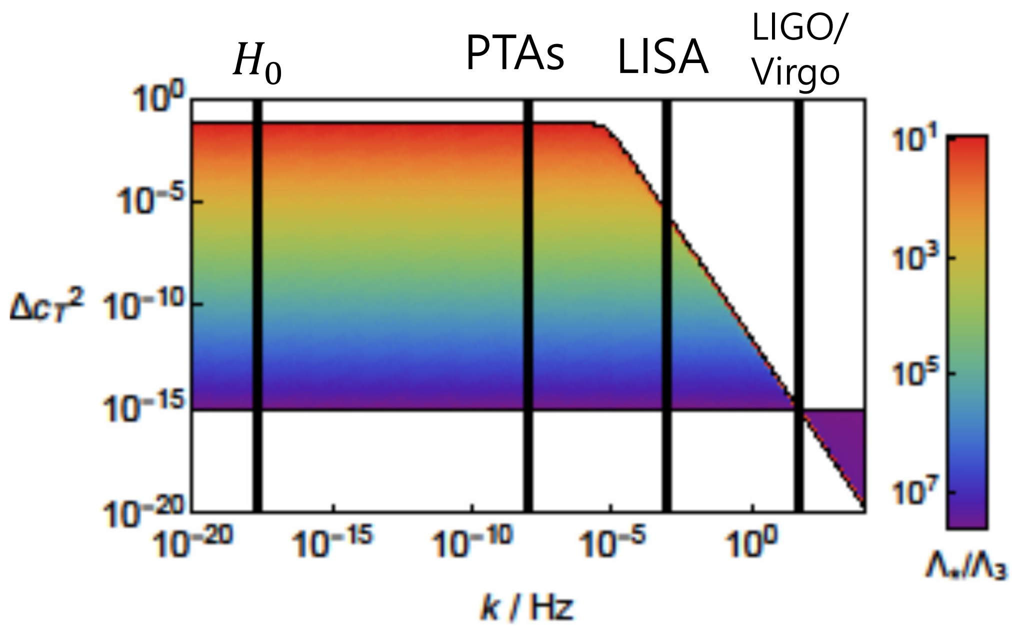

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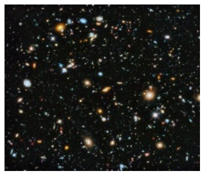

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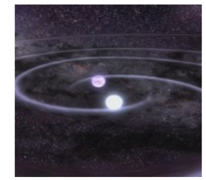
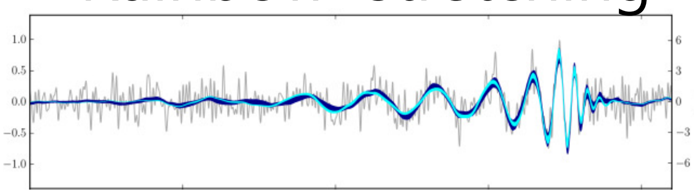
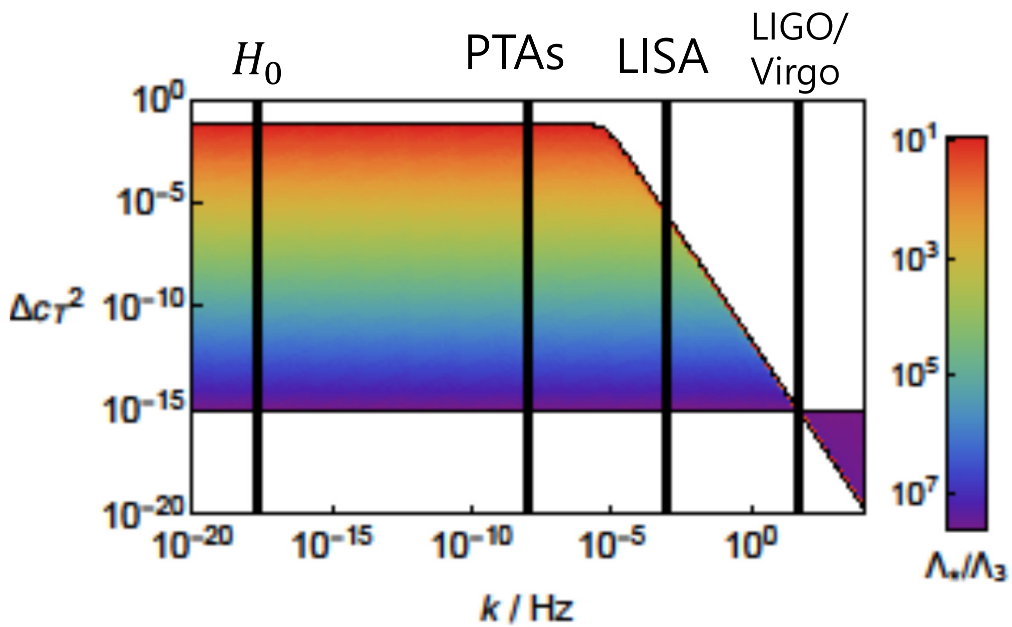


Experiment

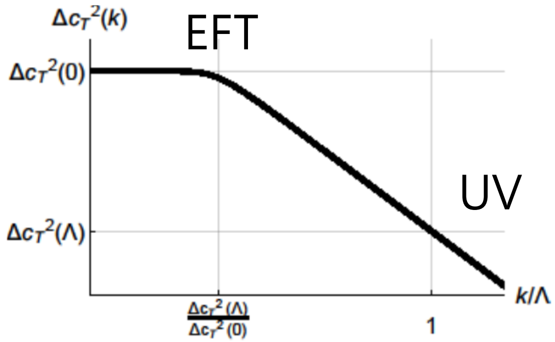
Lower energy measurements

`Rainbow' stretching

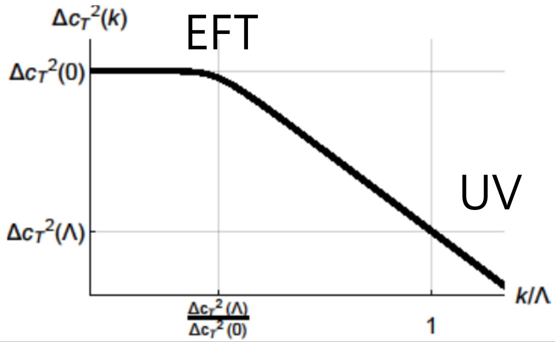




Summary



Only **low energy** measurements constrain **EFT** parameters!



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$$\Delta c_T^2(50\text{Hz}) < 10^{-15} \quad \Rightarrow \quad \sum_n^\infty c_n \left(\frac{50\text{Hz}}{\Lambda_3}\right)^n < 10^{-15} \quad \text{in EFT}$$

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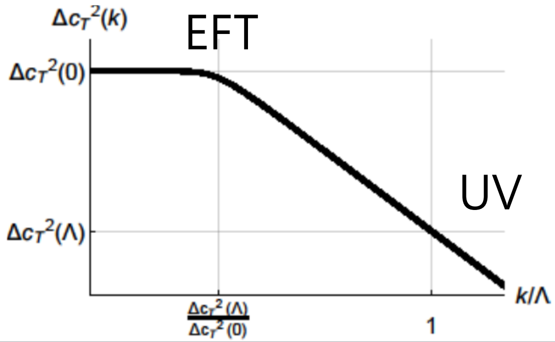

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