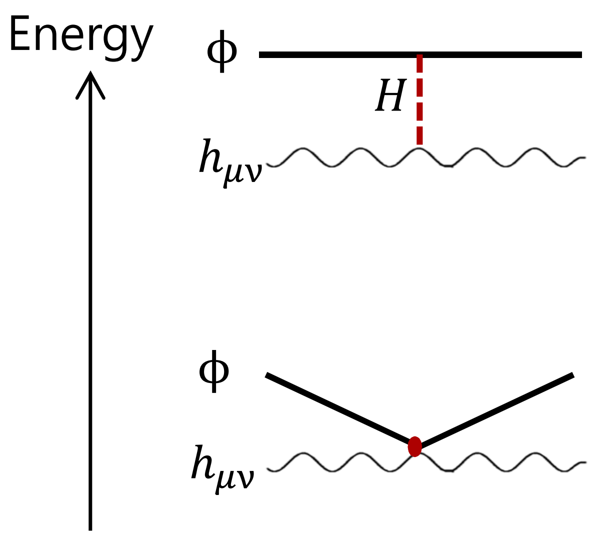
IPMU 22 Aug 2018

Speed Limits from Gravitational Waves

Scott Melville



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IPMU

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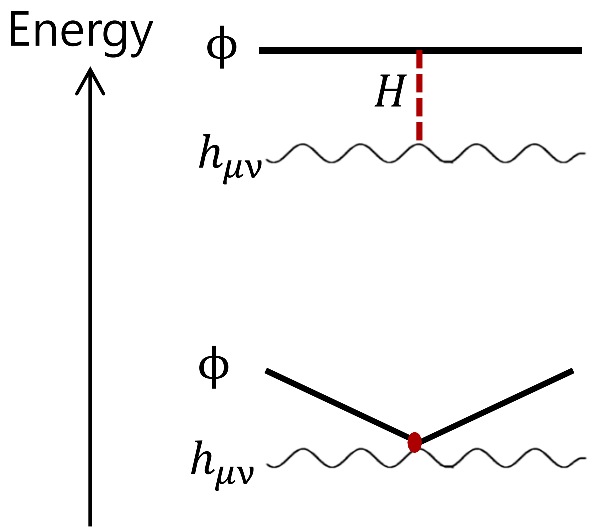

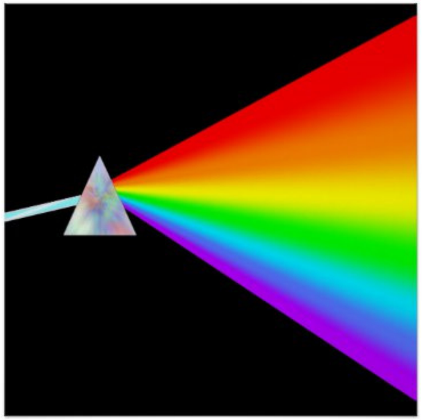

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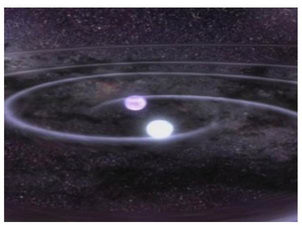

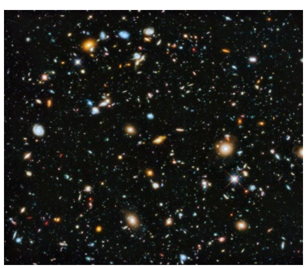

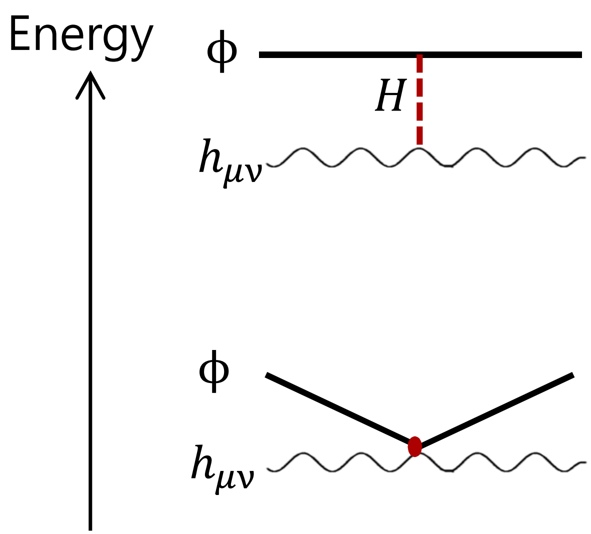

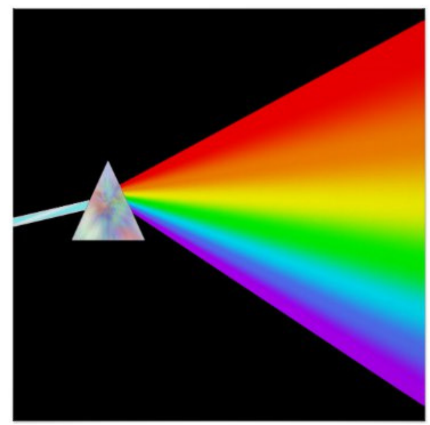

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Are GW speeds constrained by measurements?

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Are GW speeds constrained by theory?

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Are GW speeds constrained by theory?

SM, Claudia de Rham

Gravitational Rainbows: LIGO and Dark Energy at its Cutoff	1806.09417
Speed Limits from the UV	1809.xxxxx

+ Andrew Tolley, Shuang-Yong Zhou

Positivity Bounds for Scalar Theories	1702.06134
UV Complete Me: Positivity Bounds for Particles with Spin	1706.02712

- Scale Dependence — UV physics causes IR running

Are GW speeds constrained by measurements?

- GW170817 Constraints — Really constrain UV completion!

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- Scale Dependence — UV physics causes IR running

Are GW speeds constrained by measurements?

- GW170817 Constraints — Really constrain UV completion!

- Positivity Constraints — Really constrain the IR

Are GW speeds constrained by theory?

- The Future — Dark energy after GW170817

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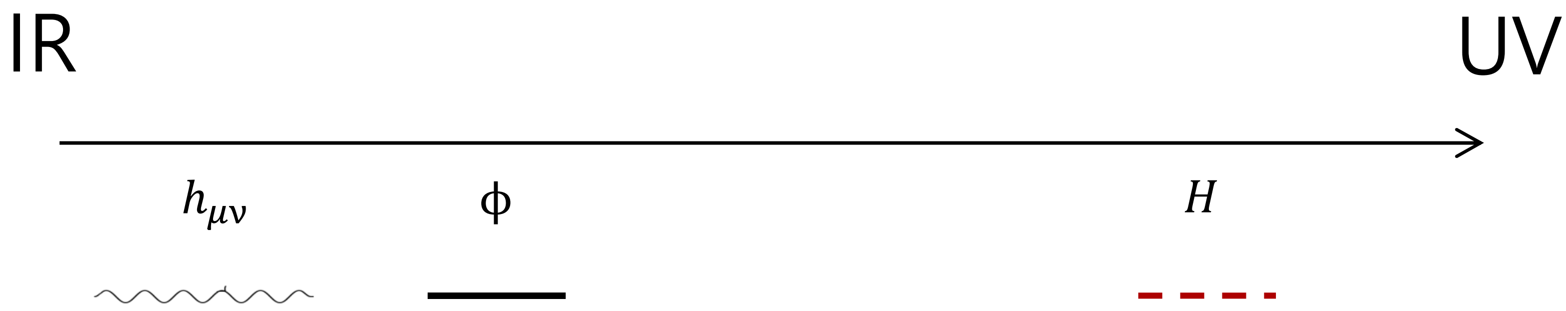
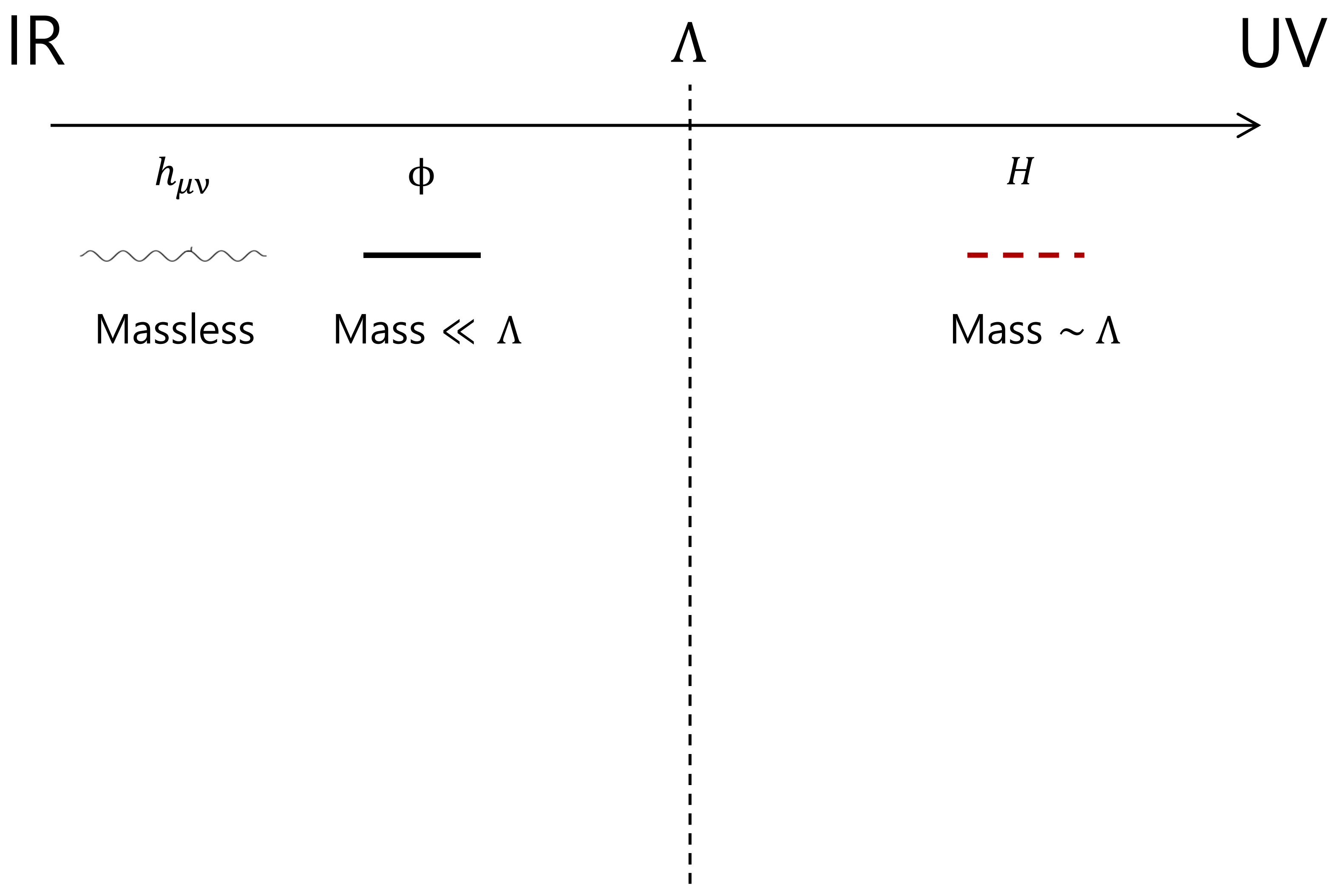
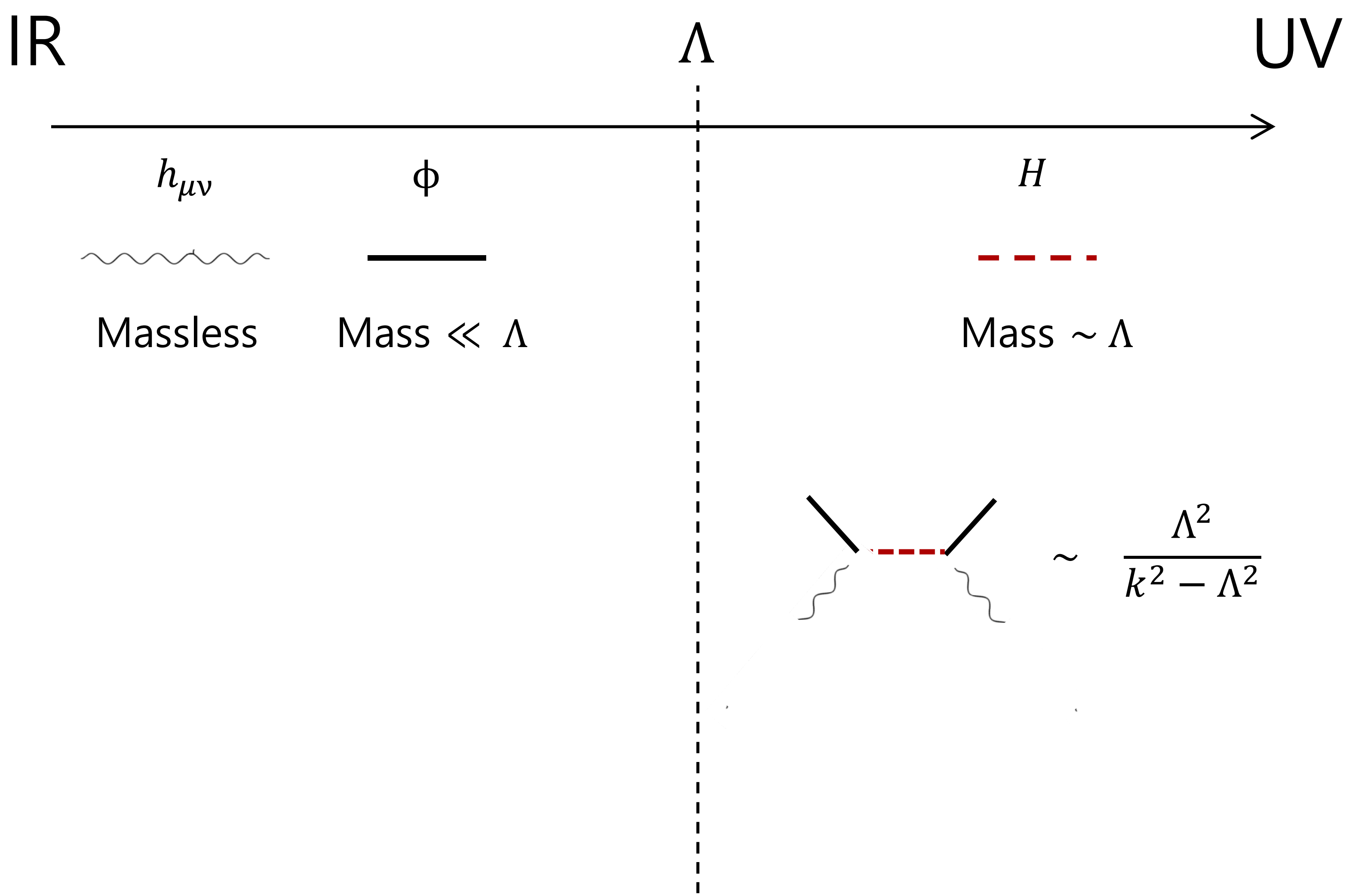
SCALE

Dependence


IR
UV
$h_{\mu\nu}$
ϕ
H


IR
Λ
UV
$h_{\mu\nu}$
ϕ
H
Massless
Mass ≪ Λ
Mass ~ Λ


IR
Λ
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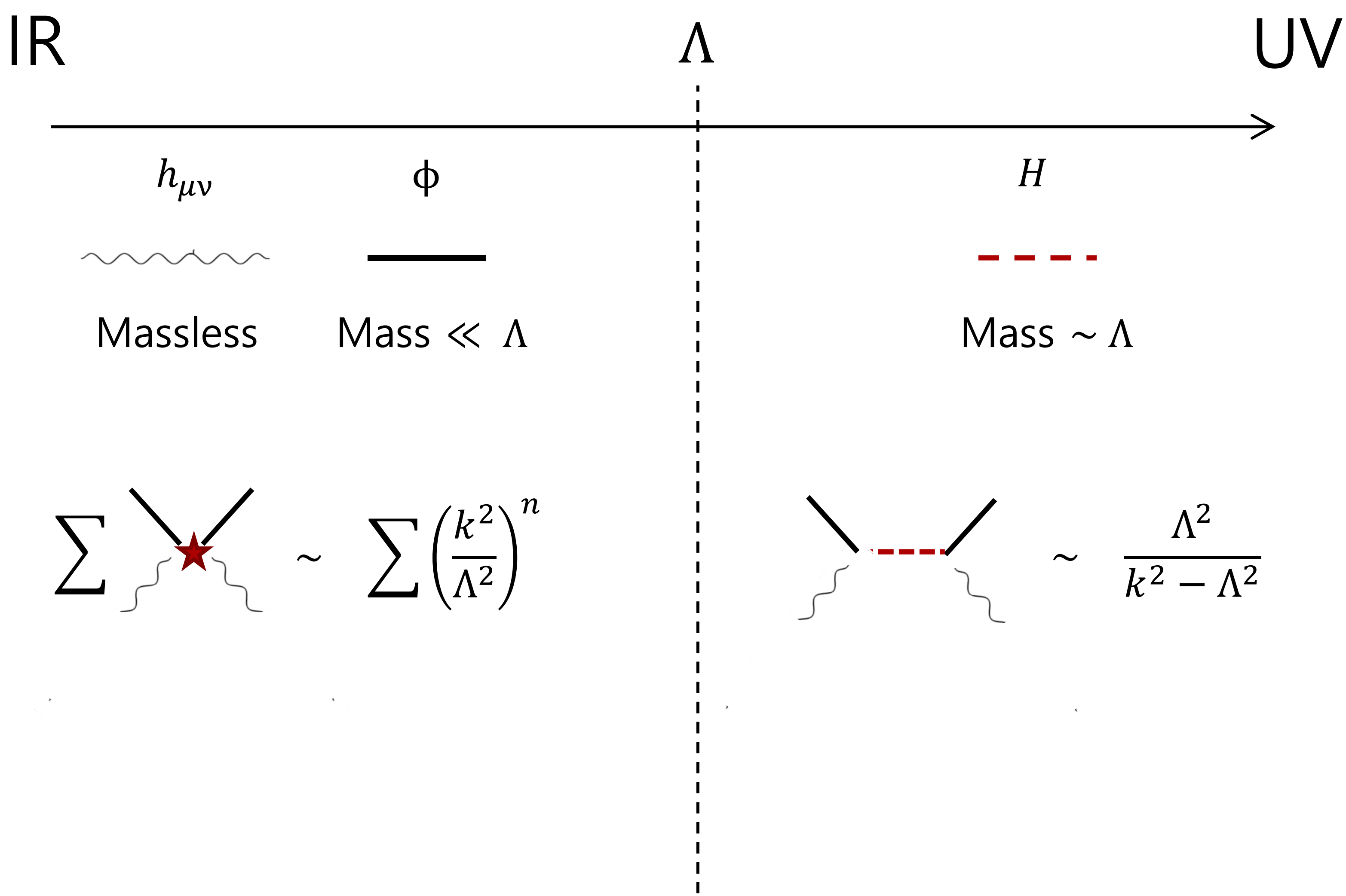
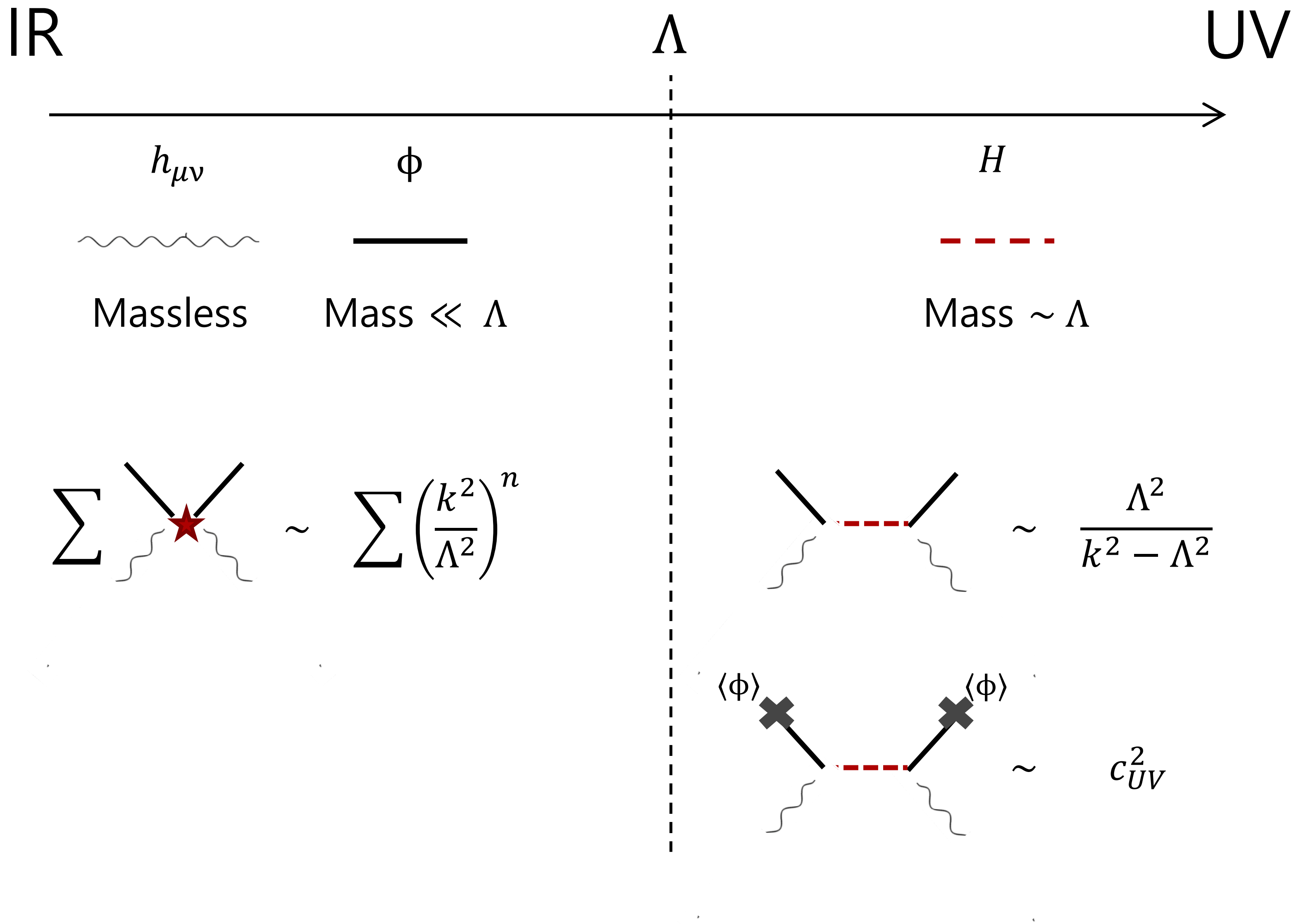
ϕ
H
Massless
Mass ≪ Λ
Mass ~ Λ
$\sim \frac{\Lambda^2}{k^2 - \Lambda^2}$


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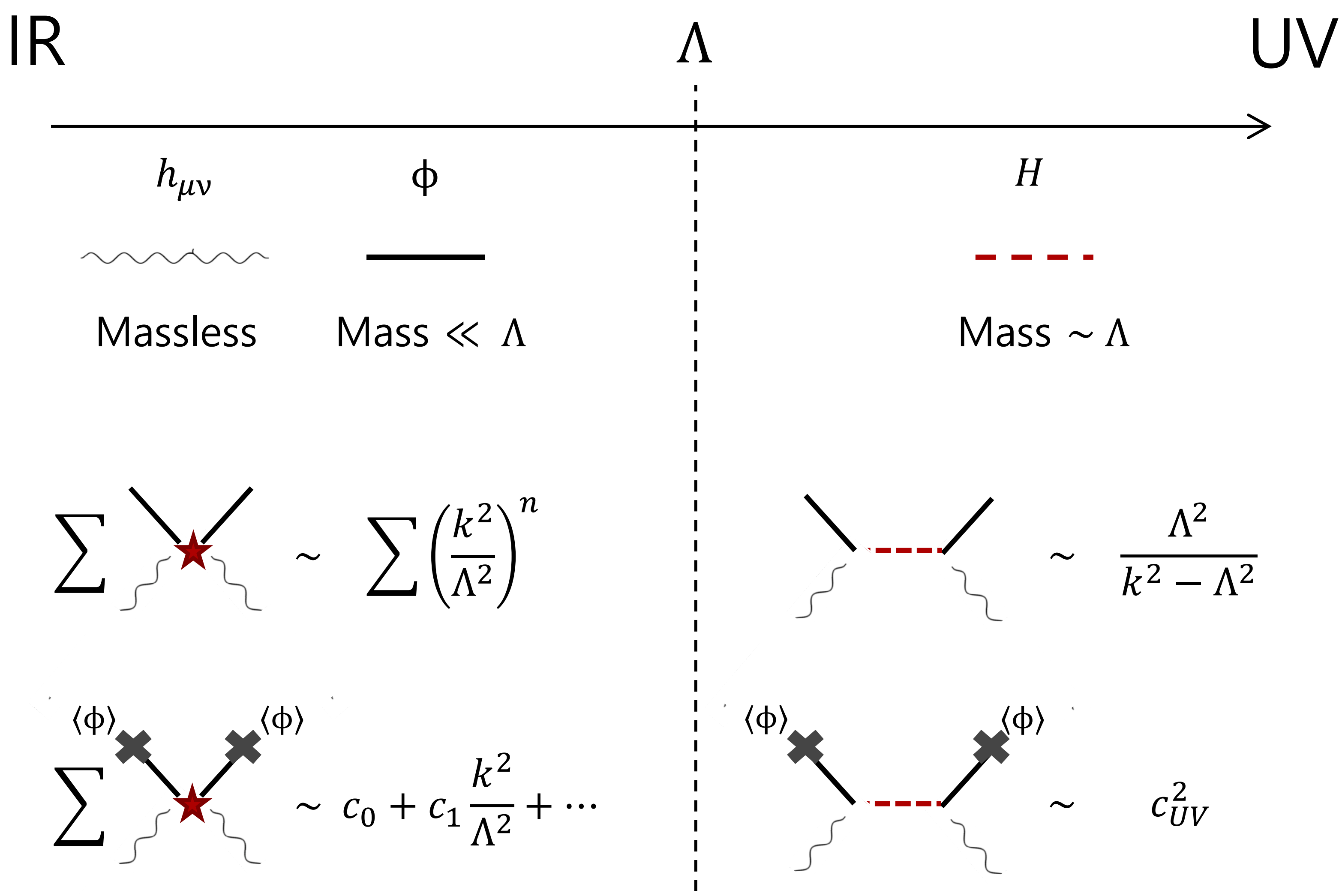
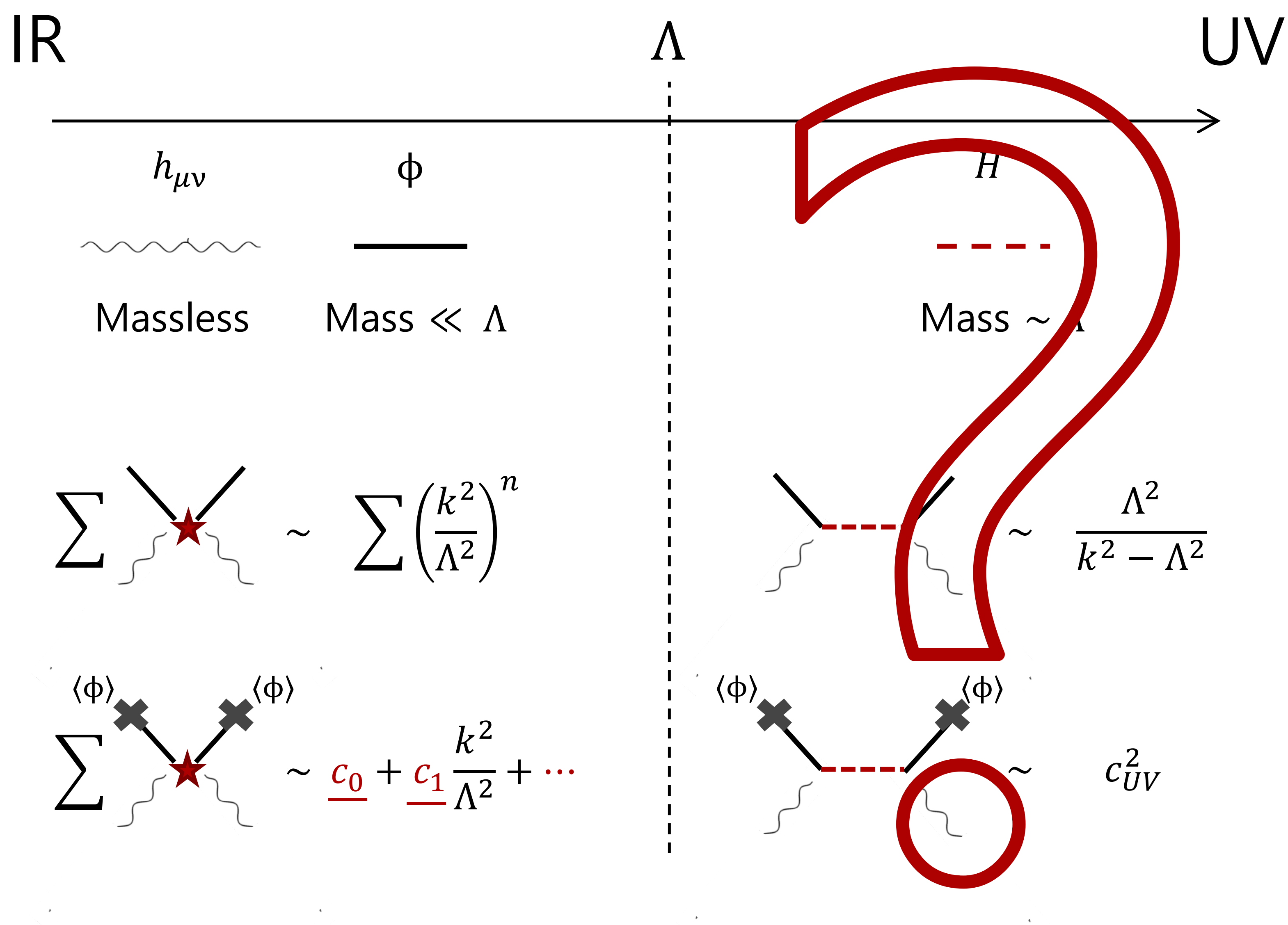
$\langle\phi\rangle$
$\langle\phi\rangle$
$\sim c_{UV}^2$


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


IR
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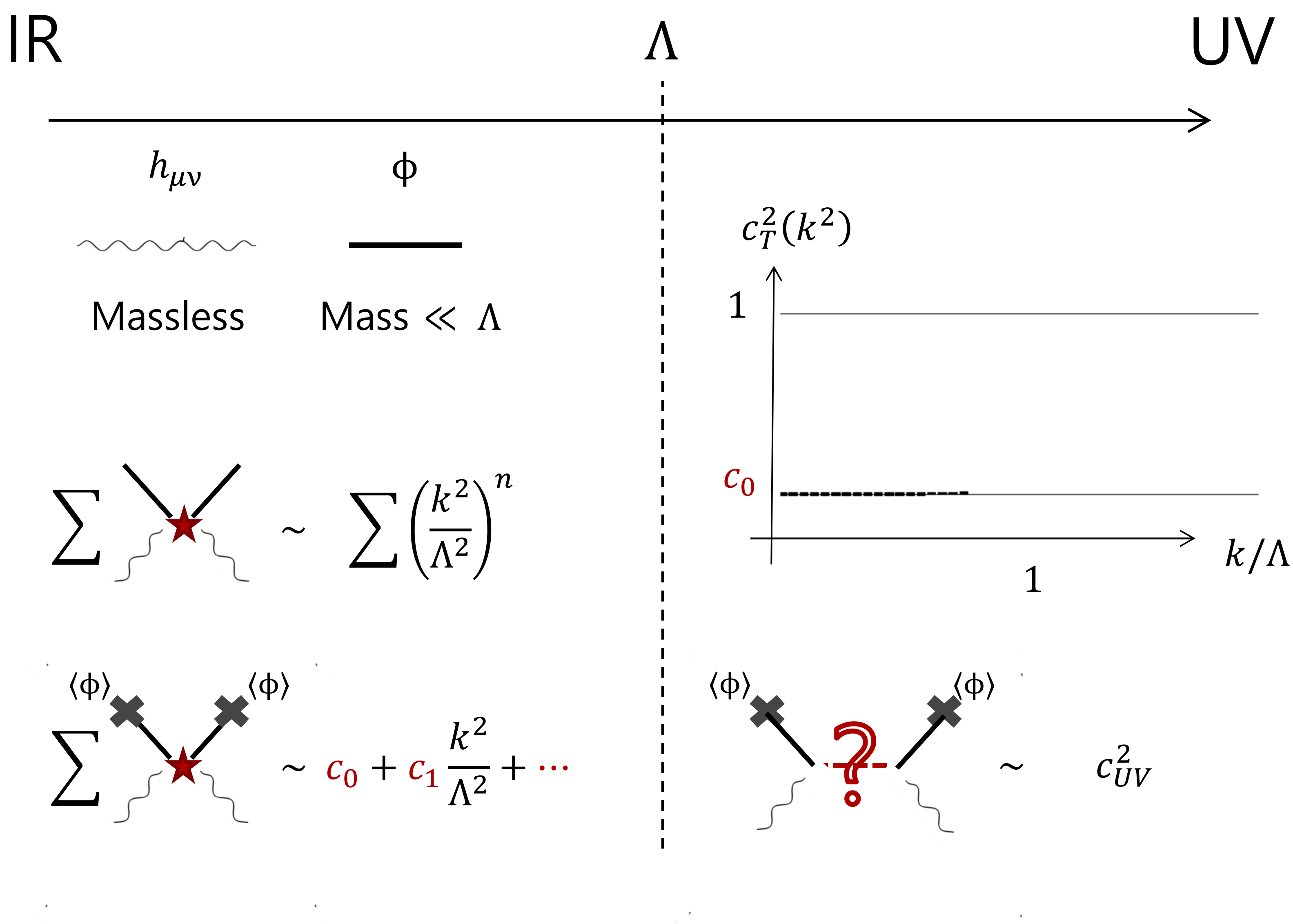
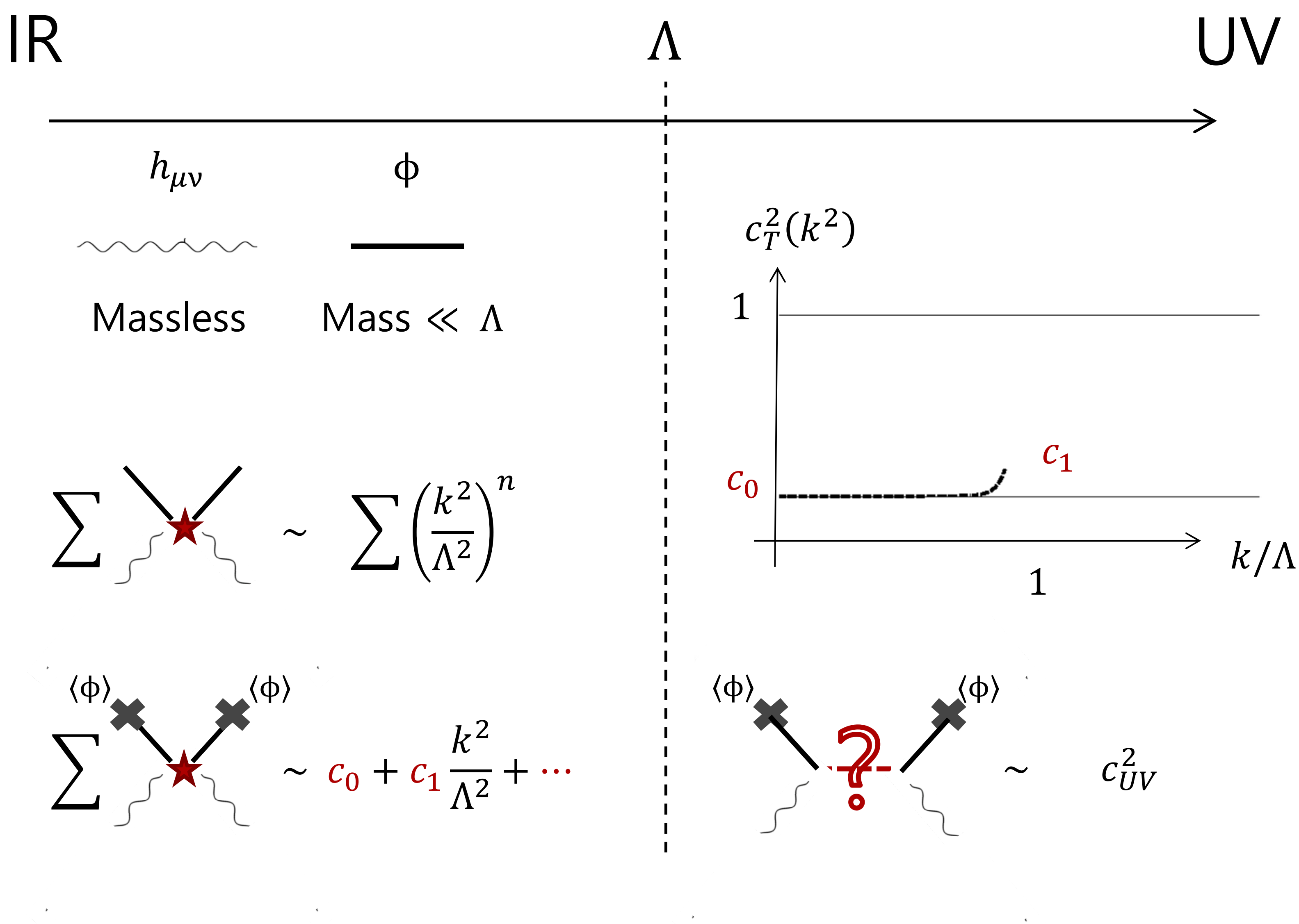
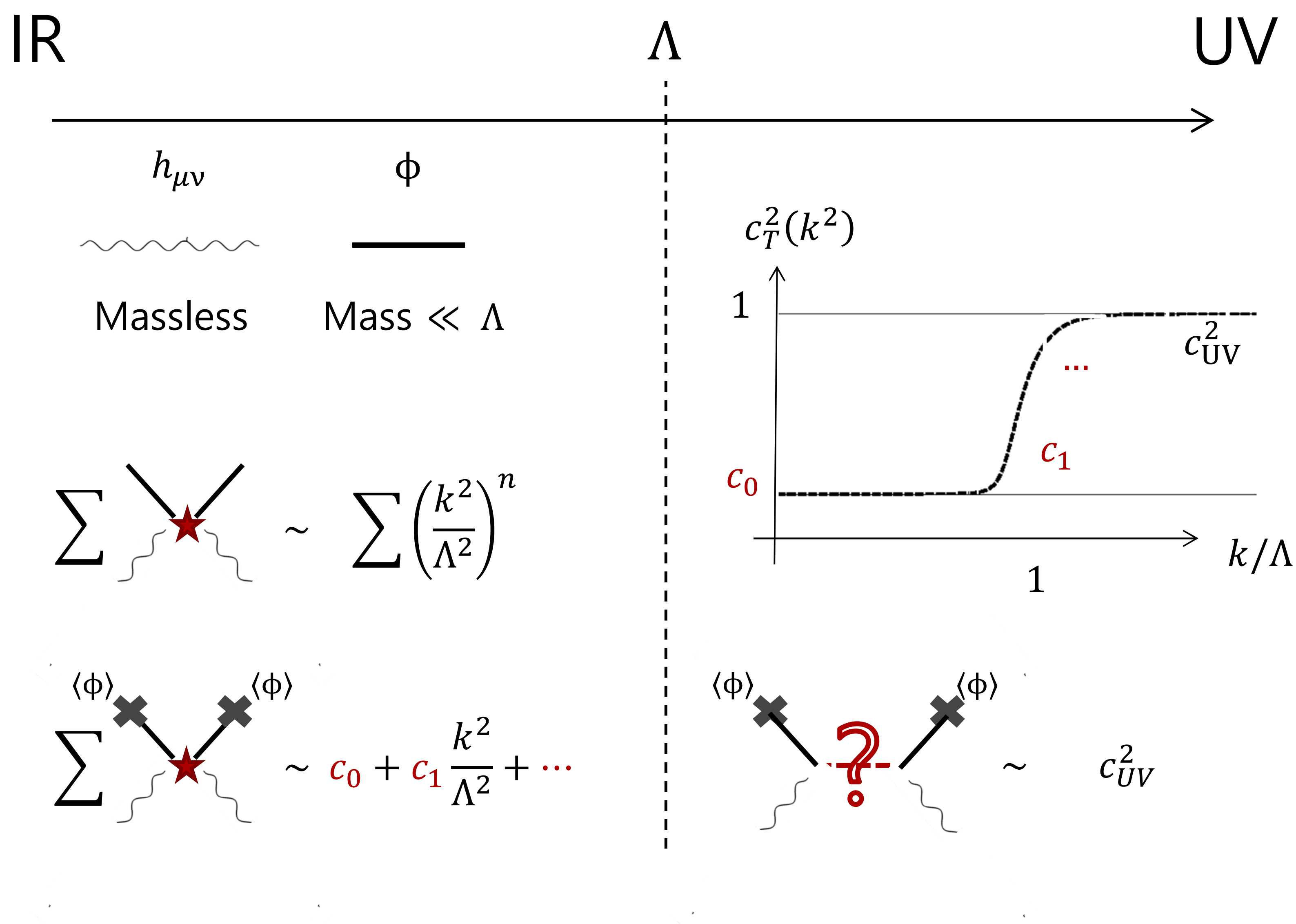


Scale Dependence



Scale Dependence

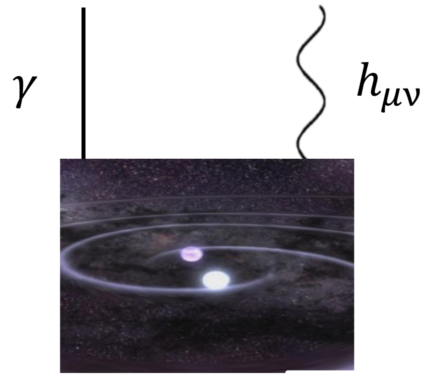


Scale Dependence

GW170817

Multi-messenger Signal

$$\left| 1 - c_T^2 \right|$$



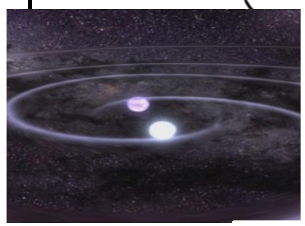
Merger

Multi-messenger Signal

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

γ $\qquad$ $h_{\mu\nu}$

Merger

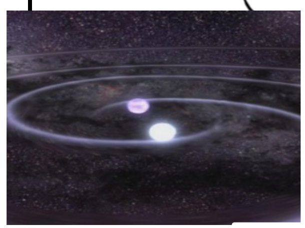


Multi-messenger Signal

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

γ $h_{\mu\nu}$

Merger $> \mathbf{50Hz}$

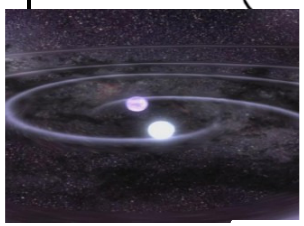


Multi-messenger Signal

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

γ $h_{\mu\nu}$

Merger $>$ **50Hz**



$\leftrightarrow$

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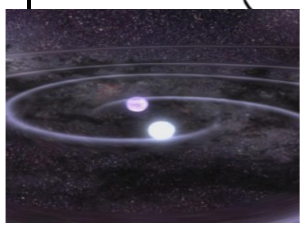
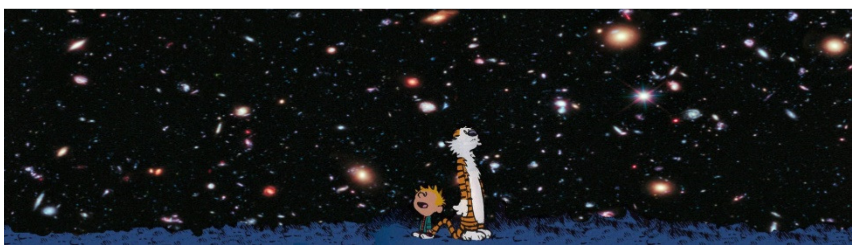


$\longleftrightarrow$



$\longleftrightarrow$

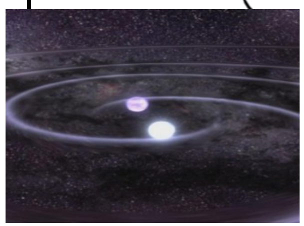
Late time cosmology $\mathbf{10^{-18}}$ **Hz**

Multi-messenger Signal

$$\Delta c_T^2(50\mathrm{Hz}) = \left| 1 \;-\; c_T^2\,(50\mathrm{Hz}) \right| \;<\; 10^{-15}$$

γ $h_{\mu\nu}$

Merger $> \mathbf{50Hz}$



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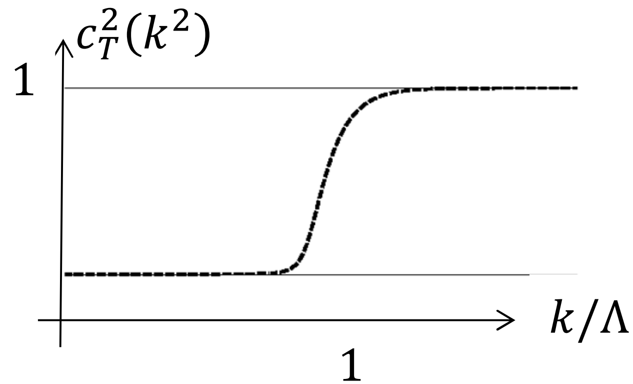

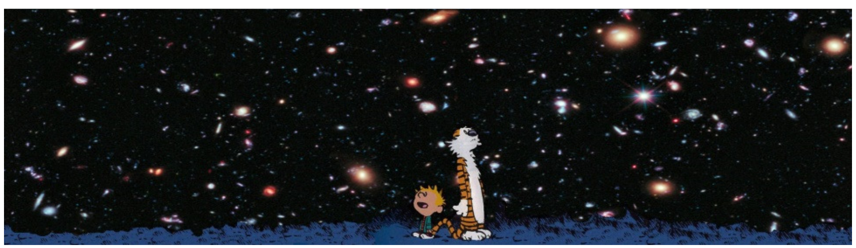

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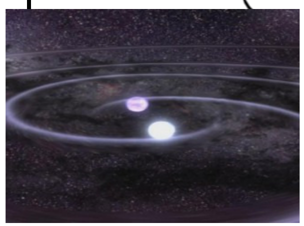

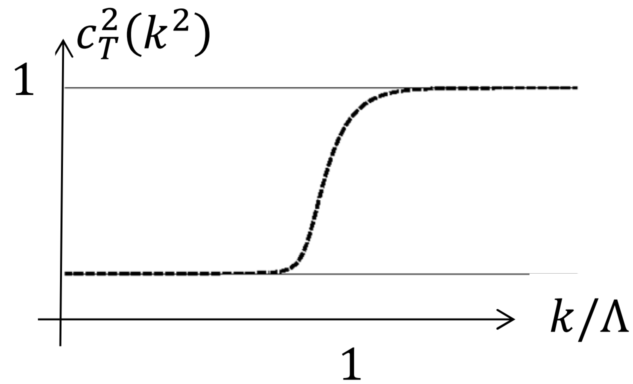

Late time cosmology $\mathbf{10^{-18}}$ **Hz**

$$\mathcal{L}_{\text{Horn.}} = M_P^2 R + G_n\left(\frac{\partial\phi}{\Lambda_2^4}, \frac{(\partial\partial\phi)}{\Lambda_3^3}\right)$$

Multi-messenger Signal

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

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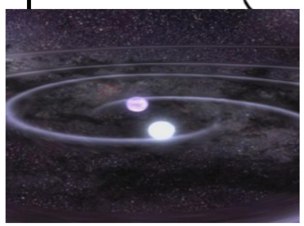
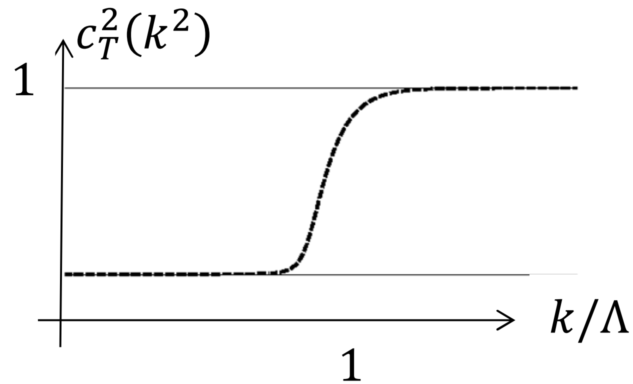
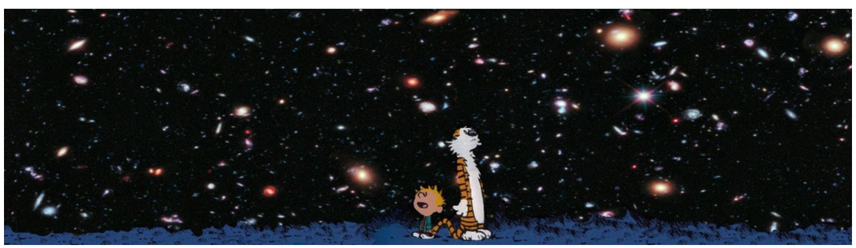
Merger $> \mathbf{50Hz}$







Late time cosmology $\mathbf{10^{-18}}$ **Hz**

$$\mathcal{L}_{\text{Horn.}} = M_P^2 R + G_n\left(\frac{\partial\phi}{\Lambda_2^4}, \frac{(\partial\partial\phi)}{\Lambda_3^3}\right)$$

$\boldsymbol{\Lambda_3 \sim 50}$ **Hz!**

Multi-messenger Signal

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

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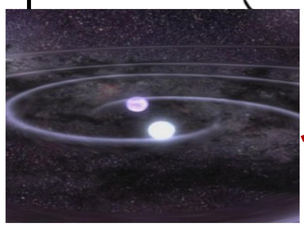
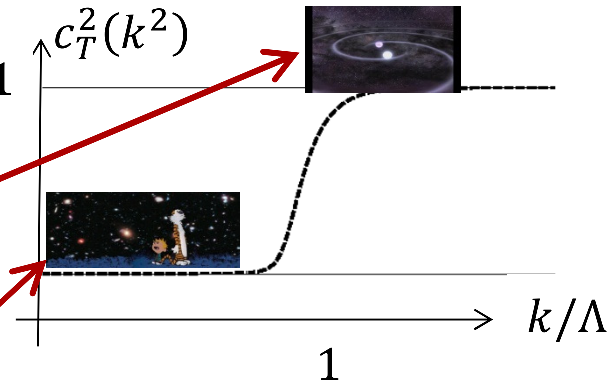


$\longleftrightarrow$



$\longleftrightarrow$

Late time cosmology $\mathbf{10^{-18}}$ **Hz**

$$\mathcal{L}_{\text{Horn.}} = M_P^2 R + G_n\left(\frac{\partial\phi}{\Lambda_2^4}, \frac{(\partial\partial\phi)}{\Lambda_3^3}\right)$$

$$\boxed{\Lambda_3 \sim \mathbf{50\ Hz!}}$$

Dark Energy

Horndeski EFT

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

Dark Energy

Horndeski EFT

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

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

Dark Energy

Horndeski EFT

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

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

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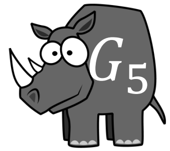

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Dark Energy

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

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

Dark Energy

Horndeski EFT

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

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

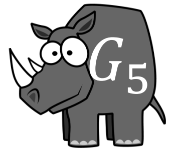
$$\Delta c_T^2(k^2) \approx 2\, c_0$$

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

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

Dark Energy

Horndeski EFT



$$\mathcal{L}_{hh} = M_P^2 [R - c_0 R^{ab} \nabla_a \phi \nabla_b \phi] + \mathcal{O}\left(\frac{\nabla^2}{\Lambda_3^2}\right)$$

$$\Delta c_T^2(k^2) \approx 2\, c_0 + \mathcal{O}\left(\frac{k^2}{\Lambda_3^2}\right)$$

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

Dark Energy

Horndeski EFT

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

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

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

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

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

Dark Energy

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

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

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

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

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

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

Dark Energy

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

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$$+ \quad \ldots$$

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

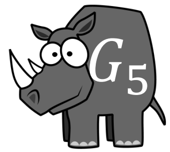
$$+ 4\, c_0 c_2 \, \frac{k^2}{\Lambda_3^2}$$

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

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

Dark Energy

Horndeski EFT



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

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

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

Dark Energy

Simple $P(X)$ Example

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{\Lambda^4}(\partial\phi)^4 + \cdots$$

$$\langle\phi\rangle = \alpha\Lambda^2 t$$

Dark Energy

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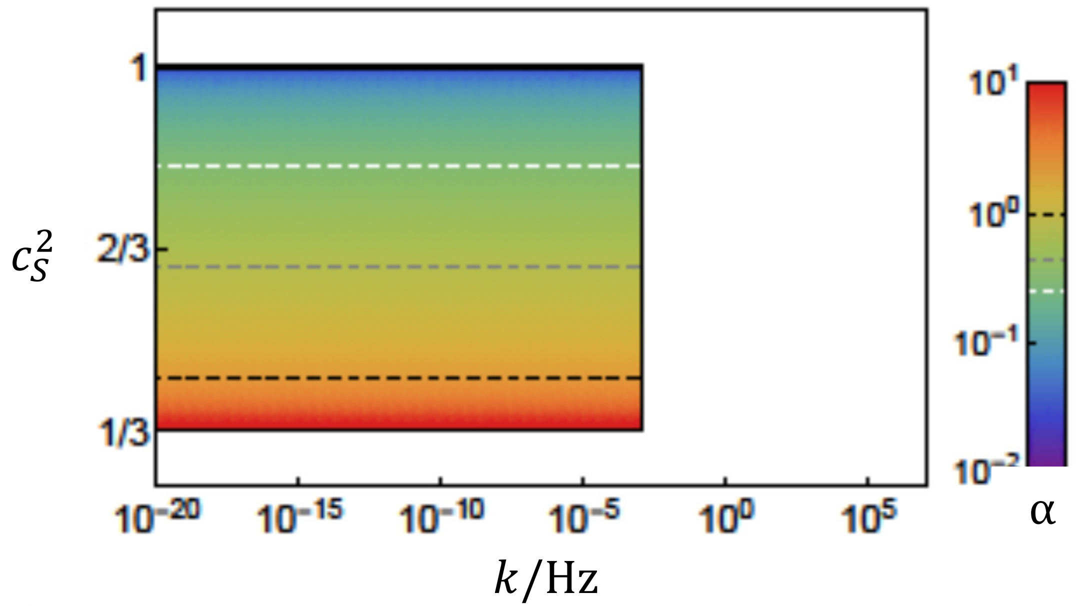

Dark Energy

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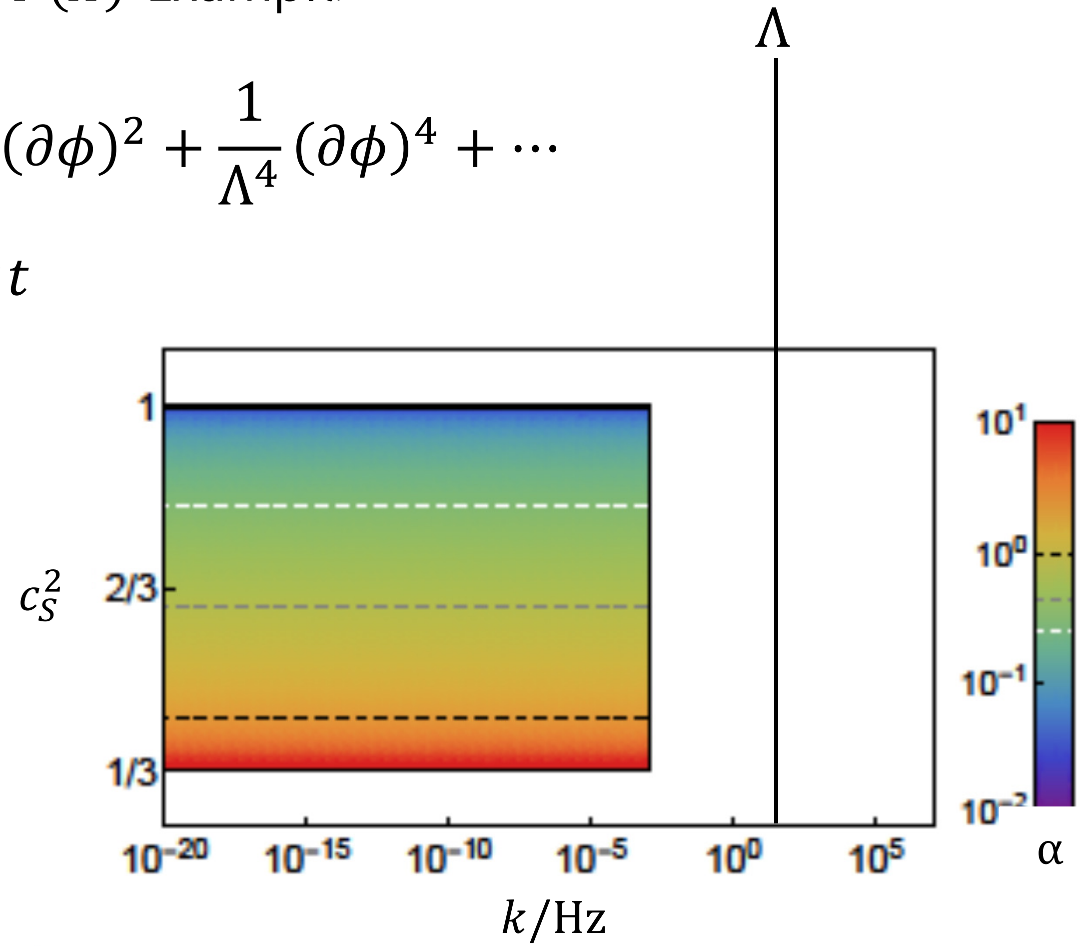

Dark Energy

Simple $P(X)$ Example

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{\Lambda^4}(\partial\phi)^4 + \cdots$$

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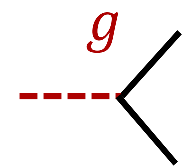
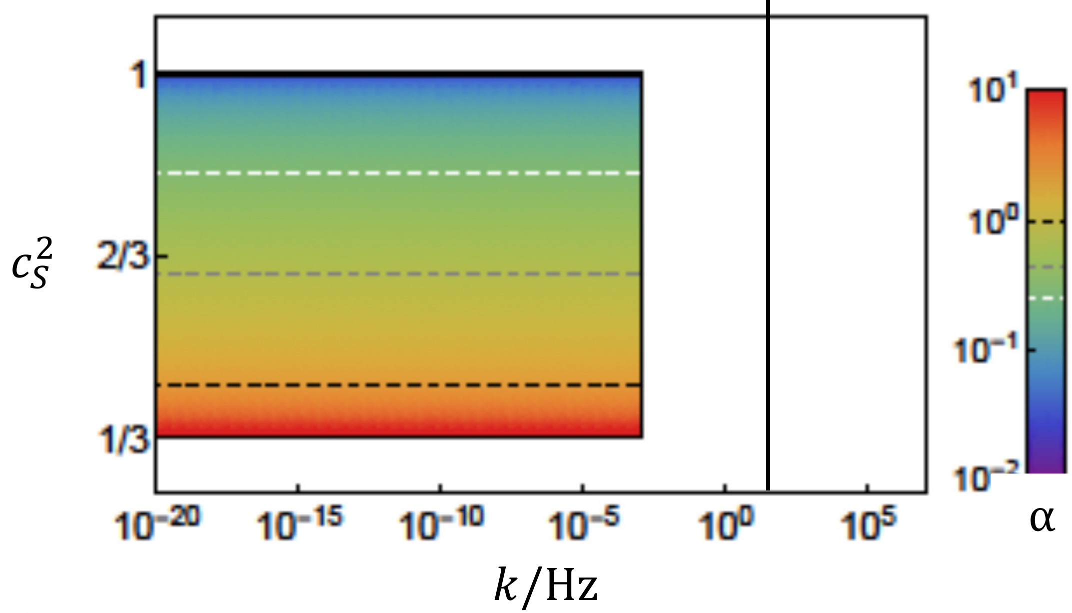


$$\mathcal{L} = -\tfrac{1}{2}(\partial\phi)^2 + g\, H(\partial\phi)^2 - \frac{1}{2}(\partial H)^2 - \frac{1}{2}M^2H^2$$

Λ



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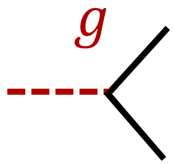

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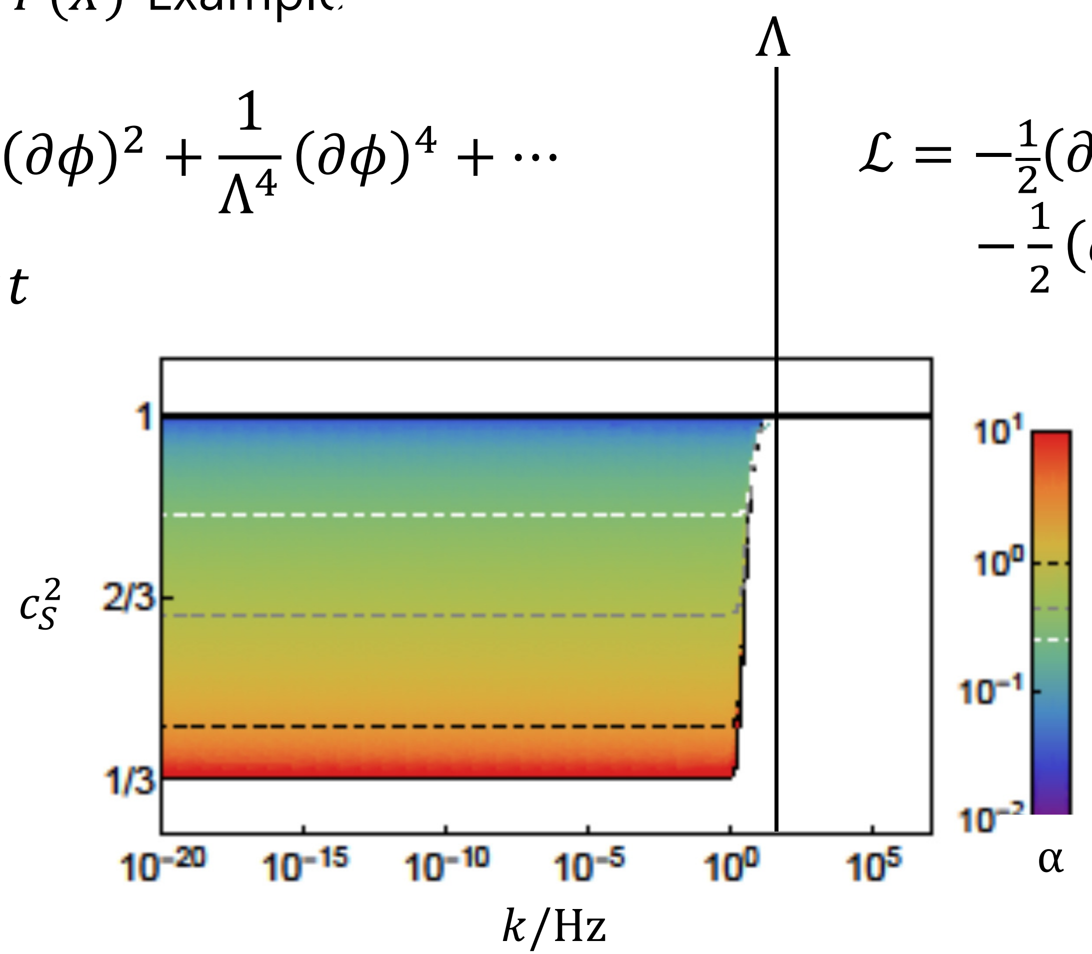
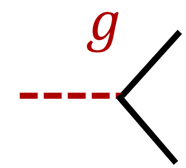


Dark Energy

Simple $P(X)$ Example



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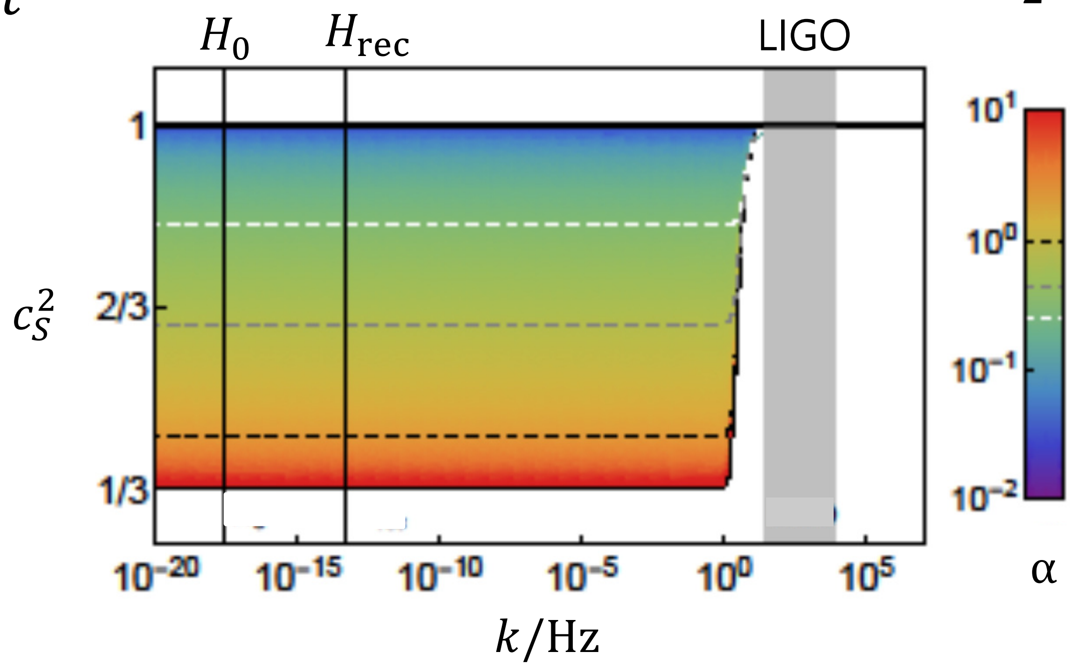
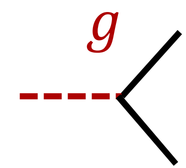


Dark Energy



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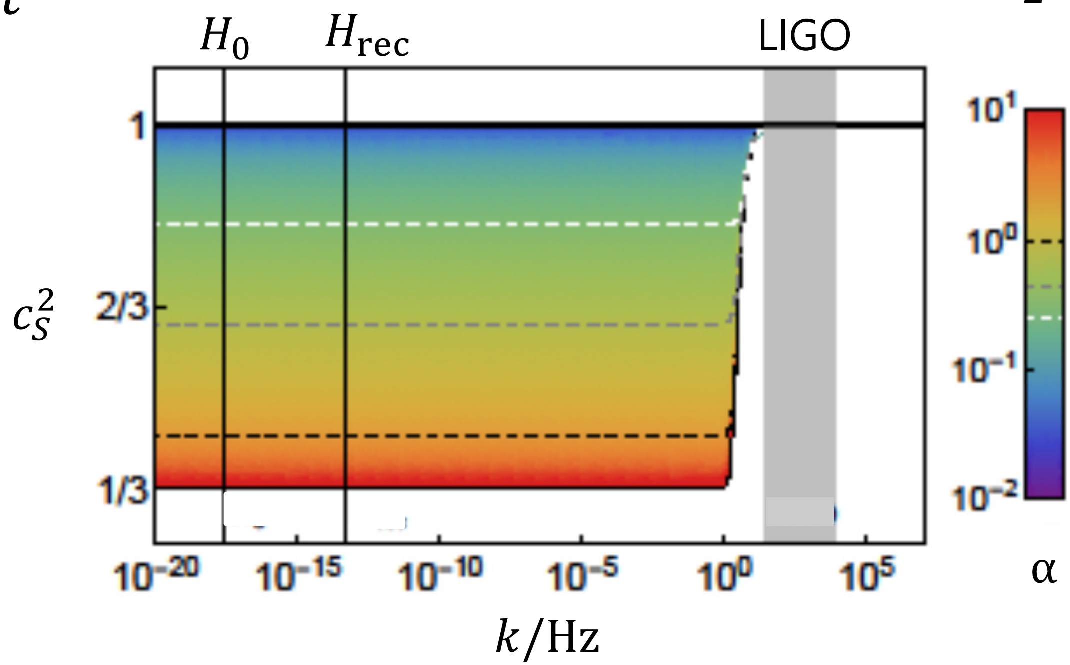


$$\boxed{g\,M > 10^{-4}}$$

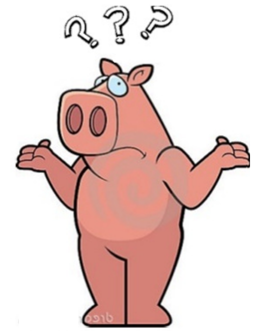
Positivity Constraints

UV

IR

UV

$$\mathcal{L}_{UV} = \quad ?$$



IR

UV

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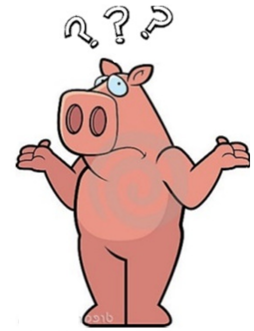


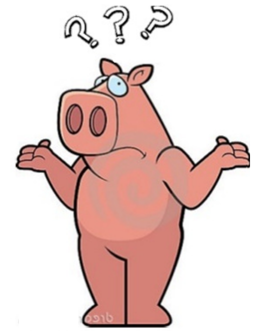
Λ

IR

$$\mathcal{L}_{EFT} = \sum \frac{c_n}{\Lambda^n} \mathcal{O}_n$$

UV

$$\mathcal{L}_{UV} = \quad ?$$



Λ

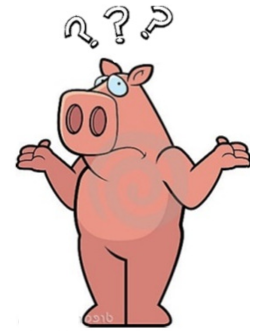
IR

$$\mathcal{L}_{EFT} = \sum^{N} \frac{c_n}{\Lambda^n} \mathcal{O}_n$$

Finite Number of Local Operators

UV

$$\mathcal{L}_{UV} = \quad ?$$



Λ

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Finite Number of Local Operators

with undetermined coefficients

UV

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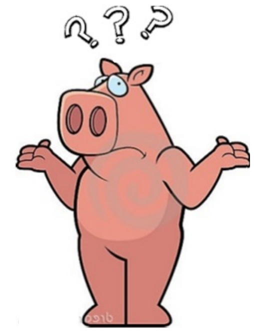

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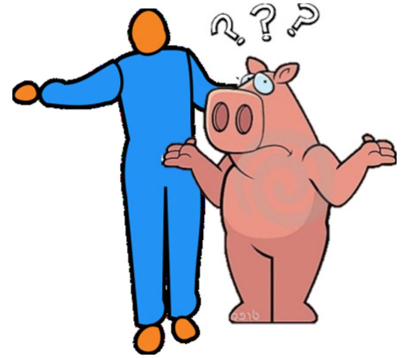

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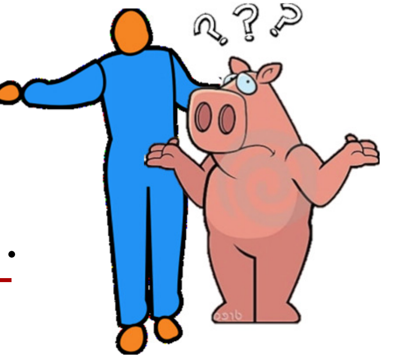
Unitary, Causal, Local, ...



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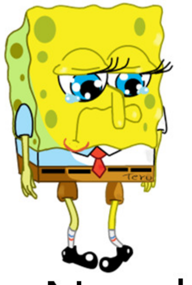

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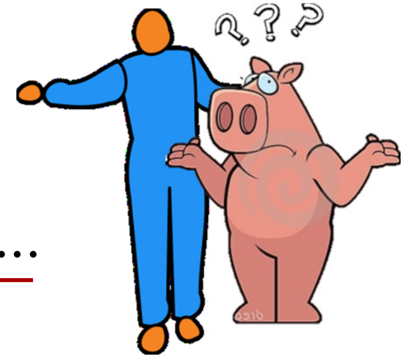

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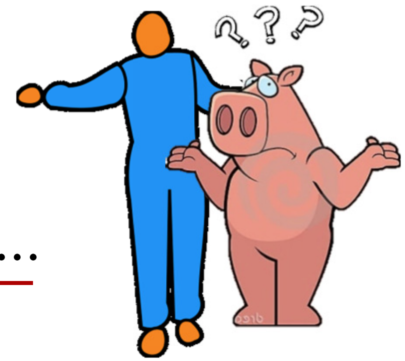

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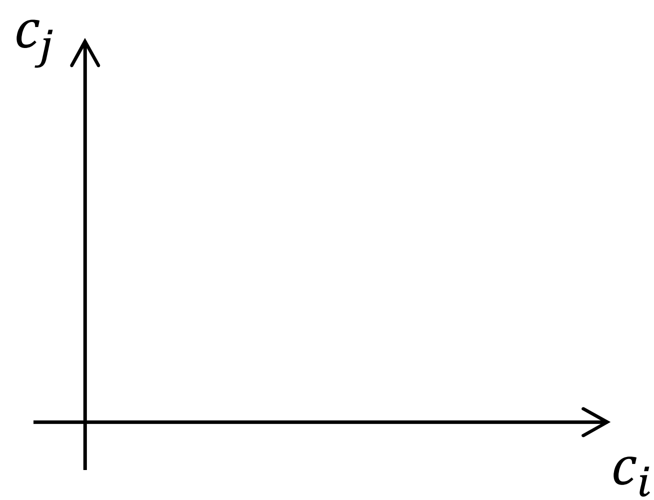

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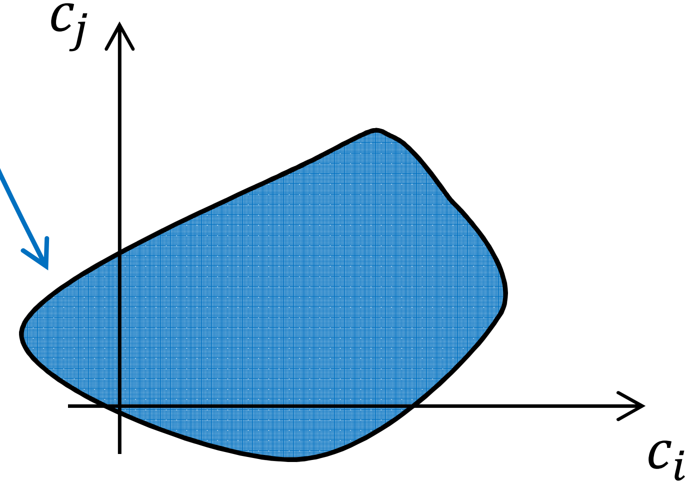

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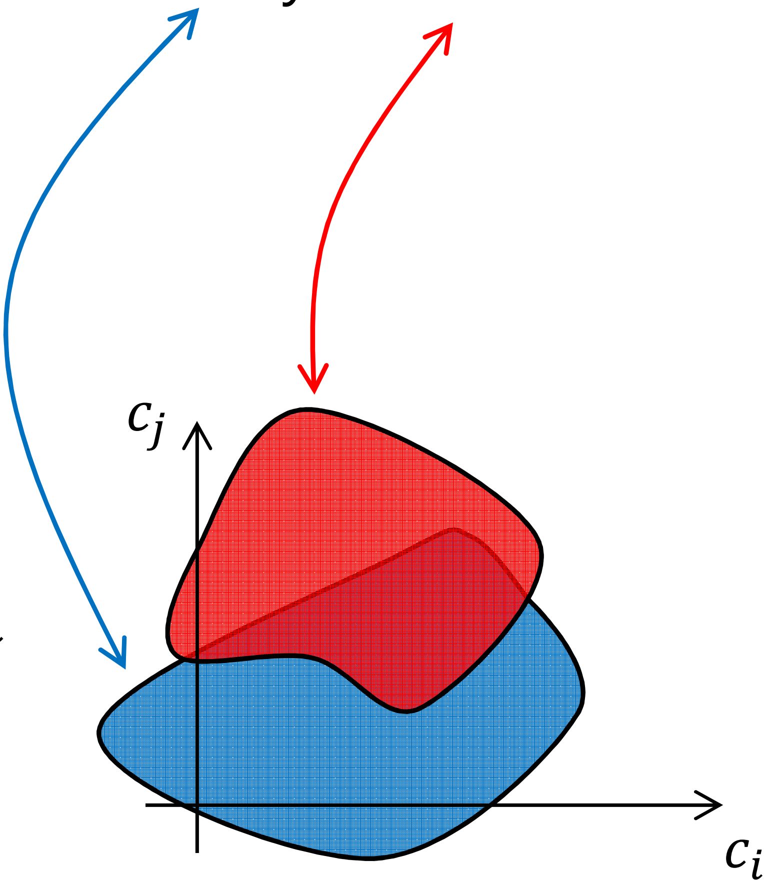

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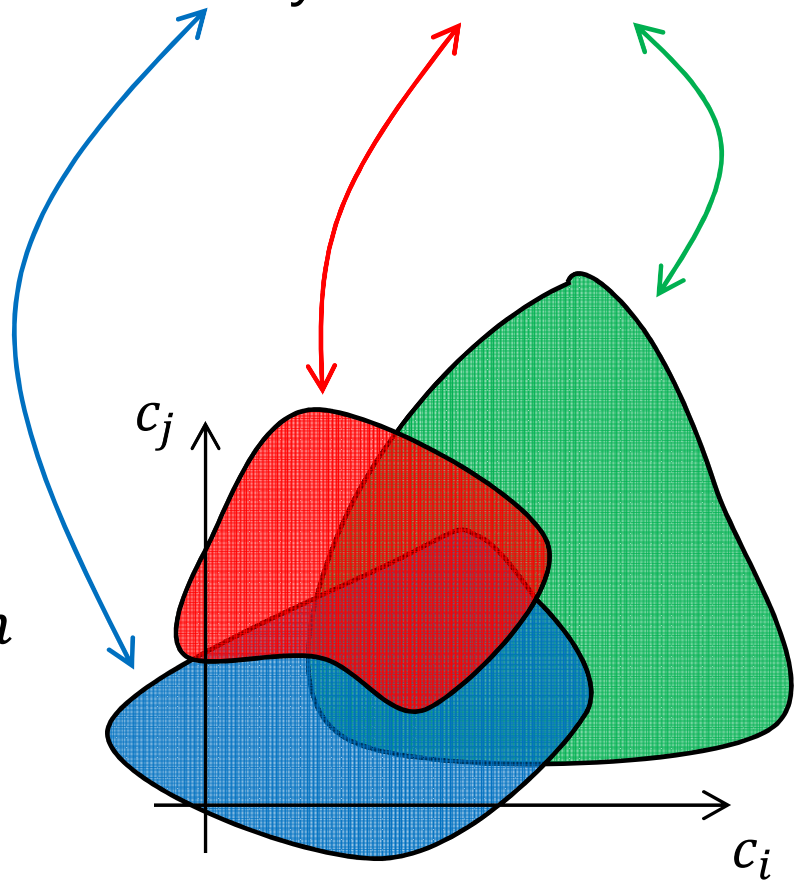

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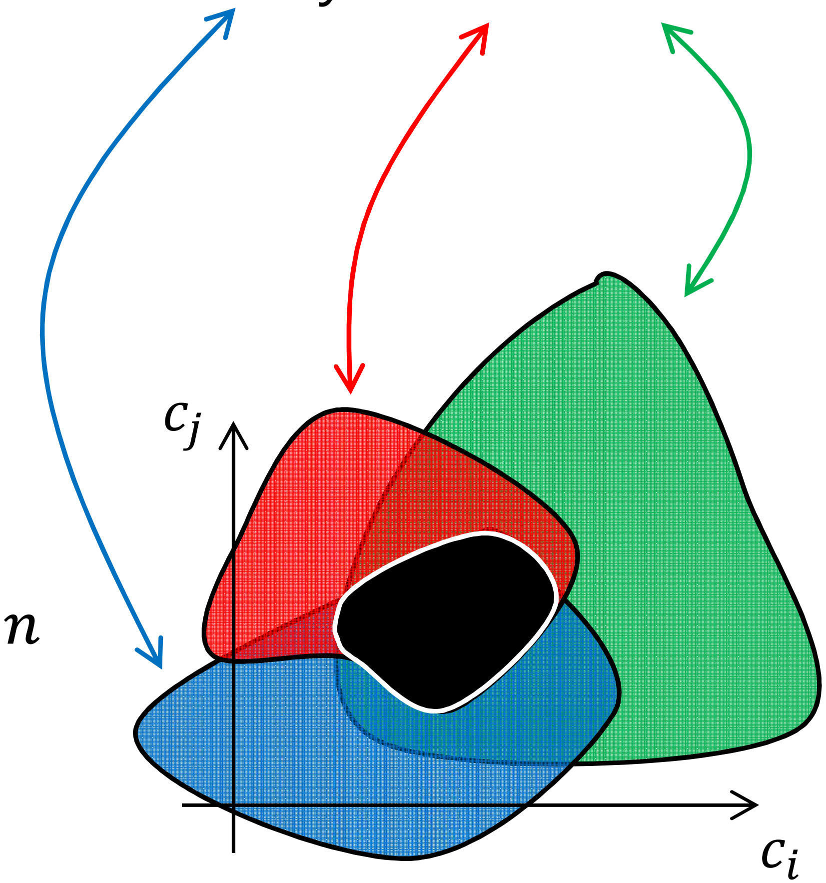

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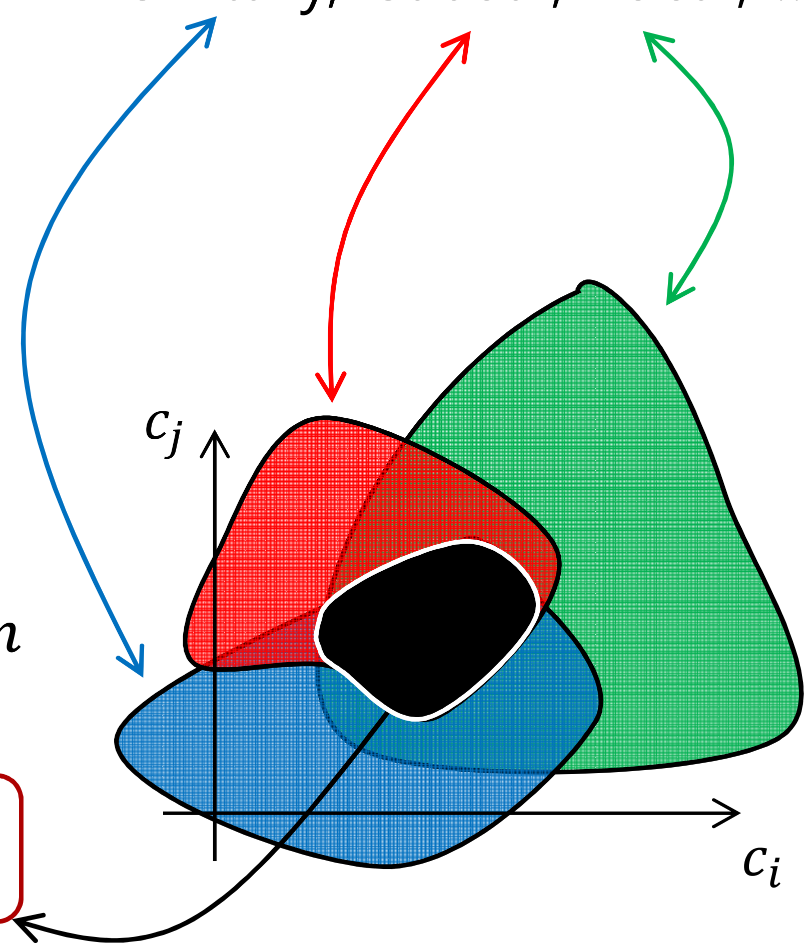

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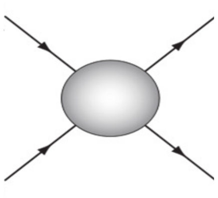


A_4

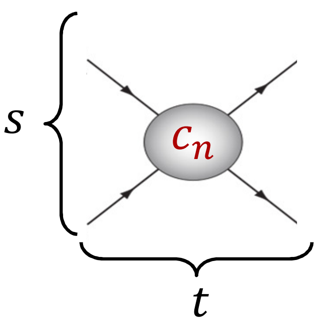
UV

$$\mathcal{L}_{UV} = \quad ?$$

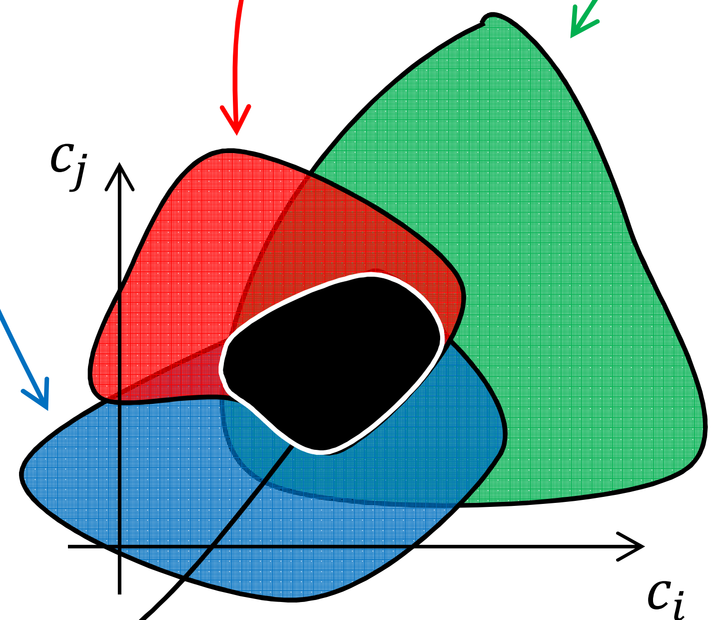
Unitary, Causal, Local, …

IR

$$\mathcal{L}_{EFT} = \sum \frac{c_n}{\Lambda^n} \mathcal{O}_n$$



A_4



UV

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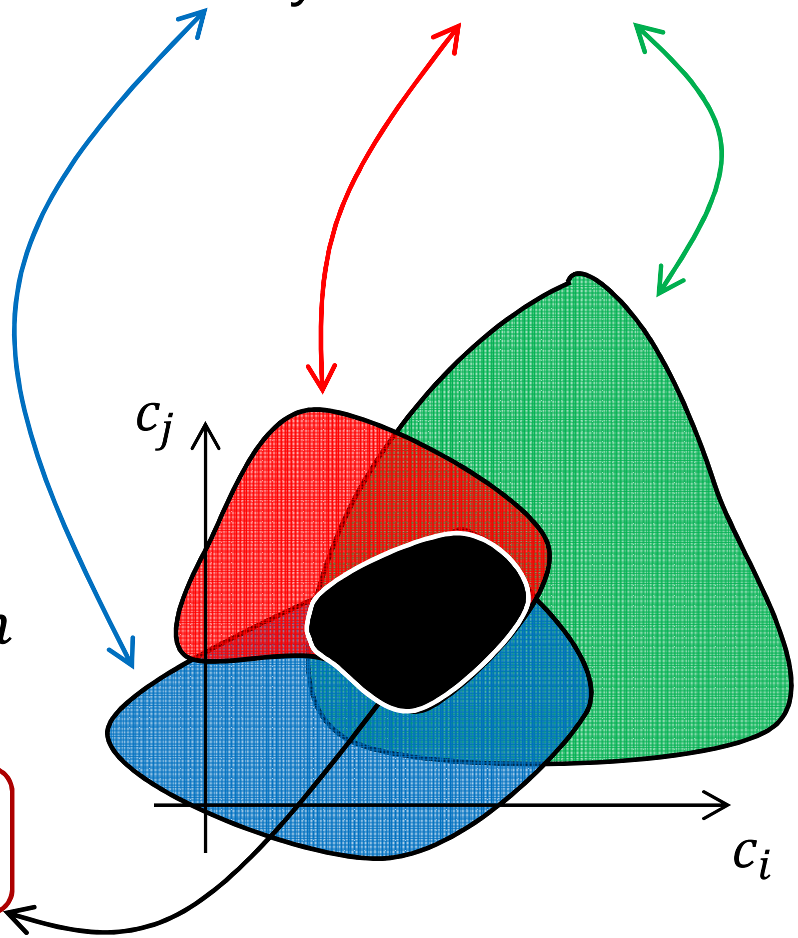
Unitary, Causal, Local, ...



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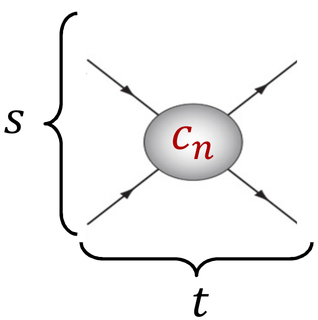


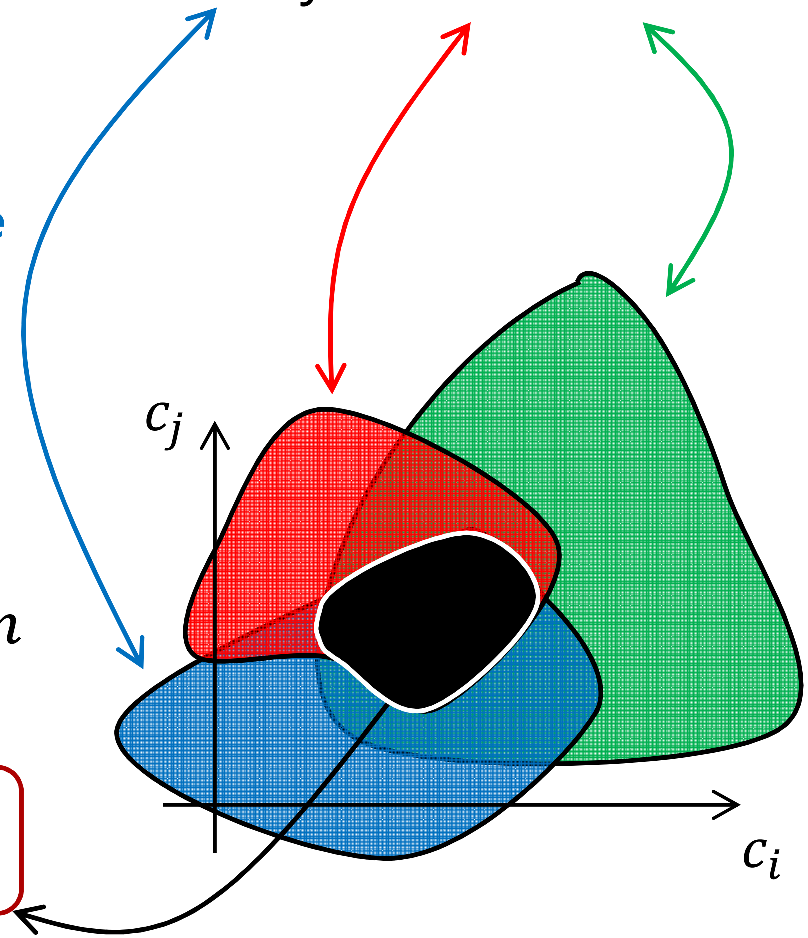
$$A_4(s, t; c_n)$$

UV

$$\mathcal{L}_{UV} = \quad ?$$

Unitary, Causal, Local, ...

Im A **positive**



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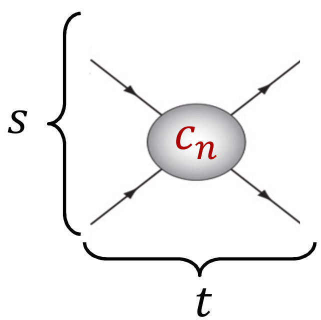


$$A_4(s, t; c_n)$$

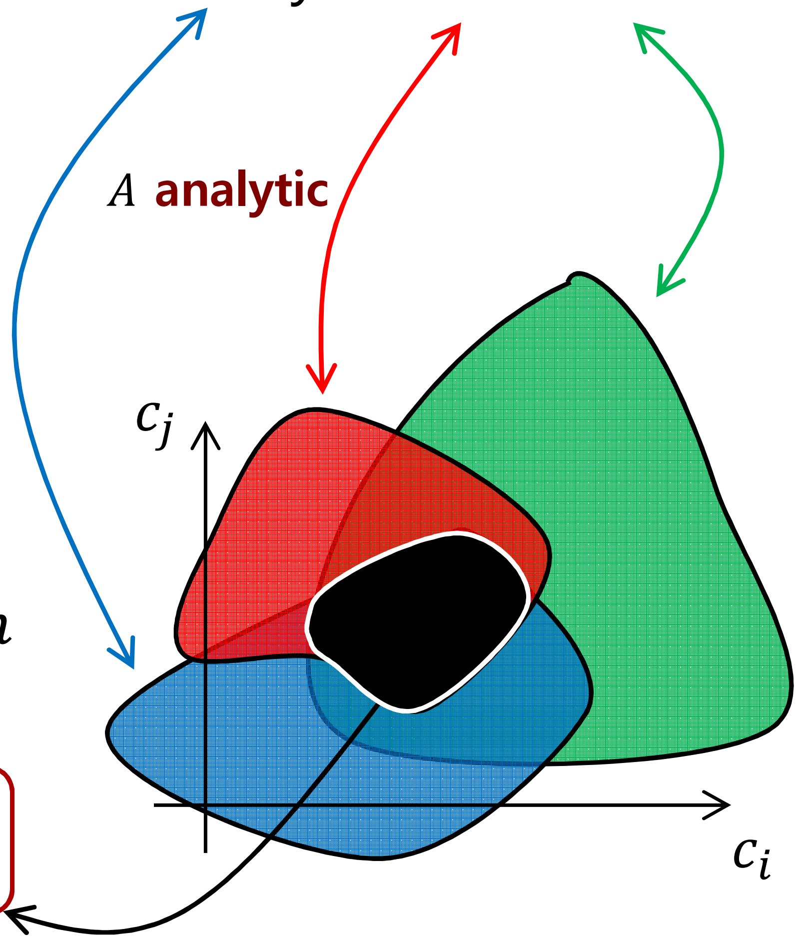
UV

$$\mathcal{L}_{UV} = \quad ?$$

Unitary, Causal, Local, …

$\mathrm{Im}\, A$ **positive**

A **analytic**



IR

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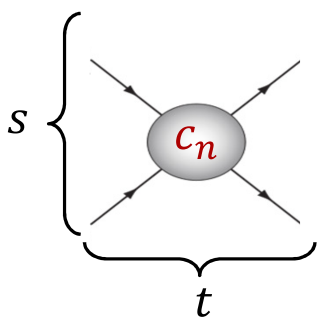

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Unitary, Causal, Local, ...

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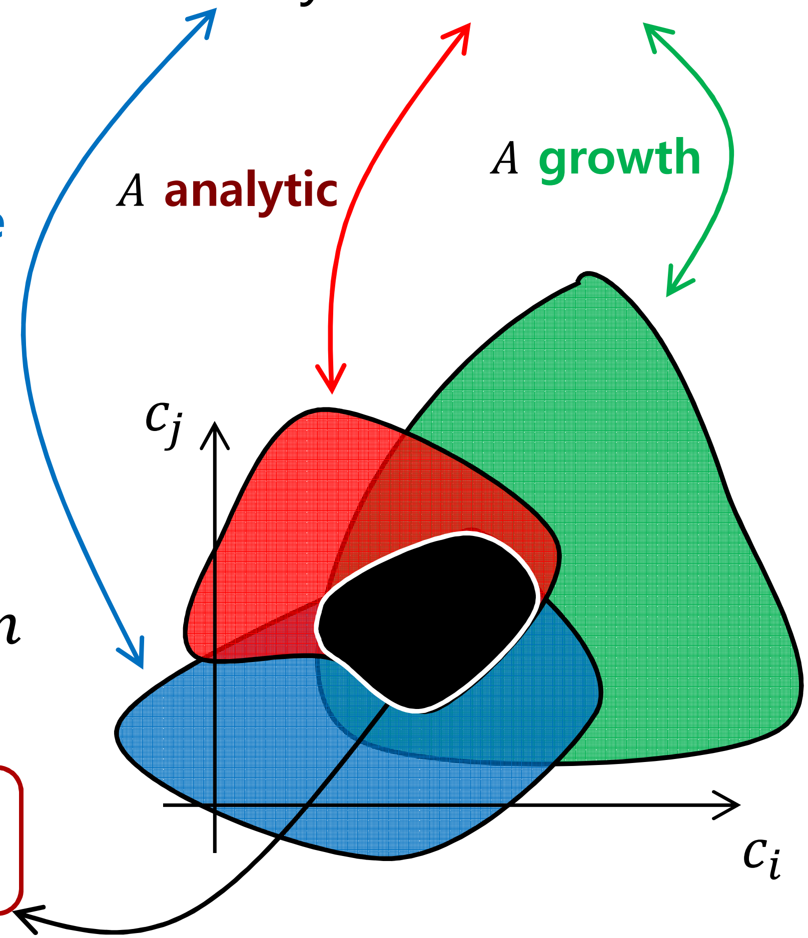

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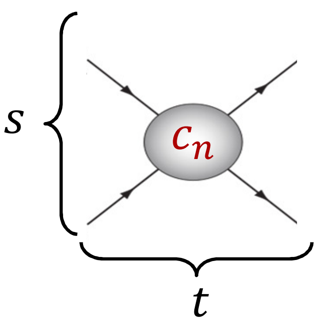


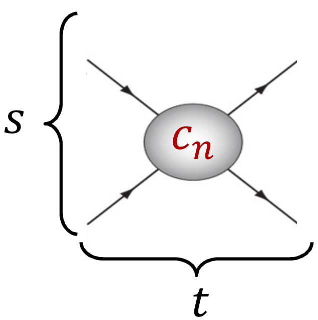
$$\boxed{A_4(s, t; c_n)}$$

UV

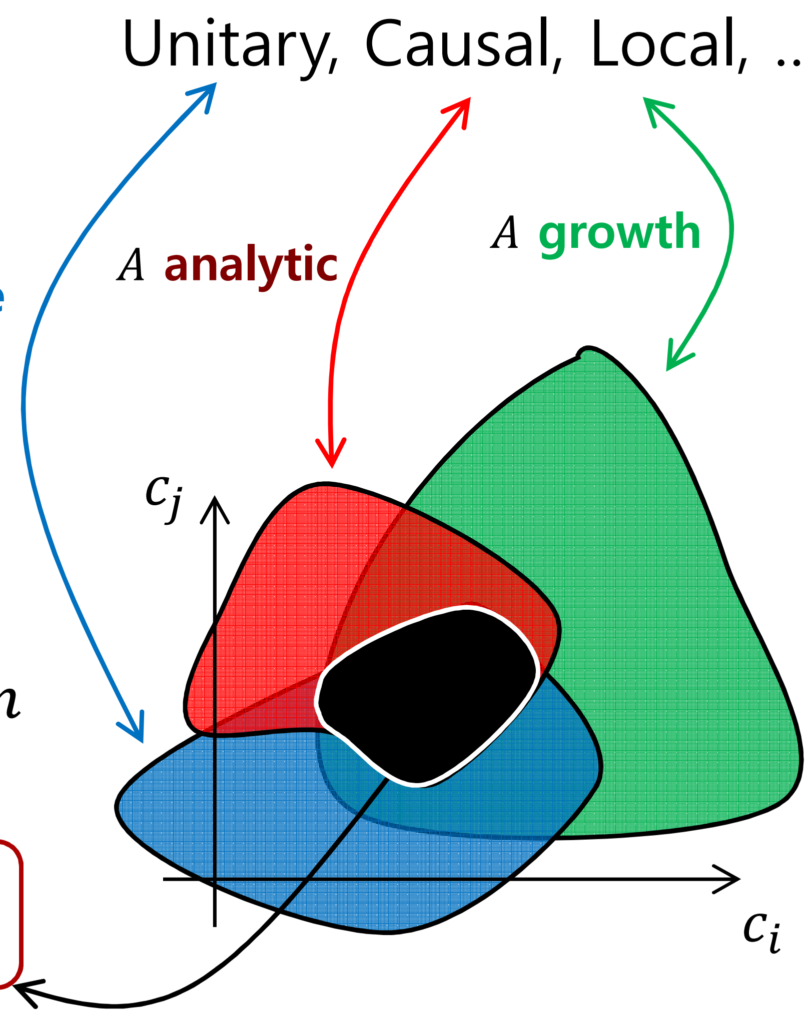
$$\mathcal{L}_{UV} = \quad ?$$

IR

$$\mathcal{L}_{EFT} = \sum \frac{c_n}{\Lambda^n} \mathcal{O}_n$$



$$\boxed{\partial_t^{\#} \partial_s^{\#} A_4(s, t; c_n) > 0}$$



UV

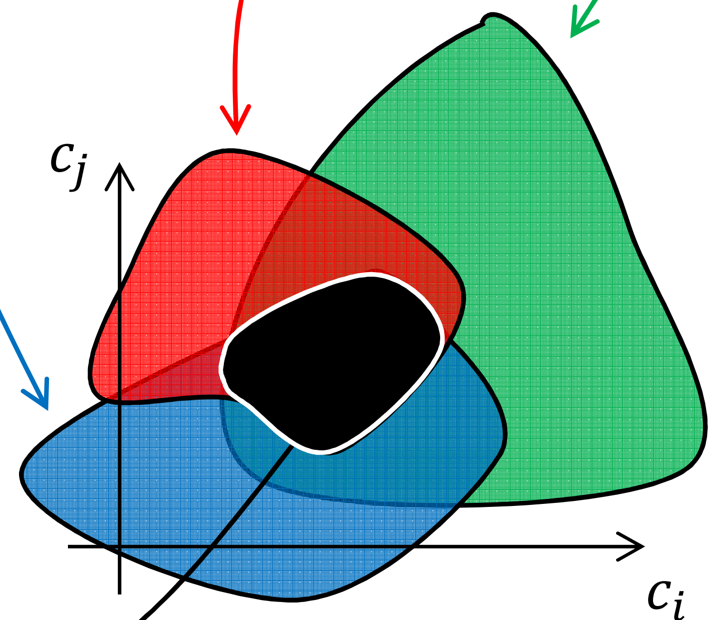
$$\mathcal{L}_{UV} = \quad ?$$

Unitary, Causal, Local, ...

$\mathrm{Im}\, A$ **positive**

A **analytic**

A **growth**



IR

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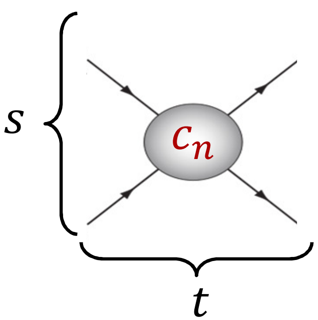

$$\boxed{\partial_t^{\#} \partial_s^{\#} A_4(s, t; c_n) > 0}$$

Positivity Bound

Positivity bounds can constrain IR sound speed without an explicit UV completion

Λ

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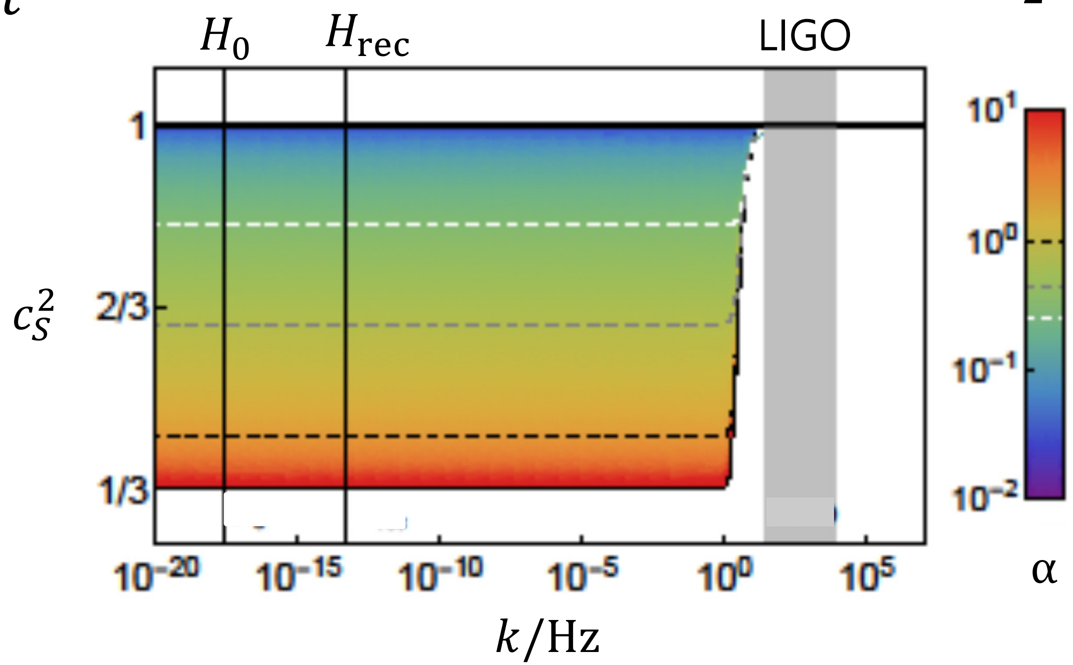
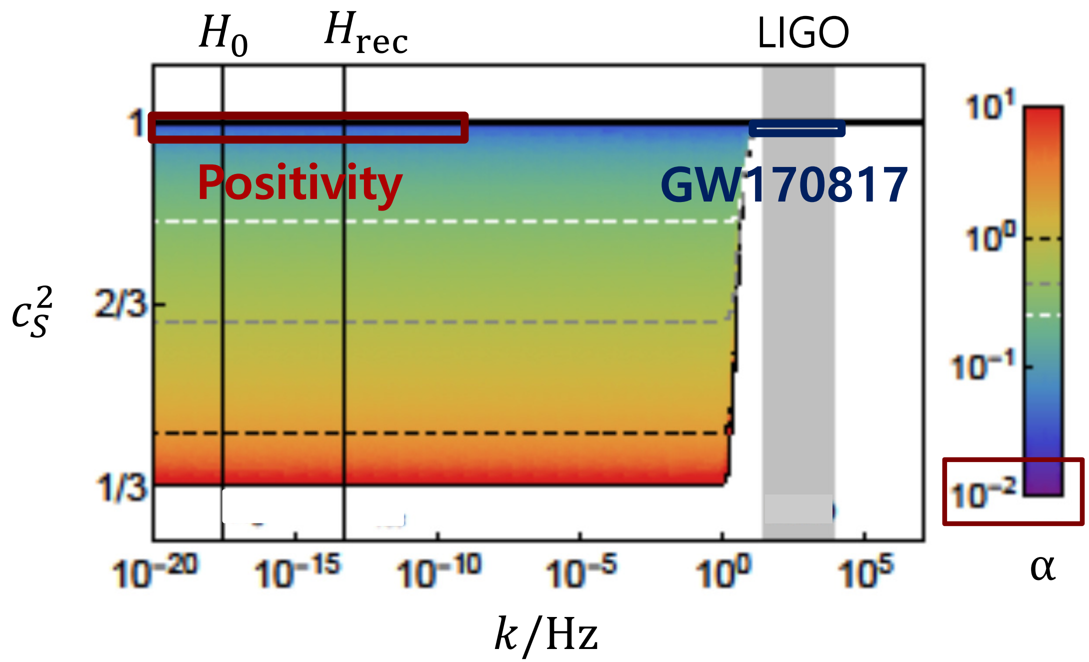


Positivity bounds can constrain IR sound speed without an explicit UV completion

Λ

$$\langle \phi \rangle = \alpha \Lambda^2 t$$

$$\mathcal{L} = \quad ???$$



The Future

Theory

Experiment

Theory

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

Experiment

Theory

e.g. Horndeski Higher Derivatives

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

Experiment

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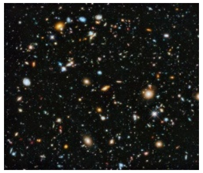
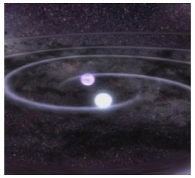


Cosmology Mergers

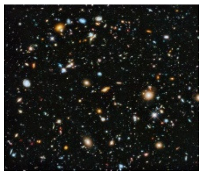


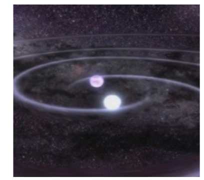
Experiment

Theory

e.g. Horndeski Higher Derivatives

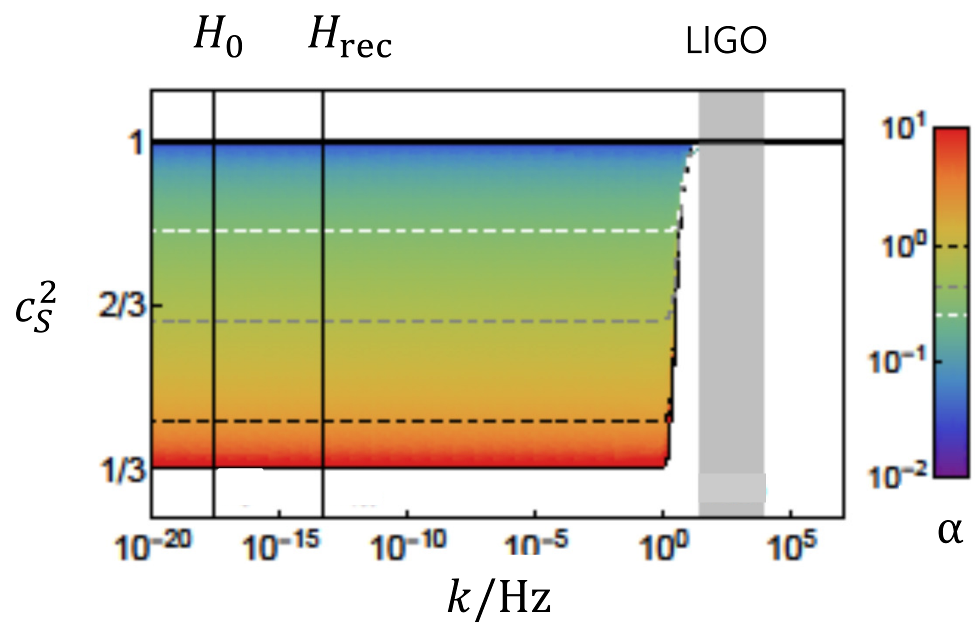
$$\mathcal{L}_{EFT} = \mathcal{L}_{LO} + \mathcal{L}_{NLO} + \cdots$$


Cosmology

Mergers


Experiment

Lower energy measurements



Theory

e.g. Horndeski Higher Derivatives

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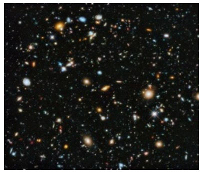
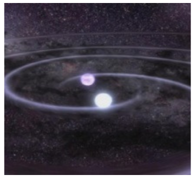


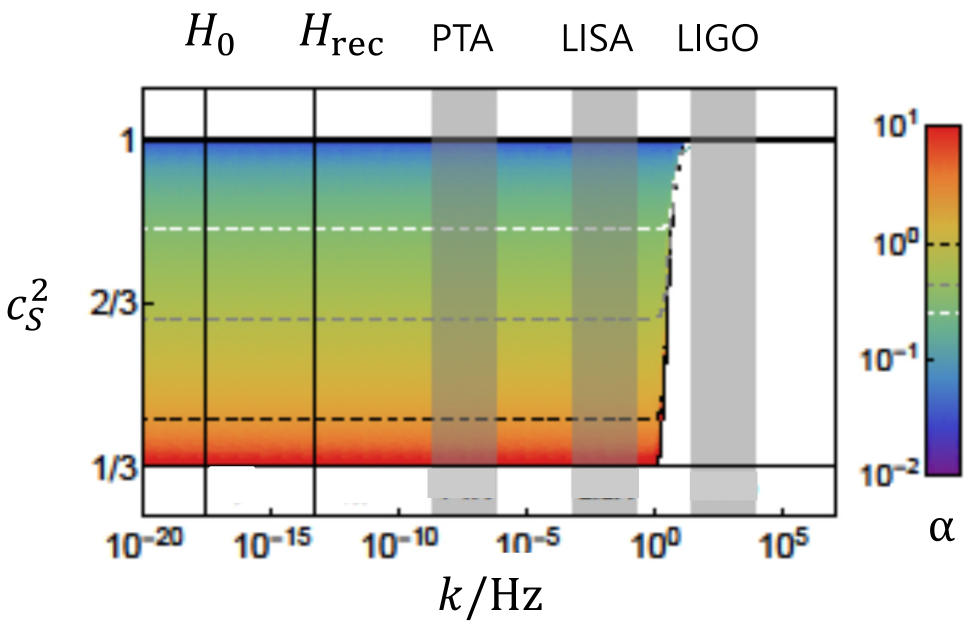
Cosmology

Mergers



Experiment

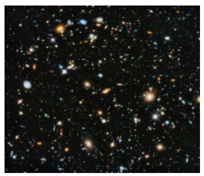
Lower energy measurements



Theory

e.g. Horndeski Higher Derivatives

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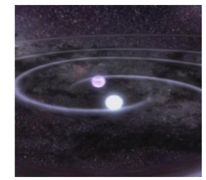
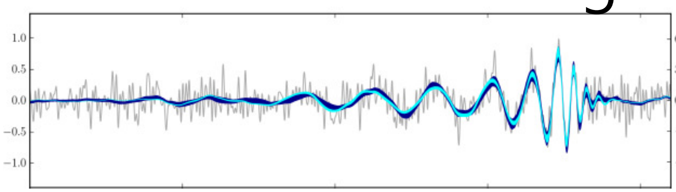
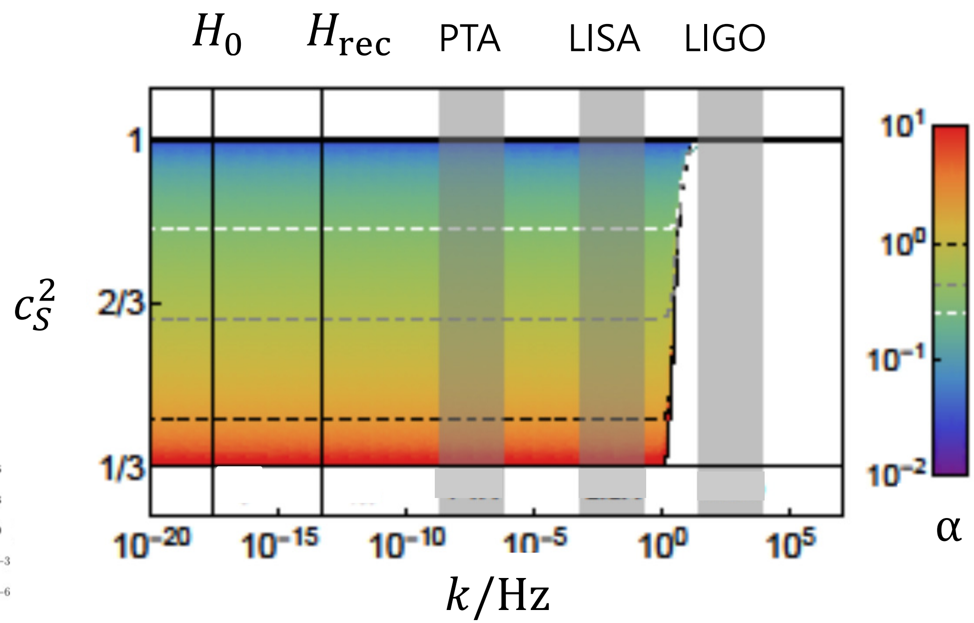


Experiment

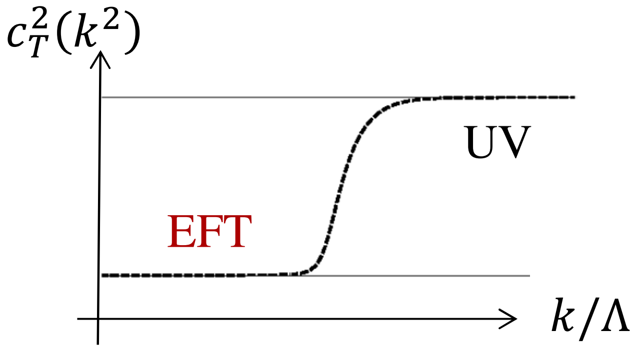
Lower energy measurements

Rainbow stretching

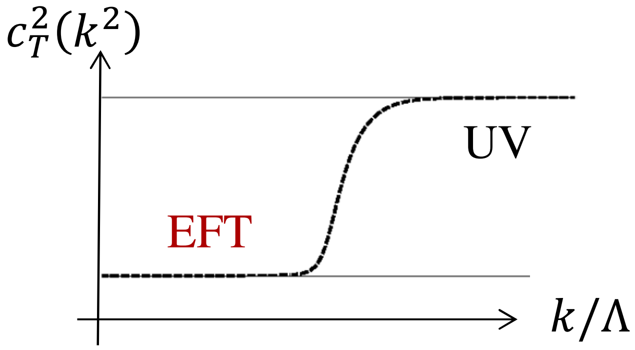




Summary

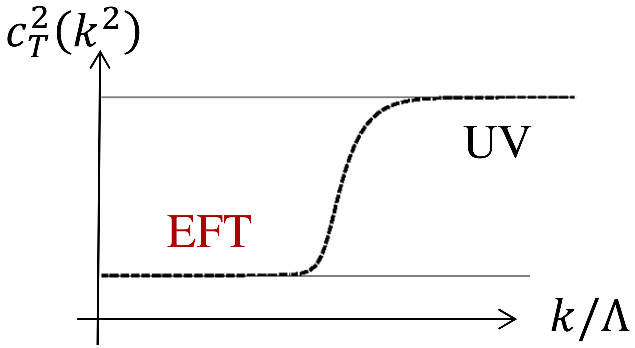


Only **low energy** measurements constrain **EFT** parameters!



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

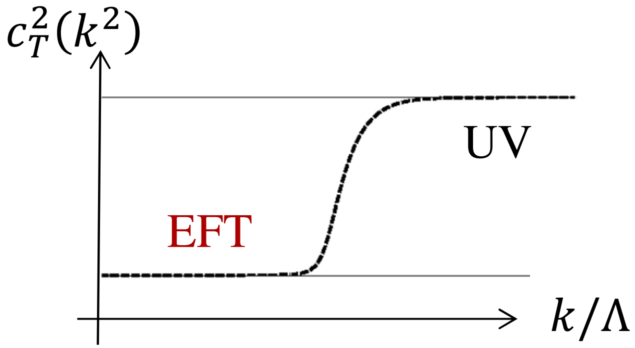
$$\Delta c_T^2(50\mathrm{Hz}) < 10^{-15} \quad \Rightarrow \quad \sum_n^\infty c_n \left(\frac{50\mathrm{Hz}}{\Lambda_3}\right)^n < 10^{-15} \quad \text{in EFT}$$



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

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

Guess UV Completion $\Rightarrow$ $g\,M < 10^{-4}$ in UV



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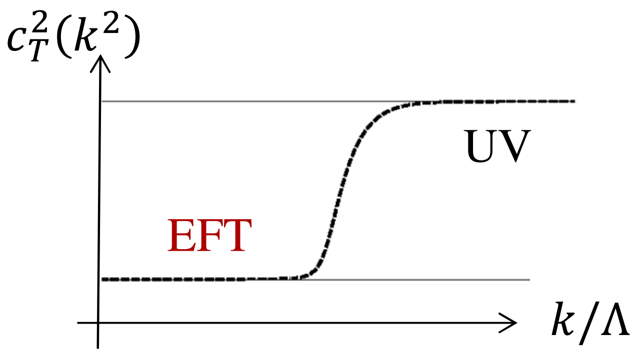
Guess UV Completion $\Rightarrow$ $g\, M < 10^{-4}$ in UV

Assume UV exists $\Rightarrow$ $\Delta c_T^2(0) < \alpha^2 \frac{m^2}{\Lambda^2} C_2$ in EFT



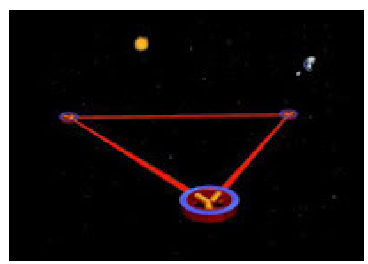
Only **low energy** measurements constrain **EFT** parameters!

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

Guess UV Completion $\Rightarrow$ $g\, M < 10^{-4}$ in UV

Assume UV exists $\Rightarrow$ $\Delta c_T^2(0) < \alpha^2 \frac{m^2}{\Lambda^2} C_2$ in EFT

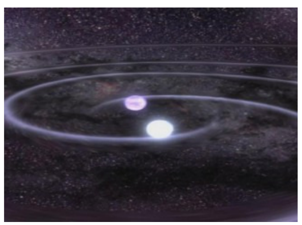
$$1 \gtrsim \Delta c_T^2(H_0) > \Delta c_T^2(\text{LISA}) > \Delta c_T^2(\text{LIGO}) \gtrsim 0$$

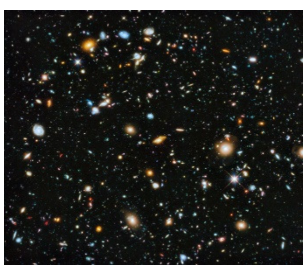


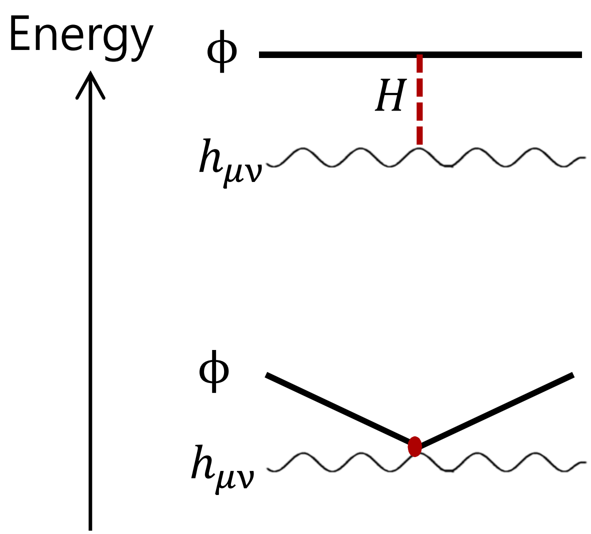
IPMU 22 Aug 2018

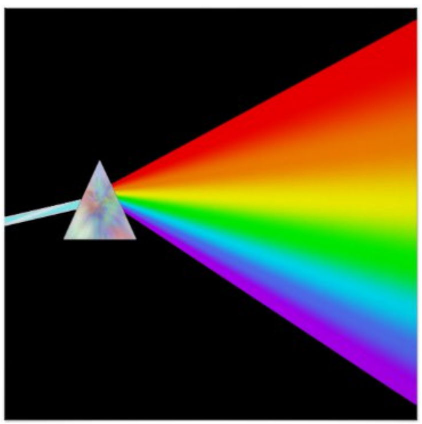
Speed Limits from Gravitational Waves

Scott Melville









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