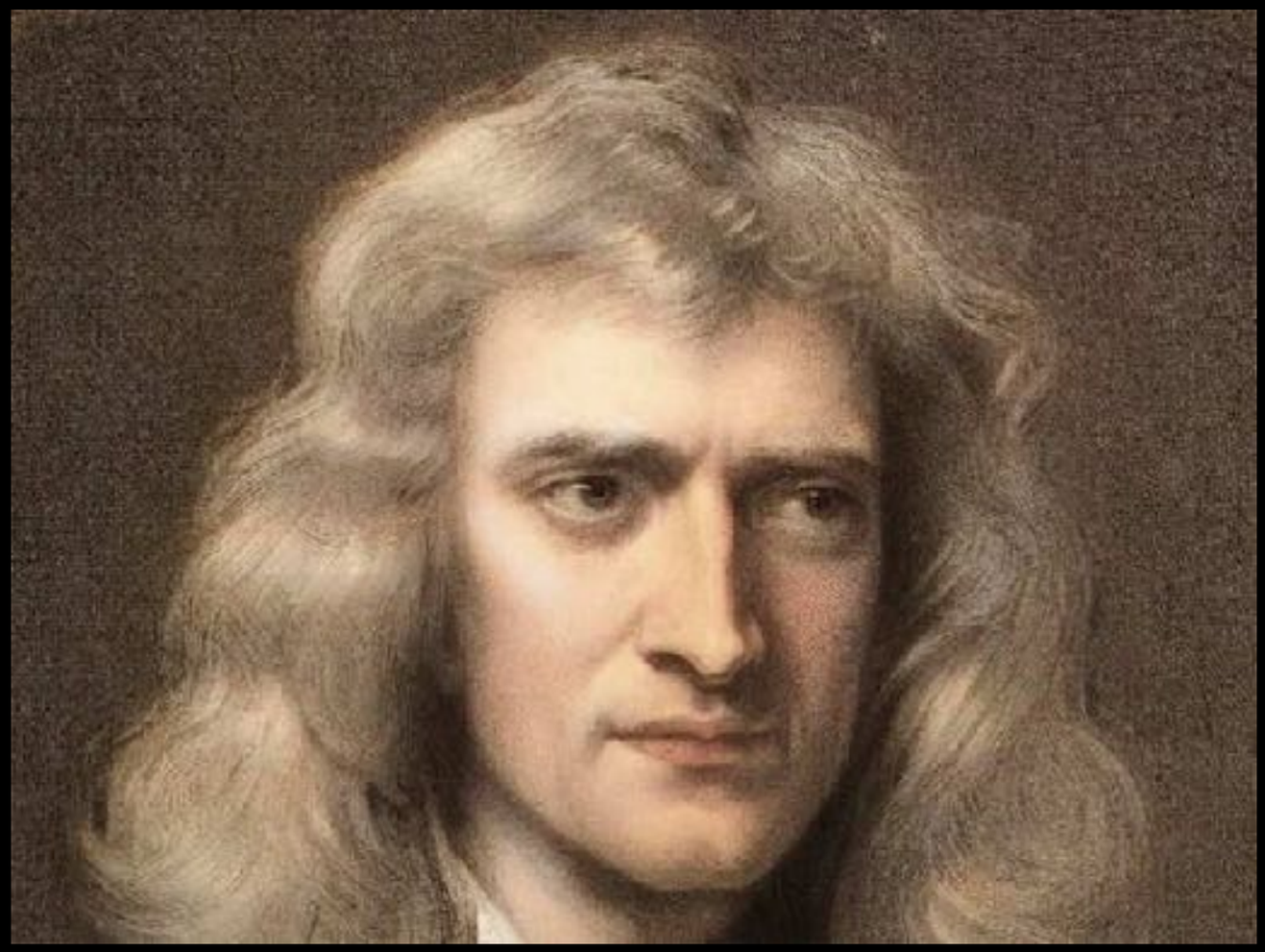
Analytical Methods in Cosmology, IHP Sept 2018

# Gravity as an Open system: Turning up the heat



La loi, c'est moi

CP Burgess

CPB, Holman, Kaplanek, Rummel Tasinato, Williams 1408.5002 & 1512.00169 & 1806.11415

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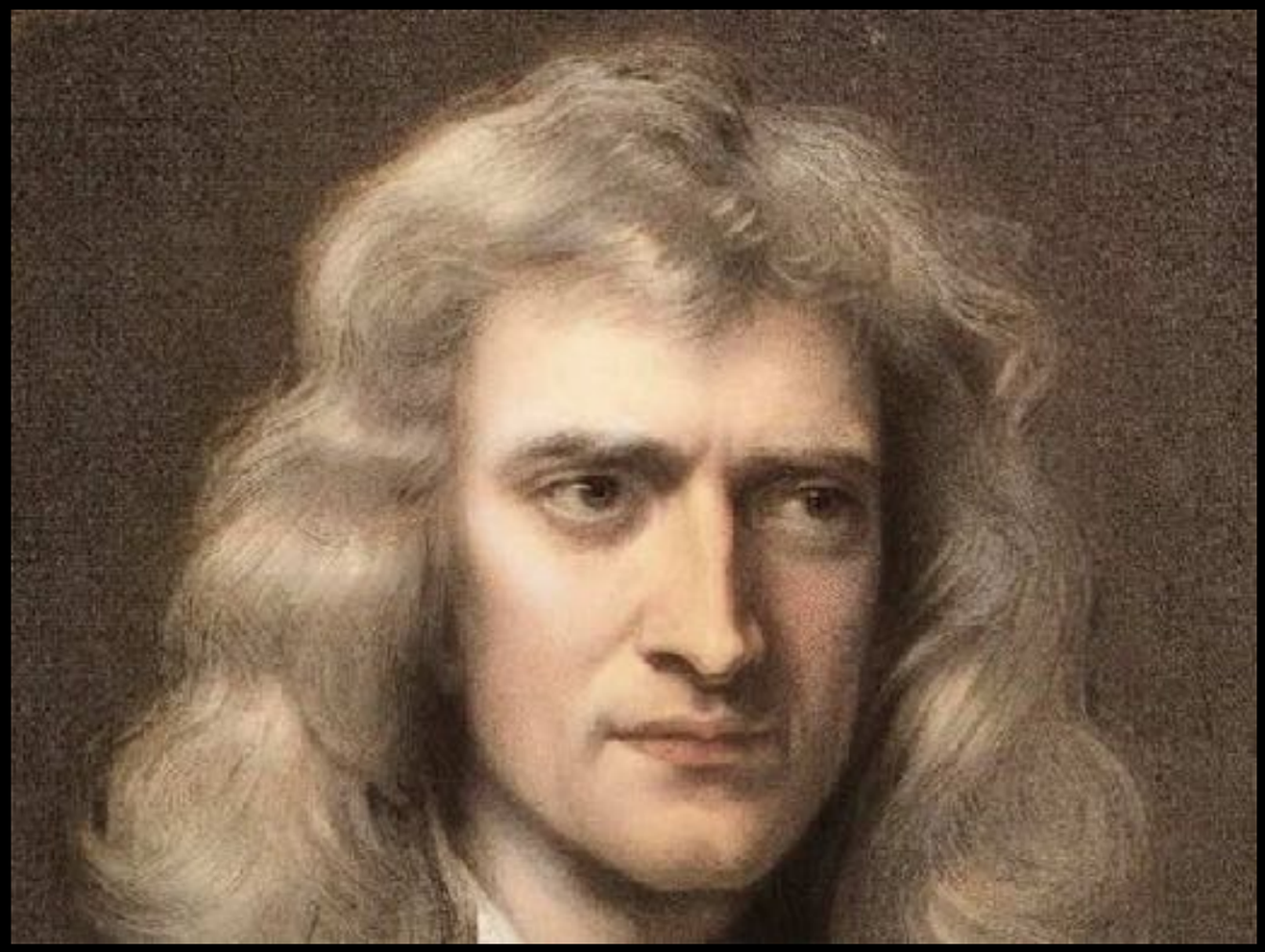
# Gravity as an Open system: Turning up the heat



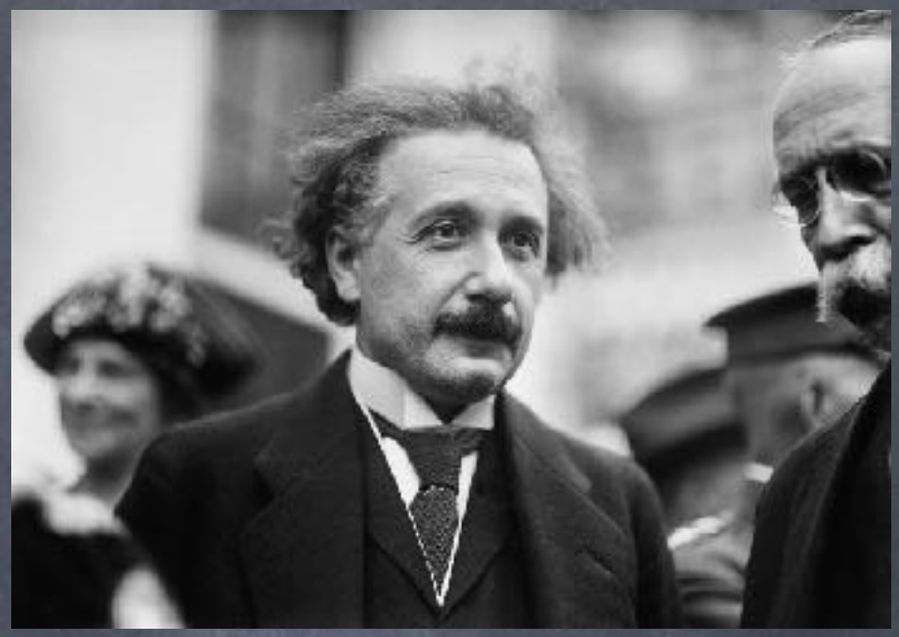
CP Burgess

La loi, c'est moi
Sylvester Stalone (Judge Dredd)

CPB, Holman,
Kaplanek, Rummel
Tasinato, Williams
1408.5002 &
1512.00169 &
1806.11415

# The Punchline

- Gravitational Exceptionalism: (quantum effects in) gravitational fields are unique, particularly for strong fields

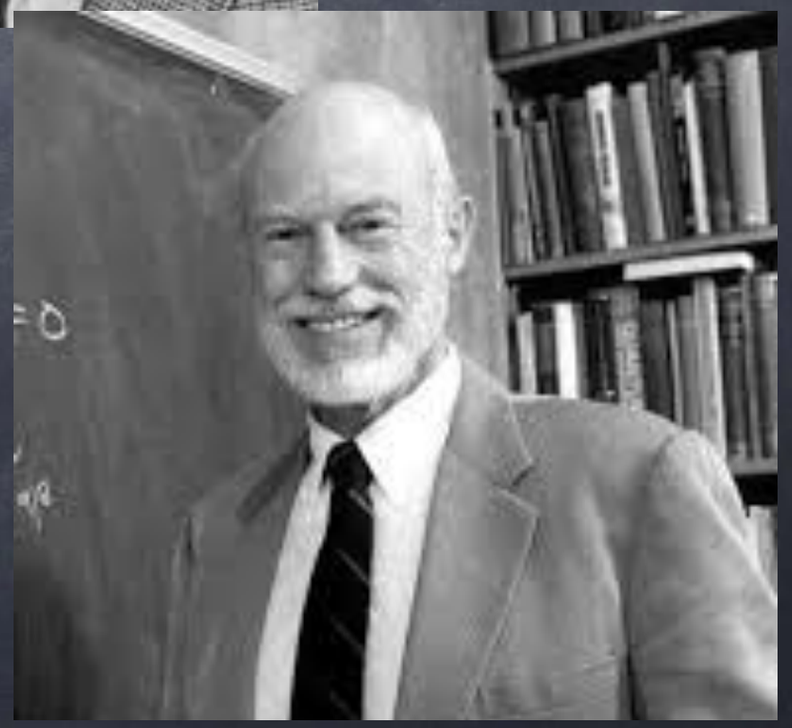


- Nothing much to be learned from other interactions

# The Punchline

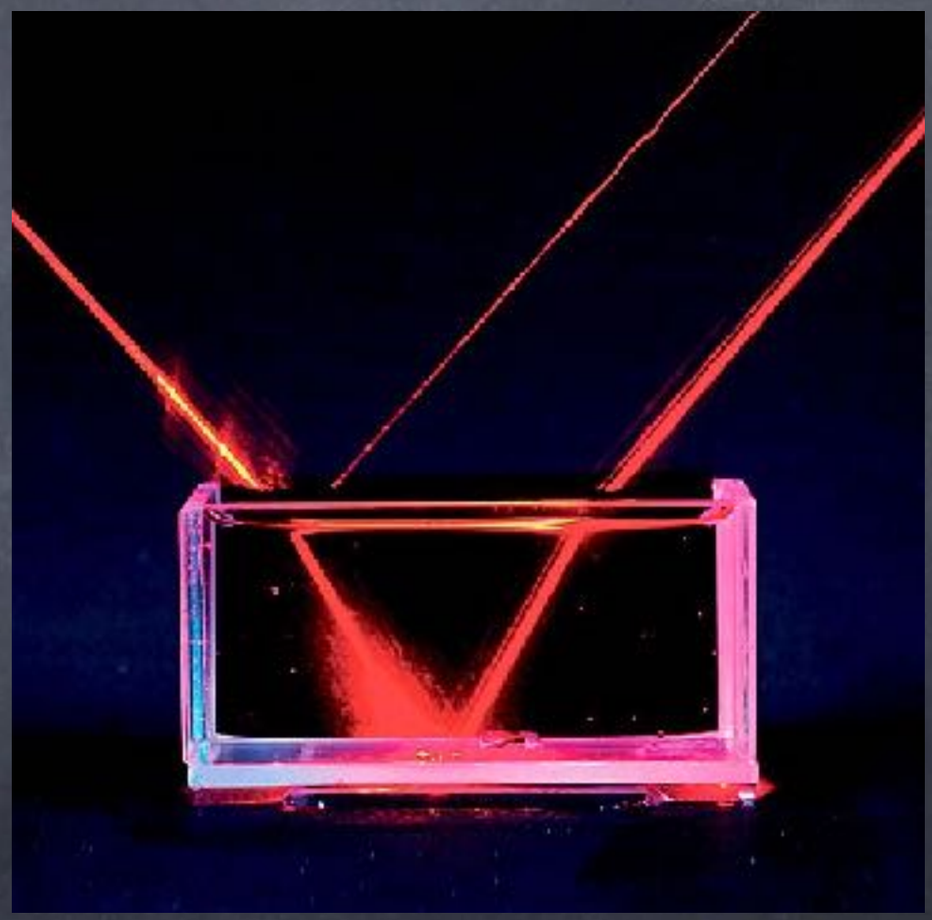
- Gravitational banality: gravity is a particular case of a gauge interaction

- Everything is a Wilsonian EFT



# The Punchline

- Both are wrong: gravitational systems are more than Wilsonian, but not unique
  - can learn much from condensed matter / optical physics



# The Punchline

- Wilsonian party line: quantum effects in gravitational fields controlled by derivative expansion
  - e.g. Hawking radiation: series in $l_p/r_s$
  - e.g. inflation: series in $H/M_p$

$$\mathcal{A}_E(Q) \sim \left(\frac{Q^2}{M_p^{E-2}}\right)\left(\frac{Q}{4\pi M_p}\right)^{2L}\prod_{i,d>2}\left(\frac{Q}{M_p}\right)^{2V_{id}}\left(\frac{Q}{m}\right)^{(d-4)V_{id}}$$

see e.g. gr-qc/0311082

# The Punchline

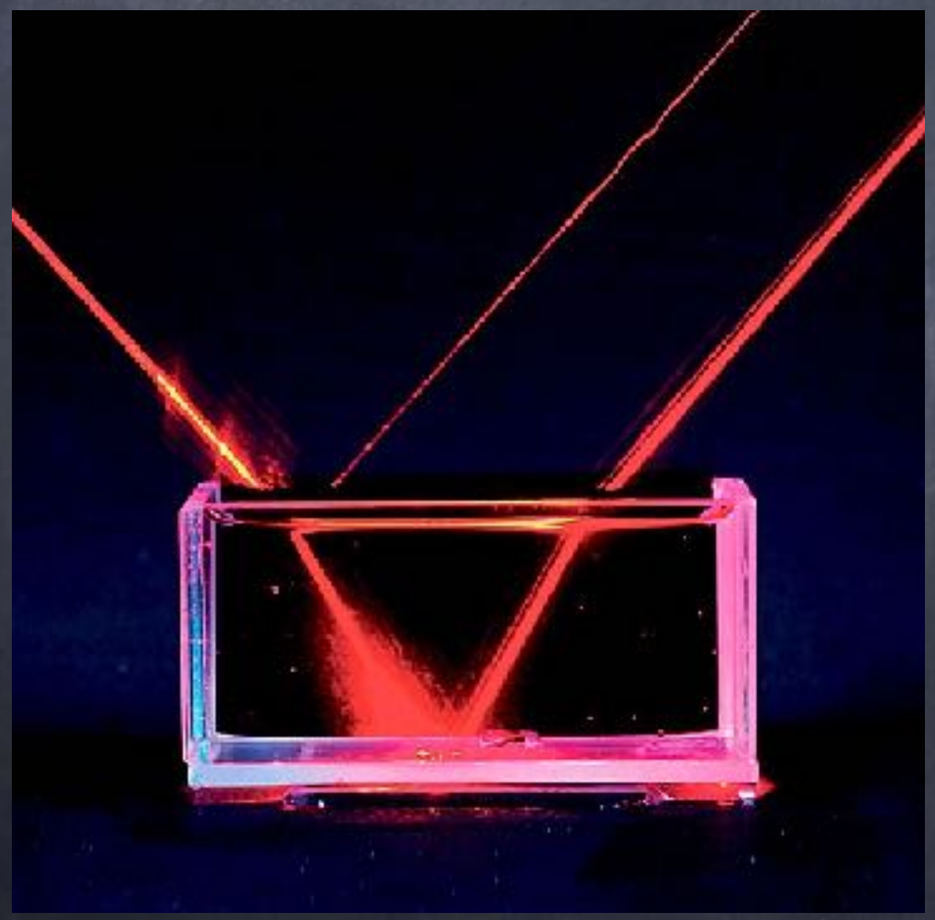
- BUT: there are suggestions EFT methods break down at late times even at small curvatures
  - secular growth and IR sensitivity in cosmological perturbations
  - information loss at late times for BHs
- Can domain of validity of EFT sometimes require more than small curvatures?

# The Punchline

- Will argue: EFT with gravity can differ from ordinary Wilsonian EFT
  - similar to effective description of particles in a medium
  - generic problems with late-time perturbative predictions (tho resummation methods exist)
  - can involve issues of open systems

# The Punchline

- Late-time breakdown of perturbation theory illustrated by geometrical optics regime



Naive perturbation theory fails at late times

Can nevertheless simplify when there is a hierarchy of scales

eg: $H_{int} = E.D$ gives $dH_A = a\ E^2$
where $a = n-1 = \langle D\ D \rangle \sim N_{atom}$

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- Motivation
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  - Secular effects near dS space
- Horizons
  - thermal and UV/IR issues
- Open vs Wilsonian EFTs
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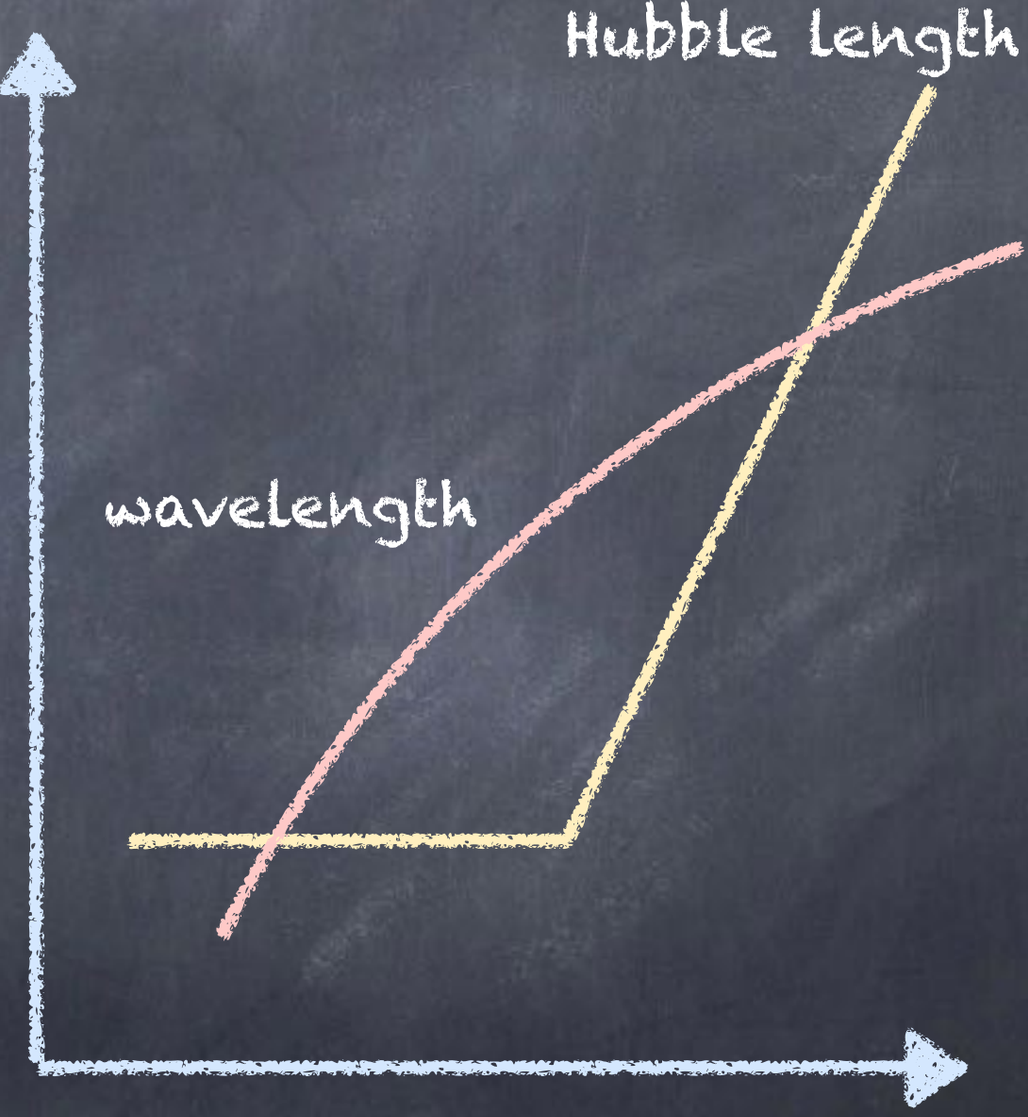
# Cosmology

- Extra-Hubble modes are key to success of inflationary predictions
  - What is their EFT?
- What quantifies theoretical error?



# Cosmology

- Predictions: free fields on curved background
- Corrections can be both IR divergent and break down at late times

$$\mathcal{L} = -\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + \frac{\lambda}{4!}\,\phi^4\right]$$

$$\langle\phi^{2n}\rangle = (2n-1)!!\left(\frac{H^2}{4\pi^2}\,\ln a\right)^n\left[1 - \frac{n(n+1)}{2}\left(\frac{\lambda}{36\pi^2}\right)\ln^2 a + \cdots\right]$$

Tsamis & Woodard

# Cosmology

- IR divergences/secular growth are gauge artefacts for single-field (single-clock) models

Senatore, Zaldarriagga
Giddings, Sloth

- General statement (multiple scalars, other massless fields, tensor modes, etc) not known, but IR divergences should cancel from physical observables

# Cosmology

- Normally IR divergences cancel for physical quantities (a la Bloch-Nordsieck)

- Often large logarithms survive IR cancellation, with IR scale that is system-dependent (not universal)

$$A \ln\left(\frac{\mu}{\omega}\right) + A \ln\left(\frac{m}{\mu}\right) = A \ln\left(\frac{m}{\omega}\right)$$

# Cosmology

- Breakdown of perturbation theory at late times has its root in a general issue when interacting with medium

$$\langle \phi^{2n} \rangle = (2n-1)!! \left( \frac{H^2}{4\pi^2} \ln a \right)^n \left[ 1 - \frac{n(n+1)}{2} \left( \frac{\lambda}{36\pi^2} \right) \ln^2 a + \cdots \right]$$

- Failure of perturbative methods generic at late times because the medium never goes away:

$$U(t) = \exp\Big[ -i(H_0 + H_{\rm int})t \Big]$$

- Resummation possible through stochastic methods

Starobinsky, Yokoyama

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# Horizons

- Do similar effects arise for black holes?
  - few explicit calculations with interactions
- Quantum systems believed thermal - use this
  - should see late-time breakdown found in thermal environments

Hawking
Unruh

- Simplest case: Rindler space
  - thermal and UV/IR issues hidden in interacting Minkowski vacuum

CB, Kaplanek,
& Rummel

# Horizons

- What late-time, IR issues occur for thermal systems?

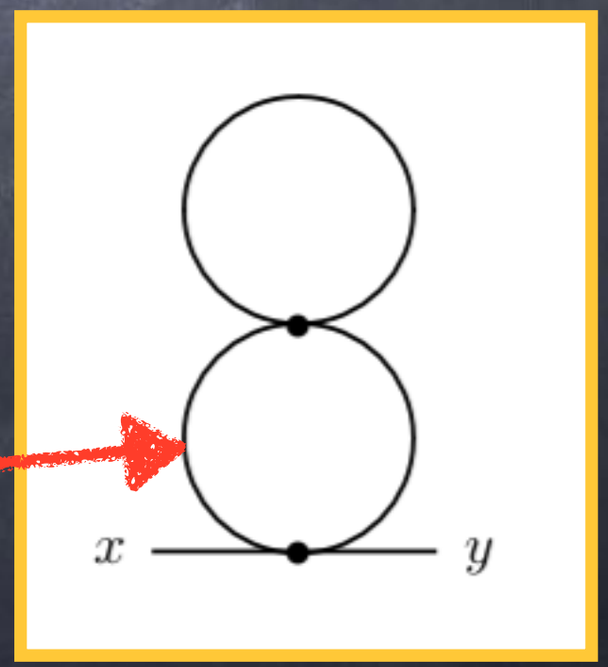
  Gross, Pisarski
  Mermin, Wagner
  Coleman
  Wilson

  - secular growth at late times
  - breakdown of mean-field theory near critical points

- Power-law IR divergences

$$\mathfrak{L}_{\rm int} = \lambda\phi^4$$

$$\int \frac{\mathrm{d}^4k}{e^{k/T}-1}\left(\frac{1}{k^2}\right)^2 \sim \int \frac{\mathrm{d}^4k}{k^4}\left(\frac{T}{k}\right)$$



# Horizons

- Loops need not be counted just by $\lambda$

$$\left(\frac{\lambda}{16\pi^2}\right)\frac{T}{m}$$

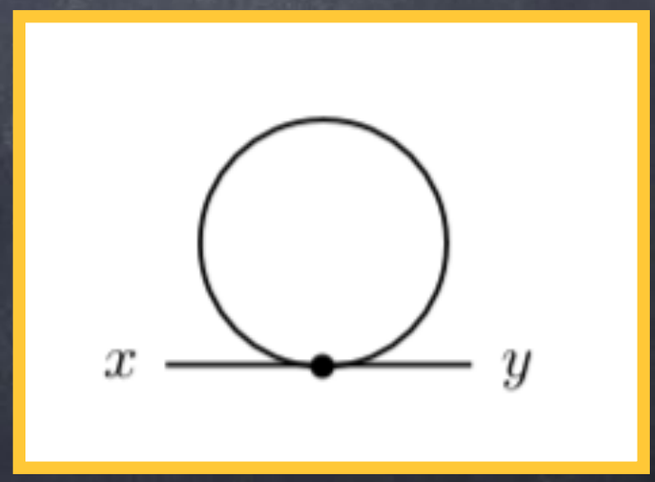
Gross, Pisarski

- Nonzero temperature gives mass shift

$$m^2(T) = m_0^2 + \frac{\lambda T^2}{4}$$

- Late-time behaviour

$$\delta G(t, \mathbf{x} = 0) \propto \lambda T^3 t$$



# Horizons

- Minkowski vacuum is thermal for Rindler observers, Rinder vacuum is thermal for Minkowski observers

- Do these show late-time secular growth?

Paradox: how can zero-temperature Minkowski vacuum show thermal late-time behaviour?

# Horizons

CB, Kaplanek, & Rummel

- Minkowski 2-point function: G(x,y)

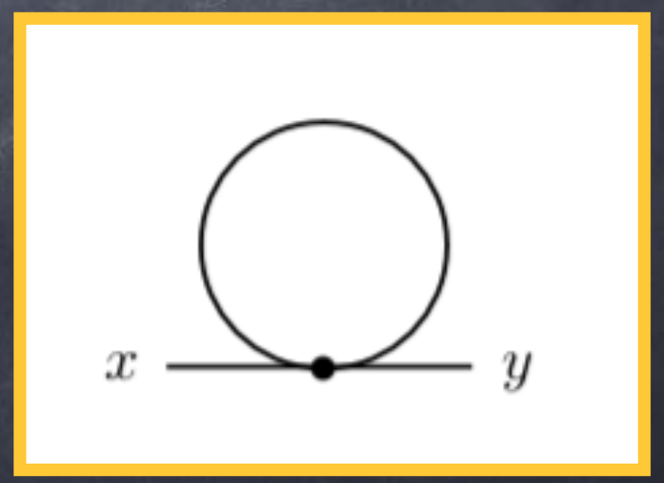
$$\delta G(x,y) \propto \delta m^2 \, \ln\left[s(x,y)\mu\right]$$

$$\delta m^2 = \lambda \left(\frac{a}{4\pi}\right)^2$$

$$s(x,y) = \frac{2}{a} \sinh\left(\frac{a\tau}{2}\right)$$

- late Rindler-time correction:

$$\delta G \propto \lambda a^3 \tau$$



# Horizons

CB, Kaplanek, & Rummel

- Minkowski 2-point function: G(x,y)

$$\delta G(x,y) \propto \delta m^2 \ln[s(x,y)\mu]$$

$$\delta m^2 = \lambda \left( \right)^2$$

$$s(x,y) = \frac{2}{a} \sin$$

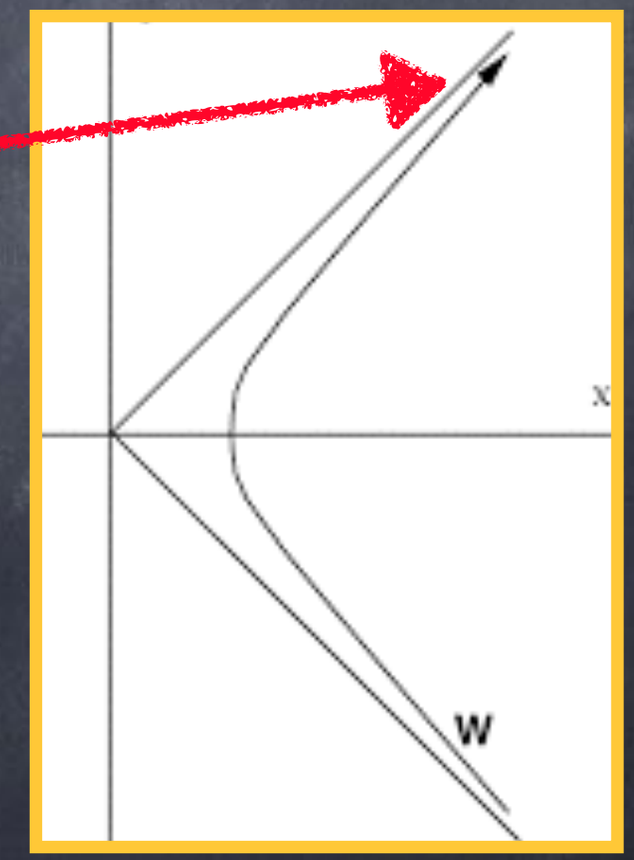
- Late Rindler-time correct

$$\delta G \propto \lambda a$$

No choice of counter term ensures both Minkowski & Rindler states have no late time growth

# Horizons

- Finite temp and Rindler agree on late-time behaviour, provided renormalized appropriately
  - Breakdown in perturbative expansion occurs along future horizon (late Rindler time)




- Can resum late-time behaviour: result falls like $\delta m^{1/2}\ s^{-3/2}$ instead of leading order $s^{-2}$

# Horizons

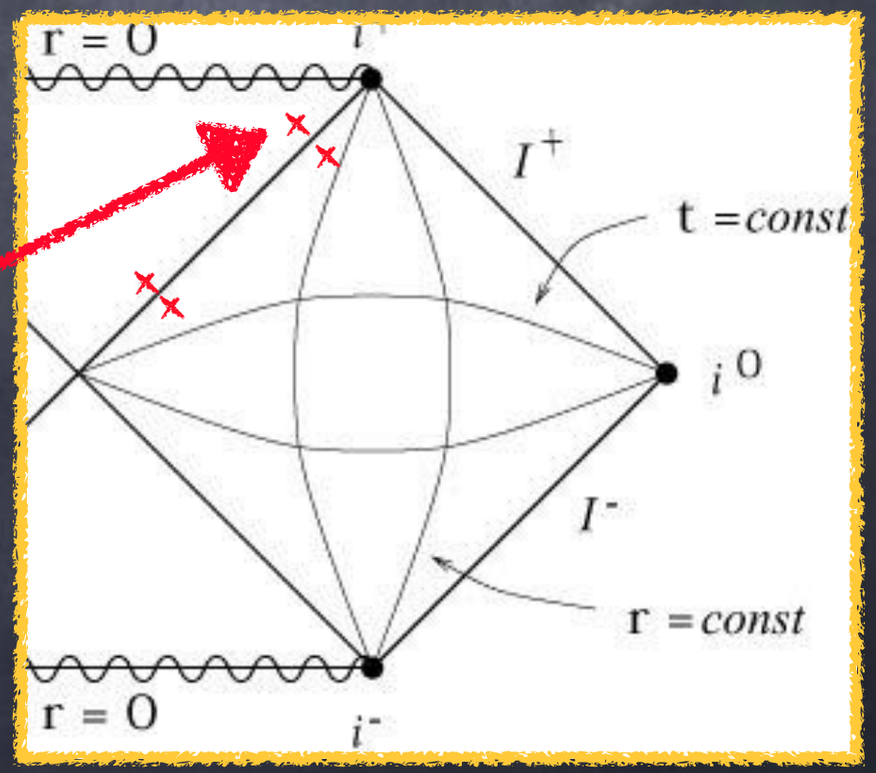
- Does the same behaviour occur for observers outside a BH?

CB, Kaplanek, & Rummel

  - Would indicate free theory in curved space is poor guide at late times

- Relevant to information arguments at Page time?

$$G(x_1, x_2, x_3, x_4)$$



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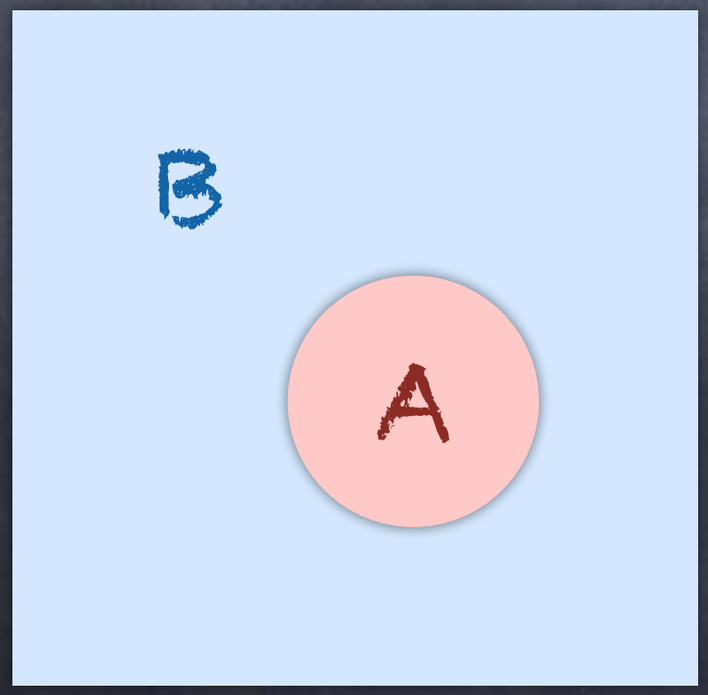
# Open EFTs

- Open EFTs: consider the evolution of a subset A of a larger system B

  eg: light in glass or neutrinos in Sun or super-Hubble modes during inflation




$$\rho_A = \mathrm{Tr}_B\, \rho$$

$$\frac{\partial \rho}{\partial t} = -i\Big[\rho, H_{\rm int}\Big]$$

# Open EFTs

- Open EFTs: direct perturbative evolution shows state generically depends on entire entanglement history

$$\rho(t) = \rho_0 - i\int_0^t \mathrm{d}\tau \Big[H_{\rm int}(\tau), \rho_0\Big] + (-i)^2 \int_0^t \mathrm{d}\tau \int_0^\tau \mathrm{d}\tilde{\tau} \Big[H_{\rm int}(\tilde{\tau}), \Big[H_{\rm int}(\tau), \rho_0\Big]\Big] + \cdots$$

but can simplify if correlations die out over time

$$\langle H_{\rm int}(t) H_{\rm int}(t+\tau)\rangle_B \to 0 \qquad \text{for} \quad \tau \gg t_c$$

provided tc << tp not so large that perturbation theory fails

# Open EFTs

- Open EFTs: can then define 'coarse-grained' time evolution for state of system A

$$\frac{D\rho_A}{dt} \equiv \frac{\rho_A(t+\Delta t) - \rho_A(t)}{\Delta t}$$

$$= -i\left[\rho_A, \overline{H}_{\rm int}\right] + \int \mathrm{d}\tau \mathrm{Tr}_B \left[\rho(t), \left[H_{\rm int}(t), H_{\rm int}(\tau)\right]\right] + \cdots$$

$$= F(\rho_A, \rho_B, H_{\rm int})$$

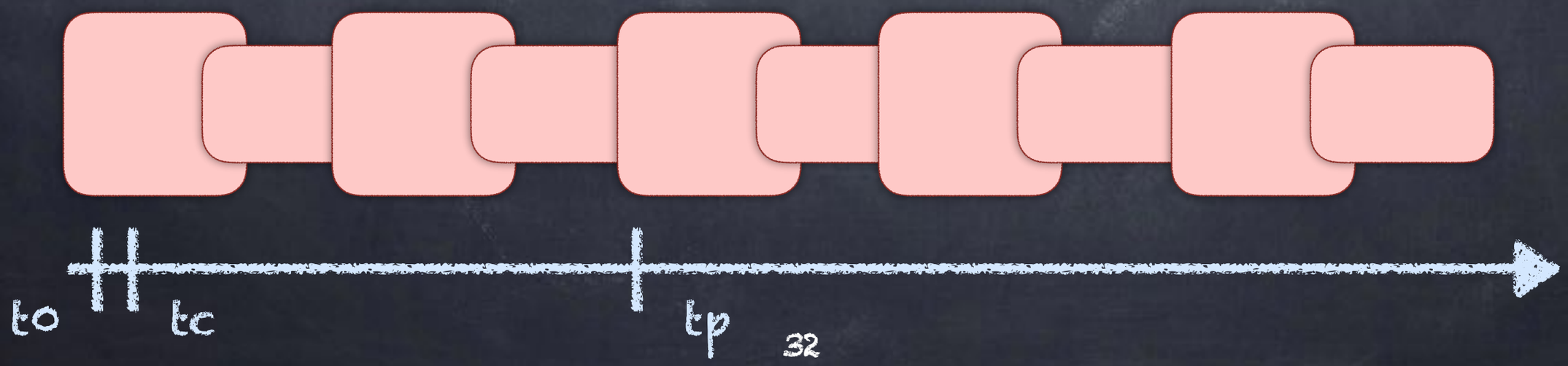
- can compute F perturbatively if $\Delta t \ll t_p$
- F depends only on instantaneous $\rho_A$ and $\rho_B$ if $\Delta t \gg t_c$.

# Open EFTs

- The point: if you can integrate the coarse-grained evolution equation

$$\frac{\partial \rho_A}{\partial t} = F(\rho_A, \rho_B, H_{\rm int})$$

can trust the solution even for t >> tp provided there are overlapping regions each of which satisfies tc << Δt << tp



# Open EFT & inflation

- For $V = \lambda\,\phi^4$ and $P[\phi] = \langle \phi \,|\, \rho_A \,|\, \phi \rangle$ find Fokker-Planck equation known to capture the IR singular part of the field theory

Tsamis & Woodard

$$\frac{\partial P}{\partial t} = \frac{H^3}{8\pi^2}\frac{\partial^2 P}{\partial \phi^2} + \frac{\lambda}{18H}\frac{\partial}{\partial \phi}\left(\phi^3 P\right)$$

plus decoherence and corrections important for IR safety

CB, Holman, Tasinato & Williams

Resummation to late time gives static solution:

$$P \propto \exp\left[-\frac{8\pi^2 V}{3H^4}\right]$$

Starobinsky & Yokohama

# Conclusions

- IR and secular issues likely generic for quantum systems in gravitational fields, and cause perturbative failure at late times
  - Small curvatures/couplings need not be sufficient for calculation control
  - Resummation techniques available: Open EFTs
- Practical implications for black hole information loss and/or late-time cosmology?