Title: The problems of quantum gravity: from high-energy scattering to black holes and cosmology

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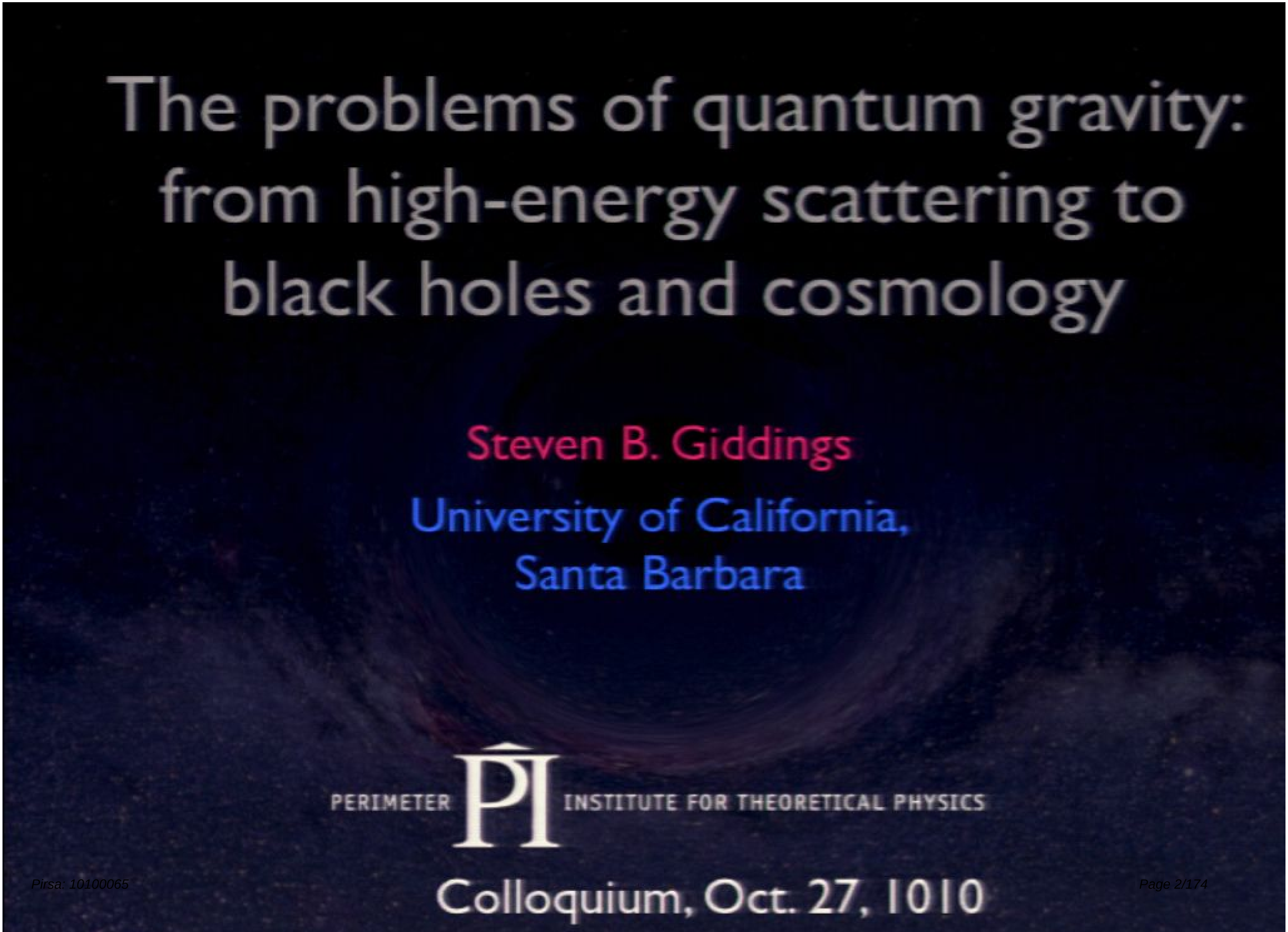
Abstract: Much work on quantum gravity has focussed on short-distance problems such as non-renormalizability and singularities. However, quantization of gravity raises important long-distance issues, which may be more important guides to the conceptual advances required. These include the problems of black hole information and gauge invariant observables, and those of inflationary cosmology. An overview of aspects of these problems, and apparent connections, will be given.



The problems of quantum gravity: from high-energy scattering to black holes and cosmology

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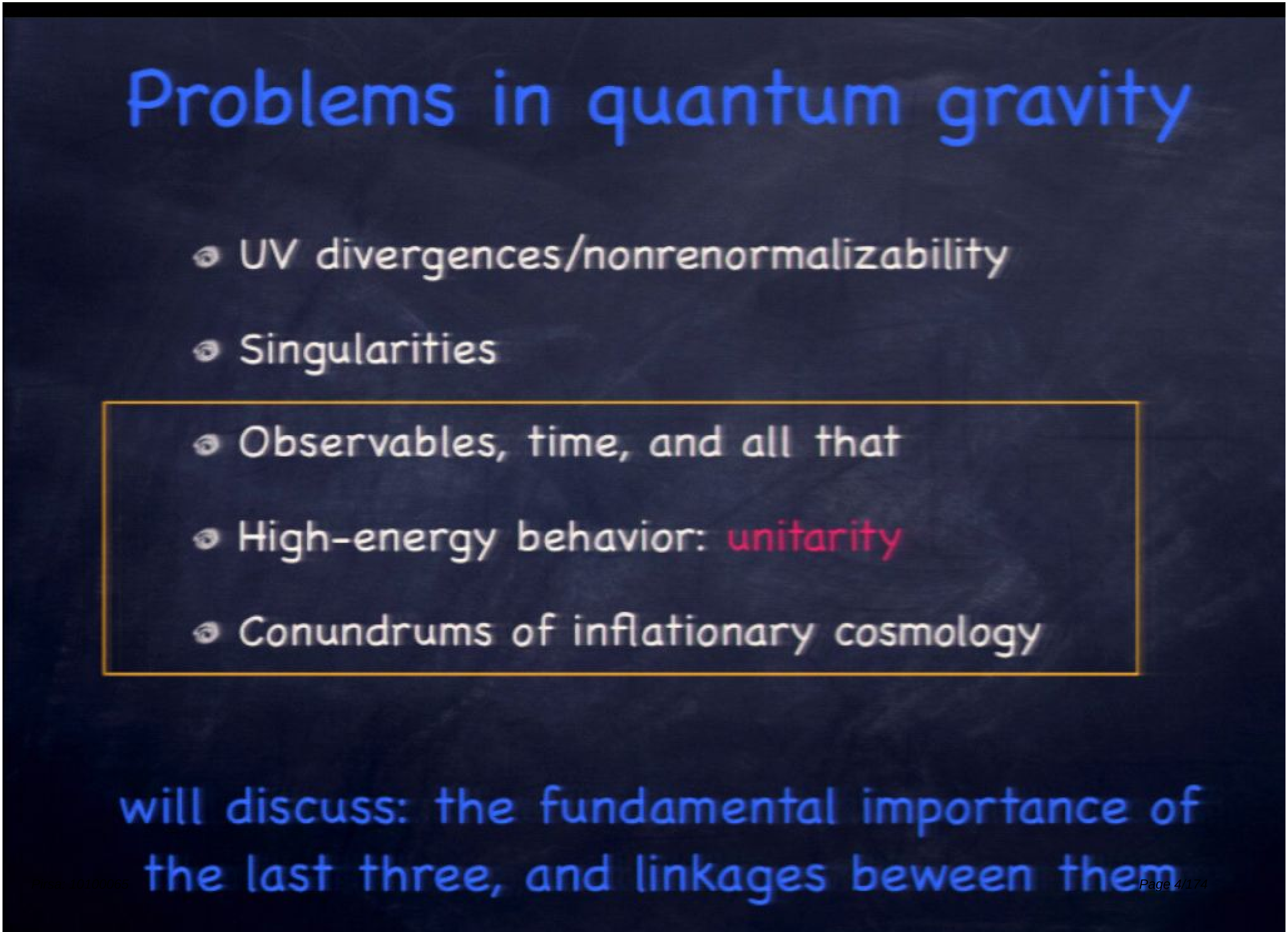
Colloquium, Oct. 27, 1010

Problems in quantum gravity

- UV divergences/nonrenormalizability
- Singularities
- Observables, time, and all that
- High-energy behavior: unitarity
- Conundrums of inflationary cosmology



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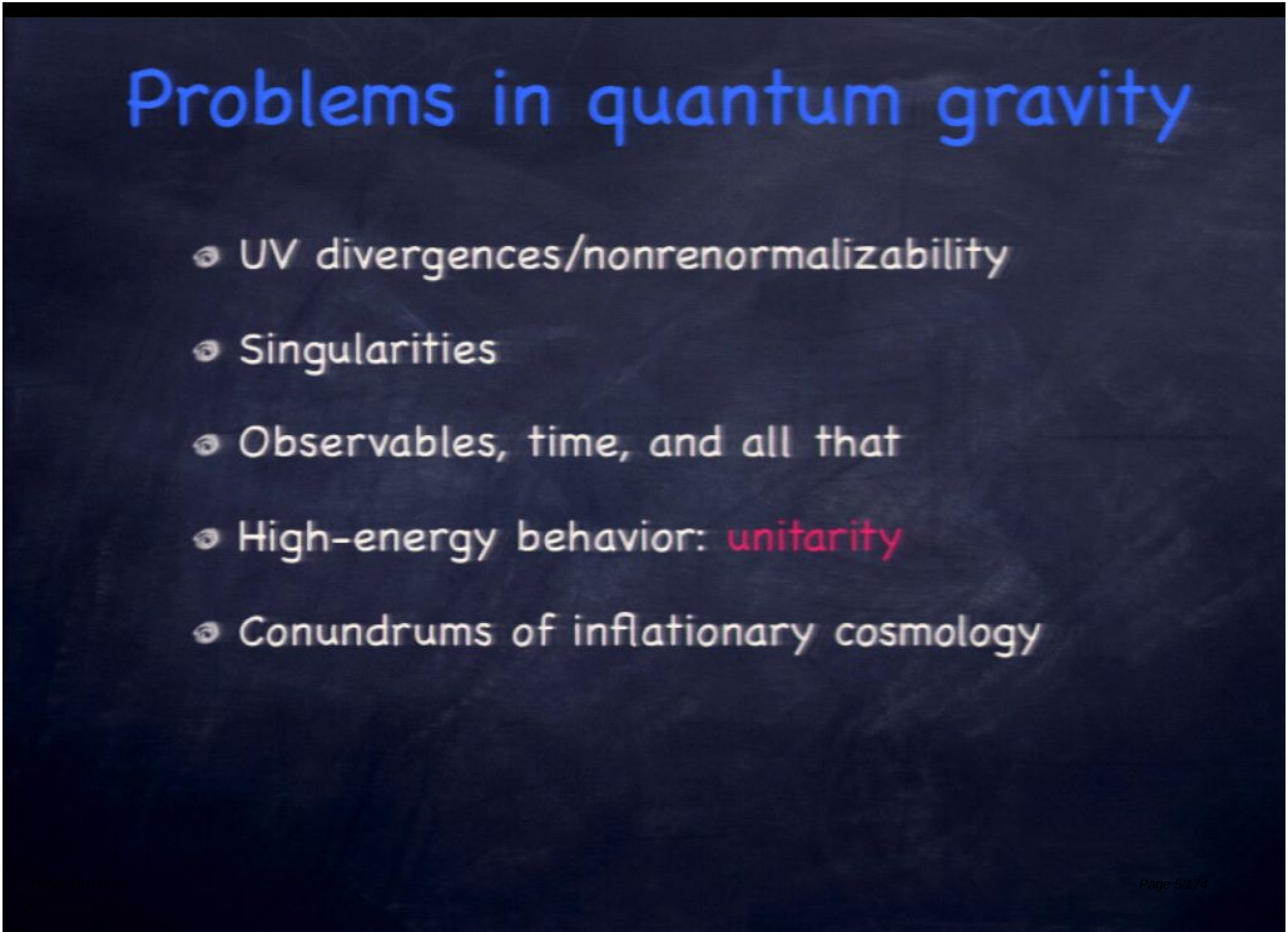

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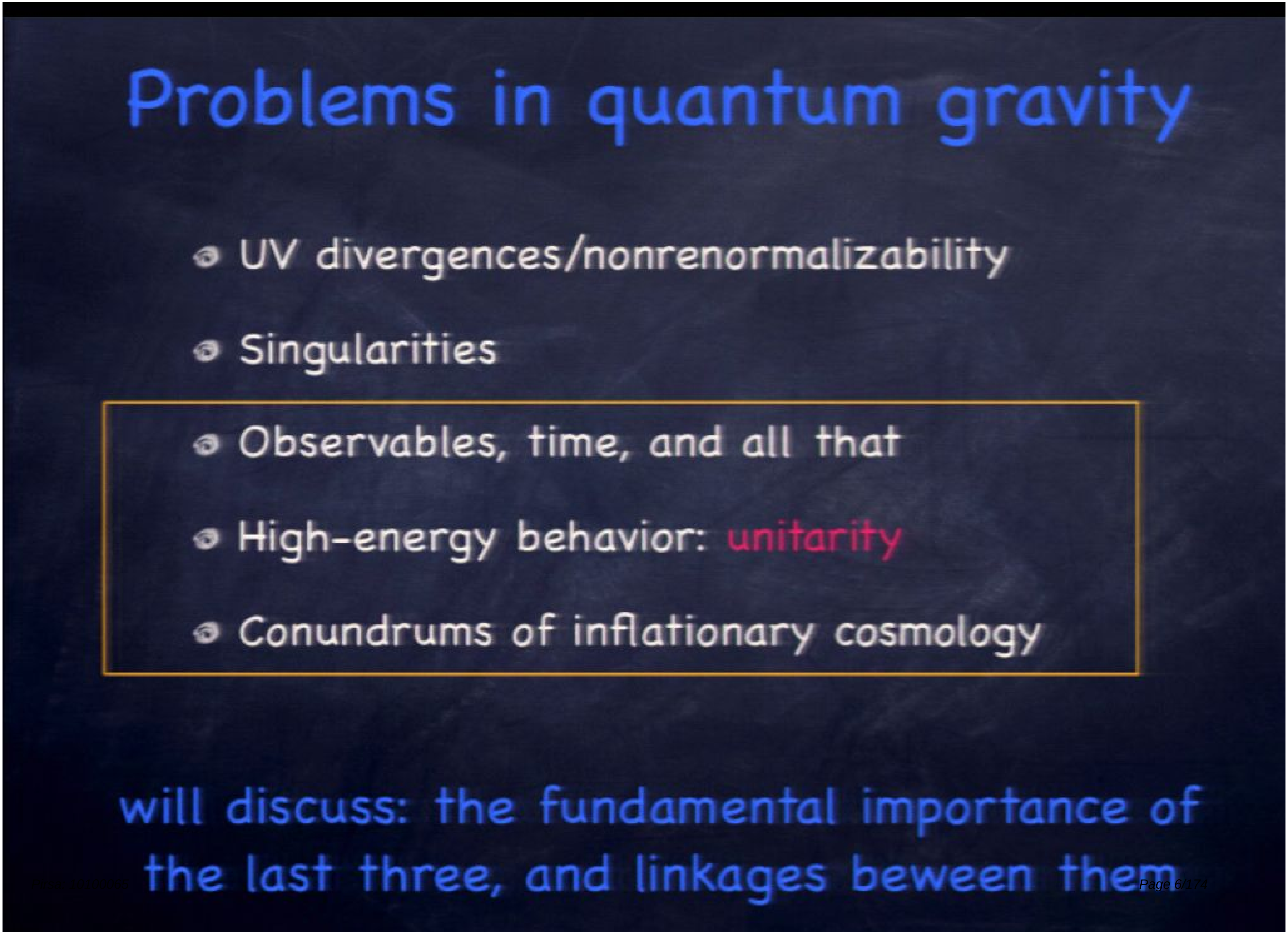

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more challenging:
will return to this

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↑

will begin with this

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- - we can scatter asymptotic multi-particle states:

$$2 \to 2\ ,\ 2 \to N\ ,\ \text{etc.}$$

Important early refs: `t Hooft; Amati, Ciafaloni, Veneziano

Recent work: SBG & Srednicki, 0711.5012; SBG & Porto, 0908.0004

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E.g. quantum amplitudes for:

- a powerful way to summarize ignorance

indeed, study of properties of S-matrices led to discovery of string theory!

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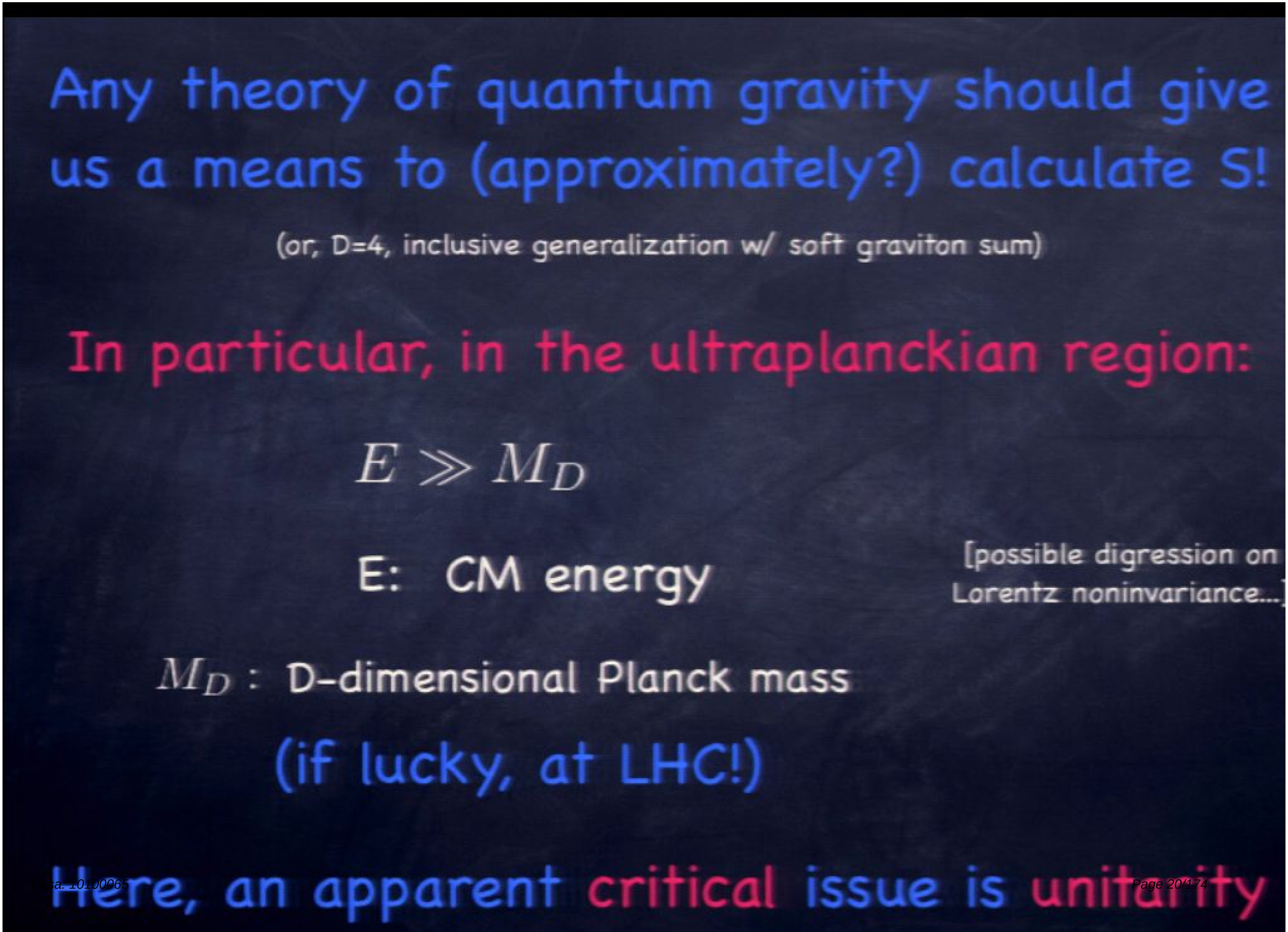
$$E \gg M_D$$

E: CM energy

[possible digression on Lorentz noninvariance...]

M_D : D-dimensional Planck mass

(if lucky, at LHC!)



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Here, an apparent critical issue is unitarity

Near Planck regime: nonrenormalizability, etc.=trouble -

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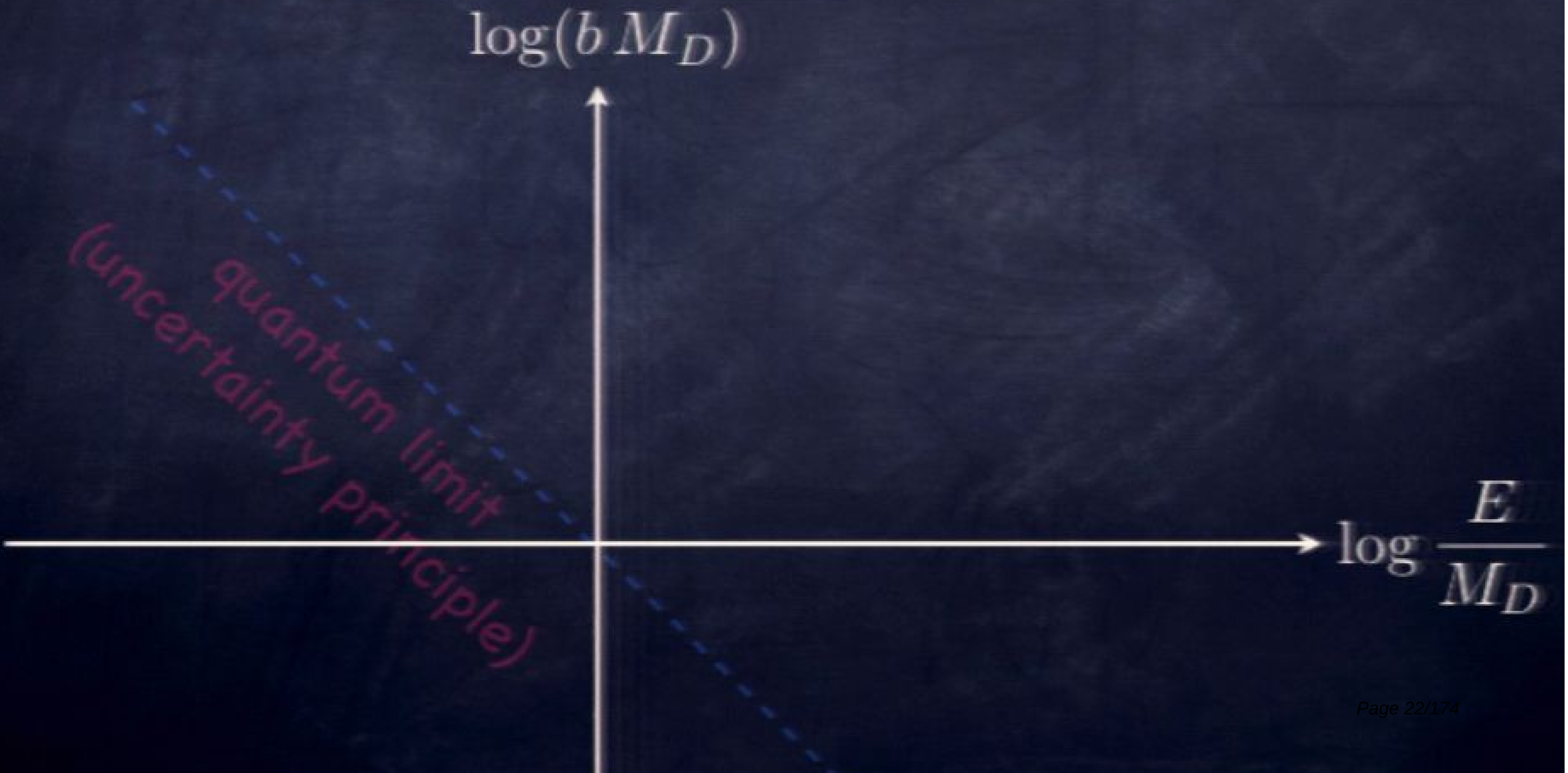
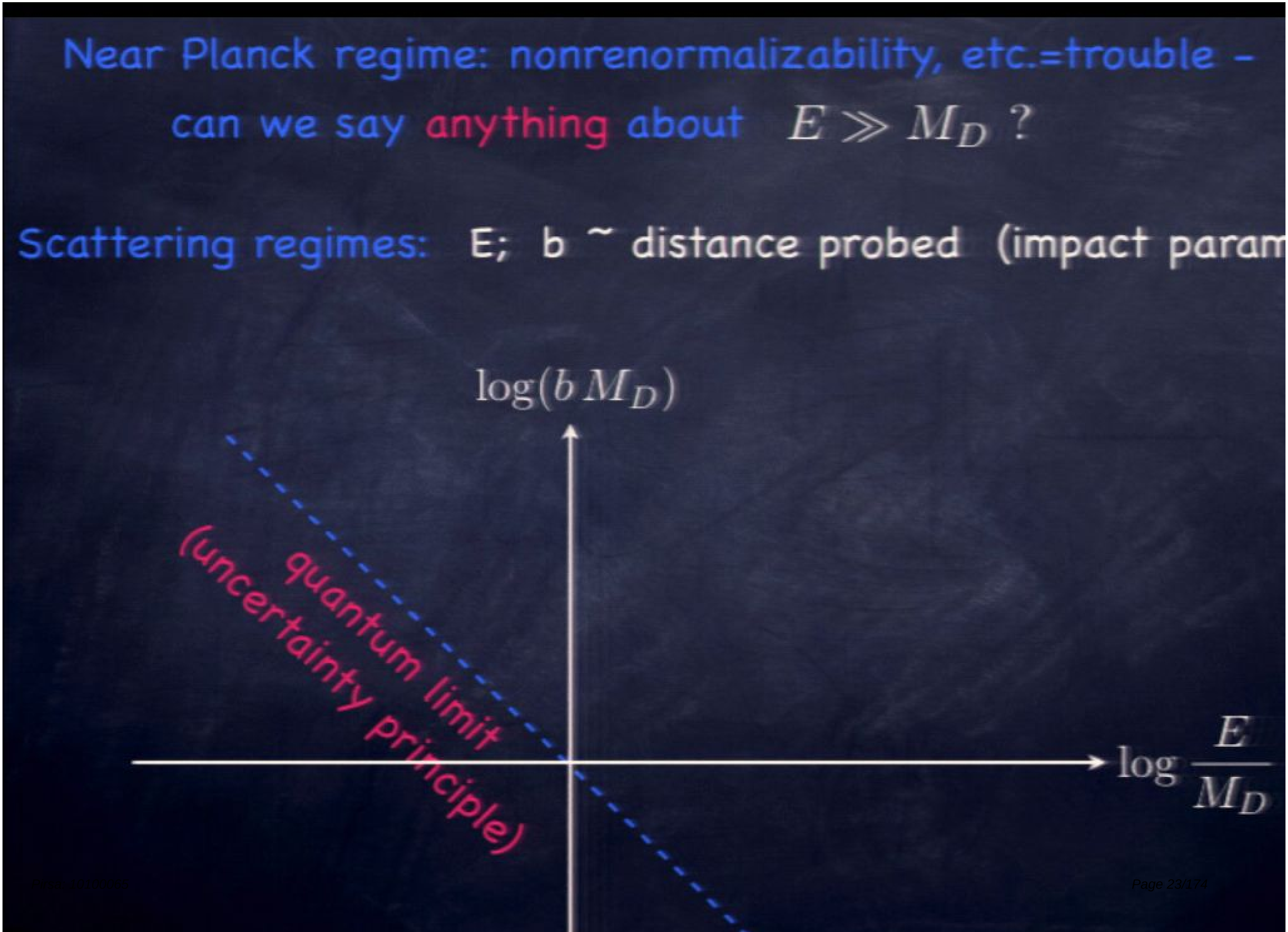
Scattering regimes: E; b ~ distance probed (impact param





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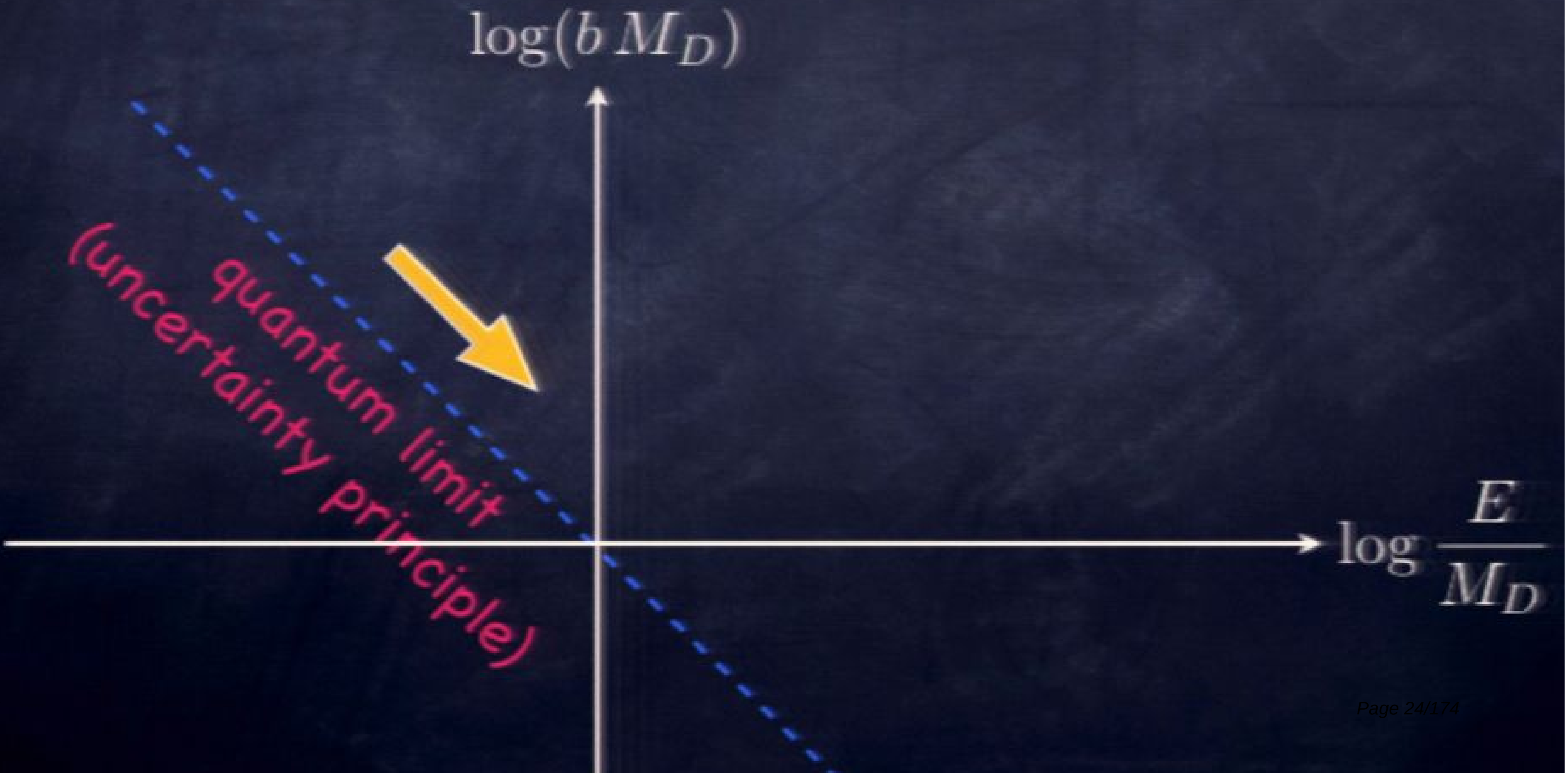

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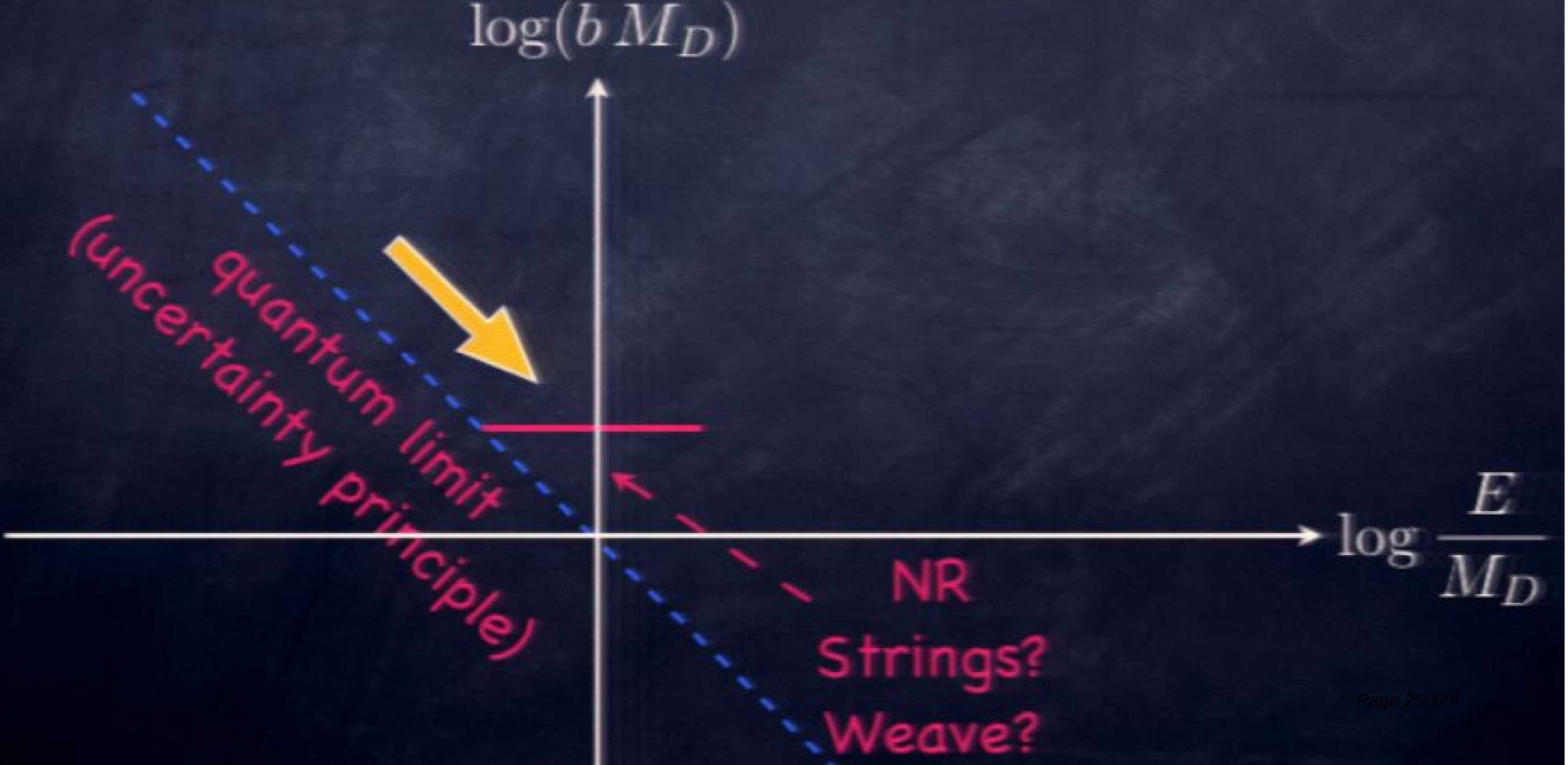

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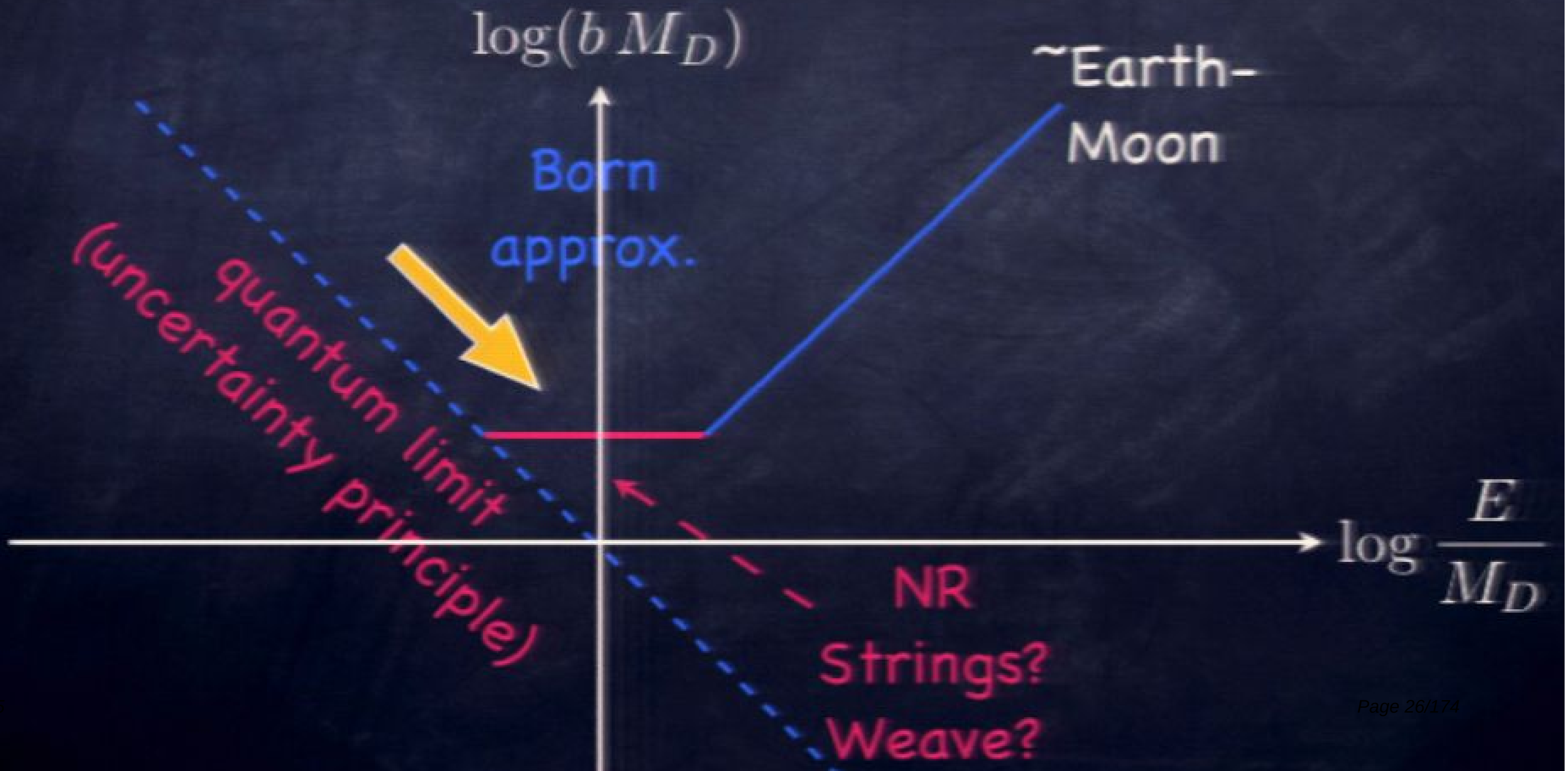

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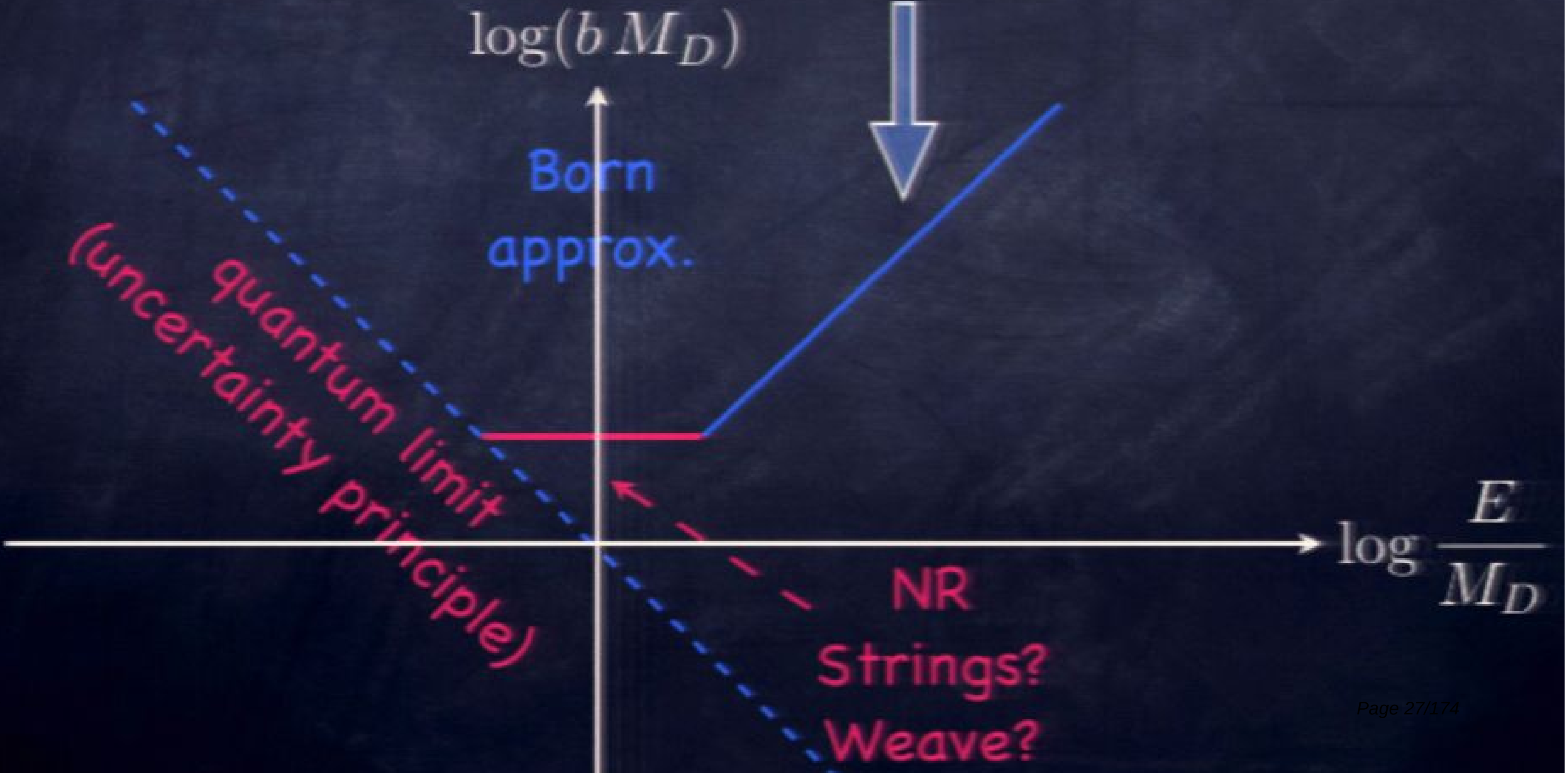
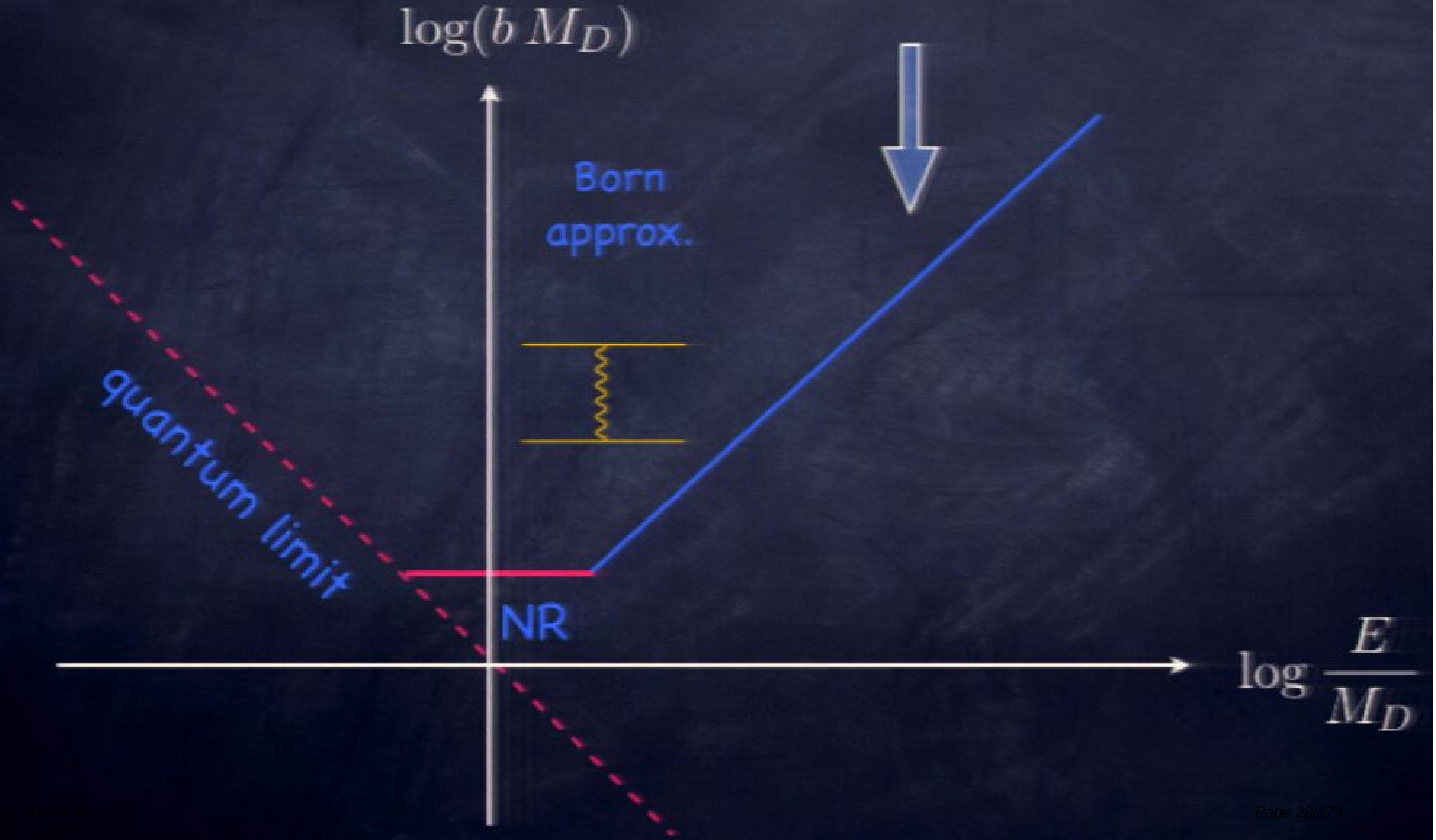


Diagram of Scattering regimes



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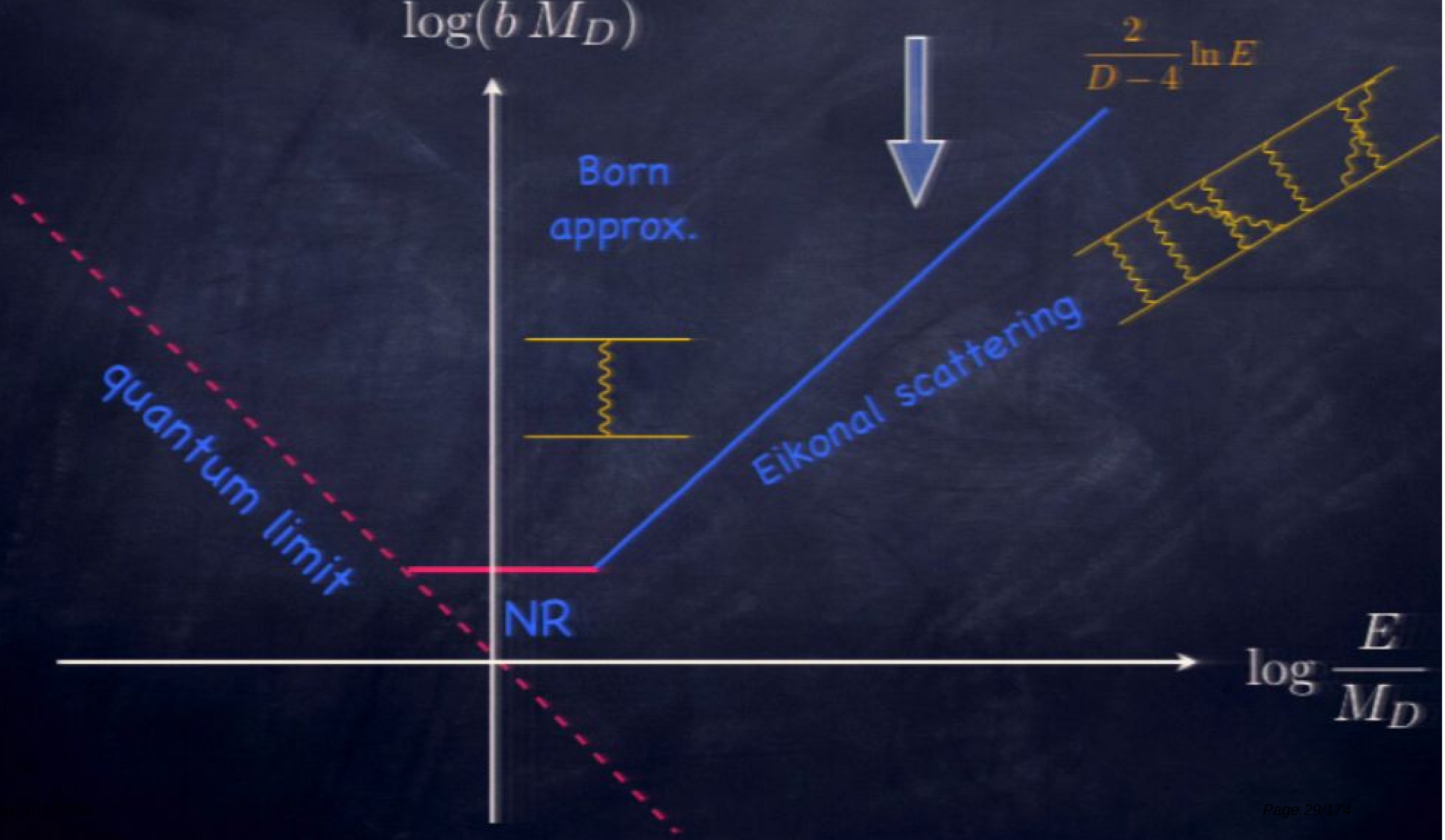

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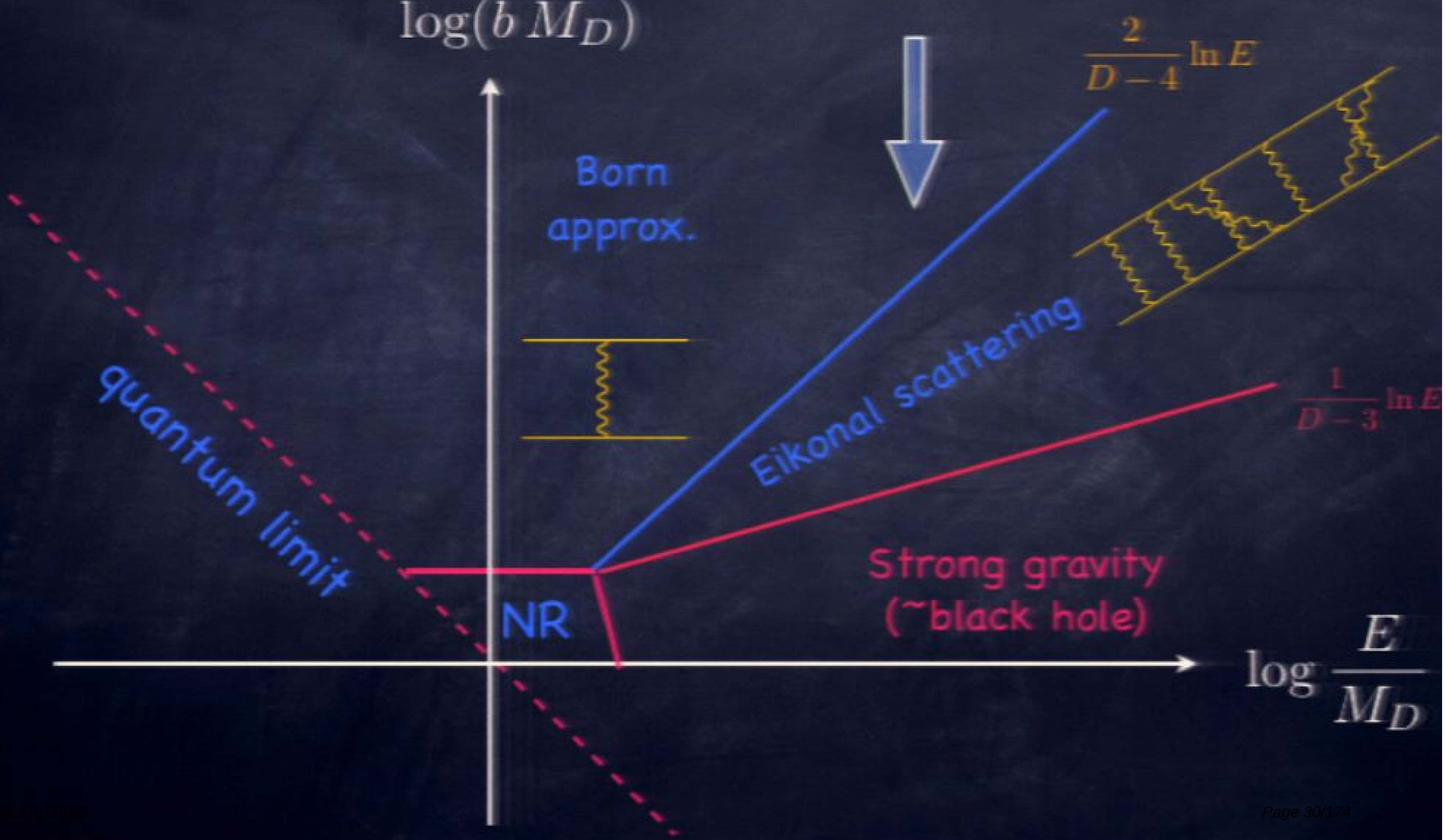

But, nonrenormalizability: can we trust anything with loops?

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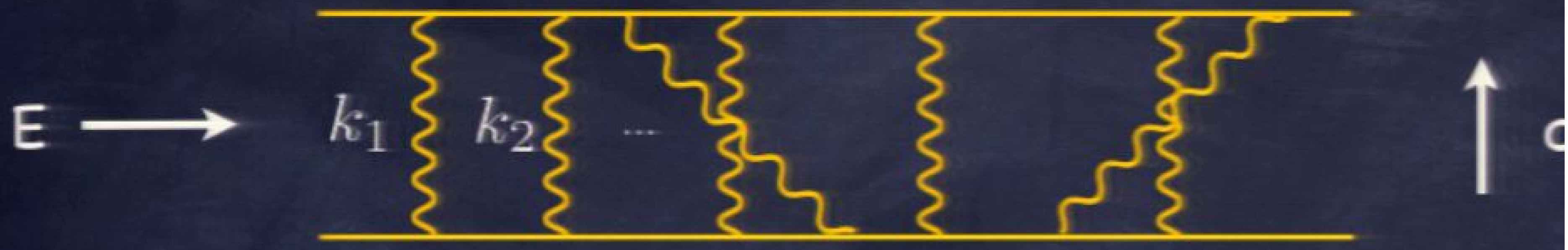
However - basic message:

This is a short-distance issue. We seem to have deeper problems at long distances!

(Can examine in the context of candidate regulators: loop momentum cutoff, SUGRA, strings)

Eikonal amplitudes



Mandelstam parameter

$$s = E^2 \quad t = -q^2$$

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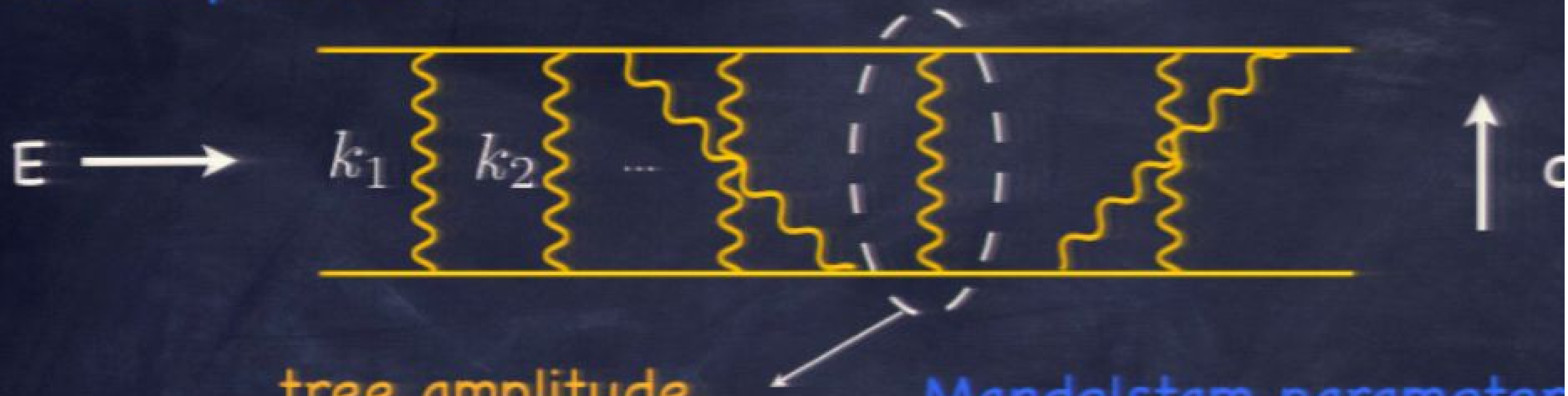

tree amplitude

$$T_{\text{tree}} \sim 8\pi G_D s^2 / k_i^2$$

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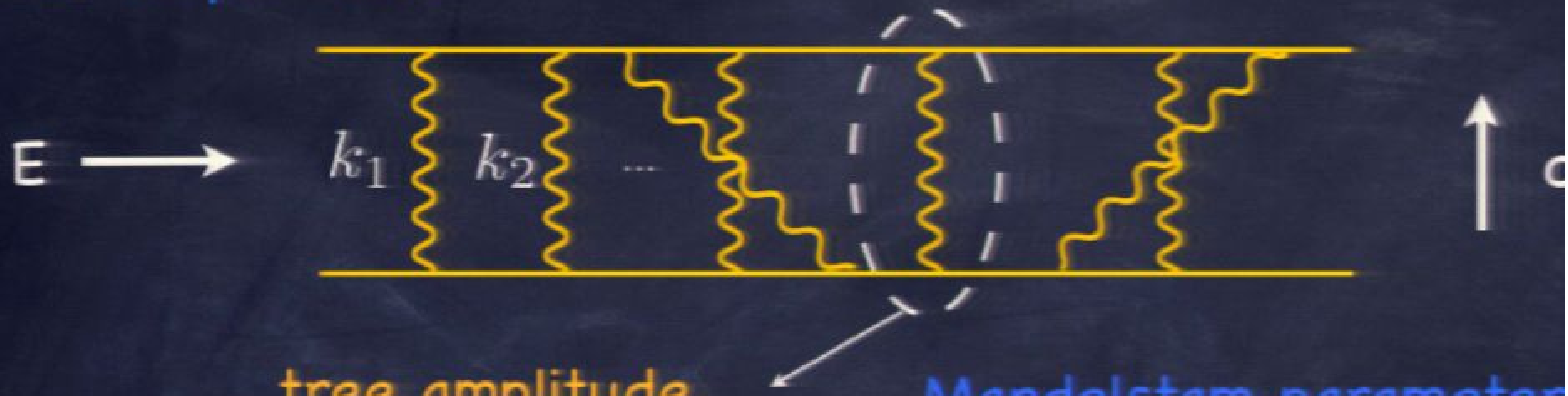

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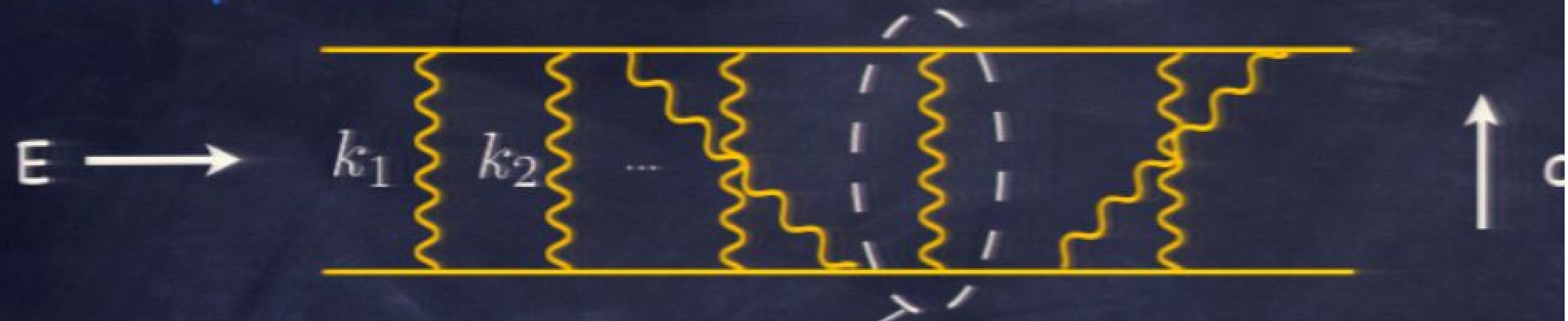
$q_\perp$ = perpindicular to CM momentum $x_\perp \sim$ impact parameter b

$$\chi(x_\perp, s) = \frac{1}{2s}\int \frac{d^{D-2}q_\perp}{(2\pi)^{D-2}} e^{-i\mathbf{q}_\perp \cdot x_\perp} T_{\text{tree}}(s, -q_\perp^2)$$

$$\propto G_D s/x_\perp^{D-4}$$

... "eikonal phase"

Eikonal amplitudes



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Sew together to get N–loop amplitude:

$$T_{\text{N}}(s,t) \sim \int d^{D-2}x_\perp e^{-iq_\perp \cdot x_\perp}[i\chi(x_\perp, s)]^{N+1}$$

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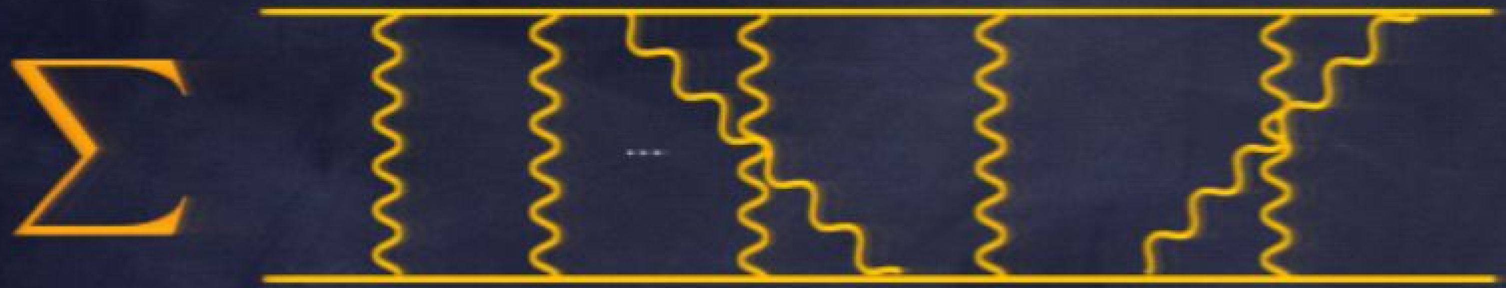
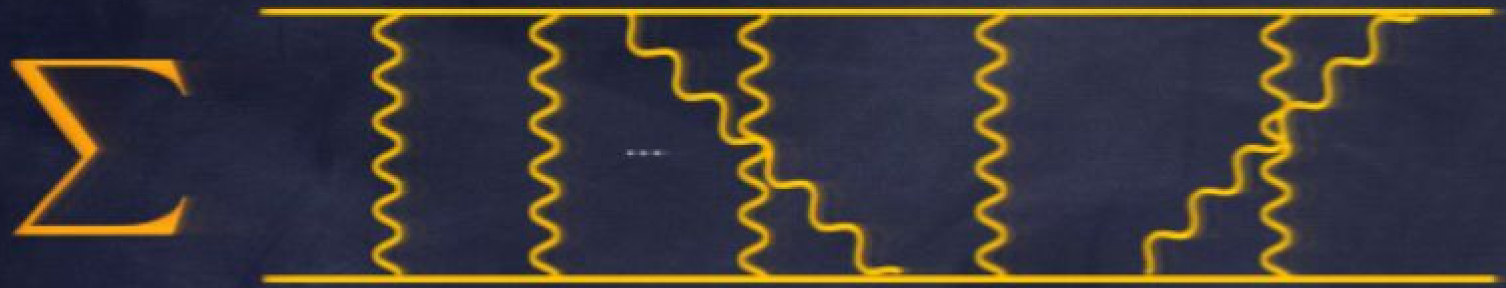
Eikonal amplitudes, cont'd



$$iT_{\rm eik}(s,t) = 2s \int d^{D-2}x_\perp e^{-iq_\perp \cdot x_\perp}(e^{i\chi(x_\perp,s)} - 1)$$

$$\chi(x_\perp, s) = (const.) G_D s / x_\perp^{D-4} \qquad q \ll E$$

Eikonal amplitudes, cont'd



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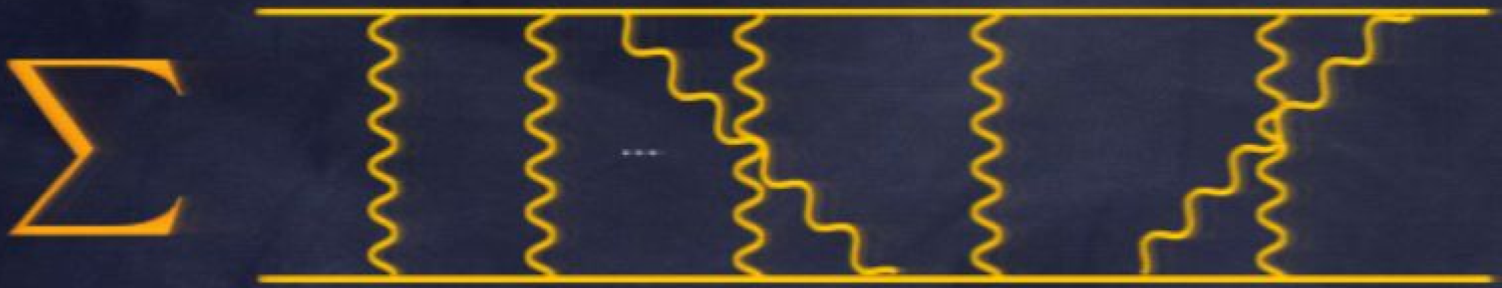

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No -- saddle at:

$$q_\perp \sim \partial\chi/\partial x_\perp \quad \Leftrightarrow \quad x_\perp^{D-3} \sim E^2/q$$

$q \ll E$:

Long
distance

Illustrate this point with a toy integral:

$$iT_{\rm eik}(s,t) = 2s\int d^{D-2}x_\perp e^{-iq_\perp\cdot x_\perp}(e^{i\chi(x_\perp,s)}-1)$$

$$\Longrightarrow \qquad I = \int_{\Lambda^{-1}}^{1} dbb^3 e^{ig/b^2}$$

Short distance cutoff

$$I(\Lambda) = \frac{1-\Lambda^{-4}}{4} + ig\frac{(1-\Lambda^{-2})}{2} - \frac{g^2}{2}\log\Lambda + \frac{ig^3}{12}(1-\Lambda^2)+\cdots$$

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$$I(\Lambda) = \frac{g^2}{4}\left[Ei(ig) + \frac{1}{g}\left(i+\frac{1}{g}\right)e^{ig} - Ei(ig\Lambda^2) - \frac{1}{g\Lambda^2}\left(i+\frac{1}{g\Lambda^2}\right)e^{ig\Lambda^2}\right]$$

"short distance dynamics doesn't matter!"

Further explanation: "Momentum fractionation"

$$iT_{\rm eik}(s,t) = 2s\int d^{D-2}x_\perp e^{-iq_\perp\cdot x_\perp}(e^{i\chi(x_\perp,s)}-1)$$

$$\chi \propto G_D s/x_\perp^{D-4}$$

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Typical exchanged momentum: $k\sim\dfrac{q}{N}\sim\dfrac{\partial\chi/\partial b}{\chi}\sim\dfrac{1}{b}$ "soft probe"

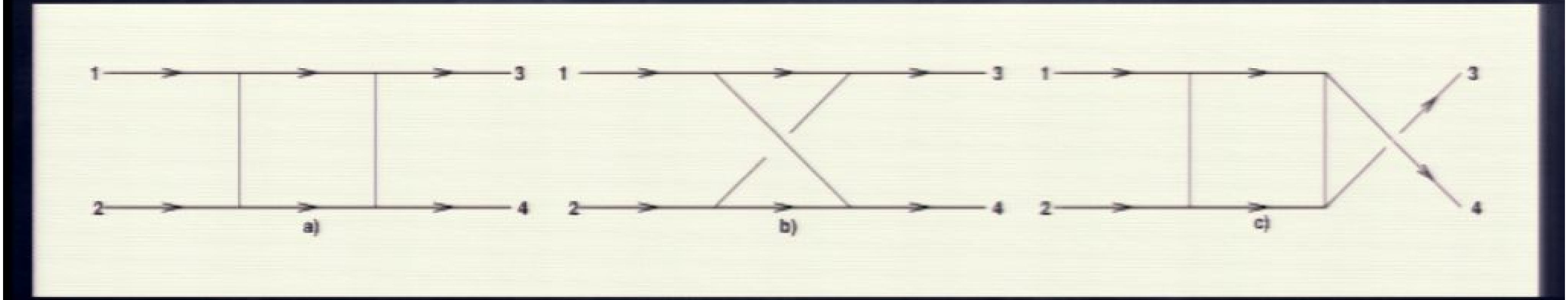
Illustrate w/ explicit SUGRA amplitudes!

One loop:

1005.5408 w/ Schmidt-Sommerfeld & Andersen

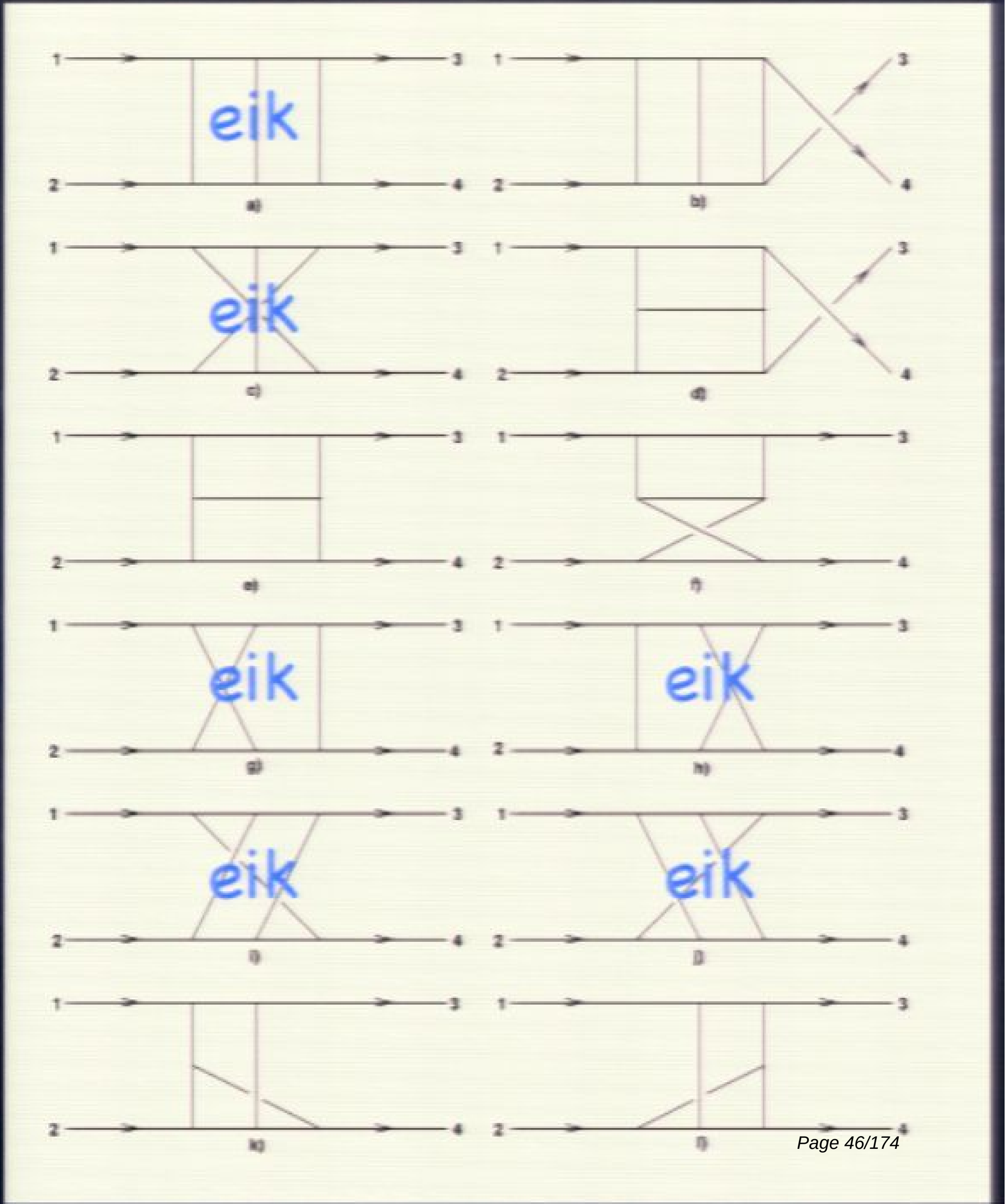
$$M_1(s,t) = -i(8\pi G_D)^2 s^4 \left[I^1(s,t) + I^1(t,u) + I^1(s,u)\right]$$

$$I^1(s,t) = \int \frac{d^D k}{(2\pi)^D} \frac{1}{k^2(p_1-k)^2(p_2+k)^2(p_1+p_3-k)^2}$$



- finite
- effective cutoff $k \sim \sqrt{s}$
- $\approx T_{eik}^{1\,loop} + \mathcal{O}(q^2/E^2) + \text{cutoff dependent}$

Two loop:



$$M_2^{SUGRA}(s,t) =$$

$$T_{eik}^{2\,loop} + \mathcal{O}(t/s)$$

$$+\text{cutoff dependent}$$

(Bern, Dixon, Dunbar, Perelstein, Rozowsky)

This illustrates another important point: graviton dominance

(High energy / long distance)

$$\text{coupling} \propto E^{\text{helicity}}$$

$\therefore$ graviton dominates dynamics in this regime,

... so behavior should be relatively generic to any theory of gravity

Momentum fractionation: apparent consequences

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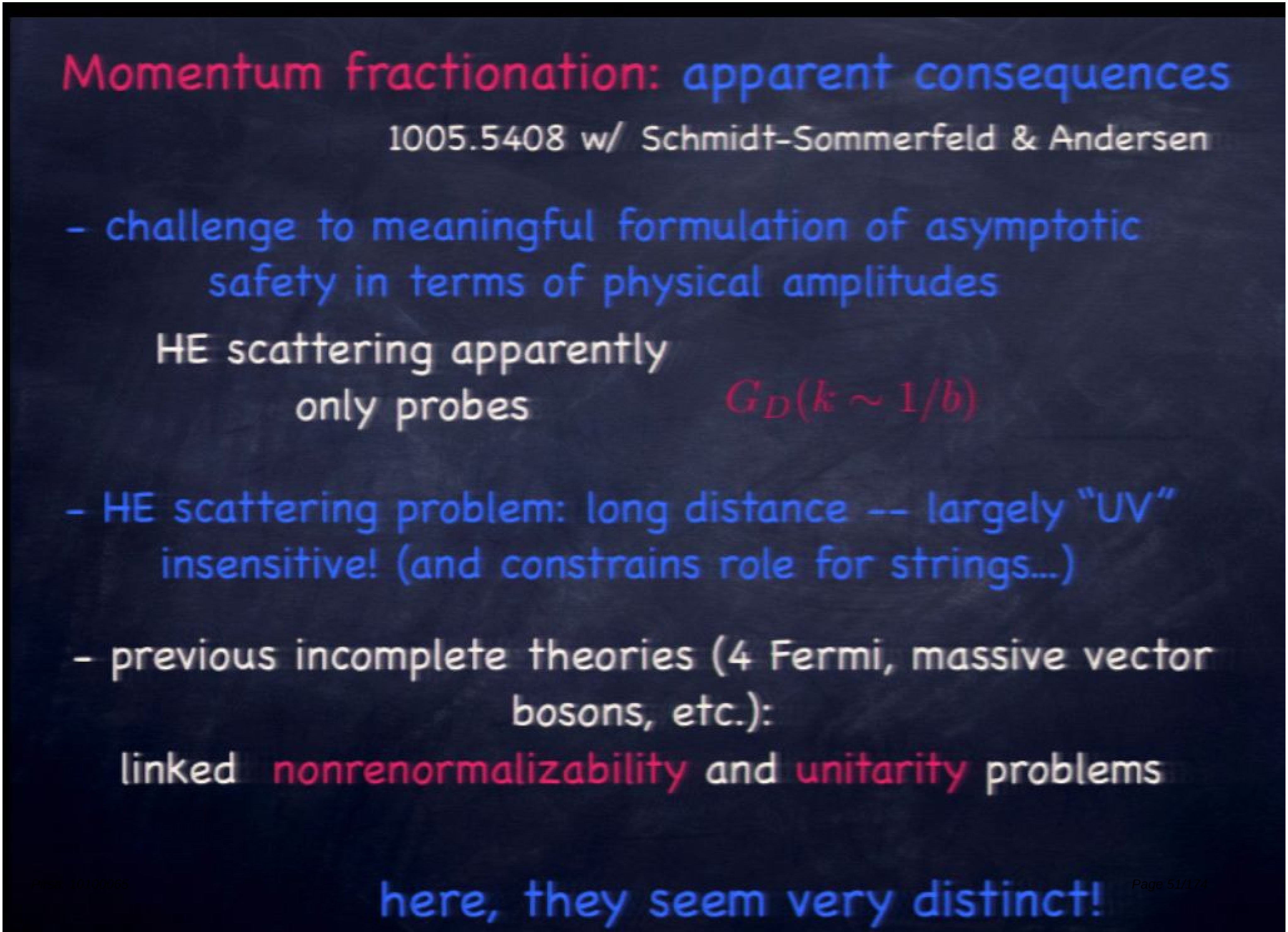

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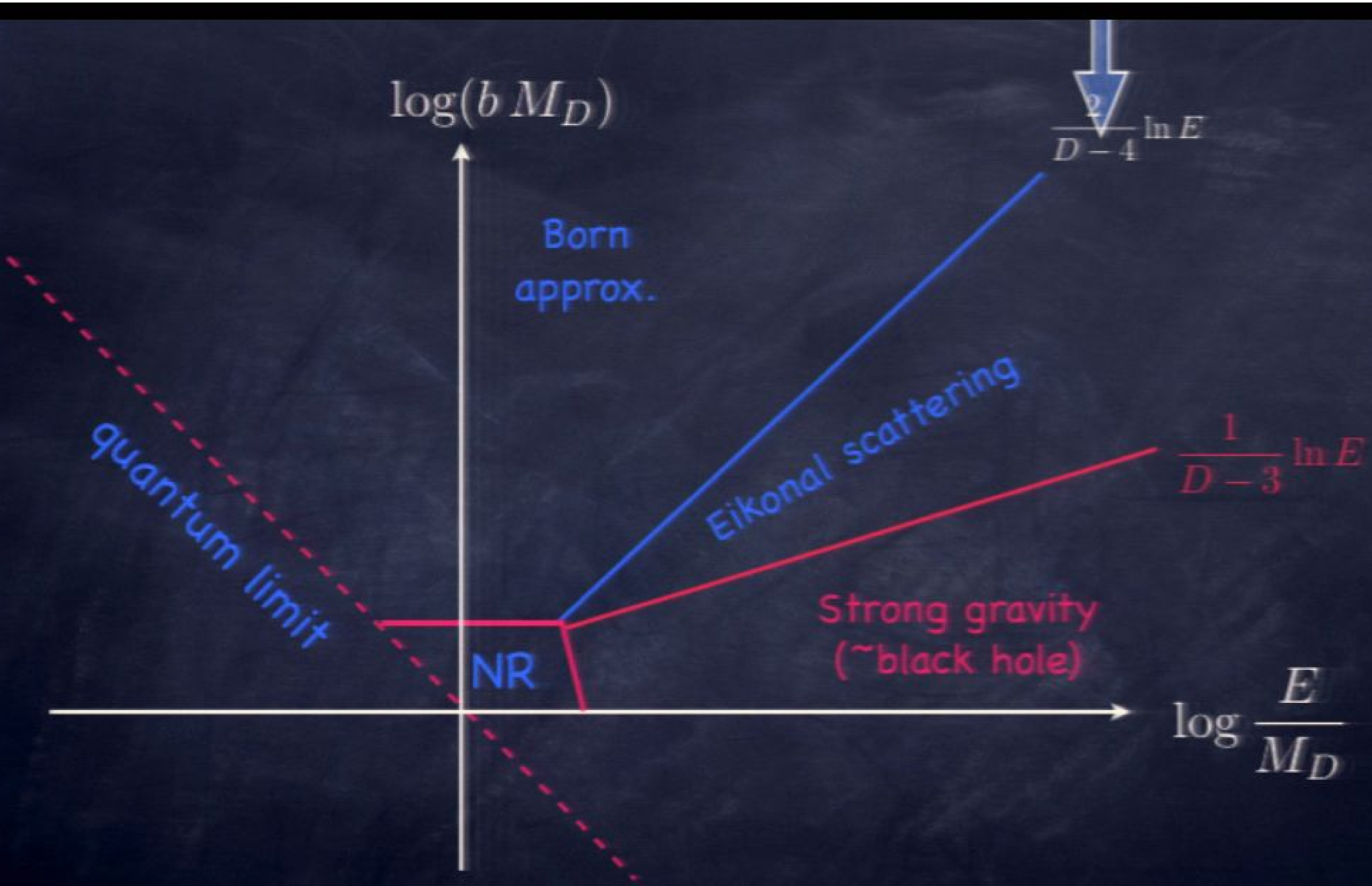
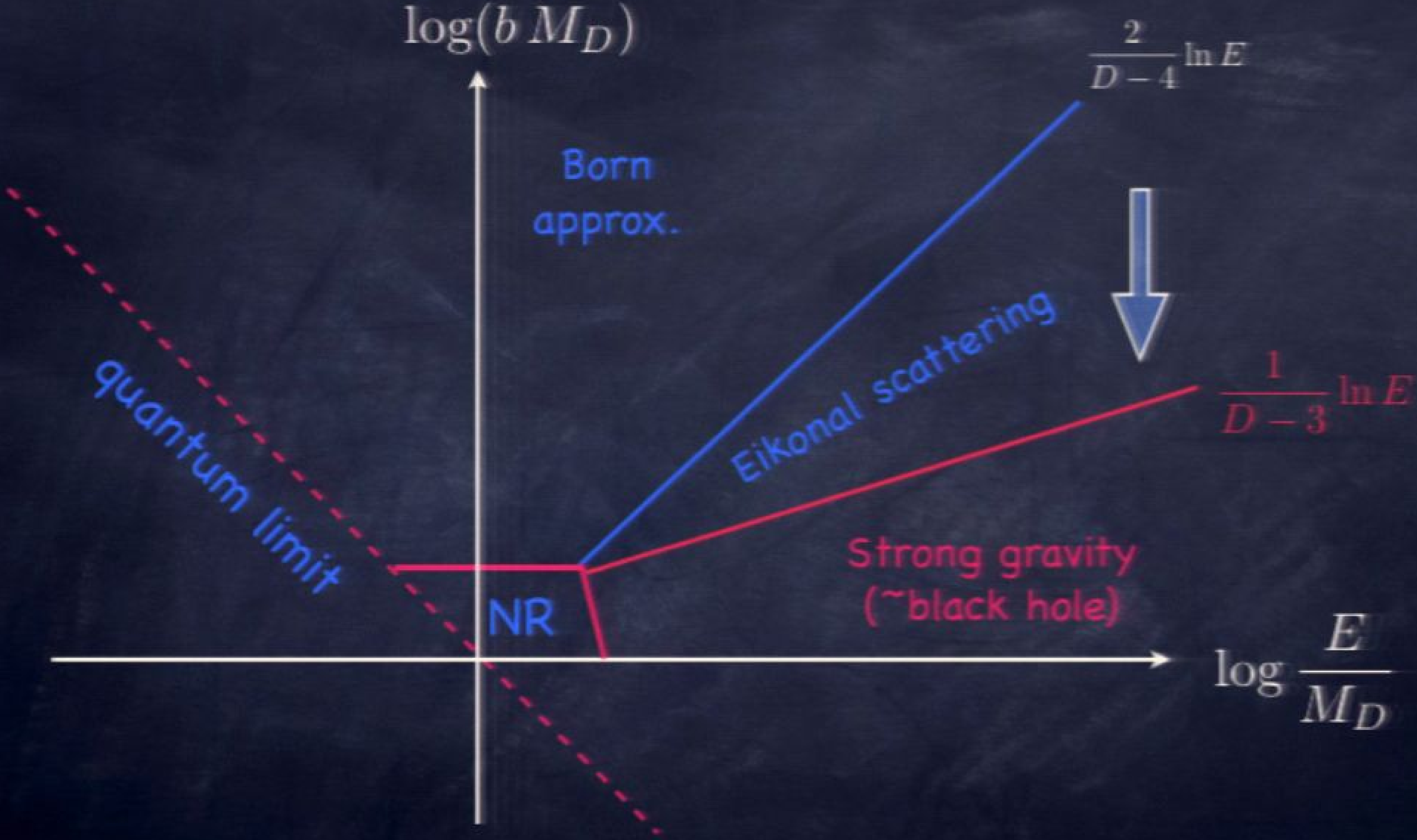
- previous incomplete theories (4 Fermi, massive vector bosons, etc.):

linked nonrenormalizability and unitarity problems

here, they seem very distinct!



$b \sim R_S(E) \sim (G_D E)^{1/D-3}$: Schwarzschild radius



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The strong gravity region, and unitarity

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$\therefore$ "subleading" corrections important

Indeed, subleading loop diagrams:

$$1 \qquad + \qquad \mathcal{O}\left[\left(\frac{R_S(E)}{b}\right)^{2(D-3)}\right]$$

saw e.g. in SUGRA amplitudes.

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perturbation series apparently diverges for

$$q/E \sim 1, \text{ or } b \sim R_S(E)$$

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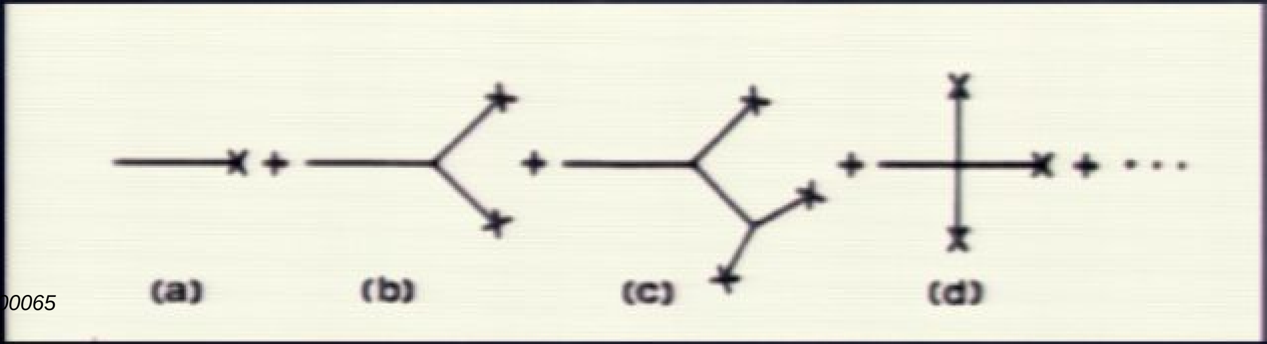
Compare Duff, 1973: Sum of graviton trees with point massive source give Schwarzschild:



(diverges at $r = R_S$)

Expect: sum of such trees gives classical collision geometry also in high-energy context

(assuming we trust the picture to this point -- have tested, more being performed)

SBG & Eardley, 2002: this geometry contains a black hole

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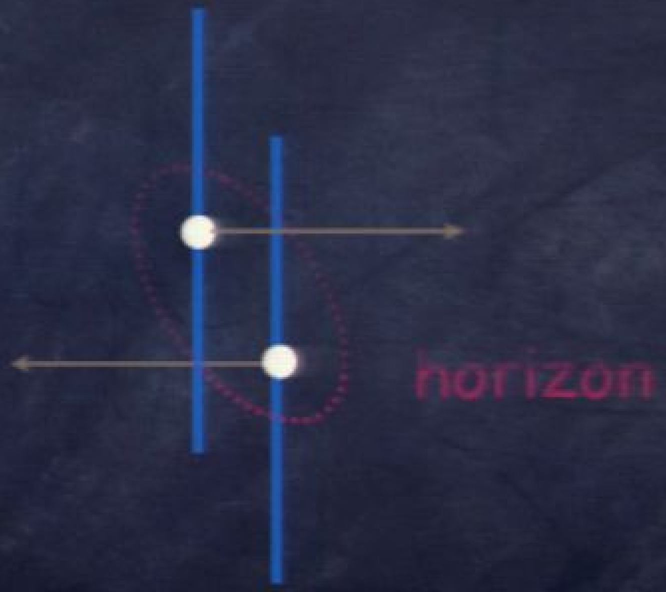

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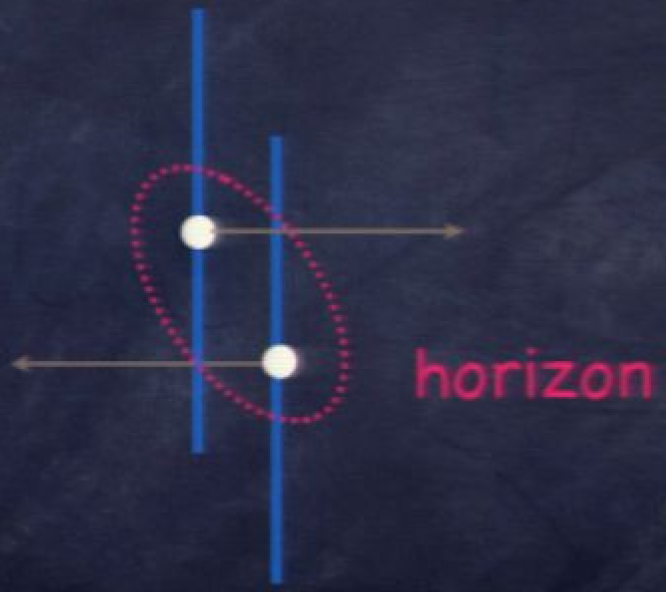

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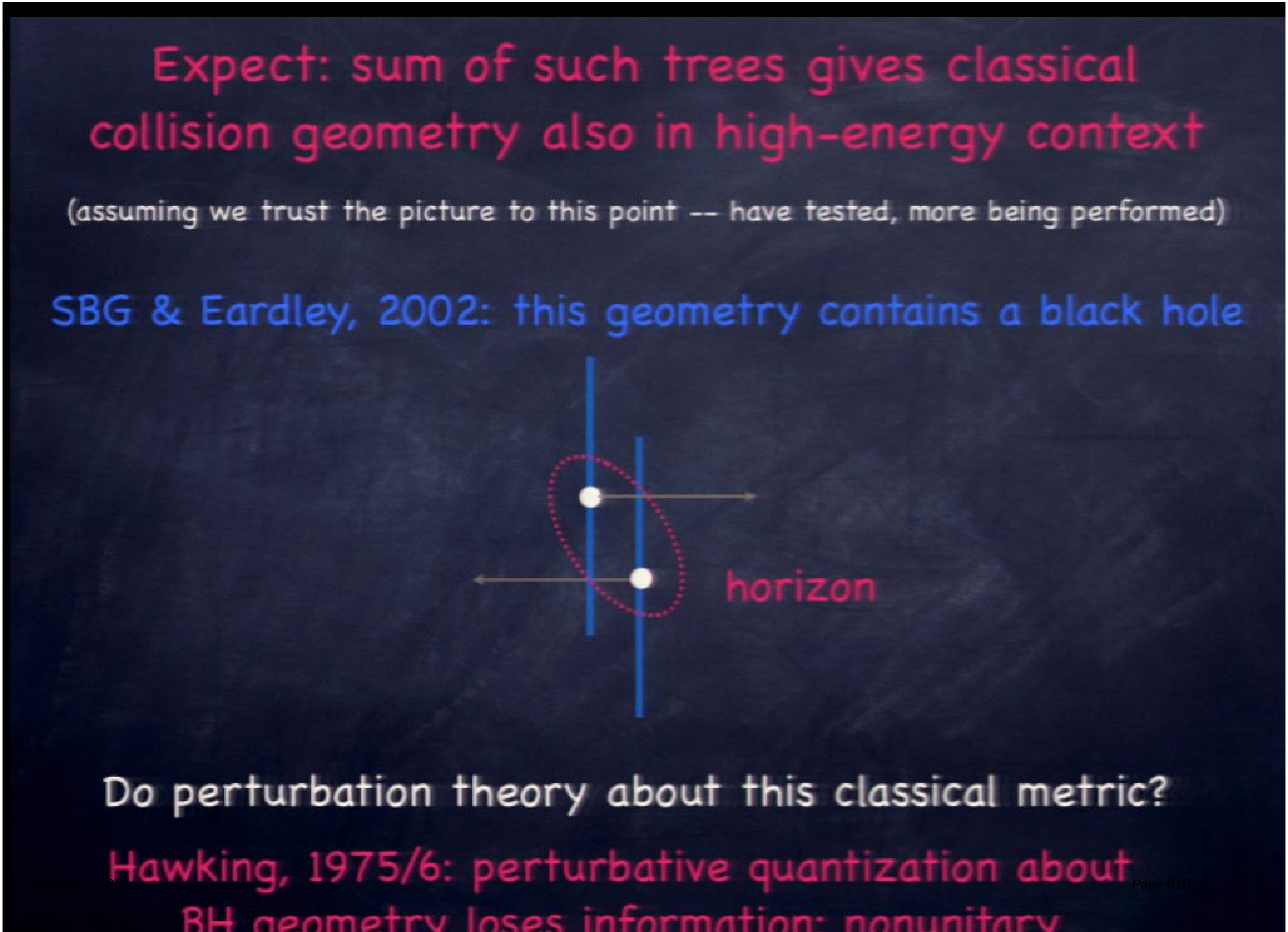

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SBG & Eardley, 2002: this geometry contains a black hole

Do perturbation theory about this classical metric?

Hawking, 1975/6: perturbative quantization about BH geometry loses information: nonunitary

Such scattering: "black hole information paradox"

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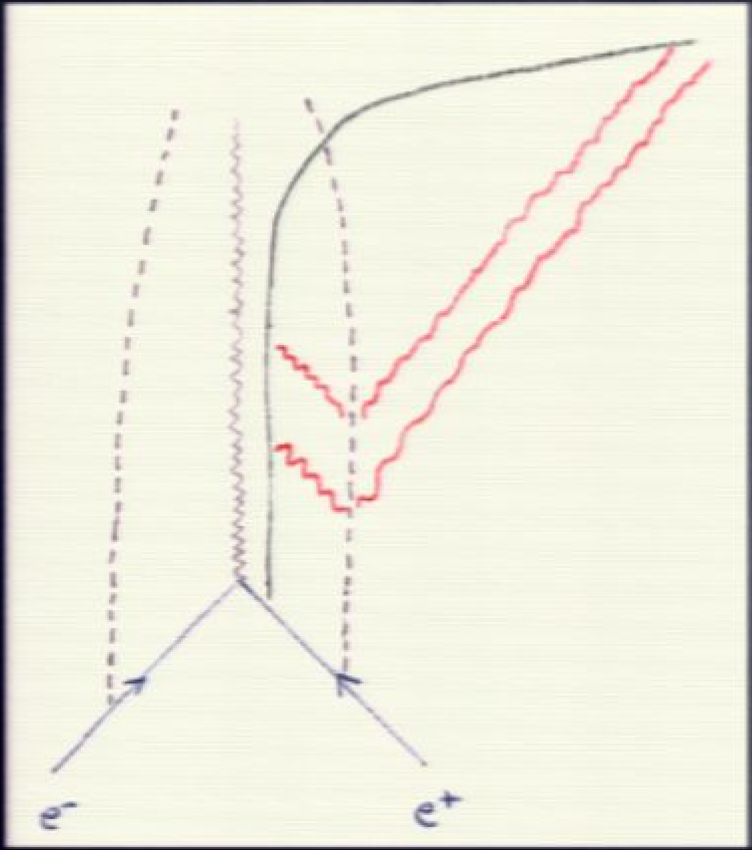
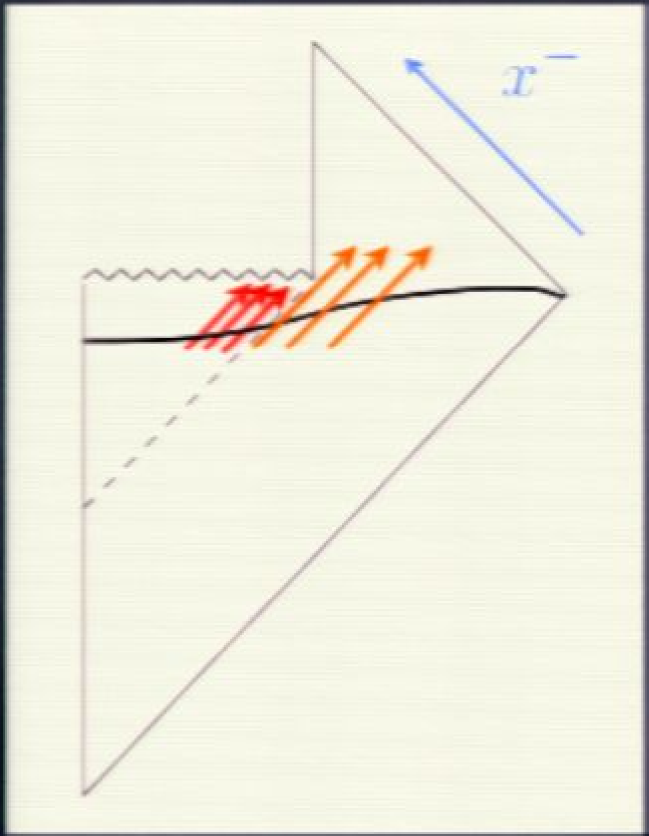
Lightening review:

Such a black hole evaporates: ~ pair prod. at horizon



Eddington-Finkelstein diagram



Penrose diagram

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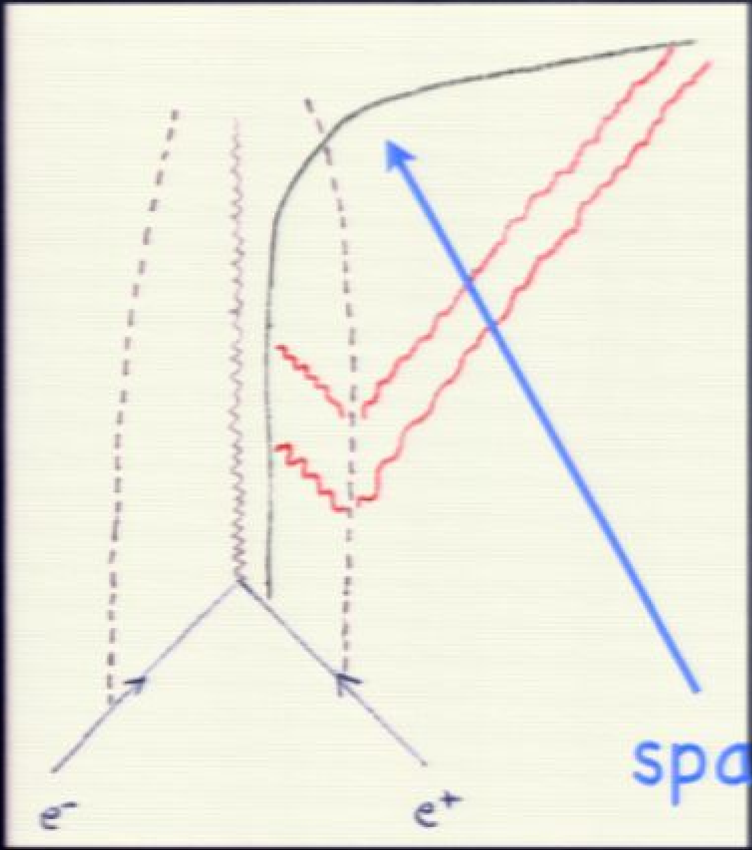
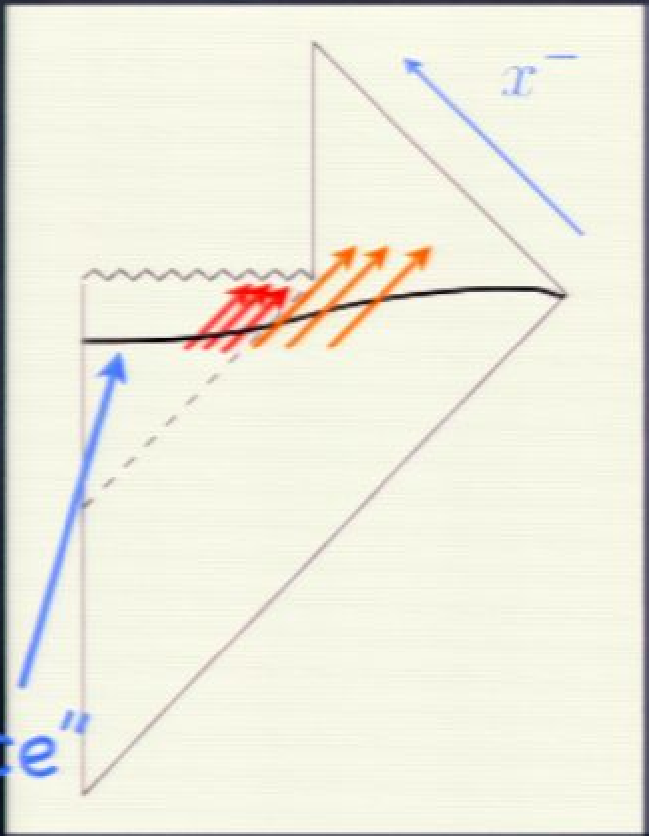


spatial “nice slice”

Eddington-Finkelstein



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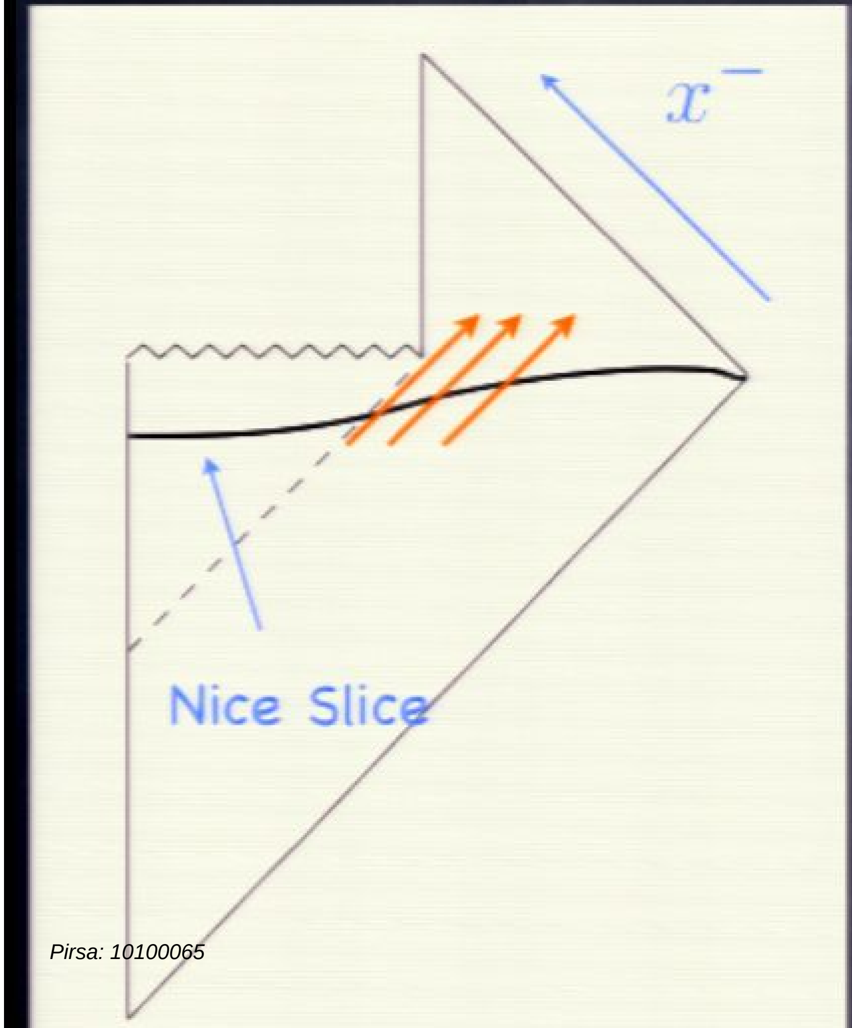
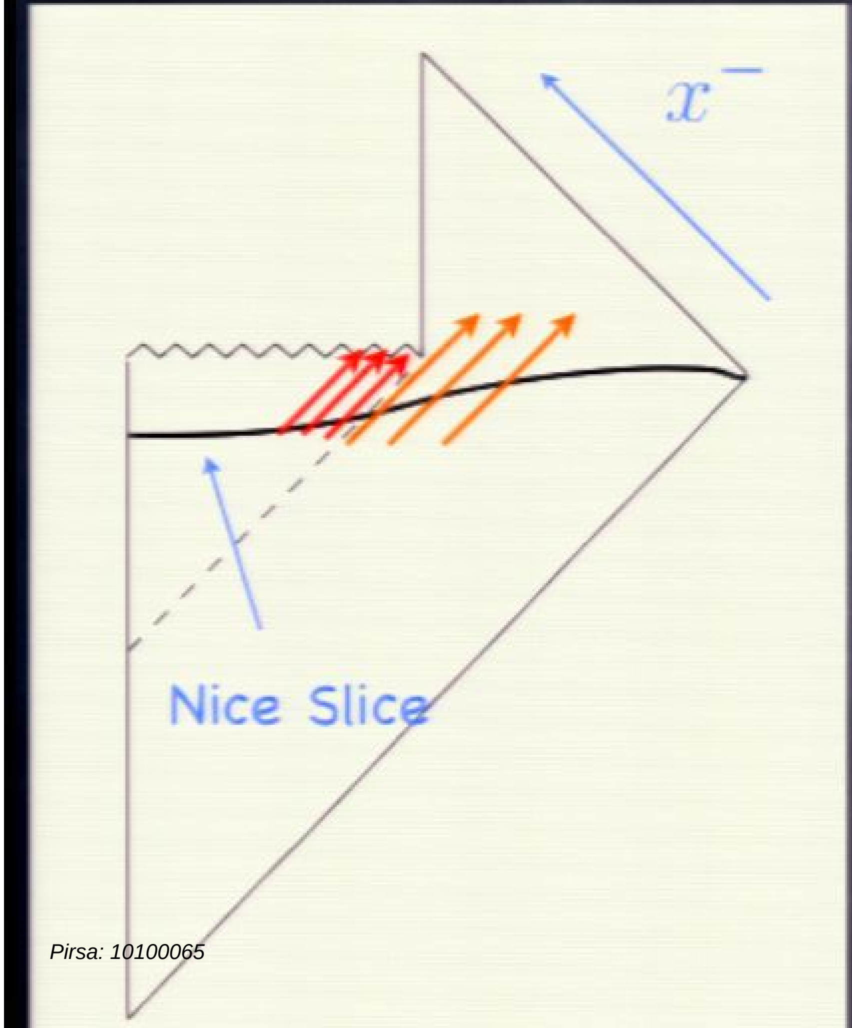
Hawking's argument for info loss, updated: nice slice argument



Hawking's argument for info loss, updated: nice slice argument

Locality: $|\psi_{NS}\rangle \sim \sum_i p_i |i\rangle_{in} |i\rangle_{out}$



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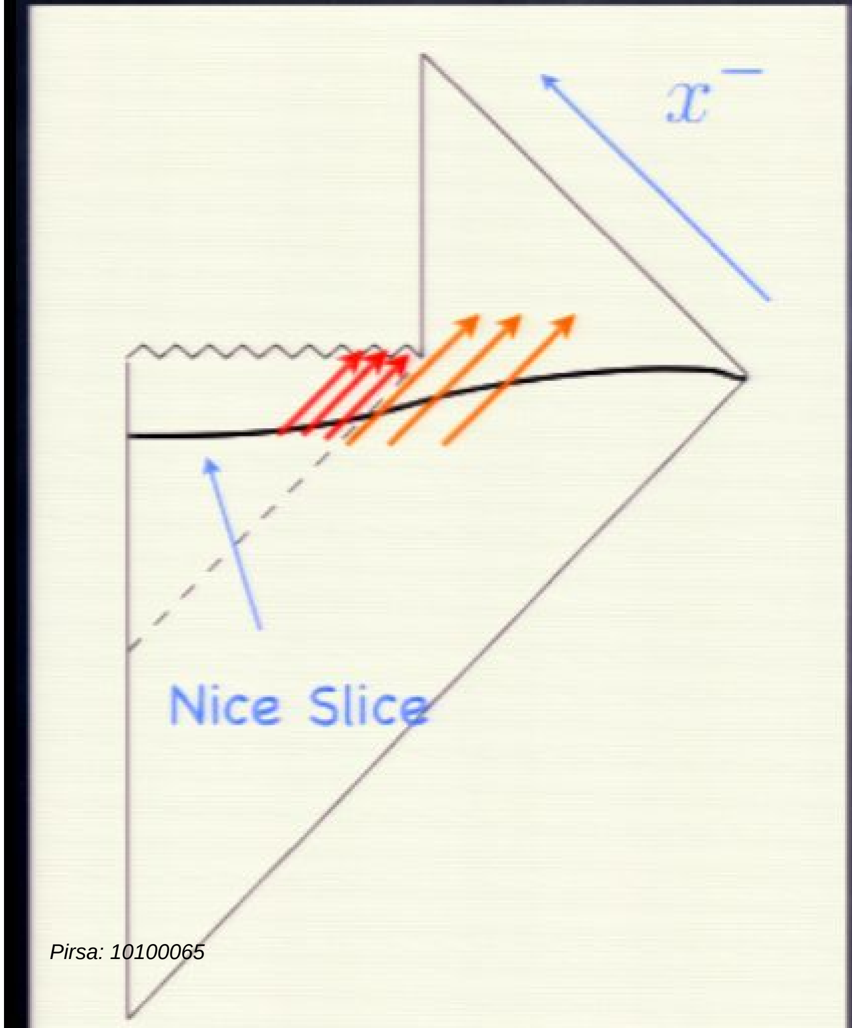

Outside description:

$$|\psi_{NS}\rangle \Rightarrow \rho_{HR} \sim \mathrm{Tr}_{in} |\psi_{NS}\rangle\langle\psi_{NS}|$$

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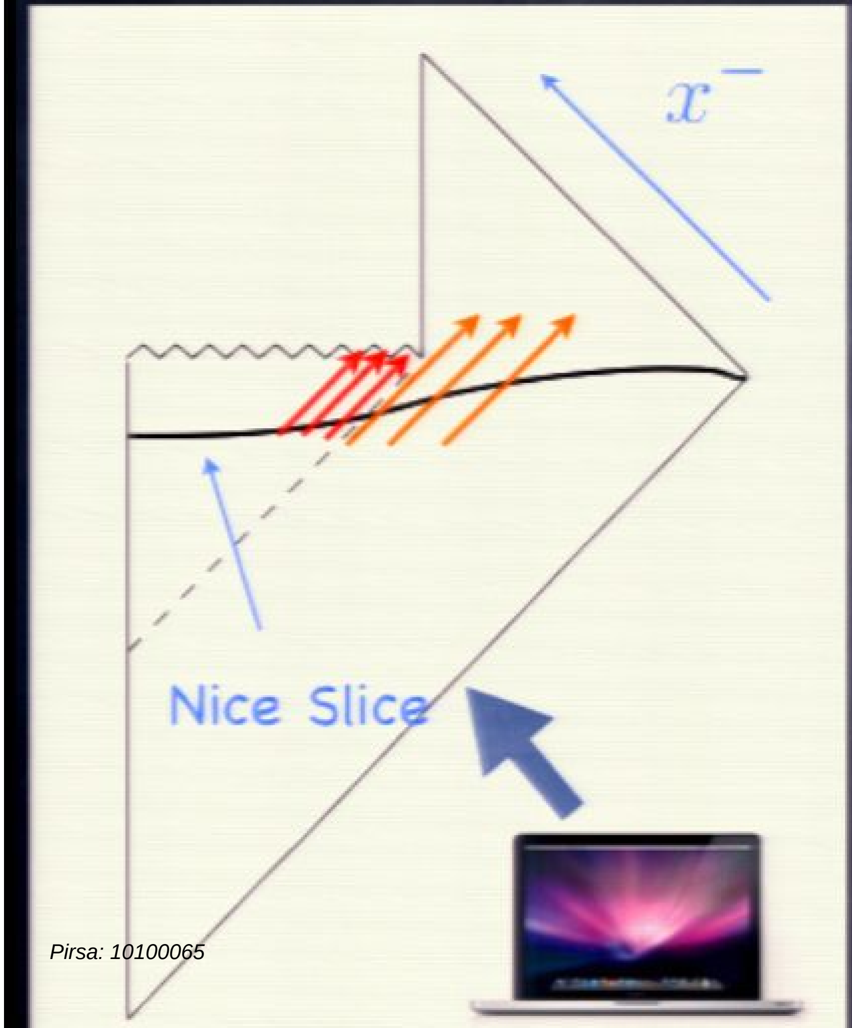

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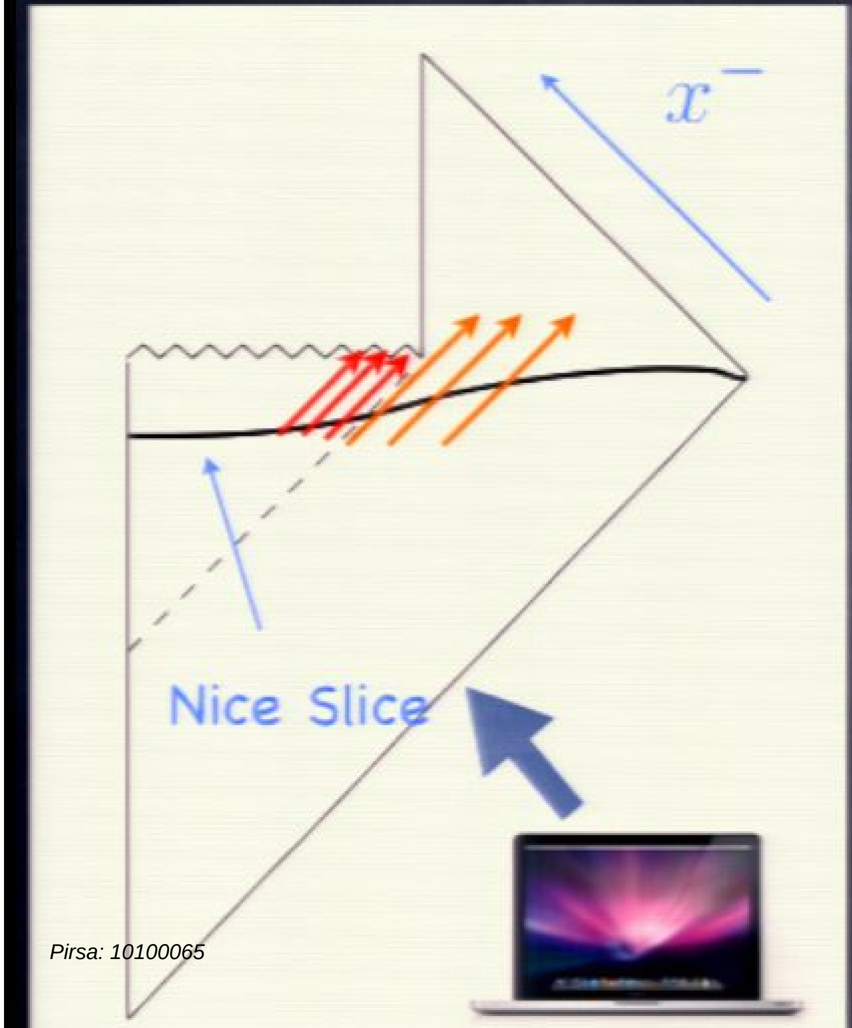

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$\therefore$ information lost

(Hawking 1976)

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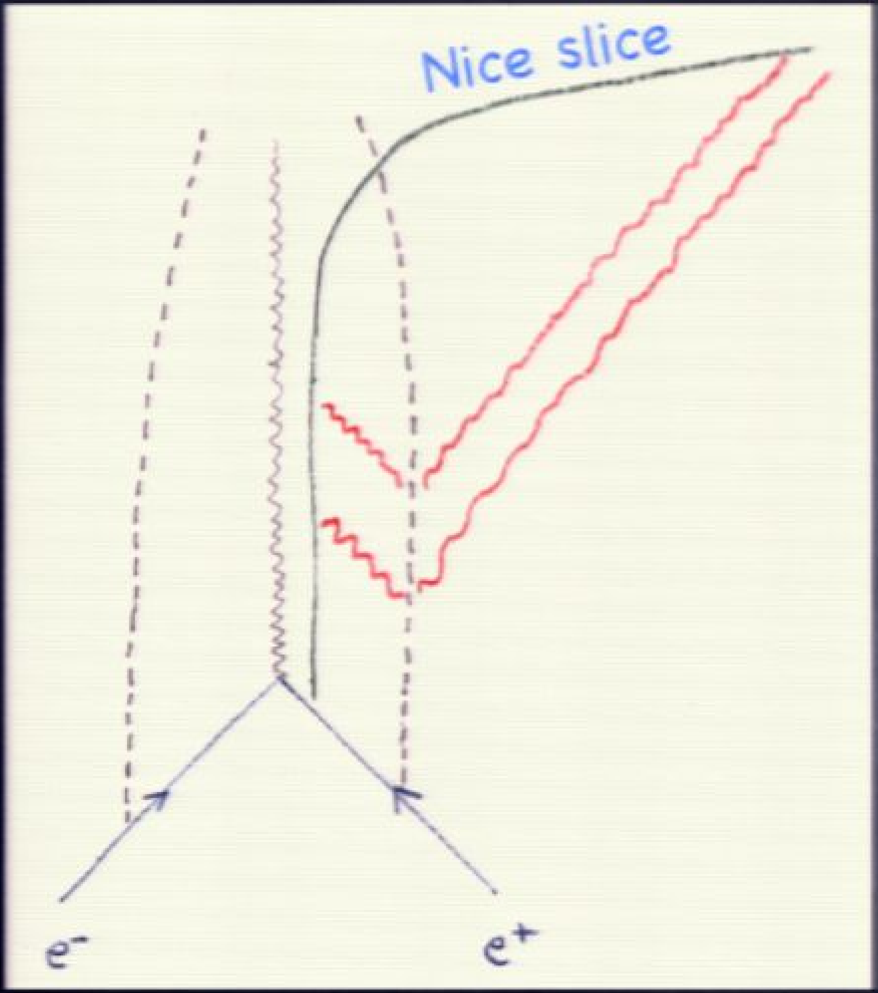

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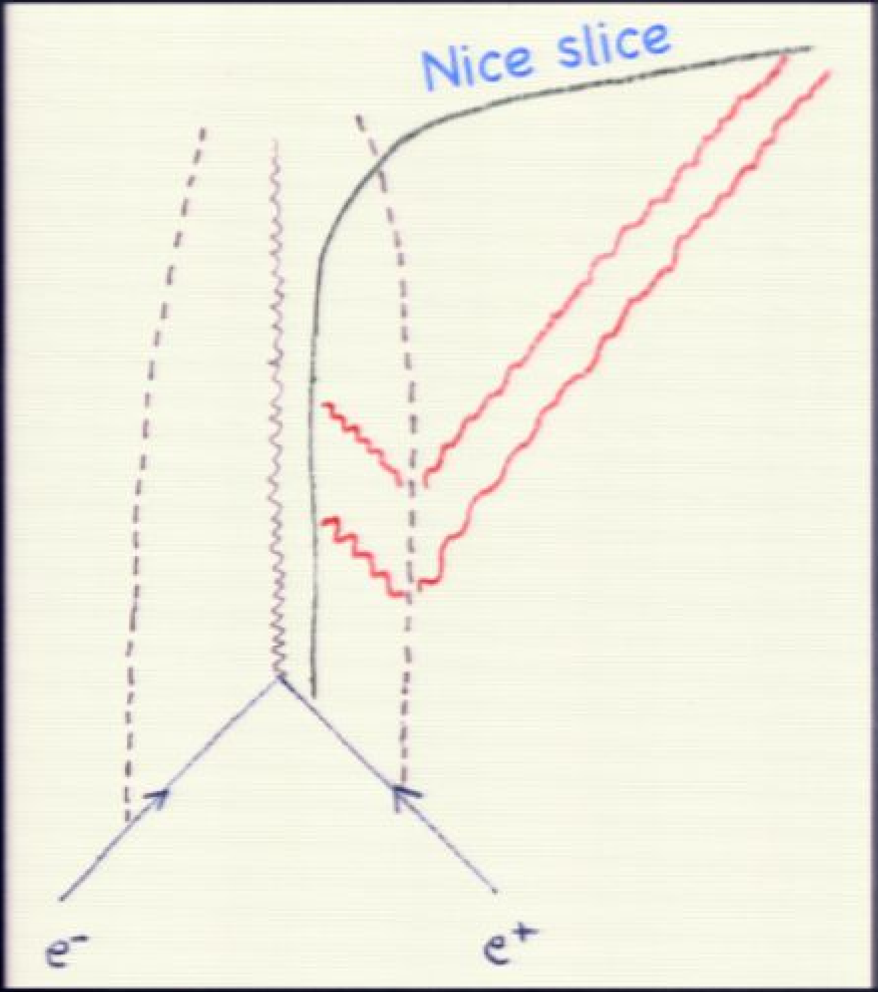

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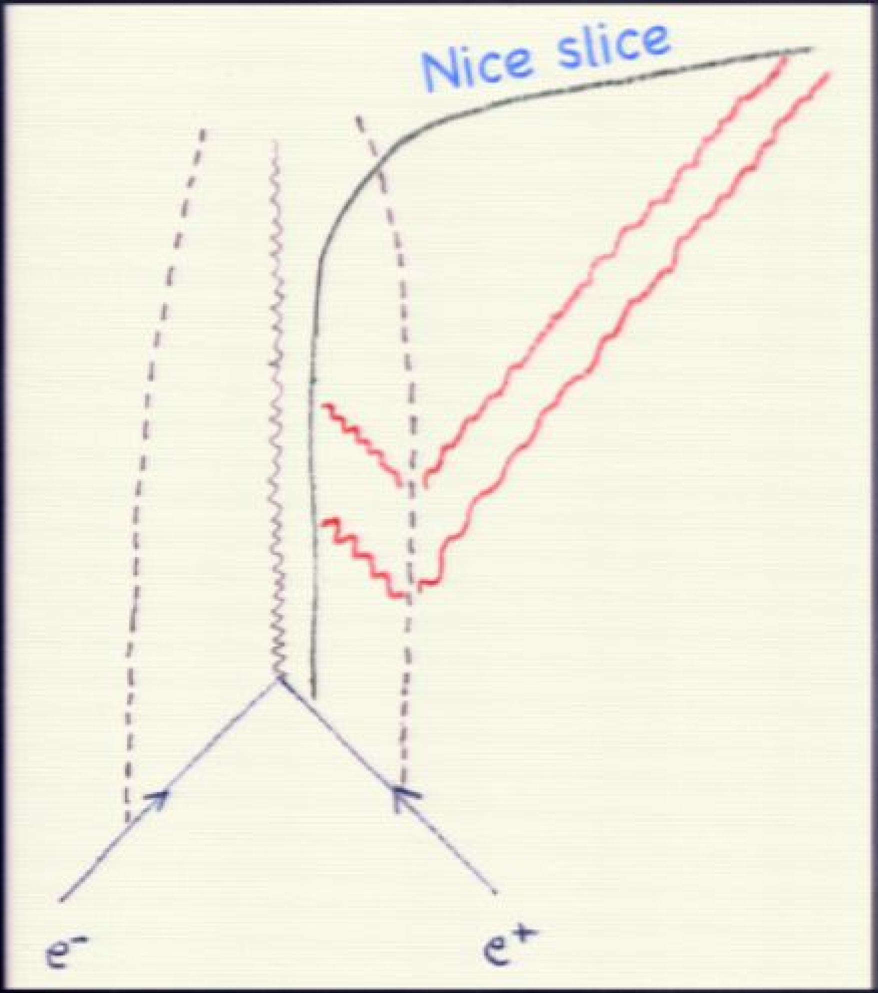

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$$E_{available} \sim M_{Planck}$$

$$\Delta I \sim S_{BH}$$

Long time!!

⇒ Remnant (long-lived or stable)

But: begin w/ arbitrarily large black hole

$\Rightarrow$ Infinite remnant species $M \sim M_{Planck}$

$\Rightarrow$ Infinite production instabilities

(See e.g. hep-th/9310101, hep-th/9412159)

"Paradox"

The "paradox:" a conflict between

Lorentz/diff invariance (macroscopic)

Quantum mechanics

Locality (macroscopic)

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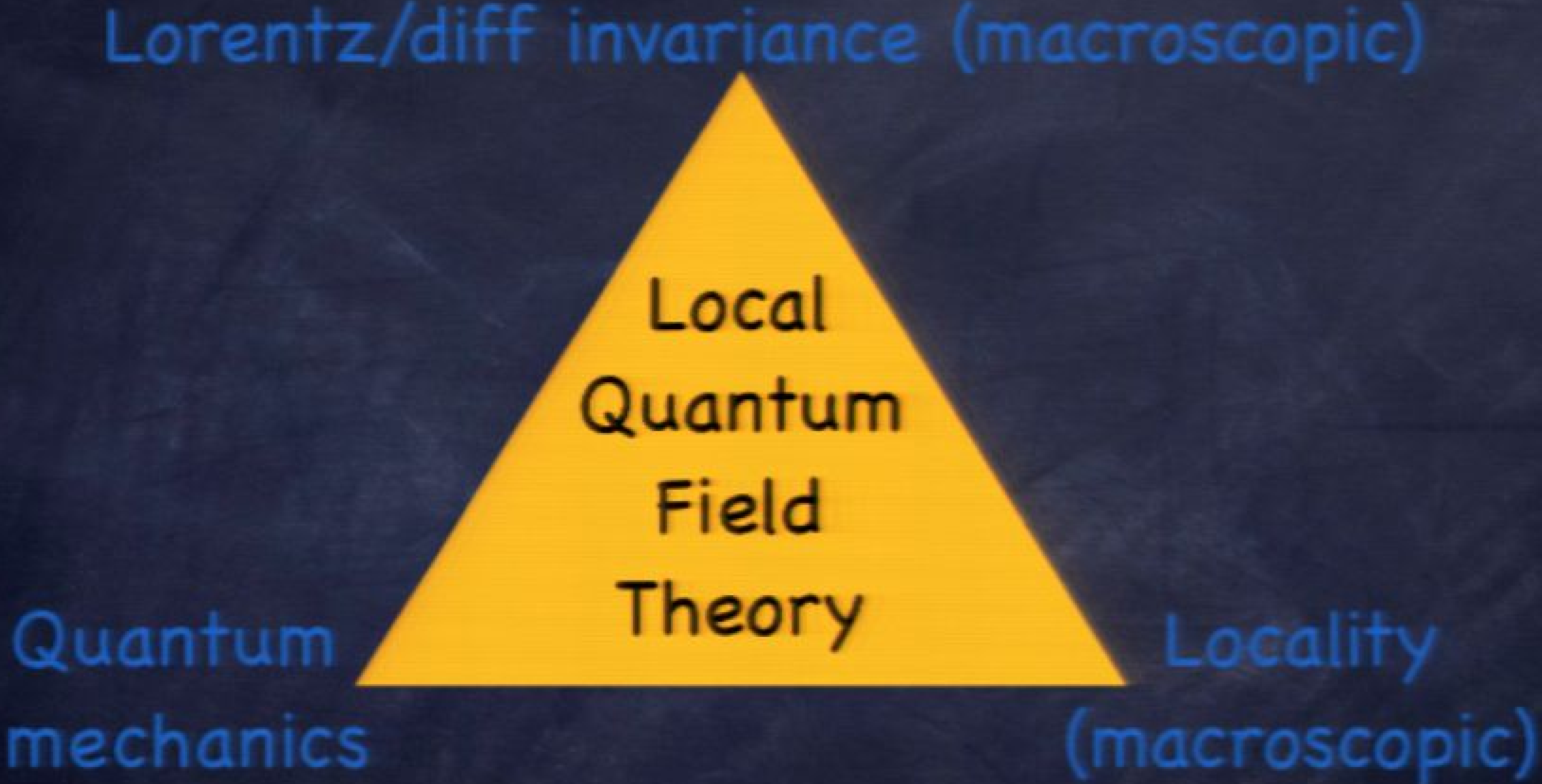

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Quantum
Field
Theory

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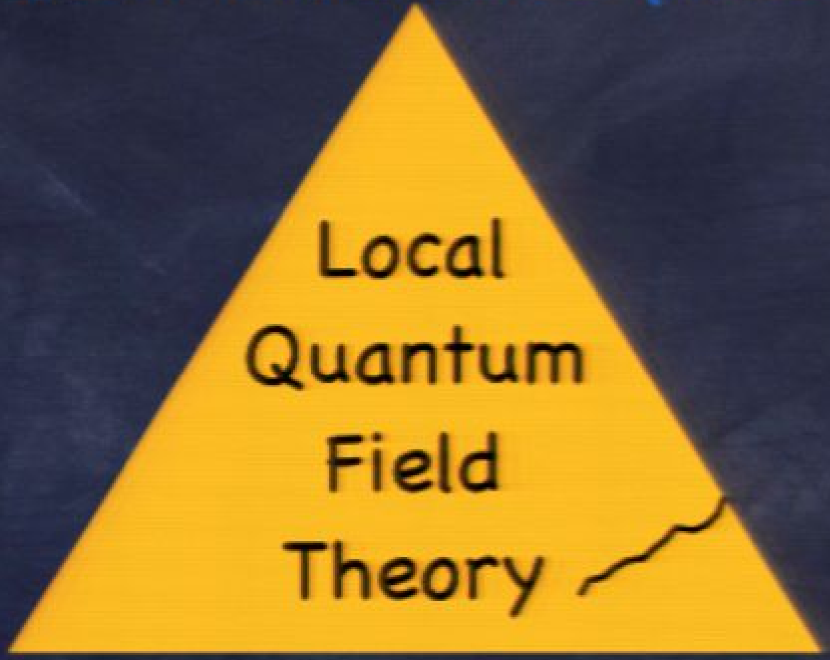

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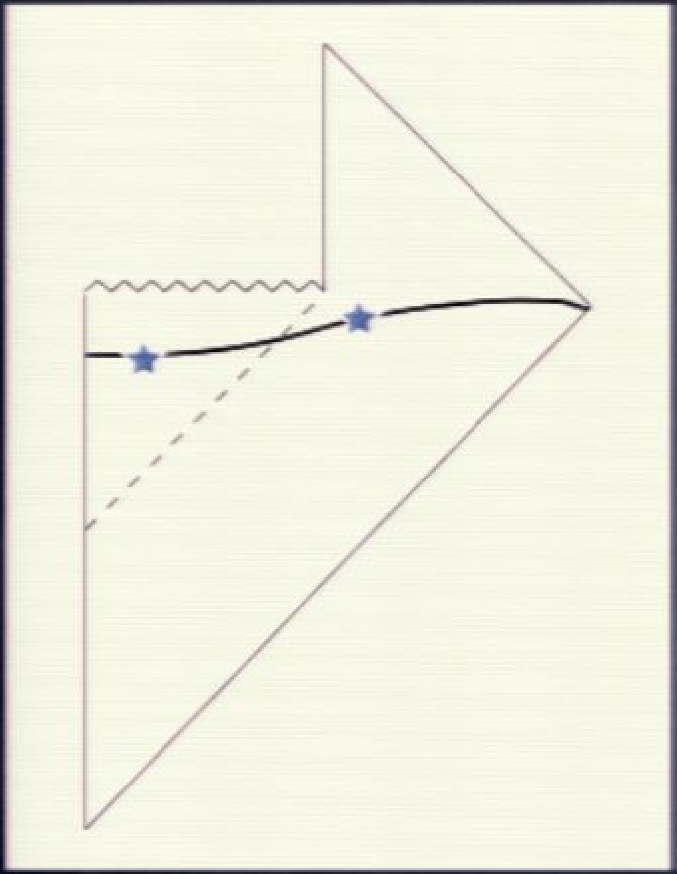
QM, LI -- can't see how to sensibly modify, respecting consistency and observation

A weak point: locality?



Good indications:
breakdown/modification
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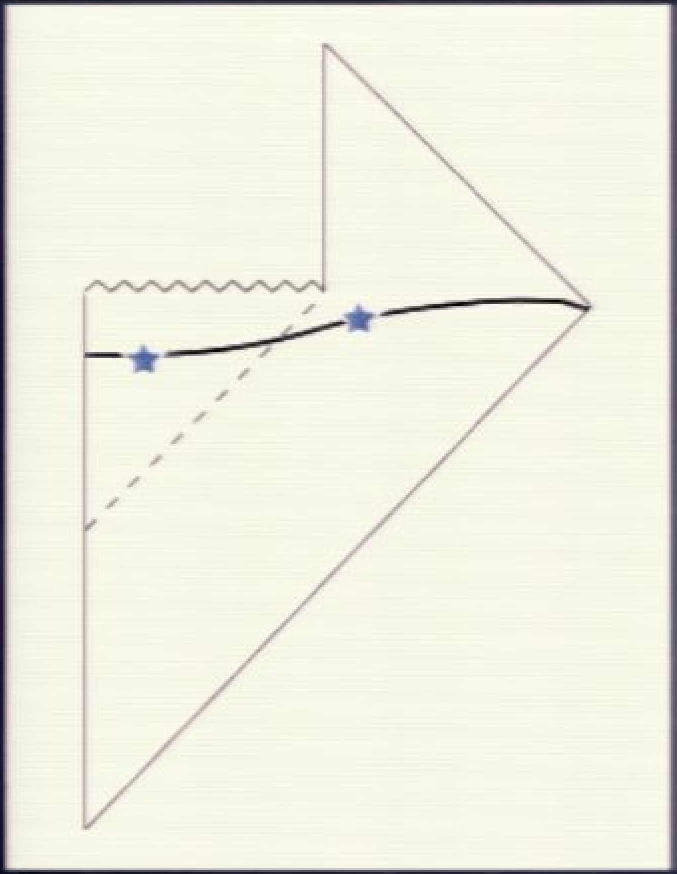

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$$r \sim R_S(E)$$

Indeed, Page (1993): basic info. theory tells us for unitary evolution, information must start to be returned by

$$t_{Page} \sim R_S S_{BH} \qquad (M^3 \text{ in D=4})$$

... BH still macroscopic

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(General concern: non local at Planck scale; no indication of needed long-distance modifications)

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- nonlocality -- extendedness
- perturbative calculations of S-matrix
- dualities - AdS/CFT, etc; "holography"

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  SBG, hep-th/0604072; SBG, Gross, Maharana, 0705.1816

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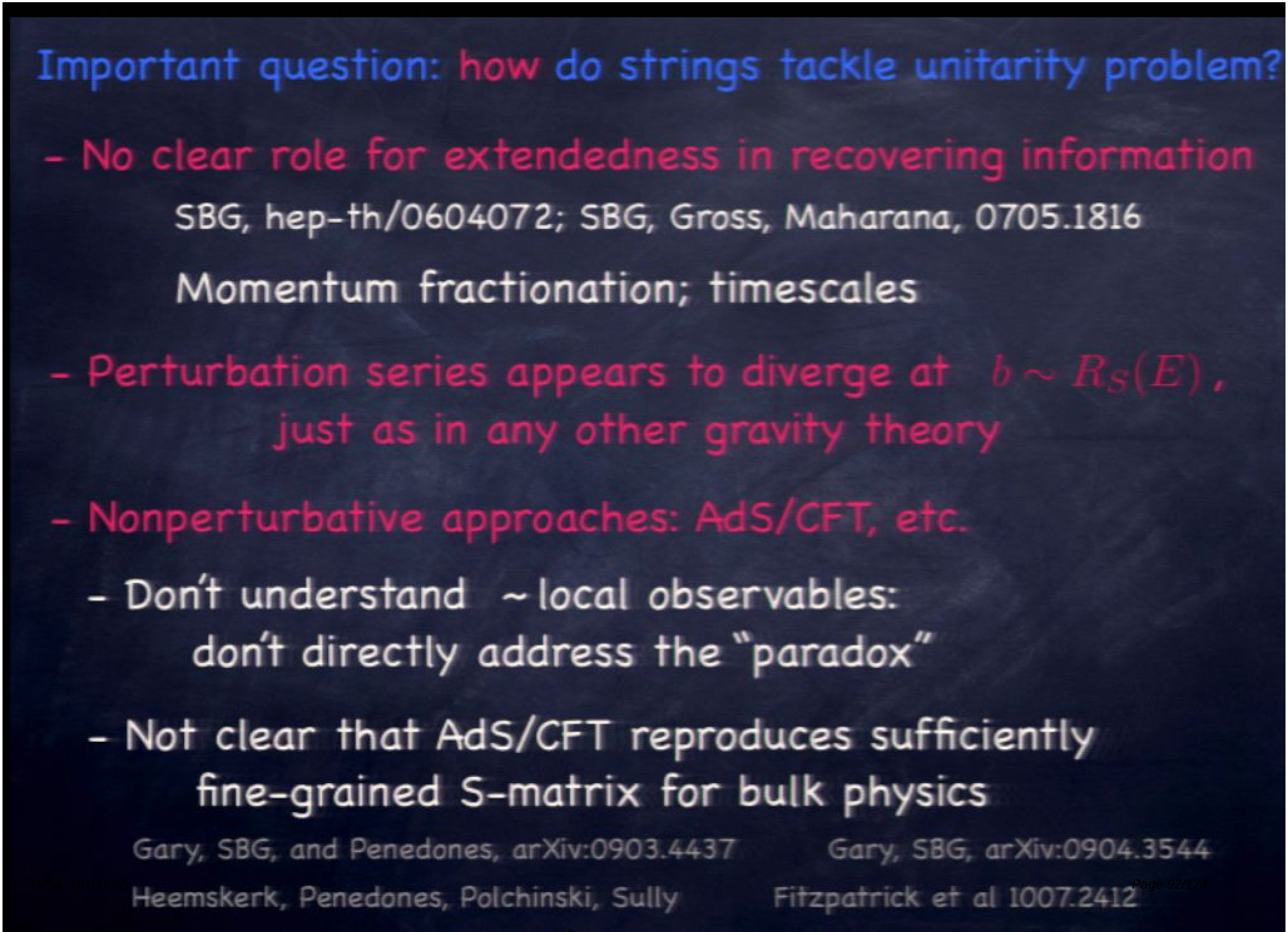

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  - Not clear that AdS/CFT reproduces sufficiently fine-grained S-matrix for bulk physics

Gary, SBG, and Penedones, arXiv:0903.4437

Gary, SBG, arXiv:0904.3544

Heemskerk, Penedones, Polchinski, Sully

Fitzpatrick et al 1007.2412

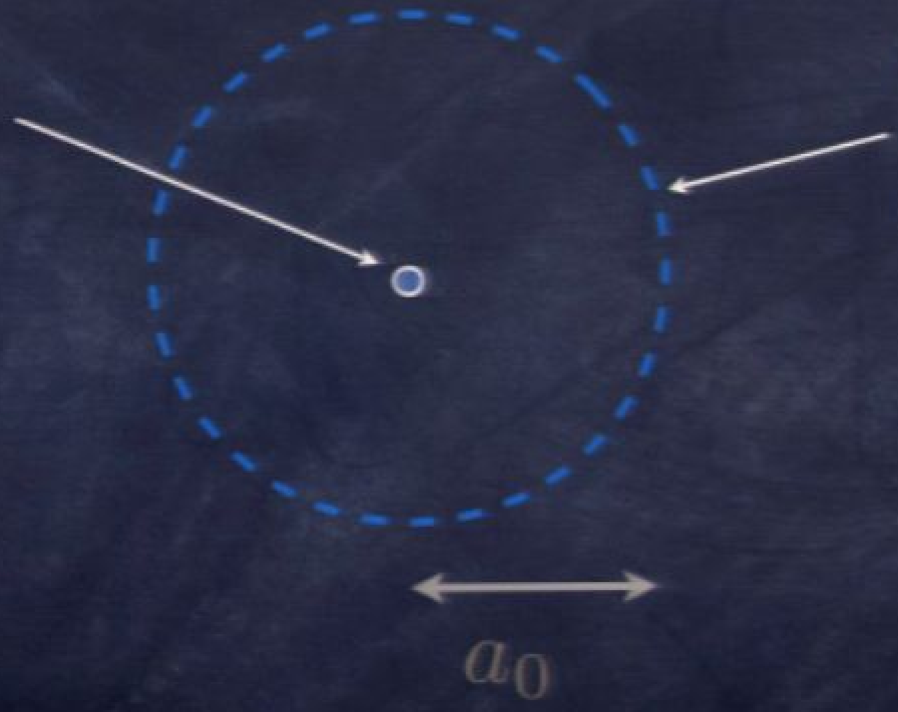
Proposal: let's take a broader viewpoint

We need to understand the basic principles and mechanisms of a consistent unitary gravitational mechanics (whether or not strings)

This appears to present profound conceptual challenges.

Recall history - we have faced a seemingly similar crises:

Classical atom



CM fails here

QM takes over
here
(CM irrelevant)

a_0

New physics was needed: Uncertainty principle

Wave mechanics...

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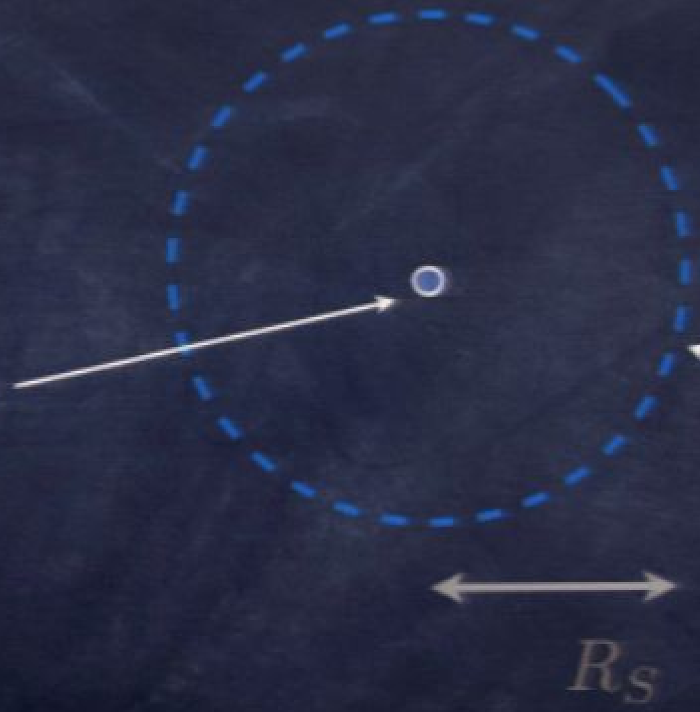
Black hole



LQFT fails here
Singularity

QG takes
over here?
(more subtle
breakdown LQFT)

New physics ~~was~~ needed:
is

~~Uncertainty principle~~
~~Wave~~ mechanics...

"Classical instability paradox"

"Black hole information paradox"

Do we need to go beyond to new principles?
(Or, find such principles in string theory??)

Perhaps the information problem is an important guide.

(As was the stability problem of the atom)

Some possible approaches to further investigation

- understand "where Hawking went wrong" -
  and what to do about it

- understand the "correspondence boundary" (~QM)
  more generally

- properties of the gravitational S-matrix
  ... how string theory was invented

- probe locality: what framework can yield the approximate locality of QFT, yet have needed "nonlocality" in the BH context?

"locality without locality"

- investigate related cosmology -- example, experiment!

Some previous proposals for a correspondence boundary for gravity:

planckian curvature: $\mathcal{R} < M_P^2$

string uncertainty principle: $\Delta X \geq \frac{1}{\Delta p} + \alpha' \Delta p$
(Veneziano/Gross)

modified dispersion: $p < M_p$

$$\left.\begin{array}{l} \Delta X \geq \frac{1}{\Delta p} + \alpha' \Delta p \\ p < M_p \end{array}\right\} \text{1 particle}$$

holographic (information) bounds: $S \leq A/4G_N$ multiparticle

Compare CM/QM

	dynamical descript.	validity
CM:	$x(t)\,,\,p(t)$	$\Delta x \Delta p > 1$

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Note: not single particle (e.g. spacetime uncertainty)

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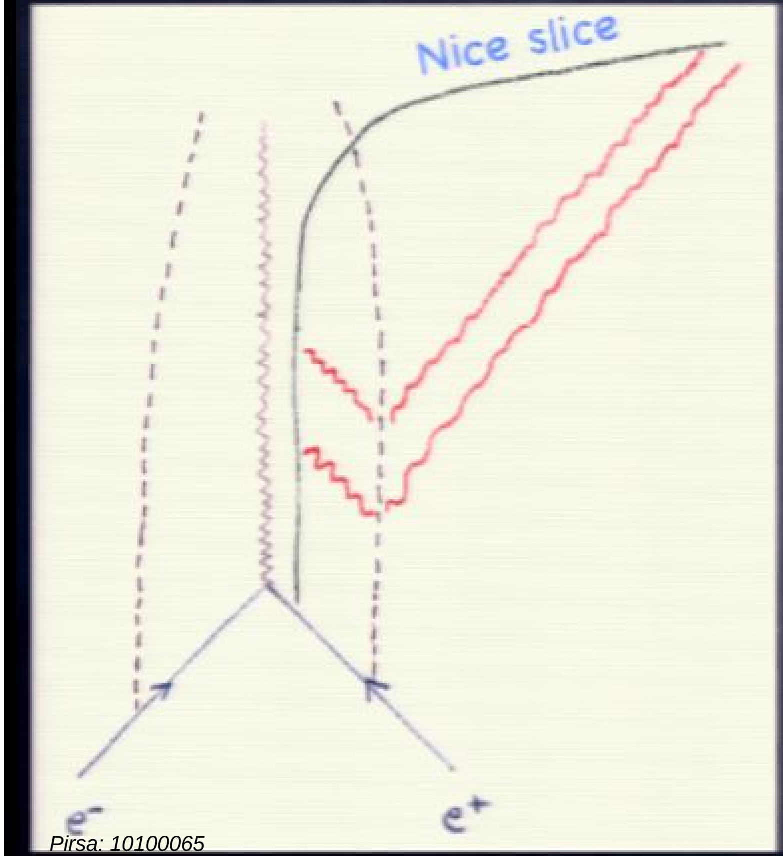
"locality bound"

SBG & Lippert;
hep-th/0605196;
hep-th/0606146

(generalizations: N-particle; dS)

Where did Hawking go wrong/is there really a paradox?

$$|\psi\rangle \rightarrow \rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$
$$\rightarrow S = -\mathrm{Tr}\rho l n \rho = \Delta I$$



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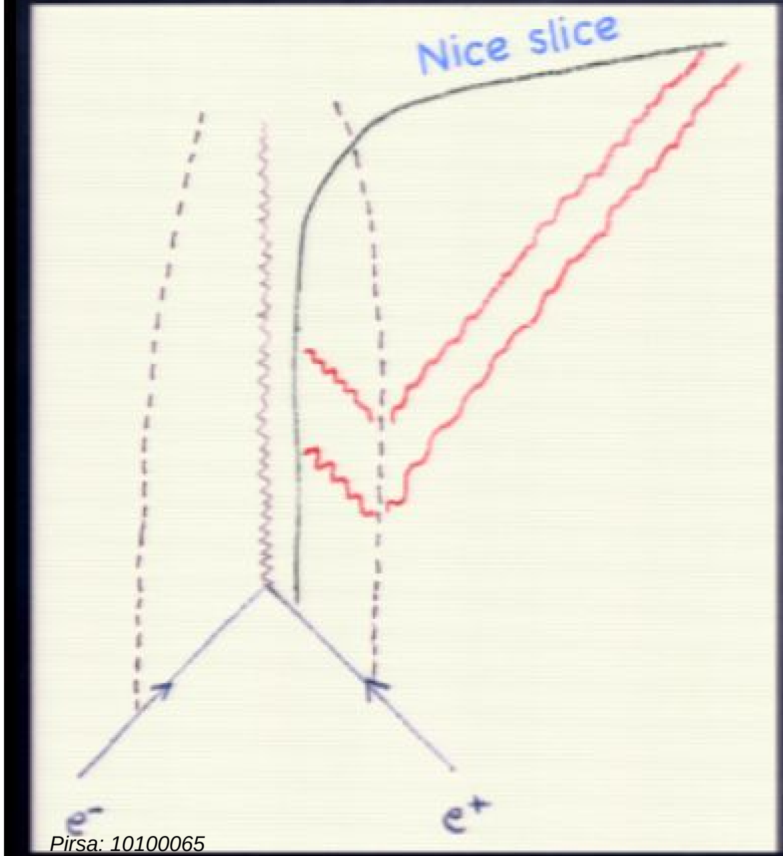
Is this a sharply defined calculation?

How to calculate $|\psi\rangle_{NS}$?



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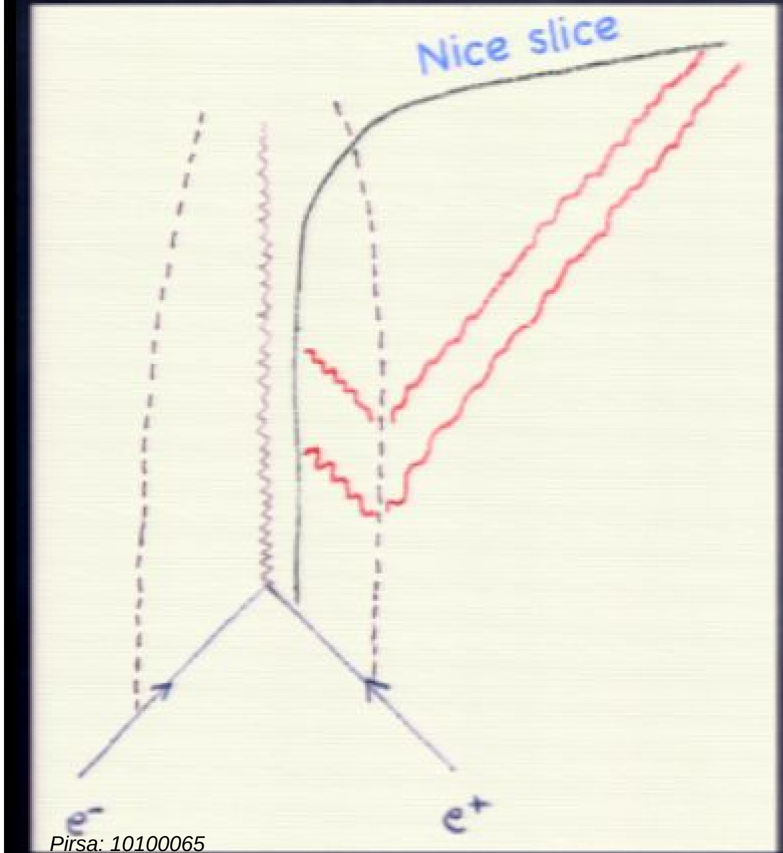


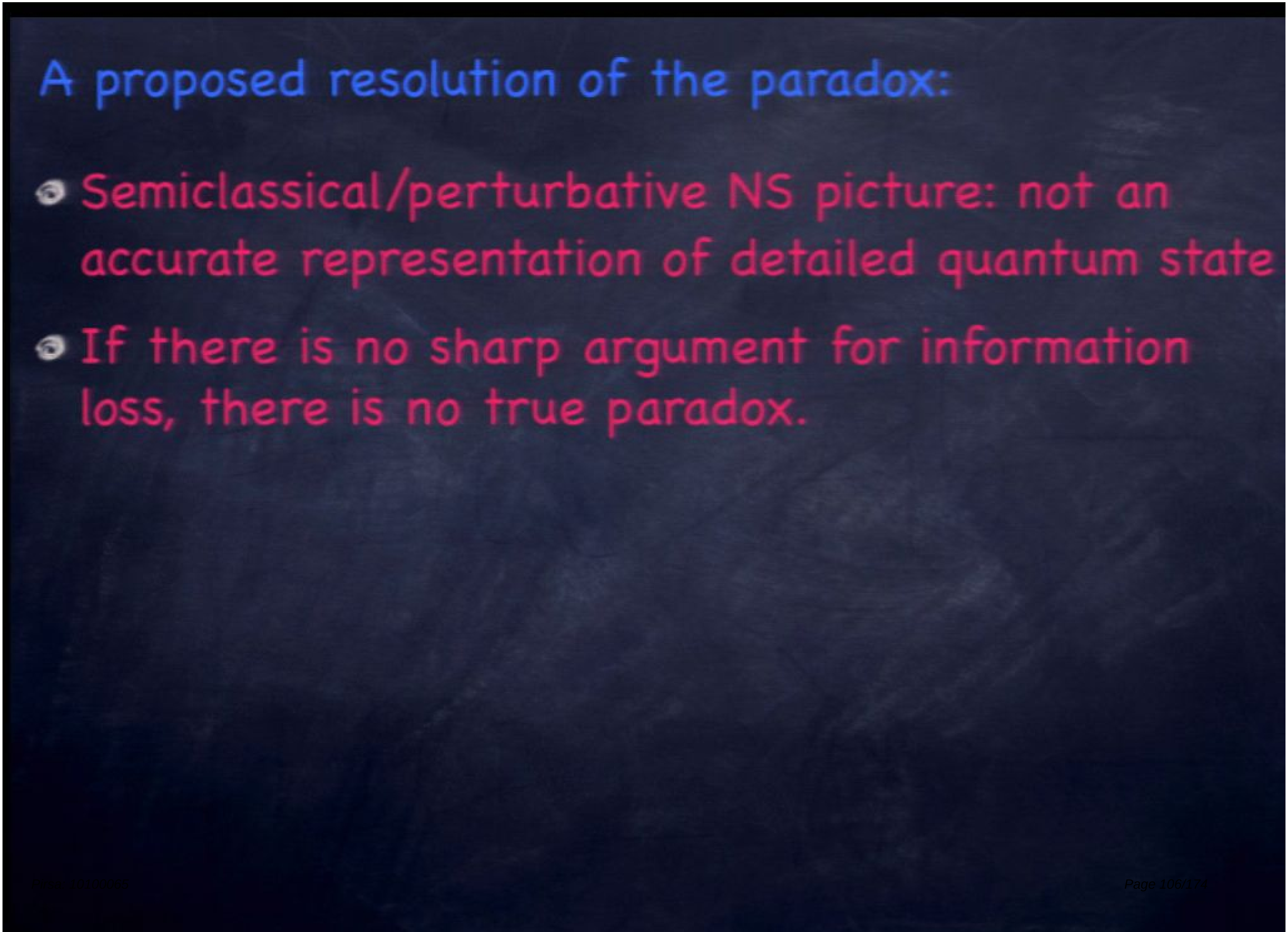
Possible issues:

(extreme, artificial construct)

1) not physically meaningful?
(gauge invariant)

2) large effect of fluctuations
at long times

SBG hep-th/0703116; 0911.3395



A proposed resolution of the paradox:

- Semiclassical/perturbative NS picture: not an accurate representation of detailed quantum state
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Nonetheless, failure of a perturbative description indicates the need for a nonperturbative completion, so there is certainly an information problem:

What is the nonperturbative gravitational dynamics that unitarizes HE scattering?

We want to sharpen our understanding of the issues with a local perturbative description of the black hole state -- and how LQFT might be modified.

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Black hole:

de Sitter space:

~ nice slice evolution

Toy model for black holes!

See also Arkani-Hamed et al. 0704.1814

Encounter parallel problems in dS/inflationary cosmo:

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“IR issues and loops in de Sitter space”

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"IR issues and loops in de Sitter space"

So: try to understand these problems here

Not just for the sake of the information problem!

(Experiment ...)

References: talks at the conference!

Quick discussion of observables:

How do we locally characterize state?

$O(x)$: local observable

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Semiclassically, done in studies of inflation: e.g. refer to observables at “reheating time”

(When inflaton takes specific value)

Proposed implementation, in QFT approximation:

SBG, Marolf, & Hartle, hep-th/0512200

SBG & Gary, hep-th/0612191 (example in 2d)

$$\mathcal{O} = \int d^D x \sqrt{-g}\, O(x) B(x)$$

local observable

reference field

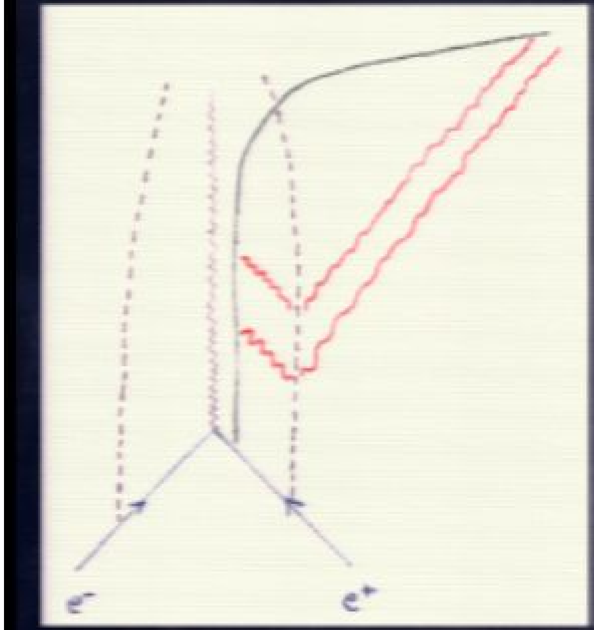
“proto-local observables”

$$\mathcal{O} = \int d^D x \sqrt{-g}\, O(x) B(x)$$

Background

- In states where background sharply localizes, get local observable in an approximation
- Thus, localization is "emergent"
- This can be a bad approximation: fluctuations of reference field B, or large backreaction ... (locality bound, ...)

A interesting estimate for BH:



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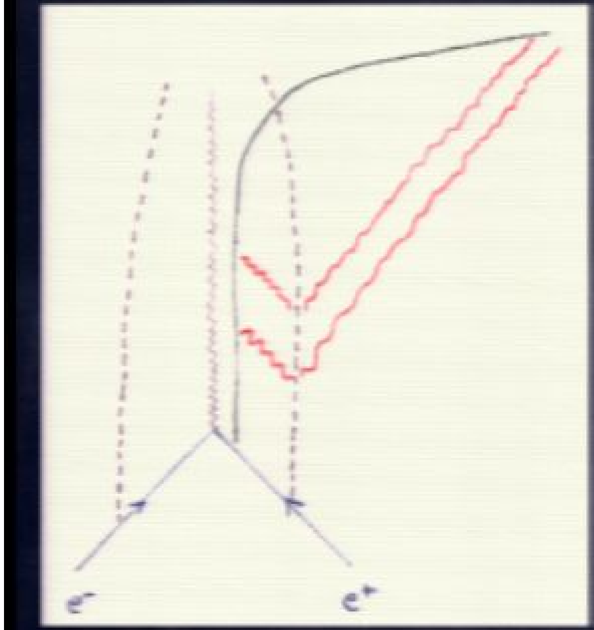

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time scale: $t \sim S_{BH} R$ ... Page time

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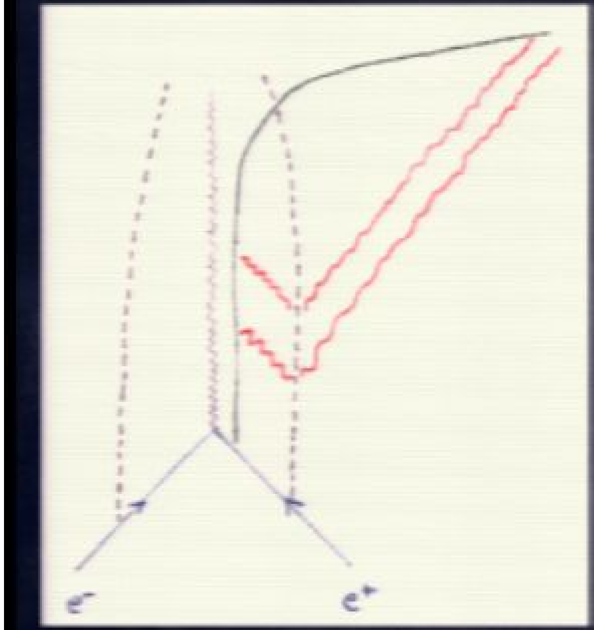

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time scale: $t \sim S_{BH} R$ ... Page time

Also, issues for dS after time $t \sim S_{dS} R_{dS}$

(See e.g. SBG & Marolf, 0705.1178)

Cosmological context: turn to the fluctuation problem (related to reference background issues)

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An apparent basic point:

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- decay of cosmological constant

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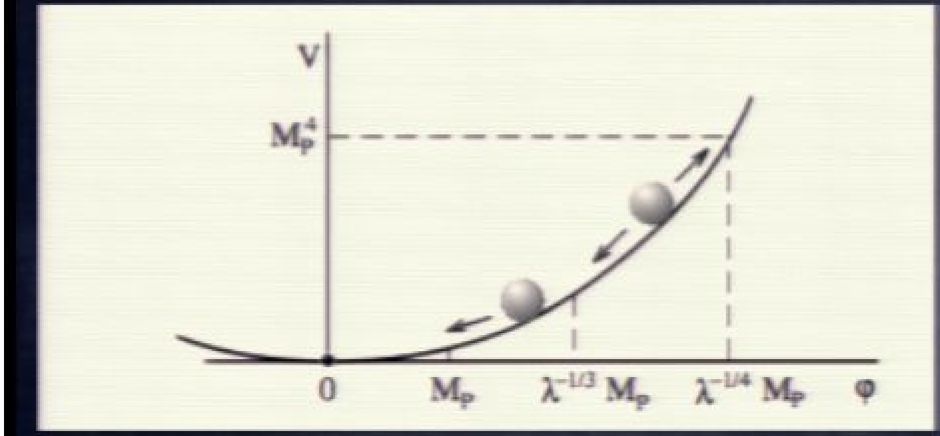
An example - self reproduction:



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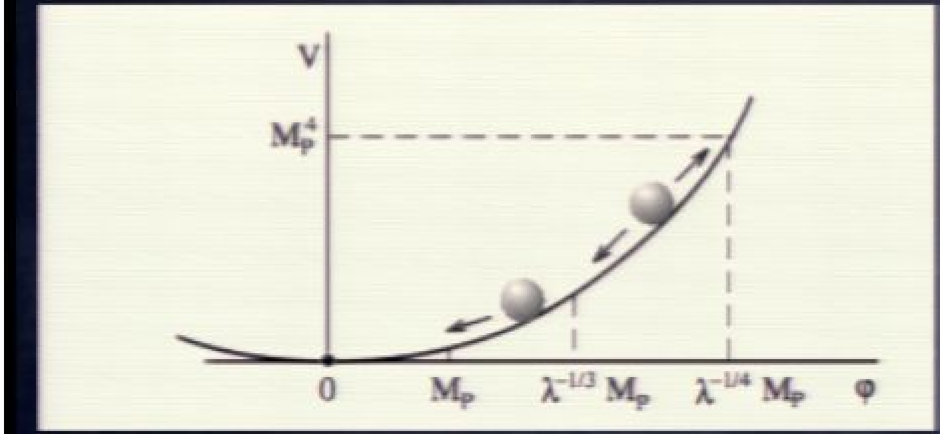

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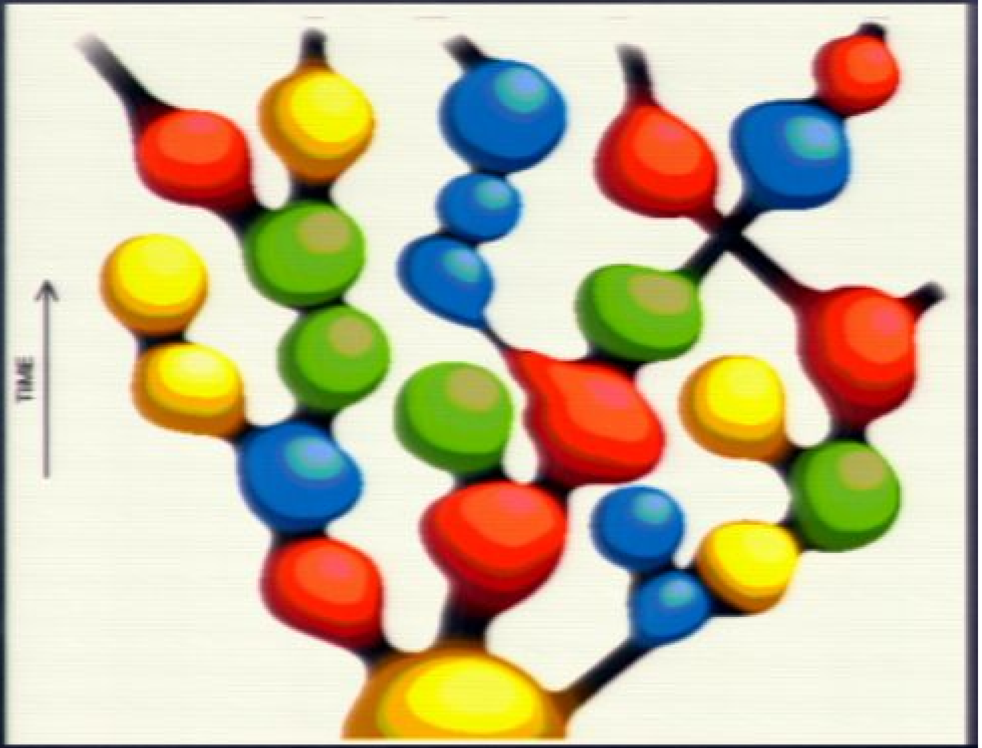

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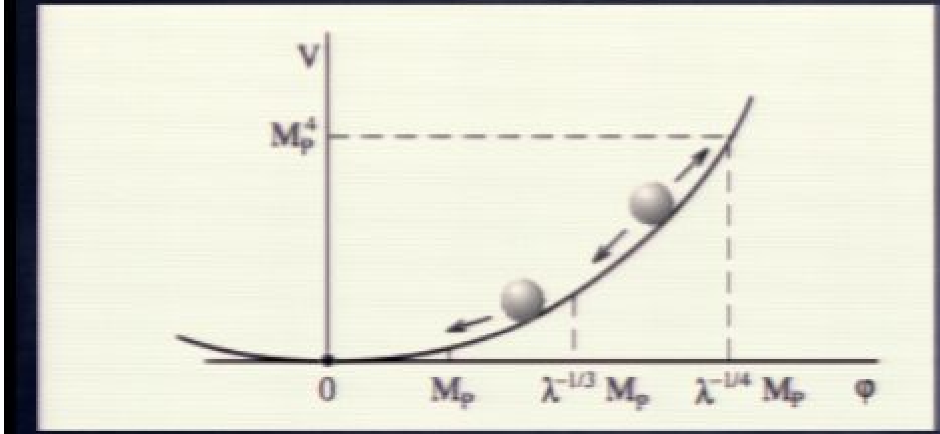

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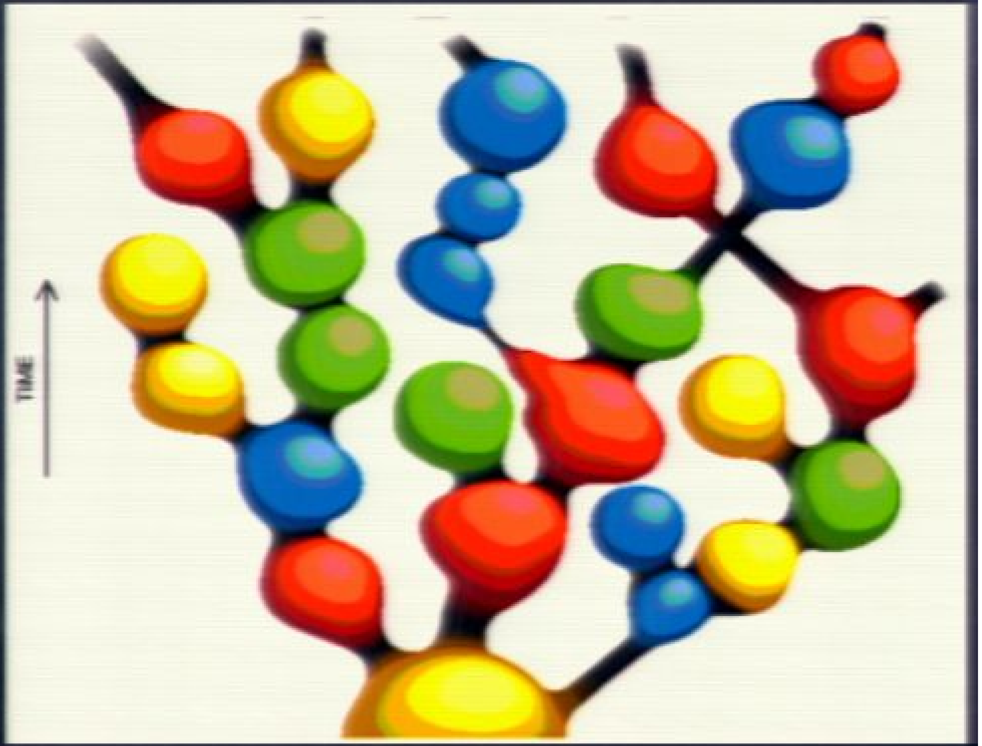


Accumulated effect of fluctuations becomes large

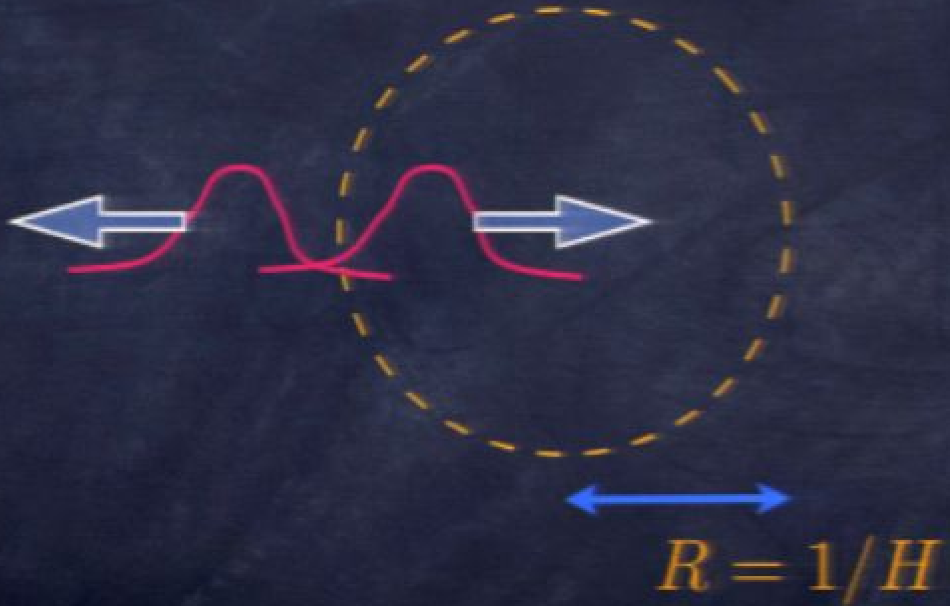
How general is this?

An essential mechanism

dS: $ds^2 = -dt^2 + e^{2Ht} dx_3^2$

(flat slicing
throughout)

Consider a massless (or light) field:



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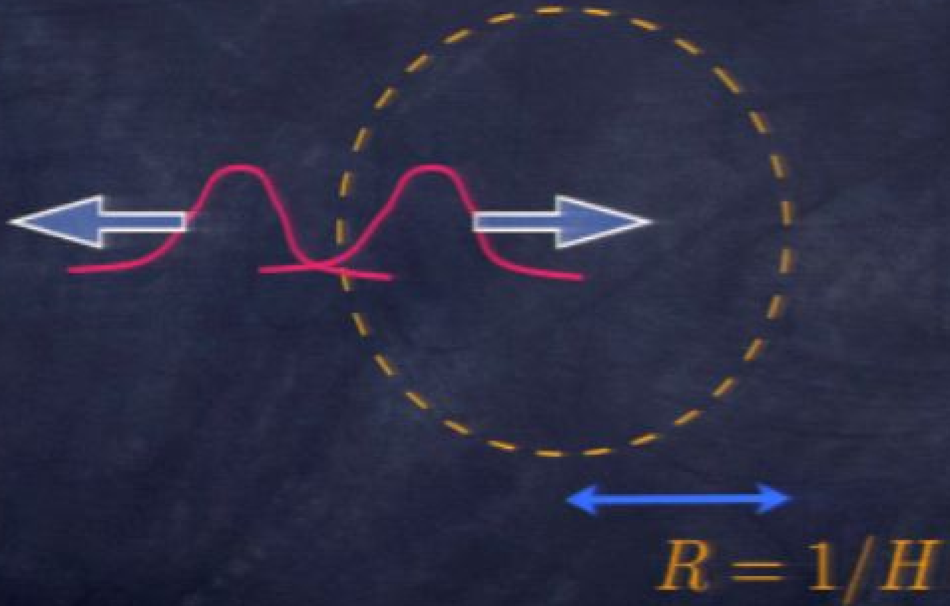

(~Hawking
radiation)

Fluctuations leave horizon, freeze,
accumulate (~classical)

For example, massless scalar field, $\sigma(x,t)$

k – comoving momentum

$$\langle\sigma(x,t)\sigma(x,t)\rangle = \int \frac{d^3k}{(2\pi)^3 2k}\left(\frac{H^2}{k^2} + e^{-2Ht}\right)$$

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How is this regulated?

1) Add a mass: $m \ll H$

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2) Finite duration inflation

$$\langle \sigma^2(x,t) \rangle = \int_{a_i H}^{aH} \frac{d^3k}{(2\pi)^3 2k} \frac{H^2}{k^2} = \left(\frac{H}{2\pi}\right)^2 2H(t - t_i)$$

largest wavelength

$$Ht_i = -\log(\Lambda_{IR})$$

Grows w/ duration of inflation

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"Portal"

e.g. self-repro $\phi \rightarrow V(\phi) \rightarrow g_{\mu\nu}$

Particularly tricky given question of gauge (diff) invariant observables!

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One possible test: loop contributions due to such fluctuations

(SBG & Sloth, see talk by Sloth)

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One possible test: loop contributions due to such fluctuations

(SBG & Sloth, see talk by Sloth)

- General method: can evaluate leading IR/long time effect via "semiclassical methods" (and check w/ full quantum calculation)
- Indeed find large contributions

E.g. corrections to $\langle\sigma(x)\sigma(x')\rangle$

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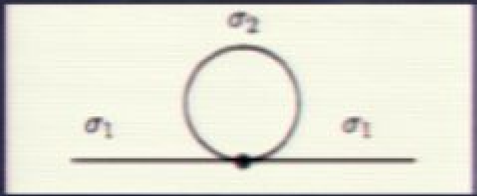
Toy model:
scalar
couplings

Marolf and Morrison



Burgess et al
(+many others)

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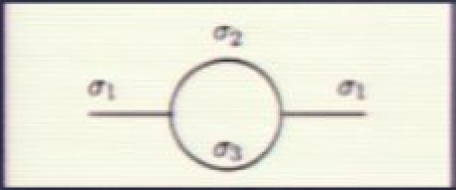

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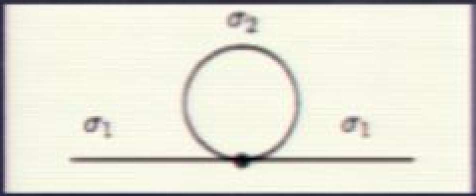

Burgess et al
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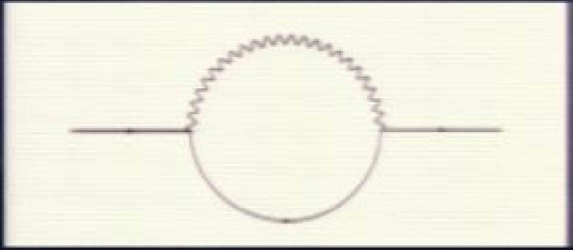
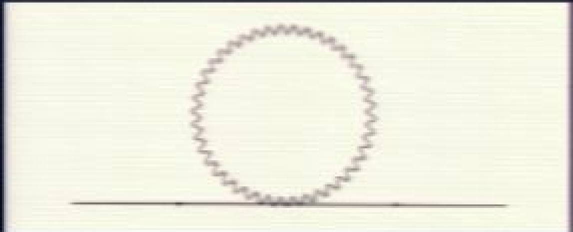
Full gravity:



SBG & Sloth



(streamlined "in-in" rules: 1005.3287)

E.g. apply to slow roll: $h_{ij} = a^2(t)e^{2\zeta}(e^{\gamma})_{ij}$

$$\langle \zeta_{k_1} \zeta_{k_2} \rangle = \langle \zeta_{k_1} \zeta_{k_2} \rangle_0 \left[1 + \frac{1}{2}(n_s - 1)^2 \left\langle \zeta^2(x) \right\rangle_* + \frac{n_s - 4}{3} \frac{n_s - 1}{5} \left\langle \gamma^2(x) \right\rangle_* \right]$$

scalar fluctuations

tensor fluctuations

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scalar fluctuations tensor fluctuations

Can give large shifts to: $r \propto \frac{\langle\gamma^2\rangle}{\langle\zeta^2\rangle}$ f_{NL} ...

Large when? $\langle\gamma^2\rangle \sim H^3 t \sim 1 \;\Leftrightarrow\; t \sim 1/H^3$

general dimension: t~RS (We've seen before)

... apparent breakdown of perturbation theory!

A question being examined at this conference.

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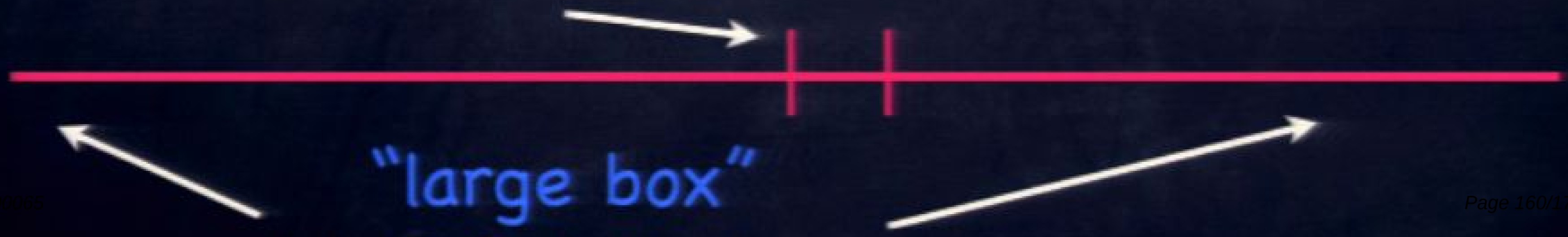
1) Perturbation theory indeed breaks down for the purposes of computing the "full state" (in the "large box"): large IR corrections



"small box" our observable universe

"large box"

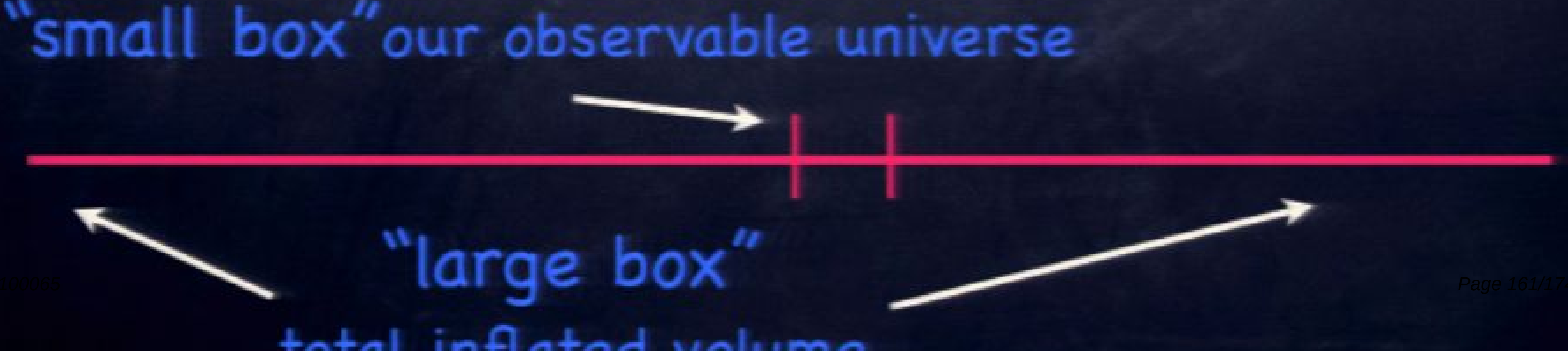
total inflated volume

A question being examined at this conference.

Proposed outlines of a story:

1) Perturbation theory indeed breaks down for the purposes of computing the "full state" (in the "large box"): large IR corrections

2) In computing more local quantities ("small box"), can in simple cases absorb the large corrections into background ("resum," etc.)



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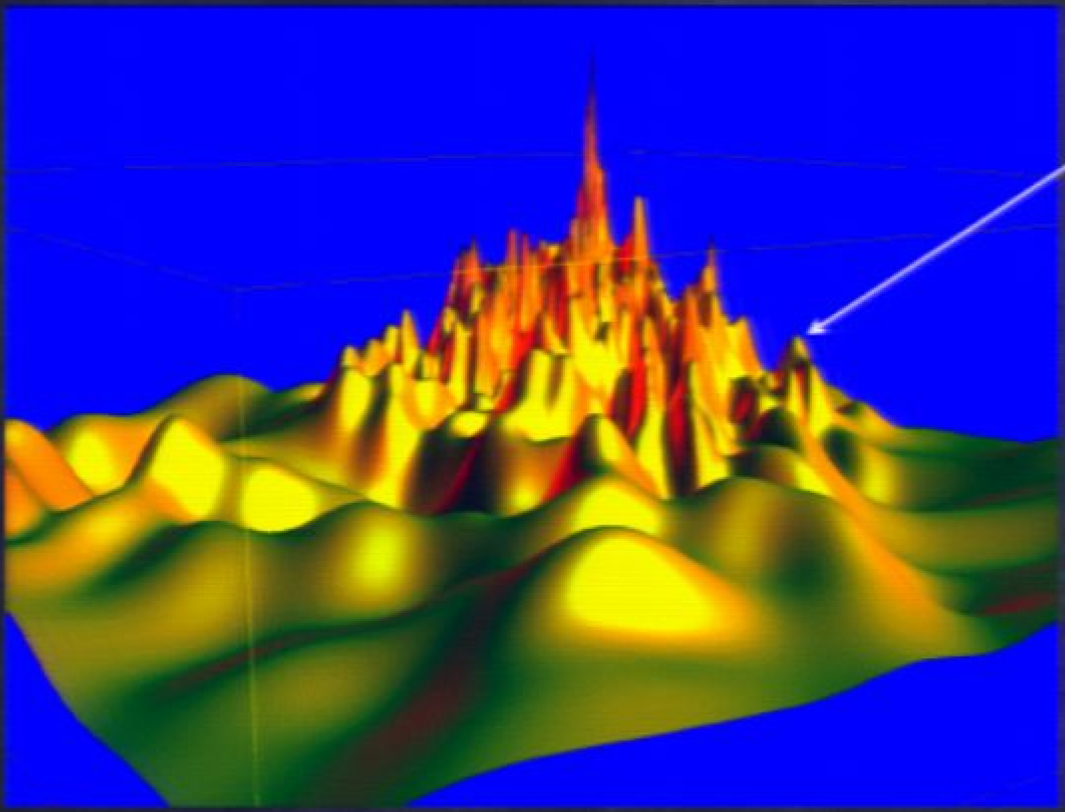
Illustrate w/ self-reproduction:



$\phi = \phi_0$

Expect can make predictions about local observables, with appropriate conditionals …

But can't calculate full quantum "wavefunction of the universe"?

"One observer's fluctuation is
another observer's background"

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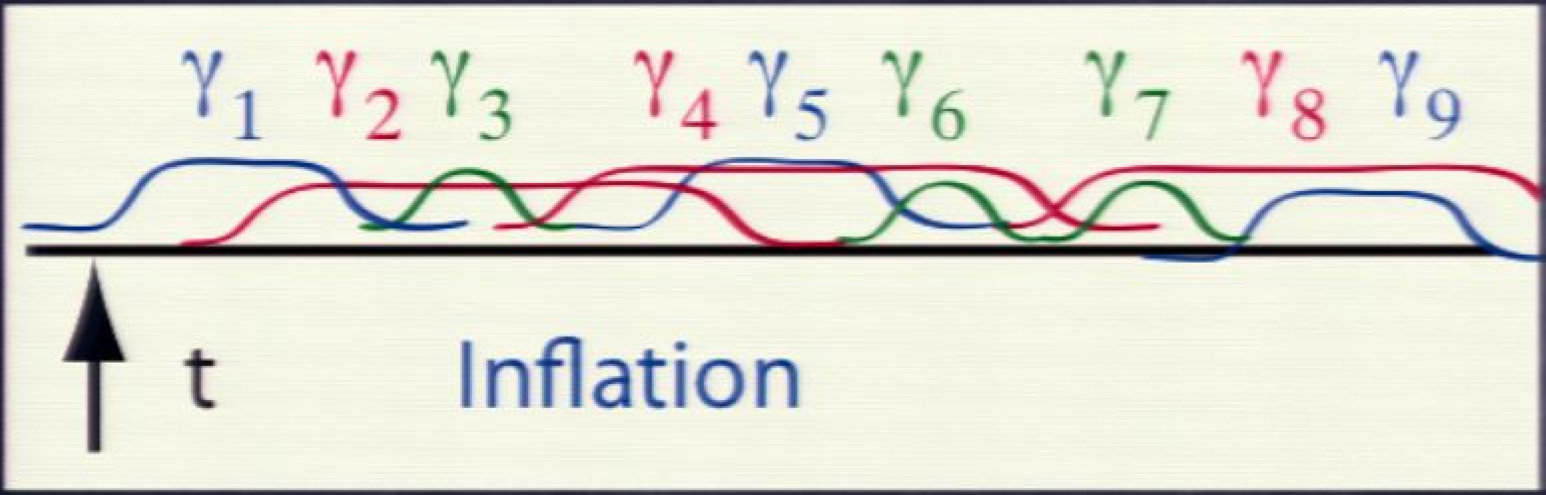
Also appears true for tensor fluctutions:



$\langle\gamma^2\rangle \propto H^3 t$ "spacetime foam, writ large"

(there are methods to measure, e.g. redshifts, etc.)

Plausible story (under investigation):

- ~local observables: resum - eliminate large effects (in sufficiently simple circumstances)
- but globally, doesn't look like can eliminate

plausible instability of dS. though, perhaps not to extinguishing cosmological constant

Observables?

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Compare self reproduction: (Creminelli et al)

$$\rho(V) \qquad\qquad V = \int d^3x\sqrt{h}$$

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γ fluctuations: volume preserving

one possibility $\displaystyle\int_\Gamma ds$

Γ :
- Curve between comoving point masses
- Nontrivial holonomy -- e.g. on T^3

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even if no practical data implications -- important point of principle; also: landscape!

Non-perturbative completion of gravity?

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Non-perturbative completion of gravity?

3) How sharp are the parallels with BH story (no perturbative nice slice state?)

Non-perturbative completion should unitarize S-matrix; plausibly not "local"


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