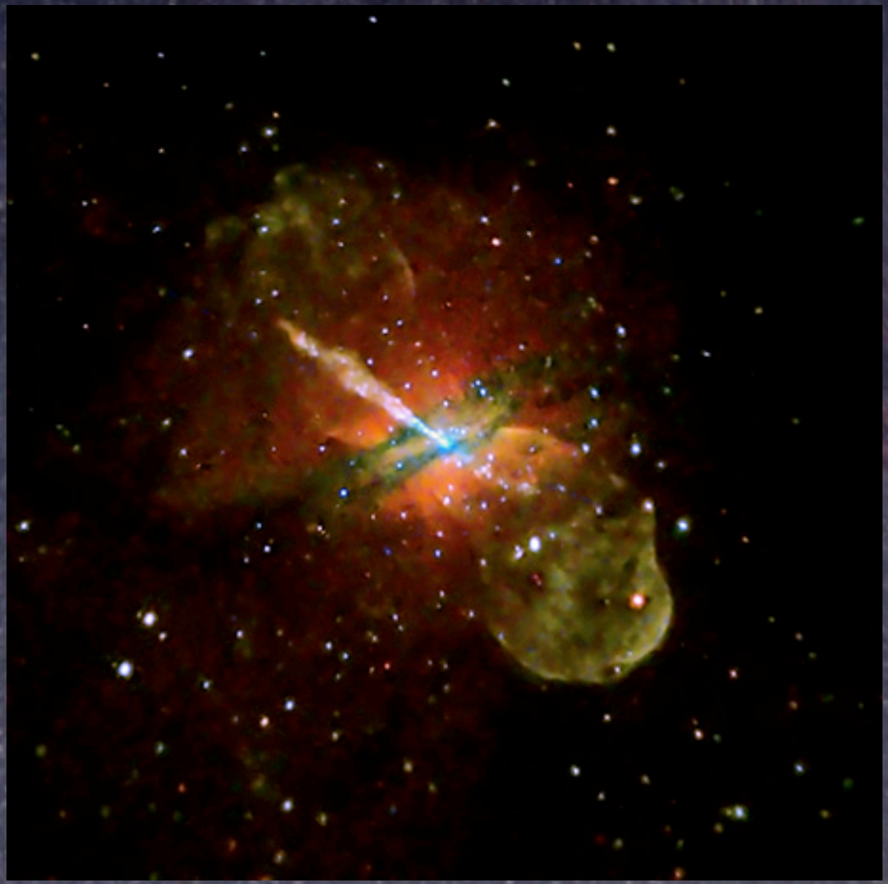
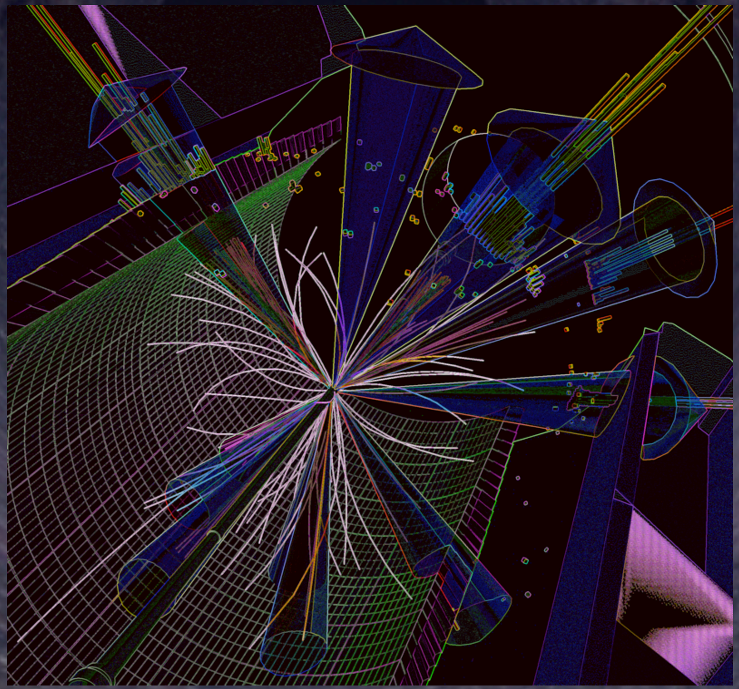
Black holes in the cosmos, in the lab, and in fundamental physics

Steven B. Giddings

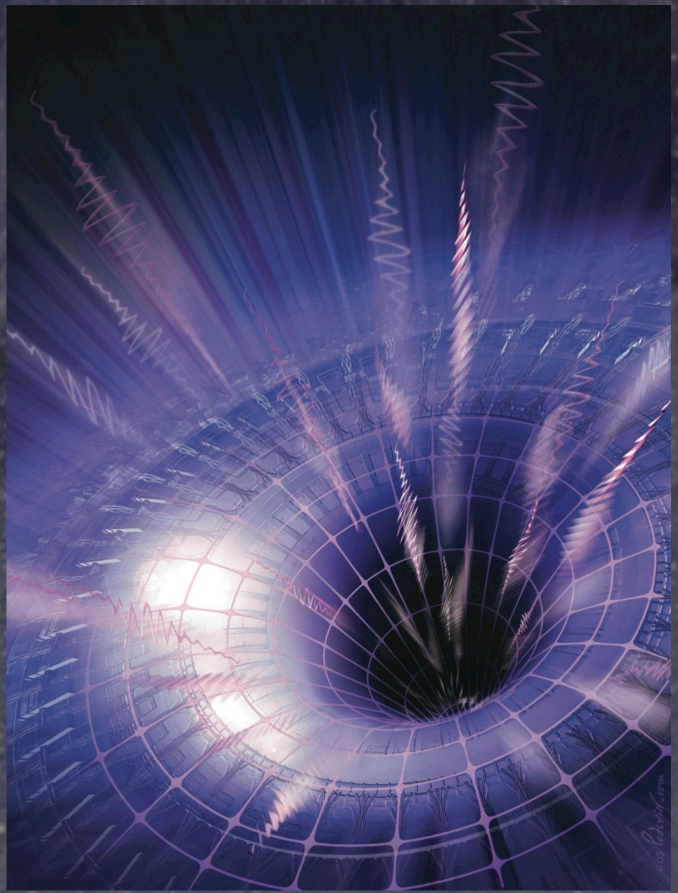
UC Santa Barbara





CERN

Sept. 6-8, 2010



Outline

Lect 1

1. Black hole basics, pt. 1: classical black holes
2. Black holes in the cosmos
   stellar endpoints, galaxies, and primordial
3. Black hole basics, pt. 2: quantum black holes
4. Black holes (not) in the lab

Lect 2

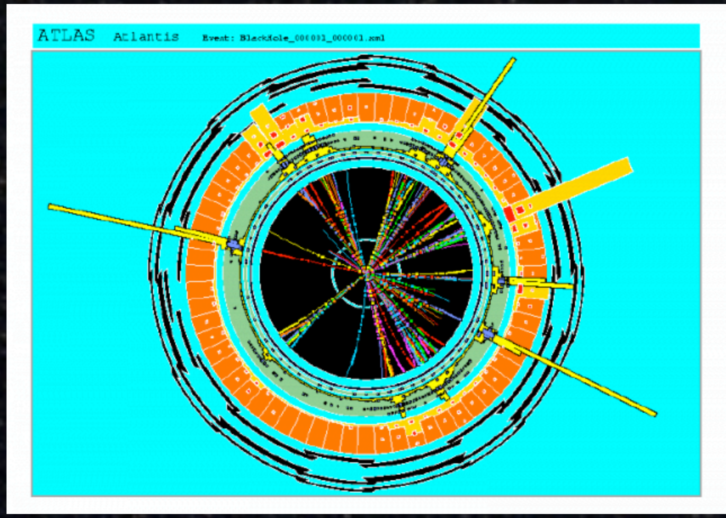
5. TeV-scale gravity -- an introduction
6. Black holes at colliders

Lect 3

7. Is it safe?
8. Black holes and the foundations of physics: "paradoxes" and new paradigms

Black holes at colliders, cont'd

Potentially significant rates



$$(I) : \sigma = 1.8 \times 10^2 fb \Rightarrow 1BH/10min$$

$$(II) : \sigma = 1.8 \times 10^3 fb \Rightarrow 1BH/min$$

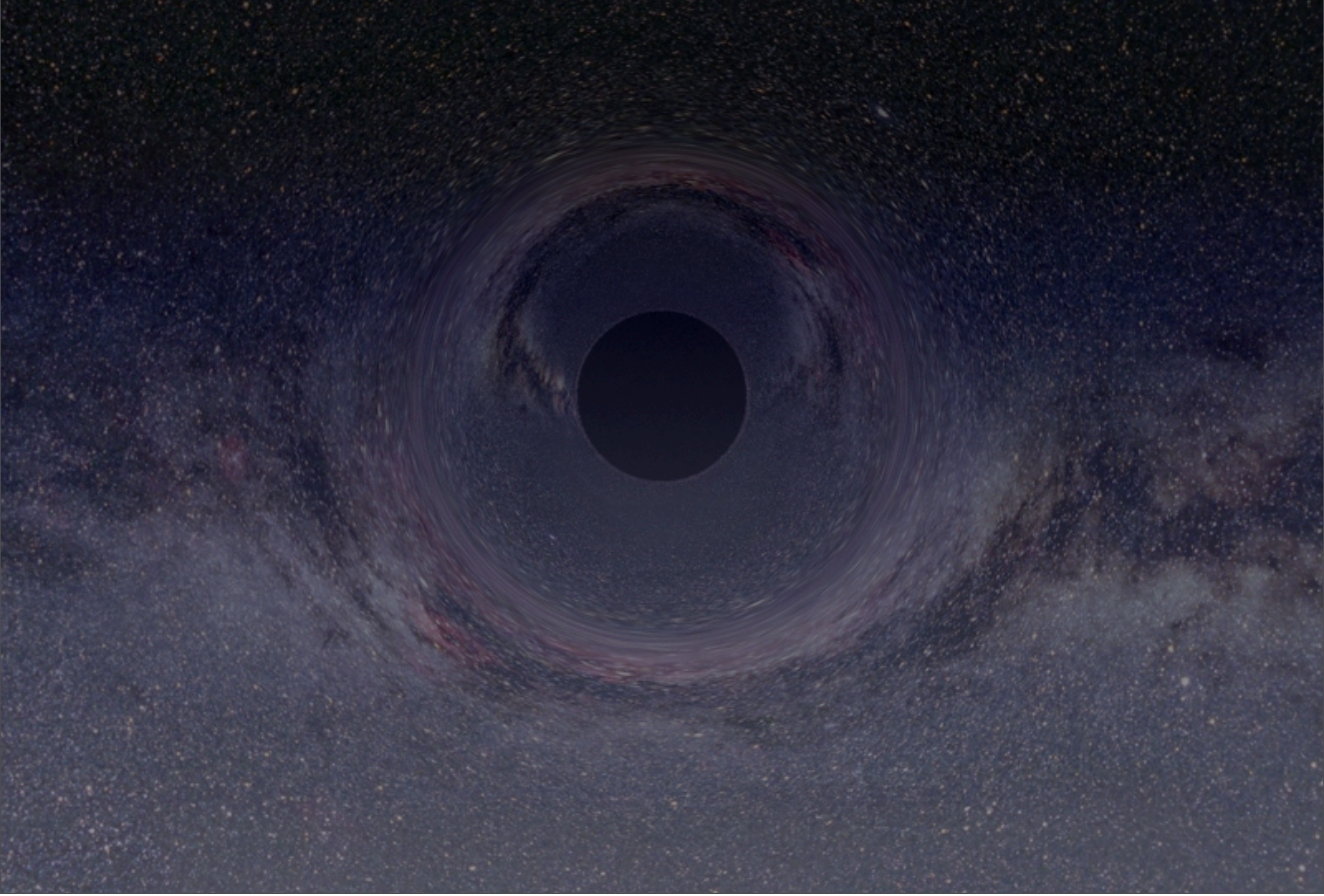
With: E=14 TeV, L=$10^{34}/cm^2 s$ If $M_D \sim TeV$

Impressive signatures

- relatively high sphericity
- high multiplicity of primaries
- hard transverse leptons and hard jets -- multiple
- ~thermally-determined ratios of species
- angular distributions characterizing spindown
- hard jet suppression
- (increase of cross section w/ energy) (LHC upgrade...)

...

Prospects for 7 TeV followed by 14:



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(parton level!)

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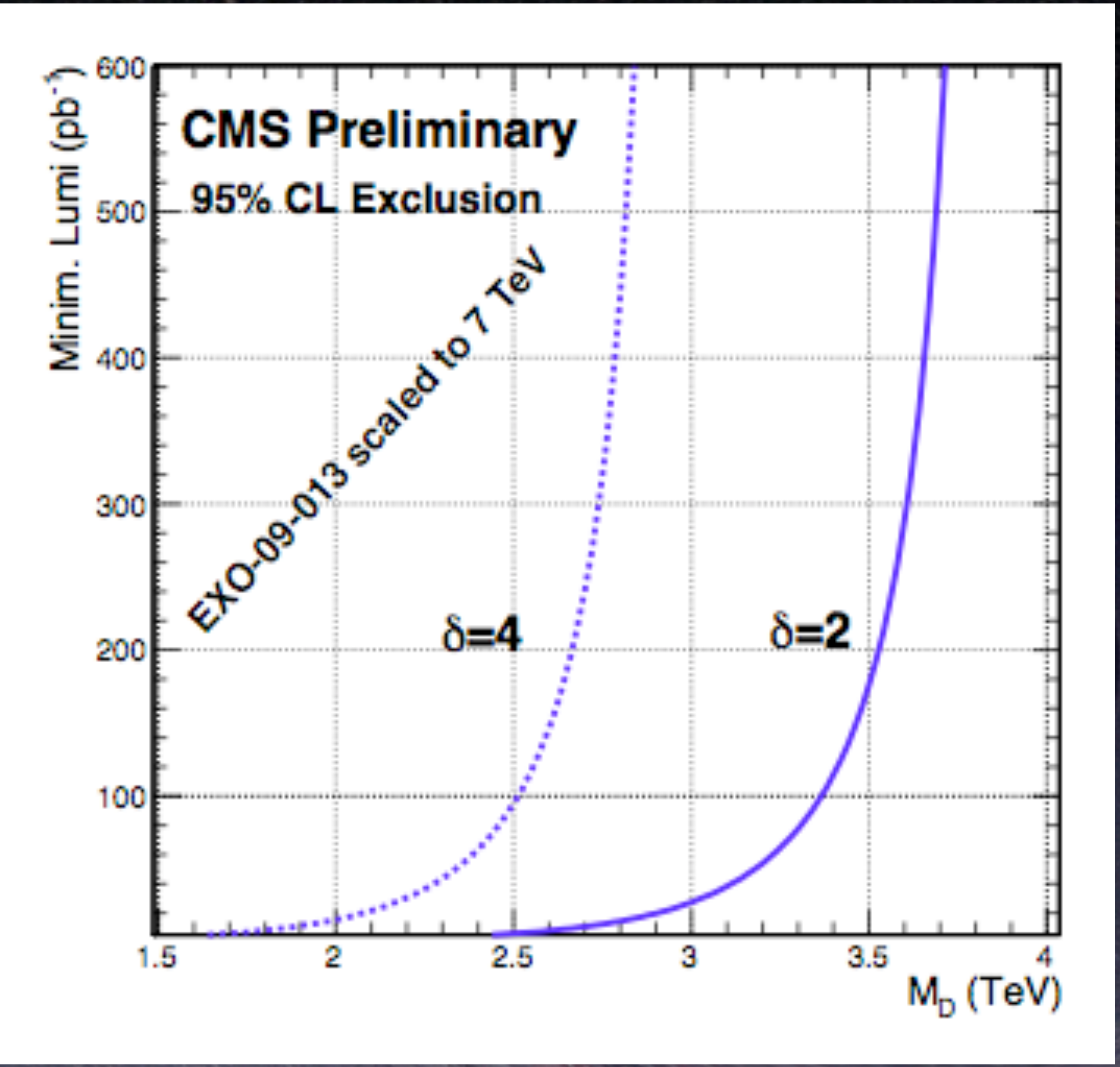
By 1/fb, expect improved bounds on M_D :

Prelim. 95% confidence limits:

CMS Note 2010/008



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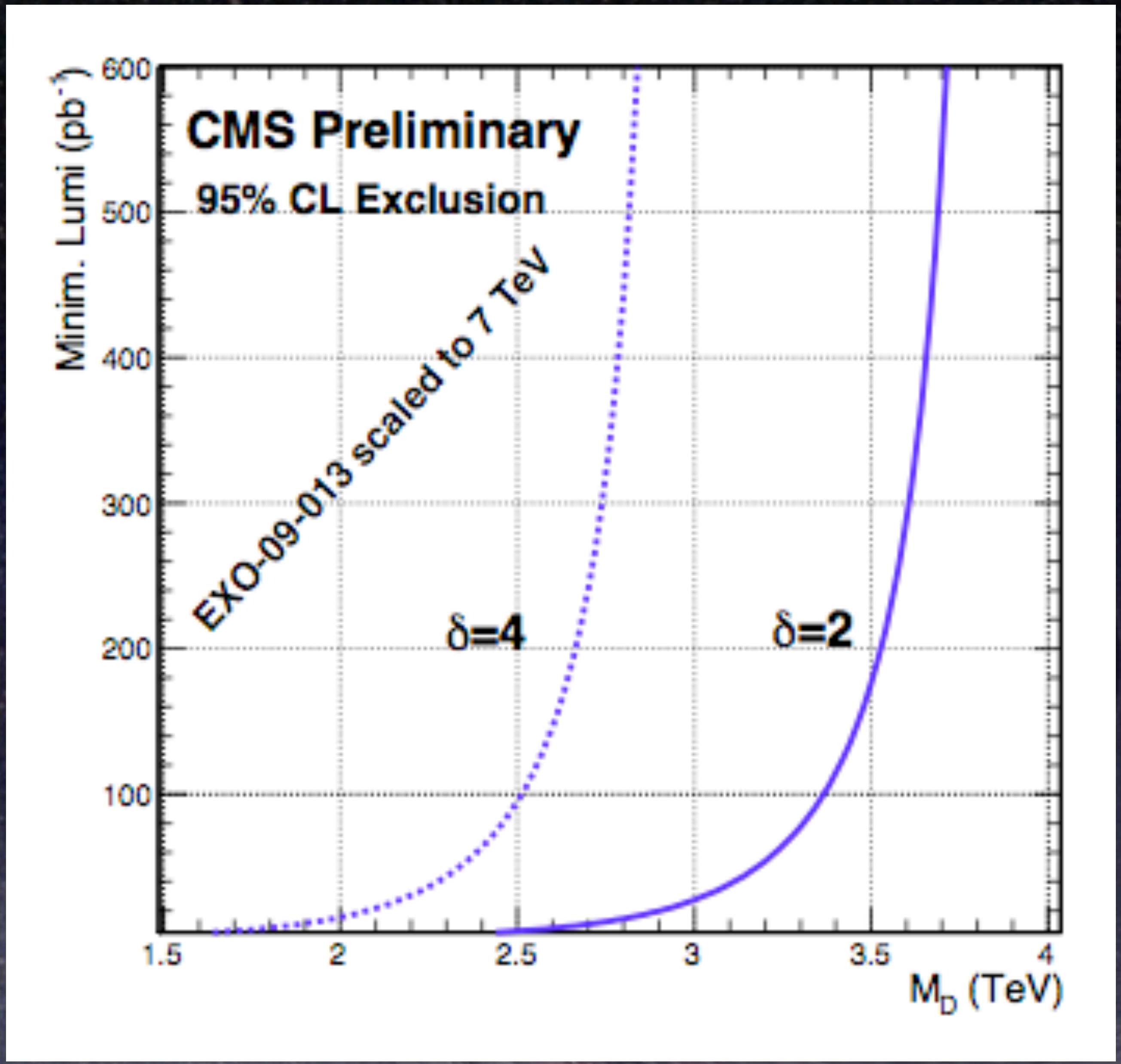

See indications here, in monojets (or diphoton) first?

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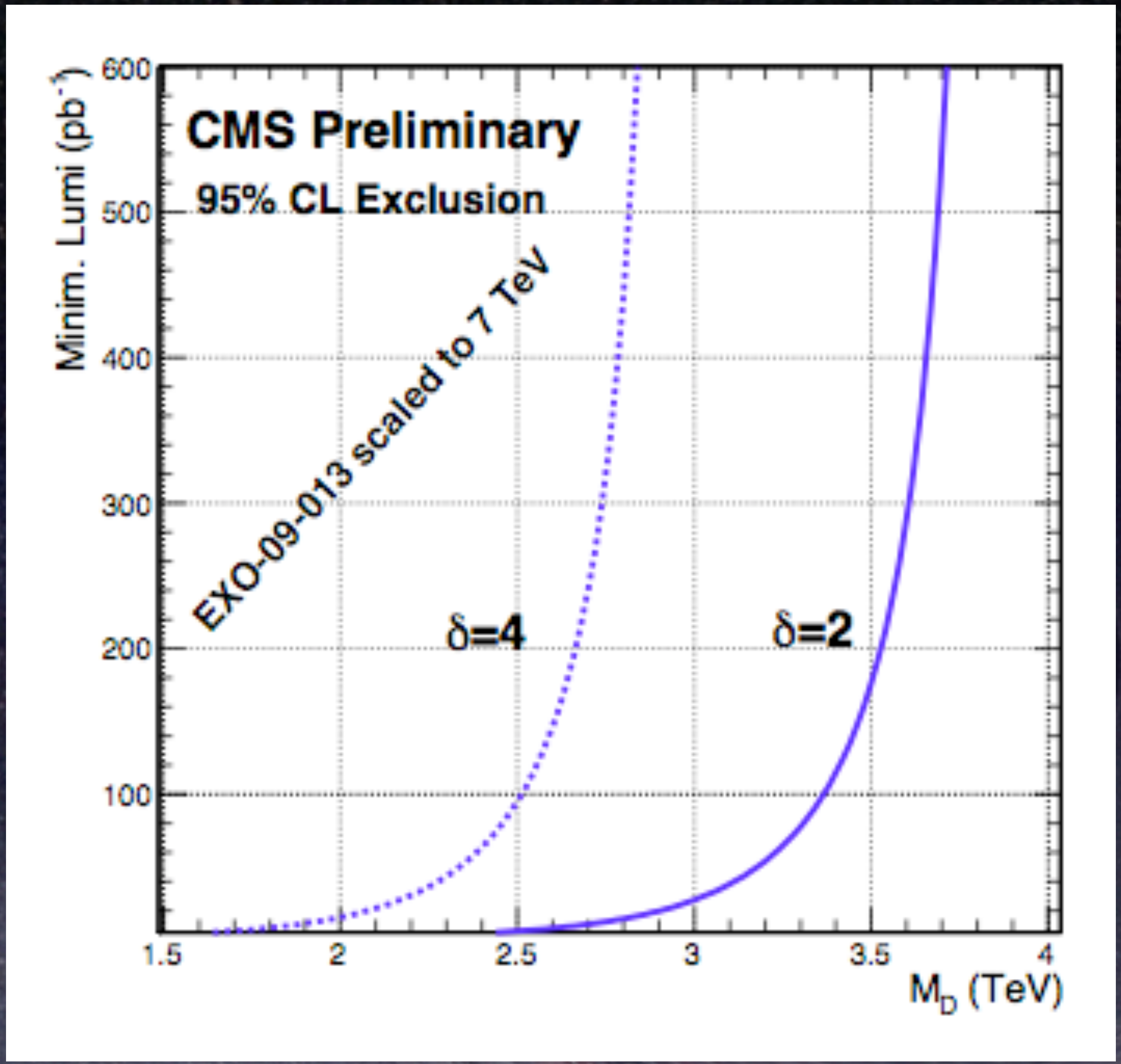
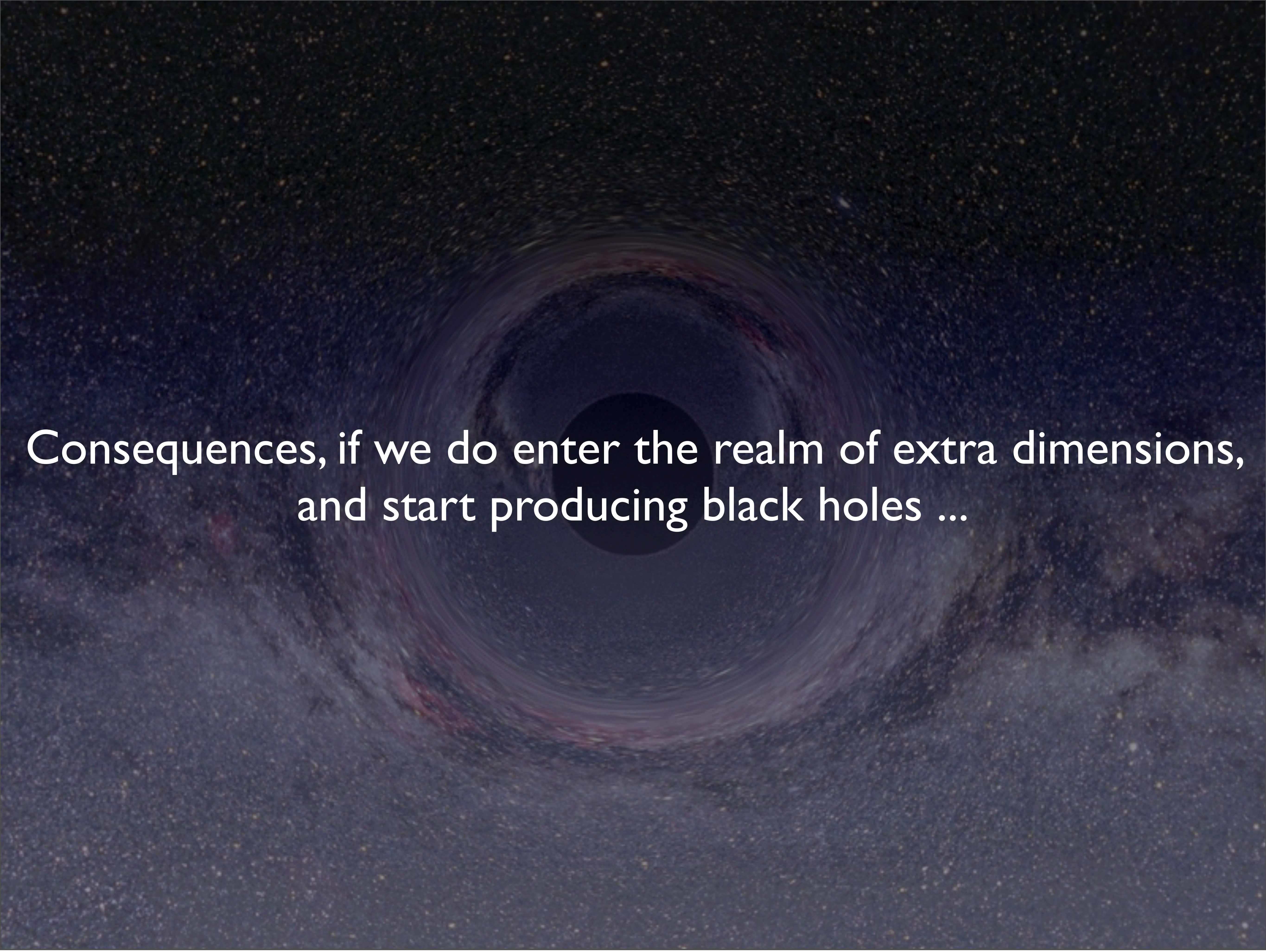
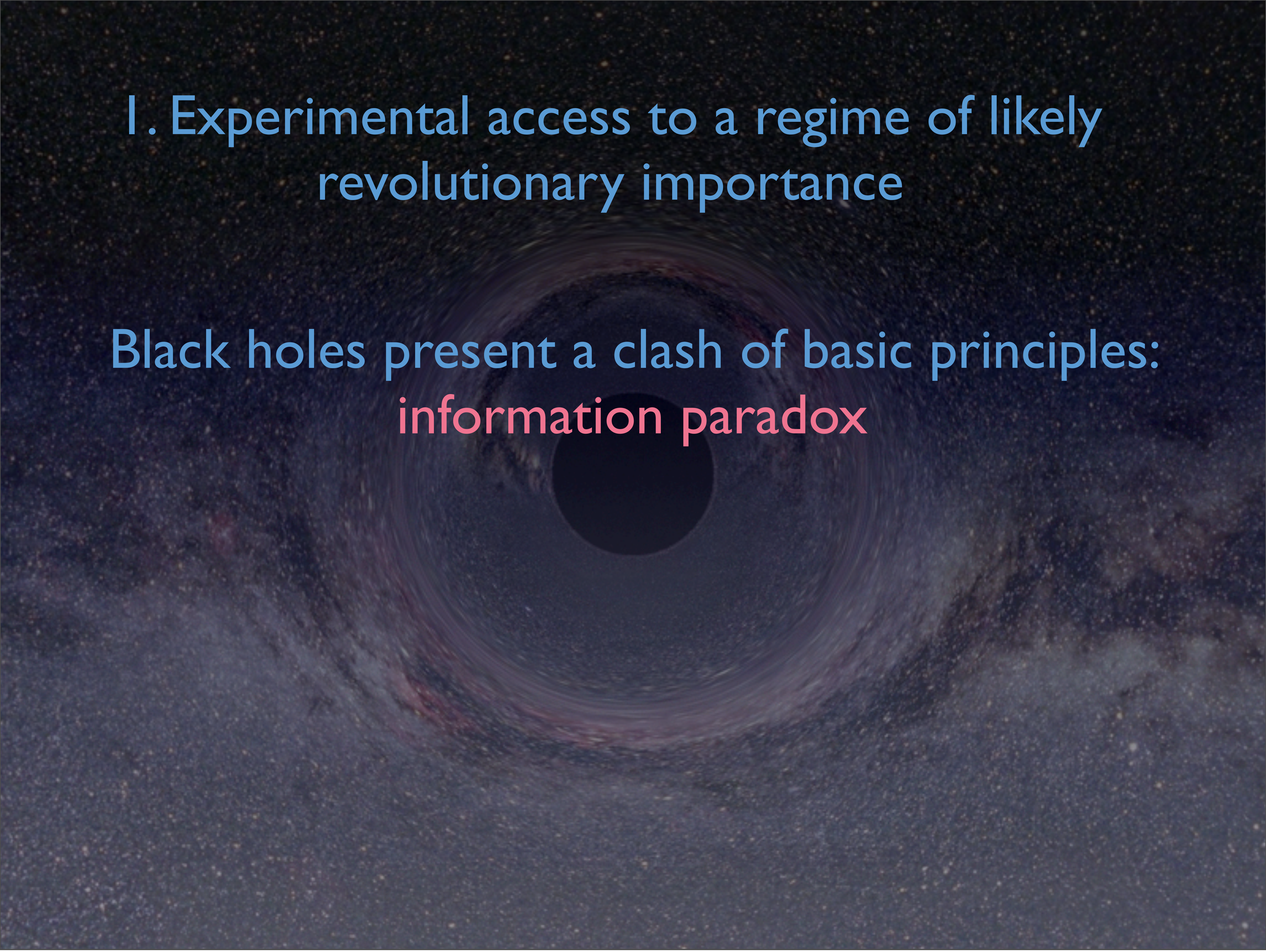


See indications here, in monojets (or diphoton) first?

If place limit $M_D > 2.8 TeV$

- not much room for semiclassical BHs @ 14 TeV!!


Consequences, if we do enter the realm of extra dimensions,
and start producing black holes ...



1. Experimental access to a regime of likely revolutionary importance

Black holes present a clash of basic principles:
information paradox

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Black holes present a clash of basic principles: information paradox

Nonlocality? -- only way to save QM?

(Related to growth of sizes w/ energy)

(Not just EPR)

2. The end of short distance physics!

(Banks & Fischler; SBG & Thomas hep-ph/0106219)

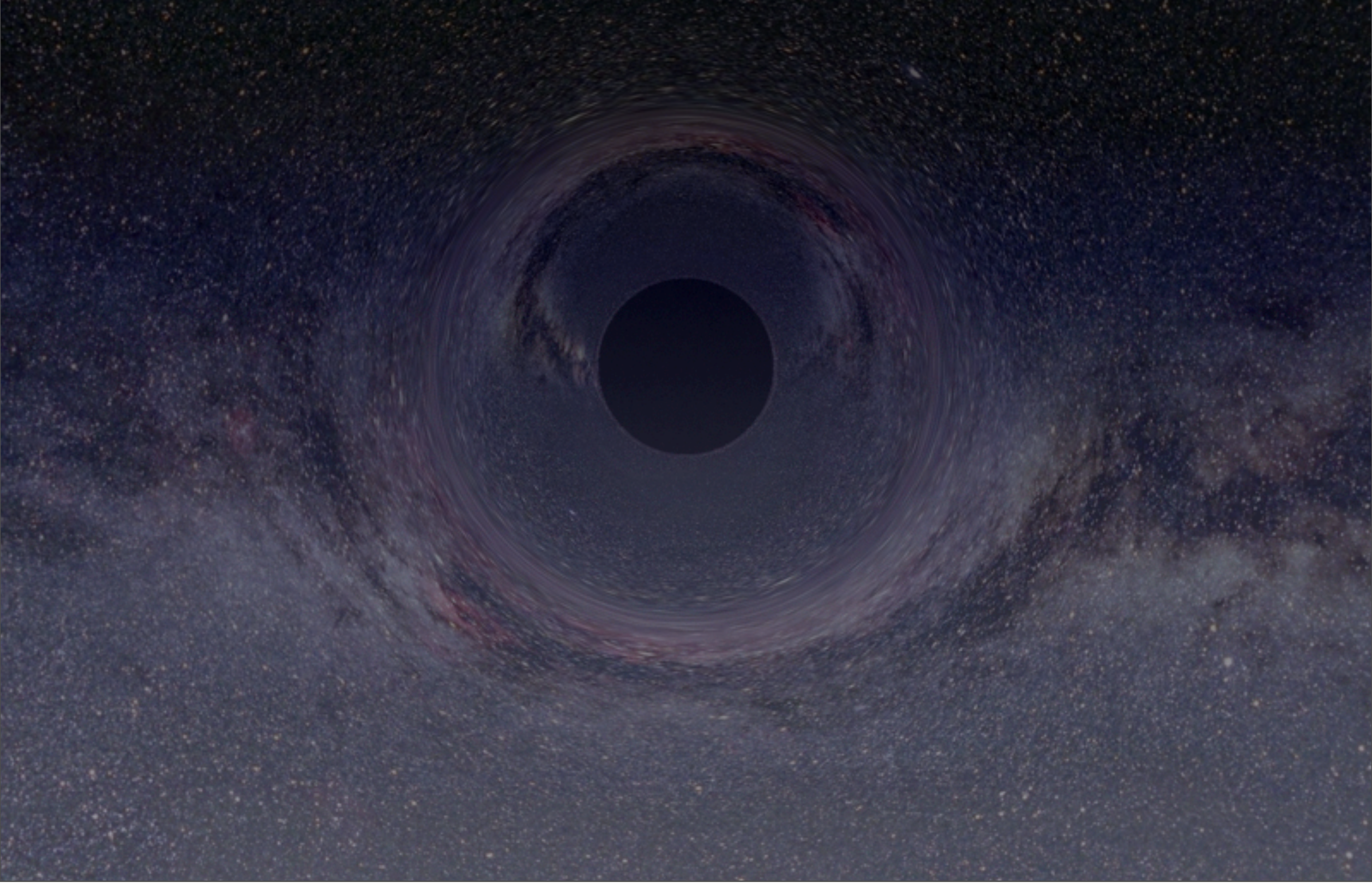
higher energies probe longer distances

$$R_S \sim \frac{1}{M_D}\left(\frac{E_{CM}}{M_D}\right)^{D-3}$$

(horizons cloak shorter distance phenomena)

future of HEP: measuring geometry, presence of other brane worlds, etc.

3. The end of the world?



3. The end of the world?

Is it safe?

(A saga that has consumed time measured in physicist years...)

The New York Times

Asking a Judge to Save the World, and
Maybe a Whole Lot More

EDITORIAL

But It's Just a Small Black Hole

OP-ED COLUMNIST

A Black Hole Rating System

ESSAY

Gauging a Collider's Odds of Creating a Black Hole

Earth Will Survive After All, Physicists Say

Government Seeks Dismissal of End-of-World Suit
Against Collider

OP-ED COLUMNIST

Digging Ourselves a Black Hole

Many more:

DOOMSDAY FEARS SPARK LAWSUIT

msnbc

HEALTH & SCIENCE

Company Sued for Potentially Ending the World

npr

New atom-smasher could fill gaps in scientific knowledge -- or open a black hole

Los Angeles Times

Instant extinction lotto

What's reasonable when scientists start gambling with our very existence?

THE DAILY SHOW WITH JON STEWART

USA TODAY · Home · News · Travel · Money · Sports · Life

Technology » Science & Space · Shop for Gadgets

Scientists: Nothing to fear from atom-smasher

(AP News article -- appeared in scores of newspapers around globe)

+ a lot in the German press, etc.

Early 2010:

BusinessWeek

Home | Top News

Bloomberg

Atom Smasher Exposes Hole in Earth's Defenses: Kevin Hassett

January 12, 2010, 08:21 PM EST

Commentary by Kevin Hassett

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A Lawyer's View of the Risk of Black Hole Catastrophe at the LHC

Enlarge

January 22, 2010 By Lisa Zyga

Is an LHC doomsday scenario a groundless fear or a legitimate concern? Image credit: CERN.

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A Lawyer's View of the Risk of Black Hole Catastrophe at the LHC

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January 22, 2010 By Lisa Zyga

Is an LHC doomsday scenario a groundless fear or a legitimate concern? Image credit: CERN.

"AT THE END OF THE DAY, WHETHER THE LHC REPRESENTS AN INTOLERABLE DANGER IS, IN MY VIEW, AN OPEN QUESTION," ... "I HAVE NOT ENDEAVORED TO PROVIDE A DEFINITIVE ANSWER. BUT I THINK THE COURTS SHOULD. …"

-E. JOHNSON,
TENNESSEE LAW REVIEW

German Federal Constitutional Court:

Feb. 2010: dismisses case against CERN

USA 9th Circuit Court of Appeals
(continuation of Hawaii suit)

Aug. 2010: Upholds dismissal of lower court

Other attempts:

European Court of Human Rights

UN

...

We will likely continued to be asked to answer this kind of question, with future upgrades, accelerators, ...

Will outline some of the discussion for black holes; other scenarios also considered

- TeV - scale gravity widely regarded as rather unlikely (though spectacular if true!)

- Hawking radiation - different specific calculations:

1. Hawking. outlined. + improvements

2. Anomaly-based

3. BH analog models

The stakes:

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Basic quantum principles: black holes evaporate

In the quantum world, "anything that can happen, will happen"

Only find stable particle-like objects when protected by a conservation law

(It's all about the probability...)

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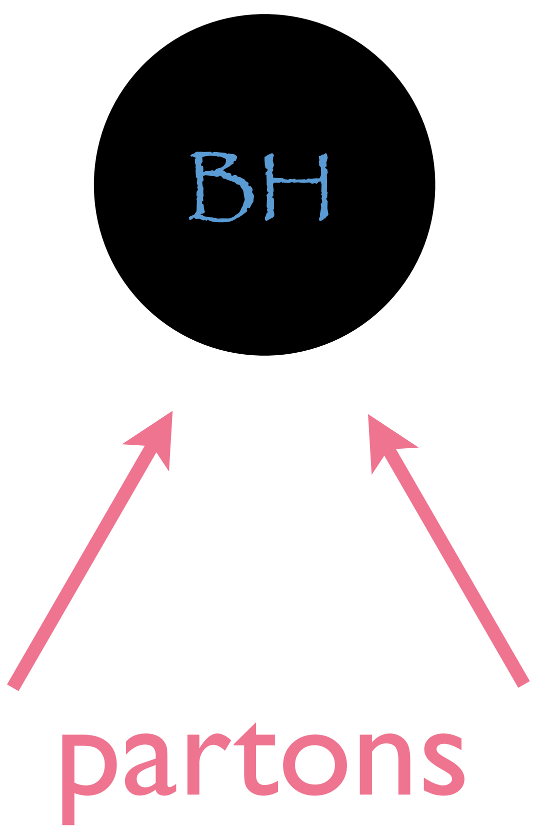
Black holes near $M = M_{Planck}$: no small parameter to suppress.

Alternately, phrase using CPT:



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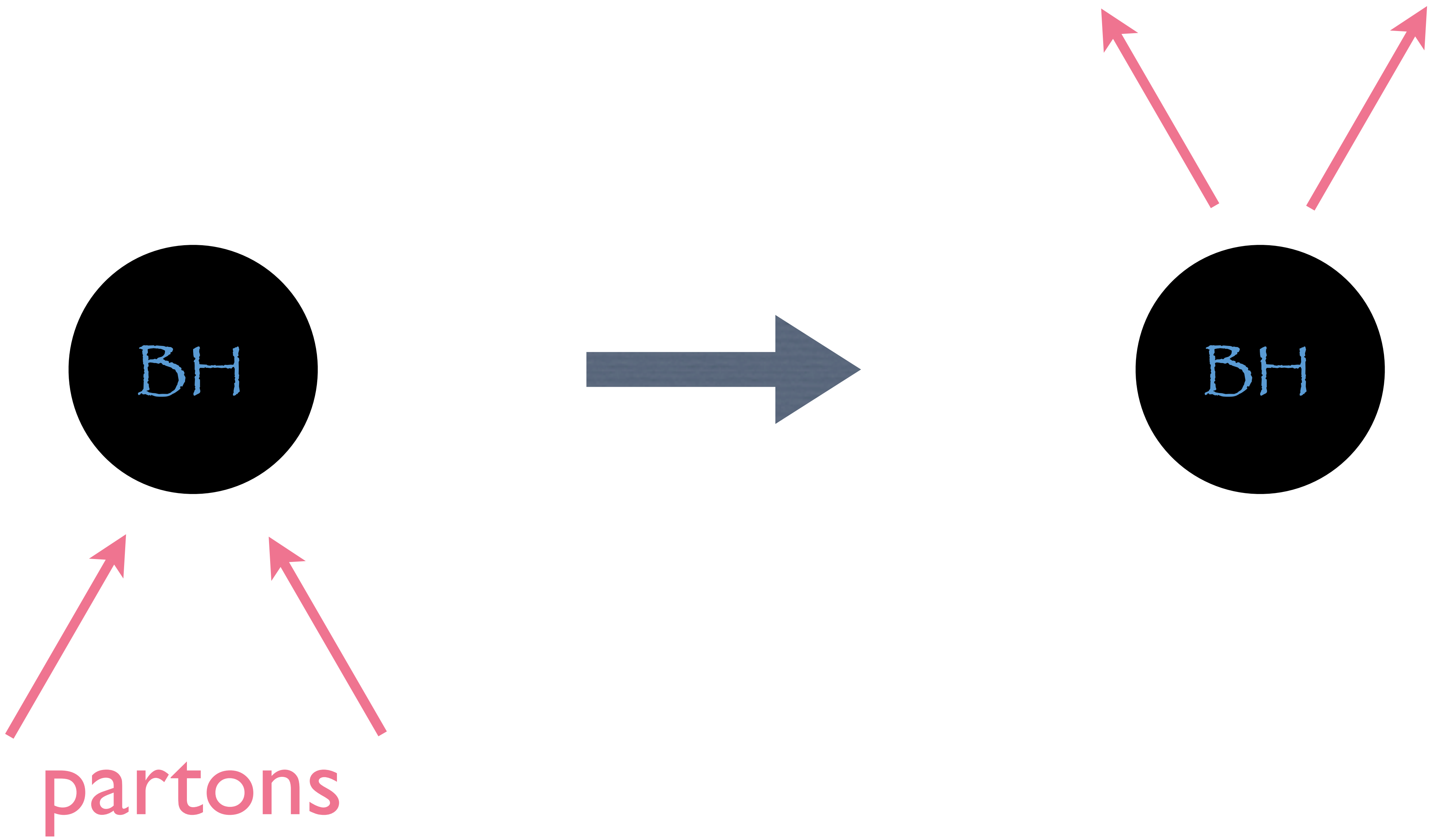
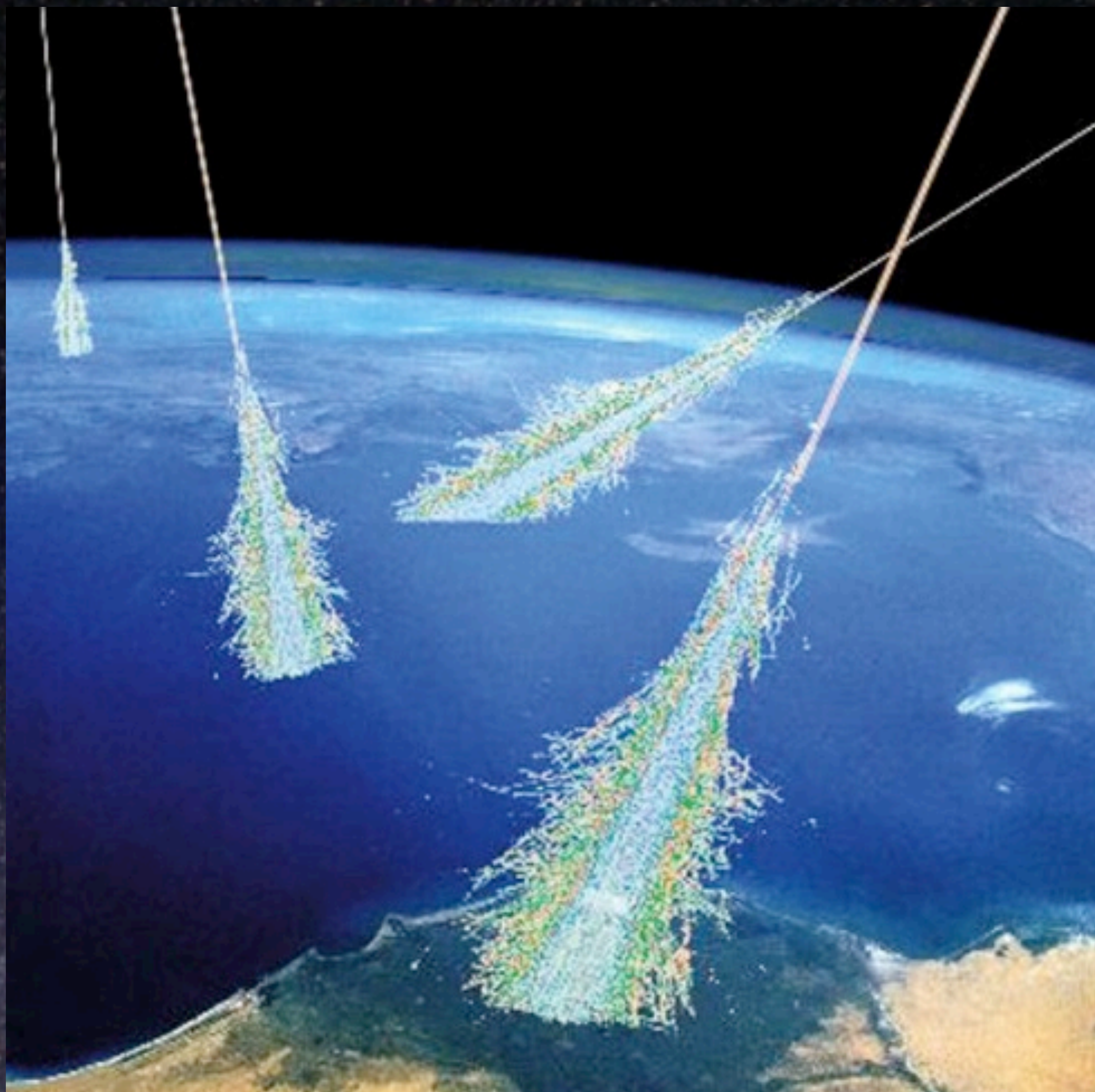


Other arguments:



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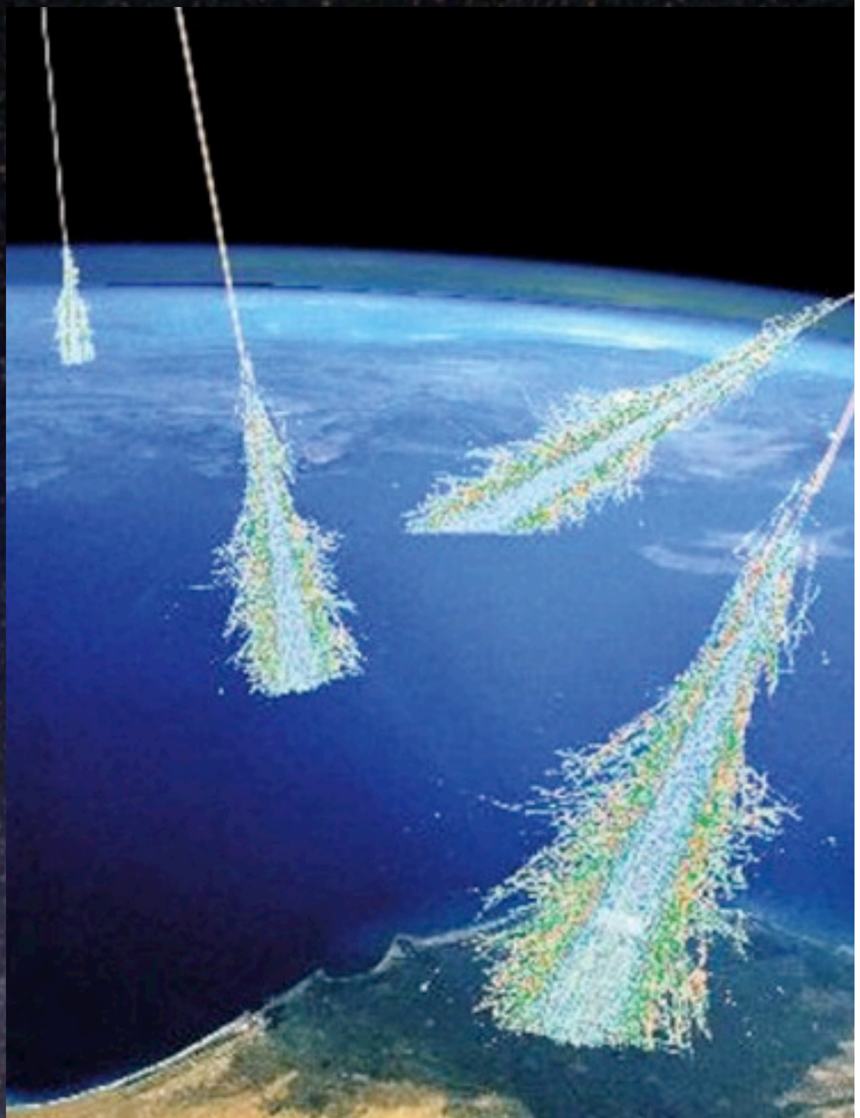
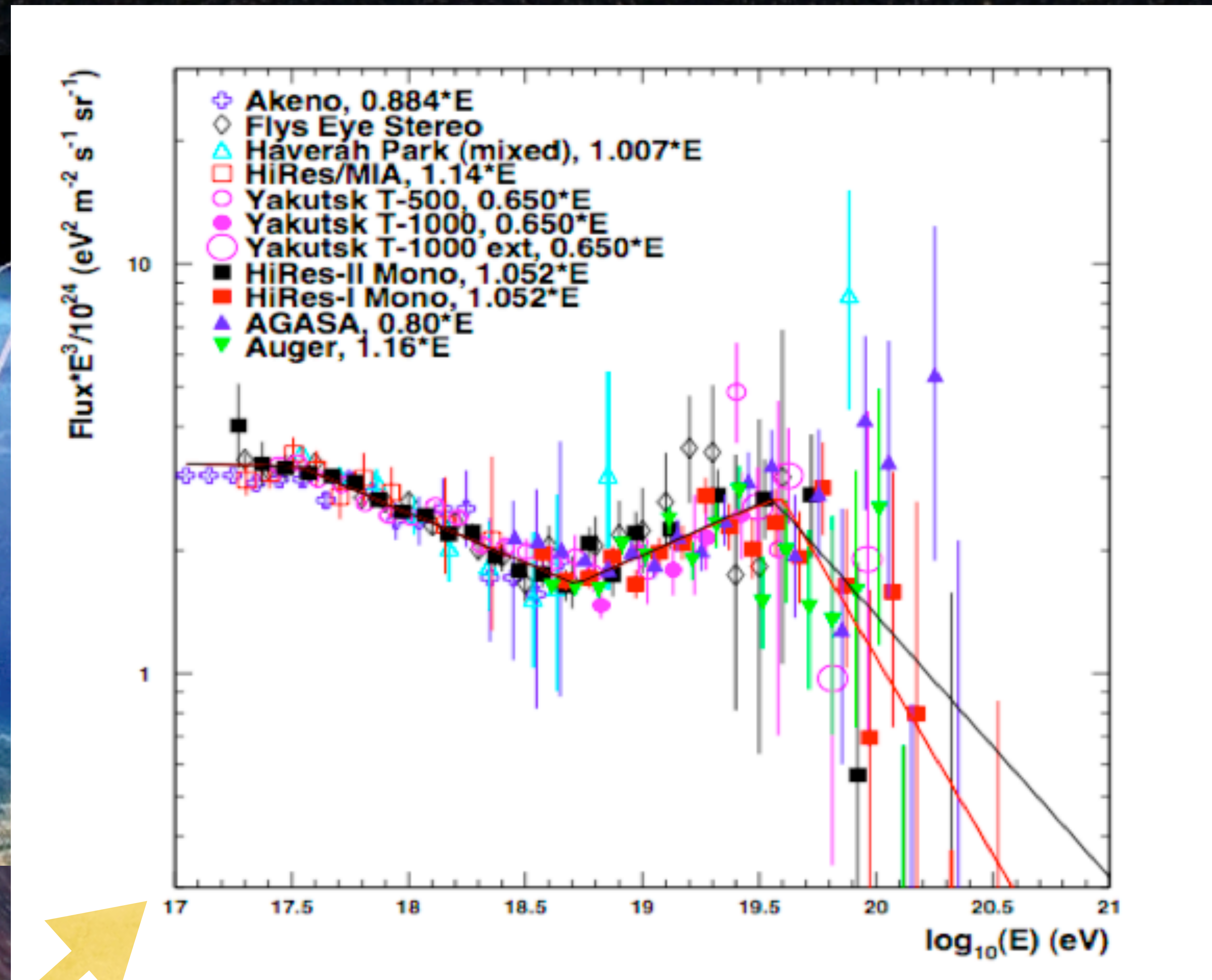
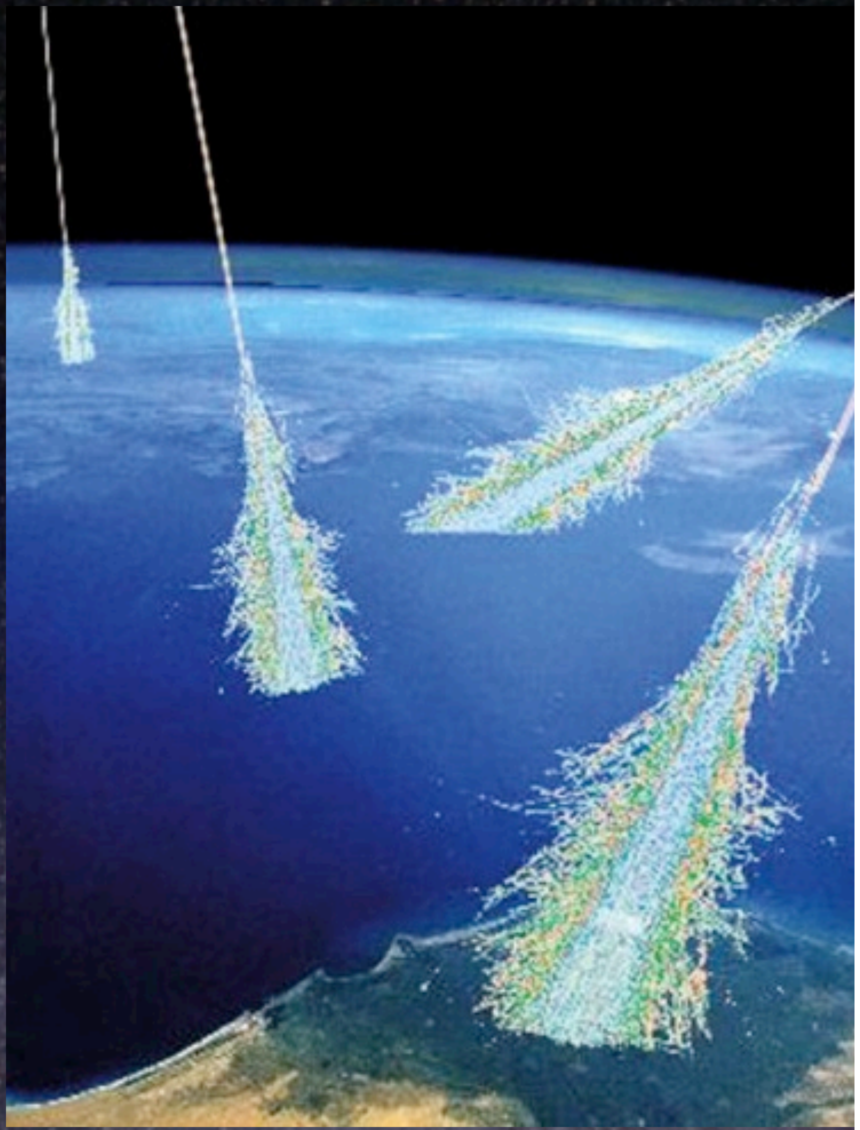


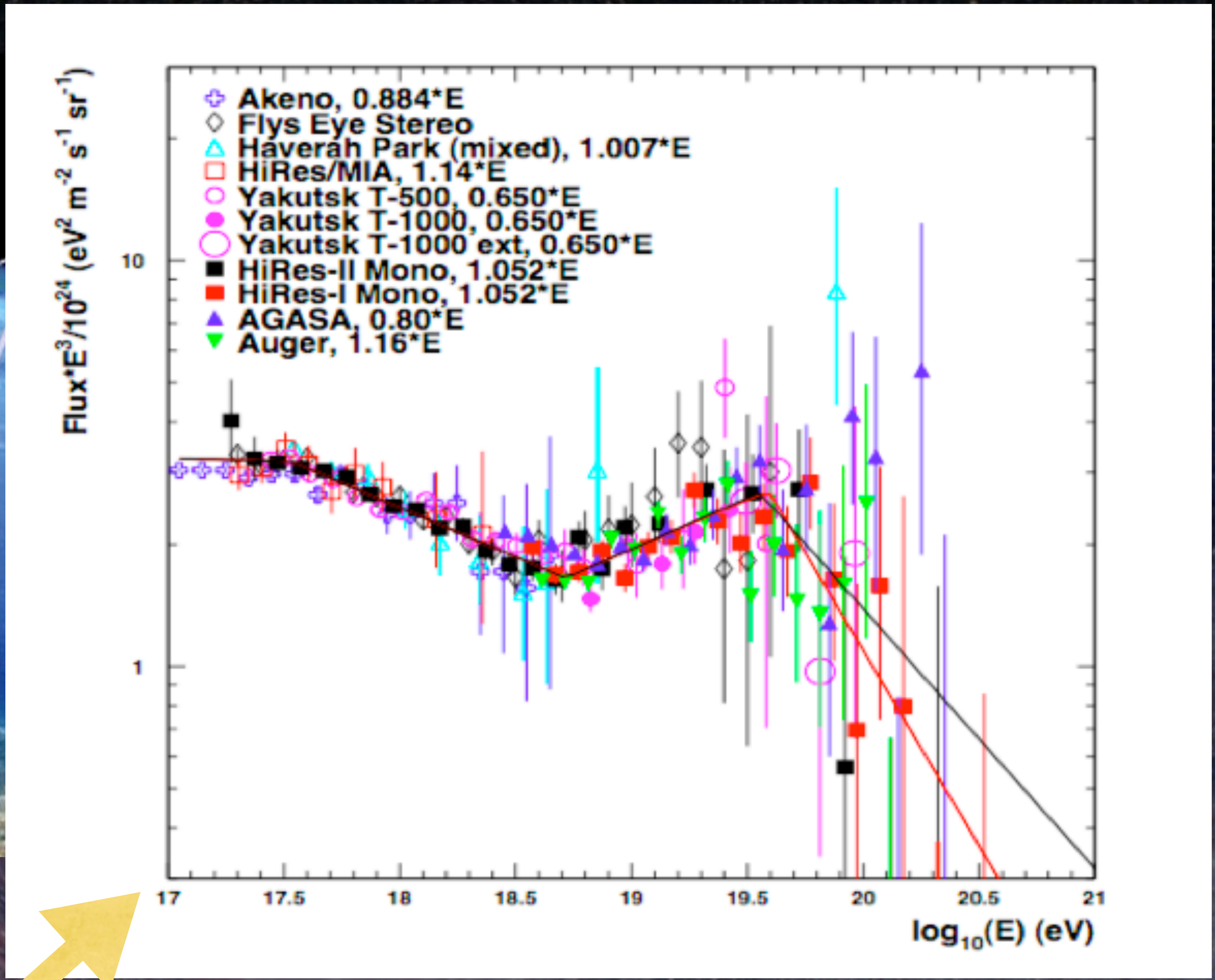


LHC equivalent

(AGN?!)

Other arguments:





LHC equivalent

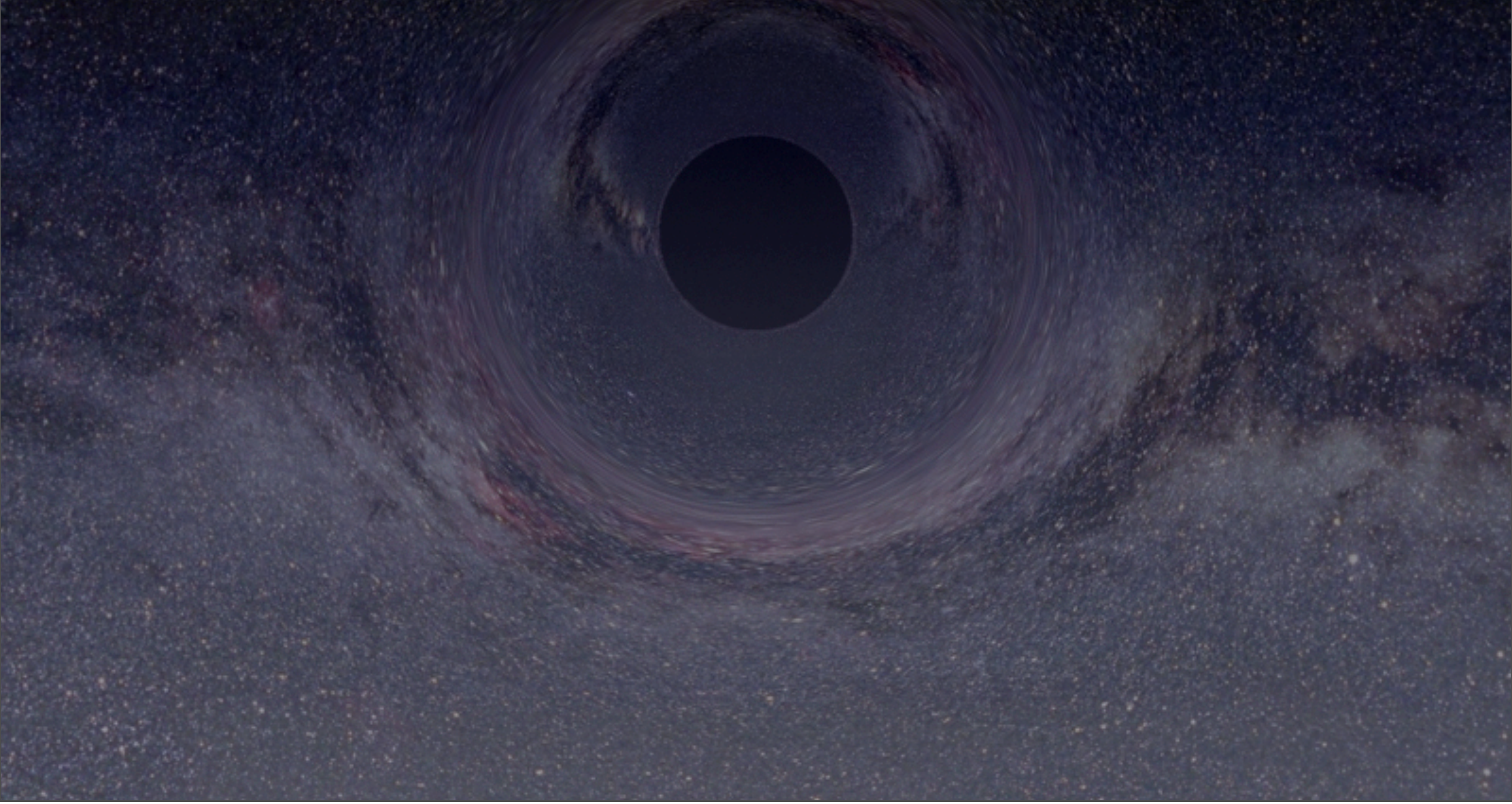
(AGN?!)

But: obvious difference -- boosted CM

Would they stop?

The answer is scenario/assumption dependent

Quantum physics (QP) says black holes evaporate nearly instantaneously (possibly leaving a remnant)



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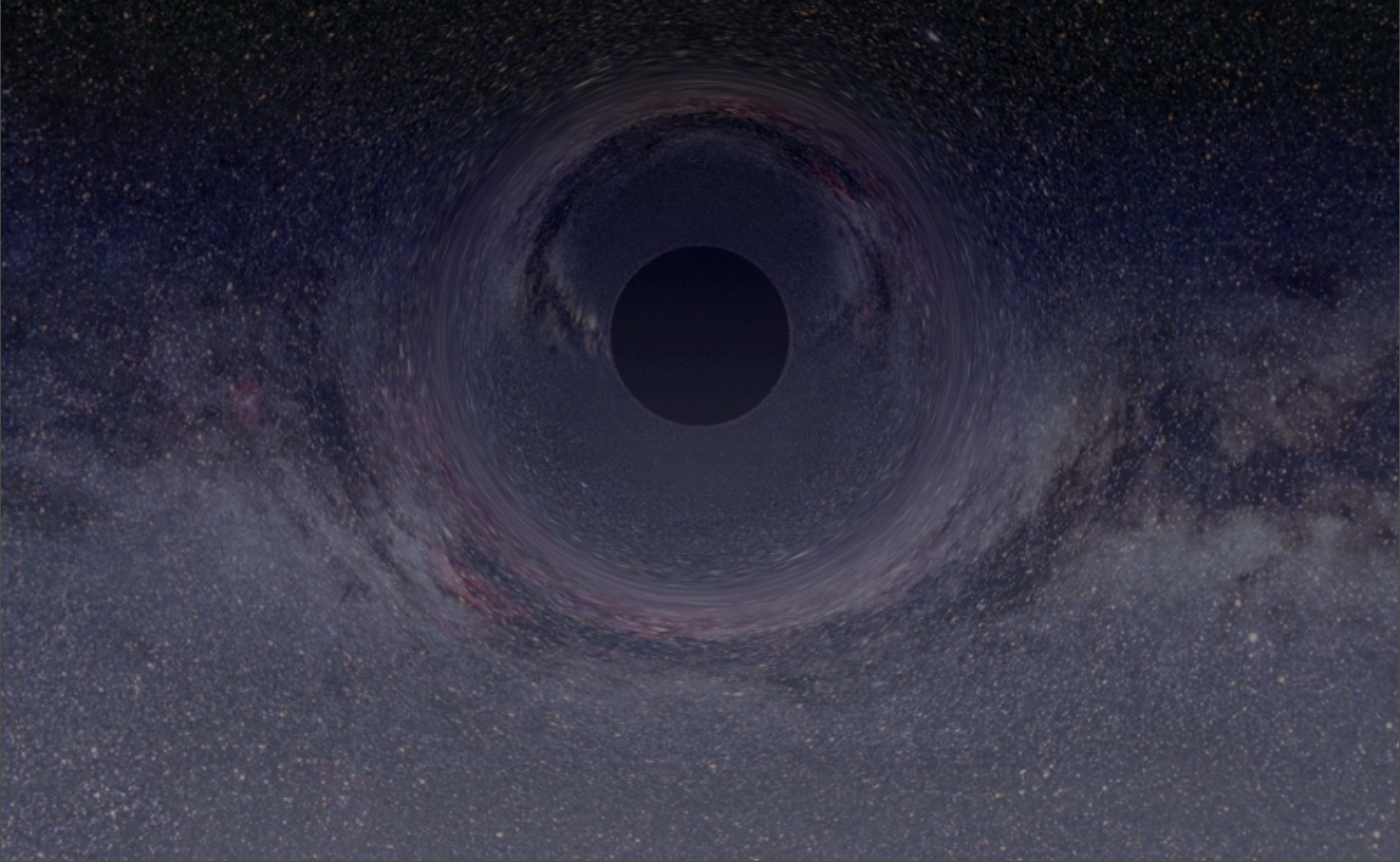
Can ask: are there consistent scenarios where "turn off" quantum mechanics, and this doesn't happen?

Can just consider artificial scenarios, "turning off" QP in different regimes



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E.g. fictional world where QP “just doesn’t apply to black holes”

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CR-produced black holes typically charged (since produced in qq collisions), stop in Earth or Sun

SBG & Mangano, arXiv:0806.3381

Or, QP discharges BHs (~Schwinger), but they otherwise behave classically

Then, BH's neutralize, don't stop in Earth or Sun

A more involved story ...

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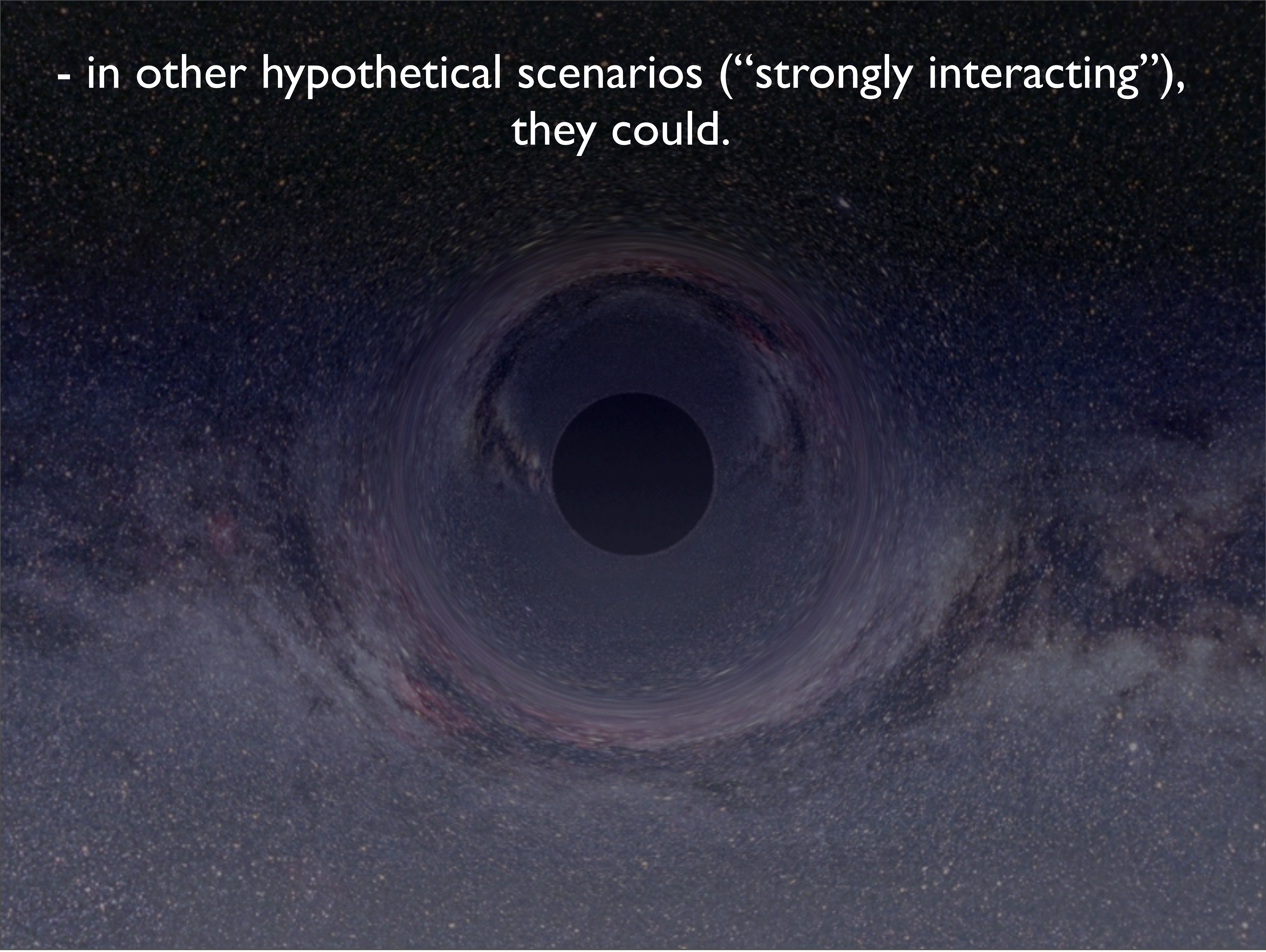
Brief overview:

- in some scenarios ("weakly interacting") BHs wouldn't grow significantly in 5 billion years.

(also scenarios where QM absorption prevents such growth - unpublished)

- in other hypothetical scenarios (“strongly interacting”), they could.



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But, much denser objects in the cosmos: white dwarfs, neutron stars - which we've discussed

These both have enormously more stopping power, and are verging on the edge of gravitational collapse

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But, much denser objects in the cosmos: white dwarfs, neutron stars - which we’ve discussed

These both have enormously more stopping power, and are verging on the edge of gravitational collapse

E.g. a useful model-independent general statement:

The amount of material impacted in crossing a neutron star is comparable to that of traveling through the Earth at escape velocity, for ~ a million years

Detailed investigation (SBG & Mangano arXiv:0806.3381; and unpublished) yields a complementary set of bounds for a wide-range of scenarios

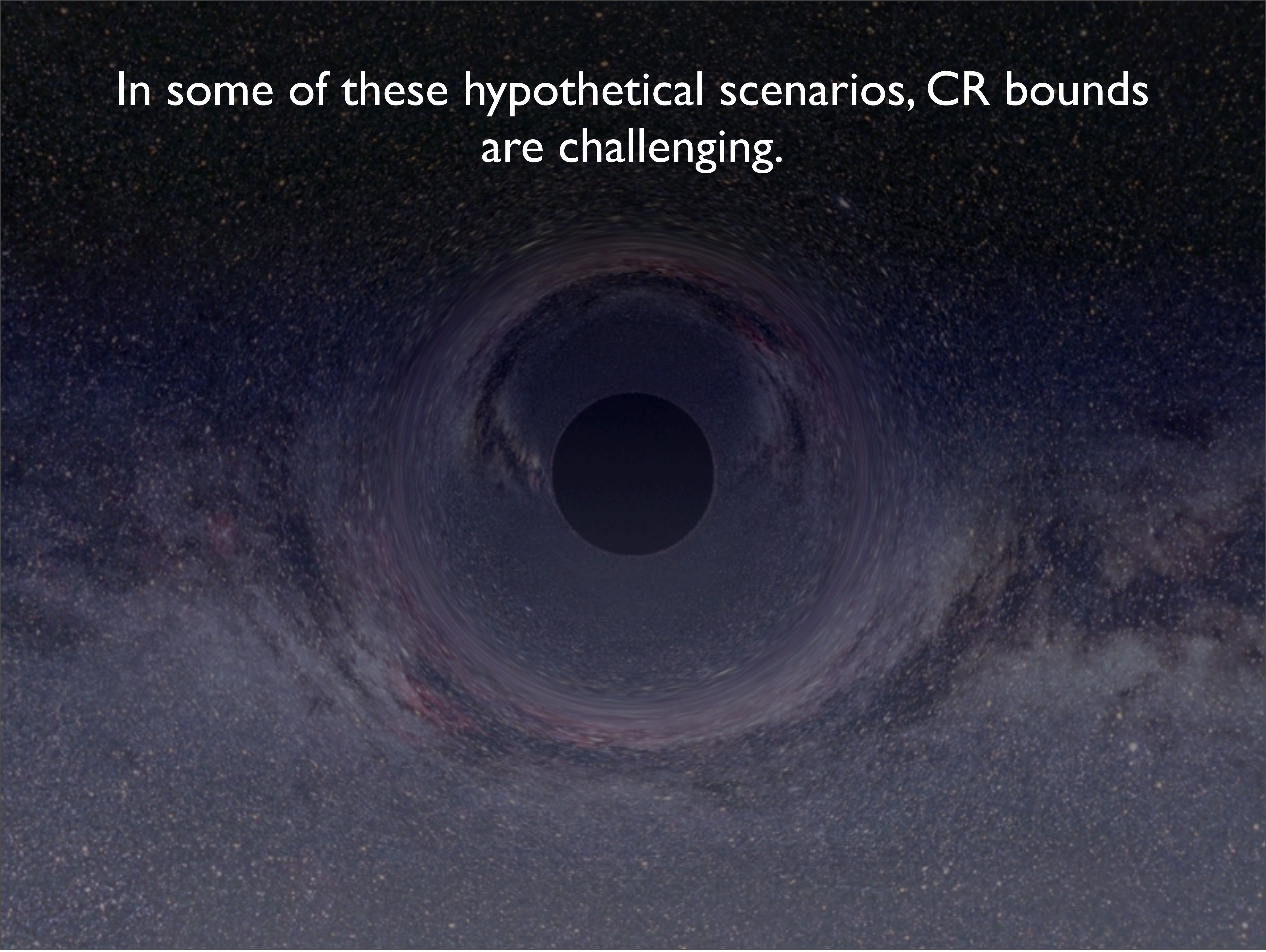
More info:

SBG & Mangano arXiv:0806.3381

Peskin, Physics 1, 14 (2008)

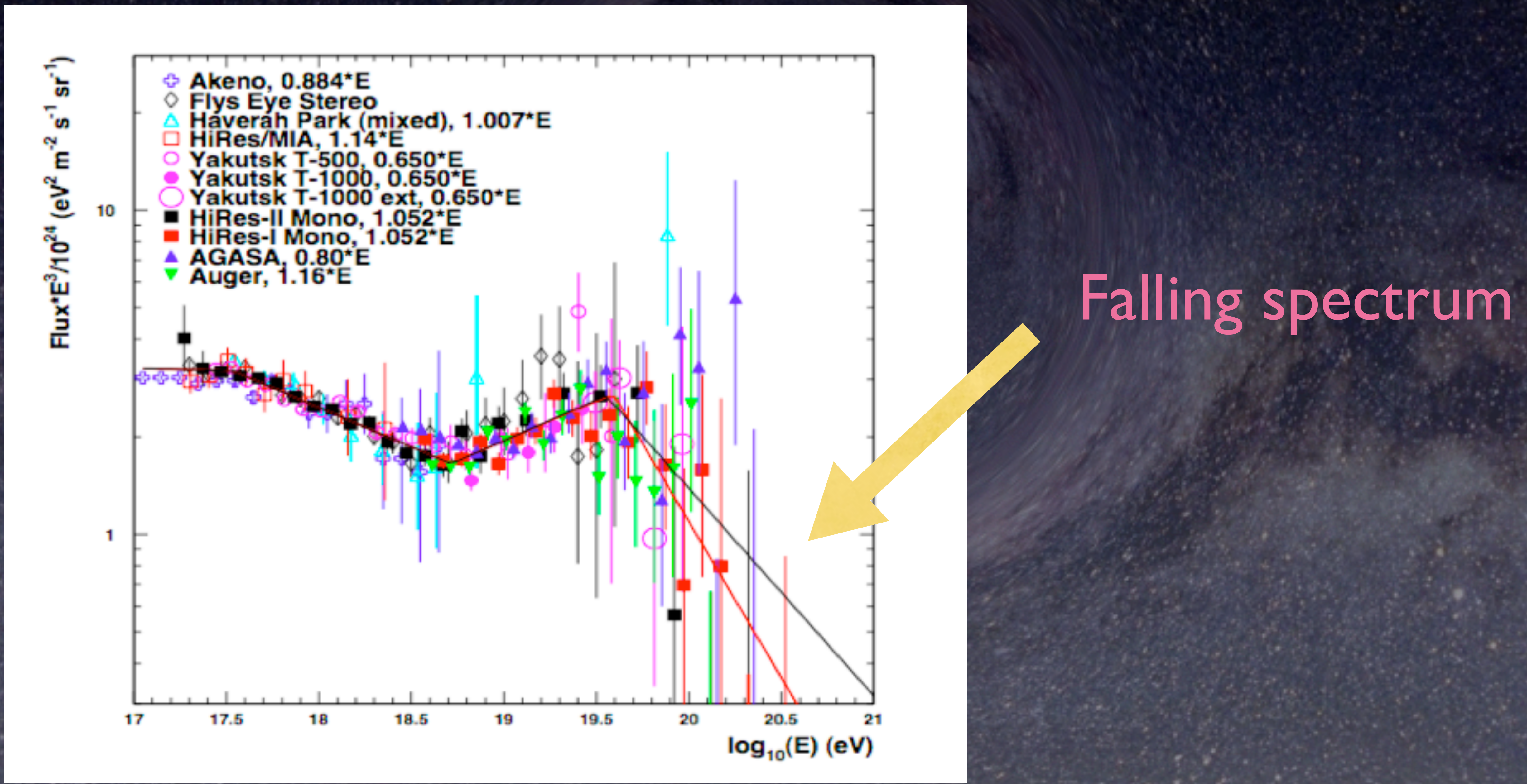
LSAG report

In some of these hypothetical scenarios, CR bounds are challenging.



In some of these hypothetical scenarios, CR bounds are challenging.

For future accelerators/scenarios, they could be more so



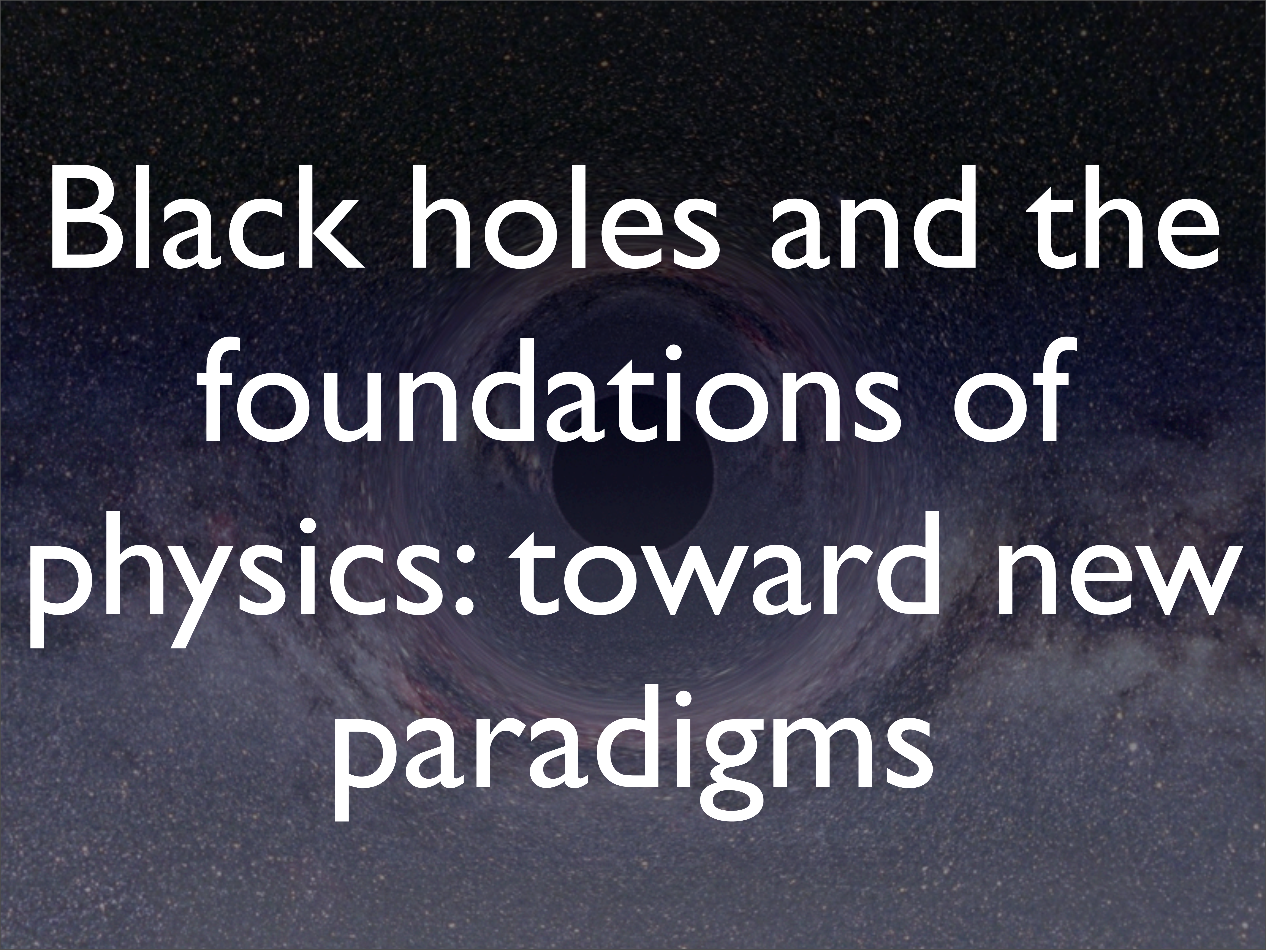
One approach: other targets

- Dark matter (once found ...)

- NS atmospheres produce electrons and photons to energies $\gtrsim 1\, TeV$

(require lower CR energies -- so higher fluxes!)

We have these and other tricks up our sleeves, which may help in case of future challenges ...



Thursday, September 9, 2010

At whatever scale it occurs, black hole production forces confrontation with profound theoretical issues. In fact

"Black hole information paradox"

Basic outcome:

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“Black hole information paradox”

Basic outcome:

Apparently must abandon a cherished principle of physics:

- unitarity and energy conservation (QM violated)
- stability (remnants)
- macroscopic locality (information escapes)

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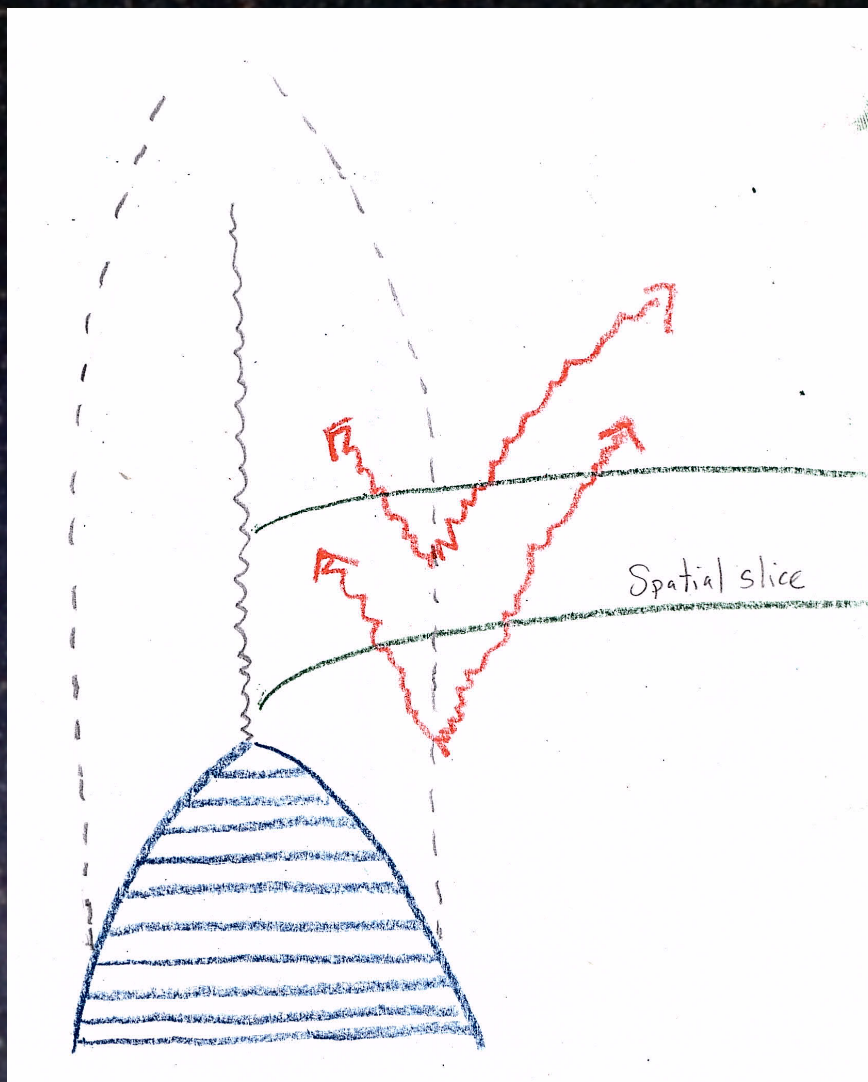
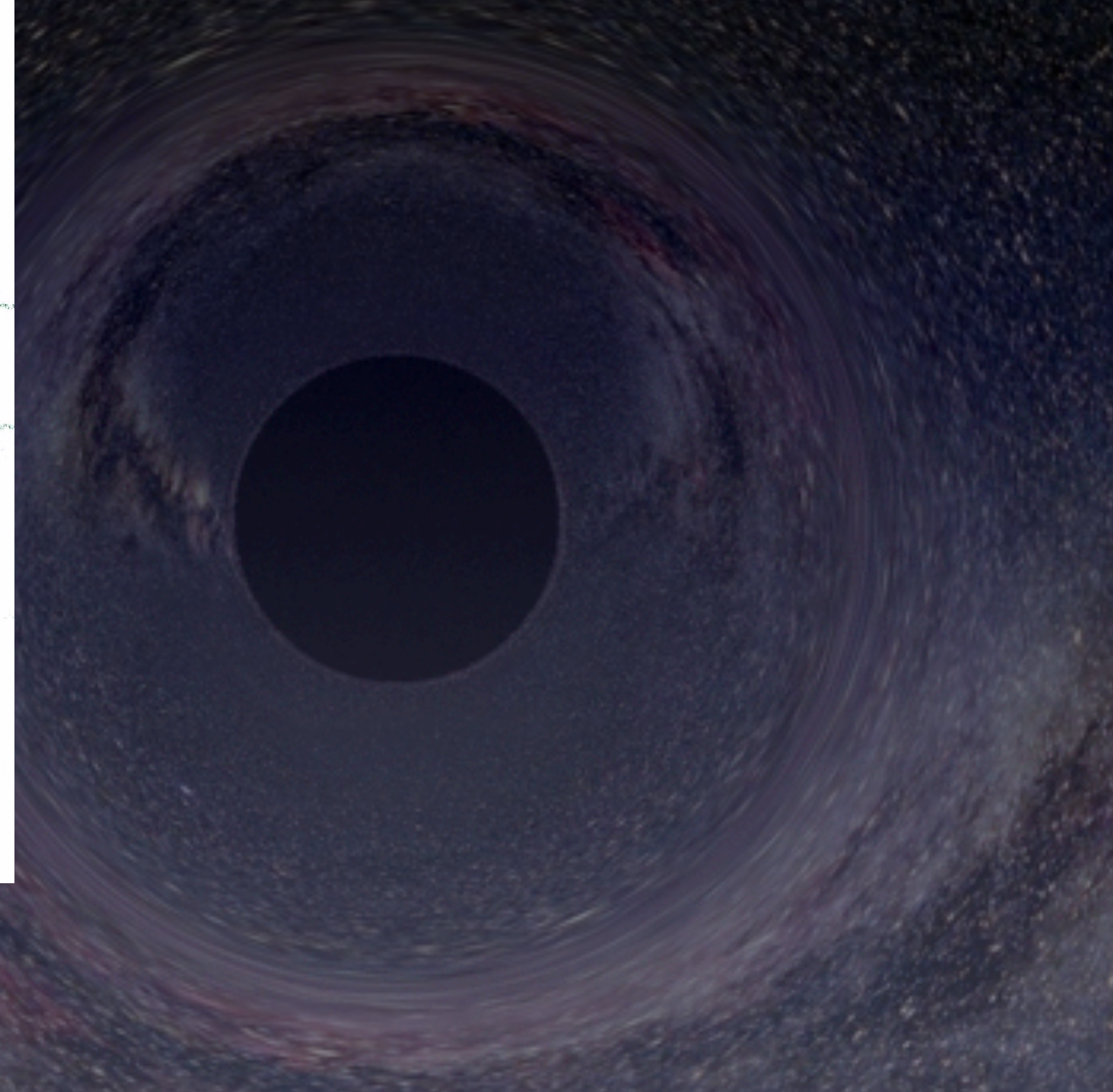
...growing belief

The black hole “information paradox” - lightening review





Eddington - Finkelstein

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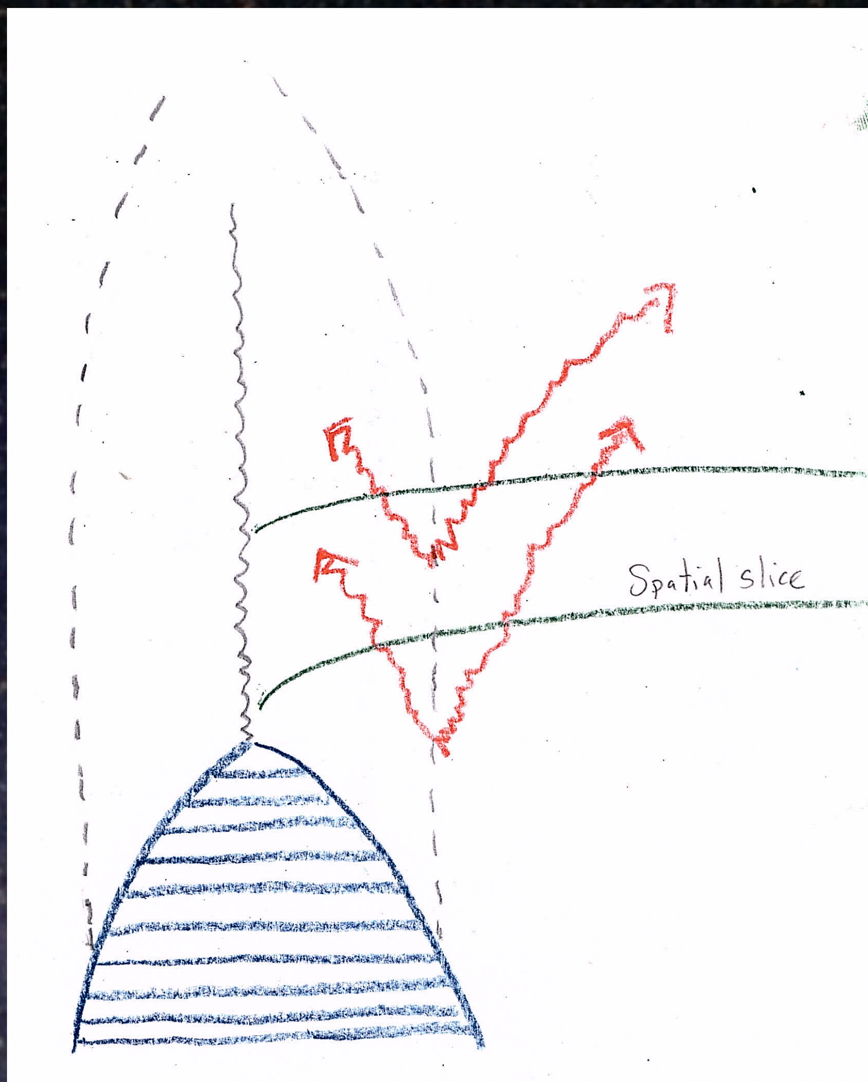

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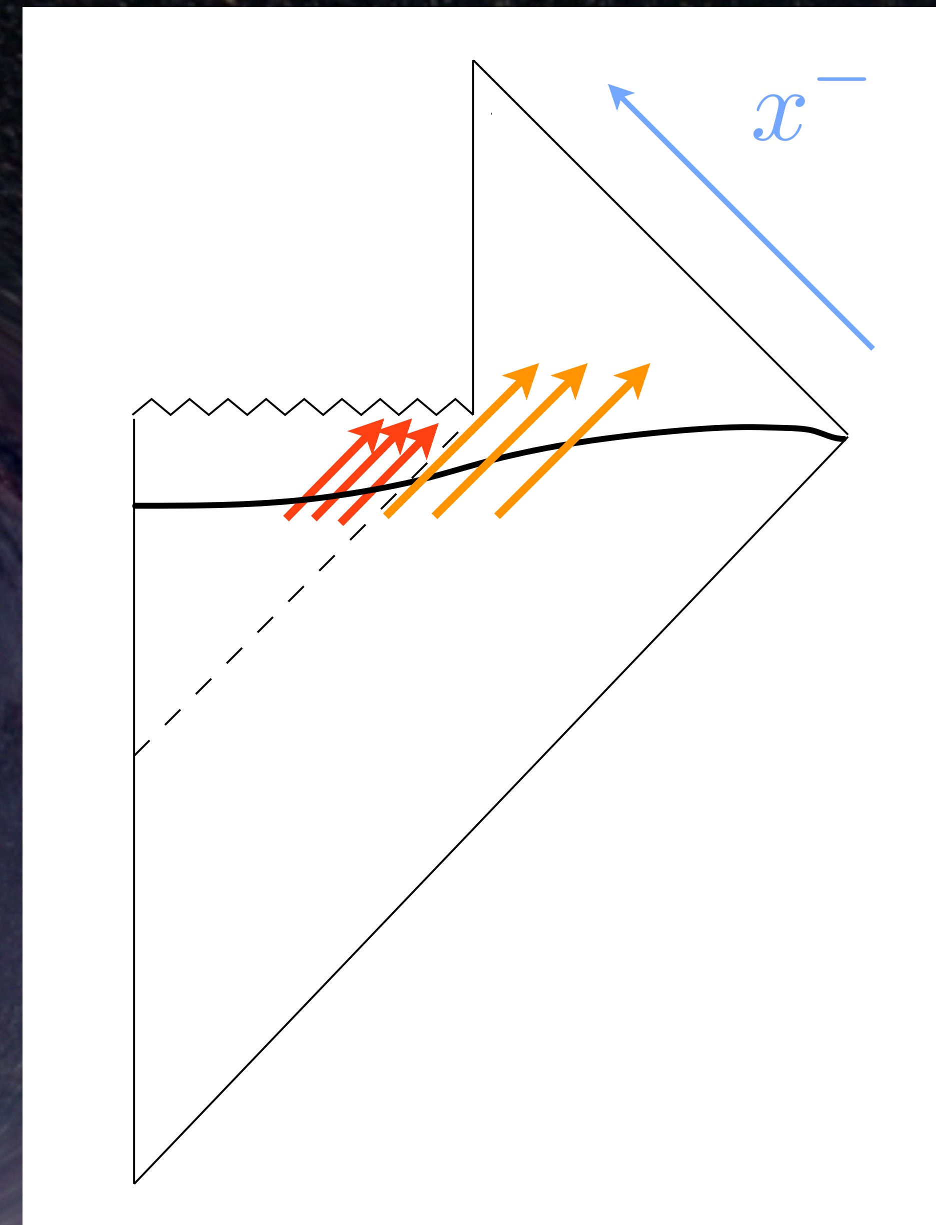
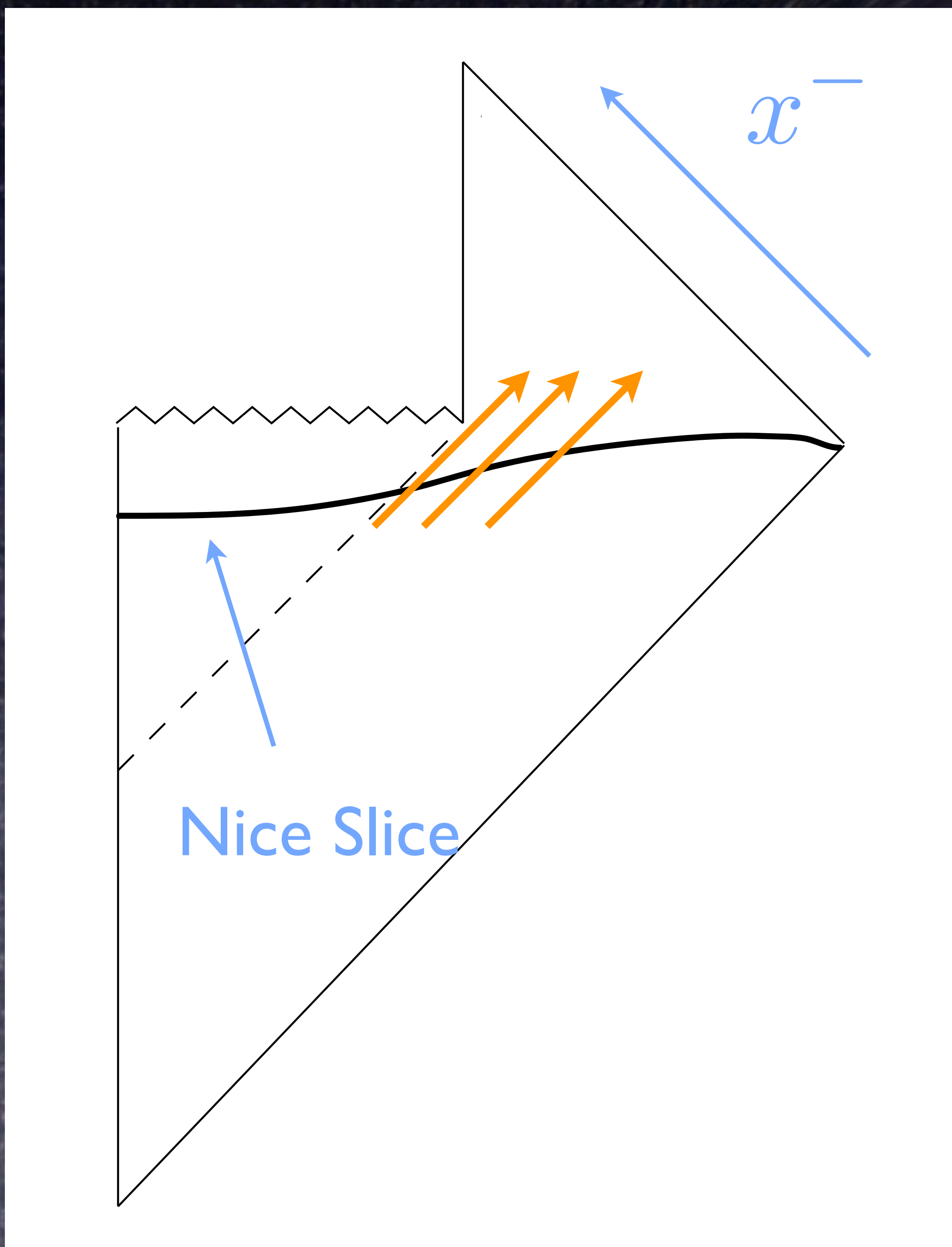


Penrose
(assuming complete evap.)
(Different slicing)

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



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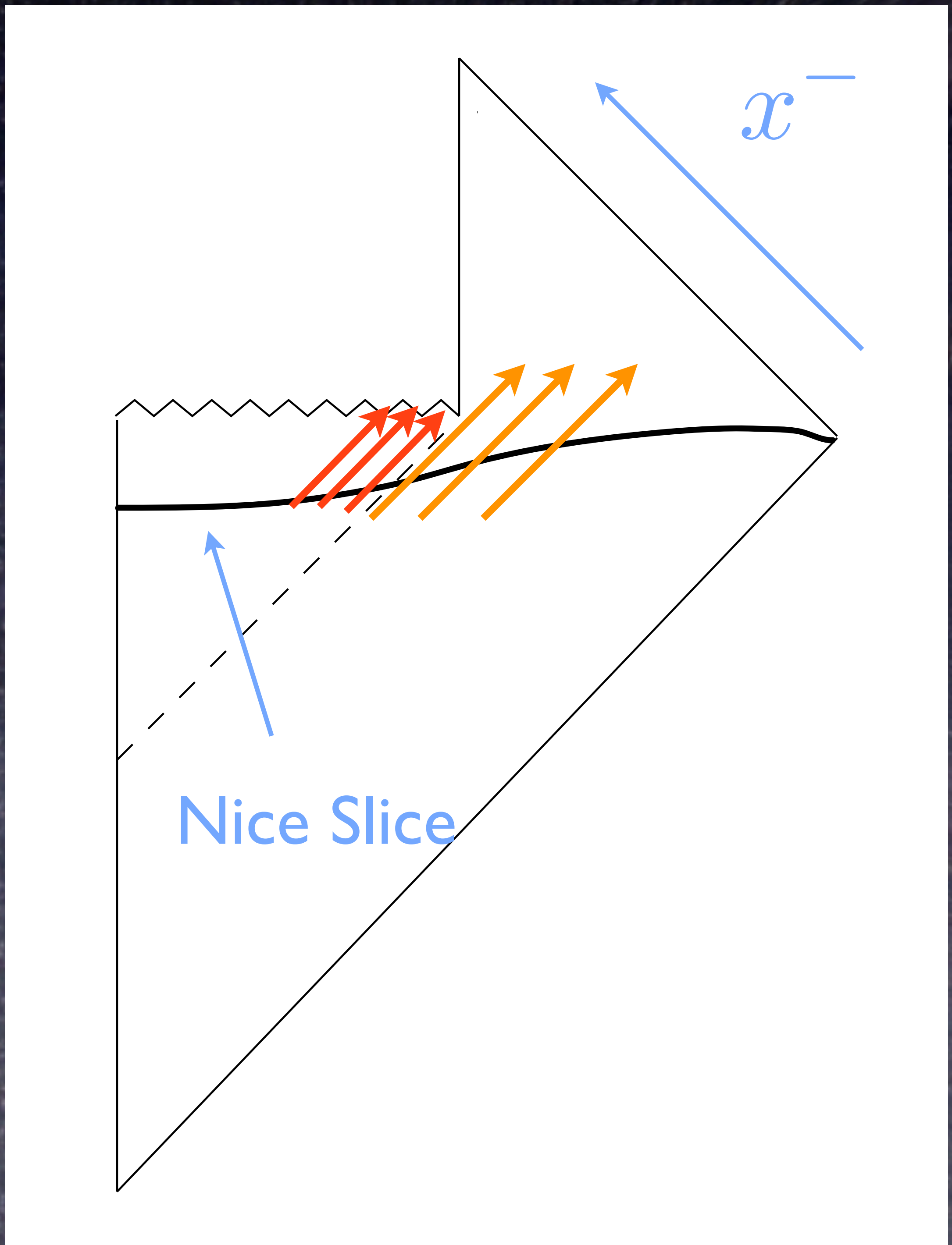

Locality: $|\psi_{NS}\rangle \sim \sum_i p_i |i\rangle_{in} |i\rangle_{out}$

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

$$S_{HR}(x^-) \sim -\mathrm{Tr}\left(\rho_{HR} \ln \rho_{HR}\right)$$

Increases to $\sim A_{BH}$ at t_{evap}

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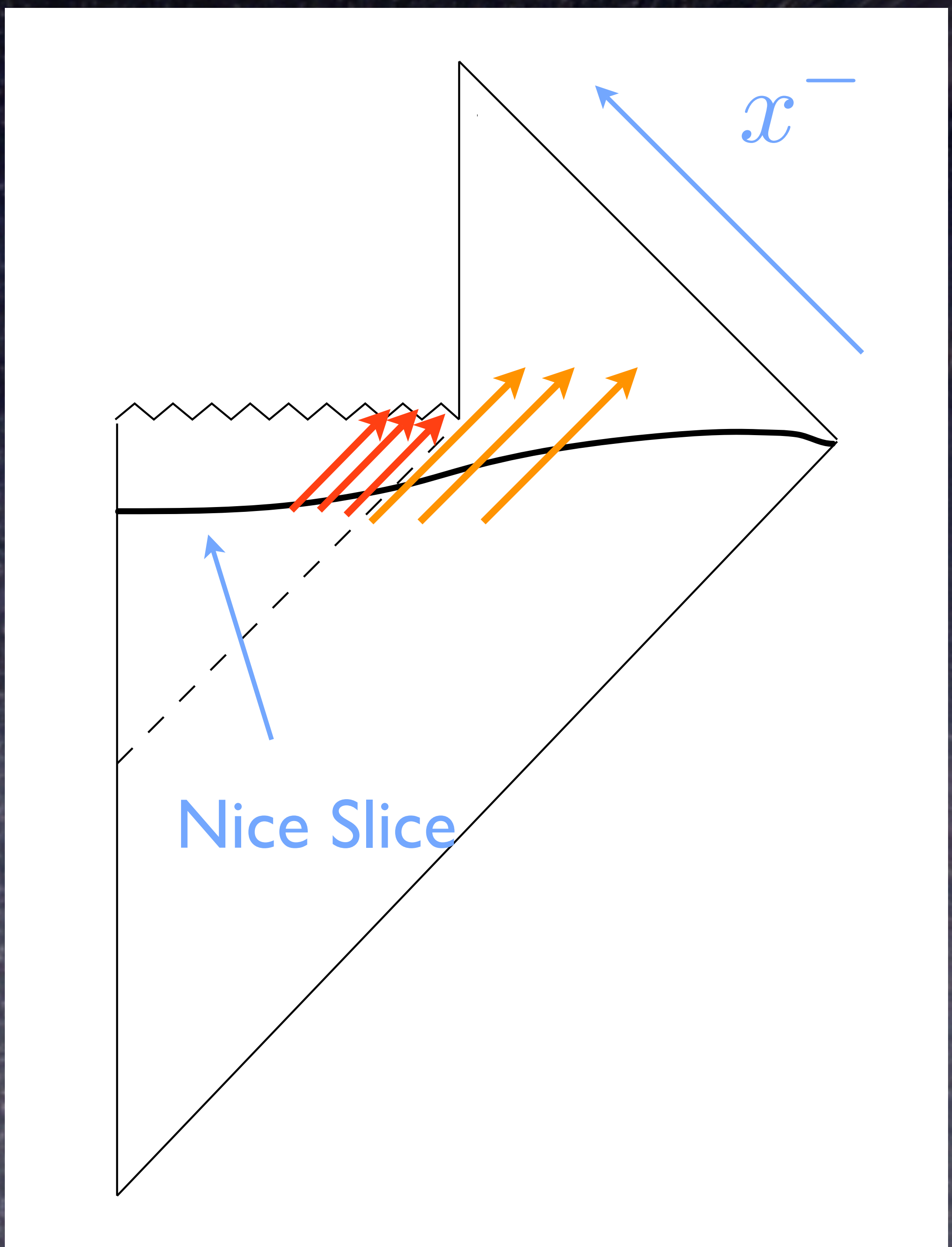

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$\therefore$ information lost

(Hawking, 1976)

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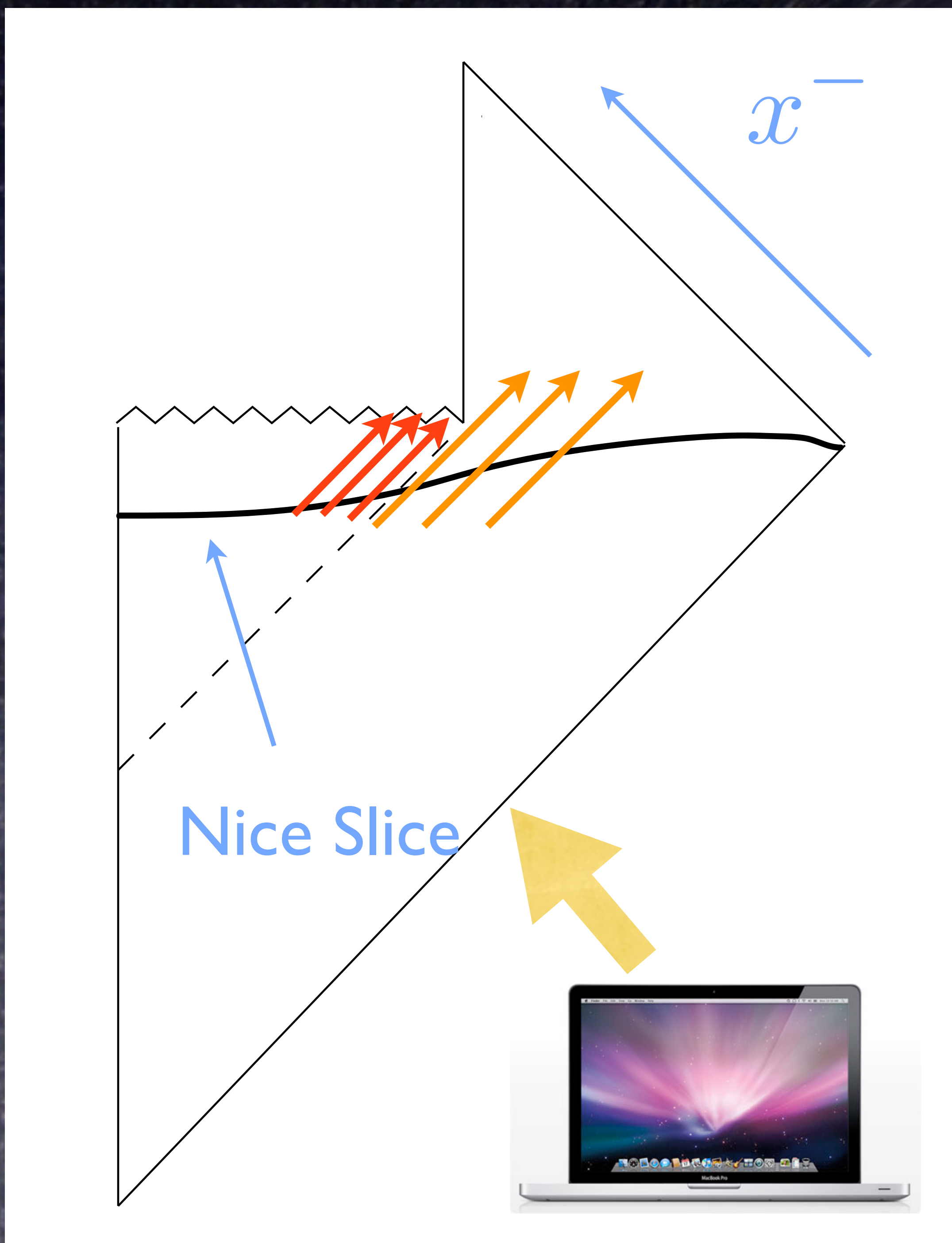

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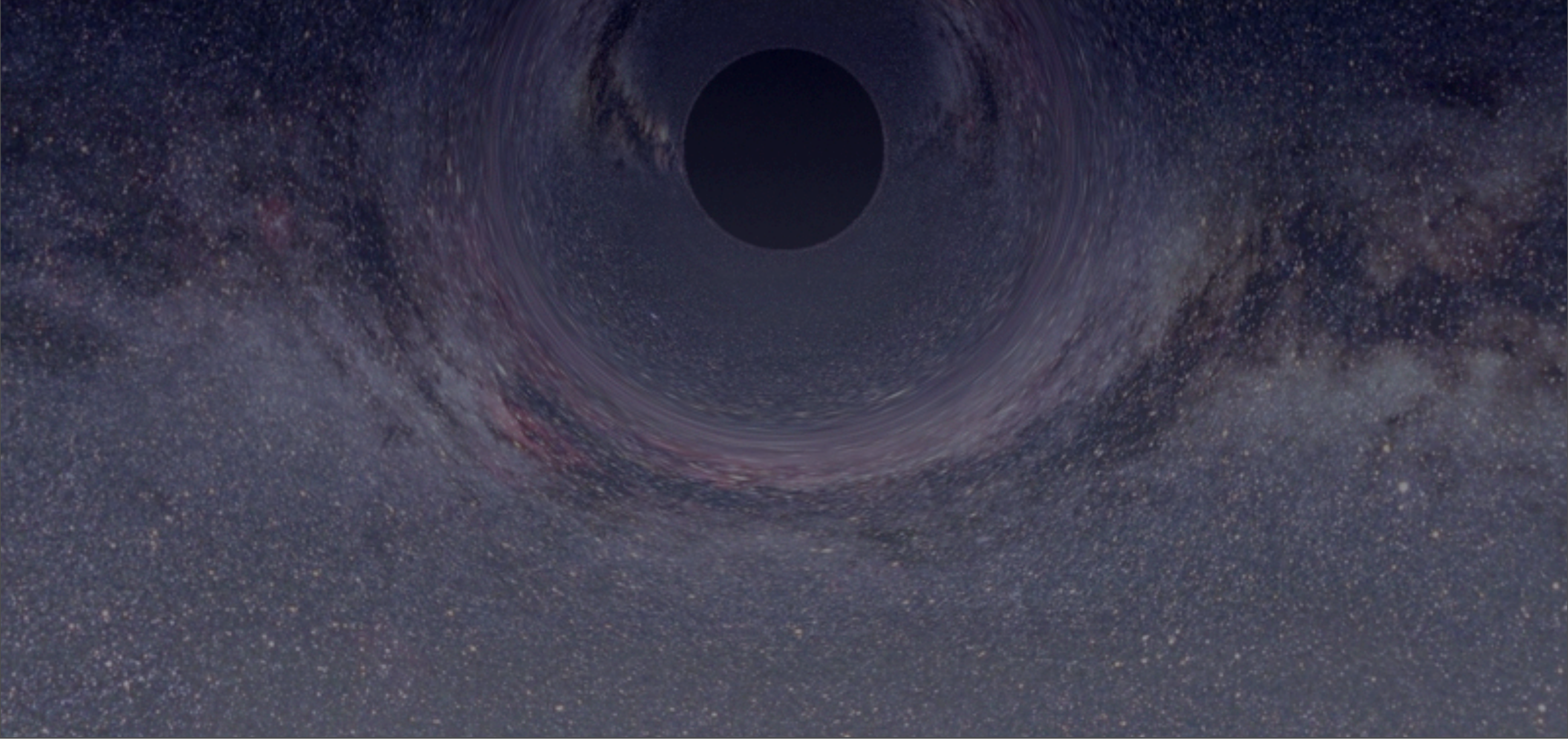
(Hawking, 1976)

Hawking's proposal (1976): fundamental nonunitarity in gravity

$$\rho \to \$\rho$$

The problem is, QM is remarkably robust:

Basic idea:



Hawking's proposal (1976): fundamental nonunitarity in gravity

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The problem is, QM is remarkably robust:

Basic idea:

- information transfer requires energy

- information loss violates energy conservation

- virtual effects: massive energy nonconservation

Hawking's proposal (1976): fundamental nonunitarity in gravity

$$\rho \to \$\rho$$

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Basic idea:

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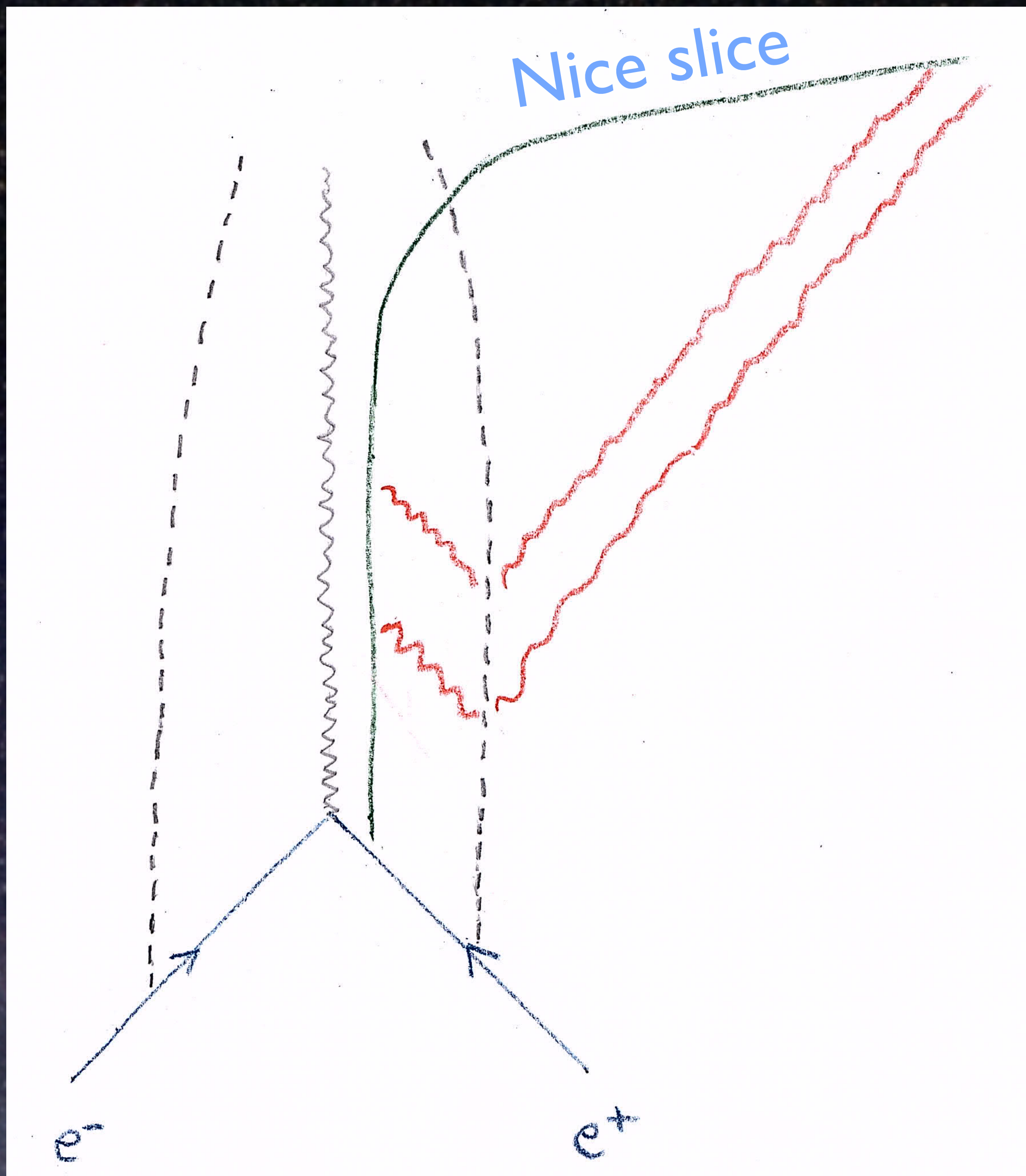
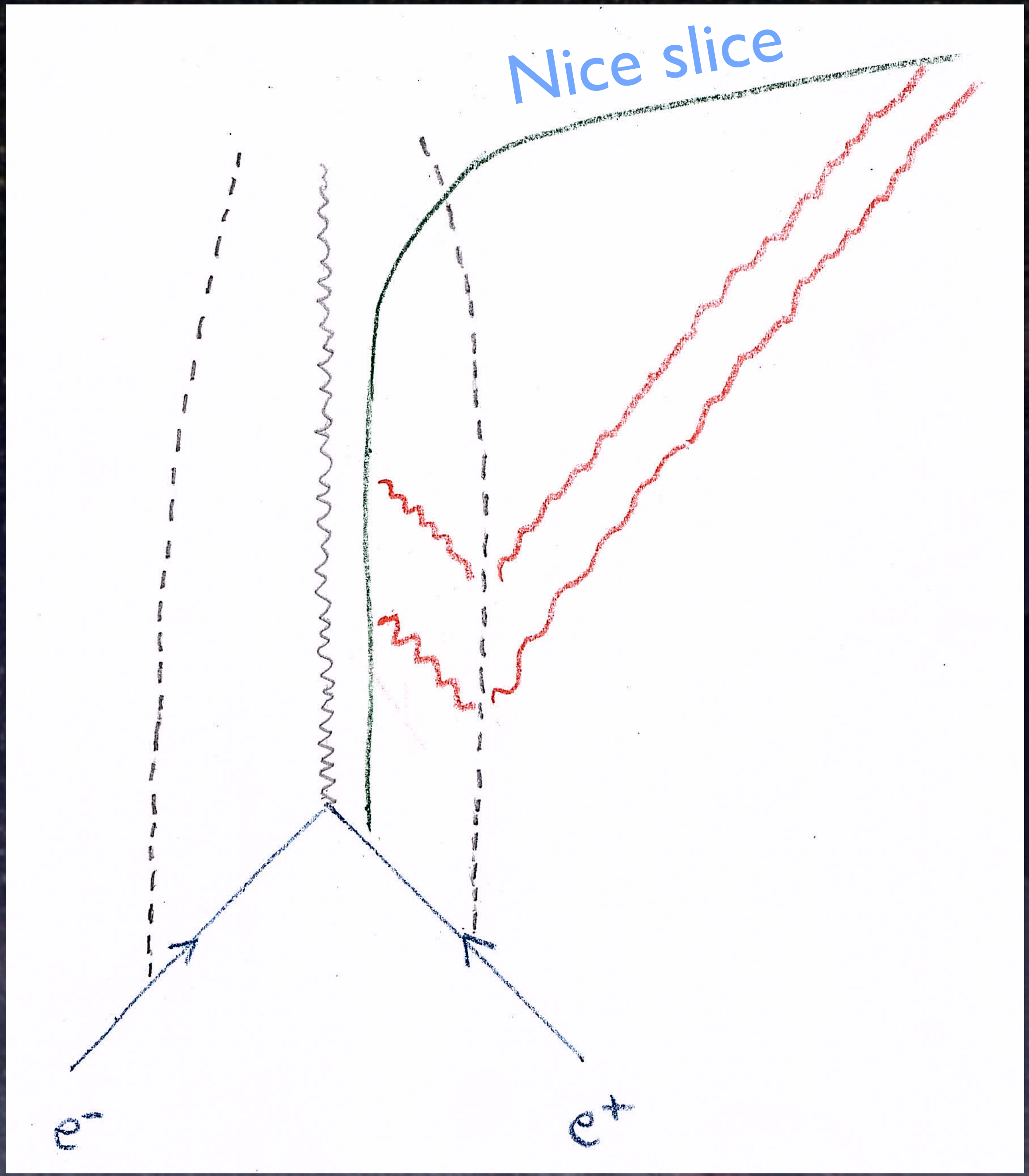
- virtual effects: massive energy nonconservation

Banks, Peskin, Susskind (1984):

Hawking's nonunitarity leads to effective thermal ensemble at $T \sim M_{\mathrm{Planck}}$



- Locality: no info escape during evap.
- E conserv/QM: info conserved



- Locality: no info escape during evap.

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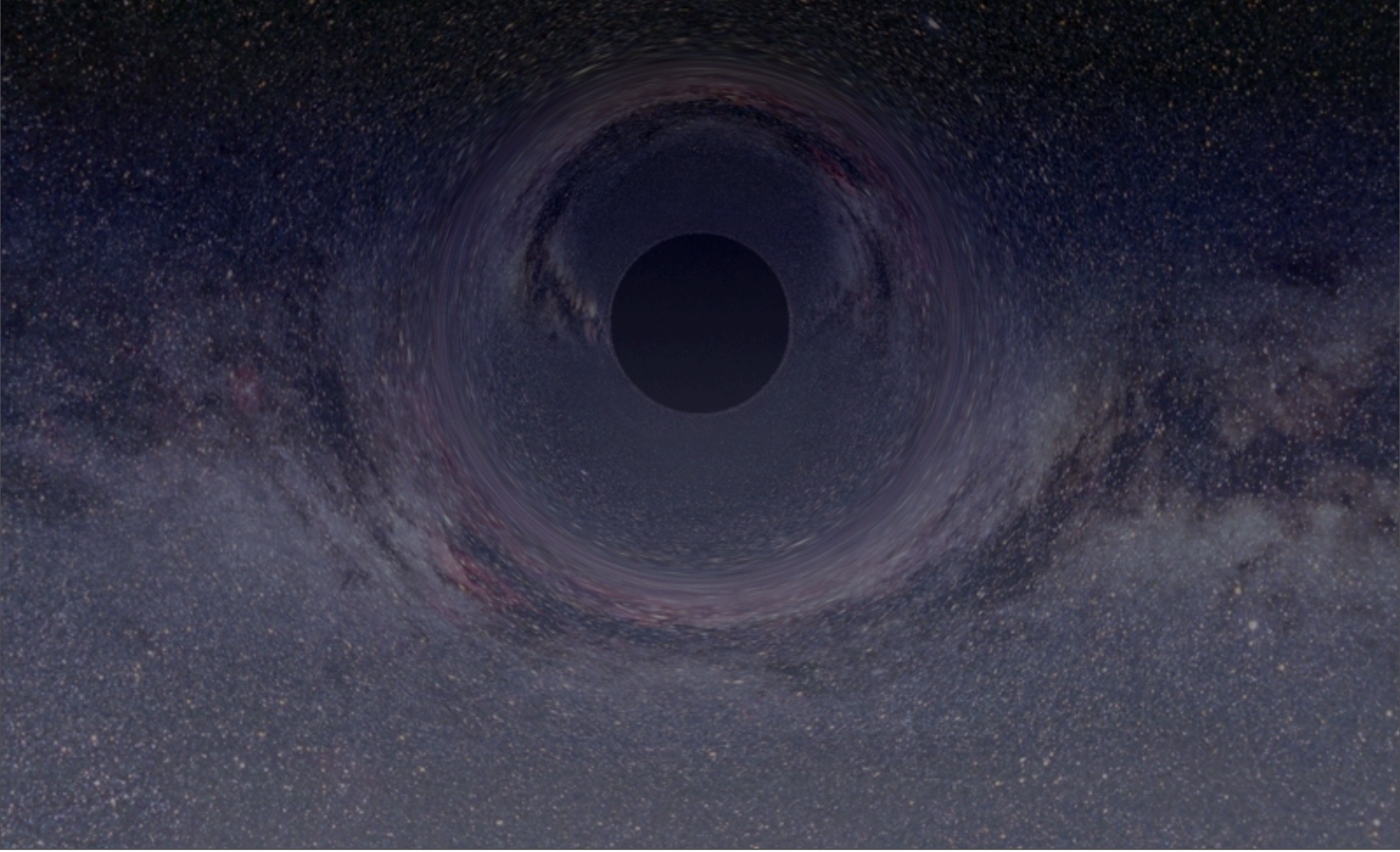
- later escape, once $R_S \sim l_{Planck}$?

Remnant

(long-lived or stable)

But: begin w/ arbitrarily large black hole



But: begin w/ arbitrarily large black hole

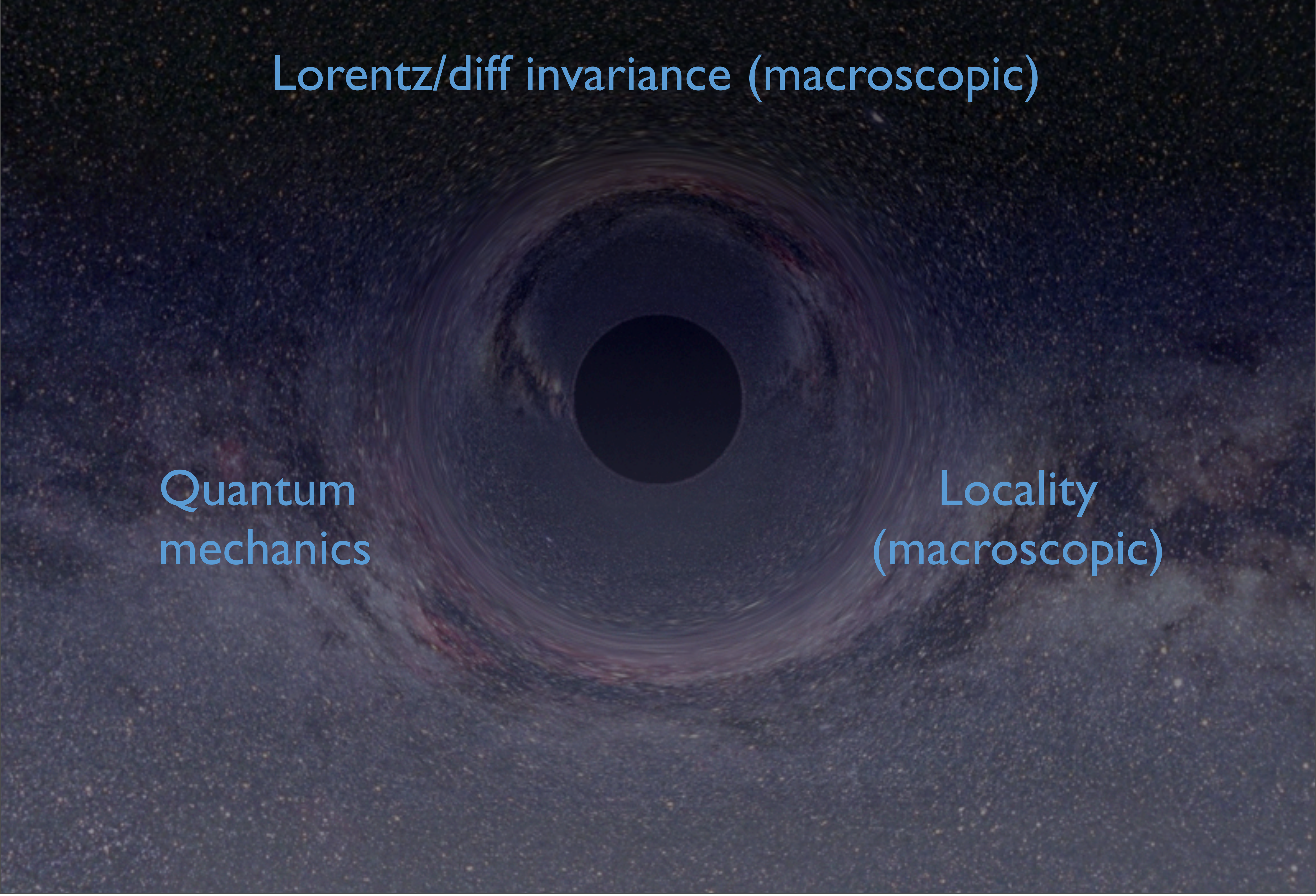
$\Rightarrow$ infinite remnant species $M \sim M_p$

$\Rightarrow$ Infinite production instabilities

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

“Paradox”

The “paradox:” a conflict between



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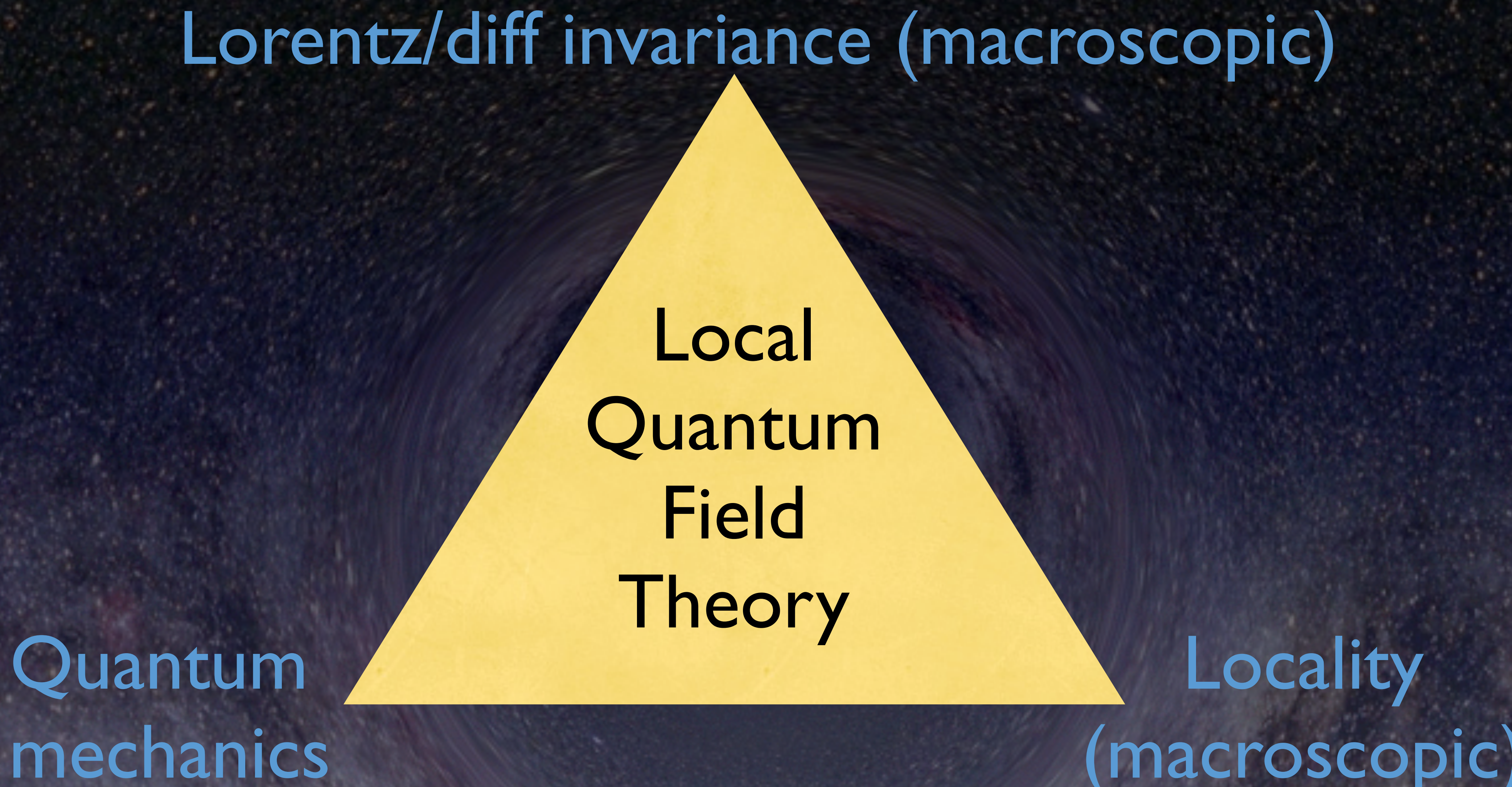

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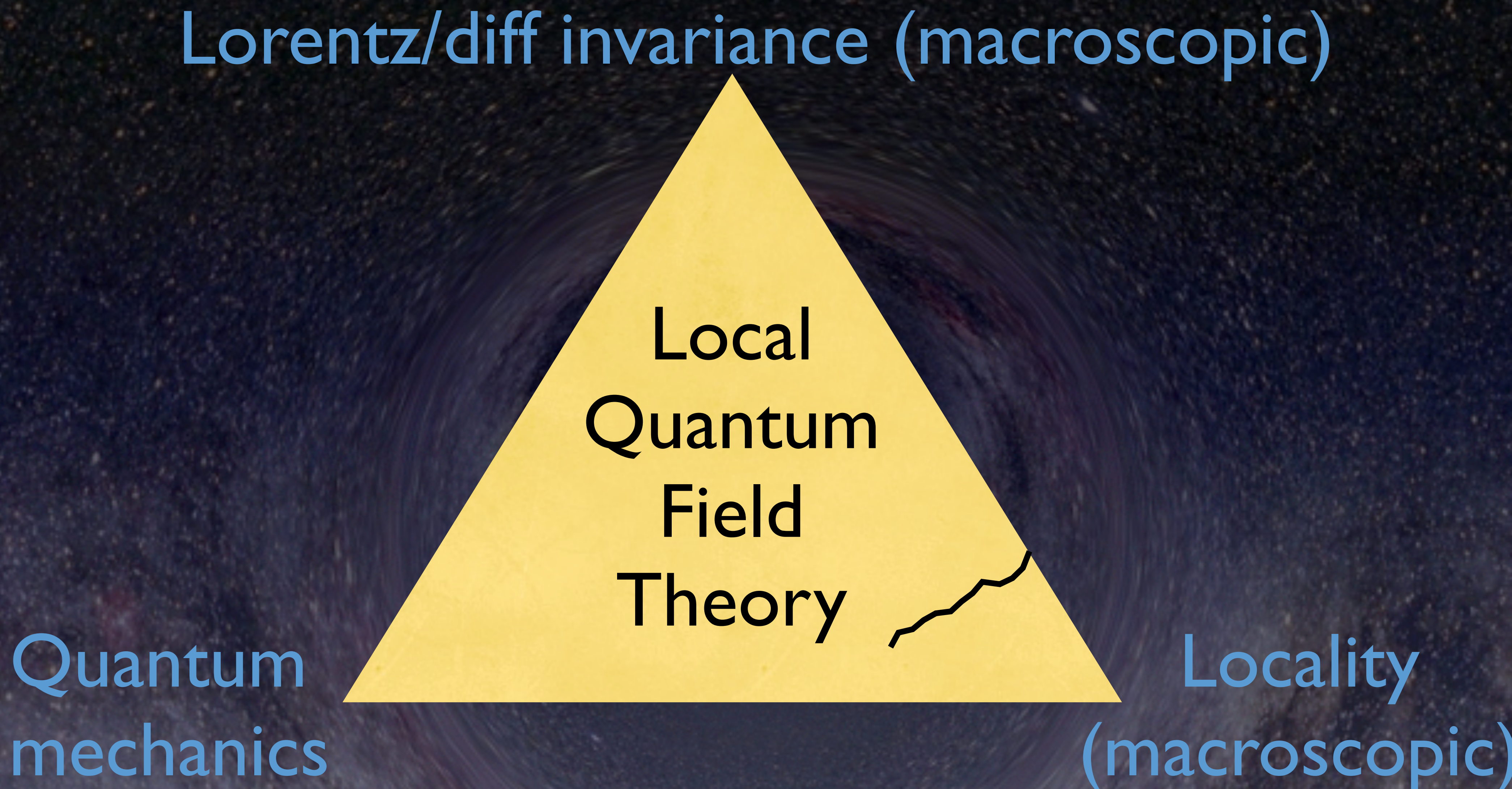

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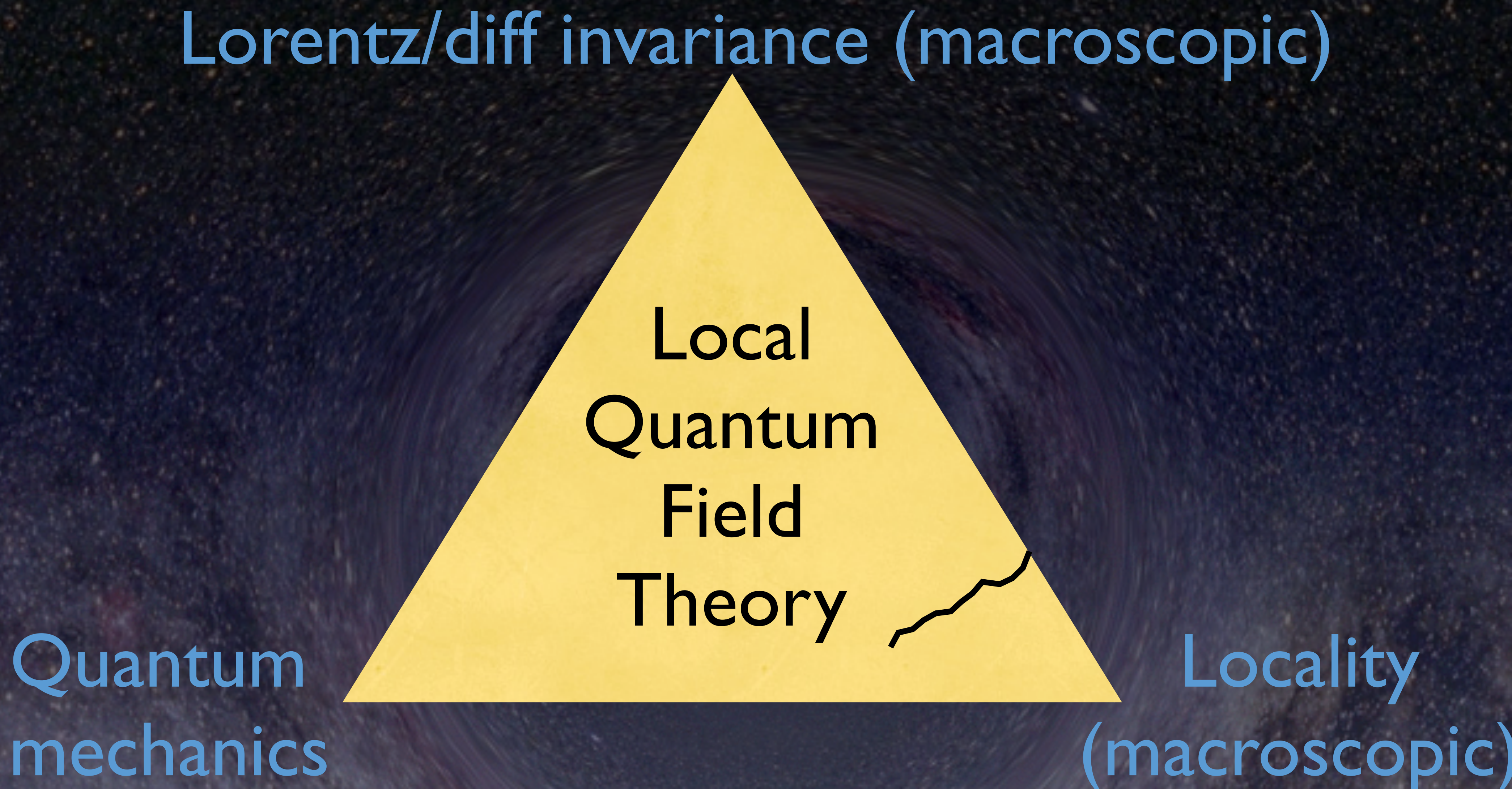
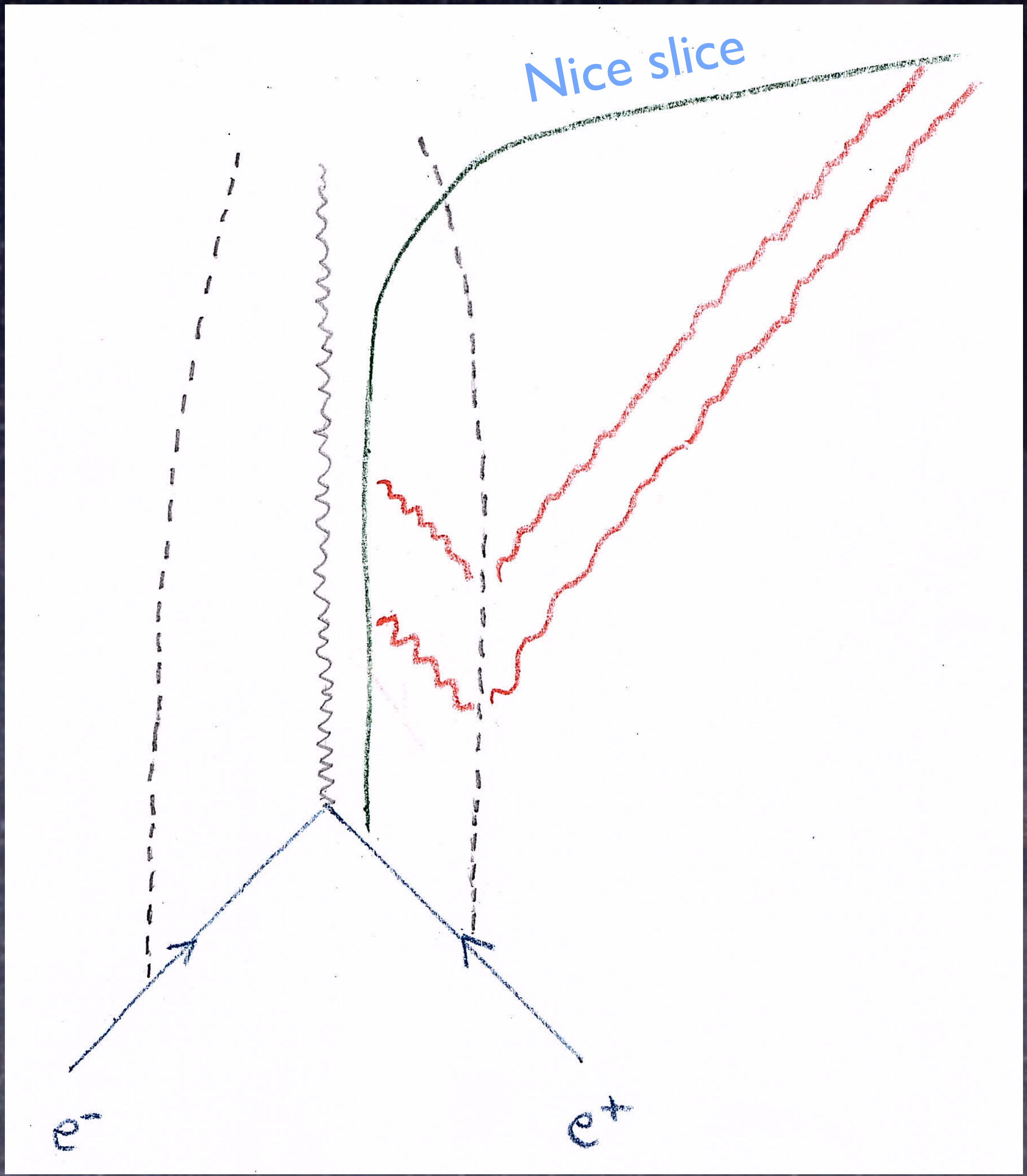


QM, LI -- can't see how to modify, respecting consistency and observation

A weak point: locality?

Is it really a paradox?

$$|\psi\rangle \to \rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$
$$\to S = -\mathrm{Tr}\rho ln\rho = \Delta I$$



Is this a sharply defined calculation?

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

(extreme, artificial construct)

Semiclassical picture: not an accurate representation of detailed quantum state?

- no physical meaning to NS state (gauge invc.)?
- large fluctuations at long times

SBG hep-th/0703116; 0911.3395

So, the nice slice argument is not clearly trustworthy/sharp.

If there is no sharp argument for information loss, there is no true paradox.

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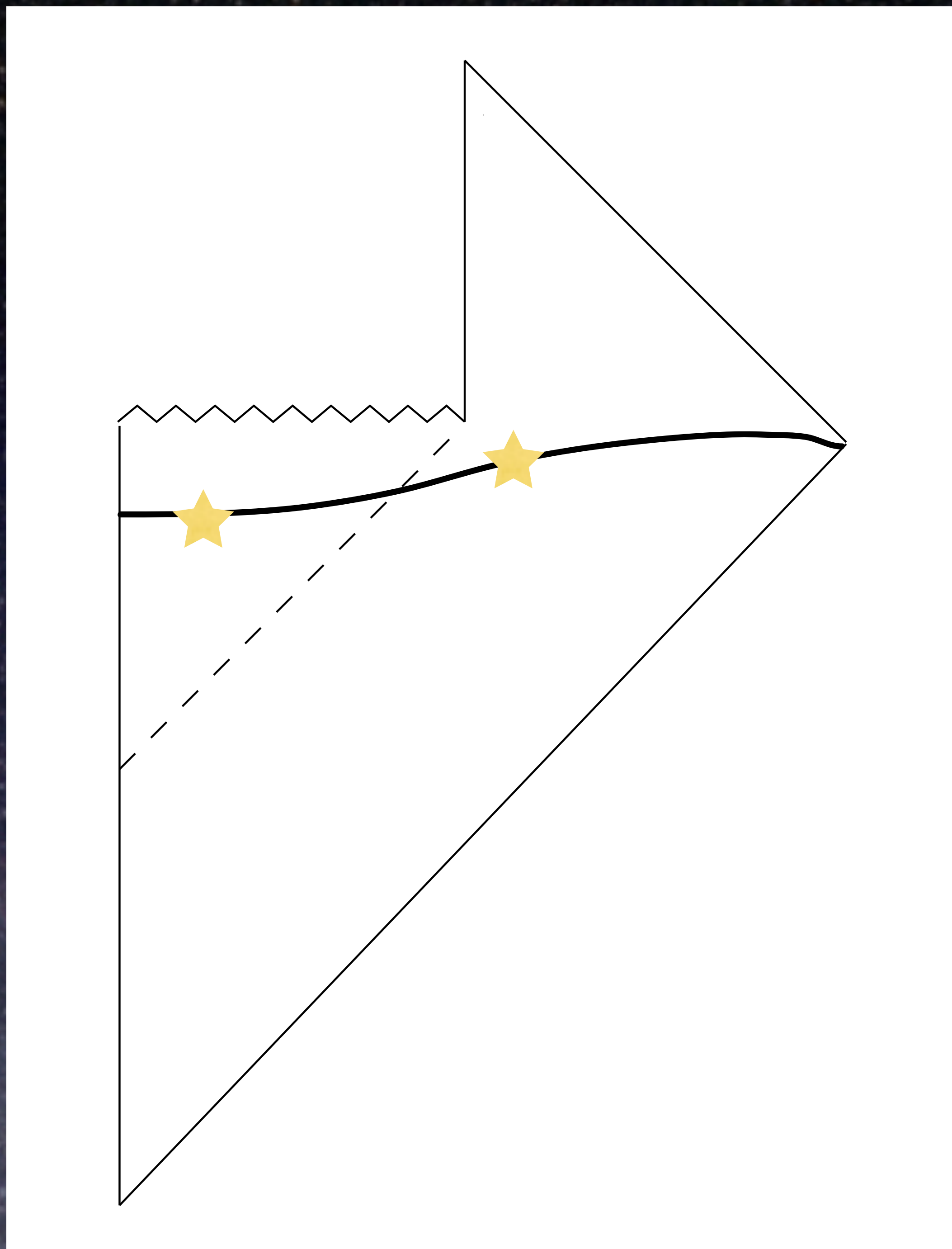
Nonetheless, a breakdown of perturbation theory in this calculation indicates the need for a nonperturbative completion, so there is certainly an information problem:

What is the nonperturbative gravitational dynamics that unitarizes HE scattering?



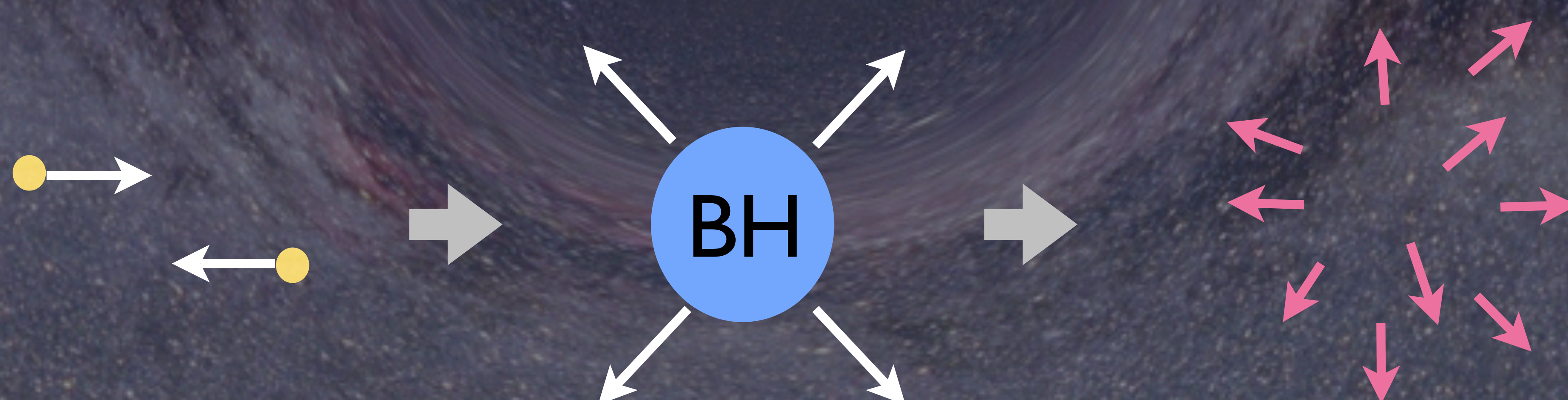
Good indications: breakdown/ modification of locality, on macroscopic scales, with respect to semiclassical picture

$$r \sim R_S(E)$$

A general way of investigating gravitational scattering:

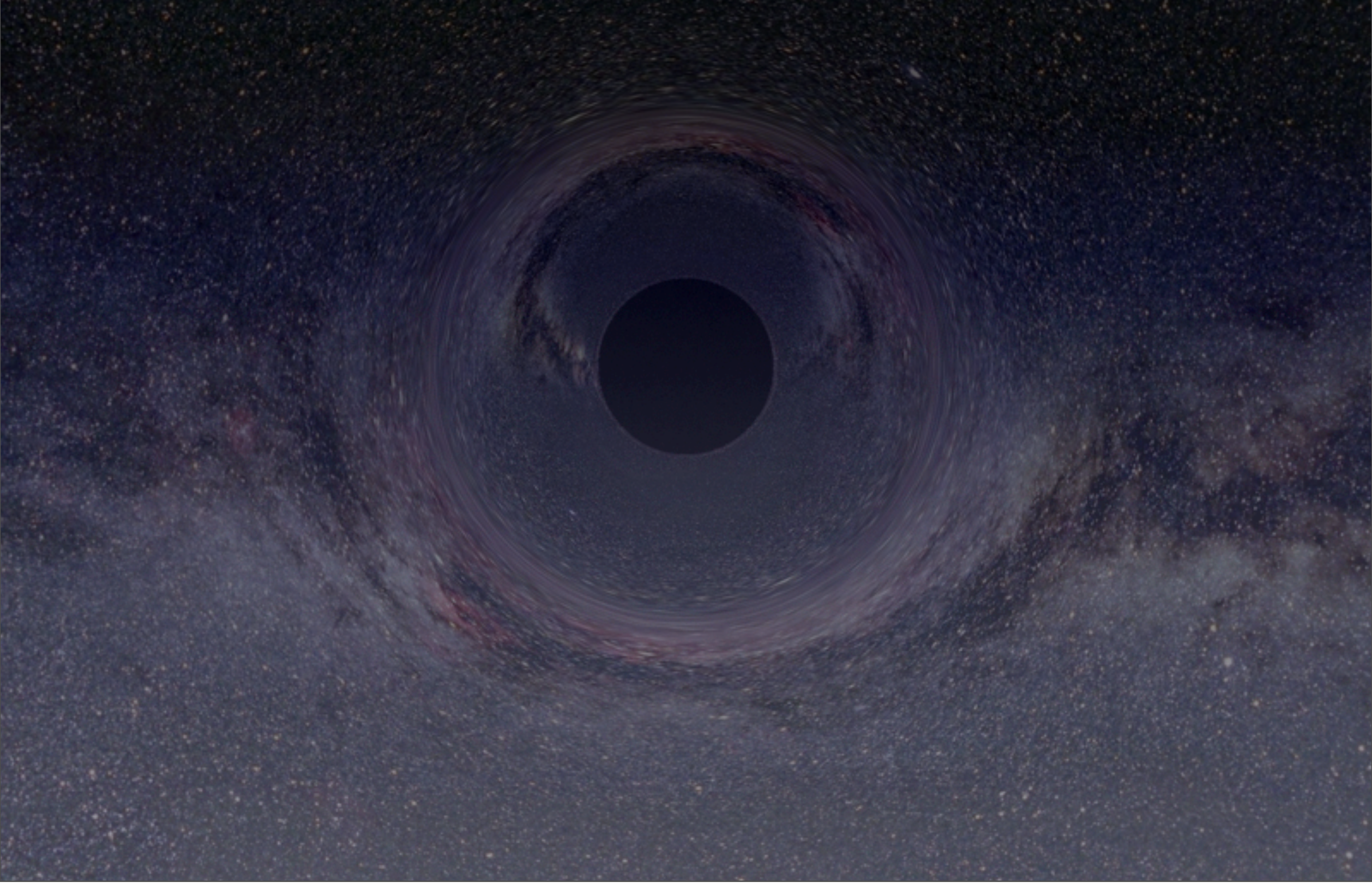
The gravitational S-matrix

E.g. quantum amplitudes for:



Approach ~Planck regime: nonrenormalizability, etc.=trouble

can we say anything about $E \gg M_D$?



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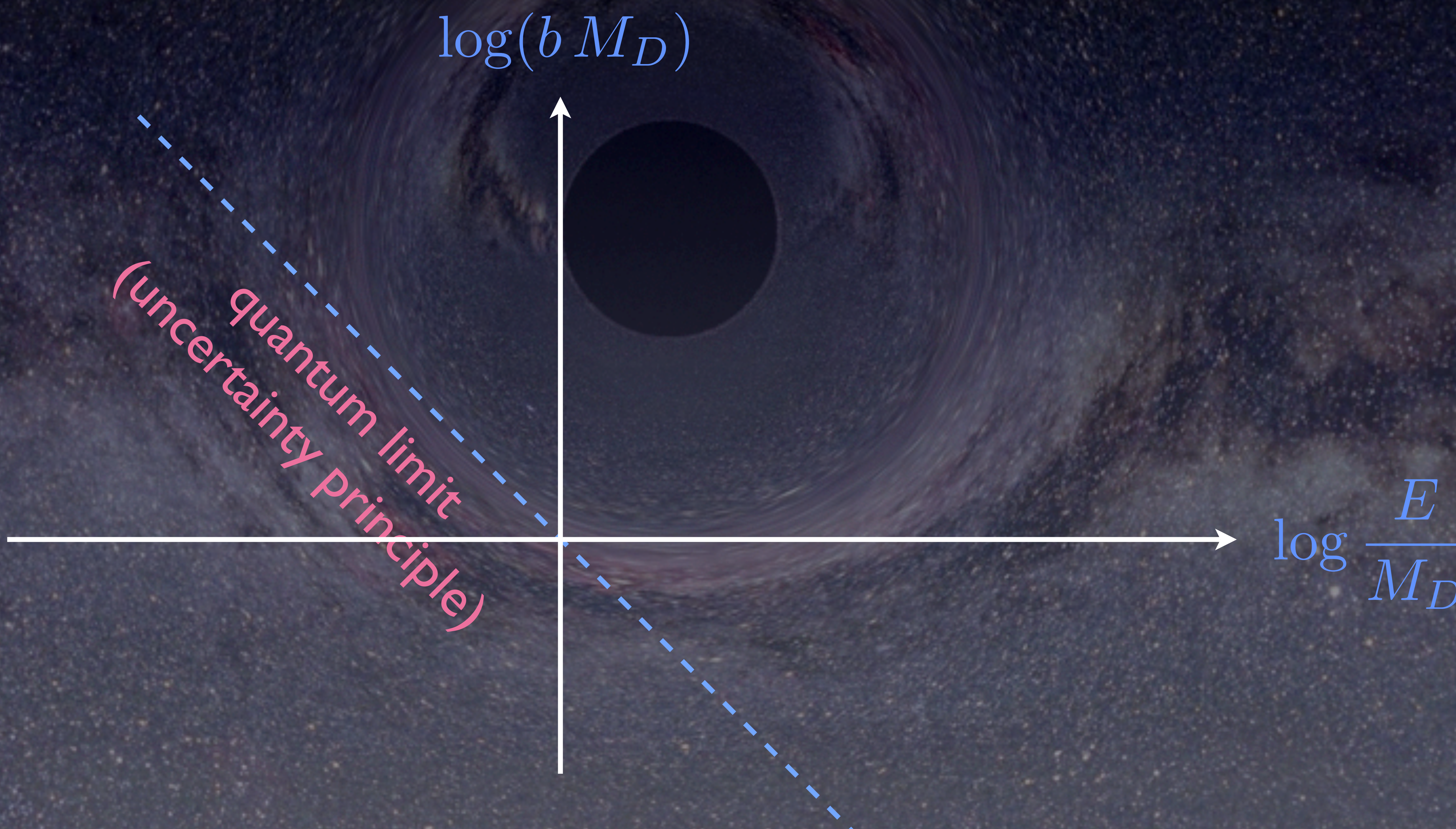

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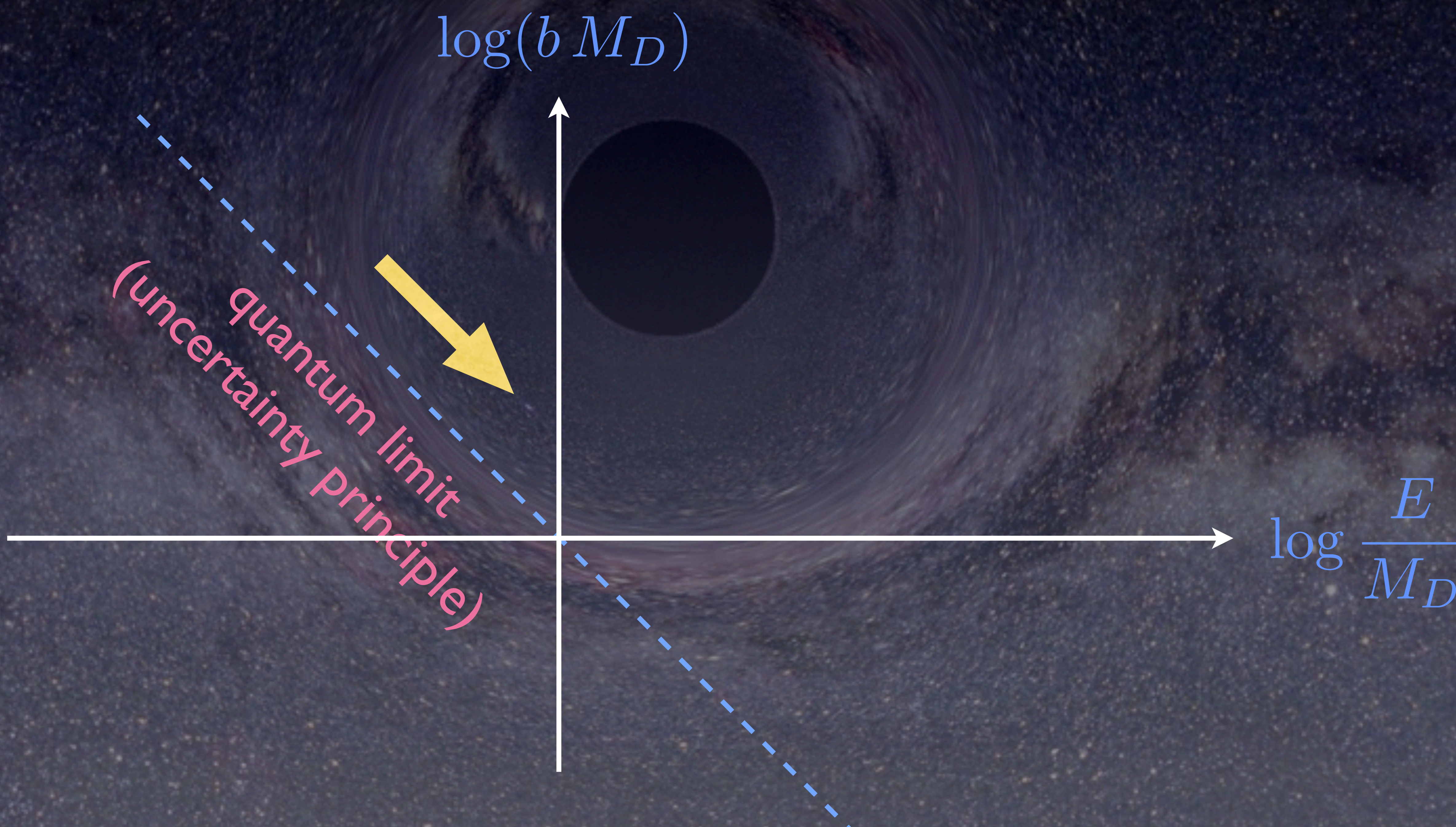

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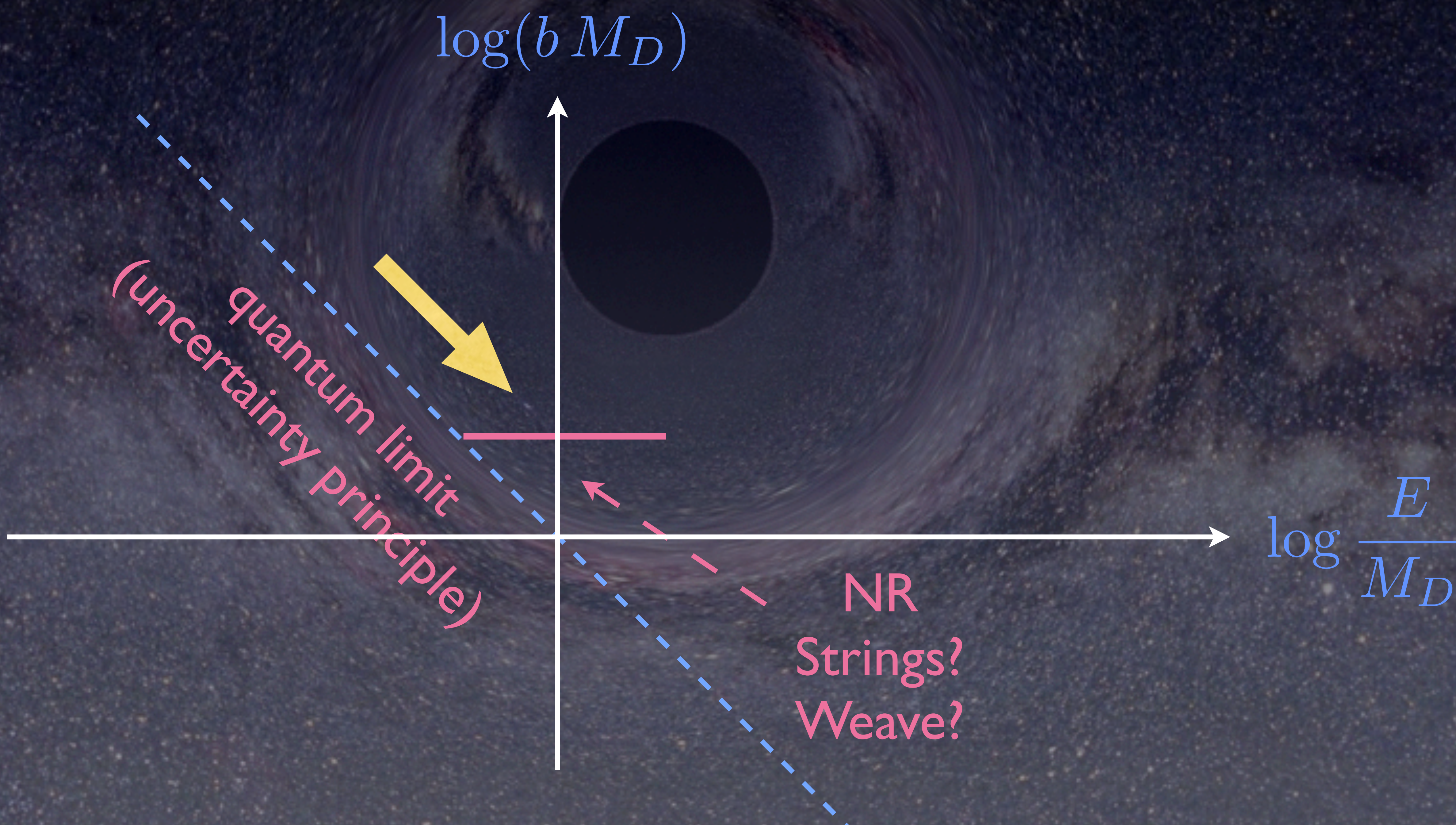

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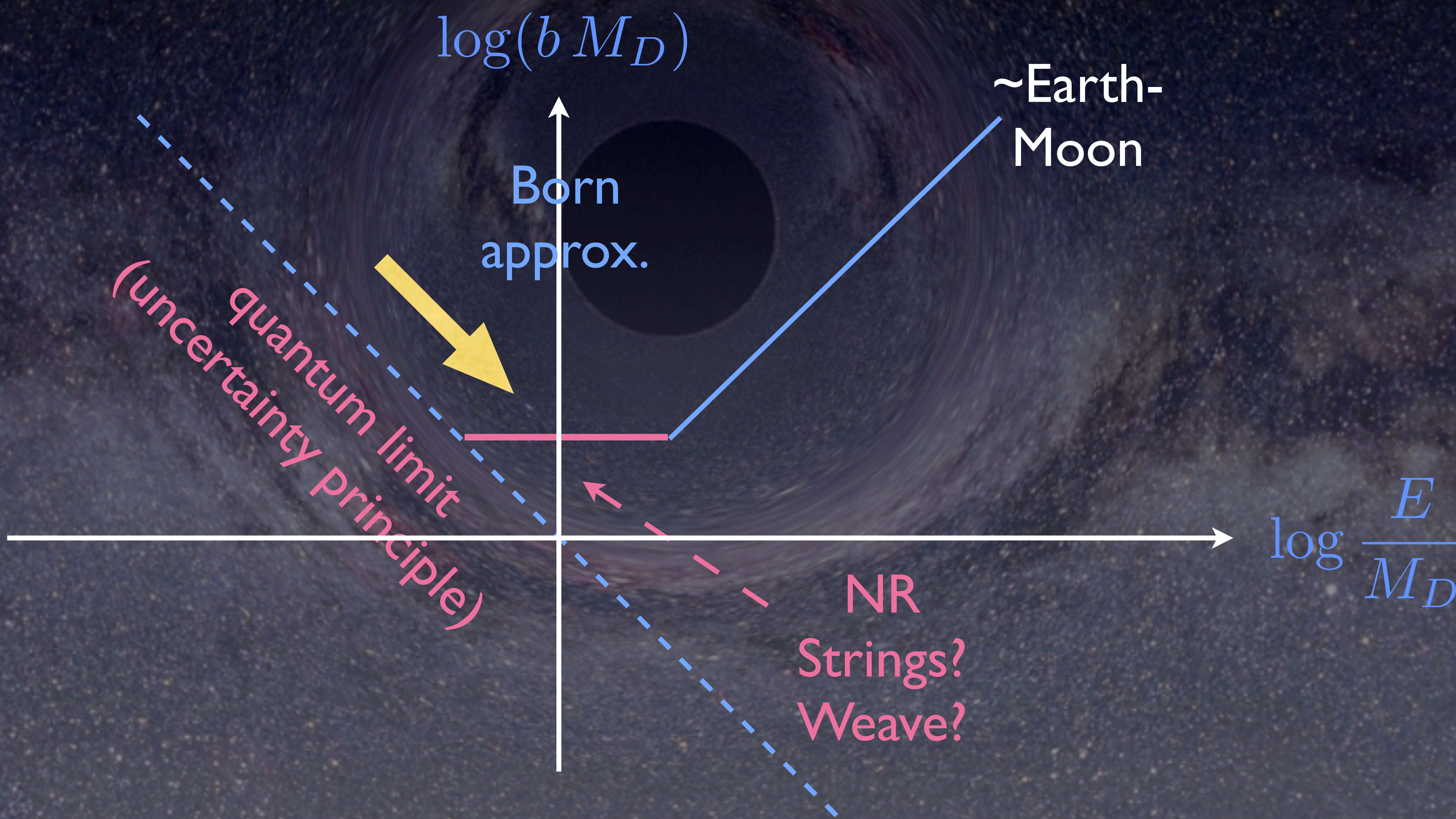

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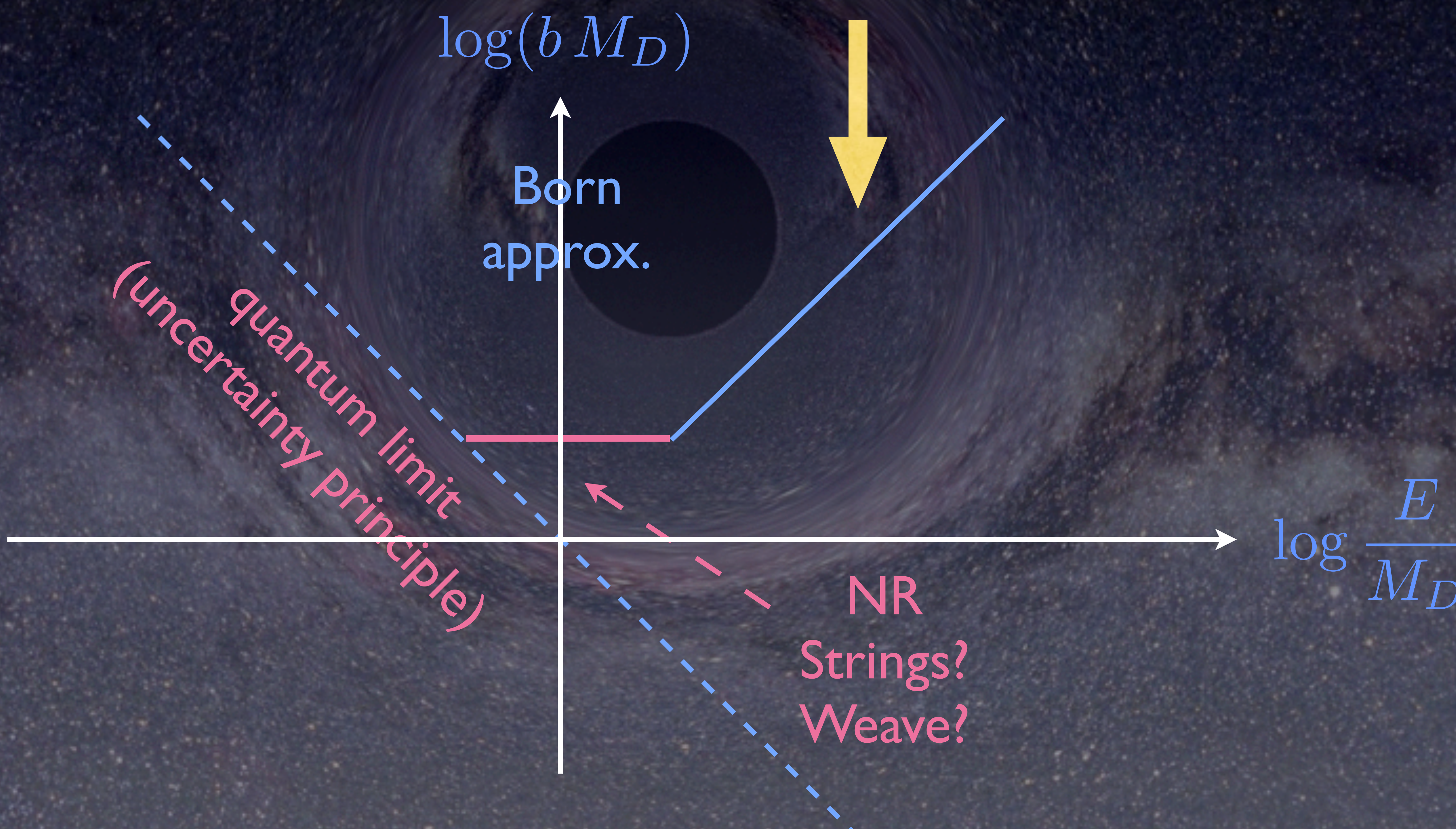
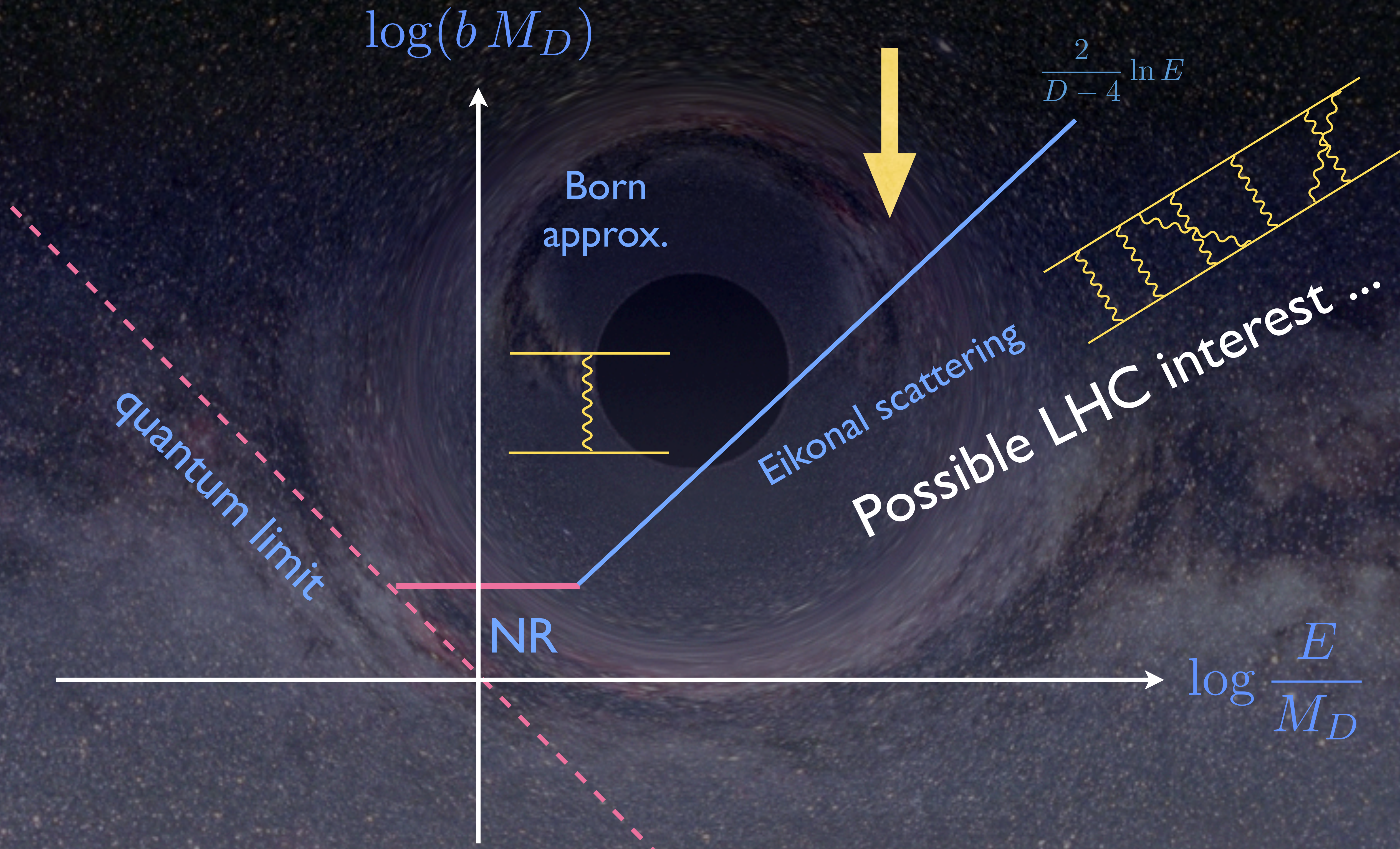


Diagram of Scattering regimes



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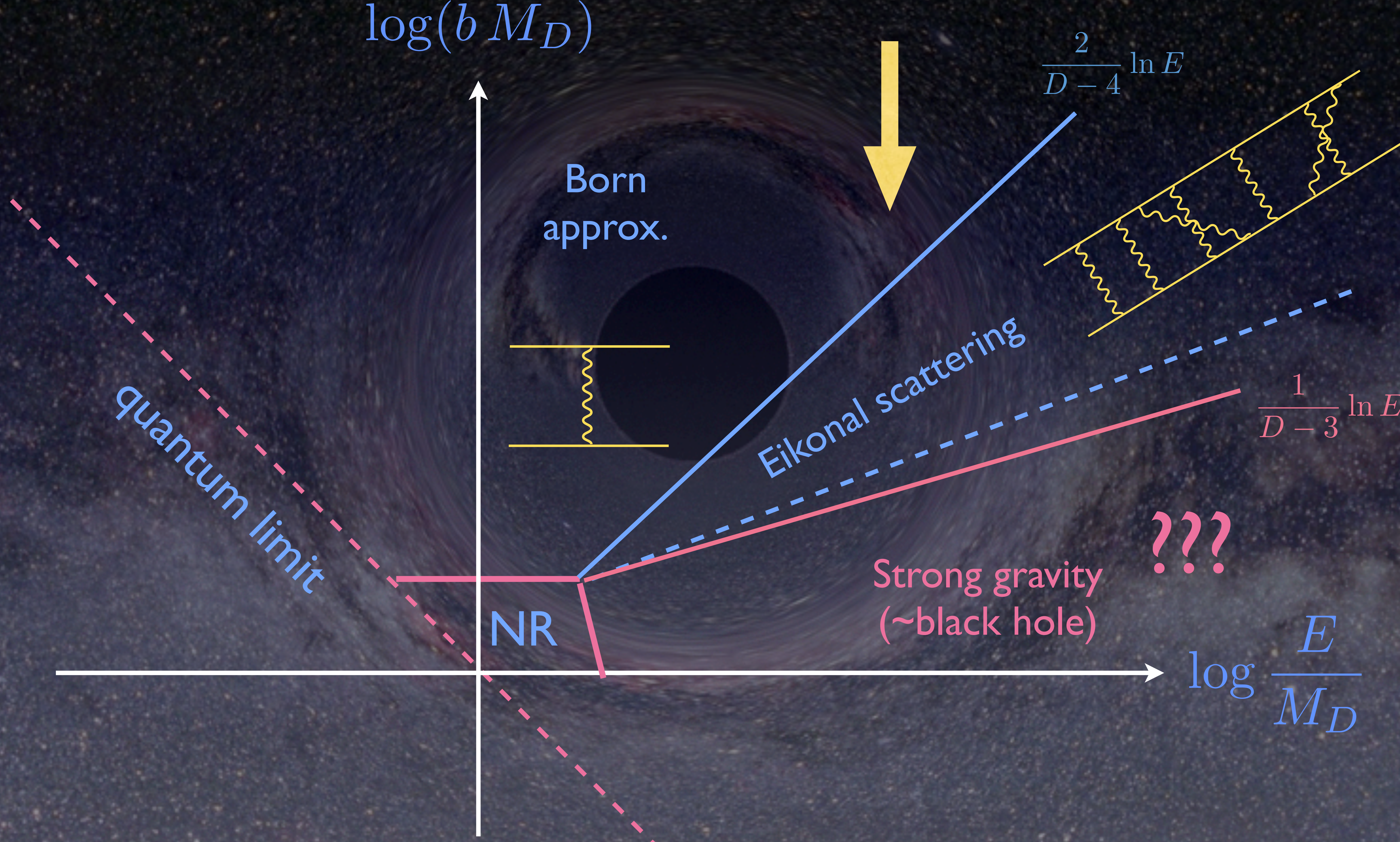

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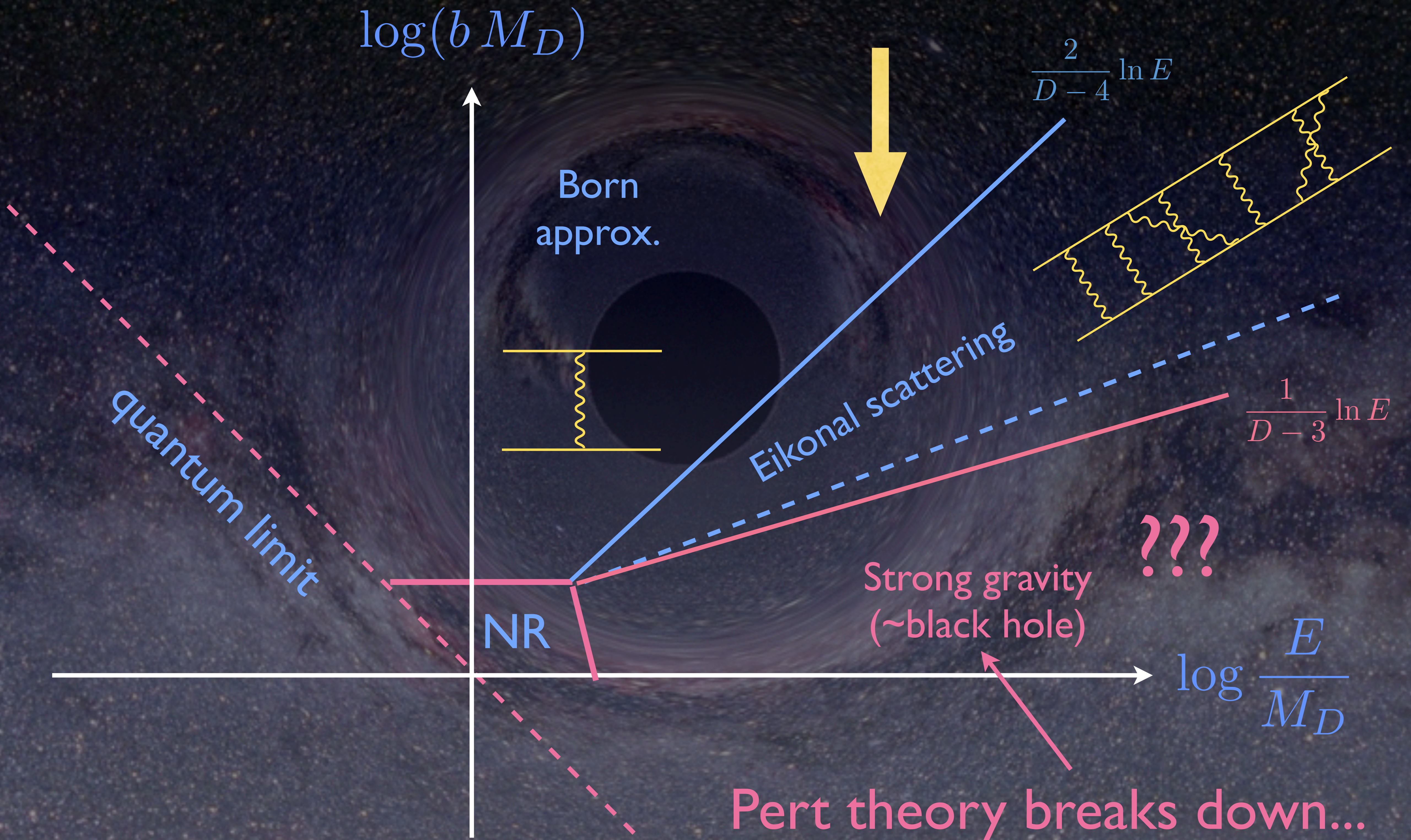
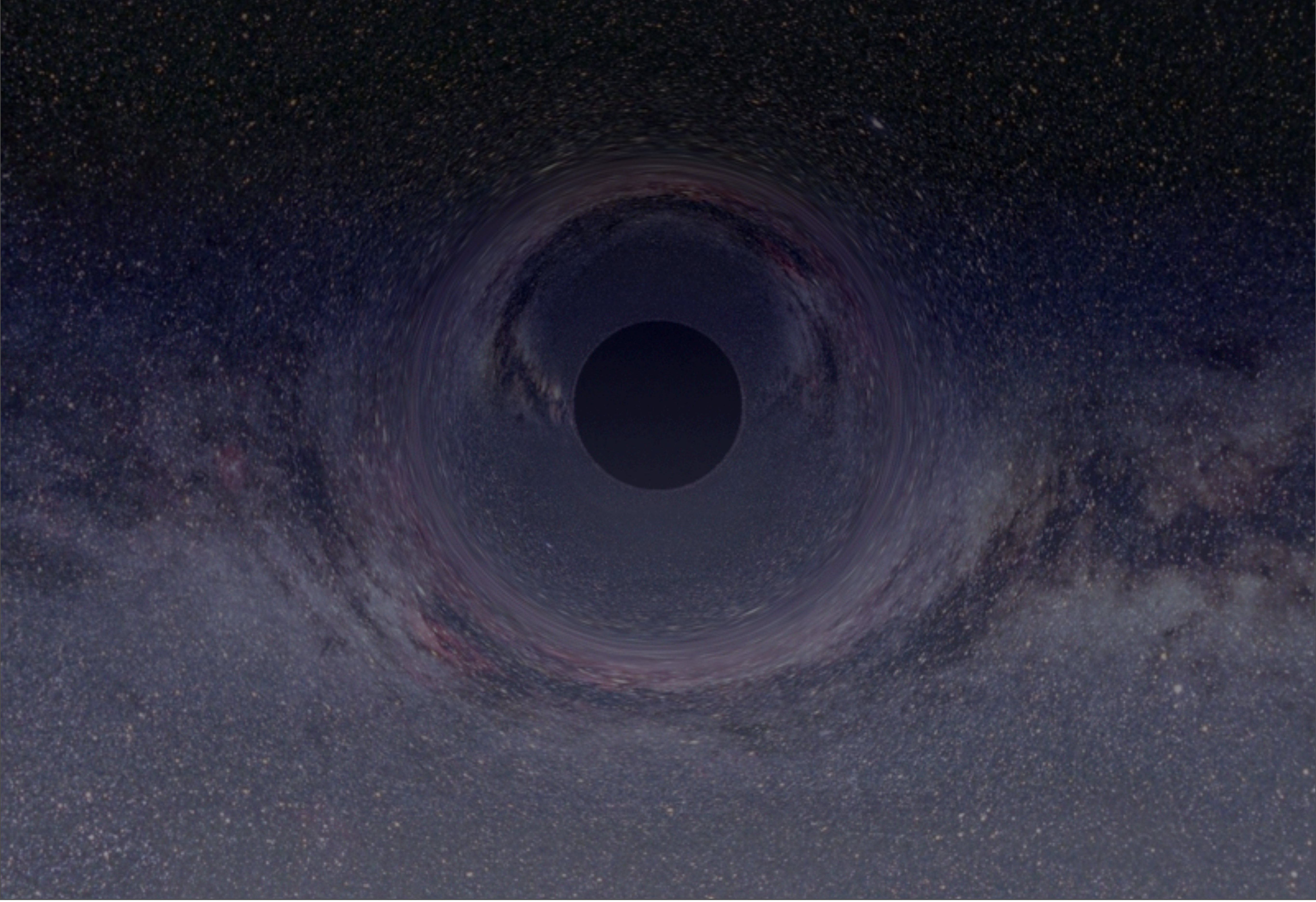


(not issue of nonrenormalizability)

What do our candidate theories say?



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Loop QG: still working to recover flat space and scattering of its perturbations

modest first goal: derive Born and eikonal amplitudes

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

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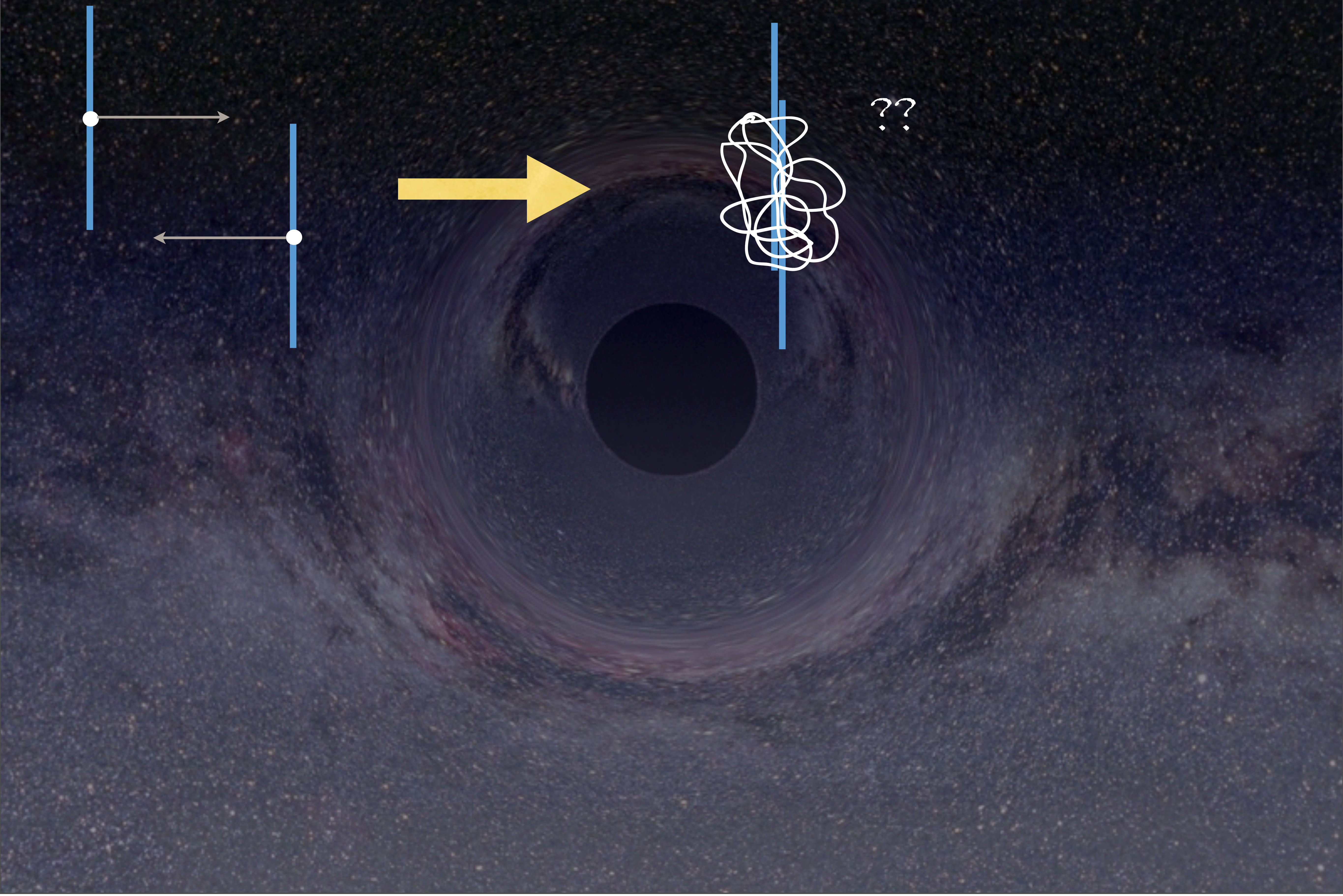
Strings:

- nonlocality -- extendedness
- perturbative calculations of S-matrix
- dualities; conjectured "holography"

Extendedness: some past confusion



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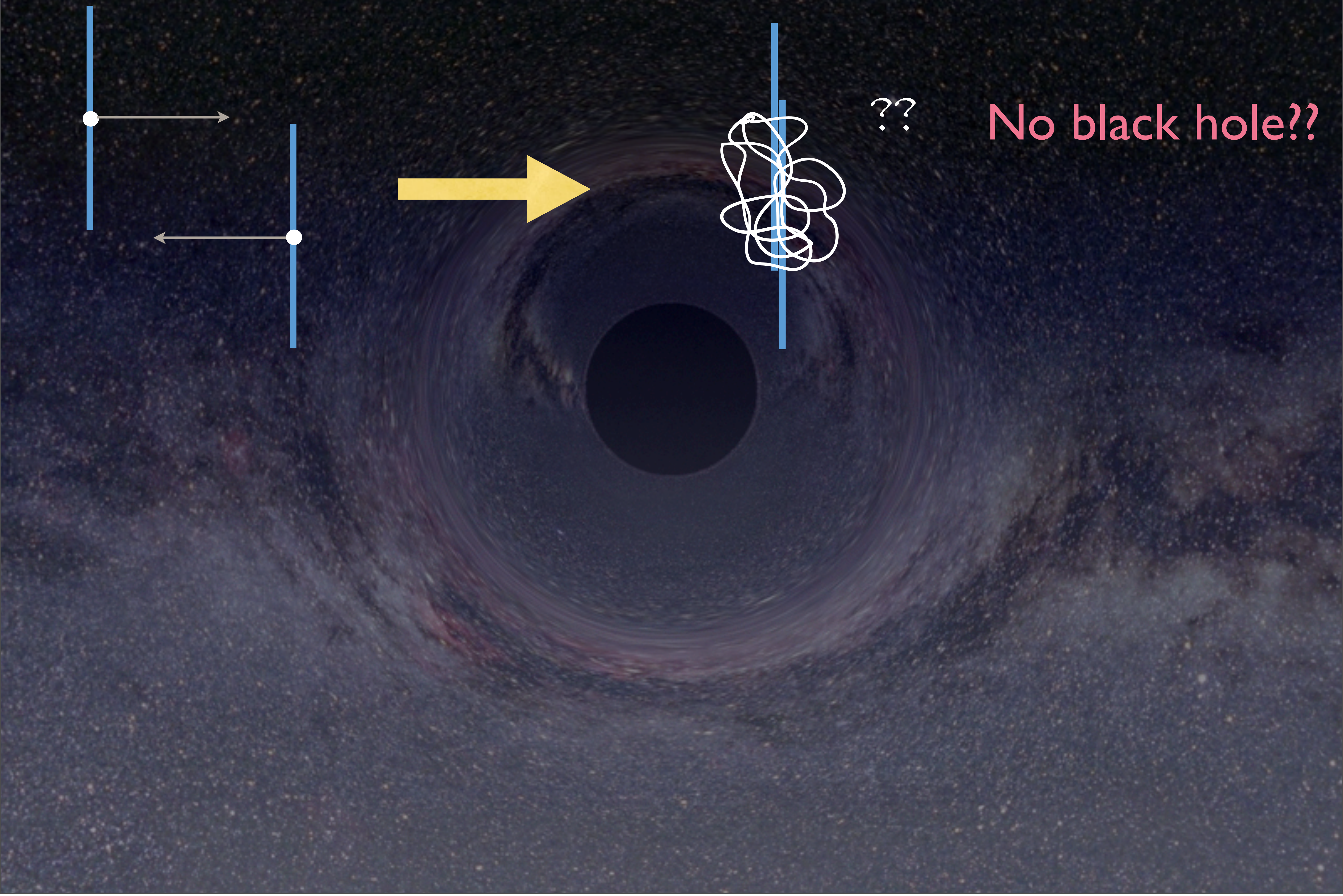

Extendedness: some past confusion

No black hole??

Info carried away?
(Veneziano, 2004)

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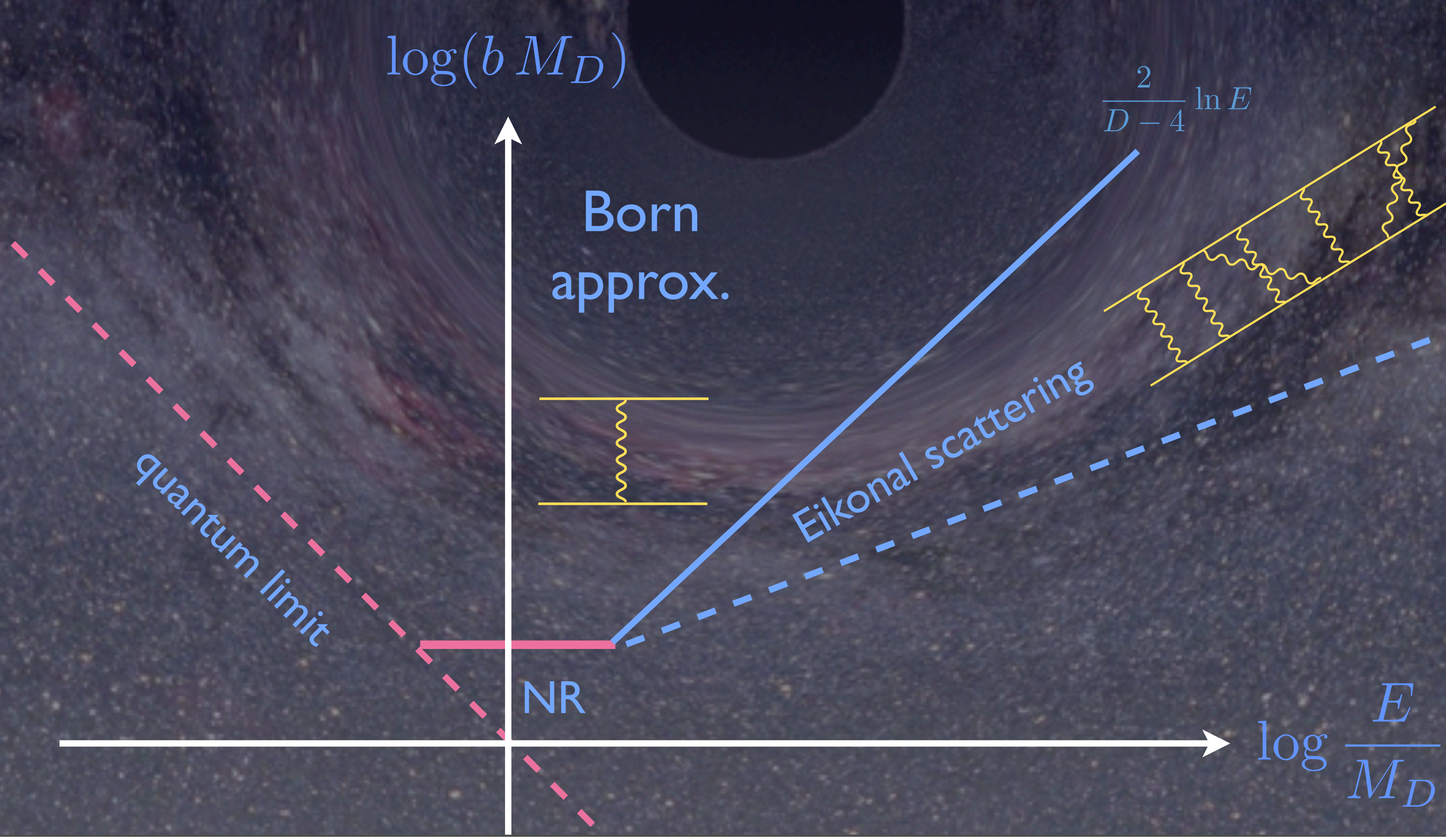

Counterargument

SBG, hep-th/0604072

SBG, Gross, Maharana, 0705.1816

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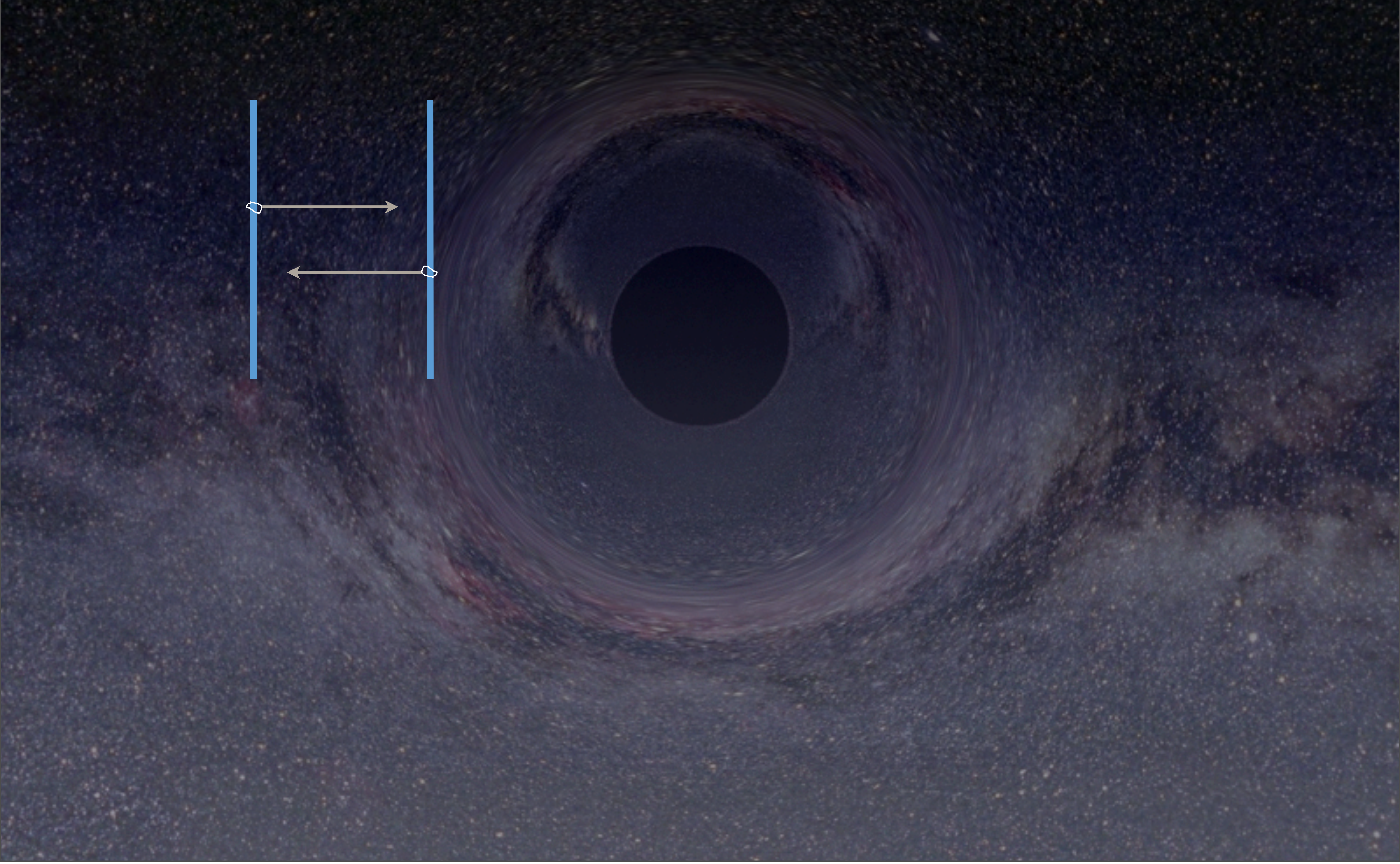

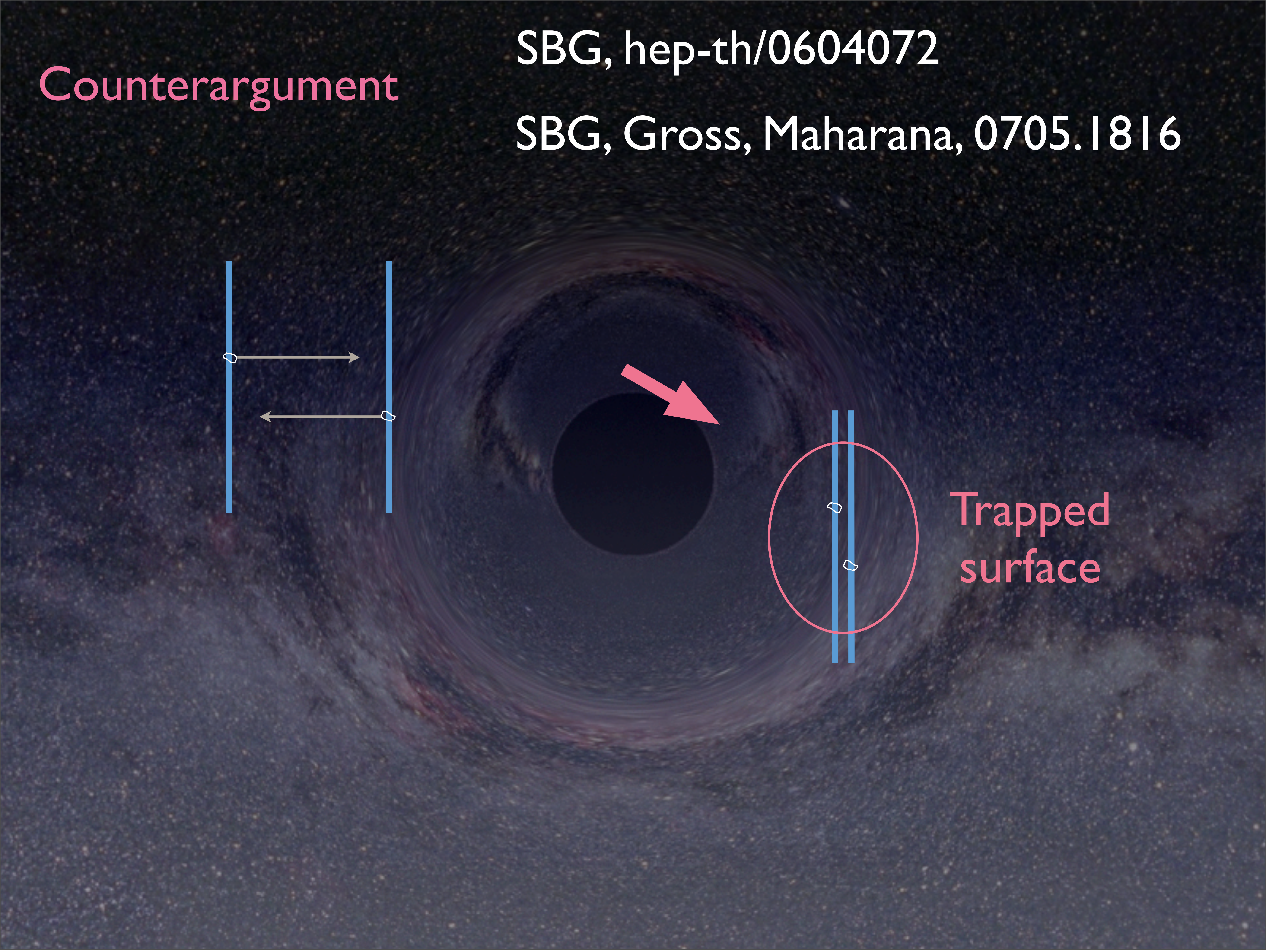
Counterargument
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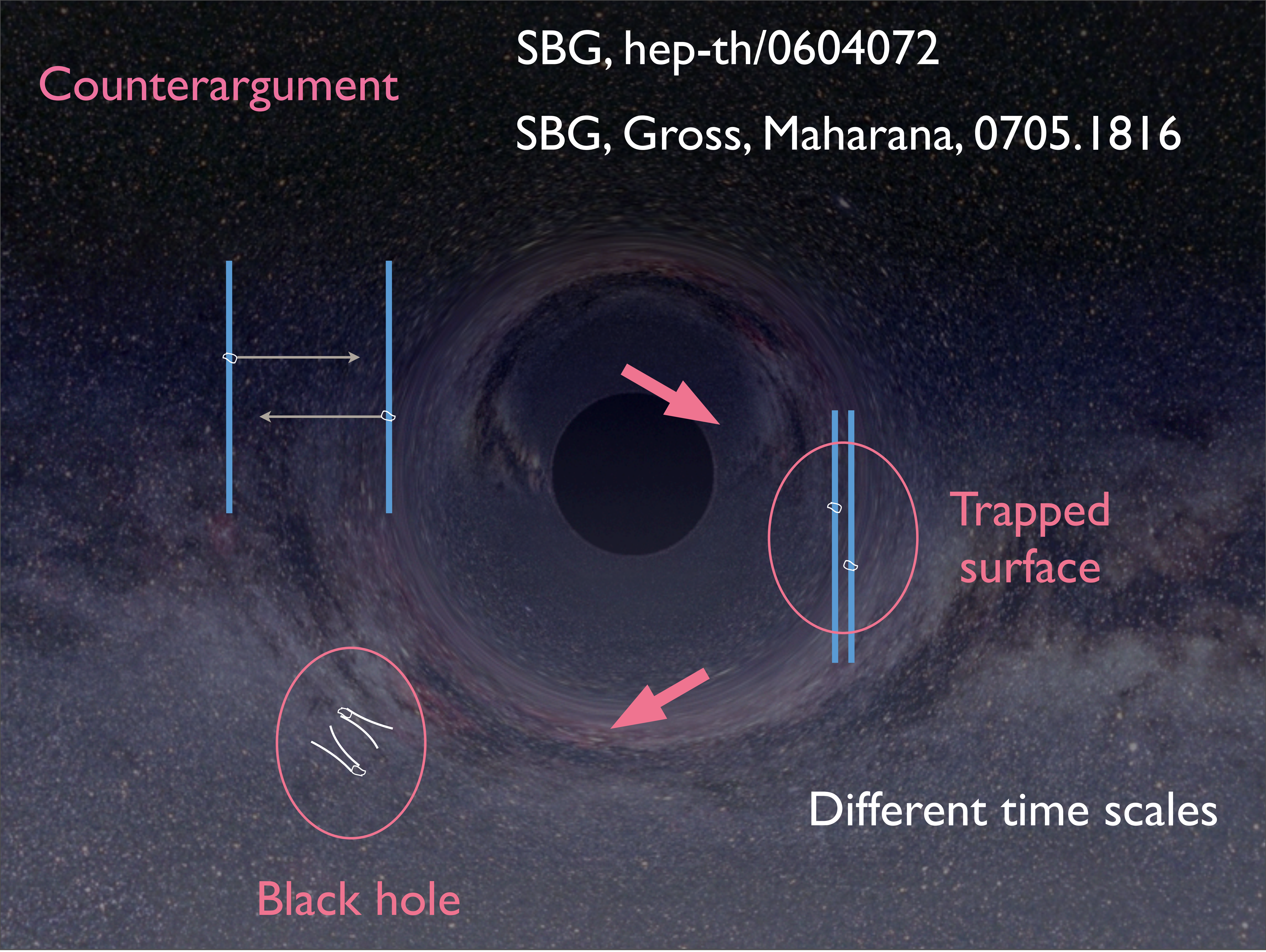
SBG, Gross, Maharana, 0705.1816
Trapped
surface

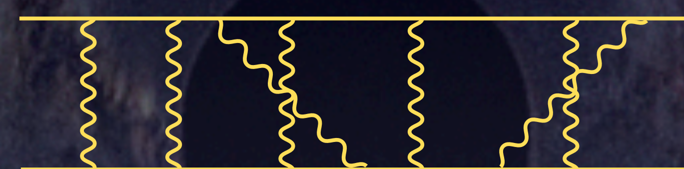

Counterargument
SBG, hep-th/0604072
SBG, Gross, Maharana, 0705.1816
Trapped
surface
Different time scales
Black hole

2) Perturbative S-matrix

Expect same divergences we find in perturbative GR for $b \sim R_S(E)$ (nonperturbative)

(This seemingly has little to do with non-renormalizability/ short distance physics -- the traditional concerns!)

(Momentum fractionation -- strings don't matter?)



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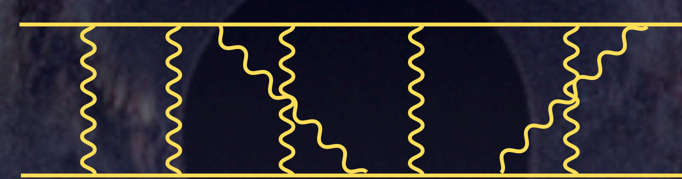


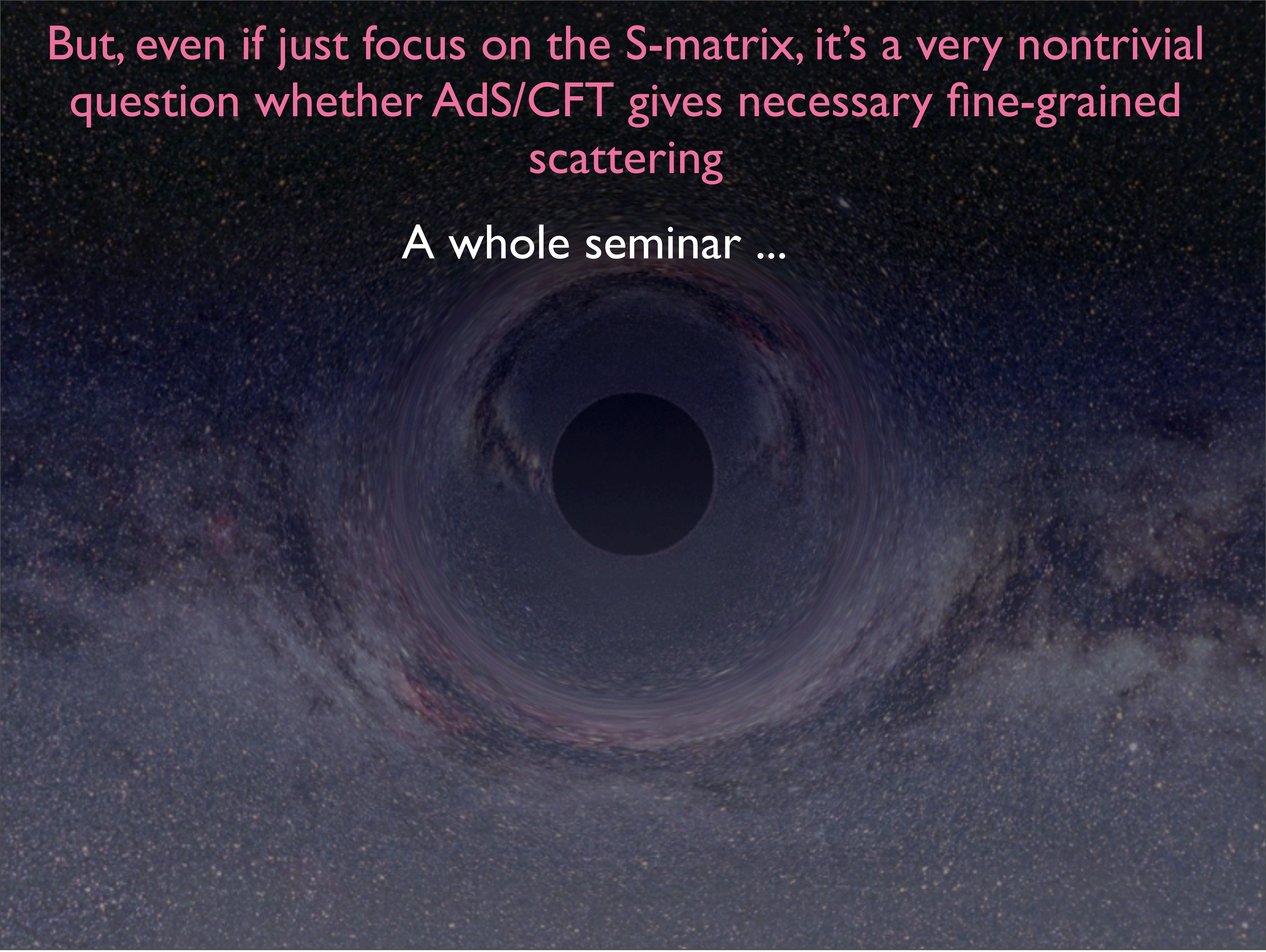
3) Nonperturbative dualities -- AdS/CFT

Observation: the "paradox" results from tension between local and S-matrix picture

not fully addressed -- need local bulk observables

But, even if just focus on the S-matrix, it's a very nontrivial question whether AdS/CFT gives necessary fine-grained scattering

A whole seminar ...



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A whole seminar ...

Basic question: can boundary theory describe correct asymptotic scattering states, and amplitudes?

Older work: Susskind Polchinski SBG

More recent: understanding of necessary conditions:

(CFT singularities)

M. Gary, SBG, Penedones, arXiv:0903.4437;

Heemskerk, Penedones, Polchinski, Sully, arXiv:0907.0151

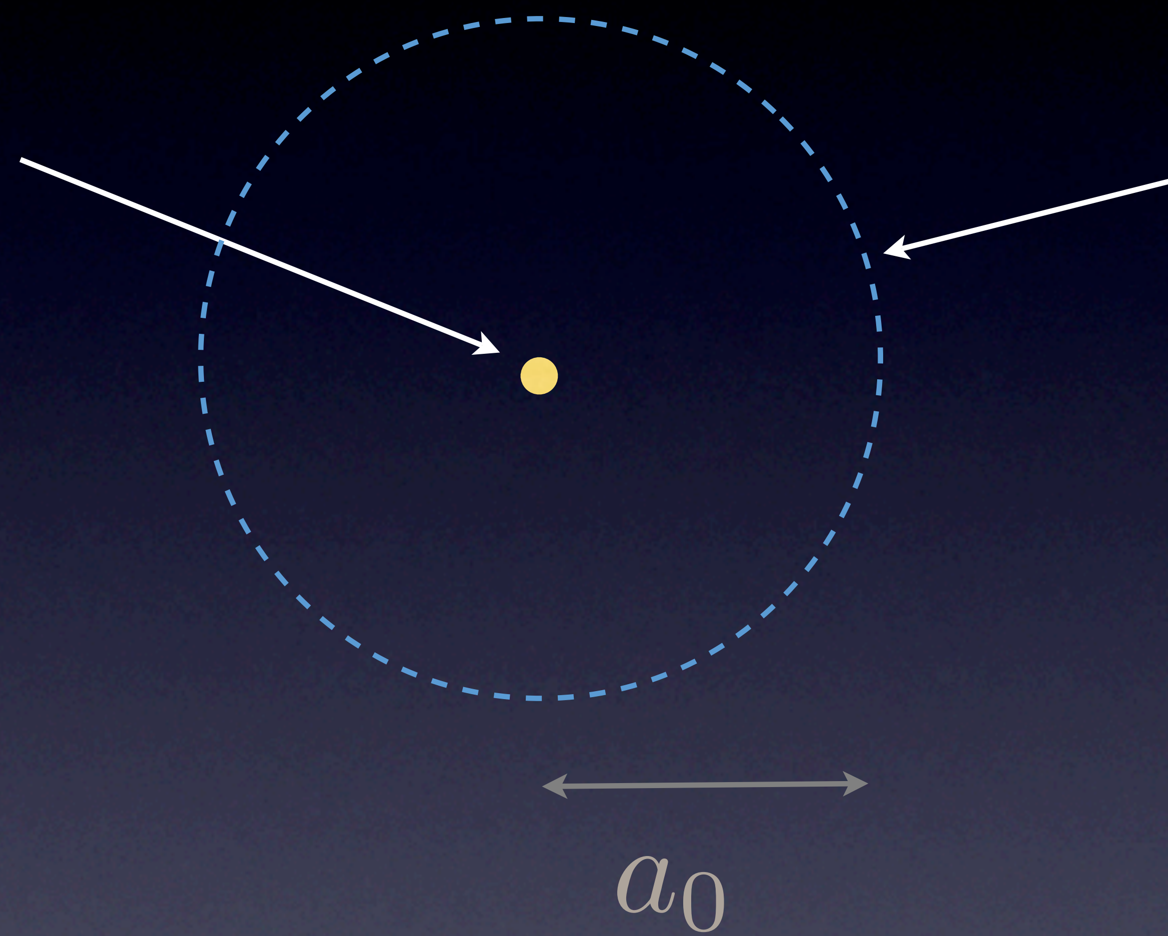
And apparent obstacles:

M. Gary & SBG 0904.3544

JURY STILL OUT!

A reminder - we have faced a seemingly similar crises:

Classical atom



New physics was needed:

Uncertainty principle

Wave mechanics...

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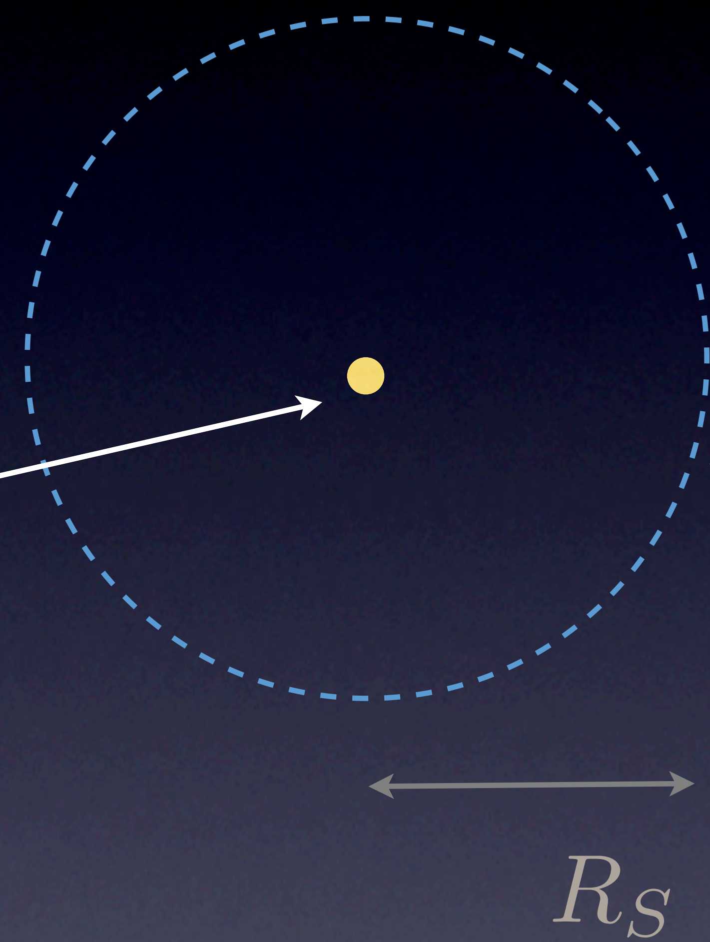
Black hole

LQFT fails here



QG takes over here? (more subtle breakdown LQFT)

New physics ~~was~~ needed:

is

~~Uncertainty principle~~

~~Wave mechanics...~~

???

“Classical instability paradox”

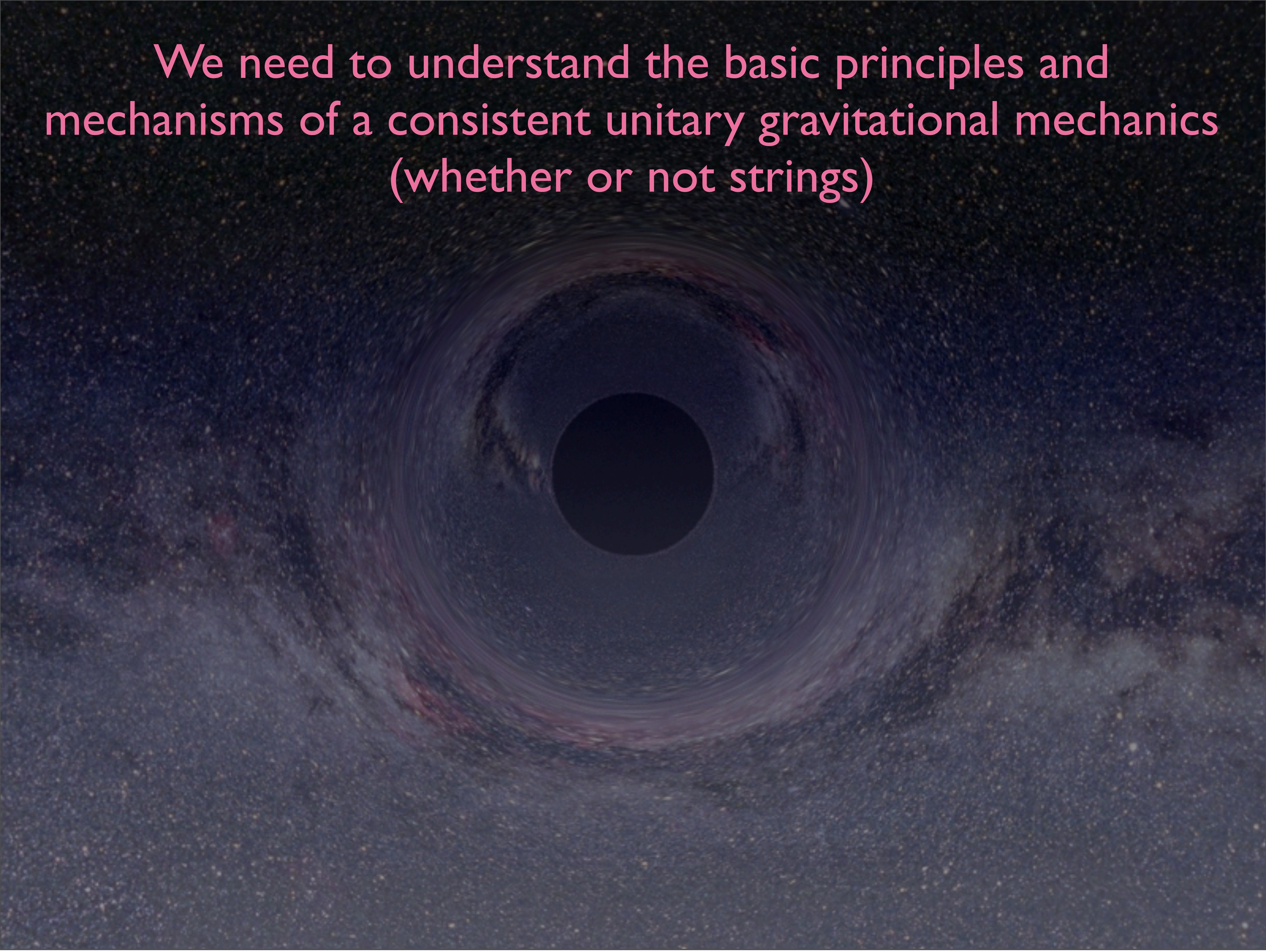
“Black hole information paradox”

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)

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



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Some possible approaches

- understand the "correspondence boundary" (~QM)

- 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?

- investigate cosmological dynamics -- 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: $p < M_p$

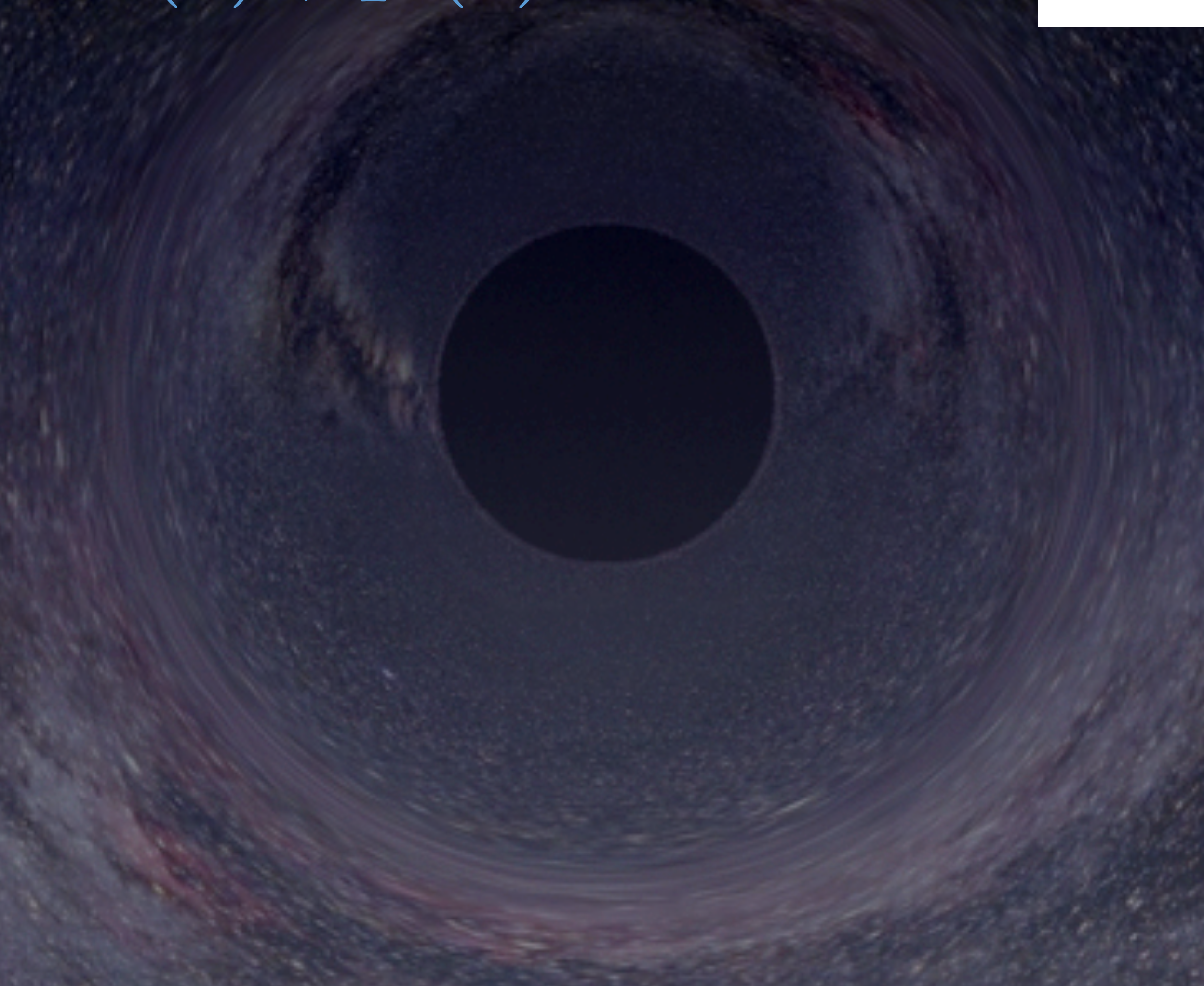
$\Big\}$ 1 particle

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)

("shortest distance" not compatible with Lorentz invariance)

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$\boxed{\text{“locality bound”}}$

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

(generalizations: N-particle; dS)

Investigating locality

- Cornerstone of local quantum field theory

$$\boxed{[\mathcal{O}(x), \mathcal{O}(y)] = 0}$$ x,y spacelike

- Necessary for consistency

If violate, "grandmother paradox"

- Can't clearly formulate in quantum gravity!

No local gauge-invariant observables $\delta\phi(x) = \xi^\mu \partial_\mu \phi(x)$

(And BH info suggests modified macroscopically)

How can it not be a fundamental property of the theory, yet emerges in an approximate sense?

This is a very interesting and challenging problem!

A basic idea how ~local observables could emerge (w/ limitations) in quantum gravity: relational (Leibniz, Einstein, ...)

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

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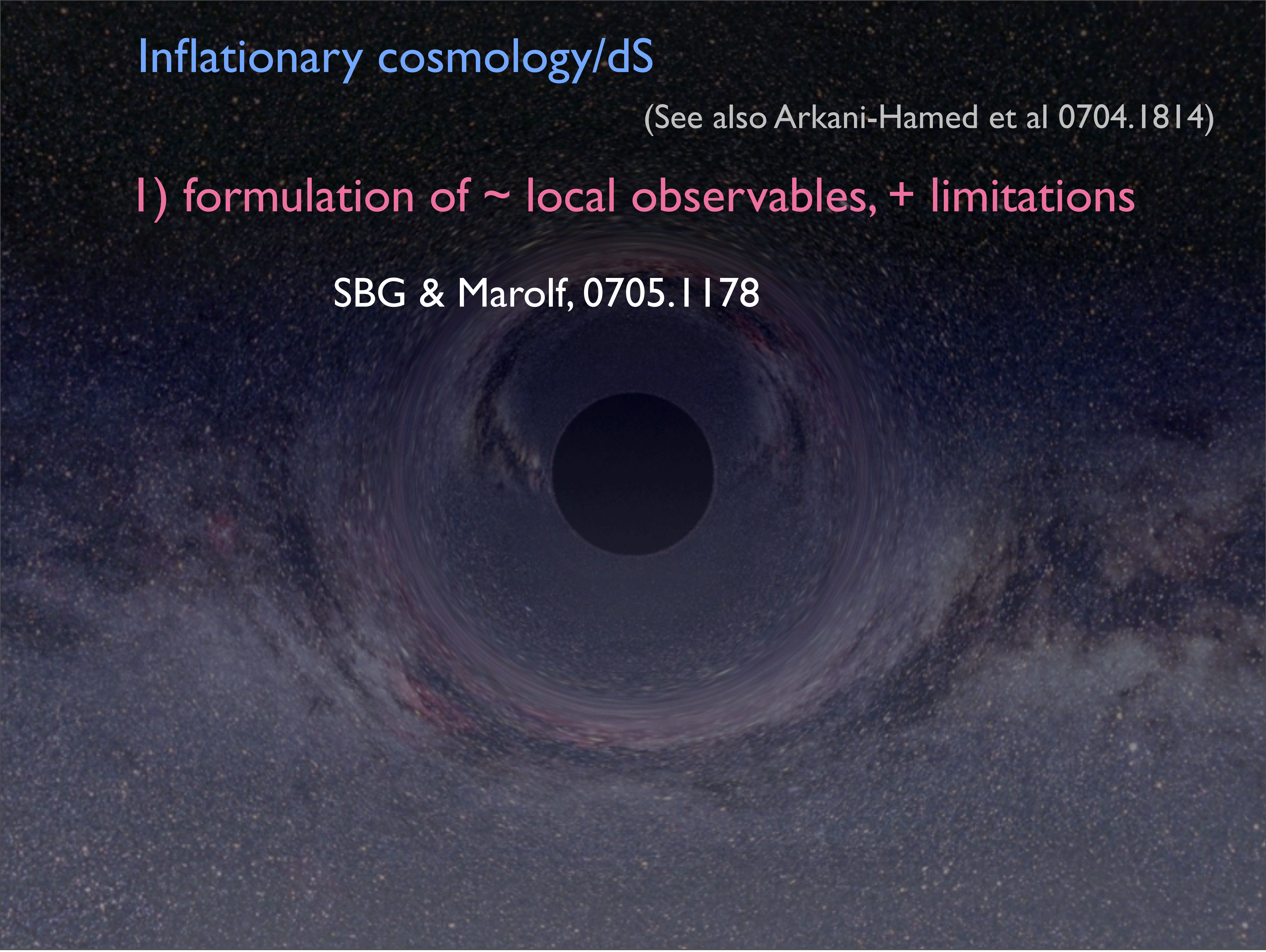
~ Semiclassical version used in current inflation studies!


Inflationary cosmology/dS
(See also Arkani-Hamed et al 0704.1814)
1) formulation of ~ local observables, + limitations
SBG & Marolf, 0705.1178

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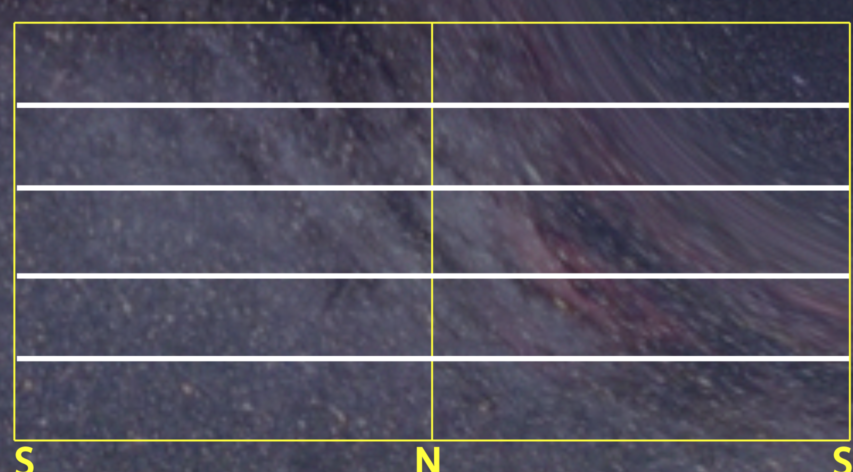
SBG & Marolf, 0705.1178

2) large fluctuations at long times (IR issues)

hep-th/0703116

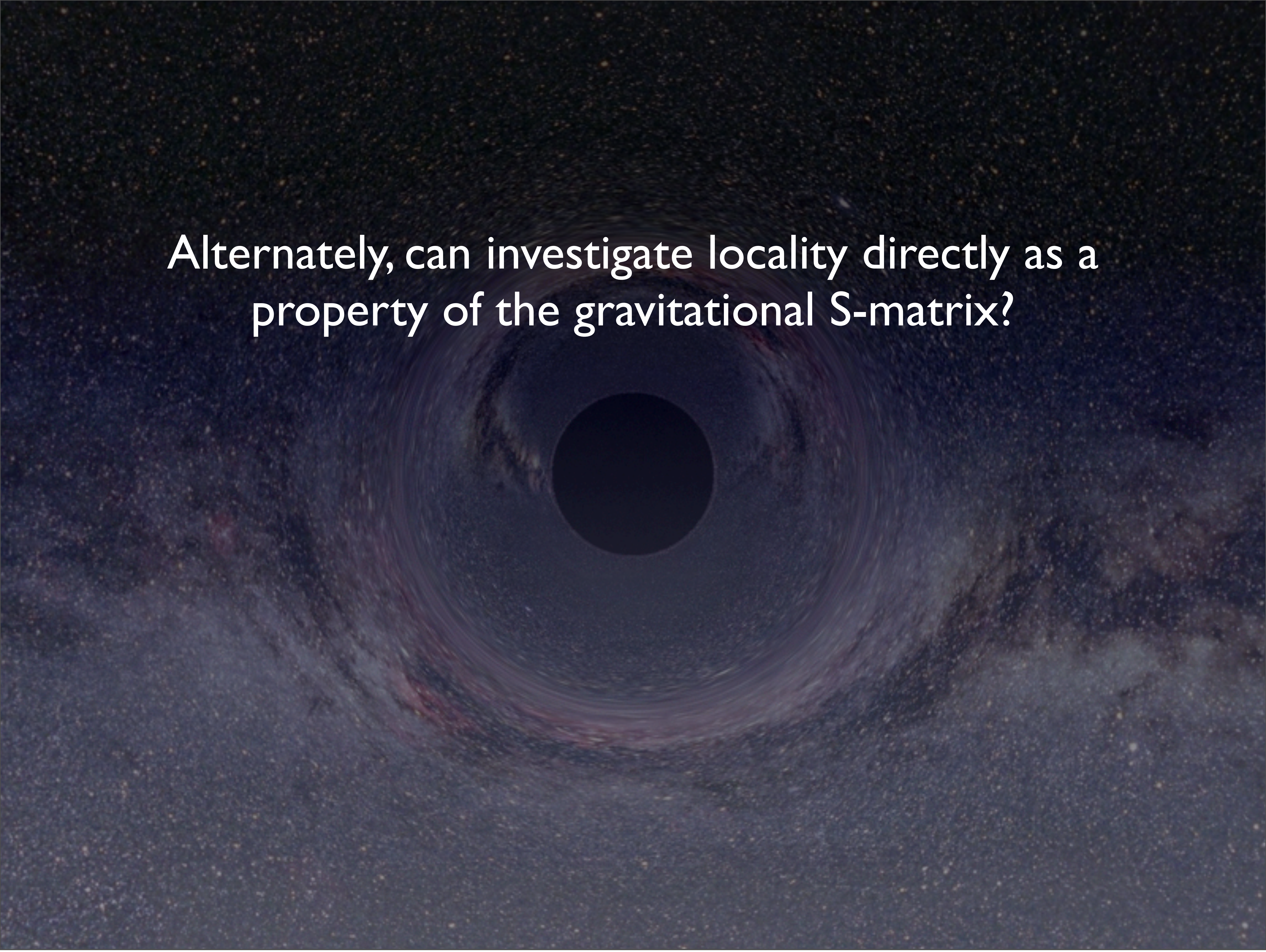
SBG & Sloth, 1005.1056

+ many refs on IR questions



~ nice slice evolution

toy model for BHs!



Alternately, can investigate locality directly as a property of the gravitational S-matrix?

This, and more generally the desire for a sharp approach to the theory, motivates study of:

General properties of the gravitational S-matrix

"Mantra:" unitarity, analyticity, crossing

+ basic properties of gravity

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locality/causality?

... some comments; for more see

SBG & Porto, 0908.0004

(SBG & Srednicki 0711.5012)

- Unitarity: assumed.

- Analyticity/crossing: more subtle/interesting in gravity

- Locality/causality encoded in high-energy behavior of S-matrix

e.g. is it polynomially bounded at high energy? $< E^p$

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- Locality/causality encoded in high-energy behavior of S-matrix

e.g. is it polynomially bounded at high energy? $< E^p$

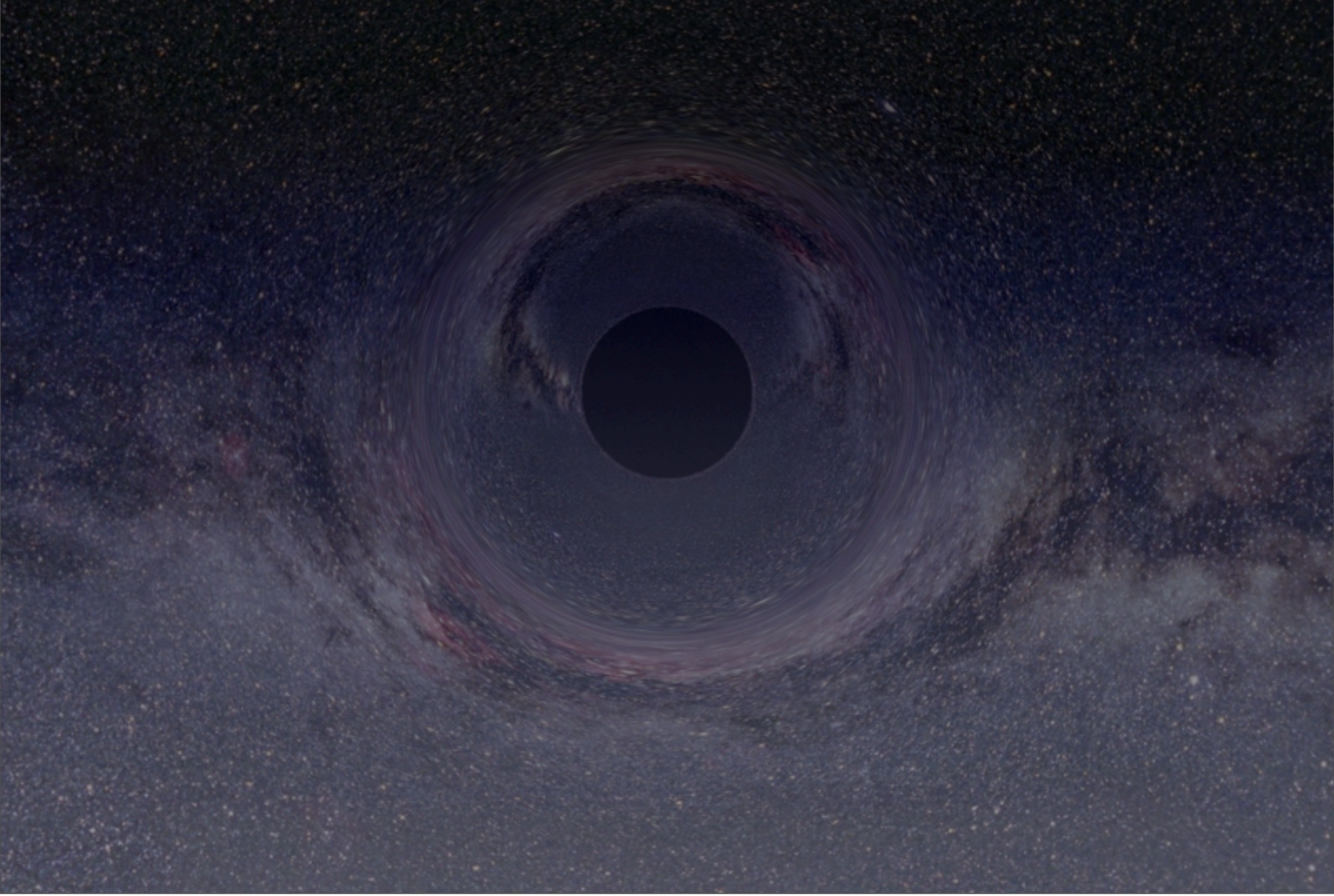
- Initial indications

sufficiently polynomially bounded
to be causal (consistent)

nonpolynomial behavior associated with long-range/nonlocal nature of gravity
(black holes; eikonal scattering)

Ongoing, intriguing investigation ...

Messages from our discussion of these fundamental issues:



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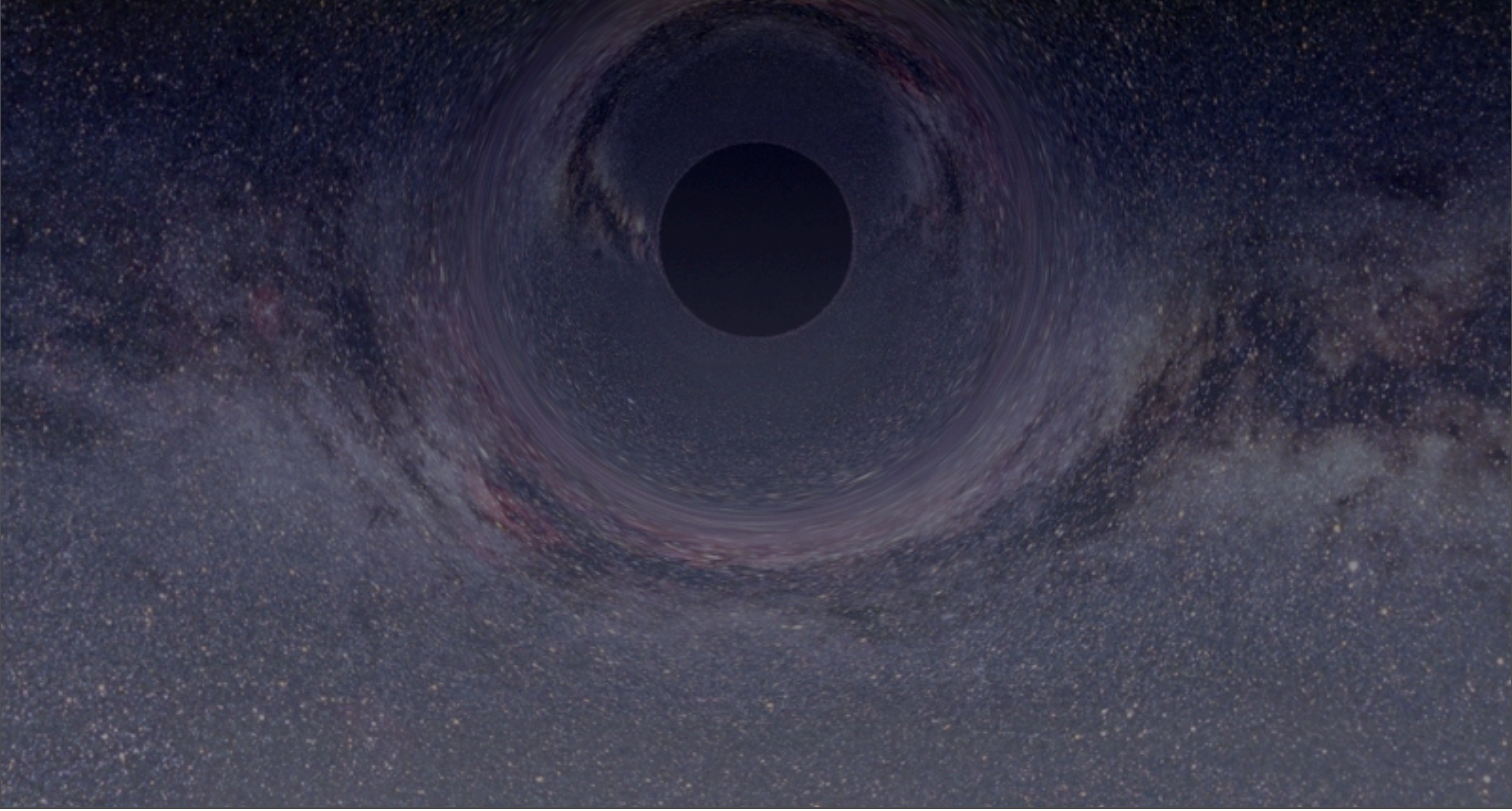

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(critical tension)

- Causality, consistency -- important guides

... strong constraints

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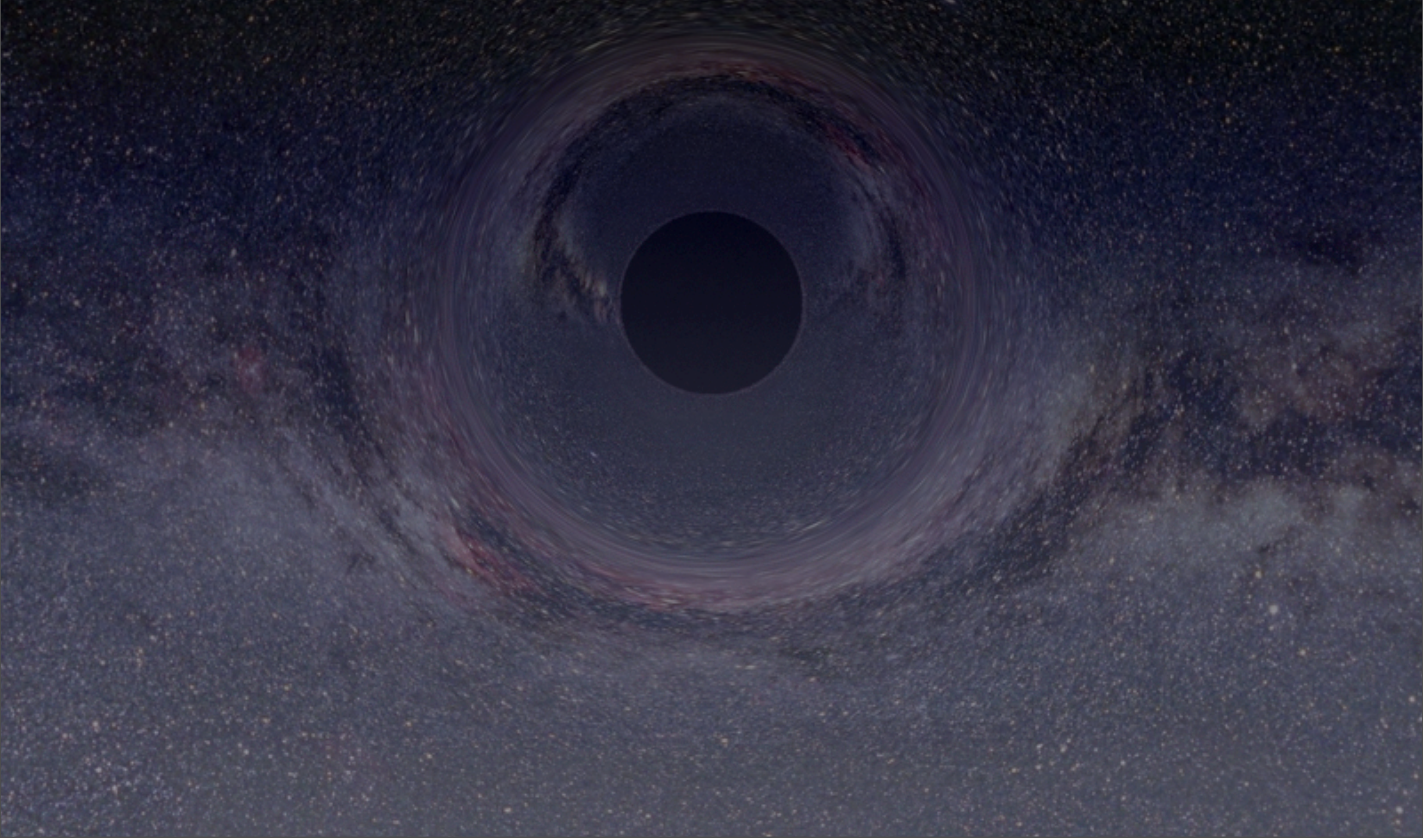
Is it string theory? ... or a more general "non- (but nearly-) local mechanics"?

Conclusion: black holes are not mathematical curiosities; they are centrally important in some of the most critical and profound questions of our age.



Conclusion: black holes are not mathematical curiosities; they are centrally important in some of the most critical and profound questions of our age.

Central role in stellar evolution:

A generic endpoint

Important role in galactic evolution

Generic central object; correlations w/ galaxy properties

Tight connections with problems of cosmology

inflation, initial conditions, observables, etc.

Ultimate endpoint of high-energy/short distance physics

We hope at LHC!

Indicate probable overthrow of local quantum field theory

new physical paradigms

Let us hope the LHC brings important clues!