Challenges of ultraplanckian scattering

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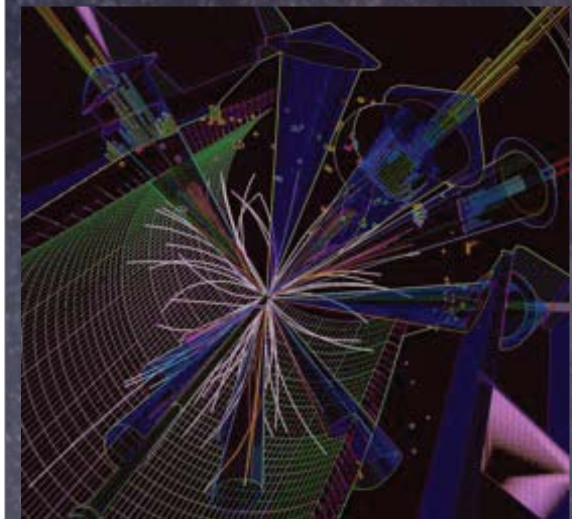
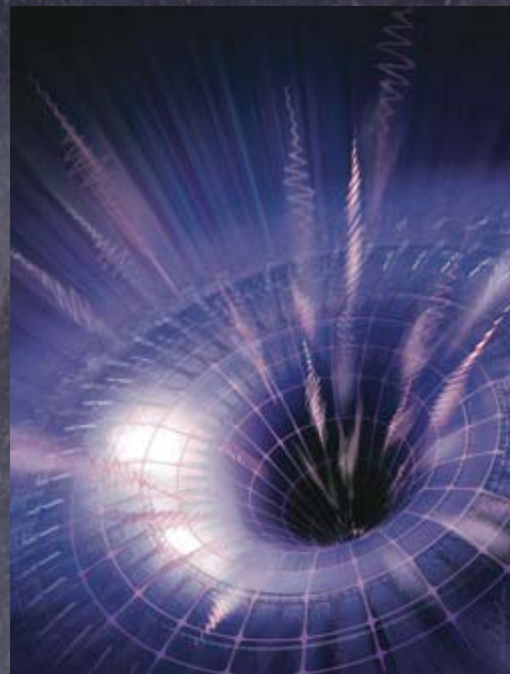


Numerical relativity and high energy physics

Sept. 1, 2011



Collision energy >> Planck mass

Why?

- Drives at likely central issue in QG:

  unitarity crisis/information "paradox"

  resolution likely requires profound conceptual advance

- Possible phenomenology: TeV-scale gravity

- Intriguing interplay: classical and quantum physics

Outline

1. Overview, phase diagram, questions

2. TeV-scale gravity and bounds

3. Ultraplanckian scattering phenomenology

4. Black holes and the foundations of physics: unitarity crisis and proposed resolution

5. Problems for the future

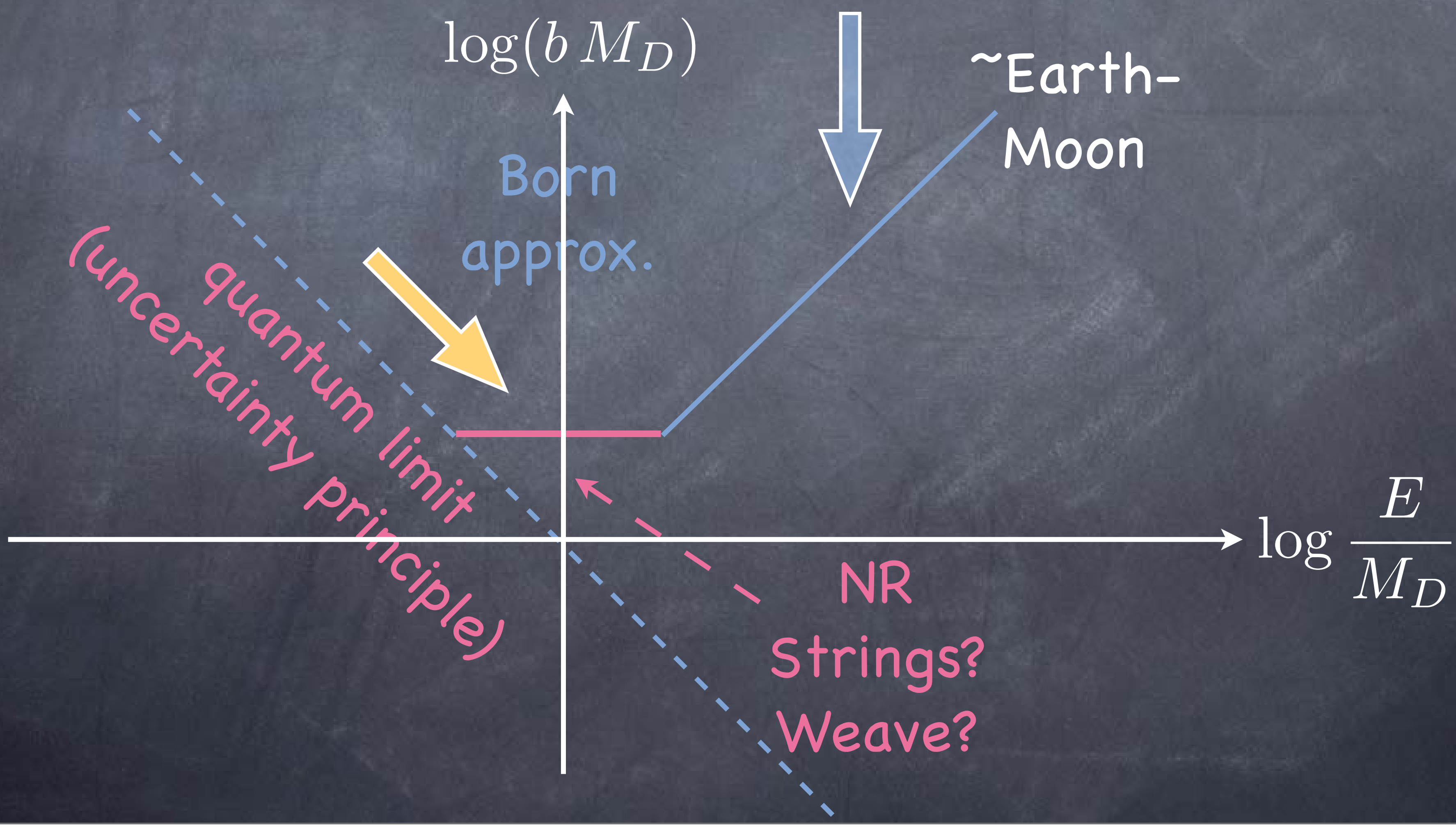
1. Overview, phase diagram, questions

Organize thinking via a phase diagram - energy vs. impact parameter:

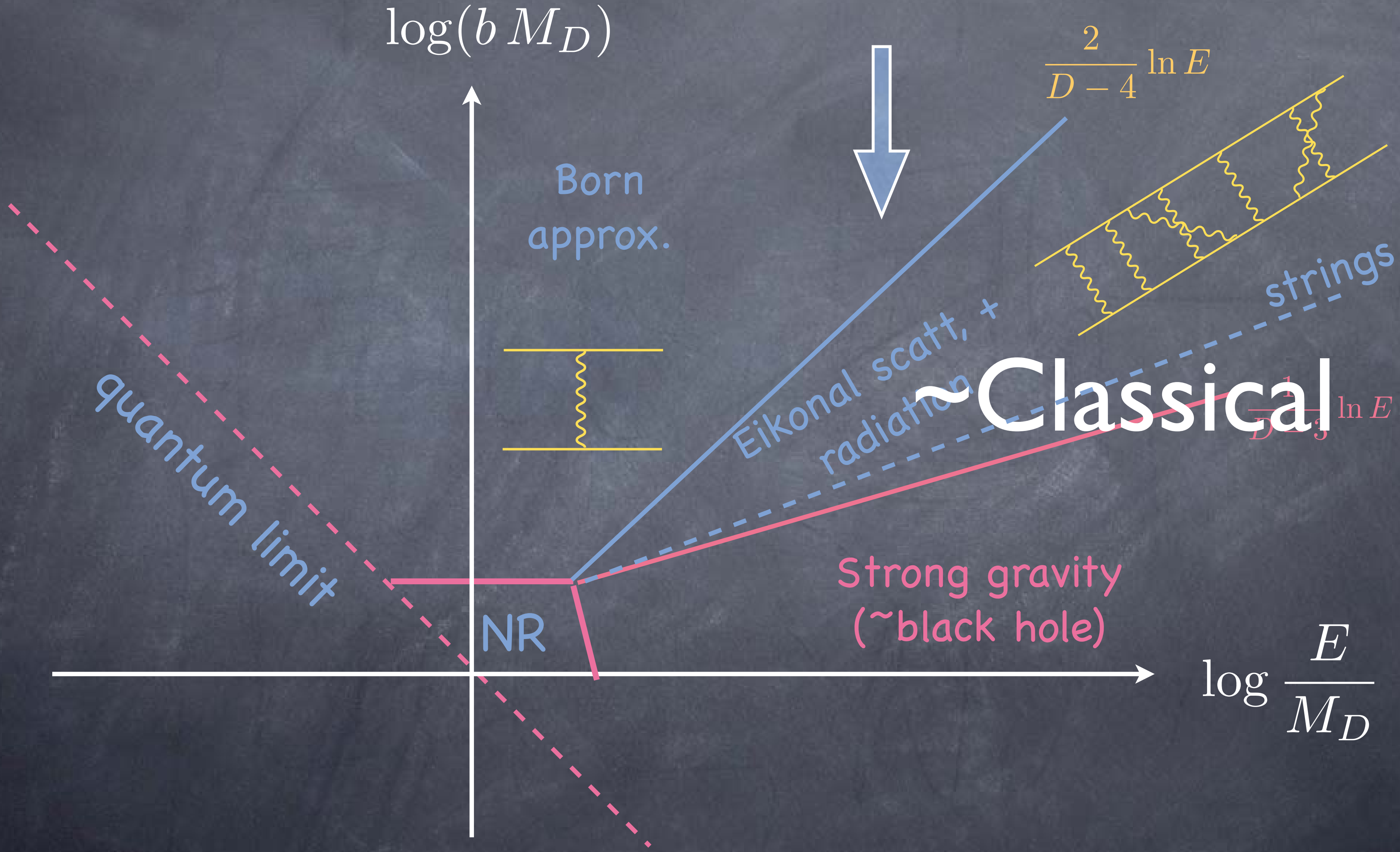
Near Planck regime: nonrenormalizability, etc.=trouble -

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

Scattering regimes: E; b = impact parameter (~dist. probed)



"Phase" diagram: Scattering regimes



~ Reason:

q = momentum transfer >> M_D

but momentum transfer/graviton $\sim 1/b << M_D$

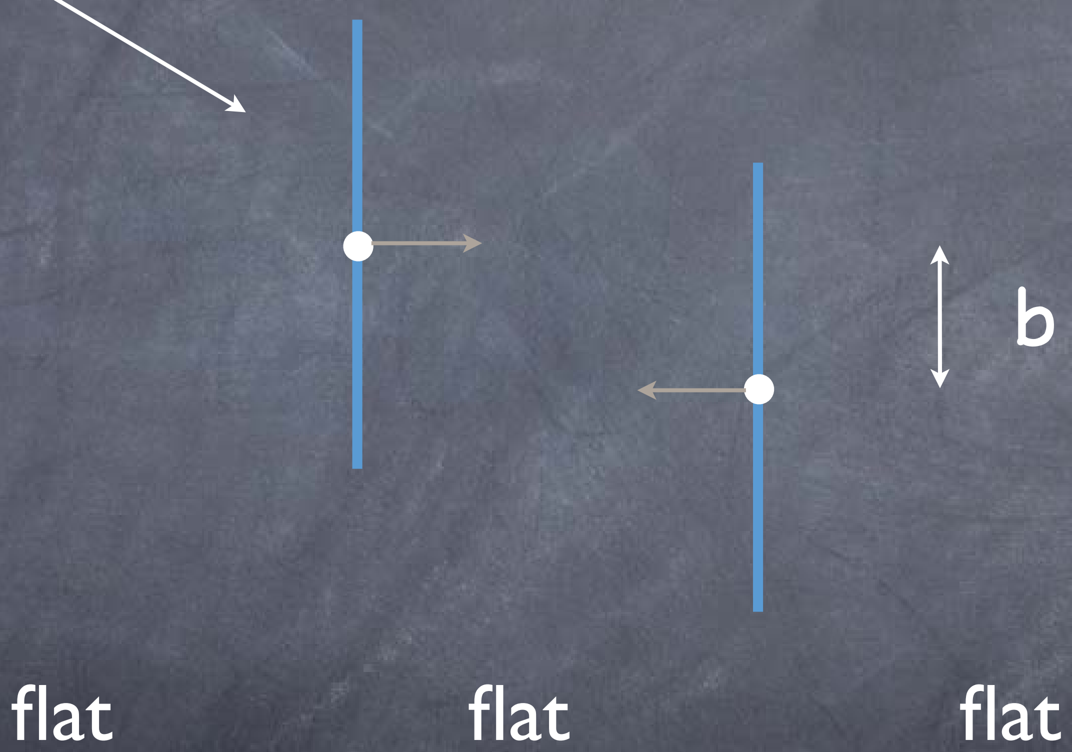
Many gravitons

~ classical field

Classical description

$M_D/E \ll 1$

"Aichelburg-Sexl" shocks
(highly boosted Schwarzschild)

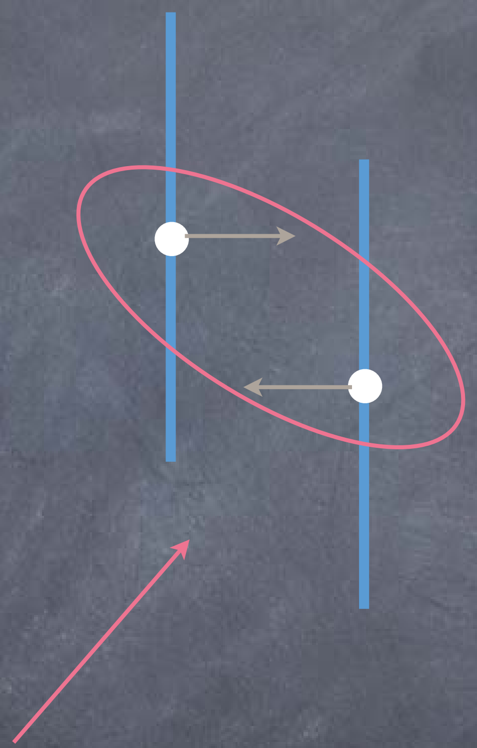


(or w/ some smoothing -- how important??)

BH formation theorem:

SBG & Eardley 2002 (b>0 and D>4)

(extending Penrose, b=0, D=4)



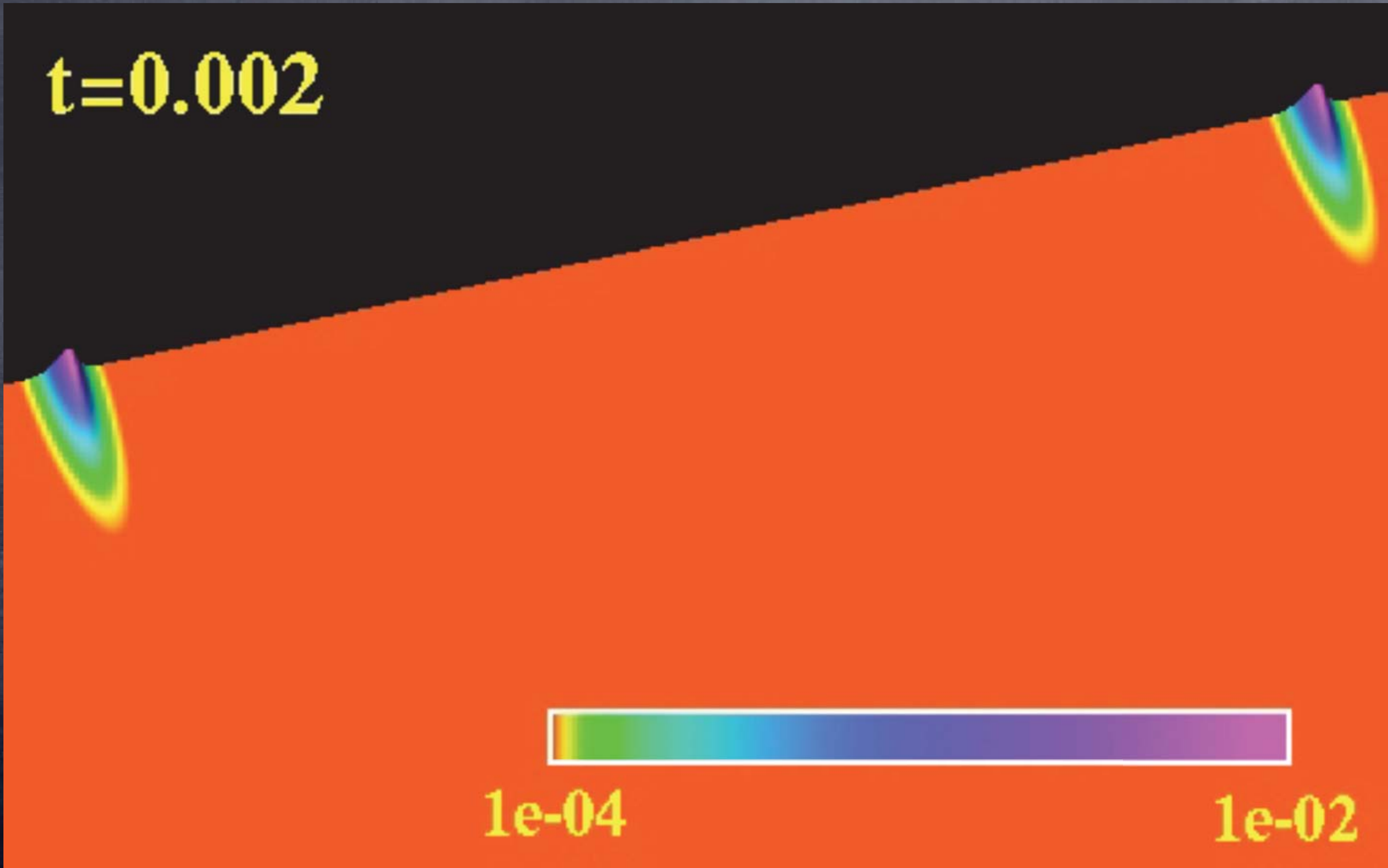
Trapped surface (therefore black hole);

forms "before" collision $b < kR(E)$

(Yoshino/Nambu: numerical soln of construction D>4)

Beautiful confirmation in D=4 via numerical relativity:

arXiv:0908.1780



(collision of "boson stars:" courtesy F. Pretorius) $\gamma = 4$

What else do we want to know?

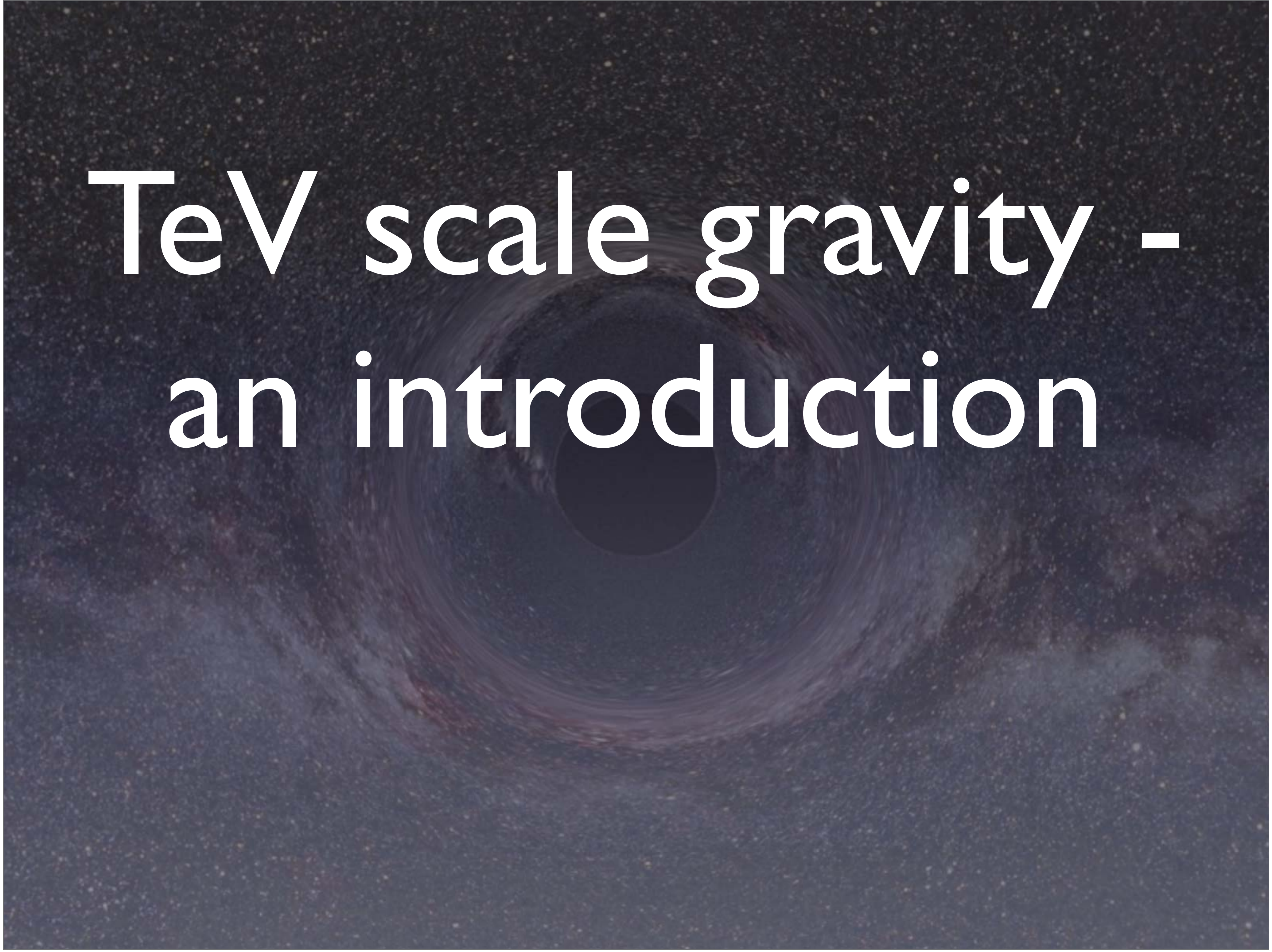
Details, D>4, b>0

Mass, cross section...

Radiation, BH or no ...

Other phenomena/exotica?

One motivation: possible phenomenology...


TeV scale gravity -
an introduction

Why TeV scale gravity?

1. Profound intellectual interest

The problems of reconciling gravity and QM (particularly the BH information paradox and related questions) seem to suggest the beginning of a revolution as profound as that from CM to QM

2. New approach to growing puzzles

Why the hierarchies?

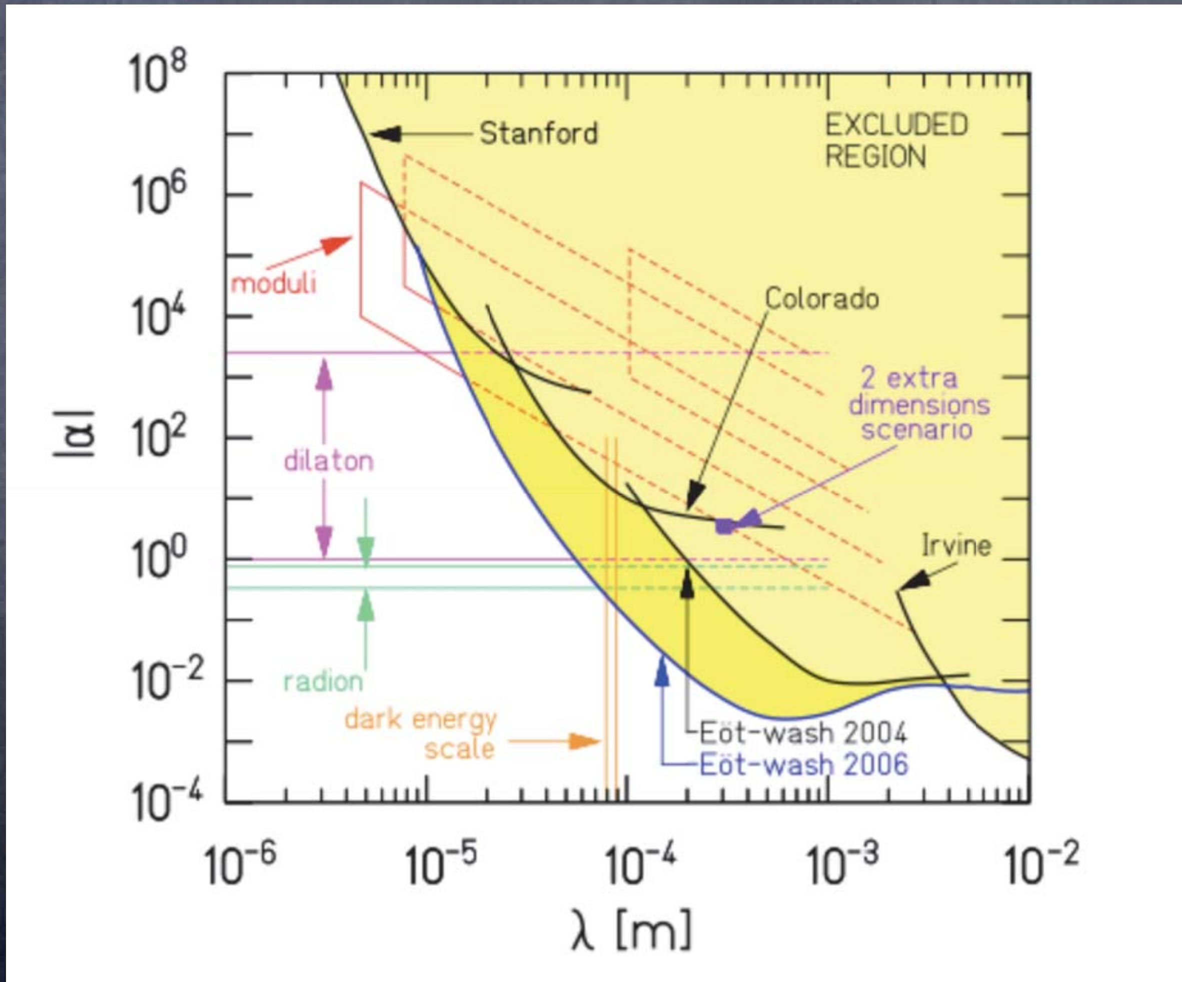
$$\frac{M_W}{M_4} \sim 10^{-16}$$

$$\frac{\Lambda^{1/4}}{M_W} \sim 10^{-15}$$

Unnatural -- spoiled by generic quantum corrections

3. It is possible!

Gravity very poorly probed below .1 mm



4. There are theoretical mechanisms to produce TeV-scale gravity

Large and/or warped extra dimensions

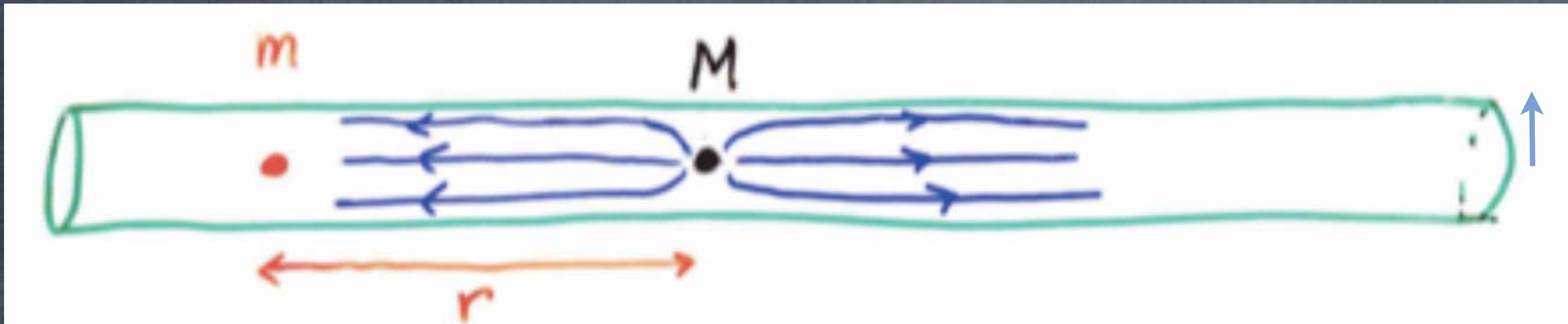
+ brane worlds

These naturally arise in the most popular candidate for a unified quantum theory of matter/forces

(string theory)

And perhaps are more generic?

Basic mechanism: D spacetime dims



Force match at R: $$F \sim \frac{G_D M m}{R^{D-2}} \sim \frac{G_4 M m}{R^2}$$

$$\Rightarrow G_4 \sim G_D / R^{D-4}$$

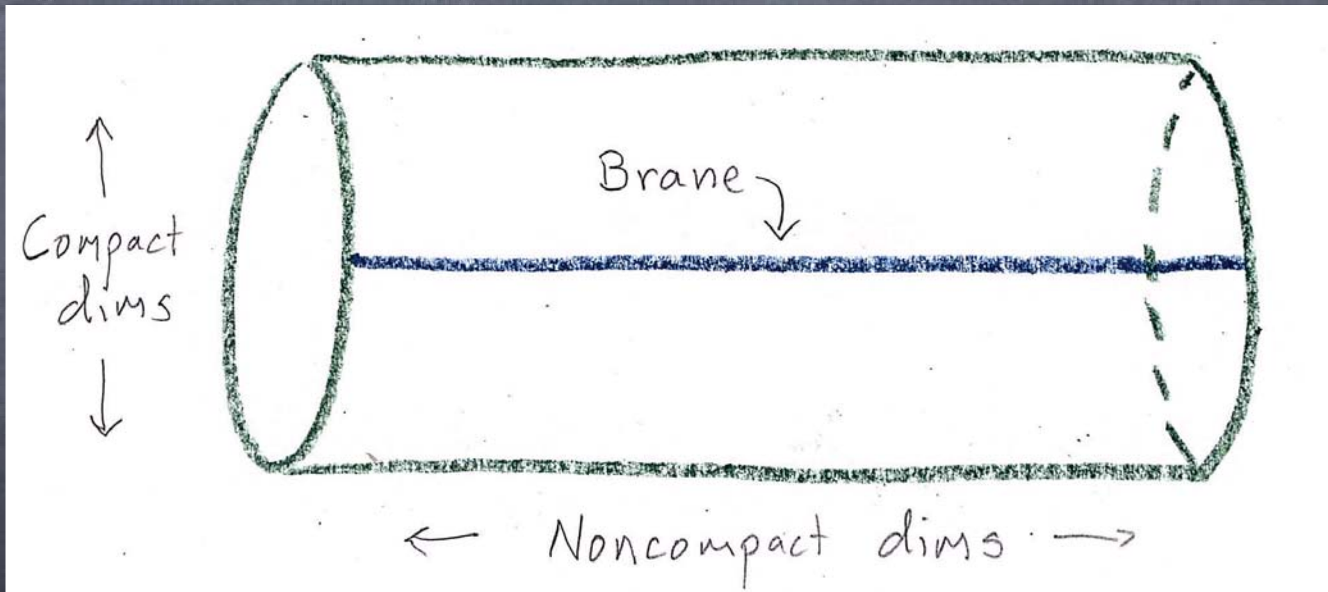
$$G_D \sim \frac{1}{M_D^{D-2}}$$

$$\left(\frac{M_4}{M_D}\right)^2 = \left(\frac{M_D}{2\pi}\right)^{D-4} V_{D-4}$$

Gauge fields 4-dimensional down to

$$\sim 10^{-16} cm \sim (100\, GeV)^{-1}$$

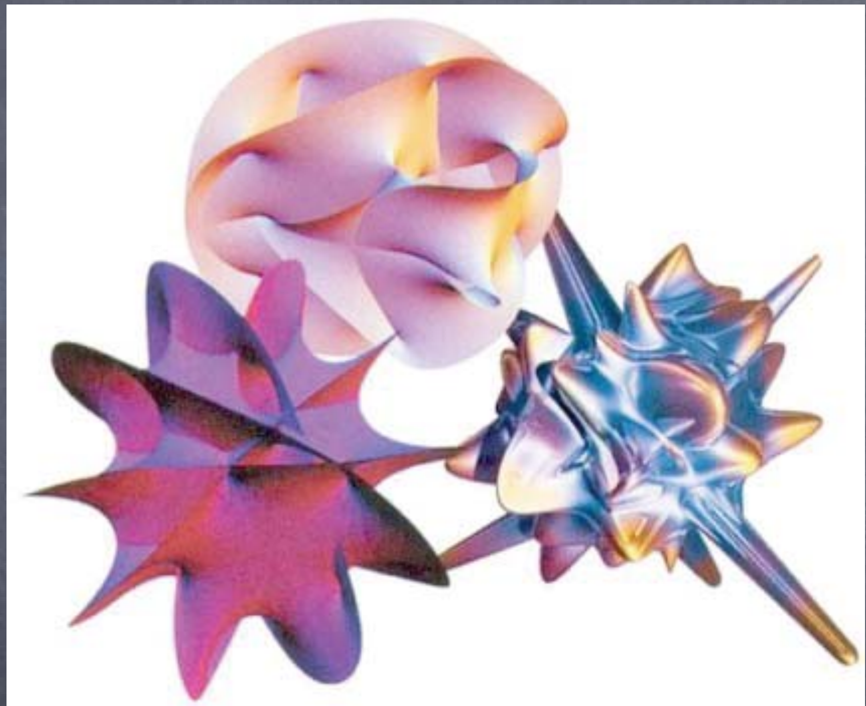
Gauge fields, fermions confined to 3+1 - dimensional "brane"



(ADD - Arkani-Hamed, Dimopoulos, Dvali; + Antoniadis)

Ingredients from string theory

- Extra dimensions, non-trivial geometry



e.g. Calabi-Yau...

- Branes with confined fermions/gauge fields

Generic configuration in string theory has branes and warping

D-dims

$$ds^2 = e^{2A(y)}\, dx_4^2 + g_{mn} dy^m dy^n$$

"Warp factor" (local redshift)

$\longrightarrow$

$$\left(\frac{M_4}{M_D}\right)^2 = \left(\frac{M_D}{2\pi}\right)^{D-4} V_W$$

with

$$V_W = \int d^{D-4}y \sqrt{g(y)}\, e^{2A}$$

$$S \sim M_D^{D-2} \int d^D X \sqrt{-g}\mathcal{R} \sim M_4^2 \int d^4x \sqrt{-g_4}\mathcal{R}_4$$

$$\left(\frac{M_4}{M_D}\right)^2 = \left(\frac{M_D}{2\pi}\right)^{D-4} V_W \qquad V_W = \int d^{D-4}y\sqrt{g(y)}e^{2A}$$

$M_4 \sim 10^{19} GeV$

$M_D \sim TeV$ for $V_W \gg M_D^{4-D}$

Hierarchy from large warped volume ...

... any combination of warping, "large radii"

c.f. toy (extreme) examples

large, flat extra dimensions (ADD)

one warped dimension (RS)

A reasonable approach for HE physics

Focus on gravitational sector

more universal, config. independent

D-dimensional gravity at $E \sim M_D \sim TeV$

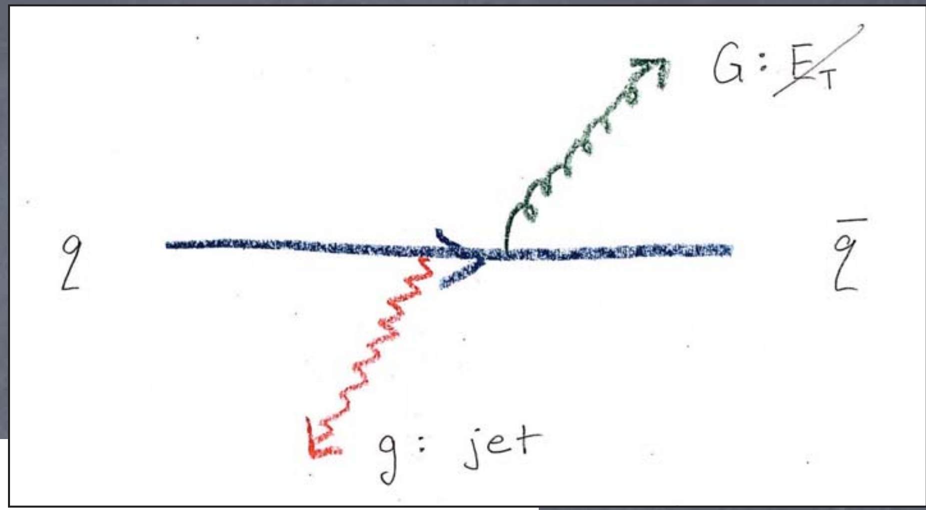
universal coupling : M_D ; universal phenomena

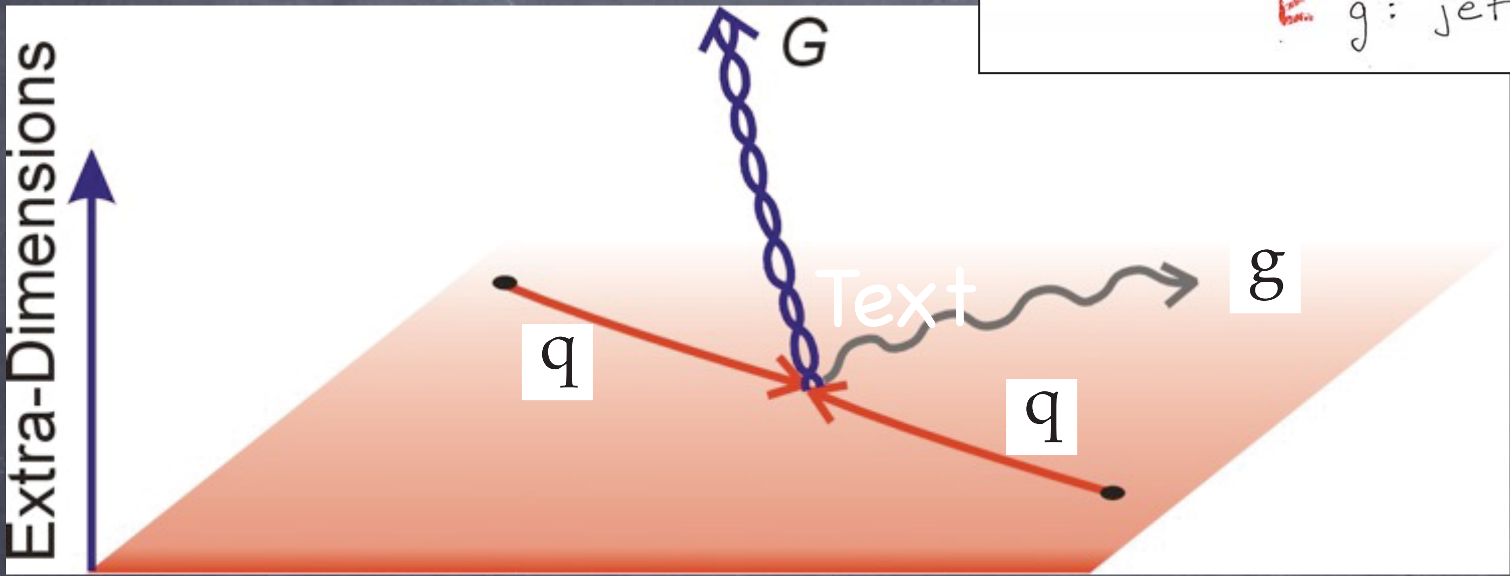
- missing energy in gravitons
- graviton exchange; "contact"

} Current bounds on M_D

- graviton scattering + radiation
- black holes

Missing energy





(For $E > M_{KK} \sim min\{1/R_i\}$)

$$\sigma \sim \frac{1}{M_D^2}\left(\frac{E}{M_D}\right)^{D-4}$$

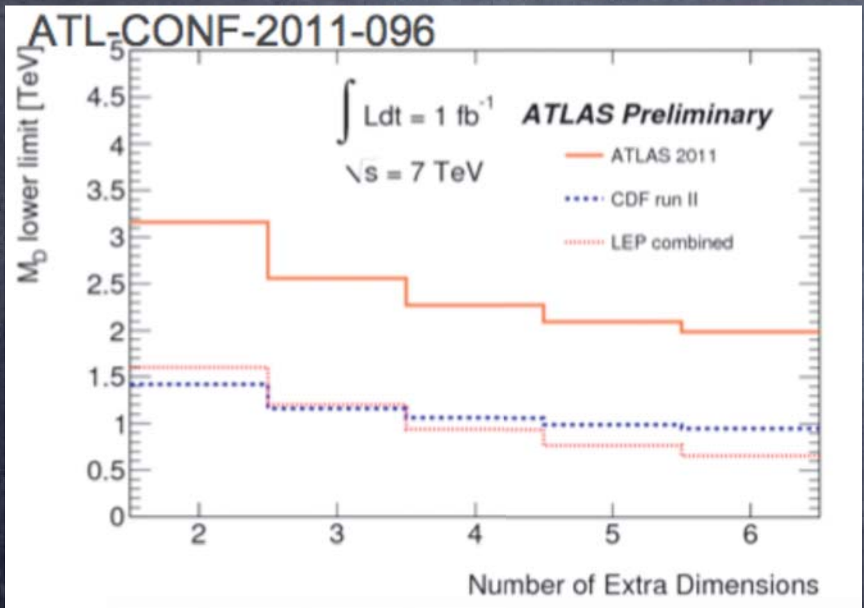
$$p\,p \longrightarrow Z + \not{E}$$

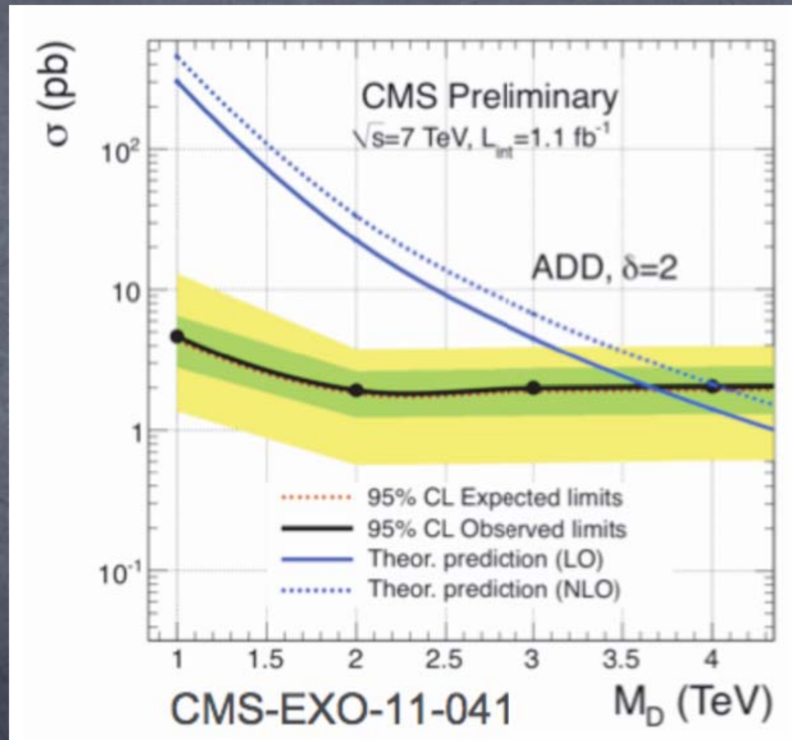
$$p\,p \longrightarrow \text{jet} + \not{E}$$

...

Bounds reported at Lepton/Photon

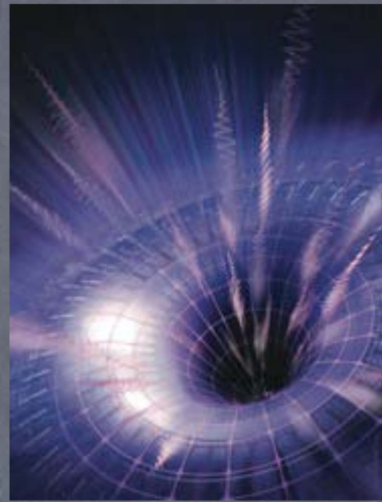
$$M_D \gtrsim 2-3\ TeV$$





(More from Landsberg?)

TeV scale gravity:



1. Is intellectually rich
2. Is apparently possible...
3. ... but increasingly highly constrained
4. Many versions; ~ universal features (and many nonuniversal ones)

   graviton missing energy, black holes ...

5. Would be one the most exciting possible results from LHC!

Other signatures?


Ultraplanckian scattering
phenomenology

The basic idea:

Lore (hoop conjecture); now "theorem":

at collision energies
$E \gtrsim M_D$
can form black holes;

in low-scale gravity scenarios,
accessible at colliders

First noted:

Antoniadis, Arkani-Hamed, Dimopoulos, Dvali
Banks & Fischler
SBG & E. Katz ...

$M_D \sim TeV$:

LHC !?!?

from Misunderstood Universe

Los Angeles Times

Instant extinction lotto

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

The New York Times

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

HEALTH & SCIENCE

Company Sued for Potentially Ending the World

npr

msnbc

DOOMSDAY FEARS SPARK LAWSUIT

The basic phenomenological scenario:

SBG & Thomas hep-ph/0106219 ($J \neq 0$)

Dimopoulos and Landsberg hep-ph/0106295 ($J = 0$)

(and further developed by many others...)

Potentially impressive signatures!

A concise review: SBG, 2007 PASCOS, arXiv:0709.1107
(others: Webber hep-ph/0511128; Kanti, arXiv:0802.2218, Landsberg, many more)

Will overview, indicating improvements in understanding; uncertainties and needs

Focus on model independent features

Small expansion parameter: M_D/E

(Not very small at LHC)

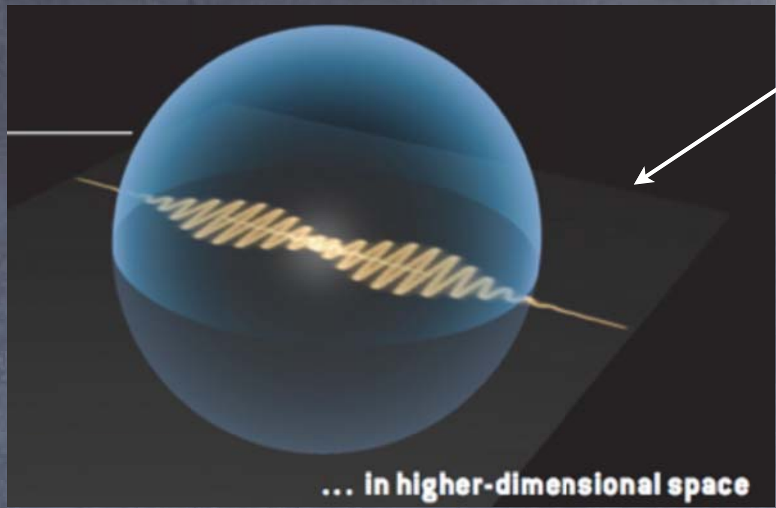
There are of course possible model dependent effects, in particular at $E \sim M_D$

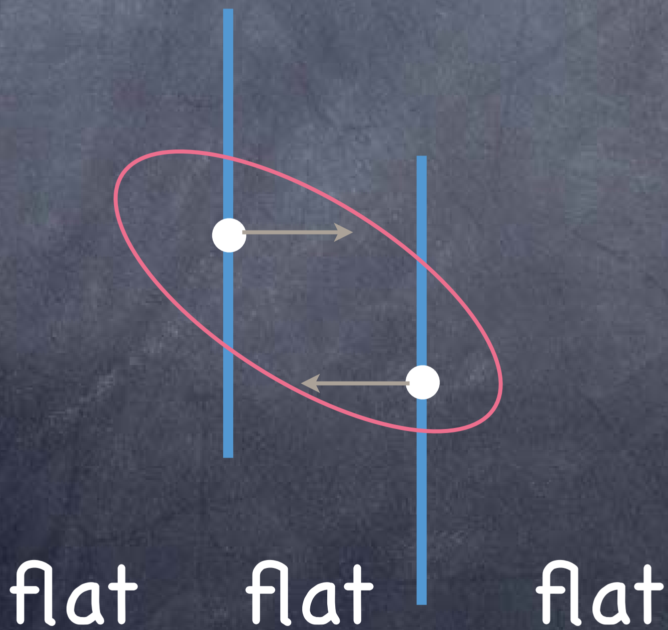
(Depend on braneworld config., quantum gravity details, ...)

Formation

trapped surface

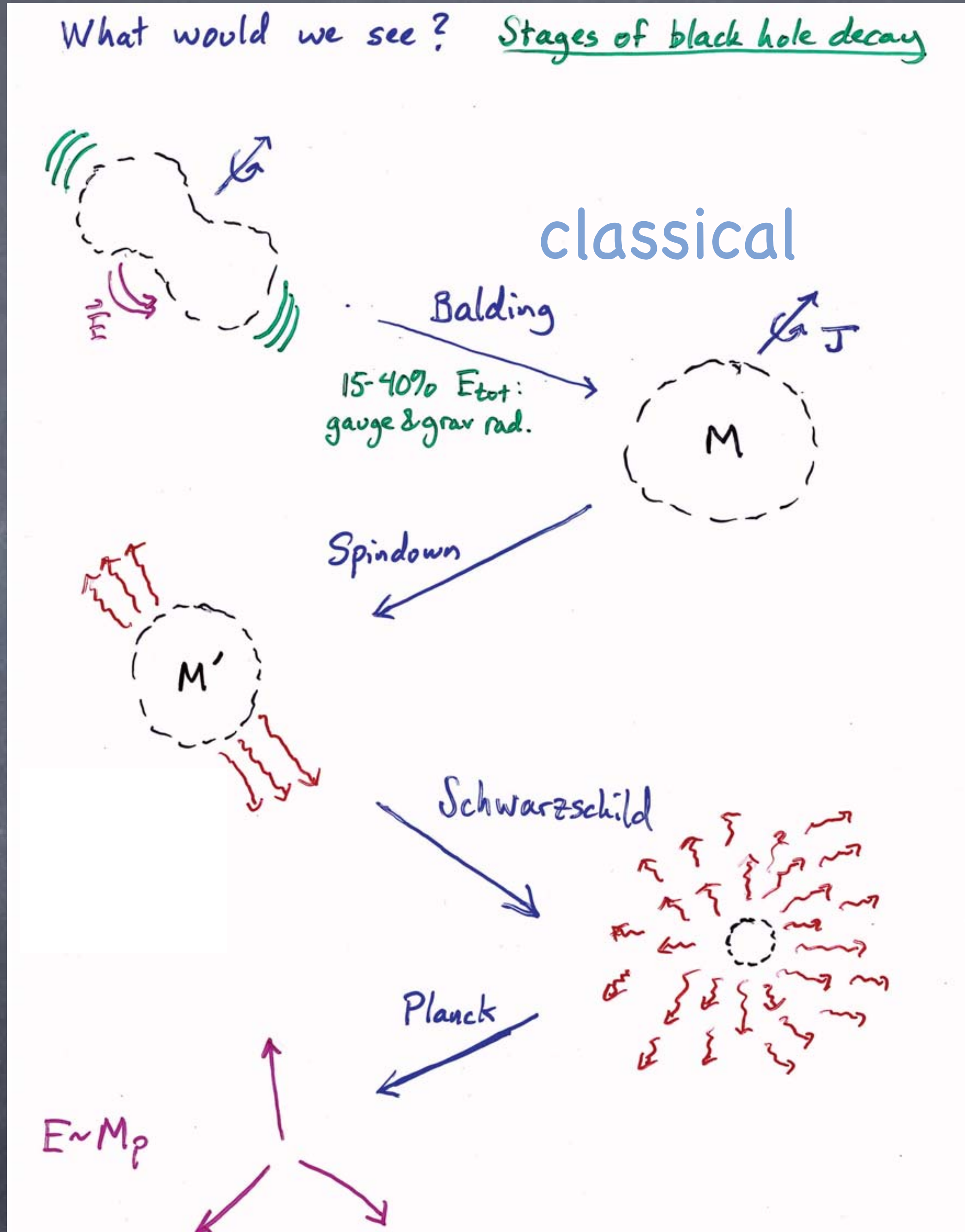
brane





Stages of decay

(cf. SBG & Thomas, hep-ph/0106219)



Focussing on the classical stages (formation, balding)

Some things we want

Cross section (rate)

Mass, vs. impact parameter

Amount of radiation, angular distribution

Gravitational: unobservable (but affects mass)

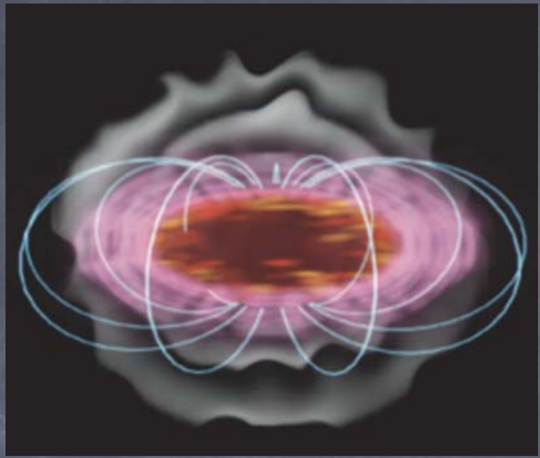
For the brave: include *charge* (gauge fields)

Analytical and numerical methods meet ...

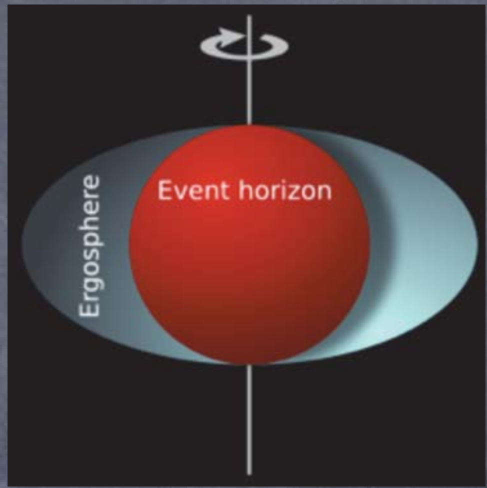
(Will focus on the analytical side...)

Decay:

1. Balding:



J, M



"black hole has no hair:" sheds multipole moments of all fields (also, charge, color)

becomes ~Kerr (rotating)

~ Myers-Perry black hole

Classical process

Classically, horizon can't shrink.

Thus, lower bound on size:

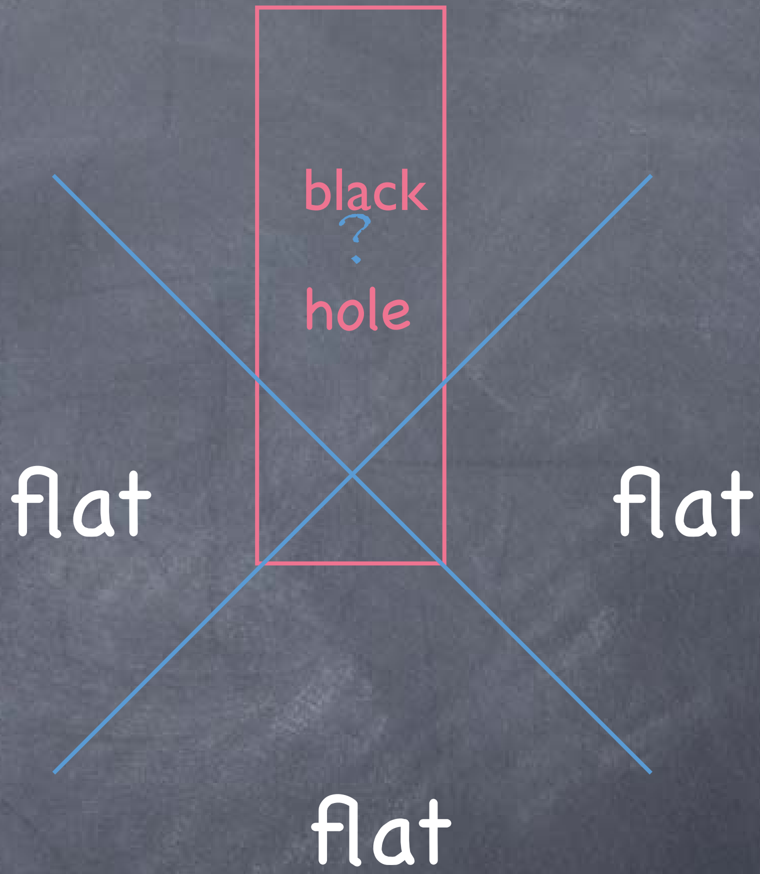
A_{TS}

Spacetime picture

Important point:

since trapped surface forms in flat region, can compute its size. This gives

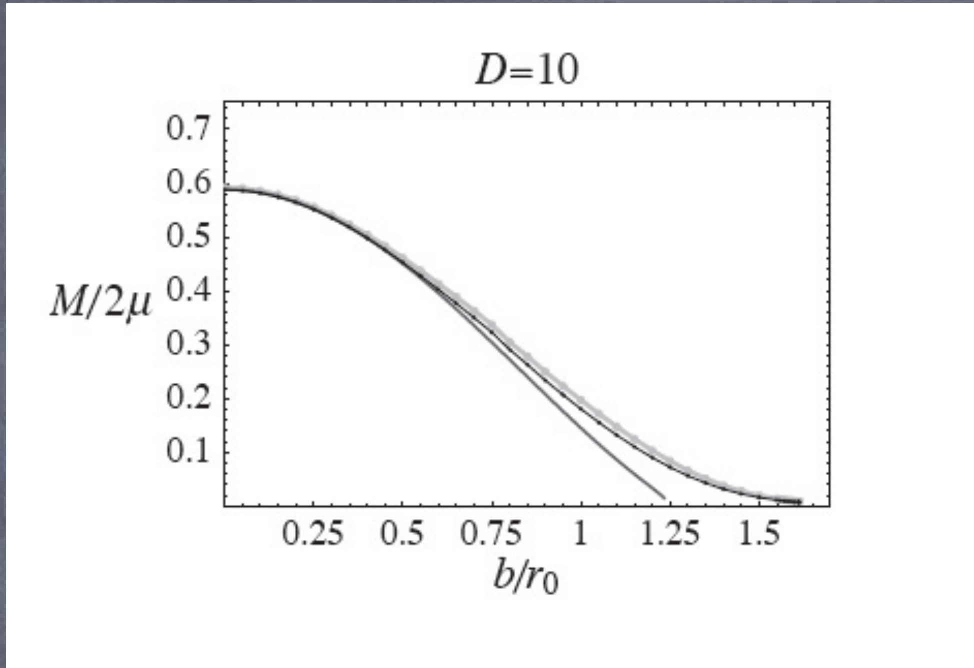
1. Cross section
2. LB on mass of BH



Ongoing improvements in computing size ...

Mass estimates via trapped surface

Lower bounds



$(2\mu = E)$

Yoshino & Rychkov

But, e.g. for D=4, b=0, lower bound is M=.71E;
improved estimates (D'Eath): M=.84E

D>4?

Herdeiro, Sampaio, Rebelo, 1105.2298,
First order Pert. theory:

Spacetime dimension	4	5	6	7	8	9	10
Apparent horizon bound (%)	29.3	33.5	36.1	37.9	39.3	40.4	41.2
First order perturbation theory (%)	25.0	–	33.3	–	37.5	–	40.0

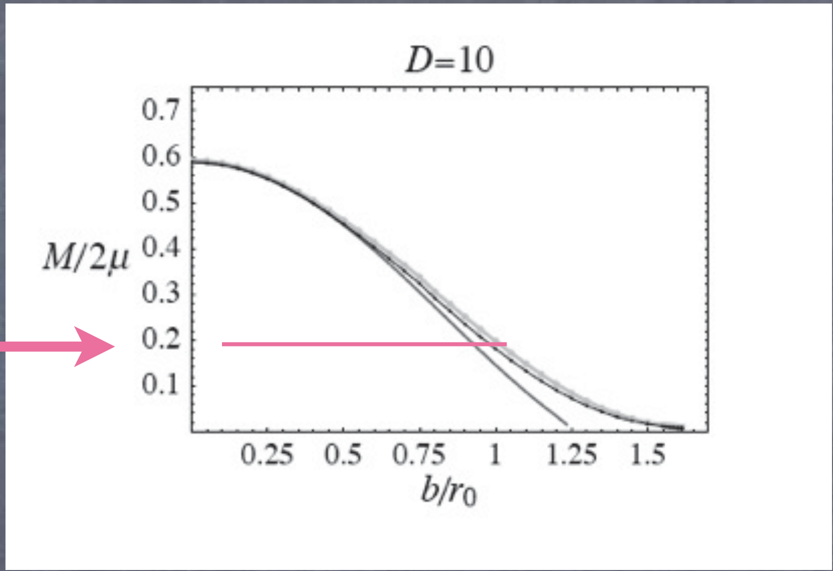
Higher D: close to TS bound!

This suggests utility of TS bound for b>0

Cross-sections (parton level-must fold w/ PDFs)

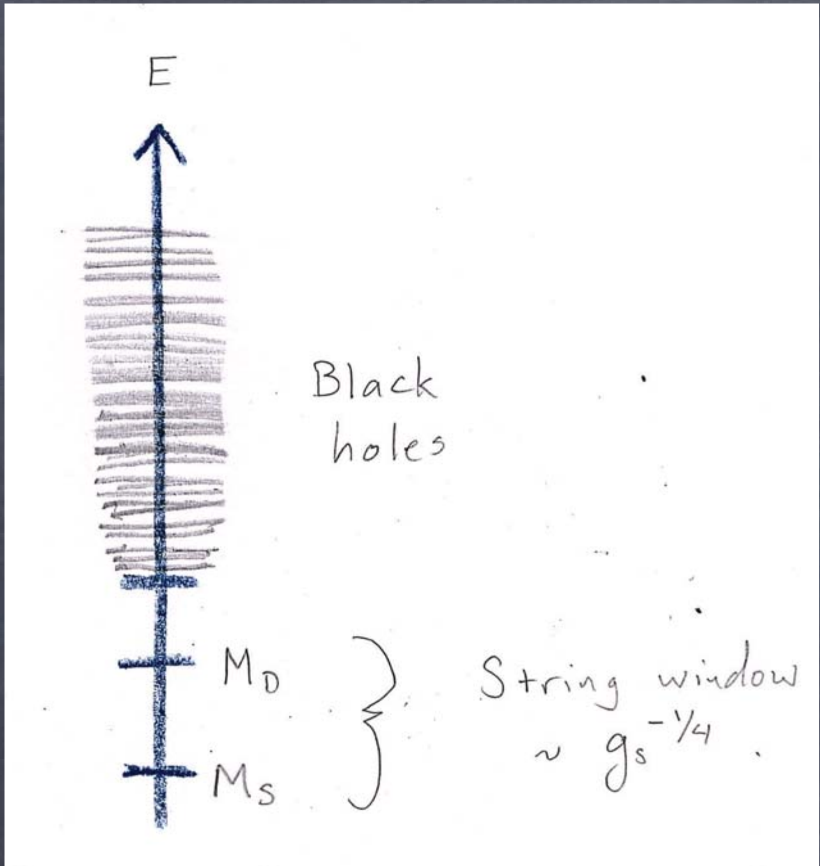
$$\sigma \approx \pi R(E)^2 \qquad R(E) \sim \frac{1}{M_D}\left(\frac{E}{M_D}\right)^{D-3}$$

BH threshhold?



(Also, charge effects -- reduce?? Yoshino & Mann -- improvement needed)

Threshhold for semiclassical BH production?



(if weak-coupled strings)

So need, e.g.,

$$M_{BH} \gtrsim 5\, M_D \quad (S_{BH} \simeq 24)$$

(Benchmark of hep-ph/0106219)

Large extra dimensions, warped compactifications: as noted $M_D \gtrsim 2-3\, TeV$

Hard to make ~classical BHs in current run. 10...14... TeV ... or higher??

Could redo rates w/ new bounds,
inelasticity estimates ...

(formerly 100-1000 fb ...)

Signatures:

1. From balding -- characteristics of radiation?

$$E_{rad} \sim 1/R(E) \ (?)$$

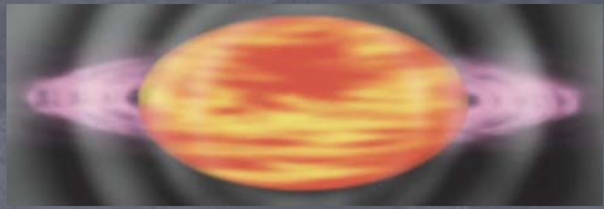
Prompt; relatively small fraction

gauge and gravitational

Other stages:

(may not cleanly separate for $M \sim 10\,\mathrm{TeV}$)

Decay: 2. Spindown



- Spinning black hole begins to Hawking radiate
- Preferentially sheds angular momentum:

  Characteristic angular distributions (SBG & Thomas);
  modifies vector/spinor/scalar ratios

- Must calculate higher-D Hawking emission rates

- HARD PROBLEM! (~thermal, +gray body)

  first approx. calcs -SBG/Thomas based on extrap. from 4d

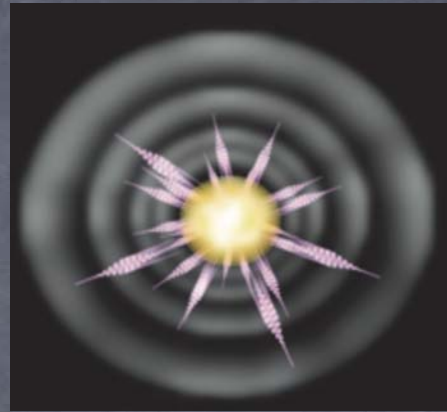
  Much ongoing work:

  Casals, Creek, Dolan, Kanti, Winstanley, Ida, Oda, Park, Webber, + many others ...

- Perhaps more prominent than est. in SBG & Thomas

  (Ida, Oda, Park claim $\sim 80\%$ of mass loss)

Decay: 3. Schwarzschild



- Possibly subdominant - 20%??

- Hawking emission (power spectrum, relative emission rates, ...) better understood

- Approx. thermal spectrum (w/ gray body modification) at $T_H \propto 1/R_S \propto M^{-1/D-3}$

- Multiplicities approx. thermal, but e.g. suppression of low-E gauge bosons, etc.

Future improvements needed:

Full study of evolution through spindown and Schwarzschild phases, properly incorporating gray body factors, and integrating over evolution, to determine

- energy spectrum
- relative multiplicities
- event shapes (angular distribution, etc.)

Particular uncertainty:

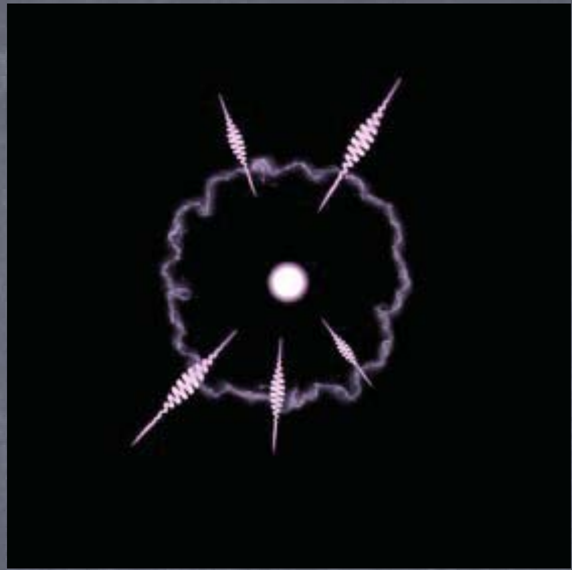
Graviton emission (invisible) during spindown

significant fraction of energy??

Most recent advances: Kanti et al, arXiv:0906.3845; Doukas et al, arXiv:0906.1515

Still not settled

Decay: 4. Planck

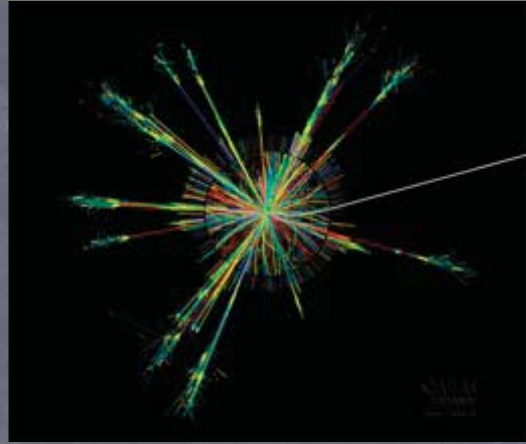


- When a BH reaches $M \sim M_D$, known physics breaks down

- The most interesting phase

- Expect: a few particles/strings w/ $E \sim M_D$ but who knows?

Despite uncertainties



Striking qualitative signatures for BH production can be inferred

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

Summarize: some important current uncertainties:

Inelasticity -- amount of energy lost to "classical" radiation

Affects cross section, ...

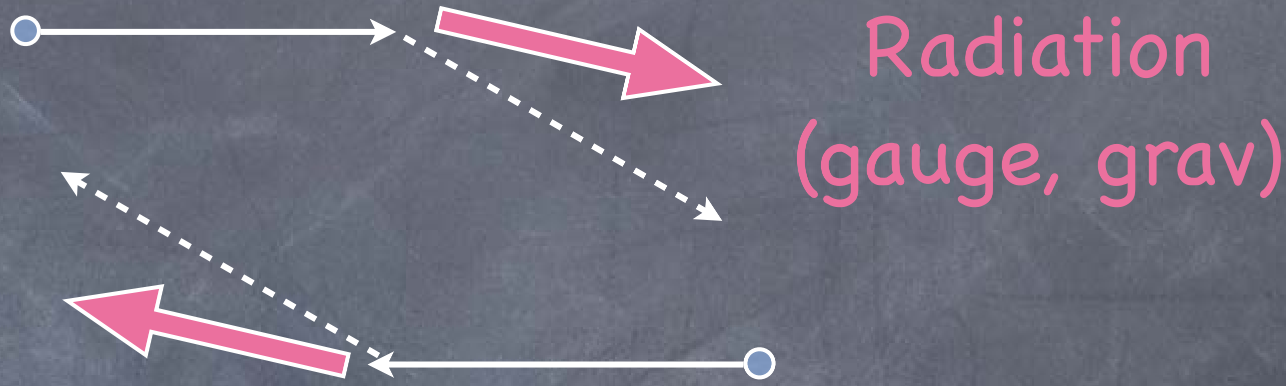
Graviton emission rates (graybody factors)

Affects observable energy; spectrum

(Also gives MET)

Final decay spectrum: Planck phase

Also gravitational scattering/radiation $b \gtrsim R(E)$



Interesting problem of principle

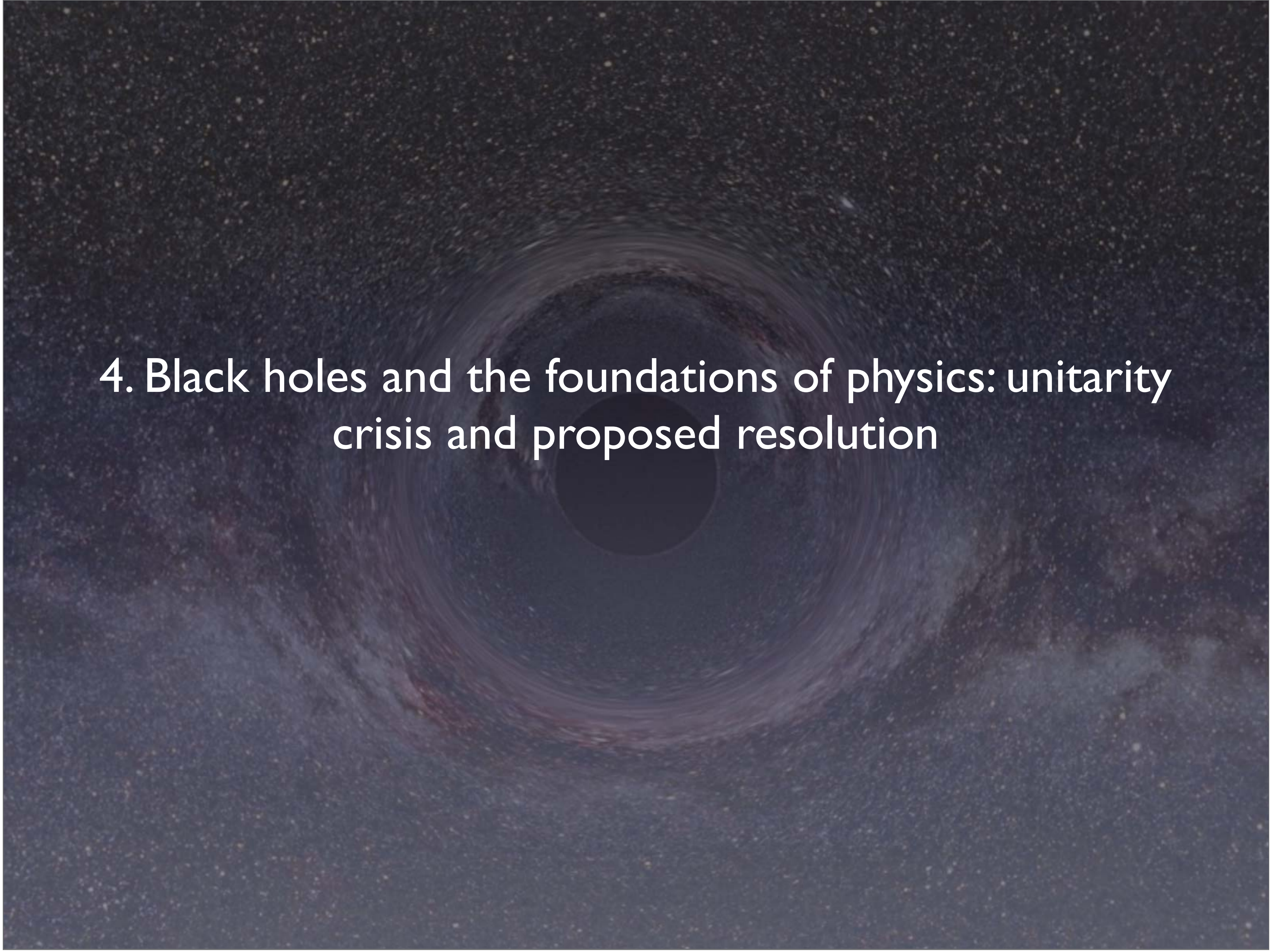
Gal'tsov, Spirin, Tomaras + collabs

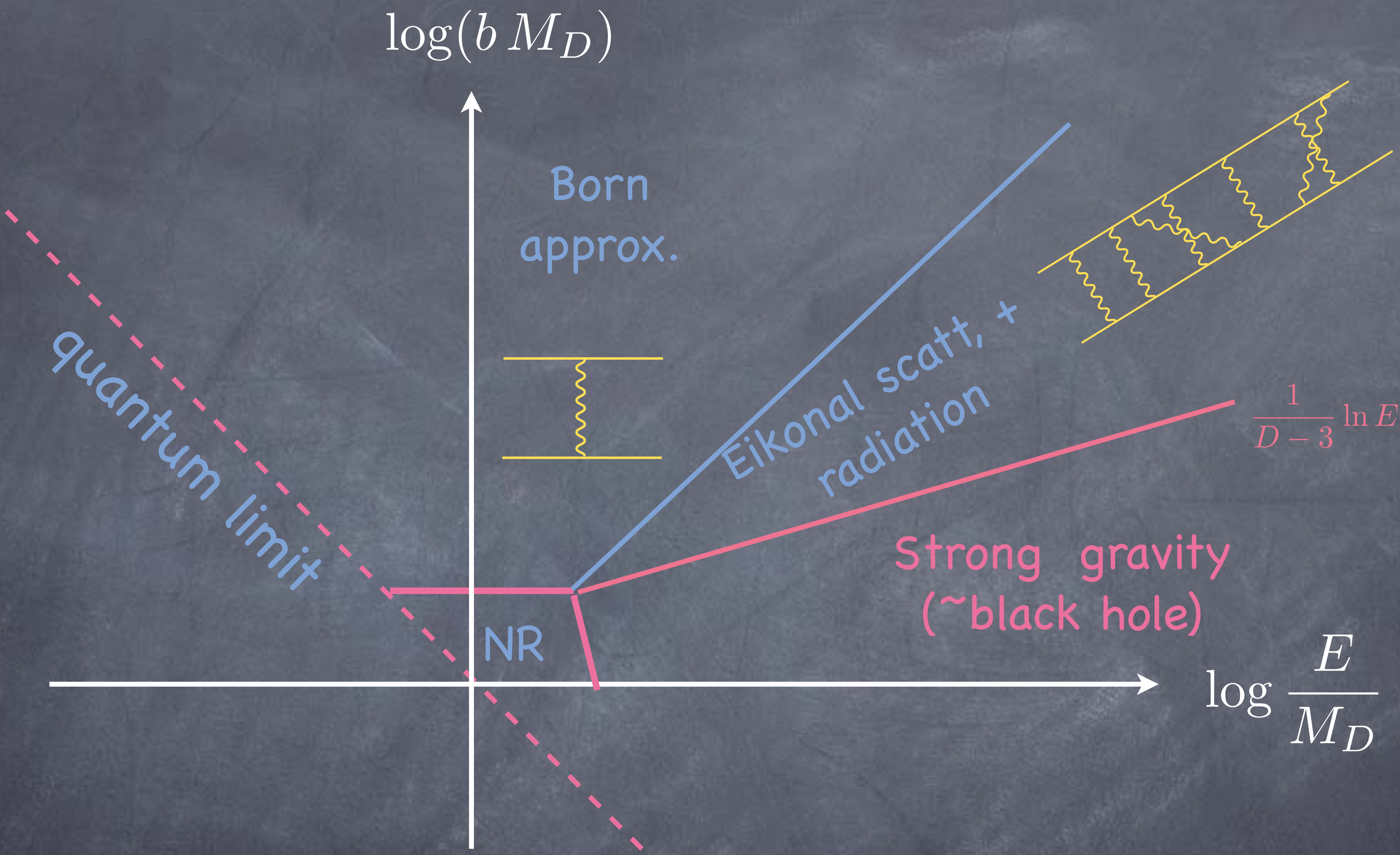
Rychkov; SBG, Porto, Schmidt-Sommerfeld (WIP)

Challenge to see @LHC? Stirling, Vryonidou, Wells

Another problem for numerical relativity? ...

4. Black holes and the foundations of physics: unitarity crisis and proposed resolution





How do we describe scattering in SG/BH regime?

Hawking evaporation: nonunitary -- QM violated

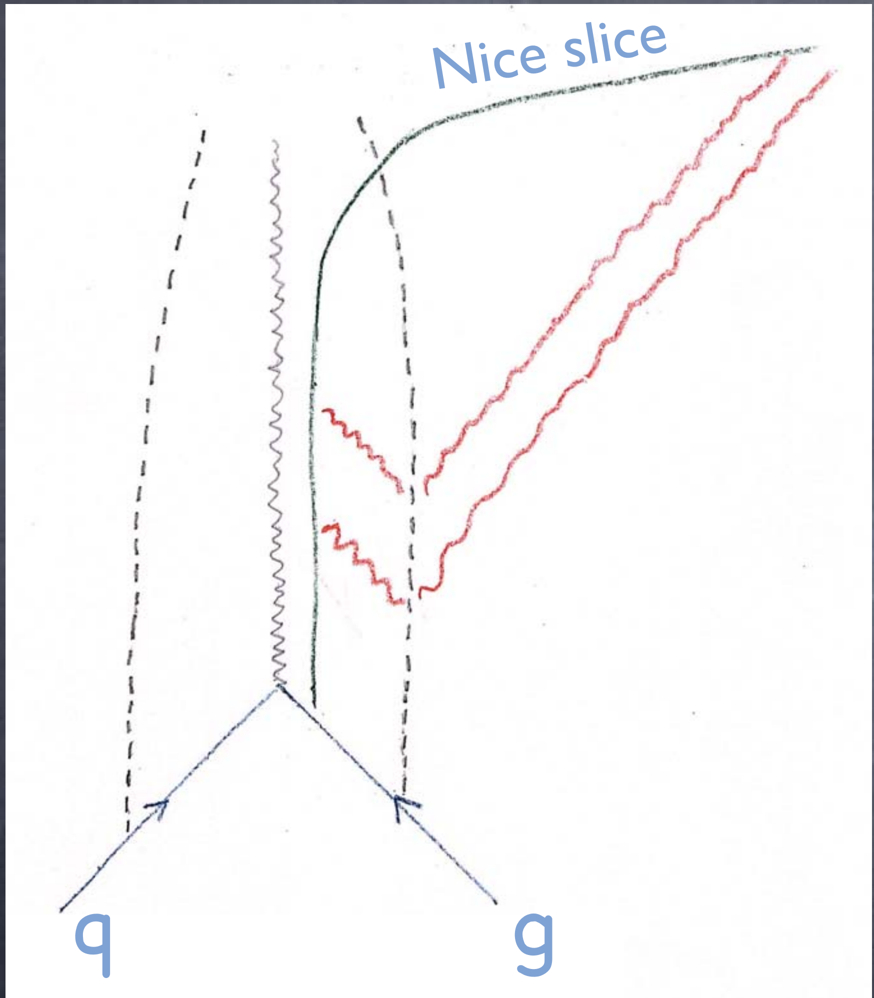
$$|0\rangle = \sum_i c_i |\hat{i}\rangle_{in} |i\rangle_{out}$$

$$c_i \sim \exp\{-E_i/2T\}$$

$$T = \frac{1}{8\pi M}$$

Hawking temperature

Modern, sharp version: "nice slice argument"



$$|\psi_{NS}\rangle \sim \sum_i c_i |\hat{i}\rangle_{in} |i\rangle_{out}$$

- Locality: no info escape during evap.

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

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

General grounds: $\sim A_{BH}$

at t_{evap}

Hawking's proposal (1976): fundamental nonunitarity in gravity $\rho \to \$\rho$

The problem is, QM is remarkably robust:

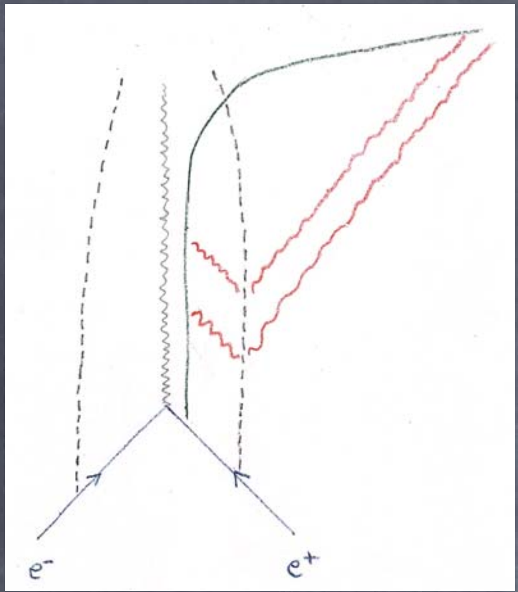
Basic idea:

- information transfer/loss requires energy

- information loss violates energy conservation
- virtual effects: massive energy nonconservation

Banks, Peskin, Susskind (1984):

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



- later escape,

once $R_S \sim l_{Planck}$?

Remnant

(long-lived or stable)

But: begin w/ arbitrarily large black hole

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

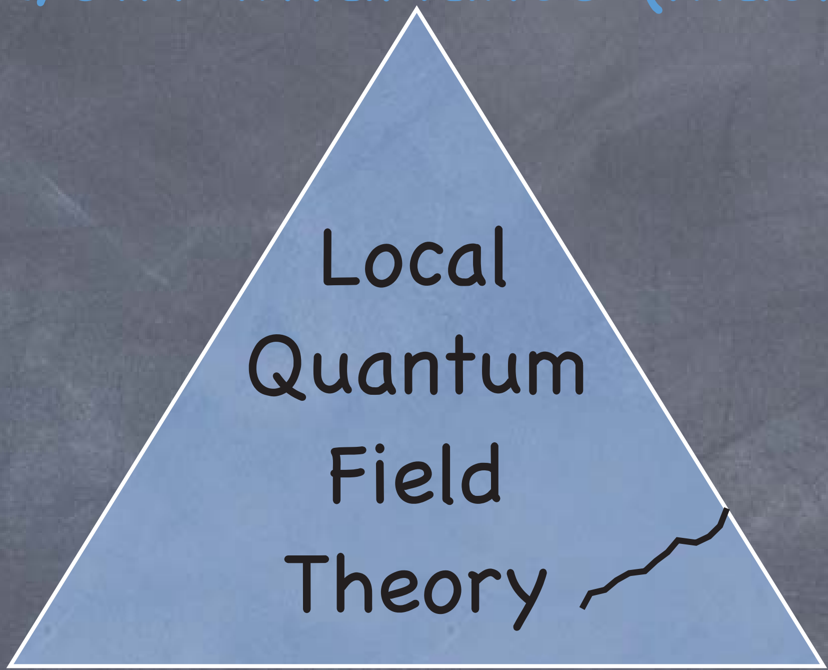
$\Rightarrow$ Infinite production instabilities

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

"Paradox"

The "paradox:" a conflict between

Lorentz/diff invariance (macroscopic)



Quantum mechanics

Locality (macroscopic)

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

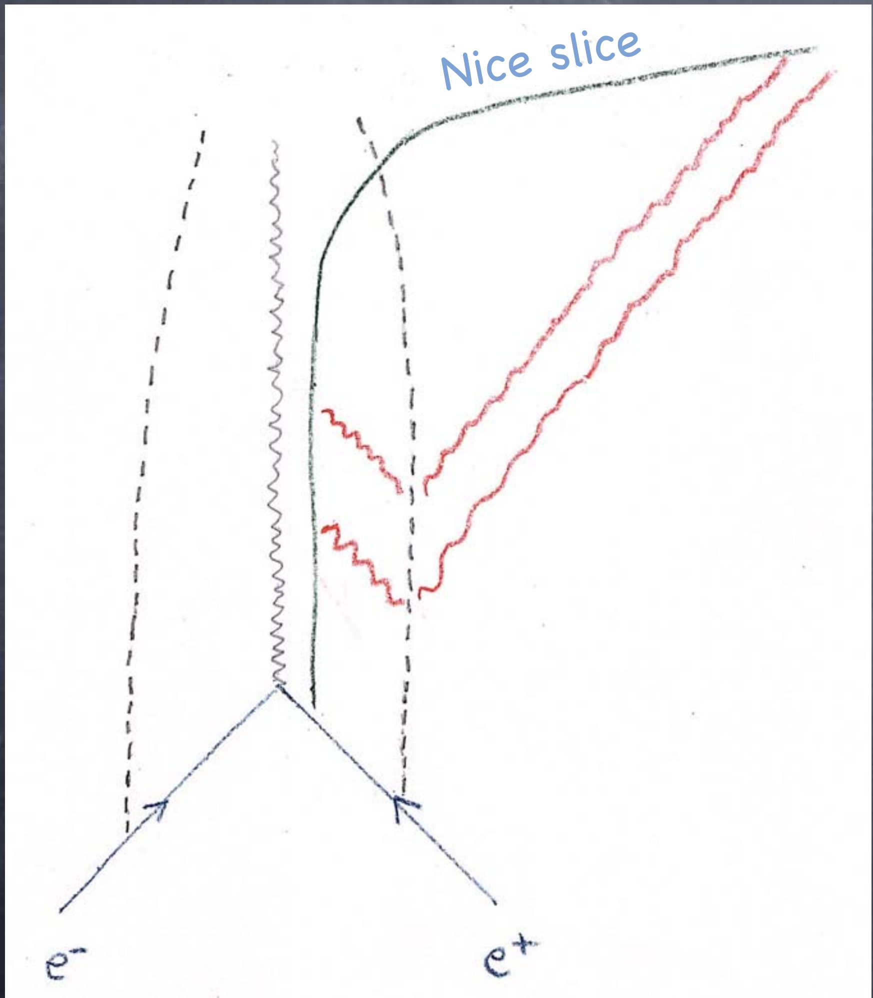
A weak point: locality?

A proposed resolution:

1. The nice slice argument is flawed: not sharp

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

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



(extreme, artificial construct)

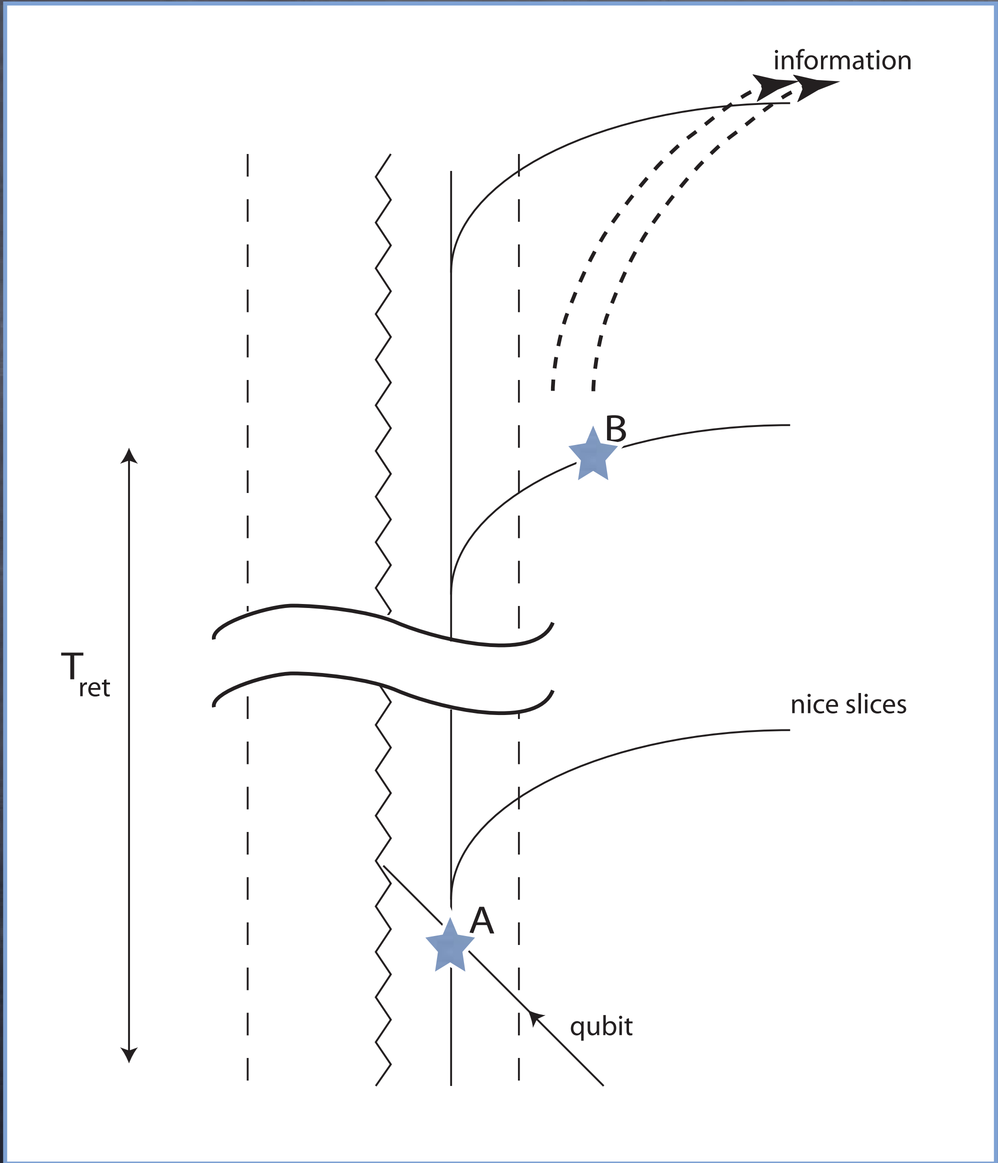
Semiclassical picture: not an accurate representation of detailed quantum state

- no physical meaning to NS state (gauge invc.)?

- large fluctuations at long times

SBG hep-th/0703116; 0911.3395

2. Nonperturbative gravity has "small" nonlocality with respect to semiclassical, geometric picture



Can parameterize in "effective Hilbert space approach"

$$\mathcal{H}_{in} \times \mathcal{H}_{out}$$

Some models for this kind of evolution:

arXiv:1108.2015

If correct, the deeper question:

What is the underlying, nonperturbative, quantum-gravitational "nonlocal mechanics" ??

(Strings ? or something else ?)

Can also study via "gravitational S-matrix:" SBG & Srednicki, Porto: see Erice - 1105.2036

5. Problems for the future

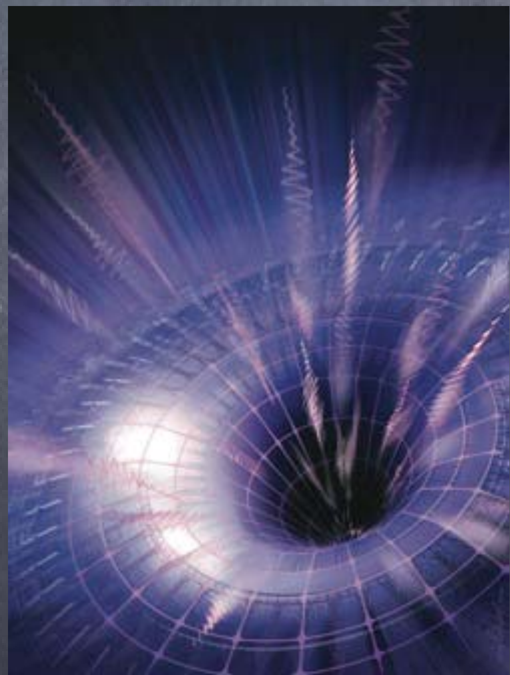
Problems:

Gravitational S-matrix; BH evolution

Quantum description: inflation

What is "nonlocal mechanics"

} Quantum, profound



Problems:

Semiclassical evolution of evaporating BHs

Gray-body factors (gravitons!)

Full evolution through spindown,
Schwarzschild phases

Spectra

Angular distributions

→ Collider signatures

(Also model dependence...)

Problems:

Classical gravitational scattering phenomena

(Possible clues on more profound quantum problems ?)

- $\gamma \gg 1$
- D > 4
- b > 0

} the frontier

Questions:

BH:

- critical b for BH formation
- M(b) for BHs
  (e.g.: $M_{crit} = 0$?)
- multi BHs? other exotica?

Radiation:

- E(b)
- Spectrum
- Angular distribution

Both subcritical and supercritical b

In conclusion:
gravitational scattering is a remarkably rich subject, with problems ranging from the foundations of physics, to diverse interesting classical phenomena, to possible phenomenology