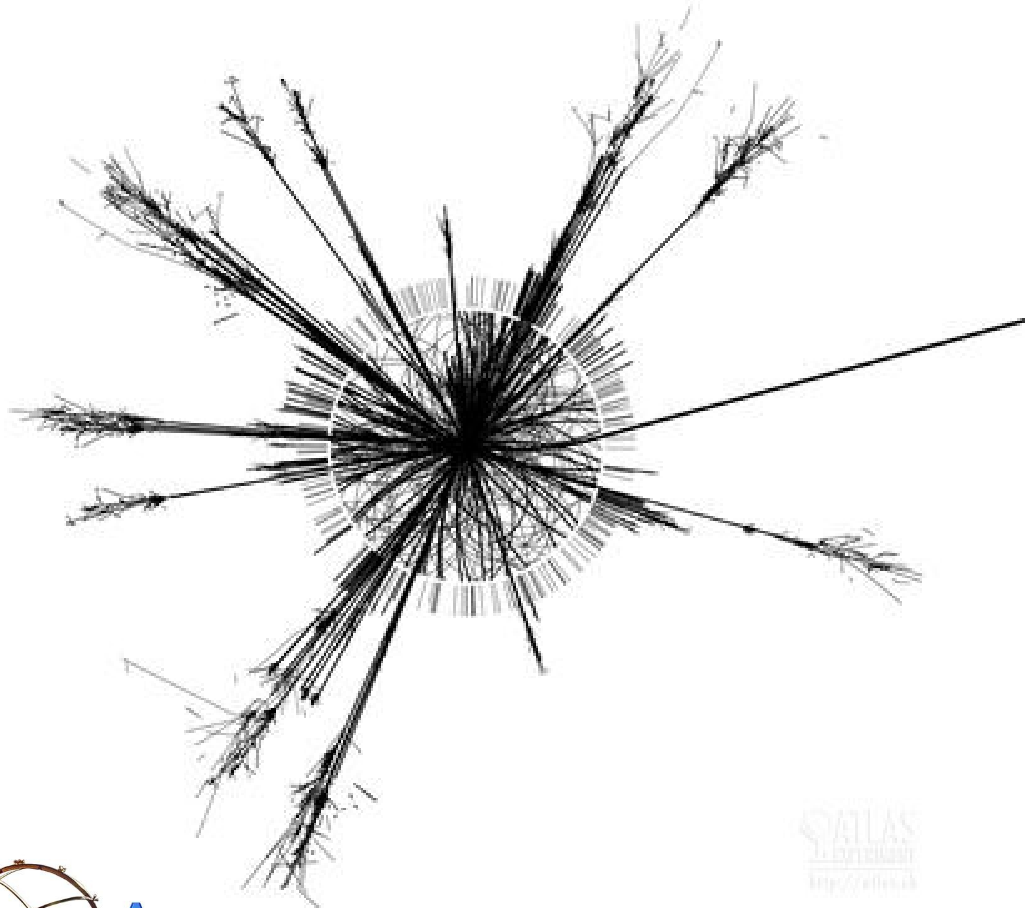
Black Holes, Extra Dimensions & the LHC



- Black Hole Recap
- The Problematic Standard Model
- Extra Dimensions & the Planck Scale
- Black Hole Production & Decay
- Current Constraints
- Signatures at the LHC

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Introduction

In last ~150 years physics has developed enormously

Three major pillars of modern physics have emerged

- general relativity 2×10^{-5} Cassini photon freq. shift close to Sun
- thermodynamics 1×10^{-7} WMAP precision of CMB fluctuations to 1%
- quantum mechanics 1×10^{-12} Measurement of electron g-2

Tested to unprecedented precision

- Black Hole studies are unique - combines all three areas
- Raises some very interesting questions about the nature of spacetime
- Ideas have very appealing simplicity
- Potential to answer one or several fundamental puzzles

Classical Black Holes

In QM all particles associated with a compton wavelength

$$\lambda = 1/E$$

In GR any object with energy-momentum ($T_{\mu\nu}$) will cause curvature of space-time ($g_{\mu\nu}$)

Force of nature interacts with spacetime itself!

Riemann tensor $R_{\mu\nu}$ describes tidal forces: residual acc^n between test masses on initially parallel geodescis

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi \frac{1}{m_{\rm p}^2} T_{\mu\nu}$$

Planck scale

Thus objects warp space-time around themselves and this modifies the objects equations of motion

For fundamental particles expect this influence at Planck Scale - M_P

$$M_p = \sqrt{\frac{\hbar c}{G}}$$ where G = Gravitational constant

$M_P \sim 10^{19}$ GeV ($\Rightarrow$ hierarchy problem)

For a spherically symmetric mass distribution the solution is 4d line element given by:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -\gamma(r) dt^2 + \gamma(r)^{-1} dr^2 + r^2 d\Omega^2$$

area element on surface of sphere

$$\gamma(r) = 1 - \frac{1}{m_P^2} \frac{2M}{r}$$

So, for masses small compared to M_P then $\gamma = 1$

For large energies metric is distorted by order E/M^2_P

At energies close to Planck Mass distortions cannot be neglected

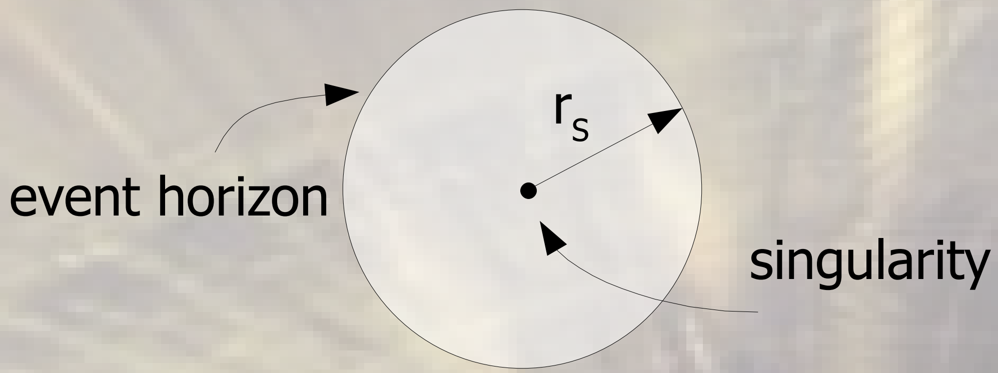
Metric becomes singular at $r = 2M/M^2_P = r_s$ the Schwarzschild radius

Schwarzchild radius is sol^n of GR in case of non-rotating uncharged BHs

First solution to GR discovered 1 month after Einstein's publication

Classical Black Holes

Alternatively, can write $r_S = \frac{2GM}{c^2}$



Bring mass M within a radius r_s and a singularity will form
Event horizon is all we can observe in ourside universe

For Earth r_S= 1cm

Rotating Kerr solution published 1963

A more generic solution was found for charged rotating black holes

Solve classical electro-dynamics in GR field equations
yields the Kerr-Newmann metric

Size of event horizon generalises to r_h

Charged rotating BH
Kerr-Newmann solution published 1965

The Problematic Standard Model

Jump to particle physics...

The Standard Model is fantastically successful

... but ...

The Problematic Standard Model

	Quarks						Leptons		
	+2/3			-1/3			-1	0	
Fermions	u	u	u	d	d	d	e	ν_e	I
	c	c	c	s	s	s	μ	ν_μ	II
	t	t	t	b	b	b	τ	ν_τ	III

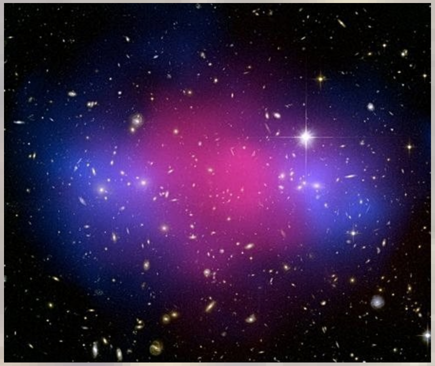
Bosons	g	g	g	g	g	g	g	g
	γ	Z^0	W^-	W^+				
	H							

61 'fundamental' particles in the SM! (including anti-particles)

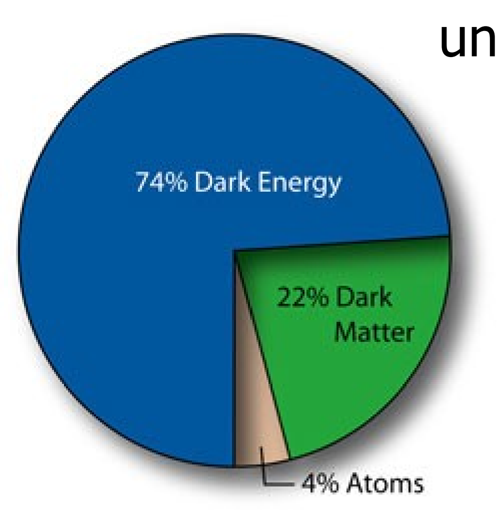
The Problematic Standard Model

22 Parameters of the SM to be measured
- 6 quark masses
- 3 charged leptons masses
- 3 coupling constants
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (other predicted from remaining EW params)
- 1 Higgs mass

(better than 105 params of generic SUSY)



We have no idea what 96% of the universe is!
unknown form of dark energy
unknown form of dark matter



No treatment of gravity in the Standard Model...
In a symmetric theory gauge bosons are massless
Higgs mechanism explains EW symmetry breaking
$\rightarrow$ EW bosons acquire mass

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

Dark energy acts to accelerate the expansion of the universe
i.e. repulsive gravity

Evidence from
- supernovae
- CMB - flat cosmological geometry
- blue shift of CMB photons in gravity wells
  (integrated Sachs-Wolfe effect)

Best guess is:
constant across cosmos
property of the vacuum

Summing zero-point vacuum fluctuations of SM fields incl. Higgs yields energy density 10^{120} times larger than measured!!!

"the worst theoretical prediction in the history of physics!"*

(not surprising that it's related to what Einstein called *"his greastest blunder"*)

Back to particle physics:
insufficient CP violation & no Baryon number violation able to account for our matter dominated universe

* MP Hobson, GP Efstathiou & AN Lasenby (2006). General Relativity: An introduction for physicists

Why is gravity ~10^{33} weaker than EW interactions?
Why is Higgs mass (~100 GeV) so much smaller than Planck mass (10^{19} GeV)?

Leads to fine tuning problem

self energy corrections to Higgs mass are quadratically divergent upto 10^{19} GeV

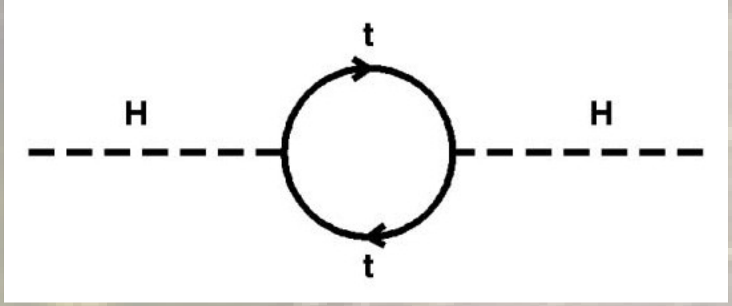
physical mass = bare mass + "loops" $m_H^2 = m_0^2 + \Delta m_H^2$

since Higgs is scalar field we get:

for top: $\Delta m_H^2 = -\frac{6}{16\pi^2} g_t^2 \Lambda^2$ (g is Yukawa coupling $\propto$ mass)

for EW bosons: $\Delta m_H^2 = +\frac{1}{16\pi^2} g^2 \Lambda^2$

for Higgs: $\Delta m_H^2 = +\frac{1}{16\pi^2} \lambda^2 \Lambda^2$ (λ is Higgs self coupling)



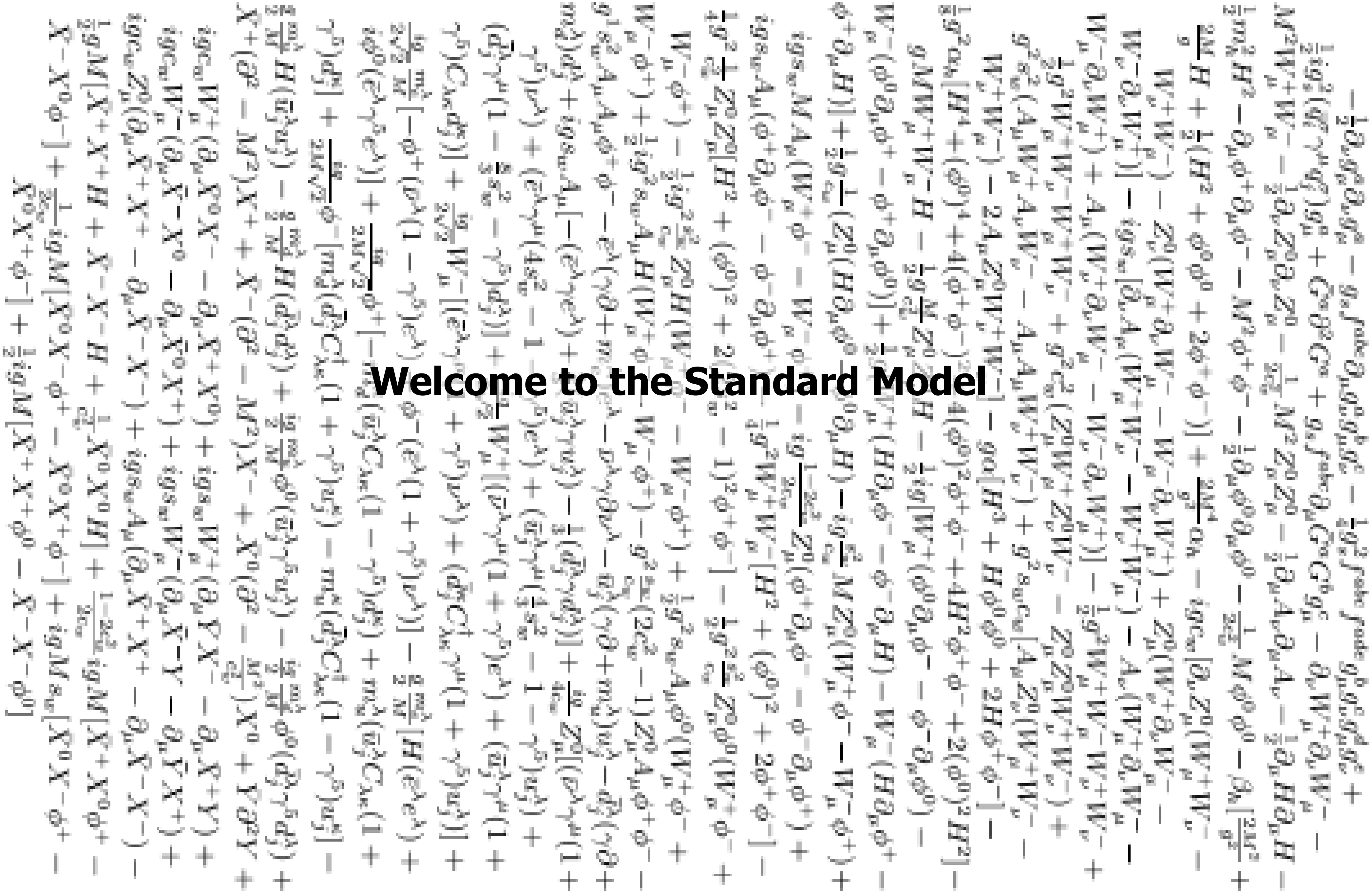
$m_H^2 = m_0^2 + \frac{1}{16\pi^2}\left(-6g_t^2 + g^2 + \lambda^2\right)\Lambda^2 -$ …new physics…

For $\Lambda^2 : (10^{19}\,\text{GeV})^2$ and $m_H : (100\ \text{GeV})^2$ then

$m_H^2 = m_0^2 + \frac{1}{16\pi^2}\left(-6g_t^2 + g^2 + \lambda^2\right)\cdot 10^{38} \approx (100\ \text{GeV})^2$

- if SM is valid to this scale (i.e. no new physics from 1 TeV - 10^{19} GeV) incredible fine tuning required between bare mass and the corrections to maintain ~ 100 GeV Higgs mass

Welcome to the Standard Model



Extra Dimensions & The Planck Scale

What if there is no new scale in particle physics upto M_P?

We will have to live with the fine tuning problem

Use anthropic arguments

(of all possible universes with different physics parameter values only universes with our parameter settings could lead to humans existing)

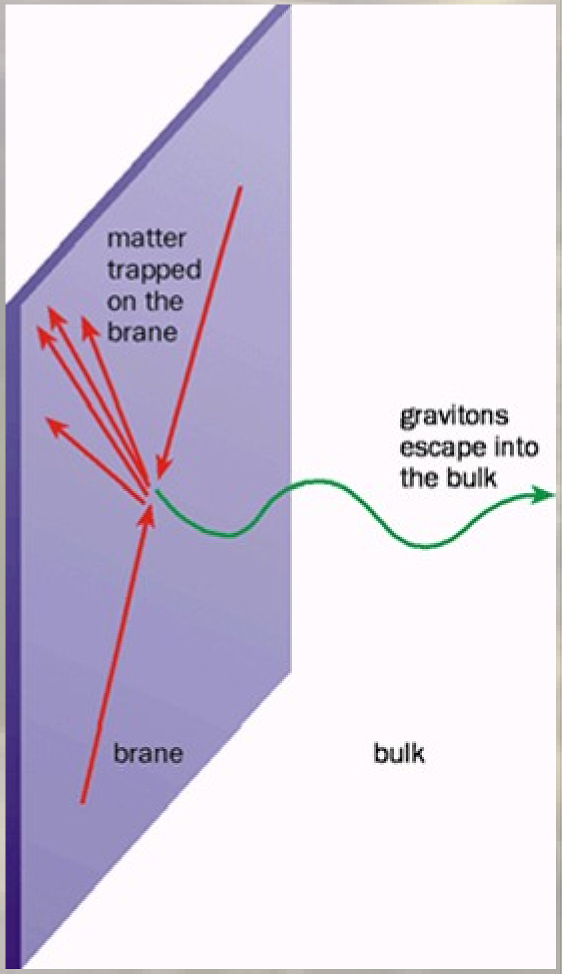
Alternative approach

$\Big($*"If the mountain will not come to Mohammed, then Mohammed must go to the mountain."*$\Big)^{-1}$

Perhaps we can bring M_P down to ~1 TeV

Introduce large extra spatial dimensions (large ~ 1mm)

- Standard Model confined to a 3-brane
- Embedded in higher dimensional space
- Only gravity propagates in extra dimensions



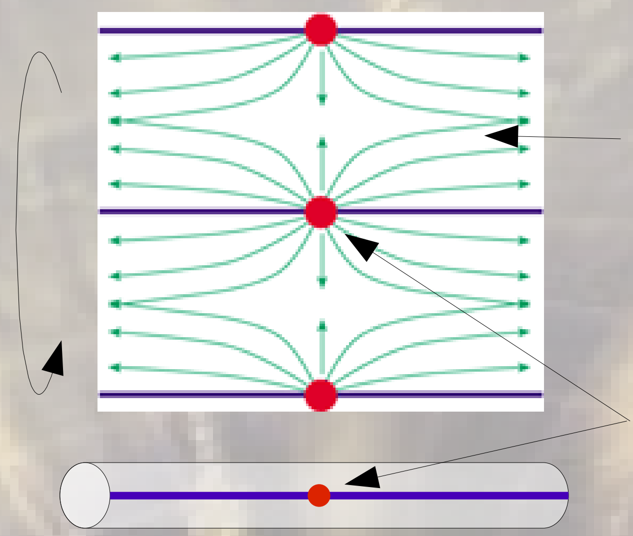
1920s - Kaluza & Klein attempted to unify general relativity & Maxwell's EM
- incorporated U(1) gauge symmetry into 5d spacetime
- if extra dimension is compactified then EM & Lorentz symmetries remain
- photon becomes 4d manifestation of 5d graviton

Theory suffered problems
- unable to explain vast difference in strengths of two interactions
- unable to combine with quantum mechanics
- later discoveries of weak & strong interactions did not fit into the scheme

Supersymmetry & string theory in 1970s / 1980s revived concept of extra dimensions

- some of gravity's non-renormalizability could be accomodated in string theory
- requires 10 / 11 spatial dimensions
- predicted spin 2 massless particle (graviton)
  - graviton is expected to be massless (gravity has infinte range)
  - graviton is expected to be spin 2
    - (since gravity is described by 2^{nd} rank energy-momentum tensor)

ADD Model of Large Extra Dimensions

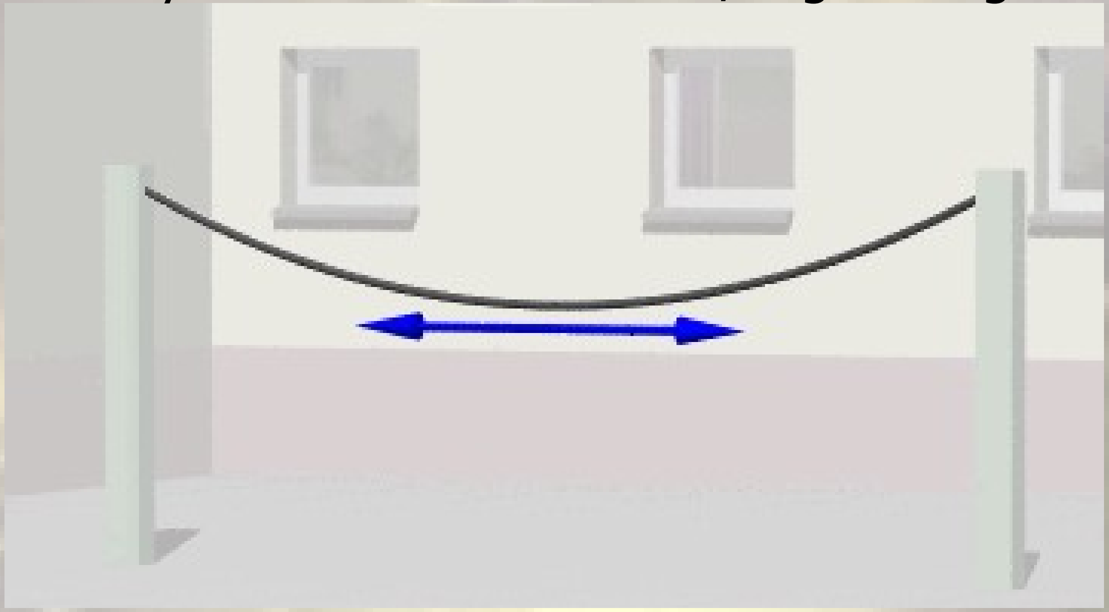


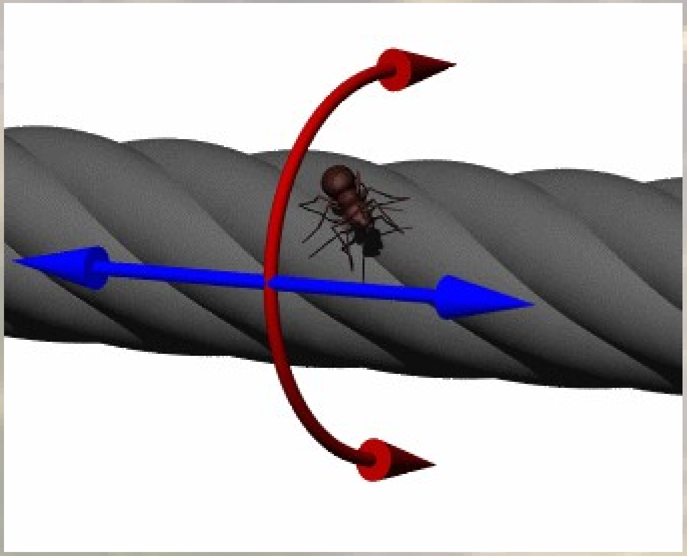
Antoniadis, Arkani-Hamed, Dimopoulos, Dvali:
hep-ph/9803315, 9804398, 9807344

- All standard model particles are trapped to surface of this hyper-cylinder
- Particles moving in the bulk have quantised wave functions (like 1d potenial well)
- Higher order modes appear as higher energy excitations
- Mass difference between successive states related to size of dimension R
- Can lead to infinte Kaluza-Klein towers of particles
  massless gravitons would appear as a tower of massive states on our brane
  momentum in extra dim appears as additional mass: $M^2 = E^2 - (P^2_x - P^2_y - P^2_z) - P^2_n$

Why are the extra dims < 1mm ?
- gravity has only been tested down to this scale!
- current torsion balance experiments set limit on $1/r^2$ dependence to <0.16mm

Where are the extra dimensions?
- curled up (compactified) and finite
- only visible at small scales / high energies





Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space

Gauss' Law for gravity: surface integral over closed volume containing vector field g gives total enclosed mass M

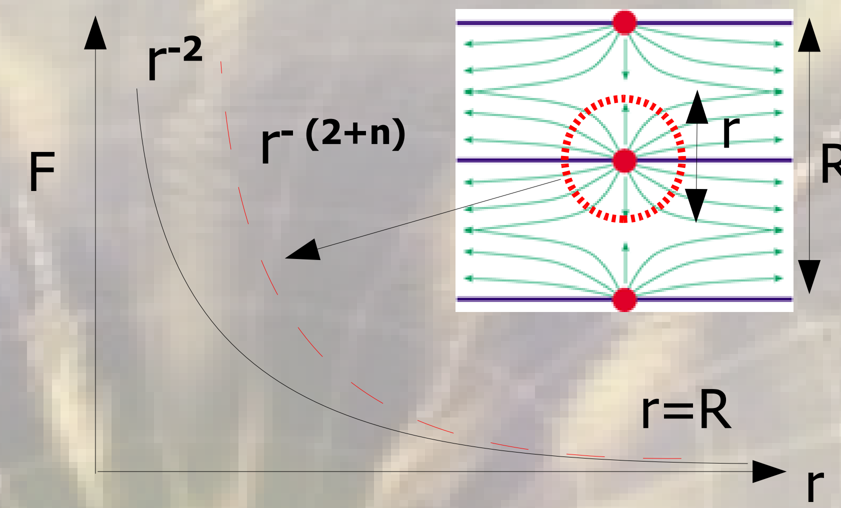
$$\int \mathbf{g}\cdot dA = -4\pi M$$ yields Newton's law $$F = G\frac{m_1 m_2}{r^2}$$

With n extra spatial dimensions each of size R

$$F = G_D \frac{m_1 m_2}{r^{2+n}}$$

$$F = \left(\frac{G_D}{R^n}\right)\frac{m_1 m_2}{r^2} \quad \text{i.e.} \quad G = \frac{G_D}{R^n}$$

For r >> R we recover Newtonian gravity



dilution due to volume of extra dimensions

Planck scale: $M_P^2 = \frac{\hbar c}{G}$

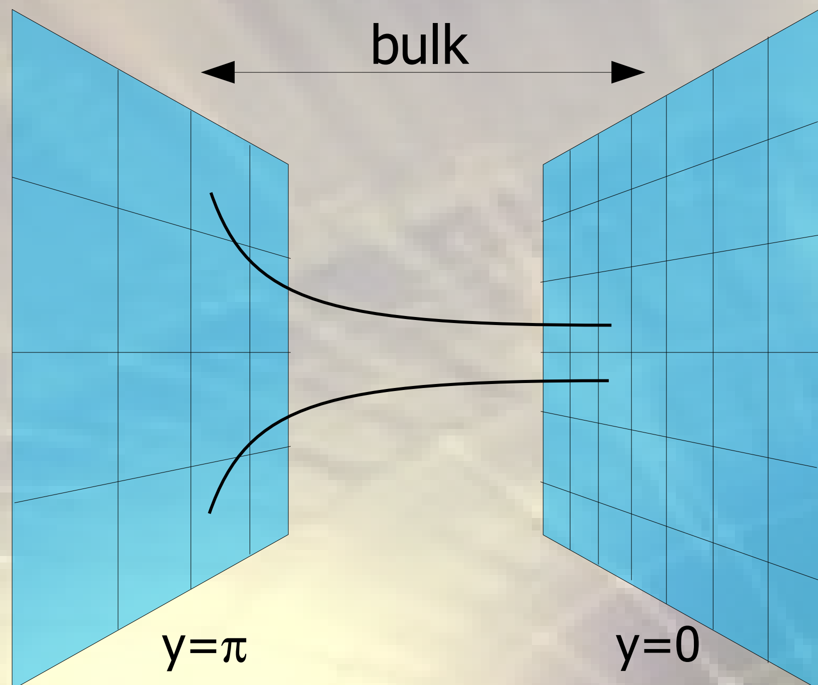
In extra dimensions full scale of gravity M_D is given by $$M_D^{2+n} = \frac{\hbar c}{G_D} = \frac{M_P^2}{R^n}$$

Thus M_D can be ~ 1 TeV when R^n is large

For n=1 and M_D=1 TeV then R ~ 10^{16}m ⇒ already excluded!

Randall-Sundrum Model of Warped Extra Dimensions

Randall, Sundrum: Phys.Rev.Lett 83, 3370(1999)
Phys.Rev.Lett 83, 4690(1999)



$$ds^2 = e^{-k\pi y}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

k = warp factor
models characterised by scale k/M_P

Spacetime is structured as two separated 3-branes: SM and Planck

Two 3-branes connected with 1 extra dimension

Gravitons propagate in the bulk

Extra dimension highly curved with an exponential warp factor
$\Rightarrow$ introduces scaling between 3-branes length $\propto$ 1/E

Gravity at Small Distances

Dark energy is ~74% of critical density of universe

$\Rightarrow$ density of dark energy $\rho_d \sim 0.0038$ MeV/cm^3

$\Rightarrow$ distance scale $L_d = \sqrt[4]{\hbar c / \rho_d} \sim 85 \mu$m

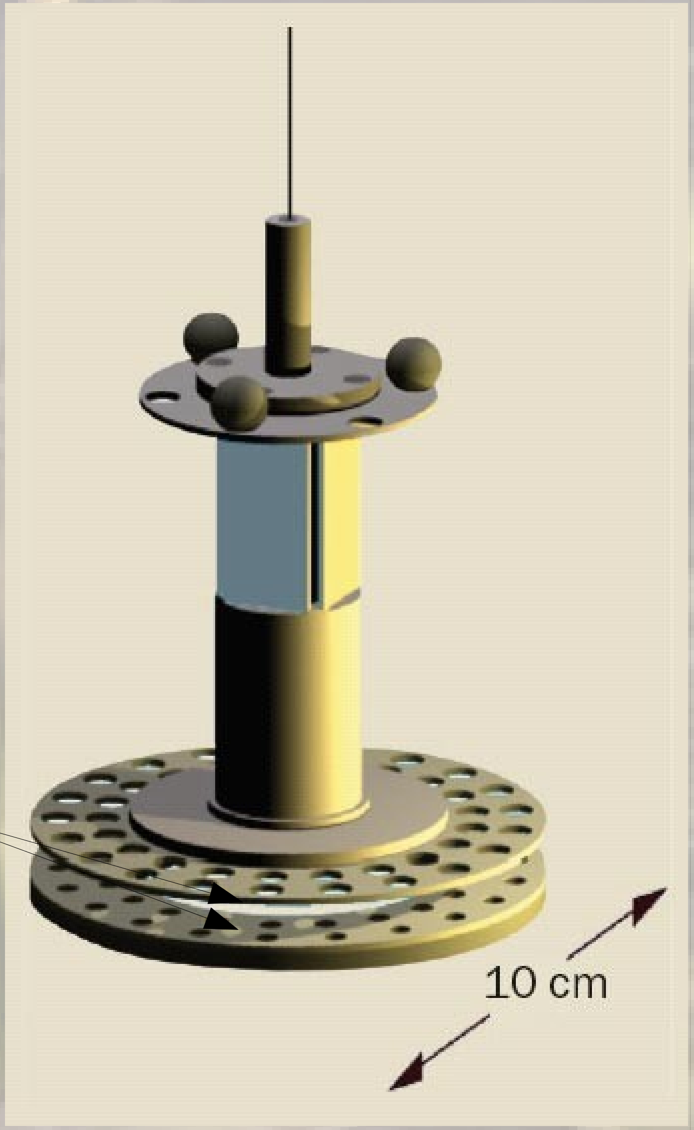
could be a fundamental distance scale...

Test inverse square law at small distances
with torsion balance experiments

Measure torsion forces between test and attractor
masses in horizontal plane (actually holes in two rings)

Measure torque vs vertical separation

Sensitive to ~1 nanoradian twists
(angle subtended by 1mm at distance of 1000 km)



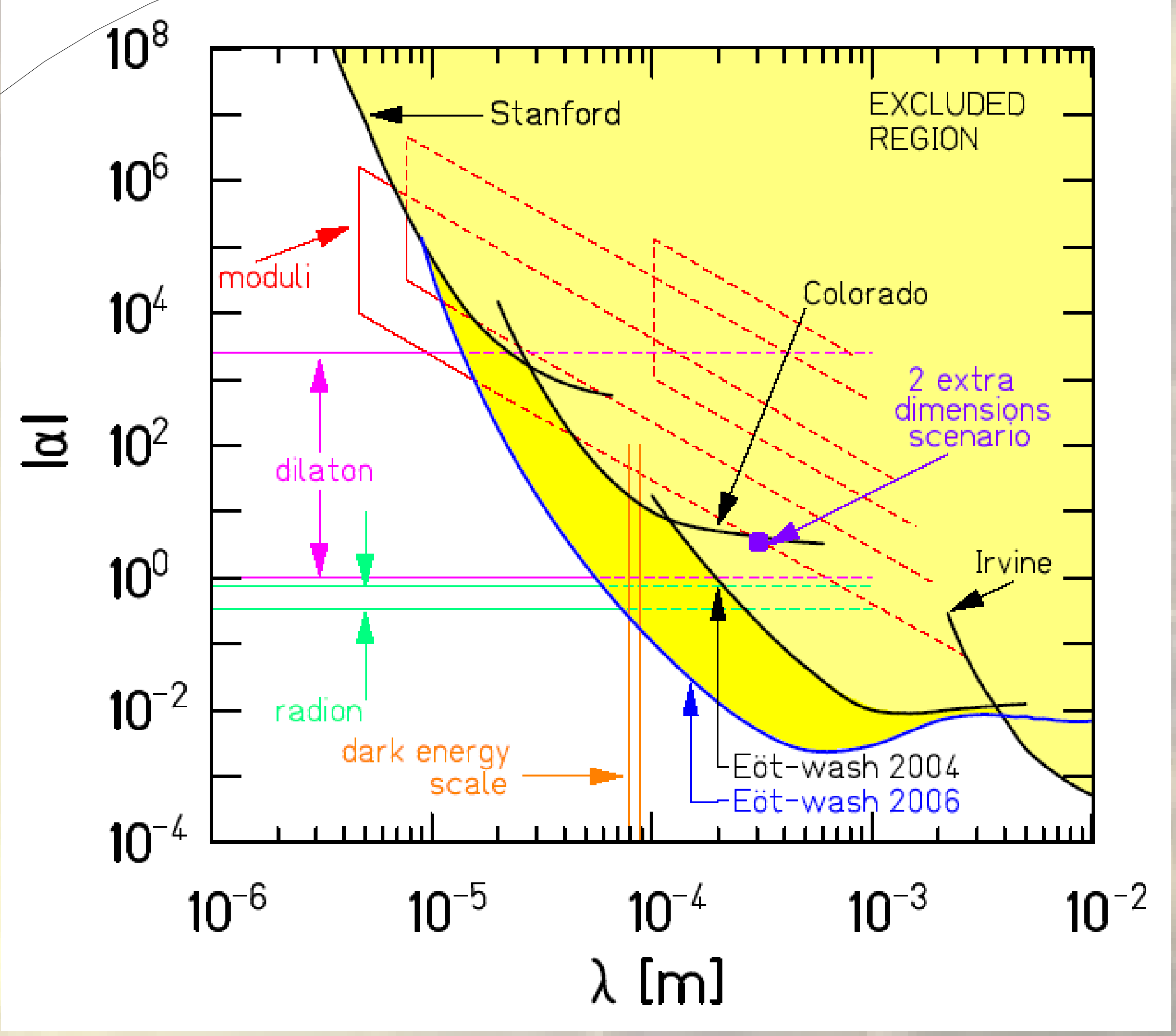
Gravity at Small Distances

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$

strength of new Yukawa-like potential

range of new Yukawa-like potential

Phys.Rev.Lett.98:021101, 2007



Inverse square law holds for $\lambda < 56\mu\mathrm{m}$

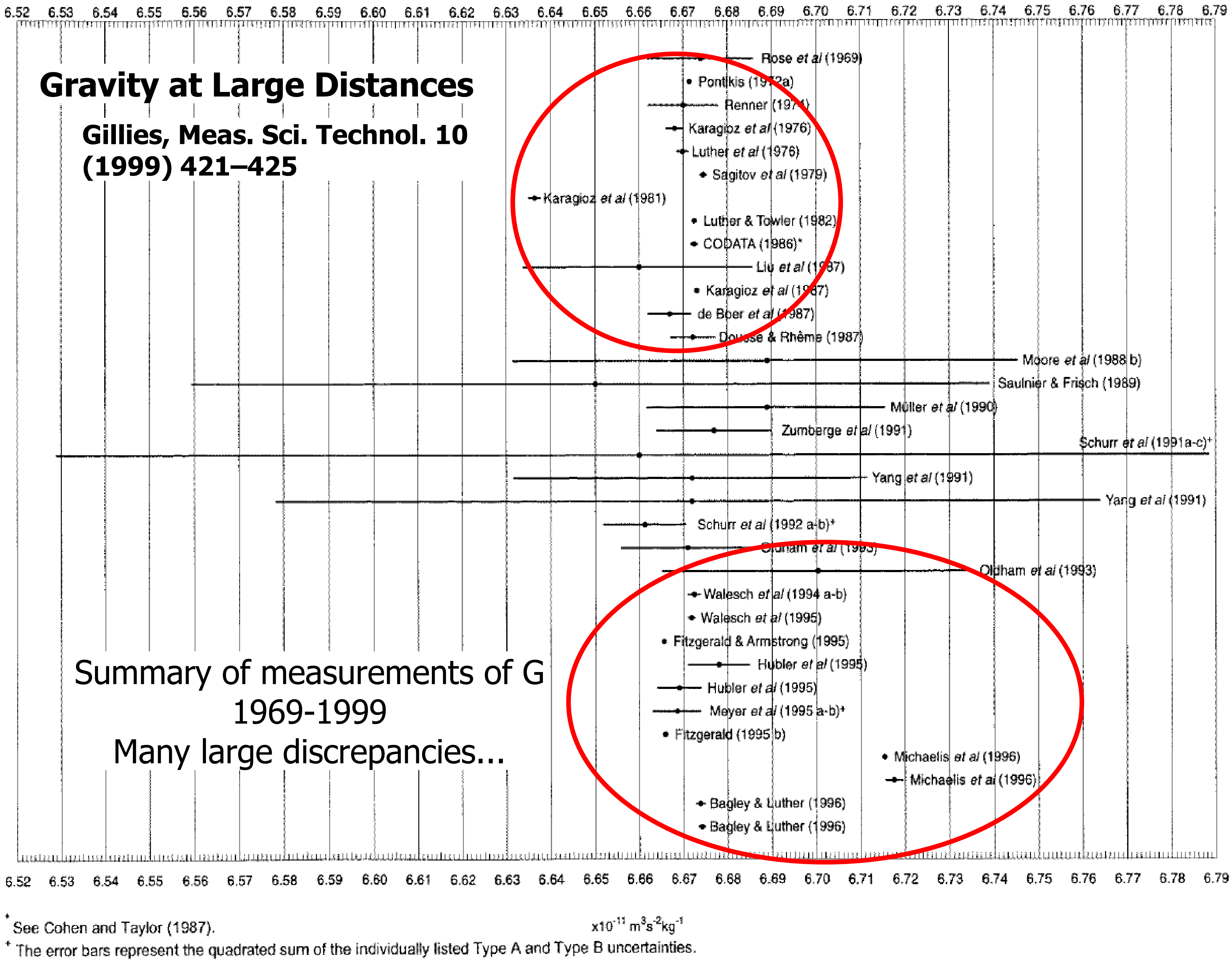
$\Rightarrow$ extra dims have

R < 44μm 95% C.L.

Gravity at Large Distances

Gillies, Meas. Sci. Technol. 10 (1999) 421–425

Summary of measurements of G
1969-1999
Many large discrepancies...

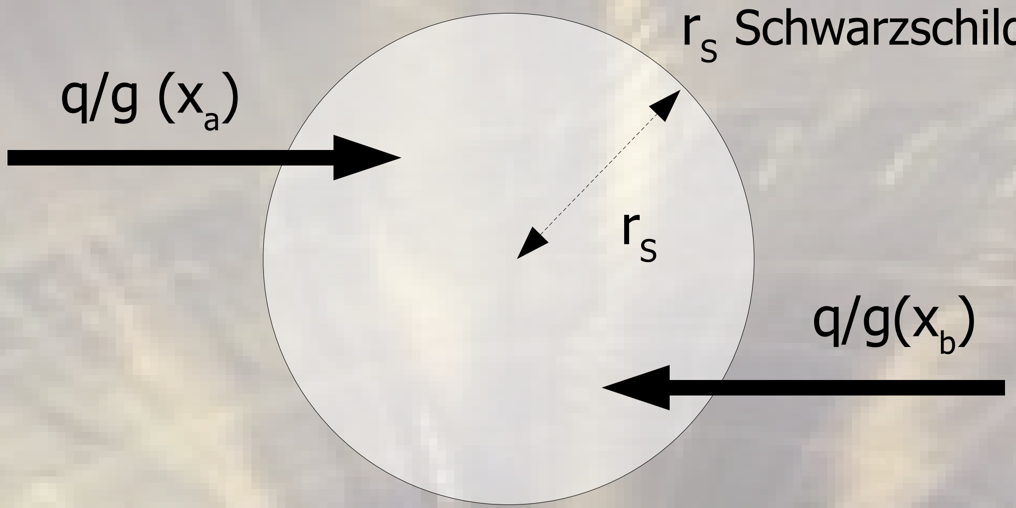


Micro Black Hole Production

Giddings, Thomas: hep-ph/0106219
Dimopolous, Landsberg: hep-ph/0106295

In collisions Black Hole forms when impact parameter < $2r_S$

$$M_{BH} = \sqrt{s \cdot x_a \cdot x_b} = \sqrt{\hat{s}}$$



r_S increased by factor R^n

$$r_S = \frac{2GR^n M_{BH}}{c^2}$$

Should observe continuous mass spectrum of BHs $M>M_D$

In absence of any real theory use classical cross section:

$$\sigma_{BH}(\hat{s}) = F\pi\, r_S^2$$

parton cross section
F = production form/fudge factors

$$\sigma_{BH}(s) = \sum_{a,b} \iint dx_a dx_b \cdot f_a(x_a) \cdot f_b(x_b) \cdot \sigma(\hat{s})$$

convolute PDFs to get total production cross section

Simple but extremely robust prediction!

Micro Black Hole Production

Cross section increases with s

For s >> M_D BH production will dominate over SM processes

For example very high E_T jets no longer produced ® form BH

Energy redistributed as lower momenta thermal emissions

"The end of short distance physics" Giddings, Thomas: hep-ph/0106219v4

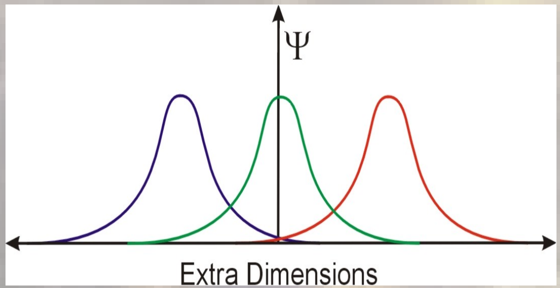
BHs do not conserve B, L, or flavour

$\Rightarrow$ Raises problems: proton decay, n-nbar oscillations...

Proton kinematically allowed to decay to any lighter fermion
Only protected by B conservation (which must be violated at GUT scale!)
Only option is $e^+ \rightarrow$ thus p decay violates lepton number too

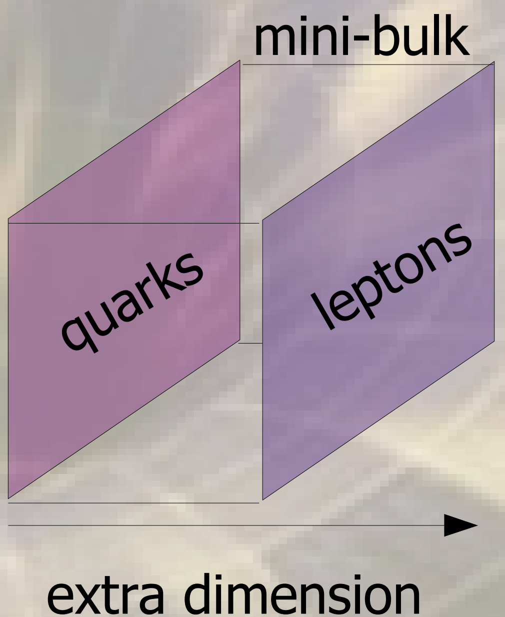
$$p \rightarrow e^+ + \gamma$$

$$p \rightarrow e^+ + \pi^0$$



Many ADD models predict too fast proton decay

(Super Kamiokande limit: $\tau \sim 10^{33}$y arXiv:0903.0676



<u>Split Fermion Model</u>

In this model spacetime structure is further modified

SM fermions exist on separated 3d branes

SM bosons propagate in the 'mini bulk' between them

Split fermion model may also explain
fermion mass hierarchy

Arkani-Hamed,Schmaltz DOI:10.1103/PhysRevD.61.033005
Dai, Starkman, Stojkovic: hep-ph/0605085

Micro Black Hole Production

Astrophysical black holes characterised by 3 numbers only

- M mass
- Q electric charge
- J angular momentum

Metaphorically: 'bald' BH has only 3 hairs

In context of micro BH - they can also carry colour charge
(astro BHs only absorb colourless hadrons anyway)

Infalling matter has entropy, 2nd law then implies BH have entropy too
BH cannot be a single microstate!
- infalling matter will always increase r_S never decrease

$$r_S = \frac{2GM_{BH}}{c^2}$$

entropy $\propto$ surface area

Then it follows that an object with entropy has a temperature...

$$\frac{\partial S}{\partial E} = \frac{1}{T}$$

Hawking Radiation

Hawking: Commun.Math.Phys.43:199-220,1975

Near event horizon vacuum fluctuations interact with warped spacetime
Negative energy particle of virtual pair falls into BH, other becomes real

⇒ BH loses mass

radiate a black body spectrum with temp T_H

$$T_H = \frac{1}{8\pi} \frac{\hbar c^3}{G k_B} \frac{1}{M_{BH}}$$

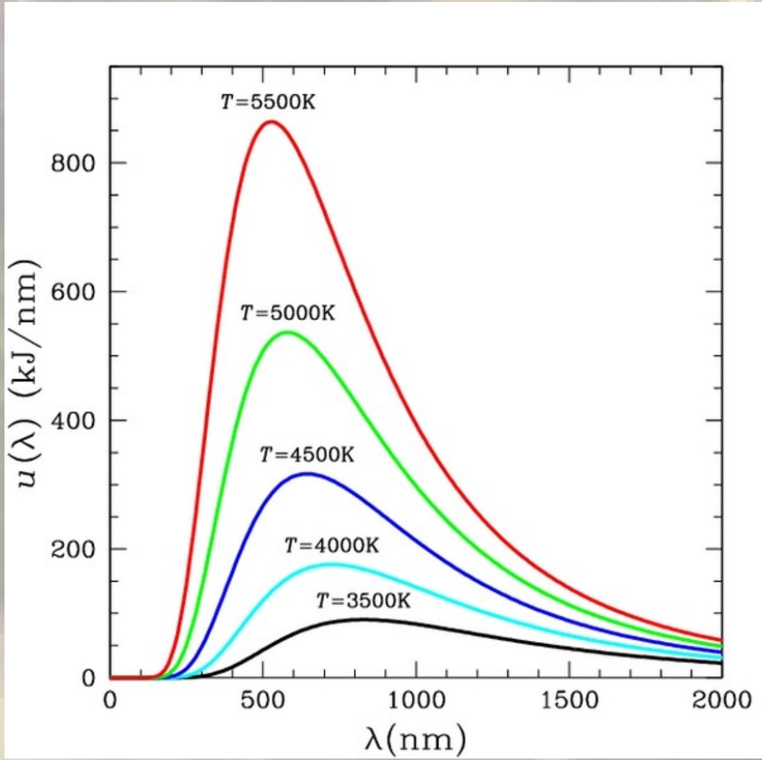
First formula to connect fundamental constants of thermodynamics, GR & QM!

Astro-BHs have temp < CMB
Micro BHs are very hot - radiate intensely

⇒ BH evaporate

Hawking radiation is purely thermal

only depends on M, Q, J, Col



Information Paradox

No hair (bald) theorem of BHs $\Rightarrow$ violation of baryon nr, lepton nr, flavour

Two BHs of equal M, J, Q, but made of matter and anti-matter are identical

Independent of all other information - i.e. what 'stuff' fell into BH

Information loss paradox - else BH must remember what it swallowed
info remains inside BH? What happens when it decays?

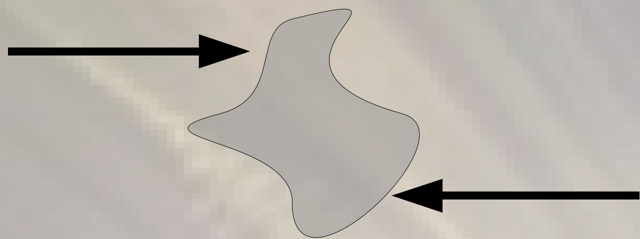
In QM time evolution is unitary transformation:

initial state $\langle \psi | \psi \rangle = \langle \psi | U^{\dagger} U | \psi \rangle = \langle \psi' | \psi' \rangle$ final state

Initial state BH transforms to final state of purely thermal radiation (M,Q,J)
this is a non-unitary transformation forbidden in QM - do not preserve probability!

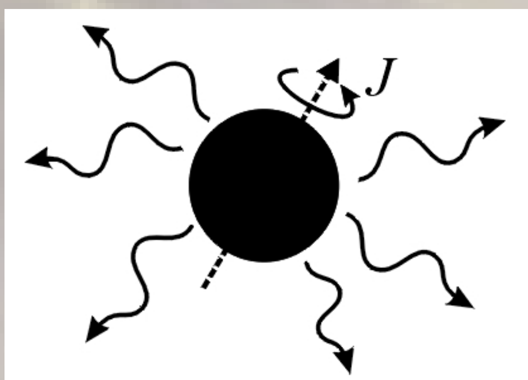
Hawking now claims non-thermal info-preserving radiation S. Hawking: hep-th/0507171

The Tragic Life of a Black Hole

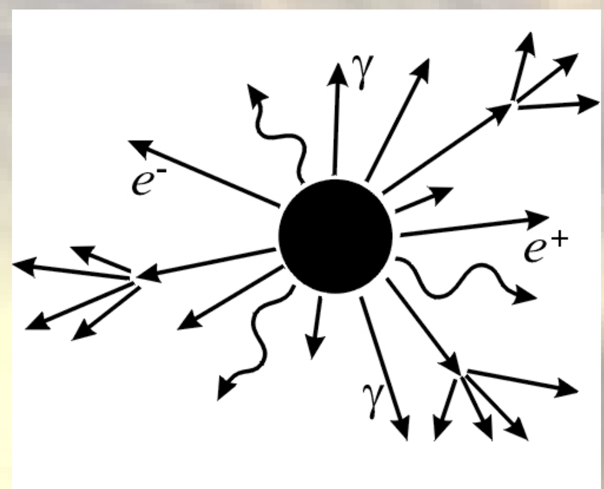


Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

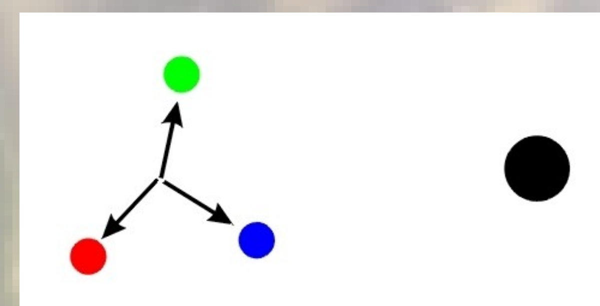
Extremely short lifetime ~ 10^{-25}s



Balding
Energy lost as BH settles into 'hairless' state



Evaporation
Thermal Hawking radiation in form of SM particles & gravitons
Greybody factors give emission probs for all quanta



Plank Phase
For $M_{BH} \sim M_D$ unknown quantum gravity effects dominates. BH left as stable remnant or final burst of particles **????**

pics: backreaction.blogspot.com

Limitations of the Models

Clearly much is missing in these models

- No knowledge of true quantum gravity
- Semi-classical approximation fails for $M_{BH} \sim M_D$
- Formation of event horizon Þ not all energy trapped inside
- Greybody emission factors - QFT in strongly curved spacetime
  - they have credence since solutions yield thermal spectra
  - i.e. conspiracy of nature to be self-consistent!
- Several calculations performed yield agreement at ~1% level

Gingrich: hep-ph/0609055

- Nevertheless calcs assume fixed metric...
- Phenomenological suppression of modes that increase |Q| or Colour

- Important to explore full phenomenological space
- Include all effects into MC simulations

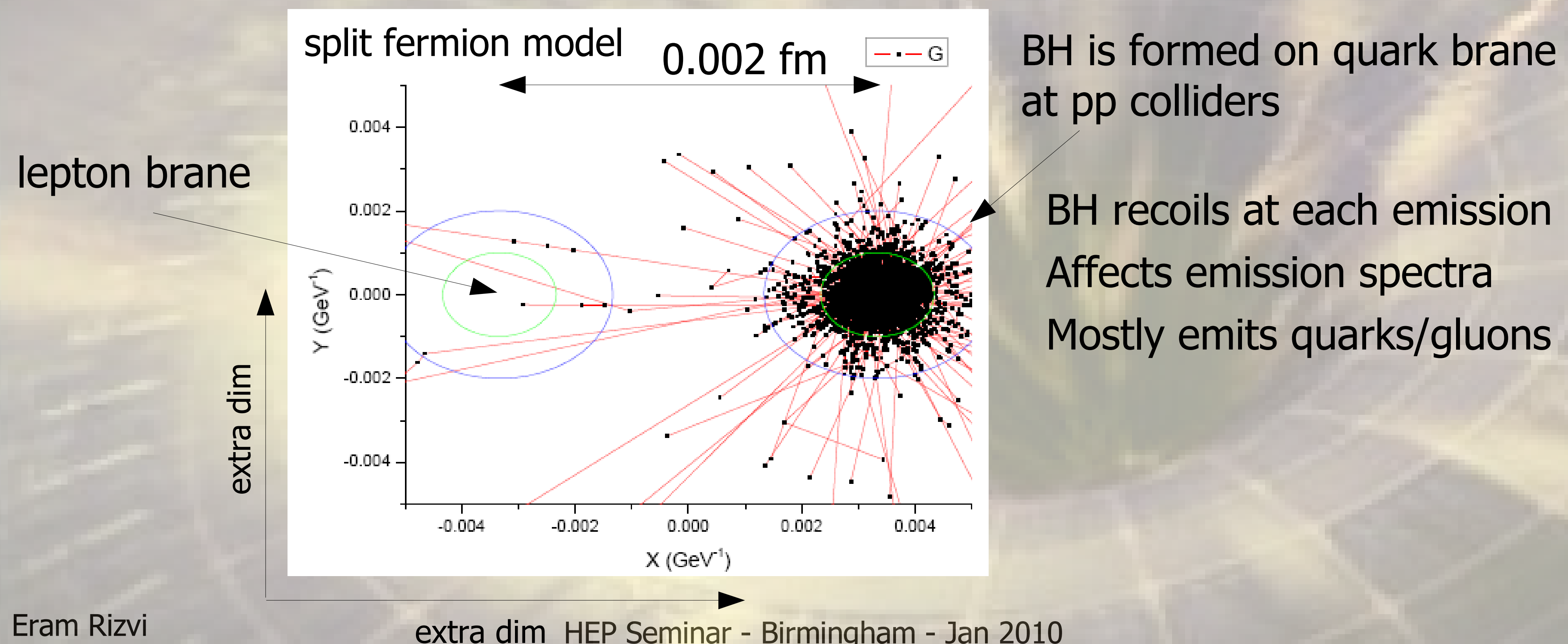
MC Generators

Incorporate all effects into MC models

- calculations of energy loss prior to horizon formation
- grey body factors
- rotation of BH (ang.mom)
- recoil of BH
- conservation/violation of B,L,flavour
- number, size & location of extra dimensions

BlackMax Dai et.al. arXiv:0711.3012
Charybdis Frost et.al. arXiv:0904.0979

Downloads: hepforge.org



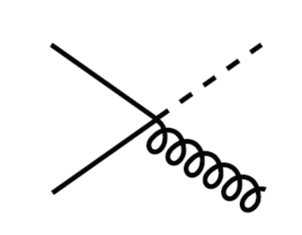
BH recoils at each emission

Affects emission spectra

Mostly emits quarks/gluons

Search for deviations from SM cross sections with increasing m Q^2 √s ...
Look for qq→ Gg scattering - monojet events (graviton unseen in extra dim)

Graviton scattering derived as low energy effective field theory
Giudice, Rattazzi, Wells: hep-ph/9811291



HERA:
H1: M_{D^-} > 0.78 TeV and M_{D^+}>0.82 TeV
ZEUS: M_{D^-} > 0.9 TeV and M_{D^+} > 0.88 TeV
coupling ±λ has unknown sign of interference with SM

LEP:
M_D = 1.5 TeV for n = 2 R = 0.2 μm
M_D = 0.75 TeV for n = 5 R = 400 fm

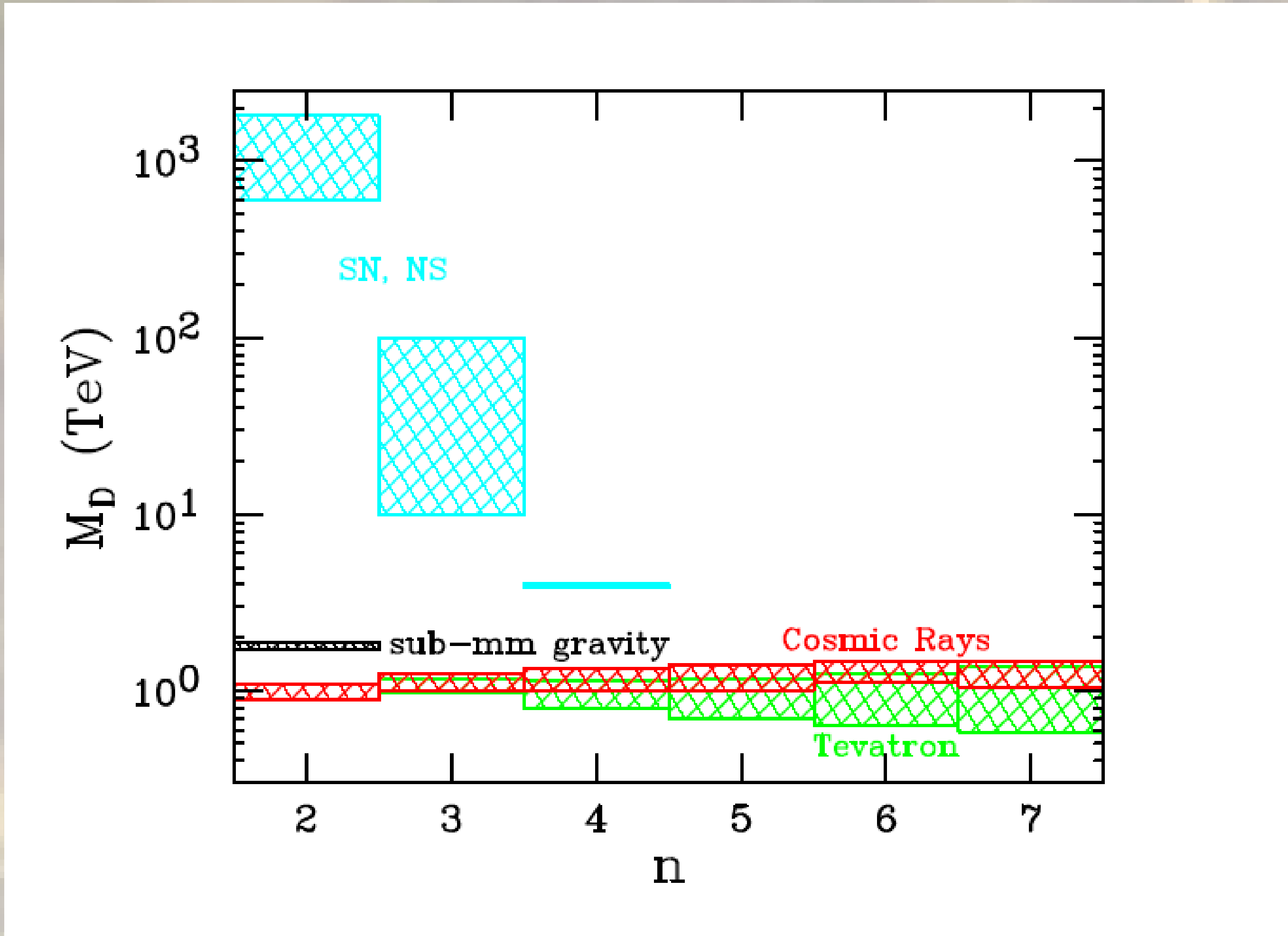
CDF:
M_D = 1.33 TeV for n = 2 R = 0.27 μm
M_D = 0.88 TeV for n = 6 R = 31fm

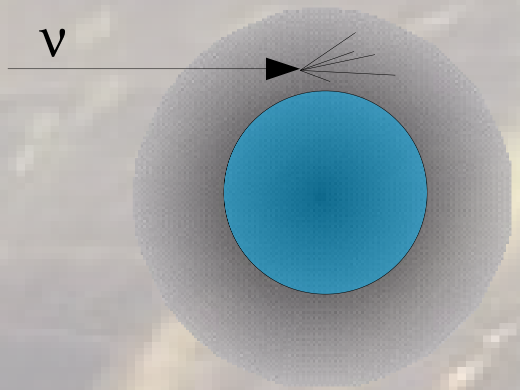
Variety of limits exclude ~ 1 TeV

D0 (ll, gg):
M_D = 1.23 TeV lower limit

Current Constraints

Anchordoqui et al: arXiv:hep-ph/0307228





ultra high energy neutrino showers deep in atmosphere horizontal

Summary of constraints from astrophysical measurements & colliders

Supernovae & neutron stars probe low n

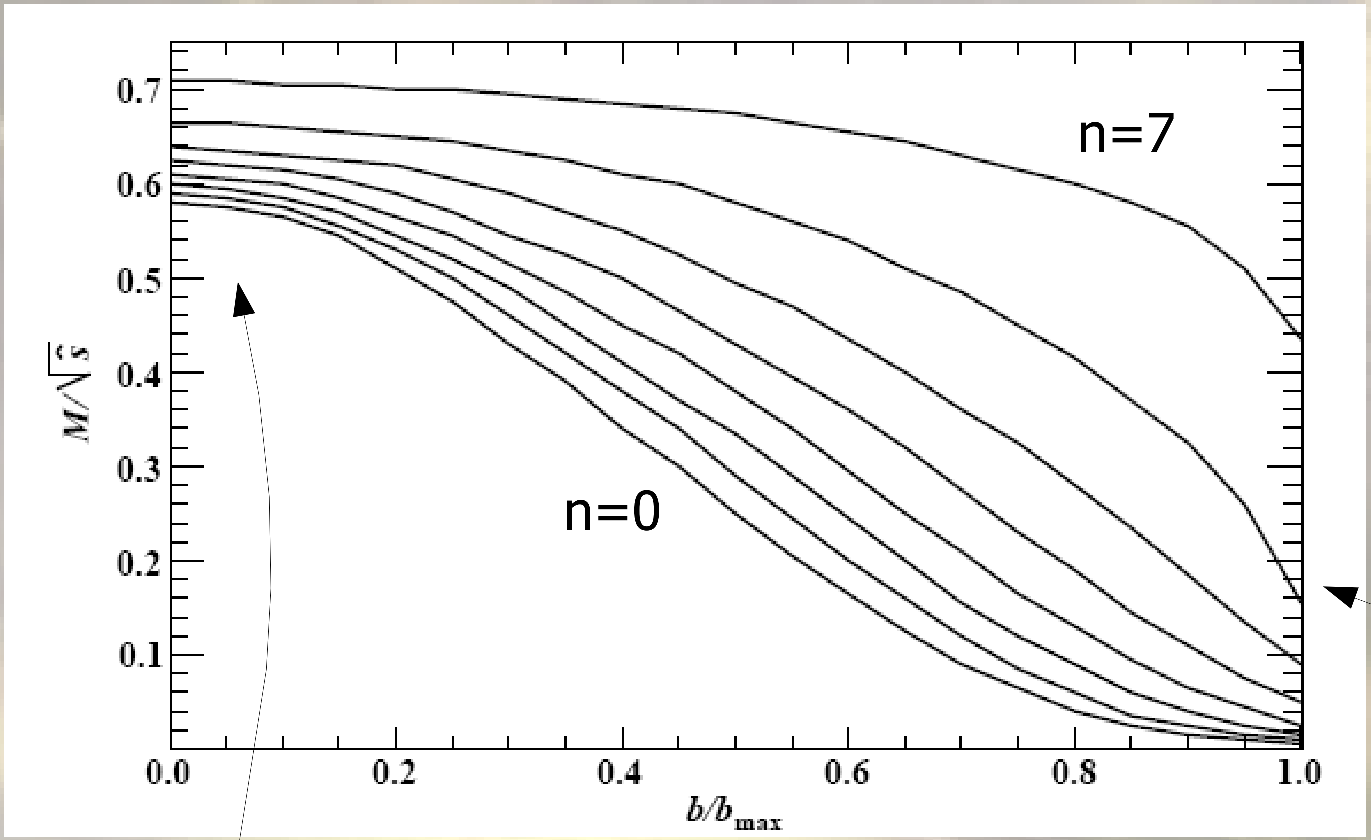
Colliders probe large n

Gingrich: hep-ph/0609055

Lower limits on fraction of trapped energy (indep. of M_D)

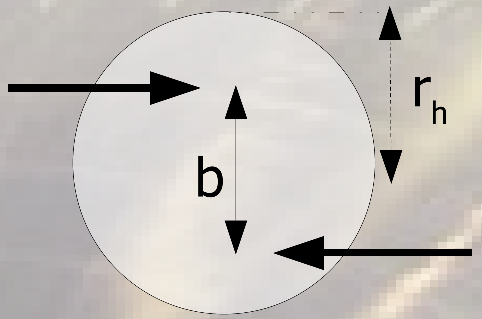
Form factors

r_h is generalisation of r_S for spinning BHs



b = impact parameter

b_{max} = horizon radius $2r_h$



Large b ⇒ large ang mom states

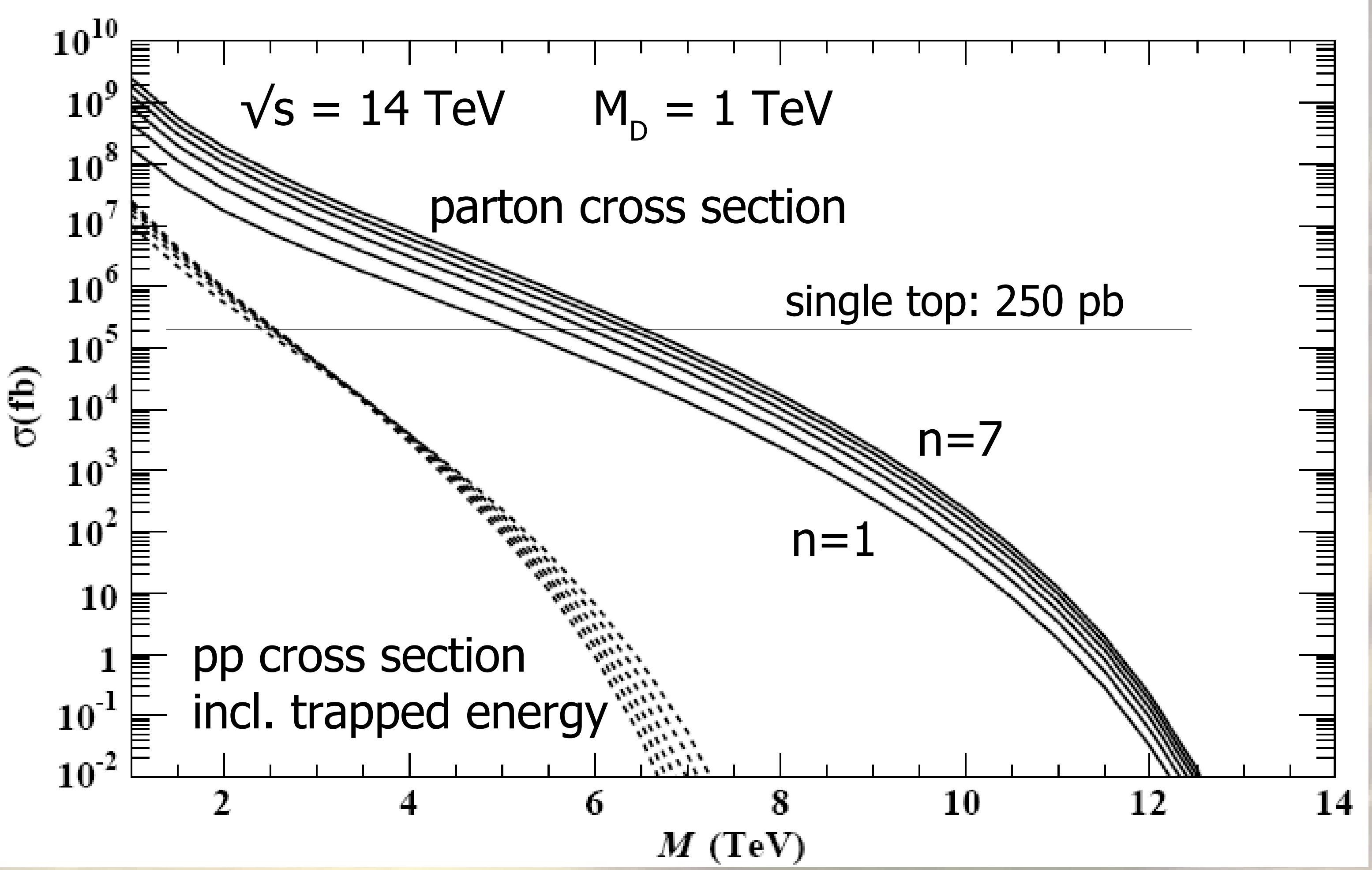
For 'head on' collisions (b=0) ~70% of energy is trapped in event horizon

For large impact parameter only 1% - 50% of energy forms BH

Cross Sections for LHC

Gingrich: hep-ph/0609055

Cross section lower limits



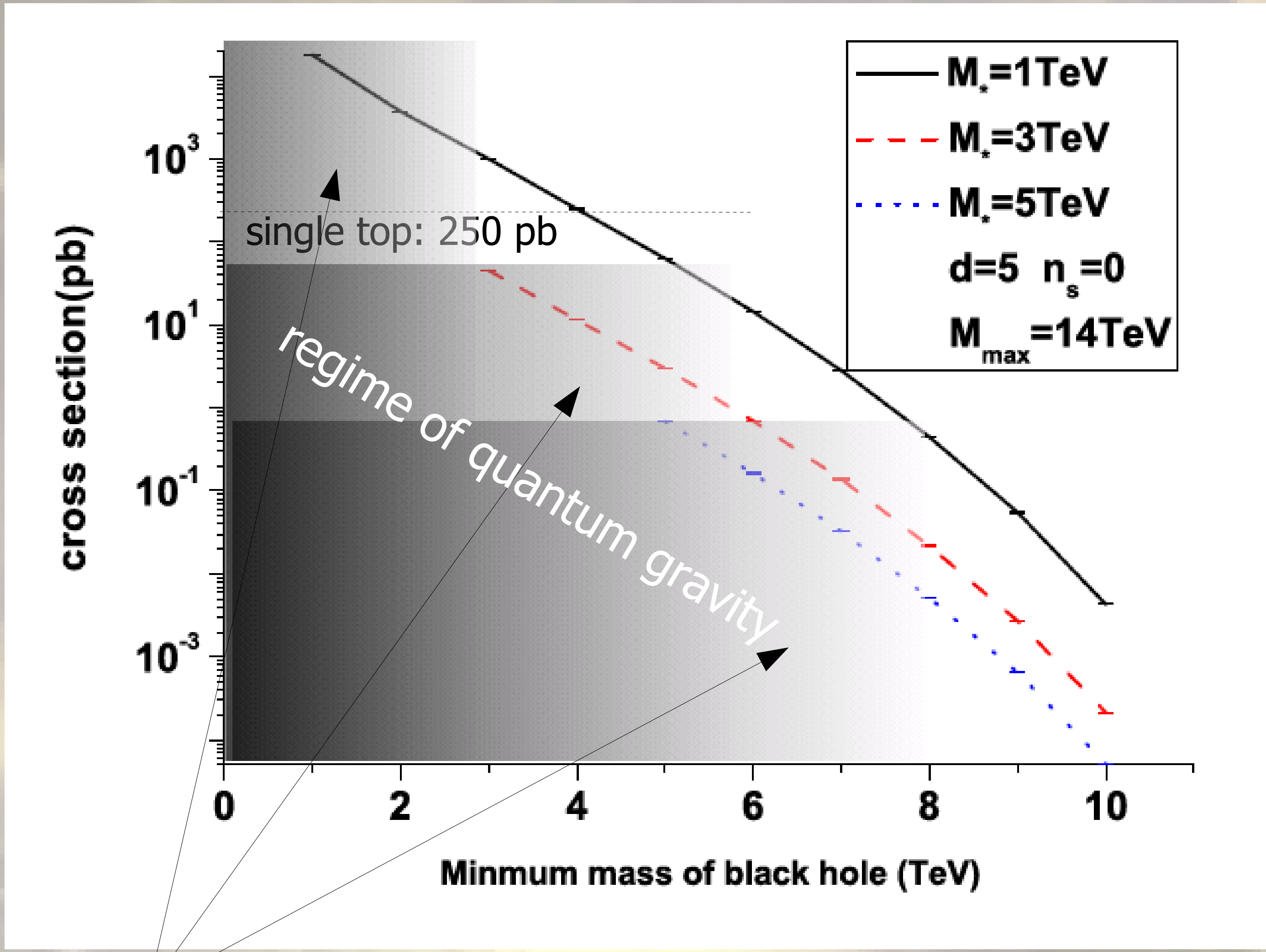
Potentially very large cross sections predicted

Horizon radius increases with n ⇒ cross sections increase with n

Cross Sections for LHC

BlackMax prediction for non-rotating BHs

Dai et al: arXiv 0711.3012



Close to M_D observe jump in 2→2 scattering?

May be dominant effect

Meade, Randall: arXiv 0808.3017

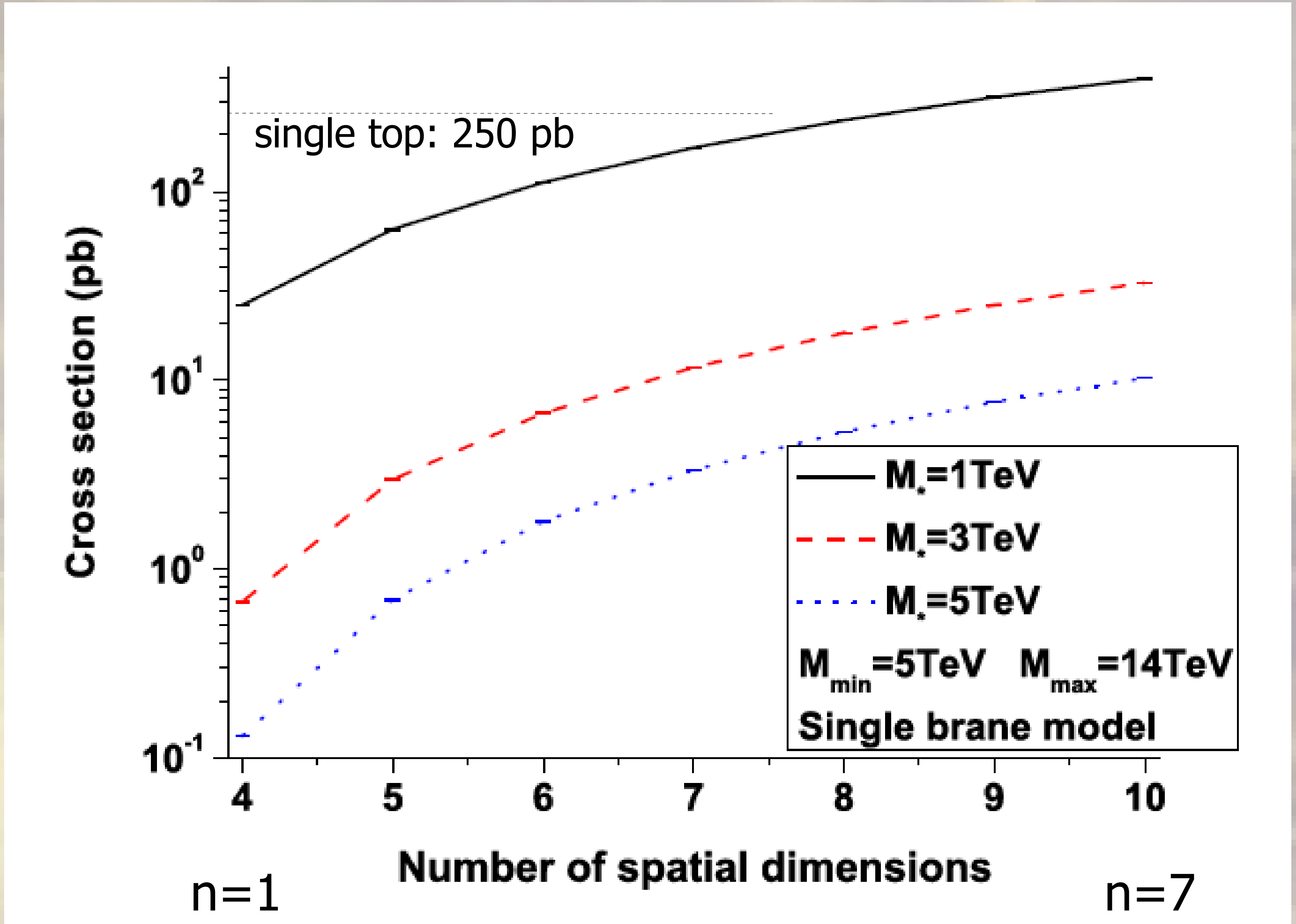
Semi-classical approach fails when $M_{BH} \sim M_D$

Don't expect BH to form - but gravitational scattering...?

Cross Sections for LHC

BlackMax prediction for non-rotating BHs

Dai et al: arXiv 0711.3012



Cross sections vary by ~ factor 10 for n=1®7

Factor ~30 suppression for M_D = 1 ® 3 TeV

Emission spectra change depending on the models chosen

Typical ratio ~ 8:1 hadrons:leptons

Leptons heavily suppressed in split fermion model

Graviton modes suppressed at low n

scenario	q+g	leptons	neutrinos	W/Z	G	H	photons
n=1 / J=0	79.0%	9.5%	3.9%	5.7%	0.2%	0.9%	0.8%
n=7 / J=0	74.0%	7.7%	3.2%	6.8%	6.5%	0.7%	1.5%
n=7 / J=0/ split=7	84.0%	1.8%	0.5%	5.4%	6.7%	0.3%	1.6%
n=7 / J>0	78.0%	6.5%	2.5%	9.6%	??	0.7%	2.6%

Uncalculated graviton greybody factors for J>0

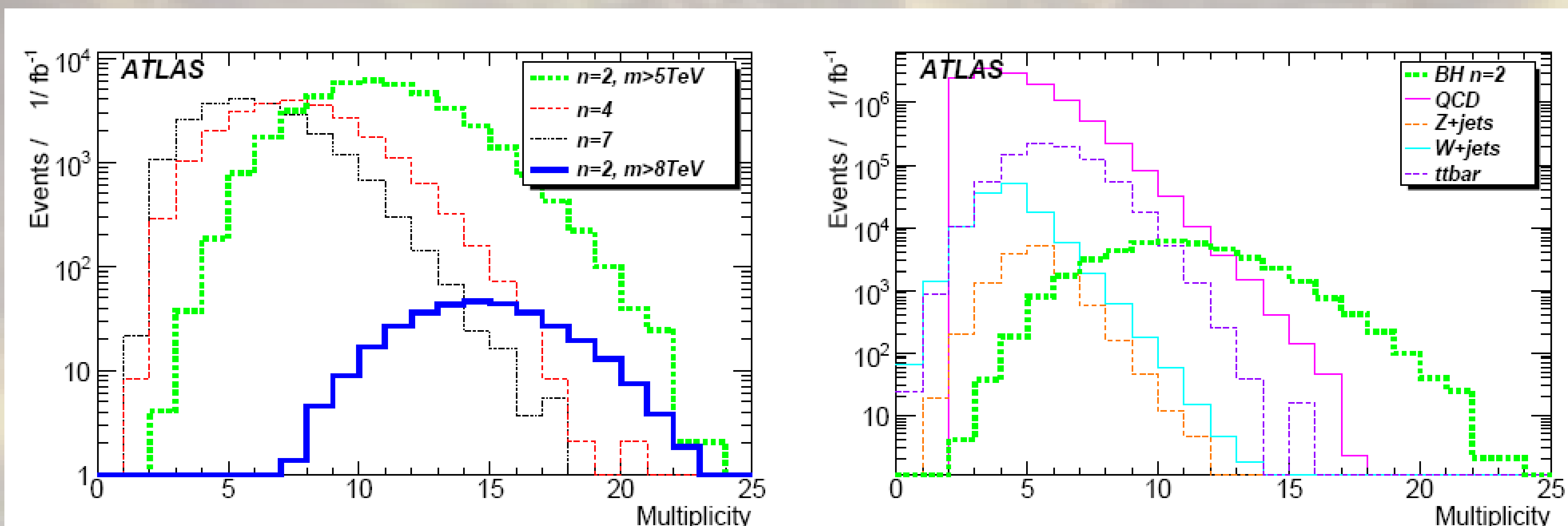
Expected to be large - super irradiance

Gravitons are spin-2 tensors

LHC Signatures

High multiplicity events: 10-40 particles from heavy state

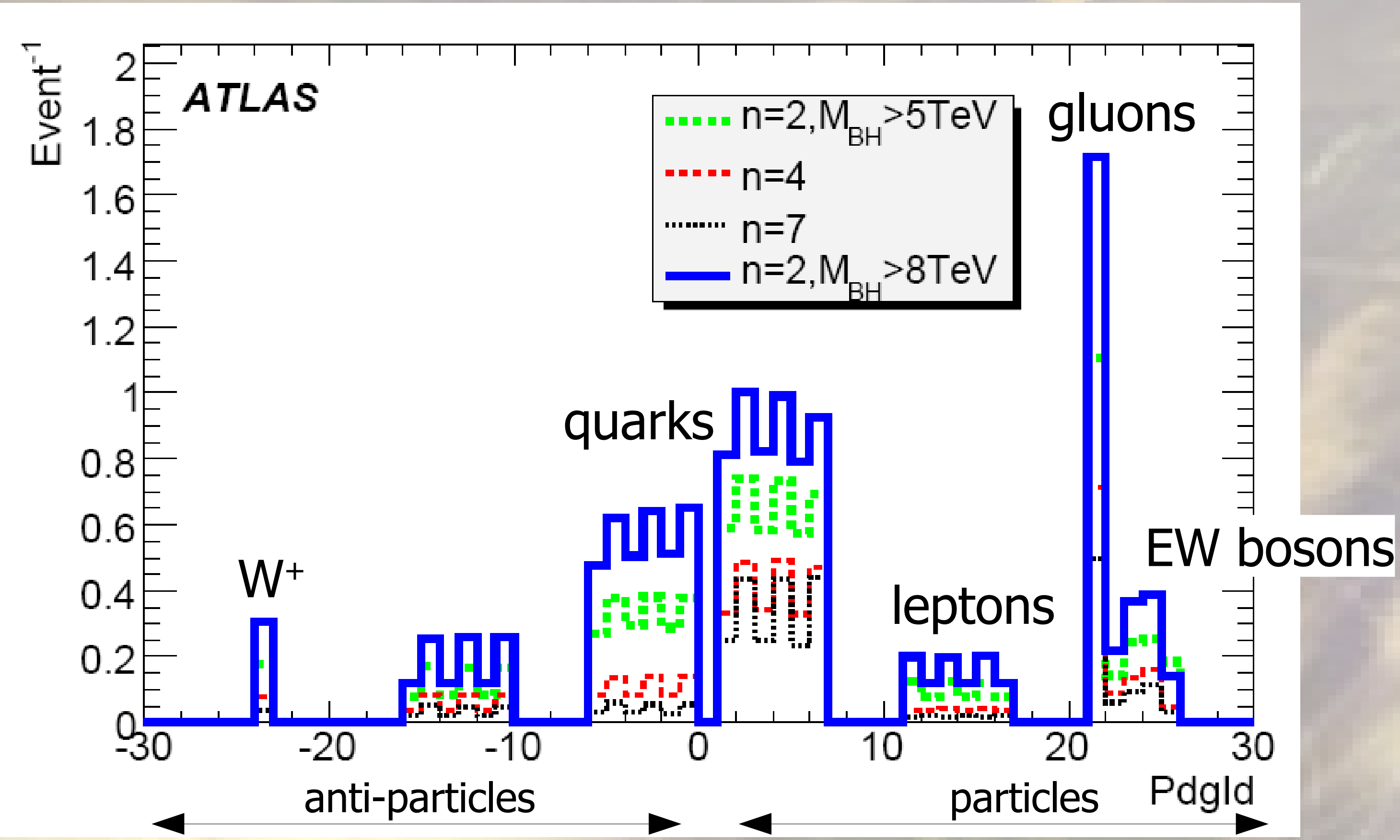
Hard P_T spectrum of decay particles



⟨N⟩ falls as n increases
(BH temp increases)

Multiplicity compared to SM

Multiplicity of particles by type in different models

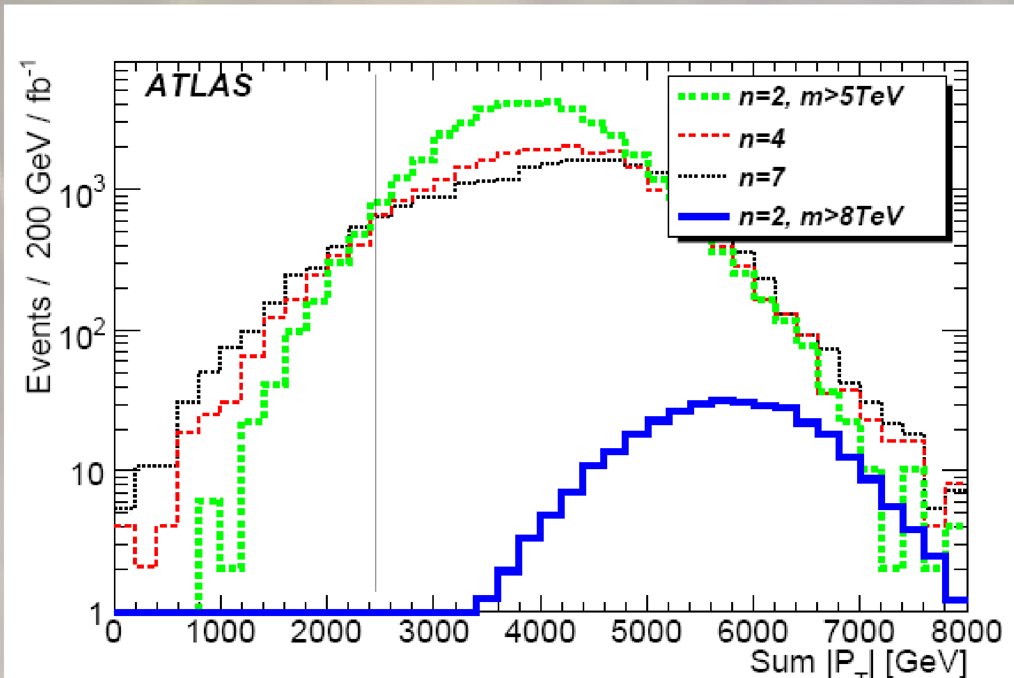


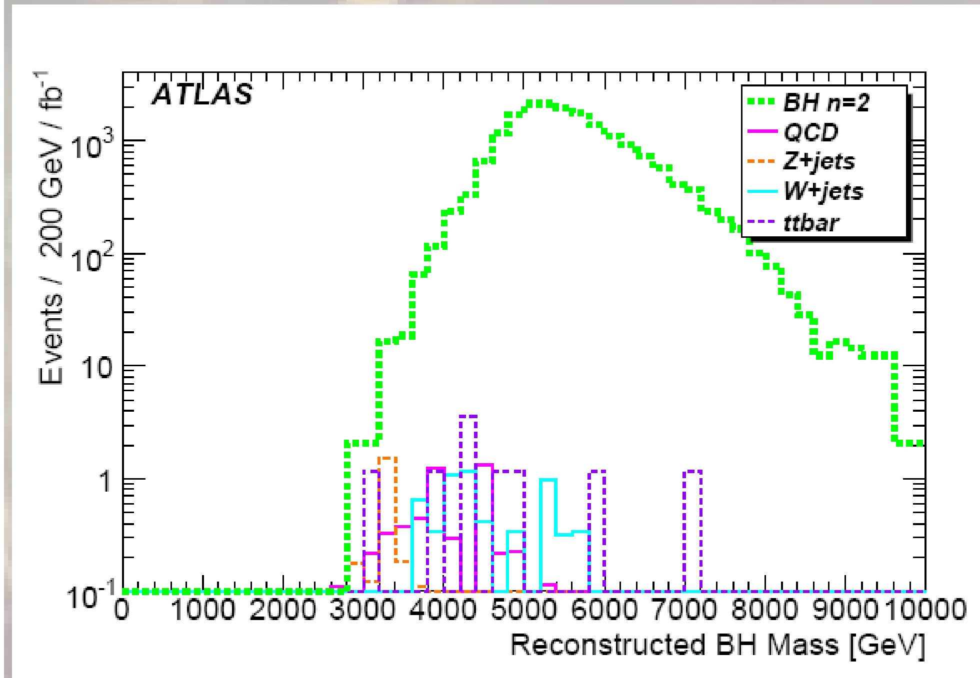
Higher multiplicity for larger mass

Quasi-democratic decays - fewer tops due to energy-momentum constraints

More particles than anti-particles due to pp initial state

$\mathcal{L}$ = 1 fb^{-1} M_{BH} > 5 TeV M_D=1 TeV n=2





$\Sigma |P_T| > 2.5$ TeV

$\Sigma |P_T| > 2.5$ TeV
lepton P_T > 50 GeV

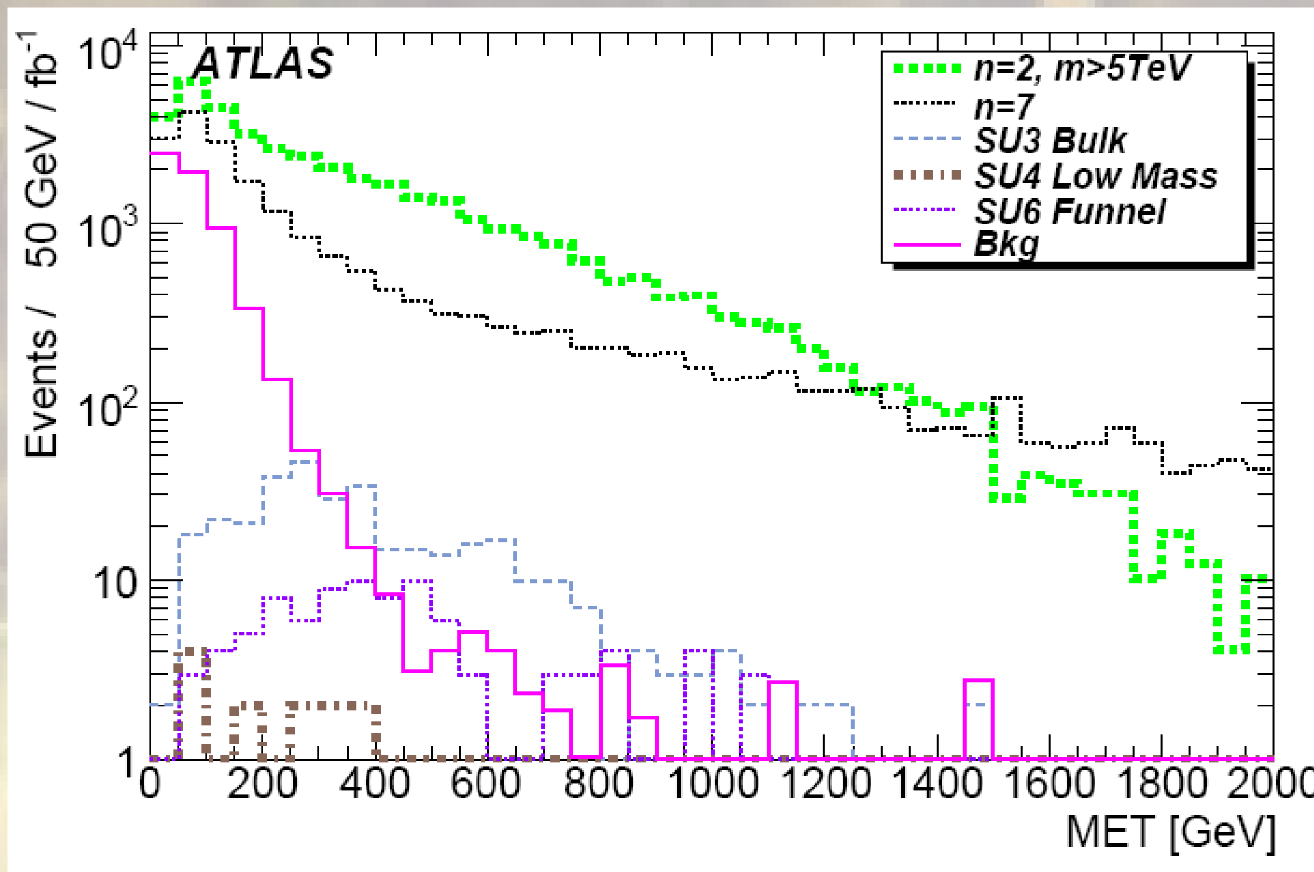
Requirement of additional high P_T lepton reduces QCD b/g dramatically

If Atlas / CMS cannot trigger these events we should give up now!
highest threshold jet trigger (400 GeV P_T) unprescaled, $\varepsilon = 100\%$

LHC Signatures

Missing E_T spectrum

Alternative selection: $\not{E}_T > 500$ GeV



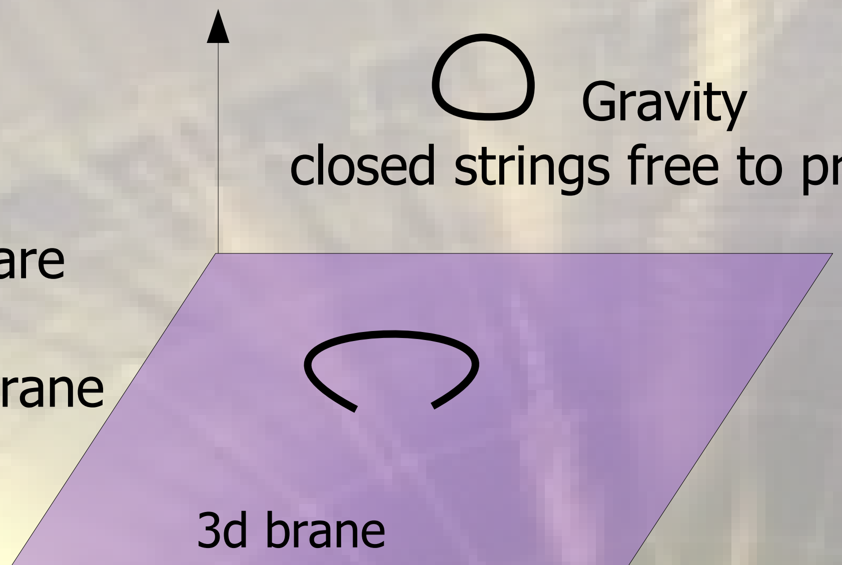
Largely from graviton emission in balding and Hawking phases

Compare:
- SUSY models at 3 different scales
- Soft SM expectation

But:
- Difficult to calibrate
- Limits M_{BH} measurement

Quantum Gravity & String Theory

True theory is missing



String theory may be candidate theory for quantum gravity

Requires 6-7 extra spatial dimensions

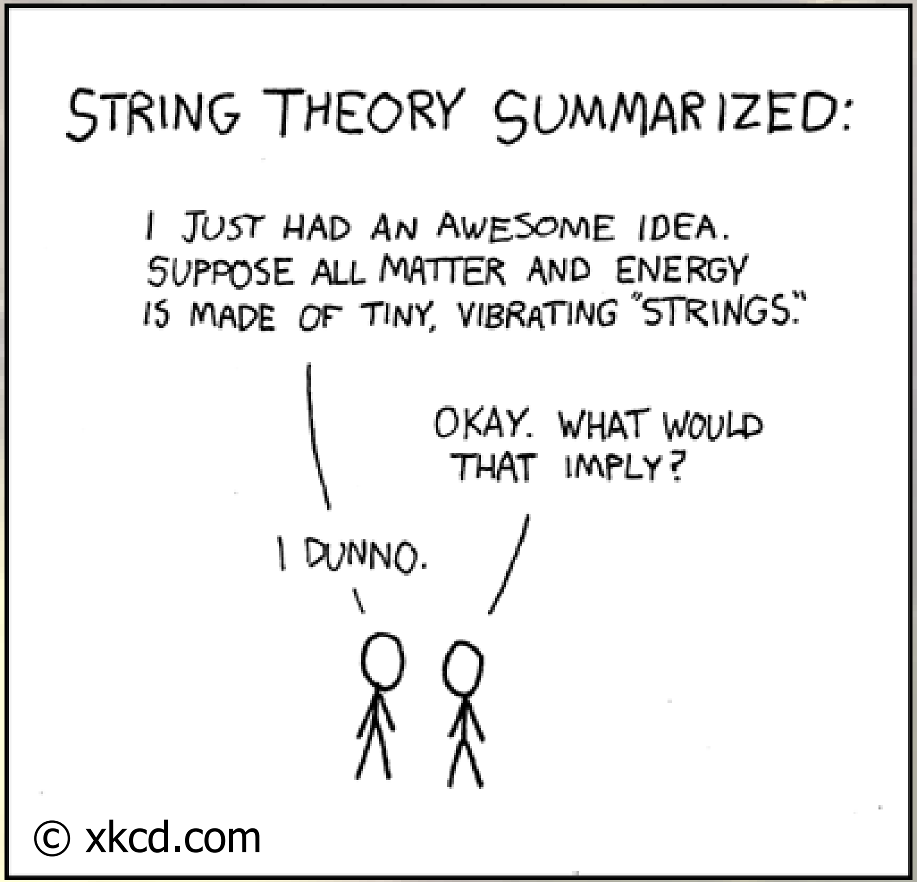
String balls: high entropy low mass string states - BH progenitors

Summary

- TeV scale gravity can potentially address many shortcomings of SM
- No fundamental theory yet - but very rich phenomenology!
- Large parameter space to be explored
- Some models do appear contrived...
  ... but nature is weird (who could have predicted quantum mechanics?)
- Nevertheless, we should look because we can!
- The 'holy grail' of quantum gravity may be experimentally within reach

"The landscape is magic, the trip is far from being over"

Carlo Rovelli
Quantum Gravity


STRING THEORY SUMMARIZED:
I JUST HAD AN AWESOME IDEA. SUPPOSE ALL MATTER AND ENERGY IS MADE OF TINY, VIBRATING "STRINGS."
OKAY. WHAT WOULD THAT IMPLY?
I DUNNO.
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