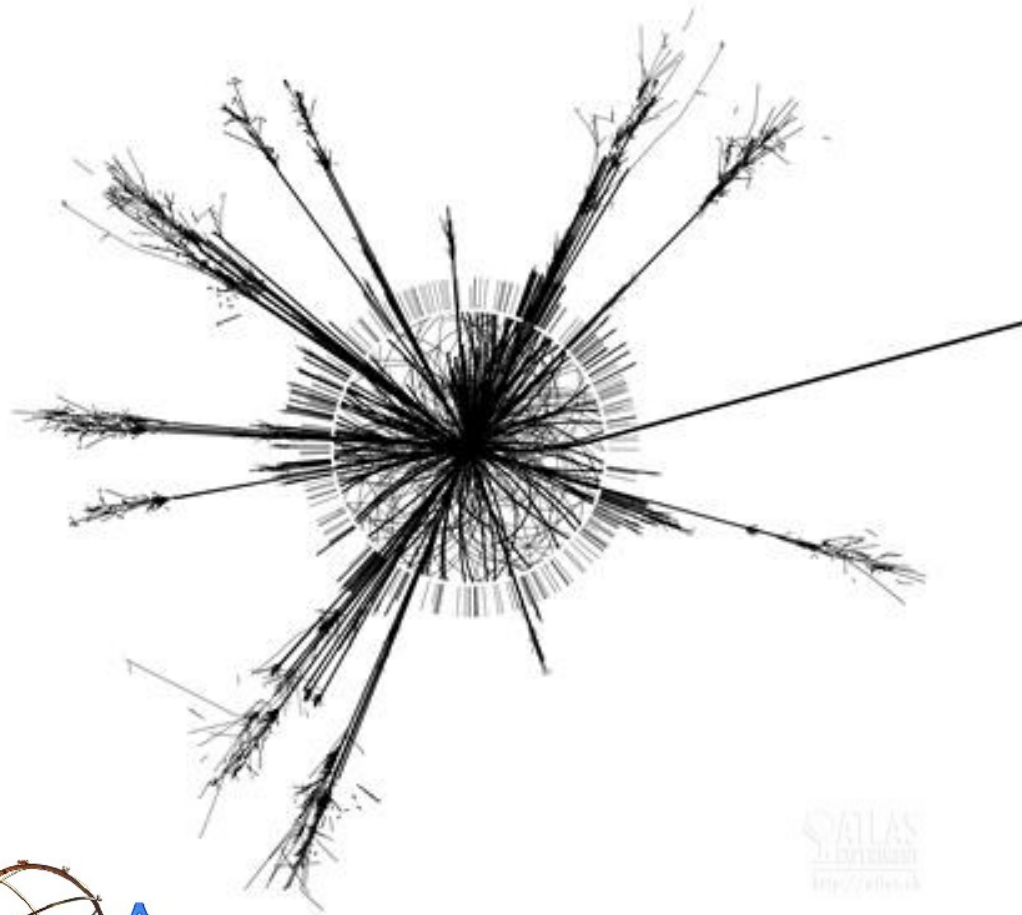
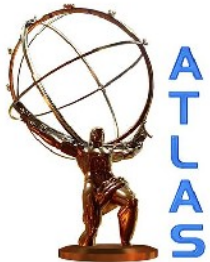


Black Holes, Extra Dimensions & the LHC



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



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



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 ($g_{\mu\nu}$)

Riemann tensor $R_{\mu\nu}$ describes tidal forces: residual accⁿ between test masses on initially parallel geodesics

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

Force of nature interacts with spacetime itself!

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

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

$$M_p \sim 10^{19} \text{ GeV} \quad (\Rightarrow \text{hierarchy problem})$$



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

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

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

area element on surface of sphere

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

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

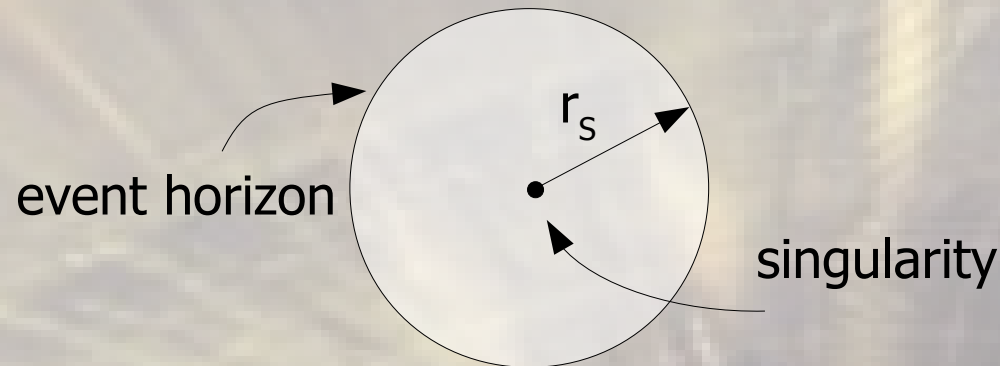
At energies close to Planck Mass distortions cannot be neglected

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

Schwarzschild radius is solⁿ of GR in case of non-rotating uncharged BHs

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

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 outside universe

For Earth $r_s = 1\text{cm}$

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

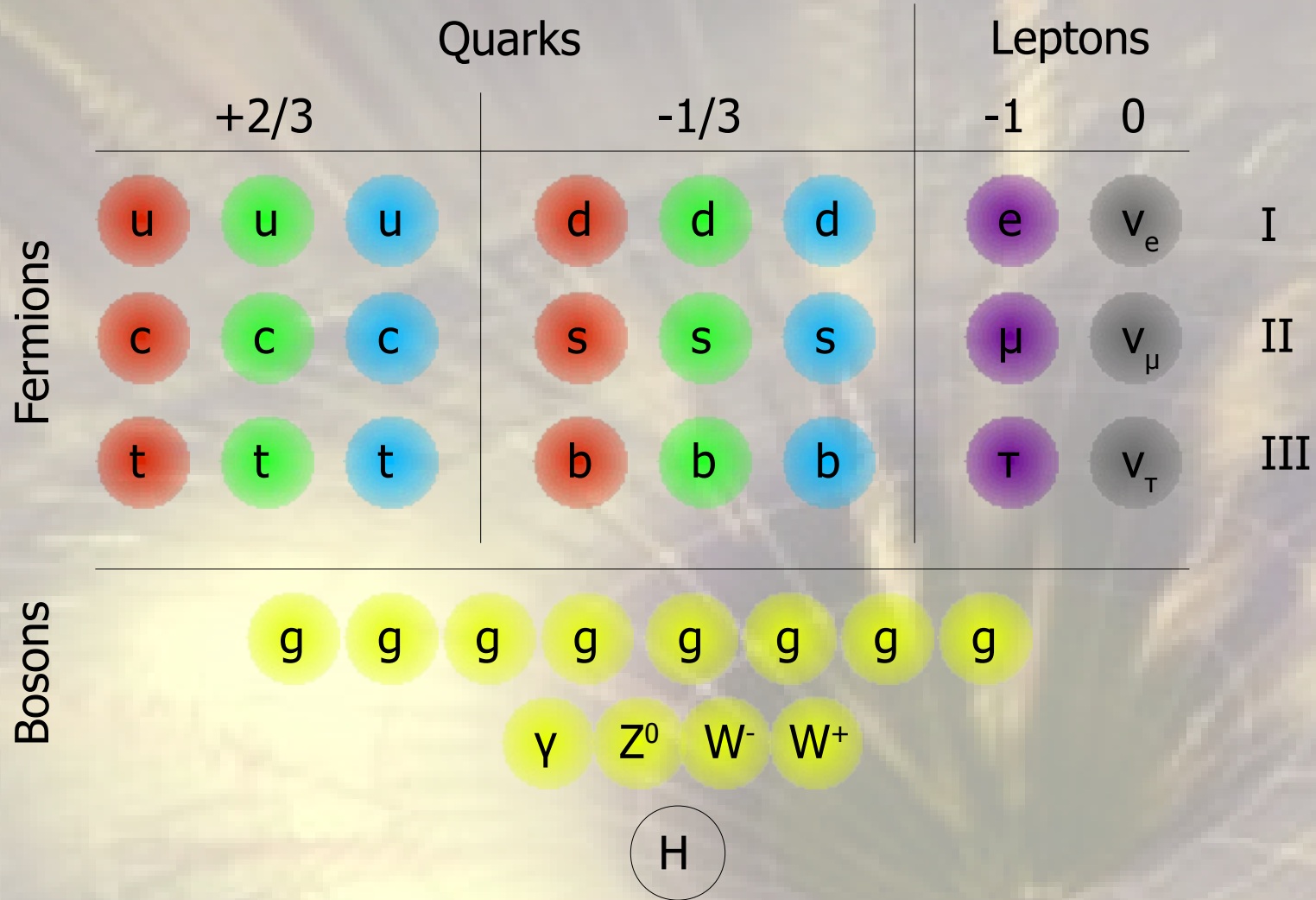


Jump to particle physics...

The Standard Model is fantastically successful

... but ...

The Problematic Standard Model



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



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

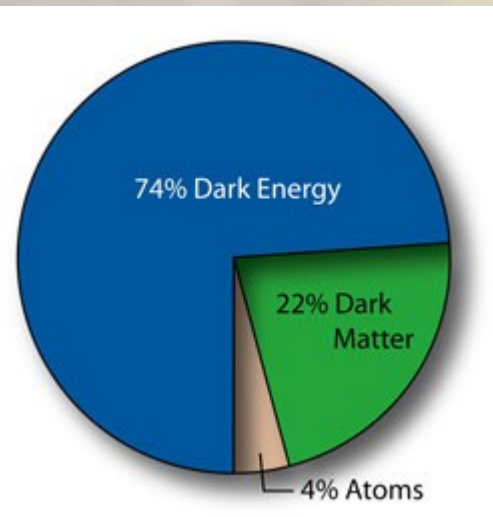
1 weak boson mass (other predicted from remaining EW params)

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

→ 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

Best guess is:
constant across cosmos
property of the vacuum

Evidence from

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

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 $\sim 10^{33}$ 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: $\Delta m_H^2 = +\frac{1}{16\pi^2} g^2 \Lambda^2$

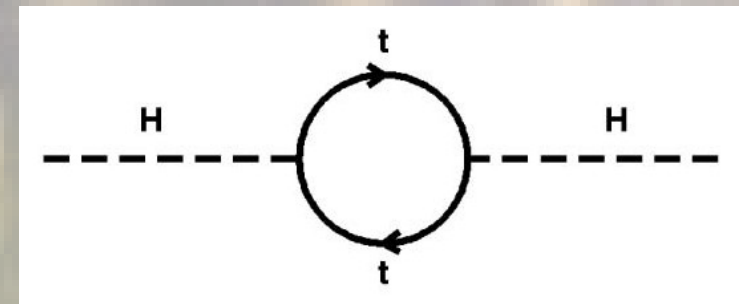
for Higgs: $\Delta m_H^2 = +\frac{1}{16\pi^2} \lambda^2 \Lambda^2$ (λ is Higgs self coupling)

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

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

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

- 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

$$\begin{aligned}
 & -\frac{1}{2}\partial_\mu g_\nu^\alpha \partial_\mu g_\nu^\alpha - g_\alpha f^{\alpha b c} \partial_\mu g_\nu^\alpha g_\mu^b g_\nu^c - \frac{1}{2}g_\nu^2 f^{\alpha b c} f^{\alpha b c} g_\mu^b g_\nu^c g_\mu^c g_\nu^\alpha + \\
 & \frac{1}{2}ig_\nu^2 (g_\mu^\alpha \gamma^\mu g_\nu^\alpha) g_\mu^\alpha + G^a \partial^2 G^a + g_\alpha f^{\alpha b c} \partial_\mu G^a G^b g_\nu^c - \partial_\mu W_\mu^+ \partial_\nu W_\nu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2\alpha} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_\Delta^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2\alpha} M \phi^0 \phi^0 - \beta_\Delta [\frac{2M^2}{g^2} + \\
 & \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_\Delta - igc_\Delta [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\nu^0 (W_\nu^+ \partial_\mu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\nu^+)] - ig s_\Delta [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_\Delta^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\nu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
 & g^2 s_\Delta^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\nu^+ W_\nu^-) + g^2 s_\Delta c_\Delta [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\nu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_\Delta [M^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_\Delta} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H) + \frac{1}{2}g \frac{1}{c_\Delta} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_\Delta}{c_\Delta} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_\Delta M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_\Delta^2}{2c_\Delta} Z_\nu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_\Delta A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_\Delta} Z_\nu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(\phi^+ \phi^- - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_\Delta^2}{c_\Delta} Z_\nu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_\Delta^2}{c_\Delta} Z_\nu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_\Delta A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_\Delta A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{2c_\Delta}{\alpha} (2c_\Delta^2 - 1) Z_\nu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_\Delta^2 A_\mu A_\nu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_\nu \gamma^\mu \nu^\lambda - \partial^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^2) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
 & m_d^2) d_j^\lambda + ig s_\Delta A_\mu [-(e^\lambda \gamma e^\lambda) + \bar{u}_j^\lambda \gamma u_j^\lambda] - \frac{1}{3}(\bar{d}_j^\lambda \gamma d_j^\lambda)] + \frac{ie}{6c_\Delta} Z_\nu^0 [(e^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_\Delta^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) u_j^\lambda) + \\
 & (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_\Delta^2 - \gamma^5) d_j^\lambda)] + \frac{ie}{2} W_\mu^+ [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
 & \gamma^5) C_{\Delta e} d_j^\lambda)] + \frac{ie}{2c_\Delta} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\Delta e} \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \\
 & \frac{ie}{2c_\Delta} \frac{m_\Delta^2}{M^2} [-\phi^+ (\partial^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\partial^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_\Delta^2}{M^2} [H (e^\lambda e^\lambda) + \\
 & i\phi^0 (e^\lambda \gamma^5 e^\lambda)] + \frac{ie}{2M\gamma^2} \phi^+ [-m_\Delta^2 (\bar{u}_j^\lambda C_{\Delta e} (1 - \gamma^5) d_j^\lambda) + m_\Delta^2 (\bar{u}_j^\lambda C_{\Delta e} (1 + \\
 & \gamma^5) d_j^\lambda) + \frac{ie}{2M\gamma^2} \phi^- [m_\Delta^2 (\bar{d}_j^\lambda C_{\Delta e}^1 (1 + \gamma^5) u_j^\lambda) - m_\Delta^2 (\bar{d}_j^\lambda C_{\Delta e}^1 (1 - \gamma^5) u_j^\lambda)] - \\
 & \frac{g}{2} \frac{m_\Delta^2}{M^2} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\Delta^2}{M^2} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ie}{2} \frac{m_\Delta^2}{M^2} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ie}{2} \frac{m_\Delta^2}{M^2} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
 & X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M^2}{c_\Delta^2}) X^0 + Y \partial^2 Y + \\
 & igc_\Delta W_\mu^+ (\partial_\mu X^0 X^- - \partial_\mu X^+ X^0) + ig s_\Delta W_\mu^+ (\partial_\mu Y X^- - \partial_\mu X^+ Y) + \\
 & igc_\Delta W_\mu^- (\partial_\mu X^- X^0 - \partial_\mu X^0 X^+) + ig s_\Delta W_\mu^- (\partial_\mu X^- Y - \partial_\mu Y X^+) + \\
 & igc_\Delta Z_\mu^0 (\partial_\mu X^+ X^- - \partial_\mu X^- X^+) + ig s_\Delta A_\mu (\partial_\mu X^+ X^- - \partial_\mu X^- X^+) - \\
 & \frac{1}{2}g M [X^+ X^+ H + X^- X^- H + \frac{1}{c_\Delta} X^0 X^0 H] + \frac{1-2c_\Delta^2}{2c_\Delta} ig M [X^+ X^0 \phi^+ - \\
 & X^- X^0 \phi^-] + \frac{1}{2c_\Delta} ig M [X^0 X^- \phi^+ - X^0 X^+ \phi^-] + ig M s_\Delta [X^0 X^- \phi^+ - \\
 & X^0 X^+ \phi^-] + \frac{1}{2}ig M [X^+ X^+ \phi^0 - X^- X^- \phi^0]
 \end{aligned}$$



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)

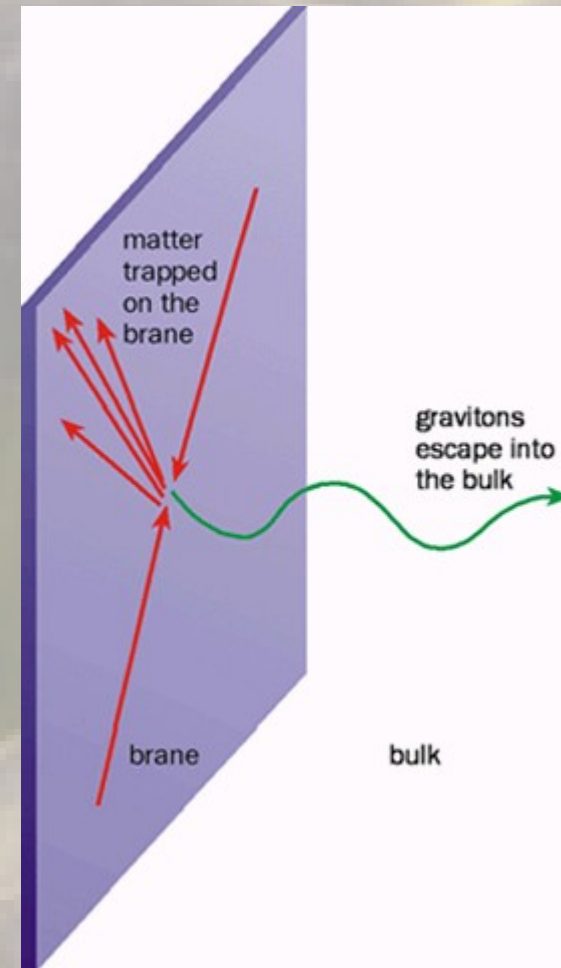
Alternative approach

"If the mountain will not come to Mohammed, then Mohammed must go to the mountain." ⁻¹

Perhaps we can bring M_p down to ~ 1 TeV

Introduce large extra spatial dimensions (large ~ 1 mm)

- 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 accommodated in string theory

- requires 10 / 11 spatial dimensions

- predicted spin 2 massless particle (graviton)

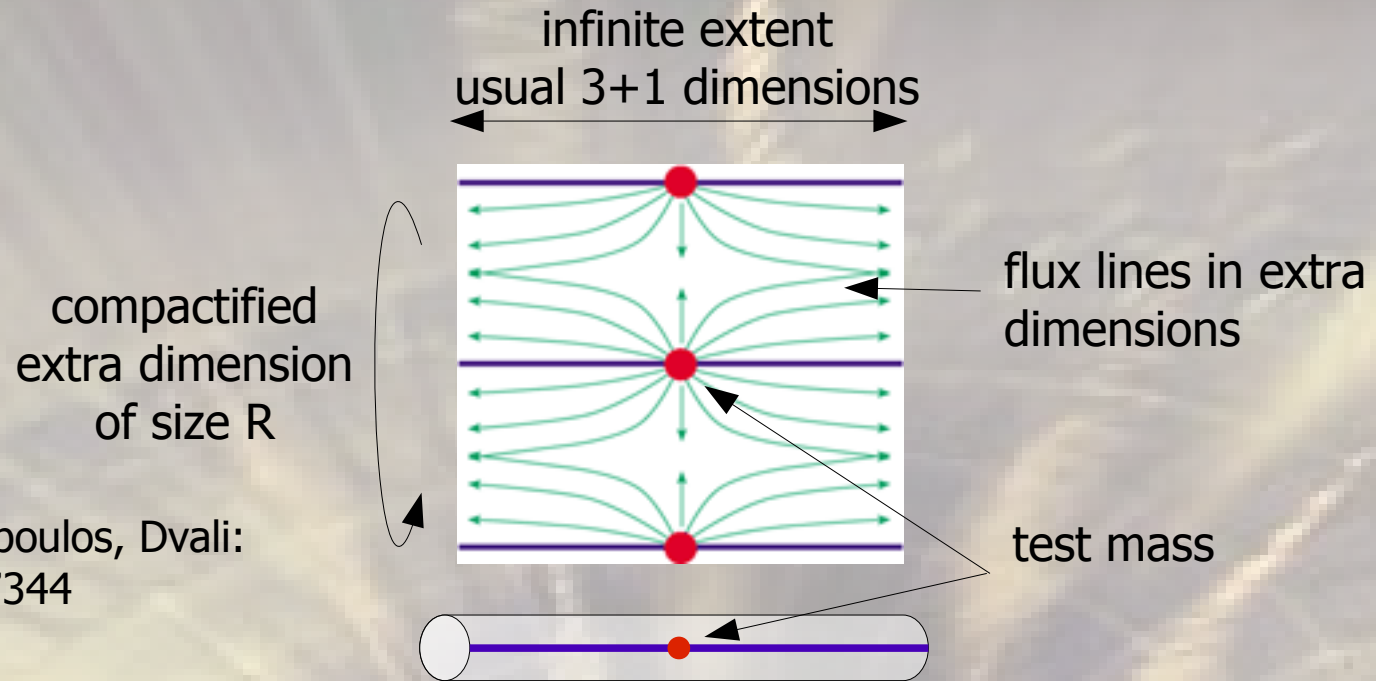
 - graviton is expected to be massless (gravity has infinite range)

 - graviton is expected to be spin 2

 - (since gravity is described by 2nd 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 potential well)
- Higher order modes appear as higher energy excitations
- Mass difference between successive states related to size of dimension R
- Can lead to infinite 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: $M^2 = E^2 - (P_x^2 - P_y^2 - P_z^2) - P_n^2$



Why are the extra dims $< 1\text{mm}$?

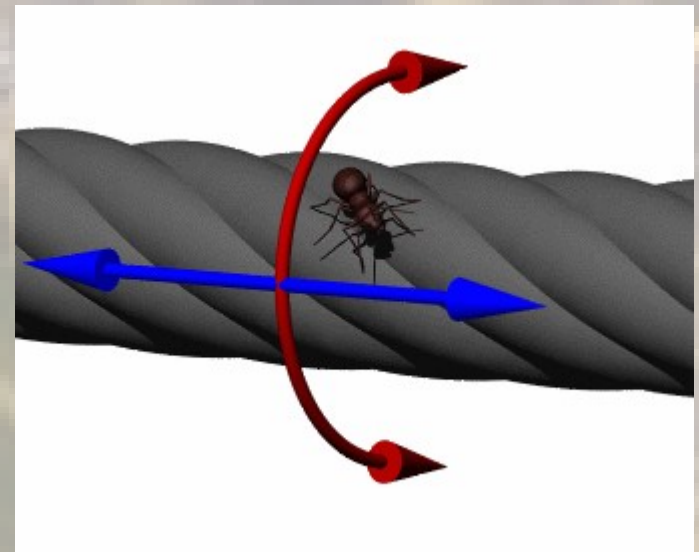
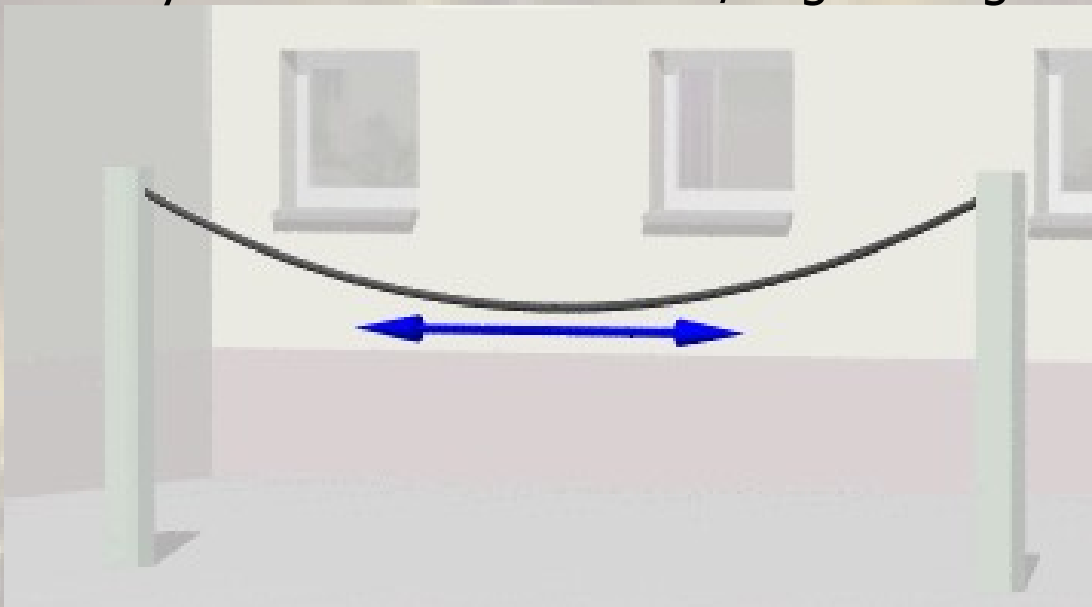
gravity has only been tested down to this scale!

current torsion balance experiments set limit on $1/r^2$ dependence to $< 0.16\text{mm}$

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

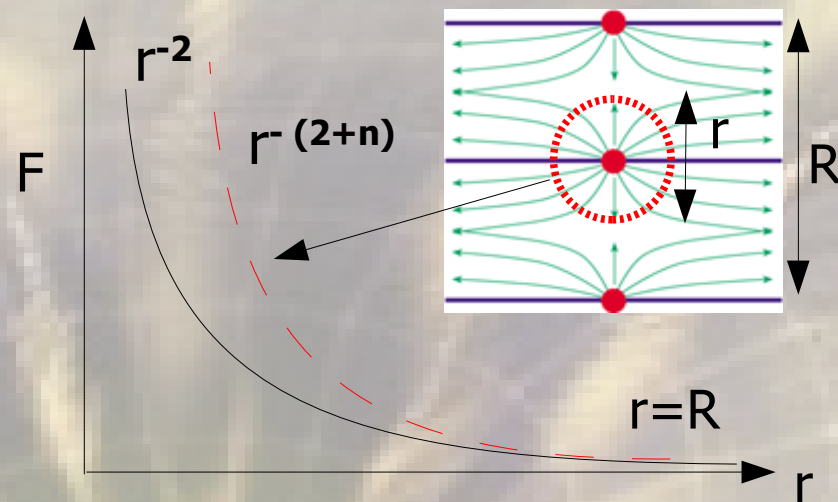
$$\int \mathbf{g} \cdot d\mathbf{A} = -4\pi M \quad \text{yields Newton's law} \quad F = G \frac{m_1 m_2}{r^2}$$

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 $r \gg R$ 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

$$M_D^{2+n} = \frac{\hbar c}{G_D} = \frac{M_P^2}{R^n}$$

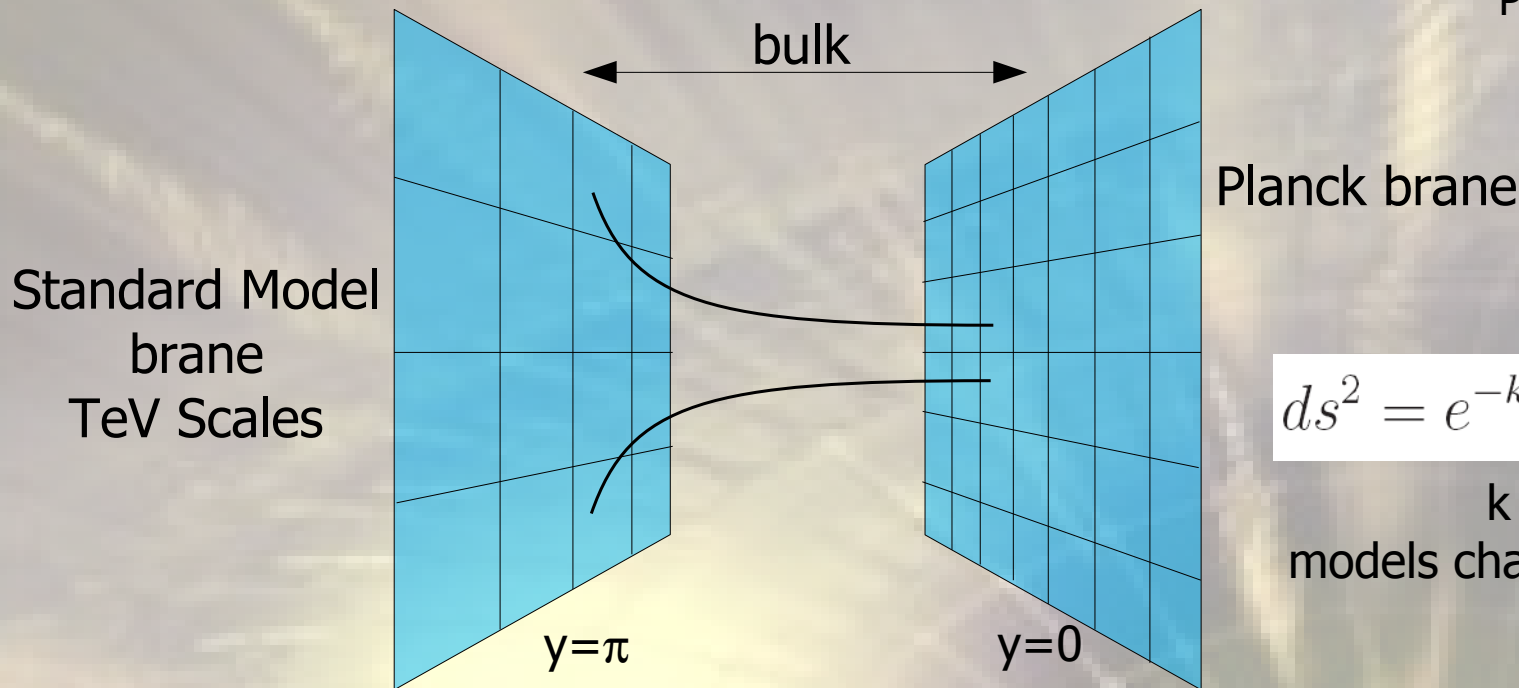
Thus M_D can be ~ 1 TeV when R^n is large

For $n=1$ and $M_D=1$ TeV then $R \sim 10^{16}m \Rightarrow$ 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 $\propto 1/E$

Dark energy is $\sim 74\%$ of critical density of universe

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

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

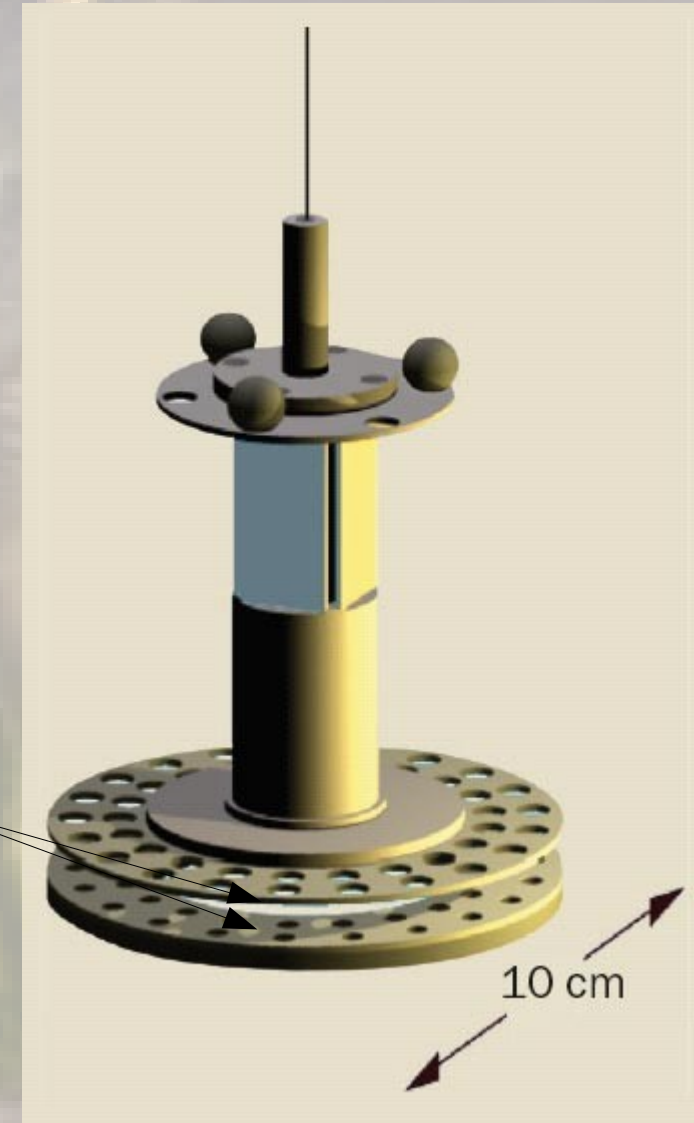
could be a fundamental distance scale...

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)



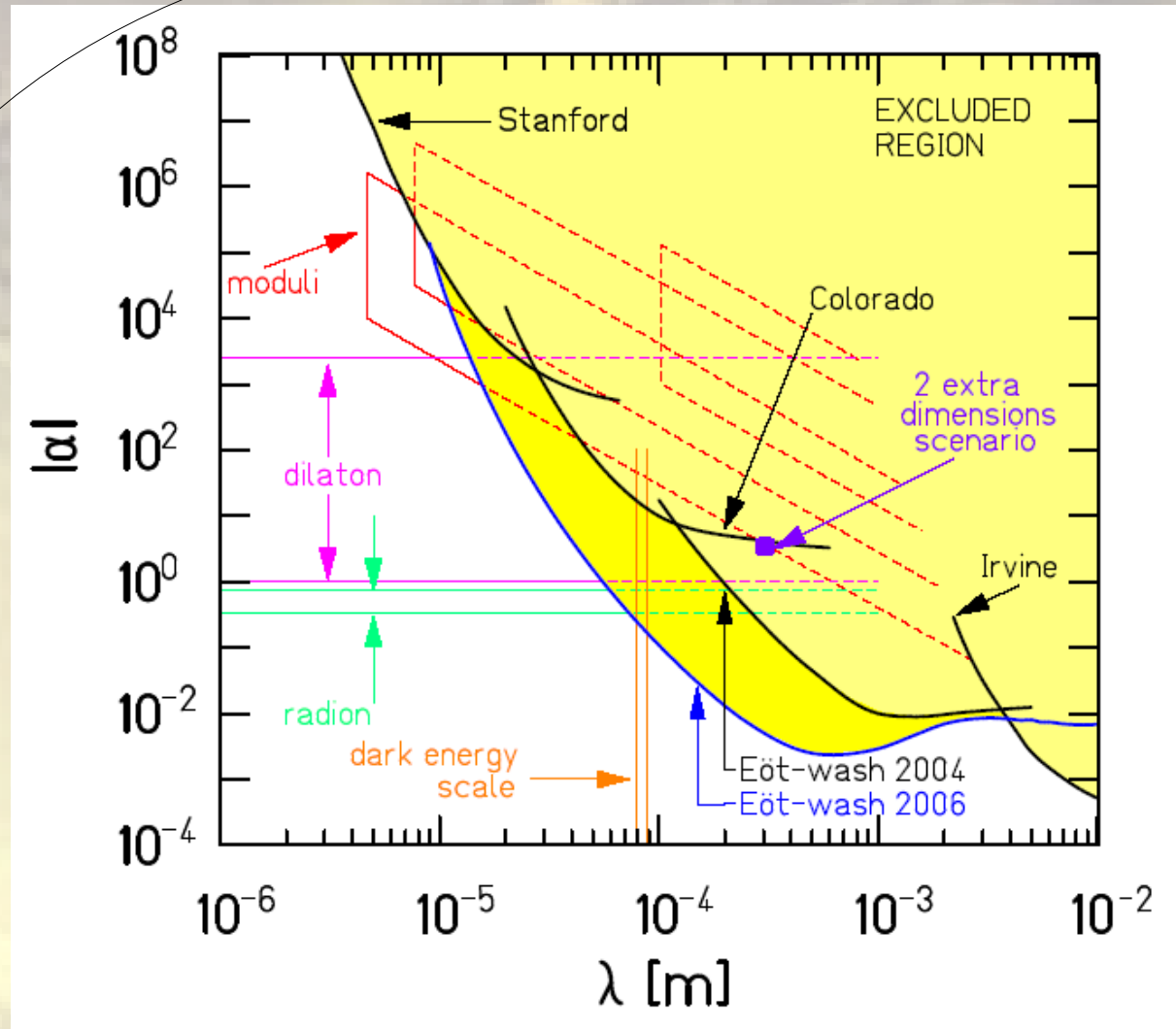


$$V(r) = -G \frac{m_1 m_2}{r} [1 + \alpha \exp(-r/\lambda)]$$

Phys.Rev.Lett.98:021101, 2007

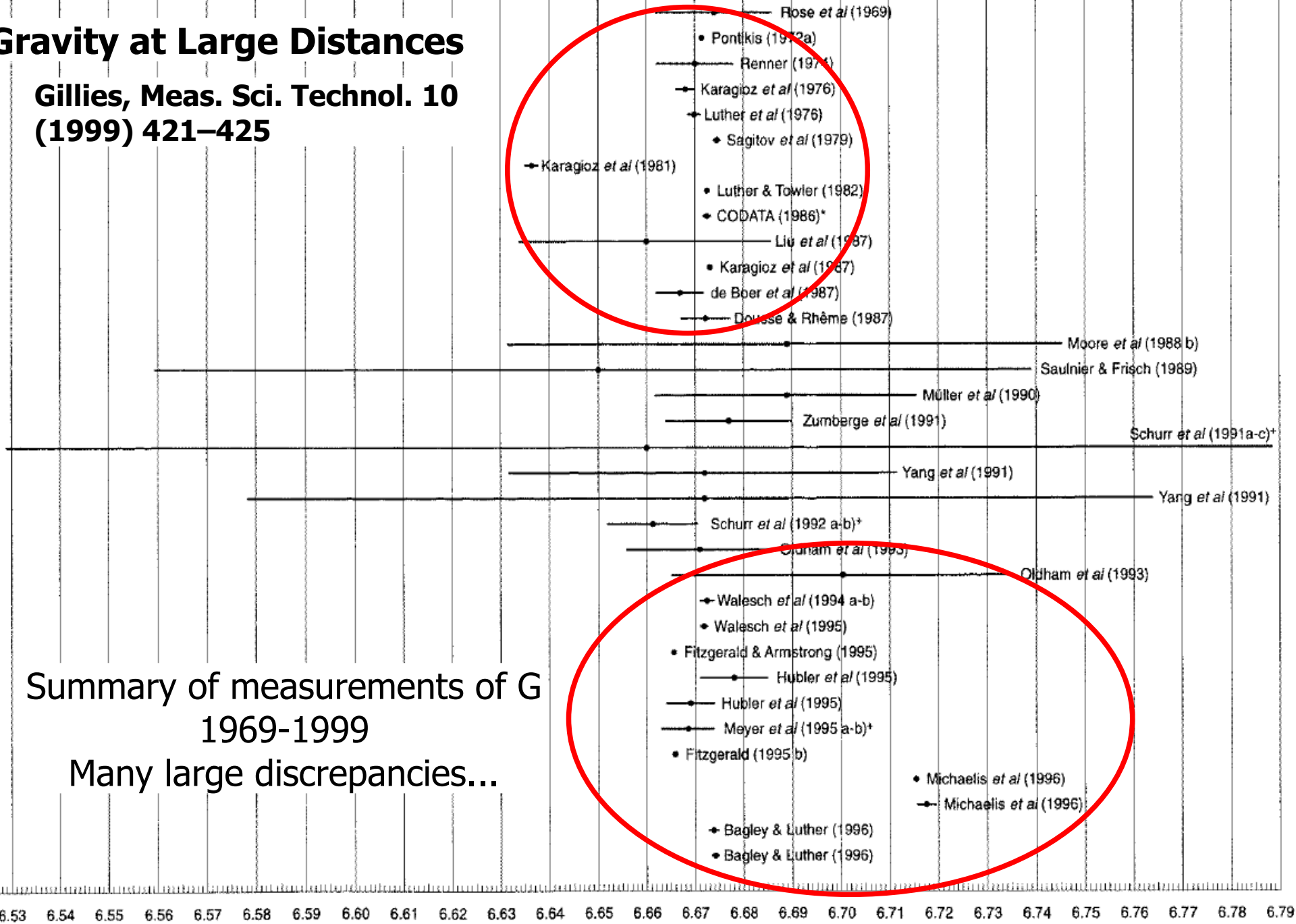
strength of new Yukawa-like potential
 range of new Yukawa-like potential

Inverse square law holds for $\lambda < 56\mu\text{m}$
 \Rightarrow extra dims have
 $R < 44\mu\text{m}$ 95% C.L.



Gravity at Large Distances

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



* See Cohen and Taylor (1987).

x10⁻¹¹ m³s⁻²kg⁻¹

* The error bars represent the quadrated sum of the individually listed Type A and Type B uncertainties.

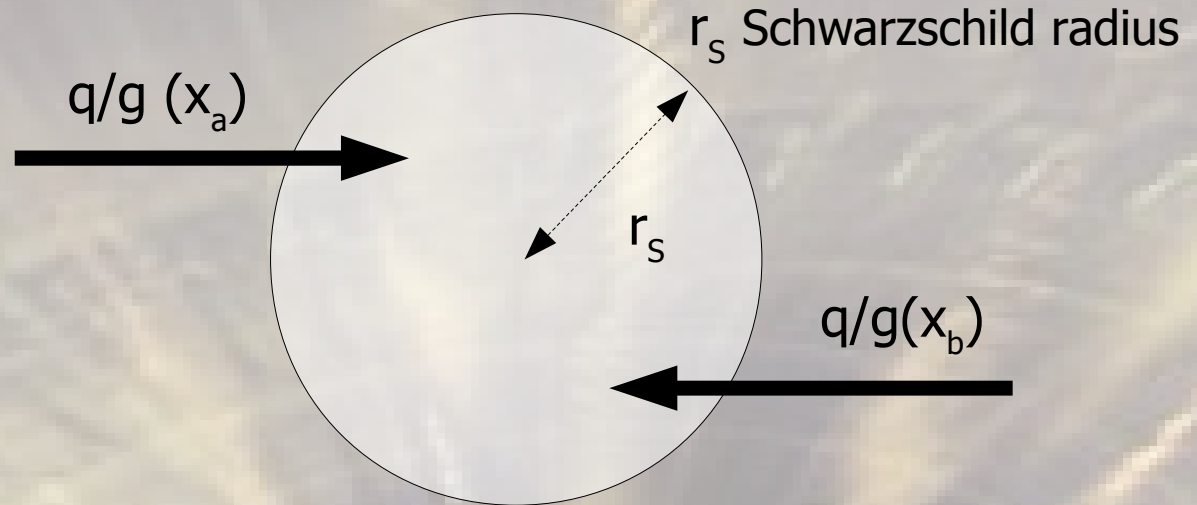


In collisions Black Hole forms when impact parameter $< 2r_s$

$$M_{\text{BH}} = \sqrt{s \cdot X_a \cdot X_b} = \sqrt{\hat{s}}$$

r_s increased by factor R^n

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



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

In absence of any real theory use classical cross section:

$$\sigma_{\text{BH}}(\hat{s}) = F\pi r_s^2$$

parton cross section

F = production form/fudge factors

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

convolute PDFs to get total production cross section

Simple but extremely robust prediction!



Cross section increases with s

For $s \gg M_D$ BH production will dominate over SM processes

For example very high E_T jets no longer produced \rightarrow 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

⇒ 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^+ → 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)

Split Fermion Model

In this model spacetime structure is further modified

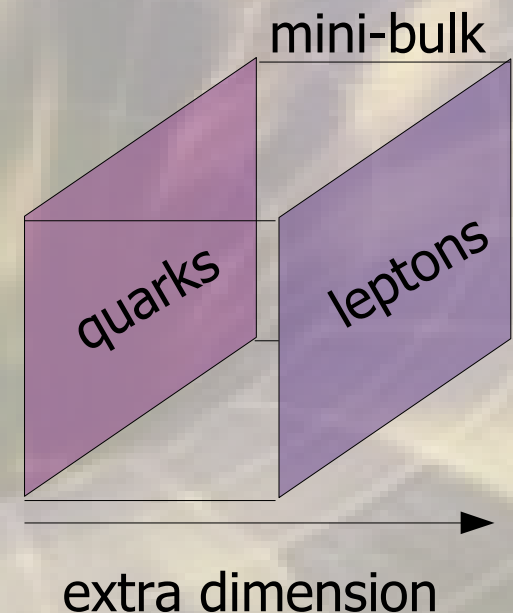
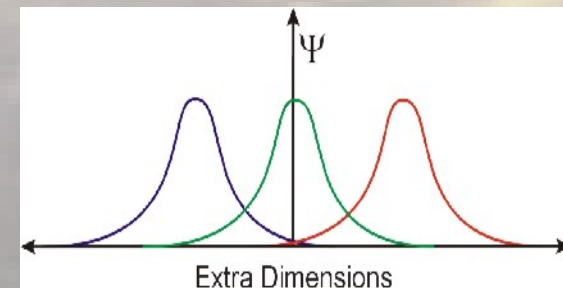
SM fermions exist on separated 3d branes

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





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

$$r_s = \frac{2GM_{\text{BH}}}{c^2}$$

entropy \propto surface area

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

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

Hawking: 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!

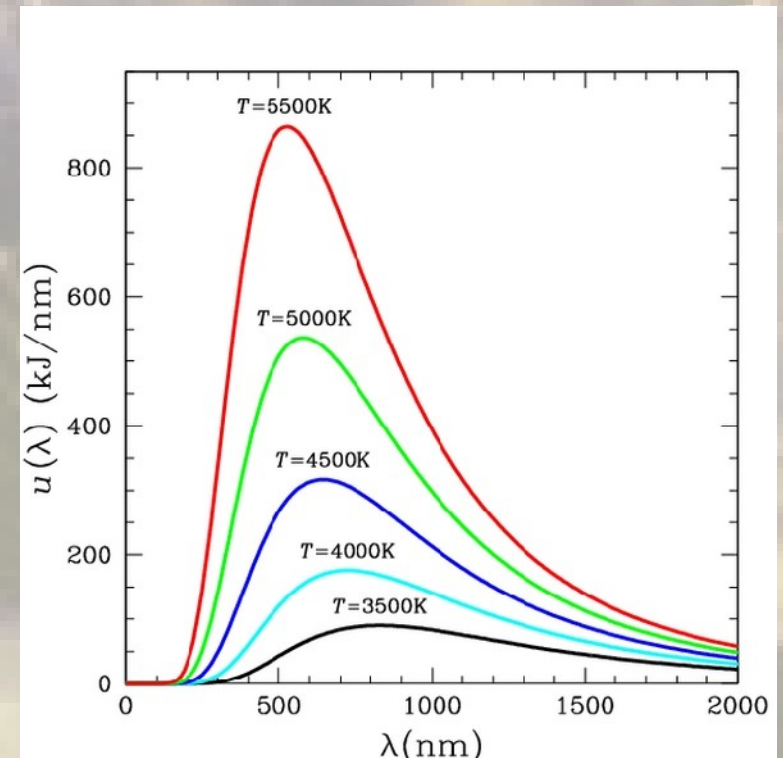
Astro-BHs have temp < CMB

Micro BHs are very hot - radiate intensely

⇒ BH evaporate

Hawking radiation is purely thermal

only depends on M, Q, J, Col





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

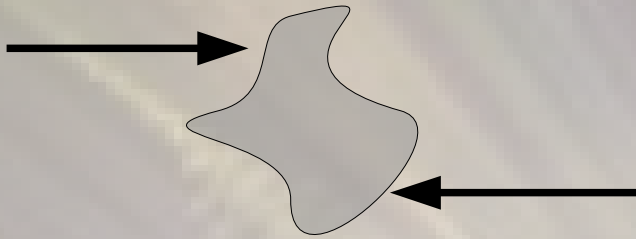
Information loss paradox - else BH must remember what it swallowed
info remains inside BH? What happens when it decays?

In QM time evolution is unitary transformation:

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

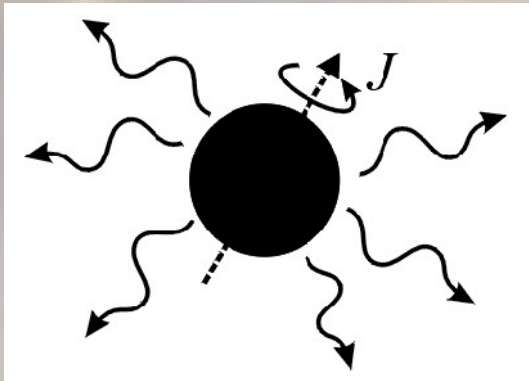
Initial state BH transforms to final state of purely thermal radiation (M, Q, J)
this is a non-unitary transformation forbidden in QM - do not preserve probability!

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

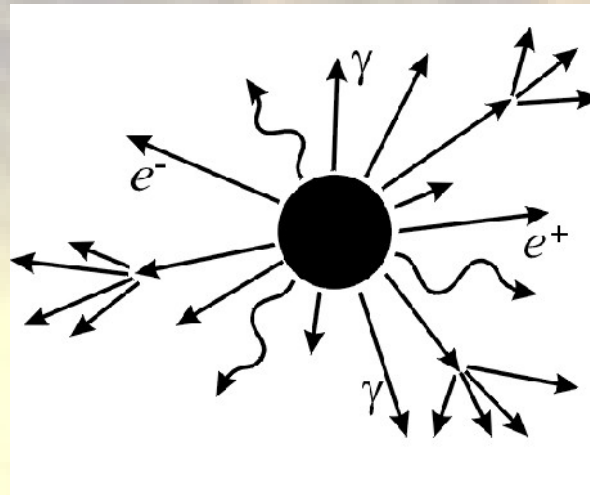


Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

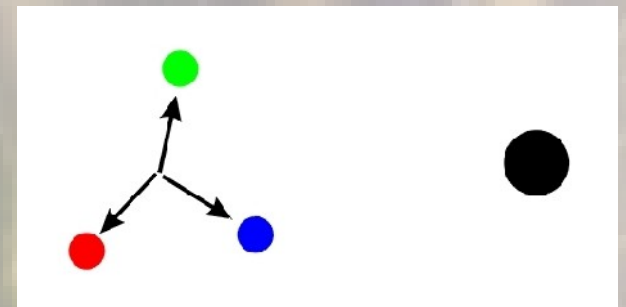
Extremely short lifetime $\sim 10^{-25}s$



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
????



Clearly much is missing in these models

No knowledge of true quantum gravity

Semi-classical approximation fails for $M_{\text{BH}} \sim M_{\text{D}}$

Formation of event horizon \Rightarrow 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 $\sim 1\%$ level

Nevertheless calcs assume fixed metric...

Gingrich: hep-ph/0609055

Phenomenological suppression of modes that increase $|Q|$ or Colour

Important to explore full phenomenological space

Include all effects into MC simulations

Incorporate all effects into MC models

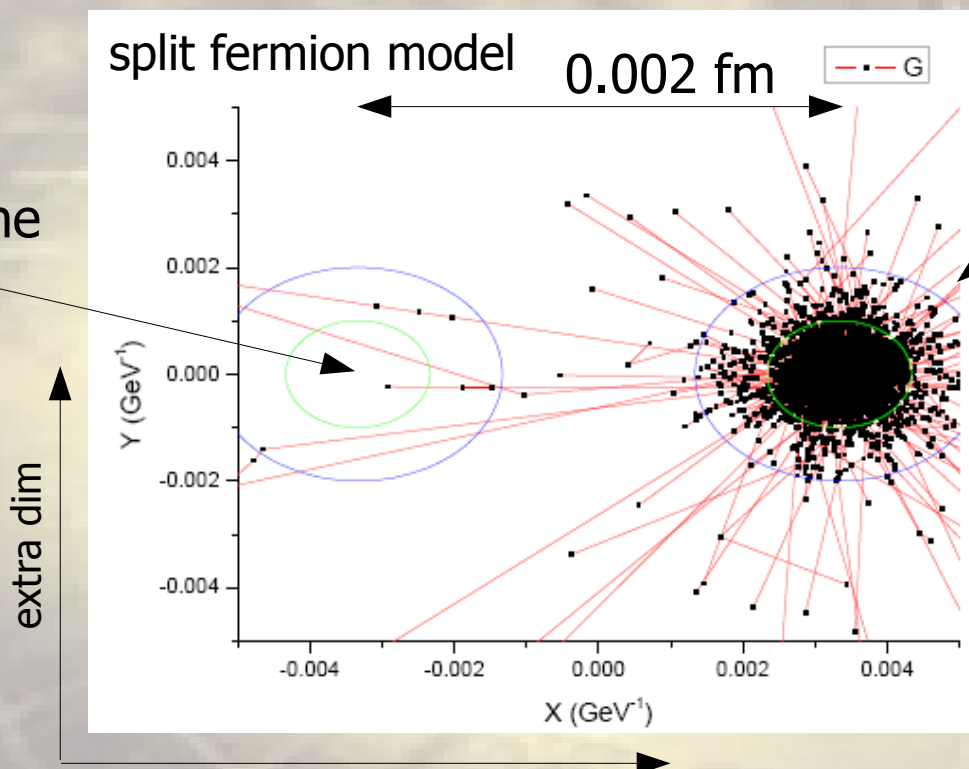
- calculations of energy loss prior to horizon formation
- grey body factors
- rotation of BH (ang.mom)
- recoil of BH
- conservation/violation of B,L,flavour
- number, size & location of extra dimensions

BlackMax Dai et.al. arXiv:0711.3012

Charybdis Frost et.al. arXiv:0904.0979

Downloads: hepforge.org

lepton brane



BH is formed on quark brane at pp colliders

BH recoils at each emission
Affects emission spectra
Mostly emits quarks/gluons

Search for deviations from SM cross sections with increasing m Q^2 \sqrt{s} ...
Look for $qq \rightarrow Gg$ scattering - monojet events (graviton unseen in extra dim)

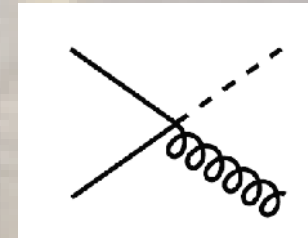
Graviton scattering derived as low energy effective field theory
Giudice, Rattazzi, Wells: hep-ph/9811291

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 $\pm\lambda$ 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:

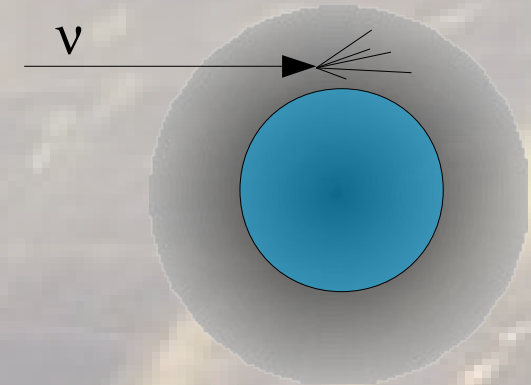
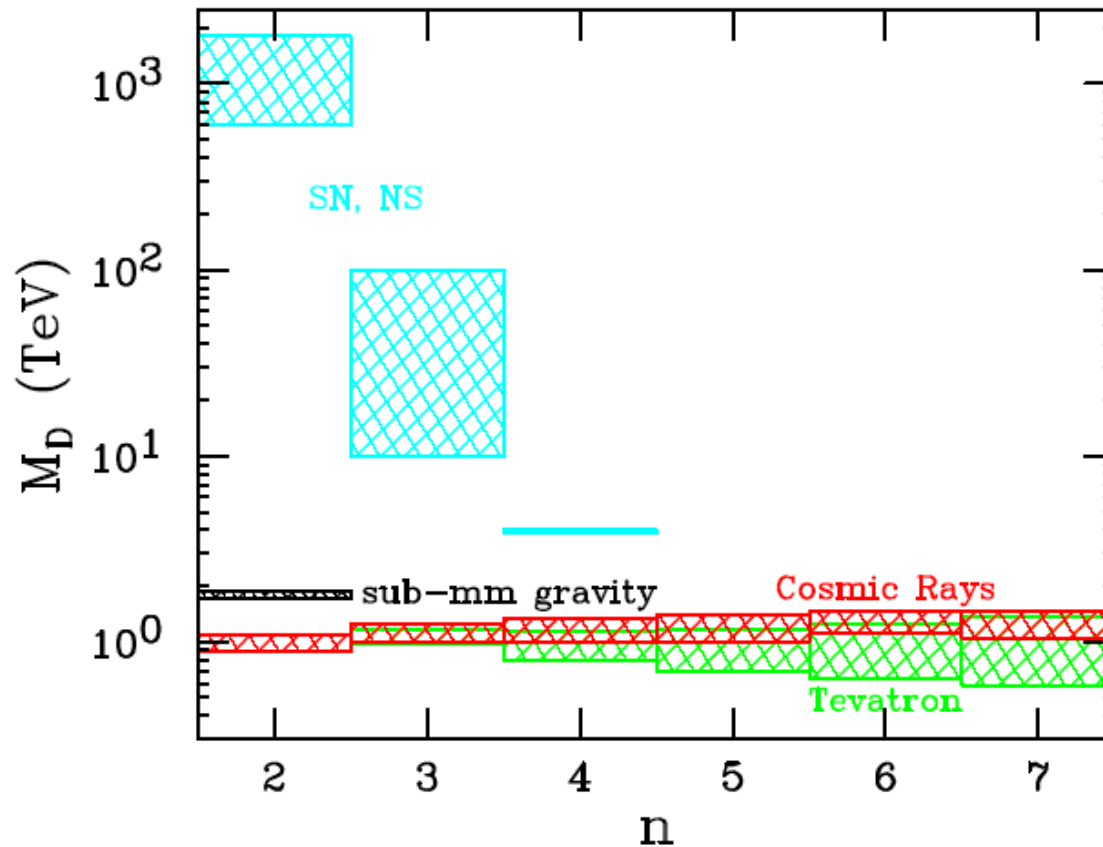
$M_D = 1.33$ TeV for $n = 2$ $R = 0.27$ μm

$M_D = 0.88$ TeV for $n = 6$ $R = 31$ fm

Variety of limits exclude ~ 1 TeV

D0 (ll, gg):

$M_D = 1.23$ TeV lower limit



- ultra high energy neutrino showers
- deep in atmosphere
 - horizontal

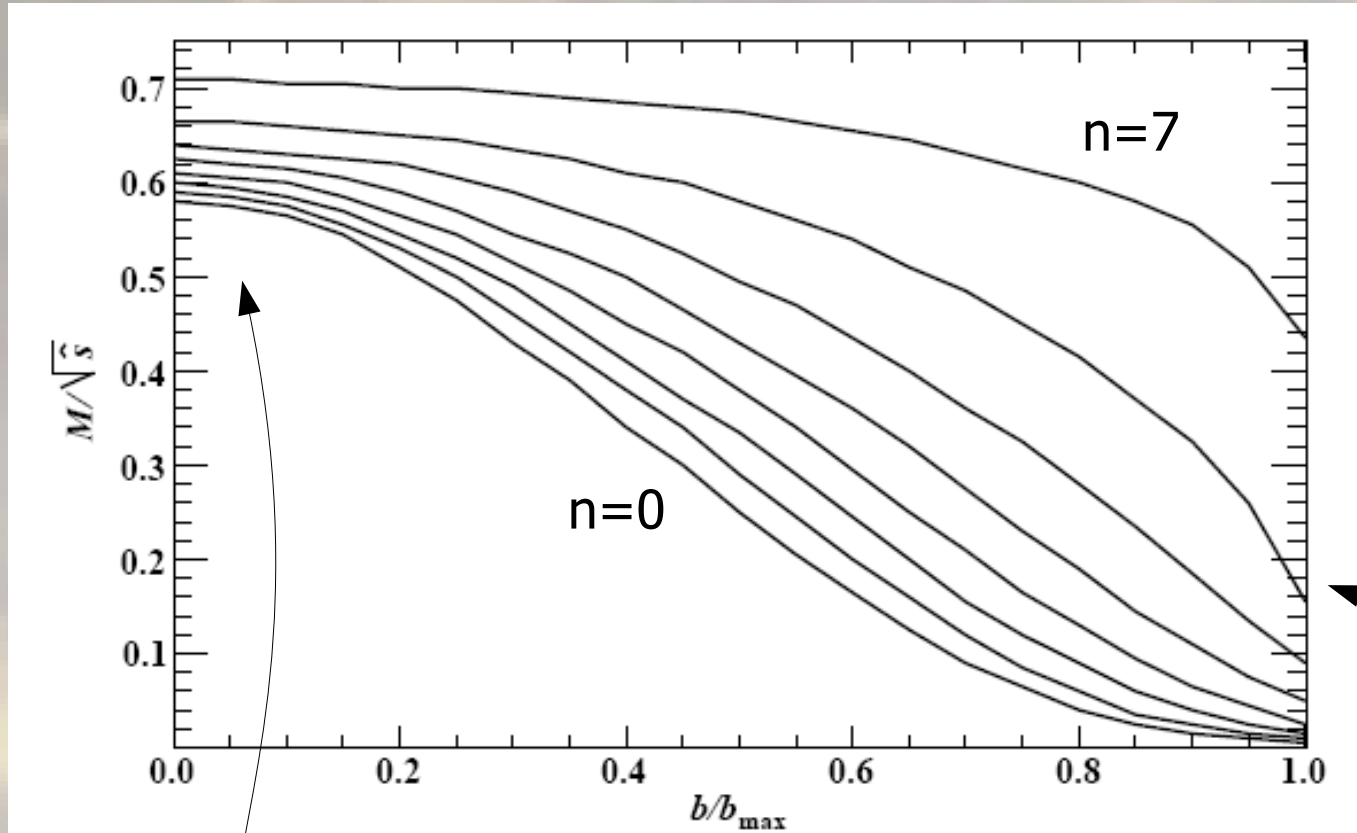
Summary of constraints from astrophysical measurements & colliders
 Supernovae & neutron stars probe low n
 Colliders probe large n



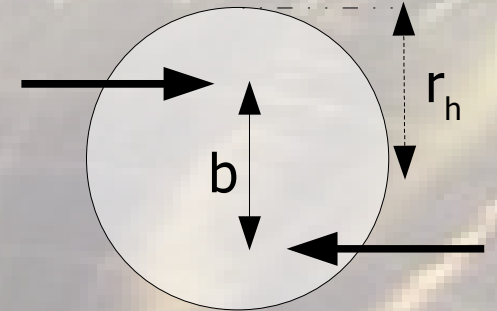
Lower limits on fraction of trapped energy (indep. of M_D)

Form factors

r_h is generalisation of r_s for spinning BHs



b = impact parameter
 b_{max} = horizon radius $2r_h$

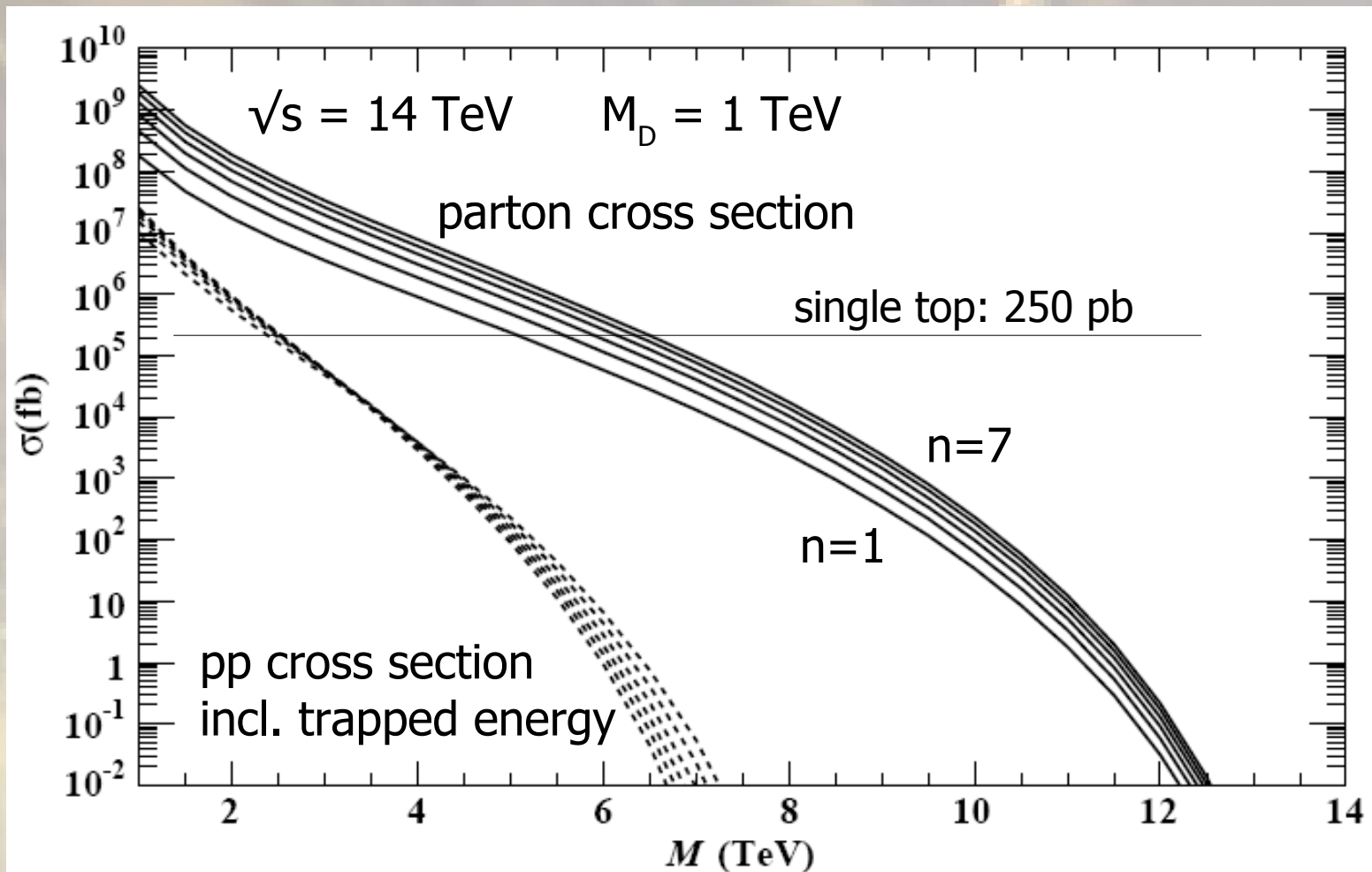


Large $b \Rightarrow$ large ang mom states

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

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

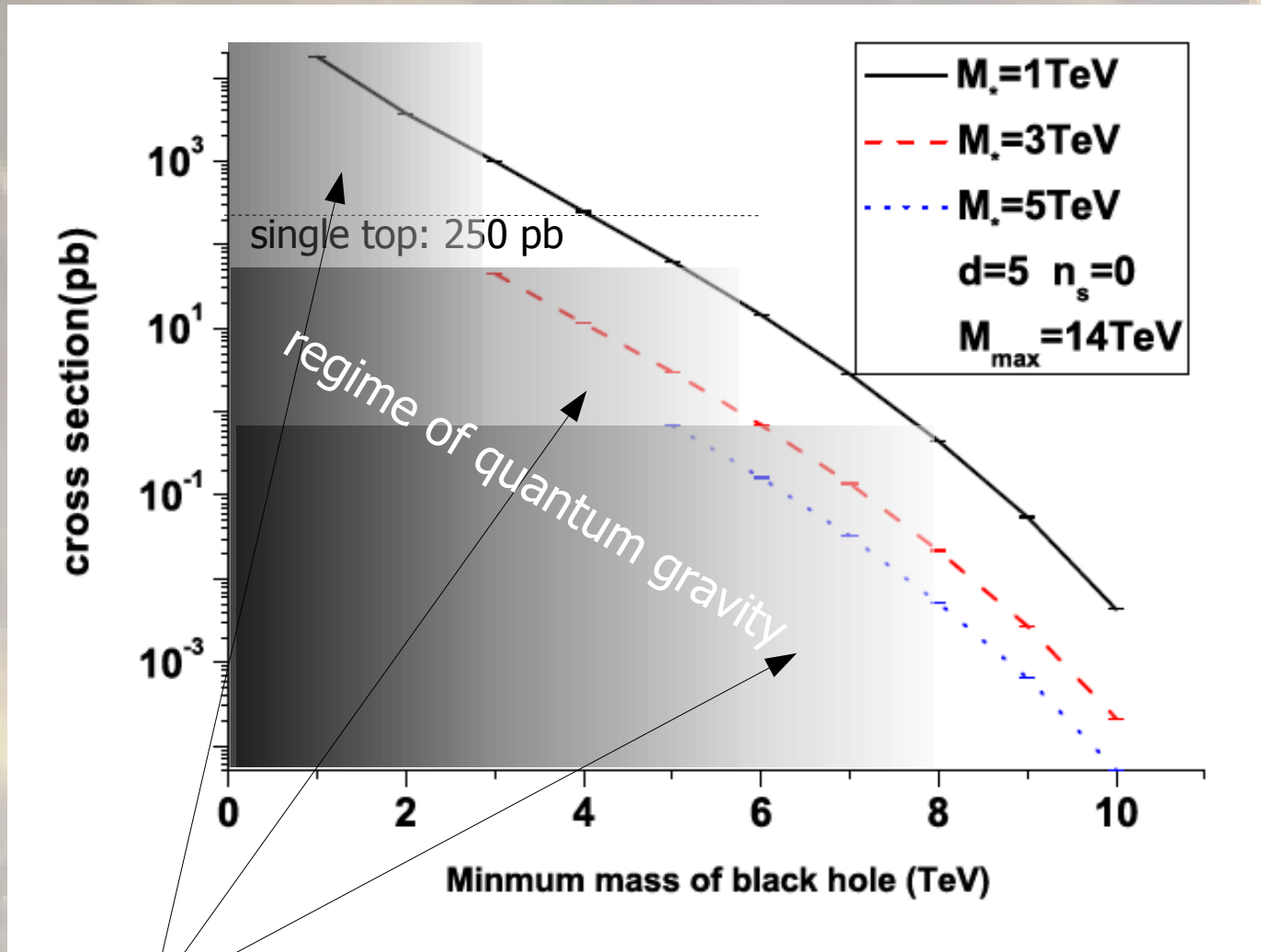
Cross section lower limits



Potentially very large cross sections predicted
 Horizon radius increases with $n \Rightarrow$ cross sections increase with n

BlackMax prediction for non-rotating BHs

Dai et al: arXiv 0711.3012



Close to M_D observe
jump in $2 \rightarrow 2$ scattering?

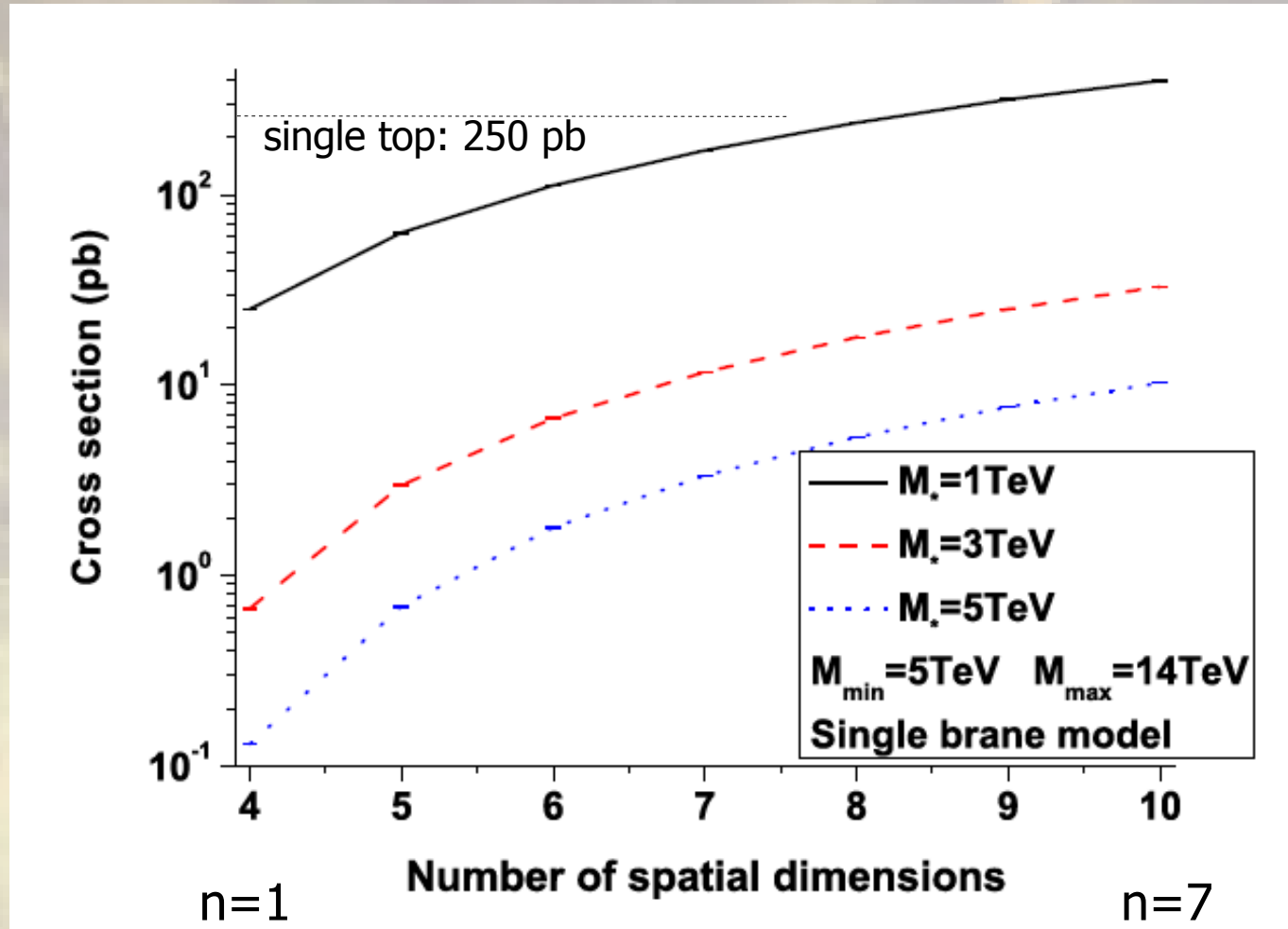
May be dominant effect
Meade, Randall: arXiv 0808.3017

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

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

BlackMax prediction for non-rotating BHs

Dai et al: arXiv 0711.3012



Cross sections vary by \sim factor 10 for $n=1 \rightarrow 7$
 Factor ~ 30 suppression for $M_D = 1 \rightarrow 3 \text{ TeV}$



Emission spectra change depending on the models chosen

Typical ratio $\sim 8:1$ hadrons:leptons

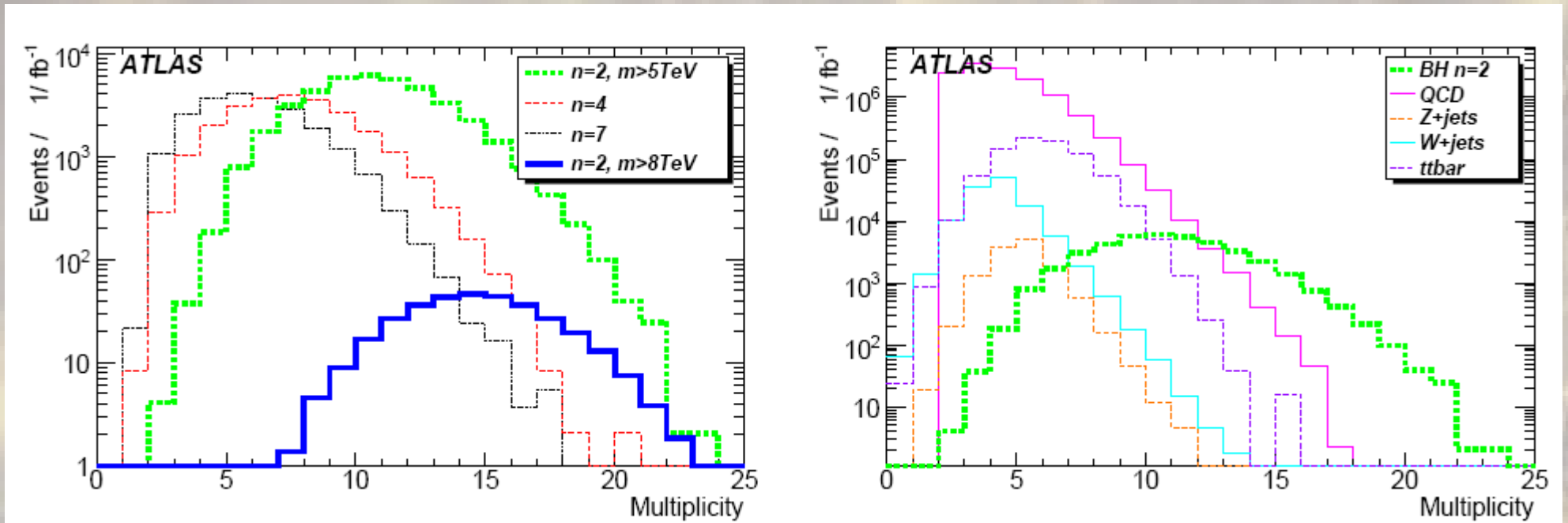
Leptons heavily suppressed in split fermion model

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

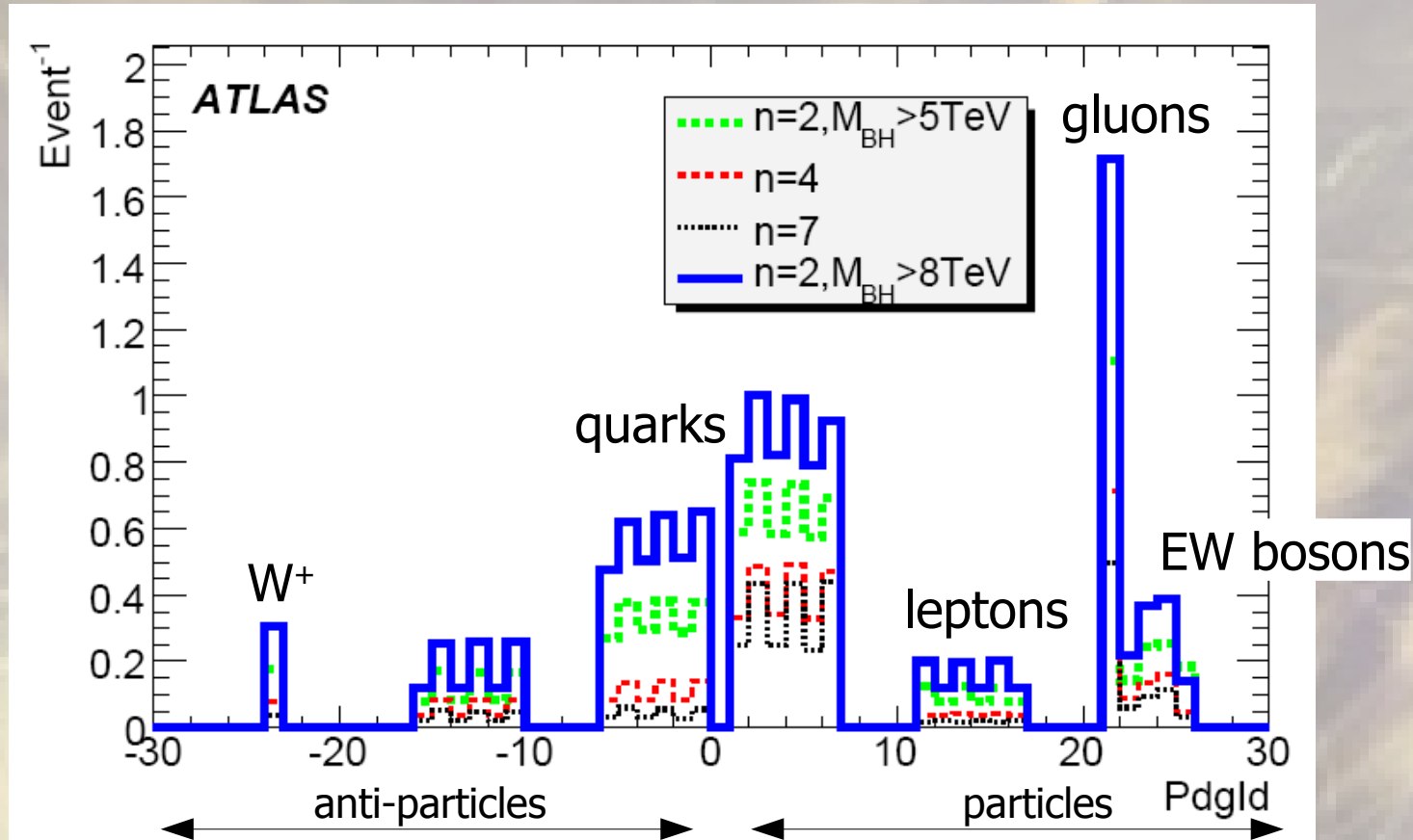
High multiplicity events: 10-40 particles from heavy state
 Hard P_T spectrum of decay particles



$\langle N \rangle$ falls as n increases
 (BH temp increases)

Multiplicity compared to SM

Multiplicity of particles by type in different models

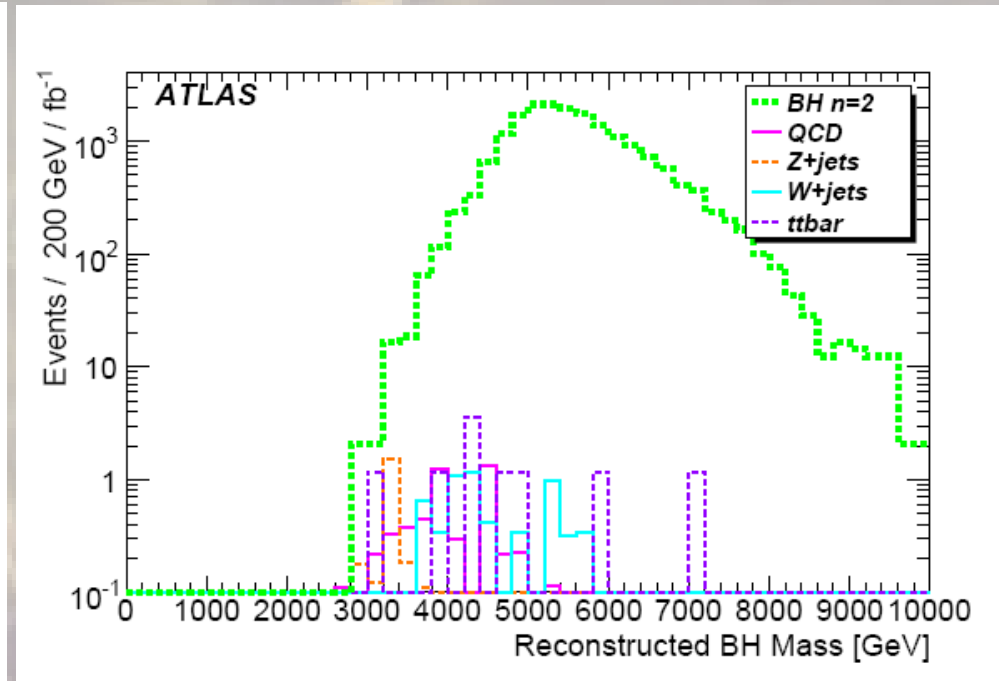
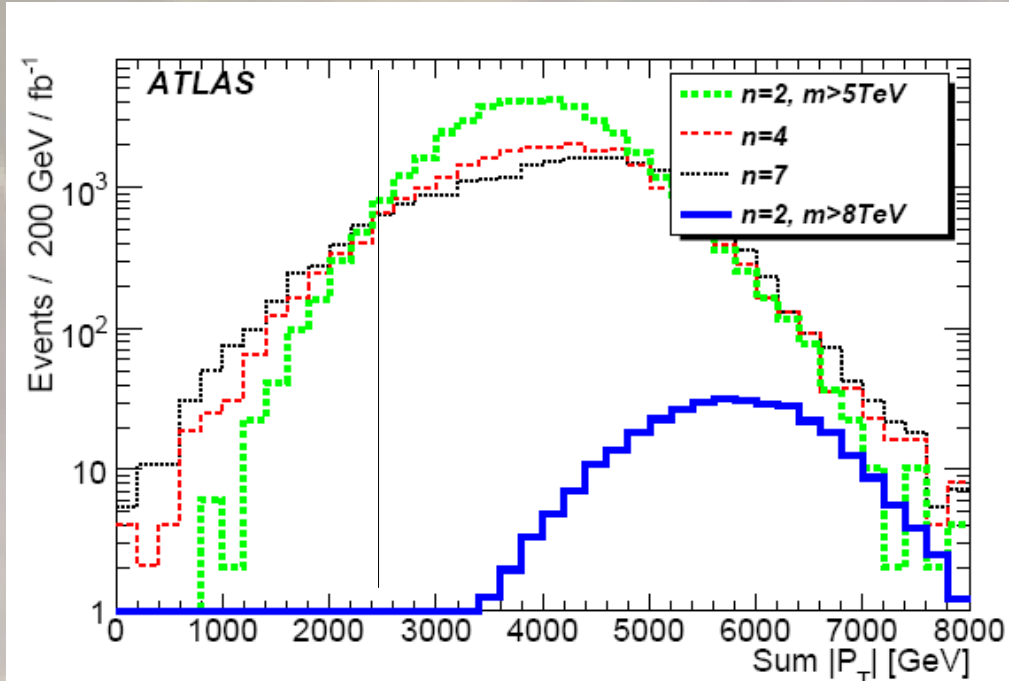


Higher multiplicity for larger mass

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

More particles than anti-particles due to pp initial state

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



- $\sum |P_{\text{T}}| > 2.5 \text{ TeV}$

- $\sum |P_{\text{T}}| > 2.5 \text{ TeV}$

- lepton $P_{\text{T}} > 50 \text{ GeV}$

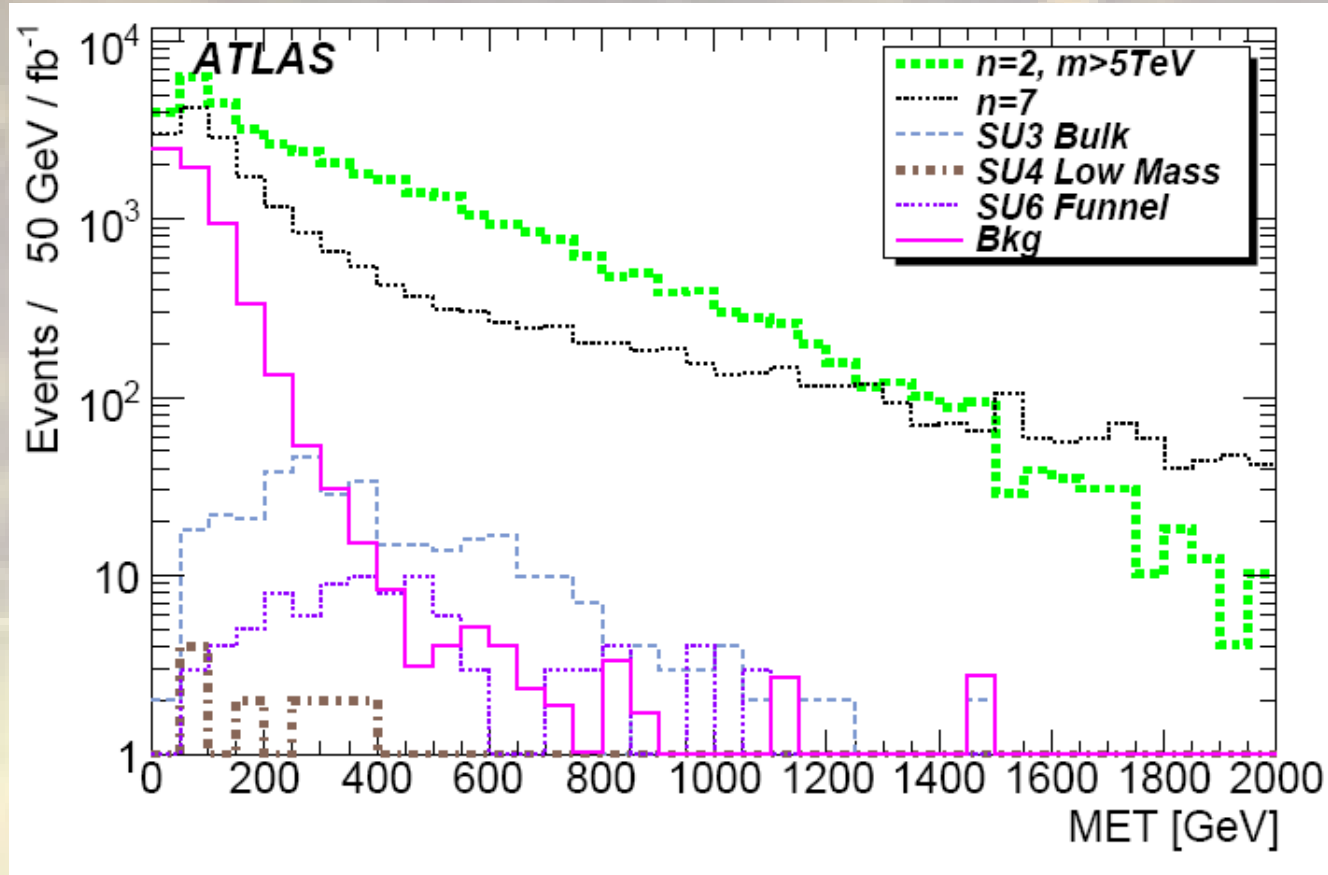
Requirement of additional high P_{T} lepton reduces QCD b/g dramatically

If Atlas / CMS cannot trigger these events we should give up now!

highest threshold jet trigger (400 GeV P_{T}) unprescaled, $\varepsilon = 100\%$

Missing E_T spectrum

Alternative selection: $E_T > 500$ GeV



Largely from graviton emission in balding and Hawking phases

Compare:

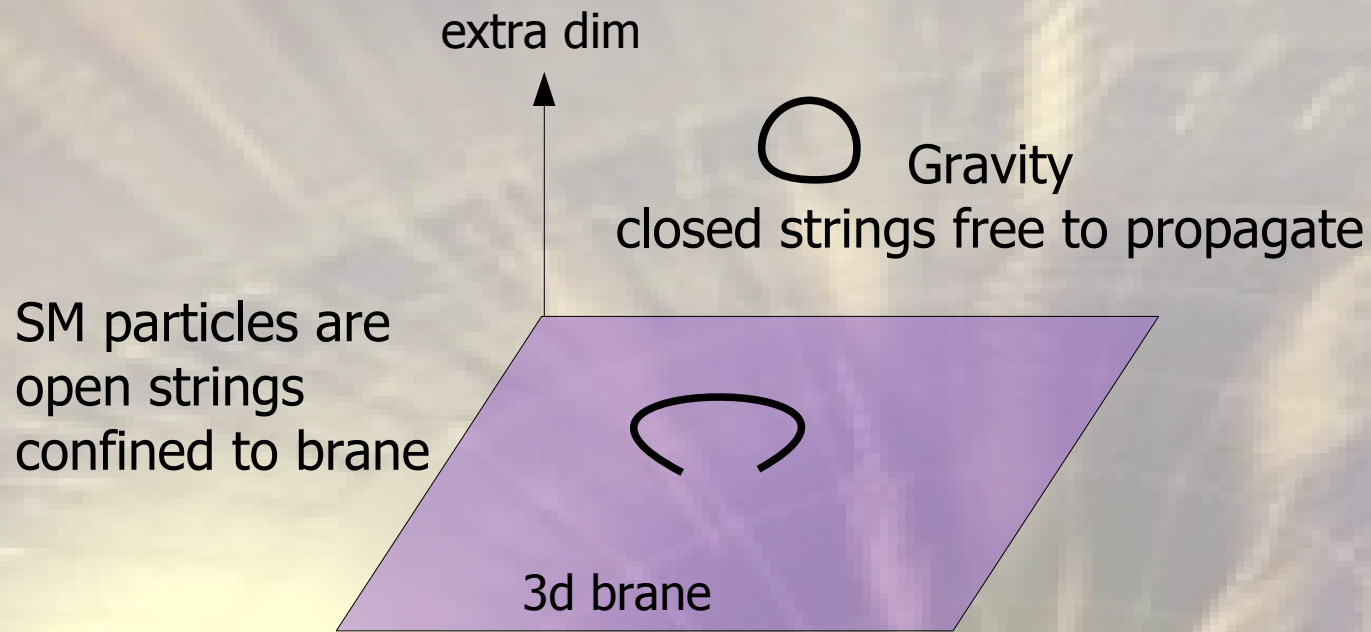
SUSY models at 3 different scales
Soft SM expectation

But:

Difficult to calibrate
Limits M_{BH} measurement



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



- 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

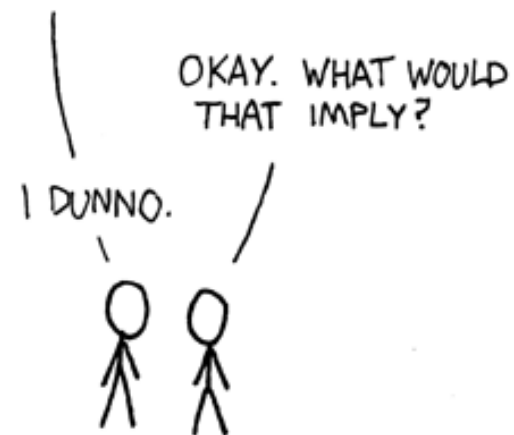
"The landscape is magic, the trip is far from being over"

Carlo Rovelli
Quantum Gravity



STRING THEORY SUMMARIZED:

I JUST HAD AN AWESOME IDEA.
SUPPOSE ALL MATTER AND ENERGY
IS MADE OF TINY, VIBRATING "STRINGS."



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