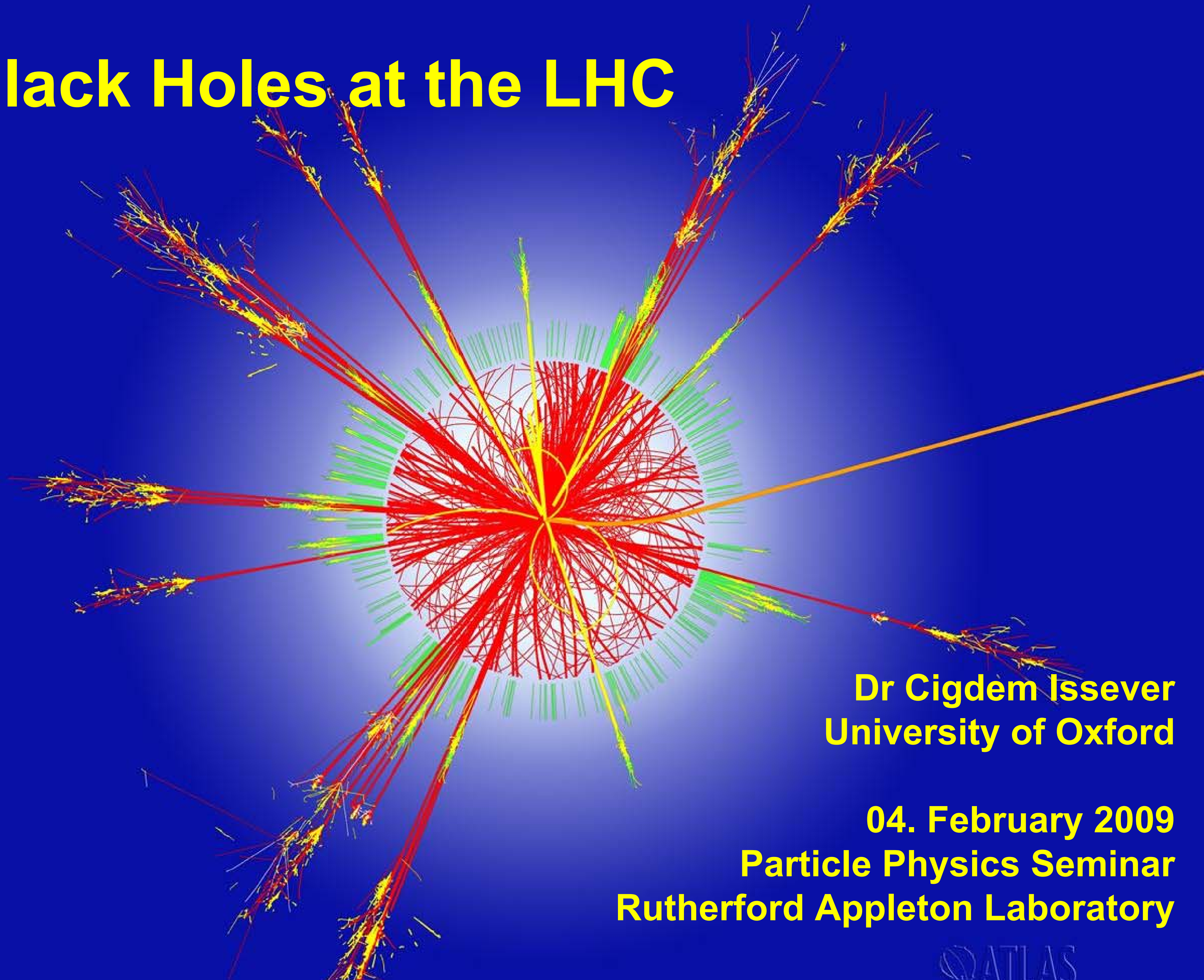
Black Holes at the LHC



Dr Cigdem Issever
University of Oxford

04. February 2009
Particle Physics Seminar
Rutherford Appleton Laboratory

Outline

- Introduction to Black Holes
- Gravity and Standard Model

- Extra Dimension Models

- Production of BH at the LHC
- Experimental Signatures

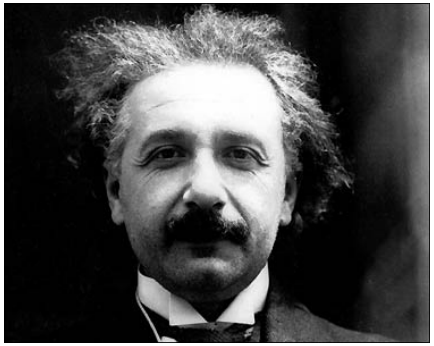
- Why the Earth is safe…

A Bit of Black Hole History

18th

Pierre-Simon Laplace
& John Michel

1915/16

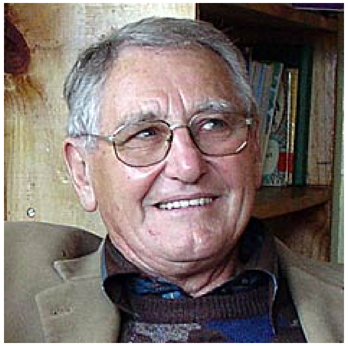


Albert Einstein

1916

Karl Schwarzschild

1963

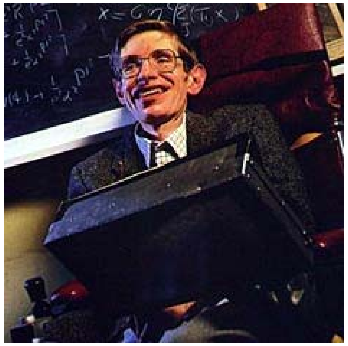


Roy Kerr

1967

John A. Wheeler

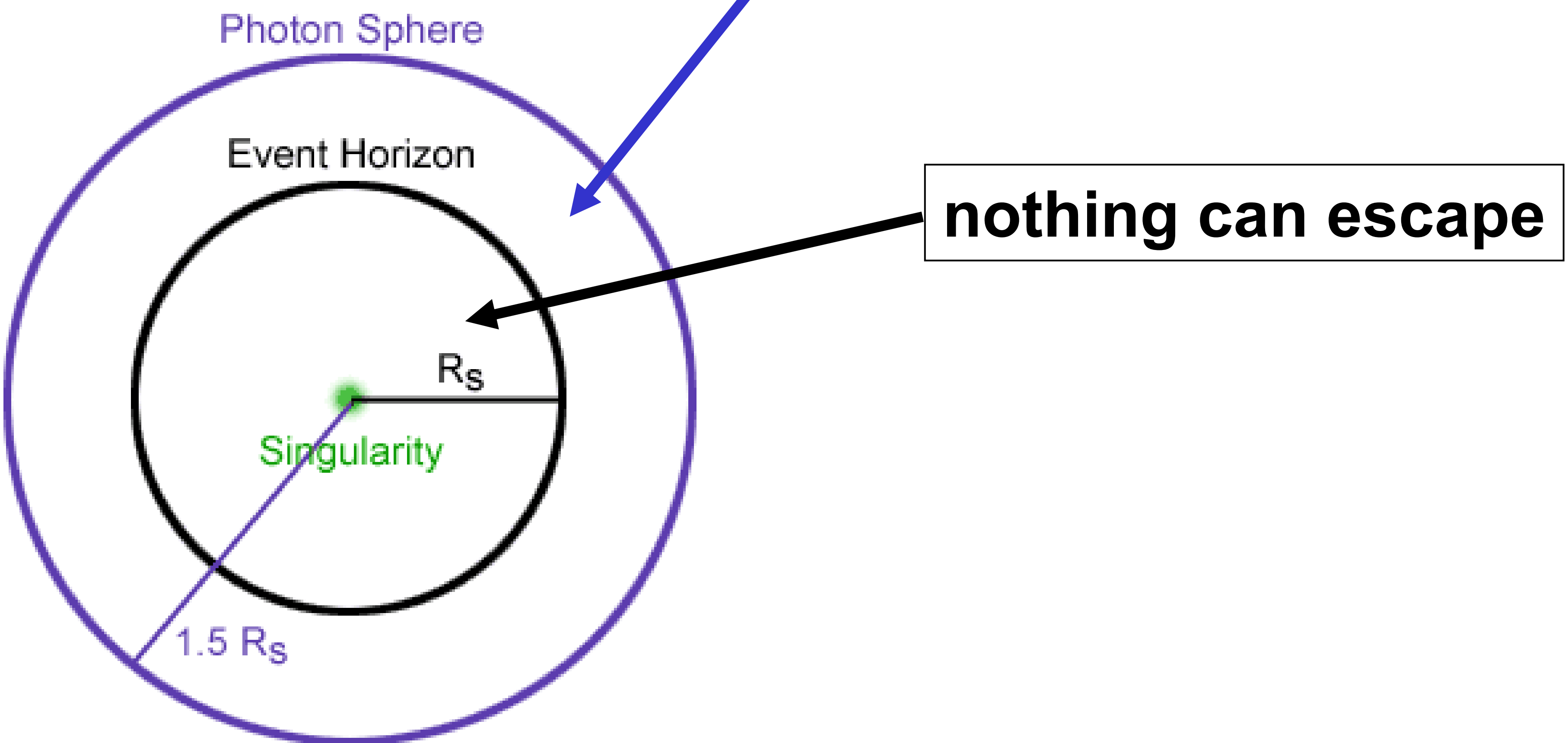
1974



Stephen Hawking

Schwarzschild Black Holes

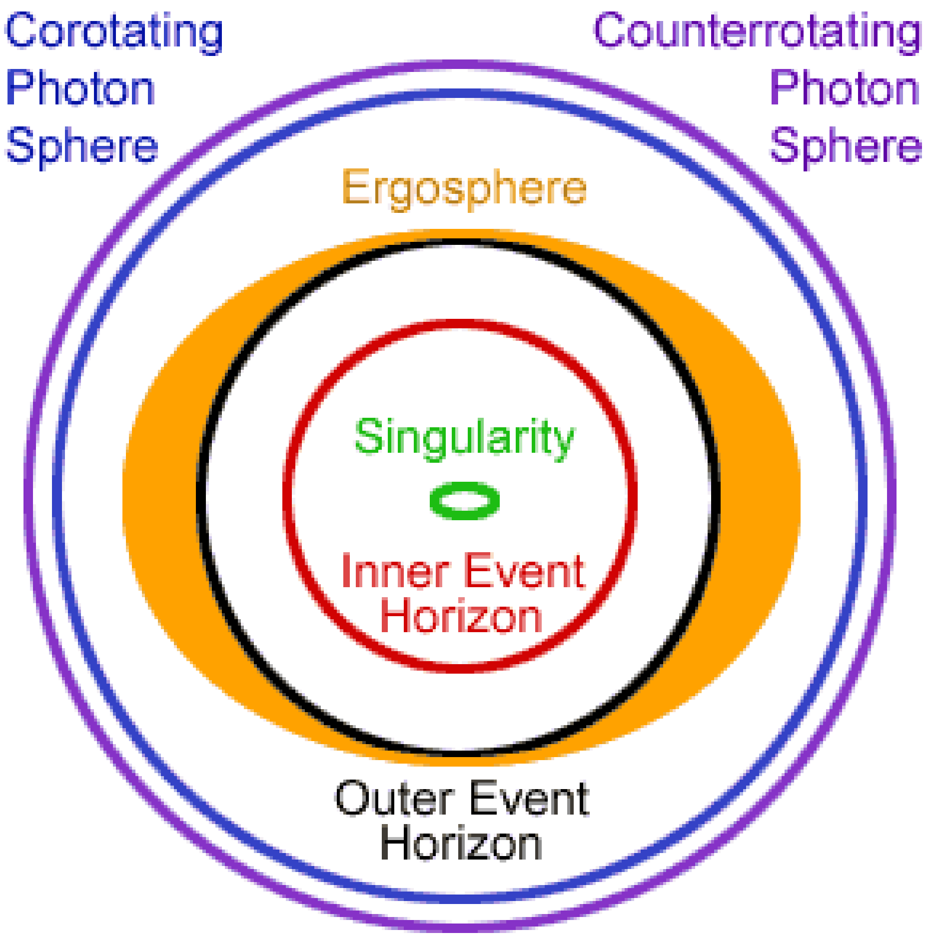
- non-rotating
- uncharged



http://www.gothosenterprises.com/black_holes/rotating_black_holes.html

Rotating Black Holes – Kerr Solution

- **rotating massive body**
- **frame dragging**
- **ergosphere:**
  - particles have to co-rotate
- **Penrose effect**
  - BH emits energetic particles→energy loss

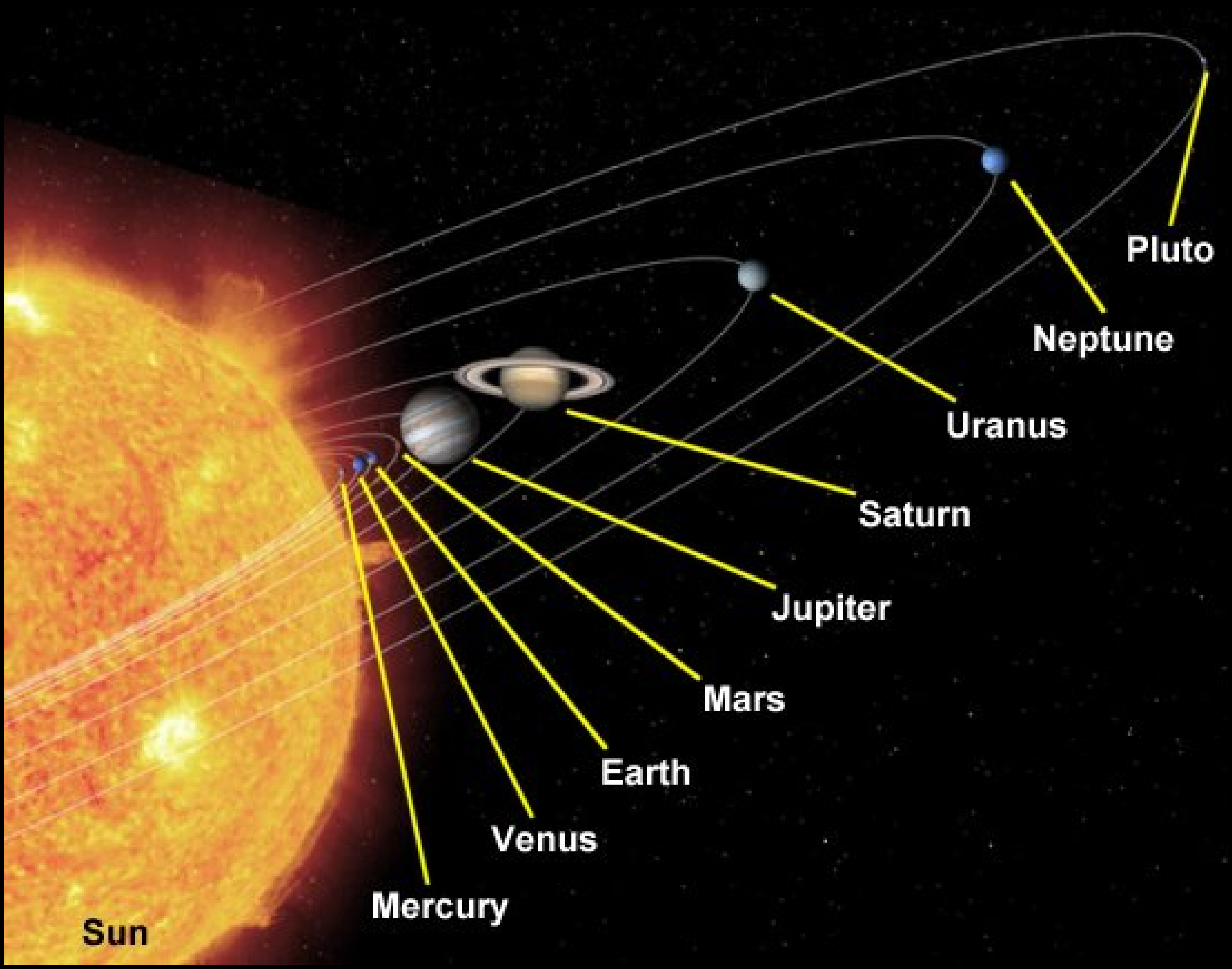


http://www.gothosenterprises.com/black_holes/rotating_black_holes.html

The “No-Hair Theorem”

- Black holes are characterized by their
  - Energy,
  - Angular momentum,
  - Electric (color) charge.
- Do **NOT** conserve B, L or flavour in ordinary world

Replace Sun by a Black Hole….

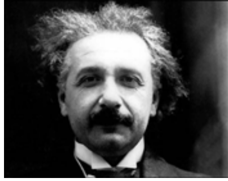


Replace Sun by a Black Hole….

It would get a bit dark and cold…..
But the planets would still orbit as before….

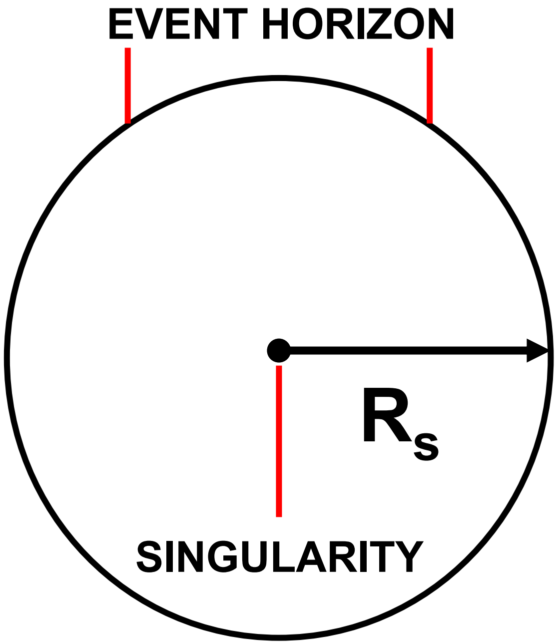
Gravitational field depends only on mass!

Production of Black Holes



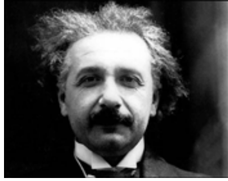
Bring mass closer than its **Schwarzschild Radius, R_S,**

$$R_S = \frac{2GM}{c^2}$$



and a black hole will form!

Production of Black Holes



Bring mass closer than its **Schwarzschild Radius, R_S,**

$$R_S = \frac{2GM}{c^2}$$

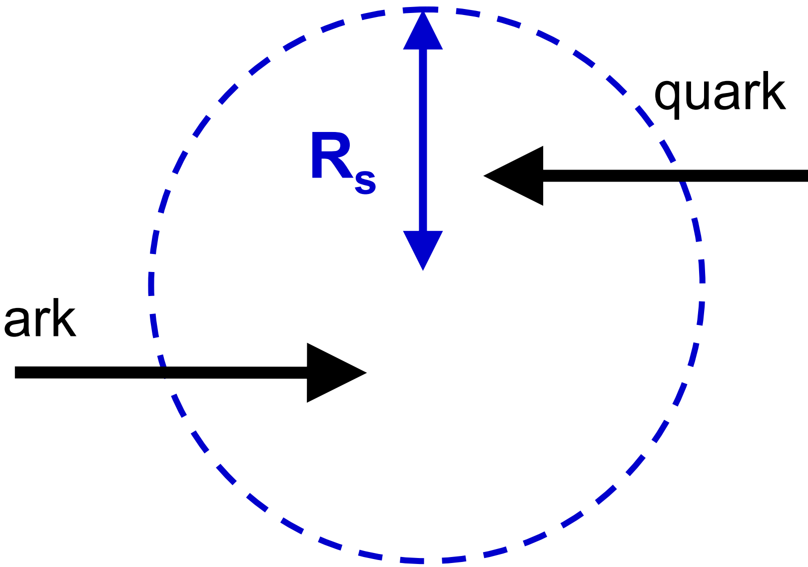
$R_S^{Earth} = 8.8mm$

and a black hole will form!

Production of Black Holes

Bring mass closer than its
Schwarzschild Radius, R_S,

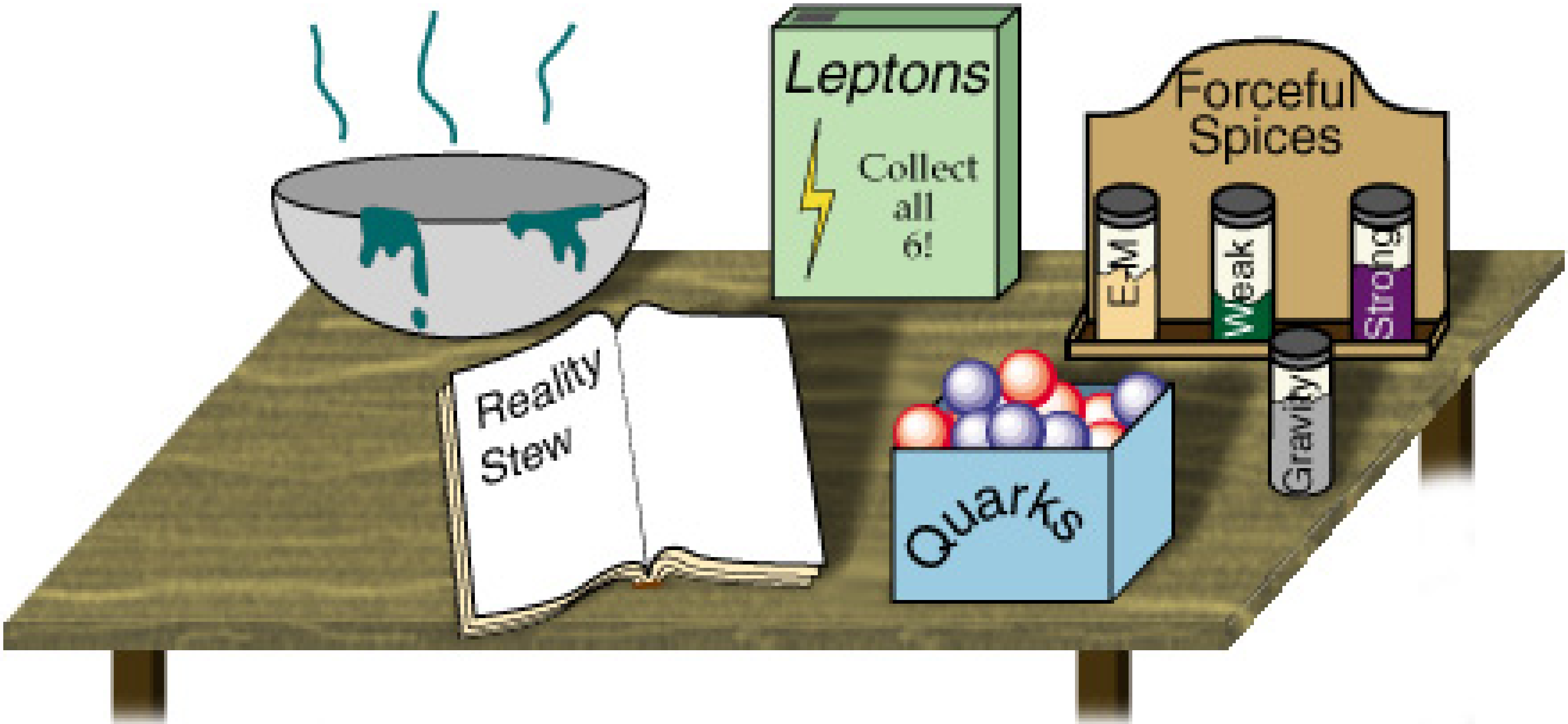
$$R_S = \frac{2GM}{c^2}$$



$$R_S^{2quarks} \leq 10^{-50}\,\mathrm{m}$$

and a black hole will form!

Gravity and Standard Model



Comparison of the Forces in Nature

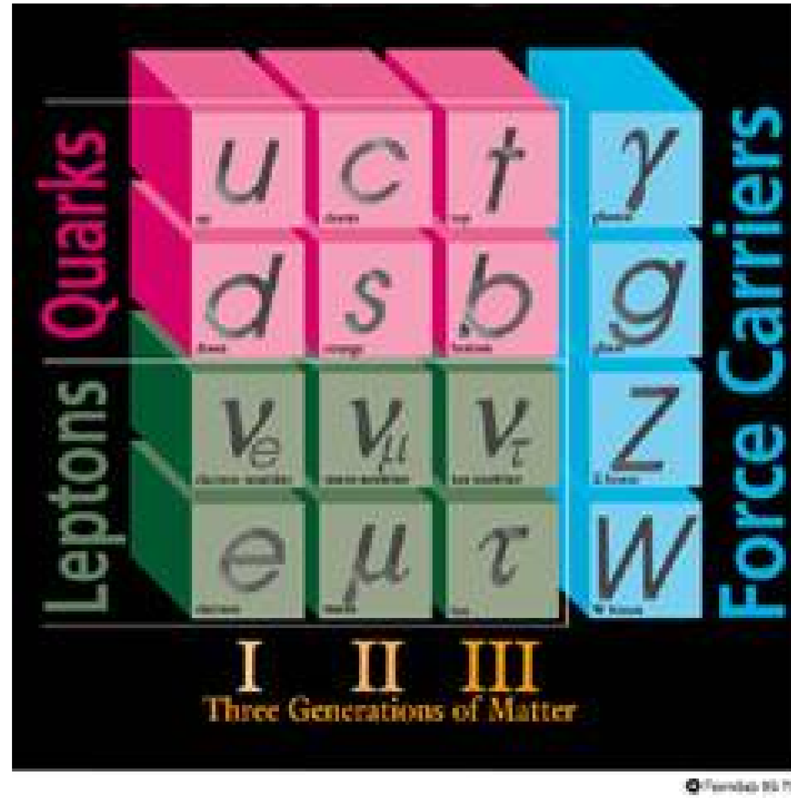
Gravity	Weak	Electromagnetic	Strong
Graviton (not observed)	W^+, W^-, Z	Photon	Gluon
All	Quarks & Leptons	Quarks, charged leptons, W^+, W^-	Quarks & gluons
10^{-41}	0.8	1	25

Gravity is very weak --- Hierarchy Problem!

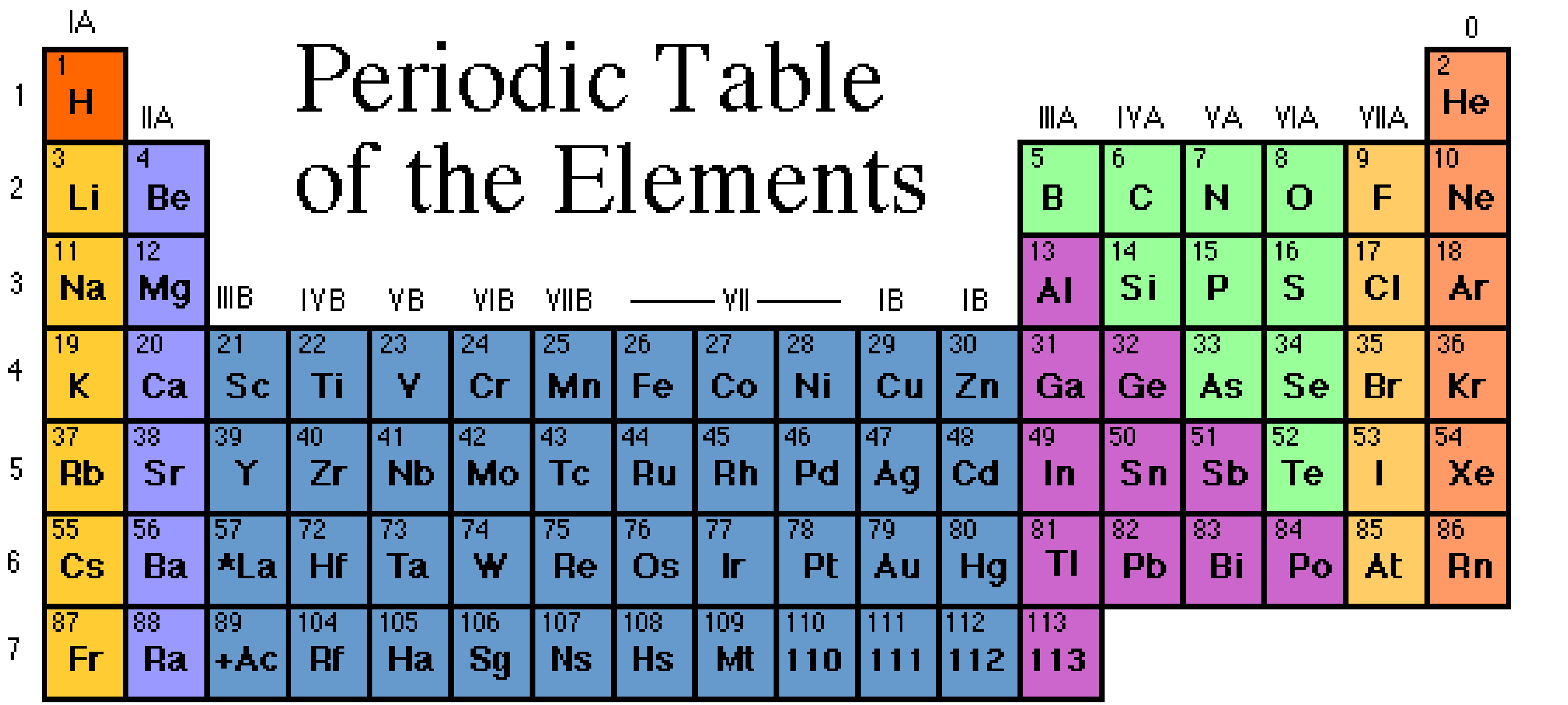
M_{PL}~10^{19} GeV : M_{EWK}~10^3 GeV

The Standard Model

- Gravity is not included
- Particles + Forces
  = Picture of nature
- Too many elementary particles: 60



The Standard Model



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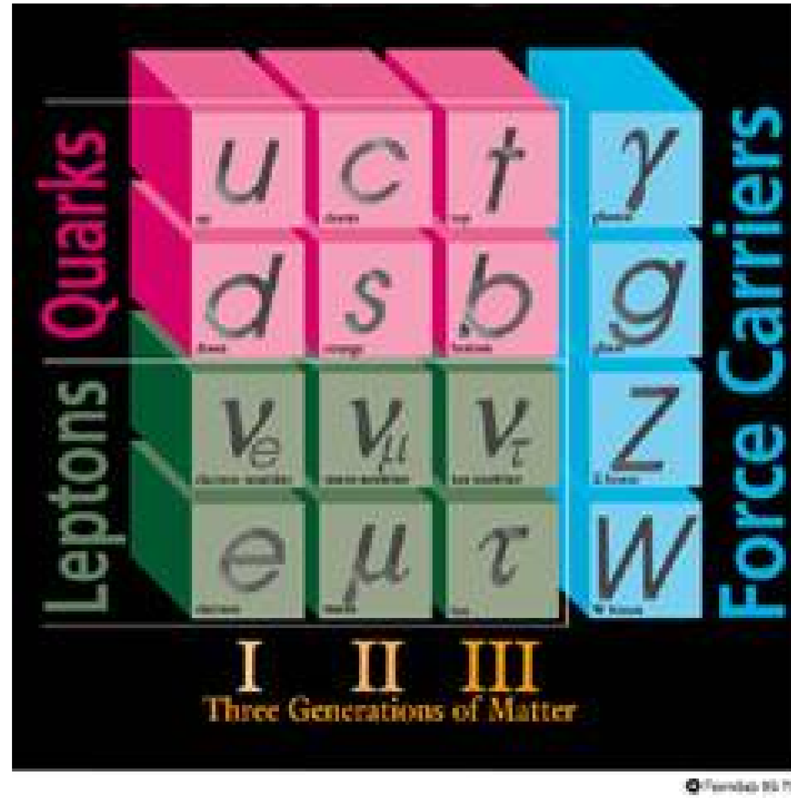


There must be something beyond it!

Extra Dimensions

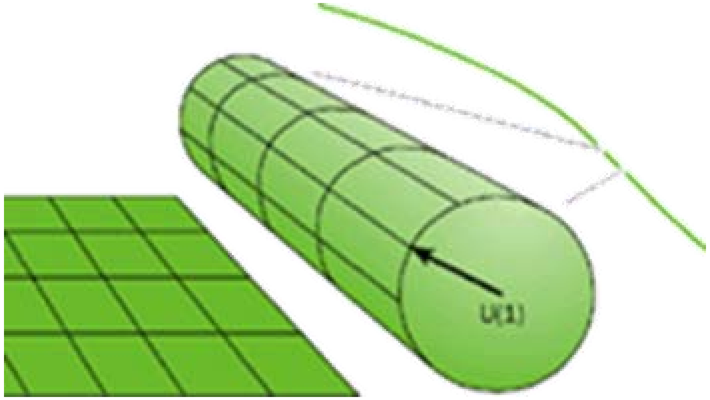
No theory of first principles

Provide simplified framework with testable results

Can help us to gain insights about the underlying theory

Extra Dimensions are not a new idea!

- 1920's Kaluza&Klein unify electromagnetism with gravity
- 1970 String Theory is born
- 1971 SUSY enters the stage
- 1974 Gravitons "pop out" of string theory

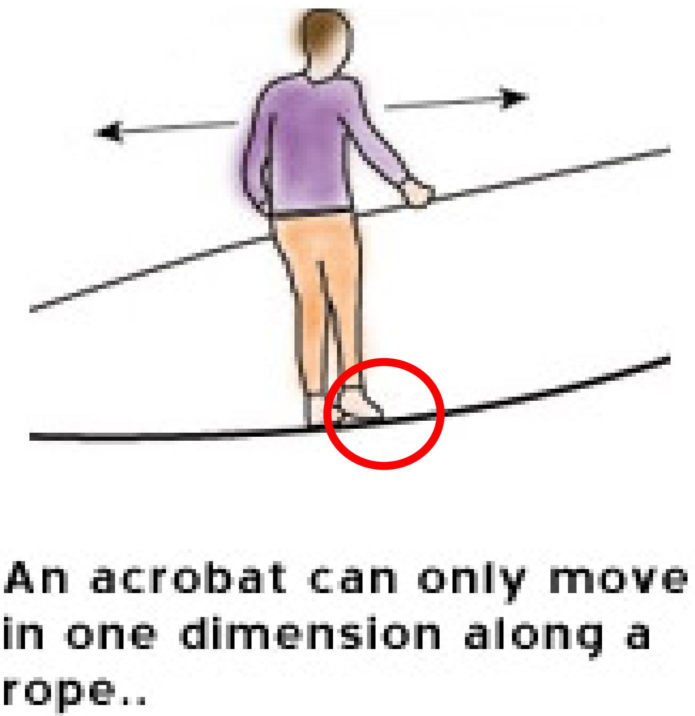


- 1984 Superstring Theory
  - 10, 11 or 26 dimensions needed
  - Compactified
- 1998 Large Extra Dim.
  - Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali

Extra Dimension (ED) Models

- ED may explain complexity of particle physics
- Where are they?

http://www.particleadventure.org/frameless/extra_dim.html



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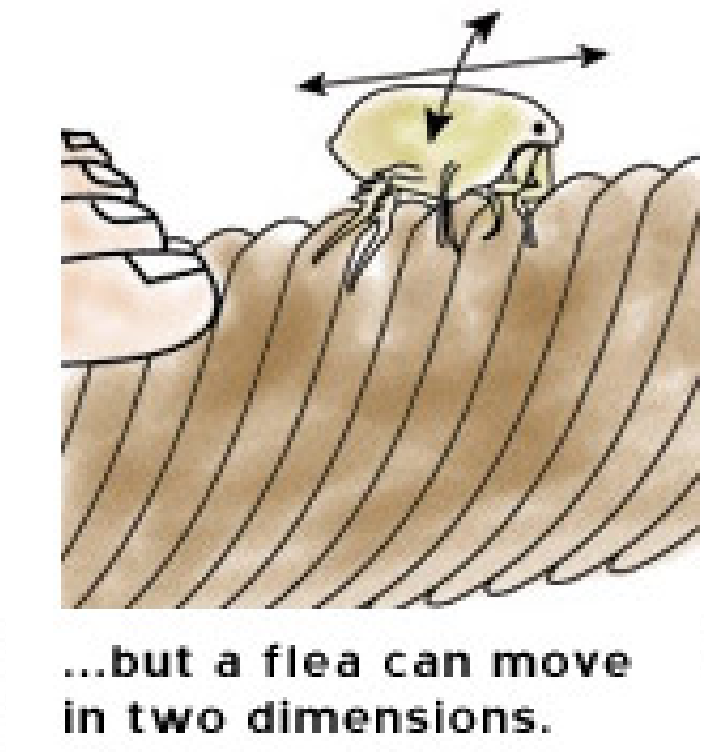

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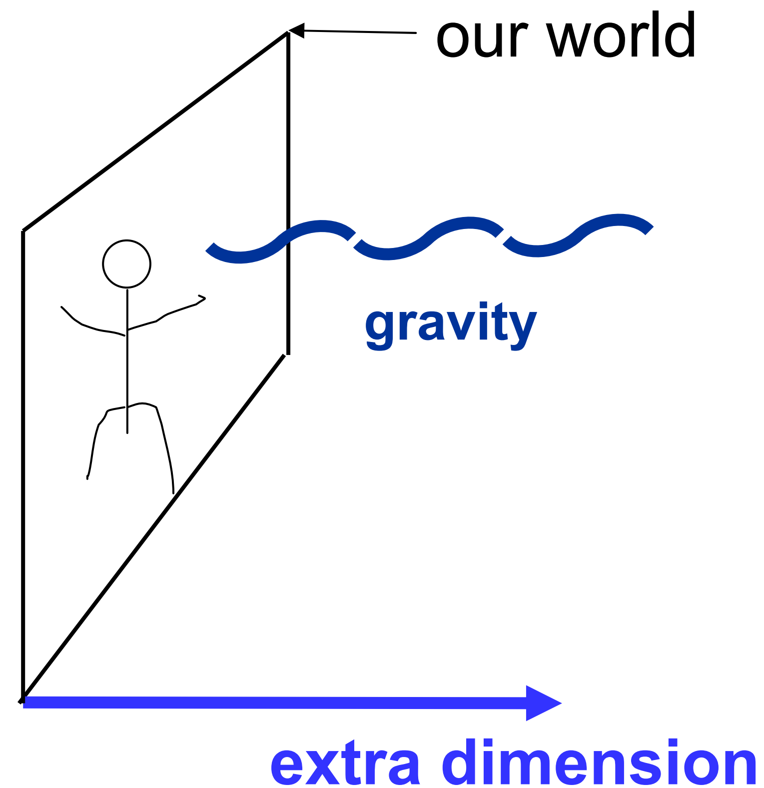


Gravity is escaping into the extra dimensions.

Gravity in Extra Dimension

At small distances gravity can be very strong,

up to 10^{38} times stronger:

$$F \approx \frac{G_D}{r^{n+2}}$$

$$G_D = GL^n$$

$$M_D^{n+2} = \frac{(2\pi)^n}{8\pi G_D}$$

At large distances gravity seems weak

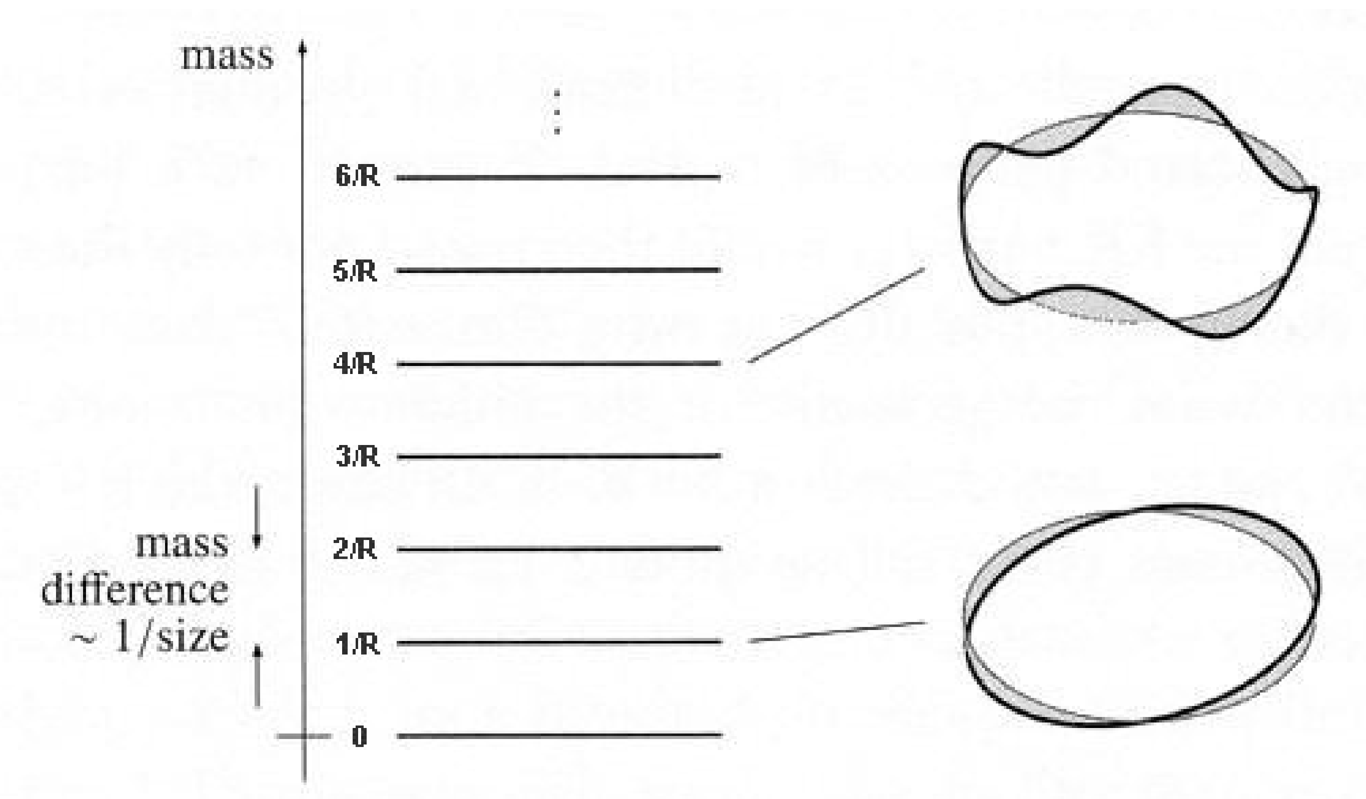
$$F \approx \frac{G_D}{L^n \cdot r^2} \approx \frac{G}{r^2}$$

G is “diluted” strength of gravity in our 3-dim. space.

G_D is the (4+n)-dimensional Newton gravity constant.

Other Predictions of Extra Dimension Models

KK particles

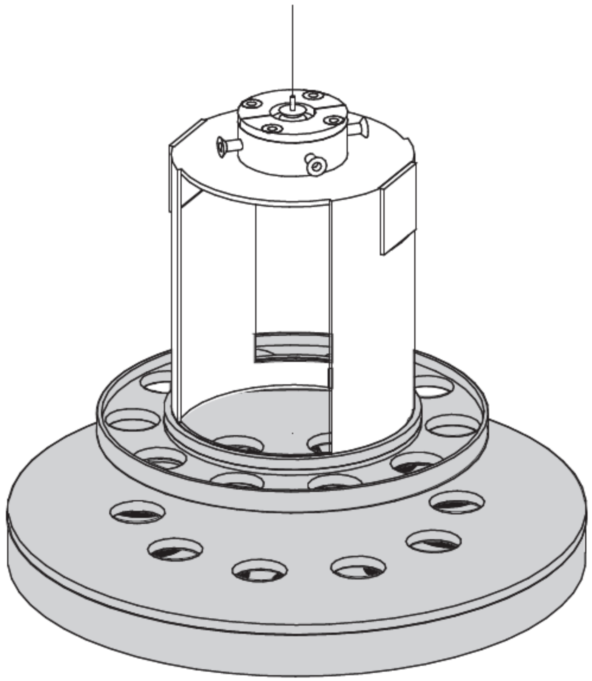


http://universe-review.ca/I15-74-KK.jpg

Experimental Limits

- Table top
- Particle accelerators
- Astrophysical observations
- Cosmic-ray measurements
- Cosmological considerations

Table Top Experiments



$1/r^2$-law valid for R=44 µm at 95%

Ann.Rev.Nucl.Part.Sci.53:77-121,2003, hep-ph/0307284

Particle Accelerators

hep-ph/0201029, hep-ex/0605101, hep-ph/9909294, hep-ex/0710.3338, hep-ex/0707.2524, Phys. Lett. B568 (2003) 35-47, ZEUS-prel-07-028

- DESY:
  - H1: $M_s^- > 0.78$ TeV and $M_S^+ > 0.82$ TeV
  - ZEUS: $M_s^- > 0.9$ TeV and $M_s^+ > 0.88$ TeV
- 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, n = 2 ⇔ R = 0.27 µm
  - $M_D = 0.88$ TeV for n = 6 ⇔ R = 31fm
- D0 (ll, gg):
  - $M_D = 1.23$ TeV lower limit

Astrophysical and Cosmological Constraints

hep-ph/0304029, hep-ph/0309173, hep-ph/0307228

- Places the most stringent lower limits on M_D in ADD
- Supernova cooling due to KK G emission
  - SN 1987A did not emit more KK G than compatible with neutrino signal durations observed by Kamiokande and IMB places the limits: $M_D > 22$ (2) TeV for n = 2 (3).
- Energetic Gamma Ray Experiment Telescope (EGRET)
  - Cosmic γ-ray-bkg:
    - $M_D > 70$ (5) TeV for n = 2 (3)
  - Neutron star halo of 100 MeV γ-rays:
    - $M_D >$ 97, 8, 1.5 TeV for n = 2, 3, 4
  - All neutron stars in the galactic bulge:
    - $M_D >$ 1130, 57, 7, 1.8 TeV for n = 2, 3, 4, 5
- Neutron star heating:
  - $M_D >$1760, 77, 9, 2 TeV for n = 2, 3, 4, 5
- Ultra high-energy cosmic-ray neutrinos:
  - lower bound M_D = 1 to 1.4 TeV , n = 4 to 7

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  - All neutron st[illegible] the galactic bulge:
    - M_D> 11[illegible], 7, 1.8 TeV for n = 2, 3, 4, 5
- Neutron [illegible]heating:
  - M_D>17[illegible], 77, 9, 2 TeV for n = 2, 3, 4, 5
- Ultra high-energy cosmic-ray neutrinos:
  - lower bound M_D = 1 to 1.4 TeV , n = 4 to 7

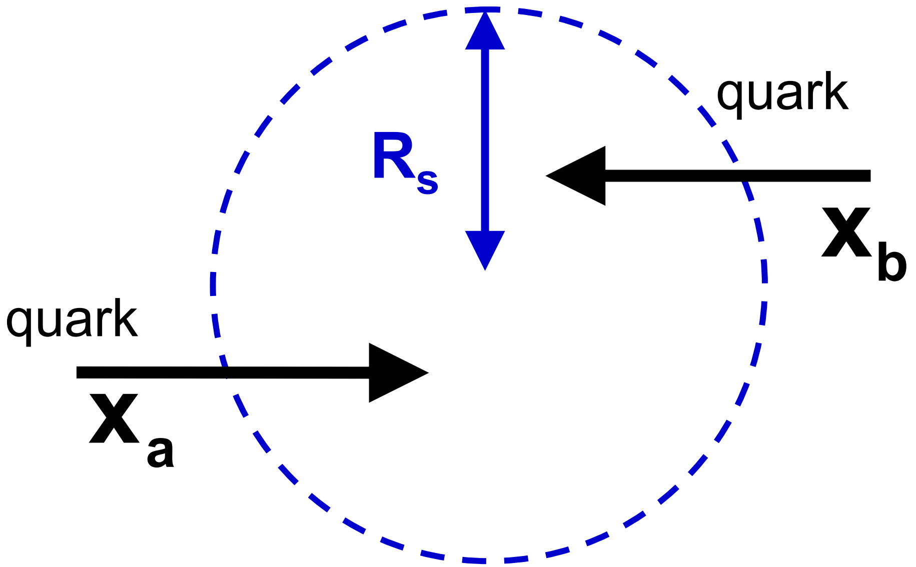
They could be in reach of the LHC

Black Holes @ LHC

Semi-classical Black Holes

Production of Black Holes at the LHC

$$R_S = \frac{2\,G^*L^n\,M}{c^2}$$



$$M = \sqrt{s x_a x_b} = \sqrt{\hat{s}}$$

$$R_S^{2quarks} \leq 10^{-18}\,m$$

BH production @ LHC

Semi Classical Production Cross Section

$$\sigma_{ab\to BH}(\hat{s}) \approx \pi R_h^2$$

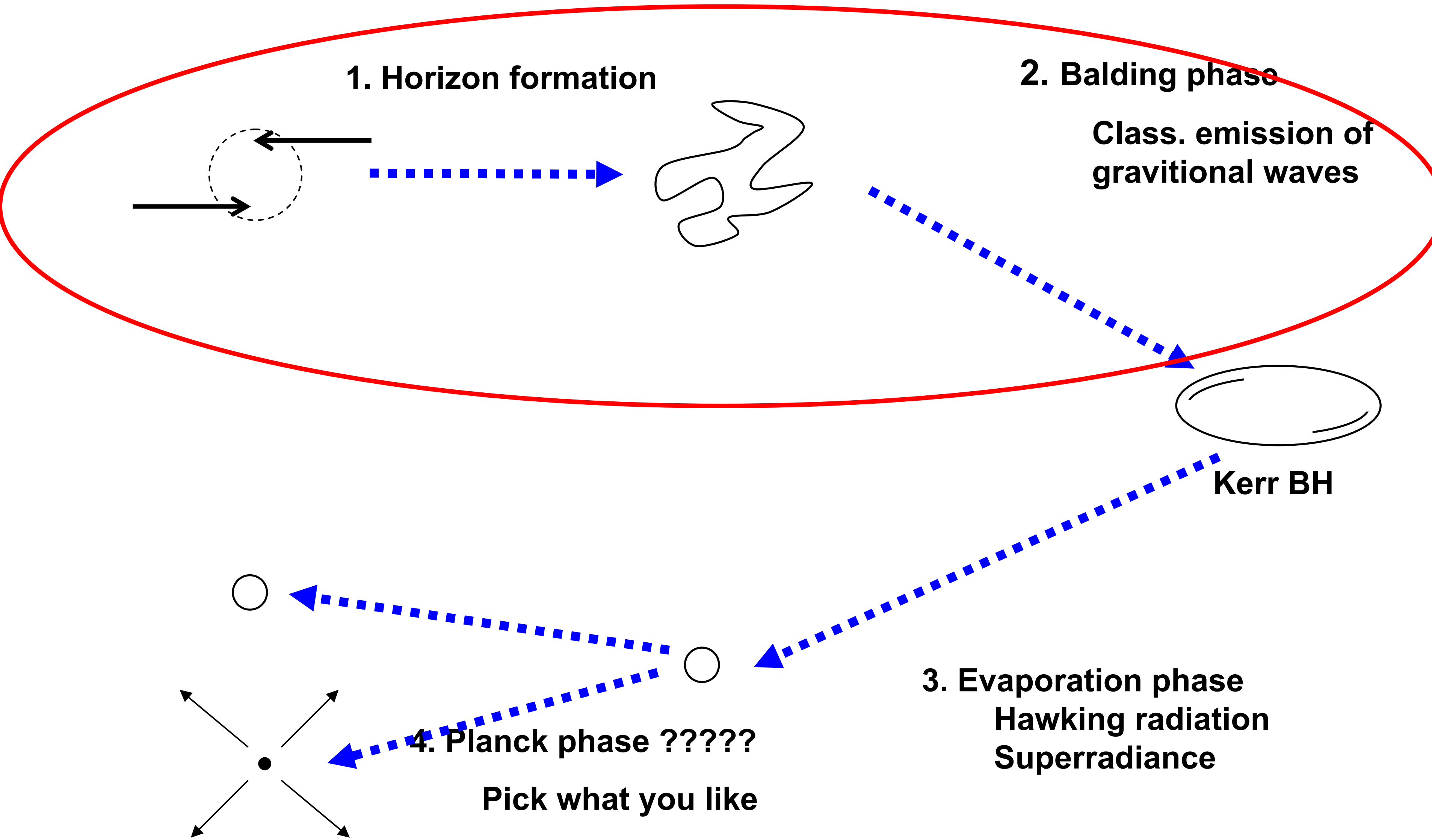
valid for $M \gg M_D$

$$\sigma_{pp\to BH+X}(s) =$$

$$\sum_{a,b} \int_{\frac{M^2}{s}}^{1} dx_a \int_{\frac{M^2}{x_a s}}^{1} dx_b\, f_a(x_a) f_b(x_b)\, \sigma_{ab\to BH}(\hat{s})$$

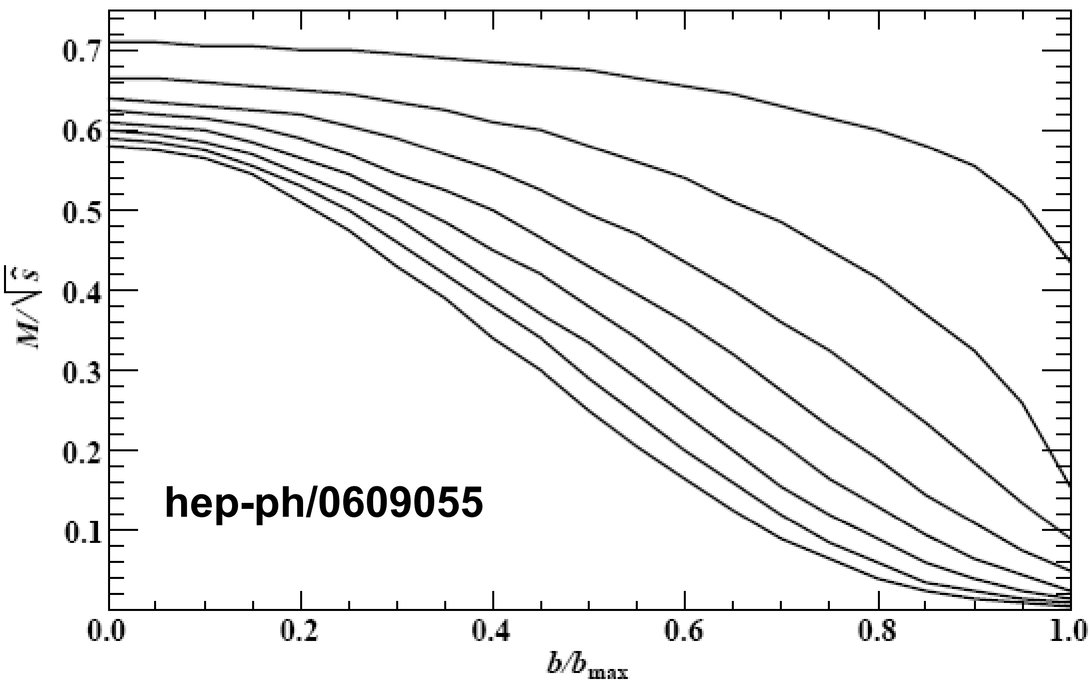
parton distribution functions

Time Evolution of Black Holes



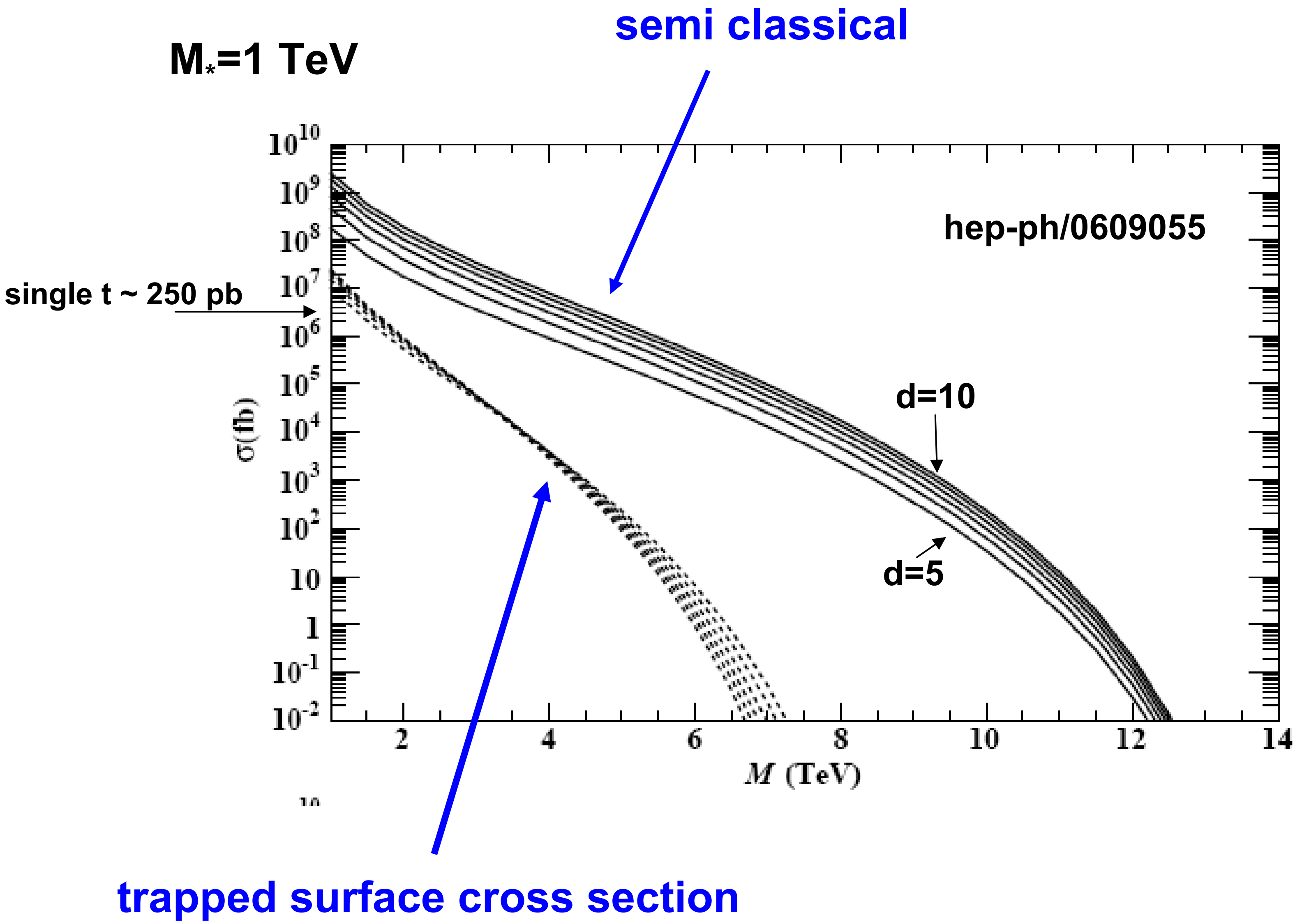
Trapped Energy Discussion

- Formation of BH is very non-linear and complicated
- $\mathbf{M_{BH} < \hat{s}}$
- Fractions of E, p and J are lost before settling to a BH!
- Yoshino & Rychkov calculated energy loss



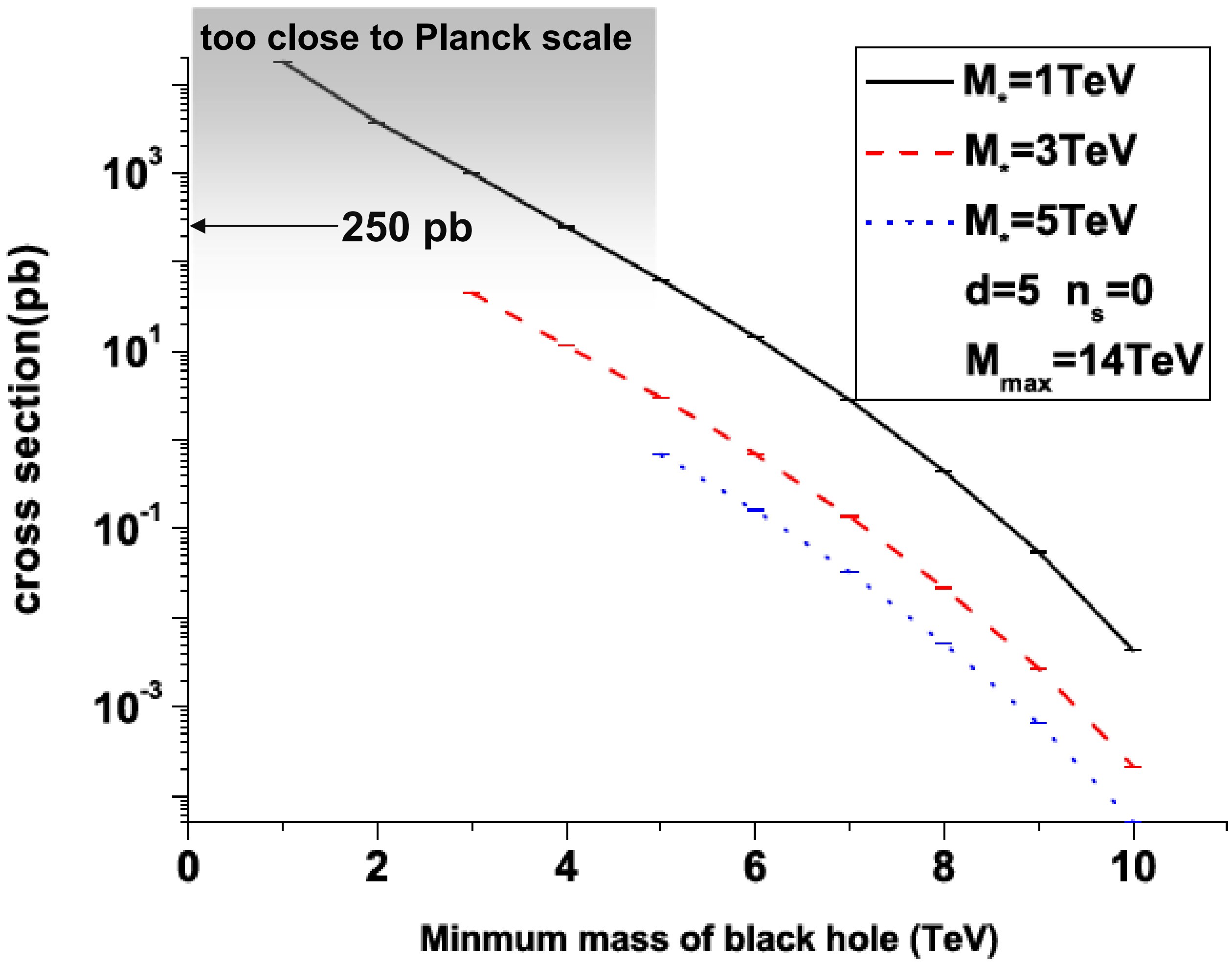
Effect of energy loss in formation and balding phase

M_*=1 TeV



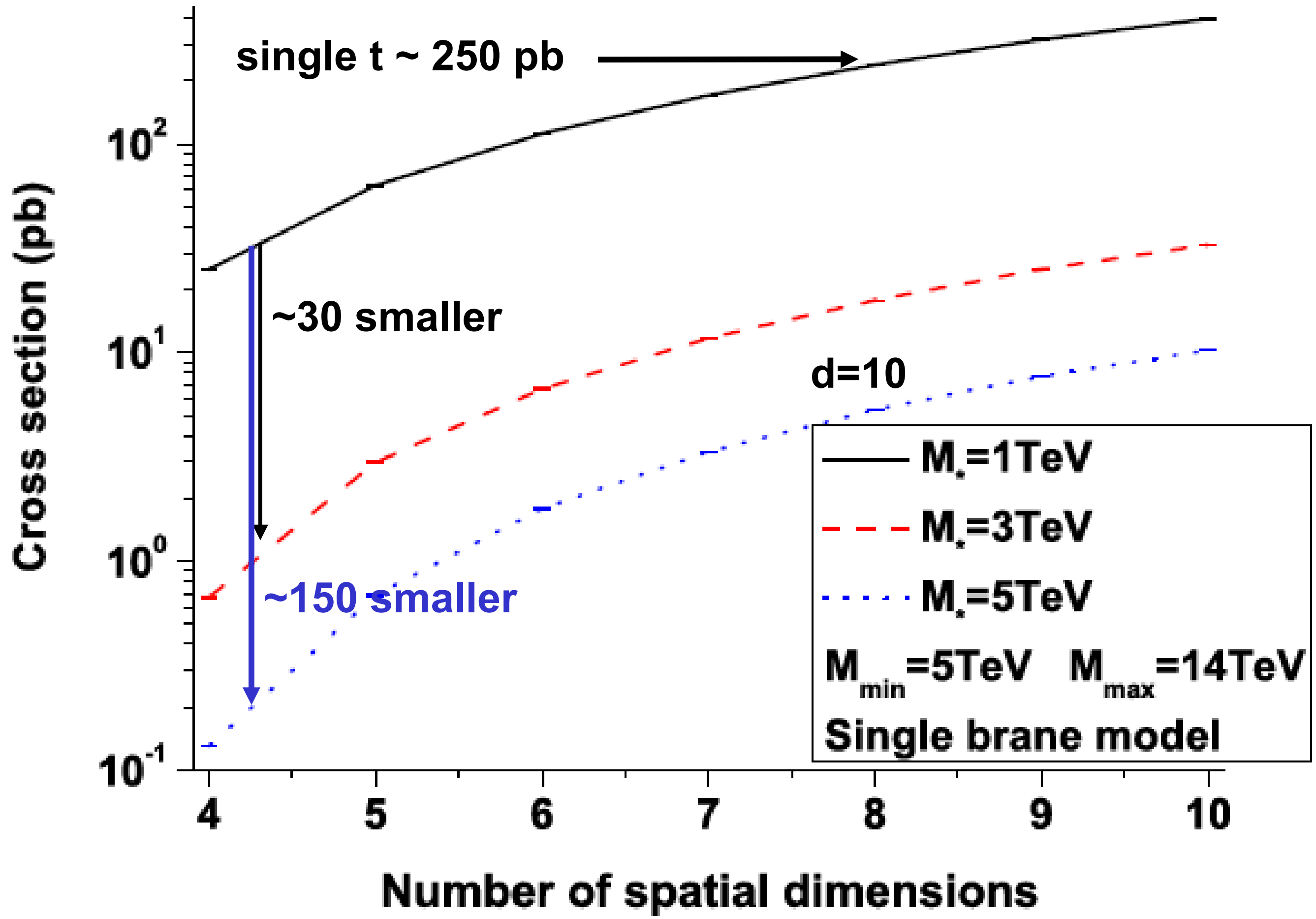
Production Cross Section for flat tensionless Brane

0711.3012 [hep-ph]



Production Cross Sections for flat, tensionless Brane

0711.3012 [hep-ph]



Split Fermion Brane Extra Dimensions

hep-ph/0605085, 0505112, 0606321, 0612018;gr-qc/0604072

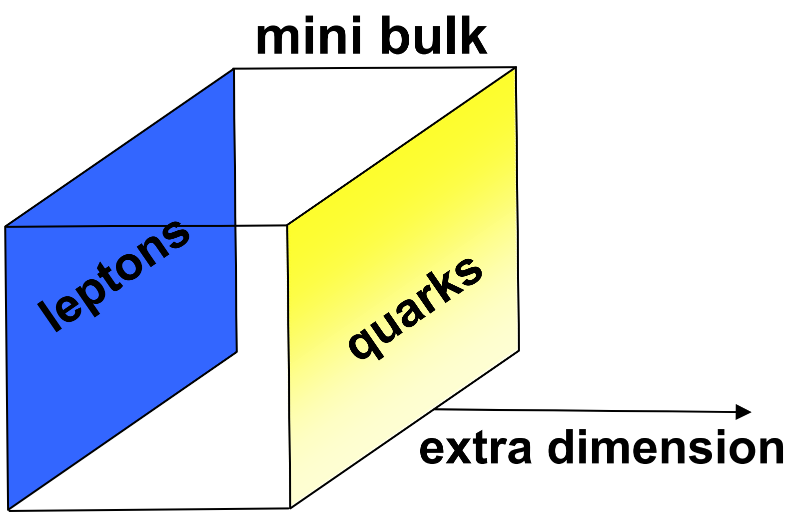
BH don't conserve B or L or flavour

- induced proton decay!
- n – nbar oscillations!
- Flavour changing neutron currents or large neutrino mixing

Introduce new symmetries

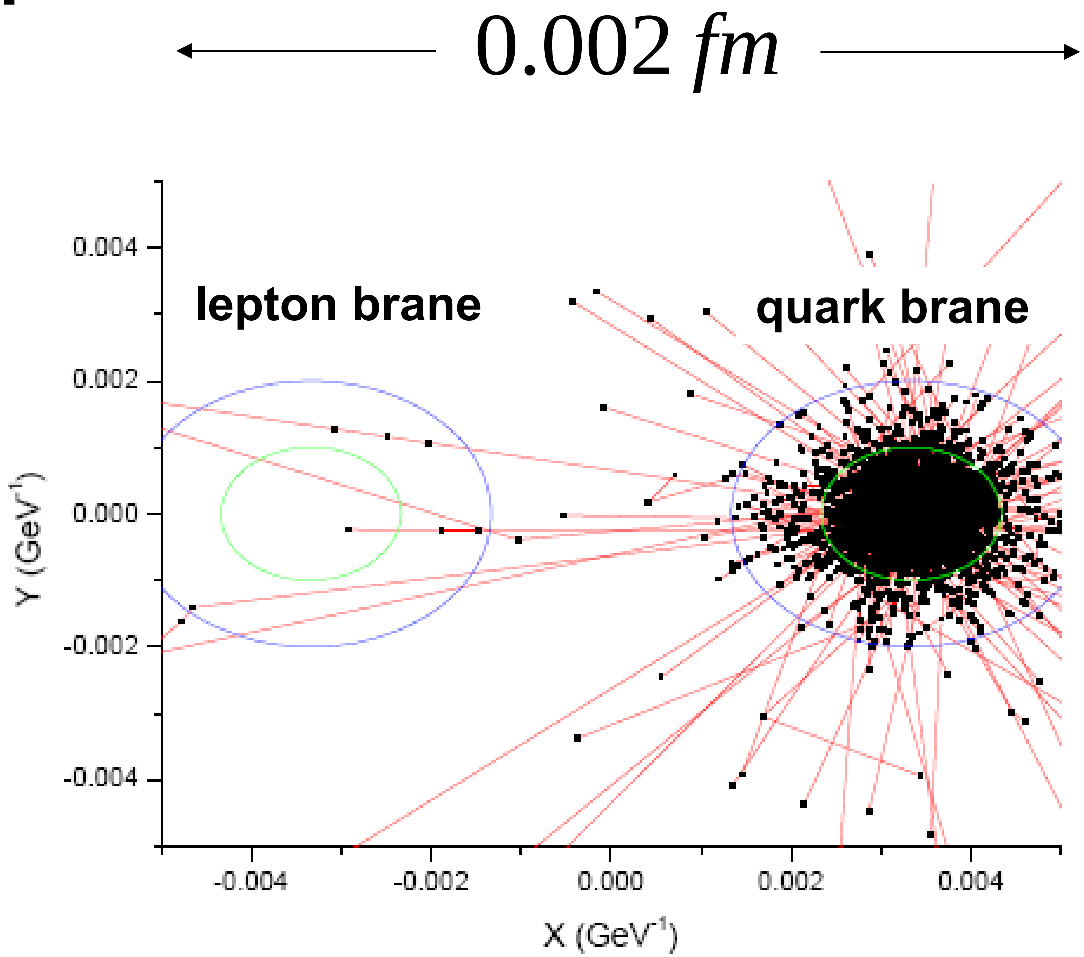
OR

SPLIT



Split Fermion Brane Extra Dimensions

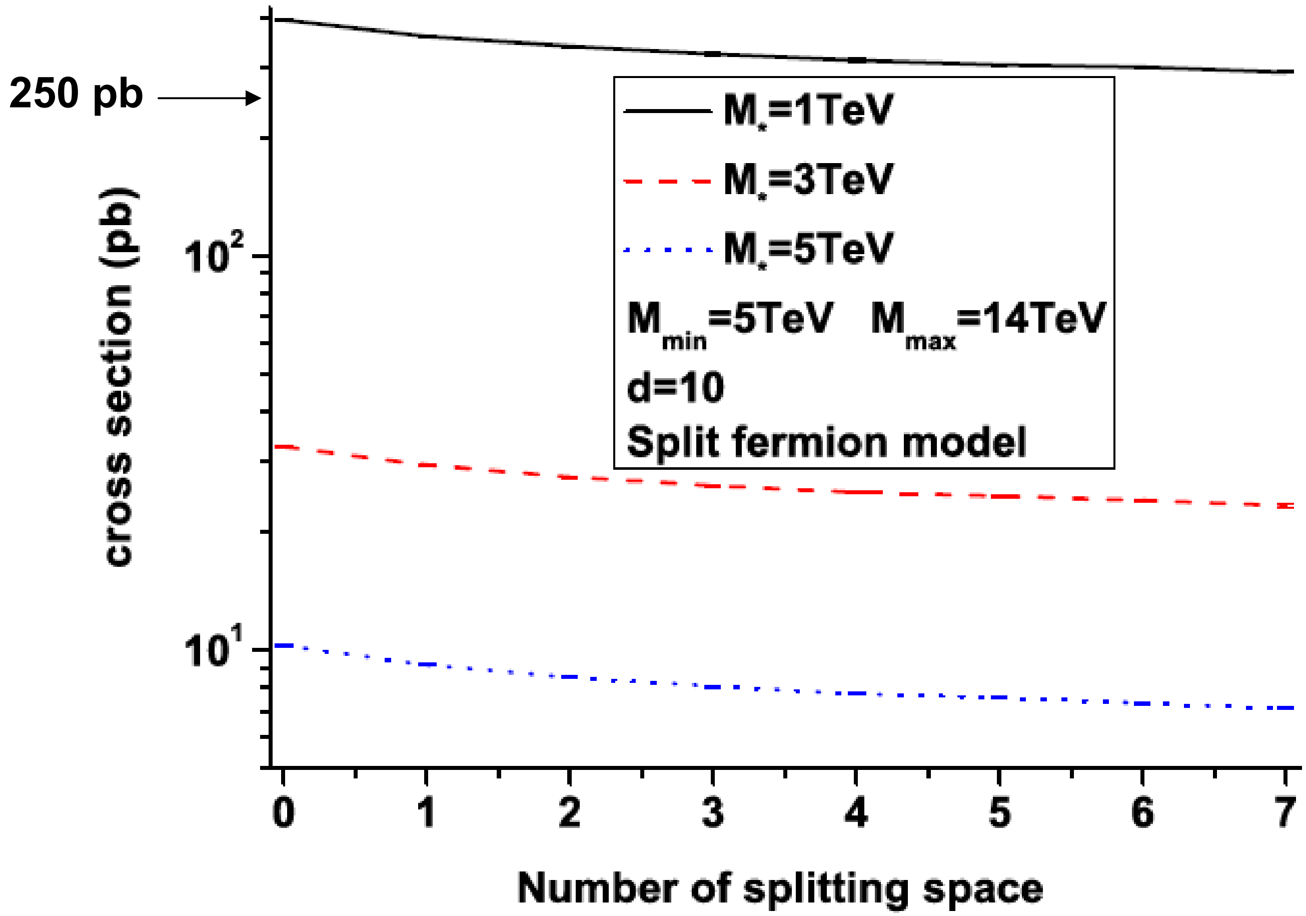
0711.3012 [hep-ph]



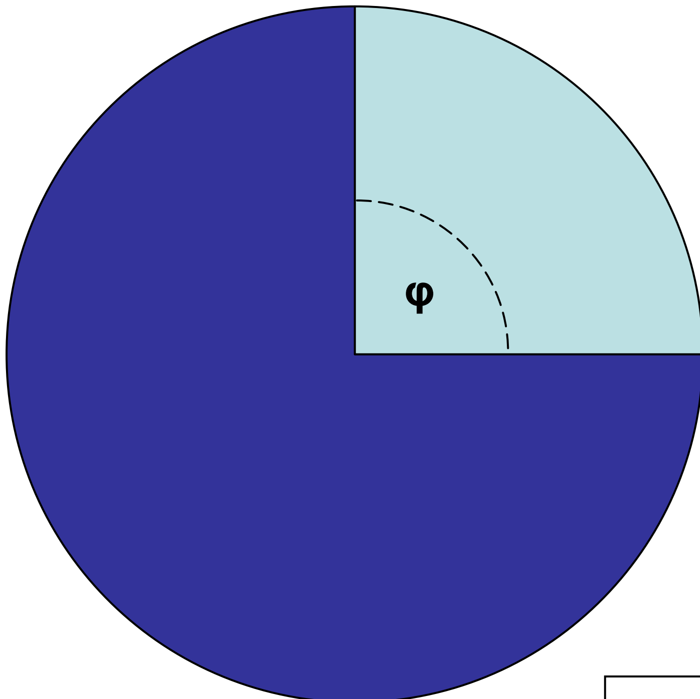
BH at the LHC will decay mainly into quarks and gluons!

Production Cross Section for Split Fermion EDs

0711.3012 [hep-ph]



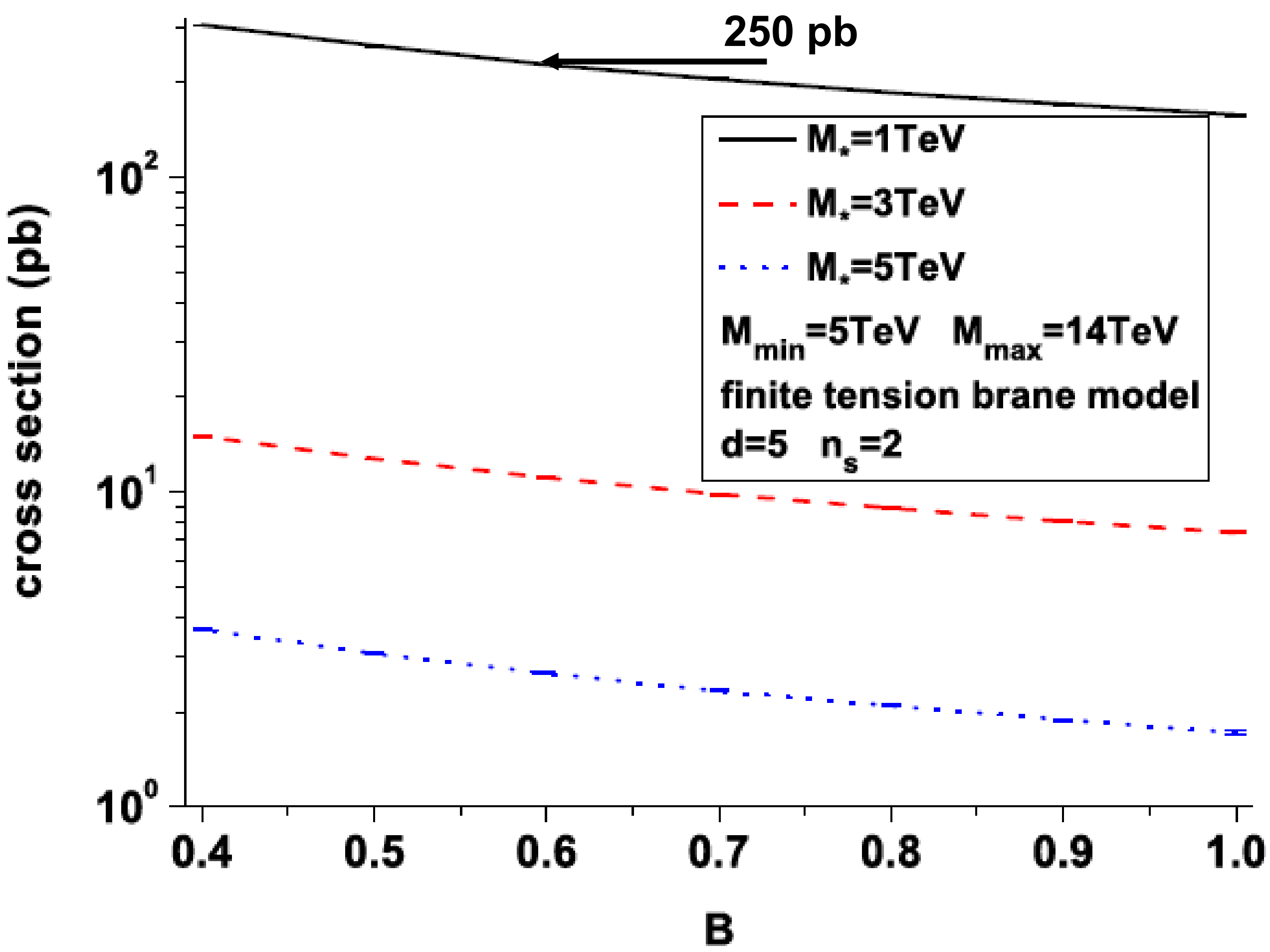
Branes with positive Tension



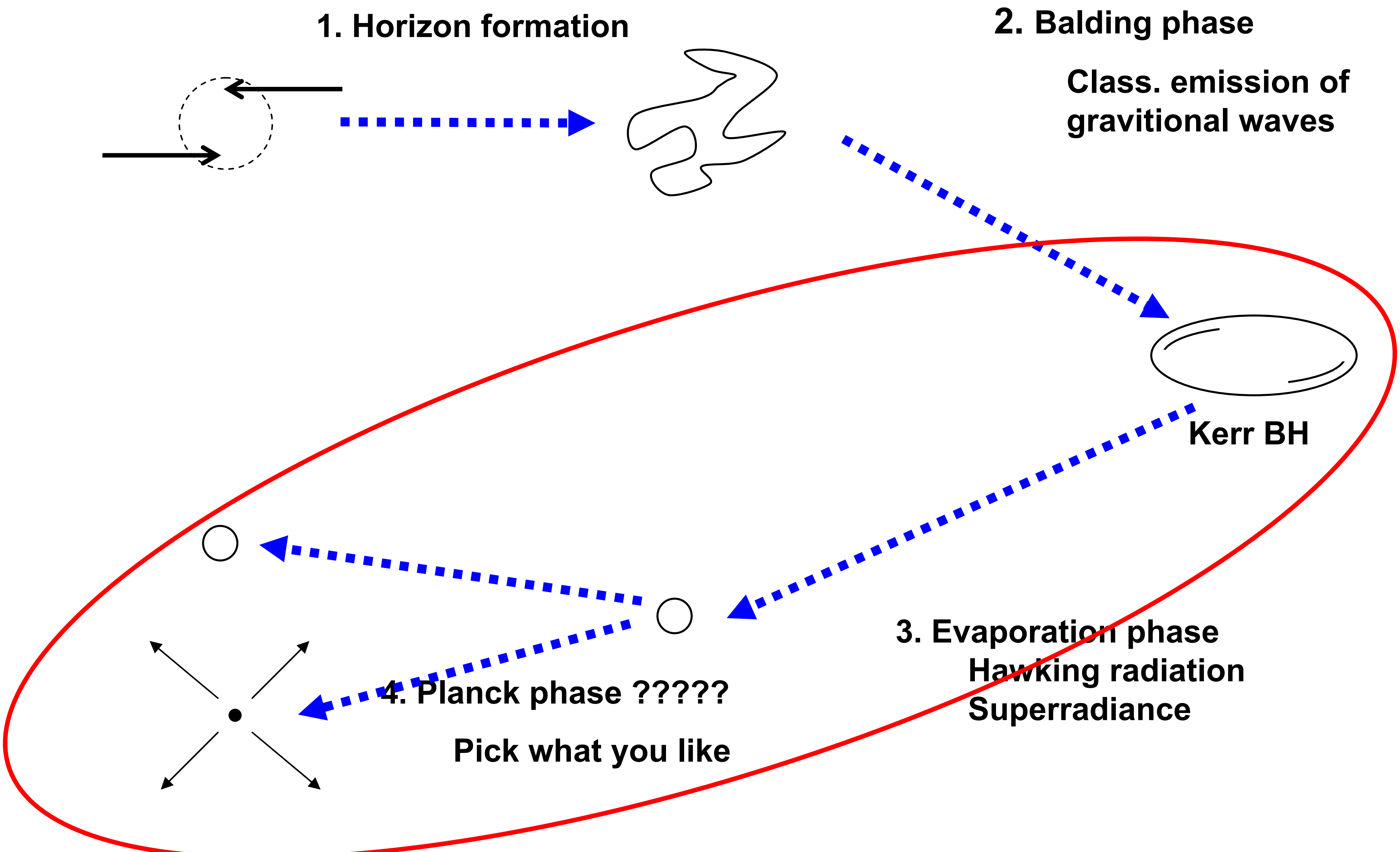
$$B \approx \frac{1}{\varphi}$$

deficit-angle parameter

Production Cross Section on Brane with Tension



Time Evolution of Black Holes

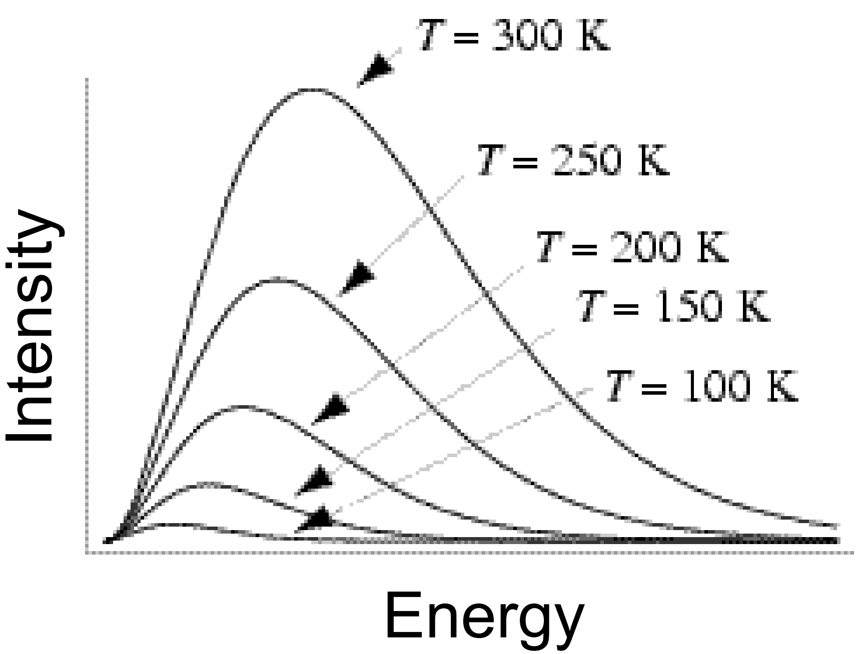


Black Holes decay!

Joins gravitation,
quantum field theory and
thermodynamics!!!

$$T_H = \frac{1}{8\pi}\frac{c^2 M_{PL}}{k_B}\frac{1}{M_{BH}}$$

emit particles ≈ **black body** thermal spectrum.



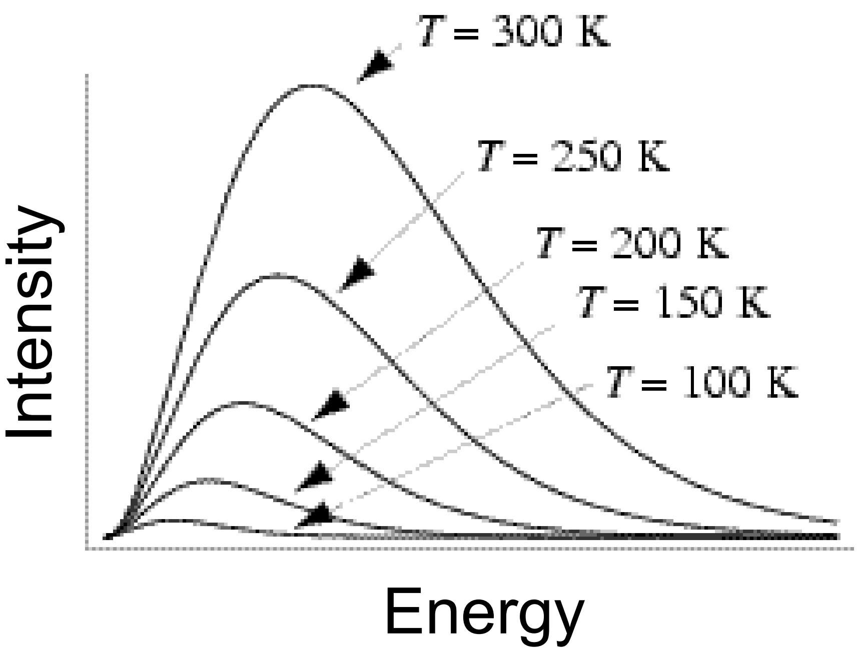
- BH lifetime @ LHC
  ~ 10^{-27}–10^{-25} s
- Decays with equal probability to all particles.

Black Holes decay!

- Astronomical BH -- **COLD**
  Low Evaporation Rate
- Micro BH -- **HOT**
  High Evaporation Rate

$$T_H \approx 10^{-6} \frac{M_{\odot}}{M} [K]$$

emit particles ≈ **black body** thermal spectrum.



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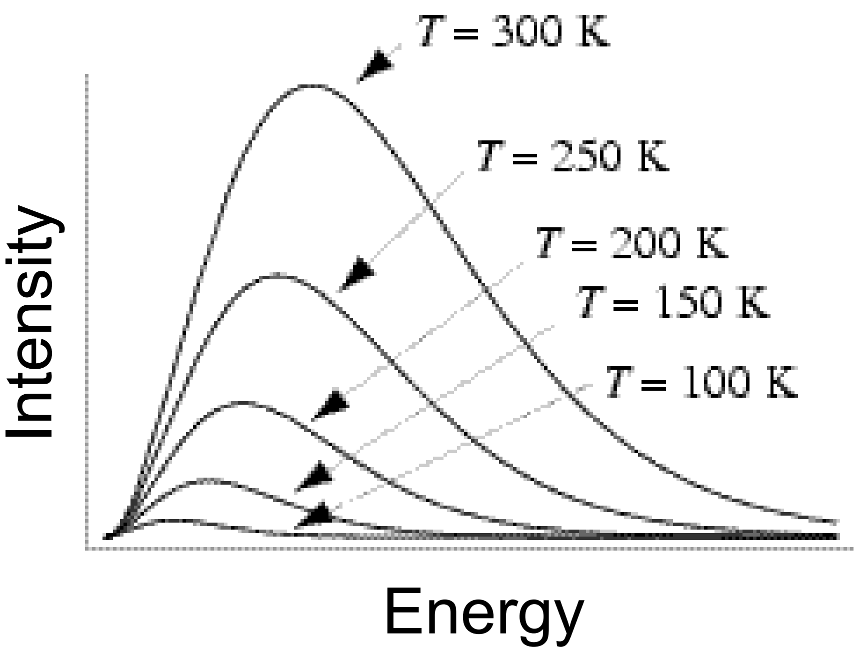
Black Holes decay!

- Astronomical BH -- **COLD**
  Low Evaporation Rate
- Micro BH -- **HOT**
  High Evaporation Rate

$$T_H \approx \frac{1+n}{M_{BH}^{1/(1+n)}}$$

emit particles ≈ **black body** thermal spectrum.



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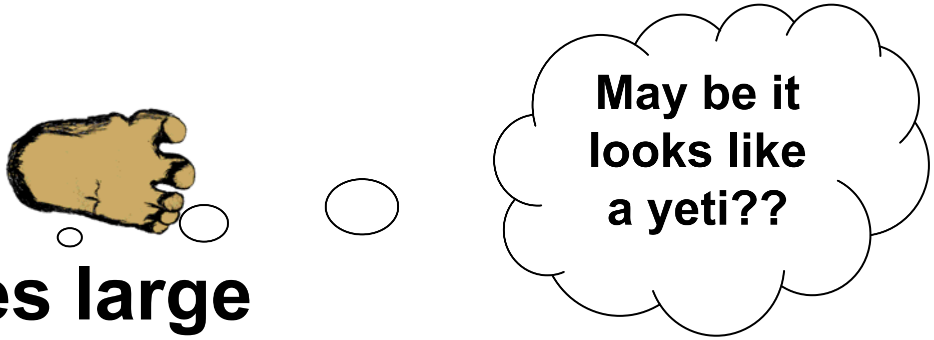
Footprints of Microscopic Black Holes



- hadron : lepton ≈ 5 : 1
- Theoretical uncertainties large
- high multiplicities

  10 – 40 particles/event
- decay product's energies up to TeV
- SM backgrounds expected to be low

0711.3012 [hep-ph]

scenario	q + g	leptons	W, Z	ν	G	H	photons
d=4, J=0	79%	9.5%	5.7%	3.9%	0.2%	0.9%	0.8%

0711.3012 [hep-ph]

scenario	q + g	leptons	W, Z	v	G	H	photons
d=4, J=0	79%	9.5%	5.7%	3.9%	0.2%	0.9%	0.8%
d=10, J=0	74%	7.7%	6.8%	3.2%	6.5%	0.7%	1.5%

0711.3012 [hep-ph]

scenario	q + g	leptons	W, Z	ν	G	H	photons
d=4, J=0	79%	9.5%	5.7%	3.9%	0.2%	0.9%	0.8%
d=10, J=0	74%	7.7%	6.8%	3.2%	6.5%	0.7%	1.5%
d=10, J=0, n_s=7	84%	1.8%	5.4%	0.5%	6.7%	0.3%	1.6%

0711.3012 [hep-ph]

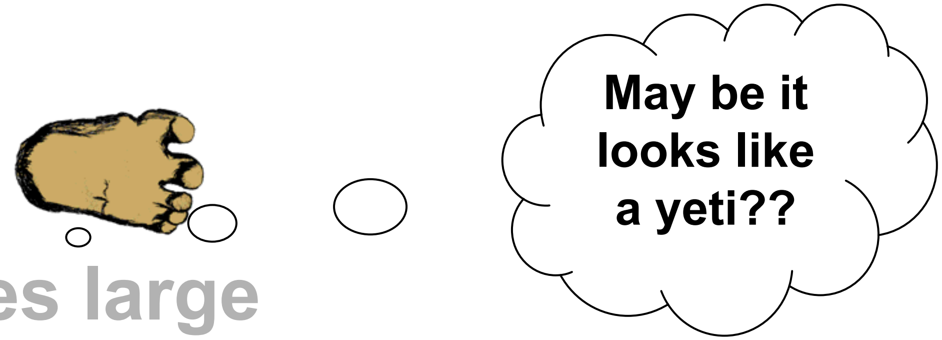
scenario	q + g	leptons	W, Z	v	G	H	photons
d=4, J=0	79%	9.5%	5.7%	3.9%	0.2%	0.9%	0.8%
d=10, J=0	74%	7.7%	6.8%	3.2%	6.5%	0.7%	1.5%
d=10, J=0, n_s=7	84%	1.8%	5.4%	0.5%	6.7%	0.3%	1.6%
d=5, J=0, n_s=2, B=0.4	96%	1.6%	1.7%	0.15%	0.4%	0.2%	0.3%

0711.3012 [hep-ph]

scenario	q + g	leptons	W, Z	ν	G	H	photons
d=4, J=0	79%	9.5%	5.7%	3.9%	0.2%	0.9%	0.8%
d=10, J=0	74%	7.7%	6.8%	3.2%	6.5%	0.7%	1.5%
d=10, J=0, n_s=7	84%	1.8%	5.4%	0.5%	6.7%	0.3%	1.6%
d=5, J=0, n_s=2, B=0.4	96%	1.6%	1.7%	0.15%	0.4%	0.2%	0.3%
d=10, J>0	78%	6.5%	9.6%	2.5%	?	0.7%	2.6%

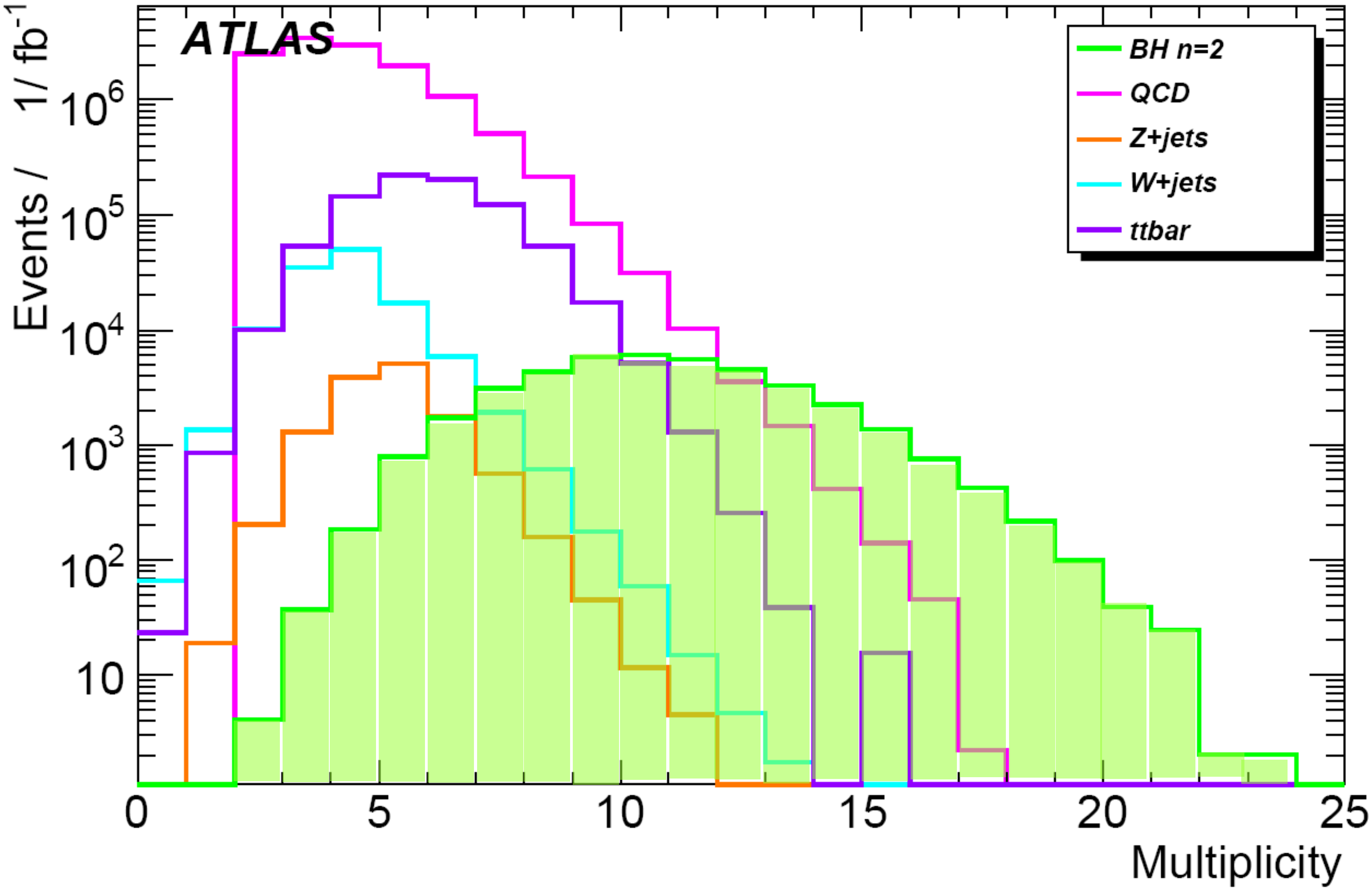
Footprints of Microscopic Black Holes

- hadron : lepton ≈ 5 : 1



- Theoretical uncertainties large
- high multiplicities
  10 – 40 particles/event
- decay product's energies up to TeV
- SM backgrounds expected to be low

Multiplicity for d = 5, M_*=1 TeV, Mbh> 5TeV



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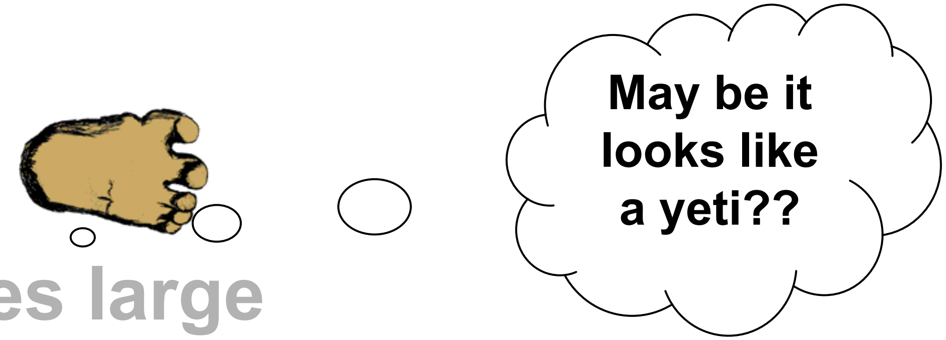


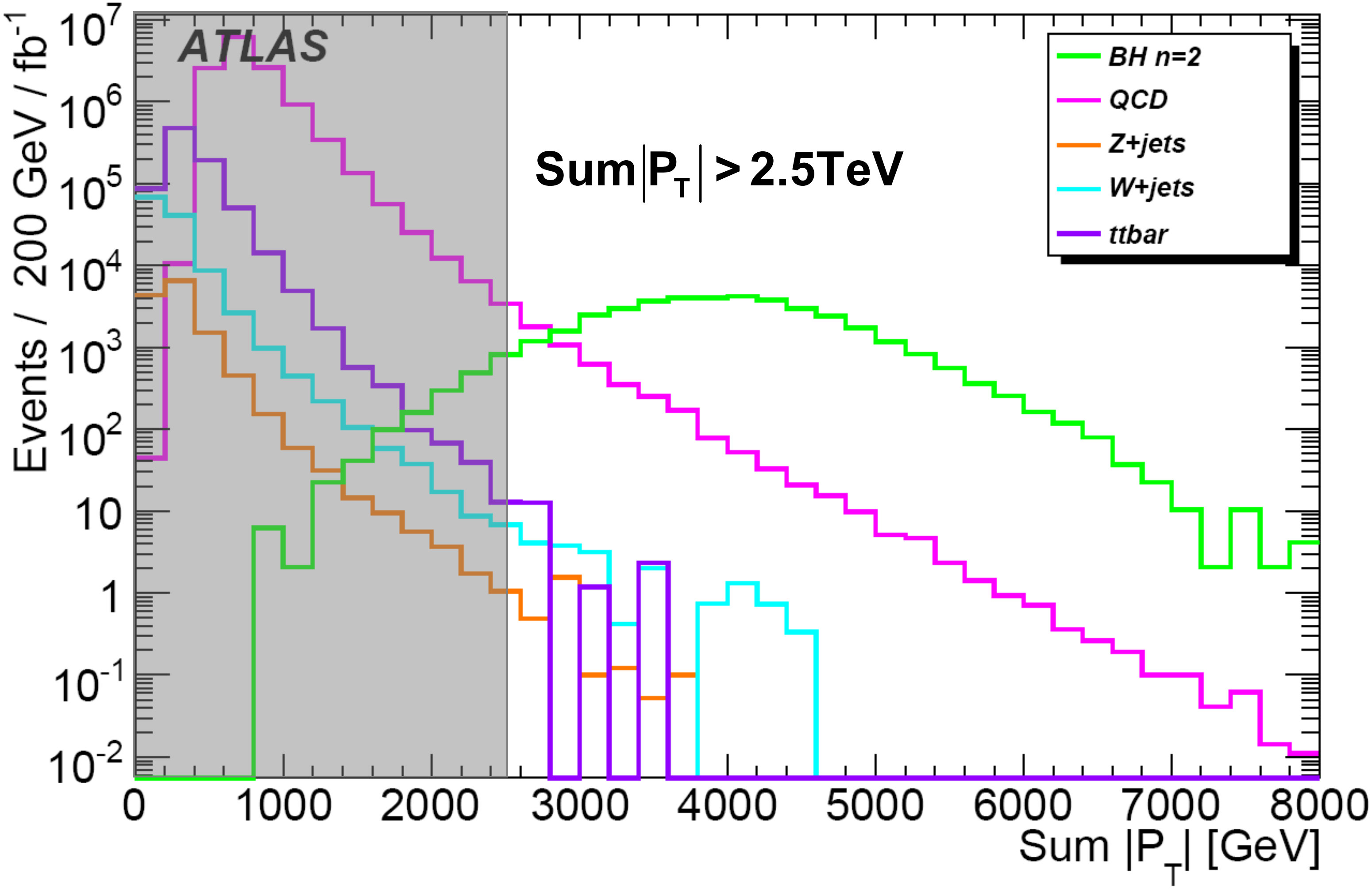
- Theoretical uncertainties large

- high multiplicities
  10 – 40 particles/event

- **decay product's energies up to TeV**

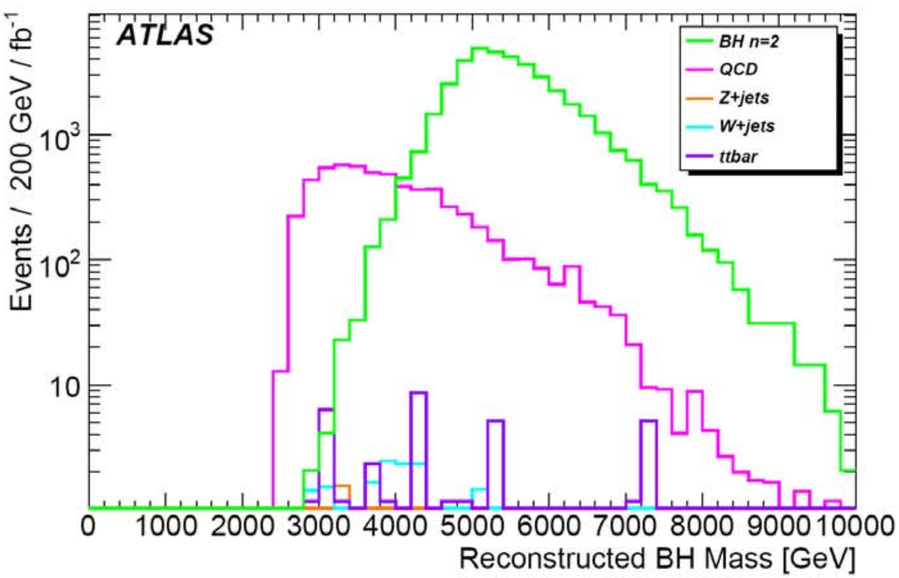
- **SM backgrounds expected to be low**

Scalar Sum Pt of Black Hole Events



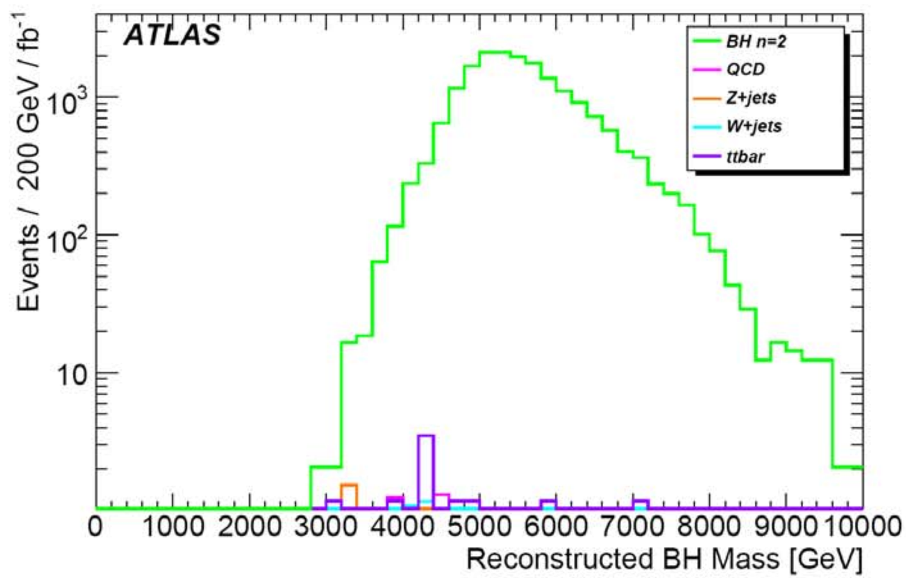
Reconstructed Mass

$\mathrm{Sum}|P_T| > 2.5\mathrm{TeV}$



$\mathrm{Sum}|P_T| > 2.5\mathrm{TeV}$

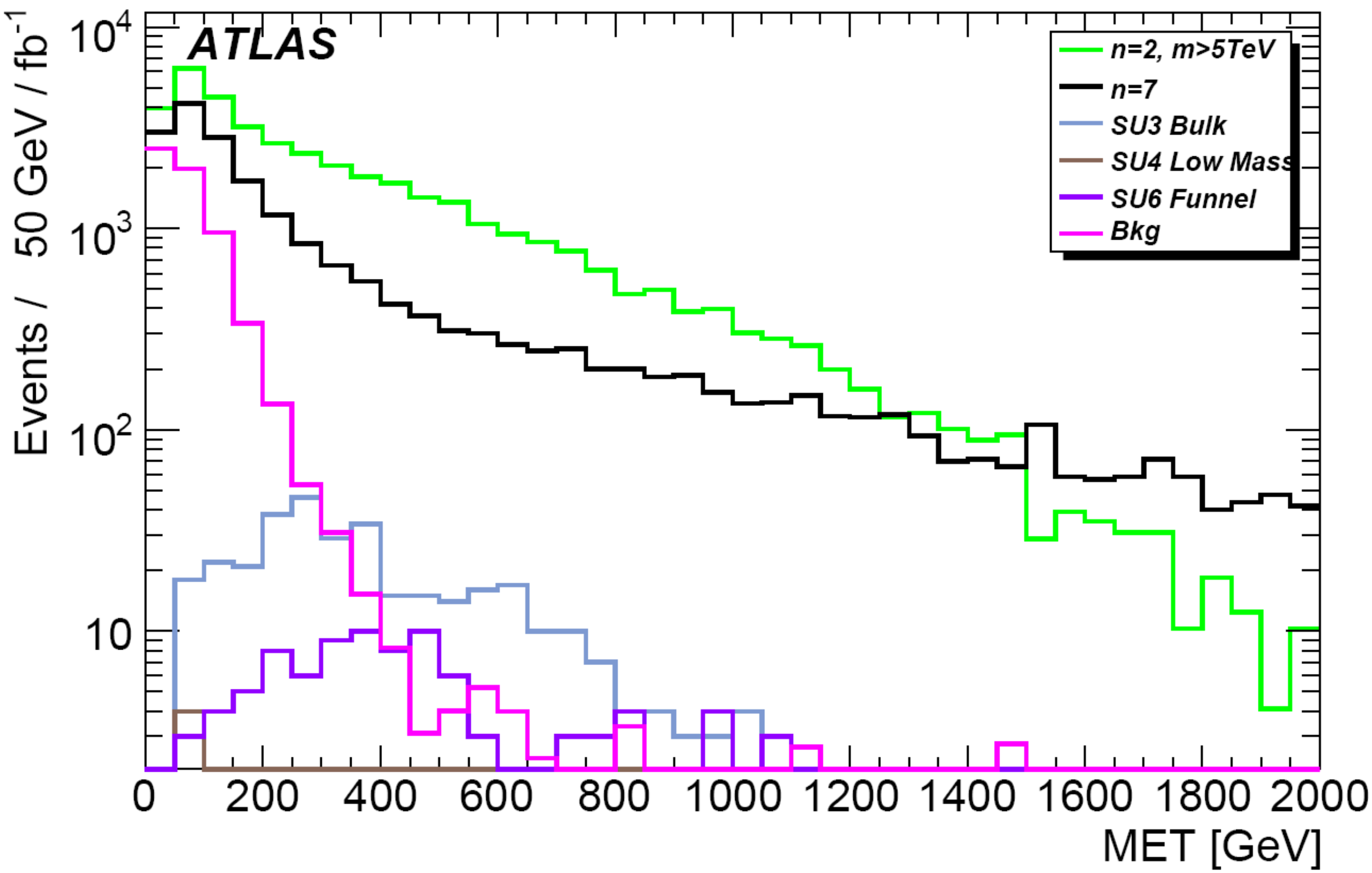
$\mathrm{LeptonP}_T > 50\mathrm{GeV}$



Backgrounds are low

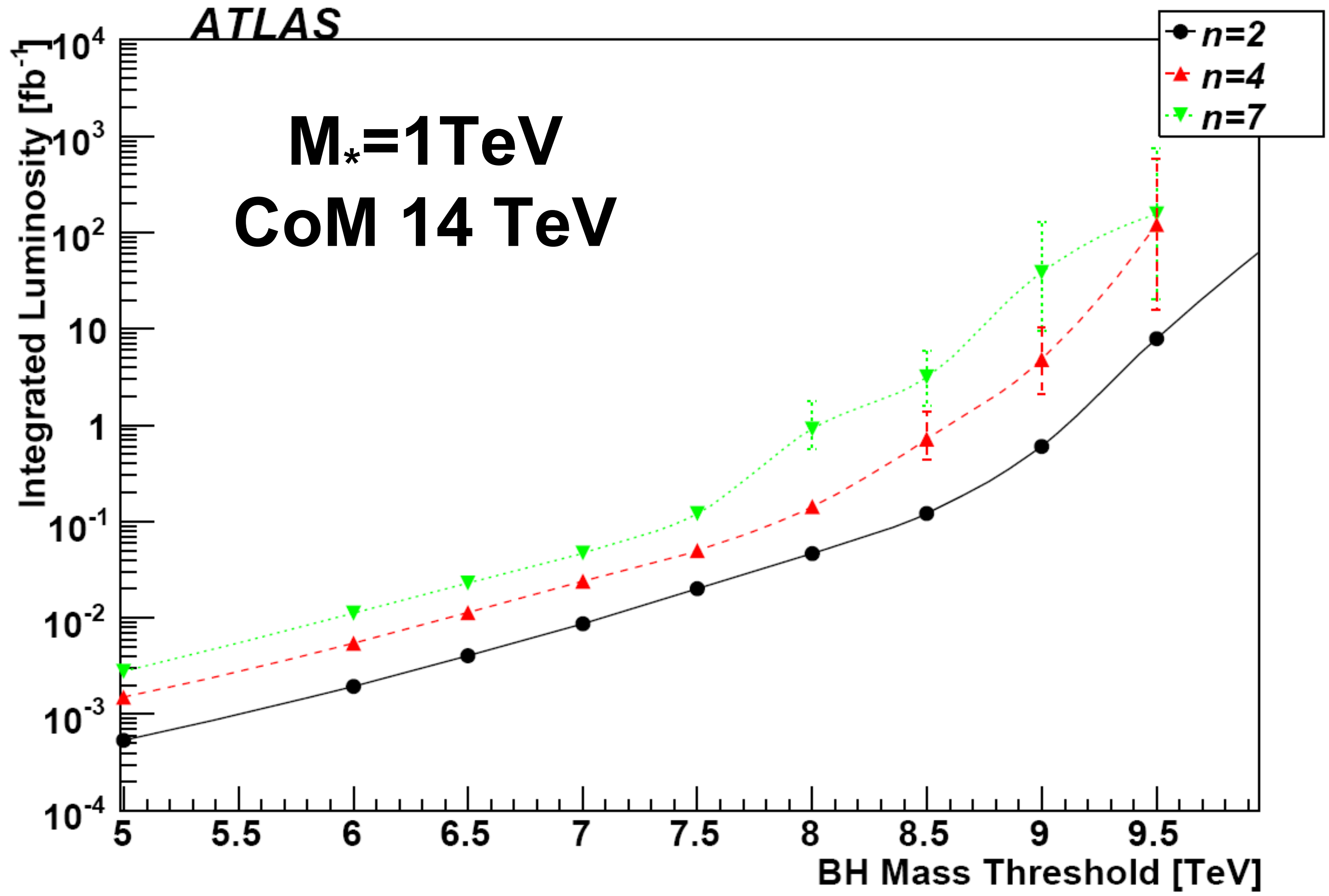
Missing Transverse Energy (MET)

$$\text{Sum}\left|P_T\right| > 2.5\text{TeV}$$



Hard to reproduce in other new physics scenarios.

Discovery Reach for S>10 and S/sqrt(B) > 5



BH with m>5 TeV with a few pb^{-1}
BH with m>8 TeV with 1 fb^{-1}

The Register®

Biting the hand that feeds IT

The US Federal Court scheduled trial to begin 16 June 2009.

The Register » Science » Physics »

Original URL:
http://www.theregister.co.uk/20… …c_cern_hawaiian_botanist_lawsuit/

Botanist sues … CERN hurling Earth into parallel univers…

B… …age
…ed Friday 28th March 2008 14:11 GMT

A lawsuit has been filed in Hawaii in an attempt to hold up the start of operations by the Large Hadron Collider (LHC) atom-smasher on the French-Swiss border.

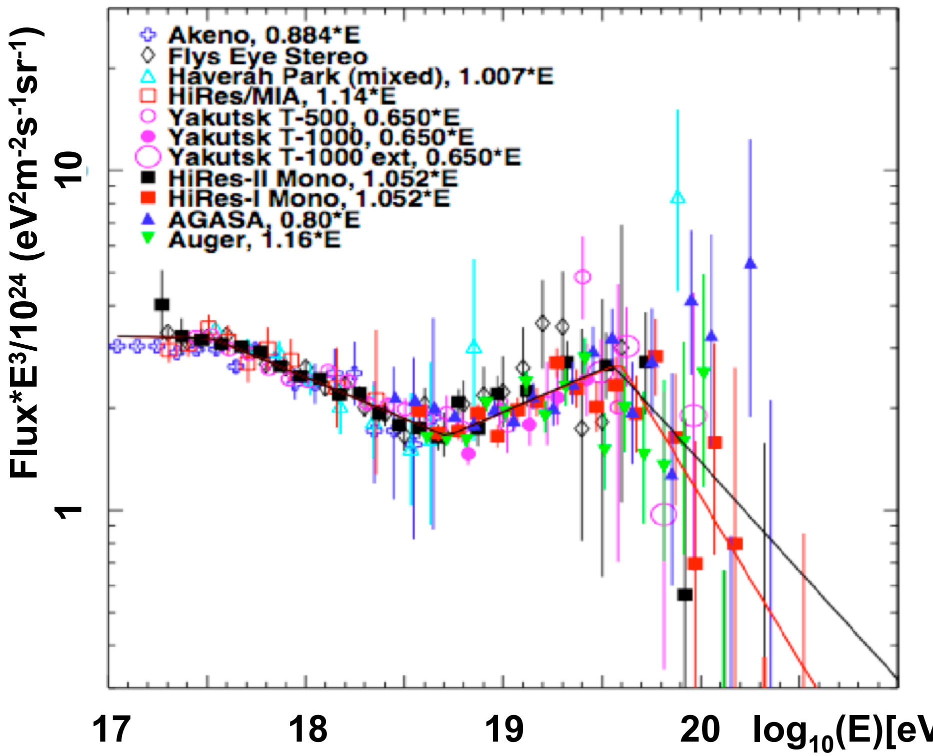
A colourful American botanist, teacher, former biologist and sometime physicist says (in outline) that the LHC may rip a hole in the fabric of the space-time continuum and so destroy the Earth. He wants the US government to act now and delay the LHC's startup while a new safety review is carried out.

LHC is safe!

J. Ellis, http://indico.cern.ch/conferenceDisplay.py?confId=39099

- LHC@14 TeV=cosmic ray@10^{17}eV
- ~ 3.10^{22} cosmic rays >10^{17} eV have struck Earth
- Equivalent to 10^5 LHC programmes
- Area of Sun 10^4 larger
- 10^{11} stars in galaxy
- 10^{11} galaxies in Universe
- Nature has performed 10^{31} LHC programmes
- Nature carries out 3.10^{13} LHC programmes per second

arXiv:0806.3414v2 [hep-ph]



ultra-high-energy cosmic rays up to 10^{20} eV

Black Holes are safe

Giddings & Mangano arXiv:0806.3381 [hep-ph]

- Concerns:
  - Will be produced in rest @ LHC
  - Will be neutral and stable
- Black Holes are unstable
  - Otherwise 2nd law of thermodynamics violated
  - Hawking, decay is related to their production
- EVEN IF stable, accretion rate negligible if high D
- EVEN IF low D, some of those produced by cosmic rays would be charged
  - would have stopped in Earth: **'We are here !`**
- EVEN IF all neutral, some would have been produced on white dwarfs and neutron stars
  - would have stopped: **`White dwarfs and neutron stars are out there!`**

Why the Earth won't be destroyed

- Small gravitational attraction
- Mass loss:

$$\frac{dM_-}{dt} \geq 10^{23}\,\text{TeV/sec}$$

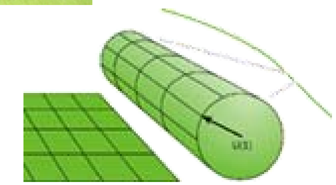
- Mass gain in quark gluon plasma:

$$\frac{dM_+}{dt} \approx 10^{11}\,\text{TeV/sec}$$

hep-ph/0412265

Summary

- Black Holes are not black!
- Extra Dimension → Strong gravity



- Probe Planck scale physics
- general relativity ⇔ quantum theory
- Discovery possible at the LHC with a few pb^{-1}
- Challenging experimental signatures

- The LHC is safe!

Backup Slides

Cygnus A (Elliptical galaxy)

- **730 million lightyears**
- This galaxy is the brightest radio source in the constellation Cygnus (Swan).
- The supermassive black hole in its center.

Gravity and Metrics

$$c^2\tau^2 = c^2dt^2 - dr^2 - r^2(d\theta^2 - \sin 2\theta d\varphi^2)$$

Minkowski metric of special relativity

$$c^2\tau^2 = (1-\frac{r_s}{r})c^2dt^2 - \frac{dr^2}{1-\frac{r_s}{r}} - r^2(d\theta^2 - \sin 2\theta d\varphi^2)$$

Schwarzschild metric, solution of Einstein's field equation in empty space

$$c^2\tau^2 = (1-\frac{r_s r}{\rho^2})c^2dt^2 - \frac{\rho^2}{\Lambda^2}dr^2 - \rho^2 d\theta^2 - (r^2 + \alpha^2 + \frac{r_s r\alpha^2}{\rho^2}\sin^2\theta)\sin 2\theta d\varphi^2 + \frac{2r_s r\alpha\sin^2\theta}{\rho^2}cdtd$$

Planck Scale Definitions

$$M_D^{n+2} = (2\pi)^n / 8\pi G_D$$ **PDG definition**

$$M_{DL}^{D-2} = 1/ G_D$$ **Dimopoulos & Landsberg**

$$M_{GT}^{n+2} = (2\pi)^n / 4\pi G_D$$ **Giddings & Thomas**

$$G_D = G * (2\pi R)^n$$ **D-dimensional Newton Gravity constant**

$$D = n + 4$$ **Total number of dimensions**

hep-ph/0106219,0110127,0007016,0110067

Laws of Black Hole Mechanics

BH Thermodynamics	Thermodynamics
0th Law: Horizon has constant surface gravity, κ	0th Law: T is constant in a body of thermal equibilirium
1st Law: $dM = \frac{\kappa}{8\pi} dA + \Omega dJ + \Phi dQ$	1st Law: $dU = dQ - dw$
2nd Law: $dA \geq 0$	2nd Law: entropy of a closed system is a non-decreasing function of time
3rd Law: No BH with κ = 0!	3rd Law: Can't reach absolute zero in a physical process

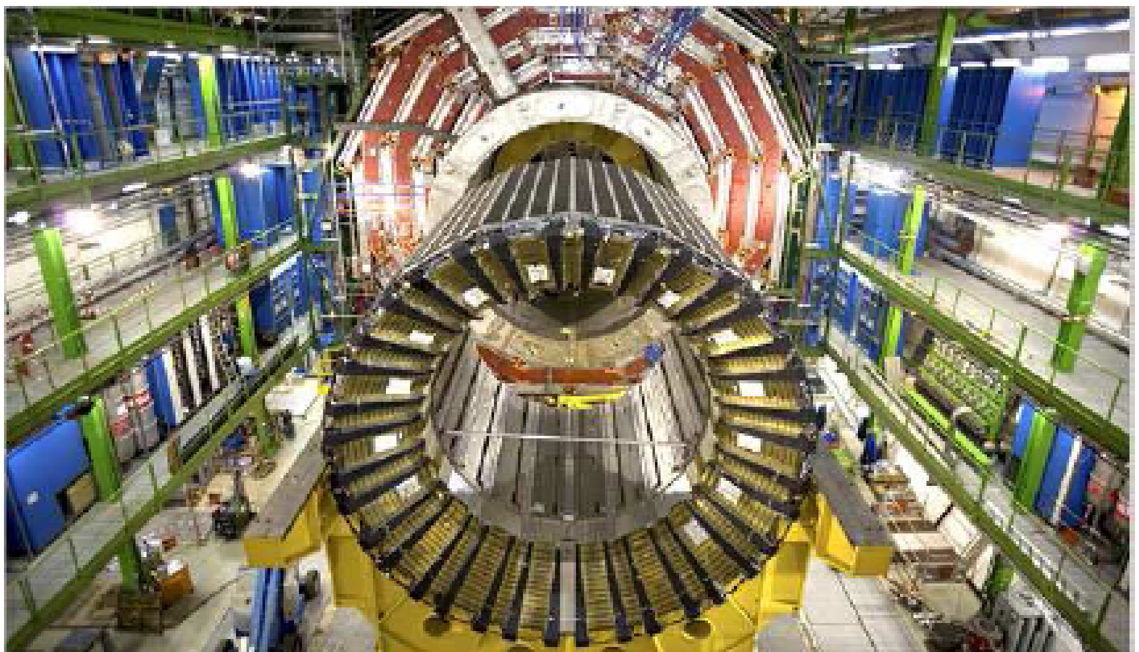
$$T_{BH} = \frac{\kappa}{2\pi}$$

$$S_{BH} = \frac{A}{4}$$

The New York Times

Science

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



Valerio Mezzanotti for The New York Times

Part of a detector to study results of proton collisions by a particle accelerator that a federal lawsuit filed in Hawaii seeks to stop.

By DENNIS OVERBYE
Published: March 29, 2008

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