Gravity measurements and black holes

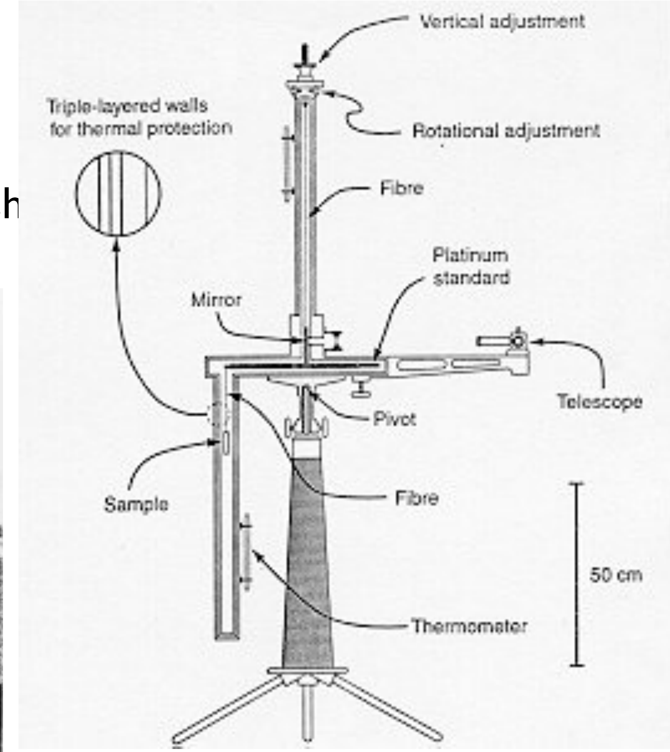
Force law, gravitational scattering and black holes

The Eötvös Experiment

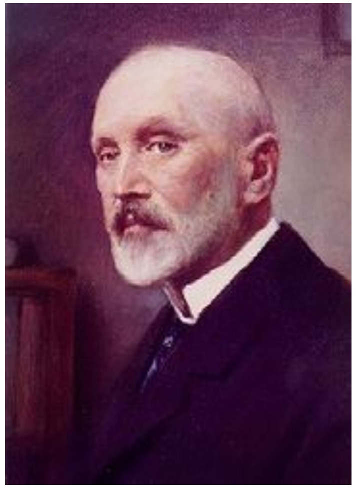
Baron Roland von Eötvös

Worked with Pekár and Fekete between 1906 and 1909 to test the weak equivalence principle using a variation on the Cavendish balance

R. von Eötvös, D. Pekár, and E. Fekete, Ann. Phys. (Leipzig) ***68, 11 (1922).***



Torsion balance has masses at different levels, hence sensitive to vertical changes in gravity.



Vásárosnaményi Báró Eötvös Loránd

Mountainer, rider, cyclist, celebrity, photographer, poet, scientist...

Deviations from Newtonian gravity

Gravity experiments present results in terms of Yukawa interaction of form

$$V(r) = -\int dr_1 \int dr_2 \frac{G\rho_1(r_1)\rho_2(r_2)}{r_{12}}[1 + \alpha e^{-r_{12}/\lambda}]$$

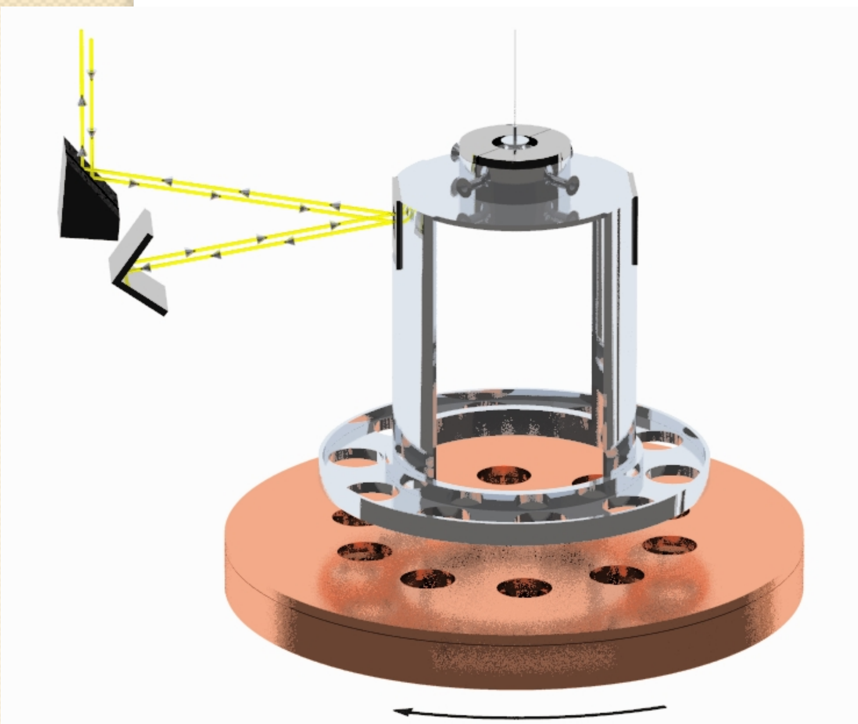
λ gives range of force

α gives strength relative to Newtonian gravity.

Torsion balances measure very small deviations from gravity, but rely on mass of Earth – hence only sensitive to long-range forces.

Is it possible that gravity deviates from normal force law at small distances, or another short-range force exists? (anti-gravity??)

Submillimetre gravity measurements: Eot-Wash



The two rings largely cancel each other out for $1/r^2$ but not for short range forces.

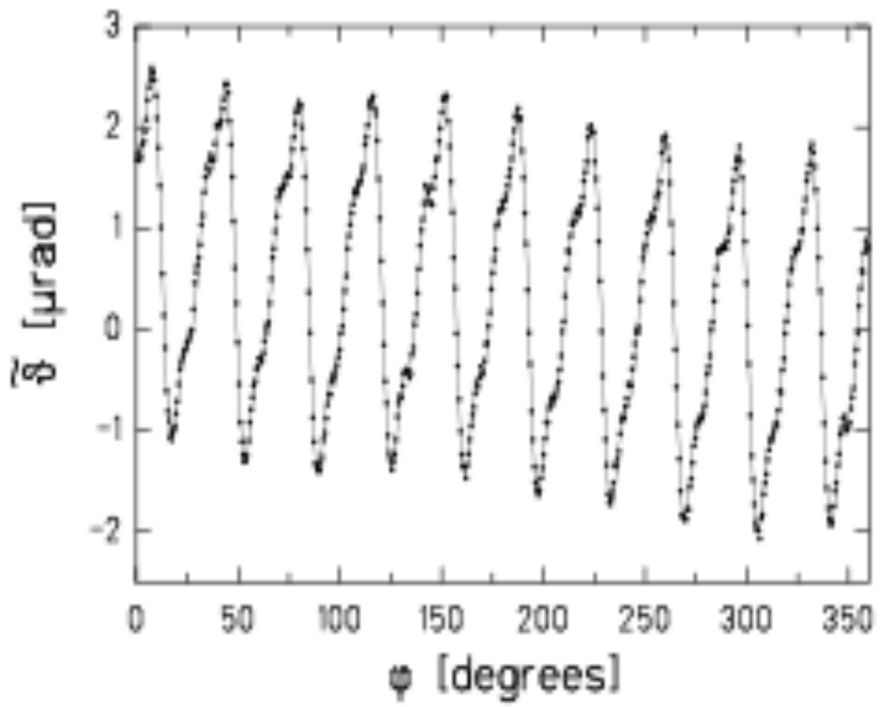
Washington group named their team Eot-Wash in honour of Eotvos.

Designed null experiment to measure gravity at short distances.

Test mass is ring with 10 holes on torsion fibre.

Attractor has two rings each with 10 holes, displaced by 18 degrees (ie halfway between). Lower ring is thicker, to compensate for larger distance from test mass. Attractor rotates steadily.

Torsional pendulum data



Data from one turn of base plate, with fitted expected curve

Signal would have higher harmonic content and different dependence on distance.

Membrane between attractor and test mass shields EM forces

All surfaces gold plated to avoid static.

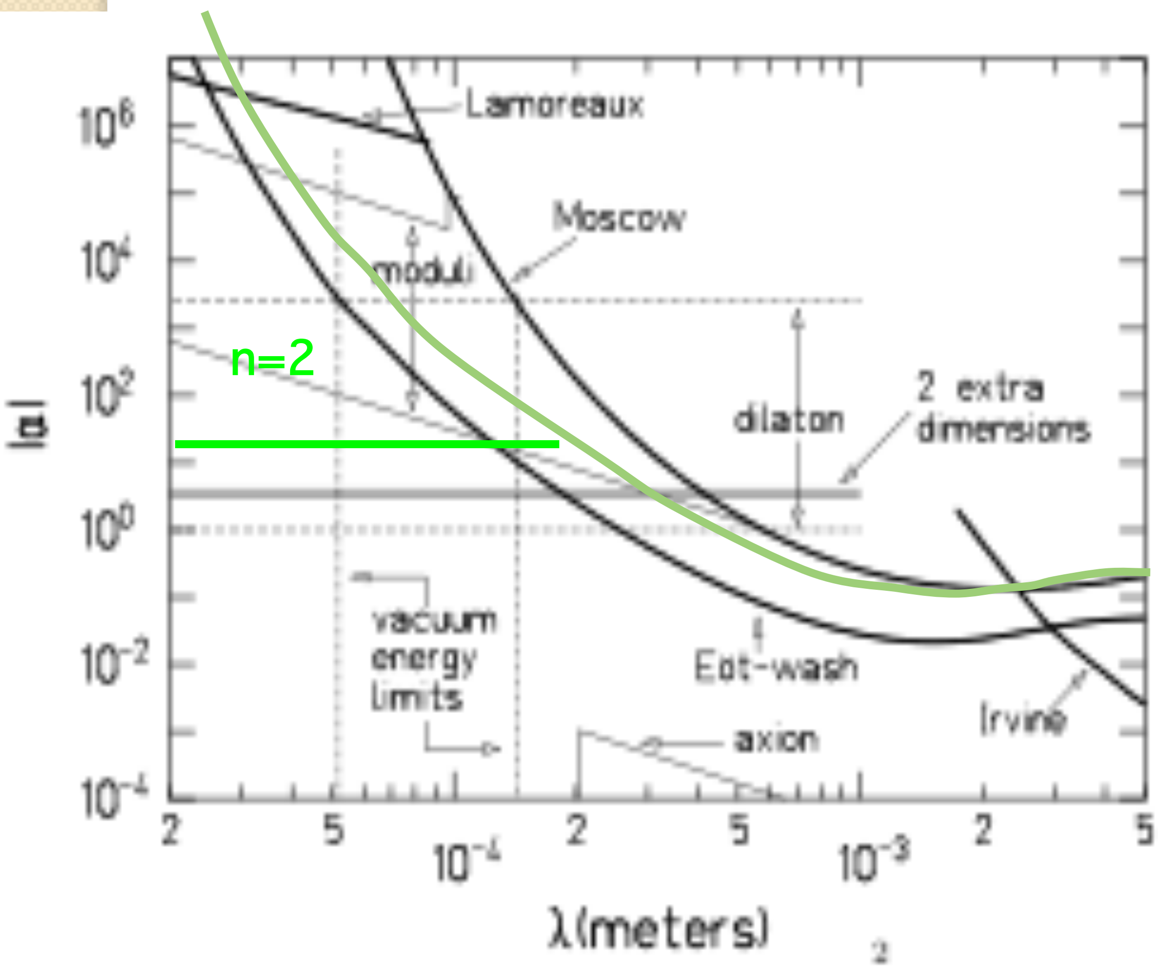
Flat geometry gets masses close together.

Signal expected at 10, 20 , 30 x frequency of rotation of attractor, reducing sensitivity to effects associated with the drive.

Separation down to 218μm

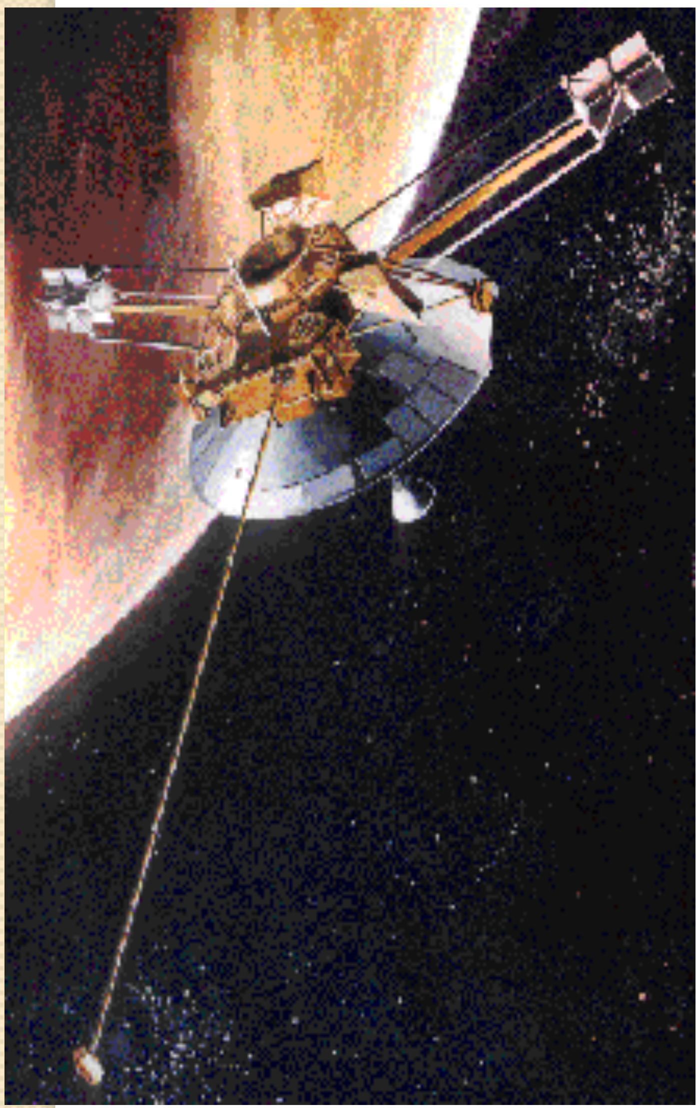
Angular precision 8nrad

Limit from torsional pendulum



Experiment sensitive to forces with twice the strength of normal gravity, with ranges as small 200 microns, for models with 2 extra space dimensions.

Pioneer 10



Pioneer 10 is leaving the solar system after 30 years in flight.

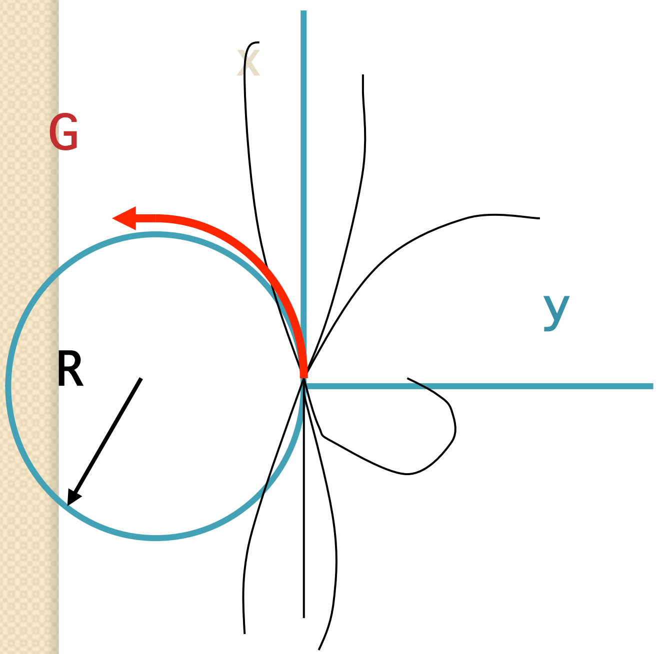
Orbit shows deceleration from force of 10^{-10} g

Radiation pressure?

- Solar?
- Antenna?
- Heat?
- Gas leaks

Time dependence?

Signatures for Large Extra Dimensions at Colliders



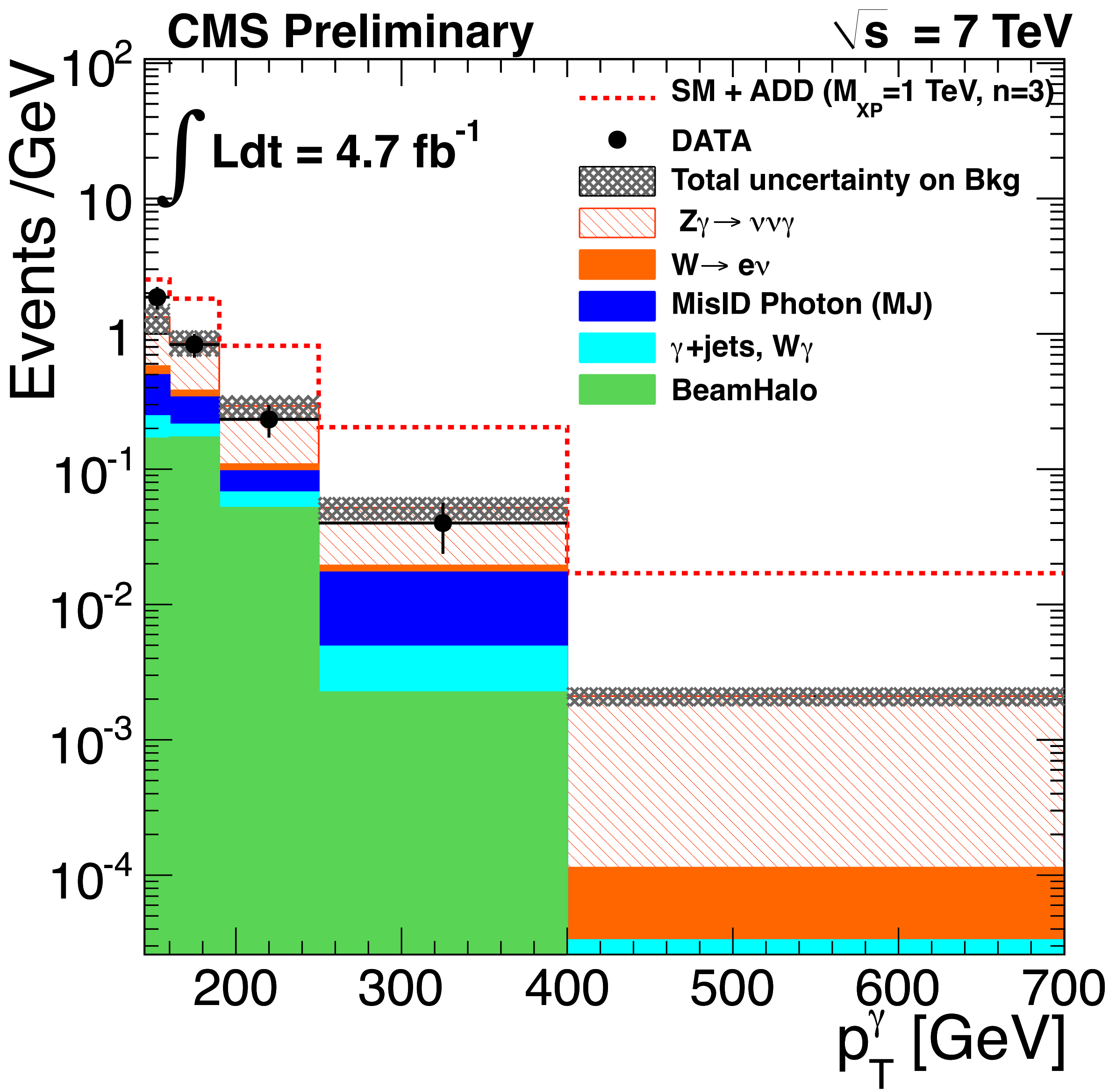
- ADD model (hep-ph/9803315)

- Each excited graviton state has normal gravitational couplings
- -> negligible effect
- LED: very large number of KK states in tower
- Sum over states is large.

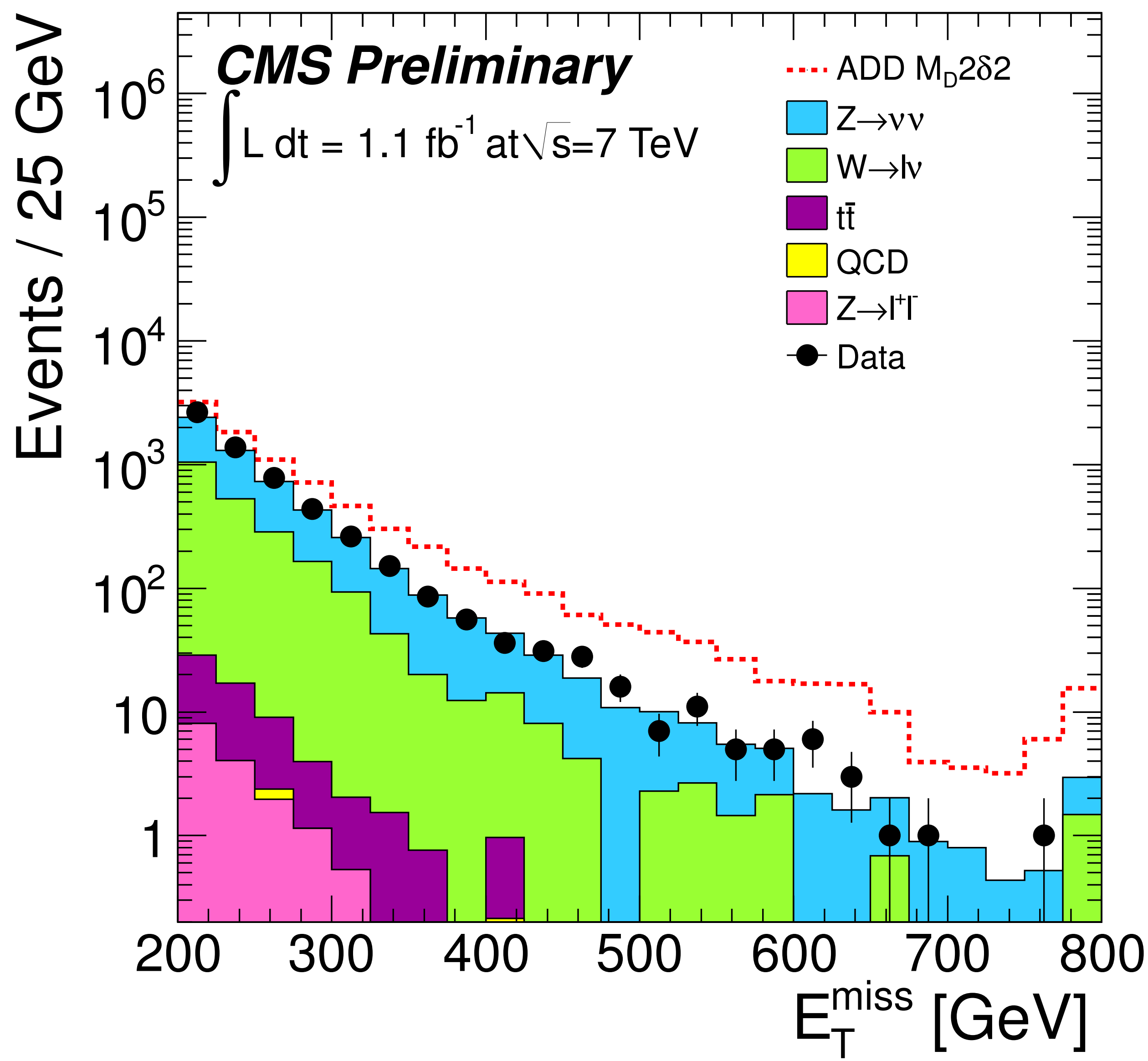
- => Missing energy signature with massless gravitons escaping into the extra dimensions

CMS Missing E_T search for LED

- pp -> $\gamma + E_T^{Miss}$
- Graviton recoils against photon and leaves into ED
- Photon easy to detect and measure



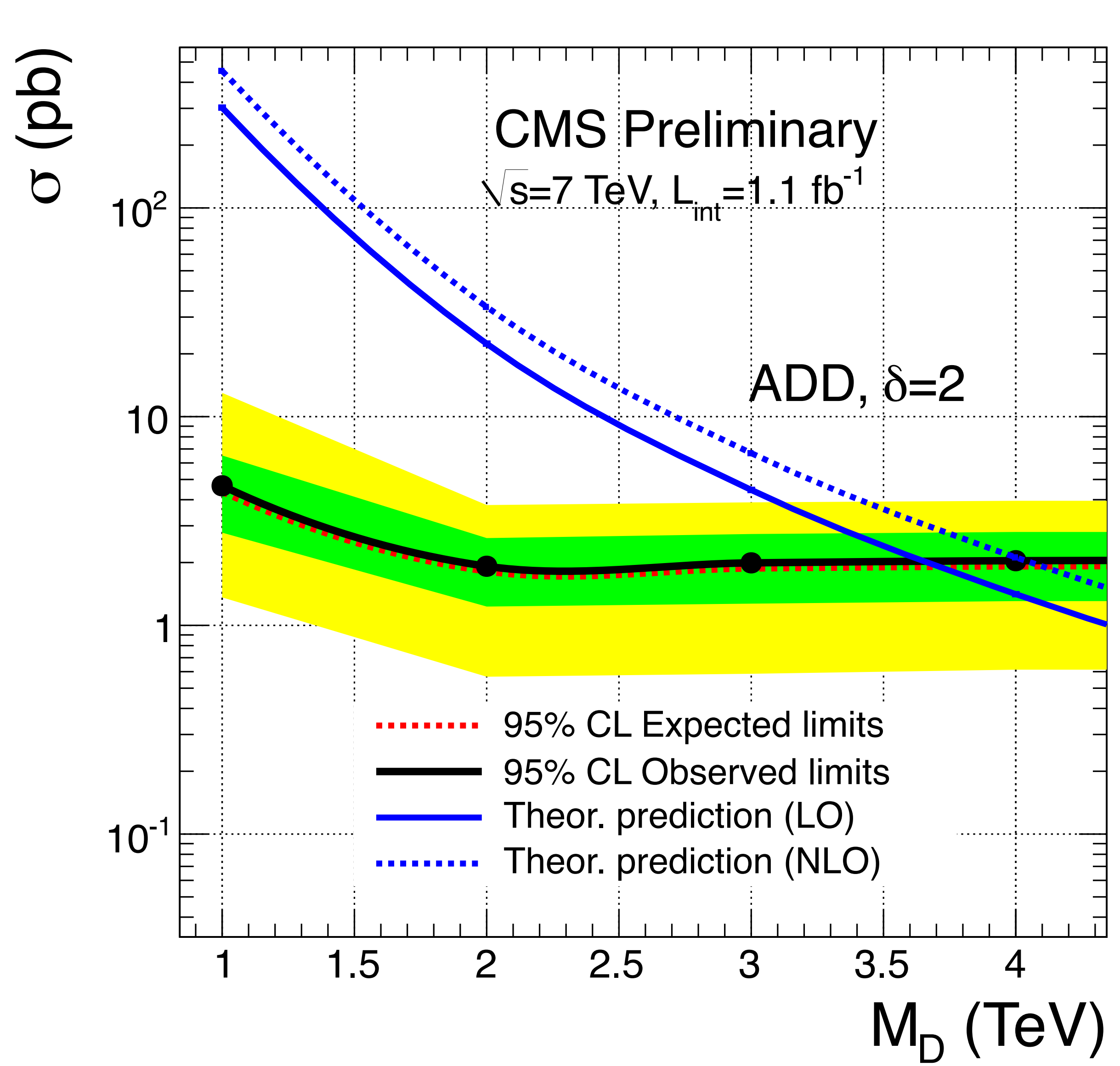
Missing Energy Distribution



- Can also search in single jet events. Graviton recoils recoils against quark and disappears. Jets have more background.

- Signal: excess of events at high E_T
- Dominant background Z->νν

Search results to date

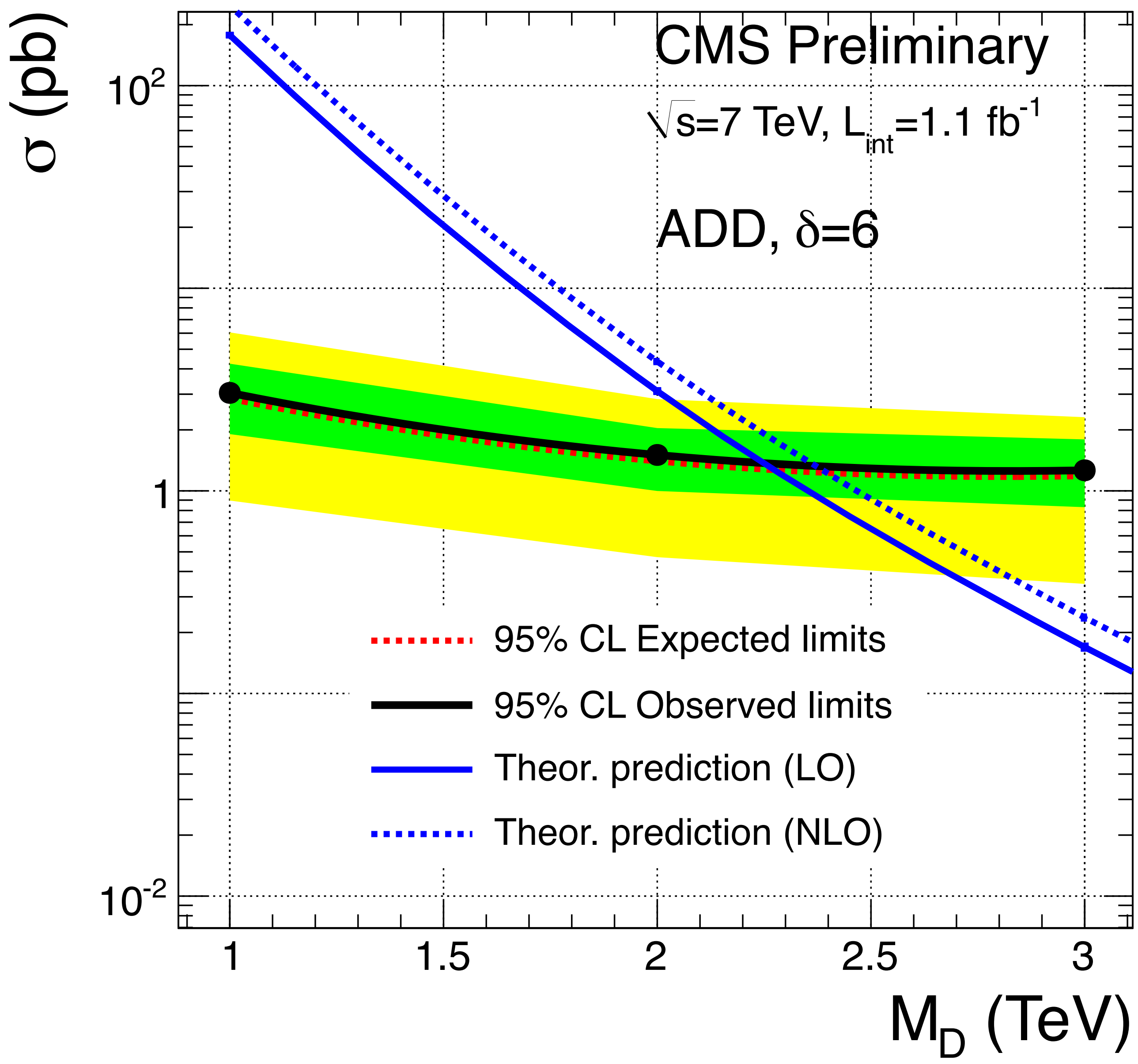


2 extra dimensions

M_D is bulk Planck mass

No evidence for M_D up to 3.5 TeV.

However, theory does not make clean predictions unless M_D>>Centre of mass energy, which is not the case with the LHC at 7 TeV.

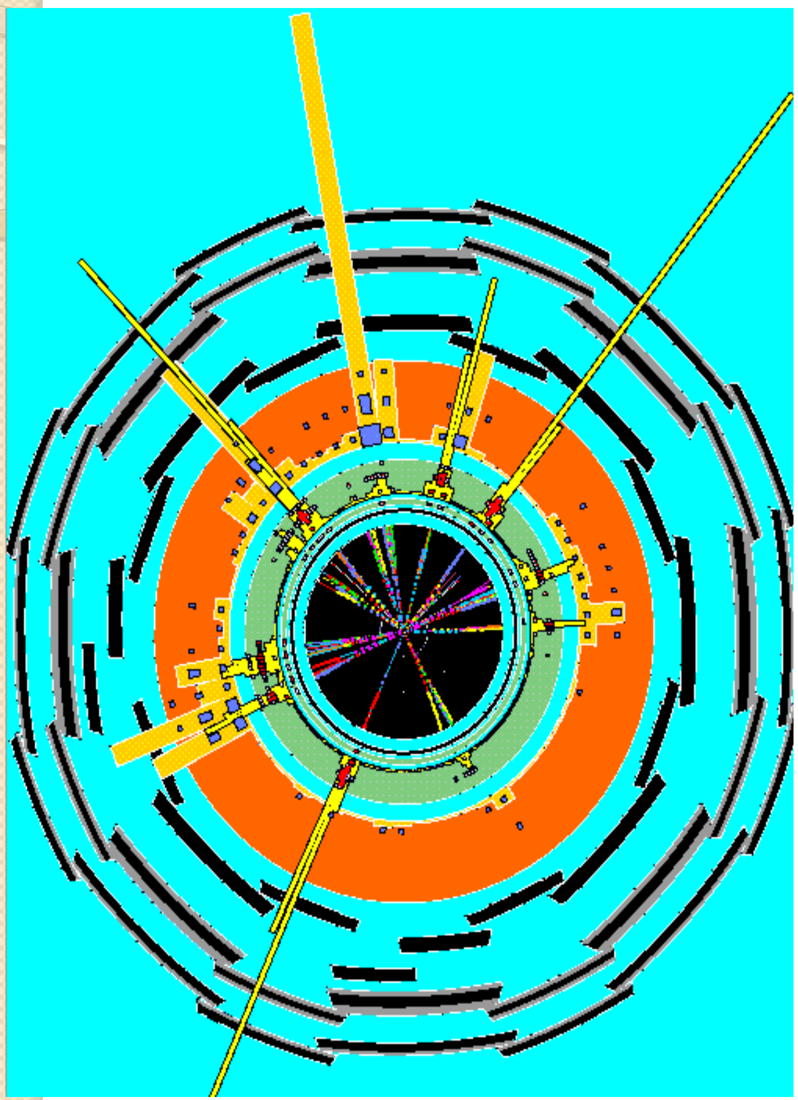


Limits are weaker for larger numbers of extra dimensions

For n=6, M_D<2.5 TeV is excluded, but with the same caveats about the theory – cannot trust results when M_D is close to C of M energy.

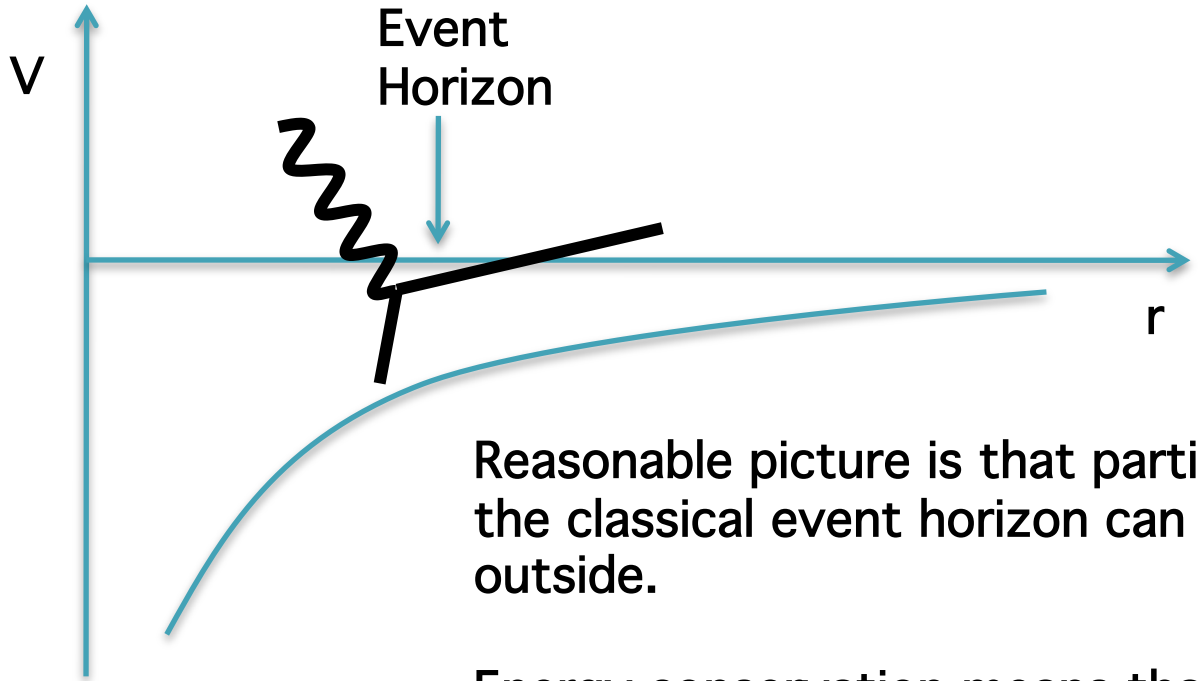
Really need theory of quantum gravity!

Black Holes



- Low scale gravity in extra dimensions allows black hole production at colliders.
- Decay by Hawking radiation (without eating the planet)
- 8 TeV mass black hole decaying to leptons and jets in ATLAS
- 8 partons produced with
- p_T>500 GeV
- Richardson, Harris, Palmer. Paper published JHEP 05(2005)053

Hawking Radiation

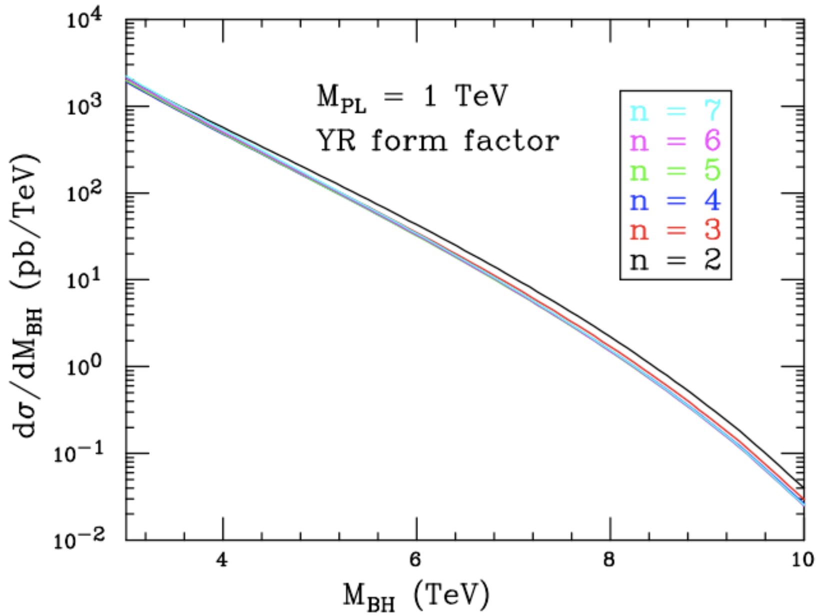


Reasonable picture is that particles inside the classical event horizon can tunnel outside.

Energy conservation means that black hole mass must reduce, causing it to evaporate at rate proportional to M^3

Get spectrum of particles emitted with spectrum very close to black body.

Black hole production cross section at LHC



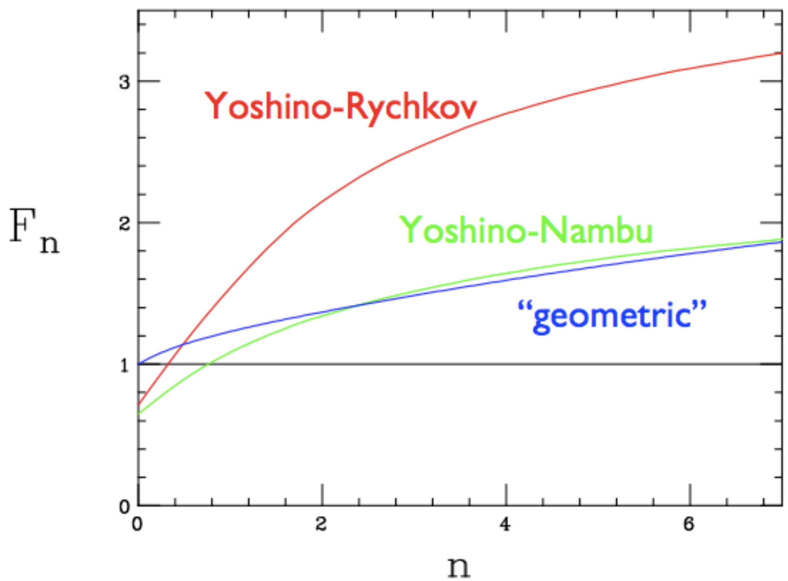
$$\sigma_{BH} \sim \pi r_h^2$$

➡ Several 5 TeV BH per minute at LHC!

- Classical approximation to cross-section
- (Controversial...)

- Very large rates for n=2-6   See hep-ph/0111230
- Almost independent of n

Black hole cross section uncertainties



- H Yoshino & Y Nambu, gr-qc/0209003
- H Yoshino & VS Rychkov, hep-th/0503171

- See nice review by Gingrich
- hep-ph/0609055

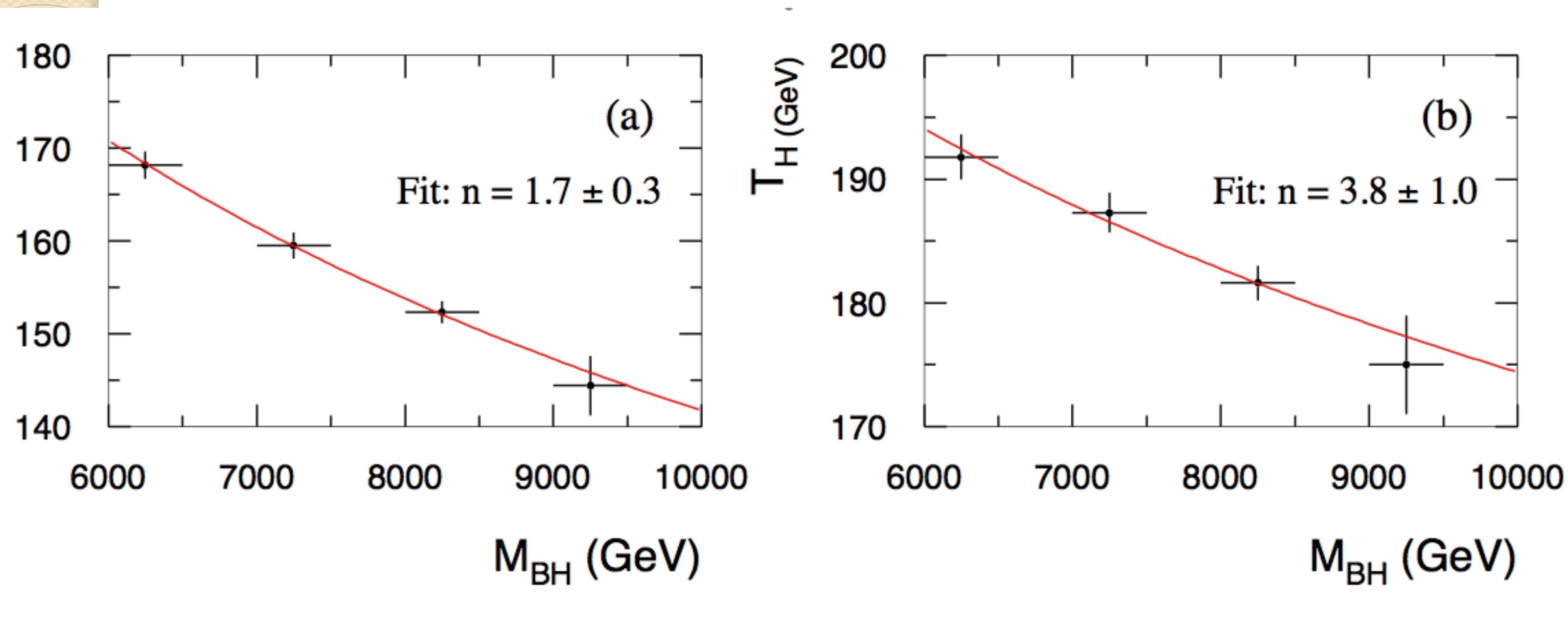
- Form factors increase cross-section
- "Trapped energy" inside event horizon is less than available parton energy -> decreases cross-section by large factor near threshold at M_{PL}

- Lower limits on cross-section have been calculated from GR
- Conclude - there is considerable uncertainty and cross-section probably smaller than semi-classical approximation

Black hole decay

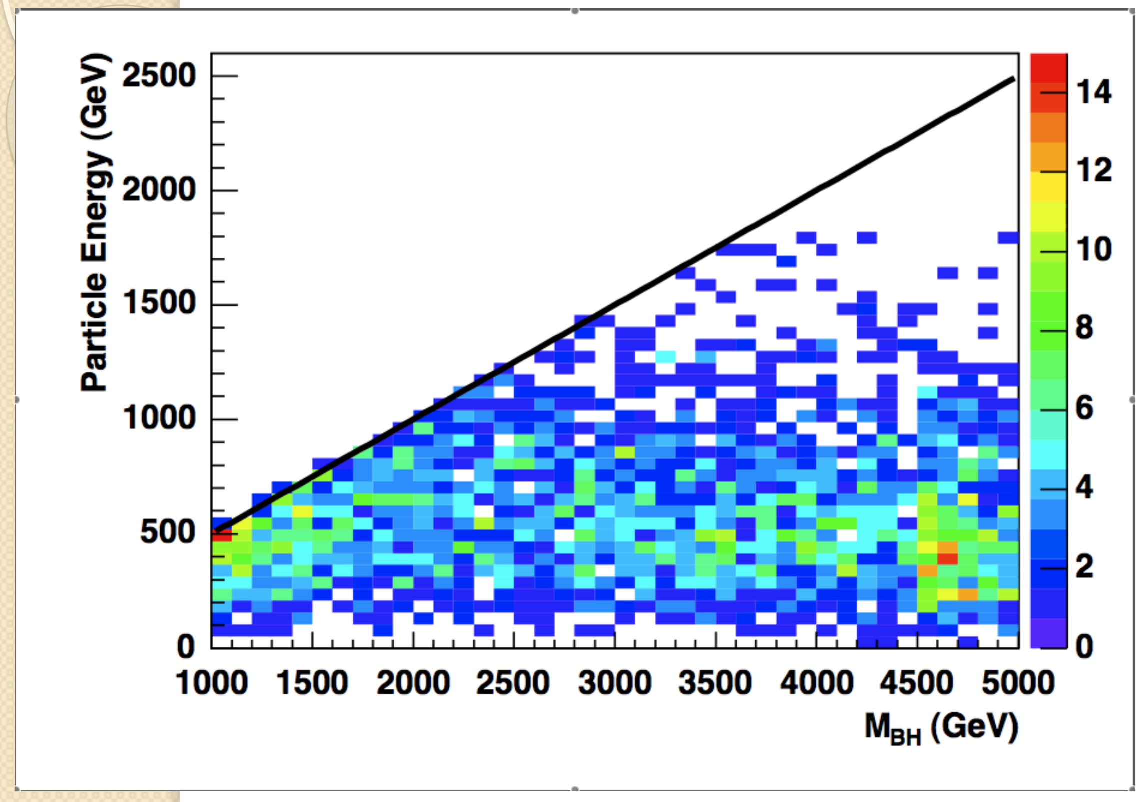
- Decay occurs by Hawking radiation, modified by "grey body" factors
- Hawking Temperature T_H $$T_H = (n+1)/4\pi r_h$$
- Black Hole radius r_h $$r_h \sim \frac{\hbar}{M_{Pl}c}\left(\frac{m_{BH}}{M_{Pl}}\right)^{1/(n+1)}$$
- Use observed final state energy spectrum to measure T_H and hence n?

Effect of varying BH temperature



- Effect of varying temperature as black hole decays. True n=2
- Fit T_H against Black Hole mass: fixed temperature - n= 1.7 ± 0.3
- varying temperature n= 3.8 ± 1.0
- Cannot measure temperature with sufficient accuracy - about 10 GeV.
- Also black hole is boosted by each decay, changing successive energy distributions

Kinematic limit on decay products



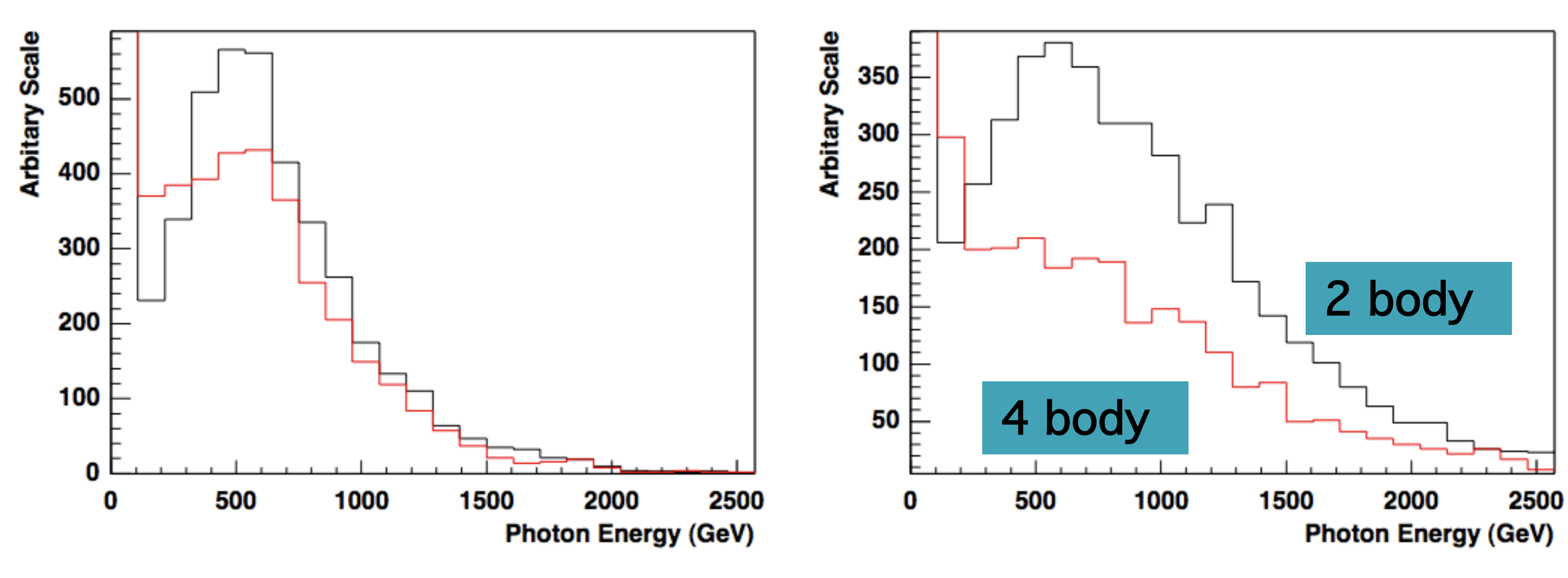
Generator can either reject unphysical decays, or jump to final stage of decay.

- 5 TeV Black hole decays, n=2

- Max energy = $M_{BH}/2$
- Predicted Hawking/ grey body radiation spectrum is cut off at high energy as mass drops and T rises.

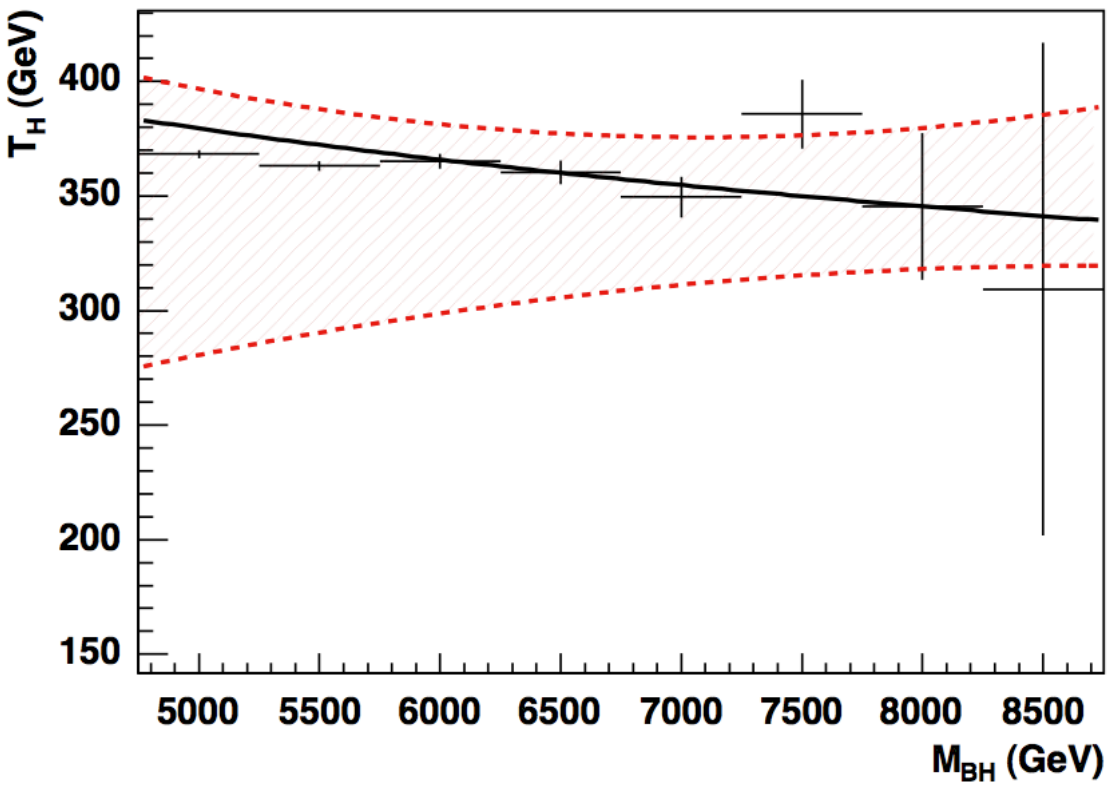
- Need to deal with cases when choice of decay is unphysical

Effect of decay of remnant



- Remnant is the final stage of decay when QG regime is reached, as M_{BH} drops to M_{PL}
- Generator can choose 2 or 4 body decay mode for remnant.
- Large effect in final energy spectrum in some cases.

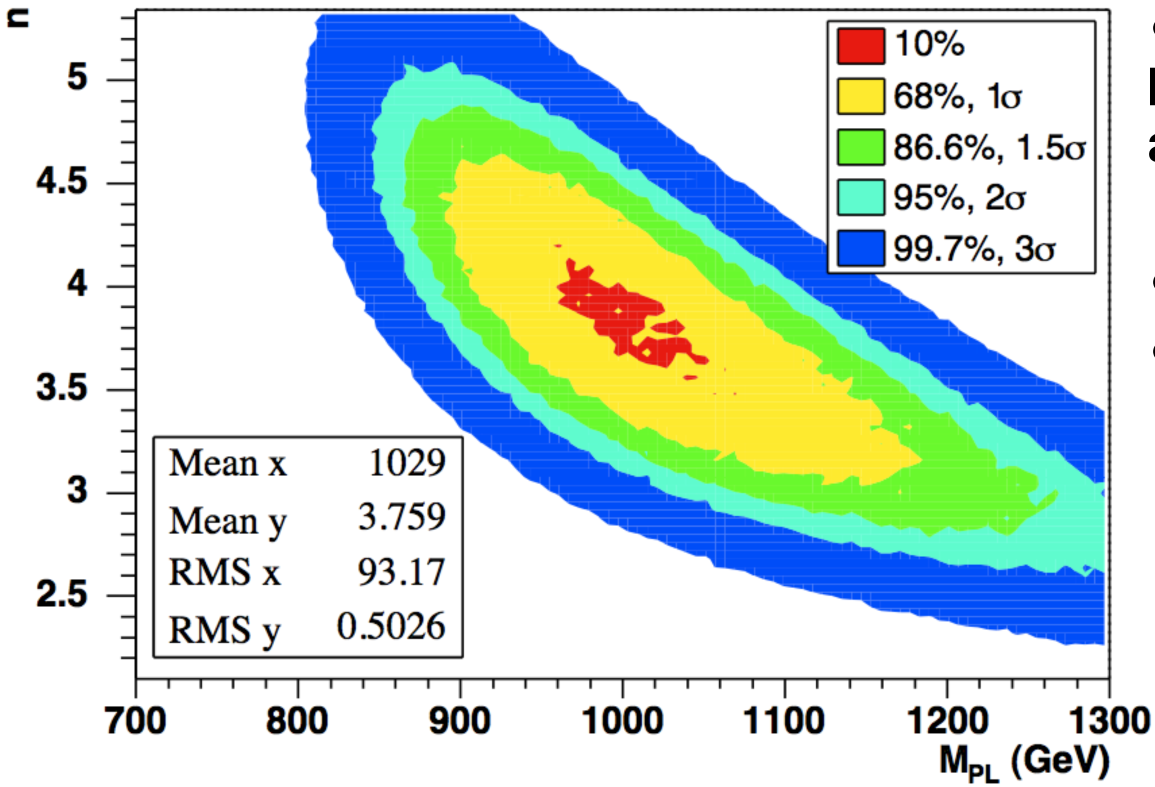
Measurement of M and T of Black hole



- T against M_{BH} for n=4, with sys error band.
- Impossible to extract variation in T
-

Can measure characteristic T at average mass -> combine this with cross section data to extract n. Assume 20% error on cross-section

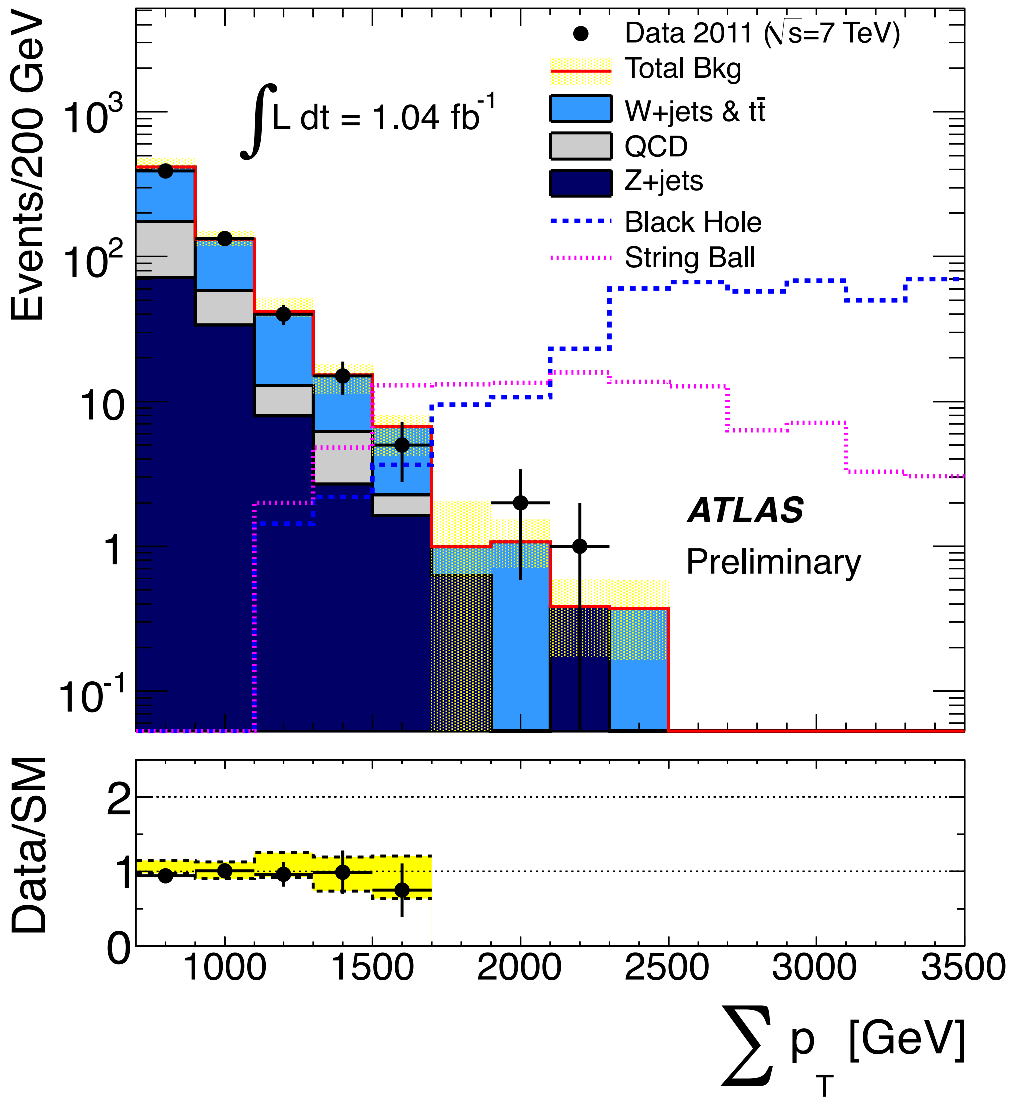
Extraction of number of dimensions



- Number of dimensions and Planck mass can be obtained in a correlated way.

- n=4.0 + 0.6 - 1.0
- M_{PL} = 1029 +200 - 100 GeV

ATLAS search for black holes



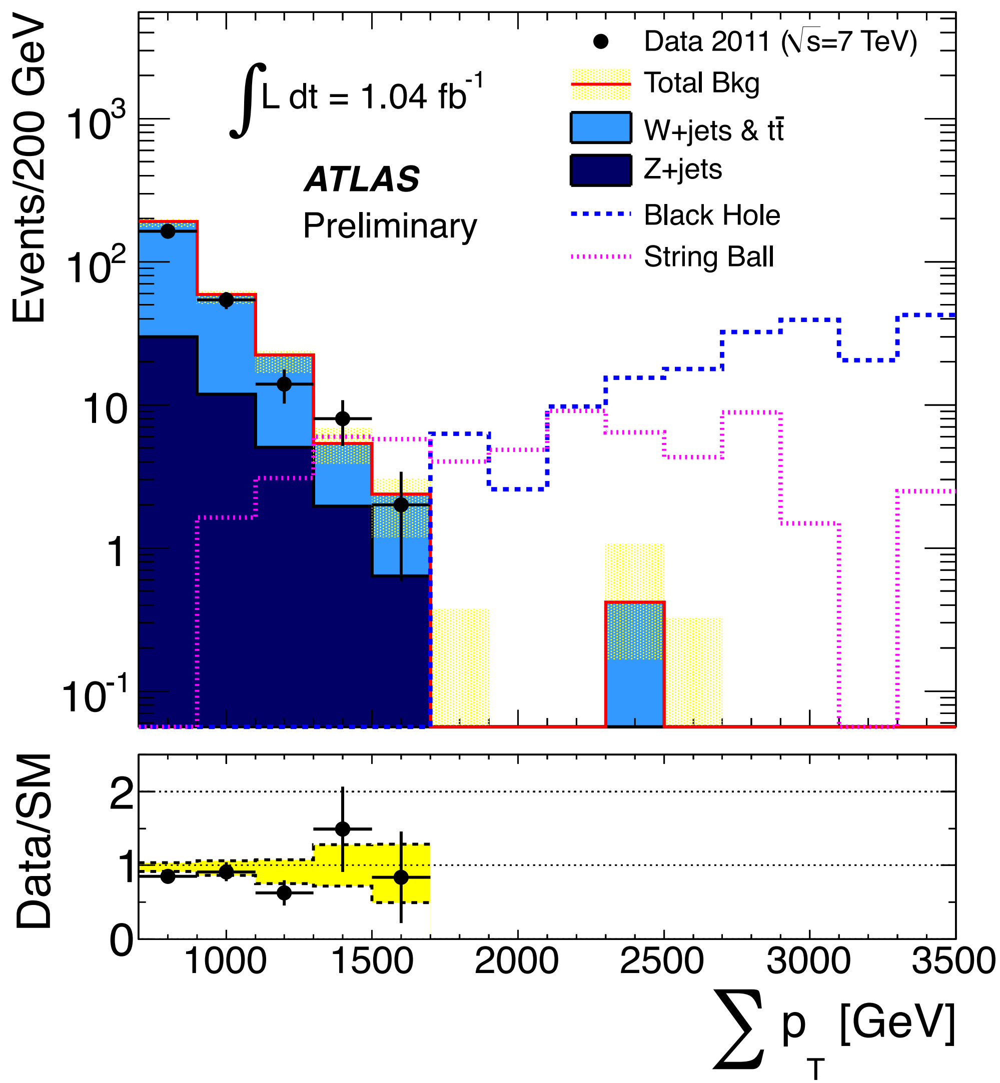
Exploit fact that gravity couples to all particle types.

Look for high energy leptons in high mass events – rare in SM

This result for events with high energy electrons.

Expect high rate for BH production.

ATLAS search for black holes



Exploit fact that gravity couples to all particle types.

Look for high energy leptons in high mass events – rare in SM

This result for events with high energy muons.

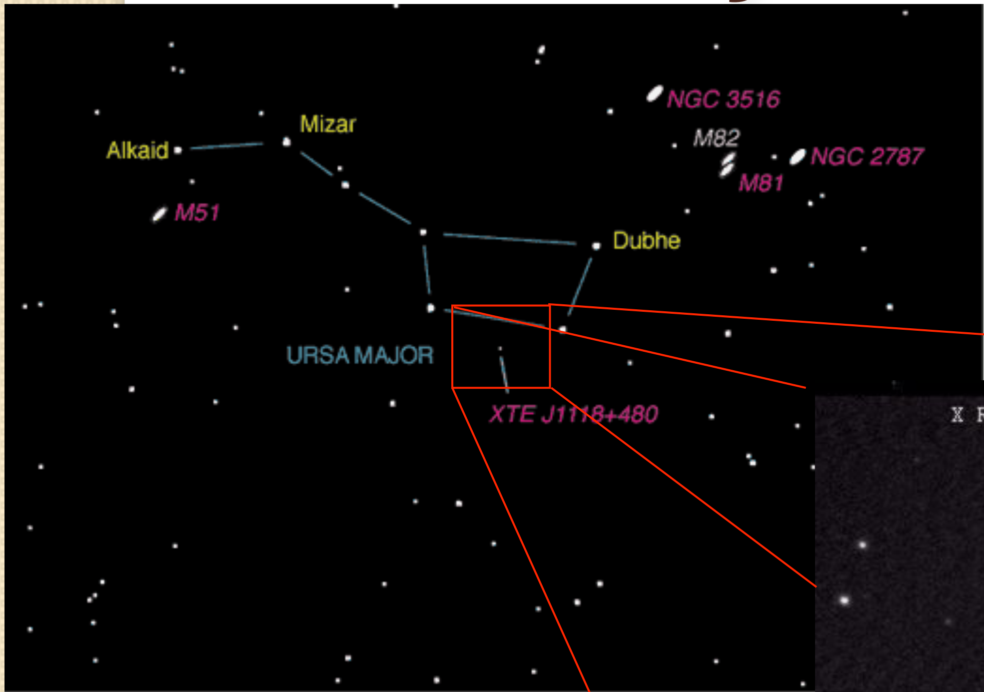
Expect high rate for BH production.

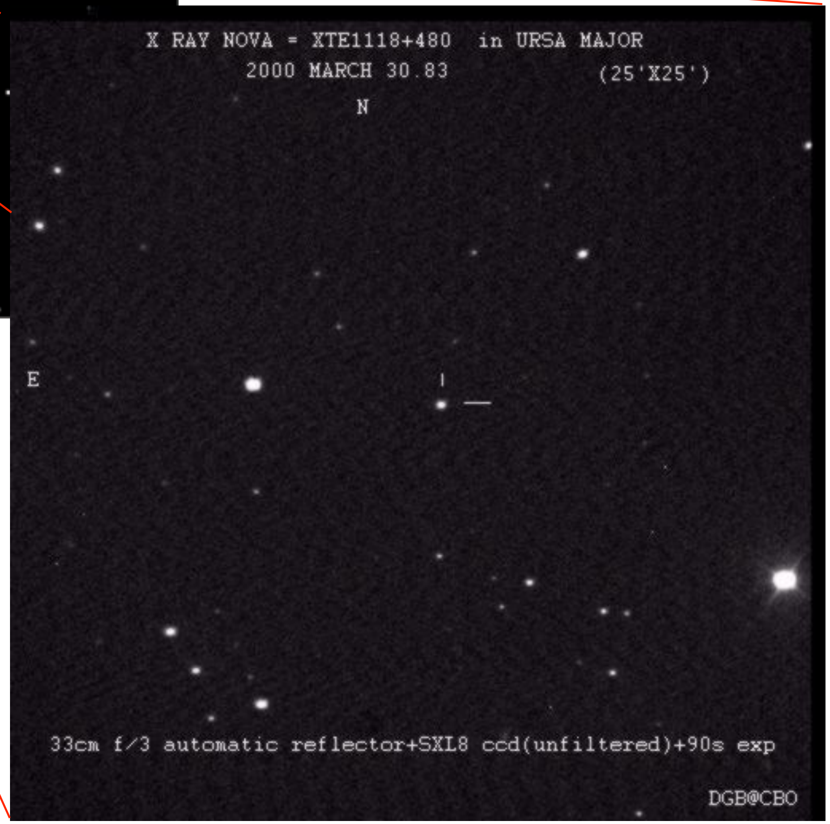
Once again – beware of lack of theoretical understanding.

XTE J1118 +480

X-ray nova observed in 2000

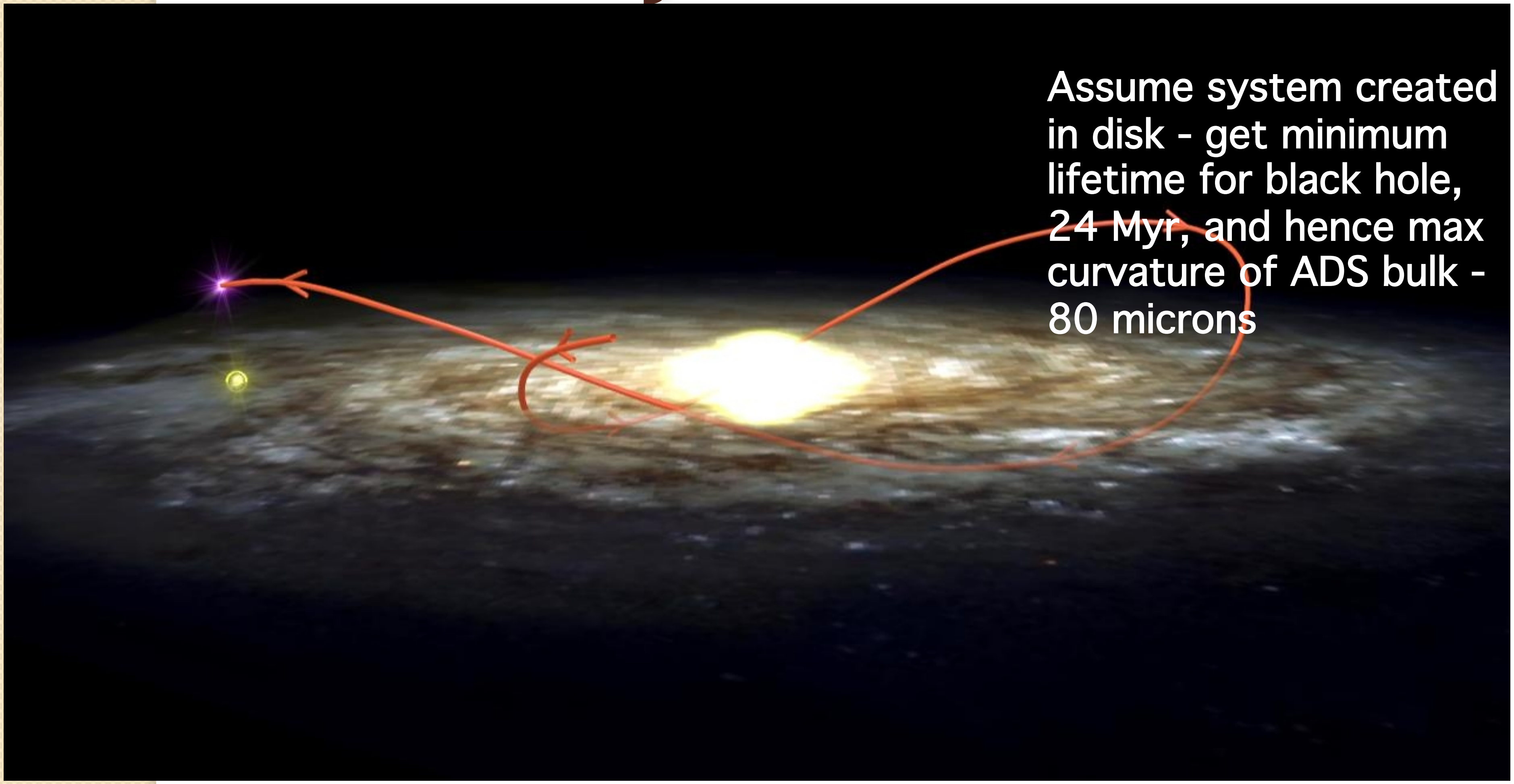
7 solar masses





Black hole with companion star, moving at 145 km/s in galactic halo

XTE J1118 +480



Inferred orbit passes through galactic plane several times.

Conclusions

- New data from Planck, LHC will directly address major questions in particle physics, cosmology and the connections between them
- New experiments searching for dark matter, neutrino masses, anomalous gravitations effects etc are reaching interesting territory
- Golden age for astroparticle physics!