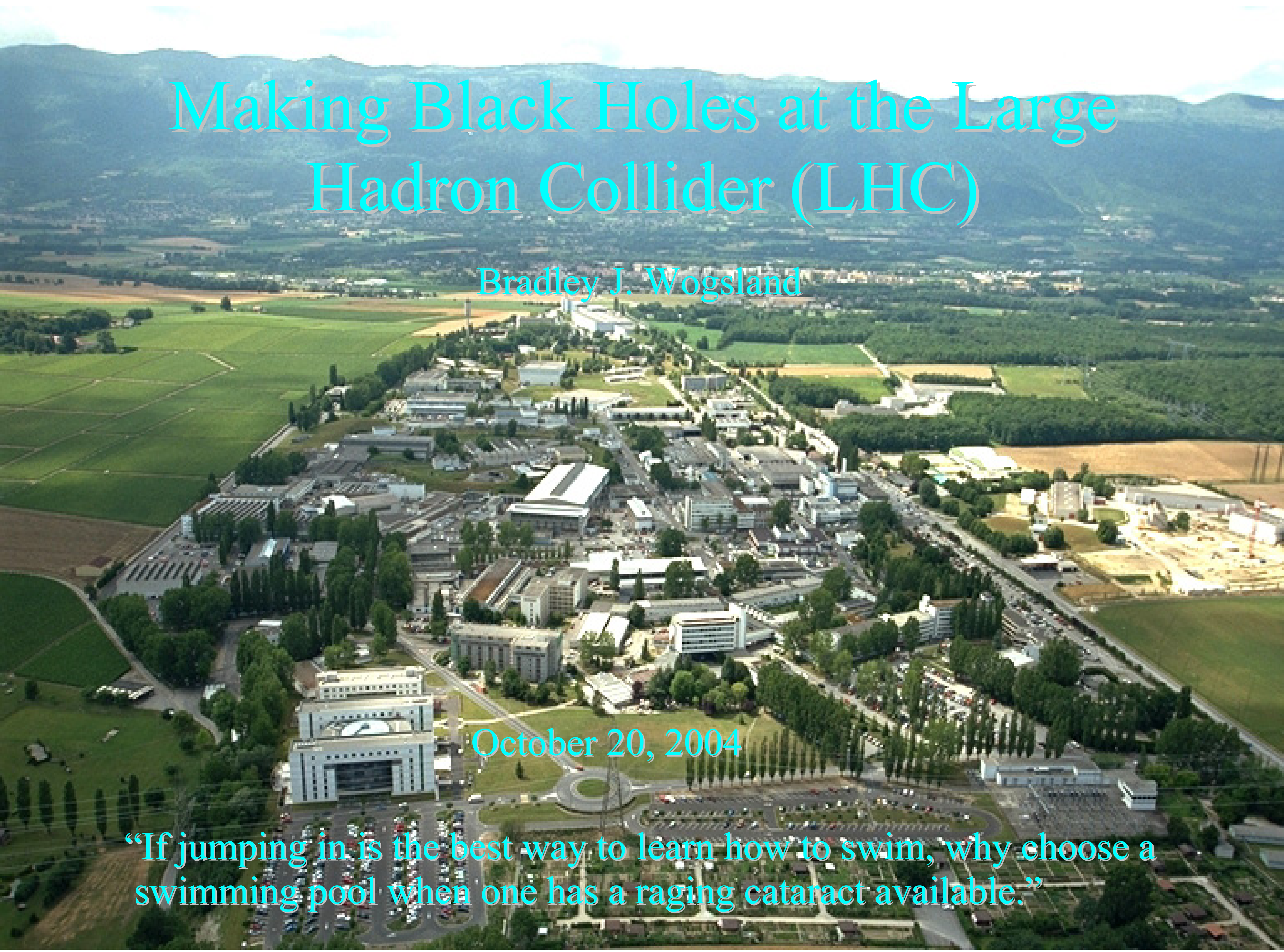


Making Black Holes at the Large Hadron Collider (LHC)

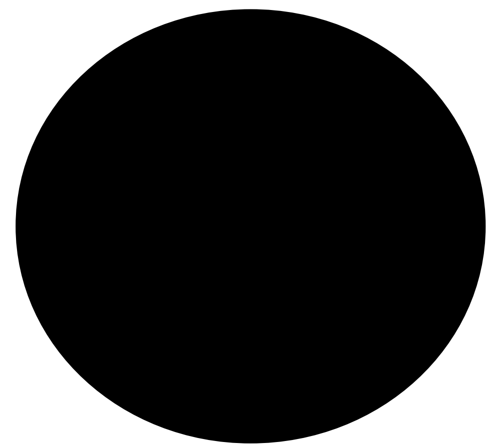
Bradley J. Wogsland

October 20, 2004

"If jumping in is the best way to learn how to swim, why choose a swimming pool when one has a raging cataract available."

Outline of Black Holes in Experiments

- Theory
  - Planck Mass
  - Extra Dimensions
  - Black Hole Radiation and Detection
- Collider Experiments
  - State of the art
  - The Large Hadron Collider (LHC)
- Cosmic Ray Experiments
  - AGASA
  - Japanese Telescope Array
  - Pierre Auger Observatory
- Conclusions



The Planck Mass (M_P)

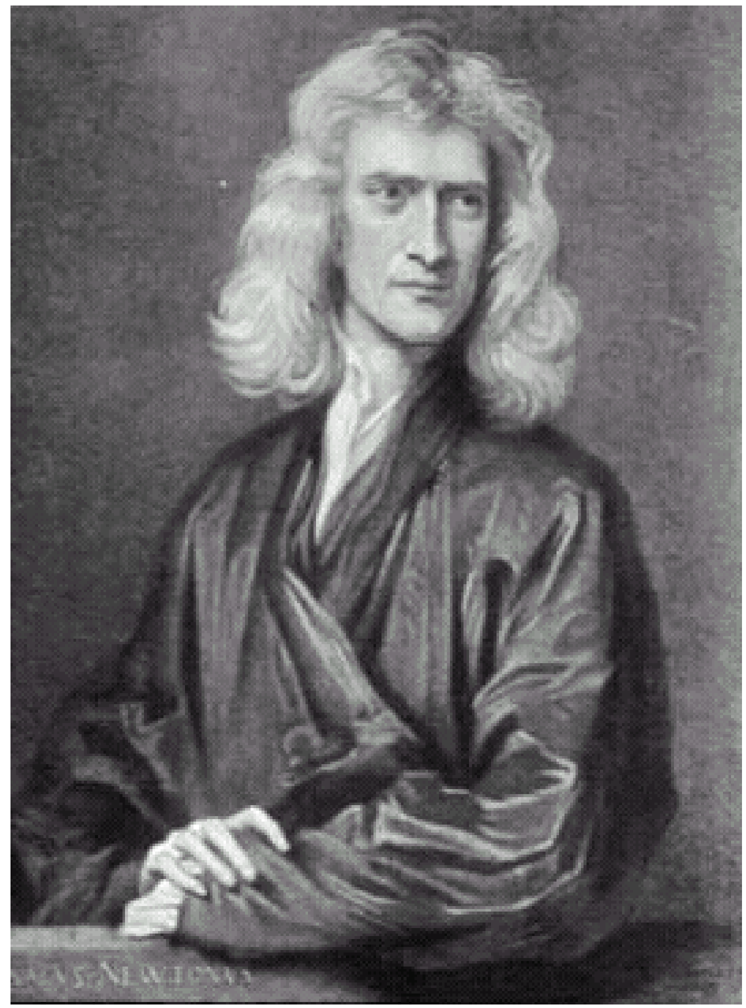
- $M_P=(\hbar c/G)^{1/2}$
- $\sim 10^{19}$ GeV
- The scale at which gravity becomes indistinguishable from electroweak force "hierarchy problem"
- Not realizable in any collider in the foreseeable future

but what if it wasn't so big...

?

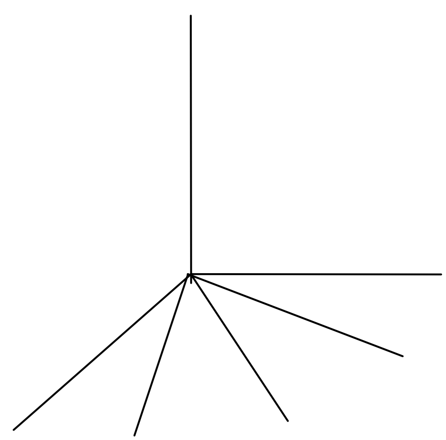
Tests of gravity

- Best ways of testing gravity on small scales are the torsion pendulum or microcantilever
- Lower limit from the size of these instruments is ~.19 mm (latest PDG Number)
- So we have no idea how gravity behaves for submillimeter distances



How to get there

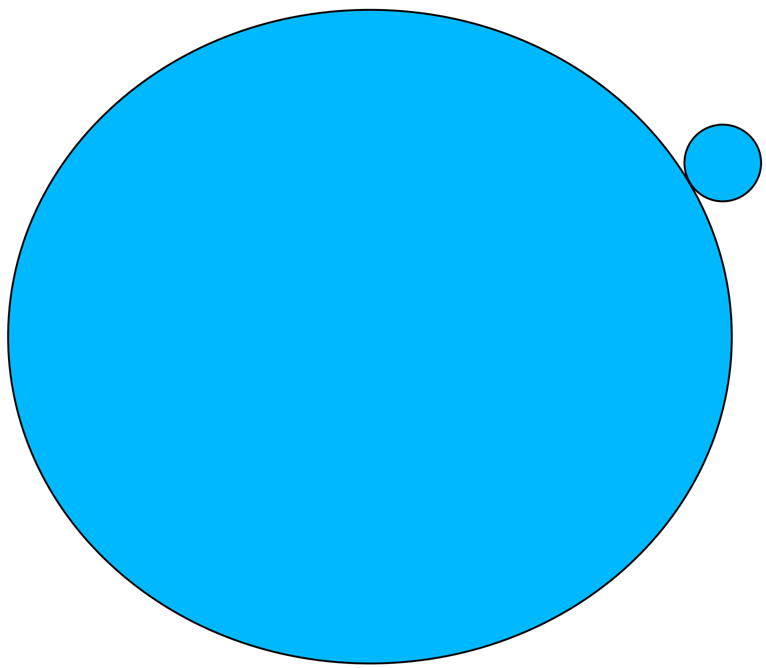
- 3+n spacelike dimensions and one for time
- Electroweak and Strong forces confined to our usual 3 spatial dimensions “3-brane”
- Gravity propagates in all dimensions
- Extra n dimensions submillimeter sized, but still “large”



Considering Gauss's law in 4+n dimensions yields

The Volume of the Extra Dimensions:

$$R^n \simeq M_p^{\,2} / M_g^{\,n+2}$$

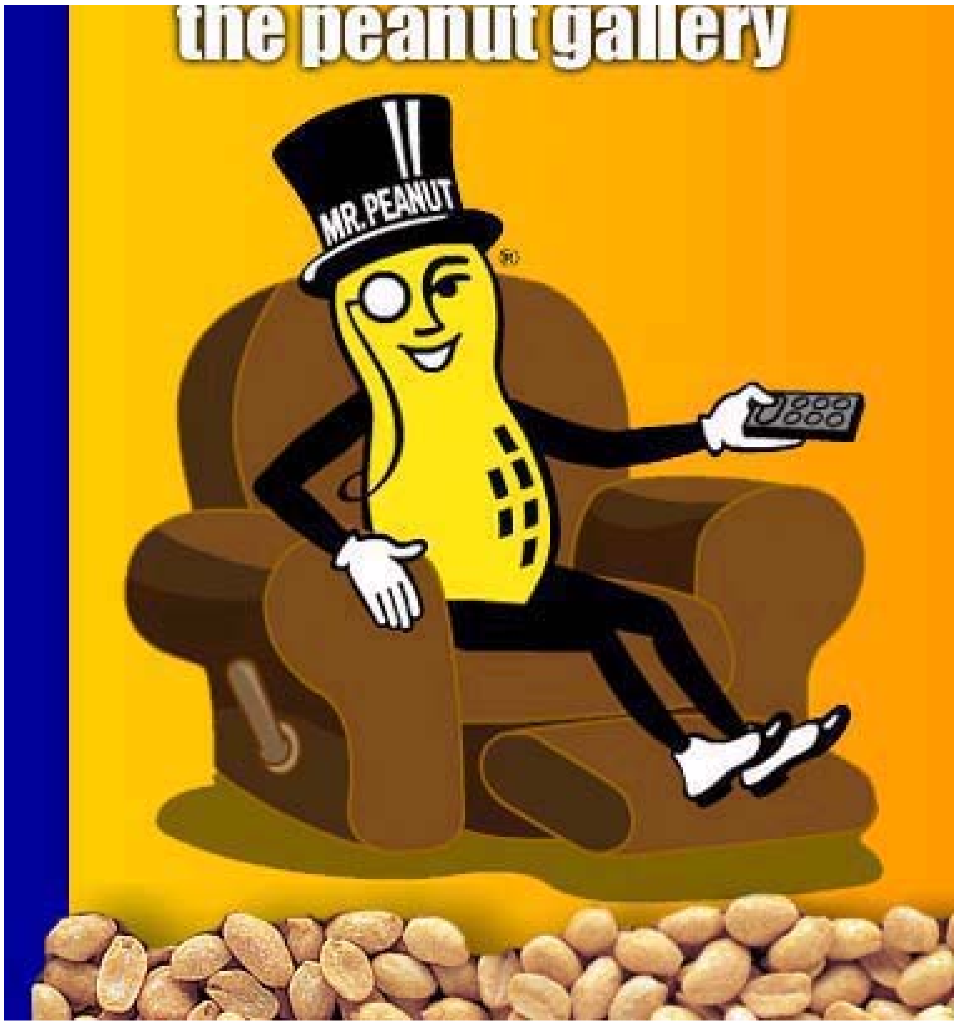


A (4+n)-dimensional World

n	M_g (TeV)	R (cm)
0	10^16	n/a
1	~1	10^13
2	>1.6	<.1
≥ 3	Interesting	<<1 (undetectable)

Clearly, cases with fewer than three extra dimensions cannot yield the desired TeV scale Gravity at small distances.

Why extra dimensions?



- Many theories postulate their existence: String Theory, M-Theory, u.s.w.
- Makes gravity probable with particle accelerators!
- Why not?

Nota Bene:

- There is an alternative theory due to Randall and Sundrum which can also lower the effective Planck Mass at short distances.
- Called "Warped Dimension" hypothesis because the curvature of the extra dimensions, not their size, changes the scale of Gravity at short distances.
- The extra dimensions can be much smaller, but the math is much harder. For example, for the case of 1 extra dimension with curvature k,

$$M_p^{2} \simeq \left(M_g^{3}/k\right)\left(1-e^{-2kR\pi}\right)$$

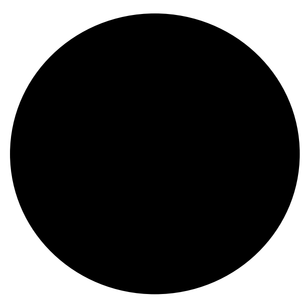
  - This case was not studied in detail, but it has similar tunable parameters to get TeV scale Gravity.

Observing a Black Hole

- Hawking Temperature:

$$T_{BH} \approx (n+1)/4\pi R$$

- Black holes decay via Hawking radiation.
- Those produced in a collider would be so small that they will rapidly decay in a spherical pattern into roughly 25 particles, mostly hadrons and some leptons with energies of order 50-100 GeV.



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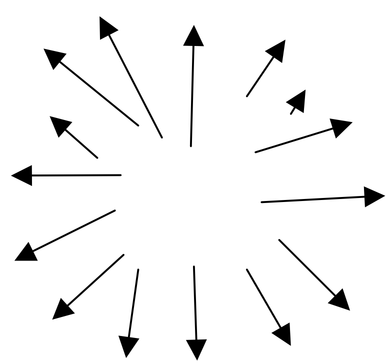
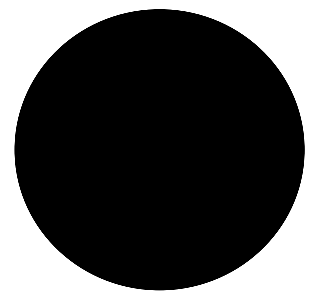


Some points of contention

- Actually that's a rather naïve decay theory, but there is less agreement on modifications to that theory:
- Will the Black Hole decay completely, or leave a Planck mass remnant? - if this is the case it could solve the dark matter problem!
- Anchordoqui and Goldberg think a Black Hole will decay into partons which will in turn form a chromosphere of quark-gluon plasma around the Black Hole



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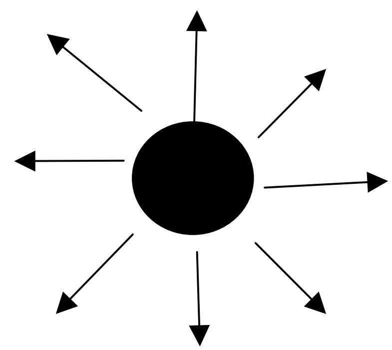

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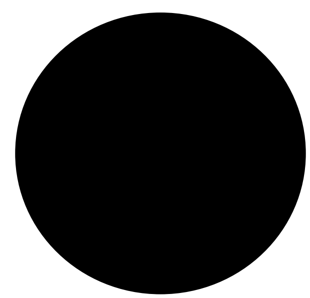

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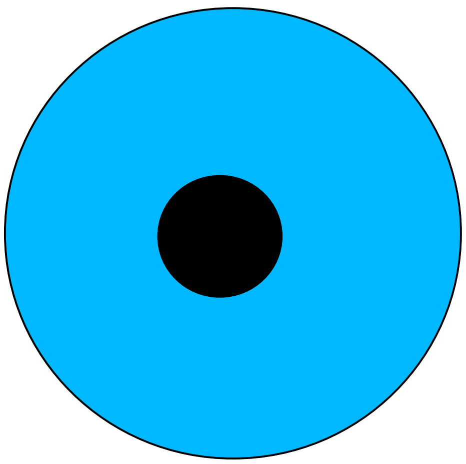

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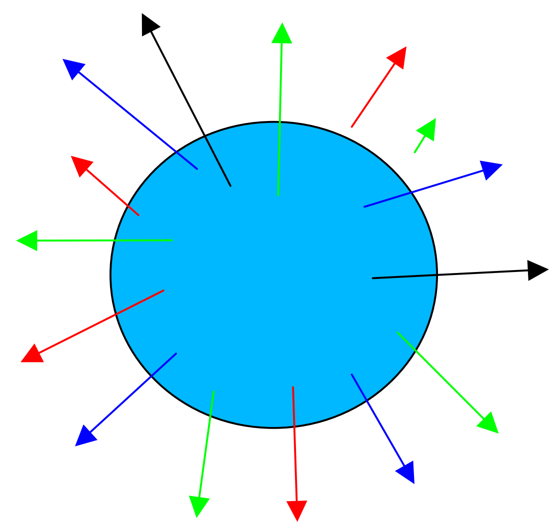

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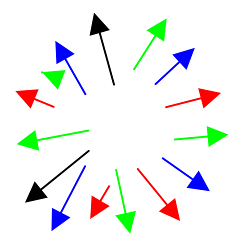


Experiments

- Particle accelerators
  - Current CM energies in colliders get as high as 1 TeV
  - Next generation will give energies ~10 TeV
  - Many collision events
- Cosmic ray observations
  - Particle collisions observed with energies >100 TeV
  - Few events

The Tevatron

(Current state of the art)

- Located at Fermilab
- Proton-antiproton collider
- CM Energy 1 TeV
- No Black Holes found
- However, the Tevatron did provide...

A Lower Bound for M_g

Parameter	Mg (TeV)				
	n=3	n=4	n=5	n=6	n=7
0.5	0.62	0.40	0.30	0.24	0.20
0.6	0.65	0.44	0.34	0.29	0.25
0.7	0.67	0.48	0.38	0.34	0.30
0.8	0.70	0.51	0.43	0.38	0.36
0.9	0.71	0.54	0.46	0.43	0.41
1.0	0.73	0.57	0.50	0.48	0.47

This shows the 95% C.L. lower limits for Mg relative to the brane softening parameter, which can range from 0.5 to 1.0, and for 3 to 7 extra dimensions.

From Anchordoqui, Feng, Goldberg and Shapere Phys. Rev. **D**, 65 124027 (2002).

The Large Hadron Collider

- Under Construction at CERN – opens 2007
- Proton-proton collider
- Designed to find the Higgs boson or exclude its existence
- CM energy ~14 TeV

Black Hole Production at the LHC

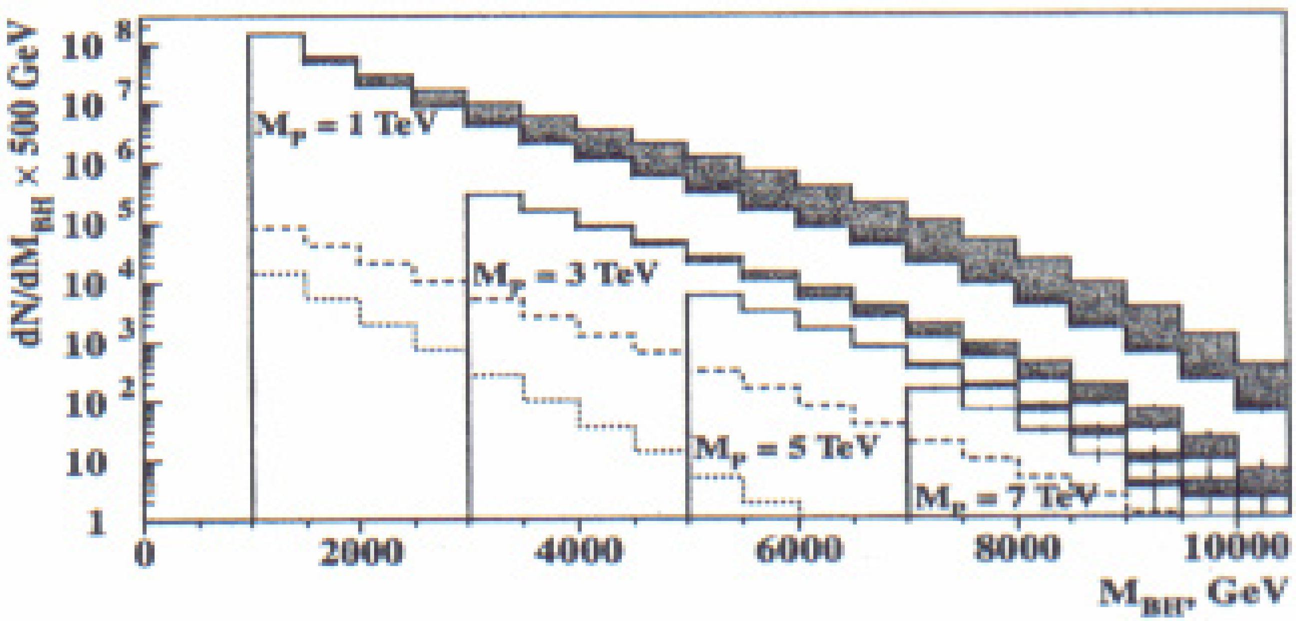
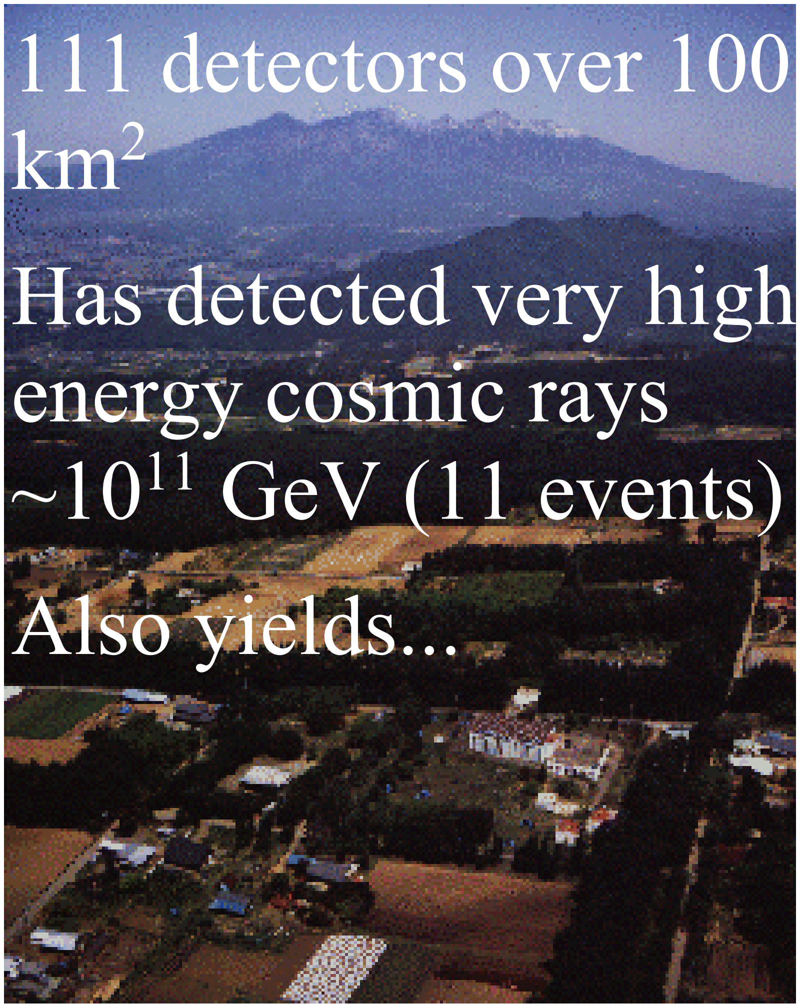


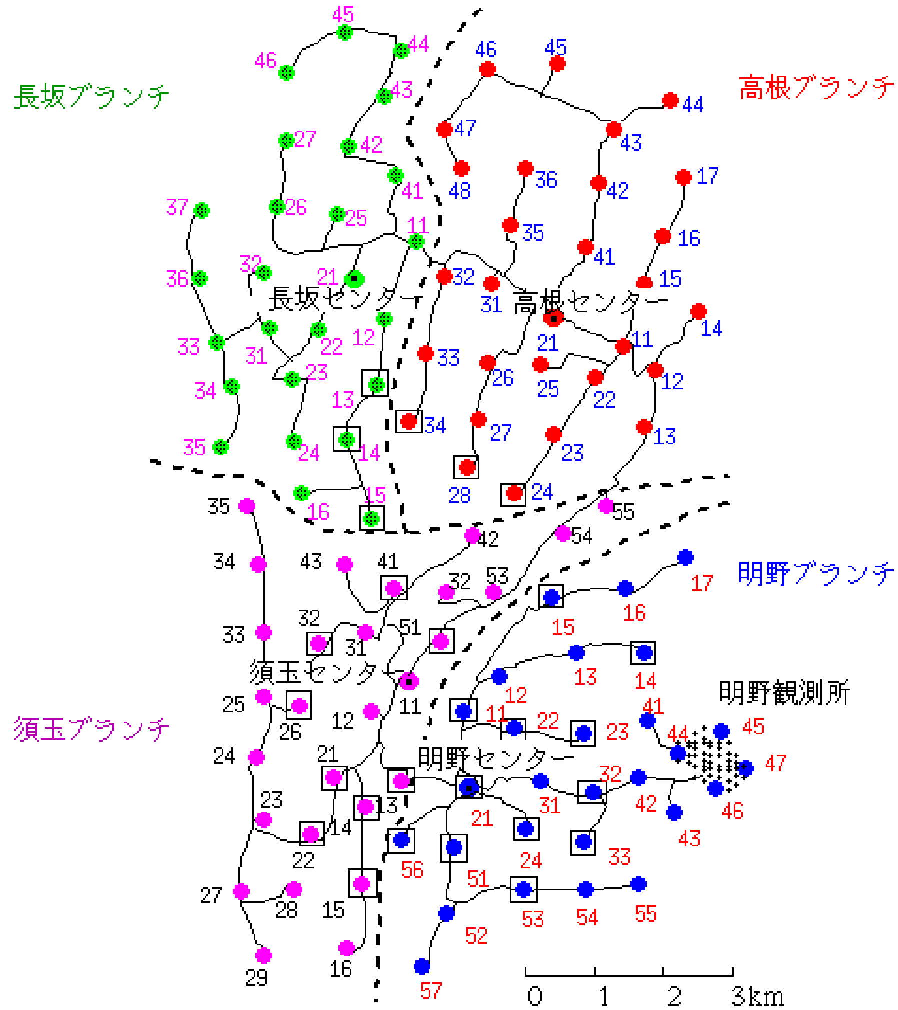
FIG. 2. Number of BHs produced at the LHC in the electron or photon decay channels, with 100 fb^{-1} of integrated luminosity, as a function of the BH mass. The shaded regions correspond to the variation in the number of events for n between 2 and 7. The dashed line shows total SM background [from inclusive $Z(ee)$ and direct photon production]. The dotted line corresponds to the $Z(ee) + X$ background alone.

From Dimopoulos and Landsberg, Phys. Rev. Lett. **87**, 161602 (2001).

The Akeno Giant Air Shower Array (AGASA)

- 111 detectors over 100 km^2
- Has detected very high energy cosmic rays ~10^{11} GeV (11 events)
- Also yields...





A Higher Lower Bound for M_g

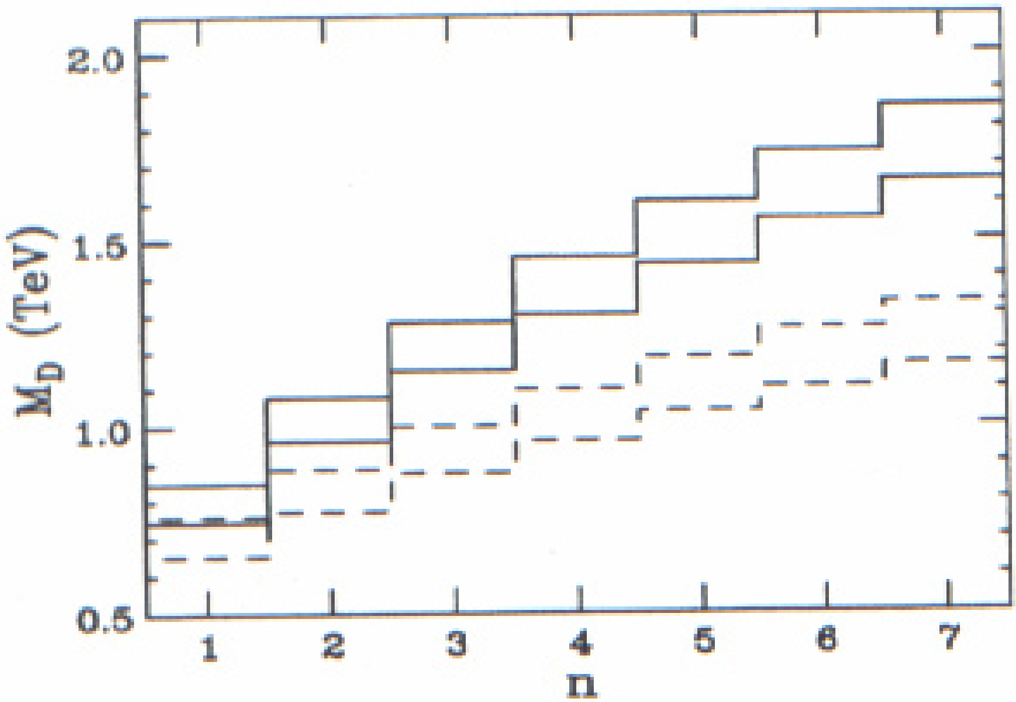


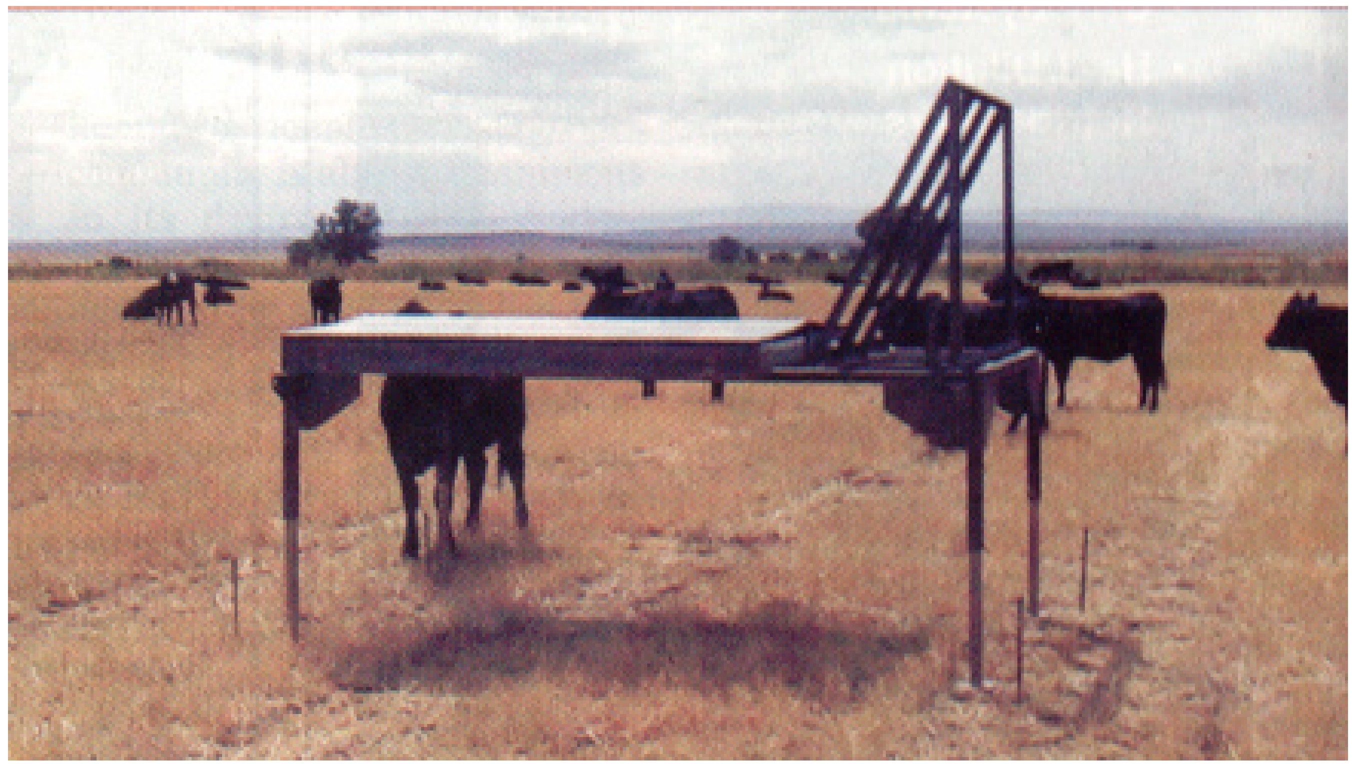
FIG. 5. 95% C.L. lower bound on M_D from nonobservation of quasihorizontal air showers in 1710.5 live days at AGASA for $x_{min}=1$ (solid) and 3 (dashed), assuming the cosmogenic neutrino flux of Protheroe and Johnson (lower) and Hill and Schramm (upper).

From Anchordoqui, Feng, Goldberg and Shapere Phys. Rev. **D**, 65 124027 (2002).

Their $M_D = \left((2\pi)^n / 8\pi \right)^{n+2} M_g$

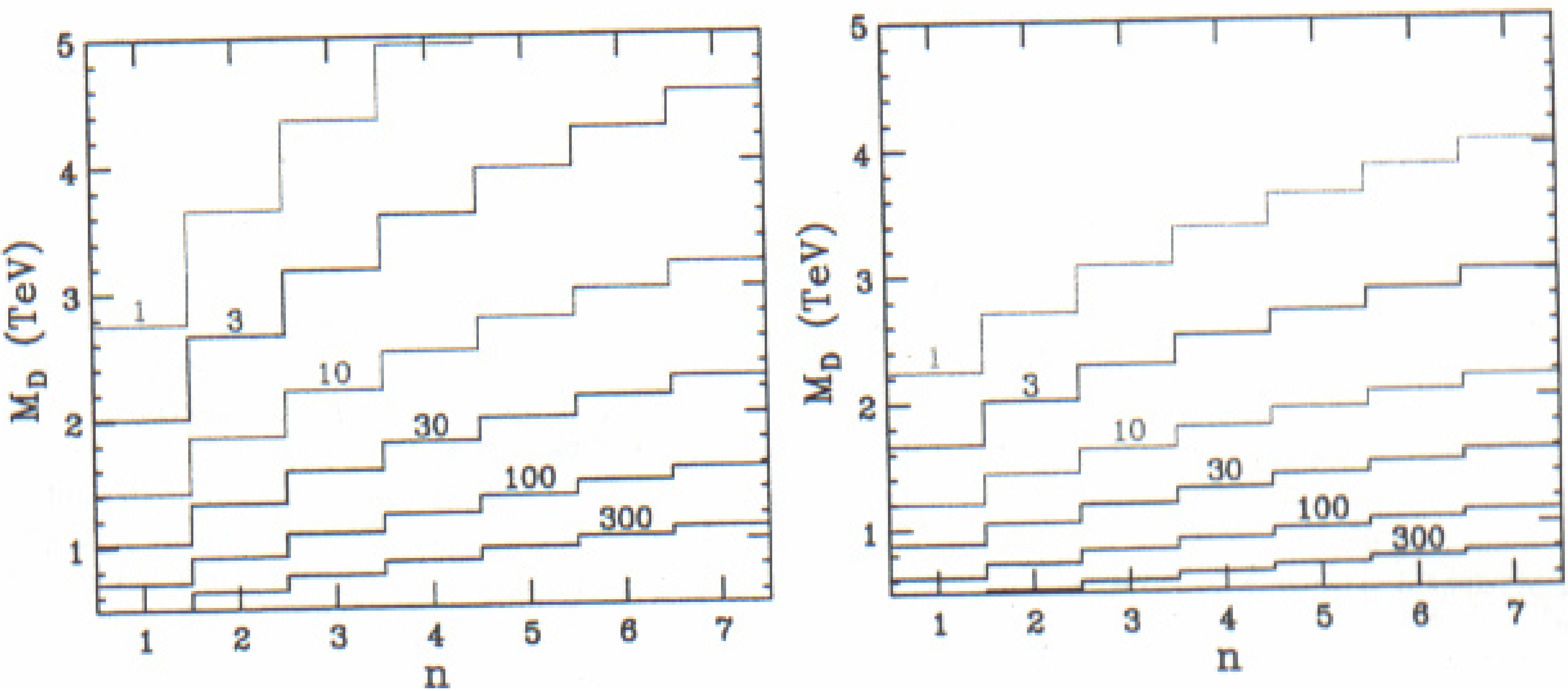
Future Cosmic Ray Observatories

- Pierre Auger Observatory (Argentina)
- Telescope Array (Utah)



“Cow Perturbations”

Expected black hole detection at Auger



Number of expected BH events at Auger over a 5 year period assuming the minimum Black Hole mass is M_P or $3M_P$.

From Anchordoqui, Feng, Goldberg and Shapere Phys. Rev. **D**, 65 124027 (2002).
Their $M_D = ((2\pi)^n/8\pi)^{n+2} M_g$

...and something for those who don't like extra dimensions

- The lower bound for M_g provides an upper bound for R from

$$R^n \simeq M_p^{\,2} / M_g^{\,n+2}$$

- Thus, when we finally build that 10^{19} GeV particle collider, we'll be able to rule out the extra dimensions (assuming we don't find any black holes before then).

Acknowledgementation

Thanx to Drs. Kamyshkov and Spanier for suggesting the subject and providing some papers which pointed me in the right direction.

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