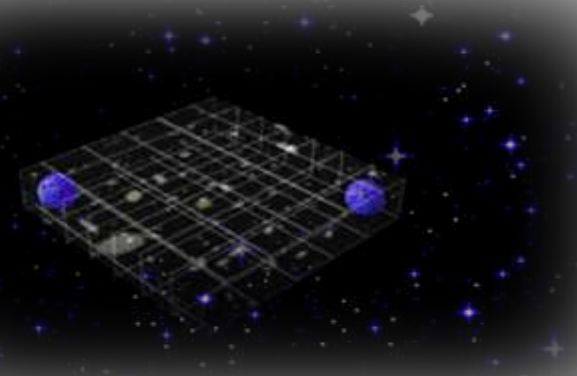


Crne rupe u kosmosu i laboratoriji

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UNIVERZITET U NISU
23 MART, 2012
NIS

UB University at Buffalo
The State University of New York



Marko Jaric

ZIRI za dodelu nagrade

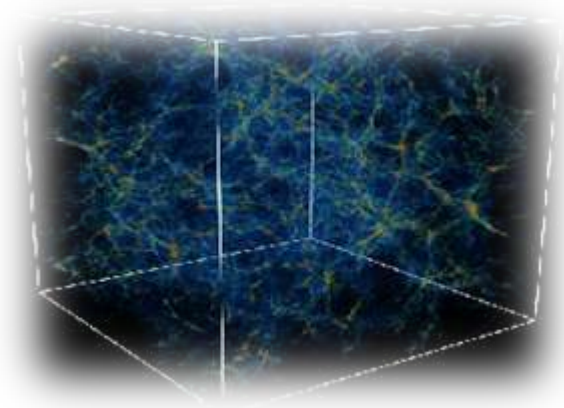
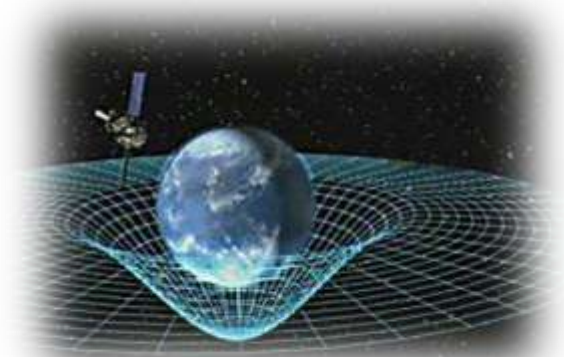
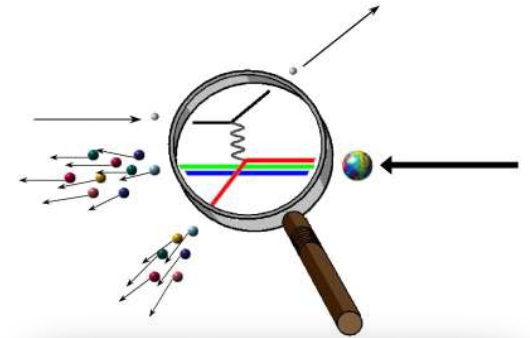
1. Prof. Dr. Milutin Blagojevic, IF
2. Prof. Dr. Milan Knezevic, PMF
3. Prof. Dr. Vitomir Milanovic, ETF
4. Dr. Dejan Pantelic, IF
5. Dr. Aleksandar Bogojevic, IF

Upravni Odbor Fonda

- Gospodja Marija Jaric, supruga Marka Jarica
- Prof. Dr. Jovo Jaric, predstavnik porodice Jaric
- Prof. Dr. Ilija Savic, PMF
- Dr. Milivoj Belic, IF
- Dr. Petar Adzic, Vinca
- Prof. Dr. Jablan Dojcilovic, PMF
- Zoran Pesic, SANU

Moj naučni rad:

- **Elementarne cestice**
- **Gravitacija**
- **Kosmologija**



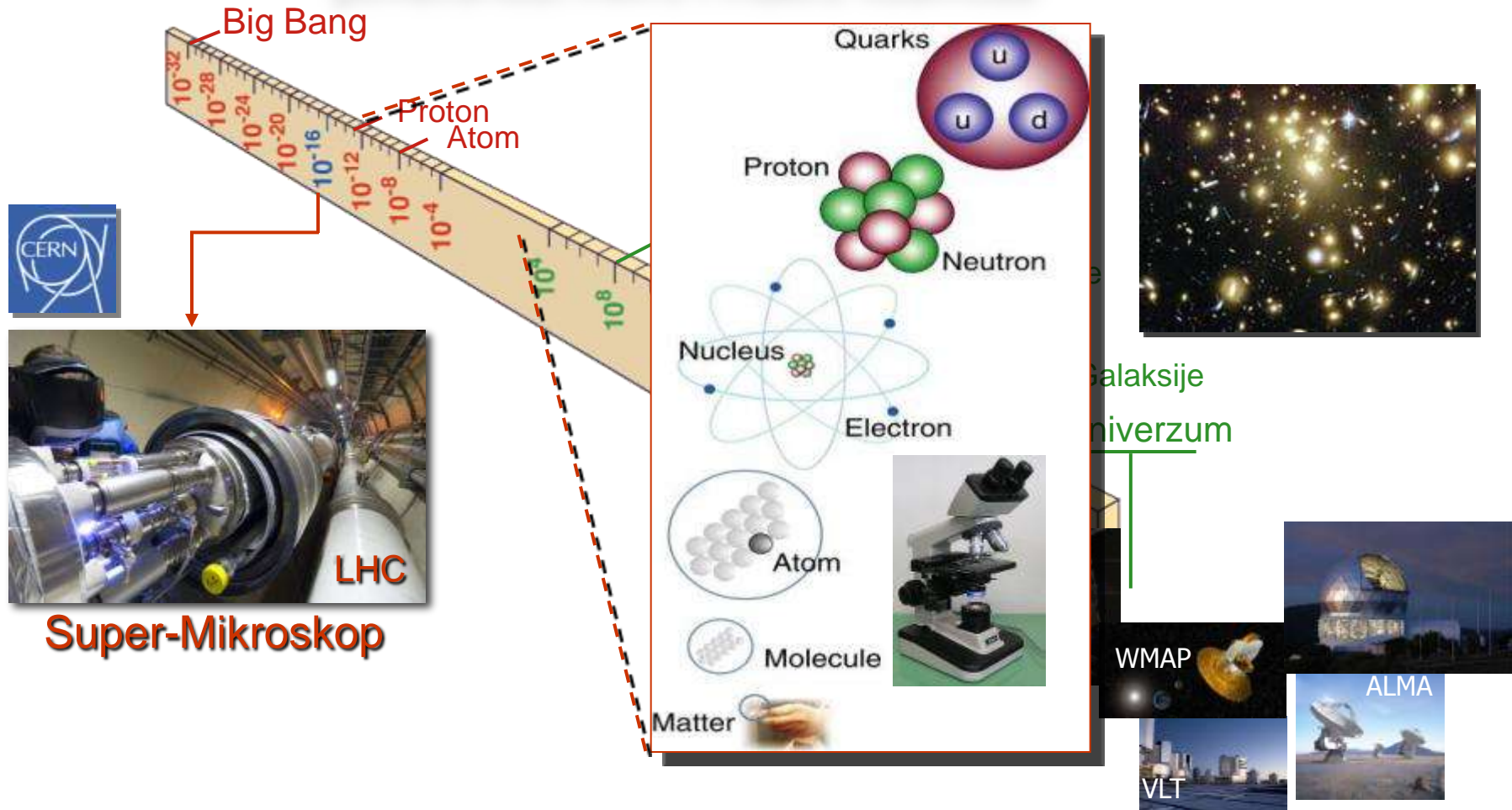


Struktura Univerzuma

Proučavanje Univerzuma na fundamentalnom nivou



povezanost mikro i makro kosmosa



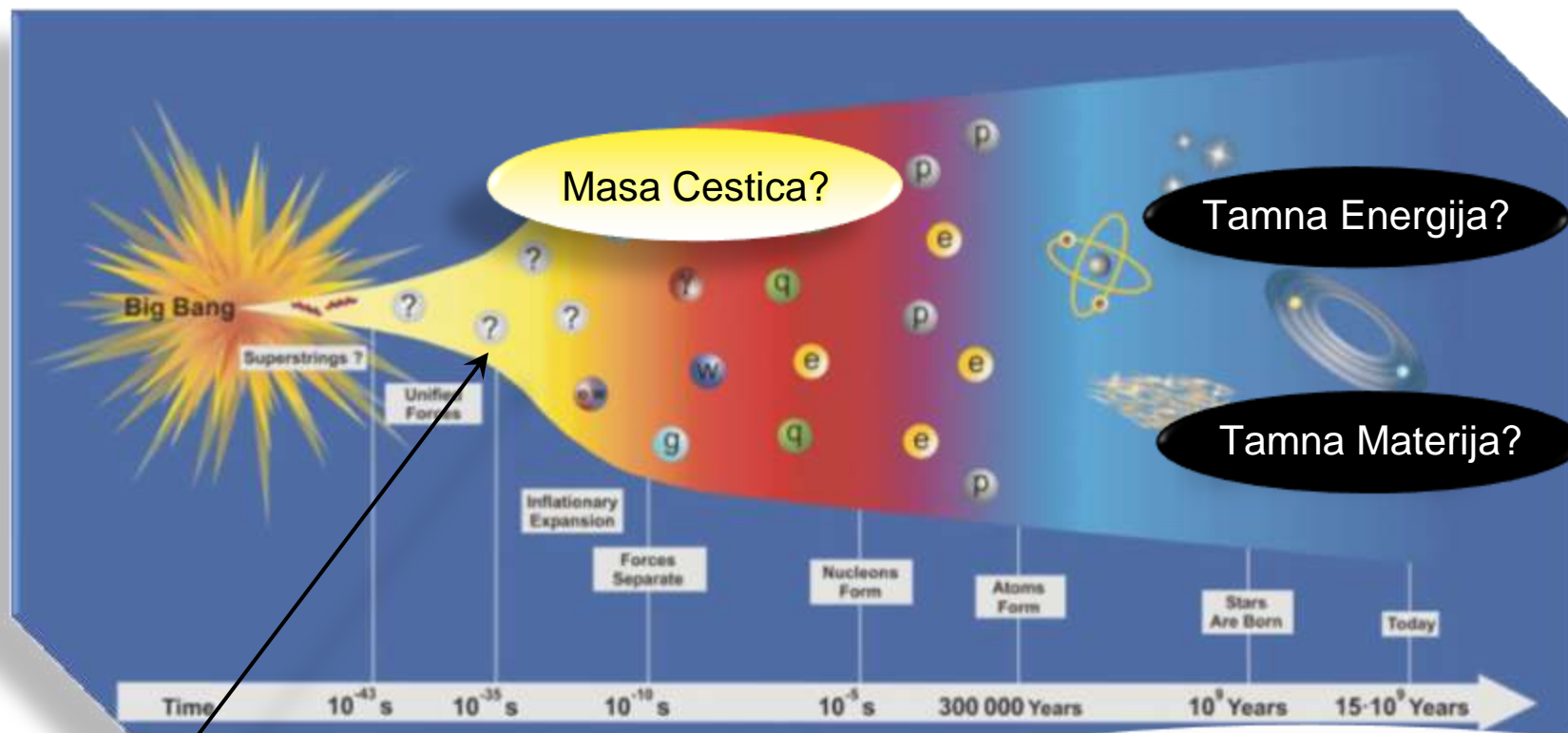
COSMOLOGY MARCHES ON



Znacajan progres je napravljen u poslednjih nekoliko hiljada godina



Otvorena Pitanja



Unifikacija Interakcija?

Asimetrija izmedju materije i antimaterije



Odgovore na ova pitanja moze nam dati
LHC u CERN-u

LHC: Ulazak u novu eru fundamentalne nauke





Mini crne rupe na LHC-u



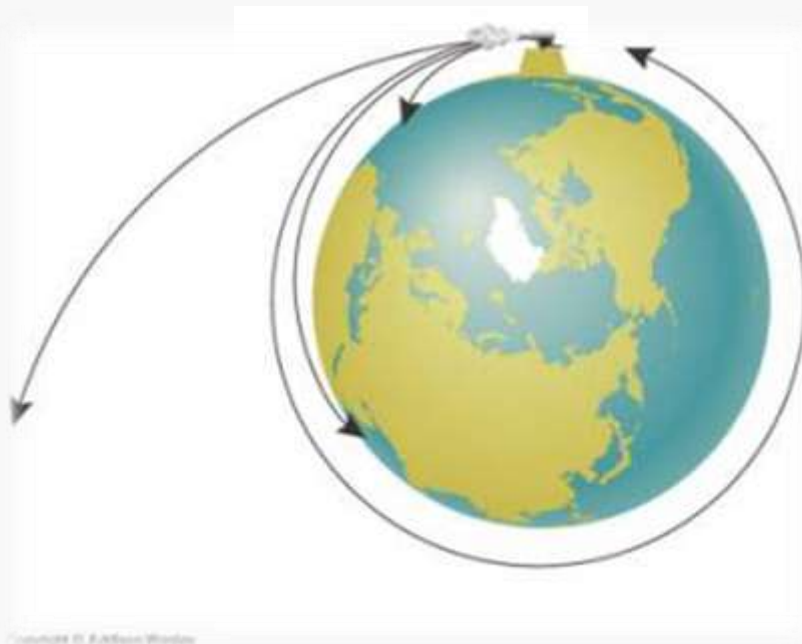
Motivacija

- **Crne rupe** su najinteresantnija i najintrigantnija rešenja Einstein-ovih jednačina
- **Ekstra dimenzije** izgleda da su neophodne u konačnoj teoriji fizike visokih energija (unifikacija)

Gravitacija + ekstra dimenzije

Crne rupe u akceleratorima!

Gravitacija



Druga Kosmicka Brzina:

Potrebna da bi se savladala gravitacija nekog objekta

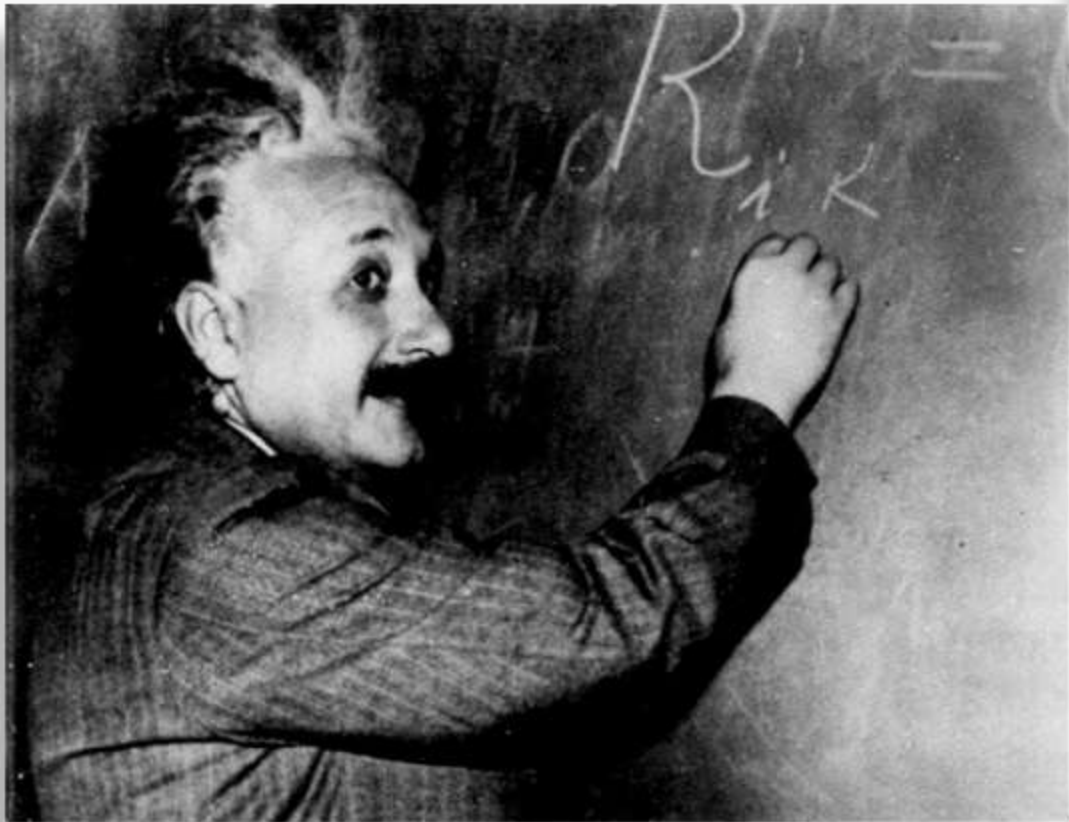
Zemlja: $V_{kos} = 11 \text{ km/s}$

Sunce: $V_{kos} = 600 \text{ km/s}$

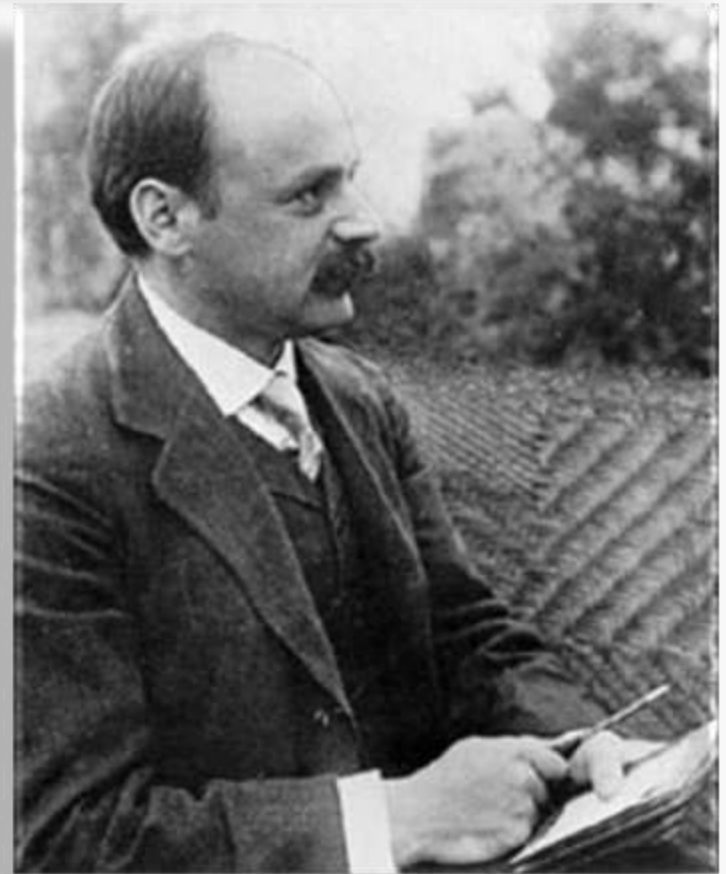
Kosmische Brzine



- **1915:** General Relativity, Einstein, Teorija Gravitacije
- **1916:** Schwarzschild pronalazi rešenje za crne rupe



Albert Einstein



Karl Schwarzschild

Schwarzschild – ovo rešenje, 1916:

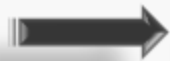
$$\Delta s^2 = -\left(1 - \frac{R_S}{R}\right) c^2 dt^2 + \frac{1}{1 - R_S / R} dR^2 + R^2 d\Omega^2$$

$R = R_S$

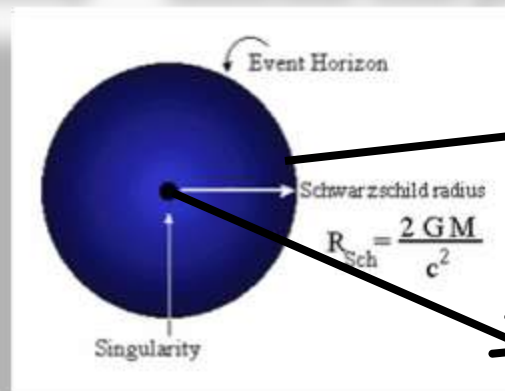


Metrika ima koordinatnu singularnost

$R = 0$

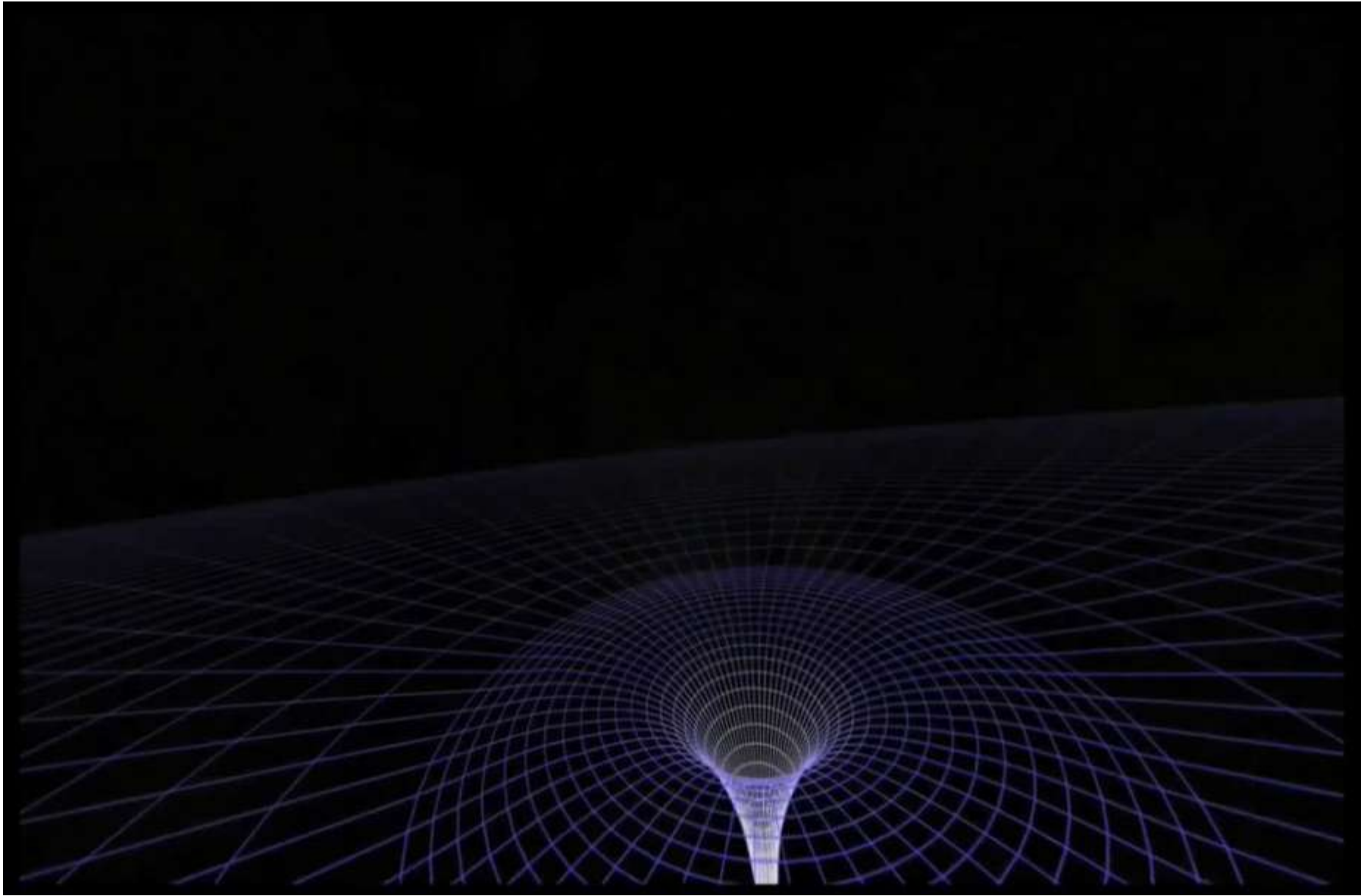


Metrika ima pravu fizicku singularnost



Nije solidna površina

Sva masa je skoncentrisana u centru



Prva upotreba termina "Crne Rupe" – Wheeler, 1967

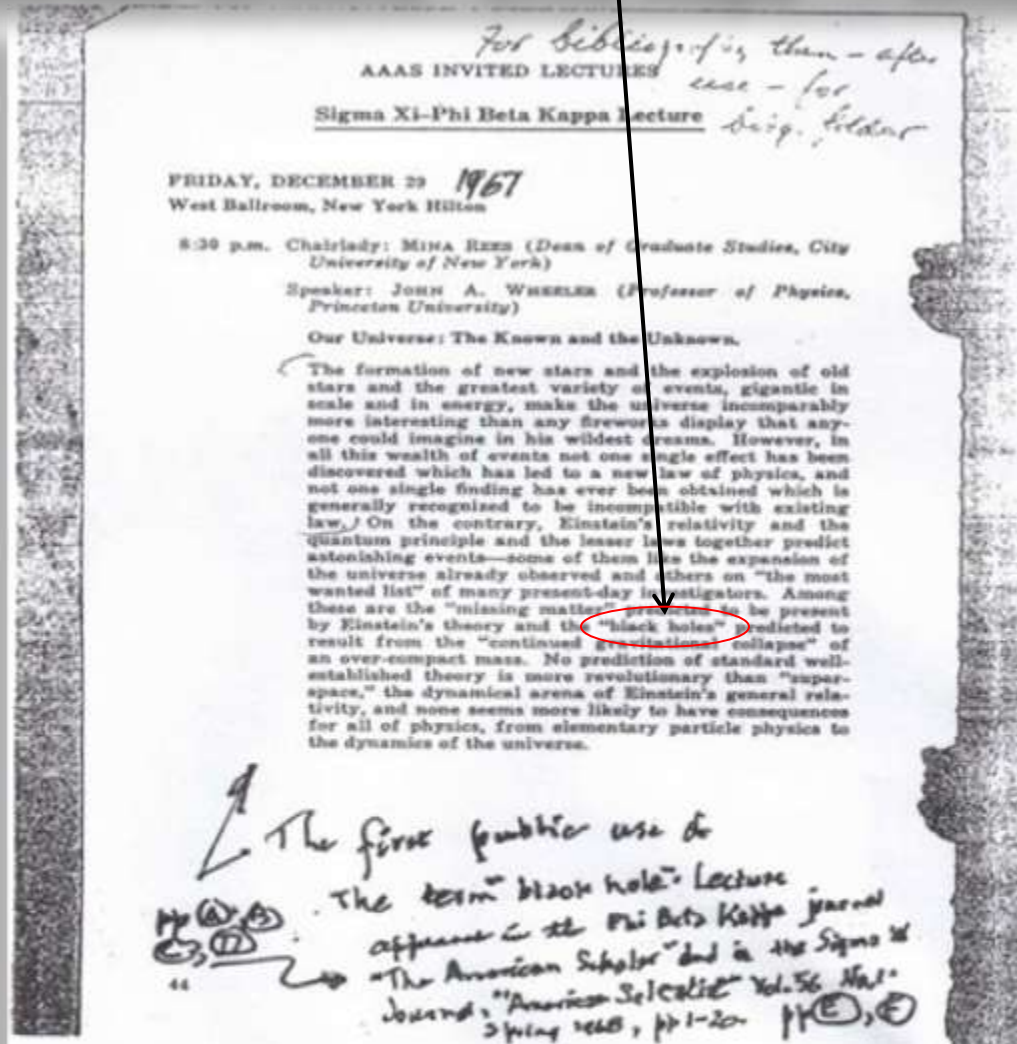
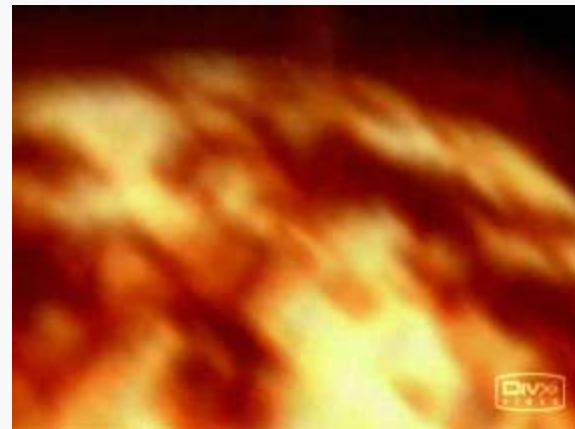


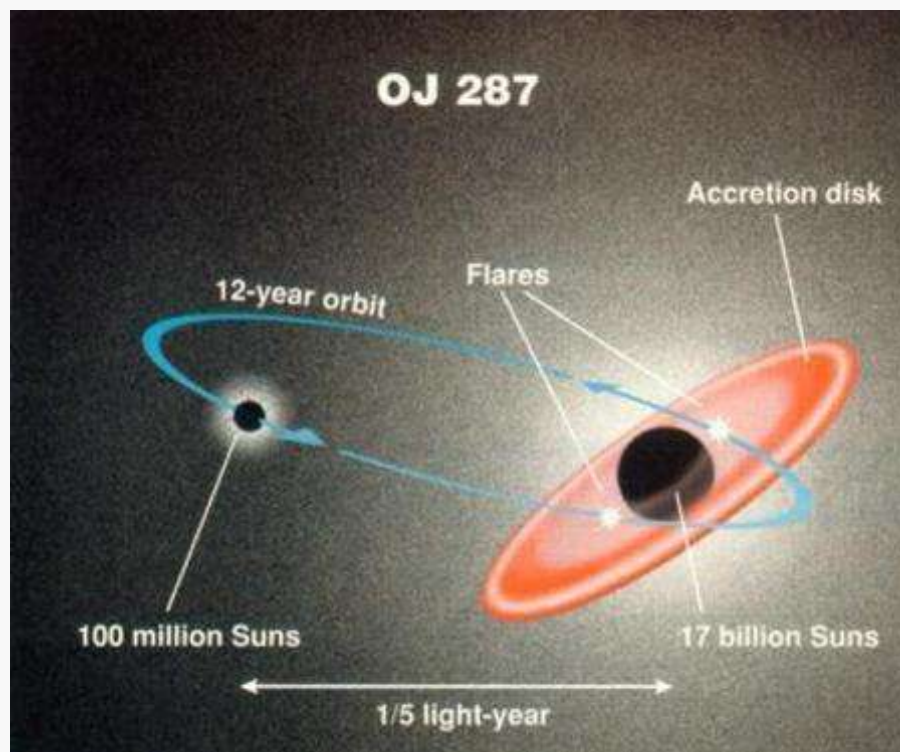
Figure 1.1: The first public use of the term "black hole". Lecture (given by J.A.Wheeler) appeared in the Phi Beta Kappa journal "The American Scholar" (Vol.37, No.2, Spring 1968, pp.248) and in the Sigma Xi journal, "American Scientist" Vol.56 No.1 Spring 1968, pp. 1-20. This page was sent to the authors by John Wheeler with his handwritten notes.

Crne rupe I

- Crne rupe formirane u kolapsu zvezdane materije
- Krajnja tacka evolucije zvezde
- Evoluiraju dalje spajanjem sa drugim crnim rupama i akumulacijom okolnog materijala
- Masa $M_{Sun} - 10^{10} M_{Sun}$



Najmasivnija crna rupa ikada otkrivena!



Sazvezdje:	Cancer
Daljina od nas:	3.5 milijarde sv. godina
Masa:	17 milijardi suncevih masa





Crne rupe II

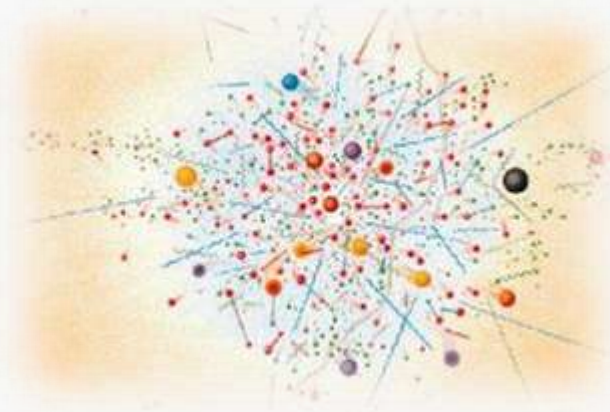
- **Male primordijalne crne rupe**

- rani univerzum, velike fluktuacije u gustini energije

- masa: $M_{Pl} - M_{Sun}$

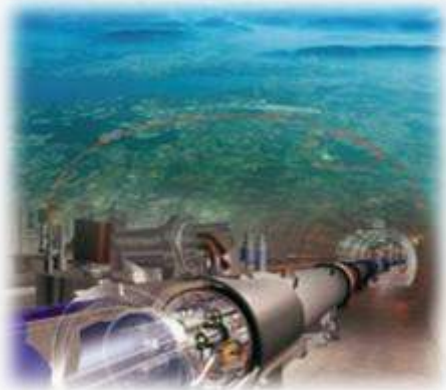
$$M_{Pl} = 10^{-5} g$$

$$M_{Sun} = 10^{33} g$$



Crne rupe III

- **Crne rupe formirane u laboratoriji**
- Sudari cestica na trans-Planck-ijevskim energijama
- Potreban akcelerator veliki kao ceo univerzum
- Masa: nekoliko M_{Pl}



Ekstra Dimenzije

- Nas svet je manifestno (3+1)-dimenzionalni na vecim rastojanjima
- Kaluza (1921) i Klein (1926) uvode petu dimenziju da bi ujedinili gravitaciju sa elektromagnetizmom



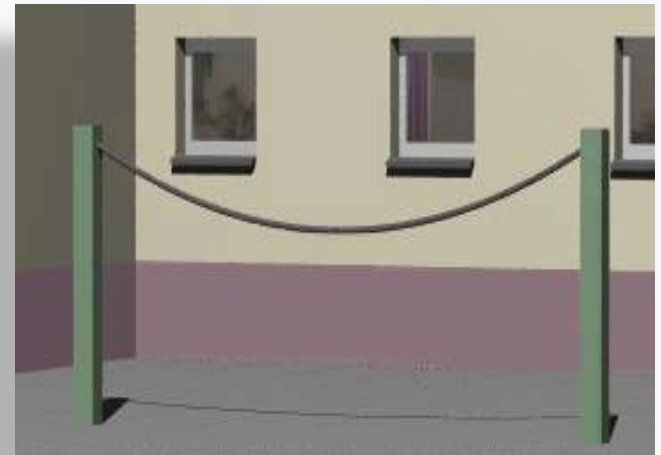
Kaluza



Klein

- Peta dimenzija je u obliku kruga
- Radijus kruga je vrlo mali:

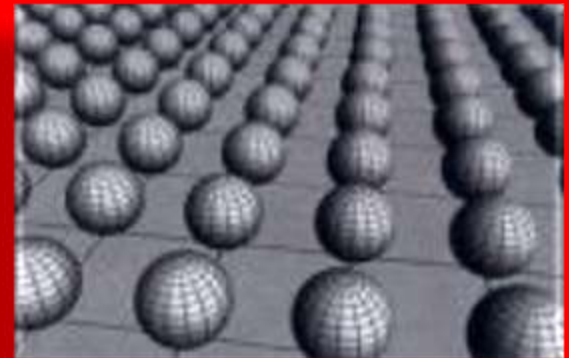
$$R = L_{Pl} = 10^{-33} \text{ cm}$$



Vise dimenzionalni objekti?

- **Da bi ujedinili sve interakcije potrebno nam je vise od 5 dimenzija**

KK modeli → najmanje 11 dimenzija
Teorija Struna → 10 ili 11 dimenzija



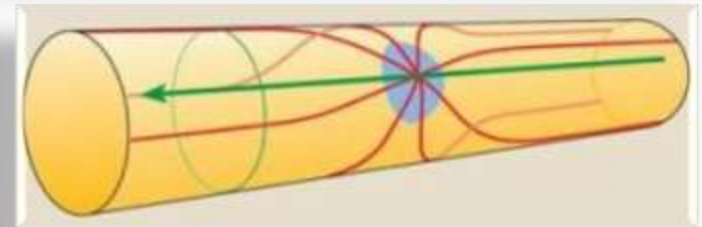
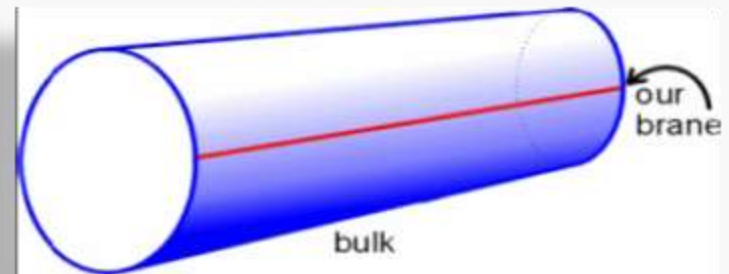
- **Interesantni vise dimenzionalni objekti mogu da postoje:
vise-dimenzionalne crne rupe, topoloski defekti (strune, membrane...)**

Jaka gravitacija: ADD model

Arkani-Hamed, Dimopoulos and Dvali, Phys. Lett. B 429, 263 (1998)

Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, Phys. Lett. B 436,257 (1998)

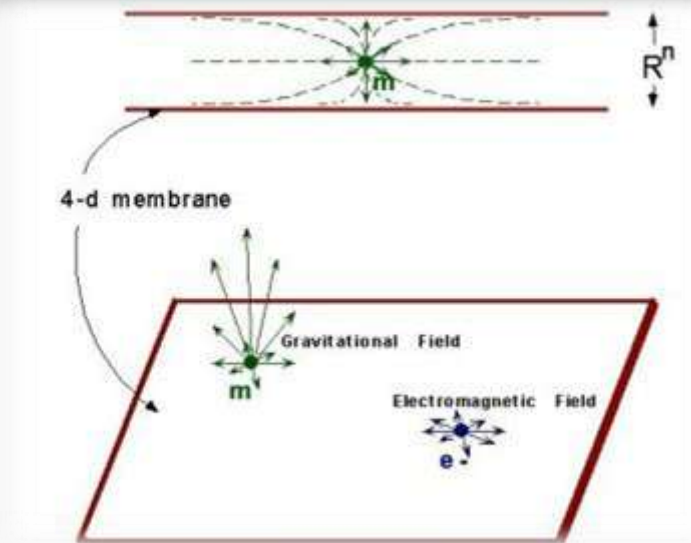
- Prostor u kome zivimo se sastoji od:
- $3+n$ space-like dimenzija (bulk)
- n ekstra dimenzija je kompaktifikovano sa radijusom R



- **Samo gravitoni mogu da propagiraju u svim dimenzijama**
- **Cestice SM su lokalizovane na 3-dim potprostoru (brane)**


U ovom modelu:

- Gravitacija je jaka kao i electroweak interakcija
- Ali je gravitaciona sila razredjena prisustvom ekstra dimenzija



Slaba gravitacija je samo iluzija za posmatraca lokalizovanog na “brane”

Ekstra dimenzije $\rightarrow M_{pl} = 1\text{TeV} = 10^3\text{GeV}$

Mozemo govoriti o ne-perturbativnim efektima kvantne gravitacije na energijama dostupnim u akceleratorima:  Mini Crne Rupe



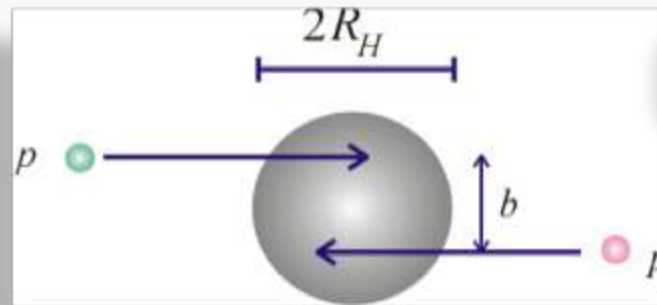
Crne rupe u akceleratorima

Akcelerator cestica (Large Hadron Collider):

Sudar dve cestice sa energijom CM E_{CM}



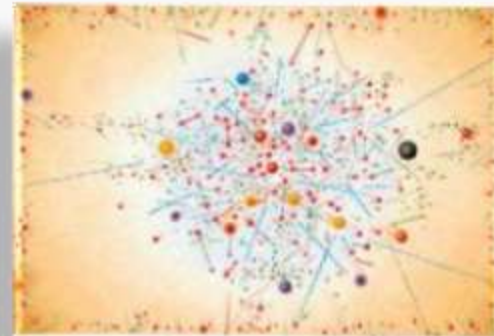
Ako je impakt parametar b manji od $2R_H$ za datu E_{CM}



Trans-Planckian energies

Crna rupa sa masom $M \sim E_{CM}$ je formirana!

Large Hadron Collider



LHC: $E_{\text{CM}} = 14 \text{ TeV}$

$$\sigma(M) \approx \pi R_H^2$$

Numericke procene:

10^7 crnih rupa godisnje ako je $M_* = 1 \text{ TeV}$



LHC – “black hole factory”!

Mart 2008. godine:

Walter Wagner, penzionisani nuklearni fizicar
Luis Sancho, spanski novinar

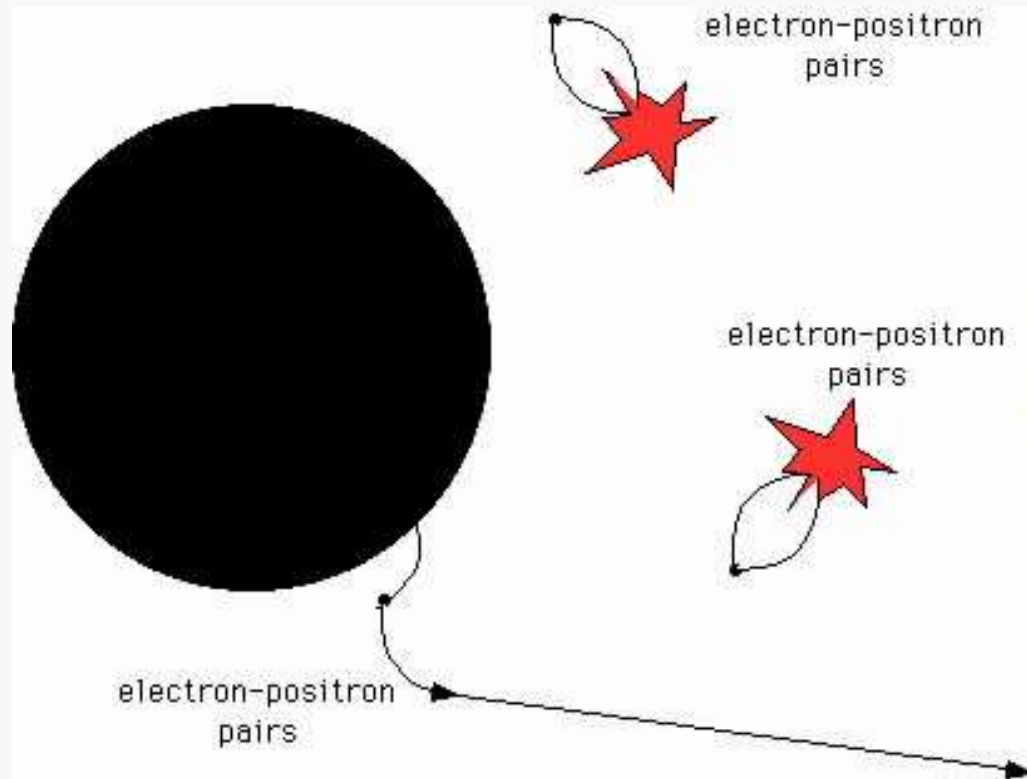


Pokrecu sudski spor da zaustave LHC





Hawking (1974): Crne rupe zrnce!







Temperatura zracenja crne rupe $T \sim 1/R_s$



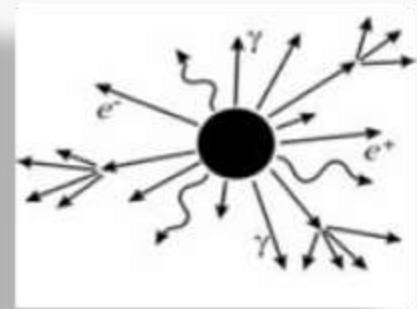
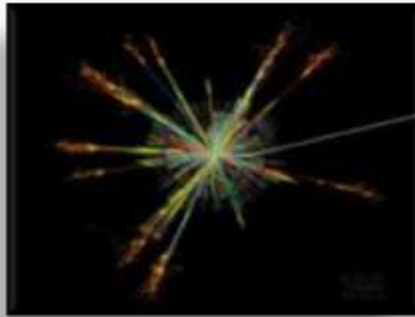
- **Velike crne rupe su vrlo hladne**
- **Vreme isparavanja je vrlo dugo**
- **Crna rupa Zemljine mase $T \sim 0.02$ K (zivot 10^{50} godina)**
- **Crna rupa Sunceve mase $T \sim 10^{-7}$ K (zivot 10^{67} godina)**

Male crne rupe su vrlo tople
Isparavaju vrlo brzo

Crne rupe mase 10^5 kg imaju zivot od 1 sekunde
To je energija od 10^{22} J oslobodjena u 1 sekundi
(ekvivalentno eksploziji 10^6 megatona TNT-a)

Zivot male crne rupe je vrlo kratak:

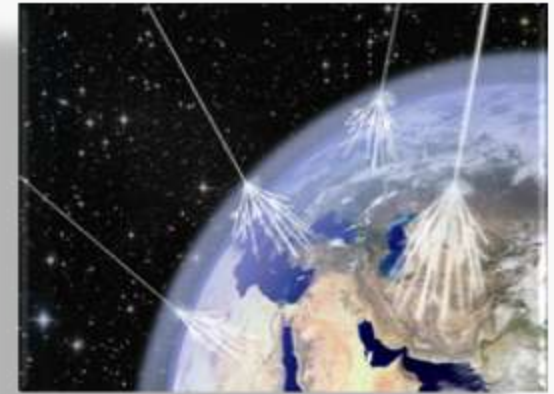
TeV (10^{-21} gram) crna rupa zivi 10^{-27} sec
→ nestaje u mini eksploziji gotovo trenutno



- Broj emitovanih cestica jednak je entropiji crne rupe: $S = \frac{n+1}{n+2} \frac{M_{BH}}{T_{BH}}$
- Na pr. 5 TeV crna rupa moze da emituje oko 30 cestica

“BH event” moze da ostavi spektakularni trag u akceleratorima
Ali ne moze da unisti Zemlju!

Kosmicki Zraci



- Zemlja je konstantno bombardovana kosmickim zracima

- Vecina dolazi sa Sunca



- Neki dolaze iz galaktickih



- A neki iz inter-galaktickih izvora



“Auger Observatory”

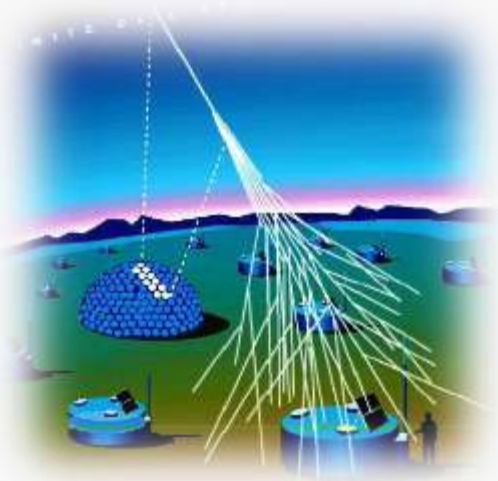


Pierre Auger

- Trenutno najmodernija opservatorija za kosmicko zracenje (uz IceCube na Juznom Polu)
- Locirana u Argentini (Pampa Amarillas)



- 1600 Cerenkovih detektora
- 4 “air fluorescence” teleskopa
- Instaliranih na površini od preko 3000 km²

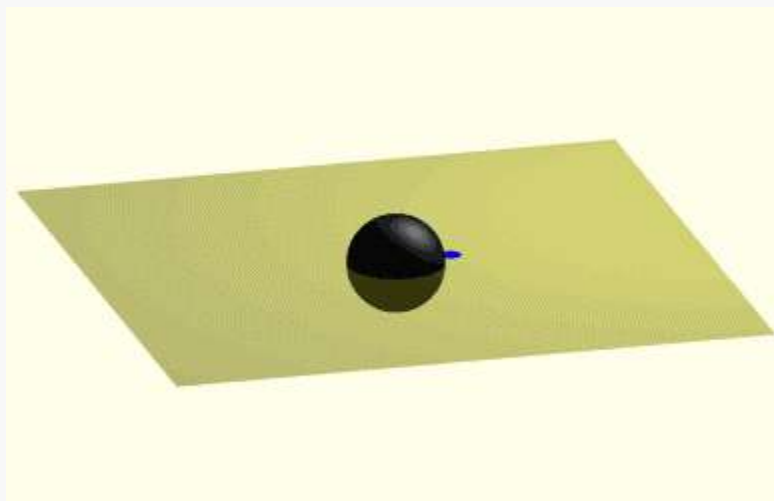


Vise-dimenzionalne crne rupe: teorija

D. Stojkovic, V. Frolov

	4D black hole	5D black hole
Parameters	M, a	M, a, b
Killing Vectors	$\partial_t, \partial_\phi$	$\partial_t, \partial_\phi, \partial_\psi$
Killing Tensor	Yes	Yes
Scalar field separation of variables	Yes	Yes
Stable circular orbits	Vreme:	Vreme:
Superradiance	Yes	Yes
Higher spin fields separation of variables	30 godina	2 godine
Decoupling	Yes	?
Algebraically special	Yes	Yes
Two principle null congruencies (PNC)	Yes	Yes
Petrov class D	Yes	Yes
PNC is shear free	Yes	No

Gde crne rupe dominantno emituju? “Brane” ili “Bulk”?



$\lambda_T > R_S$ \longrightarrow point radiator

\longrightarrow s-mod dominira \longrightarrow
Emituje ravnopravno u svim pravcima



Broj stepena slobode je mnogo veci na “brane” ?
(60 cestica SM vs. 1 graviton)

Gde crne rupe dominantno emituju? “Brane” ili “Bulk”?

Problem 1:

broj stepena slobode gravitona
u $N+1$ dimenziji je:

$$\mathcal{N} = (N + 1)(N - 2) / 2 \quad \longrightarrow \quad N = 9, \quad \mathcal{N} = 35$$

Problem 2:

- LHC: impakt parametar \rightarrow ugaoni momenat
 \rightarrow kreirane crne rupe ce biti rotirajuće
- Rotirajuće crne rupe \rightarrow “superradiance” \rightarrow
emisija gravitona dominira

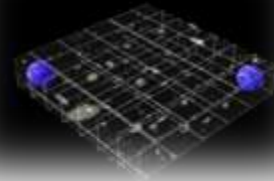
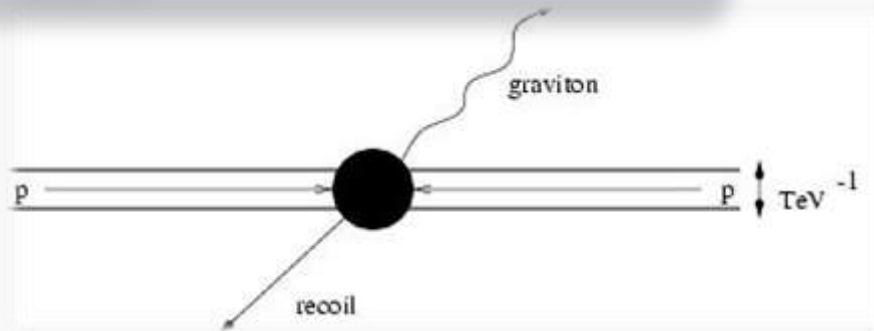
V. Frolov, D. Stojkovic, **Phys. Rev. Lett.** 89:151302 (2002)

Crne rupe emituju dominantno u “bulk”!

"Recoil" Efekat

V. Frolov, D. Stojkovic, *Phys. Rev. Lett.* 89:151302 (2002)

Cestica emitovana u "bulk" moze da izbací crnu rupu sa "brane"



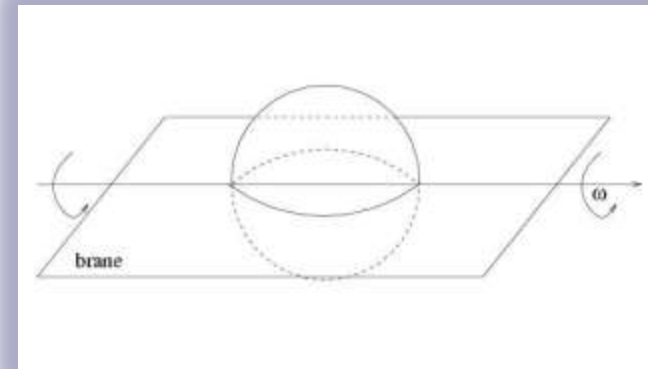
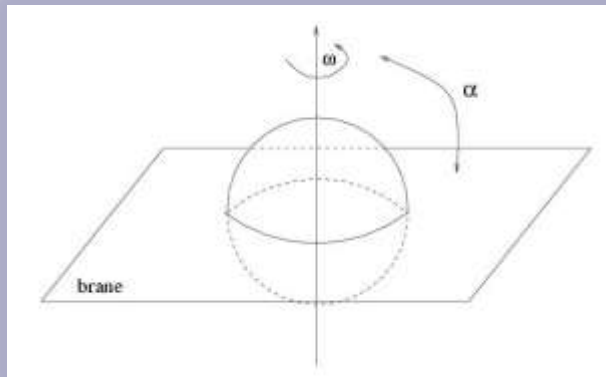
"Recoil" zbog Hawking-ovog zracenja moze da bude znacajan efekat jer mala crna rupa emituje cestice cija je energija reda velice mase crne rupe

Posledice:

- i) Hawking-ovo zracenje se iznenada prekida
- ii) posmatrac lokalizovan na "brane" registruje prividno narusenje odrzanja energije

Frikcija izmedju crne rupe i "brane"

V. Frolov, D. Fursaev, D. Stojkovic, **CQG**, 21:3483 (2004)
 D. Stojkovic, **Phys. Rev. Lett.** 94: 011603 (2005)



Brzina gubitka uganog momenta crne rupe

$$\dot{J} = \pi \sigma a R_H \cos^2 \alpha$$

$$\alpha = \pi/2 \rightarrow \dot{J} = 0$$

finalna stacionarna konfiguracija:

$$J_{bulk} = 0$$

$$\tau \approx (G \sigma \cos^2 \alpha)^{-1}$$

Uticaj tenzije “brane” na isparavanje crne rupe

D. Dai, N. Kaloper, G. Starkman, D. Stojkovic, **Phys.Rev.D75:024043,2007**

$$ds^2 = -\left(1 - \frac{r_H^3}{r^3}\right) dt^2 + \left(1 - \frac{r_H^3}{r^3}\right)^{-1} dr^2 + r^2 \{d\theta^2 + \sin^2 \theta [d\phi^2 + \sin^2 \phi (d\chi^2 + B \sin^2 \chi d\psi^2)]\}$$

6D crna rupa na “brane” ko-dimenzije 2

$$B = 1 - \frac{T}{2\pi M_*^4}$$

deficitni ugao

$$r_H = \frac{r_s}{B^{1/3}}$$

radijus horizonta

- Tenzija “brane” modifikuje standardne rezultate
- Veca tenzija znaci veci radijus horizonta
- Emitovana energija se smanjuje

© = 1/42

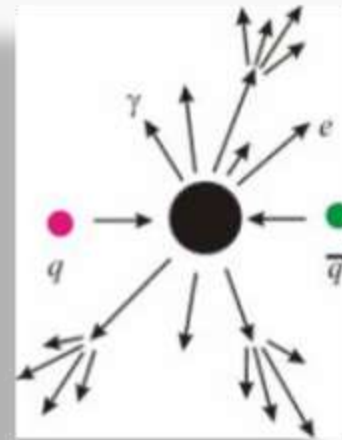
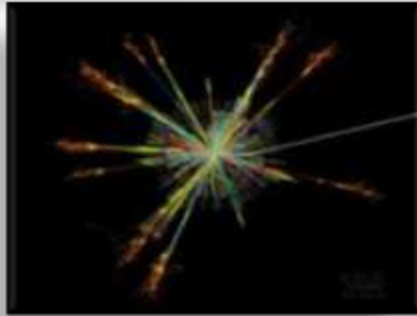
Black Max

“BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension”

D. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
Phys.Rev.D77:076007,2008

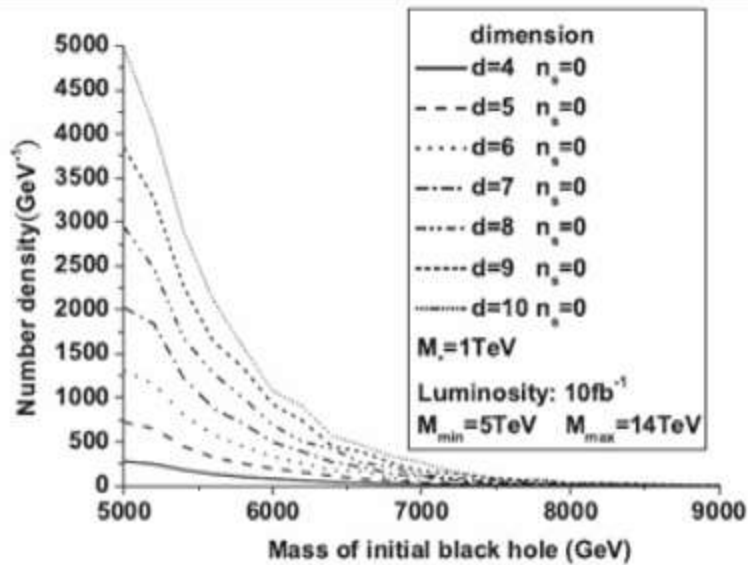
- Trenutno najkompletnije orudje za proucavanje efekata kvantne gravitacije
- Obezbedjuje realisticne predikcije za proton-proton, proton-antiproton i electron-pozitron kolajdere
- Obuhvata sve sto znamo o crnim rupama do danas (ukljucujuci sav moj rad u ovoj oblasti u protekloj deceniji)
- Generator je deo je zvanicnog software-a na CERN-u

Black Max procedura

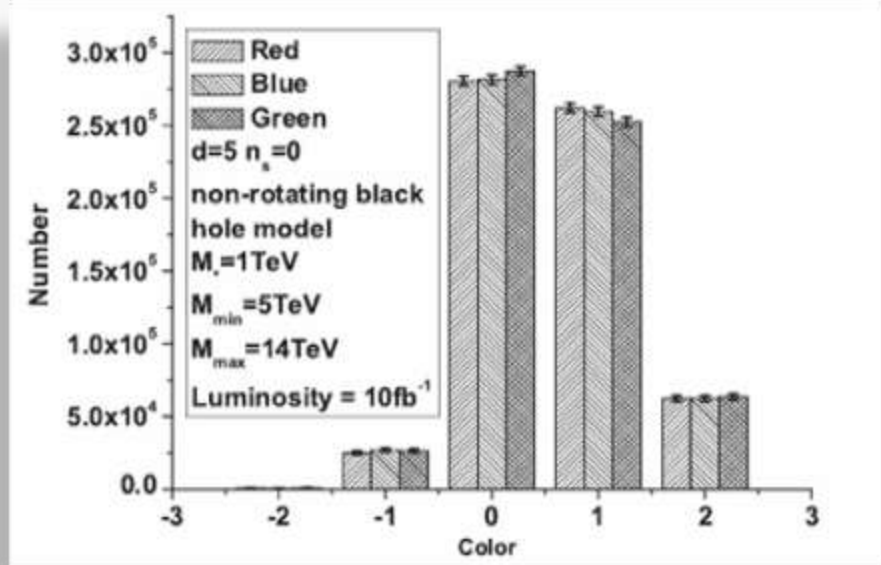


- Generator zahteva dobro definisani input, npr. dva partona u sudaru, koji se dobija iz poznatih “parton distribution functions” za proton
- Verovatnoca za produkciju crne rupe se zatim racuna, zajedno sa osnovnim karakteristikama crne rupe: masa, spin, elektromagnetni i kolor naboj
- Black Max zatim racuna karakteristicno Hawking-ovo zracenje
- Kao output, Black Max daje cestice Standardnog Modela, sa njihovim distribucijama energije, impulsa i ugaonog momenta

Black Max output



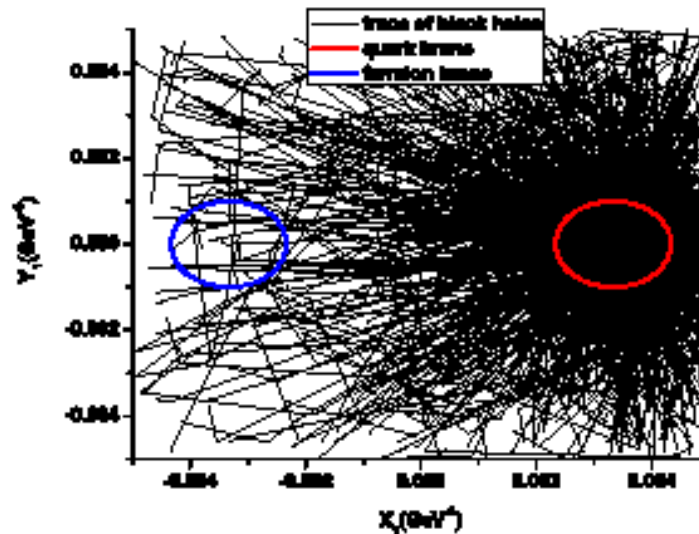
Distribucija masa proizvedenih crnih rupa kao funkcija razlicitog broja ekstra dimenzija



Inicijalna distribucija kolor naboja kreiranih crnih rupa

BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.
[D. Dai](#) [G. Starkman](#) [D. Stojkovic](#) [C. Issever](#) [E. Rizvi](#) [J. Tseng](#)
[Phys.Rev.D77:076007,2008](#)

Black Max output



Recoil efekat u split fermion modelu

- crne linije su tragovi crnih rupa
- crveni kruzic je mesto lokalizacije kvarkova
- plavi kruzic je mesto lokalizacije leptona

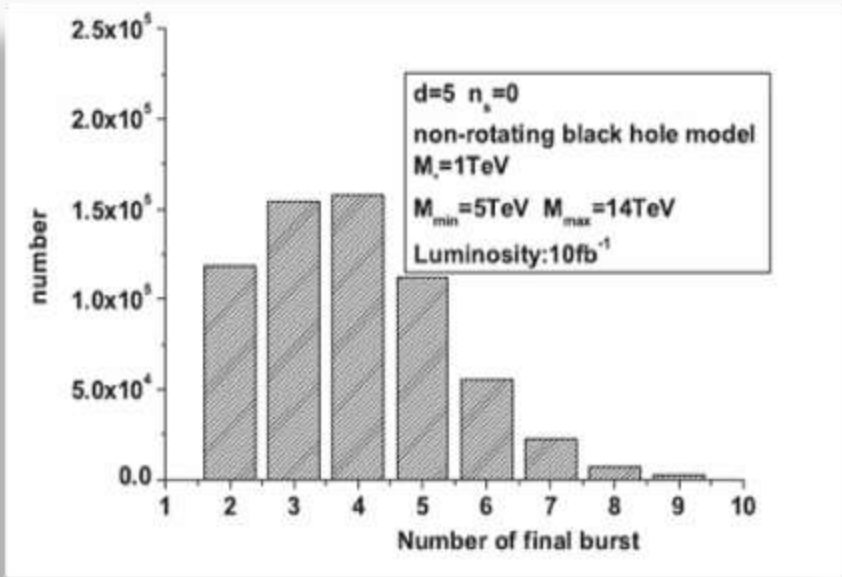
BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.

[D. Dai](#) [G. Starkman](#) [D. Stojkovic](#) [C. Issever](#) [E. Rizvi](#) [J. Tseng](#)

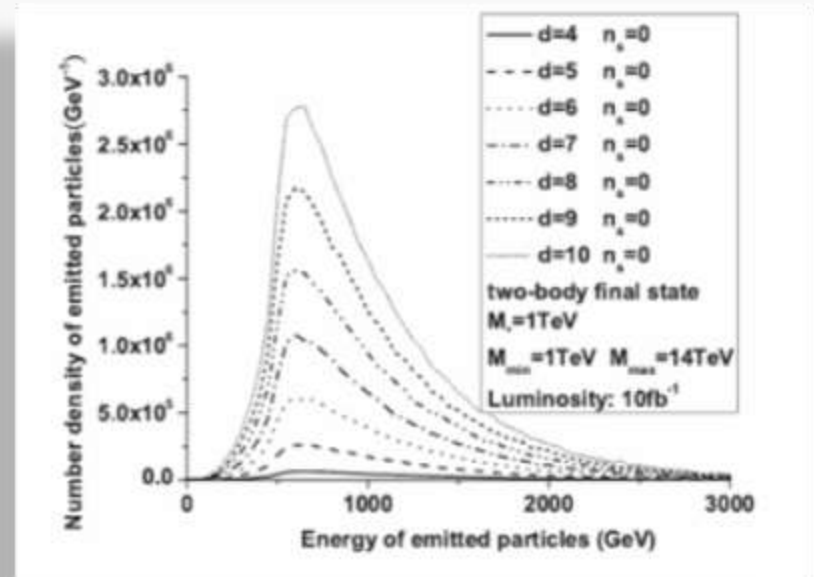
Phys.Rev.D77:076007,2008

Black Max output

$$P_2 = \frac{\sum_{n=0}^2 \frac{1}{n!} \langle N \rangle^n}{e^{\langle N \rangle}}$$



Broj čestica emitovanih u “final burst” fazi (kad masa crne rupe padne na vrednost M_* gde semiklasicna gravitacija više ne važi)



Distribucija energije emitovanih čestica u L. Randall’s “two-body final state” modelu

[BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.](#)
[D. Dai](#) [G. Starkman](#) [D. Stojkovic](#) [C. Issever](#) [E. Rizvi](#) [J. Tseng](#)
[Phys.Rev.D77:076007,2008](#)

ATLAS i CMS na LHC-u

Search for Microscopic Black Hole Signatures at the Large Hadron Collider

The CMS Collaboration

e-Print: **arXiv:1012.3375**

Search for strong gravity signatures in same-sign dimuon final states

The ATLAS Collaboration

e-Print: **arXiv:1111.0080**

ATLAS i CMS intenzivno koriste Black Max

- **Najnoviji limit (2012): minimalna masa crnih rupa > 5 TeV**

Respectfully Quoted: A Dictionary of Quotations. 1989.

Dialog between Lord Michael Faraday (1791 - 1867) and the Chancellor of the Exchequer

QUOTATION:

- Mr. Gladstone, then Chancellor of the Exchequer, had interrupted Lord Faraday in a description of his work on electricity to put the impatient inquiry:

“Very well Lord Faraday, but after all, what is the use of it?”

Like a flash of lightning came the response:

“Well sir, there is every probability that you will soon be able to tax it!”

HVALA