BH/string ball production, possibly at LHC

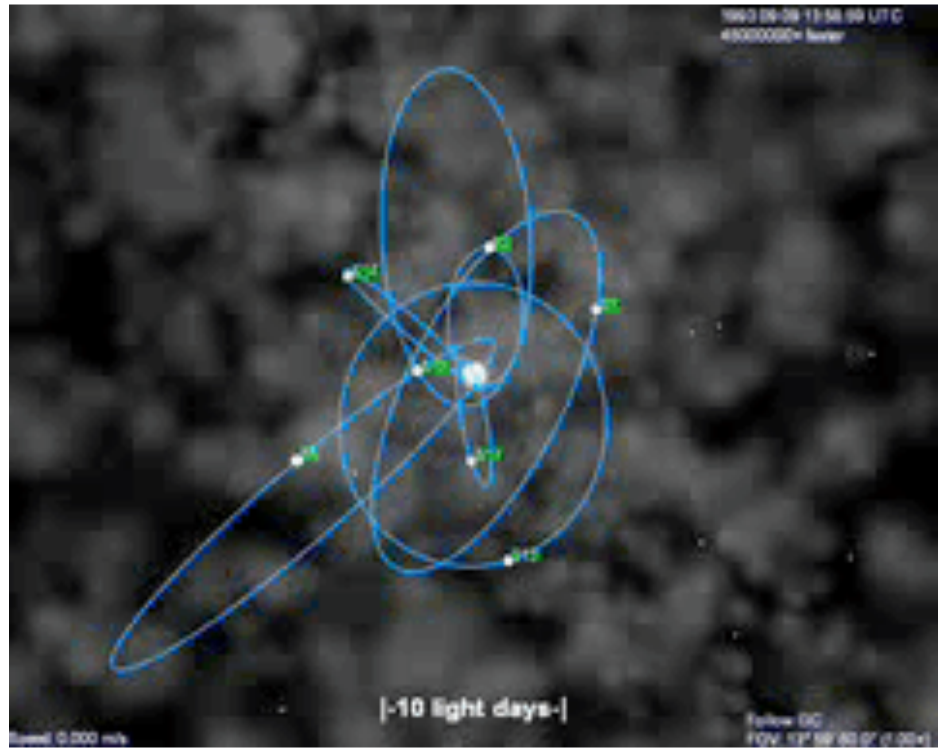
Kin-ya Oda (Osaka)
尾田欣也 (大阪)

with

T. Matsuo, PRD79 (2009)
D. Ida & S. C. Park, PRD67 (2003), 71 (2005), 73 (2006)
(C. Alig & M. Drees, JHEP0612 (2006))
(N. Okada, PRD66 (2002))

Evidence for BH existence

- Center of **our galaxy**:
  - Central mass pinned down by direct observation of the stellar move.
  - Maximum radius of central object given.
  - No known interaction can prevent gravitational collapse to form a BH!
- Message: BH is NOT mere a theoretical artifact. It IS there!!



Fruit of 16 years observation [Gillessen et al., 08]

Outline

1. BH physics is passport to **QG**
   - ◆Correspondence principle for BHs/strings
2. TeV gravity scenario
3. What can be seen at **LHC**
   i) BH production
   ii) BH decay

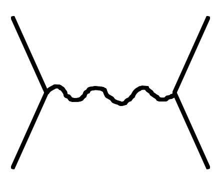
What is Planck scale

- Einstein's general relativity should be a **low energy effective theory** (a classical limit).
- Gravitational **coupling constant** is given by Newton constant G ~ $(\text{mass})^{-1/2}$.
  - Electromagnetism: $$L_g \sim \frac{1}{e^2} F_{\mu\nu} F^{\mu\nu} \quad \Rightarrow \quad V_C \sim e^2 \frac{q_1 q_2}{r}$$
  - Gravity: $$L_G \sim \frac{1}{G} R \quad \Rightarrow \quad V_G \sim -G \frac{m_1 m_2}{r}$$

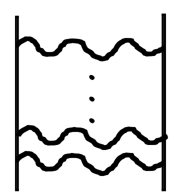
- **Interaction strength** at energy E is: ~ GE^2.
- At E ~ $G^{-1/2}$ =: M_P (Planck mass), **unitarity** (probability conservation) is violated (within effective theory).

Trans-Planckian scattering

- What happens for scattering at $E \gg M_P$?
- **BH production!**
  - It is **proven** that classical particle scattering leads to BH production. (shown later)
  - Classical treatment justified by: BH **compton wavelength** $<$ **event horizon**
- Support: Infinite closed string (~graviton) exchange within **Eikonal app.** ~ scattering by **BH.** [Amati, Ciafaloni, Veneziano, 87, 88, 89, 90, 92, 93, 07]
  - A cartoon:



$\sim -\dfrac{GM}{r}$



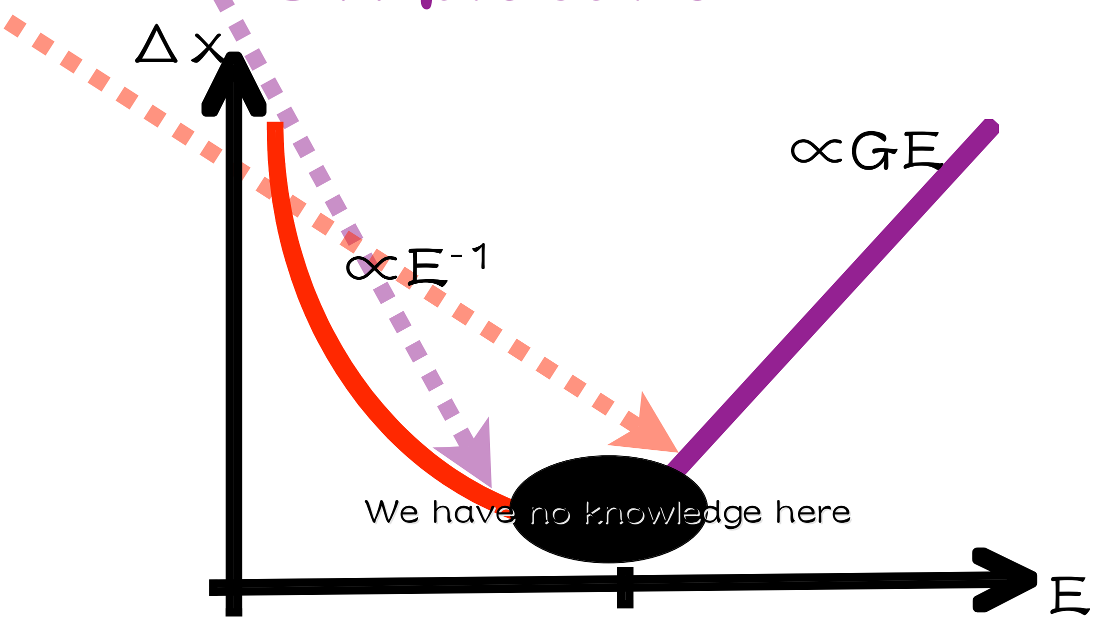
$\sim \dfrac{-1}{1-\dfrac{GM}{r}}$

End of short distance physics

- Paradigm of particle physics for a century:
  - The **higher** the **energy**, the **shorter** the **distance** we can see.
- In trans-Planckian scattering, BH prod. dominates: $\sigma \propto$ (horizon size) $\propto E^*$
  - The higher the energy, the **larger** the **EH**, **hiding** all shorter distances.

UV/IR duality in gravity

- Inverted length-energy relation at Planck scale.
- Planck scale is
  - UV cutoff of **effective theory**
  - IR cutoff of **BH picture**

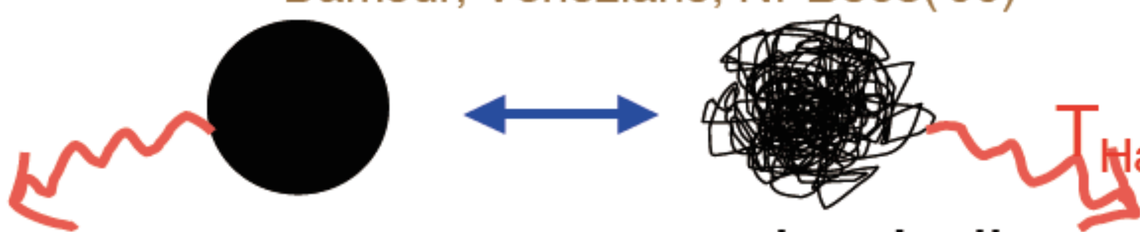


String/BH correspondence?

- What else exhibits: length $\propto$ energy?
- **Strings!** (the longer the heavier)
- Assume: a BH ~ single string
  at "**correspondence scale**" ~ M_P,
- various quantities become same order there:
  - entropy, temperature [Susskind, 93; Holowitz, Polchinski, 96]
  - size[Holowitz, Polchinski 97, Damour, Veneziano, 99]
  - production cross section [Dimopoulos, Emparan, 01]
- Also similar geometric behavior [Matsuo, **KO**, 08] (below)

Correspondence principle

Horowitz, Polchinski, PR**D55**('97); PR**D57**('98); … ;
Damour, Veneziano, NP**B568**('00)



$T_{Hagedorn}$

$T_{Hawking}$ BH

string ball
(very massive mode
of a single string)

entropy:

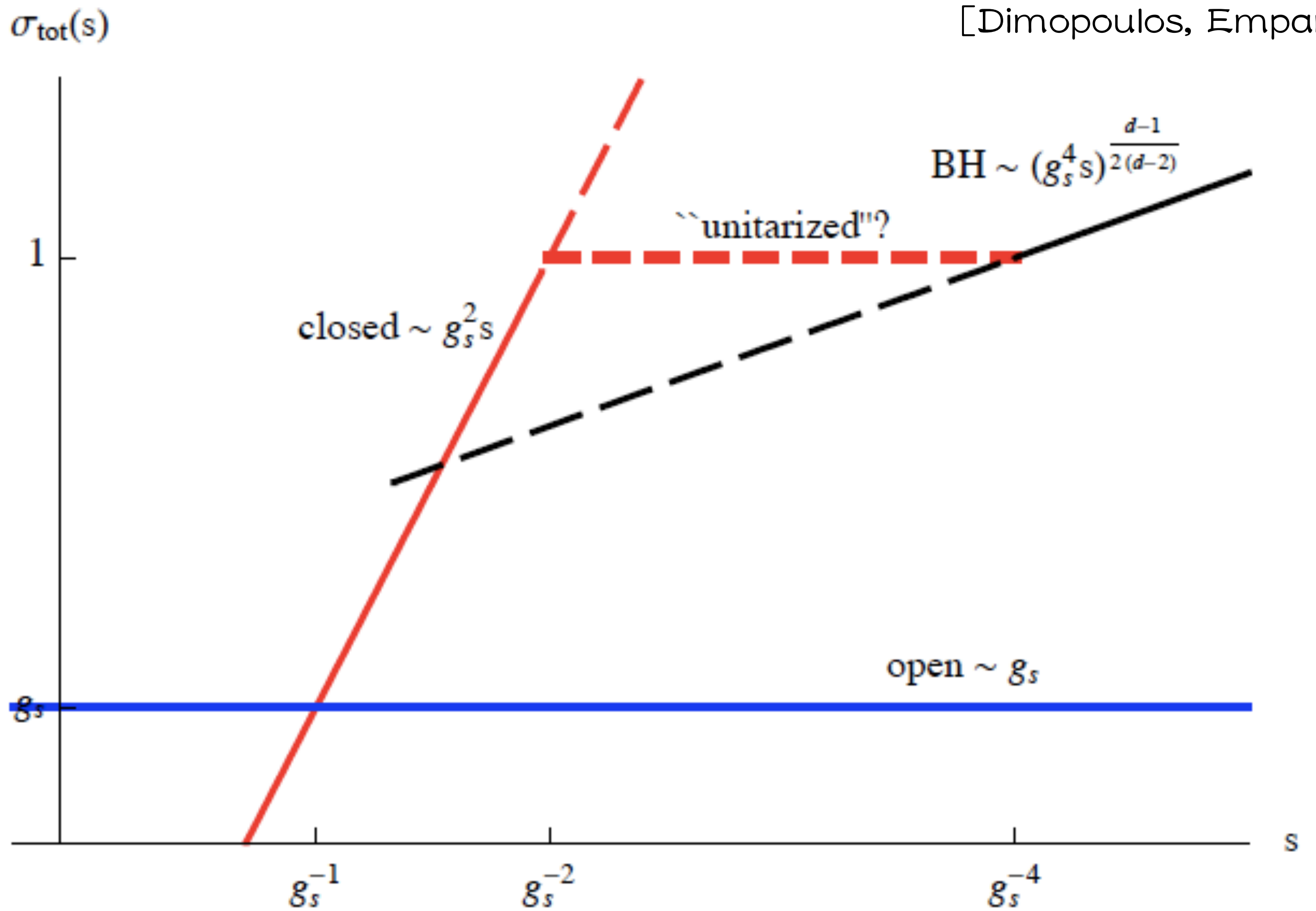
$(M \,/\, M_P)^{(n+2)\,/\,(n+1)}$ $M \,/\, M_s$

matches when
$M \sim M_{corr} = g^{-2} M_s$
in any $(4+n)$ dim.

$(M_P \sim g^{-2\,/\,(n+2)} M_S)$

Correspondence in prod. cross section

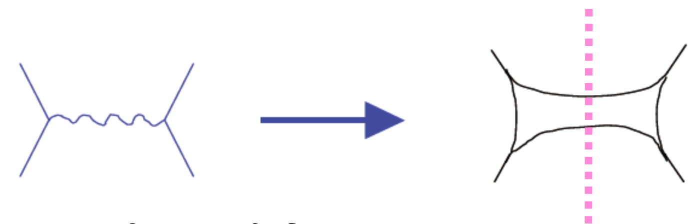
[Dimopoulos, Emparan, 01]



Geometric behavior of diff. cross sec.

[Matsuo, **KO**, PRD79 (2009)]

- It has been known that **string scattering** is soft at large **ang. mom. J**:
  $\sigma_J \propto \exp(-J^2/s \ln s)$



- We obtained **closed string production cross section** via optical theorem

$$\boxed{\sigma_J^{\text{closed}}(s) = \frac{1}{s}\mathrm{Im}\,\mathcal{A}_J^{\text{closed}}(s) = 2^{\nu+1}\pi^{\frac{5}{2}} g_s^2 \Gamma\left(\nu+\frac{1}{2}\right)\frac{[C_J^\nu(1)]^2}{N_J^\nu}\frac{s\,e^{-\lambda}}{\lambda^\nu} I_{J+\nu}(\lambda),}$$

  leading to $\boldsymbol{\sigma_J \propto J^{D-3}}$ (at $1 \ll J \ll (s \ln s)^{1/2}$).

- This resembles **geometric** behavior of **BH cross section** [Ida, **KO**, Park 02]
  $\boldsymbol{d\sigma/dJ \propto J^{D-3}}$.

To summarize,

- We want **non-perturbative** formulation of **quantum gravity.**

	Pert.	Non-pert.
classical	(easy)	general relativity
quantum	string theory	**not known**

correspondence?

- If we can produce BH, this region can be explored **experimentally**, as deviation from BH picture. For it, important to predict BH phys. as **precisely** as possible.

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2. TeV gravity scenario

3. What can be seen at **LHC**

   i) BH production

   ii) BH decay

True Planck scale

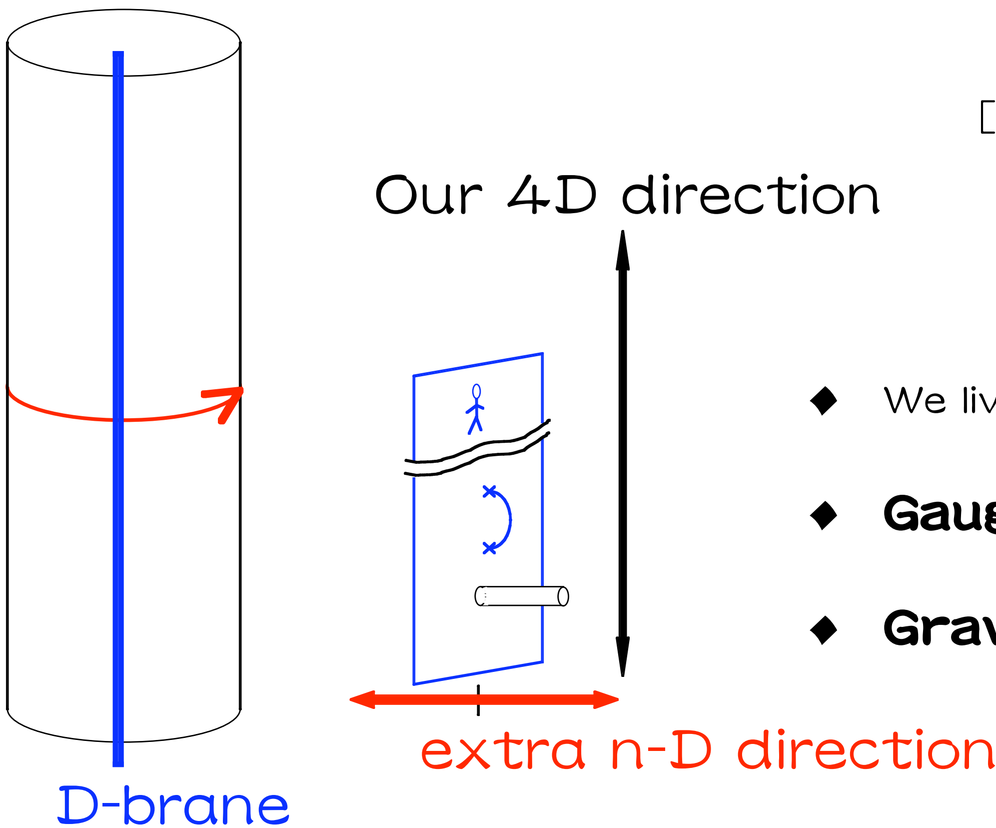
- In above argument, Planck scale has been set at: $M_P = G^{-1/2} \sim 10^{16}$ TeV
- Very much larger than LHC energy 14TeV.
- Disappointing.
- Can it be that **true Planck scale** is around TeV?

How short distance do we know?

- In superstring theory, consistent #(flat dims) is 10.
    - Other 6 dimensions must be compactified.
    - How small?
- Our 4D theory is tested up to
    - am = 10^{-18} m by **gauge** interactions
    - 0.1 mm = 10^{-4} m by **gravitational** int.
- Gravity does **not** have to live in 4D!

Brane world

[Akama 82]
[Rubakov, Shaposhnikov 83]
[Arkani-Hamed, Dimopoulos, Dvali 98]

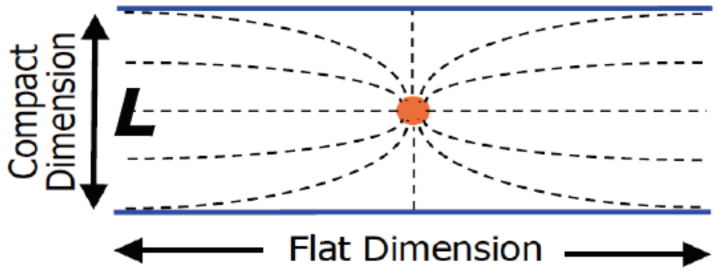


- We live on brane.
- **Gauge int.** (open string) lives on brane.
- **Gravity** (closed string) lives in bulk.

Note: **Compactification radius** is **free parameter** in current perturbative string theory.

TeV gravity

Drawing from Landsberg



- With n extra dimensions, gravity weaker at r < L:
- $F \propto r^{-(2+n)}$
- $F \propto r^{-2}$

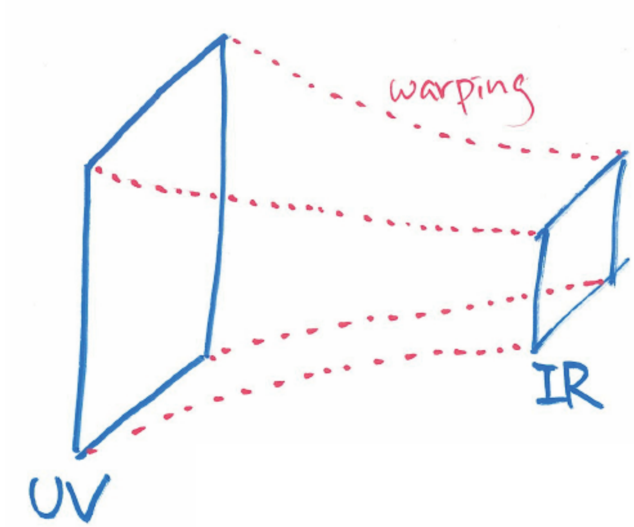
$$F(r) = G_4 \frac{m_1 m_2}{r^2} \rightarrow \begin{cases} G_D \dfrac{m_1 m_2}{r^{2+n}} & (r << L) \\ G_D \dfrac{m_1 m_2}{L^n r^2} & (r >> L) \end{cases}$$

- $G_D \sim G_4 / L^n$

- **True** (short distance) **Planck scale**, smaller than it looks at long distance.
- **M_D ~ TeV** when n=3…7, L～μm…fm.
  (※ n=2 with M_P～TeV is excluded by astro.)

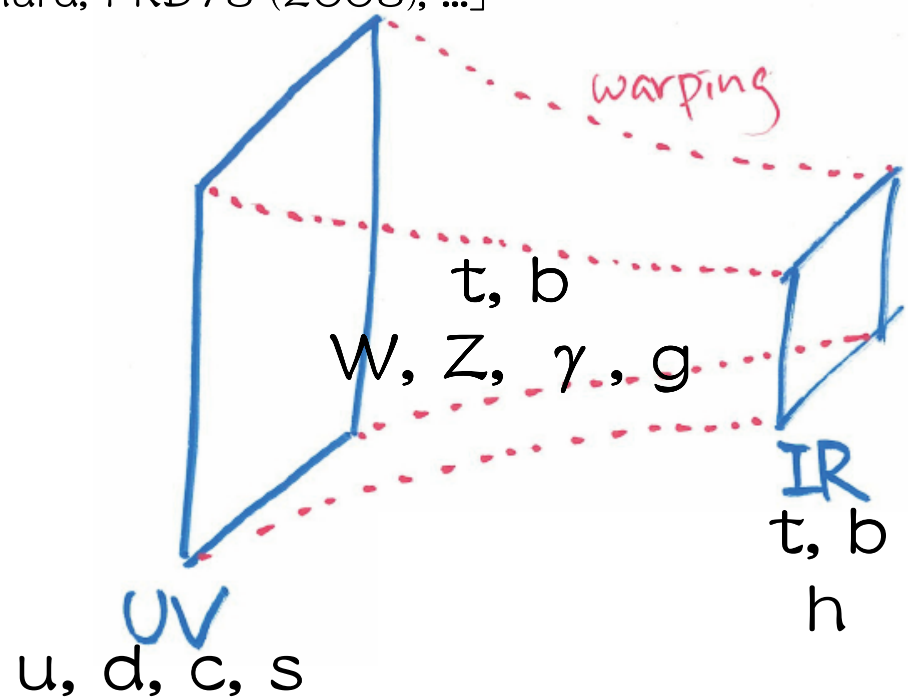
And/or warped compactification

- Generically, compactification under presence of D-branes makes our 4D metric **warped**, dependent on extra dimension. $ds^2 = e^{-ky}(-dt^2 + d\vec{x}^2) + dy^2$
- Then, **Planck scale** (as UV cutoff of low energy effective theory) **depends** on position in extra dimension.
- Can be **TeV** at IR brane, where SM fields are located.



Further models in warped space

- Sufficient to put Higgs at IR brane for gauge hierarchy.
- E.g. in **gauge-Higgs unification** model:
  Higgs as **Wilson-line phase A_5**
  [...; Hosotani, **KO**, Ohnuma, Sakamura, PRD78 (2008); ...]
- BH production by
  - gg -> BH, bb -> BH?
    [Park, **KO**(?) in progress]



To summarize,

Planck scale can be as low as TeV!

- Hereafter, we assume:
  - all SM fields being on brane
  - (horizon radius) $\ll$ (compactification length)
  - (horizon radius) $\ll$ (curvature length)

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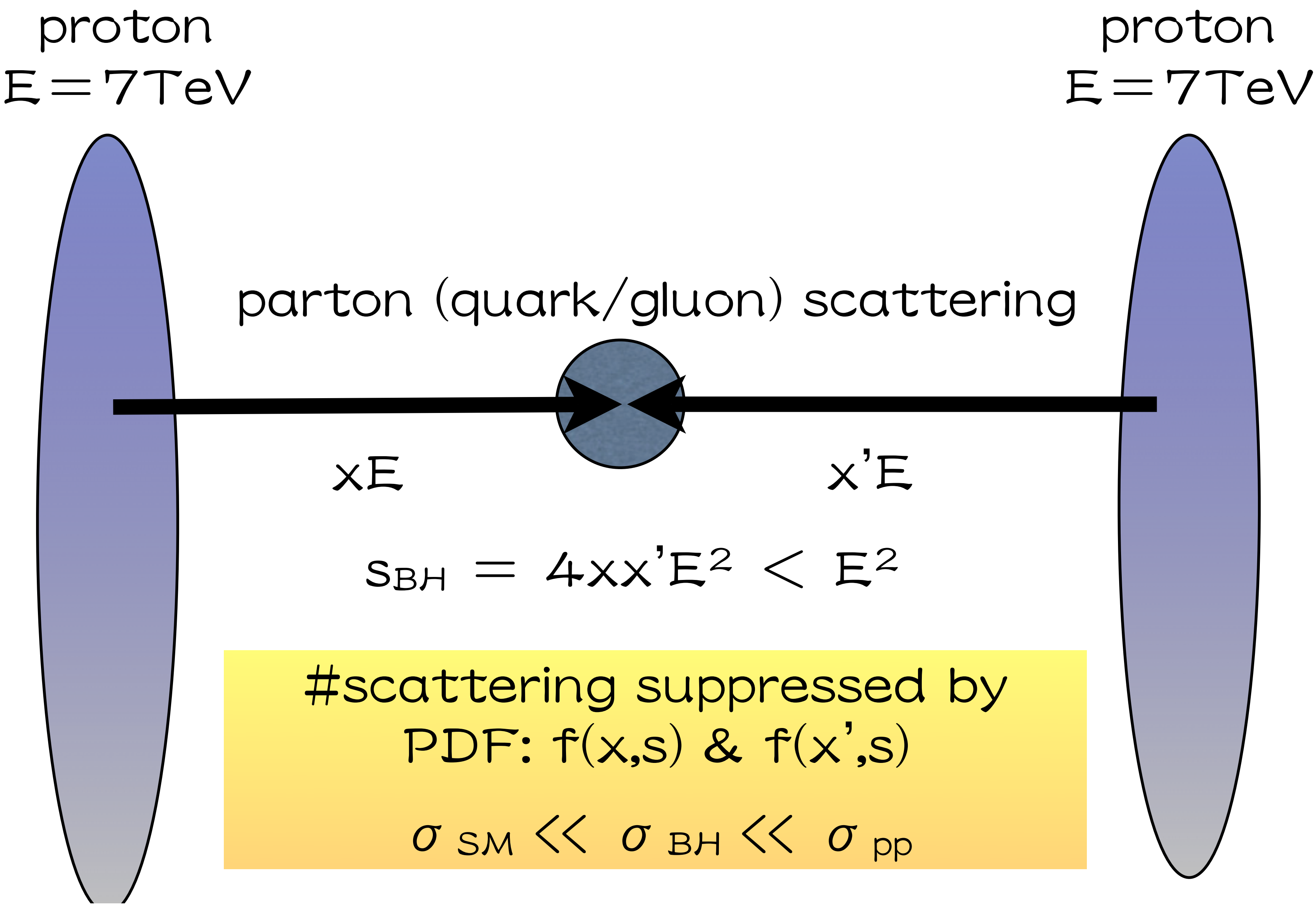
Production

LHC basics



$$s_{BH} = 4xx'E^2 < E^2$$

#scattering suppressed by
PDF: f(x,s) & f(x',s)

$$\sigma_{SM} \ll \sigma_{BH} \ll \sigma_{pp}$$

Production of TeV BH@LHC

- Classical BH production **proven.** (shown later)
  - **Increasing cross section:** $\sigma \propto s$ *
- With $M_P = 1\text{TeV}$ ~ a BH(-like object) per second
- Possible suppression:
  - **Gravitational radiation** reduces σ ?
    [Yoshino, Nambu 02, Emparan, Mayers 03]
  - Super-radiant **graviton emisson** for large J?
  - Not to have BH-like object due to QG effects?
    - Still 100 BHs per year (10fb) if we cut by $M > 10\text{TeV}$.
      (200pb if cutting by $M > 5\text{TeV}$)

Geometrical cross section

'BH forms whenever $b<R_S$'   't Hooft '87

$$R_S \propto \frac{1}{M_P}\left(\frac{M_{\mathrm{BH}}}{M_P}\right)^{\frac{1}{n+1}}$$

$$M_{\mathrm{BH}} = \sqrt{\hat{s}}$$

$(M_P \sim \mathrm{TeV})$

R_S: Schwarzschild radius of the BH.

$$\sigma_{\mathrm{prod}} = \pi R_S^2 \propto \hat{s}^{\frac{2}{n+1}}$$

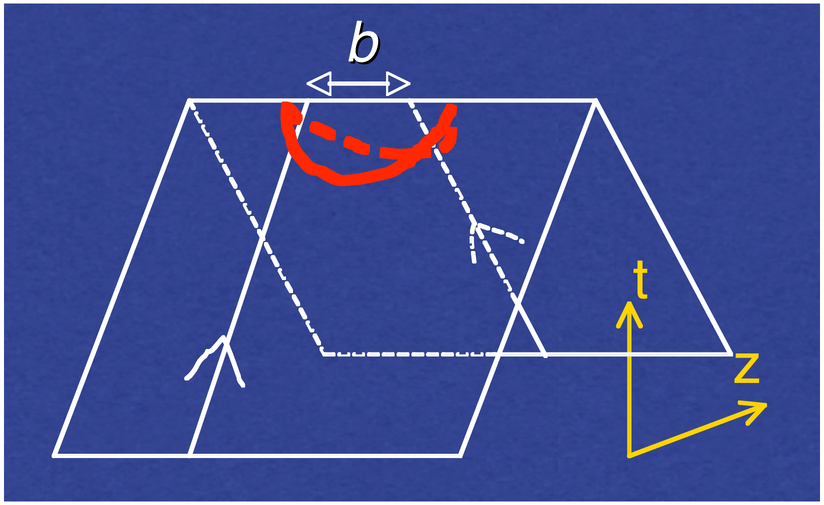
(for $R_S << L$)

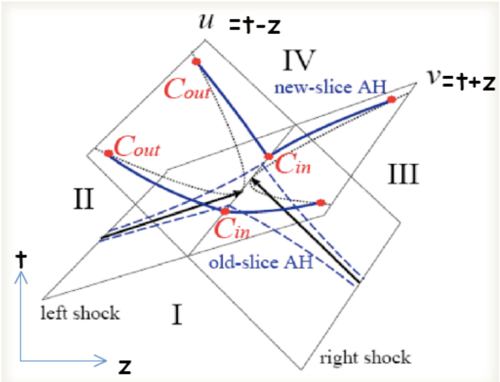
Cross section rises with energy!

BH production proven

4 D: [Eardley, Giddings, 02]
higher D: [Yoshino, Nambu, 02]

- **w/ Aichelburg-Sexl solution:**
  - Infinite boost ($v \to c$) and mass$\to$0 with fixed energy from Schwarzshild BH. Gravity of massless particle.



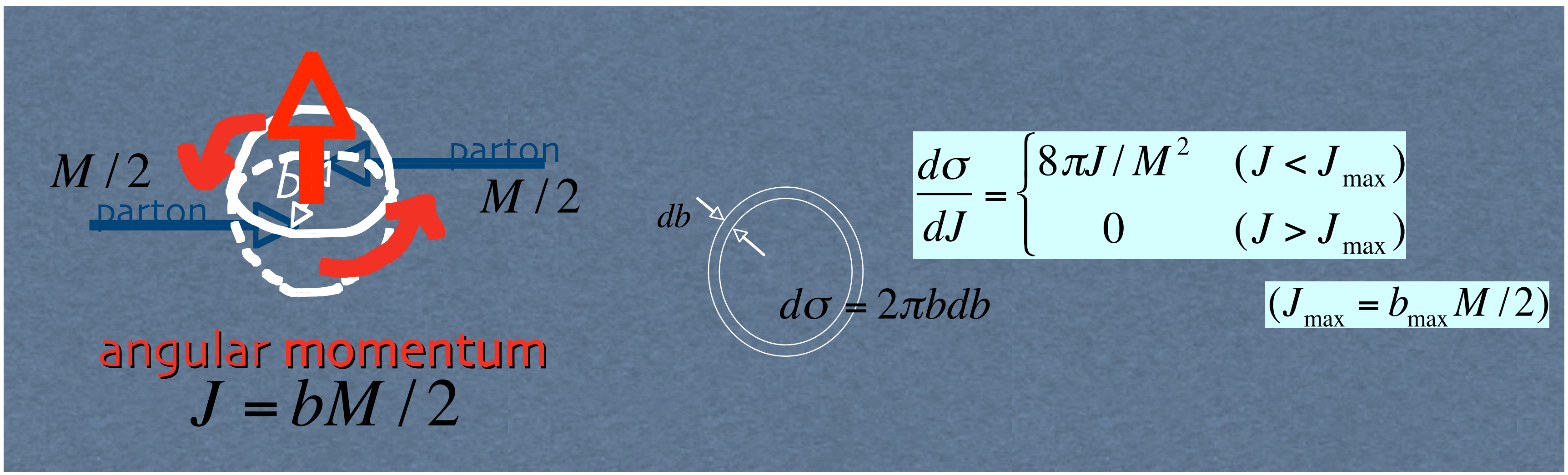


[Yoshino, Rychkov, 06]

- Trapped surface forms when $b < b_{max} \sim$(horizon radius) (with $M = s^{1/2}$) .
- Also formation from wave packets. [Giddings, Rychkov, 04]

BH produced with large J [Ida, KO, Park 02]

- impact parameter b ∝ (angular momentum J)

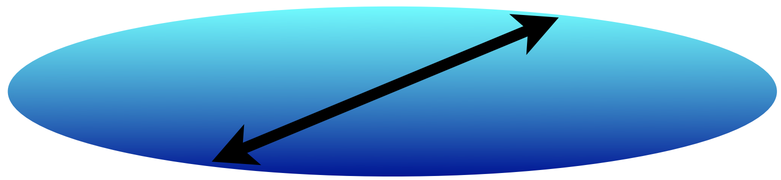


- Hoop conjecture: $\boxed{b < 2r\_h(b)}$ gives a b_{max}. → J_{max}
- "Large" means $J_{max} \sim 3 \ldots 10$ for $D = 5 \ldots 10$ at LHC
  - LHC energy is near boundary for classical treatment.

Ultra-spinning, and even black string?

- Should use **pancake radius** rather than thickness?

  [Emparan, Myers, 03]



pancake radius
$\sim a_* \, r_h$

thickness is our r_h,
used in previous slides
(ours is conservative)

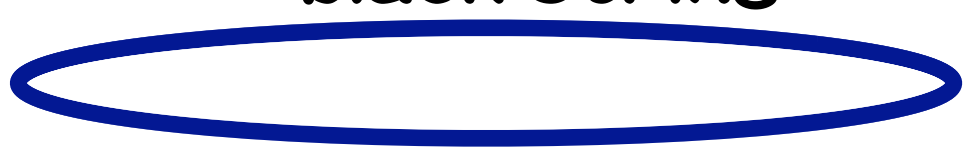
- If we use $a_* \, r_h$ instead, we have infinite cross section!

  Classicality condition: $r_h <$ (Planck length) to be used.

  [Appendix D in Matsuo, **KO**, 0808.3645v2]

- It is unstable. It might become a **black string.**

  [ibid; also Ida, **KO**, Park, 02]



decay

BH life at detector

1. **Balding Phase** (negligible?)
    - Dynamical production phase
    - BH loses its "hair".
2. **Spin Down Phase**
    - BH loses its mass and angular momentum.
3. **Schwarzschild Phase**
    - Angular momentum is small.
    - BH loses its mass.
4. **Planck Phase**
    - Truly QG, highly unpredictable
    - A few quanta would be emitted.

Temperature gets higher and higher.

We pointed out & verified importance of this phase.

[Ida, **KO**, Park 02, 06].

Decay of BH@LHC

- Through **Hawking radiation** (Computable decay rate, widths etc.)
- Radiates mainly on **brane**, into SM matter (quarks/leptons/gauge fields) [Emparan, Horowitz, Mayers 00]
- Branching ratio $\sim$#d.o.f. in SM.
- Into tens of SM particles with $E > 100$GeV in $\sim 10^{-27}$ sec. [Giddings, Thomas 02; Dimopoulos, Landsberg 02; ...]
- Decays into multi-jets, but decay products does not form quark-gluon plasma (because of large energy). [Alig, Drees, **KO**, 06]

What follows from BH production

Giddings, Thomas;
Dimopoulos, Landsberg; …

- Decay
  - Radiates mainly on brane
  - decay proportional to #(dof)
    $h : q : l : v = 4 : 72 : 18 : 24$
- Typically at LHC
  - Produced every second
  - $M \sim$ 1-10 TeV
  - $T >$ 0.1 TeV
  - Tens of multiple emissions
  - Life time ~ 10^{-27}sec

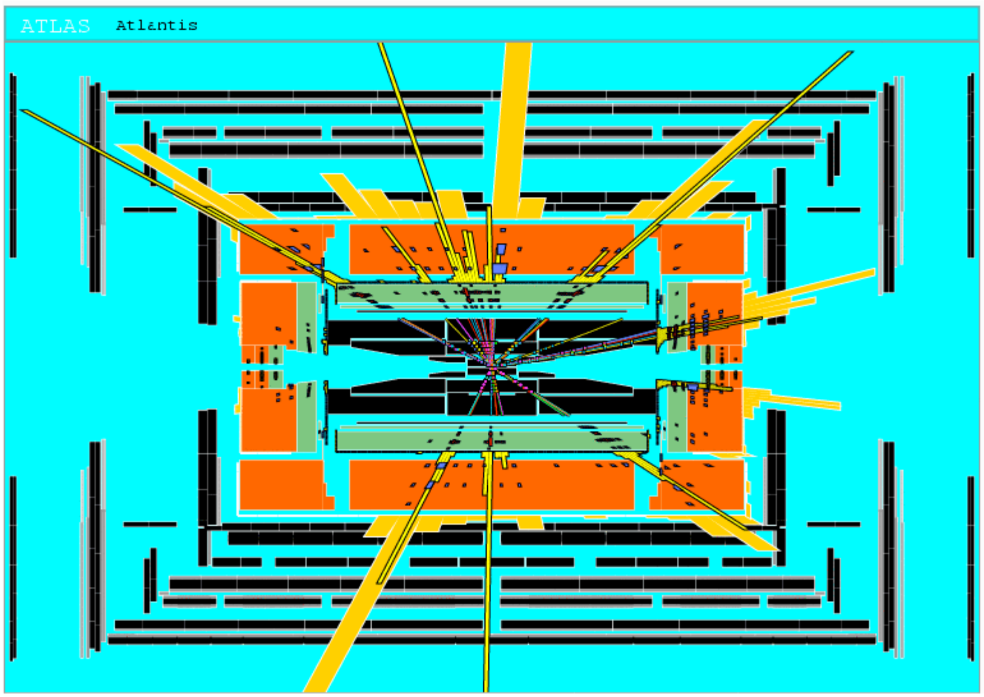
Fig in higher dim

Hawking radiation

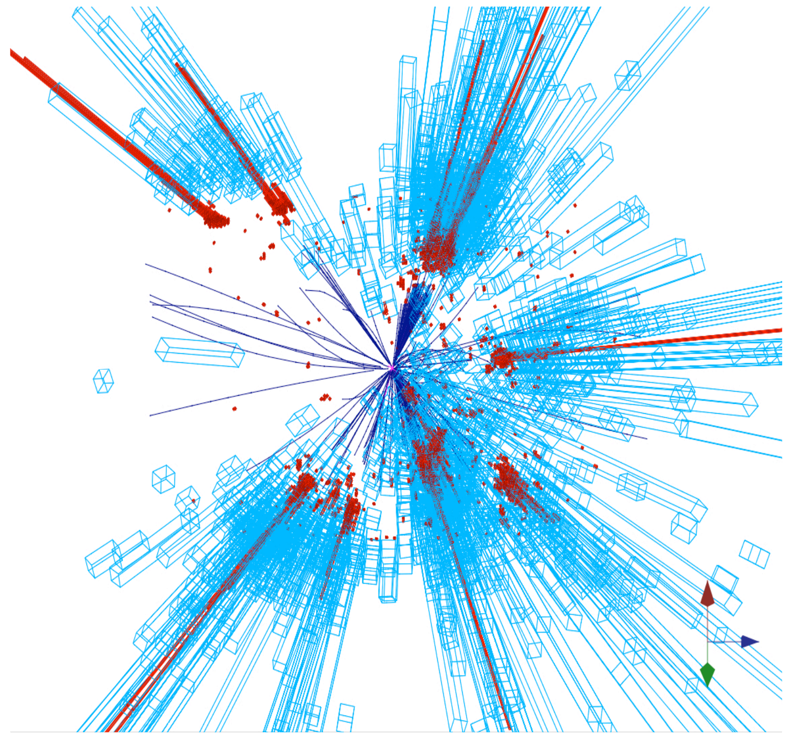
3-brane

Clean Signal!

Simulation with M_{BH} ~ 8 TeV in ATLAS



... and in CMS



from Kobayashi DPF/JPS 06

Hawking radiation from TeV BH

[Ida, **KO**, Park, 02, 05, 06;
Kanti et al., 02, 03, 05, 06, 07]

- From field equations on brane [Ida, **KO**, Park 02],
- Compute **greybody factors** (~effect of backscattering by curved spacetime itself) ,
- And we can get **power spectra** for BH decay products.
- **Time evolution** become available. [Ida, **KO**, Park 06]
- Rotating BH **event generators** being developed for LHC by several groups, e.g. BlackMax, arXiv:0902.3577.

  "It includes all of the black-hole gray-body factors known to date and incorporates the effects of black-hole rotation, splitting between the fermions, non-zero brane tension and black-hole recoil due to Hawking radiation (although not all simultaneously)."

Higher dim. Kerr metric
(just to show how it looks)

Mayers, Perry

$$ds^2 = g^{(4)}(r,\vartheta) + r^2\cos^2\vartheta\, d\Omega_n^2$$

vanishes on the brane

$$g^{(4)}(r,\vartheta) = \begin{bmatrix} -\dfrac{\Delta - a^2\sin^2\vartheta}{\Sigma} & \dfrac{(\Delta - r^2 - a^2)a\sin^2\vartheta}{\Sigma} & 0 & 0 \\ * & \dfrac{[(r^2+a^2)^2 - \Delta a^2\sin^2\vartheta]\sin^2\vartheta}{\Sigma} & 0 & 0 \\ 0 & 0 & \dfrac{\Delta}{\Sigma} & 0 \\ 0 & 0 & 0 & \Sigma \end{bmatrix}$$

$$\Sigma = r^2 + a^2\cos\vartheta$$

$$\Delta = r^2\left(1 - \frac{\mu}{r^{n+1}} + \frac{a^2}{r^2}\right)$$

Newman Penrose formalism (just to show)

Null tetrads:

$$
\begin{aligned}
n &= \partial_t - a\sin^2\vartheta\,\partial_\varphi - \frac{\Sigma}{\Delta}\partial_r,\\
n' &= \frac{\Delta}{2\Sigma}(\partial_t - a\sin^2\vartheta\,\partial_\varphi) + \frac{1}{2}\partial_r,\\
m &= \frac{i\sin\vartheta}{\sqrt{2}(r+ia\cos\vartheta)}\left[a\partial_t - (r^2+a^2)\partial_\varphi\right] - \frac{r-ia\cos\vartheta}{\sqrt{2}}\partial_\vartheta,\\
m' &= \bar{m}.
\end{aligned}
$$

$$\Sigma = r^2 + a^2\cos\vartheta$$

$$\Delta = r^2\left(1 - \frac{\mu}{r^{n+1}} + \frac{a^2}{r^2}\right)$$

Scalar: $g^{(4)\mu\nu}\nabla_\mu\partial_\nu\phi = 0$

Spinor:

$$
\begin{aligned}
D\psi_1 - \delta'\psi_0 &= (\beta'-\tau')\psi_0 + (\rho-\epsilon)\psi_1\\
\delta\psi_1 - D'\psi_0 &= (\epsilon'-\rho')\psi_0 + (\tau-\beta)\psi_1
\end{aligned}
$$

Vector:

$$
\begin{aligned}
D\phi_1 - \delta'\phi_0 &= (2\beta'-\tau')\phi_0 + 2\rho\phi_1 - \kappa\phi_2\\
D\phi_2 - \delta'\phi_1 &= \sigma'\phi_0 - 2\tau'\phi_1 + (\rho-2\epsilon)\phi_2\\
D'\phi_0 - \delta\phi_1 &= (\rho'-2\epsilon')\phi_0 - 2\tau\phi_1 + \sigma\phi_2\\
D'\phi_1 - \delta\phi_2 &= -\kappa'\phi_0 + 2\rho'\phi_1 + (2\beta-\tau)\phi_2
\end{aligned}
$$

Field equations on brane

Separation of variables

Ida, KO, Park

$$\Sigma = r^2 + a^2 \cos\vartheta$$

$$\Delta = r^2\left(1 - \frac{\mu}{r^{n+1}} + \frac{a^2}{r^2}\right)$$

Decomposition:

$$\phi, \psi_0, \phi_0 \sim \sum_{\omega,l,m} e^{-i\omega t + im\varphi} R^{\omega}_{s,l,m}(r) S^{\omega}_{s,l,m}(\vartheta)$$

angular part:

$$\frac{1}{\sin\vartheta}\frac{d}{d\vartheta}\left(\sin\vartheta\frac{dS_s(\vartheta)}{d\vartheta}\right) + \left[(s - \omega a\cos\vartheta)^2 - (s\cot\vartheta + m\csc\vartheta)^2 - \omega a(\omega a - 2m) - |s|(|s|+1) + \lambda_{|s|}\right] S_s(\vartheta) = 0,$$

radial part:

$$\Delta^{-|s|}\frac{d}{dr}\left(\Delta^{1+|s|}\frac{dR_s(r)}{dr}\right) + \left[\frac{K^2 - isK\Delta_{,r}}{\Delta} + 2isK_{,r} + |s|\Delta_{,rr} - \lambda_{|s|}\right] R_s(r) = 0.$$

$$K = (r^2 + a^2)\omega - ma$$

Greybody factor determines Hawking radiation and BH evolution

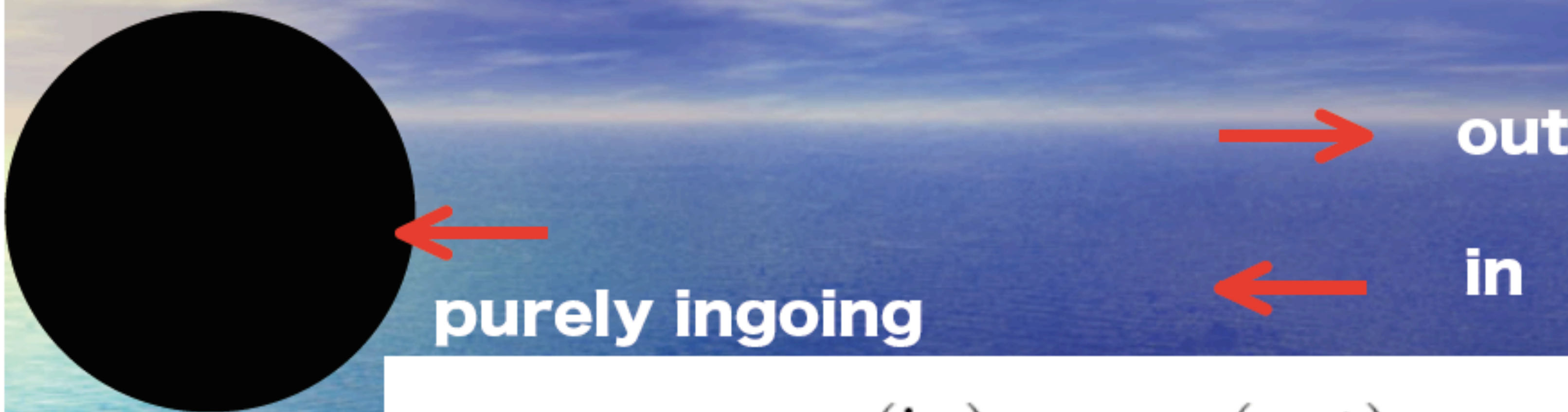
BH radiates mainly into the brane (SM) fields via Hawking radiation.

$$\frac{dN_{s,l,m}}{dt\, d\omega\, d\Omega} = \frac{1}{2\pi} \frac{\Gamma_{s,l,m}(\omega)}{e^{(\omega - m\Omega_{\mathrm{BH}})/T} \mp 1} \left| S_{s,l,m}(\omega,\Omega) \right|^2$$

Greybody factors for Brane fields determine the evolution of BH mass and angular momentum (up to Planck phase).

$$-\frac{d}{dt}\begin{pmatrix} M \\ J \end{pmatrix} = \frac{1}{2\pi} \sum_{s,l,m} g_s \int d\omega \frac{\Gamma_{s,l,m}}{e^{(\omega - m\Omega_{\mathrm{BH}})/T} \mp 1} \begin{pmatrix} \omega \\ m \end{pmatrix}$$

greybody factor



$$\Gamma_{lm} = \frac{\dot{N}^{(\mathrm{in})}_{lm} - \dot{N}^{(\mathrm{out})}_{lm}}{\dot{N}^{(\mathrm{in})}_{lm}}$$

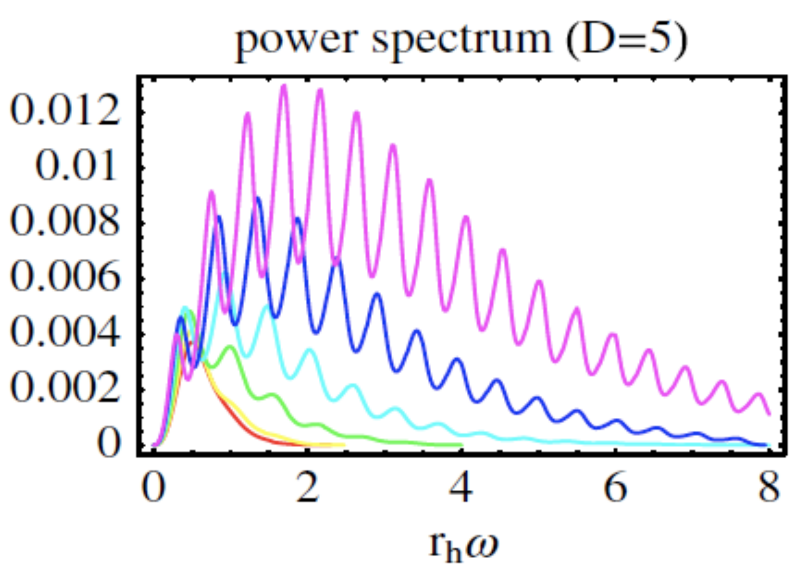
absorption rate
= penetration rate of grav. pot. well
in a "time-reversed" sense

Radiation of quarks and leptons

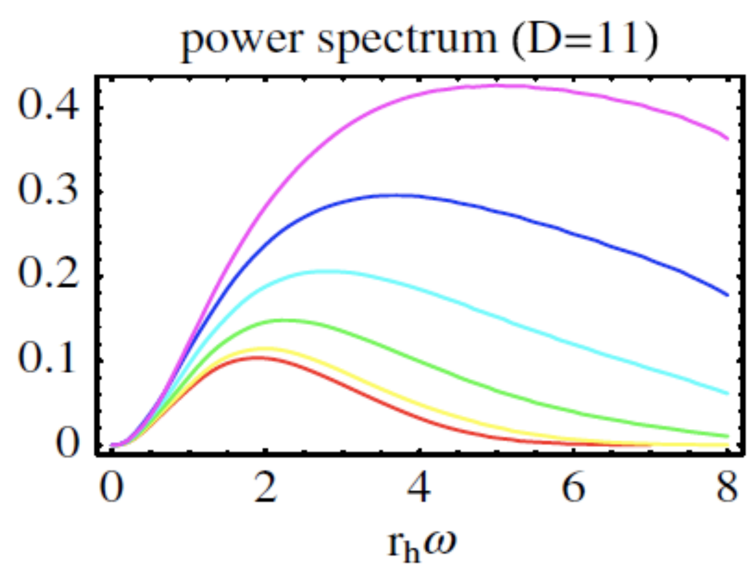
(Ida, **KO**, Park 06)

Can also **distinguish** RS/ADD!

Randall-Sundrum BH



ADD BH



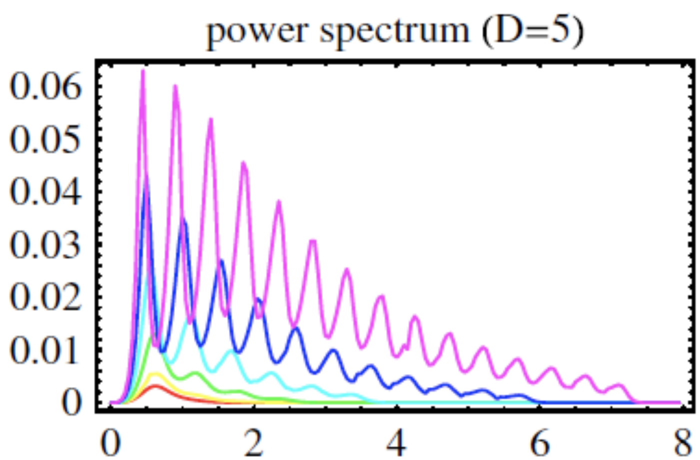
non-rotating to highly rotating

$a_* = 0, 0.3, \ldots, 1.5$ from lower left to upper right.

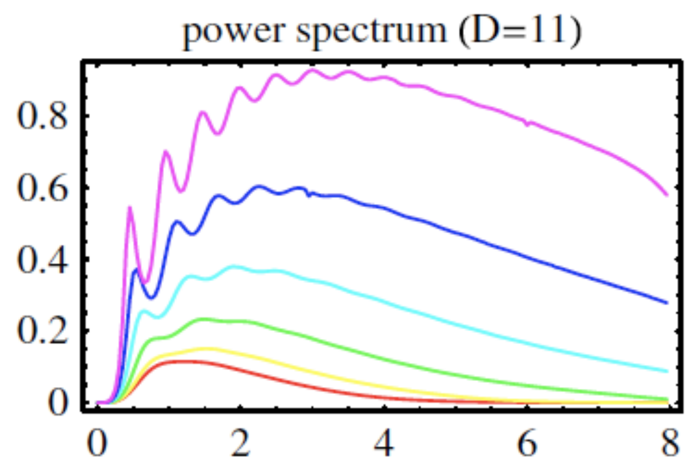
Radiation of gauge fields

(Ida, **KO**, Park, 06)

Radalll-Sundrum BH



ADD BH



non-rotating to highly rotating

$a_* = 0, 0.3, \ldots, 1.5$ from lower left to upper right.

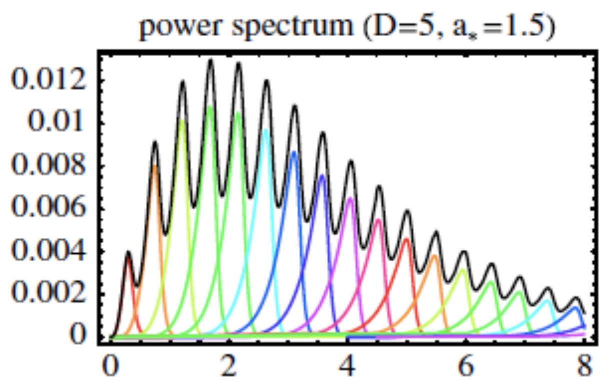
Each angular modes

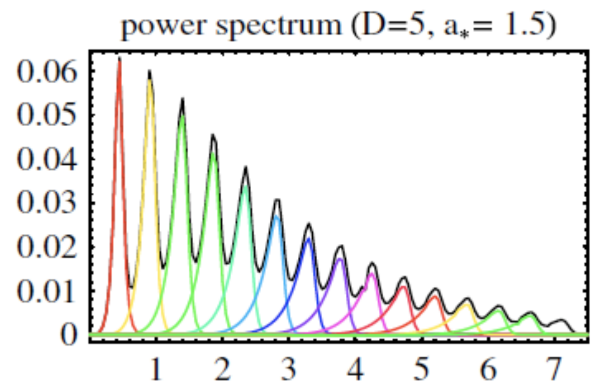
(Ida, **KO**, Park 06)

All highly-rotating example

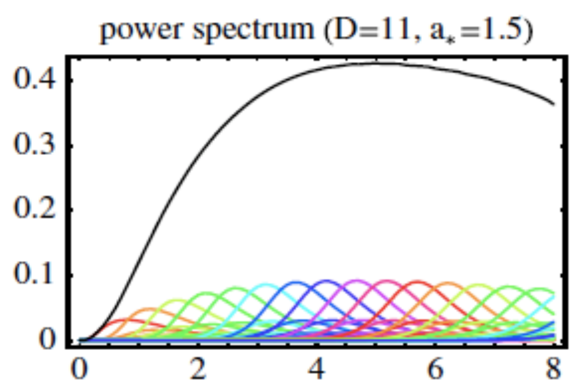
quark/lepton | gauge field

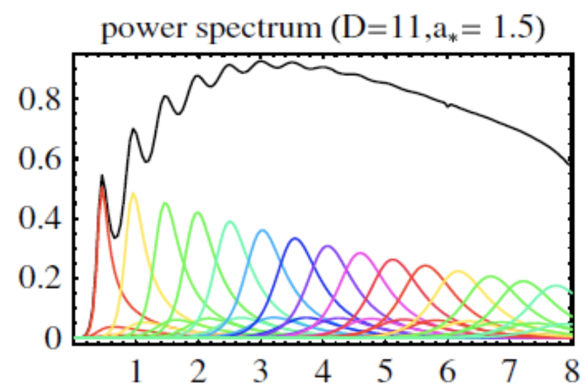
RS





ADD





Angular dependence

[Figs from Casals, Doran, Kanti 06]

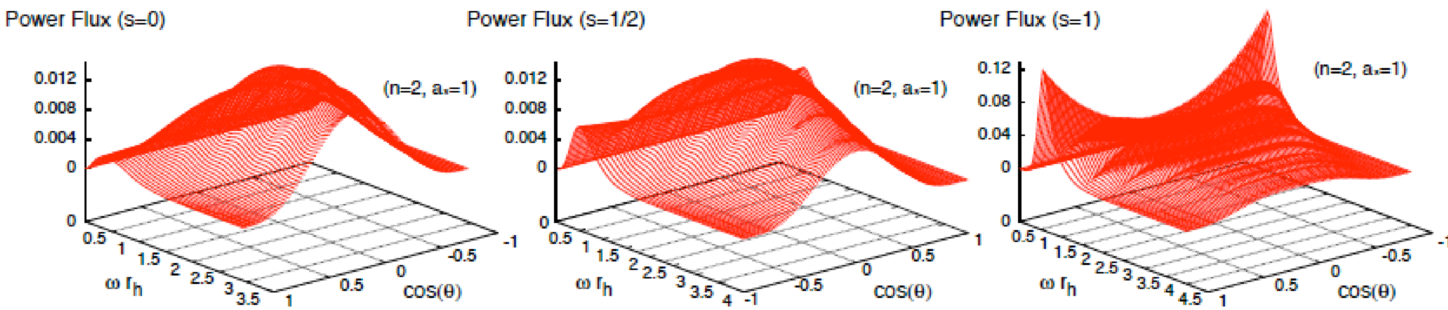
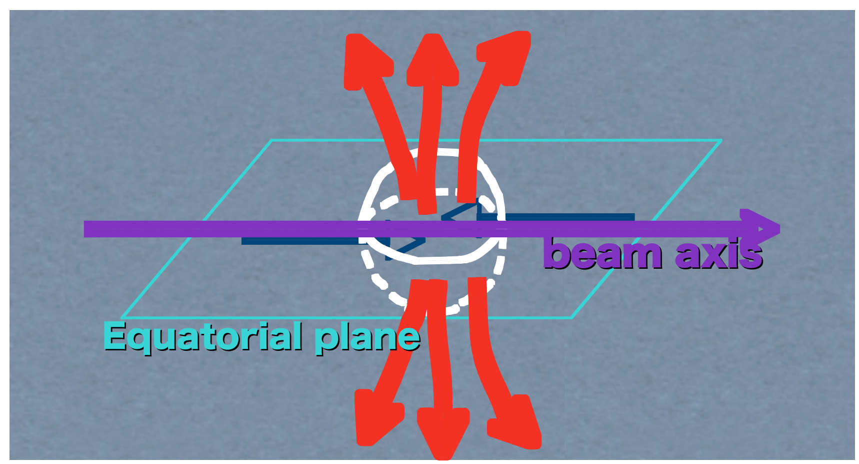


Figure 16: Angular distribution of the power spectra for (a) scalars, (b) fermions, and (c) gauge bosons on the brane from a 6-dimensional black hole with $a_* = 1$.

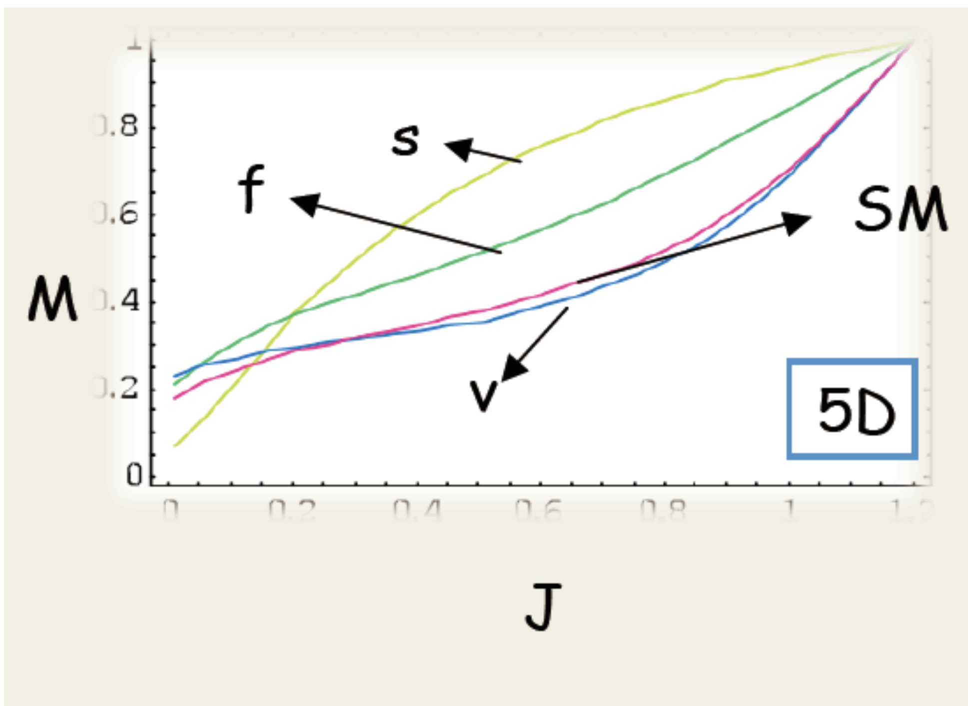
Gauge fields emitted along polar direction perpendicular to beam axis[Ida, **KO**, Park 02, Casals, Doran, Kanti 06]



BH time evolution

[Ida, **KO**, Park 06]

- Highly rotating BH mainly decays into **gauge fields** (v)
- **Spin-down phase** is indeed **important** as we have claimed in [Ida, **KO**, Park 02].



More than half of total mass is radiated during spin-down phase

Summary

- BH physics is a **passport to quantum gravity**.
  →Inverted energy-length relation.

- Planck scale can be around **TeV**.

- **BH production** dominates over everything.
  →huge production cross section

- TeV BH decays into multiple SM particles via Hawking radiation.→Clean signal.

- We can see **quantum gravity effects** as deviation from BH picture, **experimentally**.