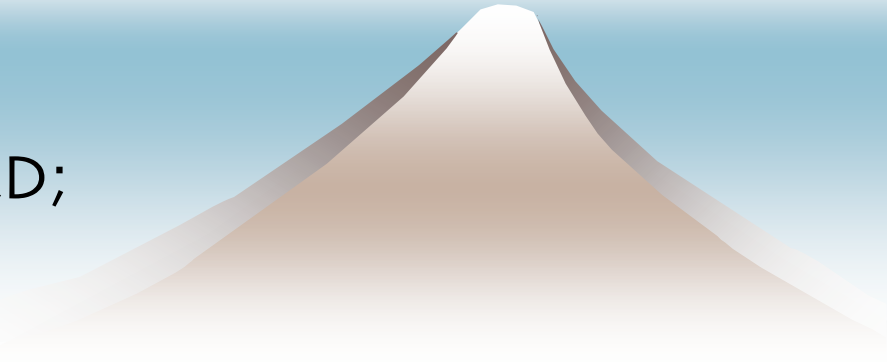
BH production and evaporation at Collider

Kin-ya Oda (Bonn)

based on work with **Daisuke Ida** (Gakushuin)
and **Seong Chan Park** (Cornell)

PRD67 (2003) 064025;
hep-th/0503052, to appear in PRD;
hep-?h/0506???; …

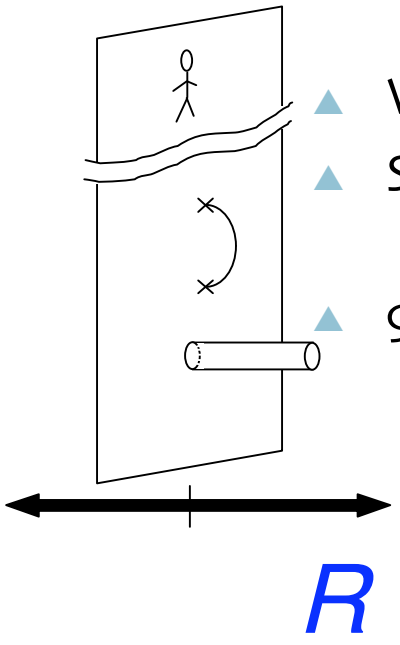


Outline

1. **Planck scale** can be as low as **TeV**
2. **TeV gravity** inevitably leads to **BH production**
3. **Precise determination** of BH event provides hints for (yet unformulated) **quantum gravity / string theory**
4. Summary & Outlook

Planck scale can be as low as TeV

Arkani-Hamed, Dimopoulos, Dvali '98



- We are living in 3-brane in (4+n)-dim bulk.
- SM fields = trapped on the brane;
  massless modes of open strings
- gravitons = may propagate in bulk;
  massless modes of closed strings

- (4+n)-dim Planck scale
- 4-dim Planck scale
- compactification radius

'Gauss law' $\rightarrow$ $M_P^{2+n} = M_4^{\,2}\, R^{-n}$

free! $\leftarrow$ exp free

Fundamental gravitational scale can be as low as M_P=TeV!

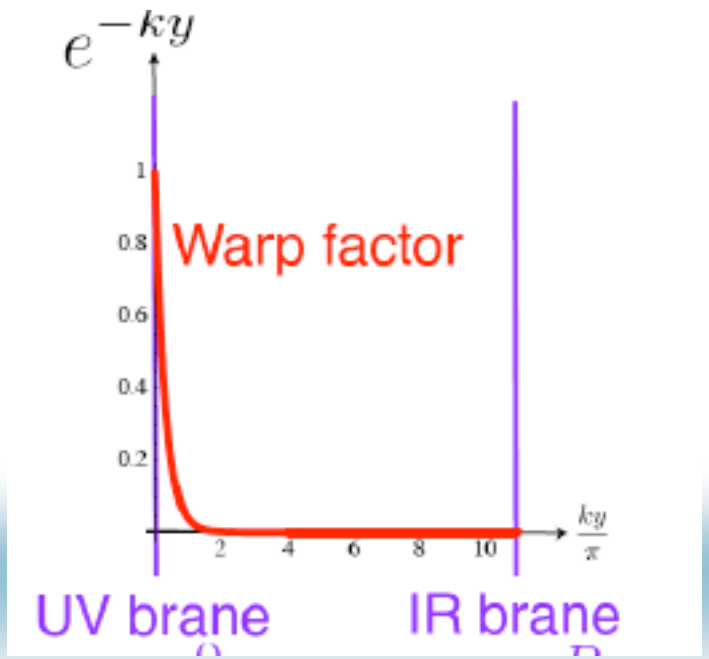
Alternative: Warped comp'n

Randall-Sundrum '99

Metric

$$e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

(k: [AdS radius]$^{-1} \lesssim M_{\text{Planck}}$)



- M_{UV} will be observed as:

$$m_{IR} = e^{-k\pi R} M_{UV},$$

by an observer at IR brane.

- If $kR \simeq 11$, large hierarchy generated

$$a \equiv e^{-k\pi R} \simeq 10^{-15}.$$

Is TeV gravity "natural"?

- Answer 1: "Don't think. Feel." Yoda in STARWARS
  - Naturalness argument thrives when theory is desperately untestable.
  - Why bothered by metaphysical question when LHC is coming **next-to-next year**?

Is TeV gravity "natural"?

- Answer 2: "Yes, it's as natural as $M_P \sim 10^{18}$GeV."
  - ADD: We need a little hierarchy $R \sim 10^3\ M_P^{-1}$.
    So what? Anyway, R is a modulus to be fixed dynamically. When lifting up flat direction, it's all common to have a huge shift.

    Note: Comp'n radius R is **flat direction** in the moduli space of (perturbative) string vacua and totally free parameter in (perturbative) string theory.
  - RS: Warped comp'n, "throat", is now everywhere in string theory.

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TeV gravity **inevitably** leads to **BH production**

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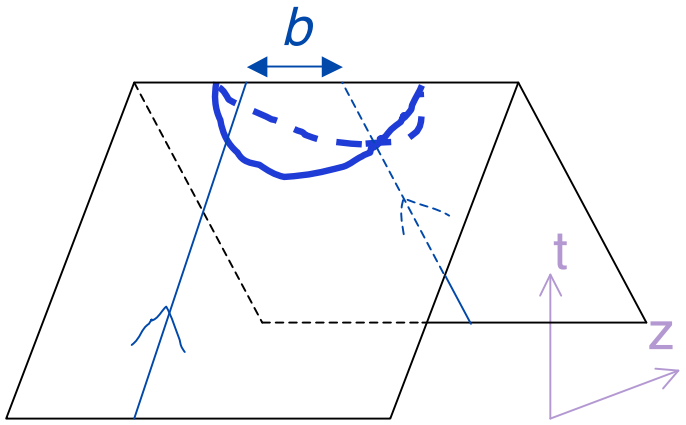
Classical production



Closed trapped surface forms when $b < b_{max}$.

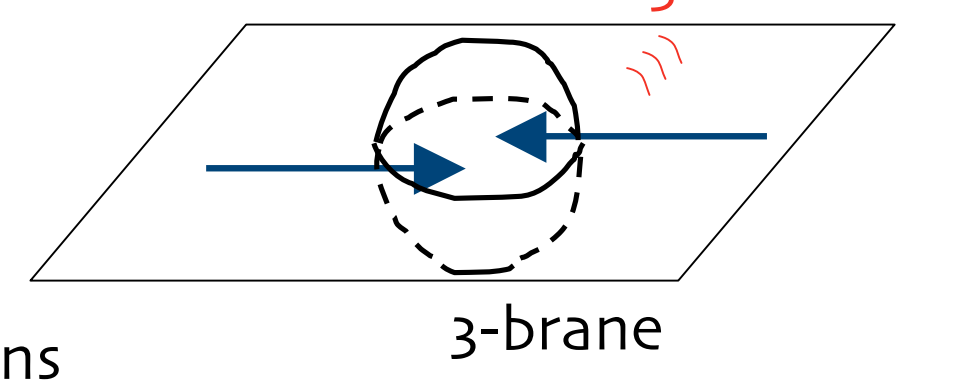
- Classical cross section **grows** with energy: BH production **dominates** over all other interactions above TeV.
- String theory predicts that **string picture** will be altered by **BH picture** (correspondence principle)
- "The end of short distance physics"

What follows from BH production

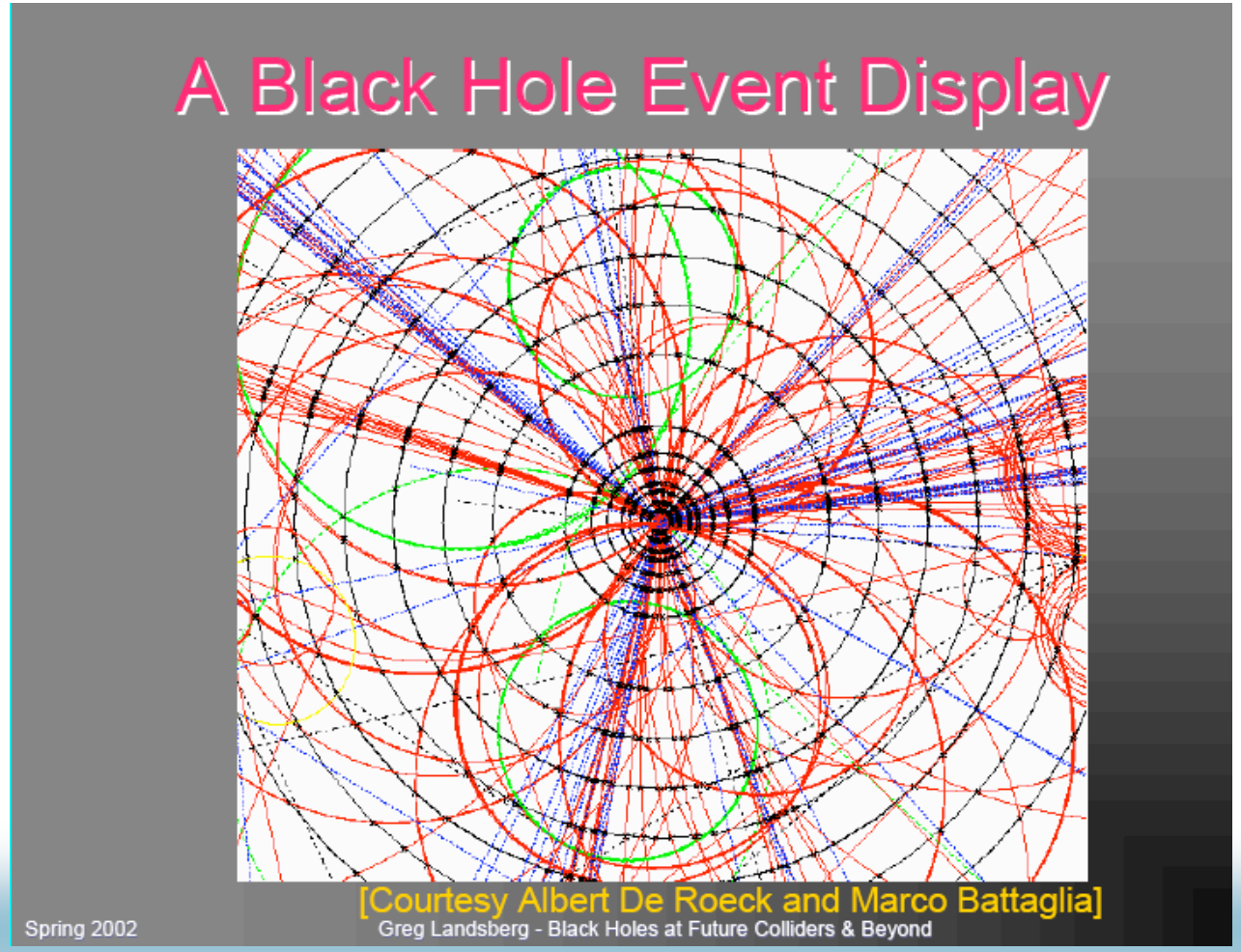
Giddings, Thomas;
Dimopoulos, Landsberg; …

- Decay
  - Radiates mainly on brane
  - decay proportional to #(dof)
    $h : q : l : v = 4 : 72 : 18 : 12$
- At LHC
  - Produced every second
  - M ~ 10 TeV
  - T ~ 0.3 TeV
  - Tens of multiple emissions
  - Life time ~ 10^{-27}sec

Fig in higher dim

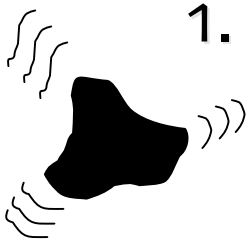


Typical BH event at LHC

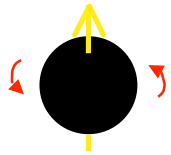


from
G. Landsberg

BH life in detector



1. Balding Phase (likely to be negligible)
   - Dynamical production phase
   - BH loses its "hair".



2. Spin Down Phase
   - BH loses its mass and angular momentum.

3. Schwartzschild 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.

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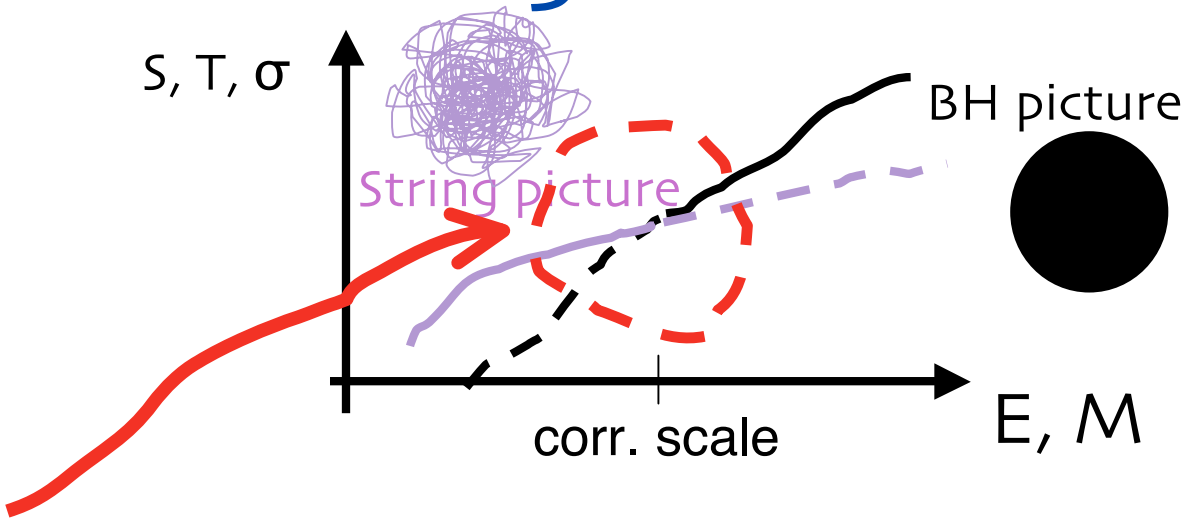
What can we do with BH events?

- Test higher dimensional general relativity,
- Explore the **geometry** of extra dimensions (if we get enough budget),
- Get hints for **quantum gravity**, e.g., through string/BH correspondence. KO, Okada, PRD66 (2002)

Want to make prediction in BH picture as precisely as possible!!

Correspondence between string and BH



There is no complete description at this non-perturbative region.

Truly QG effects will be observed as the **deviation** from the asymptotic behavior (in BH picture).

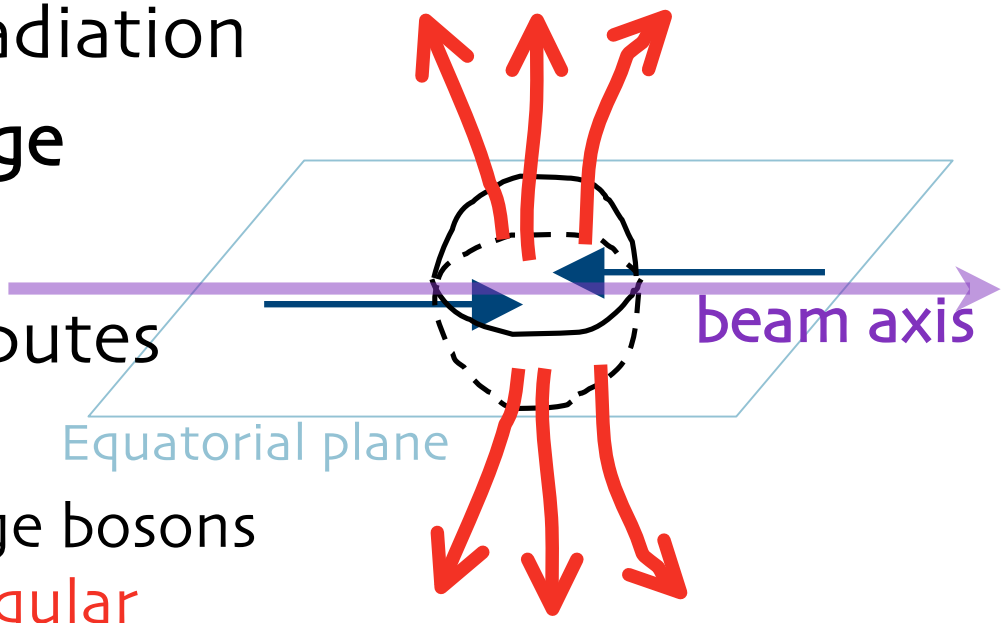
It is **essential** to predict BH behavior **as precisely as possible!**

What we found

Ida, KO, Park

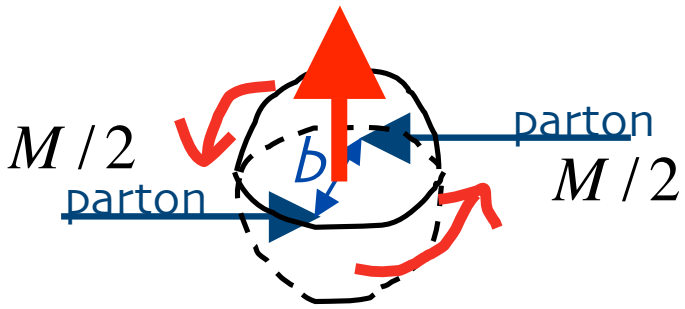
- Obtained **brane field equations** essential for Hawking radiation
- BH is produced with **large angular momentum.**
- **Spin down phase** contributes **a lot.**
  - Quarks, leptons and gauge bosons are emitted **along** the angular momentum axis **perpendicular** to beam axis. "polar emission"
- (**Black ring** might form)

(Fig now in 3 dim)



BH is produced with large angular momentum

Ida, KO, Park



Angular momentum

$$J = bM/2$$

$$\sigma = \pi b_{\max}^2 = (1.1 \sim 1.9)\pi r_S^2$$

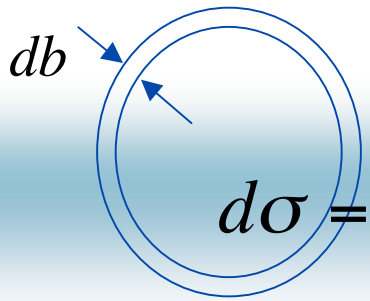
- Fits numerical results nicely:

Yoshino et.al.

  - Increased from r_S-disc
  - becomes larger for higher dim

- **Cross section increases with angular momentum!!**

$$\frac{d\sigma}{dJ} = \begin{cases} 8\pi J/M^2 & (J < J_{\max}) \\ 0 & (J > J_{\max}) \end{cases}$$

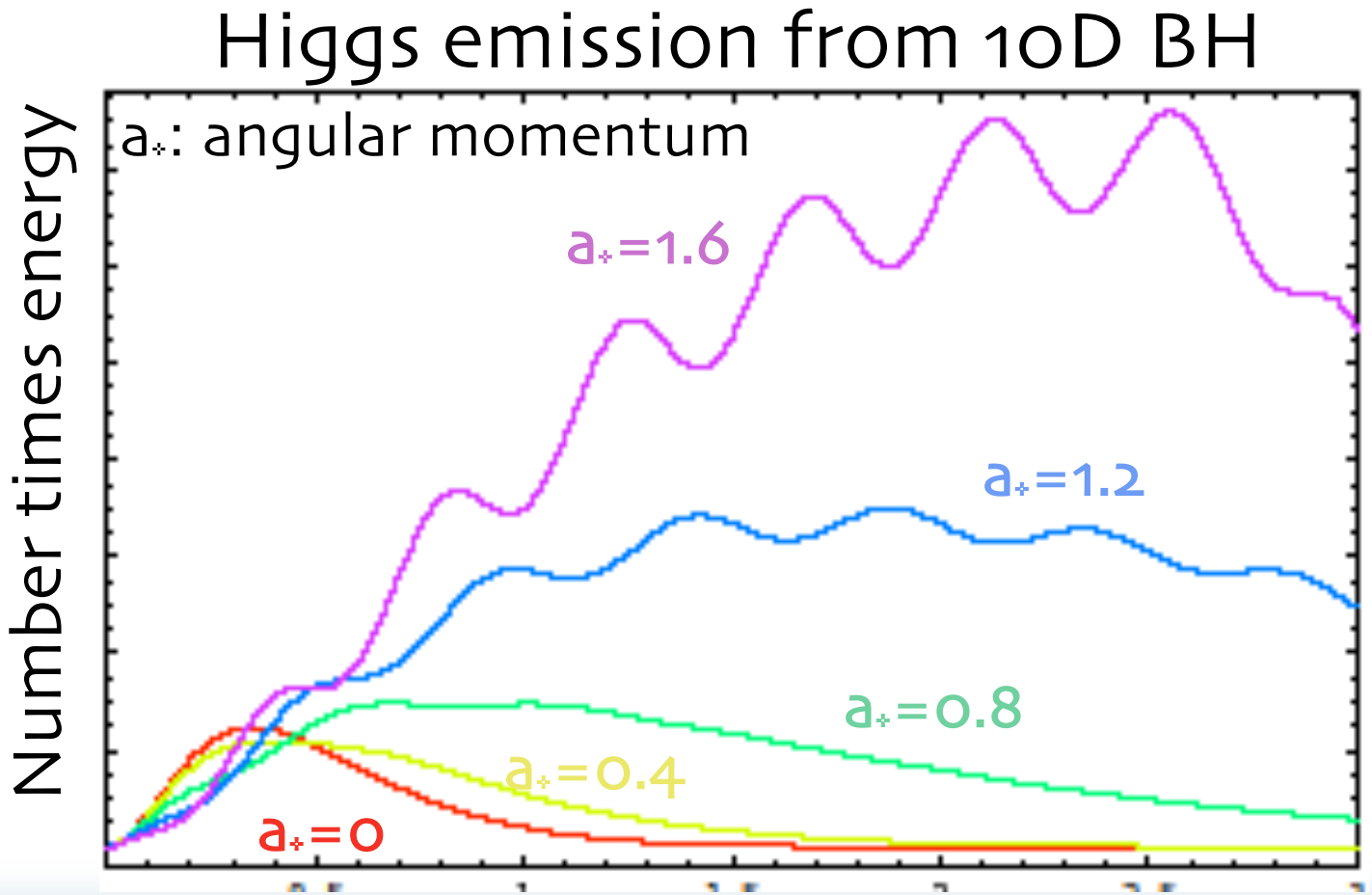


$$d\sigma = 2\pi b db$$

$$(J_{\max} = b_{\max} M/2)$$

Hawking radiation

Ida, KO, Park

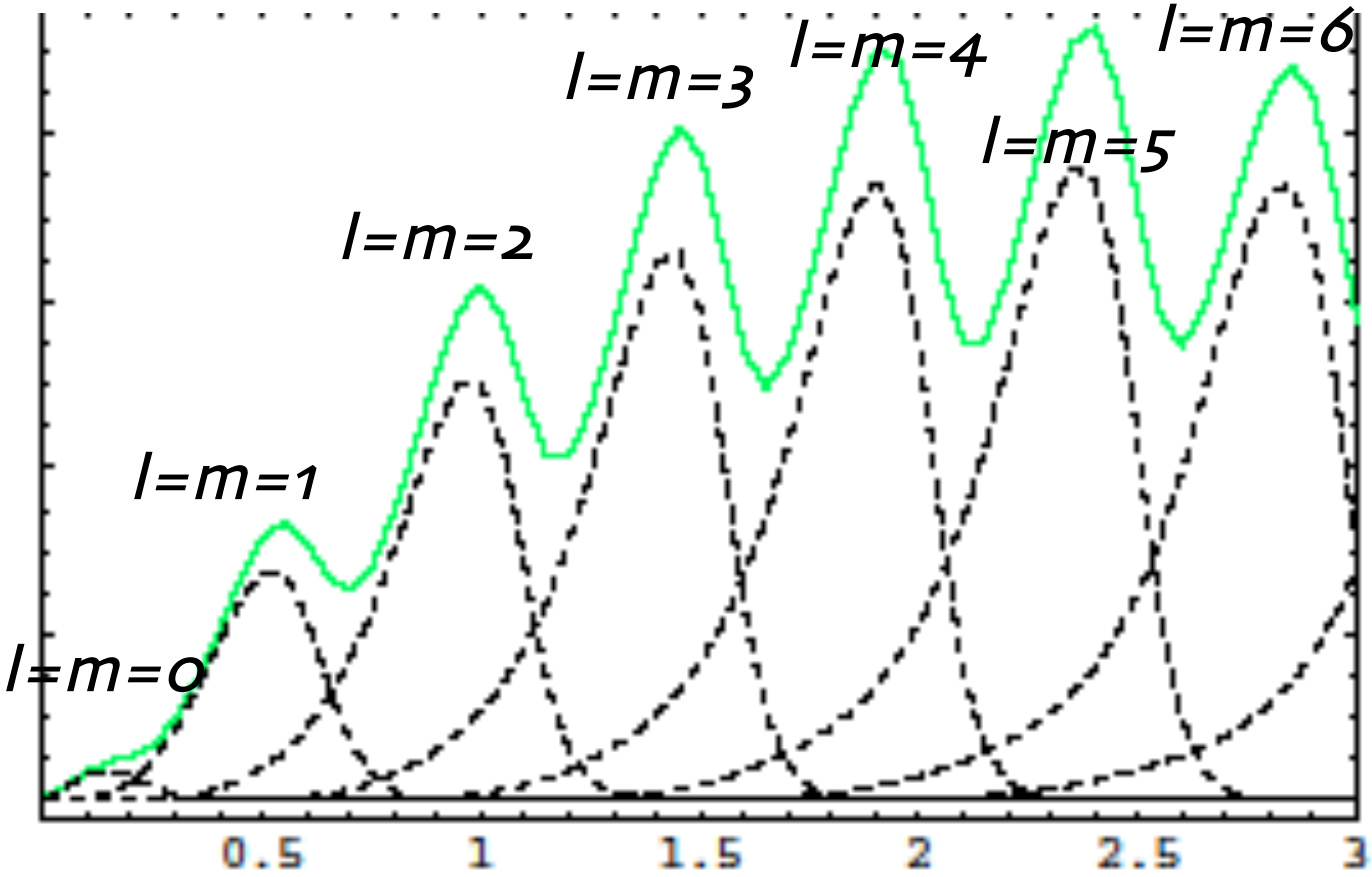


Angular momentum **is** important!!!

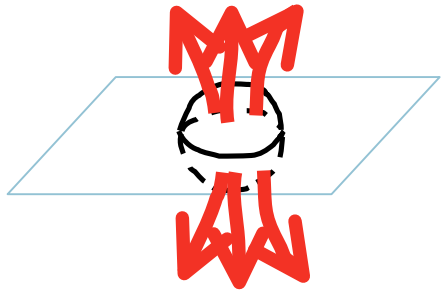
Superradiant emission

Ida, KO, Park

Higgs emission from 5D BH



Note: $l=m$ modes give

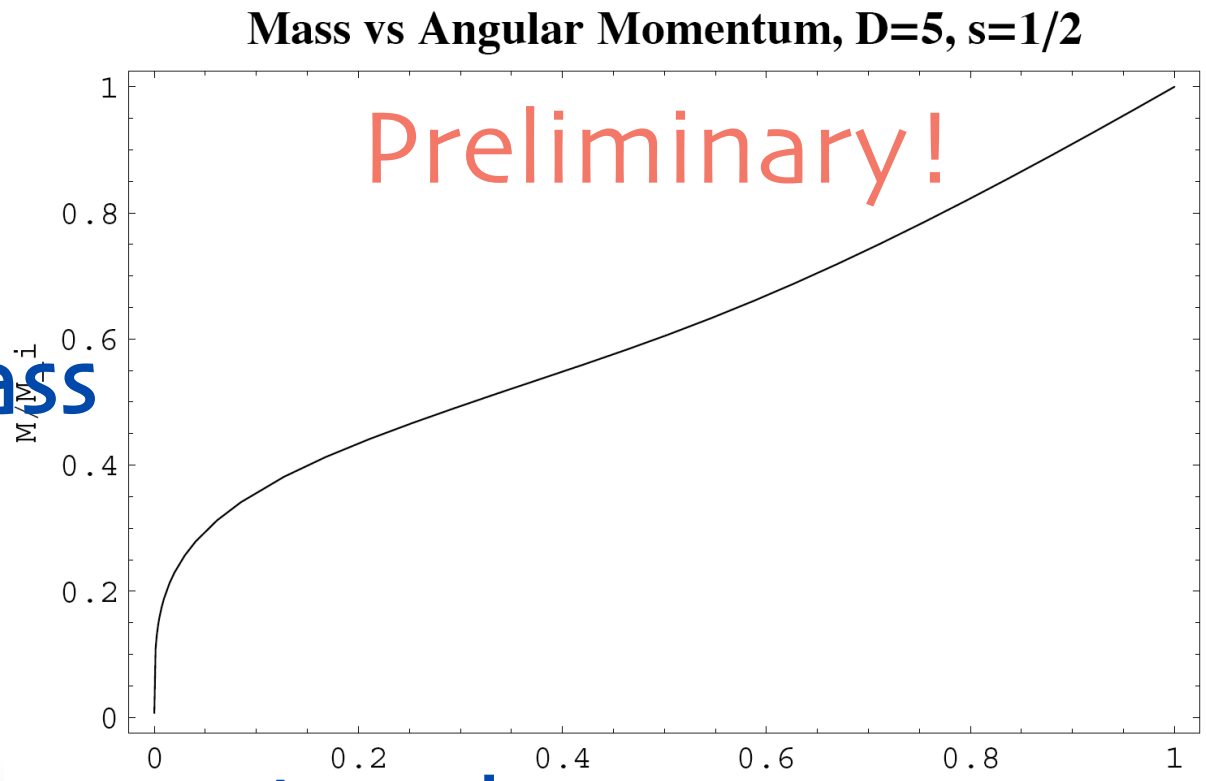


polar emission for quark, lepton, and gauge bosons

Integrating and summing up all these modes… -> Next slide

Spin-down phase is sizable

Ida, KO, Park



Mass

Angular momentum

~**half** of total energy is radiated during spin-down phase

Summary & Outlook

- Planck scale can be as low as TeV.
- TeV gravity inevitably leads to **BH production**.
- Precise determination of BH event important
  - BH is produced with **large angular momentum**.
  - Hawking radiation is highly anisotropic: **polar emission** for quarks, leptons and gauge bosons.
- (Black ring might form.)
- Numerical results for quarks, leptons and gauge bosons are coming soon. (Preliminary result shown here.)
- Can complete time evolution up to **Planck phase**.
- Comparison with this prediction will guide the way to **quantum gravity**, or yet unknown non-perturbative formulation of string theory.