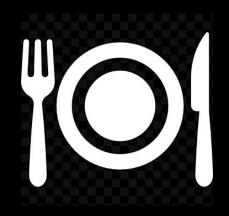


19–20 Dec 2022 ISCTE - University Institute of Lisbon

# Virial identities in relativistic gravity

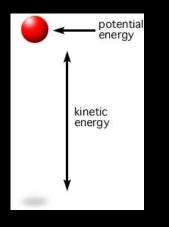
Alexandre M. Pombo

# Introduction



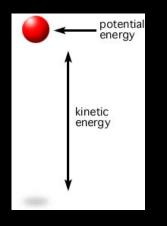
#### **Introduction:** Virial Theorem

- The virial theorem relates the **average** kinetic and potential energy
- It allows the average kinetic energy to be calculated even for very complicated systems
- The theorem has found applications in several areas



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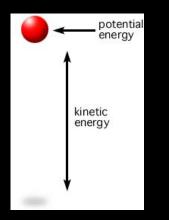
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#### **Introduction:** Virial Theorem

- The virial theorem relates the average kinetic and potential energy
- It allows the average kinetic energy to be calculated even for very complicated systems
- The theorem has found applications in several areas







- Integral identities that are virial-like
- In field theory rather than particle mechanics
- It is obtained from scaling arguments
- Computed independently from the equations of motion
- Applicable to stationary spacetimes
- We present an approach for curved spacetimes

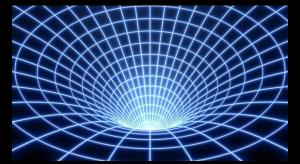
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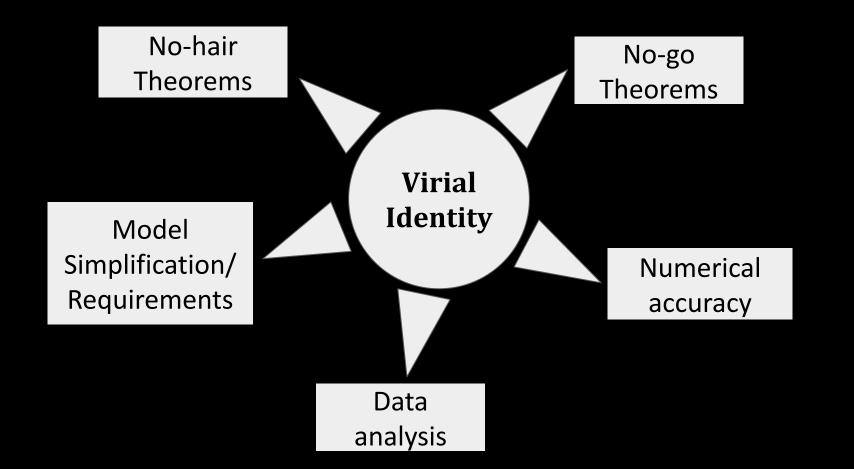
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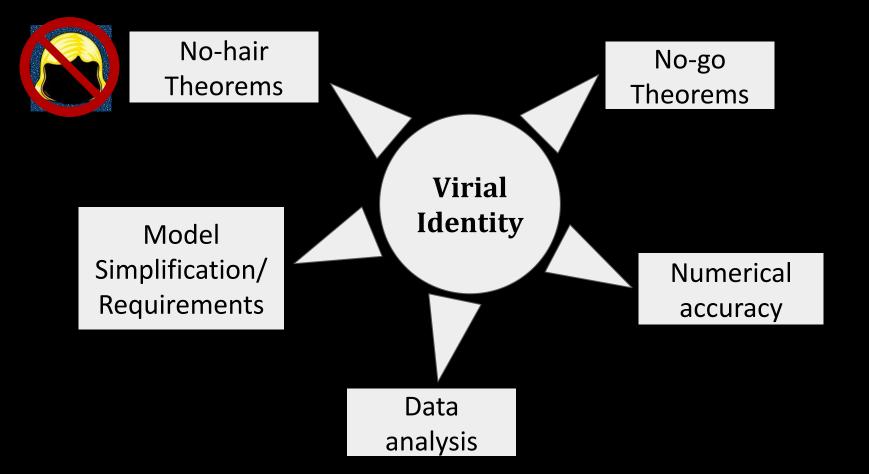
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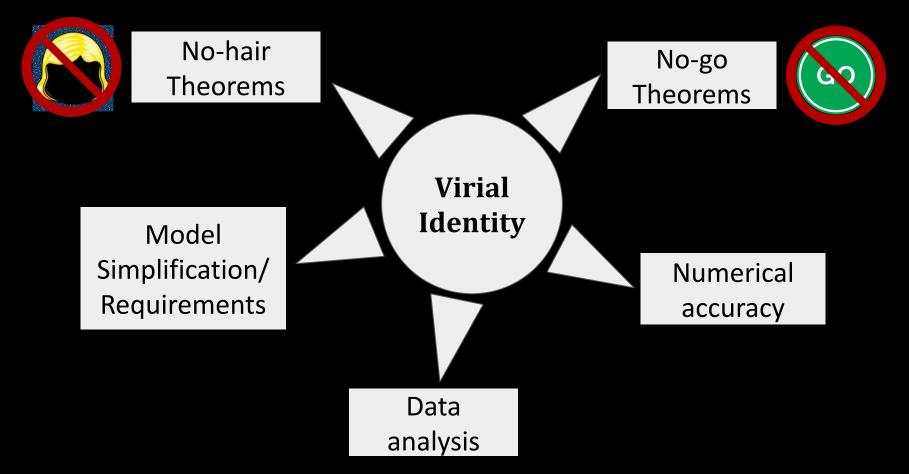
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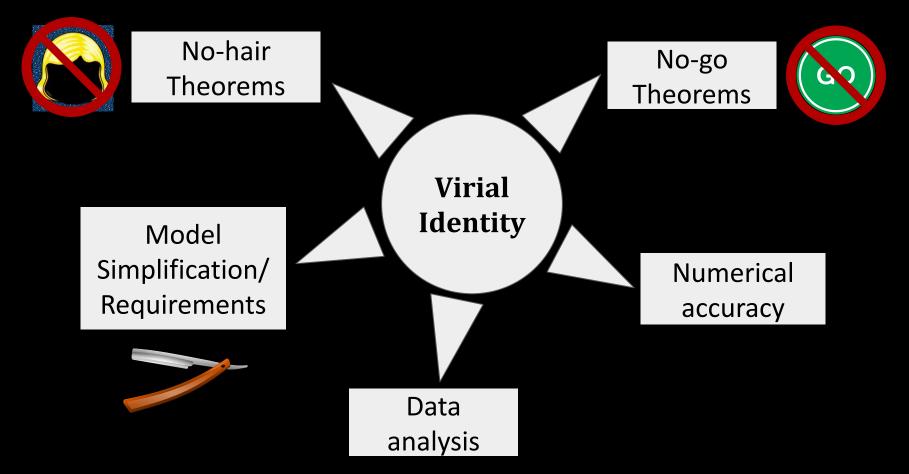


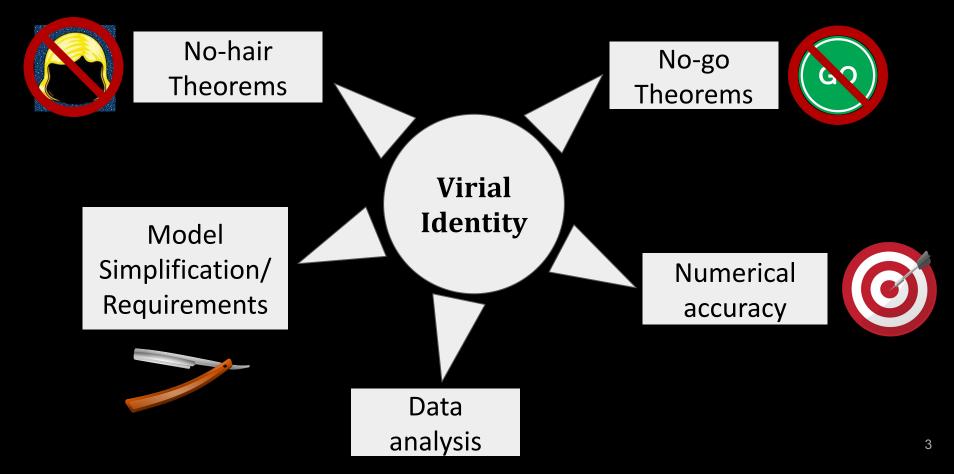


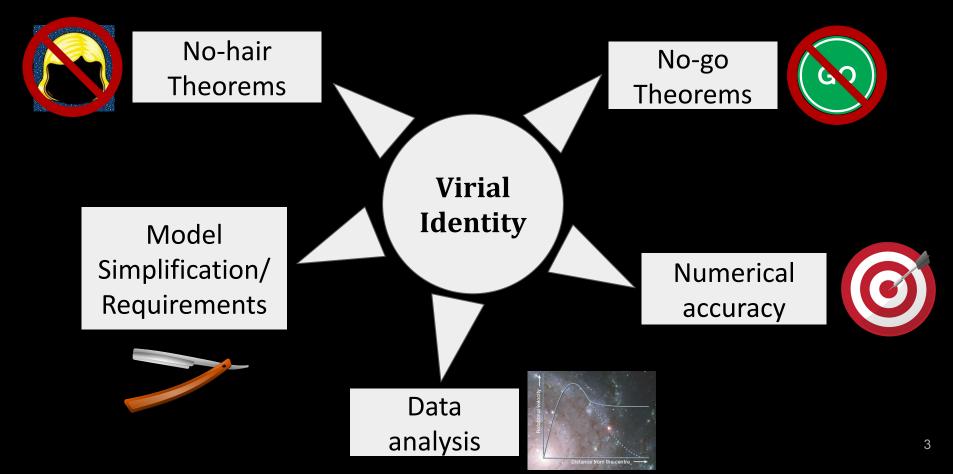
















Recipe

# Ingredients:

- Action *S*
- Metric ansatz  $g_{\mu\nu}$
- Matter ansatz
- Gibbons-Hawking-York term (gravity)



Recipe

# Ingredients:

- Action *S*
- Metric ansatz  $g_{\mu\nu}$
- Matter ansatz
- Gibbons-Hawking-York term (gravity)

# Material:

- Derrick's scaling argument
- Hamilton's principle
- Love and patience

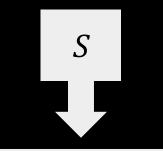


### Step-by-step:

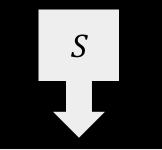
## Model



### Model

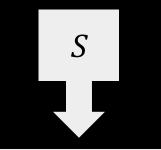


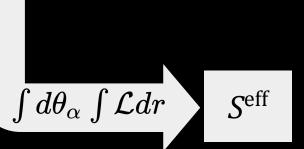
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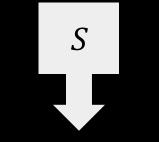


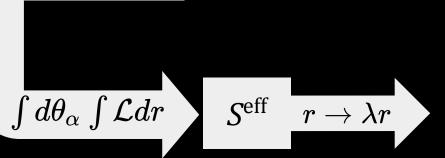


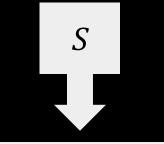
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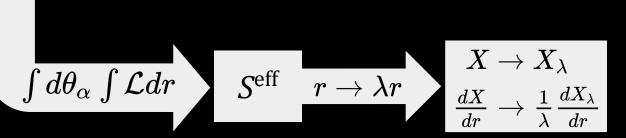


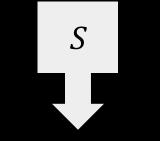


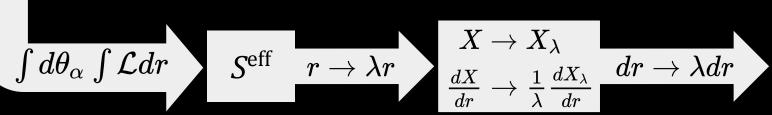


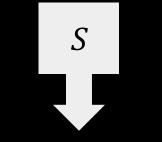


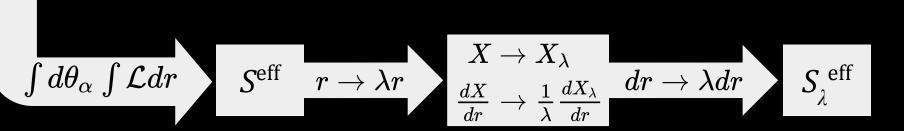




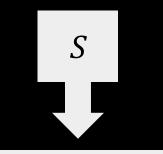








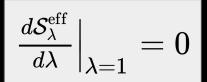
Model



#### metric/matter ansatz X

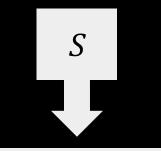
## Scaling





$$\int d heta_lpha \int \mathcal{L} dr \hspace{0.5cm} S^{ ext{eff}} \hspace{0.5cm} r o \lambda r \hspace{0.5cm} \sum egin{array}{c} X o X_\lambda \ rac{dX}{dr} o rac{1}{\lambda} rac{dX_\lambda}{dr} \ rac{dX o \lambda dr \ eta 
angle S_\lambda^{ ext{ eff}} \end{array}$$

Model

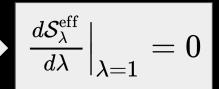


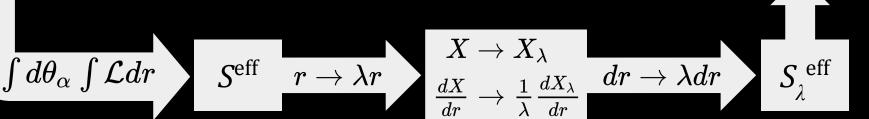
metric/matter ansatz X



Virial

Hamilton's principle





Preparation

#### Derrick's argument

• The action of a real scalar field

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$${\cal S}^{\Phi}=\int d^4x \Big[-\Phi_{,\mu}\Phi^{,\mu}-U\Big]$$

#### Derrick's argument

 $S_0$ 

The action of a real scalar field 

u

 $\boldsymbol{x}$ 

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$$egin{aligned} \mathcal{S}^{\Phi} &= \int d^4x \Big[ - \Phi_{,\mu} \Phi^{,\mu} - U \Big] \ &\equiv \int d^3x \ \dot{\Phi}^2 \ , \qquad S_1 \equiv \int d^3x (
abla \Phi)^2 \ , \qquad S_2 \equiv \int d^3x \, d^3x \,$$

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)

,

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abla \Phi)^2 \;, \qquad S_2 \equiv \int d^3x U \end{aligned}$$

• The scaled configuration

$$r
ightarrow ilde{r}=\lambda r$$

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$$r 
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$$\Phi_\lambda({f r})=\Phi(\lambda{f r})$$

• The scaled configuration

$$r o ilde{r} = \lambda r 
onumber \ \Phi_\lambda({f r}) = \Phi(\lambda {f r}) \qquad \Phi_\lambda' = rac{\Phi'}{\lambda}$$

'n

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$$egin{aligned} &r o ilde{r}&=\lambda r\ &\Phi_\lambda(\mathbf{r})=\Phi(\lambda\mathbf{r}) &\Phi_\lambda'=rac{\Phi'}{\lambda} &dr o\lambda dr\ &\left(rac{d\mathcal{S}_\lambda}{d\lambda}
ight)\Big|_{\lambda=1}=0 \end{aligned}$$

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abla\Phi)^2=-3\int d^3x\;U \end{aligned}$$

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# Plating Axial Symmetry

arXiv:2206.02813

$${\cal S}^{\Phi} = \int d^4 x \sqrt{-g} \Big[ - rac{1}{2} g^{\mu
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) \Big]$$

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$$\Phi=\phi(r, heta)e^{-i\omega t+imarphi}$$

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u} 
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onumber \ \Phi=\sigma^{\mu}(r, heta)e^{-$$

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$$S^{\Phi} = \int d^{4}x \sqrt{-g} \Big[ -\frac{1}{2} g^{\mu\nu} \left( \Phi_{,\mu} \Phi_{,\nu}^{*} + \Phi_{,\mu}^{*} \Phi_{,\nu} \right) - U(|\Phi|) \Big]$$

$$\Phi = \phi(r,\theta) e^{-i\omega t + im\varphi}$$

$$\int_{0}^{\pi} d\theta \int_{0}^{+\infty} dr r^{2} \sin\theta \left[ -3\omega^{2}\phi^{2} + \phi'^{2} + \frac{\phi_{,\theta}^{2}}{r^{2}} + \frac{m^{2}\phi^{2}}{r^{2}\sin^{2}\theta} + 3U \right] = 0$$

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u} 
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 $\int_0^\pi d heta$ 

0

$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$

• The gravitational action

$$egin{aligned} \mathcal{S}_{grav} &= \mathcal{S}_{EH} + \mathcal{S}_{GHY} \ &= rac{1}{4} \int_{\mathcal{M}} d^4x \, \sqrt{-g} R + rac{1}{2} \int_{\partial \mathcal{M}} d^3x \, \sqrt{-\gamma} ig(K-K_0ig) \end{aligned}$$

r = 0

 $r = +\infty$ 

• The gravitational action

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R

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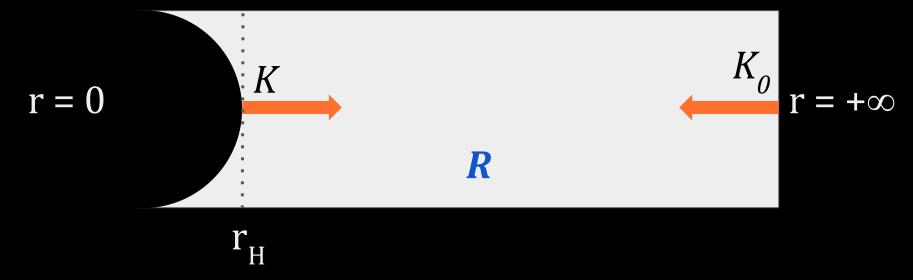
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The boundary term is needed since the gravitational Lagrangian density, *R*, contains second order derivatives of the metric tensor

## Derrick's argument: Black hole

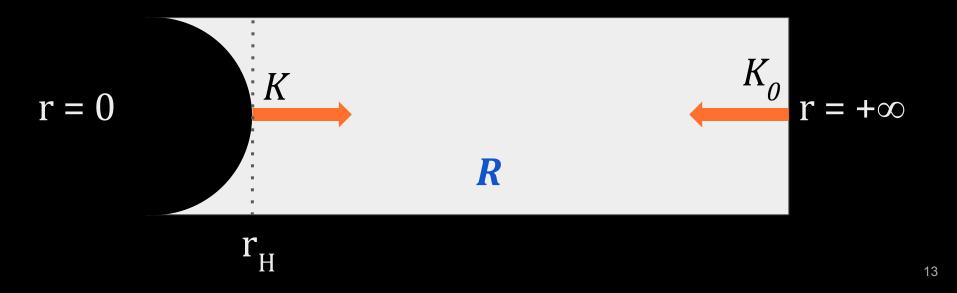
• In the presence of an horizon



## Derrick's argument: Black hole

• In the presence of an horizon

$$r 
ightarrow ilde{r} = r_H + \lambda (r - r_H)$$



$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$

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$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$



 $\int_{0}^{\pi} d heta \, \int_{r_{H}}^{+\infty} dr \, I_{R} = I_{GHY}$ 

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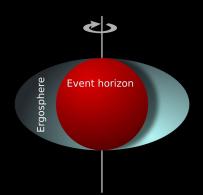


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$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$

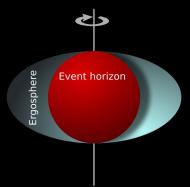


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$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$
 and  $\int_0^\pi d heta \int_{r_H}^{+\infty} dr \, I_R = I_{GHY}$ 

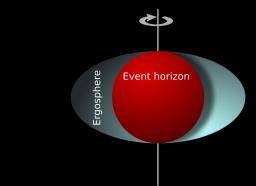
$$ds^2 = -e^{2F_0} N dt^2 + e^{2F_1} \left( rac{dr^2}{N} + r^2 d heta^2 
ight) + e^{2F_2} r^2 \sin^2 heta (darphi - W dt)^2$$



 $N=1-rac{r_H}{r}$ 

$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$
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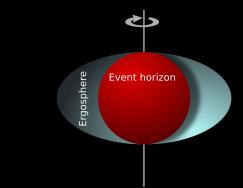
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$$F_0pprox rac{c_t}{r}+\cdots \qquad F_1=F_2pprox -rac{c_t}{r}+\cdots \qquad Wpprox -rac{c_t}{r^3}+\cdots$$

$$ds^2 = -e^{2F_0} N dt^2 + e^{2F_1} \left( rac{dr^2}{N} + r^2 d heta^2 
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$$F_0 pprox rac{c_t}{r} + \cdots \qquad F_1 = F_2 pprox - rac{c_t}{r} + \cdots \qquad W pprox - rac{c_t}{r^3} + \cdots$$

$$ds^2 = -e^{2F_0} N dt^2 + e^{2F_1} \left( rac{dr^2}{N} + r^2 d heta^2 
ight) + e^{2F_2} r^2 \sin^2 heta (darphi - W dt)^2$$

$$F_0pprox rac{c_t}{r}+\cdots \qquad F_1=F_2pprox -rac{c_t}{r}+\cdots \qquad Wpprox -rac{c_t}{r^3}+\cdots$$

$$egin{split} \sqrt{-\gamma} &= e^{F_0+F_1+F_2} \sqrt{N} \, r^2 \, \sin heta \ , \ K &= rac{e^{-F_1}}{r\sqrt{N}} \Big[ rac{rN'}{2} + 2N + Nrig(F_0'+F_1'+F_2'ig) \Big] \ , \ K_0 &= 2 rac{e^{-F_1}}{r} \ , \end{split}$$

$$ds^2 = -e^{2F_0} N dt^2 + e^{2F_1} \left( rac{dr^2}{N} + r^2 d heta^2 
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$$F_0pprox rac{c_t}{r}+\cdots \qquad F_1=F_2pprox -rac{c_t}{r}+\cdots \qquad Wpprox -rac{c_t}{r^3}+\cdots$$

$$egin{aligned} &\sqrt{-\gamma} = e^{F_0 + F_1 + F_2} \sqrt{N} \, r^2 \, \sin heta \, , \ &K = rac{e^{-F_1}}{r\sqrt{N}} \Big[ rac{rN'}{2} + 2N + Nrig(F_0' + F_1' + F_2'ig) \Big] \, , &I_{GHY} \, = \, 4 \, c_t \ &K_0 = 2 rac{e^{-F_1}}{r} \, , \end{aligned}$$

$$ds^2 = -e^{2F_0} N dt^2 + e^{2F_1} \left( rac{dr^2}{N} + r^2 d heta^2 
ight) + e^{2F_2} r^2 \sin^2 heta (darphi - W dt)^2$$

$$F_0pprox rac{c_t}{r}+\cdots \qquad F_1=F_2pprox -rac{c_t}{r}+\cdots \qquad Wpprox -rac{c_t}{r^3}+\cdots$$

$$egin{aligned} &\sqrt{-\gamma} = e^{F_0 + F_1 + F_2} \sqrt{N} \, r^2 \, \sin heta \, , \ &K = rac{e^{-F_1}}{r\sqrt{N}} \Big[ rac{rN'}{2} + 2N + Nrig(F_0' + F_1' + F_2'ig) \Big] \, , &I_{GHY} = 4 \, c_t \ &K_0 = 2 rac{e^{-F_1}}{r} \, , \end{aligned}$$

$$I_R = rac{\sin heta}{2} e^{F_1 - F_0} \left[ \ \cdots 
ight]$$

$$I_R = rac{\sin heta}{2} e^{F_1 - F_0} \left[ \begin{array}{c} \dots \end{array} 
ight]$$
Complicated

$$I_R = rac{\sin heta}{2} e^{F_1 - F_0} igg[ igcdots igces igcdots igcdots igcdots igces ig$$

$$I_{GHY} = 4 c_t$$

$$I_R = rac{\sin heta}{2} e^{F_1 - F_0} \left[ egin{array}{c} \cdots \end{array} 
ight]$$
 Complicated  $\int_0^\pi d heta \int_{r_H}^{+\infty} dr \ I_R = rac{4 \ c_t}{2}$ 

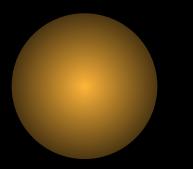
$$I_{GHY} = 4 \, c_t$$

$$I_R = rac{\sin heta}{2} e^{F_1 - F_0} \left[ egin{array}{c} \cdots \end{array} 
ight] egin{array}{c} \mathbf{Complicated} \end{array}$$

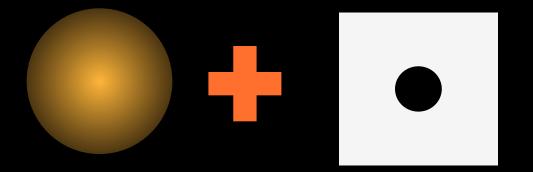
$$I_{GHY} = 4 \, c_t$$

$$egin{aligned} &I_R = rac{\sin heta}{2} e^{F_1 - F_0} igggledowdeltowde$$

$${\cal S}^{\Phi} = {\cal S}_{grav} + \int d^4 x \sqrt{-g} \Big[ - rac{1}{2} g^{\mu
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) \Big]$$



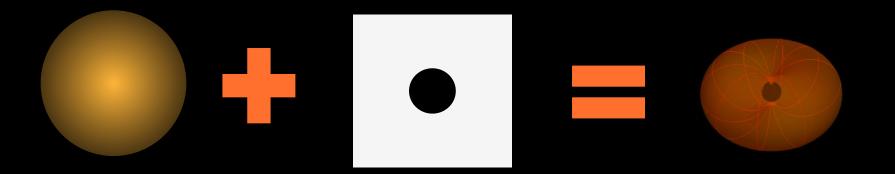
$${\cal S}^{\Phi} = {\cal S}_{grav} + \int d^4 x \sqrt{-g} igg[ - rac{1}{2} g^{\mu
u} \left( \Phi_{,\mu} \Phi^*_{,
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ight) - U(|\Phi|) igg]$$



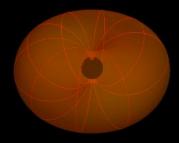
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u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
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ight) - U(|\Phi|) igg]$$



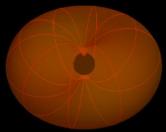
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u} \left( \Phi_{,\mu} \Phi^*_{,
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ight) - U(|\Phi|) igg]$$



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$$egin{aligned} \mathcal{S}^{\Phi} &= \mathcal{S}_{grav} + \int d^4x \sqrt{-g} iggl[ -rac{1}{2} g^{\mu
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) iggr] \ &e^{F_0 + F_2} \sin heta iggl[ r^2 N^2 \phi^2_{,r} + \phi^2_{, heta} + e^{2(F_1 - F_2)} rac{m^2 \phi^2}{\sin^2 heta} \ &+ e^{2F_1} r^2 iggl\{ iggl( 1 - rac{2r_H}{3r} iggr) U - e^{-2F_0} iggl( \omega - mW iggr)^2 \phi^2 iggr\} iggr] \end{aligned}$$



 $I_R$ 

 $\theta e$ 

$$\begin{split} \mathcal{S}^{\Phi} &= \mathcal{S}_{grav} + \int d^4x \sqrt{-g} \bigg[ -\frac{1}{2} g^{\mu\nu} \left( \Phi_{,\mu} \Phi_{,\nu}^* + \Phi_{,\mu}^* \Phi_{,\nu} \right) - U(|\Phi|) \bigg] \\ &= \ell^{F_0 + F_2} \sin \theta \bigg[ r^2 N^2 \phi_{,r}^2 + \phi_{,\theta}^2 + e^{2(F_1 - F_2)} \frac{m^2 \phi^2}{\sin^2 \theta} \\ &+ e^{2F_1} r^2 \bigg\{ \bigg( 1 - \frac{2r_H}{3r} \bigg) U - e^{-2F_0} \bigg( \omega - mW \bigg)^2 \phi^2 \bigg\} \bigg] \\ &= -\frac{1}{2} \sin^2 \theta \\ &= -\frac{1}{2} \sin^2 \theta \bigg\} \\ = -\frac{1}{2} \sin^2 \theta \bigg( 2\left( (r - r_H) \left( F_0^{\mu} + F_1^{\mu} + F_2^{\mu} \right) + F_2^{\mu} + (r - r_H) F_2^{\prime 2} \right) + F_0^{\prime} (2(r - r_H) F_2^{\prime 2} + 3) + 2(r - r_H) F_0^{\prime 2} + F_1^{\prime} \bigg) \\ &= 2e^{2F_0} \bigg( 2\left( (r(r - r_H) \left( F_0^{\mu} + F_1^{\mu} + F_2^{\mu} \right) + r(r - r_H) F_2^{\prime 2} + (3r - 2r_H) F_2 \right) - F_0^{\prime} (-2r(r - r_H) F_2^{\prime 2} - 4r + r_H ) + 2\hat{F_0} + 2r(r - r_H) F_0^{\prime 2} + 2\hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg( 2\left( r(r - r_H) \left( F_0^{\mu} + F_1^{\mu} + F_2^{\mu} \right) + r(r - r_H) F_2^{\prime 2} + (3r - 2r_H) F_2 \right) - F_0^{\prime} (-2r(r - r_H) F_2^{\prime 2} - 4r + r_H ) + 2\hat{F_0} + 2r(r - r_H) F_0^{\prime 2} + 2\hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg( 2\left( r(r - r_H) \left( F_0^{\mu} + F_1^{\mu} + F_2^{\mu} \right) + r(r - r_H) F_2^{\prime 2} + (3r - 2r_H) F_2 \right) - F_0^{\prime} (-2r(r - r_H) F_2^{\prime 2} - 4r + r_H ) + 2\hat{F_0} + 2r(r - r_H) F_0^{\prime 2} + 2\hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg( 2\left( r(r - r_H) \left( F_0^{\mu} + F_1^{\mu} + F_2^{\mu} \right) + r(r - r_H) F_2^{\prime 2} + (3r - 2r_H) F_2 \right) - F_0^{\prime} \left( -2r(r - r_H) F_2^{\prime 2} - 4r + r_H \right) + 2\hat{F_0} + 2r(r - r_H) F_0^{\prime 2} + 2\hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg( \hat{F_0} + 2 \cot \theta \bigg) + 4e^{2F_0} \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg( \hat{F_0} + 2 \cot \theta \bigg) + 4e^{2F_0} \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} + \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) \Big) + 4e^{2F_0} \hat{F_0} \bigg) \Big) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) + 4e^{2F_0} \hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) \Big) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) \Big) \Big( \hat{F_0} + \hat{F_0} \bigg) \Big) \\ \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) \Big) \\ &= 2e^{2F_0} \bigg) \Big( \hat{F_0} + \hat{F_0} \bigg) \Big) \\ \\ &= 2$$



# Plating Convenient metric



arXiv:2207.12451

• Let us introduce the a new metric ansatz:

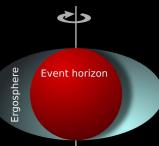
$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$



• Let us introduce the a new metric ansatz:

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$



• Let us introduce the a new metric ansatz:

 $ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$ 

$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$

Ergosphere

<u>را</u>م

Event horizon

• Let us introduce the a new metric ansatz:

 $ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$ 

Event horizon

• Let us introduce the a new metric ansatz:

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

$$\mathcal{S}_{grav} = \mathcal{S}_{EH} + \mathcal{S}_{GHY}$$

Event

• The Gibbons-Hawking-York term:

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

$$egin{aligned} &\sqrt{-\gamma} = rac{1}{\sqrt{H}\,F_1}\;, \ &K = rac{1}{(r-r_H)F_0F_1^2F_2\sqrt{H}}\left[(r-r_H)F_1F_2F_0' + F_0\left(ig(r-r_Hig)F_2F_1' + F_1ig(F_2+(r-r_H)F_2'ig)
ight)
ight], \ &K_0 = rac{2}{(r-r_H)F_1}\;, \end{aligned}$$

Ergosphere

• The Gibbons-Hawking-York term:

$$egin{aligned} ds^2 &= -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2 \ \sqrt{-\gamma} &= rac{1}{\sqrt{H} F_1} \,, \ K &= rac{1}{(r-r_H)F_0 F_1^2 F_2 \sqrt{H}} igg[ (r-r_H)F_1 F_2 F_0' + F_0igg( (r-r_H)F_2 F_1' + F_1igg( F_2 + (r-r_H)F_2' igg) igg) igg] \,, \ K_0 &= rac{2}{(r-r_H)F_1} \,, \ I_{GHY} &= \int_0^\pi d heta \, 0 igg|_{r_H}^\infty = 0 \end{aligned}$$

• The Gibbons-Hawking-York term:

$$egin{aligned} ds^2 &= -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2 \ \sqrt{-\gamma} &= rac{1}{\sqrt{H}\,F_1} \ , \ K &= rac{1}{(r-r_H)F_0F_1^2F_2\sqrt{H}} \Big[ (r-r_H)F_1F_2F_0' + F_0 \Big( (r-r_H)F_2F_1' + F_1ig(F_2+(r-r_H)F_2'ig) \Big) \Big] \ , \ K_0 &= rac{2}{(r-r_H)F_1} \ , \end{aligned}$$

$$I_{GHY}=\int_{0}^{\pi}d heta \left| 0
ight| _{r_{H}}^{\infty}=0$$

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

• The Einstein-Hilbert part:

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

$$\begin{split} &\sqrt{-gR} \\ &= \frac{1}{2F_0F_1^2H^{3/2}(r-r_H)} \left\{ F_1^2F_2^2H \Big( H\hat{F}_W^2 + (r-r_H)^2F_W'^2 \Big) + 2F_0F_1^2 \left[ -2H^2\partial_\theta(\hat{F}_0F_2) + (r-r_H) \Big( -2\partial_r[F_0'F_2H(r-r_H)] + 3F_0'F_2H'(r-r_H) \Big) \right] \\ &+ 2F_0^2 \left[ 2F_2H \Big( H\hat{F}_1^2 + (r-r_H)F_1'^2 \Big) - 2H^2F_1(\hat{F}_1F_2 + F_1\hat{F}_2) + (r-r_H) \Big( \left[ (r-r_H)H' - 2H \right]F_1\partial_r(F_1F_2) - 2F_1H(r-r_H)(F_2\hat{F}_2 + F_1F_2'') \\ &+ F_2F_1^2H' \Big) \right] \right\} \end{split}$$

• The Einstein-Hilbert part:

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For each radial derivative  $F_i$  there is an  $(r-r_H)$ 

• The Einstein-Hilbert part:

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

$$\begin{split} &\sqrt{-g}R \\ &= \frac{1}{2F_0F_1^2H^{3/2}(r-r_H)} \left\{ F_1^2F_2^2H \Big( H\hat{F}_W^2 + (r-r_H)^2F_W'^2 \Big) + 2F_0F_1^2 \left[ -2H^2\partial_\theta(\hat{F}_0F_2) + (r-r_H) \Big( -2\partial_r[F_0'F_2H(r-r_H)] + 3F_0'F_2H'(r-r_H) \Big) \right] \\ &+ 2F_0^2 \left[ 2F_2H \Big( H\hat{F}_1^2 + (r-r_H)F_1'^2 \Big) - 2H^2F_1(\hat{F}_1F_2 + F_1\hat{F}_2) + (r-r_H) \Big( \left[ (r-r_H)H' - 2H \right]F_1\partial_r(F_1F_2) - 2F_1H(r-r_H)(F_2\hat{F}_2 + F_1F_2'') \\ &+ F_2F_1^2H' \Big) \right] \right\} \end{split}$$

For each radial derivative  $F_i$  there is an  $(r-r_H)$ 

$$\sqrt{-g_\lambda}R_\lambda=rac{1}{\lambda}\sqrt{-g}R$$

• The Einstein-Hilbert part:

$$ds^2 = -F_0^2 dt^2 + HF_1^2 dr^2 + (r-r_H)^2 F_1^2 d heta^2 + F_2^2 (darphi - F_W dt)^2$$

$$\begin{split} &\sqrt{-gR} \\ &= \frac{1}{2F_0F_1^2H^{3/2}(r-r_H)} \left\{ F_1^2F_2^2H \Big( H\hat{F}_W^2 + (r-r_H)^2F_W'^2 \Big) + 2F_0F_1^2 \left[ -2H^2\partial_\theta(\hat{F}_0F_2) + (r-r_H) \Big( -2\partial_r[F_0'F_2H(r-r_H)] + 3F_0'F_2H'(r-r_H) \Big) \right] \\ &+ 2F_0^2 \left[ 2F_2H \Big( H\hat{F}_1^2 + (r-r_H)F_1'^2 \Big) - 2H^2F_1(\hat{F}_1F_2 + F_1\hat{F}_2) + (r-r_H) \Big( \left[ (r-r_H)H' - 2H \right]F_1\partial_r(F_1F_2) - 2F_1H(r-r_H)(F_2\hat{F}_2 + F_1F_2'') \\ &+ F_2F_1^2H' \Big) \right] \right\} \end{split}$$

 $\lambda dr$ 

For each radial derivative  $F_i$  there is an  $(r-r_H)$ 

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For each radial derivative  $F_i$  there is an  $(r-r_H)$ 

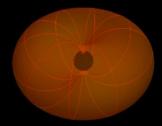
$$\sqrt{-g_\lambda}R_\lambda=rac{1}{\lambda}\sqrt{-g}R$$

 $\lambda dr$ 

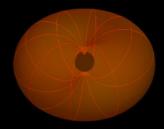
### $I_R=0$

$${\cal S}^{\Phi} = {\cal S}_{grav} + \int d^4 x \sqrt{-g} \Big[ - rac{1}{2} g^{\mu
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) \Big]$$

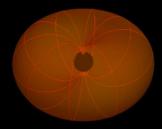
$${\cal S}^{\Phi} = {\cal S}_{grav} + \int d^4 x \sqrt{-g} \Big[ - rac{1}{2} g^{\mu
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) \Big]$$



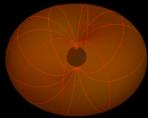
$${\cal S}^{\Phi} = {\cal S}_{g \kappa a v} + \int d^4 x \sqrt{-g} \Big[ - rac{1}{2} g^{\mu 
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) \Big]$$



$${\cal S}^{\Phi} = {\cal S}_{g \kappa a v} + \int d^4 x \sqrt{-g} \Big[ - rac{1}{2} g^{\mu 
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) \Big]$$



$$egin{aligned} \mathcal{S}^{\Phi} &= \mathcal{S}_{g lpha v} + \int d^4 x \sqrt{-g} iggl[ -rac{1}{2} g^{\mu 
u} \left( \Phi_{,\mu} \Phi^*_{,
u} + \Phi^*_{,\mu} \Phi_{,
u} 
ight) - U(|\Phi|) iggr] \ &\int d^3 x \, \left( r - r_H 
ight) F_1^2 iggl[ rac{\sqrt{H}}{F_0 F_2} iggl( m^2 F_0^2 - F_2^2 iggl( \omega - m F_W^2 iggr) iggr) \phi^2 \ &+ F_0 F_2 U(\phi) iggr] = 0 \end{aligned}$$







#### Master Identities: Hairy Kerr

• Matter part:

$$\mathcal{V}_{scalar} = \int d^3x \sqrt{-g} iggl\{ \left(1 - rac{3r_H}{2r}
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$$\int d^3x \,\, \sqrt{-g} \Big[ 2 ig( T^t_t - T^r_r - T^ heta_ heta ig) + ig( T^t_t - T^arphi_arphi ig) \Big( 1 - rac{4 \omega F_2 (\omega - m F_W)}{m^2 F_0^2 + F_2^2 (\omega^2 - m^2 F_W^2)} \Big) \Big] = 0$$

## The stress energy tensor is multiplication parameters is matter dependent

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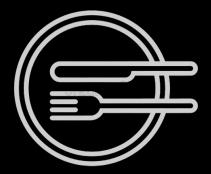
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# The stress energy tensor is multiplication parameters is matter dependent

Can be seen as a generalization of Desert's theorem as a sum of pressures

### Conclusion



- We presented a generic recipe to compute virial identities in field theory
- The GHY term is required due to the presence of second-order derivatives of the metric
- One noticed that, for a generic metric, relations are too complex
- There is a special "gauge" choice that trivializes the gravitational contribution
- The identities can be recast as combinations of the equations of motion
- This has allowed us to obtain some master form identities

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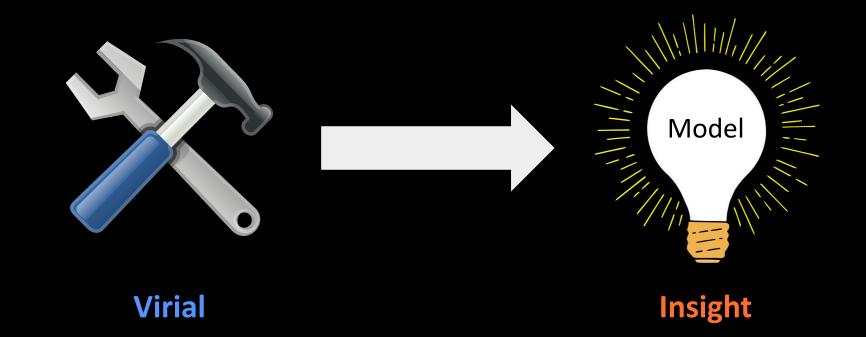
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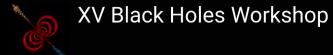
#### Conclusion

Virial identities are a helpful tool that can be used to have a better insight into the models



Thanks Obrigado!





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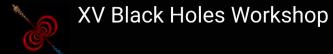
# Virial identities in relativistic gravity

2109.05027 2206.02813 2207.12451

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Thank you! Obrigado!





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# Virial identities in relativistic gravity

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