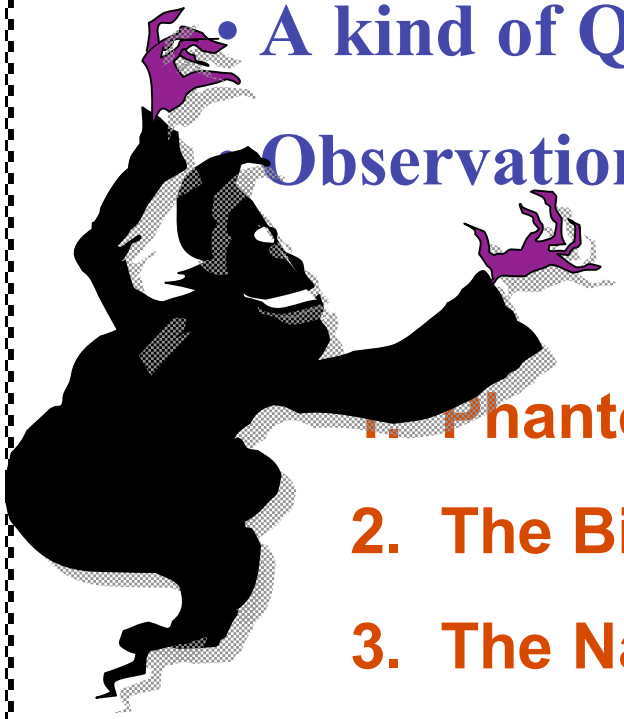
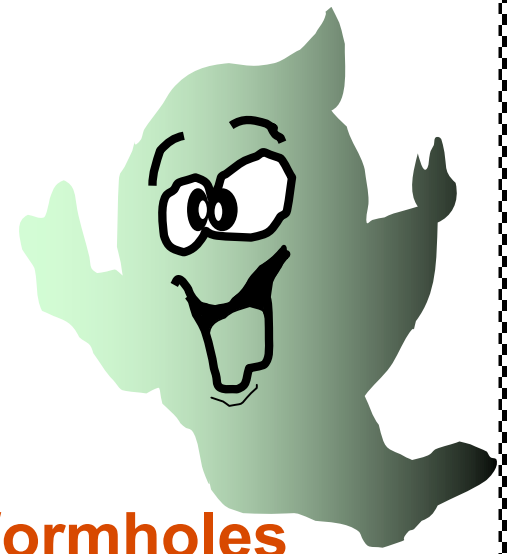
The Cosmic Phantom Field



- A kind of Quintessence Field
- Observational Constraints ➡ ω around -1

SUMMARY

1. Phantom Energy
2. The Big Rip
3. The Nature of Phantom Field
4. Accretion on Black Holes and Wormholes
5. Thermodynamics
6. Conclusions



Phantom energy

Fluid

- Equation of State: $p = \omega\rho$
- Energy Density: $\rho(a) = \rho_0 a^{-3(1+\omega)}$
- Violation of DEC: $p + \rho < 0 \Rightarrow \omega < -1$

(The Natural Scenario where Wormholes Crop up !)

- Definition of Field: $\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

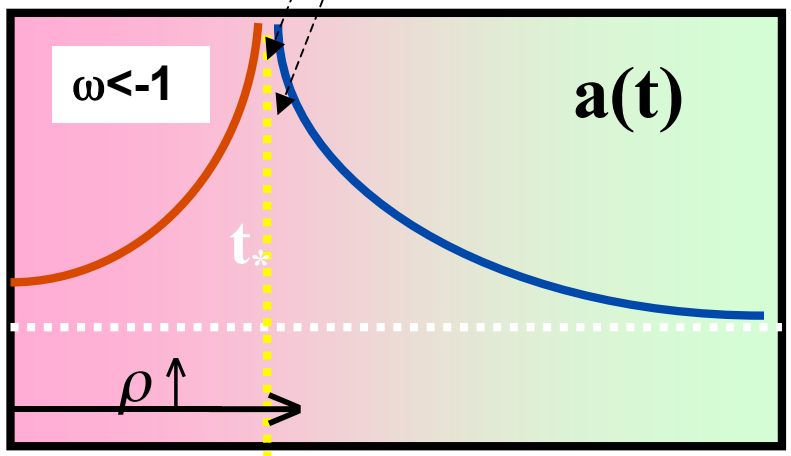
$$\Rightarrow \dot{\phi}^2 = (1+\omega)\rho$$

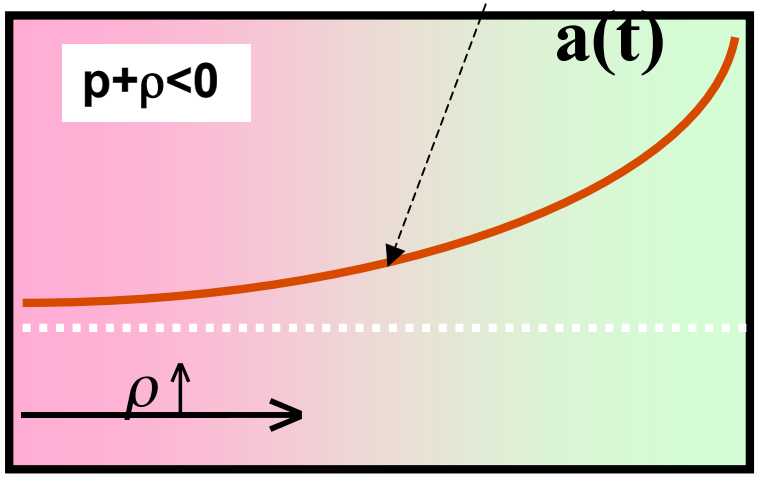
The Big Rip

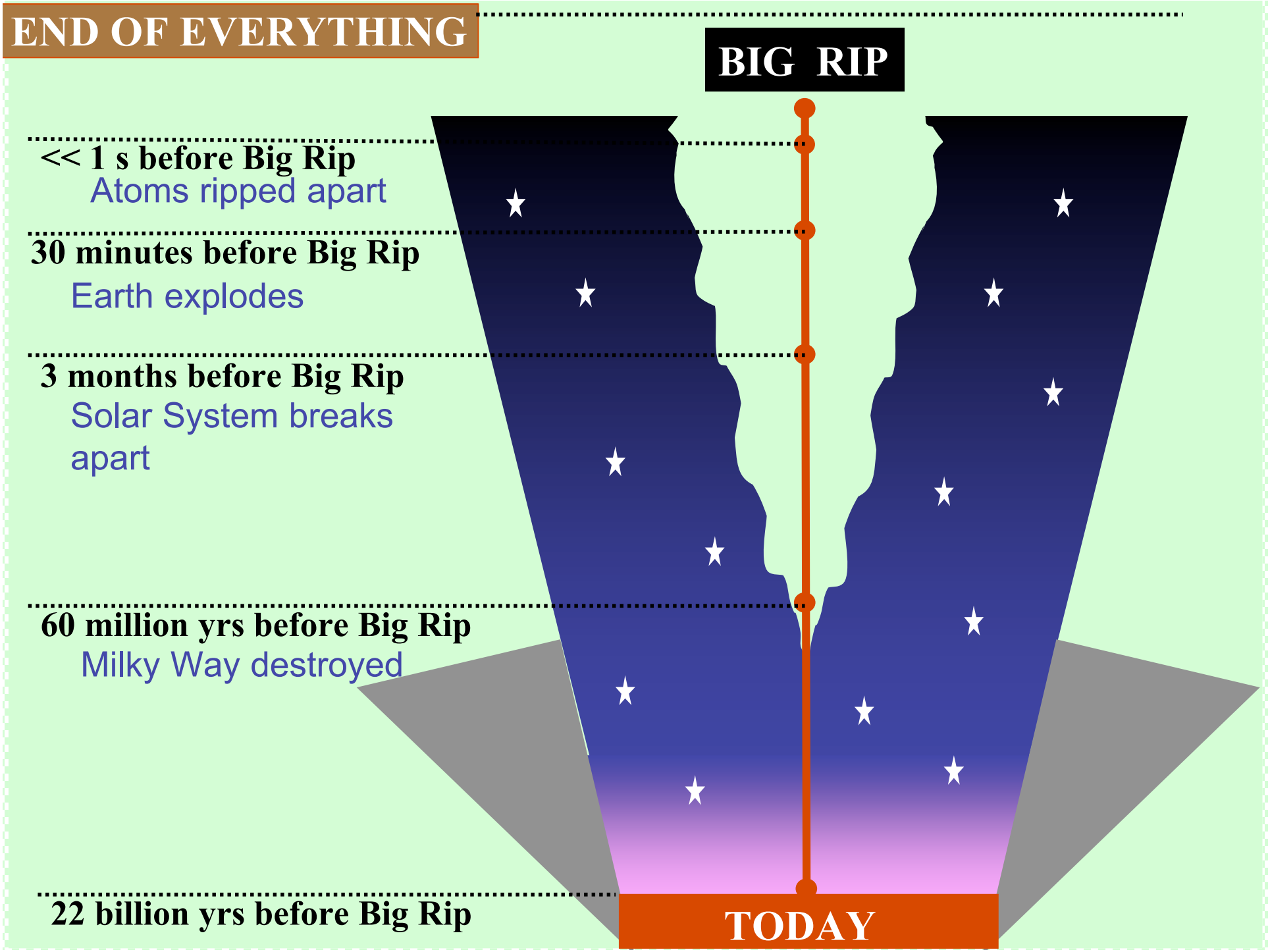
[Caldwell, Kamionkowski & Weinberg, PRL91, 071301 (2003)]

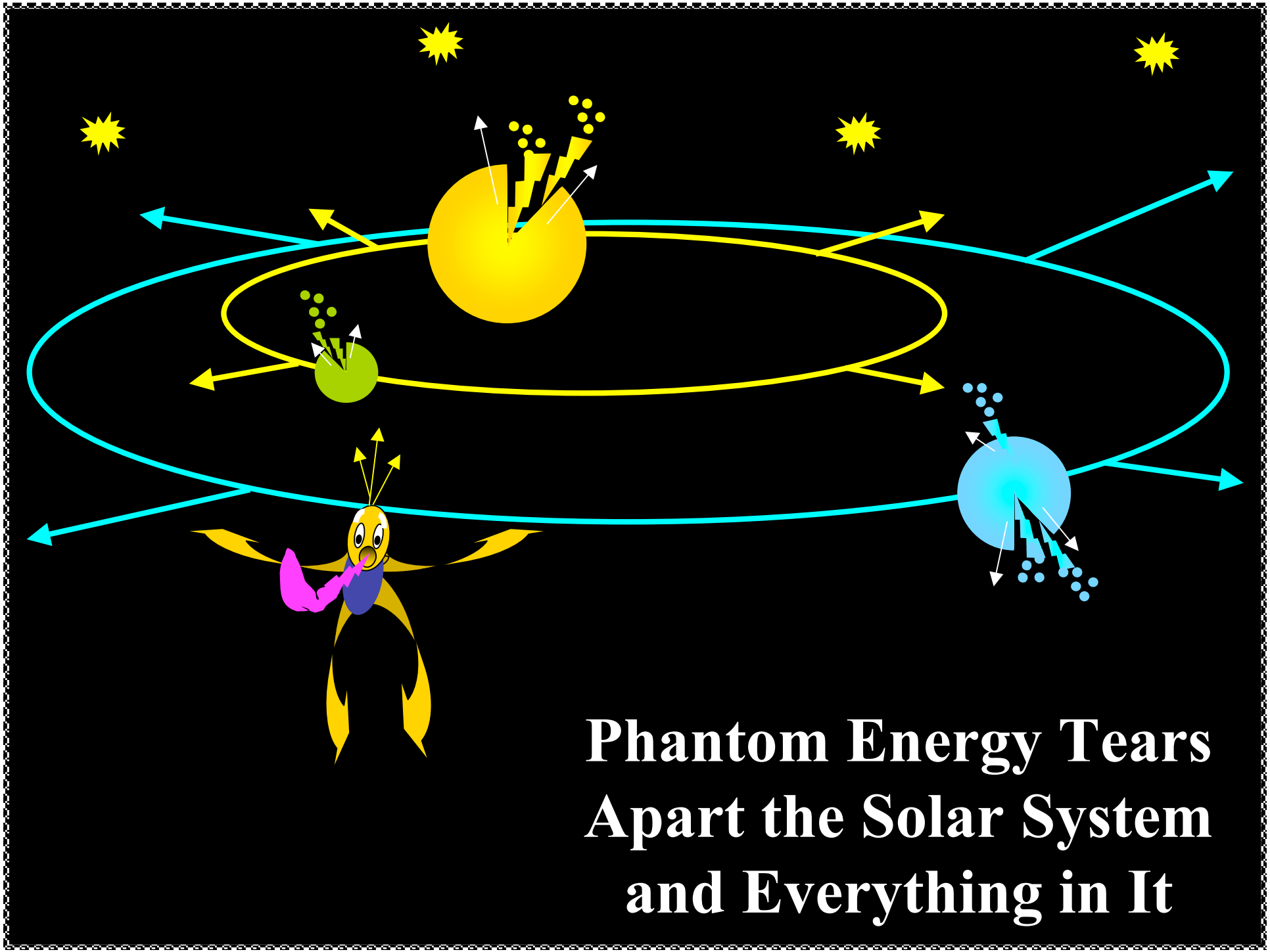
- **K=0 Quintessence:** $a(t) = \left(a_0^{-3(|\omega|-1)/2} - \frac{3}{2}(|\omega|-1)t \right)^{-2/[3(|\omega|-1)]}$
- **K=0 K-Essence:** $a(t) \propto (t - t_*)^{-2\beta/[3(1-\beta)]}, 0 < \beta < 1$
- **Chaplygin Gas:** $t \propto F\left(1, \frac{1+2\alpha}{2(1+\alpha)}; \frac{3+4\alpha}{2(1+\alpha)}; 1 + Ca^{-3(1+\alpha)}\right)$

$(\alpha > -1/2)$






END OF EVERYTHING
BIG RIP
<< 1 s before Big Rip
Atoms ripped apart
30 minutes before Big Rip
Earth explodes
3 months before Big Rip
Solar System breaks apart
60 million yrs before Big Rip
Milky Way destroyed
22 billion yrs before Big Rip
TODAY


Phantom Energy Tears
Apart the Solar System
and Everything in It

Is phantom energy made up of Axions ?

[PFG-D, PR D69, 063522 (2003)]

W.E.C.: $\rho = \dfrac{\dot{\phi}^2}{1+\omega} \geq 0 \underset{\omega<-1}{\longrightarrow} \phi \equiv$ **Pure Imaginary** !

Axion: *Rank-three Antisymmetric Tensor Field (Supergravity)*

$$S_A = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G} - A^2 + L_M\right)$$

$A^2 = A_{\mu\nu\alpha}A^{\mu\nu\alpha}$

- **FRW**
- $A = f(r)\varepsilon$

ε : **Volume Form**

$$G_{\mu\nu} = 16\pi G\left(3A_{\mu\nu}{}^2 - \frac{1}{2}A^2 + T_{\mu\nu}^{(M)}\right)$$

$d^*A = 0$

$A_{\mu\nu}{}^2 = A_{\mu\alpha\beta}A^{\alpha\beta}{}_\nu$: **Thee-Form Field Strength**

*** = Hodge Dual**

The solutions to the Equations of Motion for Spherically Symmetric Axion in FRW are the Same as the Solutions to the Equations of Motion obtained from the FRW Action for a Scalar Field with a Boundary Term

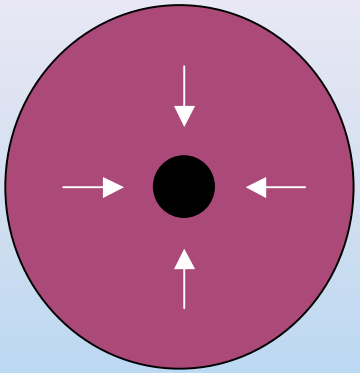
$$S_S = \frac{1}{16\pi G}\int_0^T dt a^3\left(-\frac{\dot{a}^2}{N}+8\pi G\frac{\dot{\phi}^2}{N}\right)-a^3\frac{\dot{\phi}\phi}{N}\Big|_0^T$$

Or from the Same Action with the Scalar Field Rotated to Imaginary Axis, Without that Boundary Term.

Phantom Energy can be Interpreted as Being Made of Axions !!

Accretion of Phantom energy onto Black Holes

[Babichev, Dokuchaev & Eroschenko, gr-qc/0402089, PRL (in press, 2004)]



$$\dot{M} = 4\pi A M^2 (1+\omega)\rho$$

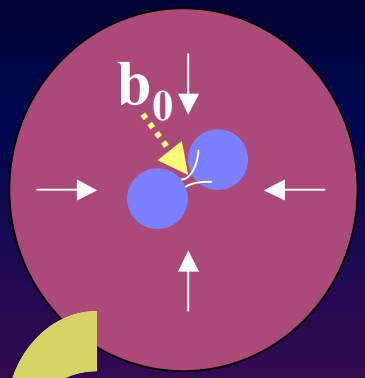
$$M(t) = \frac{M_i}{1 - \frac{(1+\omega)M_i}{\dot{M}_0 C}\left(\frac{t}{a(t)^{3(1+\omega)/2}}\right)}$$

$\omega < -1 \Rightarrow$

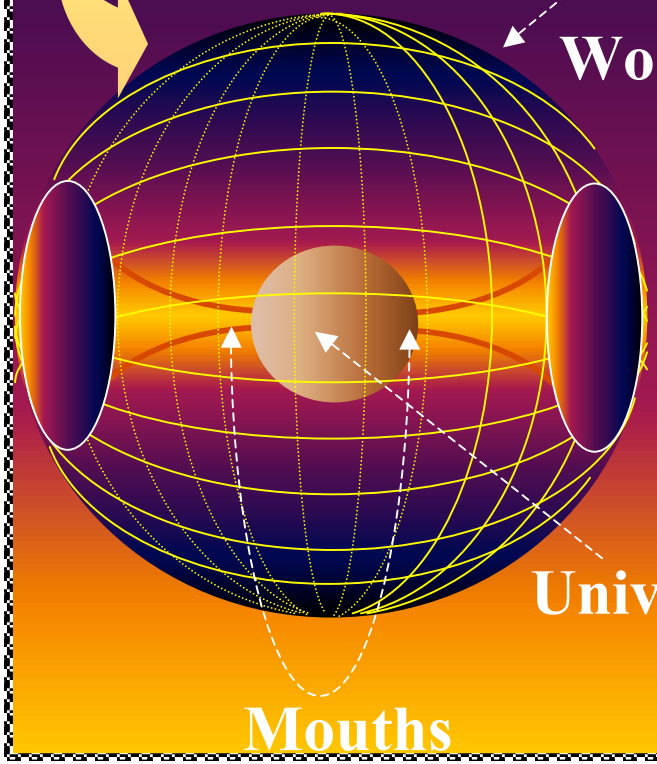
- Black holes steadily loss their mass and vanish at the Big Rip
- That process prevails over Hawking thermal radiation
- Conflict with thermodynamics?

Accretion of Phantom energy onto Wormholes

[PFG-D, astro-ph/0404045, PRL (in press, 2004)]



$$\dot{b}_0 = -2\pi^2 B b_0^2 (1+\omega)\rho$$



$$b_0 = \frac{b_{0i}}{1 + \dfrac{b_{0i} t}{\dot{b}_{0i} C a^{3(1+\omega)/2}}}$$

Big Trip ?

- **Avoiding the Big Rip ?**
- **Non-causal evolution ?**

Phantom thermodynamics

[PFG-D & Sigüenza, PLB589, 78 (2004)]

- **Temperature**

$$T = -\kappa(|\omega| - 1)a^{3|\omega|}$$

1. "hotter" than anything !!
2. Conflict with BH accretion Solved

- **Entropy**

$$S = C_0 \left(\frac{|T|}{|\omega| - 1} \right)^{-1/|\omega|} V$$

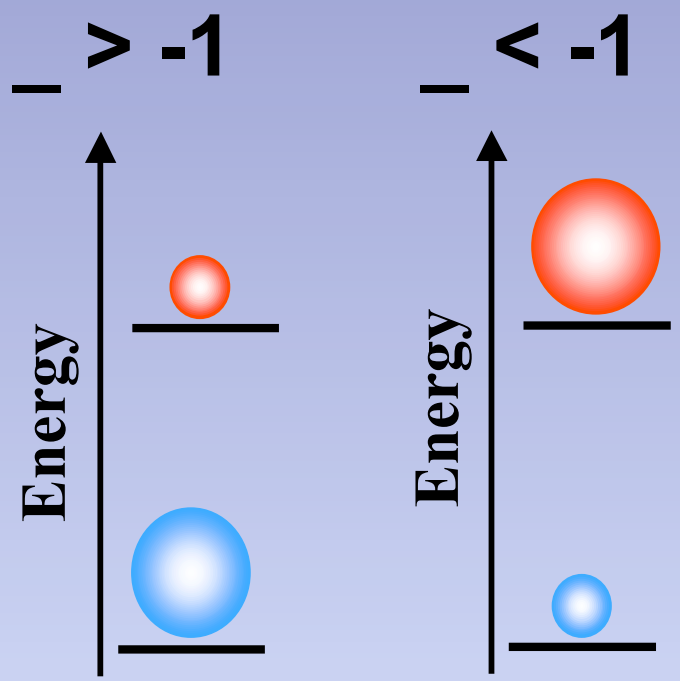
Always Positive

- **Occupation Number**

$$\rho_T(\nu) = \frac{\alpha \nu^{1/\omega}}{e^{h\nu/(k_B|T|)} \pm 1}$$

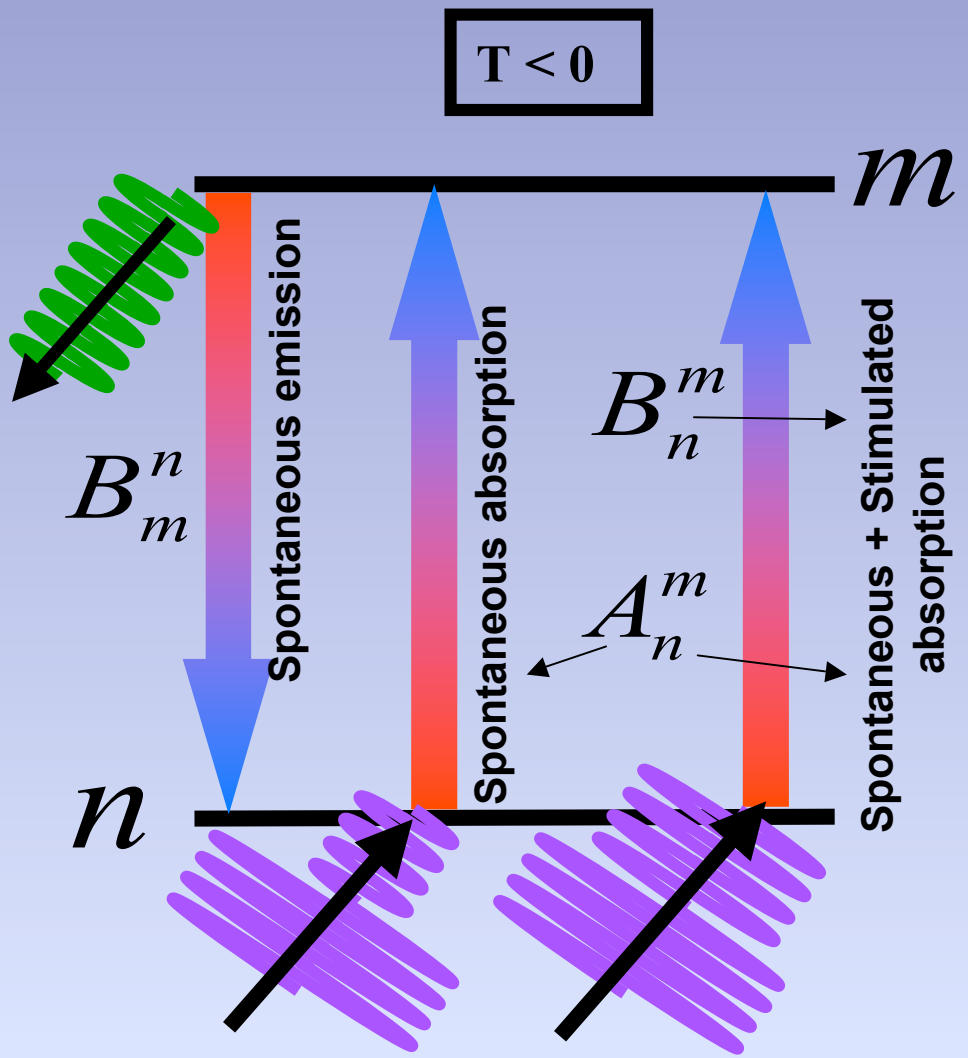
Same Expression, different Physics

Phantom "Anti-Laser" Effect



$P = e^{-E/T}$ $P = e^{+E/|T|}$

Population "Inversion"



"New" Einstein Coefficients

Conclusions ?

- *The subject of the Phantom Field is rather speculative, but not more than other stuffs also assumed to make up Dark Energy.*

- *The properties of phantom energy are rather weird and include an increasing energy density as the universe expands in a super accelerated fashion, so as the big rip and the possibility for a big trip.*

- *Phantom energy may be made up of axions with an extremely small mass.*

- *Phantom energy is accreted by black holes and Lorentzian wormholes in which it produces unexpected effects that can remarkably affect the future evolution of the universe.*

- *If the universe is filled with phantom energy, then it can be also characterized by a negative temperature.*