GR21 Jul 14 2016

From Quantum to Classical Instability in Relativistic Stars

André G. S. Landulfo (Center for Natural and Human Sciences/ UFABC)

In collaboration with W. Lima (York), G. Mastsas (ift), and D. Vanzella (usp)

Unstable Relativistic Systems

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Fernando Botero: Equilibrist with Umbrella

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Amplitude ~ $\sqrt{\hbar}$

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- W. Lima, R. Mendes, G. Matsas, D. Vanzella, PRD (2013)
- R. Mendes, G. Matsas, and D. Vanzella, PRD (2014)
- J. Santiago, AL, W. Lima, R. Mendes, G. Matsas, and D. Vanzella, PRD (2015)

Amplitude $\sim \sqrt{\hbar}$

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Awaking the vacuum

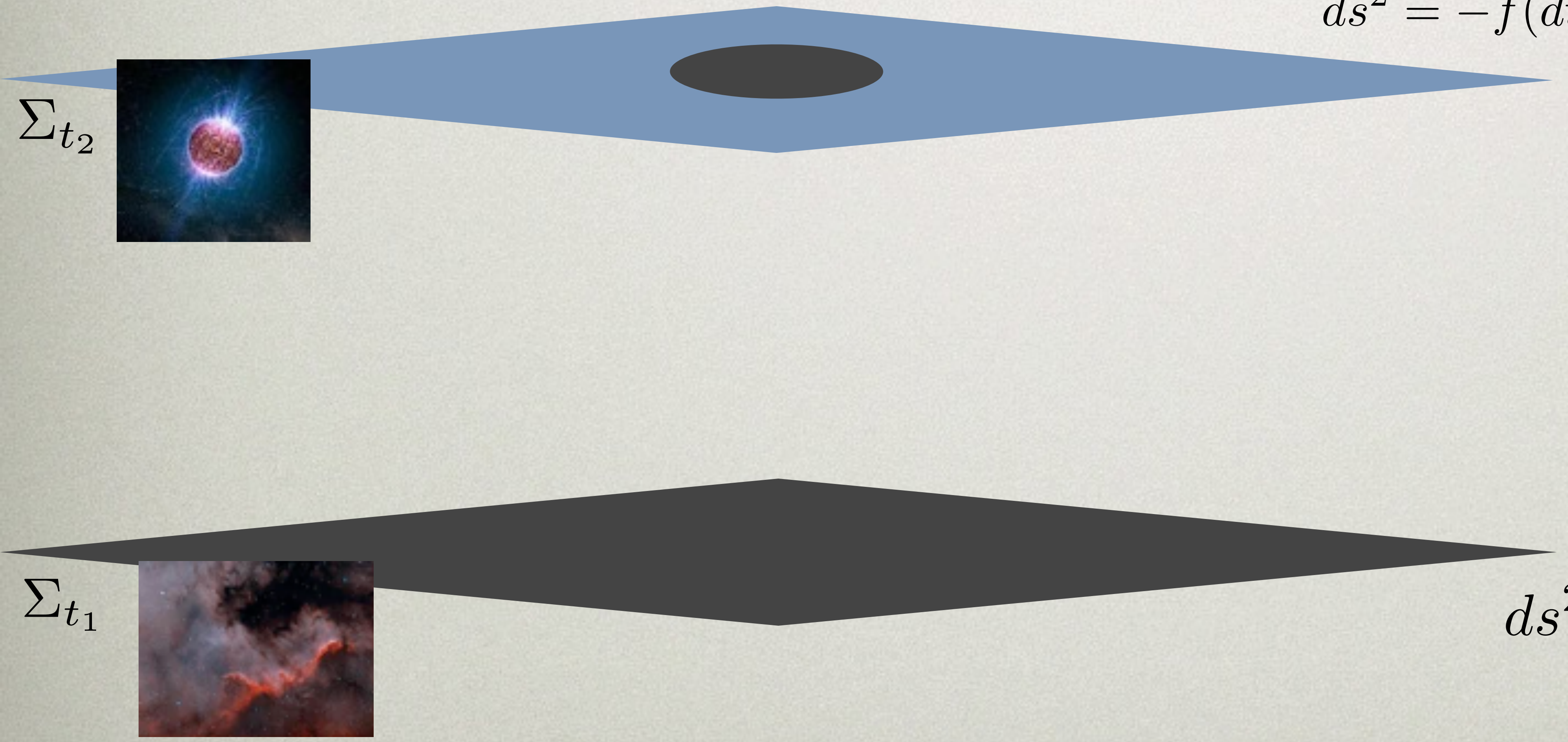
Awaking the vacuum

Σ_{t_1}

$$ds^2 = -dt^2 + d\mathbf{x}^2$$

Awaking the vacuum

$$ds^2 = -f(dt^2 - d\chi^2) + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$



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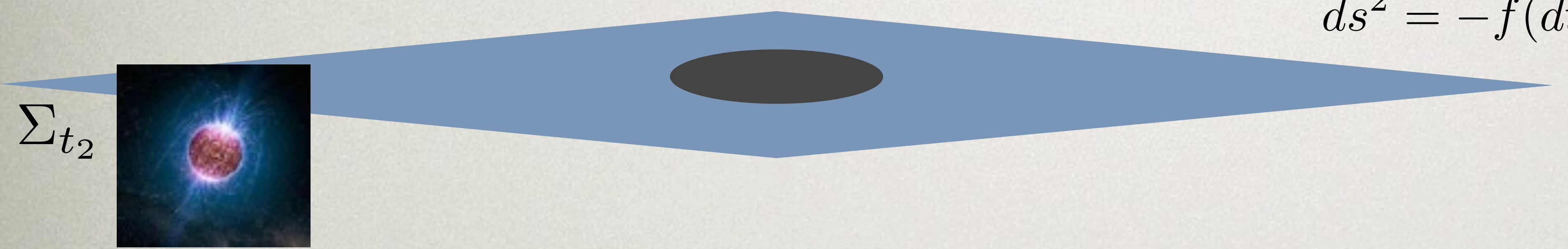

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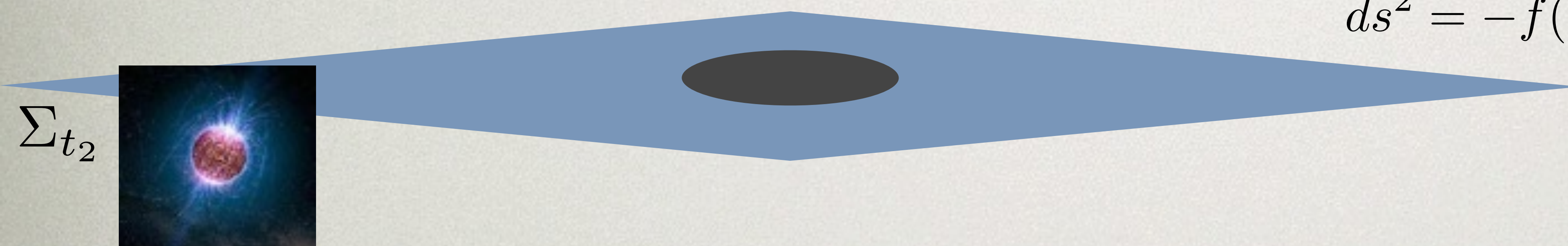

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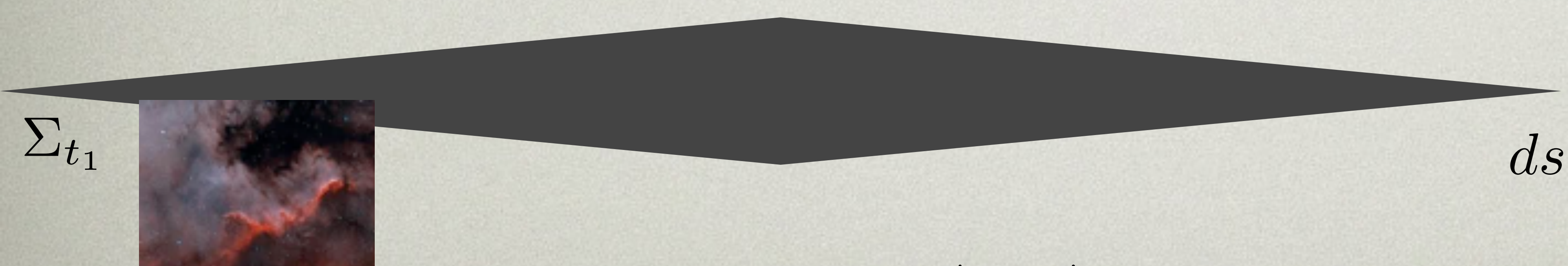

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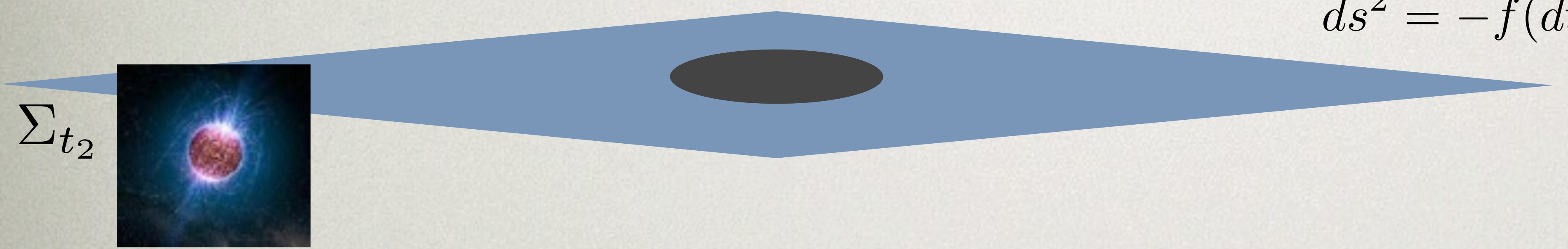

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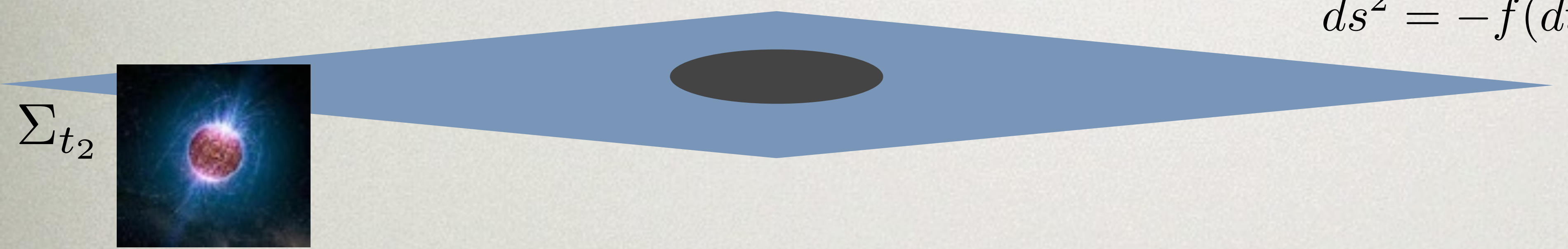

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Vacuum dominance

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- The unstable phase must be detained by backreaction effects which should be responsible to bring the vacuum back to some stationary regime.

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- P. Pani, V Cardoso, E. Berti, J. Read, and M. Salgado, PRD (2011)

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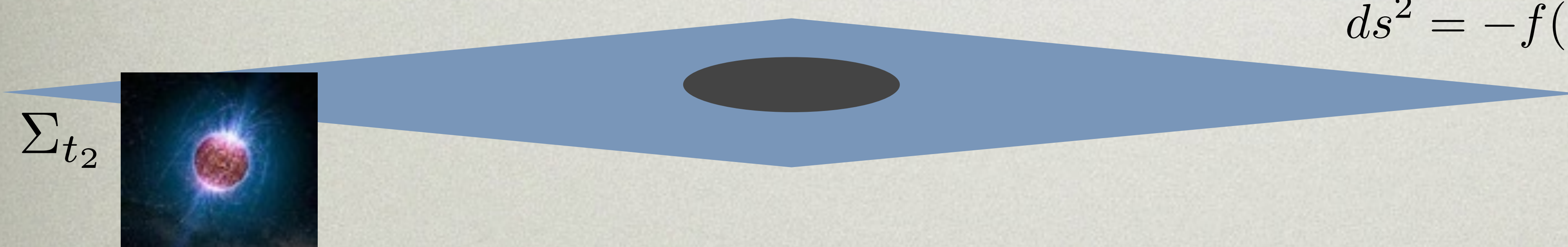

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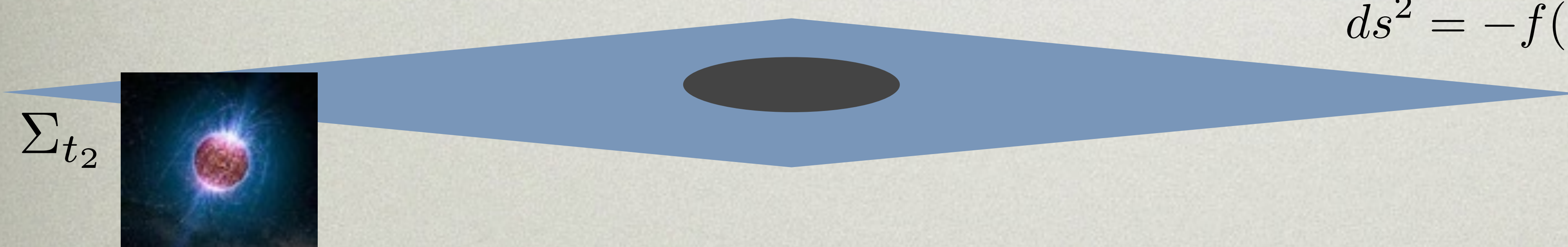

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- T. Harada, Prog. Theor. Phys, (1993), PRD (1997)
- M. Ruiz et. al., PRD (2012)
- R. Mendes and N. Ortiz, PRD (2016)

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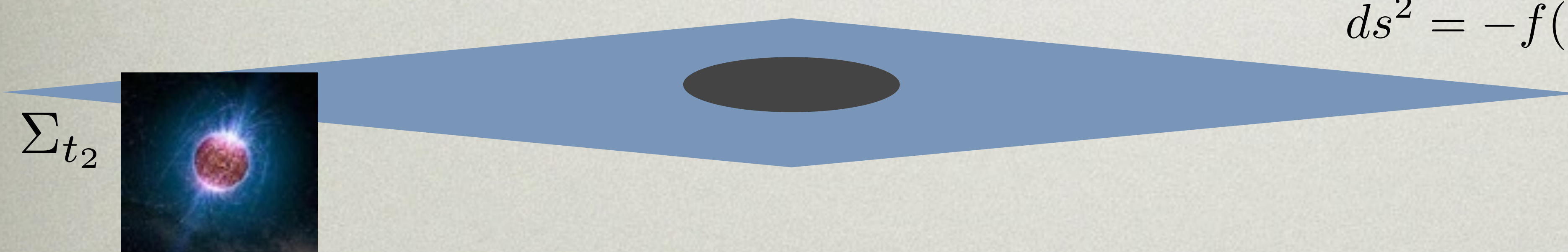

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Awaking the vacuum

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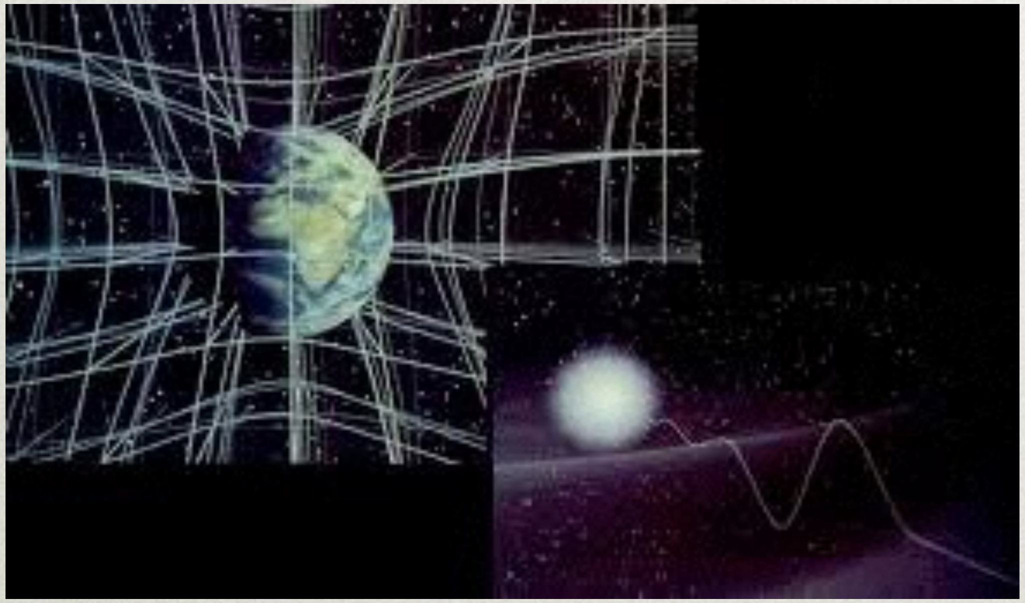
- Einstein semiclassical equation:

$$R_{ab} - \frac{1}{2} g_{ab} R = 8\pi \langle T_{ab} \rangle_\omega$$



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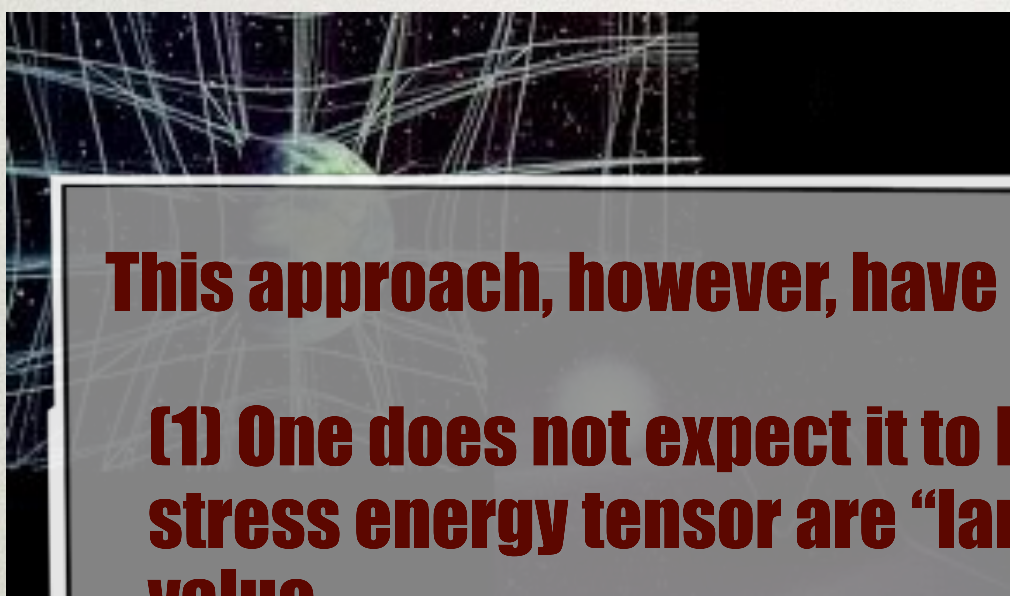


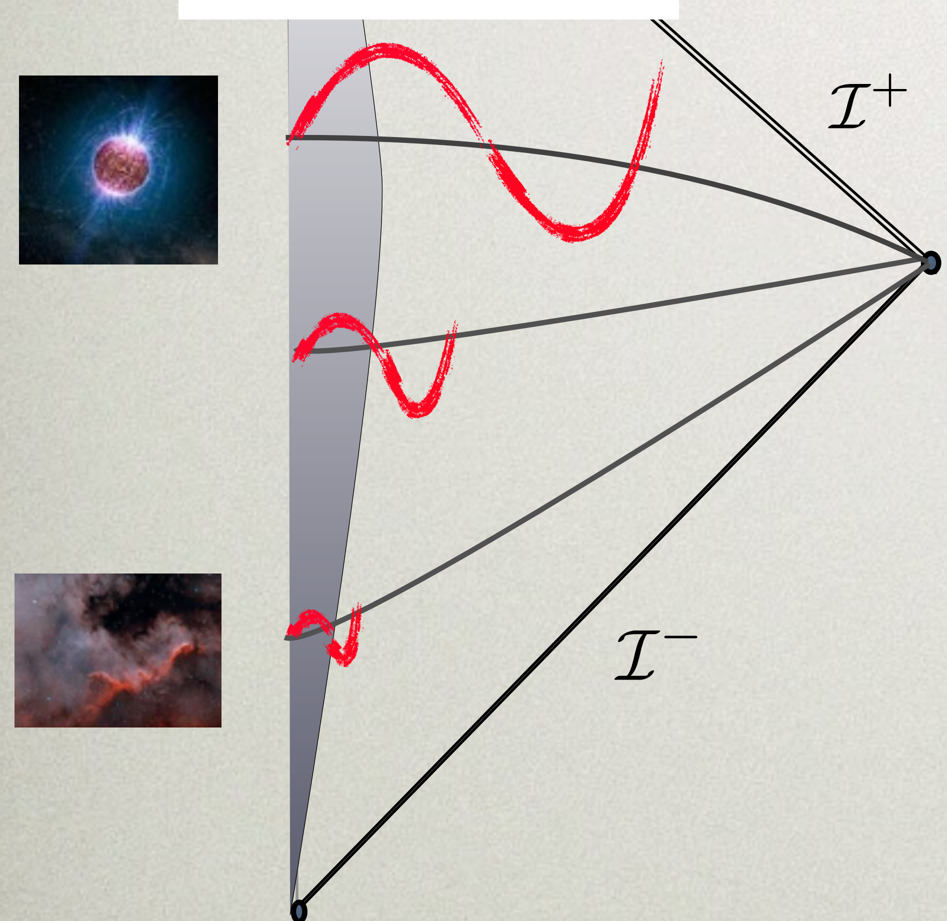
This approach, however, have many difficulties, e.g.,

(1) One does not expect it to be valid when the fluctuations of the stress energy tensor are "large" when compared to its mean value

(2) Even if/when it is valid, it is, in general, prohibitively difficult to solve it.

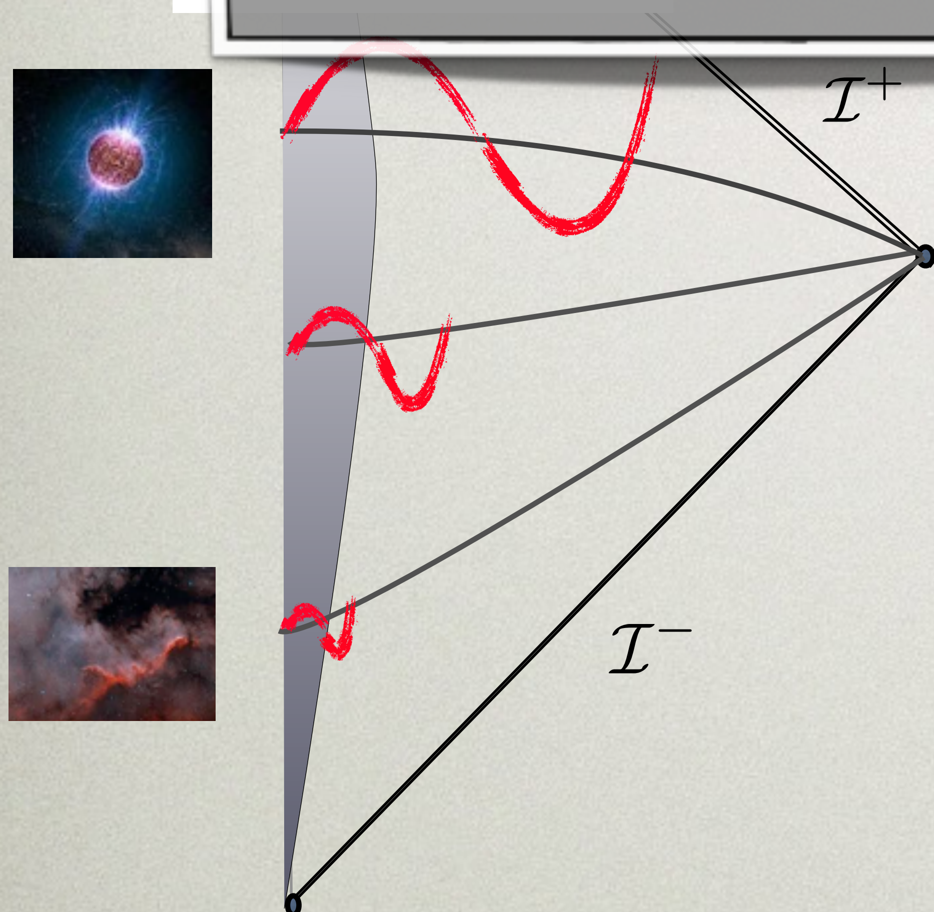
⋮

Awaking the vacuum



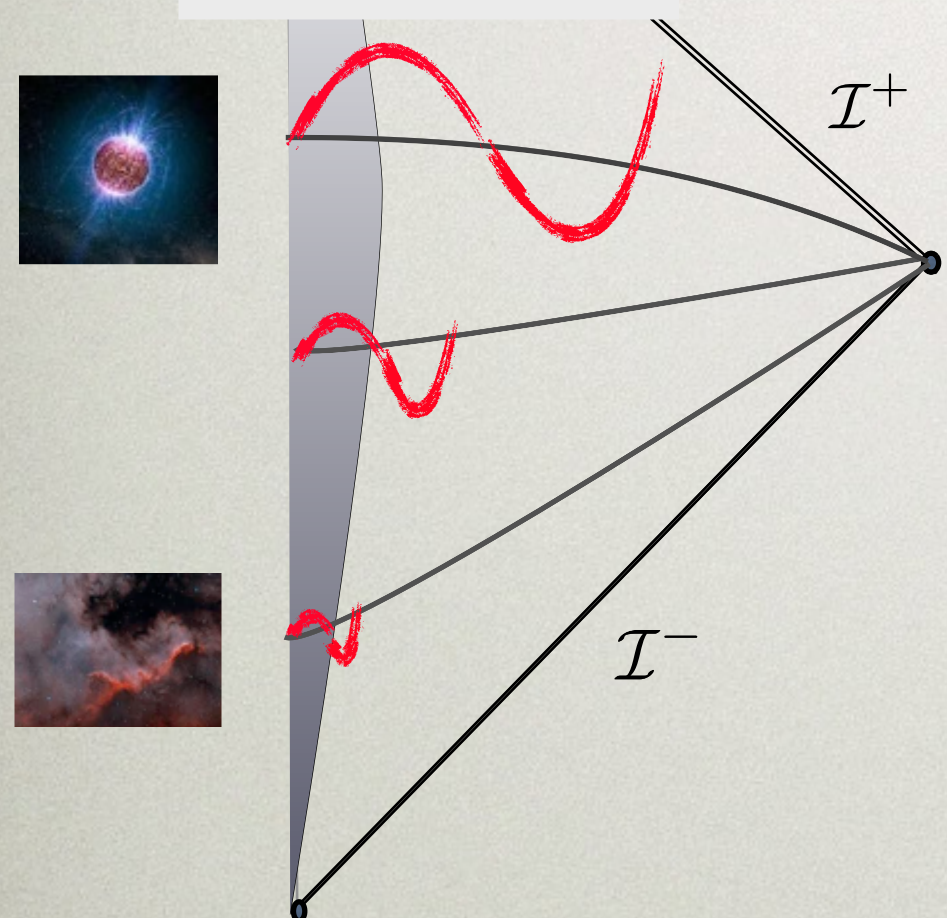
Awaking the vacuum

it seems reasonable to believe that quantum fluctuations amplified enough to menace the stability of relativistic stars cannot remain ``quantum" for too long.



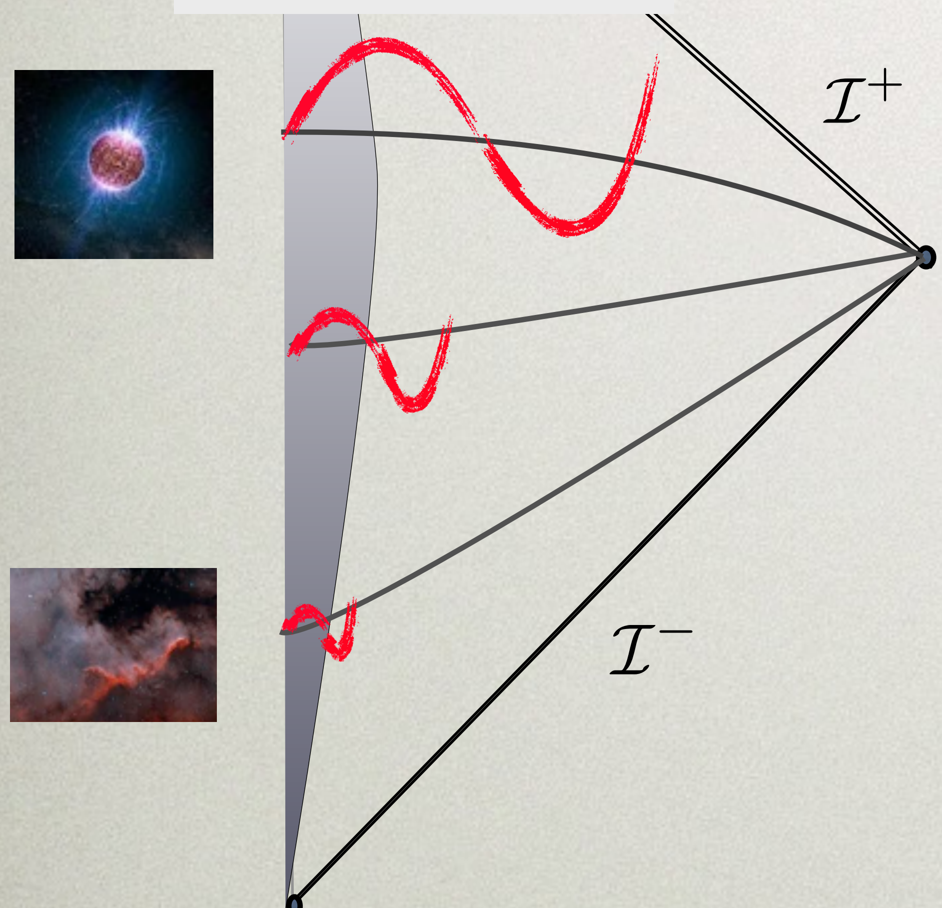
If the quantum phase ends before vacuum fluctuations dominate the system, we expect backreaction to be well described by the <u>CLASSICAL</u> general-relativistic equations.

Awaking the vacuum



Awaking the vacuum

- For this quantum to classical transition to occur one must have:



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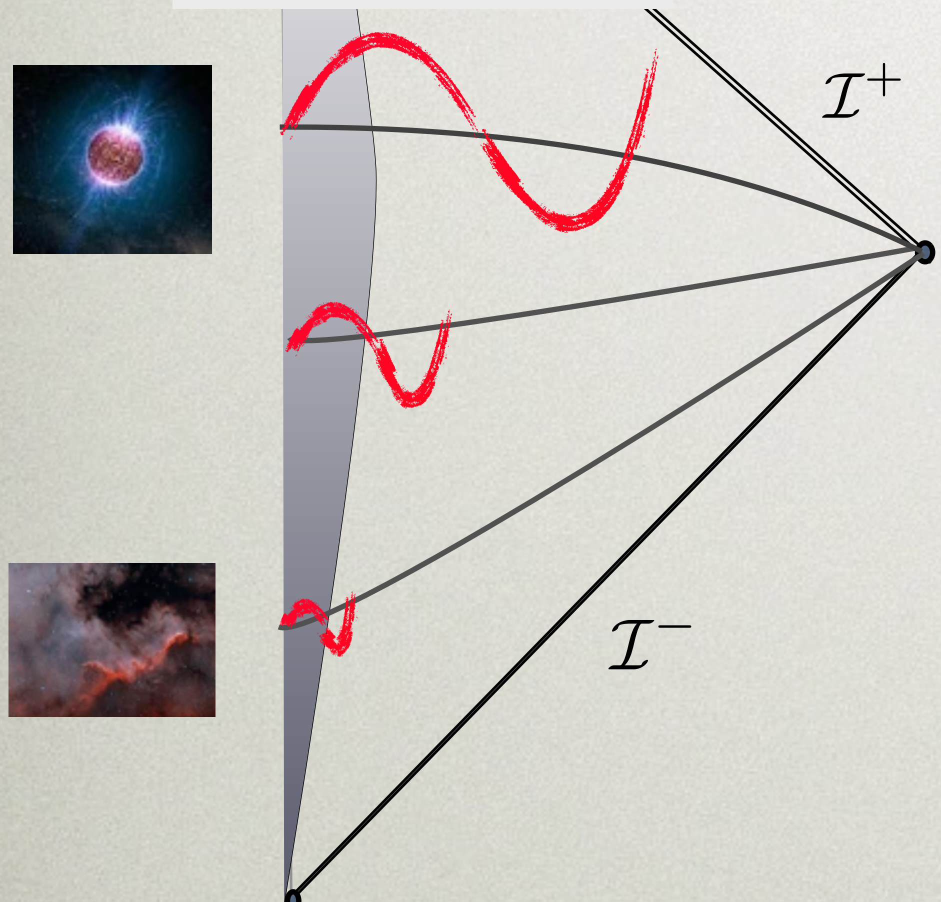
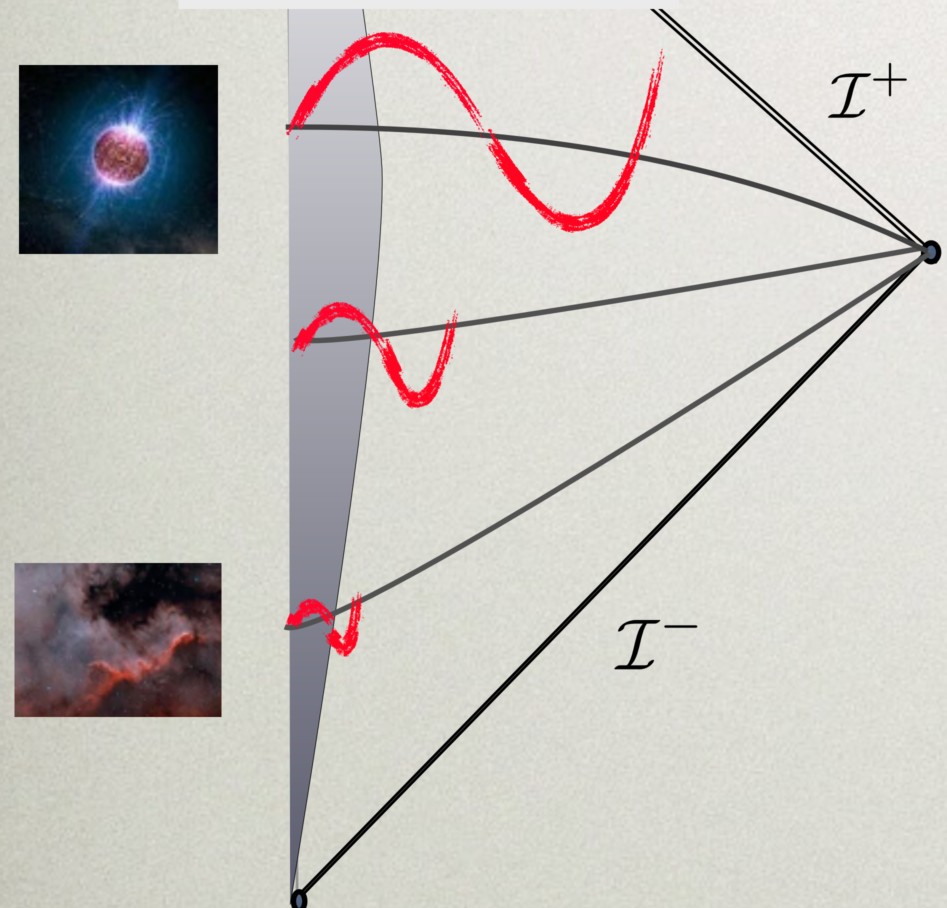


(1) The appearance of of certain "classical" correlations

Awaking the vacuum



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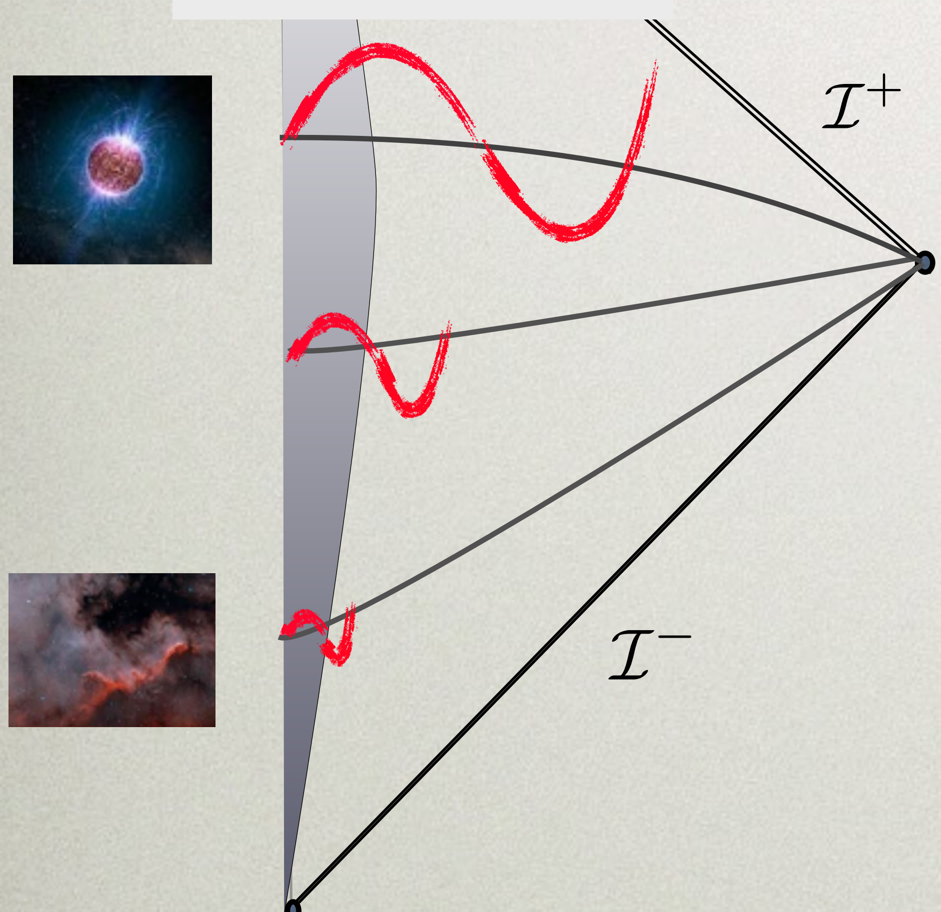

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System
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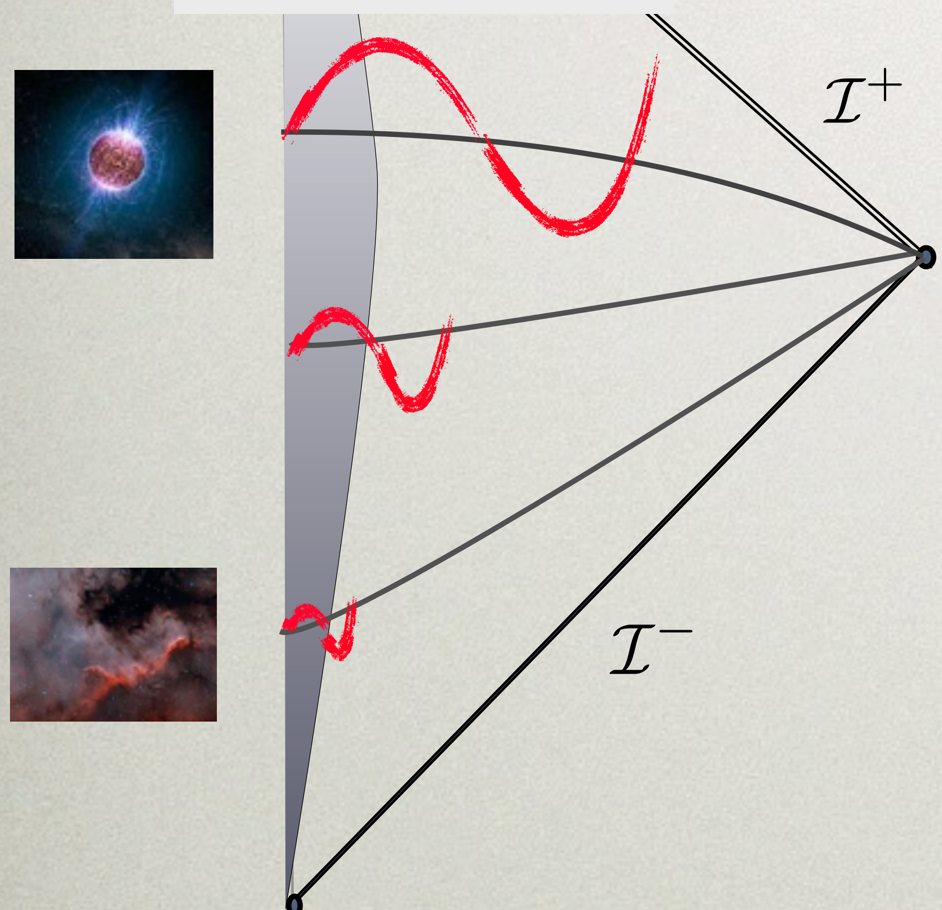

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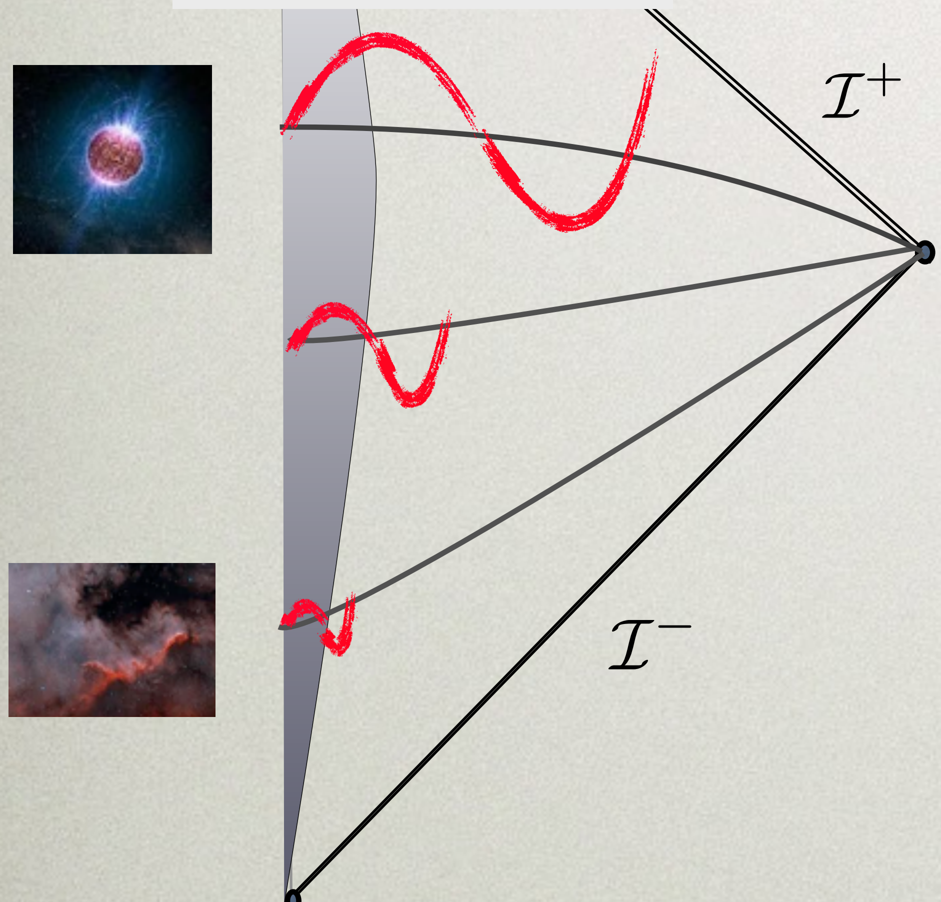

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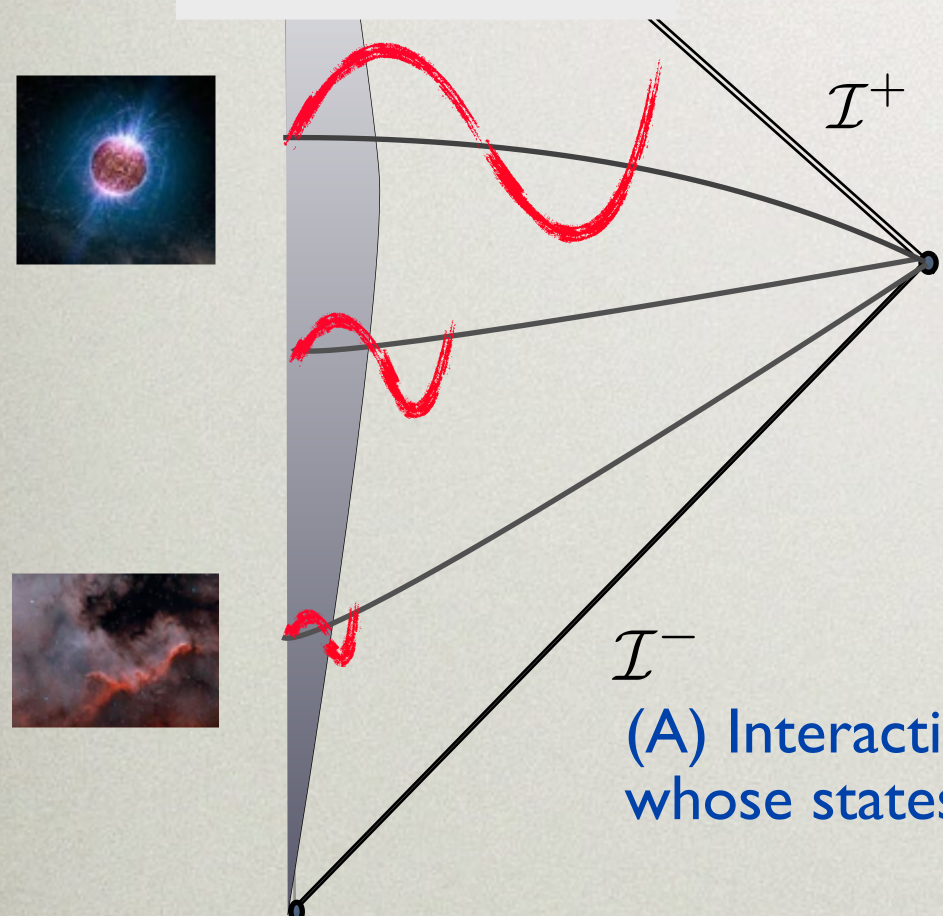

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System + Environment

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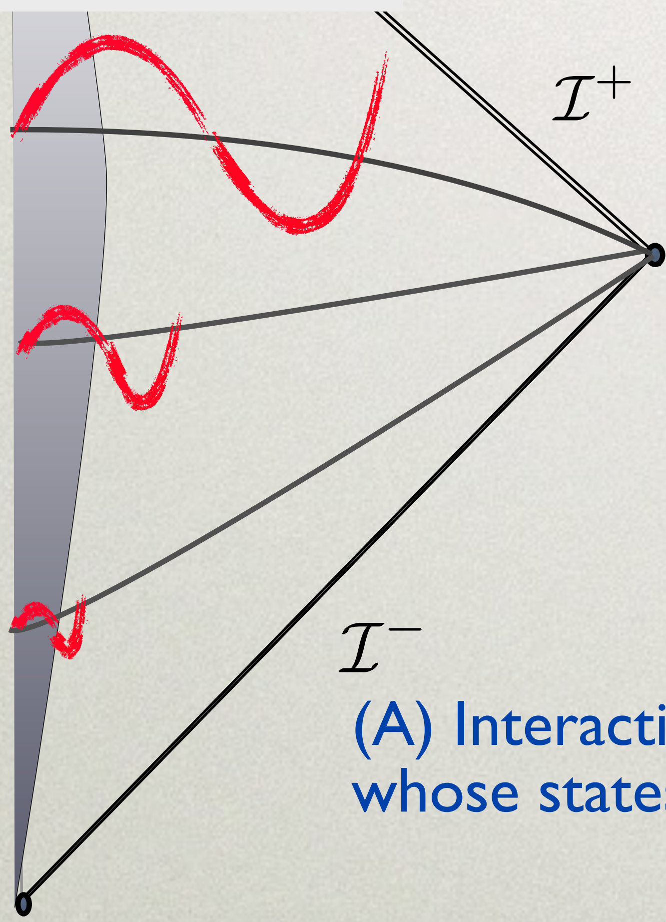
Awaking the vacuum



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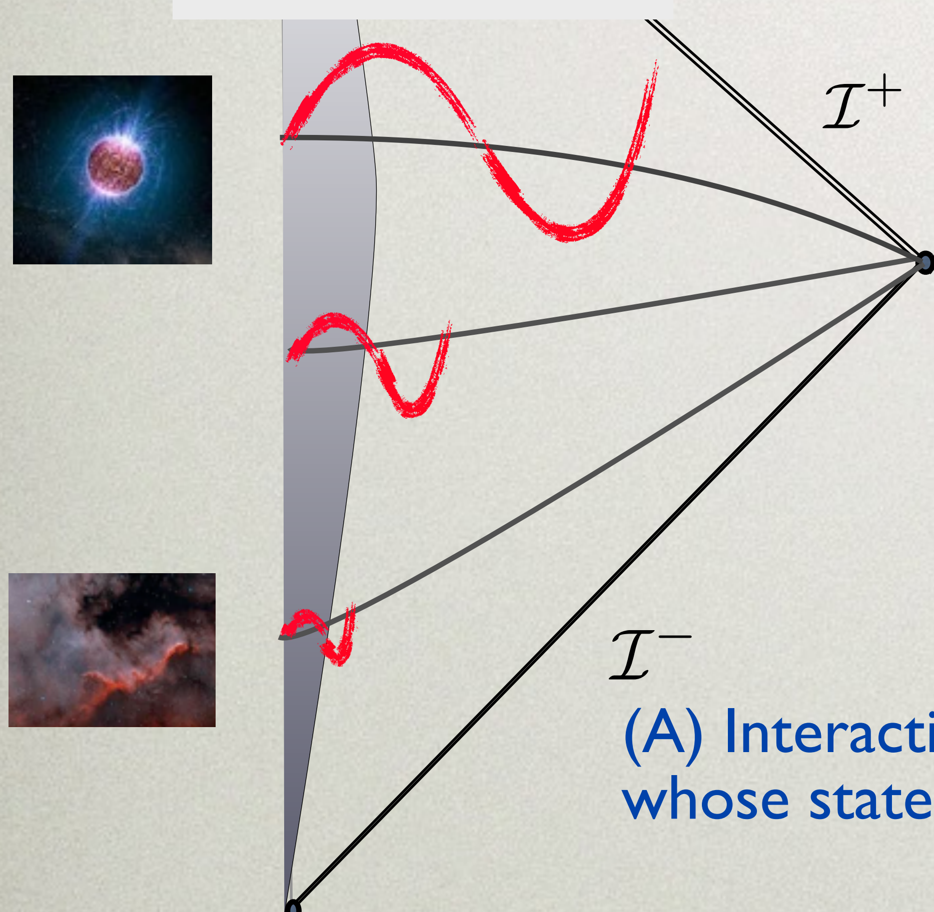

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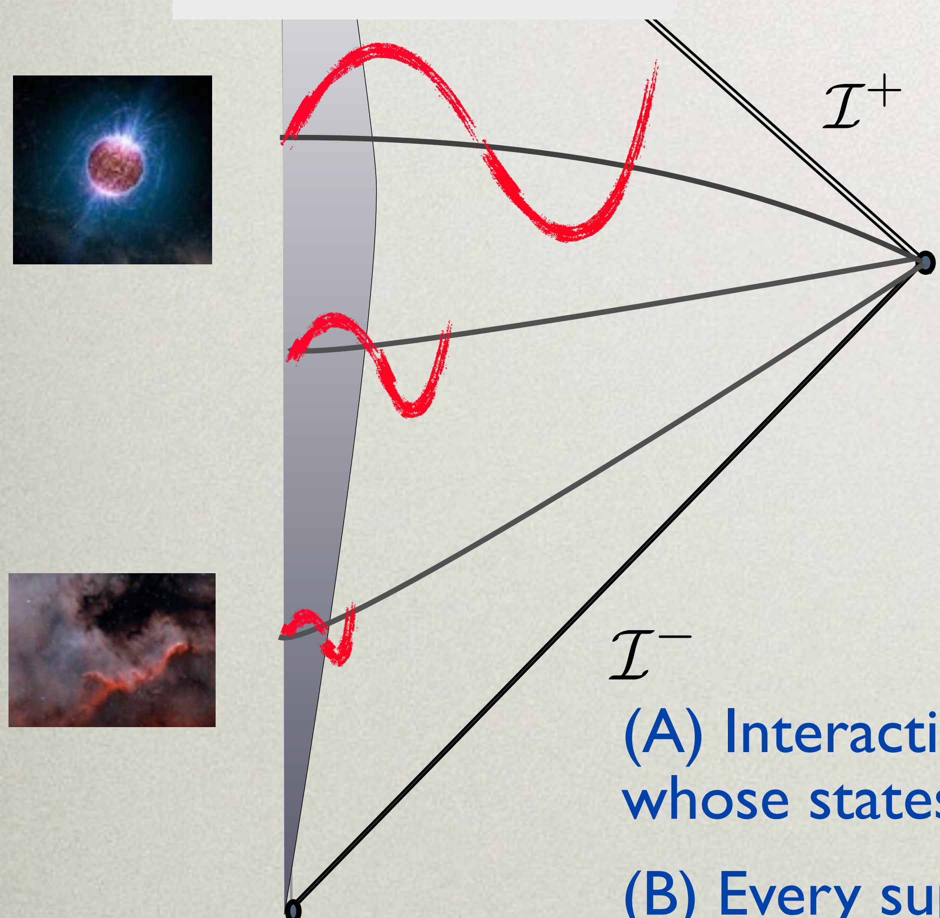

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System	+	Environment
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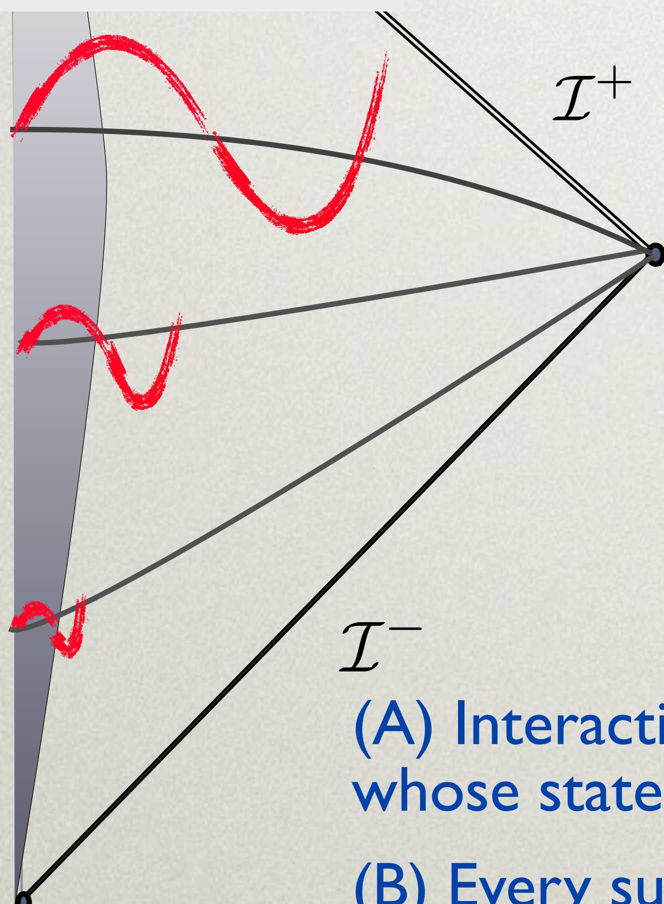

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W. Zurek, RMP (2003), W. Zurek, Nature Phys. (2009)

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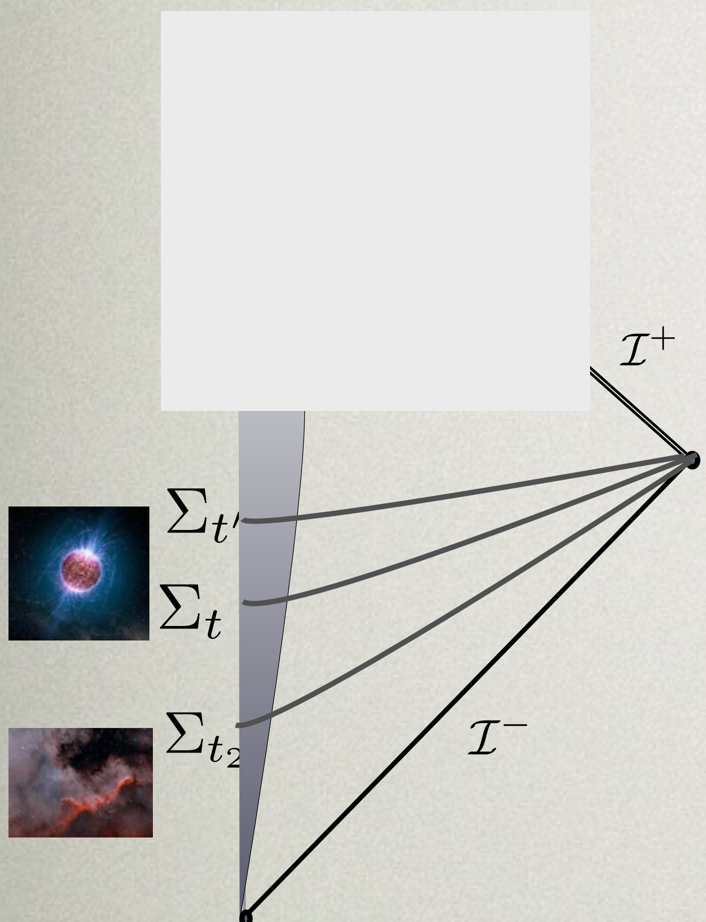

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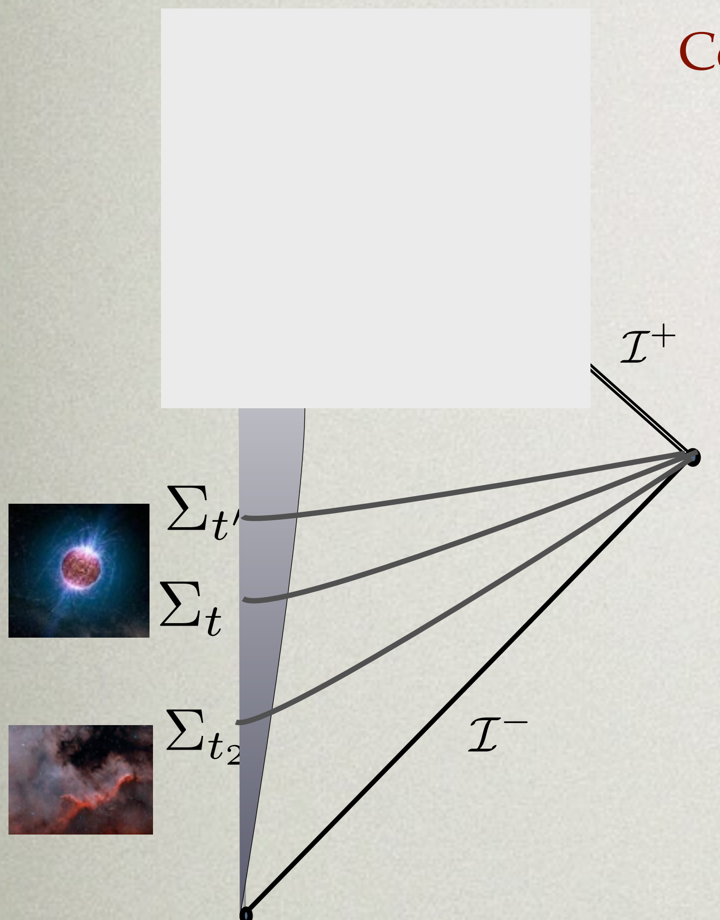

Complete orthonormal set of solutions of KG equation

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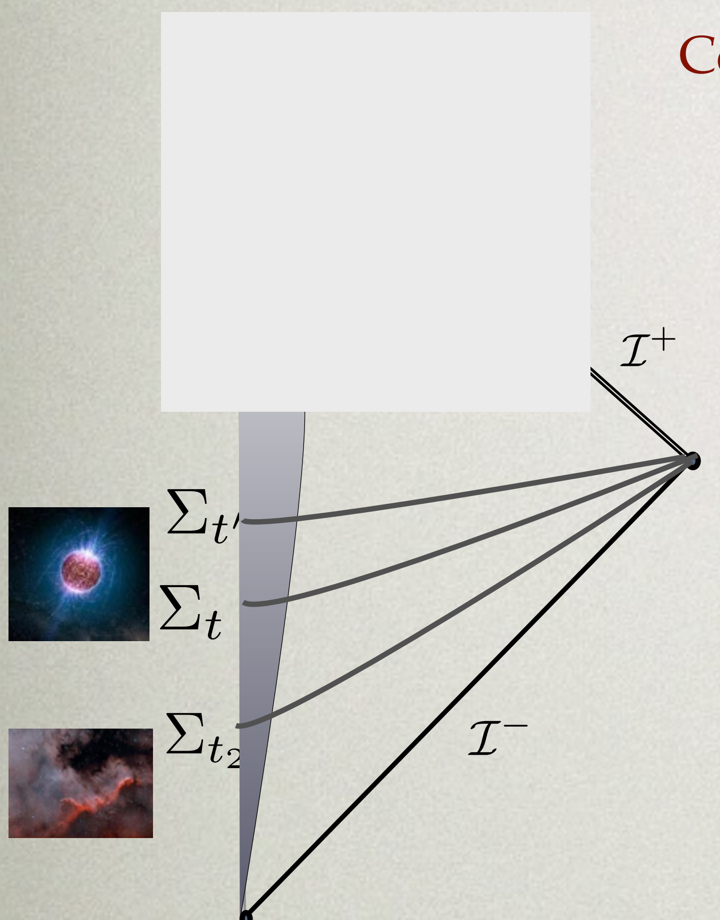

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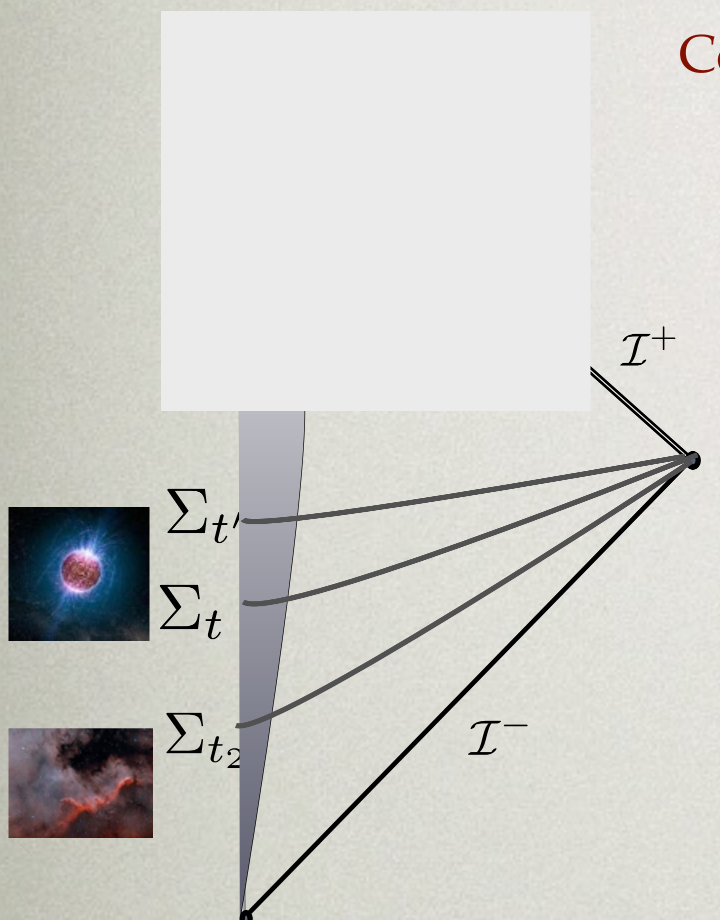

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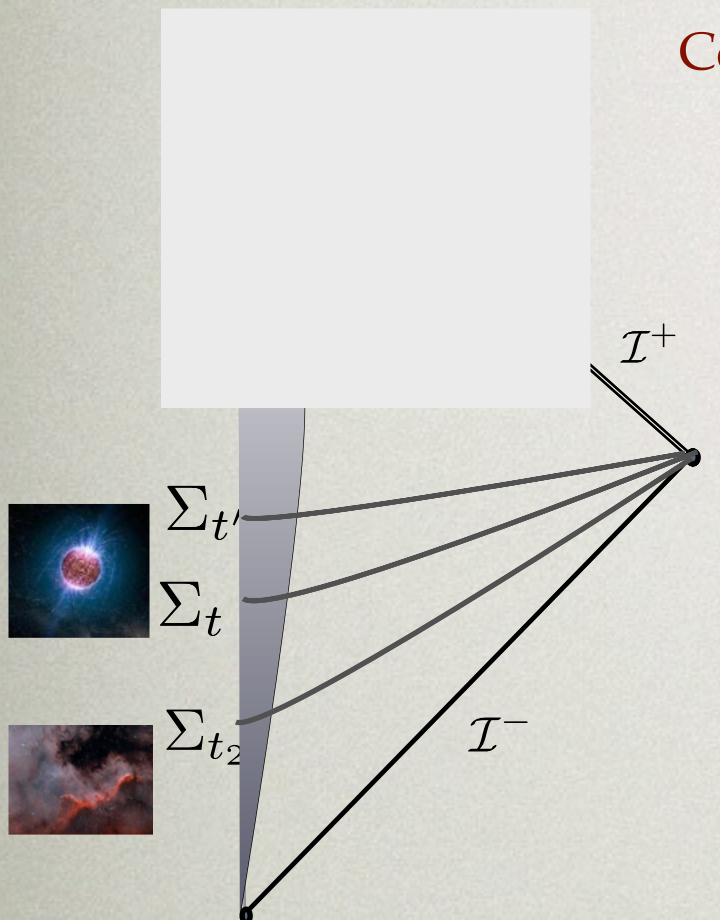

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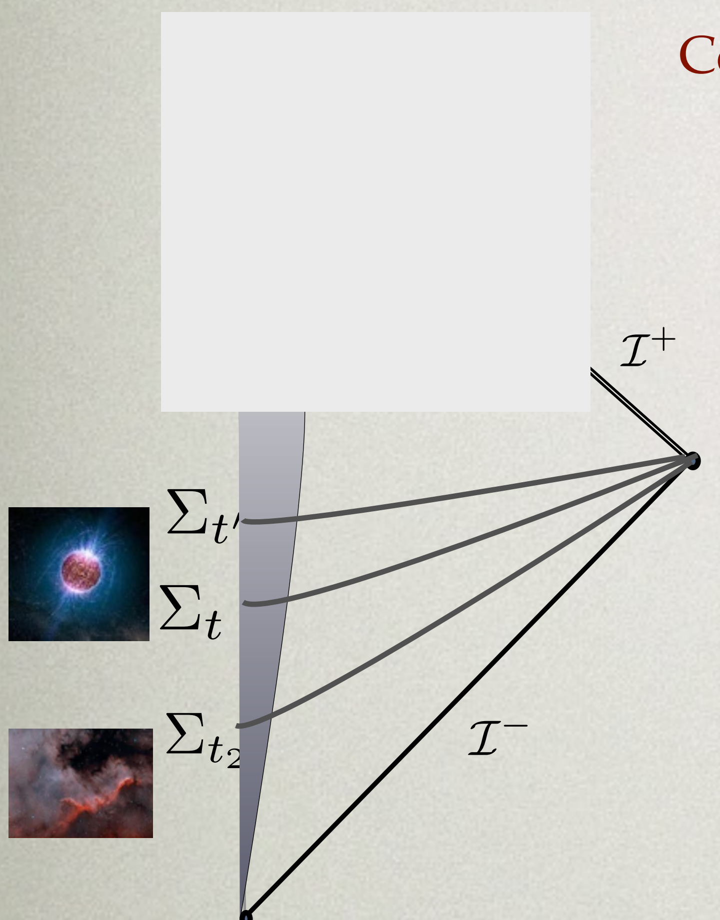

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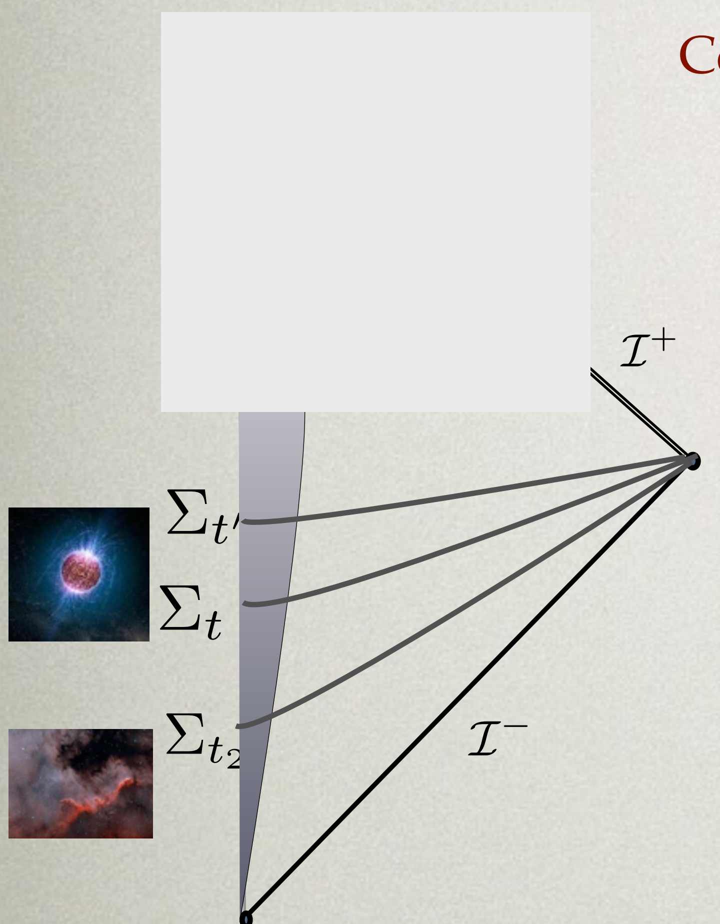
Upside down harmonic oscillator

$$\hat{q}_{\Omega} \equiv \frac{1}{\sqrt{2\Omega}}(\hat{a}_{\Omega} + \hat{a}_{\Omega}{}^{\dagger}) \qquad \hat{p}_{\Omega} \equiv -i\sqrt{\frac{\Omega}{2}}(\hat{a}_{\Omega} - \hat{a}_{\Omega}{}^{\dagger})$$

From quantum to classical

A. Landulfo, W. Lima, G. Mastsas, and D. Vanzella, PRD (2015)



Complete orthonormal set of solutions of KG equation

$$v^{(+)}_{\varpi l\mu} = e^{-i\varpi t}\frac{F_{\varpi l}(\chi)}{\sqrt{2\varpi}\,r(\chi)}Y_{l\mu}(\theta,\phi),$$

$$w^{(+)}_{\Omega} = \frac{e^{\Omega t - i\pi/4} + e^{-\Omega t + i\pi/4}}{\sqrt{4\Omega}}\frac{F_\Omega(\chi)}{r(\chi)}Y_{00}(\theta,\varphi)$$

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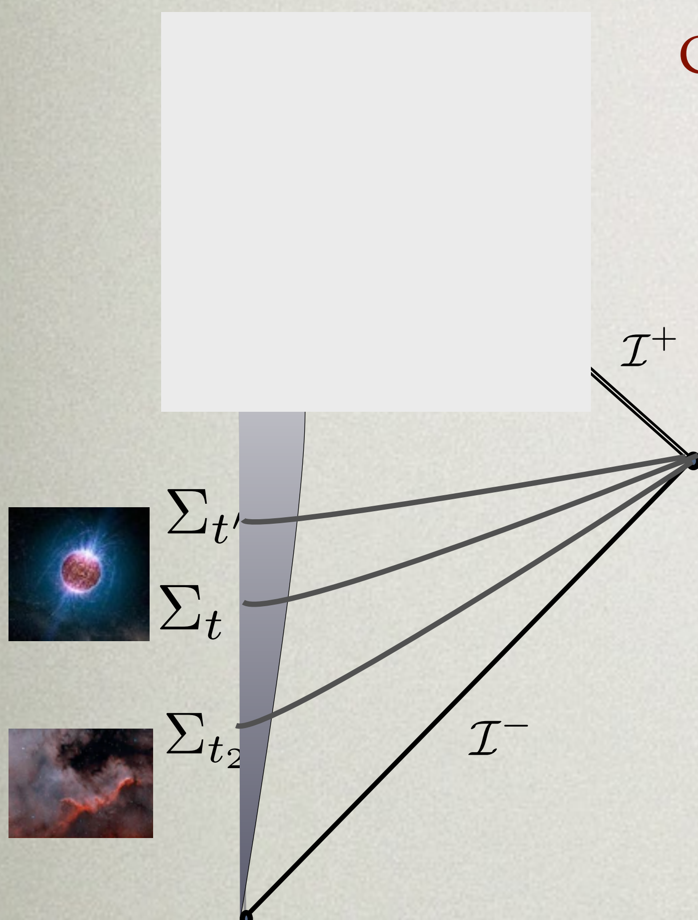

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From quantum to classical

- Unstable Phase

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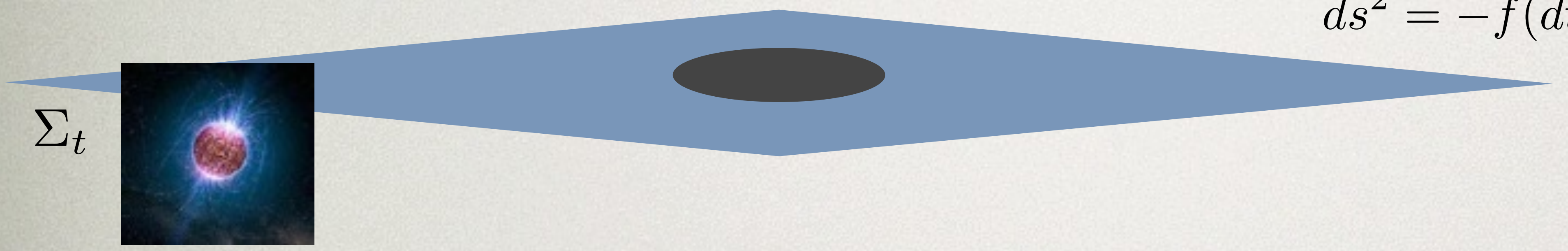

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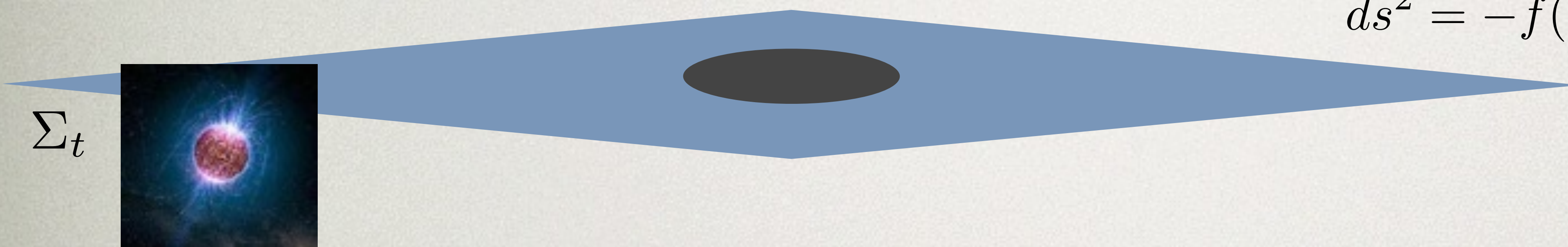
Σ_t



- Wigner Function

$$W(t,q,p) \equiv \frac{1}{2\pi}\int_{-\infty}^{+\infty} dy\varrho(t, q-y/2, q+y/2)e^{ipy},$$

From quantum to classical

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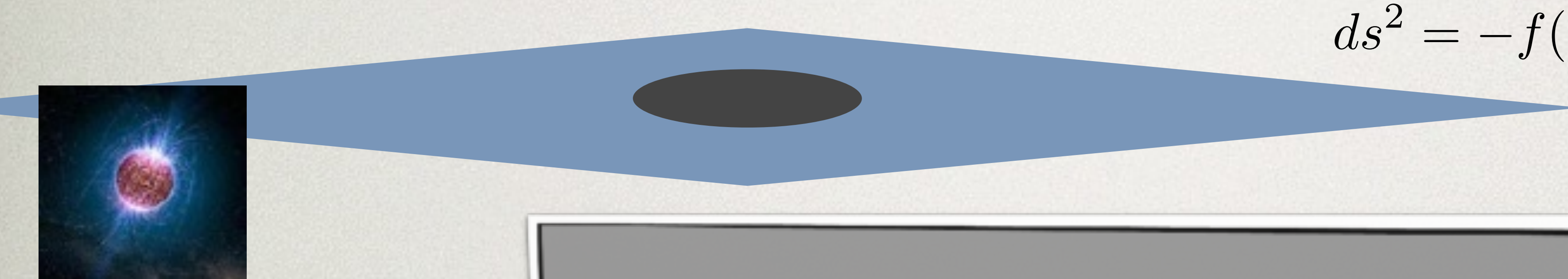

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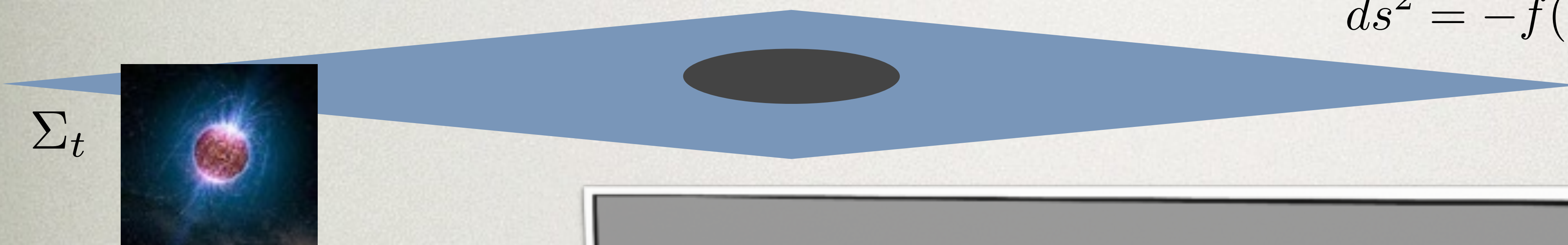

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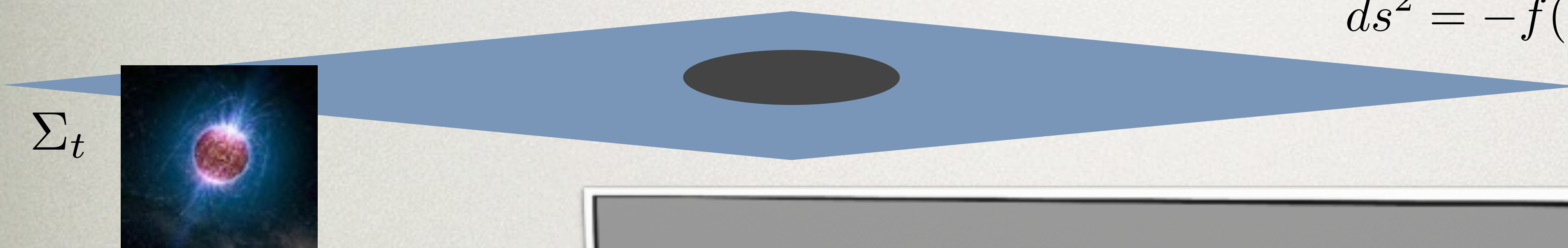

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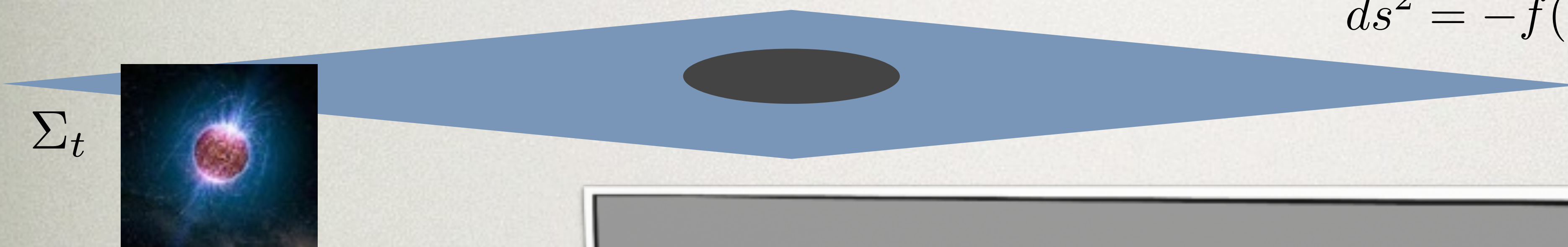

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From quantum to classical

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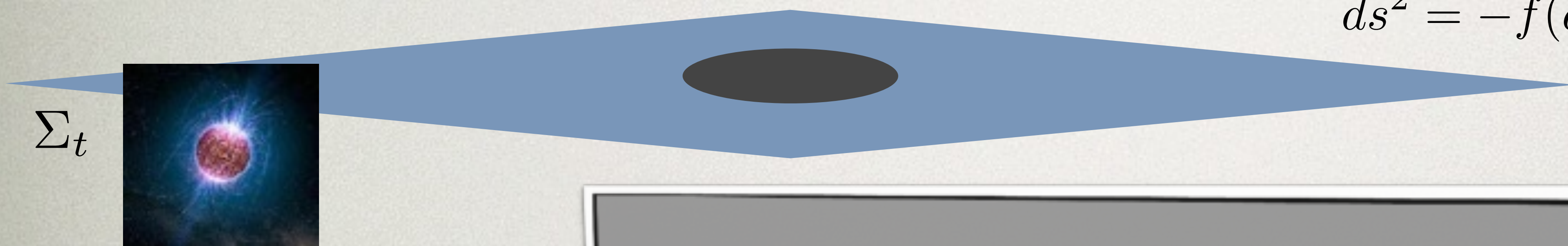

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Liouville equation

From quantum to classical

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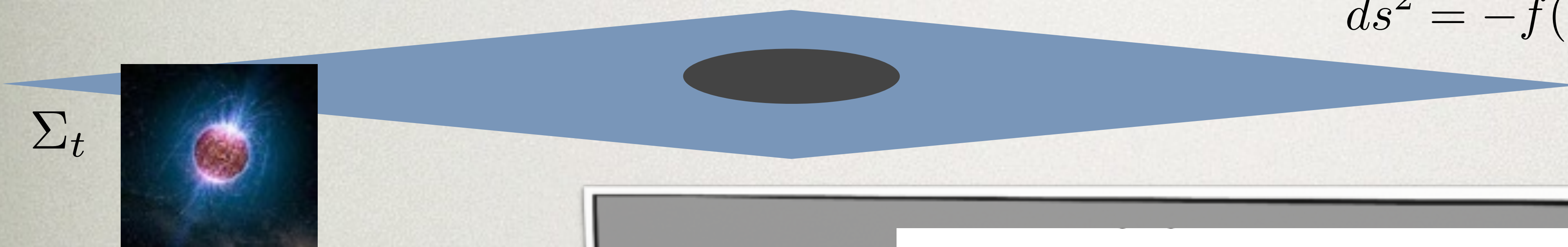

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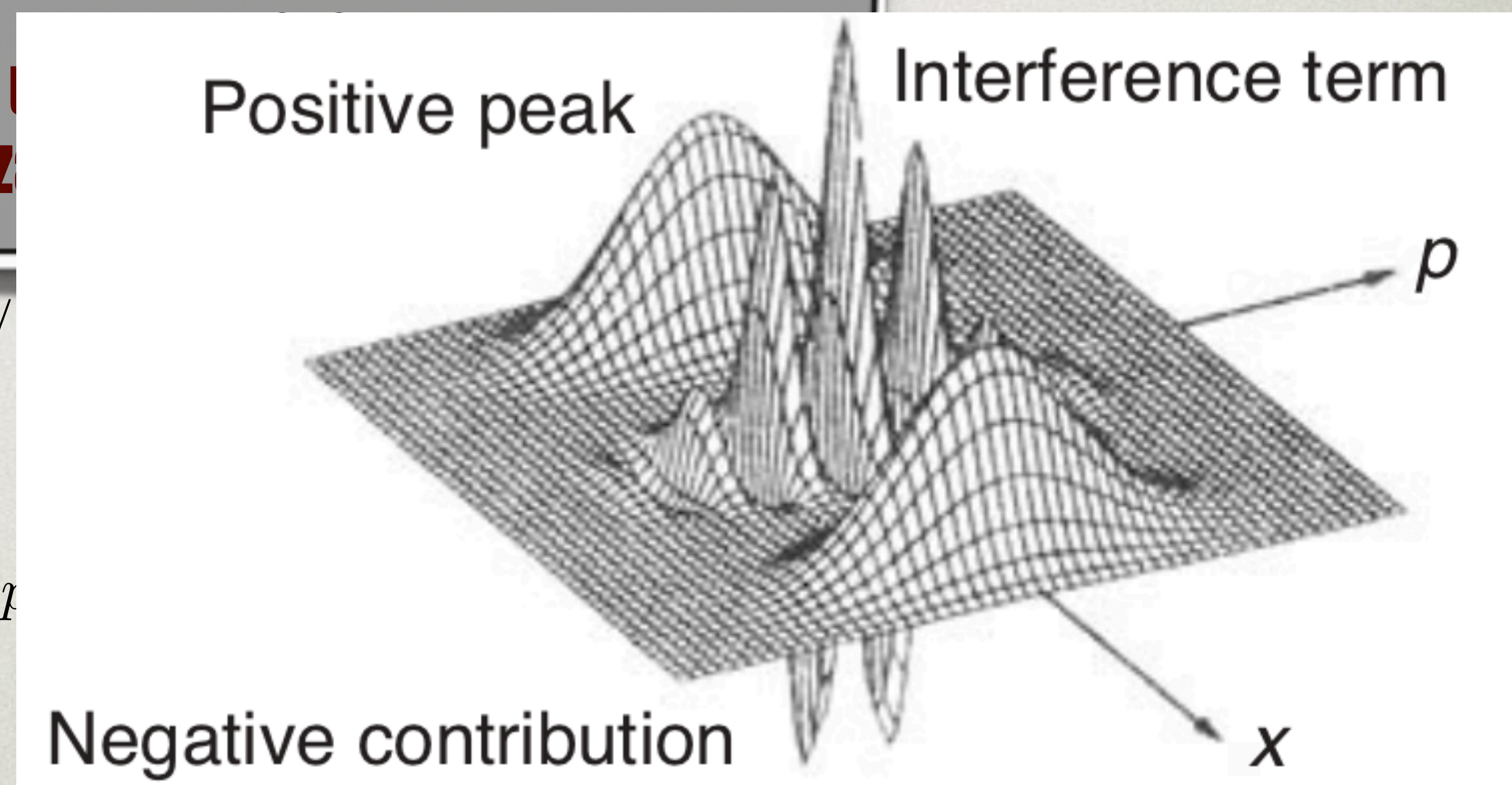

W. Zurek, Decoherence and the Transition from Quantum to Classical—Revisited

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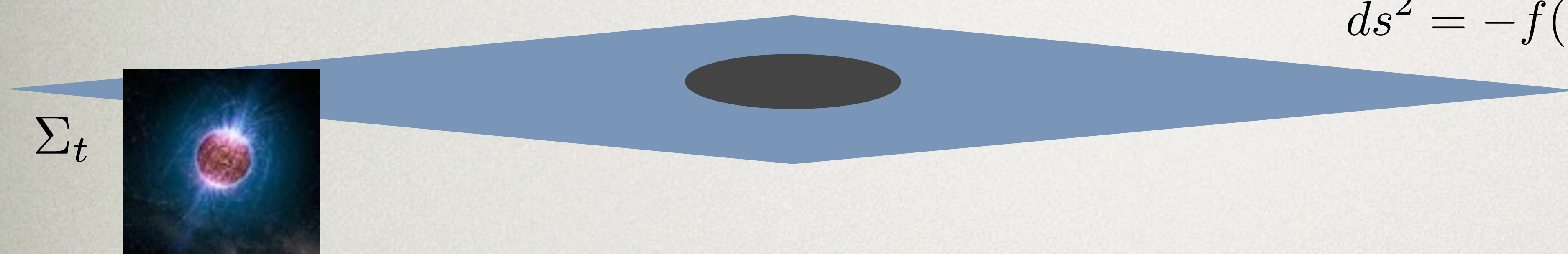

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From quantum to classical

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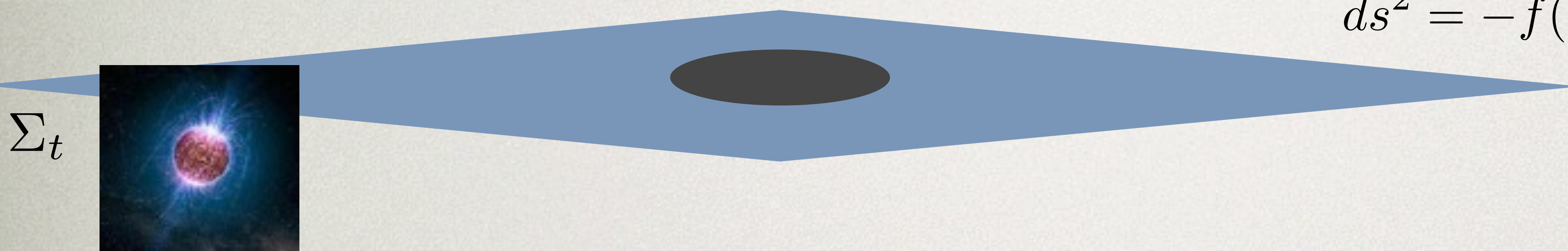

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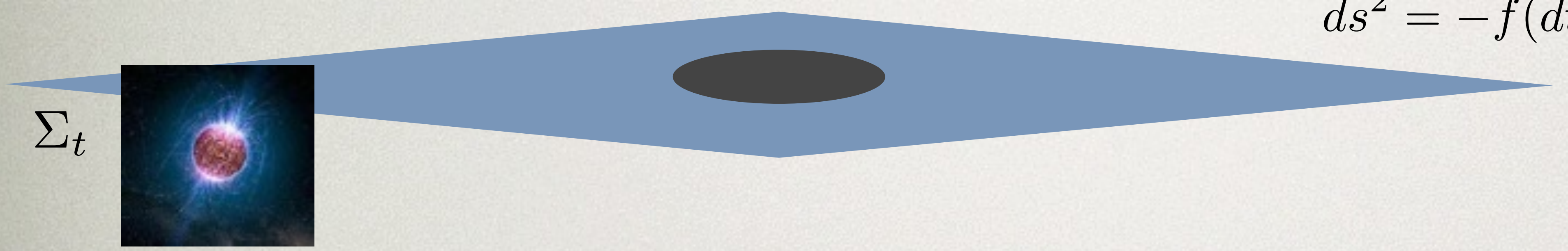

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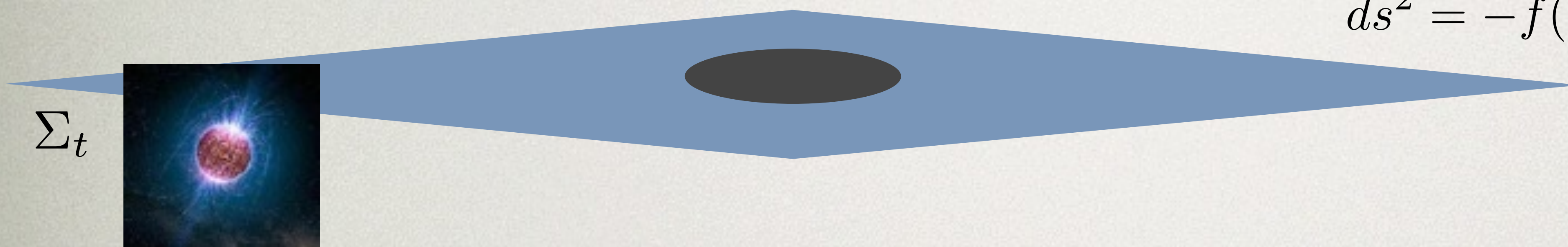

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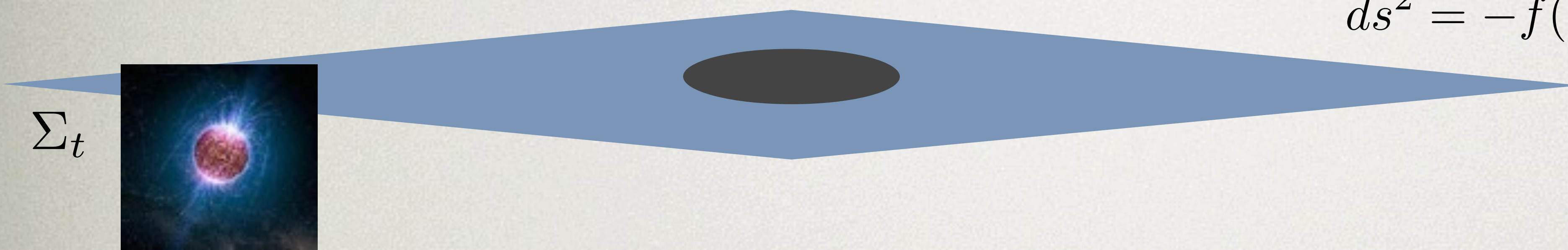

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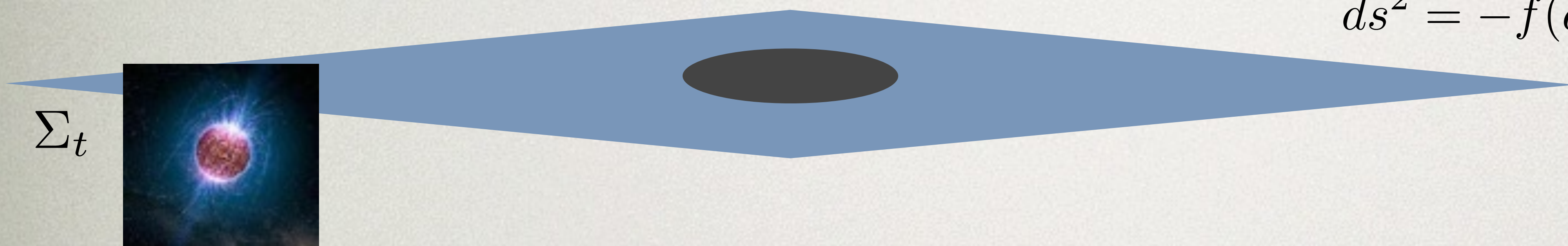

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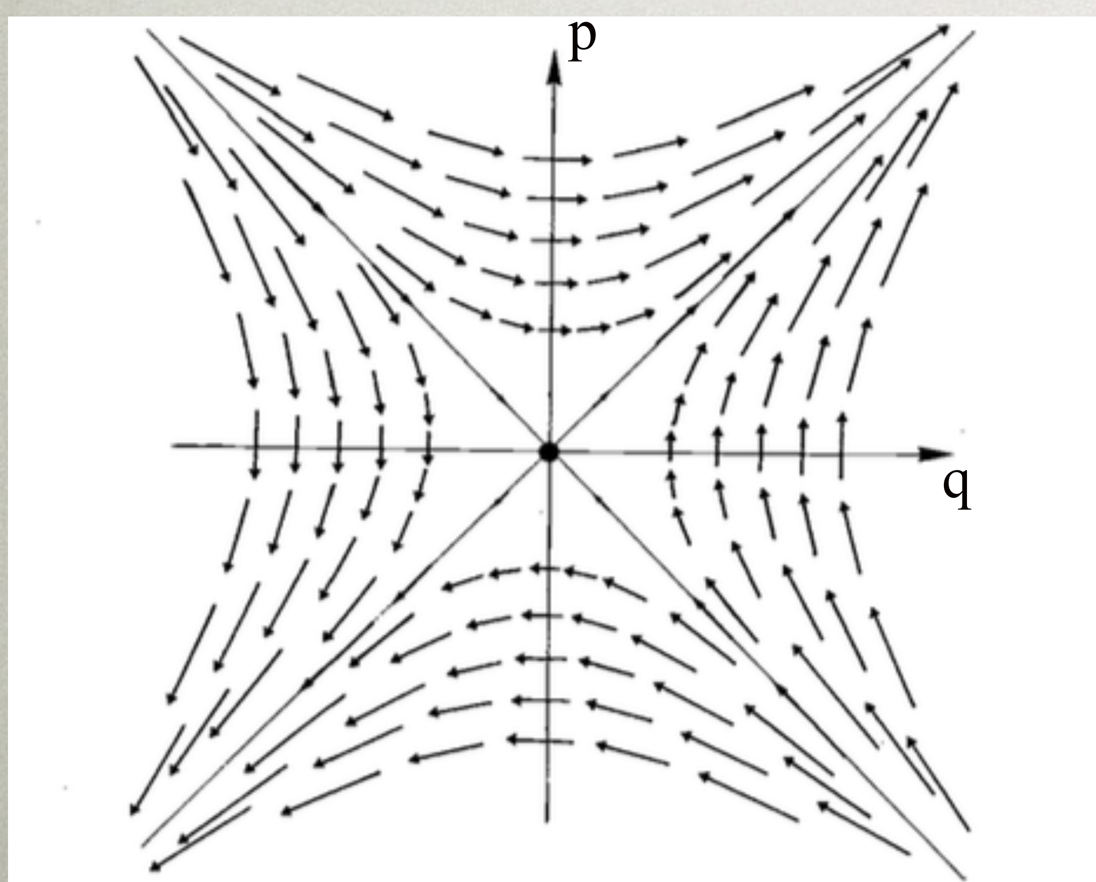

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FROM QUANTUM TO CLASSICAL

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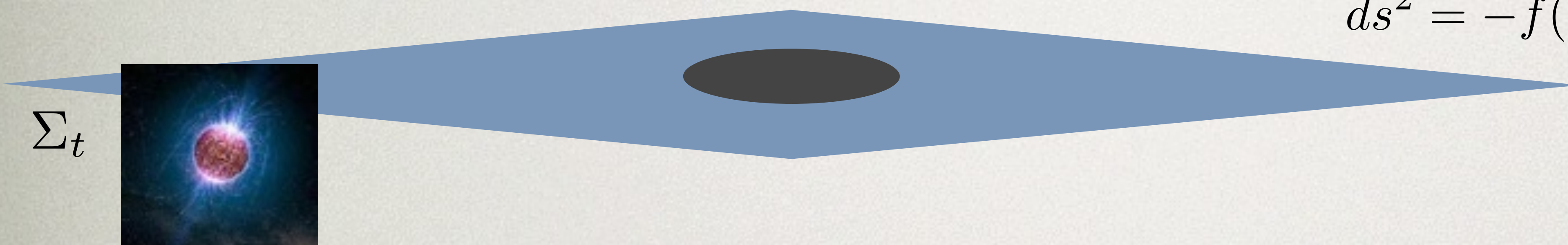

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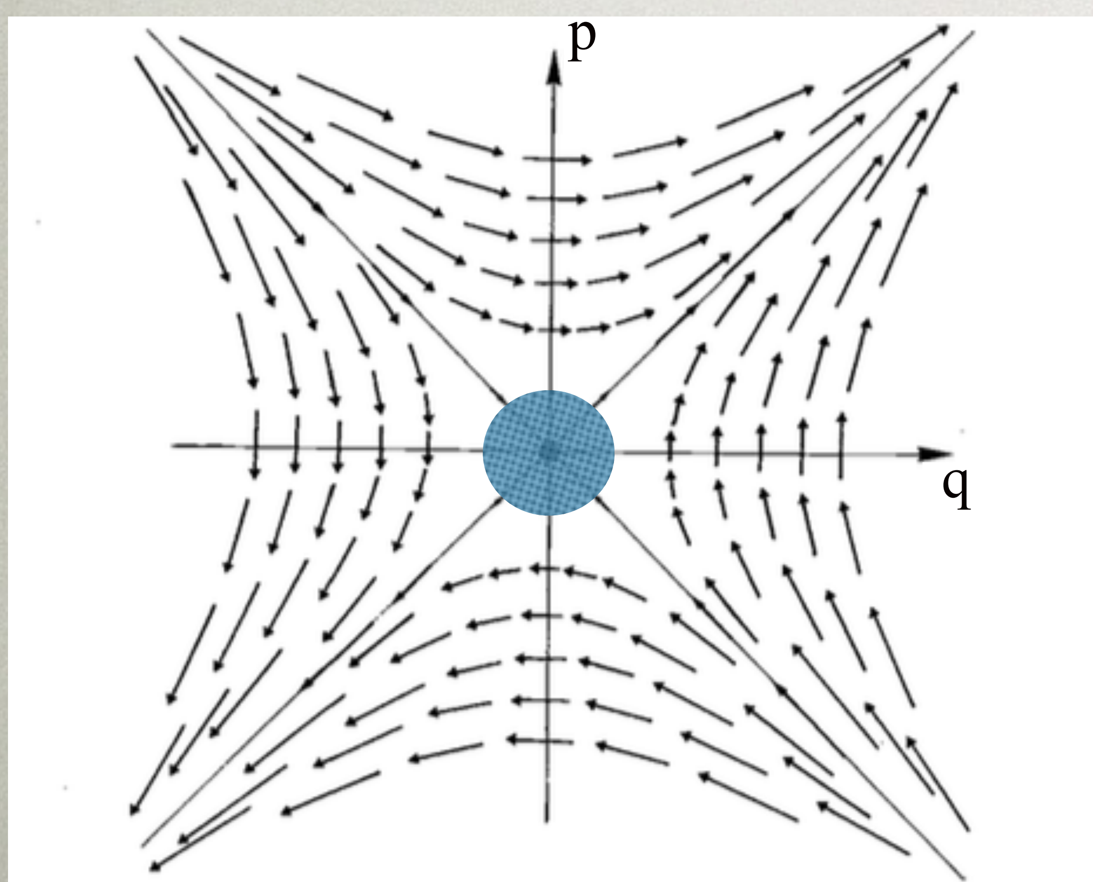

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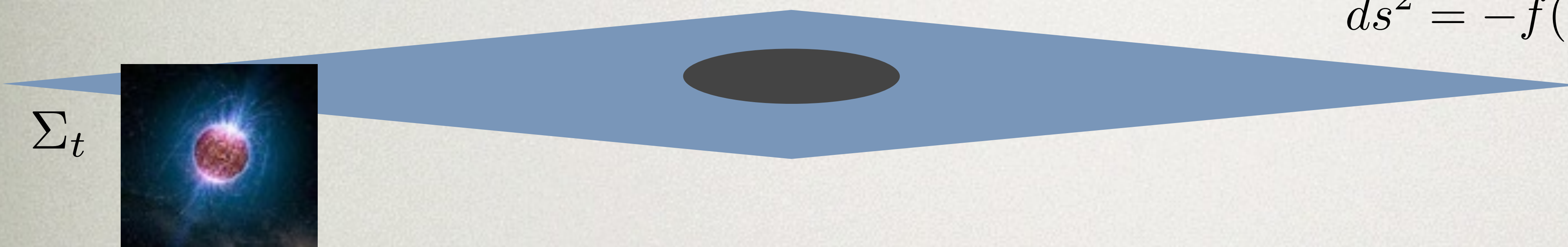

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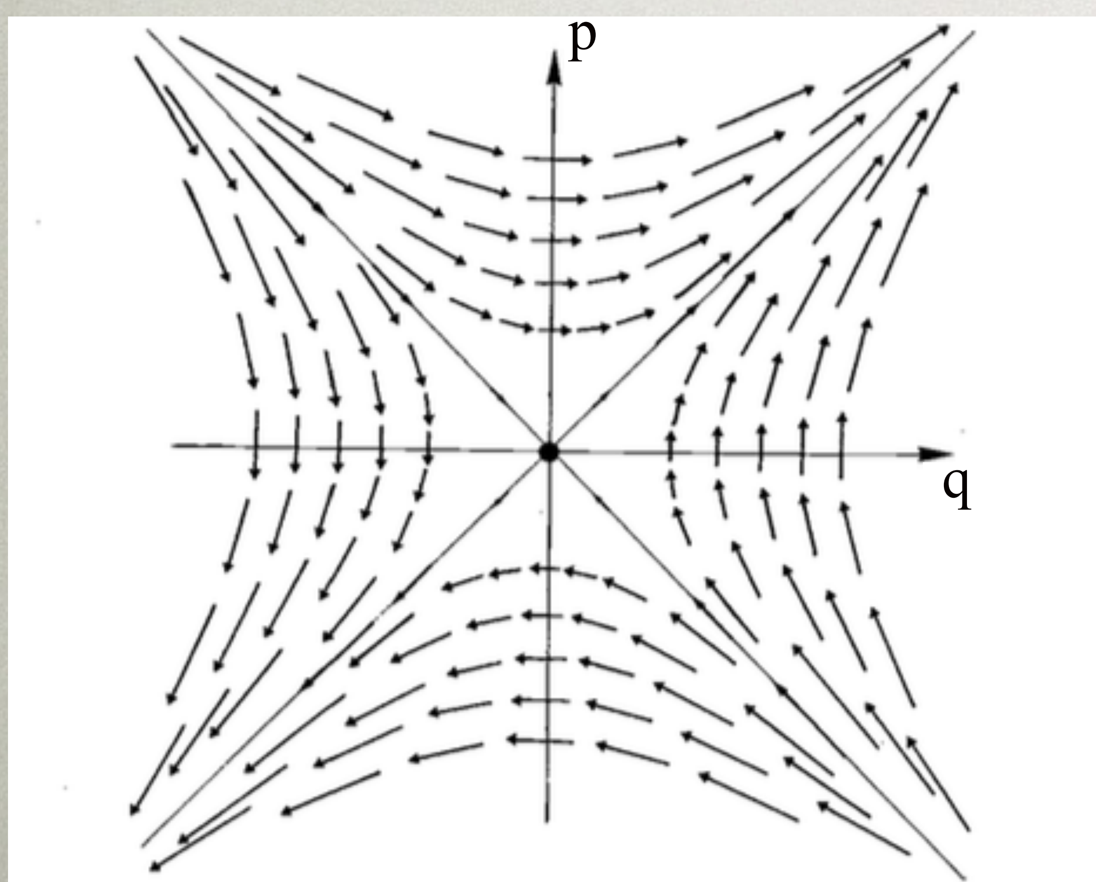

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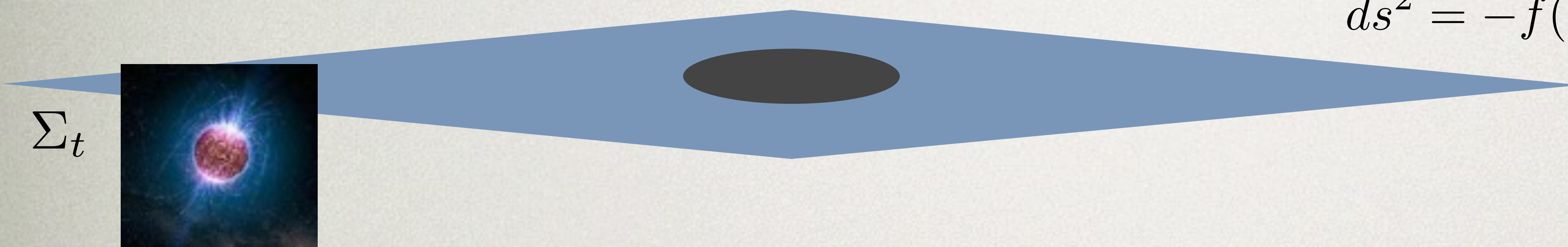

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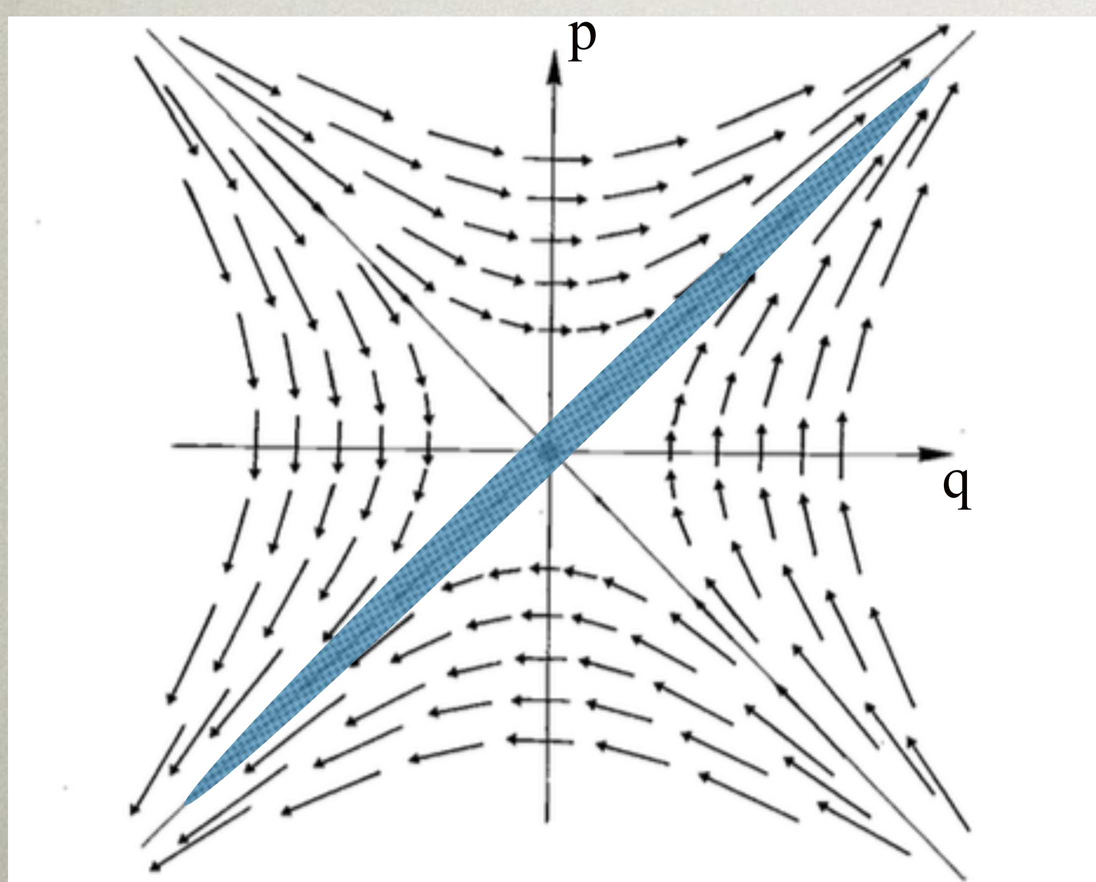

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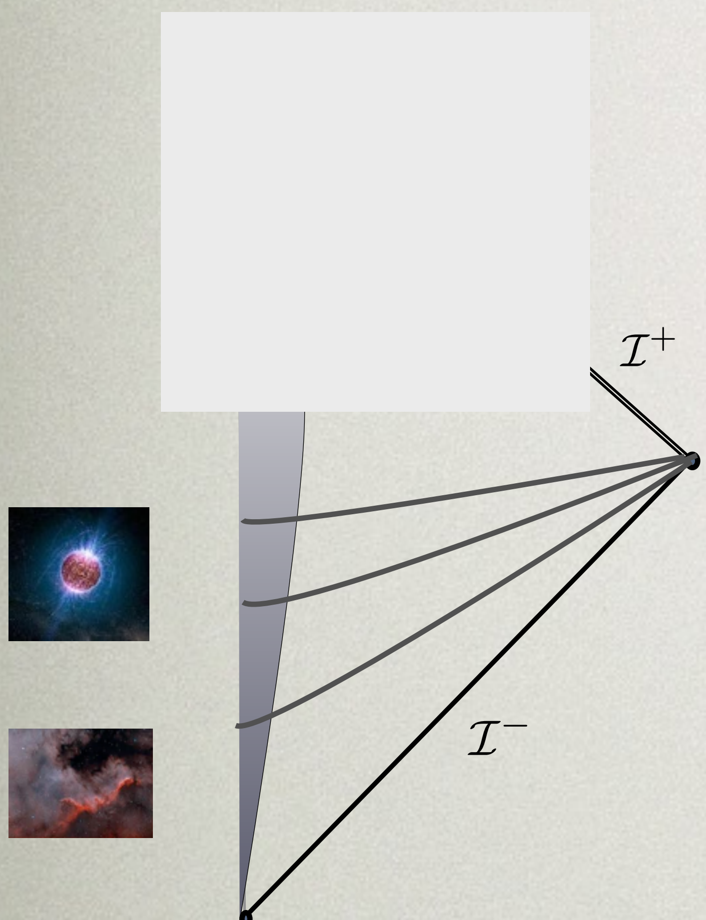

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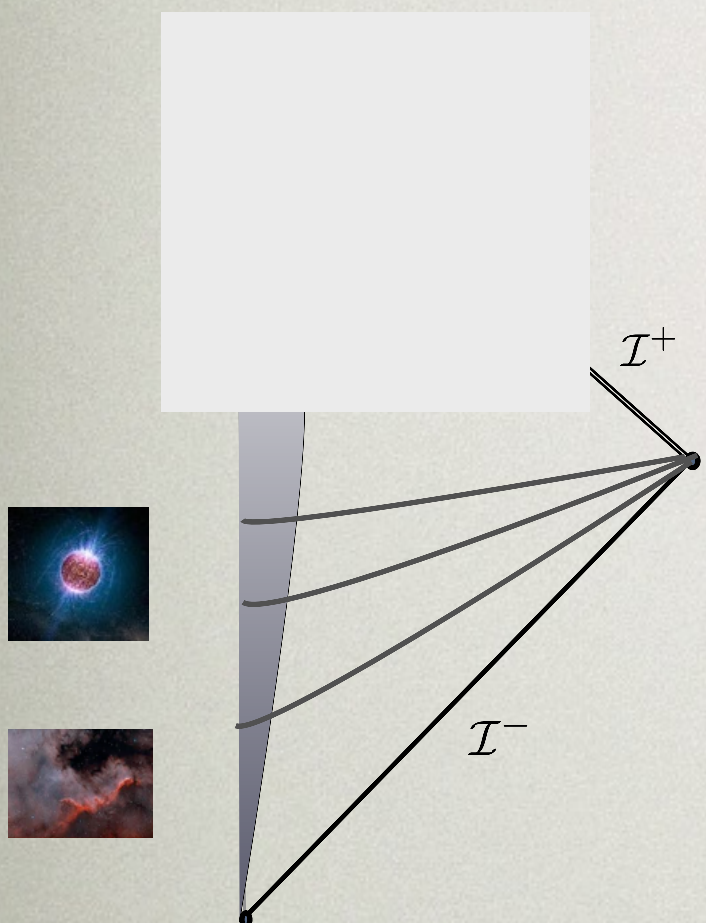

free scalar field

$$S_\phi[\phi] \equiv -\frac{1}{2}\int_{\mathcal{M}} d^4x\sqrt{-g}\phi P\phi,\ P \equiv -(\nabla^a\nabla_a + m^2 + \xi R)$$

From quantum to classical

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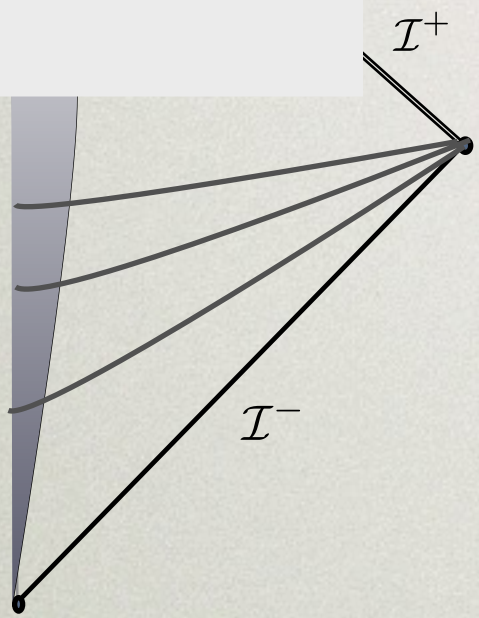
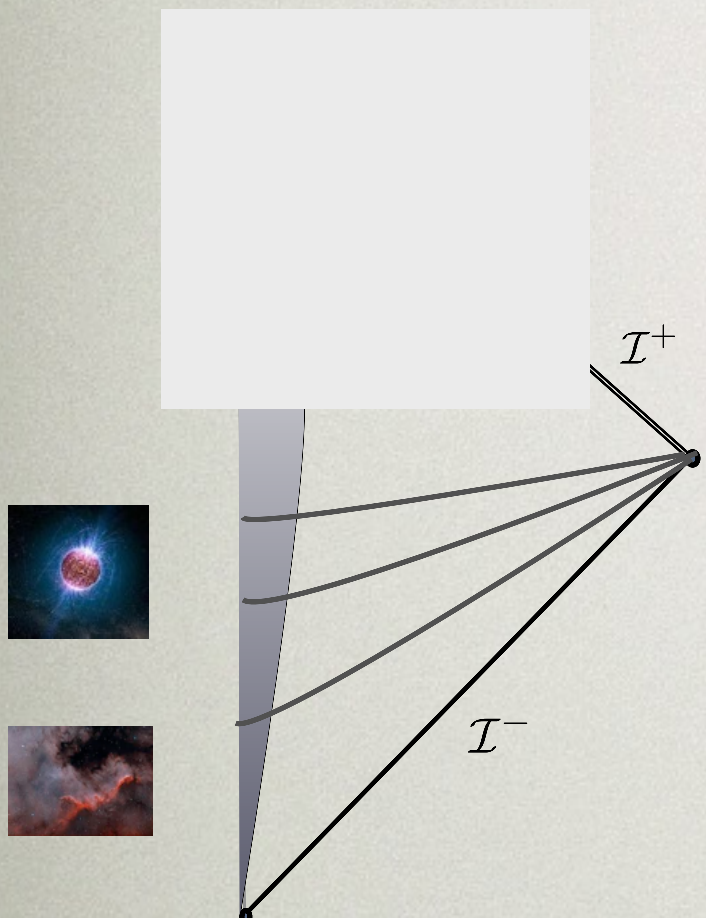


$$g_{ab} \to g_{ab} + \kappa\gamma_{ab}, \Phi \to \Phi + \phi\ (\Phi = 0)$$

From quantum to classical



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free graviton (with gauge fixing term)

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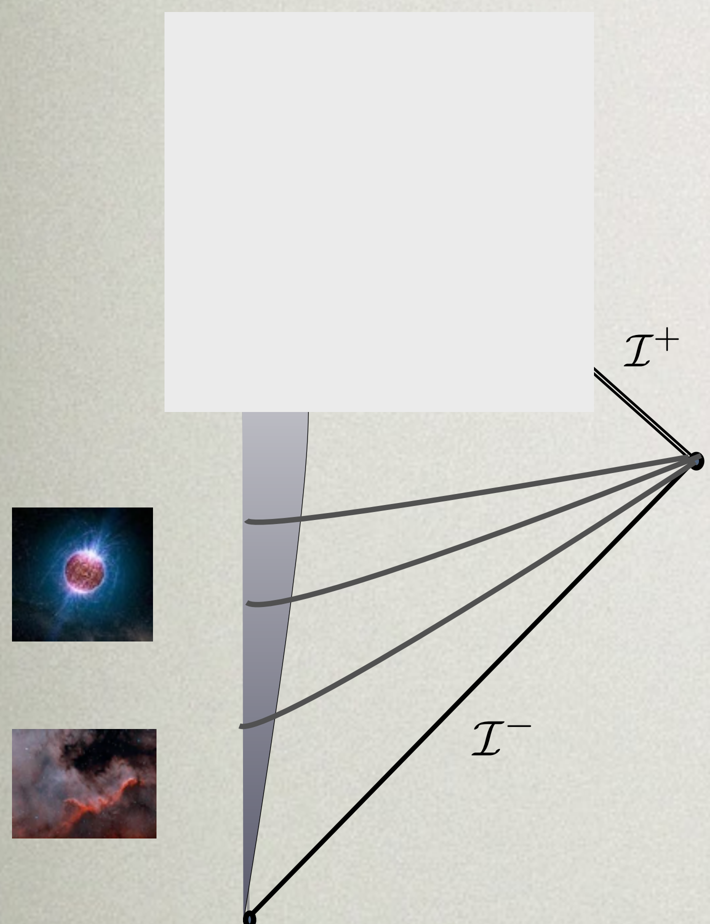

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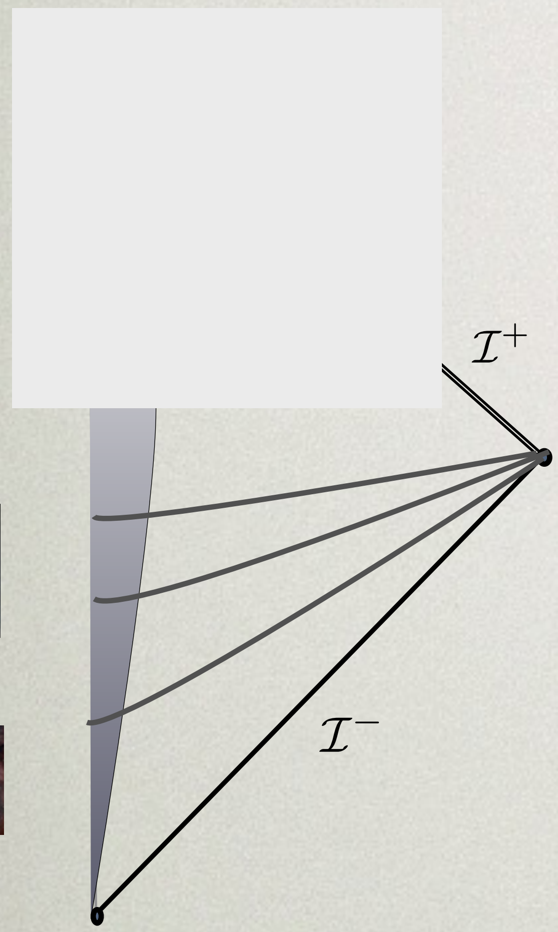

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Interaction

$$S_{int}[\phi,\gamma_{ab}] \equiv \frac{\kappa}{2}\int_{\mathcal{M}} \sqrt{-g}d^4xT_{ab}\gamma^{ab}$$

From quantum to classical

- Unstable Phase

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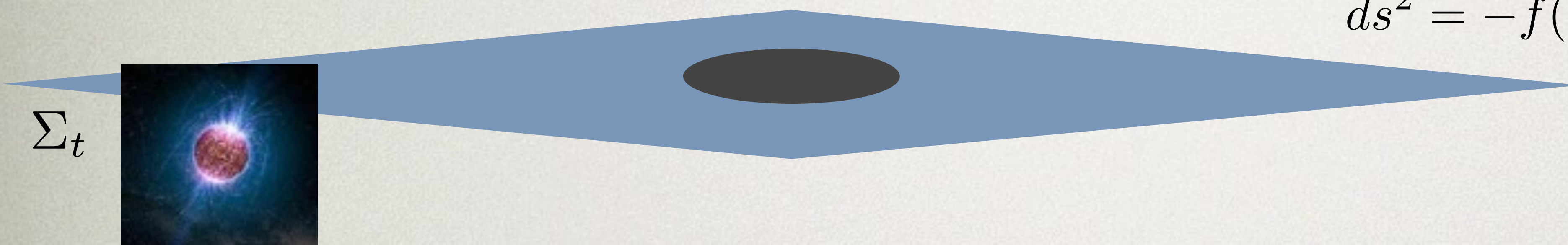
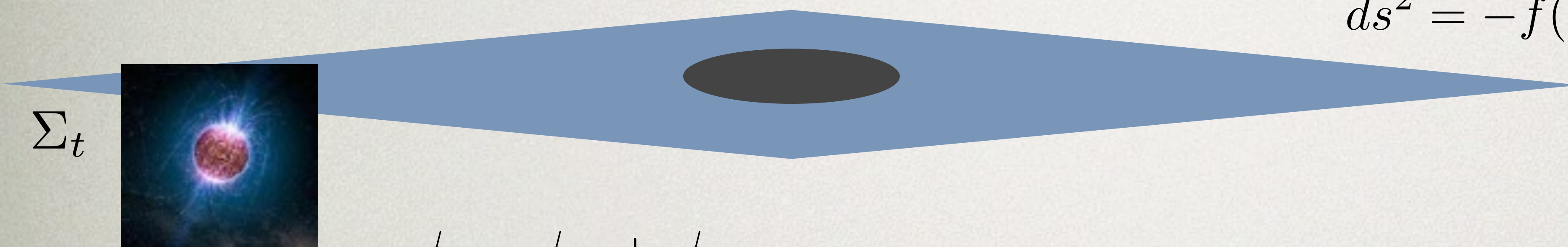


From quantum to classical

- Unstable Phase

$$ds^2 = -f(dt^2 - d\chi^2) + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

Σ_t



$$\phi = \phi_s + \phi_u$$

System of interest - Unstable mode (which is the one we expect that "classicalize")

$$\phi_u$$

Environment - Stable modes and graviton

$$\phi_s,\ \gamma_{ab}$$

From quantum to classical

- Unstable Phase

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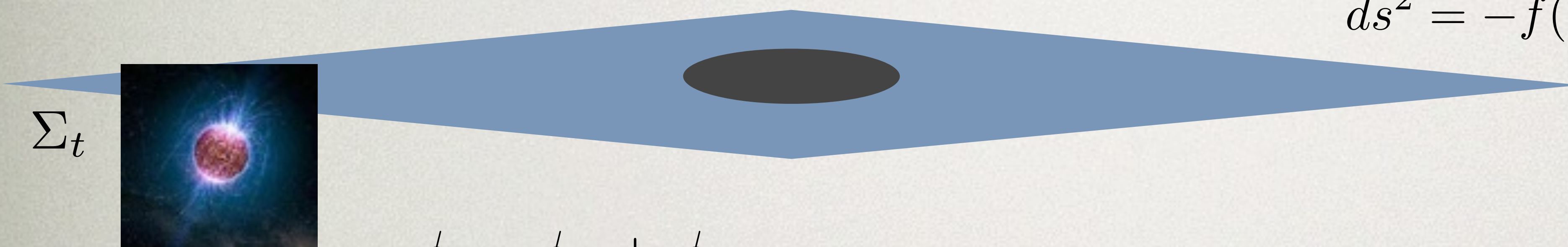

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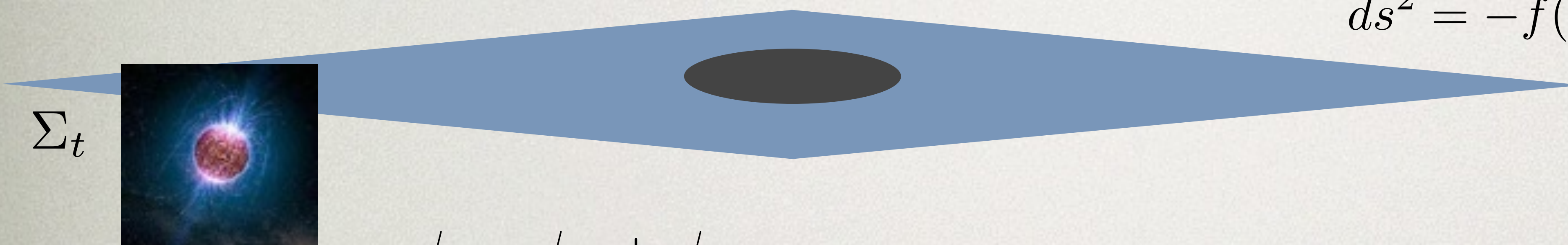

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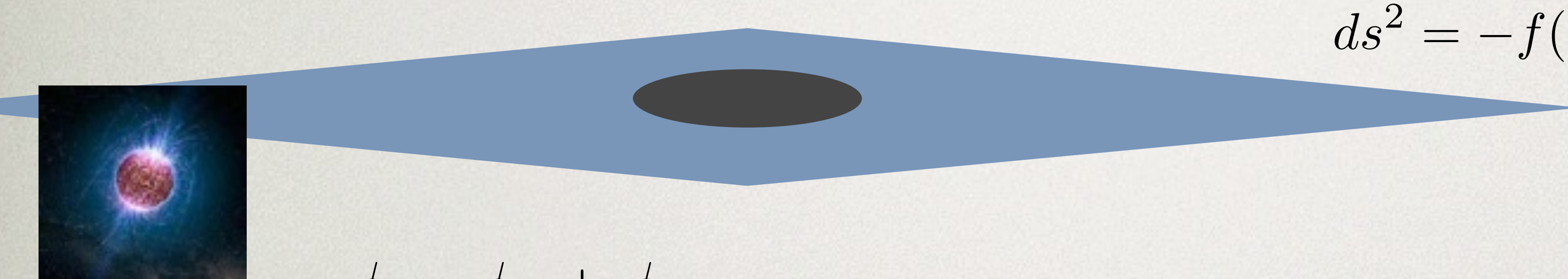
From quantum to classical

- Unstable Phase



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$$\phi_s,\ \gamma_{ab}$$

$$S_\phi[\phi] = S_\phi[\phi_{\rm s}] + S_\phi[\phi_{\rm u}]$$

$$T_{ab} = T^{(\rm s)}_{ab} + T^{(\rm u)}_{ab} + t_{ab}$$

$$S_{\rm int}[\phi, \gamma_{ab}] \equiv \frac{\kappa}{2}\int_{\mathcal{M}} d^4x\sqrt{-g}T^{(s)}_{ab}\gamma^{ab} + \frac{\kappa}{2}\int_{\mathcal{M}} d^4x\sqrt{-g}T^{(u)}_{ab}\gamma^{ab} + \frac{\kappa}{2}\int_{\mathcal{M}} d^4x\sqrt{-g}t_{ab}\gamma^{ab}$$

From quantum to classical

- Unstable Phase

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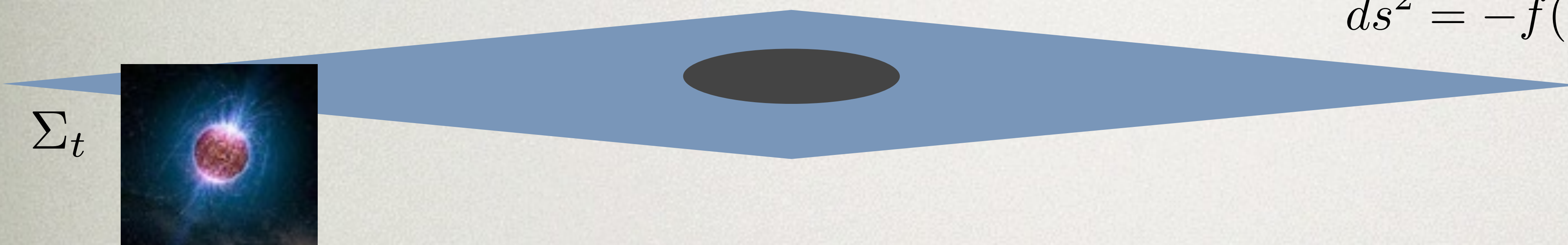

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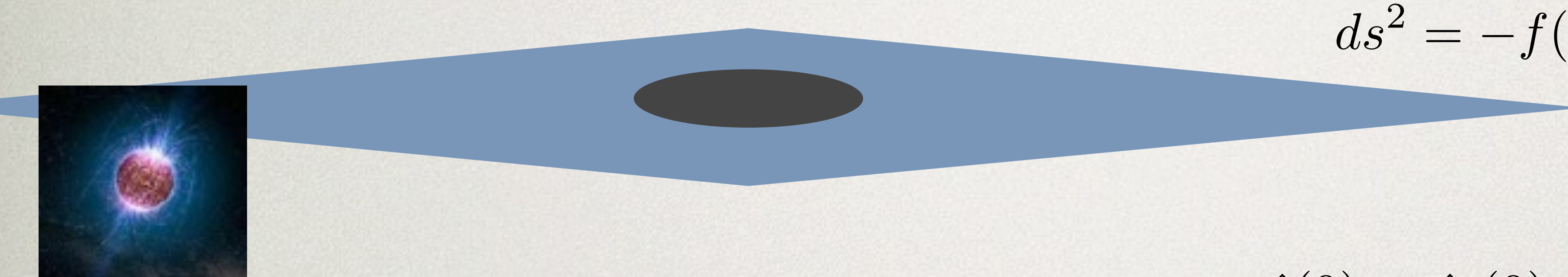

Initial state of the full system

$$\hat{\varrho}(0) = \hat{\varrho}_{\rm s}(0) \otimes \hat{\varrho}_{\rm u}(0) \otimes \hat{\varrho}_\gamma(0),$$

$$\hat{\varrho}_{\rm s}(0) = |0_{\rm s}\rangle\langle 0_{\rm s}| \qquad \hat{\varrho}_{\rm u}(0) = |0_{\rm u}\rangle\langle 0_{\rm u}|$$

$\hat{\varrho}_\gamma(0) = \text{thermal state with temperature } T$

From quantum to classical

- Unstable Phase

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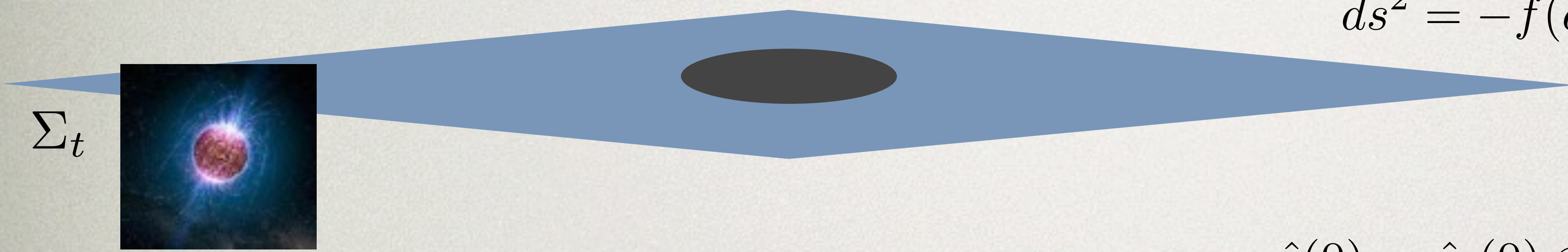

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From quantum to classical

- Unstable Phase

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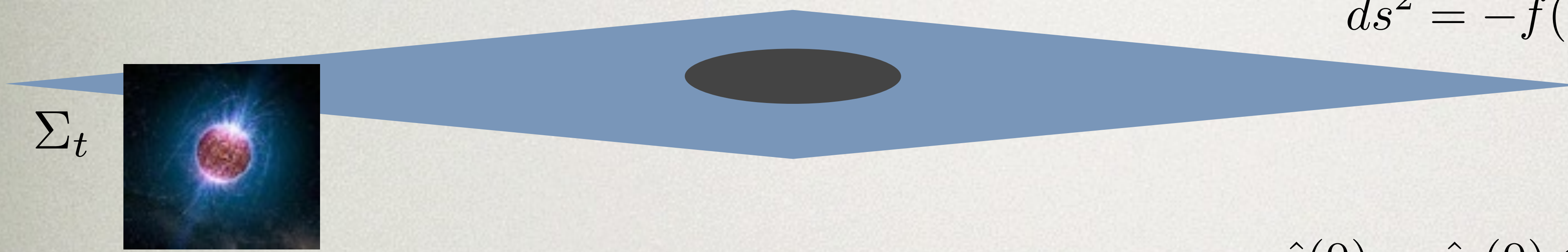

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$$\hat{\varrho}_{\gamma}(0) = \text{thermal state with temperature } T$$

$$\hat{\rho}(0) \underset{\hat{U}_{\mathrm{u}\gamma\mathrm{s}}(t)}{\longrightarrow} \hat{\rho}(t)$$

trace out the environment

From quantum to classical

- Unstable Phase

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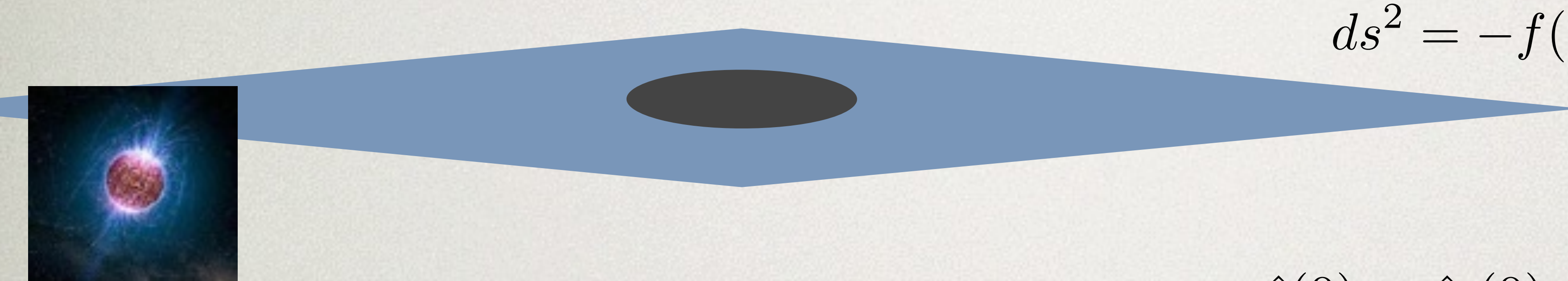

Σ_t

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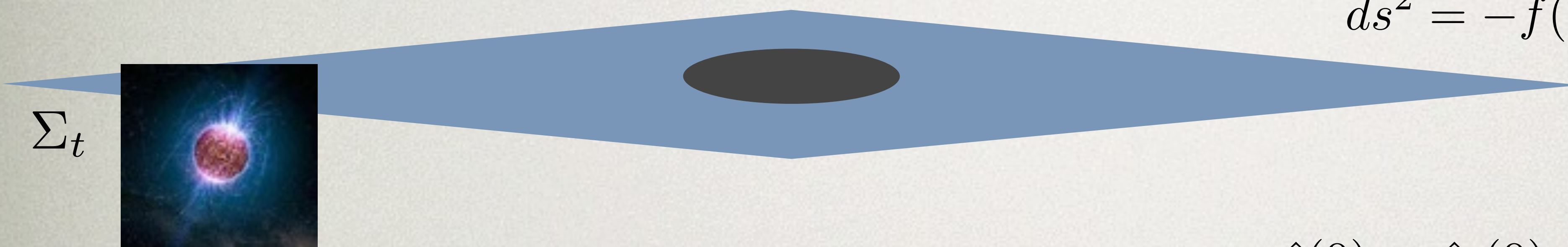
$$\hat{\rho}(0) \underset{\hat{U}_{\mathrm{u}\gamma\mathrm{s}}(t)}{\longrightarrow} \hat{\rho}(t) \xrightarrow[\text{trace out the environment}]{} \hat{\rho}_{\mathrm{u}}(t) = \mathrm{tr}_{\gamma\mathrm{s}}\hat{\rho}(t)$$

From quantum to classical

- Unstable Phase

$$ds^2 = -f(dt^2 - d\chi^2) + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

Σ_t



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$$\hat{\rho}(0) \underset{\hat{U}_{{\rm u}\gamma{\rm s}}(t)}{\longrightarrow} \hat{\rho}(t)$$

trace out the environment

$$\hat{\rho}_{\rm u}(t) = {\rm tr}_{\gamma{\rm s}}\hat{\rho}(t)$$

$$\varrho_{\rm u}(0, \psi_{\rm u}, \psi_{\rm u}{}') \equiv \langle \psi_{\rm u} | \hat{\varrho}_{\rm u}(0) | \psi_{\rm u}{}' \rangle$$

From quantum to classical

- Unstable Phase

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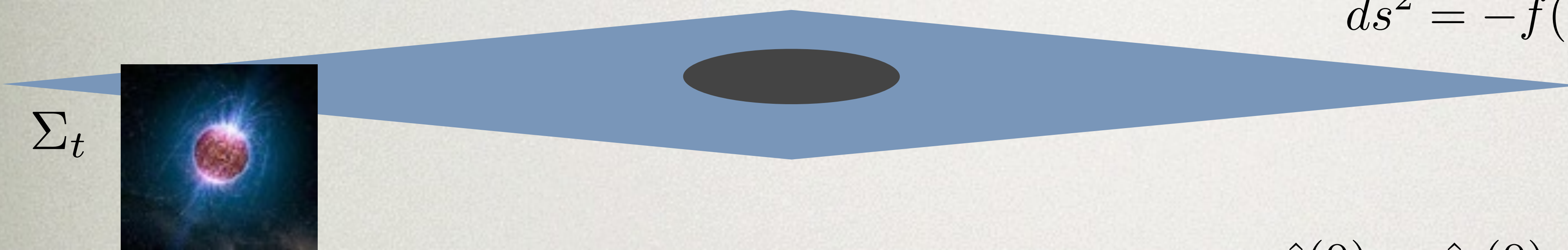

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$$\varrho_{\mathrm{u}}(0, \psi_{\mathrm{u}}, \psi_{\mathrm{u}}') \equiv \langle\psi_{\mathrm{u}}|\hat{\varrho}_{\mathrm{u}}(0)|\psi_{\mathrm{u}}'\rangle$$

$$\varrho_{\mathrm{red}}(t, \varphi_{\mathrm{u}}, \varphi_{\mathrm{u}}') = \int d\psi_{\mathrm{u}} d\psi_{\mathrm{u}}' \varrho_{\mathrm{u}}(0, \psi_{\mathrm{u}}, \psi_{\mathrm{u}}') \times J_{\mathrm{red}}(t, \varphi_{\mathrm{u}}, \varphi_{\mathrm{u}}'; 0, \psi_{\mathrm{u}}, \psi_{\mathrm{u}}'),$$

$$\hat{\phi}_{\mathrm{u}}(0, \mathbf{x})|\psi_{\mathrm{u}}\rangle = \psi_{\mathrm{u}}(\mathbf{x})|\psi_{\mathrm{u}}\rangle$$

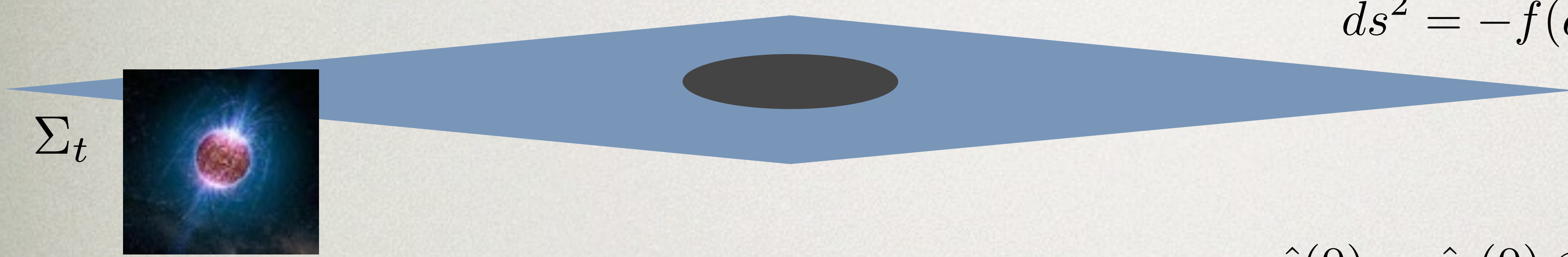
$$J_{\mathrm{red}}(t, \varphi_{\mathrm{u}}, \varphi_{\mathrm{u}}'; 0, \psi_{\mathrm{u}}, \psi_{\mathrm{u}}') \equiv \int_{\psi_{\mathrm{u}}}^{\varphi_{\mathrm{u}}} \mathcal{D}\phi_{\mathrm{u}} \int_{\psi_{\mathrm{u}}'}^{\varphi_{\mathrm{u}}'} \mathcal{D}\phi_{\mathrm{u}}' e^{i\{S_{\phi}[\phi_{\mathrm{u}}] - S_{\phi}[\phi_{\mathrm{u}}']\}} F[\phi_{\mathrm{u}}, \phi_{\mathrm{u}}']$$

From quantum to classical

- Unstable Phase

$$ds^2 = -f(dt^2 - d\chi^2) + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

Σ_t



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Feynman-Vernon Influence Functional

$$\varrho_{\rm u}(0, \psi_{\rm u}, {\psi_{\rm u}}') = \langle\psi_{\rm u}|\hat\varrho_{\rm u}(0)|{\psi_{\rm u}}'\rangle$$

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$$\hat\phi_{\rm u}(0, \mathbf{x})|\psi_{\rm u}\rangle = \psi_{\rm u}(\mathbf{x})|\psi_{\rm u}\rangle$$

$$J_{\rm red}(t, \varphi_{\rm u}, {\varphi_{\rm u}}'; 0, \psi_{\rm u}, {\psi_{\rm u}}') \equiv \int_{\psi_{\rm u}}^{\varphi_{\rm u}} \mathcal{D}\phi_{\rm u} \int_{{\psi_{\rm u}}'}^{{\varphi_{\rm u}}'} \mathcal{D}{\phi_{\rm u}}' e^{i\{S_\phi[\phi_{\rm u}] - S_\phi[{\phi_{\rm u}}']\}} \boxed{F[\phi_{\rm u}, {\phi_{\rm u}}']}$$

From quantum to classical

- Unstable Phase

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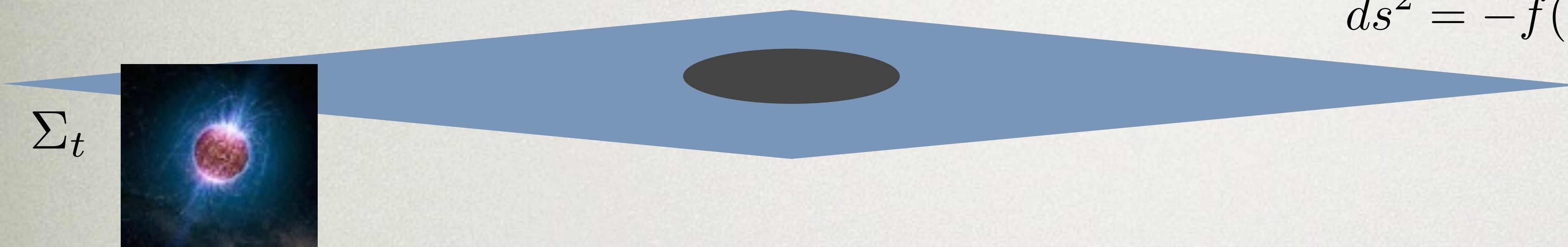
Σ_t



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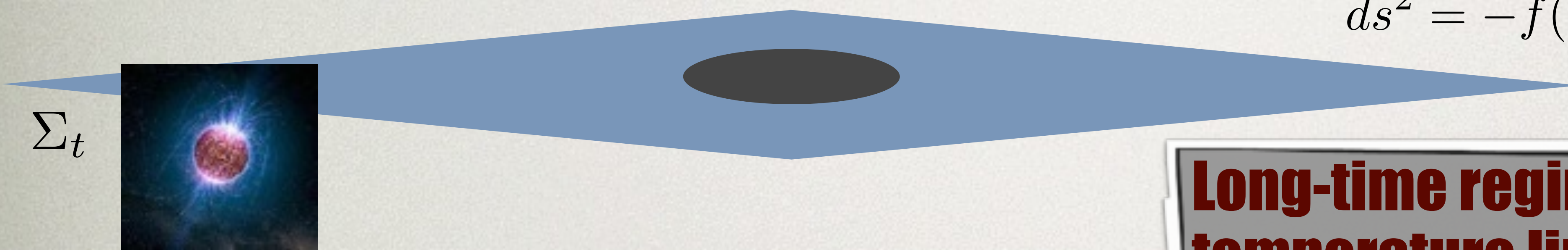

Long-time regime and high temperature limit

$\Omega t \gg 1$ $\qquad$ $k_{\mathrm{B}} T \gg \Omega$

From quantum to classical

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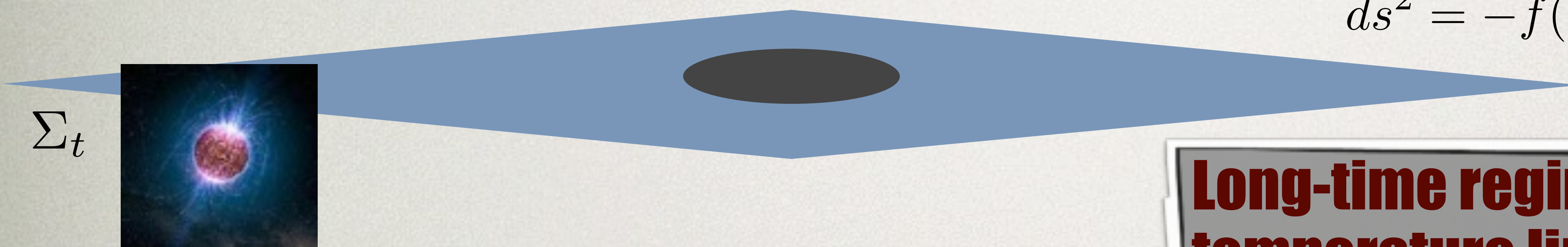

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Master equation for the state of the unstable mode

$$\partial_t \varrho_{\mathrm{red}} \approx -i\left[\frac{1}{2}(-\partial_q^2 + \partial_{q'}^2) - \frac{\Omega^2}{2}(q^2 - q'^2)\right]\varrho_{\mathrm{red}} - D(q-q')^2\varrho_{\mathrm{red}} + \ldots$$

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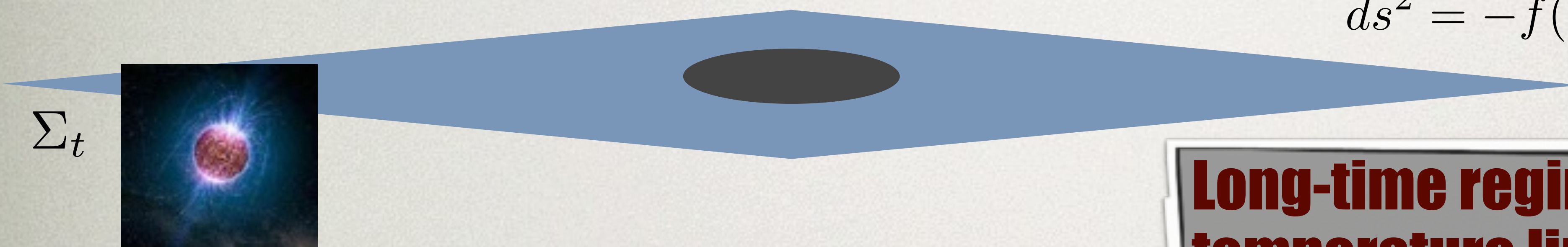

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Wigner function for the unstable mode

$$\partial_t W_{\mathrm{red}} \approx \{H(q,p), W_{\mathrm{red}}\} + D\partial_p^2 W_{\mathrm{red}} + \dots$$

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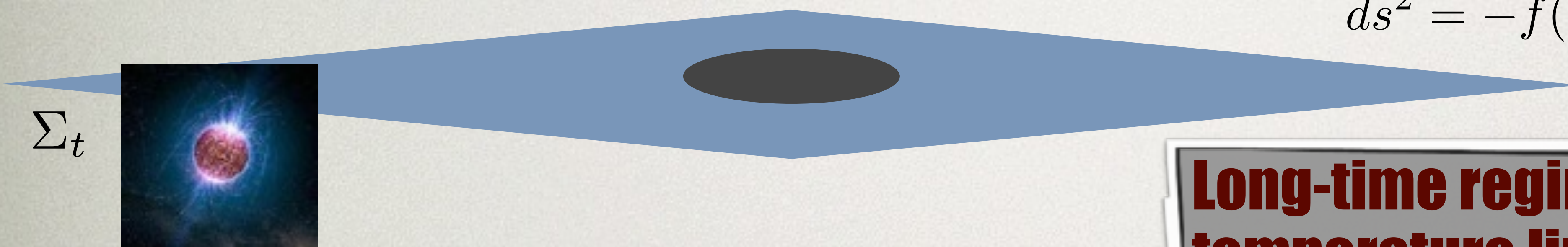

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$$D = 8\pi\Delta\left(\frac{\ell_{\mathrm{P}}}{\mathrm{R}}\right)^2\left(\frac{k_{\mathrm{B}}T}{\Omega}\right)\Omega^2$$

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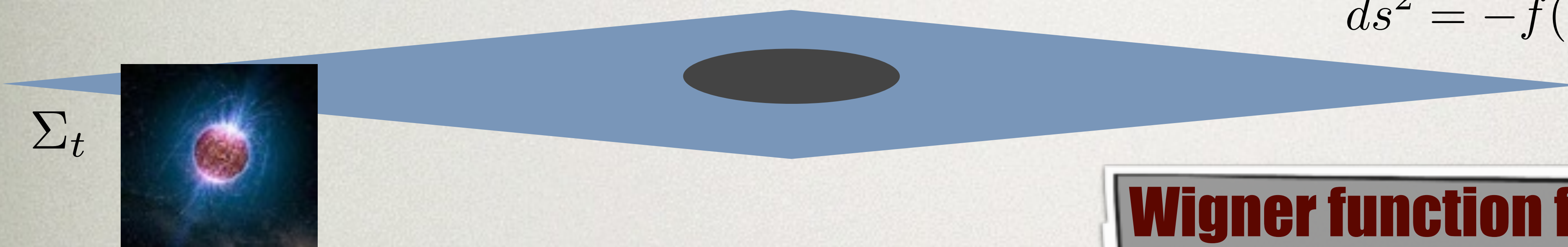

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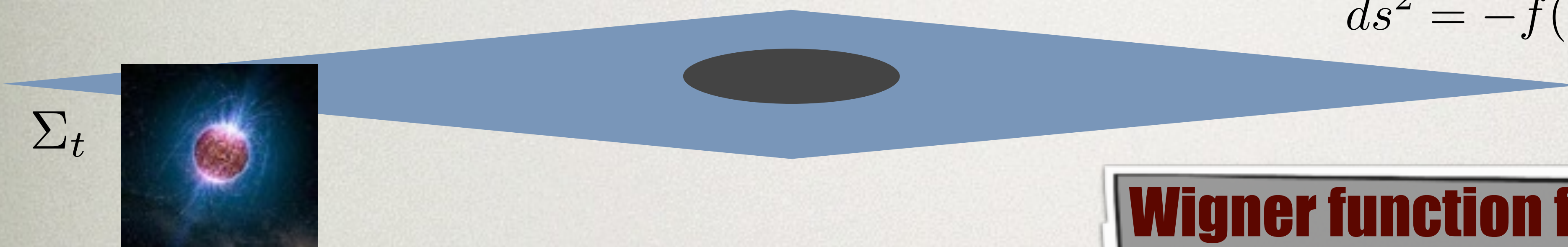

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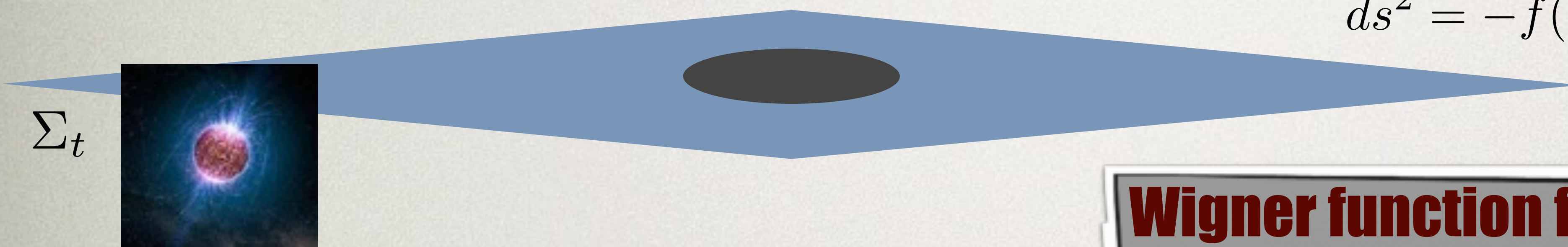

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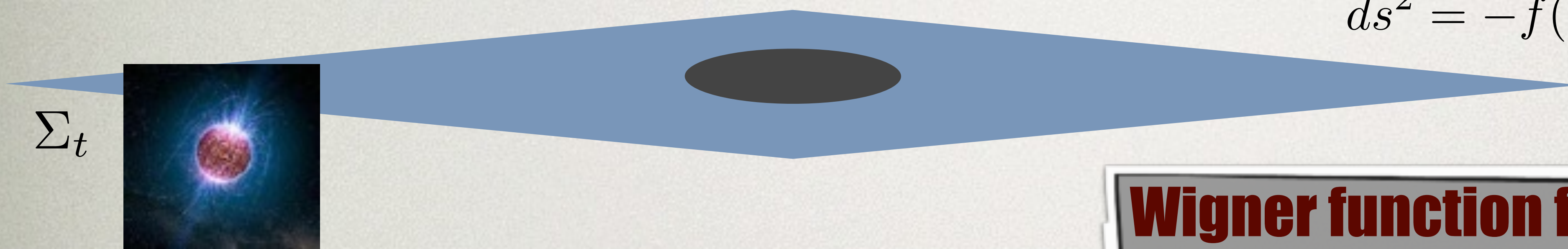

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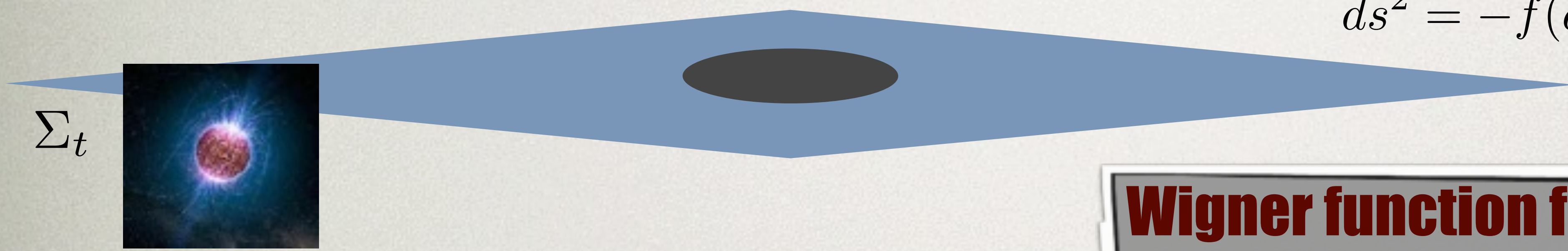

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- For a R~10km neutron star and T~1K

$t_{\rm d} \sim 160 \times \Omega^{-1} \sim 160 \times \mathsf{R}$ which is of the order of $t_{\rm br} \sim 10^{-3}\,{\rm s}$

From quantum to classical

- Unstable Phase

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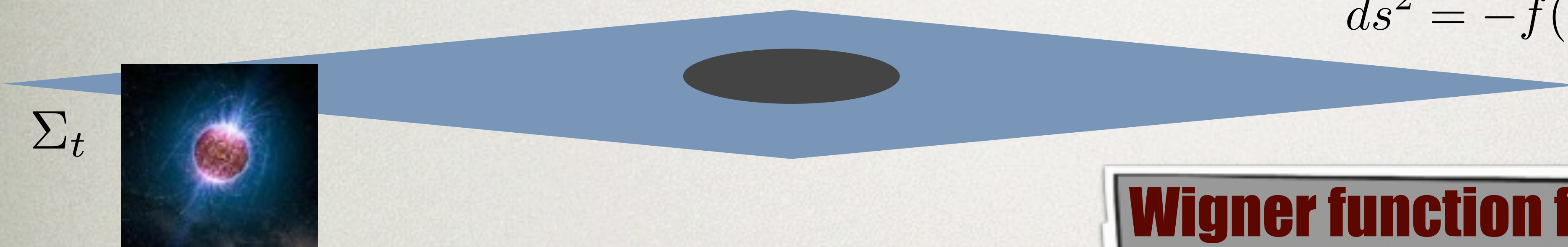

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Thus, by the time backreaction becomes ineluctable the (unstable sector of the) initially pure vacuum state has evolved into a statistical mixture of (very) localized states in the field amplitude and momentum representation.

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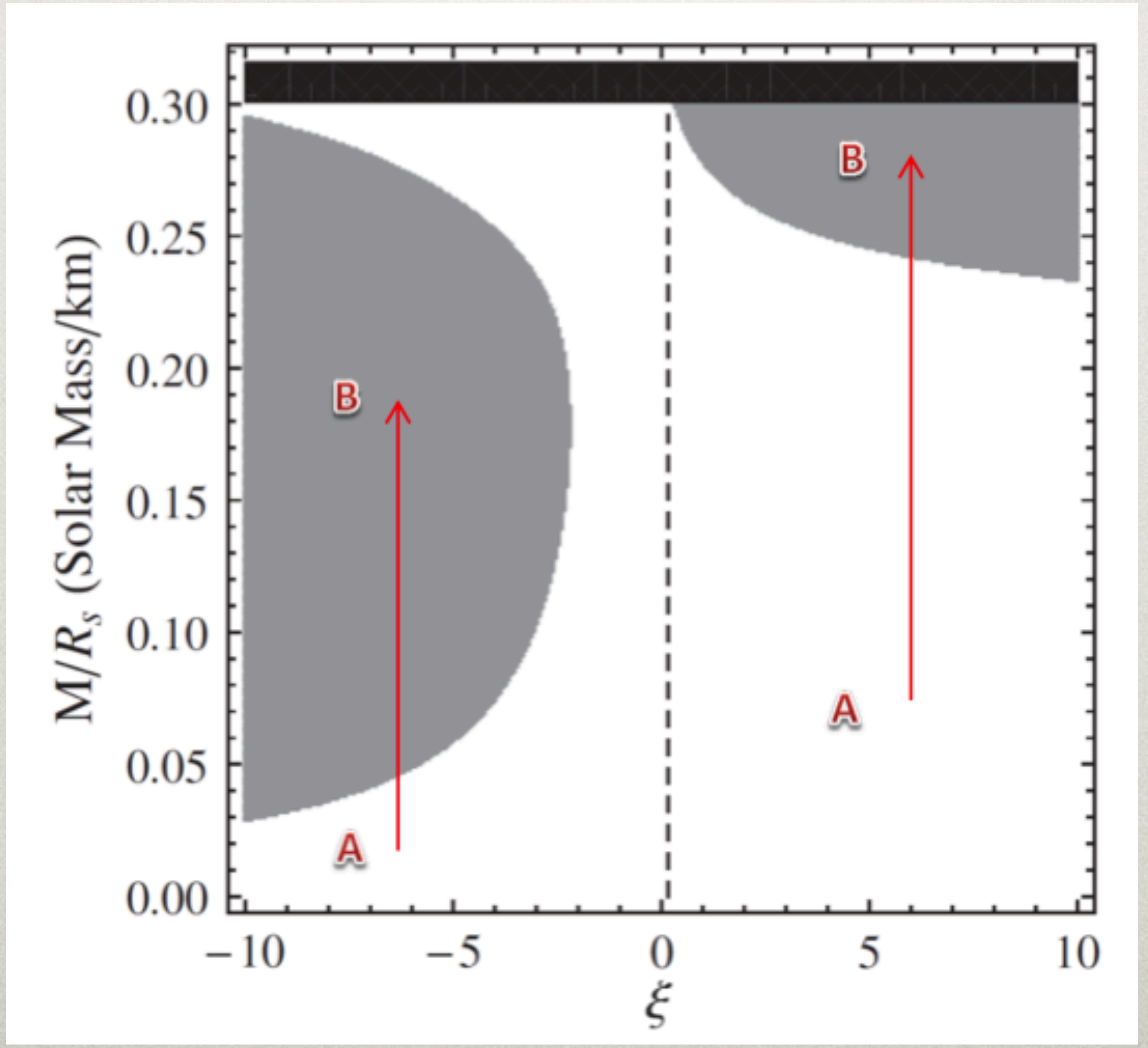
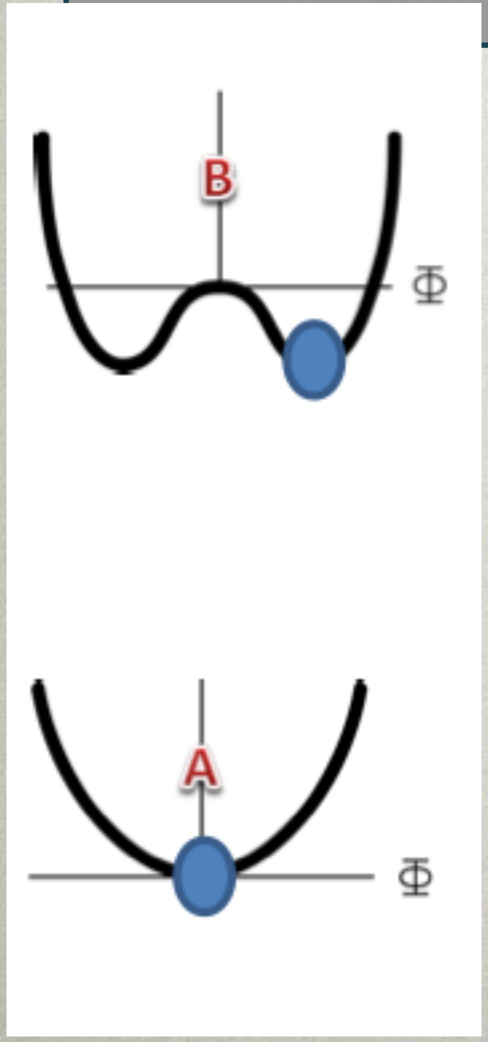
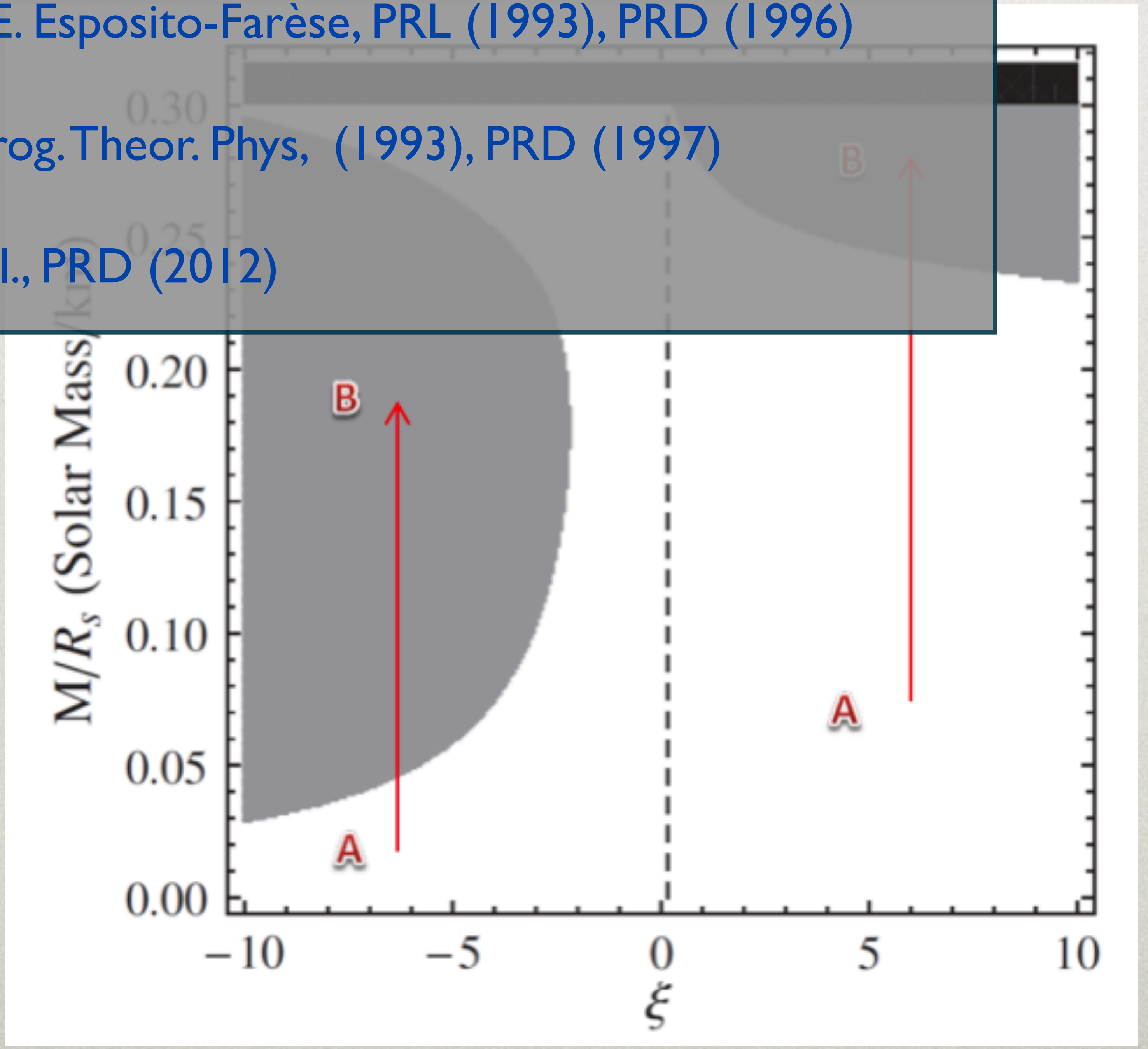
Backreaction



Backreaction

- P. Pani, V Cardoso, E. Berti, J. Read, and M. Salgado, PRD (2011)
- T. Damour, E. Esposito-Farèse, PRL (1993), PRD (1996)
- T. Harada, Prog. Theor. Phys, (1993), PRD (1997)
- M. Ruiz et. al., PRD (2012)





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- P. Pani, V Cardoso, E. Berti, J. Read, and M. Salgado, PRD (2011)
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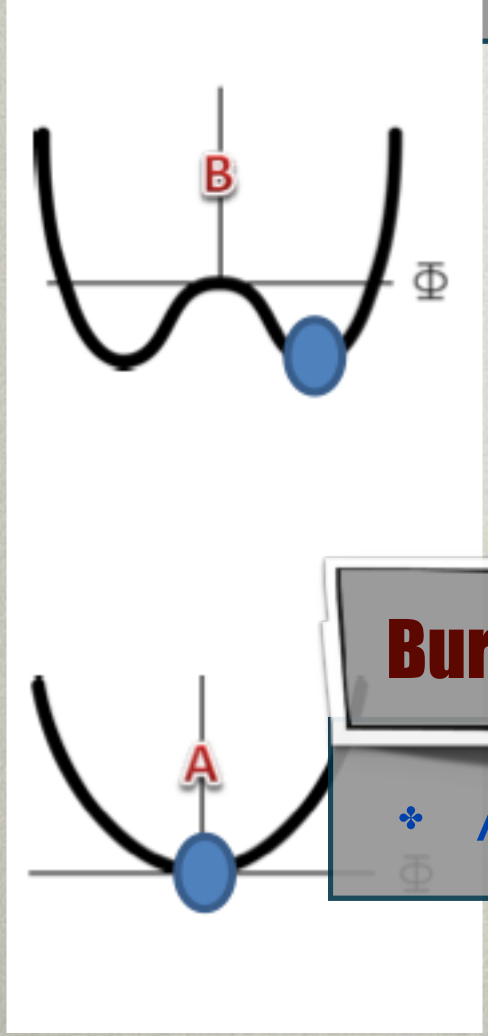
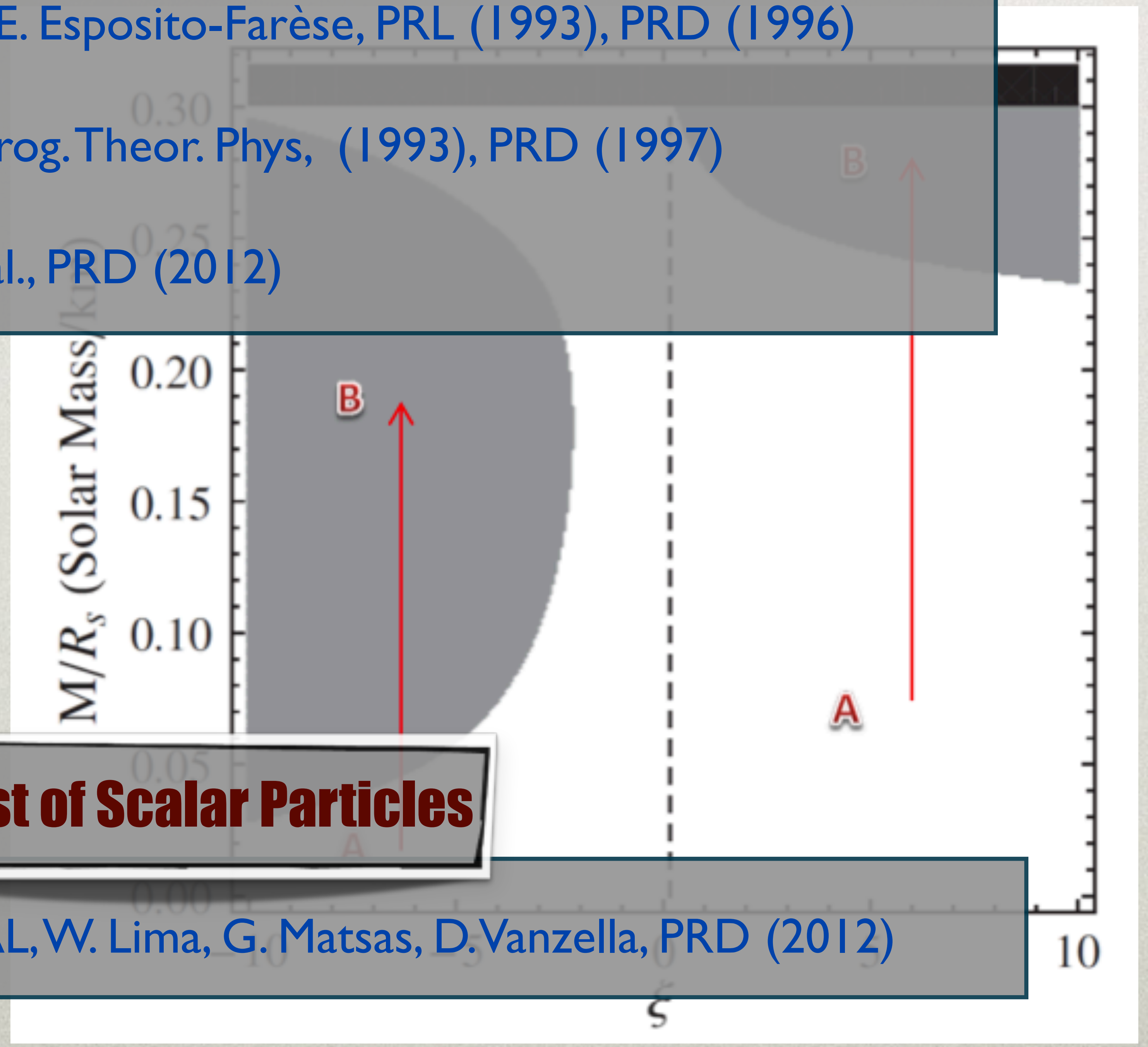




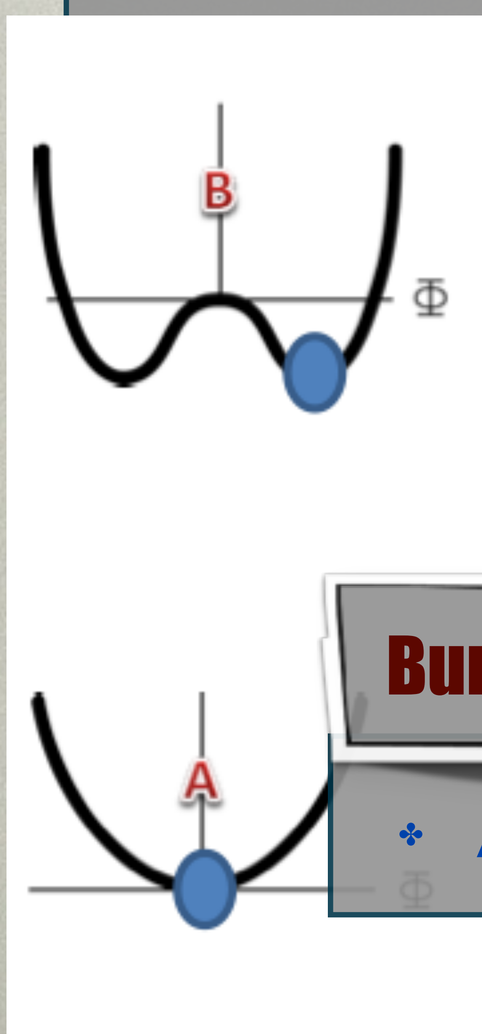
Burst of Scalar Particles

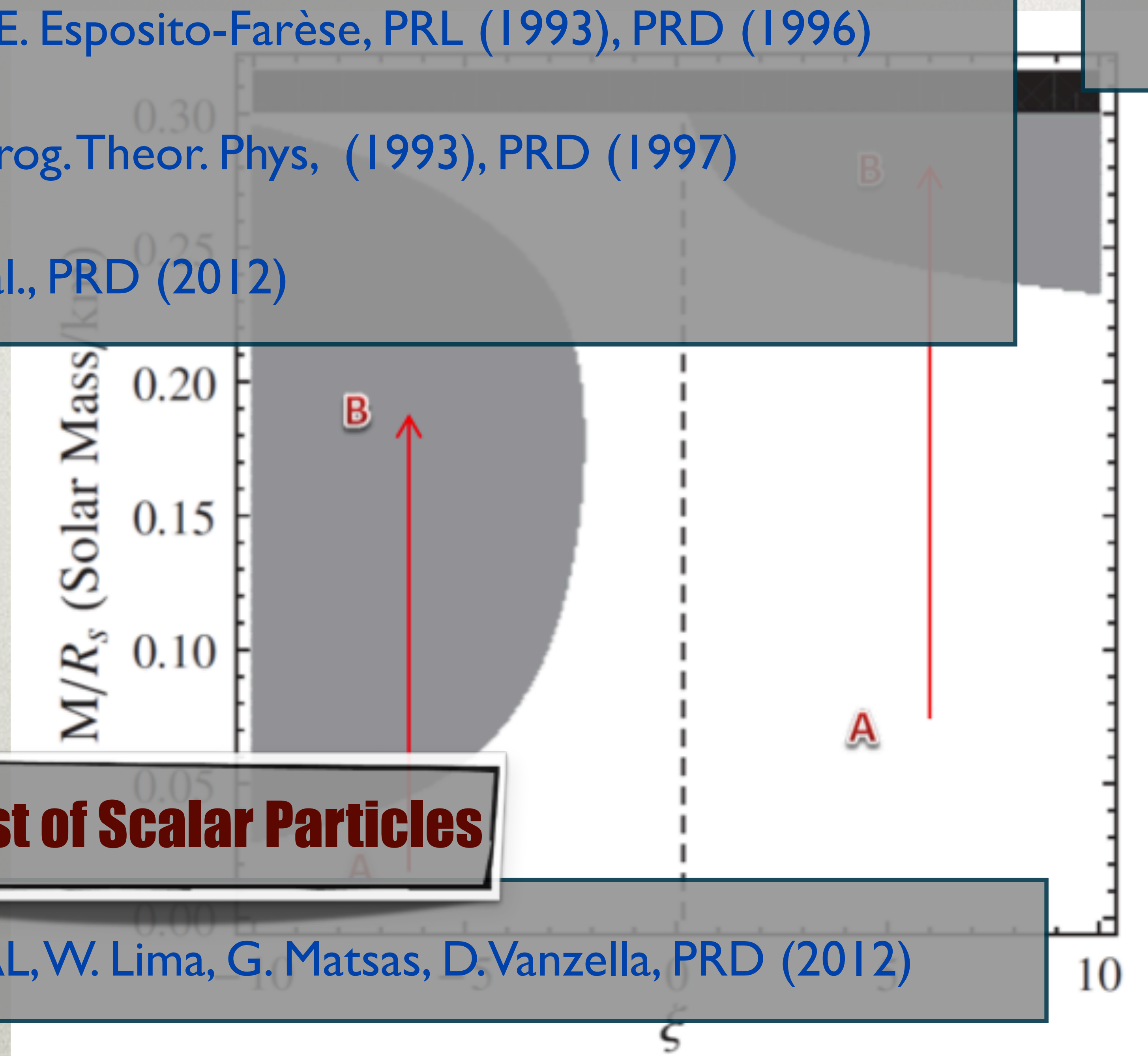
- AL, W. Lima, G. Matsas, D. Vanzella, PRD (2012)

Backreaction

- P. Pani, V Cardoso, E. Berti, J. Read, and M. Salgado, PRD (2011)
- T. Damour, E. Esposito-Farèse, PRL (1993), PRD (1996)
- T. Harada, Prog. Theor. Phys, (1993), PRD (1997)
- M. Ruiz et. al., PRD (2012)

- R. Mendes and N. Ortiz, PRD (2016)





Burst of Scalar Particles

- AL, W. Lima, G. Matsas, D. Vanzella, PRD (2012)