Title: Some Ideas (not to try!) on Quantum Gravity Phenomenology

Date: Aug 12, 2010 03:00 PM

URL: http://pirsa.org/10080044

Abstract:

Some Ideas on Quantum Gravity Phenomenology

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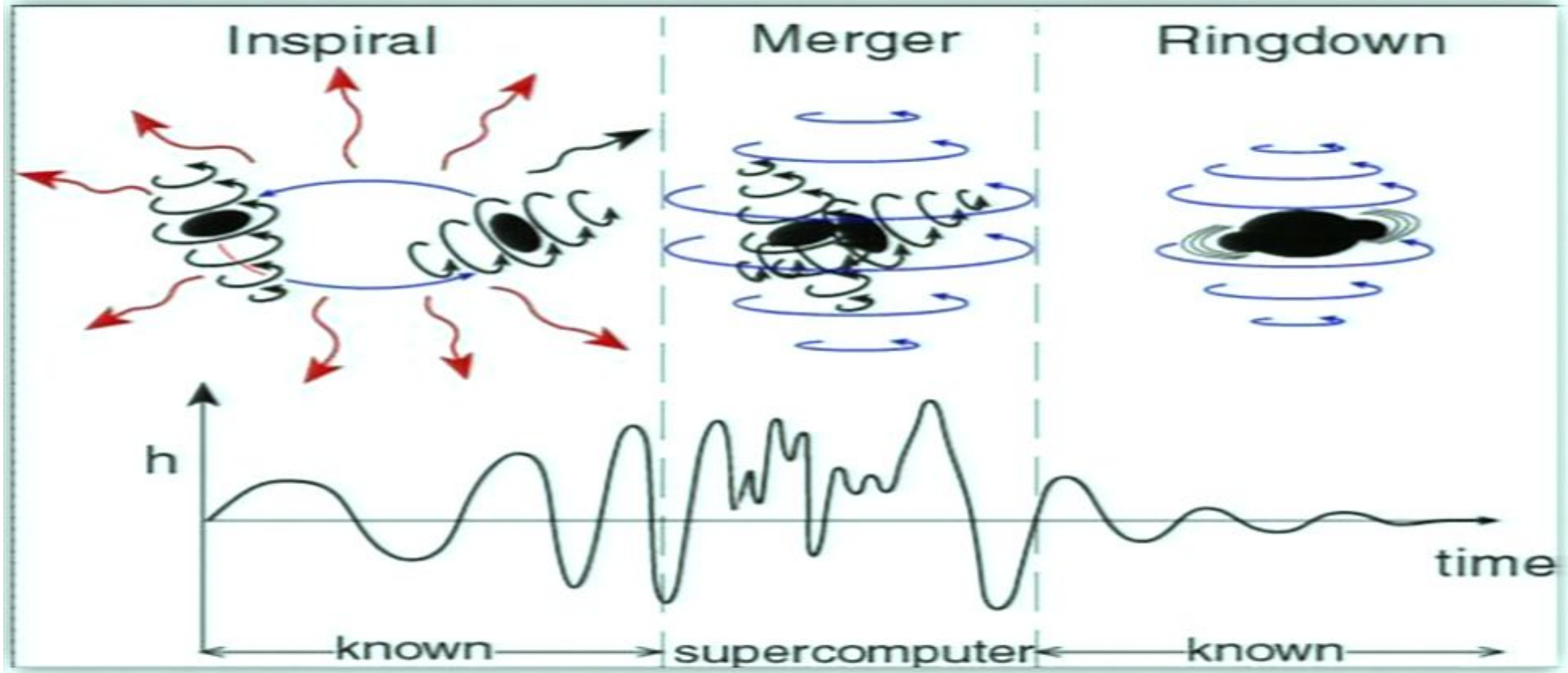
Outline

- Quasi-Normal Modes
  - Classical Case
    - WKB method, Continuous fraction
    - Detection, Parameter estimation
  - Self-Dual Blackholes
    - The metric and the quantum correction
    - Connection with surface gravity
    - The present plots & possible phenomenology
- Dark Matter
  - Cosmic Rays, QNMs and structure formation
- Effective Lorentz Invariance Violation
  - GRBs
    - Neutrinos
    - Gravitons?
- Initial Orbital Configuration of LISA
- Astrophysical Test of "no hair"

The Life of a Black Hole



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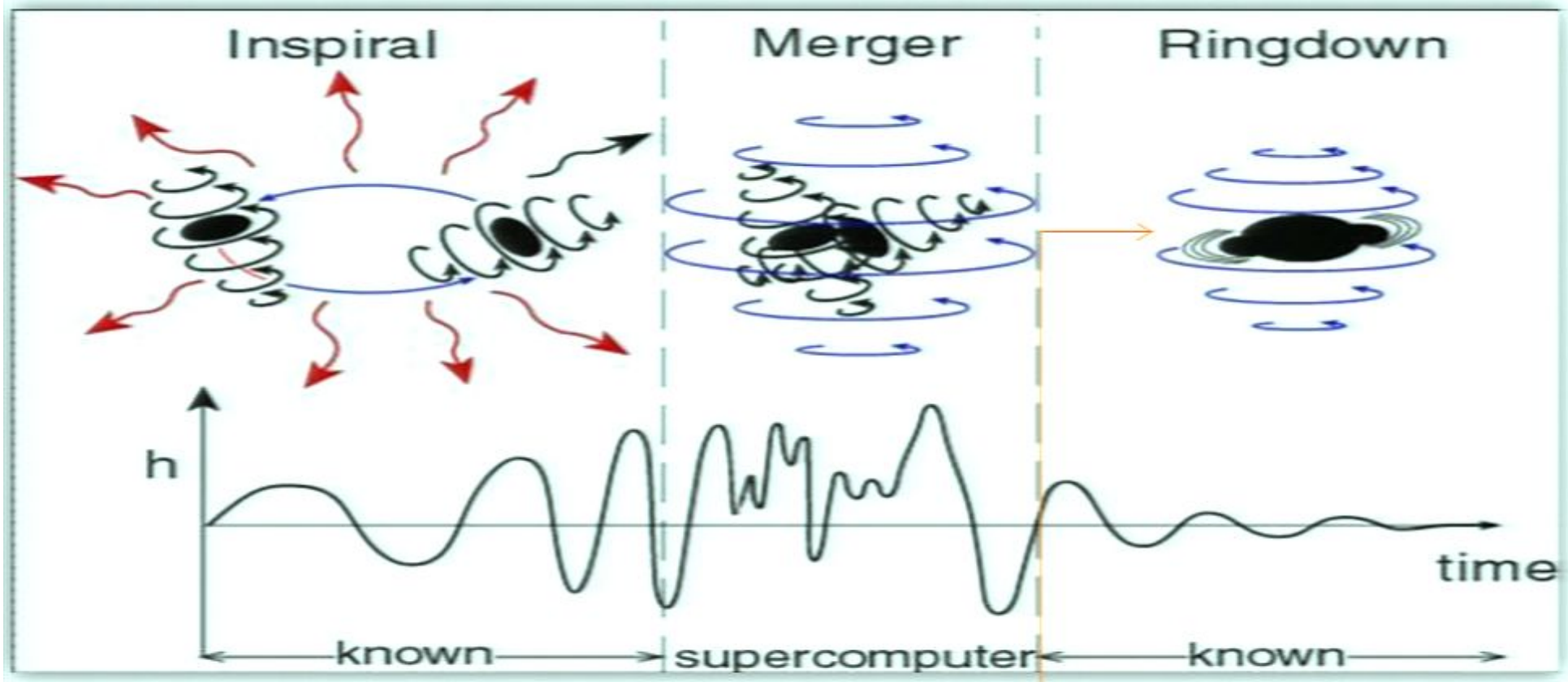

Quasi-Normal Modes

- Exponential decay
- Perturbation of metric outside event horizon
- Directly connected to parameters of BH (mass, spin)

QNM for Schwarzschild BH

QNM for Schwarzschild BH

$$ds^2 = g^0_{\mu\nu} dx^\mu dx^\nu = -e^{v(r)} dt^2 + e^{\lambda(r)} dr^2 + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2\right)$$

Perturb the metric: $g_{\mu\nu} = g^0_{\mu\nu} + h_{\mu\nu}$

Leading to variation in Einstein equations: $\delta G_{\mu\nu} = 4\pi \delta T_{\mu\nu}$

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Assuming scalar decomposition of $\boldsymbol{h}$: $\chi(t, r, \theta, \phi) = \sum_{\ell m} \frac{\chi_{\ell m}(r,t)}{r} Y_{\ell m}(\theta, \phi)$

For radial component of perturbation outside event horizon,

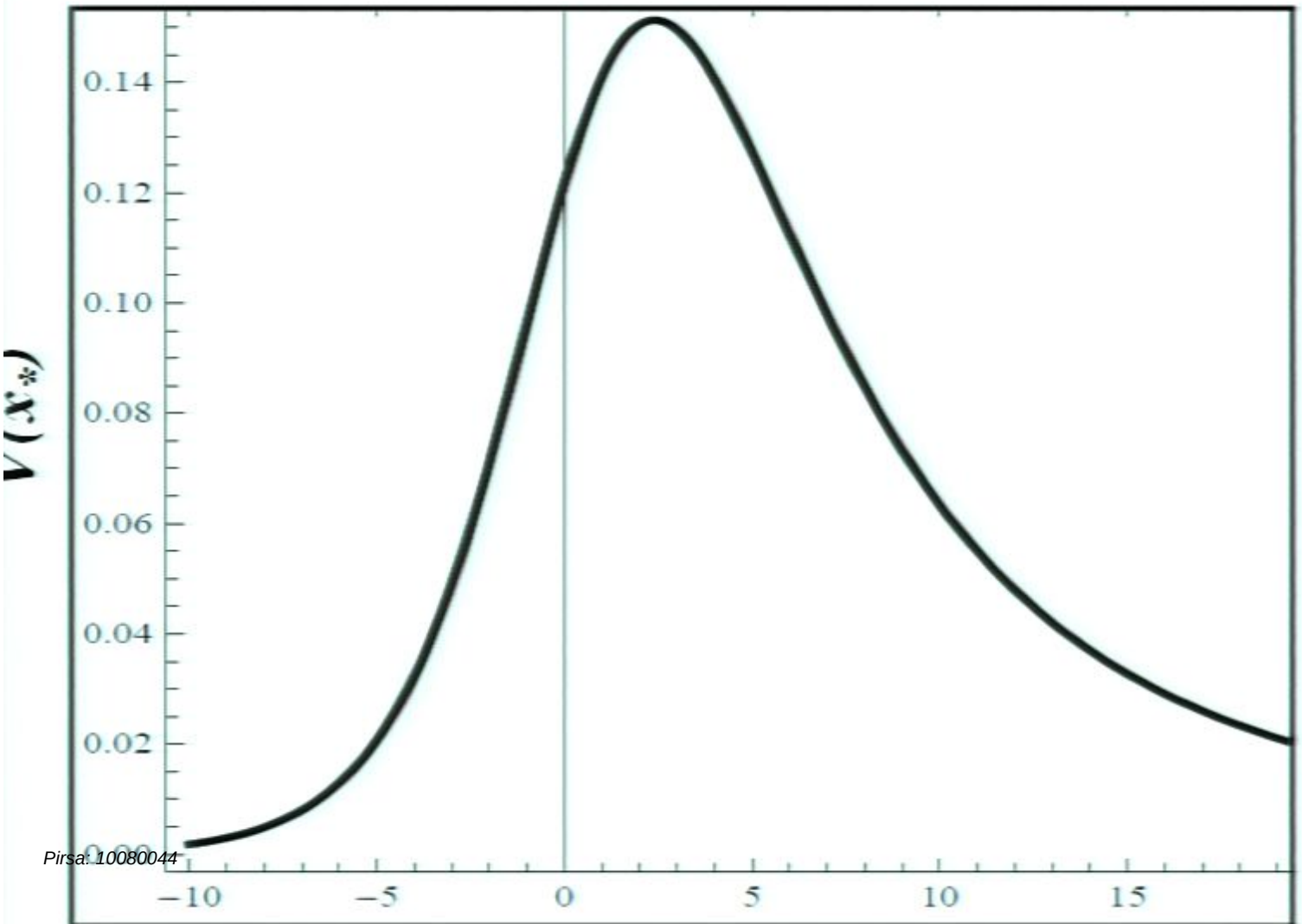
$$\frac{\partial^2 \chi_l}{\partial r_*^2} + \left(\omega^2 - V_l(r)\right) \chi_l = 0$$

where $\frac{\partial^2 \chi_l}{\partial t^2} = -\omega^2 \chi_l$, Tortoise radius: $r_* = r + 2M \log(r/2M - 1)$

& Regge-Wheeler Potential: $V_\ell(r) = \left(1 - \frac{2M}{r}\right) \left[\frac{\ell(\ell+1)}{r^2} + \frac{2\sigma M}{r^3}\right]$

A Closer Look at the Potential

$M = 1\ M_{Solar}$, $l = 2$ & $\sigma = 1 - s^2 = 1$ (for Scalar perturbation)



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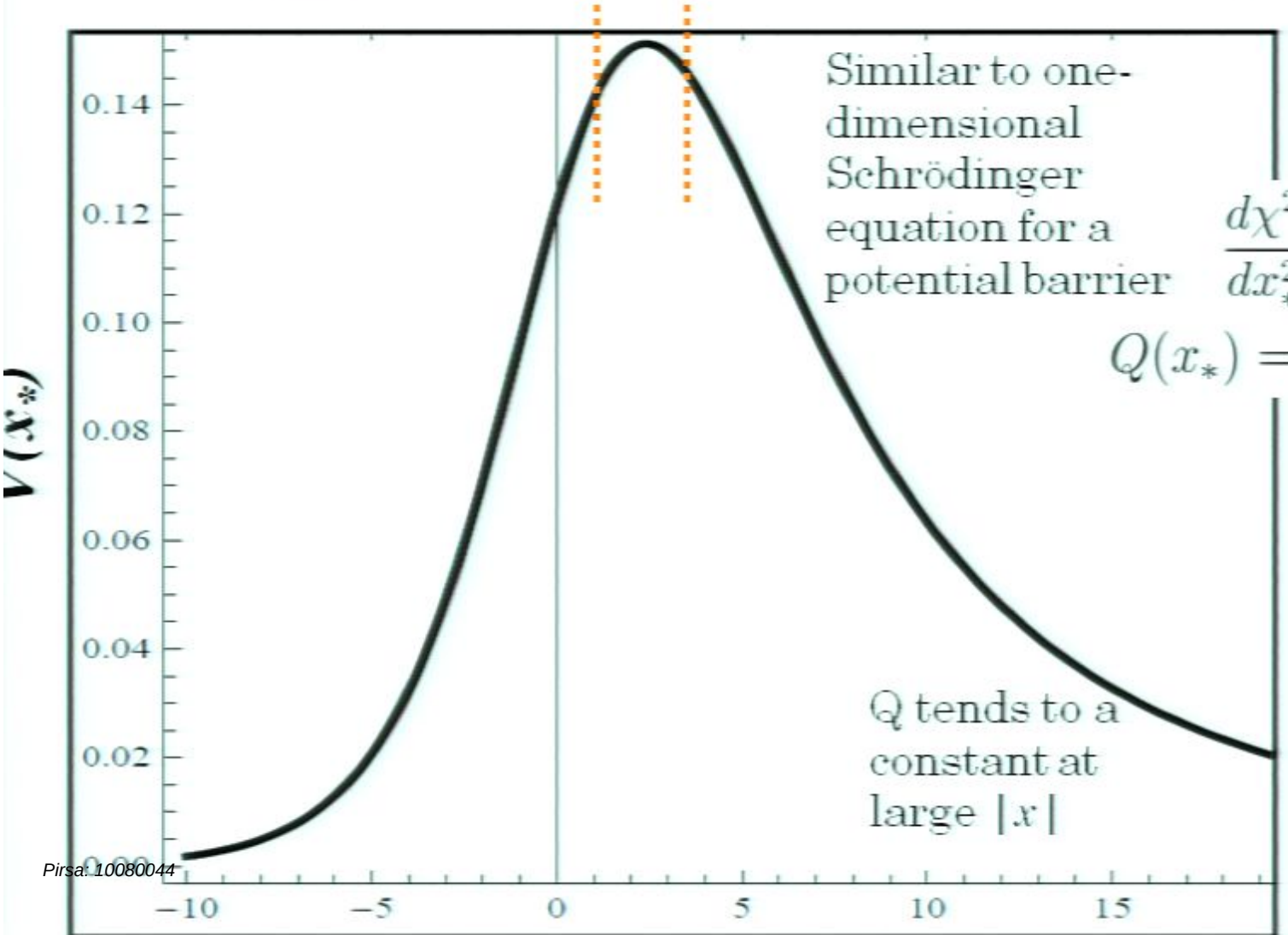


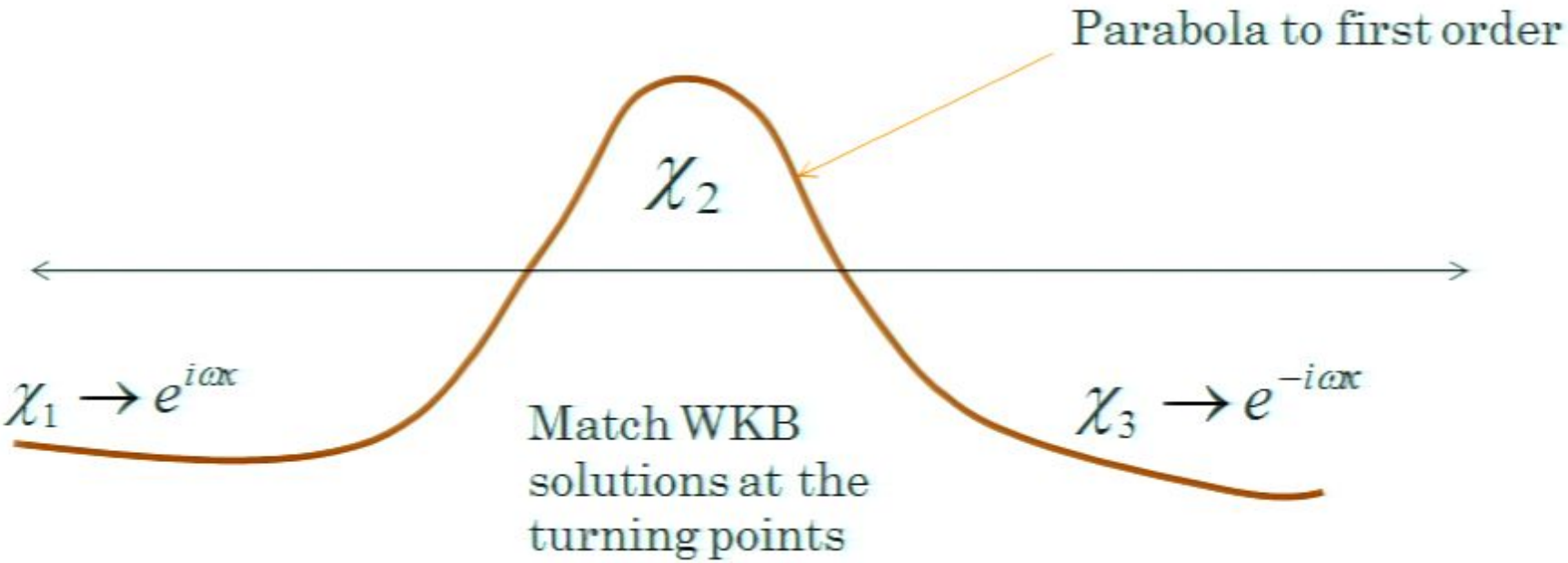
Similar to one-dimensional Schrödinger equation for a potential barrier

$$\frac{d\chi^2}{dx_*^2} + Q(x_*)\chi = 0$$

$$Q(x_*) = (M\omega)^2 - V(x_*)$$

Q tends to a constant at large $|x|$

WKB Approximation Method



Condition for normal modes: $\dfrac{Q_0}{\sqrt{2Q_0''}} = i\left(n + \dfrac{1}{2}\right)$

$$(M\omega_n)^2 = V_\ell(r_0) - i\left(n + \frac{1}{2}\right)\left[-2\frac{d^2V_\ell(r_0)}{dr_*^2}\right]^{1/2}$$

Schutz & Will (1985)

RHS Independent of M

Method of Continued Fractions

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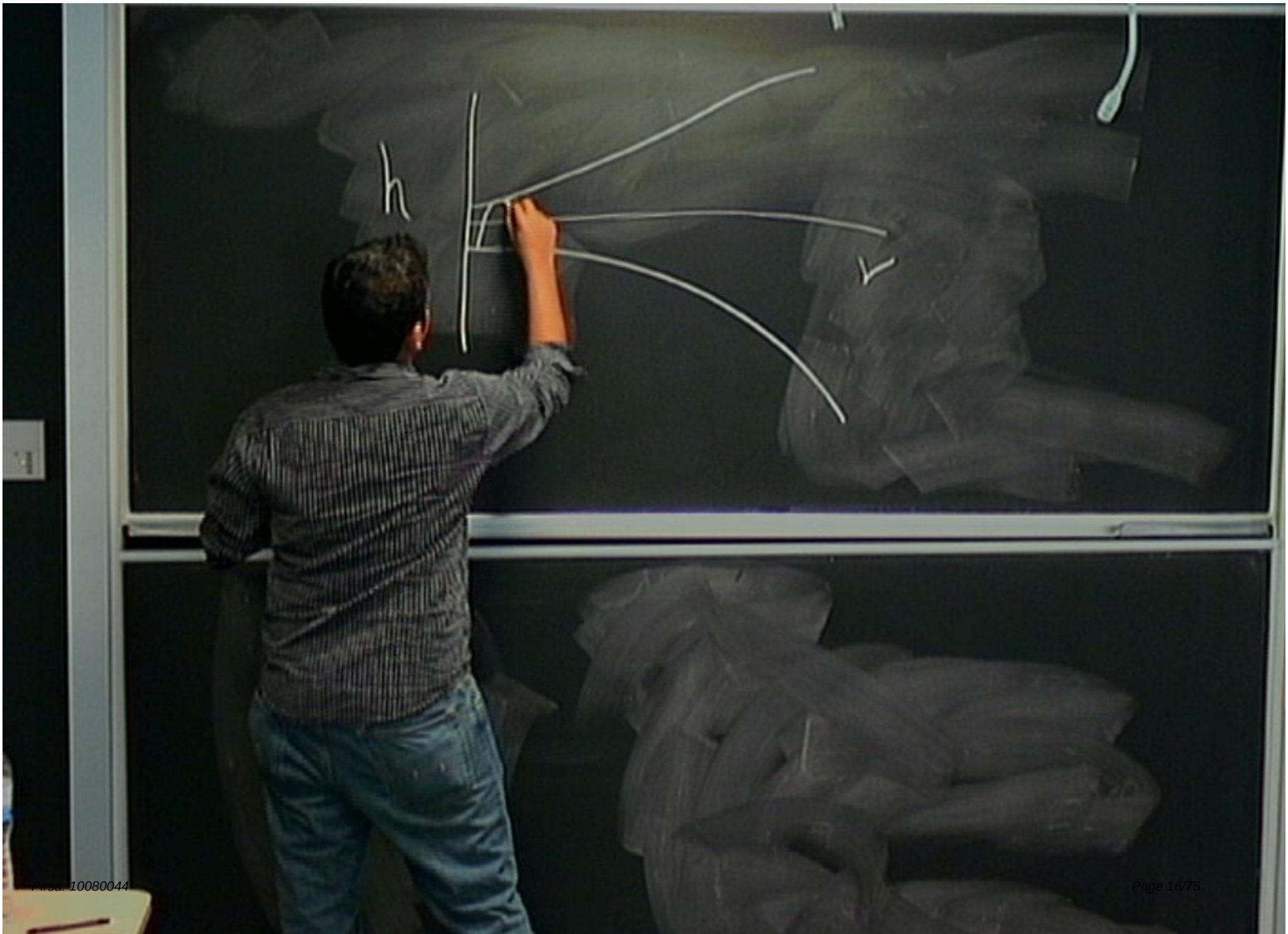
Radial Equation: $r(r-1)\frac{d^2\chi_l}{dr^2} + \frac{d\chi_l}{dr} - \left(l(l+1) - \frac{\rho^2 r^3}{r-1} - \frac{\sigma}{r}\right)\chi_l = 0$

where $2M = 1$ & $\rho = i\omega$

Assume the following solution from boundary condition:

$$\chi_l(r) = (r-1)^{\rho} r^{-2\rho} e^{-\rho(r-1)} \sum_{n=0}^{\infty} a_n \left(\frac{r-1}{r}\right)^n$$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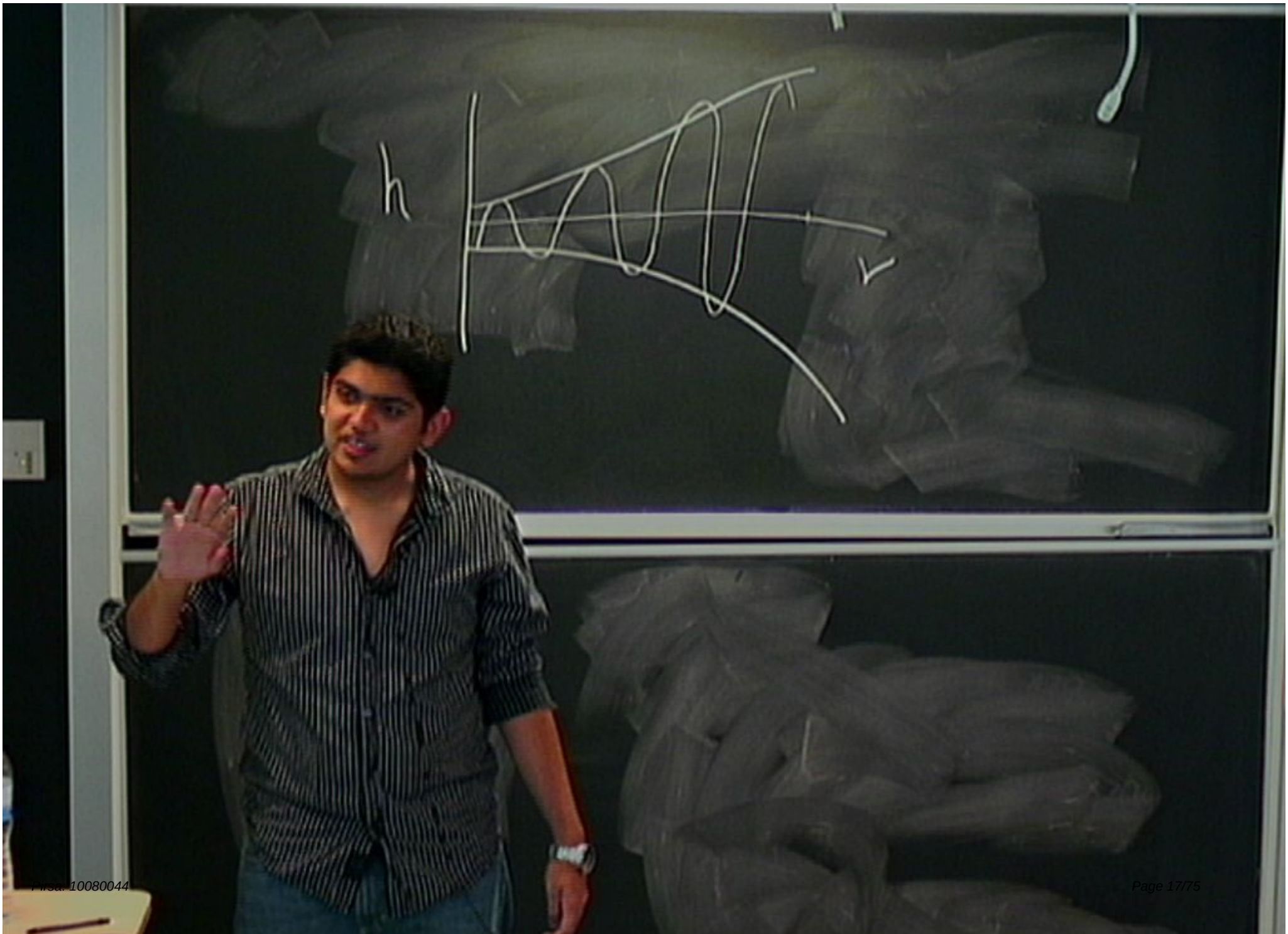
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Then we get the following relations:

$$\alpha_0 a_1 + \beta_0 a_0 = 0, \quad \alpha_n a_{n+1} + \beta_n a_n + \gamma_n a_{n-1} = 0,$$

where : $\alpha_n = n^2 + (2\rho+2)n + 2\rho + 1$, $\gamma_n = n^2 + 4\rho n + 4\rho^2 - \sigma - 1$

$$\beta_n = -(2n^2 + (8\rho+2)n + 8\rho^2 + 4\rho + l(l+1) - \sigma)$$

Detection of QNMs

- In physical units: $\omega = (\omega M) 2\pi\,(5142\ Hz)\dfrac{M_{solar}}{M}$
  - For LIGO (~10 – 10000 Hz) : stellar BHs
  - For LISA (~0.1 – 0.00001 Hz) : Super- Massive BHs
- Only first couple of modes '*n*' observable (exponential damping)
- If QNM spectrums inconsistent with isolated BH then:
  - We are not observing isolated BH approaching equilibrium
  - It might be neutron star or some exotic Boson star (?) Thus, it could be used as a test for "no-hair" theorem
  - GR is not true in strong field regime

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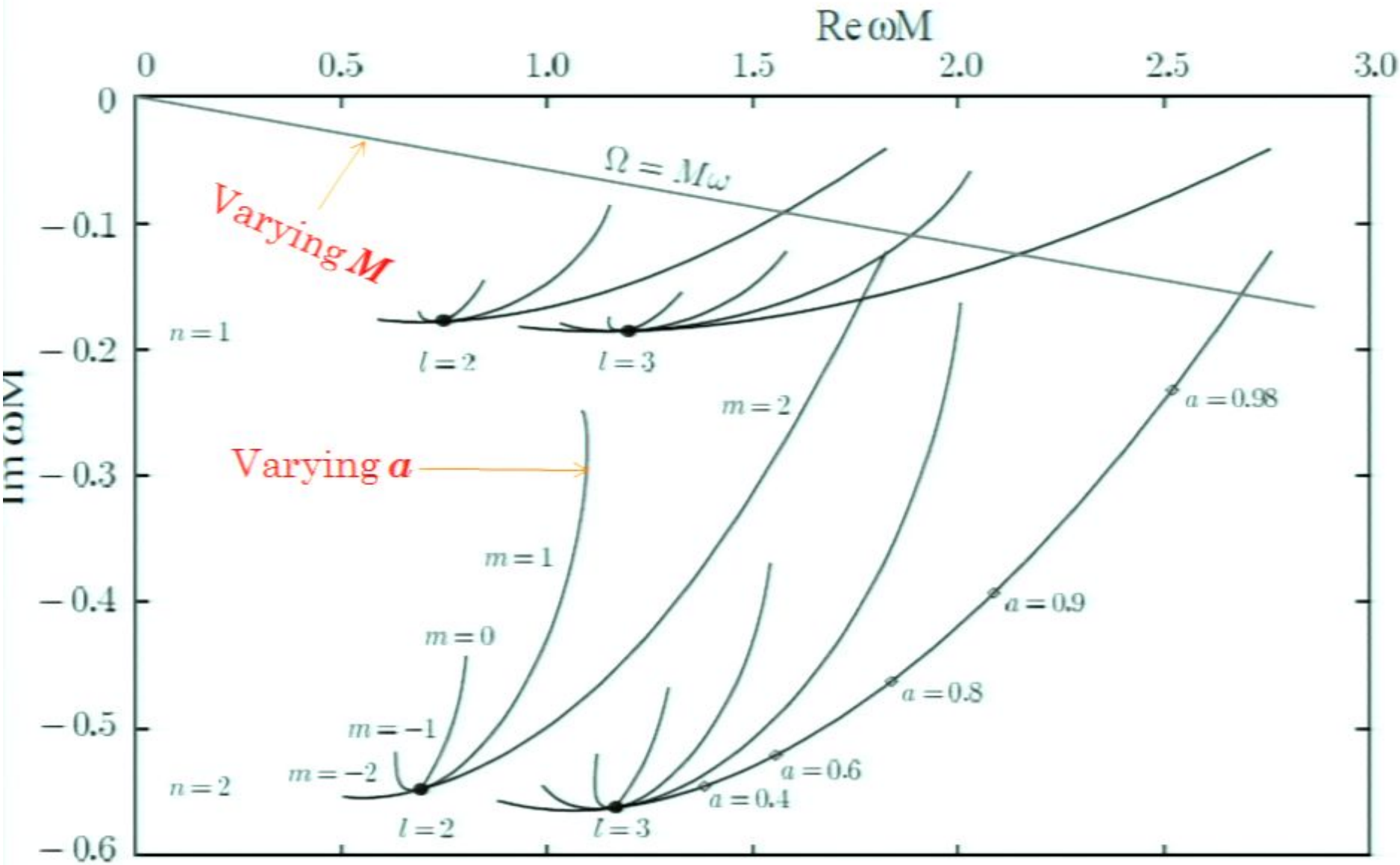
Determining Parameters



Parameters (Kerr BH): n, l , m , *Mass (M)* , *Spin (a)*

Self-dual BHs

- Semi classical metric obtained from a classical analysis of the Loop Quantum BH

$$ds^2 = -G(r)dt^2 + \frac{dr^2}{F(r)} + H(r)d\Omega^{(2)}$$

$$d\Omega^{(2)} = d\theta^2 + \sin^2\theta d\phi^2$$

$$G(r) = \frac{(r-r_+)(r-r_-)(r+r_*)^2}{r^4+a_o^2}$$

$$F(r) = \frac{(r-r_+)(r-r_-)r^4}{(r+r_*)^2(r^4+a_o^2)},$$

$$H(r) = r^2 + \frac{a_o^2}{r^2}.$$

$$r_+ = 2m,\ r_- = 2mP^2$$

$$r_* = \sqrt{r_+ r_-} = 2mP.$$

$$P = (\sqrt{1+\epsilon^2}-1)/(\sqrt{1+\epsilon^2}+1)$$

$a_0 \propto A_{\min}$ (*Minimum Area in LQG*)

$\varepsilon \propto \gamma$ (*Immirzi Parameter*)

- Free from singularity & invariant under: $r \to a_0 / r$
- Area of event horizon (X^2) > Compton wavelength:

$$X = \sqrt{(2M)^2 + \left(\frac{a_0}{\ }\right)^2} > \hbar / 2M$$

QNM for Self-Dual BHs

Mass of scalar field

Wave-equation for a scalar field in a general spherical surface:

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(g^{\mu\nu}\sqrt{-g}\partial_\nu\Phi\right) - m_\Phi^2\Phi = 0,$$

(As LQG is not developed to involve perturbation we assume this classical result)

Assuming the scalar field: $\Phi(r,\theta,\phi,t) := T(t)\,\varphi(r)\,Y(\theta,\phi)$

Radial Equation:

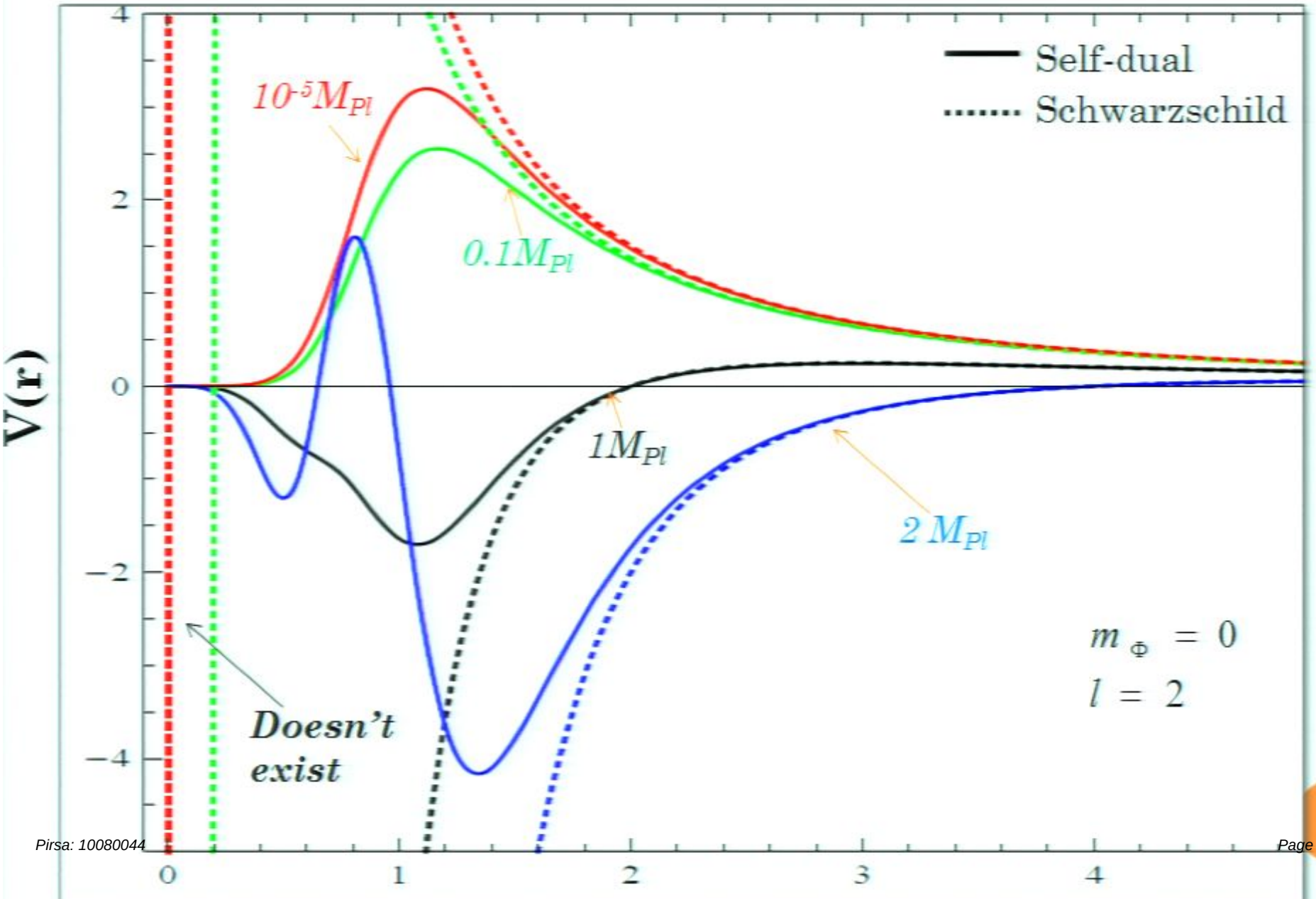
$$\left[\frac{\partial^2}{\partial r^{*2}} + \omega^2 - V(r(r^*))\right]\psi(r) = 0,$$

where, $r^* = \int \frac{1}{\sqrt{GF}}\,dr$

$K^2 = l\,(l+1)$

$$V(r) = G\left(m_\Phi^2 + \frac{K^2}{H}\right) + \frac{1}{2}\sqrt{\frac{GF}{H}}\left[\frac{\partial}{\partial r}\left(\sqrt{\frac{GF}{H}}\frac{\partial H}{\partial r}\right)\right]$$

Potential of Self-Dual BH



Surface Gravity and QNMs

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Always TRUE!

$$\boxed{\omega_n = i\kappa\left(n+\frac{1}{2}\right)+\frac{\ln 3}{2\pi}\kappa + O[n^{-1/2}]} \quad \text{as} \quad n \to \infty$$

Nollert (1993)
Medved et al. (2003)

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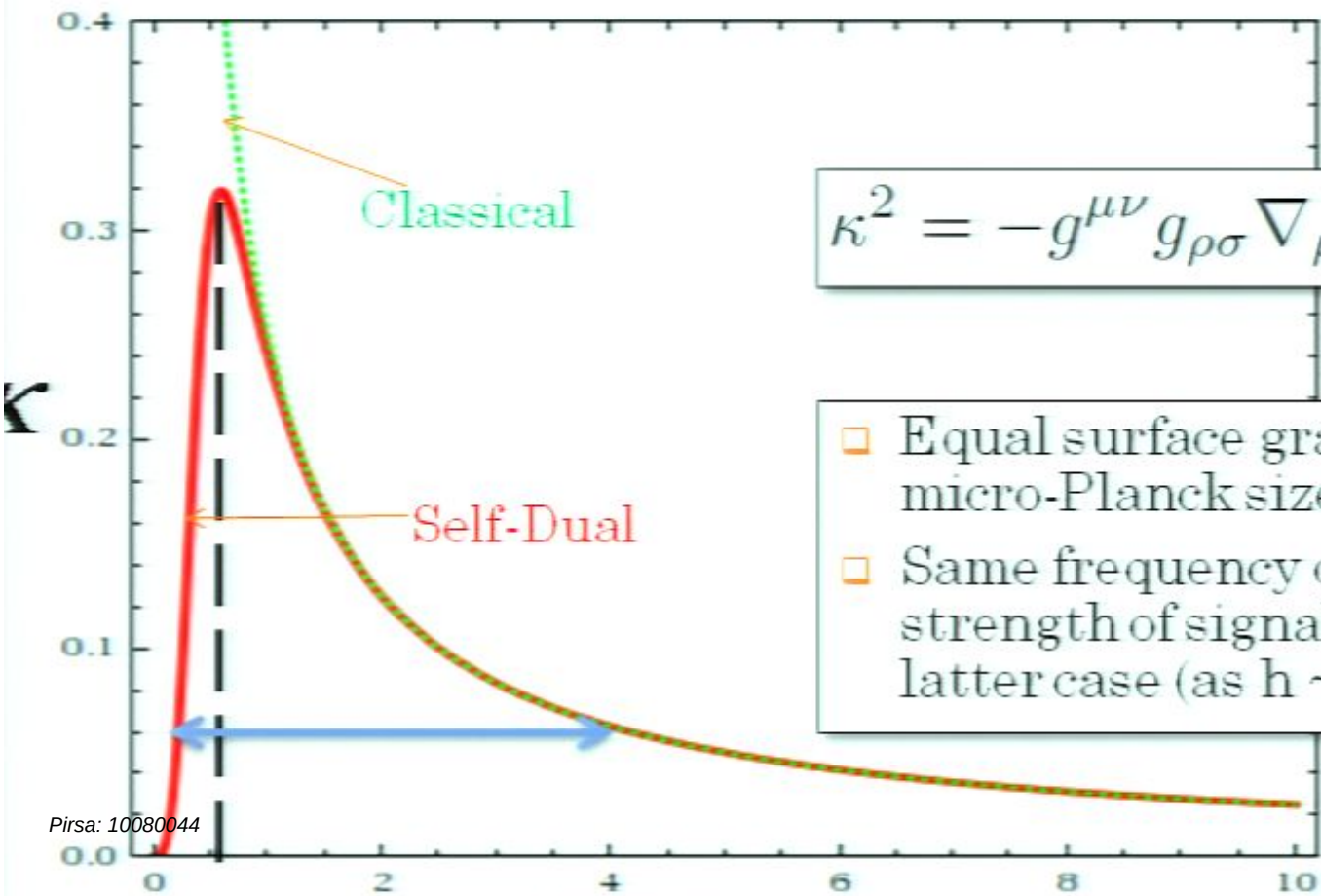

$$\kappa^2 = -g^{\mu\nu}g_{\rho\sigma}\nabla_\mu\chi^\rho\nabla_\nu\chi^\sigma/2$$

- Equal surface gravity for SMBH and micro-Planck size BH
- Same frequency of GW although strength of signal very weak in the latter case (as h ~ M/r)

Computing QNMs (for small 'n')

- Small 'n' is what we observe
  - In principle, easier to compute!
  - In the case of self-dual BHs – slightly non-trivial!
- WKB method might fail at $M < M_{planck}$
  - More than one turning points in the potential (doesn't have a peak at $r = 3M$!)
  - It might work at $M > M_{planck}$ as only $r = 3M$ dominates
    - *As consistency check, $a_0 = 0 = P$ should match with Schwarzschild case*
- Continuous fraction – most reliable but extremely difficult to compute the expressions !
  - Should work for all M

- Evolving the time dependent wave equation

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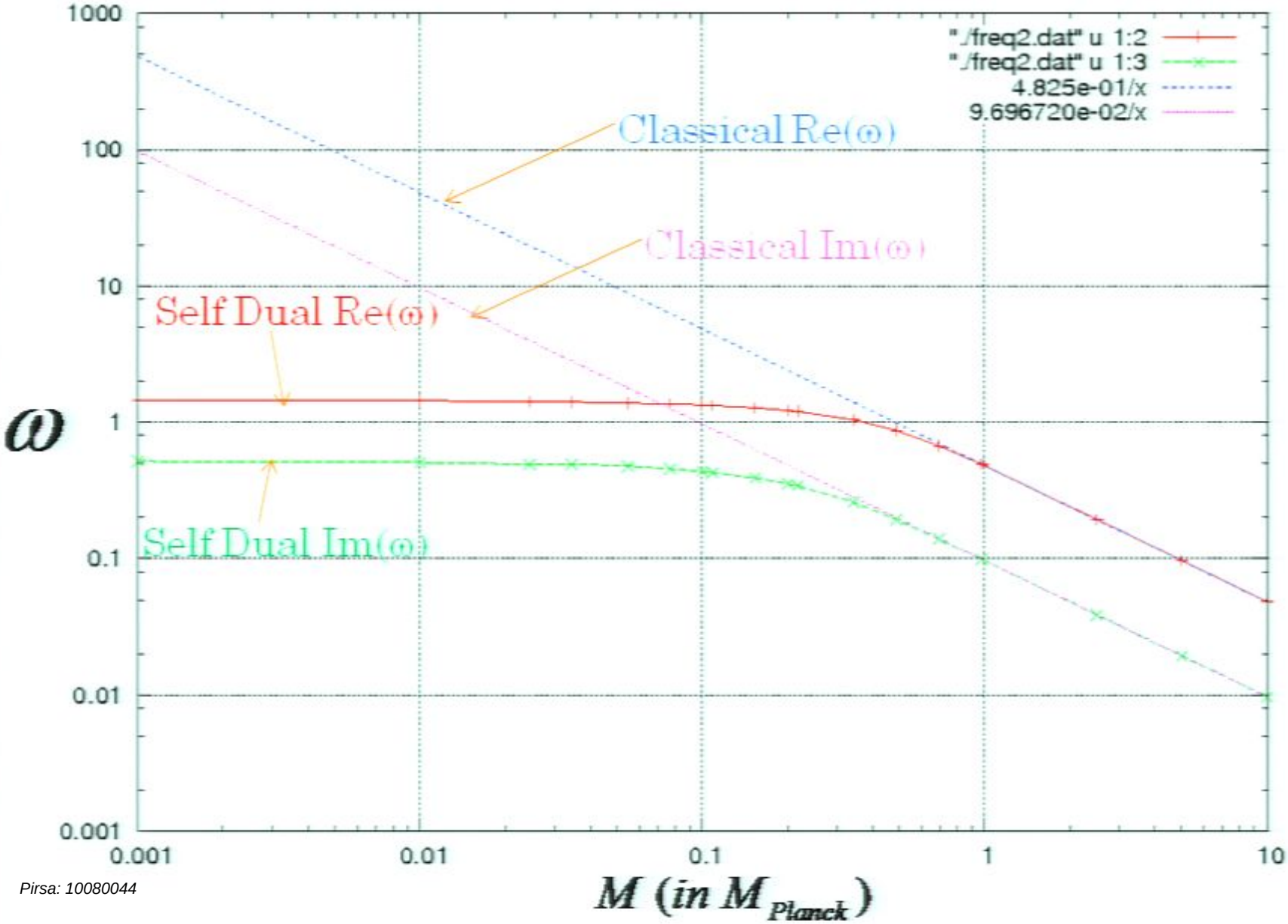
- Evolving the time dependent wave equation
  - Works only for n=1

Plots of QNM (for n = 1)



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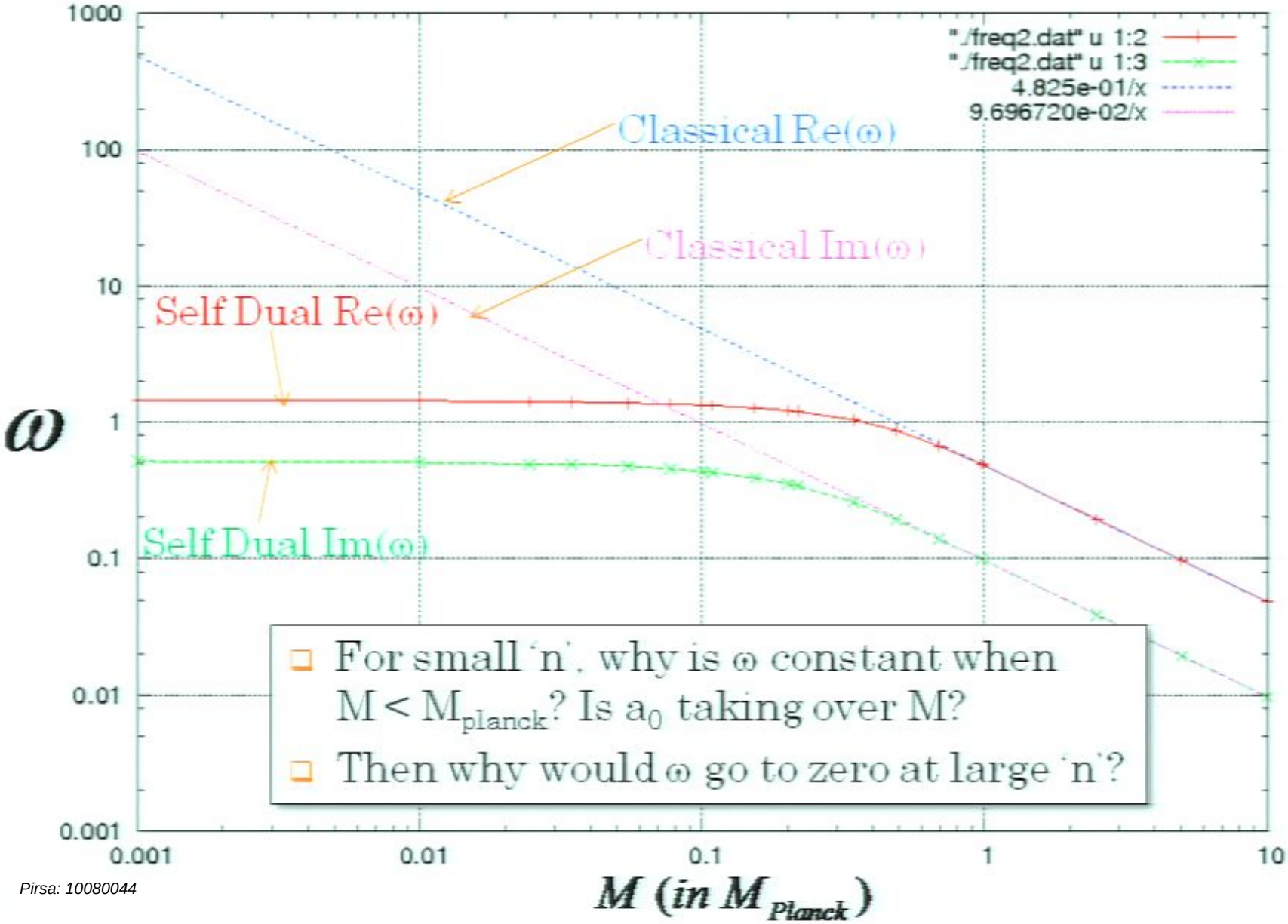
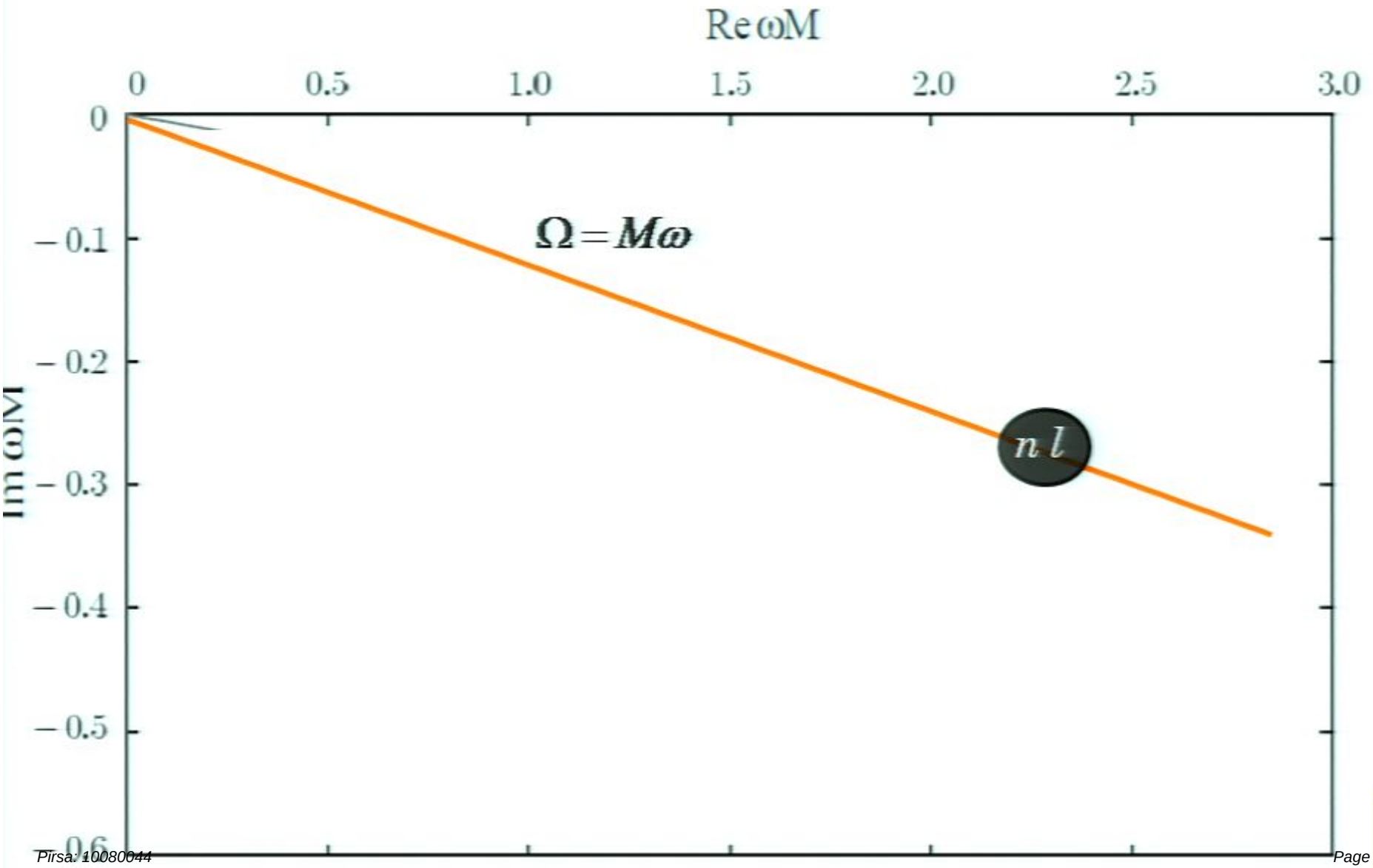


- For small 'n', why is ω constant when $M < M_{planck}$? Is a_0 taking over M?
- Then why would ω go to zero at large 'n'?

Possible Phenomenology for Astrophysical BHs



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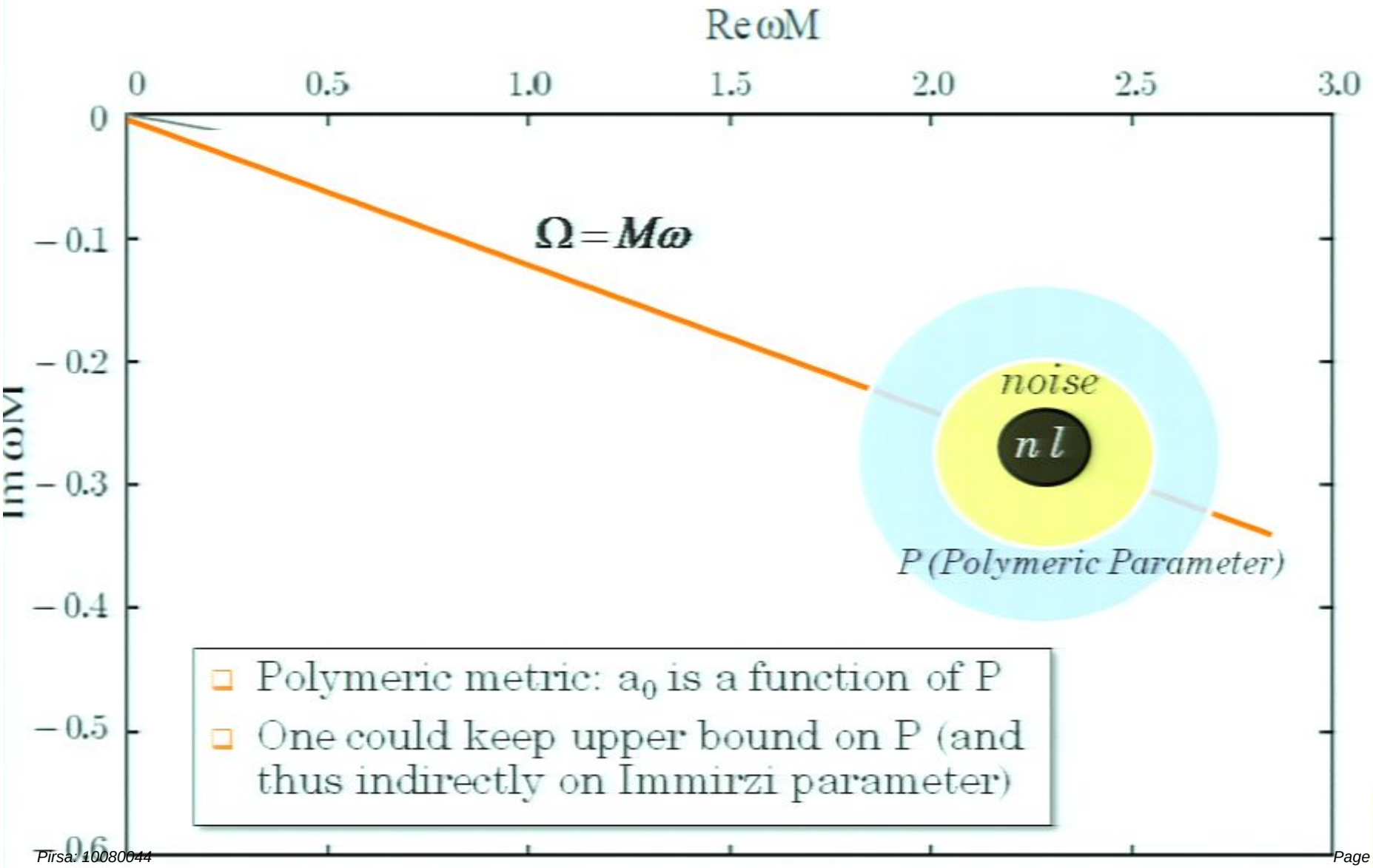

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- One could keep upper bound on P (and thus indirectly on Immirzi parameter)

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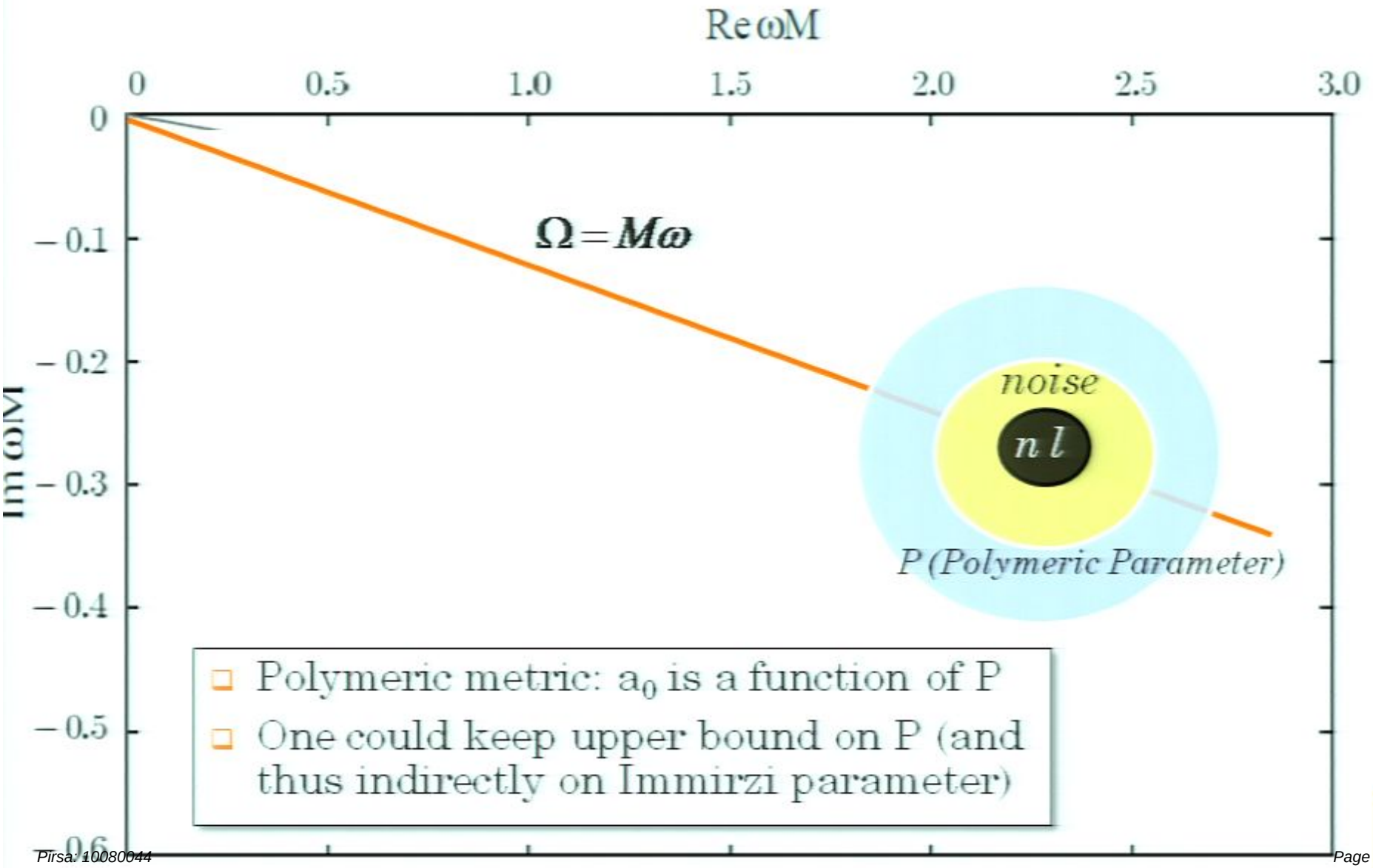

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  - Primordial – formed due to statistical thermal fluctuations at the end (during?) of inflation
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Quantum BH as DARK MATTER

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  - Assuming they constitute ALL the observed DM

$$\int_0^\infty \frac{(a(t_i))^3 m_0(m_i)\rho_{max}(m_i)}{(a(t_0))^3} dm_i = 0.22\rho_{crit}$$

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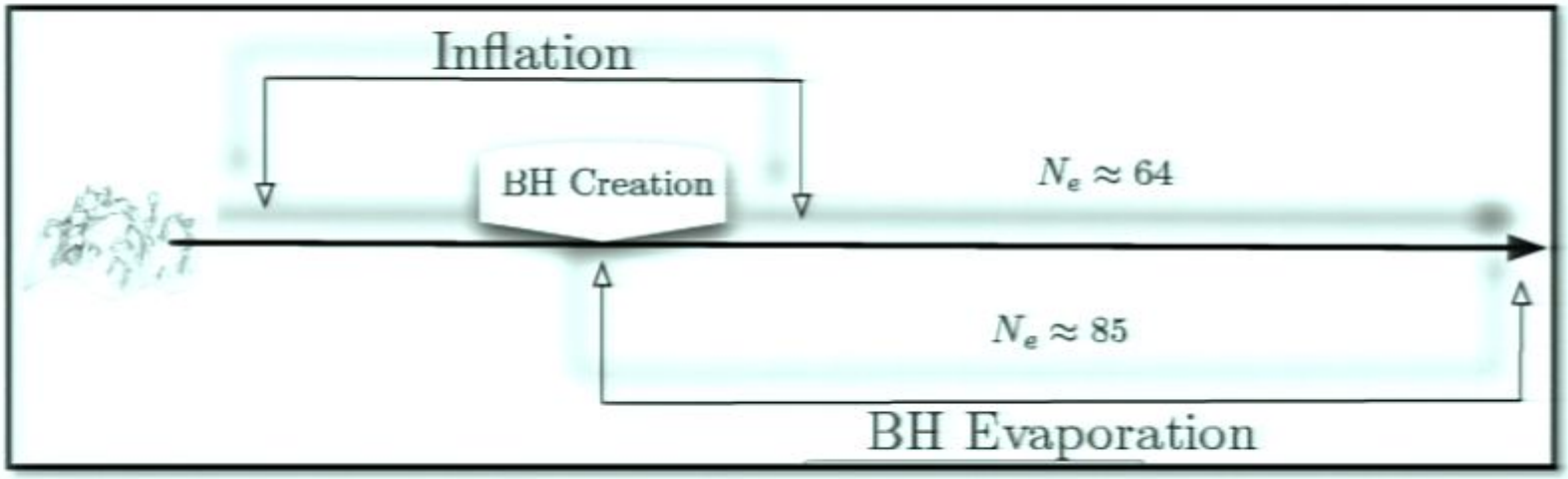

DM Phenomenology

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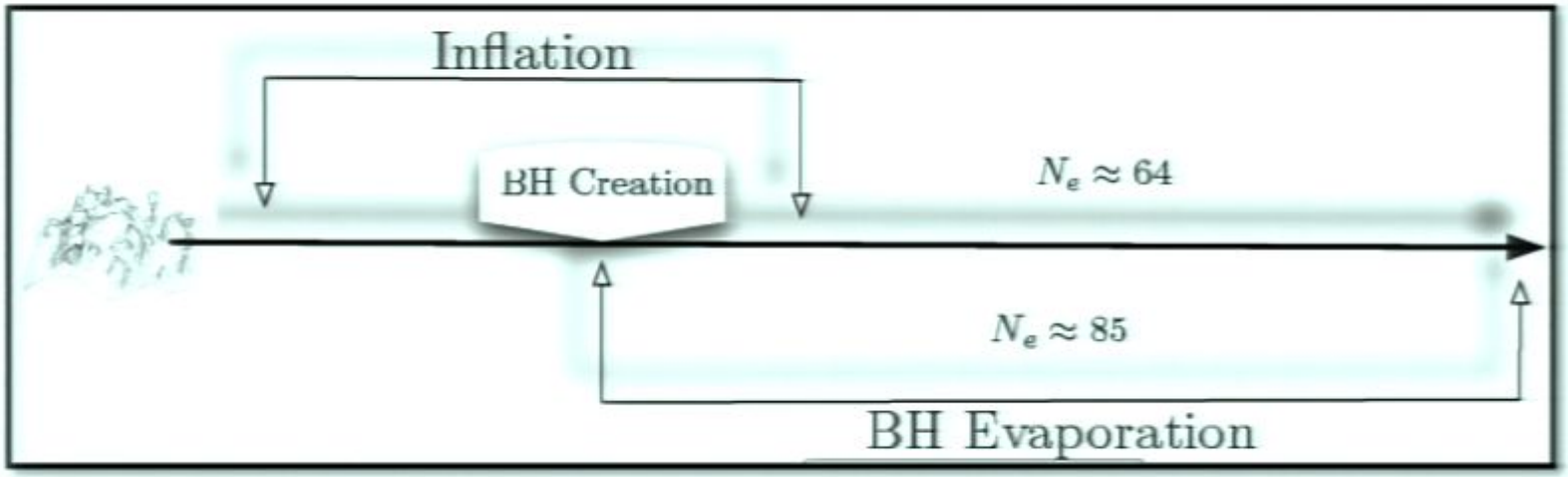

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- Self-Dual BHs to rescue!

$$\sigma_{th} = \int_{m_0=0}^{\infty} \int_{6\times10^{19}\,\text{eV}}^{m_0} \frac{2A_{min}\,\rho_{MWBH}(m_0)\,\nu^2}{\pi(e^{\frac{\nu}{T_{BH}(m_0)}}-1)} d\nu$$

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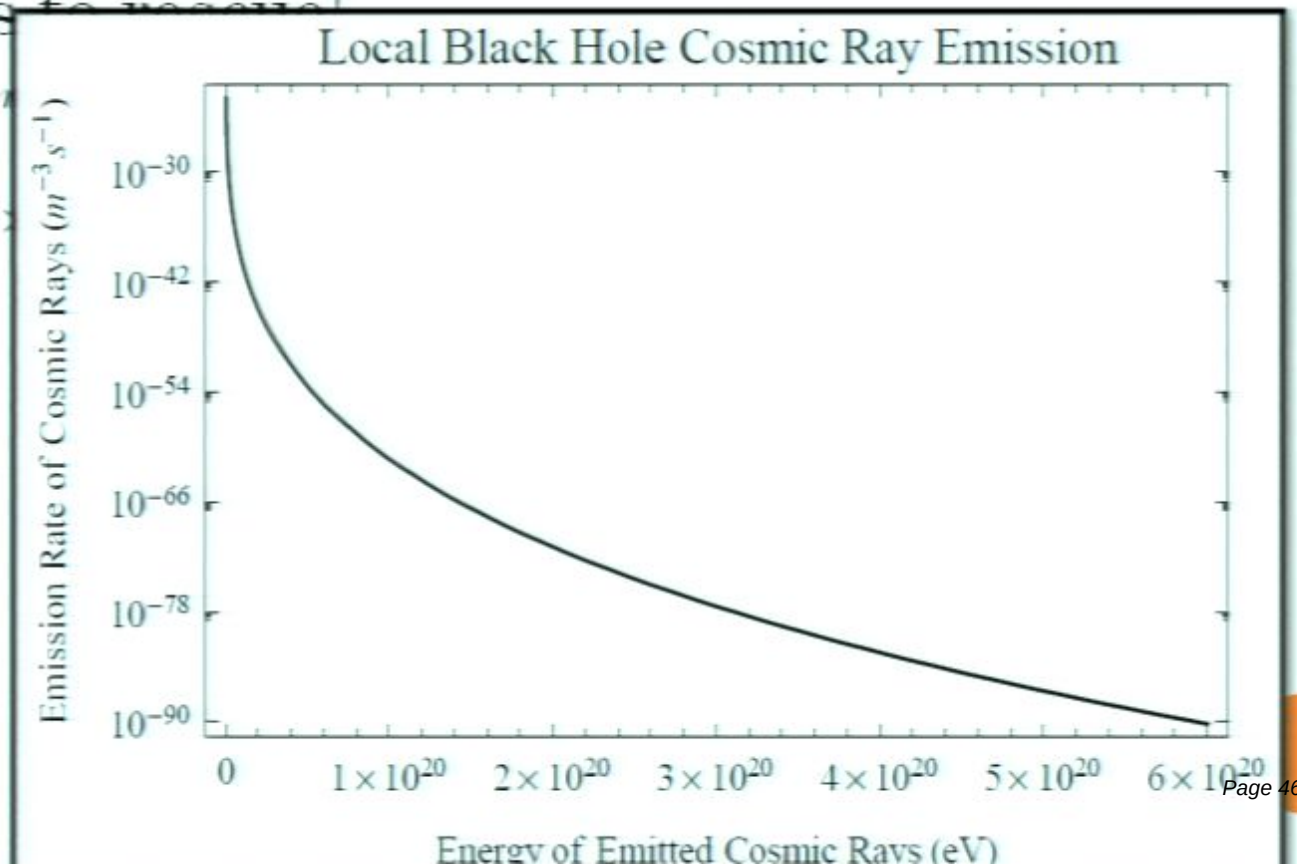

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- Assuming all of the DM BHs haven't reached equilibrium (WHY?)
  - And also assuming their distribution is homogenous & isotropic & we assume a neat fraction of them in phase
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Lorentz Invariance Violation

- Deformed Special Relativity:

$$m^2 = E^2 - p^2 + \Delta_{qg}(E, p^2; M_{QG})$$

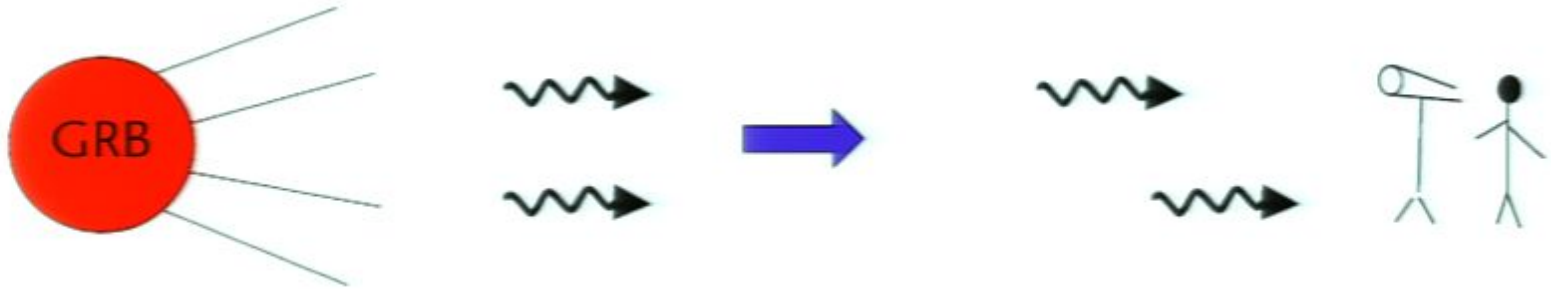
- Vacuum has an energy dependent refractive index (?)

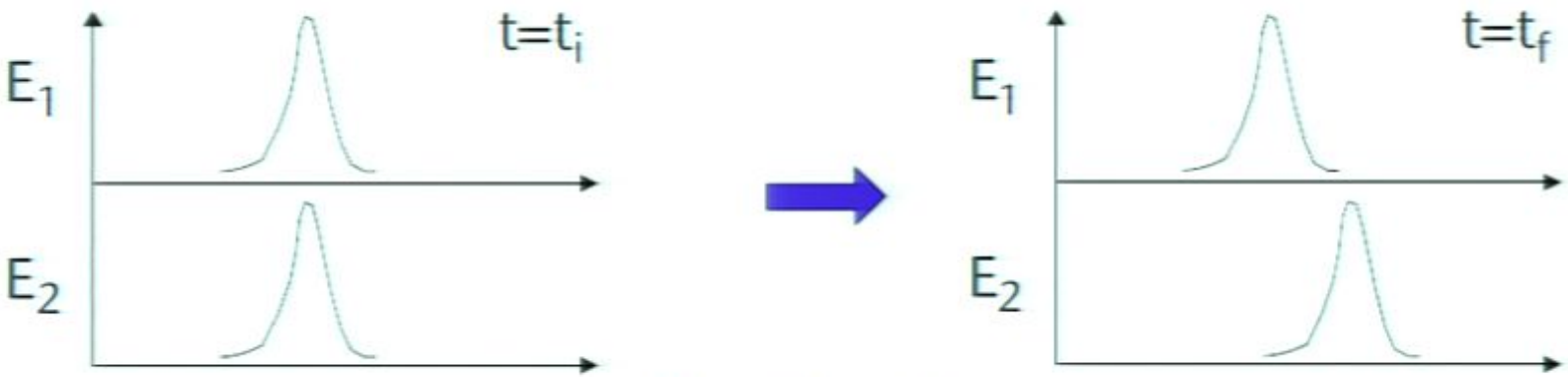
- No longer invariant:

$$c(\varepsilon) = 1 - \zeta \frac{E}{E_{QG}} = 1 - \varepsilon \qquad ds^2(\varepsilon) \neq ds^2(\varepsilon')$$

- Where is the relativity ?
  - Observers agree on E_{QG}
  - Observers agree on the wavelength of a color

Phenomenon of Time Delay





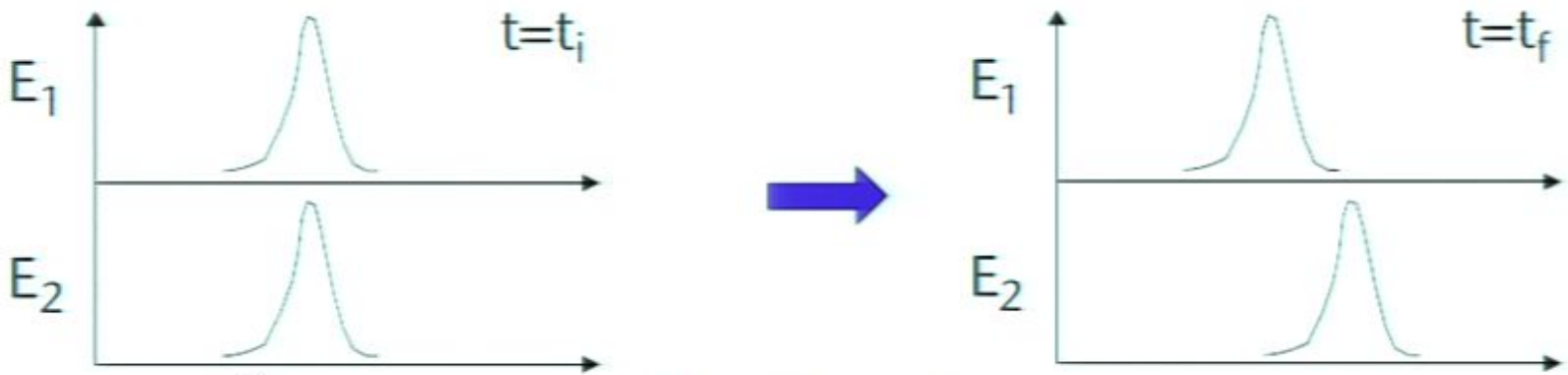
$\Delta t=0$

Here $E_1 > E_2$

$$\Delta t = \frac{L}{c}\frac{\Delta E}{E_{QG}}$$

Phenomenon of Time Delay

Assuming attenuation of gamma photons has negligible effects



Here $E_1 > E_2$

$$\Delta t = \frac{L}{c}\frac{\Delta E}{E_{QG}}$$

Assuming both were emitted at 'almost' same time

Assuming we know the distance to the source pretty well

Phenomenon of Time Delay (cont.)

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Flat FRW Metric: $ds^2 = -dt^2 + a(t)^2[d\chi^2 + \chi^2(d\theta^2 + \sin^2\theta d\phi^2)]$

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For $m = 0$ *(QG phenomenology)*

$$\Delta t = \frac{\zeta}{E_{QG}} D(f_e' - f_e)$$

$$D \equiv \frac{1}{H}\int_0^z dz \frac{1+z}{\sqrt{\Omega_\Lambda + (1+z^3)\Omega_{Matter}}}$$

For $\zeta = 0$ *(Bounding graviton mass)*

$$\Delta t = \frac{m^2}{2} D\left(\frac{1}{f_e^2} - \frac{1}{f_{e'}^2}\right)$$

$$D \equiv (1+Z)^2 \int_{t_e}^{t_a} \frac{a(t)}{a(t_a)} dt$$

Sources for Phenomenology of LIV

- **Gamma Ray Bursts**
  - Distance ~Gpc, energy ~ GeV
    - *GRB 080916:* $z = 4.35$, $E_{max} = 13.2$ GeV , $E_{QG} \sim 0.1\ E_{Planck}$
    - *GRB 090510:* $z = 0.903$, $E_{max} = 31$ GeV , $E_{QG} \sim 10\ E_{Planck}$
- **Active Galactic Nuclei**
  - Distance ~0.1 z, total energy TeV
    - *PKS 2155-304:* $E_{QG} \sim 0.1\ E_{Planck}$
- **Pulsars**
  - Distance ~kpc, energy ~ 100 MeV but nano –second precision in pulsation

Multi-Messenger Phenomenology for LIV

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  - GRB: $E > 10^2$ TeV
  - Detection probability for a short burst ~ 10^{-2}, so unlikely to have two neutrinos detected from same source
  - Comparison with low energy photon could be used (even if there is an intrinsic delay!)

U. Jacob & T. Piran (2007)

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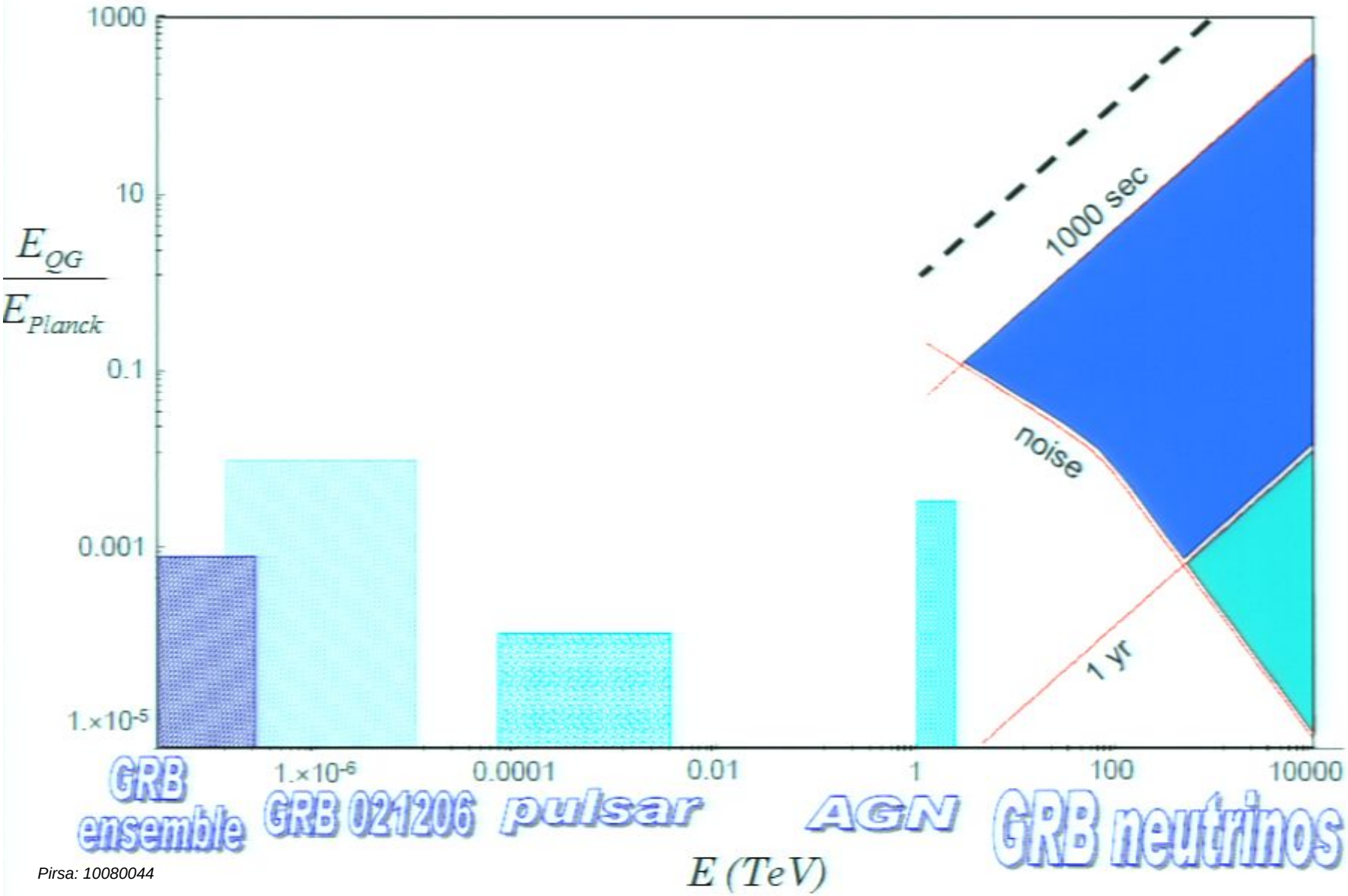
  - Easier to model merging of SMBH + cosmological scale (entire universe) – energy to low (~10^{-3} Hz) = Almost unaffected by QG !
  - EM signal during coalescence (accretion & transients of relativistic gas)

B. Kocsis et al. (2008)

    - Similar as keeping bound on mass of graviton, but here one favors graviton to have no delay (massless) !

Summarizing The Bounds



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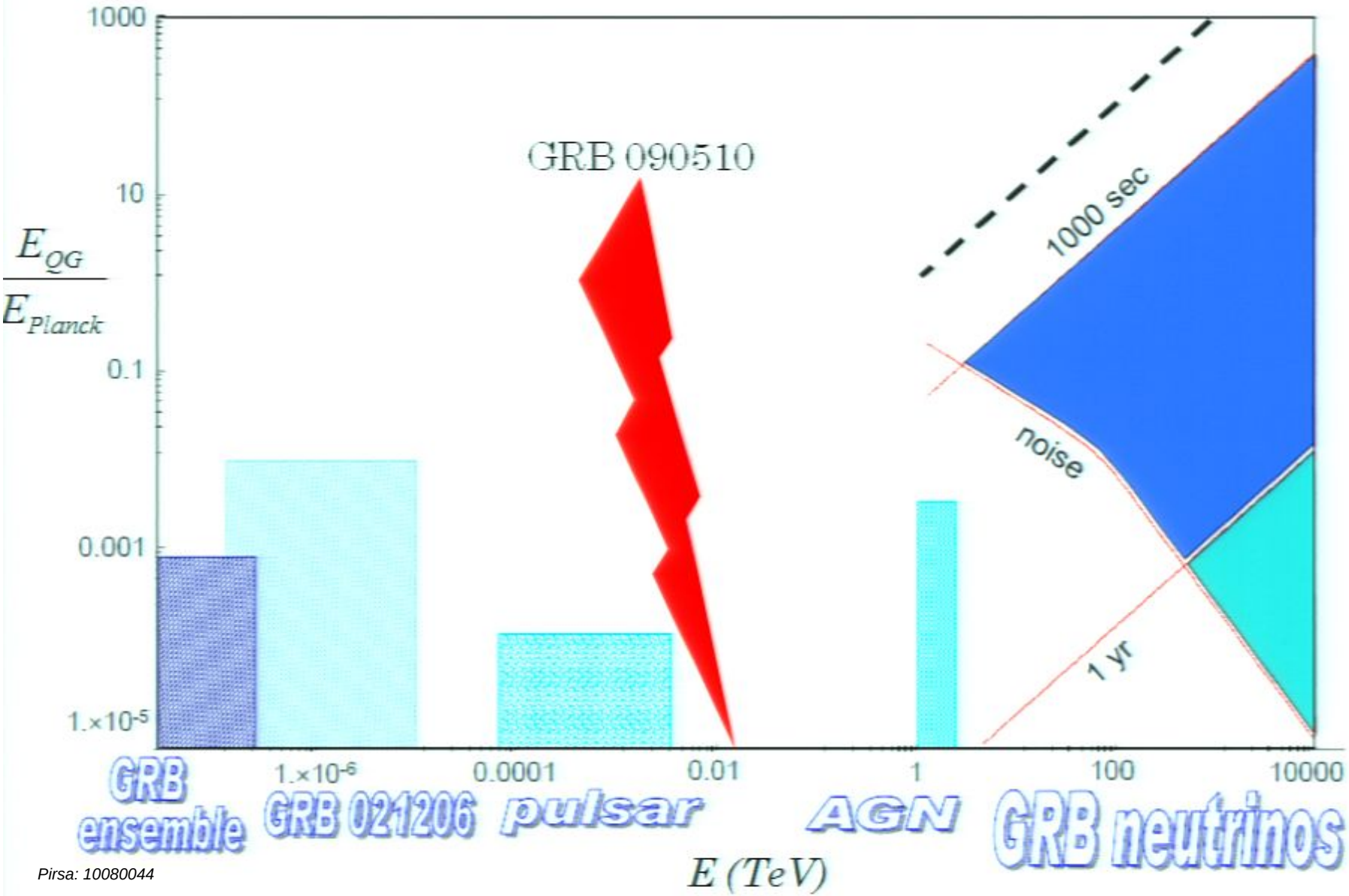

"THOUGH THE SOURCE BE OBSCURE, STILL THE STREAM FLOWS ON... "

- Taken from *NUMBER – THE LANGUAGE OF SCIENE by Tobias Dantzig*

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- **GRB** (?) = Photons + Neutrinos + GWs

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COMPUTING QNMs (FOR SMALL 'n')

- Small 'n' is what we observe
  - In principle, easier to compute!
  - In the case of self-dual BHs – slightly non-trivial!
- WKB method might fail at $M < M_{planck}$
  - More than one turning points in the potential (doesn't have a peak at $r = 3M$!)
  - It might work at $M > M_{planck}$ as only $r = 3M$ dominates
    - *As consistency check, $a_0 = 0 = P$ should match with Schwarzschild case*
- Continuous fraction – most reliable but extremely difficult to compute the expressions !
  - Should work for all M
- Evolving the time dependent wave equation
  - Works only for n=1

Work in progress!

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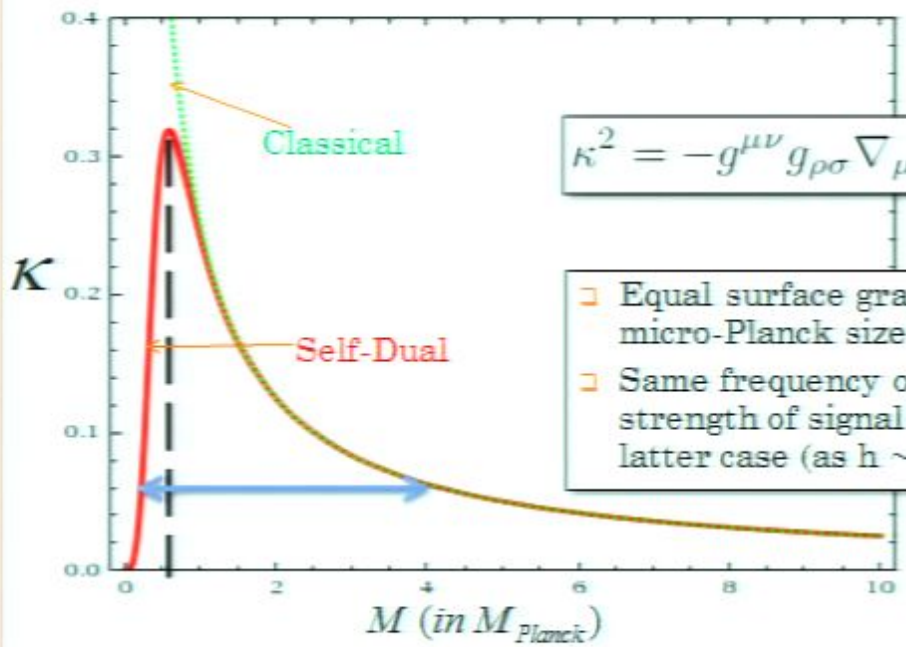
Surface Gravity and QNMs

Always TRUE!

$$\omega_n = i\kappa\left(n+\frac{1}{2}\right)+\frac{\ln 3}{2\pi}\kappa + O[n^{-1/2}] \quad \text{as} \quad n \to \infty$$

Nollert (1993)
Medved et al. (2003)



$$\kappa^2 = -g^{\mu\nu} g_{\rho\sigma} \nabla_\mu \chi^\rho \nabla_\nu \chi^\sigma / 2$$

- Equal surface gravity for SMBH and micro-Planck size BH
- Same frequency of GW although strength of signal very weak in the latter case (as h ~ M/r)

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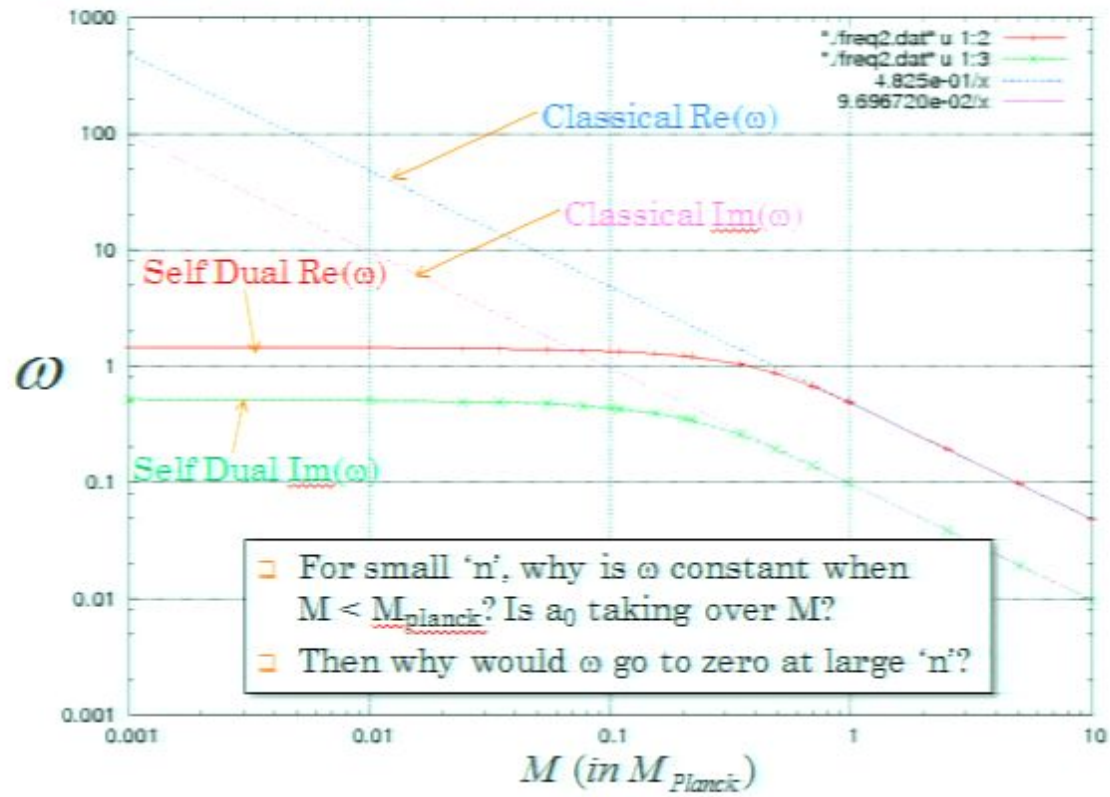
Plots of QNM (for n = 1)



- For small 'n', why is ω constant when $M < M_{planck}$? Is a_0 taking over M?
- Then why would ω go to zero at large 'n'?

Courtesy Alberto Montina

Work in progress!

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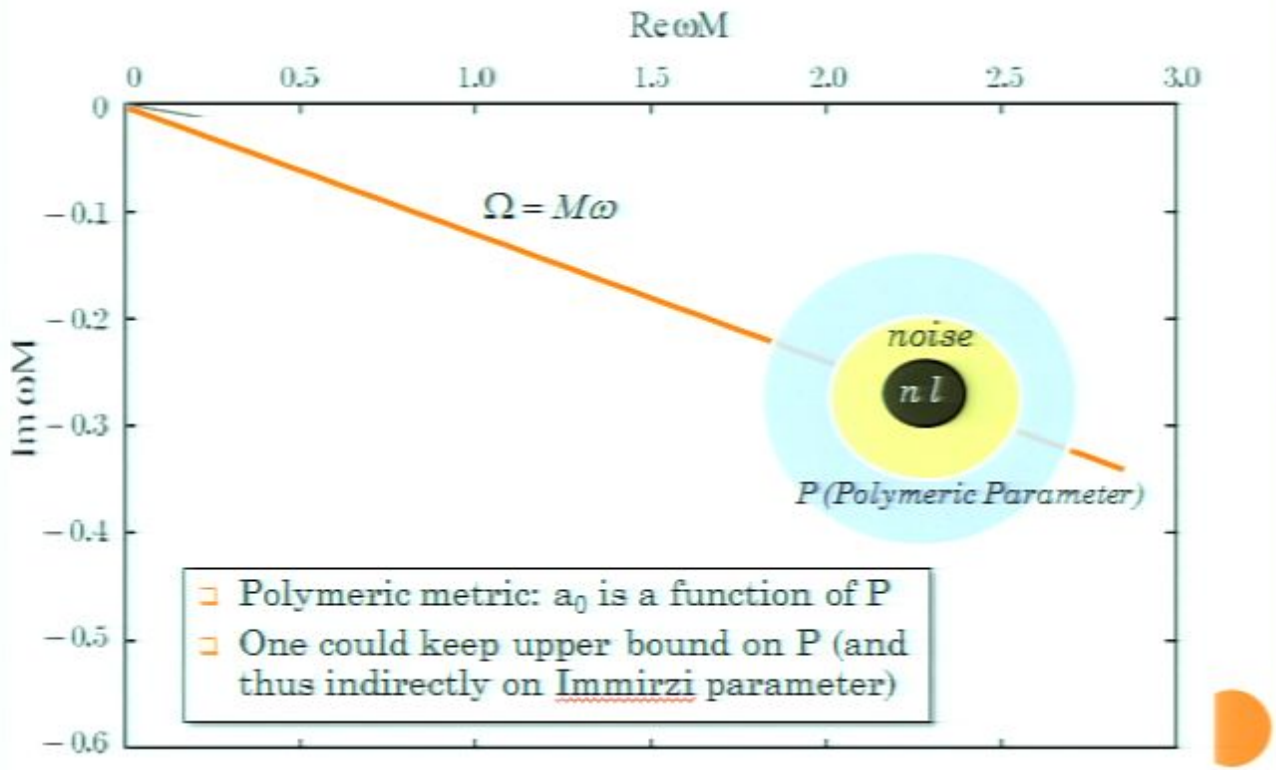
Possible Phenomenology for Astrophysical BHs



- Polymeric metric: a_0 is a function of P
- One could keep upper bound on P (and thus indirectly on Immirzi parameter)

Work in progress!

Click to add notes