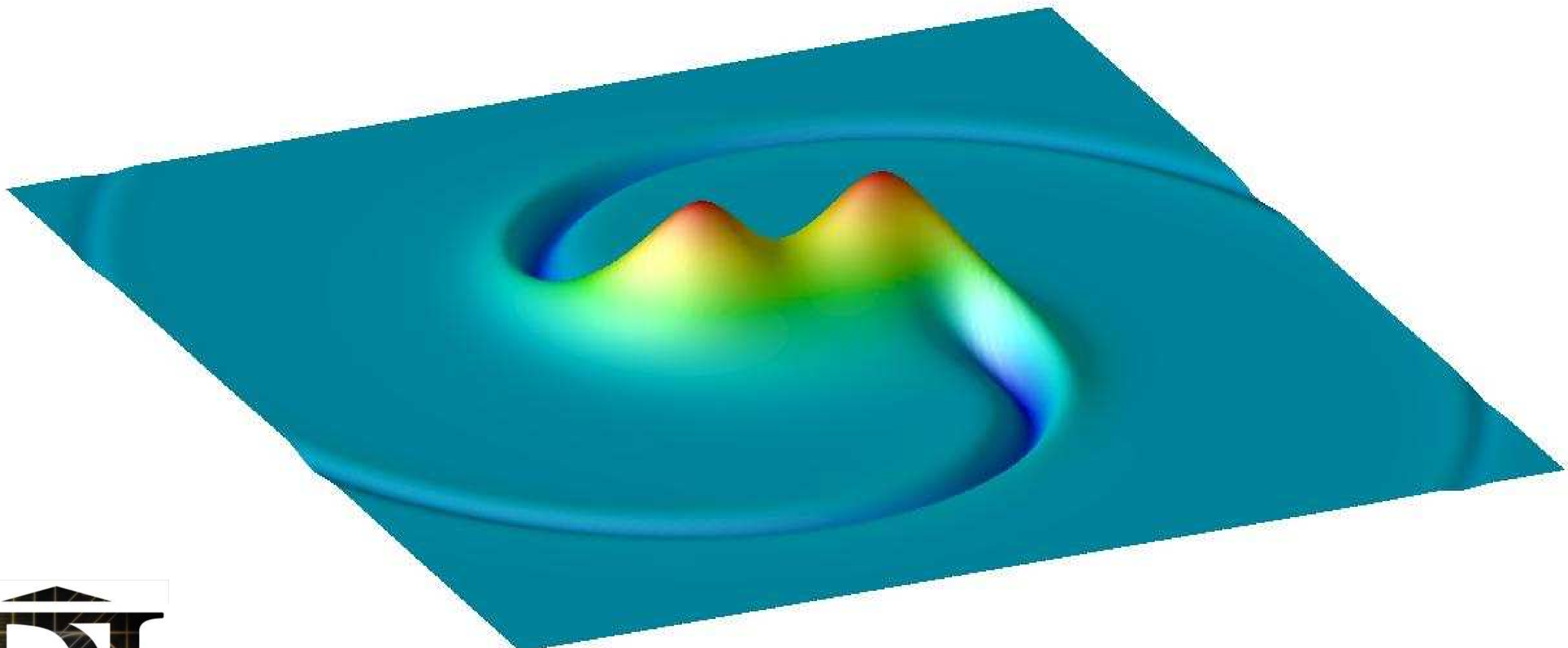
The fast life of holographic mesons

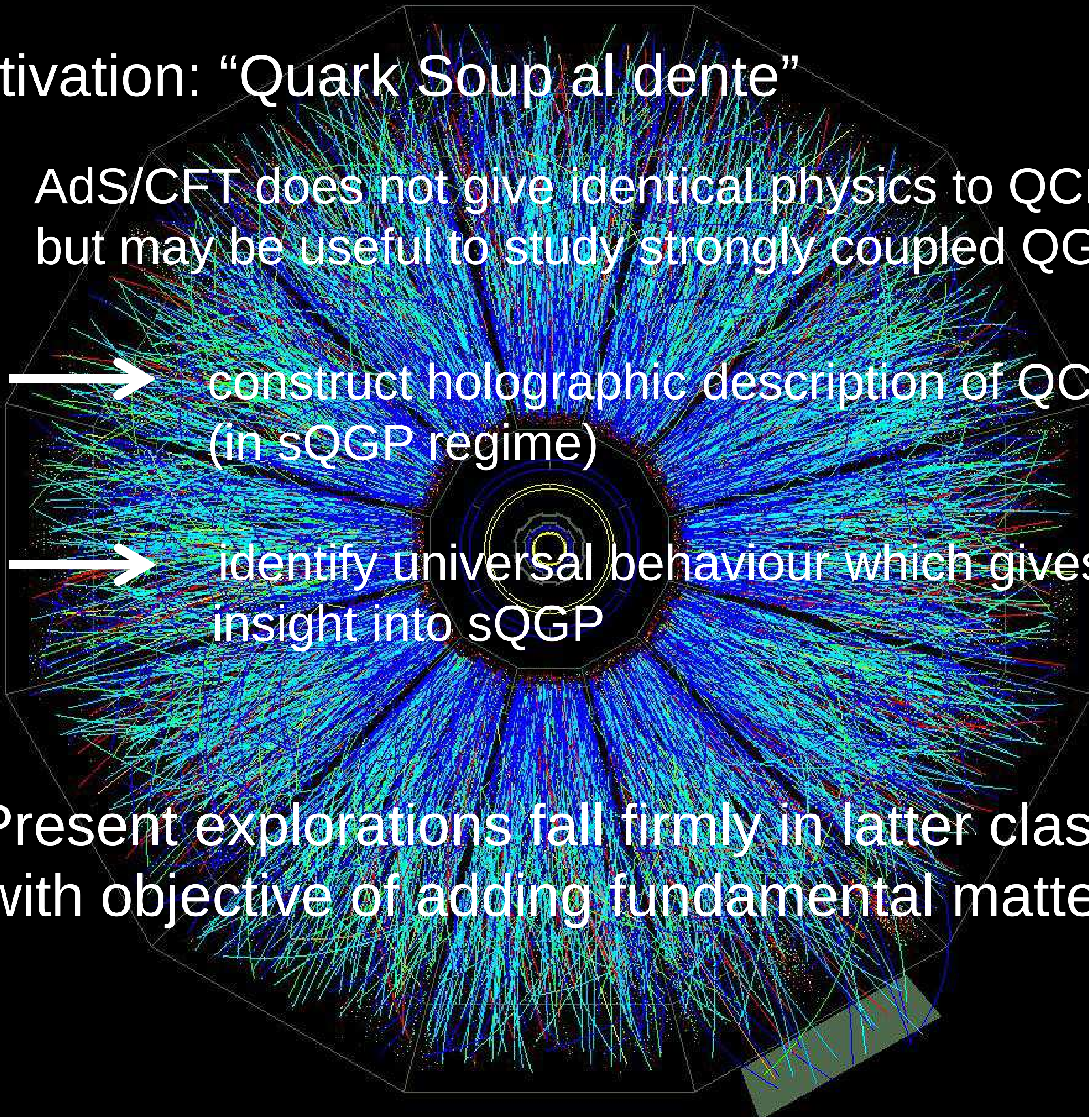


PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

with Aninda Sinha [*arXiv:0804.2168*]

(*Rowan Thomson, Andrei Starinets & David Mateos*)

Motivation: “Quark Soup al dente”



AdS/CFT does not give identical physics to QCD, but may be useful to study strongly coupled QGP

→ construct holographic description of QCD (in sQGP regime)

→ identify universal behaviour which gives insight into sQGP

Present explorations fall firmly in latter class with objective of adding fundamental matter

Field theory story: (Reader's Digest version)

$\mathcal{N}$=2 SU(N_c) super-Yang-Mills with (N_f+1) hypermultiplets

fundamental ↑ ↑ adjoint

adjoint fields: vector: $(A_\mu)^a{}_b,\ (\psi_{1,2})^a{}_b,\ (\phi_3)^a{}_b$

1 hyper: $(\phi_{1,2})^a{}_b,\ (\psi_{3,4})^a{}_b$

} $\mathcal{N}$ =4 SYM content

fundamental fields: N_f **massive** hyper's "quarks"

2 complex scalars : $(q_i)^a,\ (\tilde{q}^i)_a$

2 Weyl fermions: $(\psi_i)^a,\ (\tilde{\psi}^i)_a$

} fund. in U(N_c) & global U(N_f)

- work in limit of large N_c and large λ **but** N_f fixed

"quenched approximation": $N_f/N_c \longrightarrow 0$

- note **not** a confining theory:

$$\text{free quarks} \sim m_q$$

$$\text{“mesons” } (f\bar{f} \text{ bound states}) \sim m_q/\sqrt{\lambda}$$

Finite Temperature:

- low temperatures:

$$\text{free quarks} \sim m_q - \Delta m(T)$$

$$\text{mesons } (f\bar{f} \text{ bound states}) \sim m_q/\sqrt{\lambda} - \Delta m'(T)$$

  - unusual dispersion relations: $v_{lim} < c$
  - quasi-particle widths increase dramatically near v_{lim}

- phase transition: $T \sim m_q/\sqrt{\lambda}$ (strong coupling!!)

- high temperatures:

  NO quark or meson quasi-particles

  “quarks dissolved in strongly coupled plasma”

Holographic Results

- note **not** a confining theory:

free quarks $\sim m_q$

"mesons" ($f\bar{f}$ bound states) $\sim m_q/\sqrt{\lambda}$

Finite Temperature:

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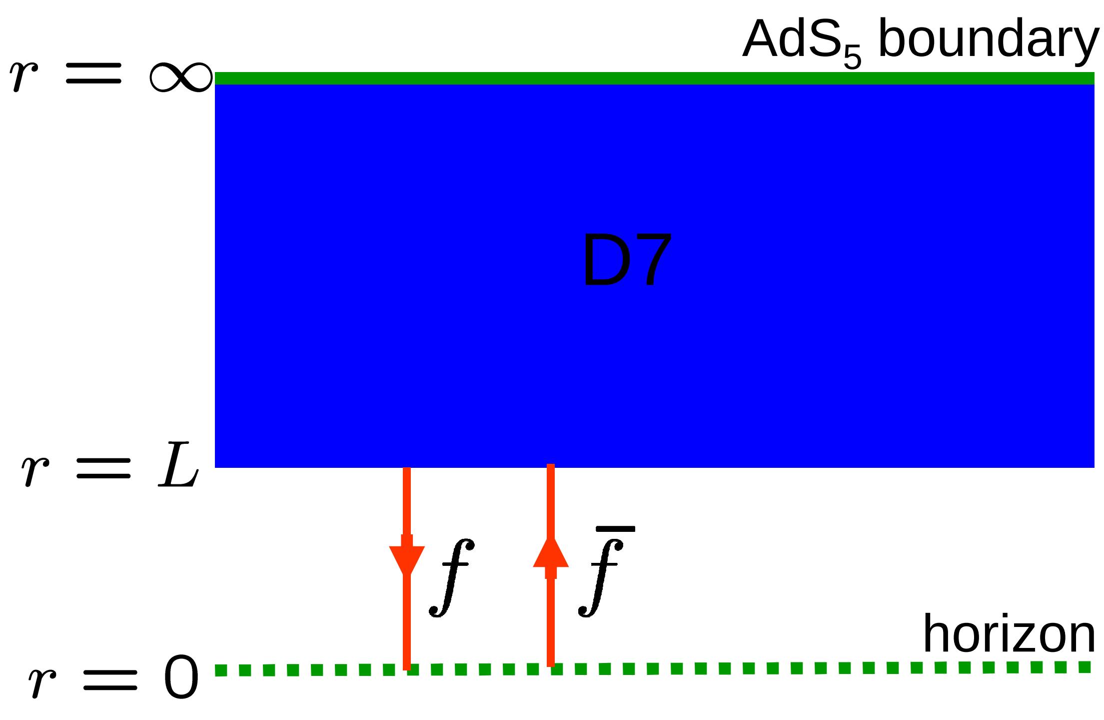
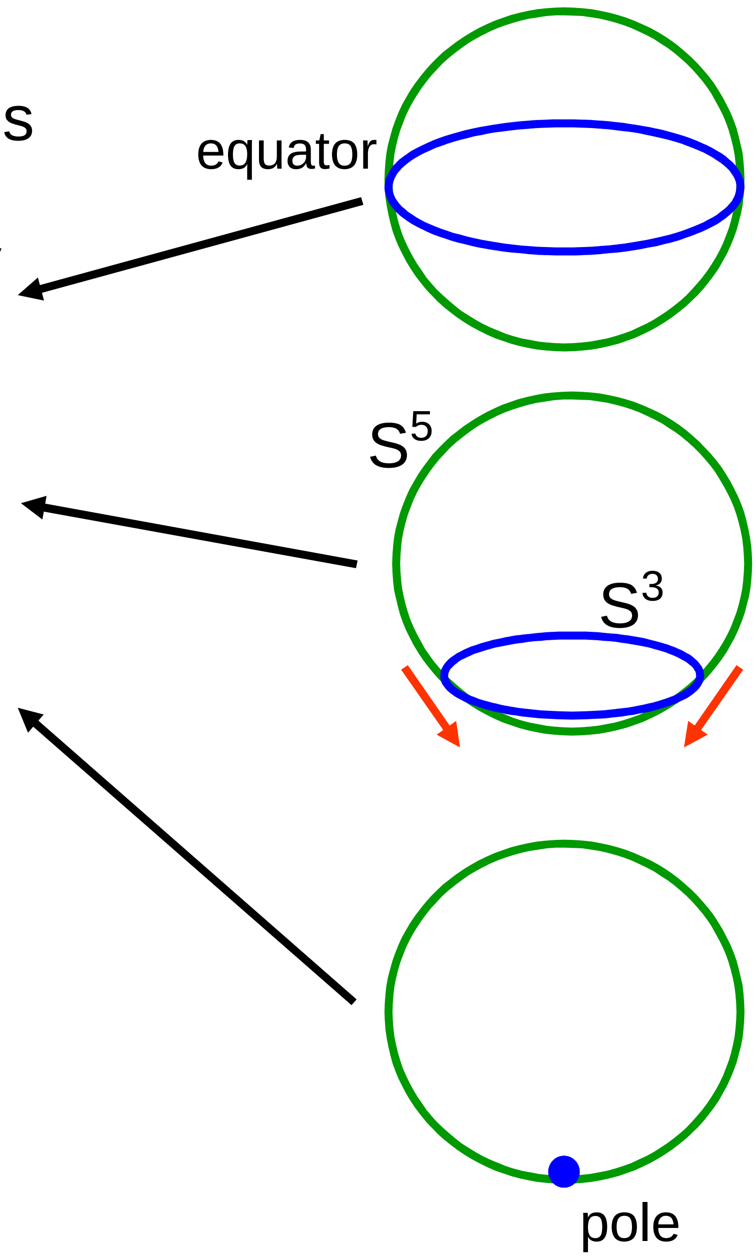
"quarks dissolved in strongly coupled plasma"

Aharony, Fayyazuddin & Maldacena (hep-th/9806159)
Karch & Katz (hep-th/0205236)

Adding flavour to AdS/CFT

add N_f probe D7-branes





Free quarks appear with mass:

$$m_q = \frac{L}{2\pi\alpha'}$$

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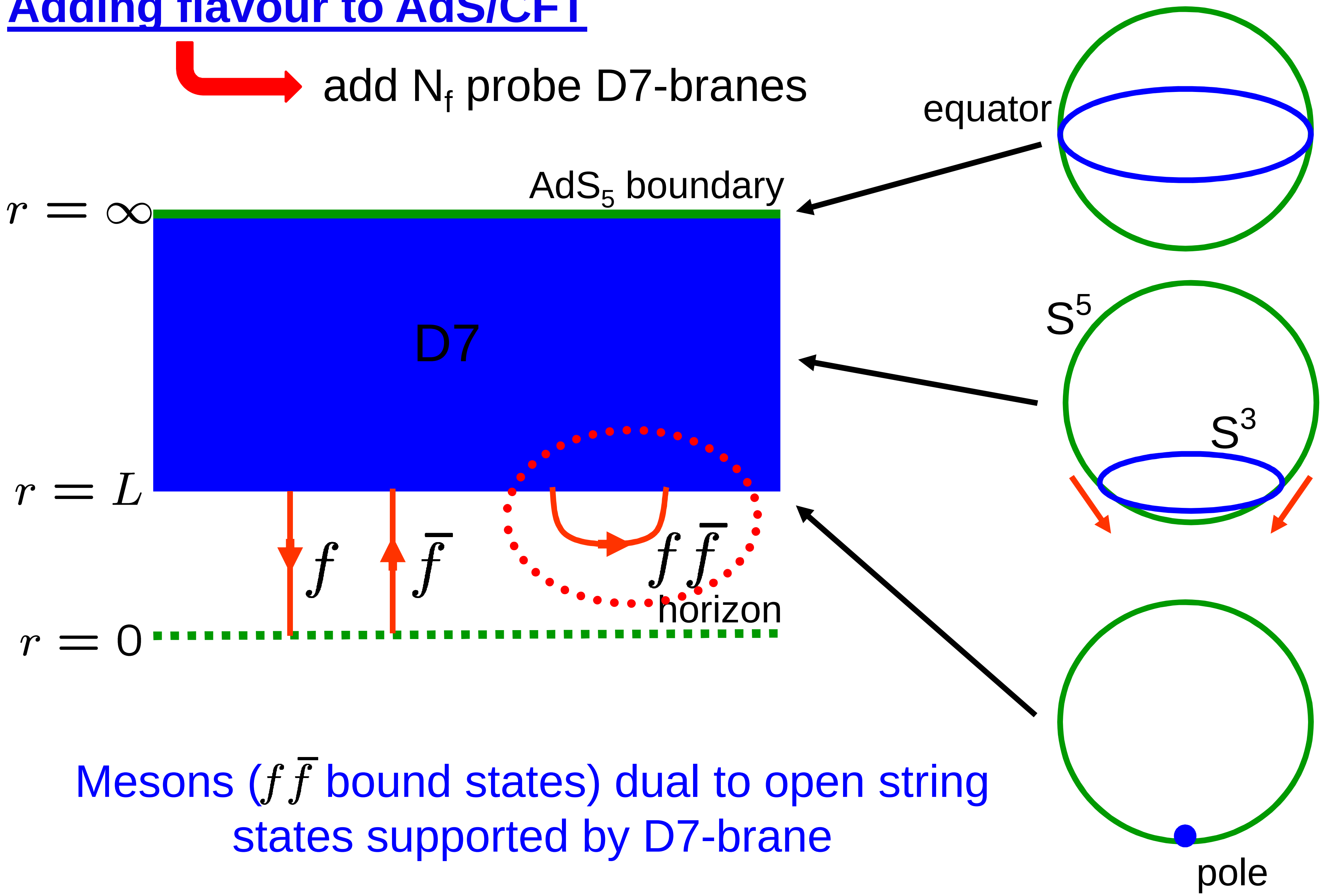


Mesons ($f\,\bar{f}$ bound states) dual to open string states supported by D7-brane

Gauge/gravity dictionary:

supergravity modes: $h_{\mu\nu} \quad \leftrightarrow \quad T_{\mu\nu}$

D7-brane modes:

$$A_\mu^{ij} \;\leftrightarrow\; J_\mu^{ij} \simeq \text{Tr}\left[\bar{\psi}^i \gamma_\mu \psi^j + \Phi^i D_\mu \Phi^j\right]$$

Probe approximation: $N_f / N_c \to 0$

Above construction does not take into account the “gravitational” back-reaction of the D7-branes!

$\to$ considering large-N_c limit with N_f fixed

(see, however: Burrington et al; Kirsch & Vaman; Casero, Nunez & Paredes, ...)

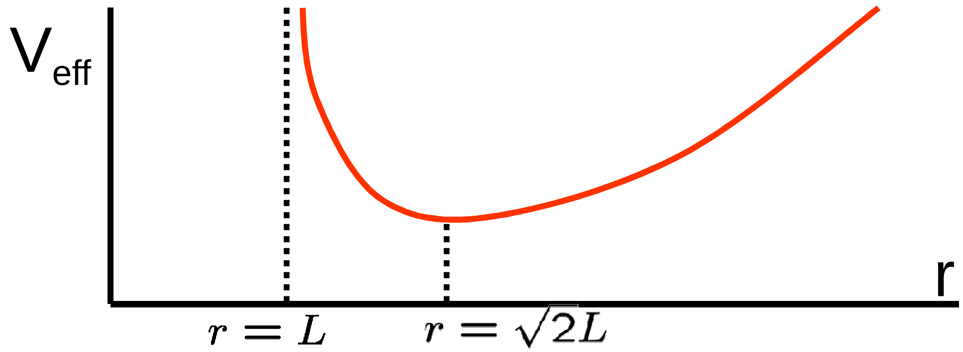
Kruczenski, Mateos, RCM & Winters [hep-th/0304032]

Mesons:

lowest lying open string states are excitations of the massless modes on D7-brane: vector, scalars (& spinors)

(free) spectrum:

- expand worldvolume action to second order in fluctuations
- solve linearized eq's of motion by separation of variables



Discrete spectrum:

$$M^2(n,\ell) = \frac{4L^2}{R^4}(n+\ell+1)(n+\ell+2)$$

n = radial AdS #
ℓ = angular # on S^3

$$n=\ell=0\ :\quad m_{\text{gap}} = 2\sqrt{2}\frac{L}{R^2} = 4\pi\frac{m_q}{\sqrt{g_{YM}^2 N_c}} = 4\pi\frac{m_q}{\sqrt{\lambda}}$$

Witten (hep-th/9803131); …..

Gauge/Gravity thermodynamics:

Gauge theory thermodynamics = Black hole thermodynamics

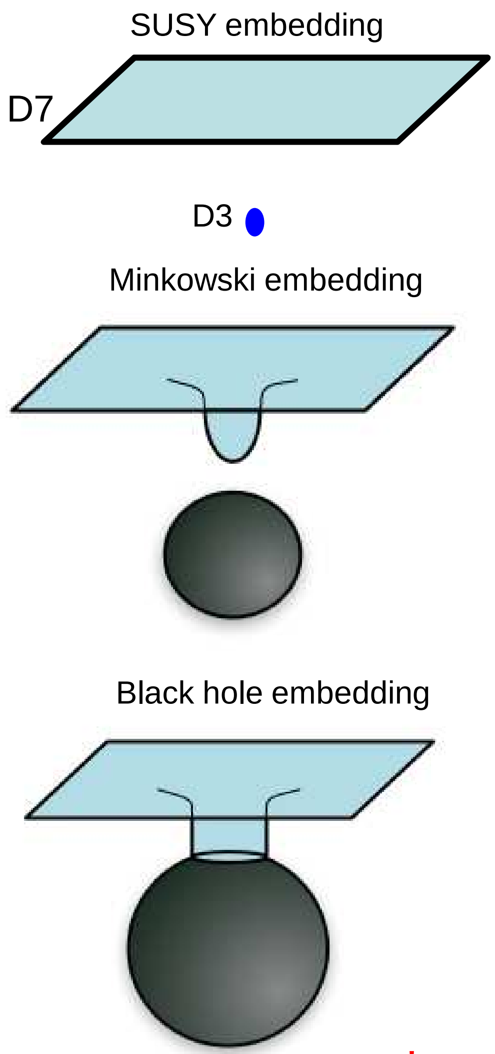
- Replace SUSY D3-throat with throat of black D3-brane
- Wick rotate and use euclidean path integral techniqes
- . . . . .

Extend these ideas to include
contributions of probe branes/fundamental matter

Babington, Erdmenger, Evans, Guralnik & Kirsch [hep-th/0306018]
Mateos, RCM &Thomson [hep-th/0605046]; . . . . .

Gauge/Gravity thermodynamics with probe branes:

put D7-probe in throat geometry of black D3-brane



T=0: “brane flat”

raise T: horizon expands and increased gravity pulls brane towards BH horizon

Low T: tension supports brane;
D7 remains outside BH horizon

Phase transition†

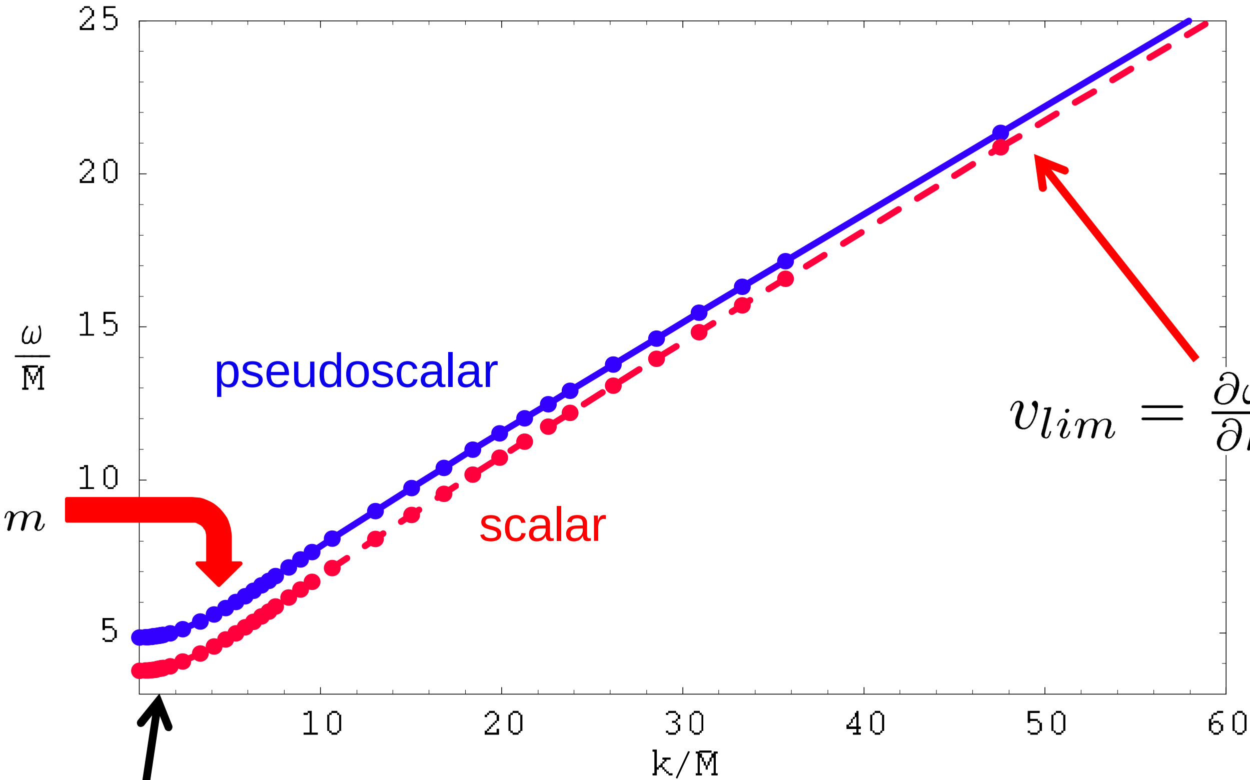
High T: gravity overcomes tension;
D7 falls through BH horizon

(†This **new** phase transition is **not** a deconfinement transition.)

Mesons in Motion:

Mateos, RCM &Thomson [hep-th/0701132]

Ejaz, Faulkner, Liu, Rajagopal & Wiedemann [arXiv:0712.0590]



$$v_{lim} = \frac{\partial \omega}{\partial k} < 1$$

$$v_{max} > v_{lim}$$

$$\omega(k) \simeq M_0 + \frac{\mathbf{k}^2}{2M_{kin}}$$

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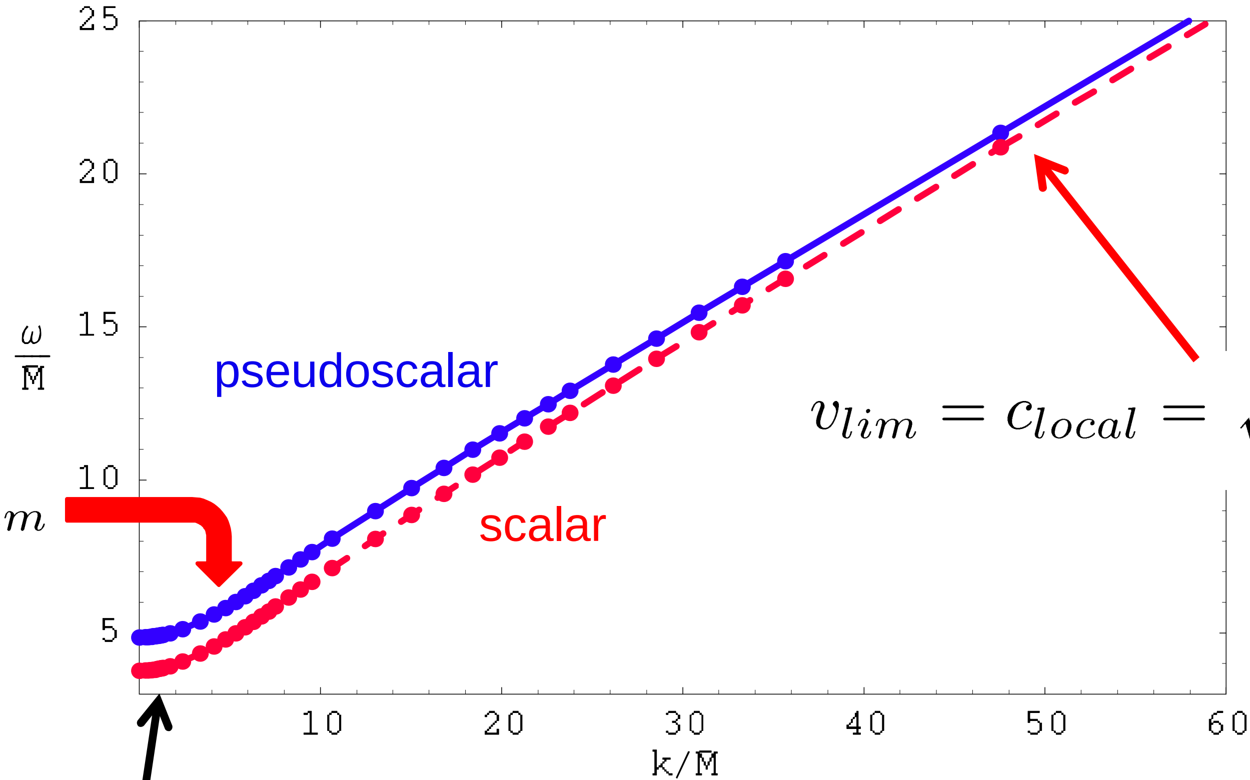
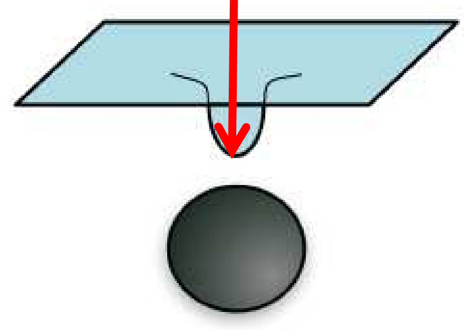


$$v_{max} > v_{lim}$$

$$v_{lim} = c_{local} = \sqrt{-\frac{g_{tt}}{g_{zz}}}\Bigg|_{r=R_0}$$

$$\omega(k) \simeq M_0 + \frac{\mathbf{k}^2}{2M_{kin}}$$



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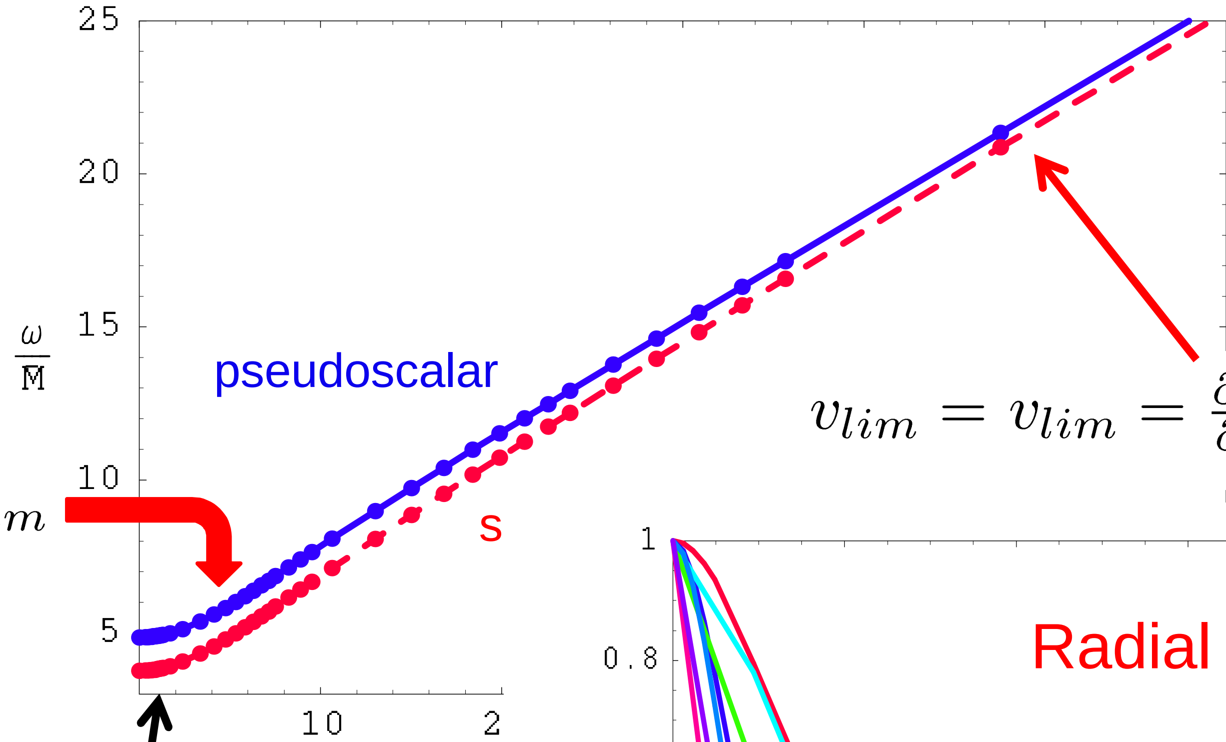

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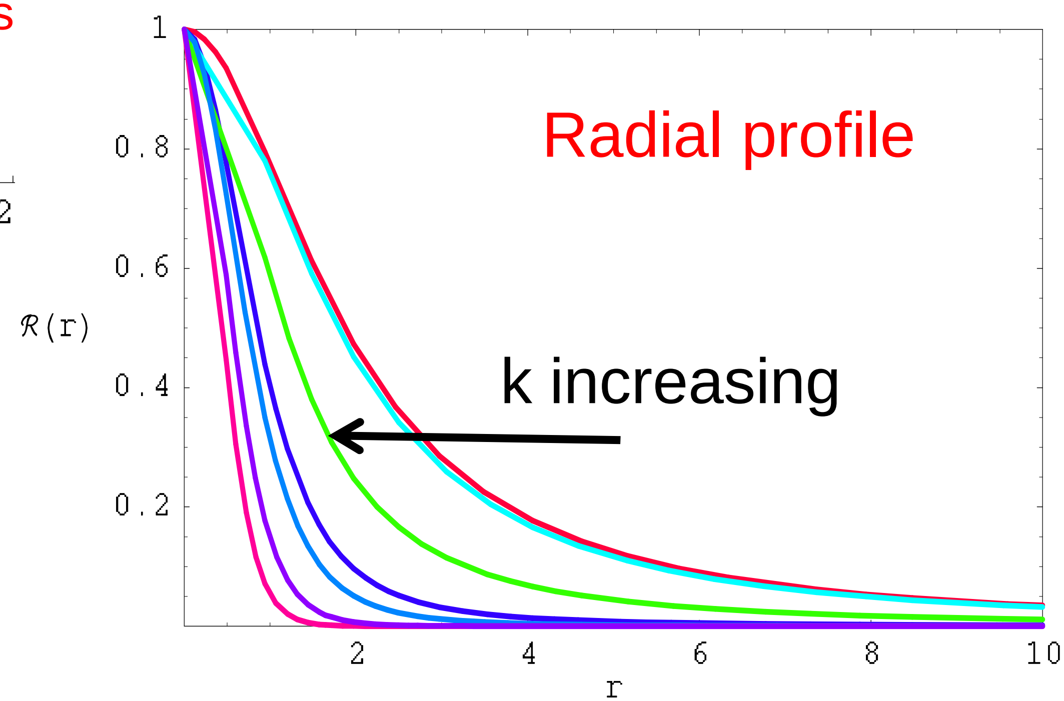


- holographic model shows $f\bar{f}$ bound states persist above T_c and have interesting dispersion relation

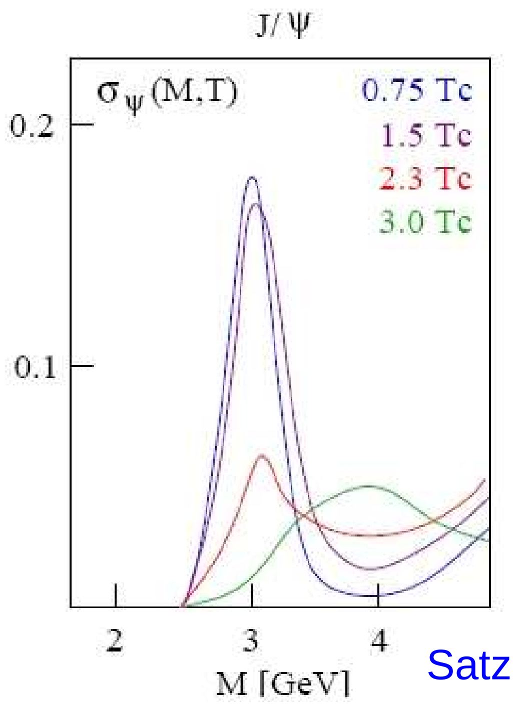
- lattice QCD indicates heavy quark bound states persist above T_c

$$J/\psi\ (\bar{c}c)\ :\ T_{dissoc} \simeq 2.1\ T_c$$

$$\Upsilon\ (\bar{b}b)\ :\ T_{dissoc} \simeq 3.6\ T_c$$

Asakawa & Hatsuda [hep-lat/0308034]

Datta, Karsch, Petreczky & Wetzorke [hep-lat/0312037]



Satz [hep-ph/0512217]

J/ψ's have finite width!

but in Mink. phase, holographic mesons are absolutely stable (for large N_c)

can we do better in AdS/CFT?

Spectral functions: diagnostic for "meson dissociation"

$$\chi(\omega, \mathbf{q}) = -2\,\mathrm{Im}\,G^R(\omega, \mathbf{q})$$
$$= \int d^4x\; e^{-i\omega t + i\mathbf{q}\mathbf{x}} \langle [\mathcal{O}(t, \mathbf{x}), \mathcal{O}(0)] \rangle$$

- simple poles in retarded correlator:

$$G^R \sim \frac{1}{\omega - \Omega(q,\alpha) + i\Gamma(q,\alpha)}$$

yield peaks: $\chi(\omega) \sim \dfrac{\Gamma}{(\omega - \Omega)^2 + \Gamma^2}$

"quasi-particle" if $\Gamma \ll \Omega$

- characteristic high "frequency" tail:

$$\lim_{(t^2 - \mathbf{x}^2)\to 0} \langle \mathcal{O}(t,\mathbf{x})\, \mathcal{O}(0) \rangle = \frac{\mathcal{A}}{|t^2 - \mathbf{x}^2|^\Delta} + \cdots \Longrightarrow \chi \sim \mathcal{A}\,(\omega^2 - q^2)^{\Delta - 2}$$

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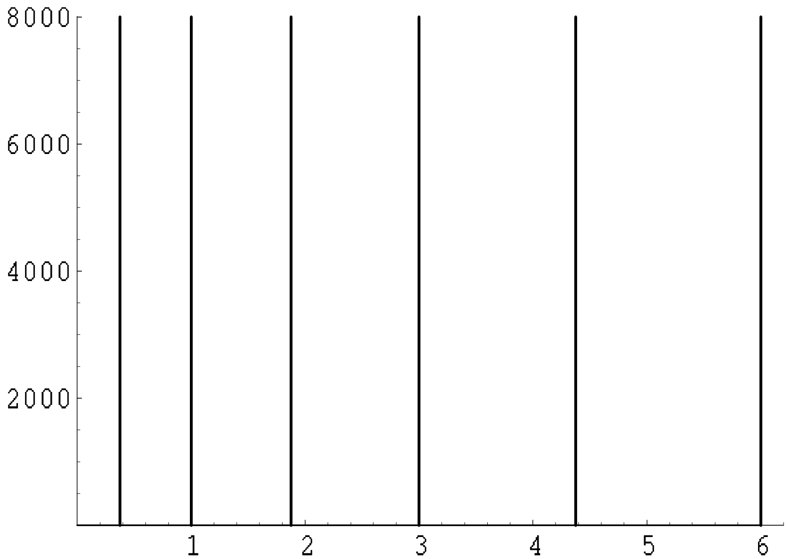
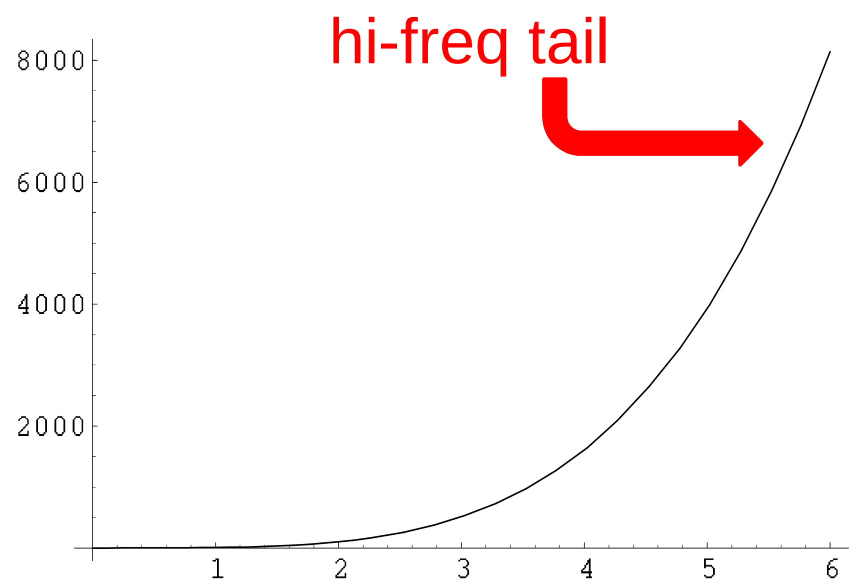




discrete spectrum;
low temperature Mink. phase

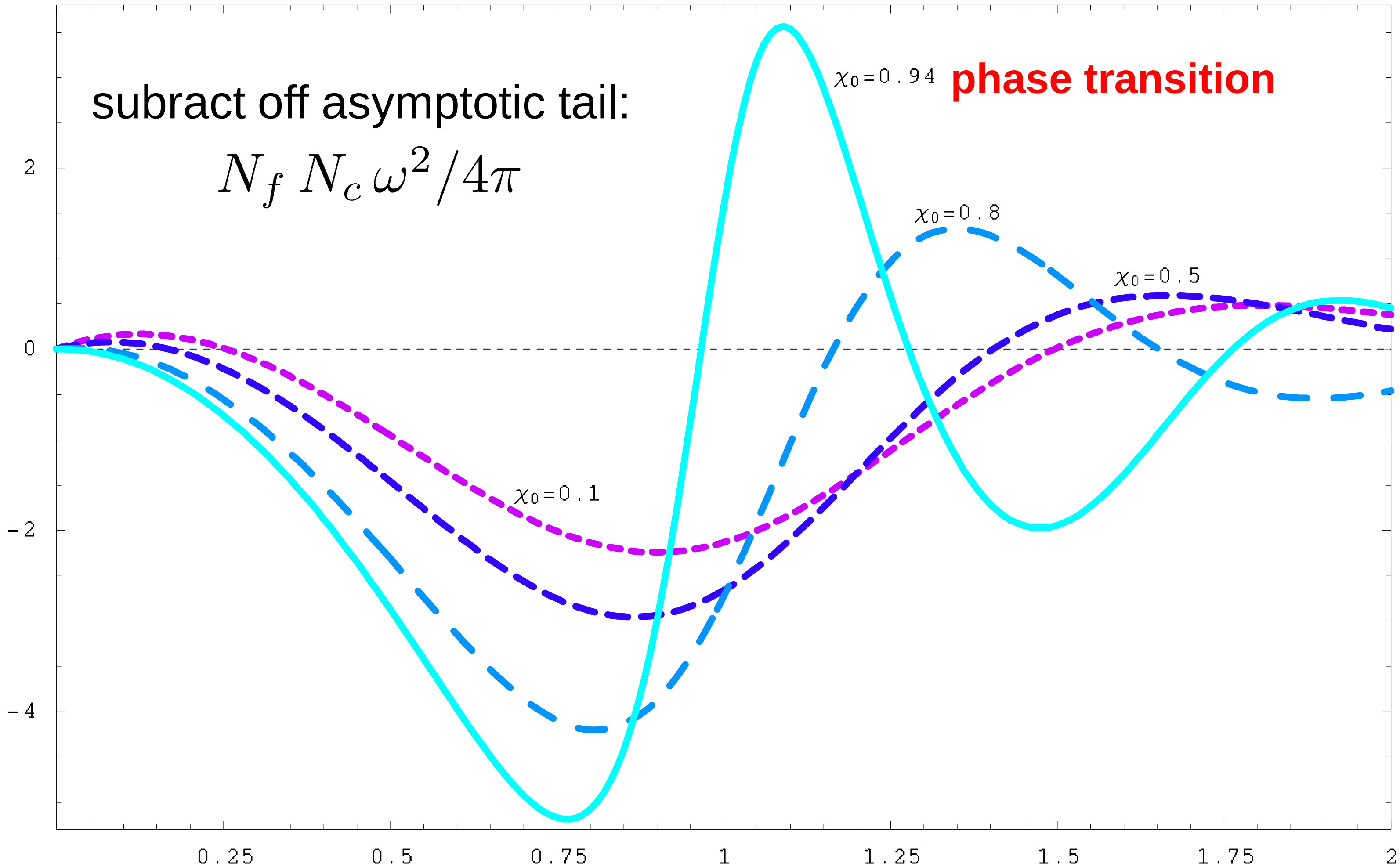
mesons stable (at large N_c)

continuous spectrum;
high temperature BH phase

no quasi-particles

RCM, Rowan Thomson & Andrei Starinets [arXiv:0706.0162]

Thermal spectral function:



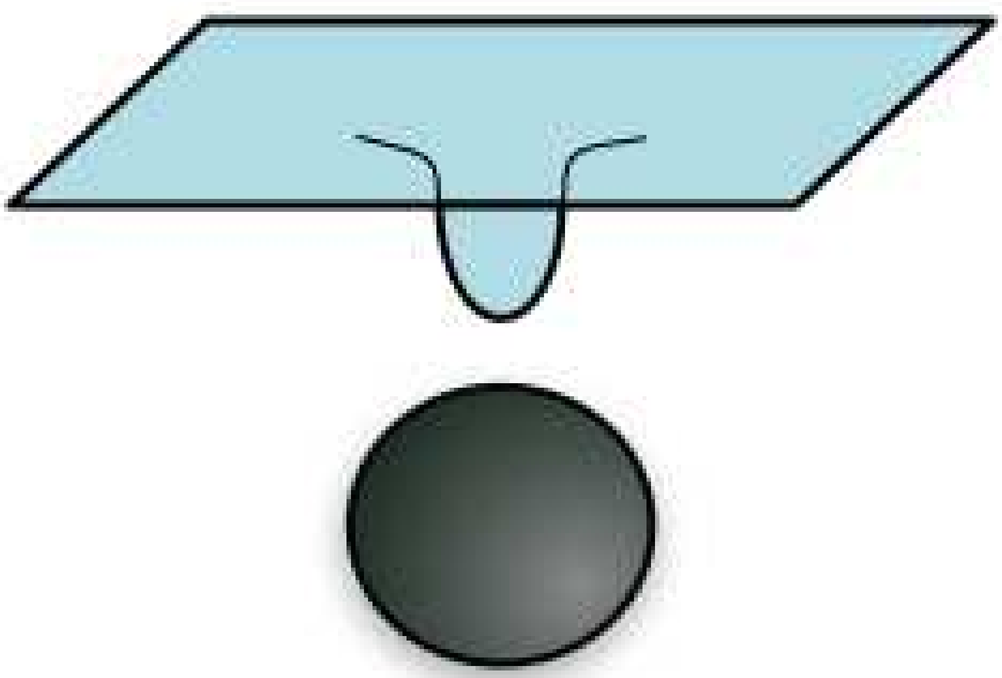
- approaching phase transition, structure builds
  → quasinormal frequencies approach real axis

see also: Hoyos, Landsteiner & Montero [hep-th/0612169]

Kobayashi, Mateos, Matsuura, RCM & Thomson [hep-th/0611099]
Mateos, Matsuura, RCM & Thomson [arXiv:0709.1225]; . . . . .

Need an extra dial: "Quark" density

D7-brane gauge field: $A_\mu \;\leftrightarrow\; J_\mu \simeq \left[\bar{\psi}\gamma_\mu\psi + \Phi D_\mu \Phi\right]$



asymptotically (ρ→∞):

$$A_t \simeq \mu - \frac{n_q}{\rho^2} + \cdots$$

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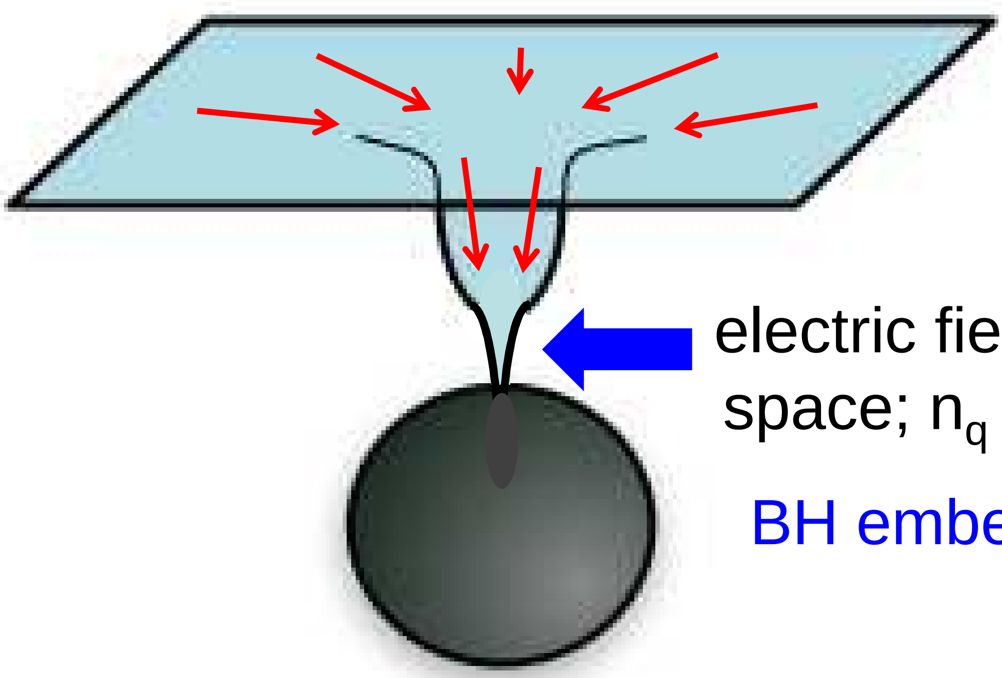


asymptotically (ρ→∞):

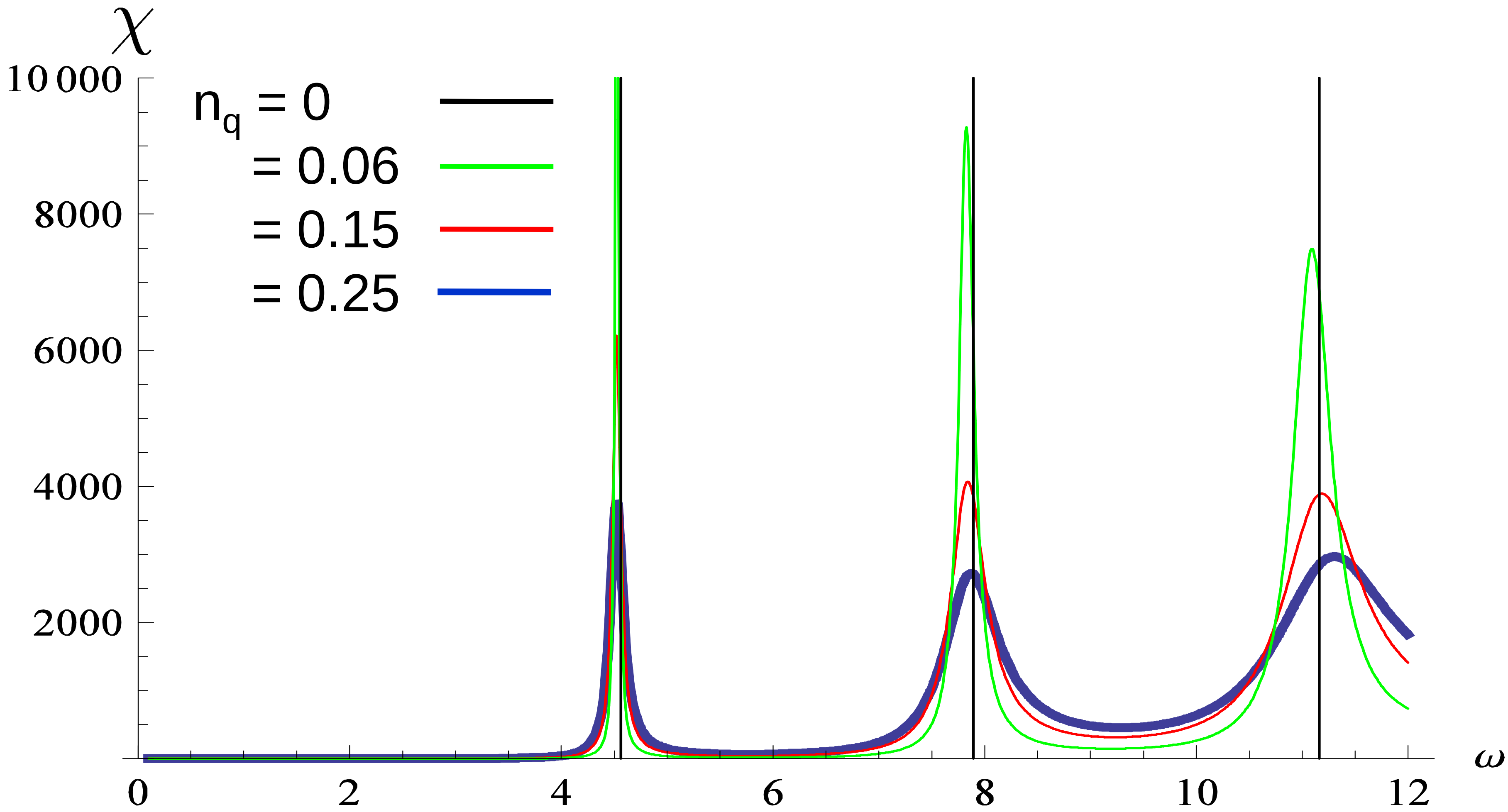
$$A_t \simeq \mu - \frac{n_q}{\rho^2} + \cdots$$

electric field lines can't end in empty space; n_q produces neck →

BH embedding with tunable horizon

Spectral functions:

Increasing n_q, increases width of meson states

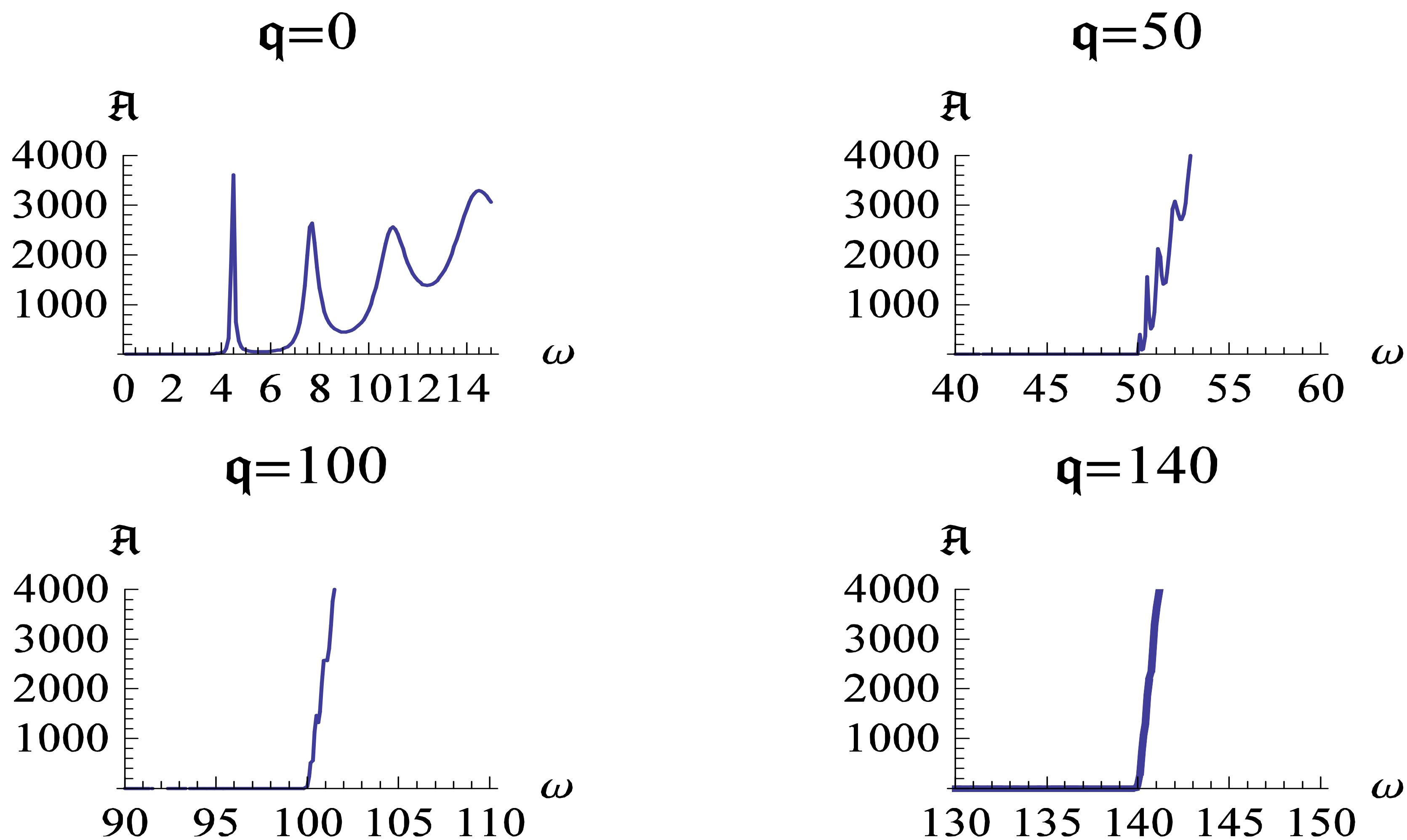


at rest: q=0

See: Erdmenger, Kaminski & Rust [arXiv:0710.033]

Spectral functions: $(n_q = 0.25)$

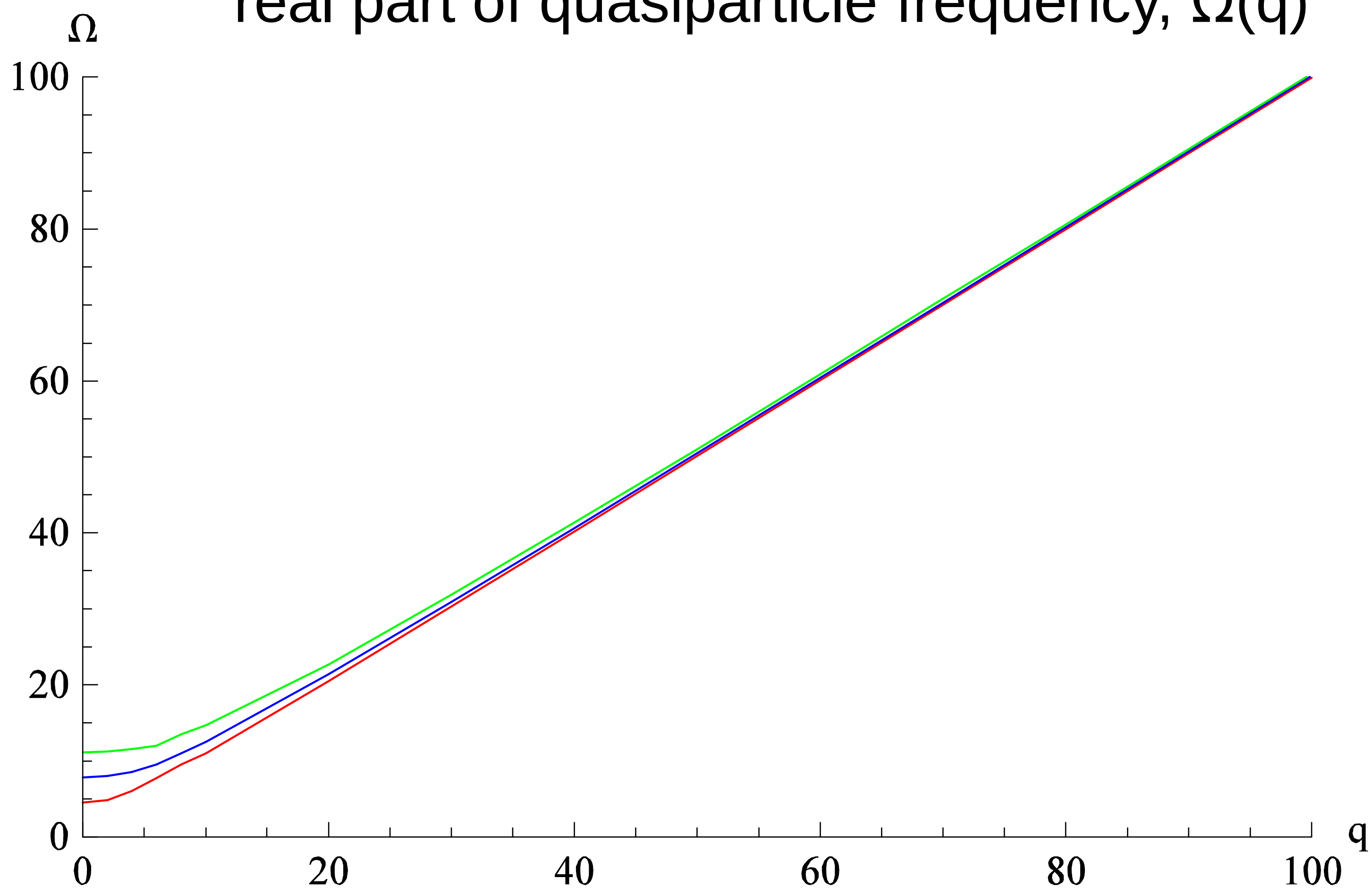
introduce nonvanishing momentum



Spectral functions:

(n_q = 0.25)

follow positions of peaks → real part of quasiparticle frequency, $\Omega(q)$



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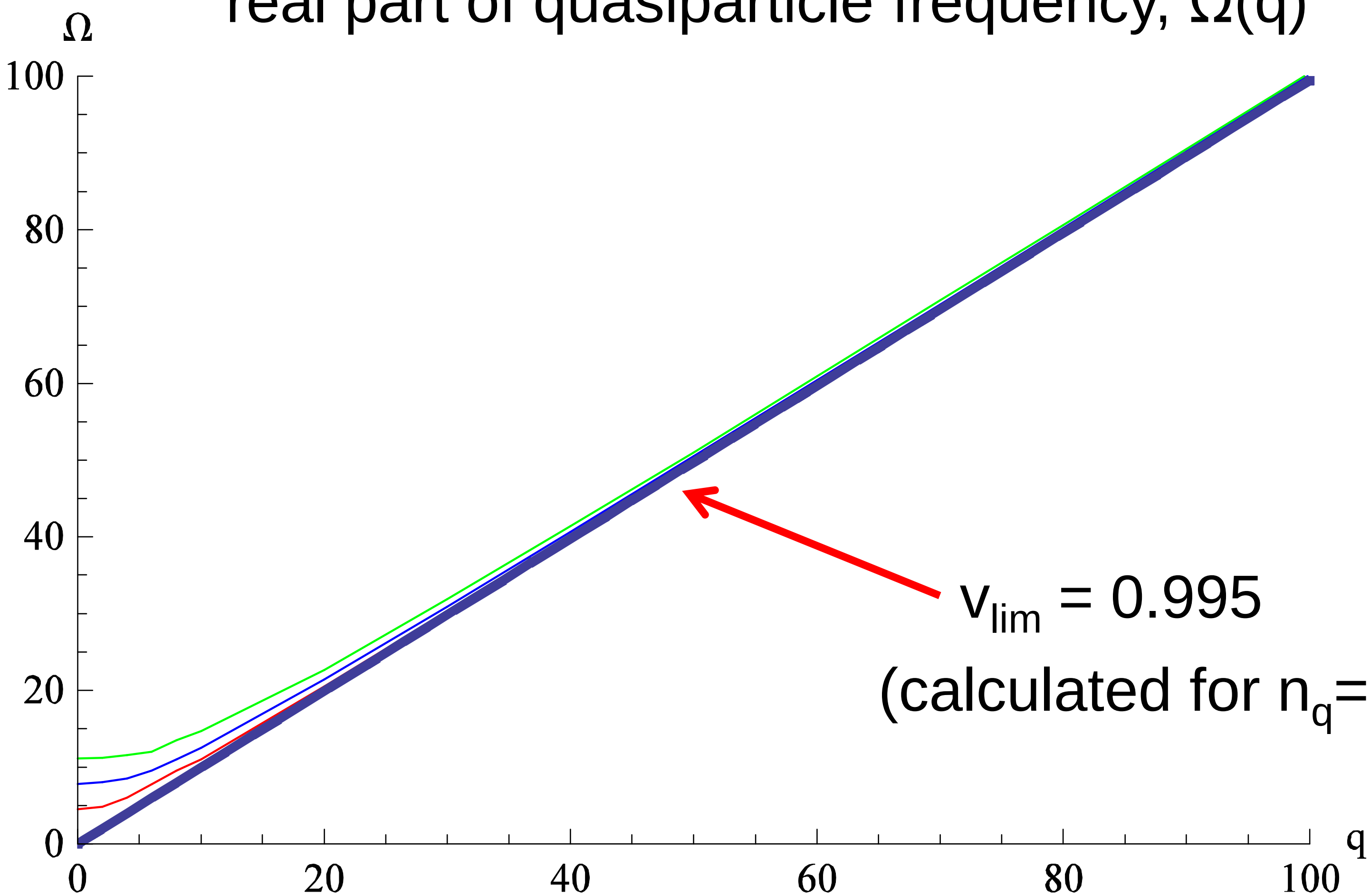
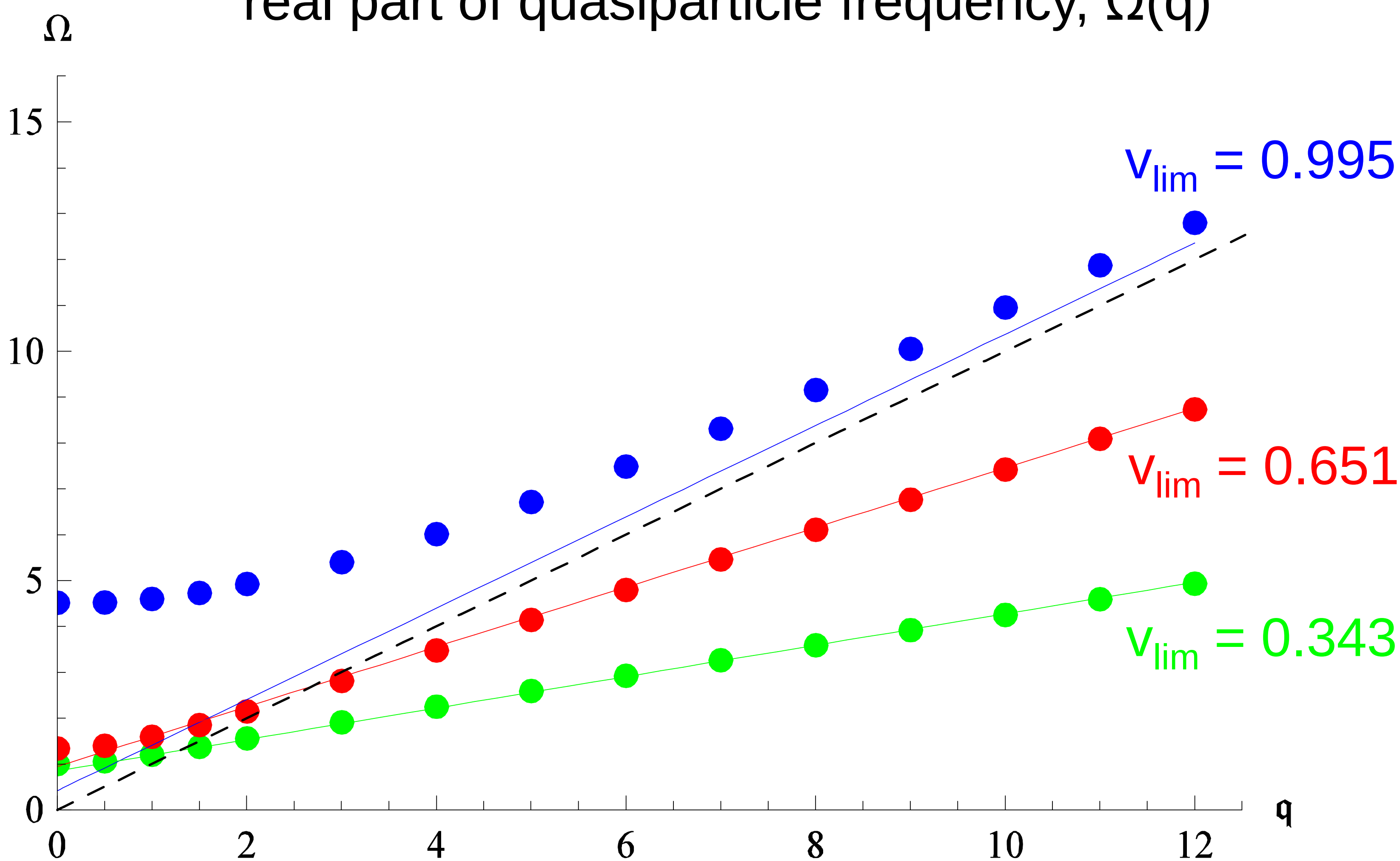


Quasiparticles obey same speed limit!

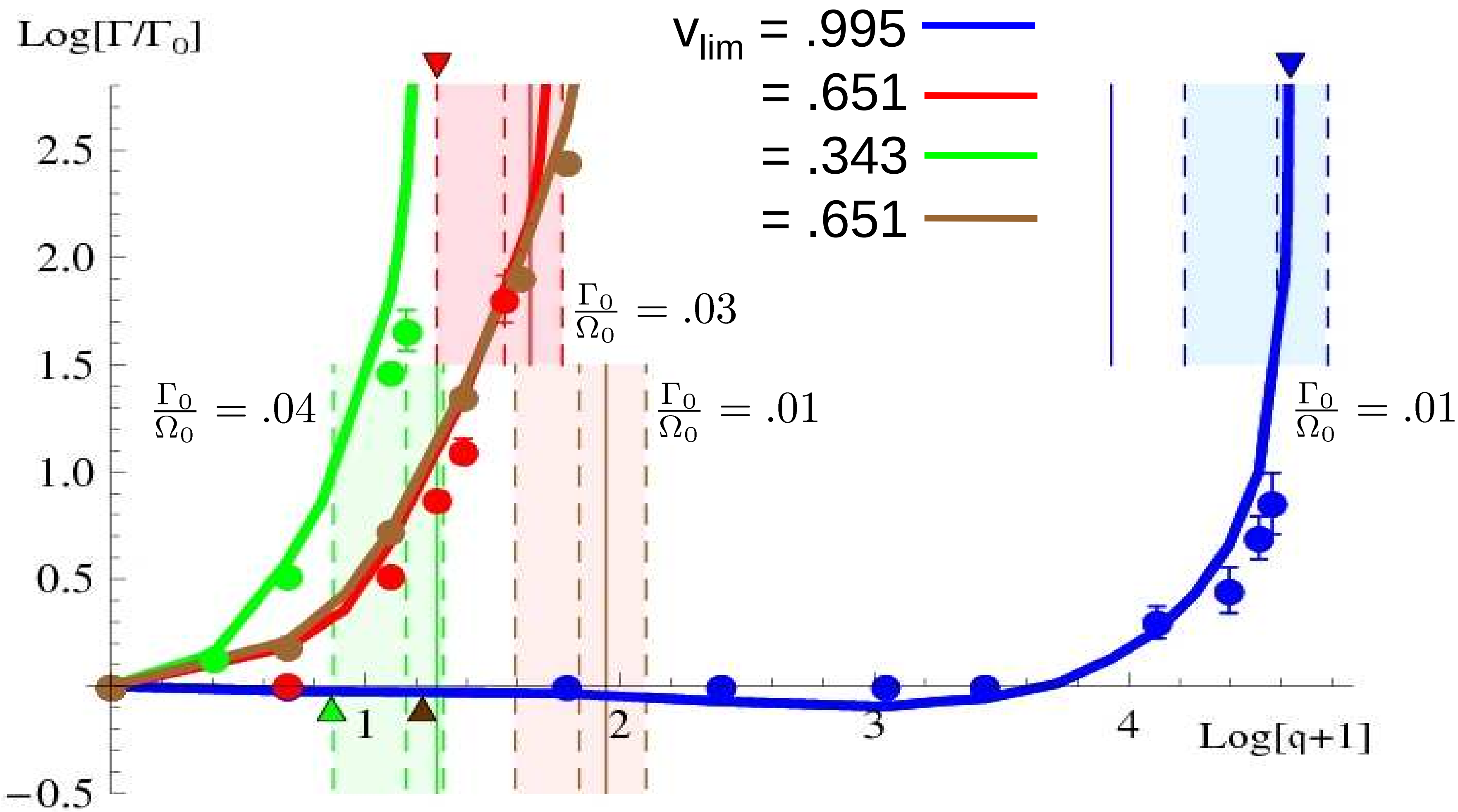
Spectral functions:

follow positions of peaks → real part of quasiparticle frequency, $\Omega(q)$

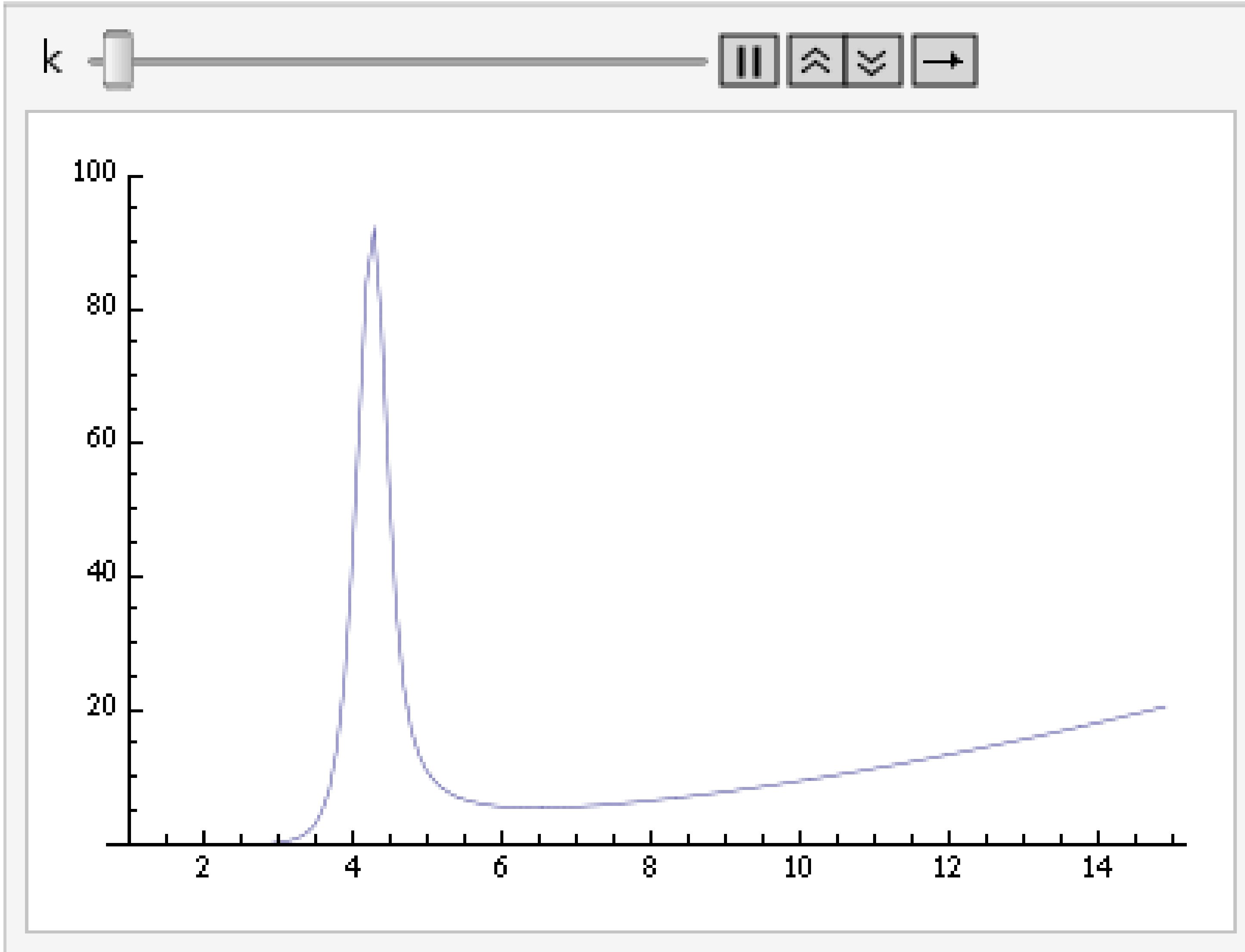


Quasiparticles obey same speed limit!

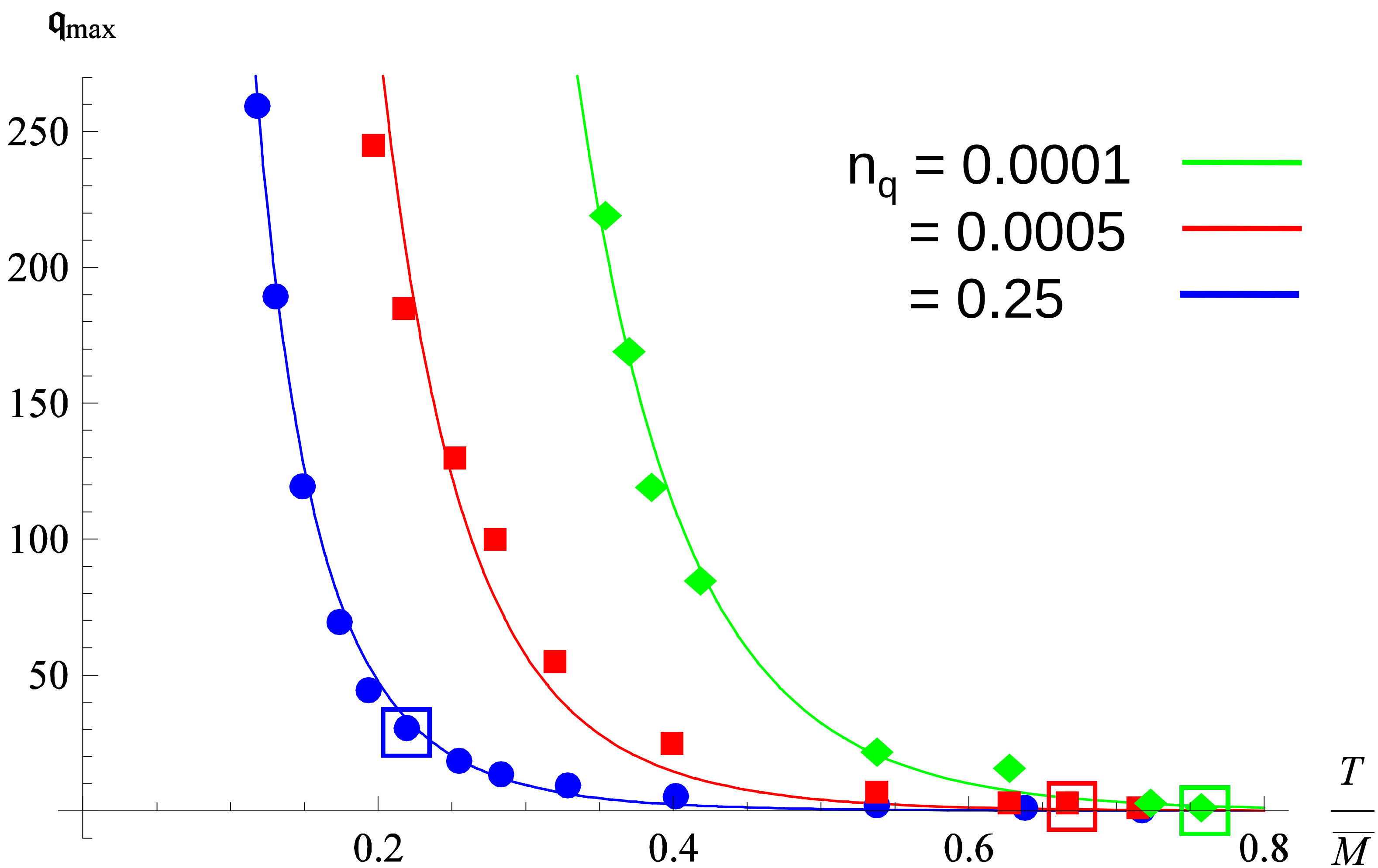
follow widths of peaks → imaginary part of quasiparticle frequency, Γ(q)



examine Schrodinger potential for quasinormal modes



Quasiparticle peaks disappear beyond critical momentum q_{crit}
(define q_{crit} as value where V_{eff} has inflection point)



continuous curves fit with form: $\frac{1}{x^2}\exp(-8x)$

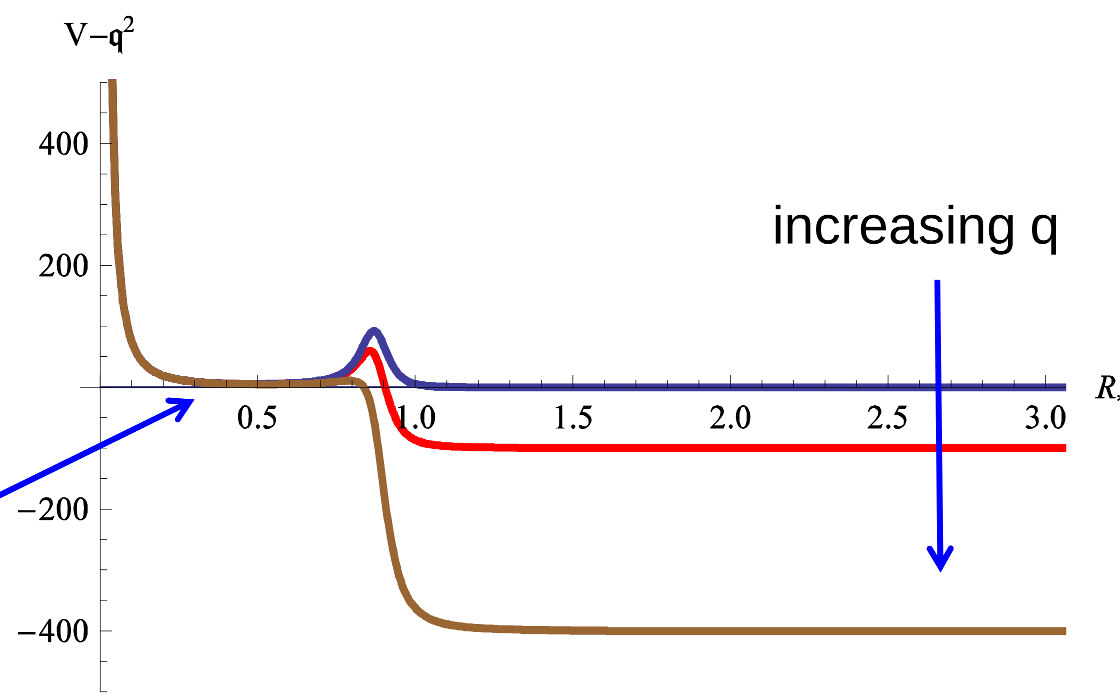
Beyond q_{crit}

- quasiparticle peaks disappear in spectral function
- poles in thermal correlator wandered off into complex plane

→ **where do they go??**

- need to examine quasinormal modes directly (in progress) 
- gain insight from effective Schrodinger problem:

$$-\partial^2_{R_*}\psi + V\,\psi = \omega^2\,\psi$$

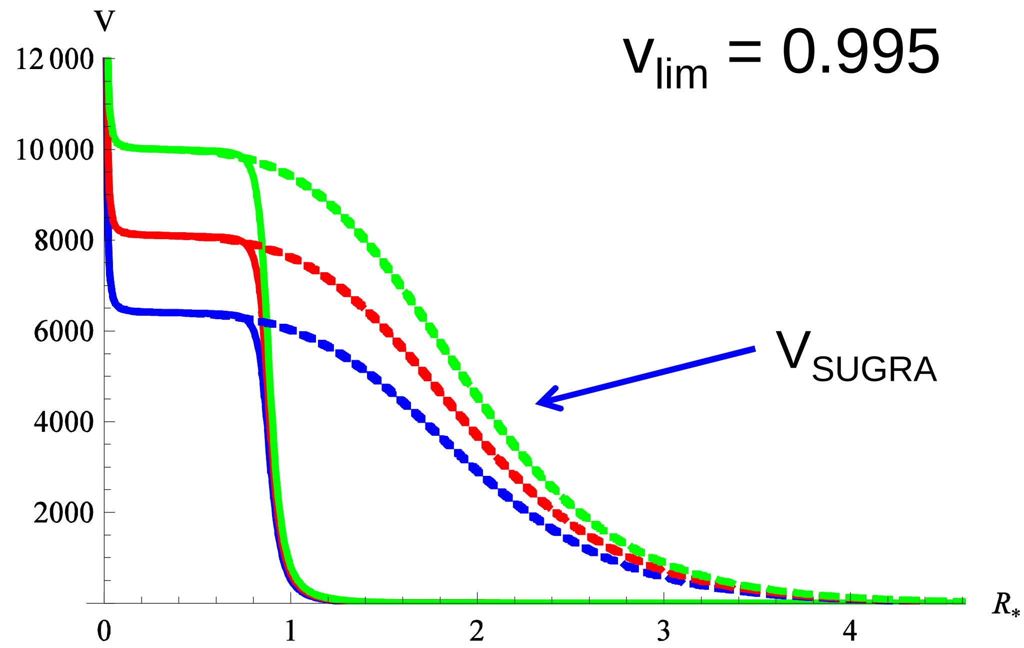


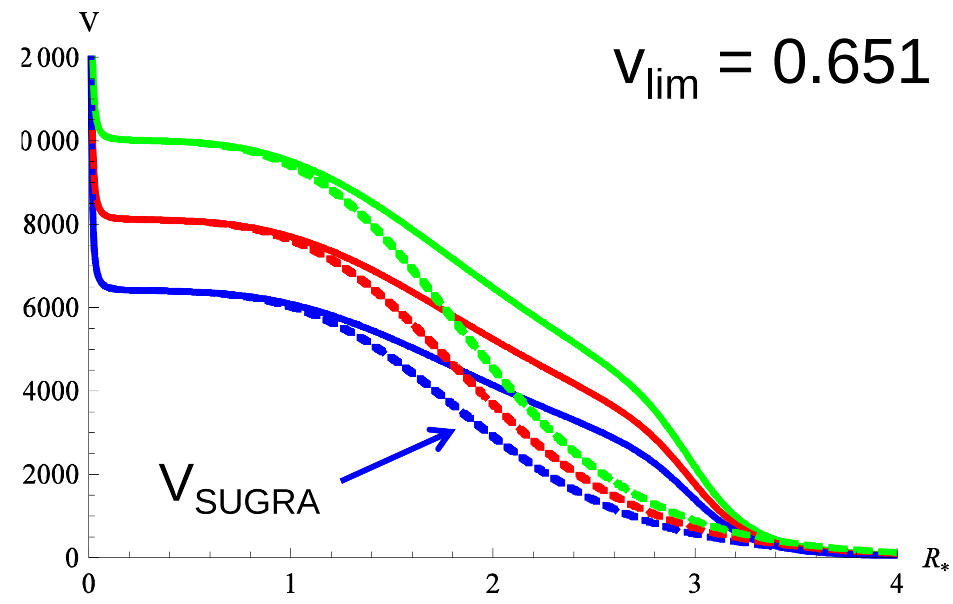
ledge with $V\sim q^2$
in asymptotic region

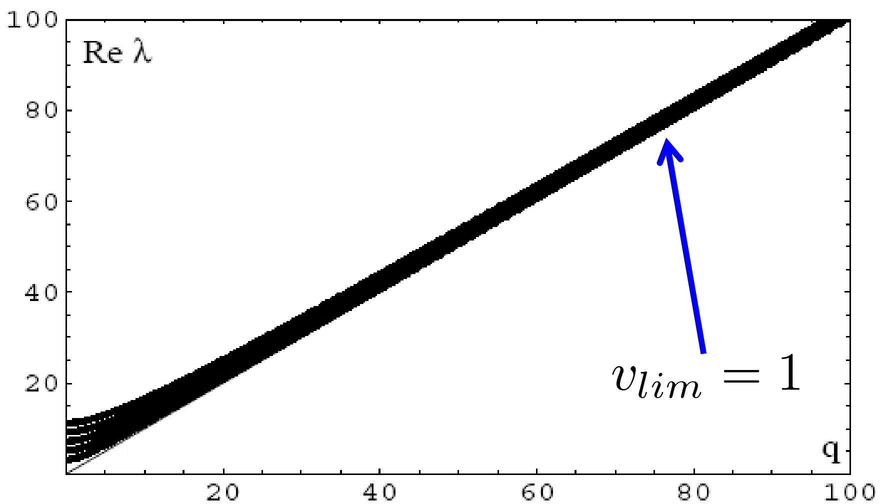
ledge with $V \sim q^2$
in asymptotic region

compare to SUGRA calc's:

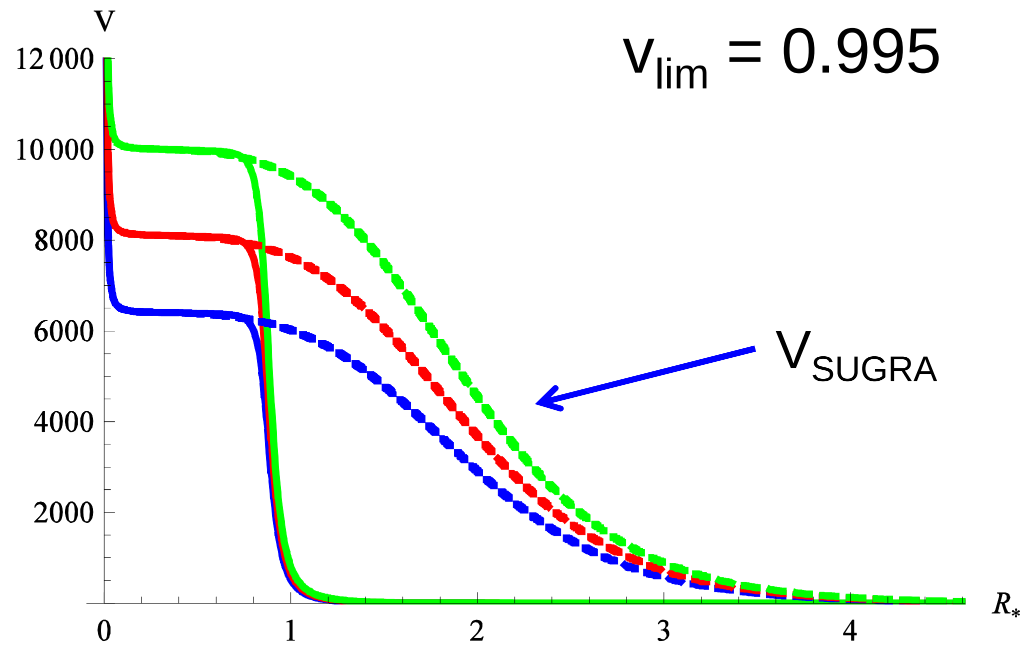
Starinets [hep-th/0207133];
Nunez & Starinets [hep-th/0302026]







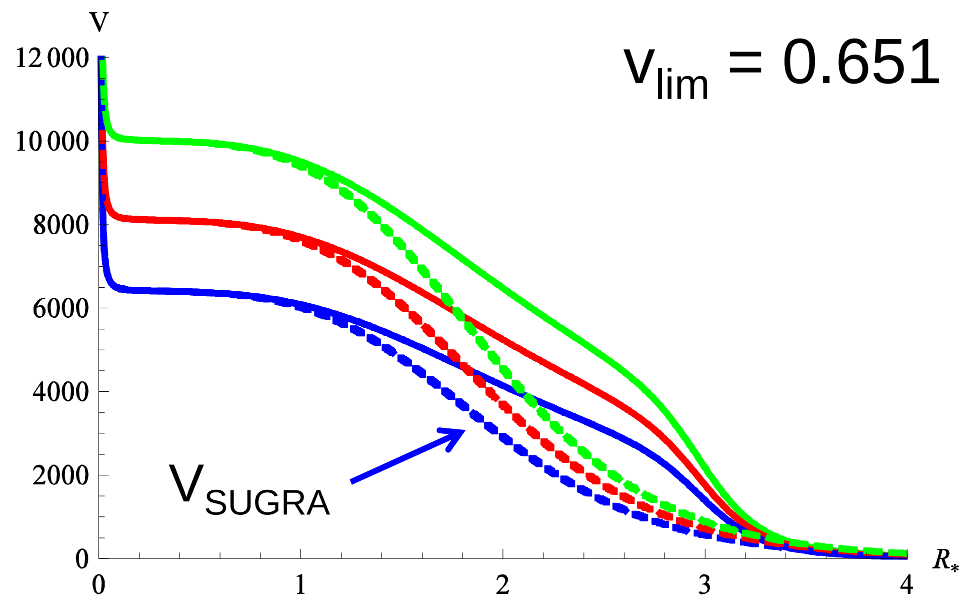
ledge with $V \sim q^2$
in asymptotic region



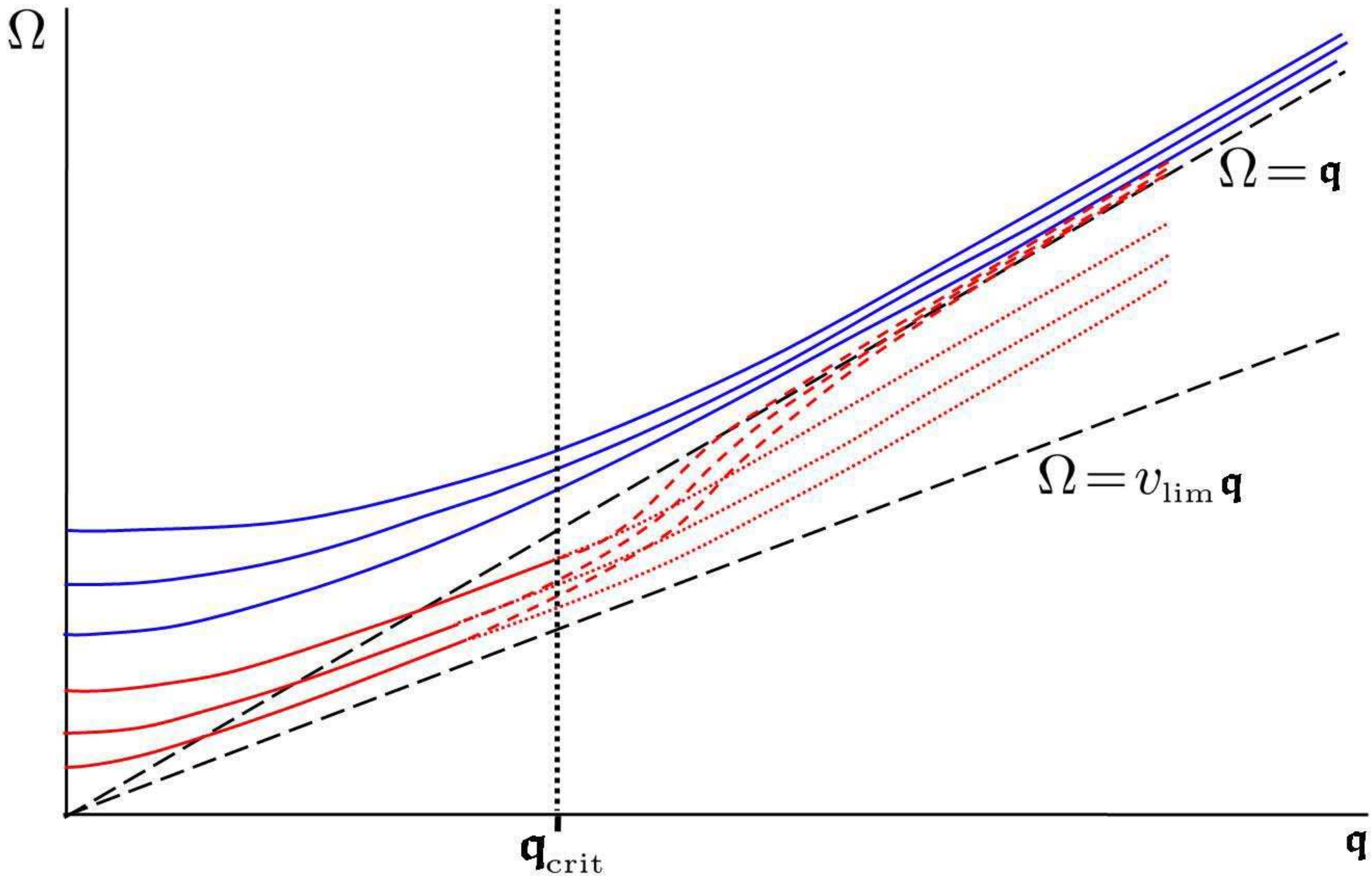
WKB approximation:

$$|\psi|^2 \simeq \frac{1}{P(R_*)} \simeq \frac{1}{\sqrt{\Omega^2 - V(R_*)}}$$

modes with $\Omega \sim q$ have support in asymptotic region, hence expect to find: $v_{lim} = 1$



Dispersion relations beyond q_{crit}:



Conclusions/Outlook:

- D3/D7 system: interesting framework to study quark/meson contributions to strongly-coupled nonAbelian plasma

- first order phase transition appears as universal feature of holographic theories with fundamental matter ($T_f > T_c$)
  → how robust is this transition?

- "speed limit" universal for holographic theories

$$v_{lim}^2 \simeq 1 - 4\left(2\pi \frac{T}{E_0}\right)^4$$

  → extended excitations? QCD??

- quasiparticle widths increase dramatically with momentum
  → more analytic control; quasinormal spectrum
  → find q_{crit} *in present holographic model*
  → universal behaviour? real world effect? **(INVESTIGATING)**