

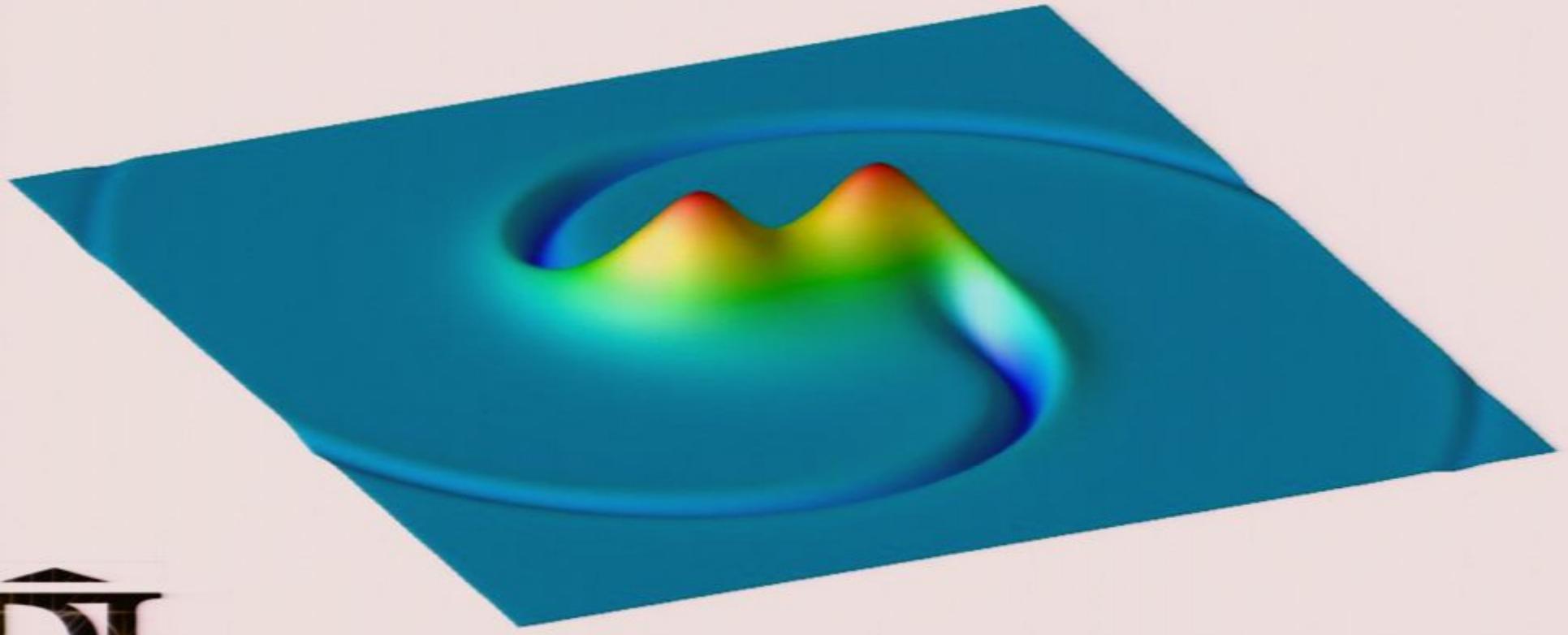
Title: The fast life of holographic mesons

Date: Mar 18, 2008 11:00 AM

URL: <http://pirsa.org/08030072>

Abstract:

The fast life of holographic mesons



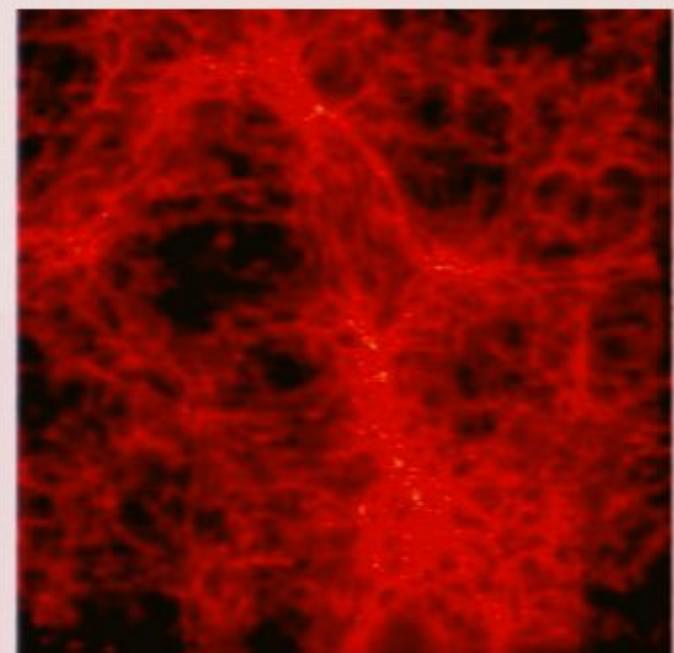
Pirsa: 08030772

with Aninda Sinha [arXiv:0802.nnnn]

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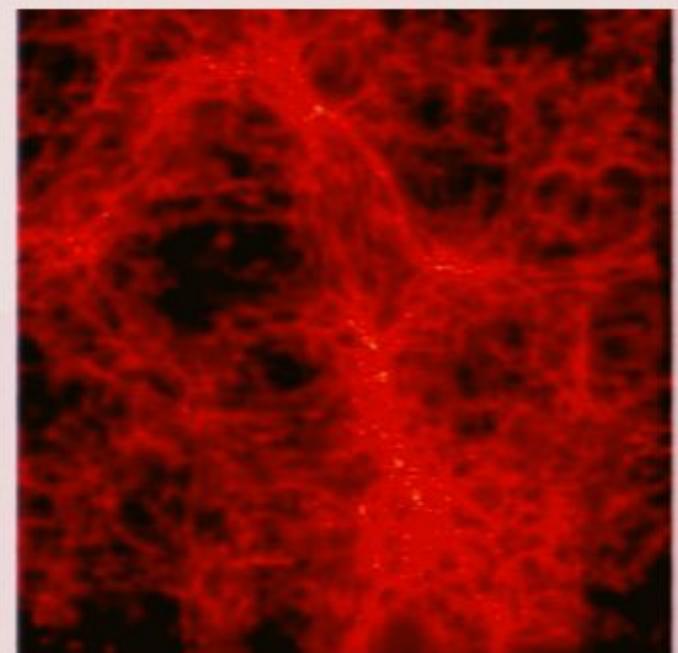
(Also with David Mateos, Rowan Thomson, Andrei Starinets, ...)

Behaviour (e.g., real-time dynamics) of **strongly-coupled** QCD plasma is of interest for RHIC and early universe cosmology



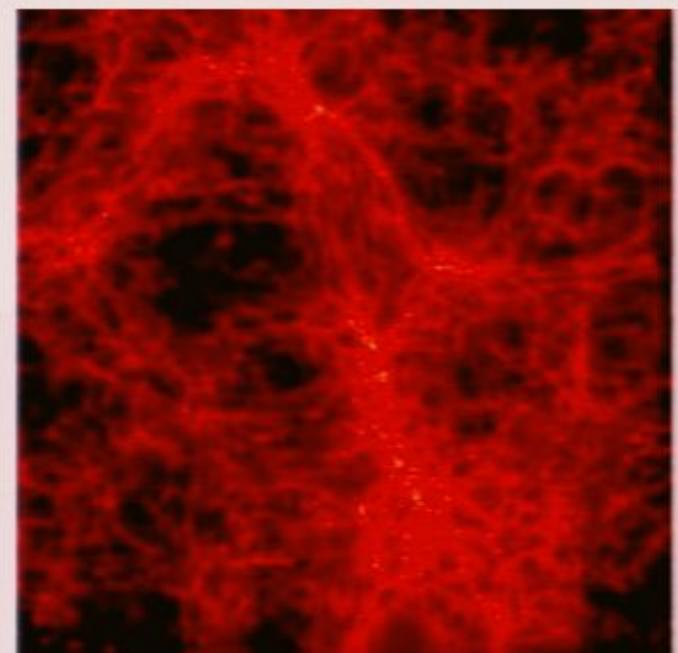
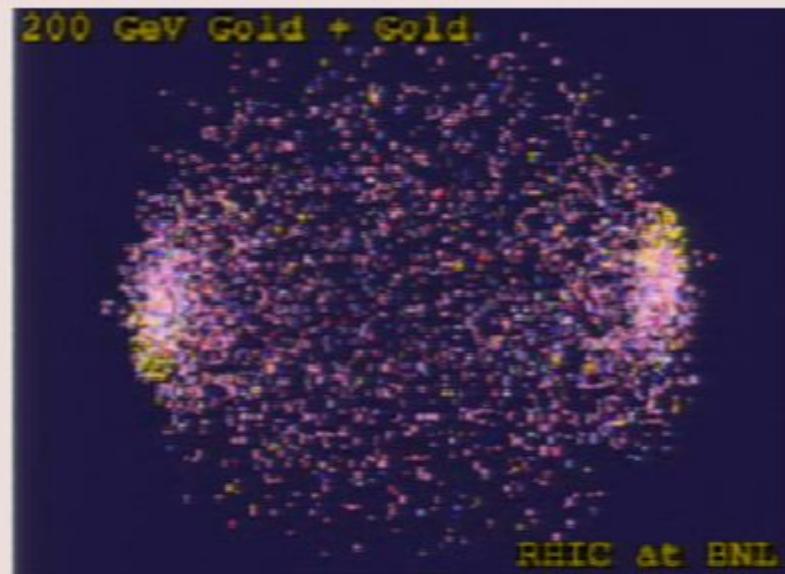
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Theoretical tools to study such strongly-coupled systems are very limited (e.g., nonexistent)



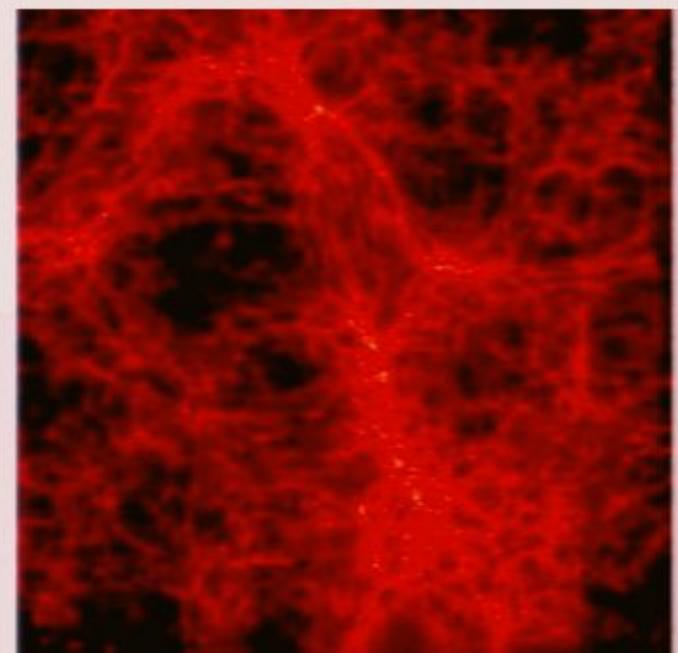
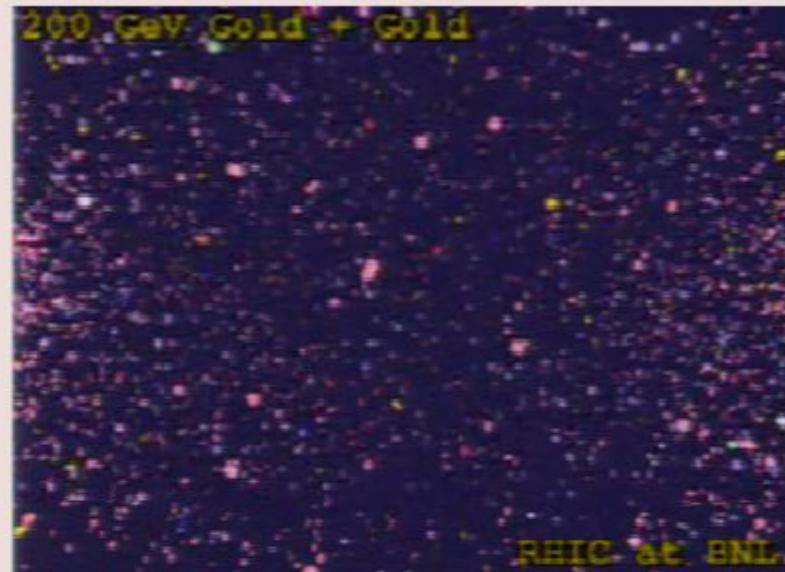
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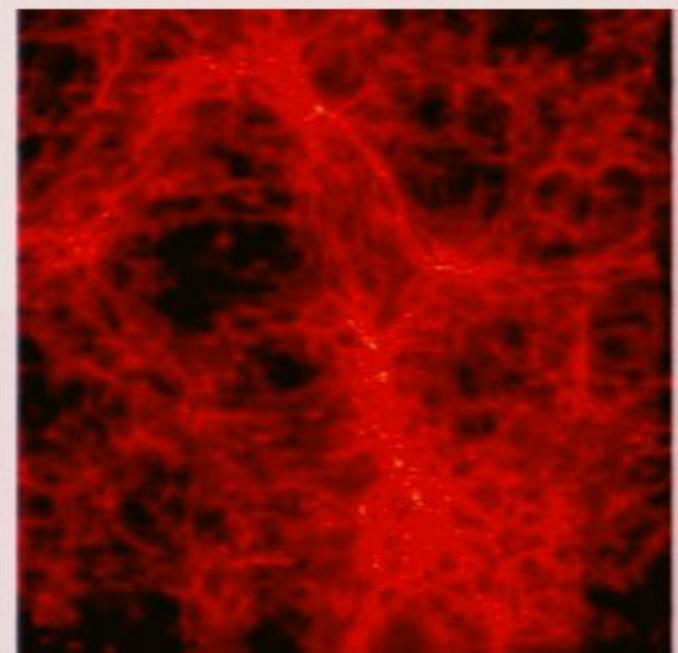
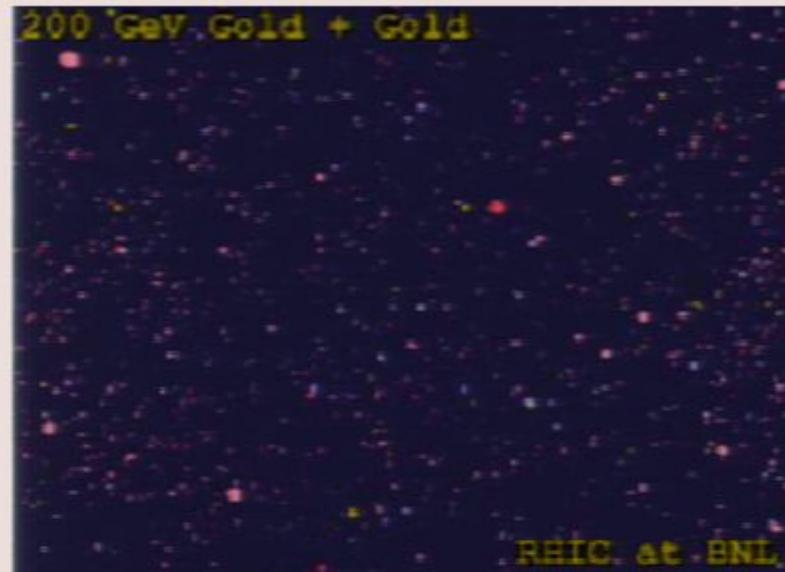
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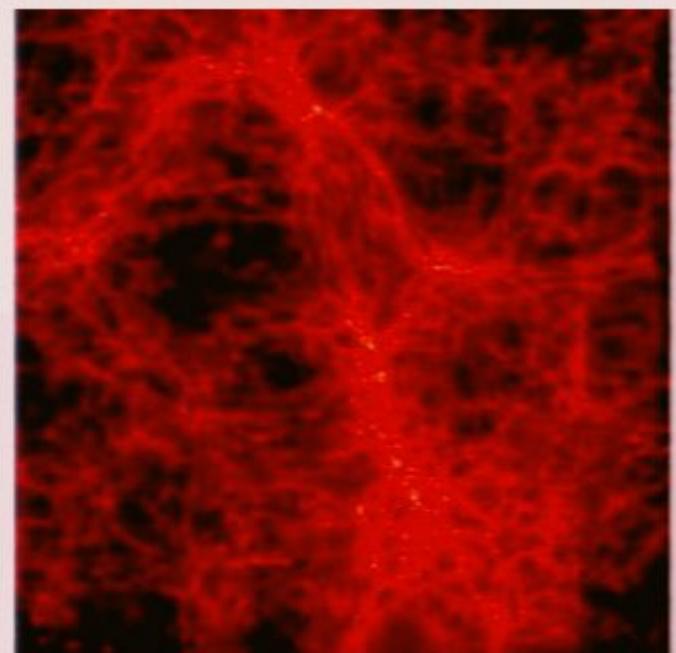
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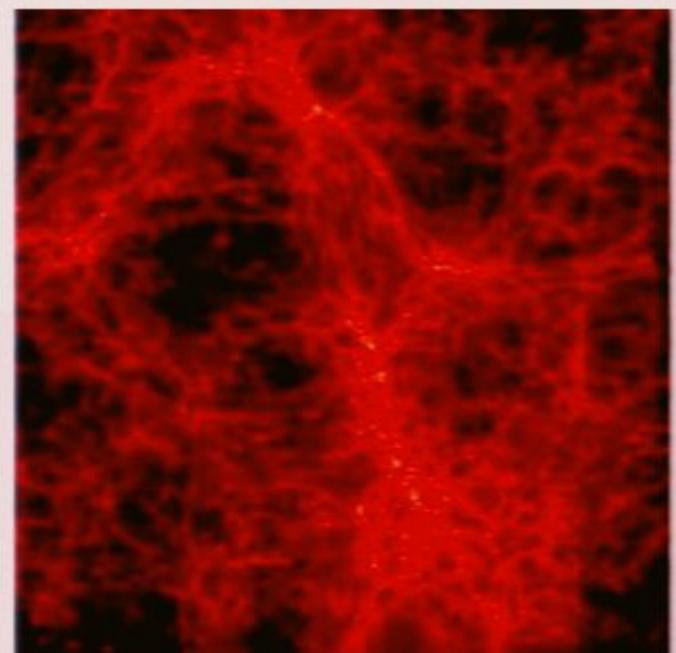
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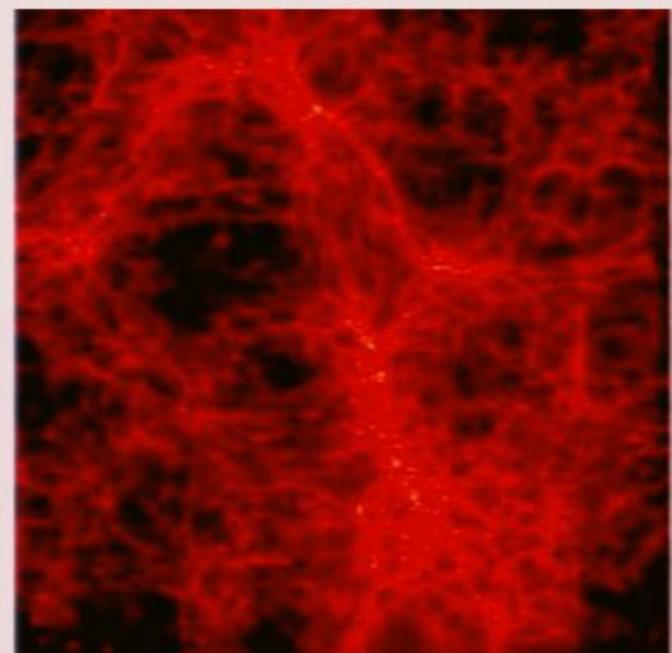
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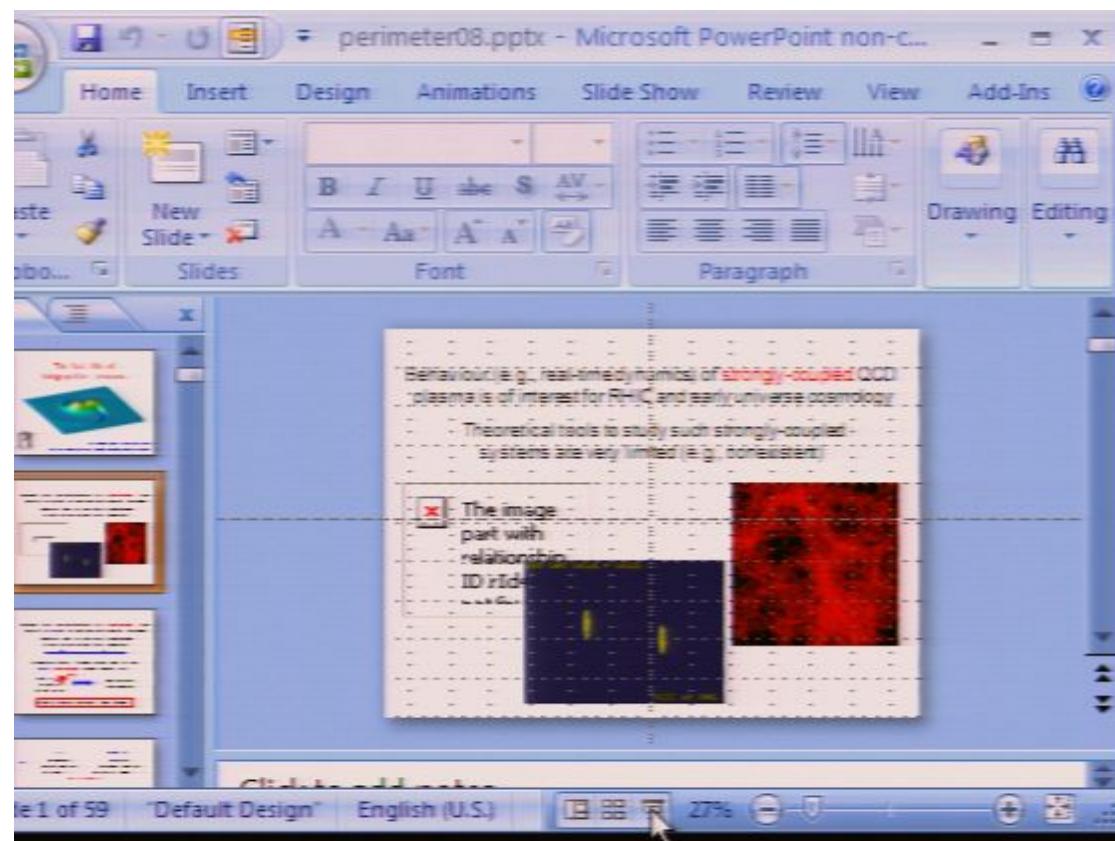
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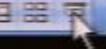
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Behavior (e.g., real-time dynamics) of strongly-coupled QCD plasmas is of interest for RHIC and early universe cosmology.

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Font Paragraph Drawing Editing

Slides

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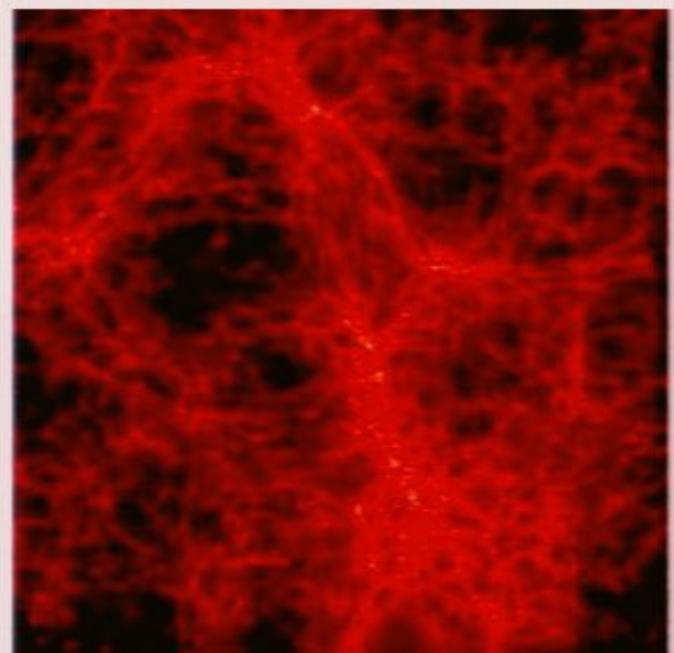
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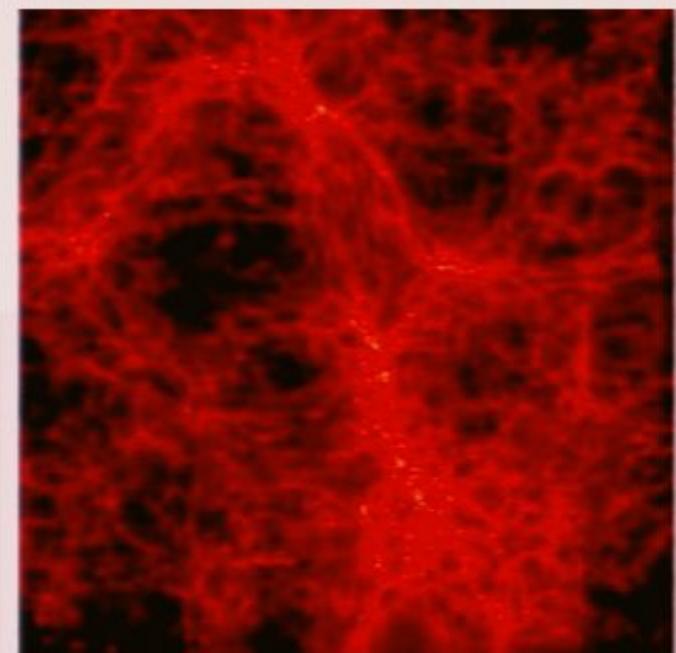
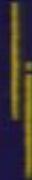


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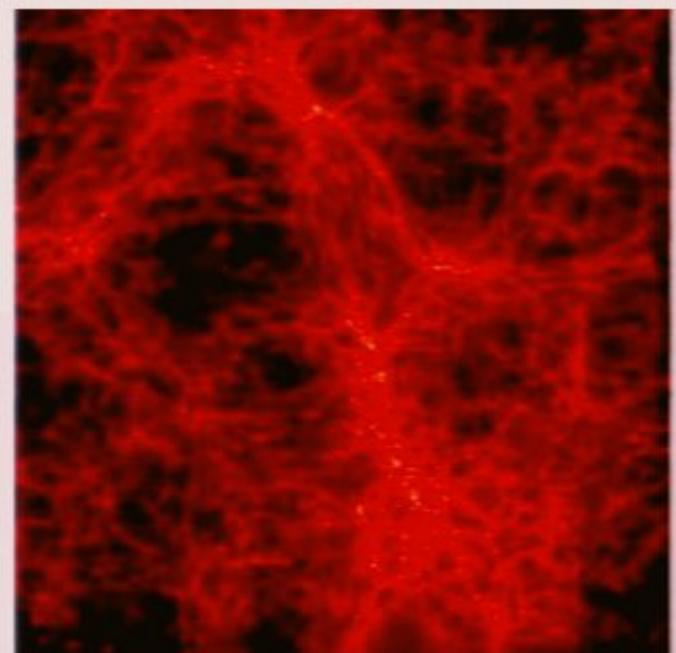
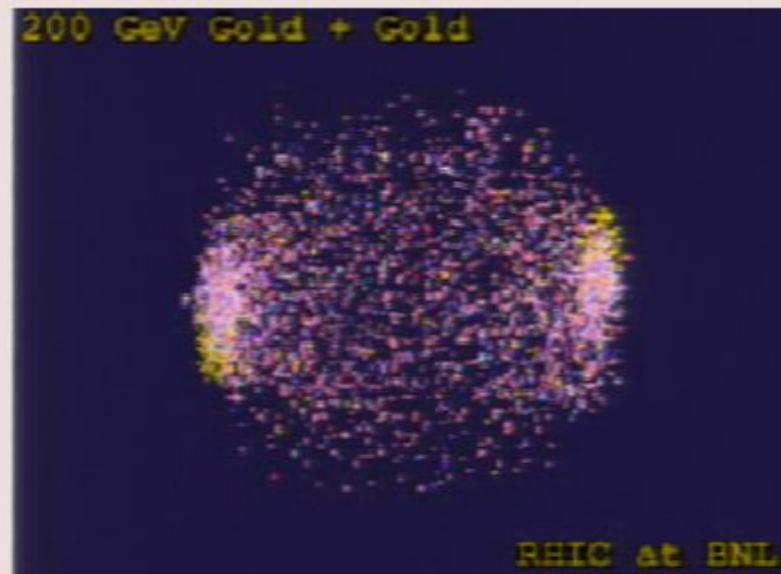


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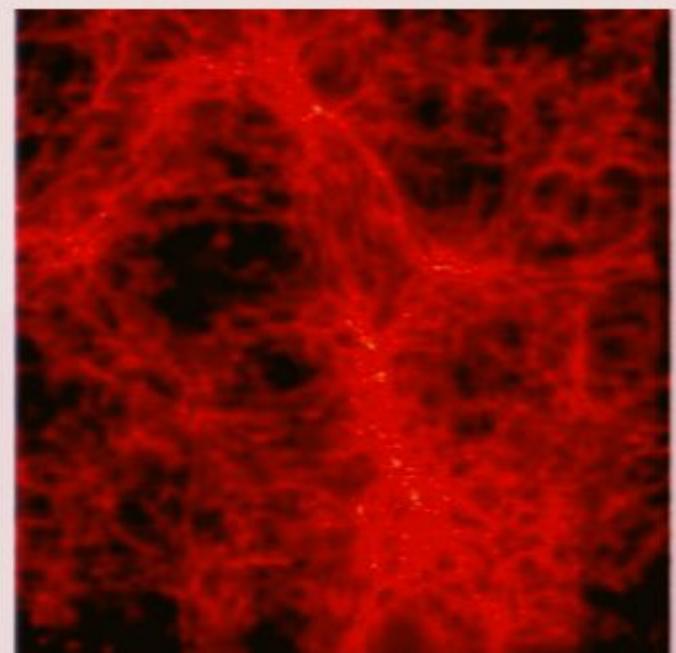
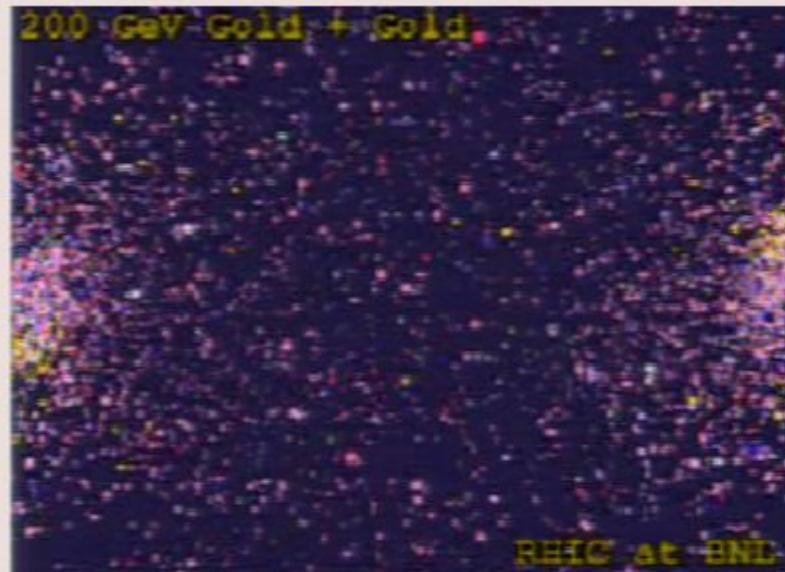
200 GeV Gold + Gold



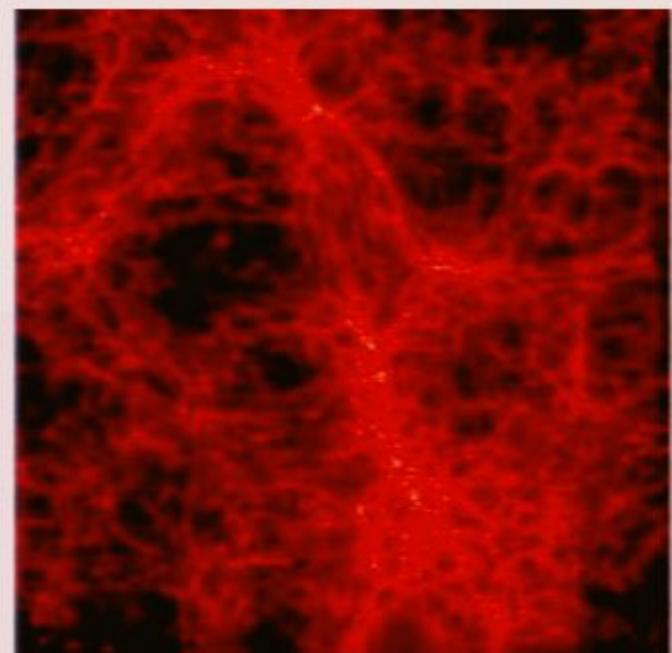
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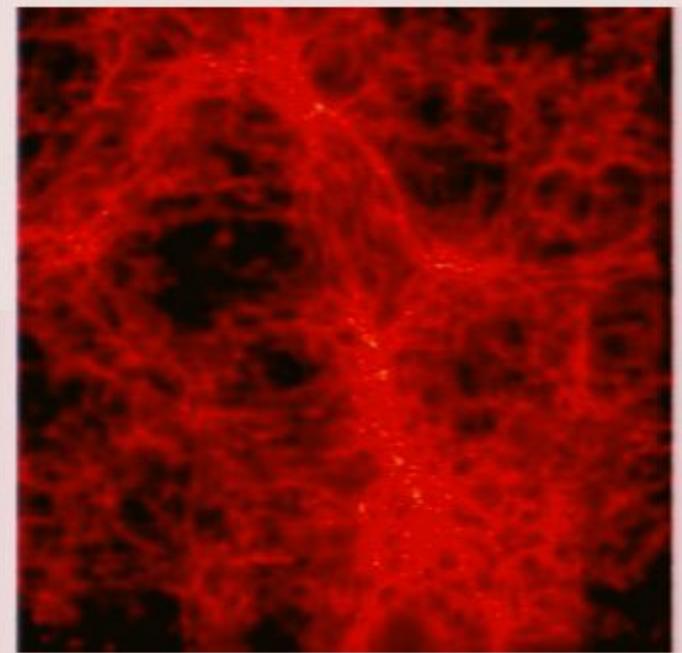
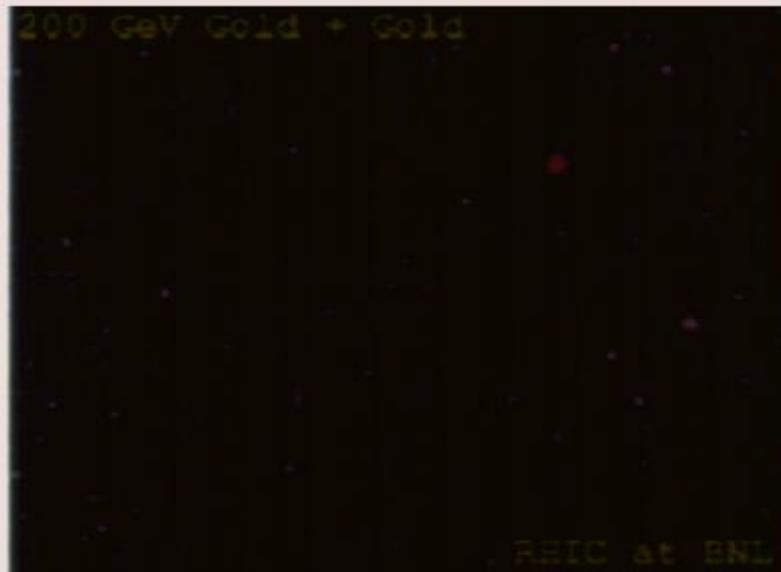
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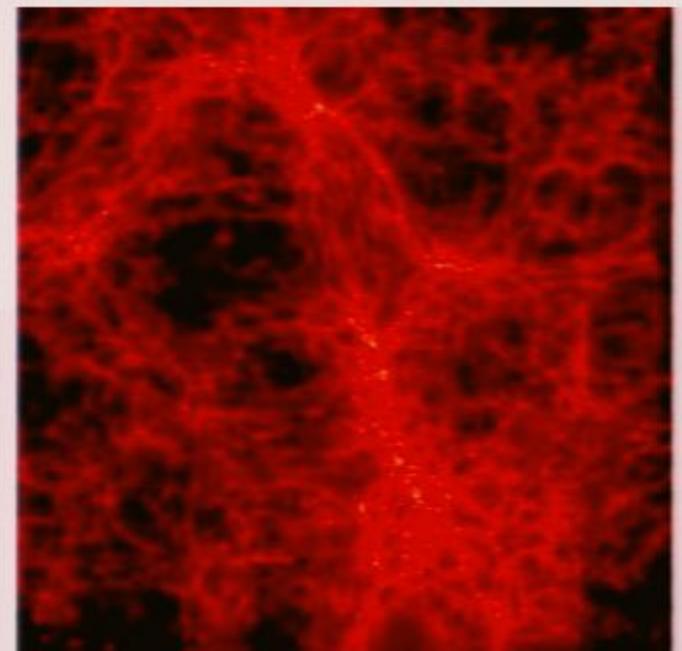
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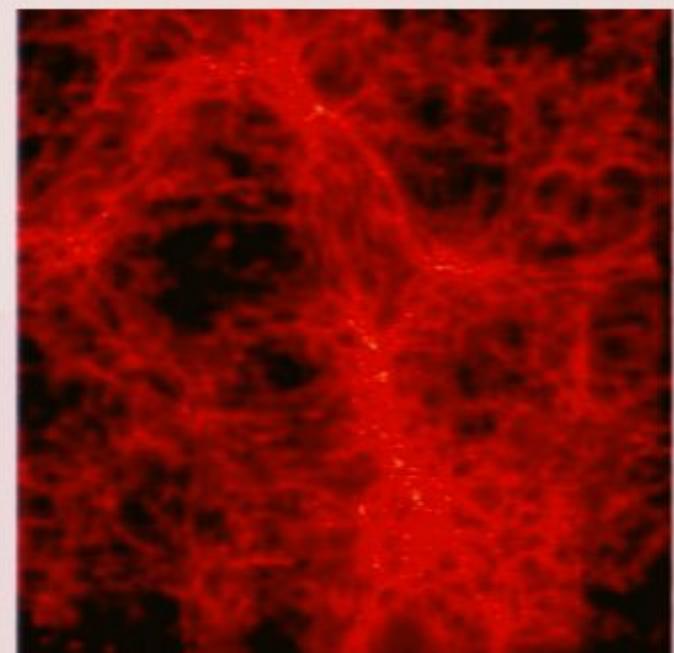
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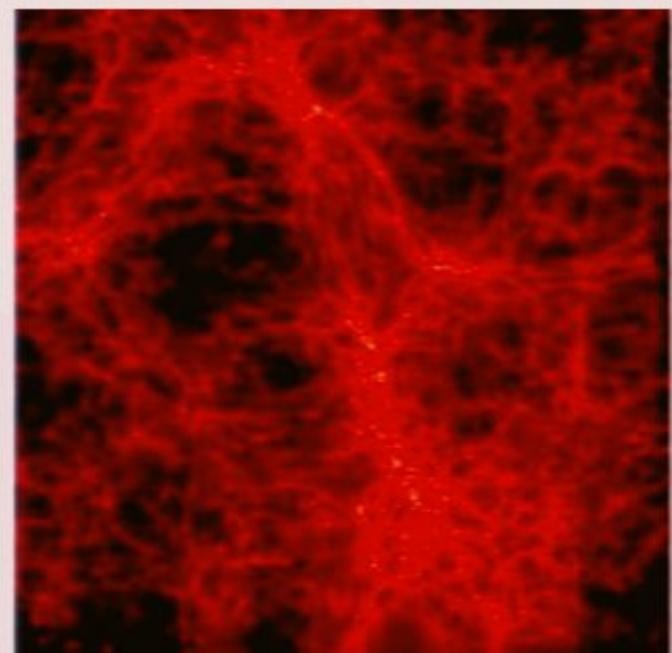
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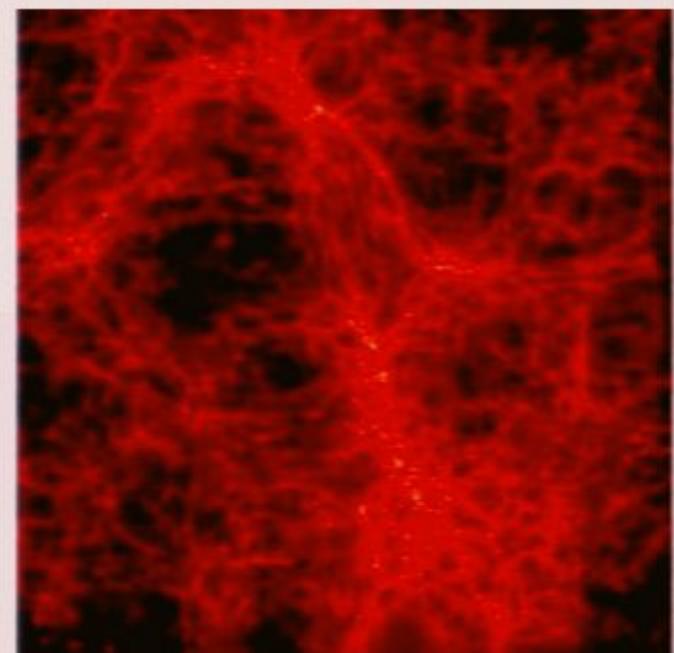
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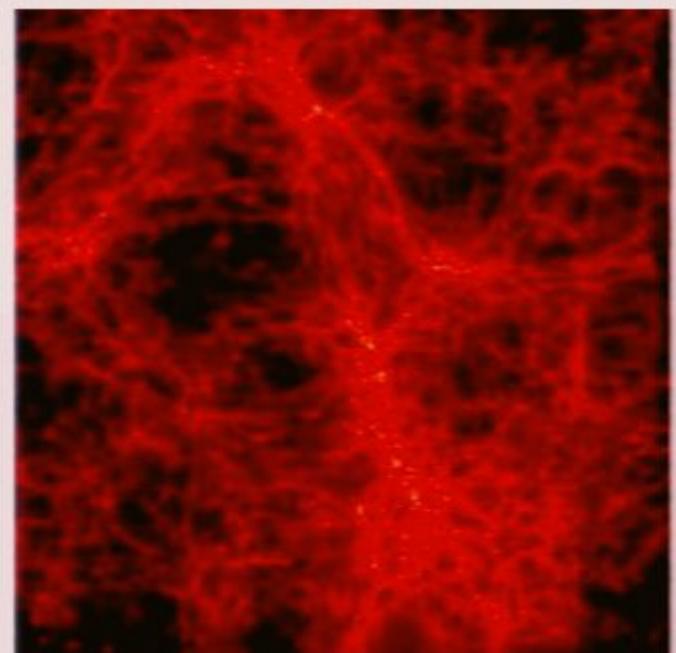
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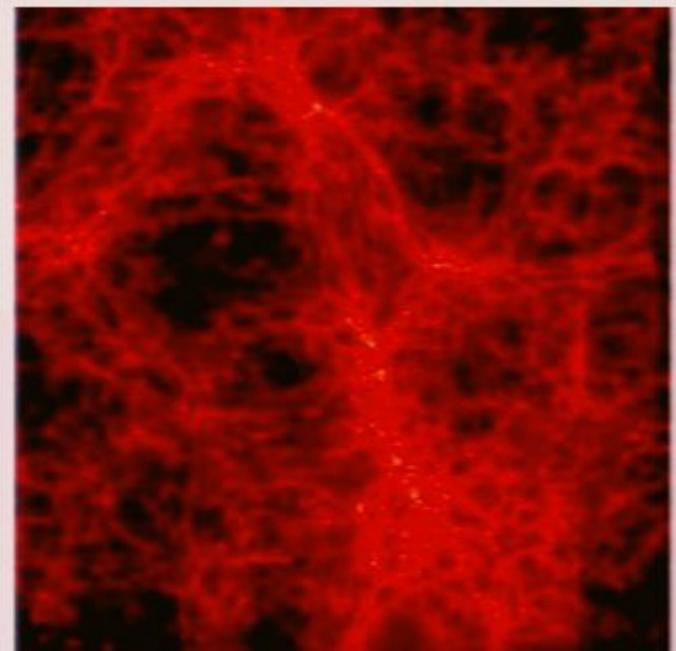
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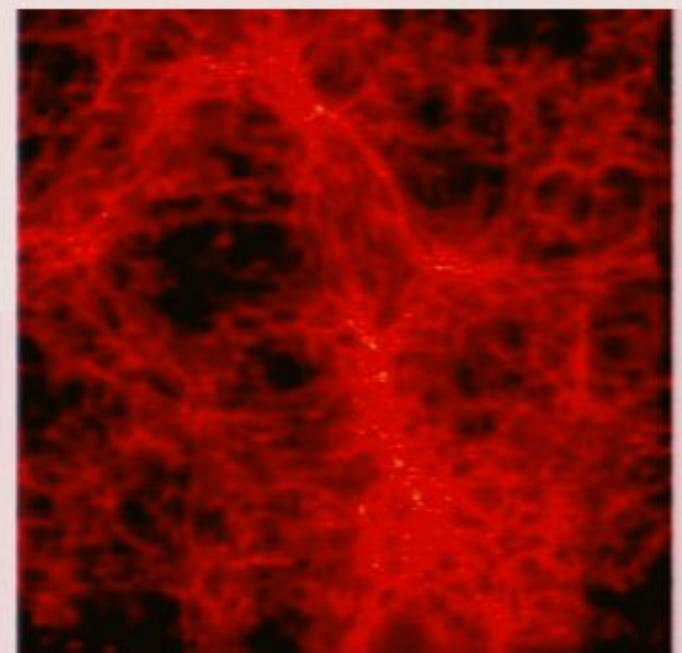
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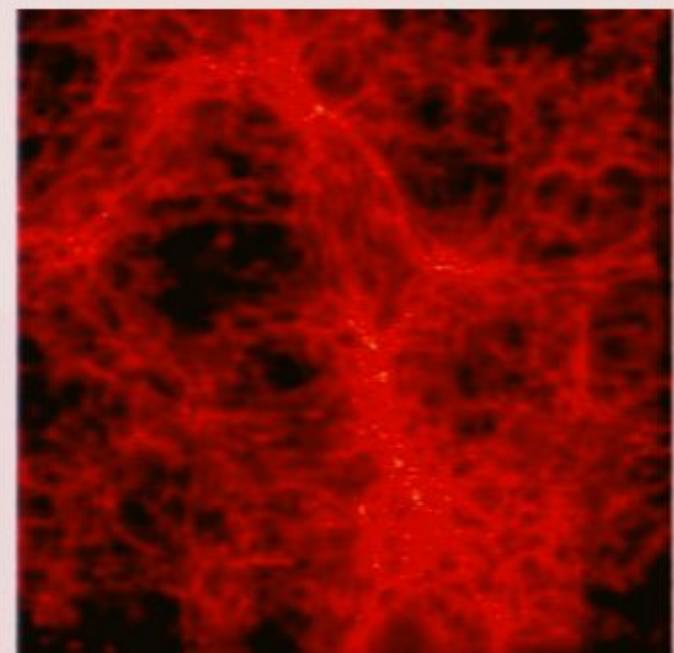
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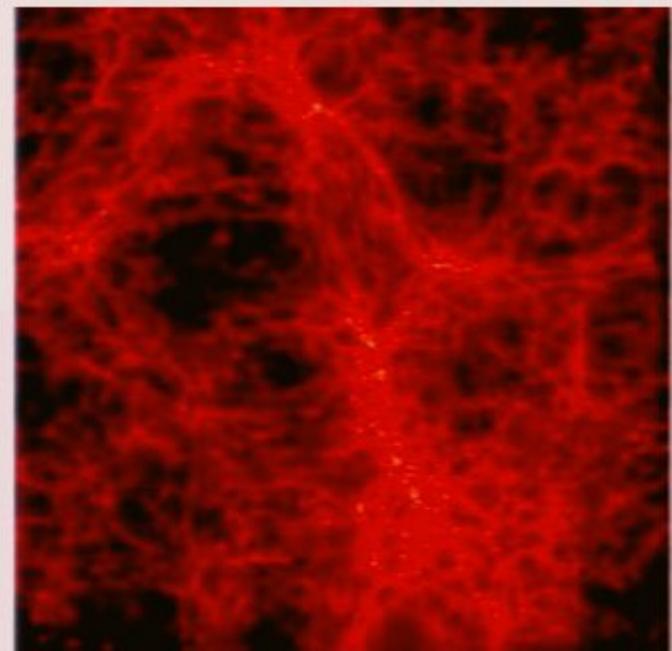
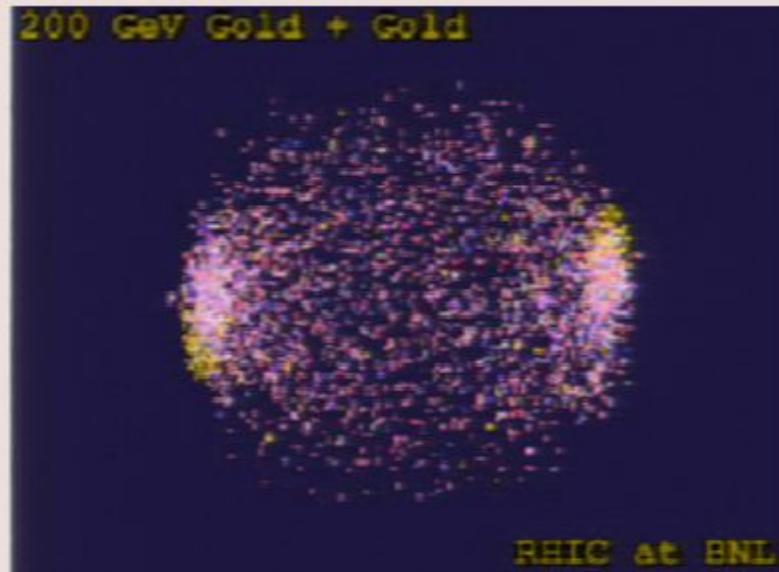
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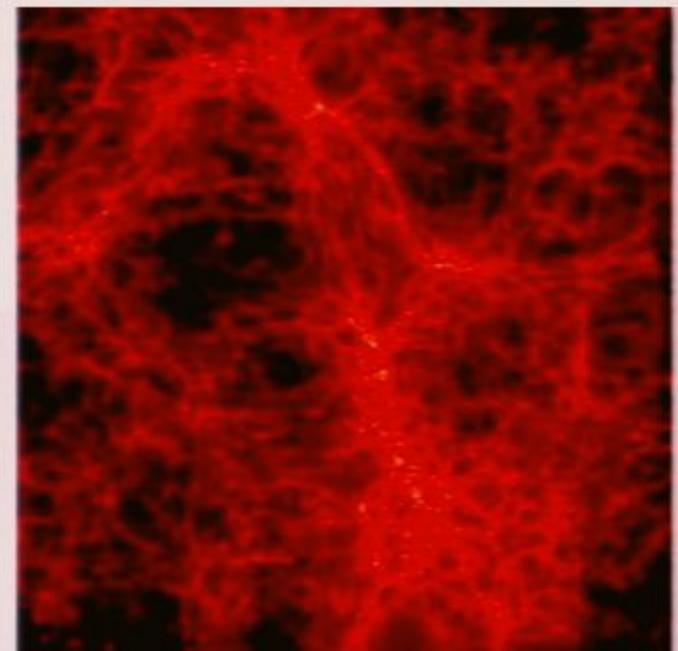
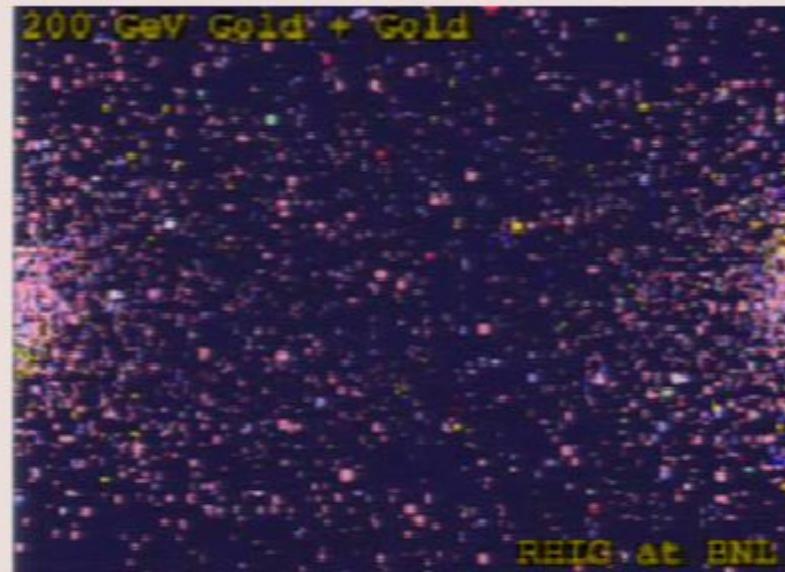
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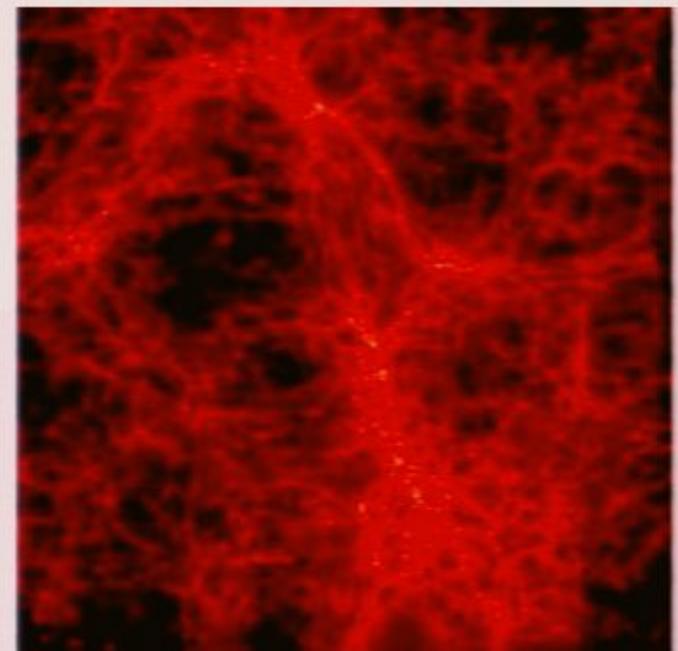


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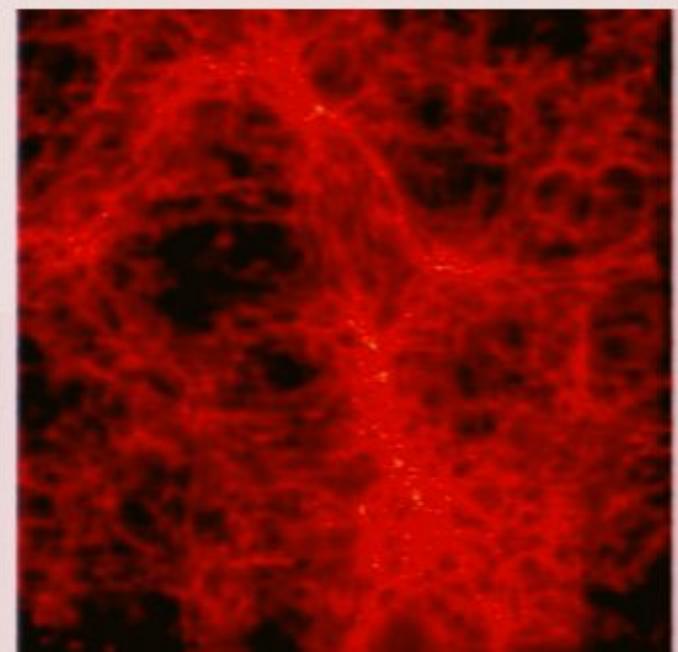
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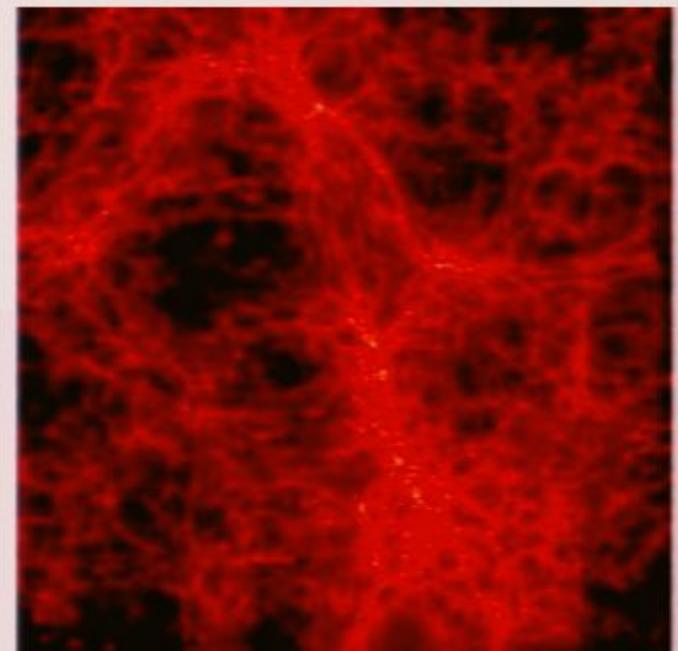
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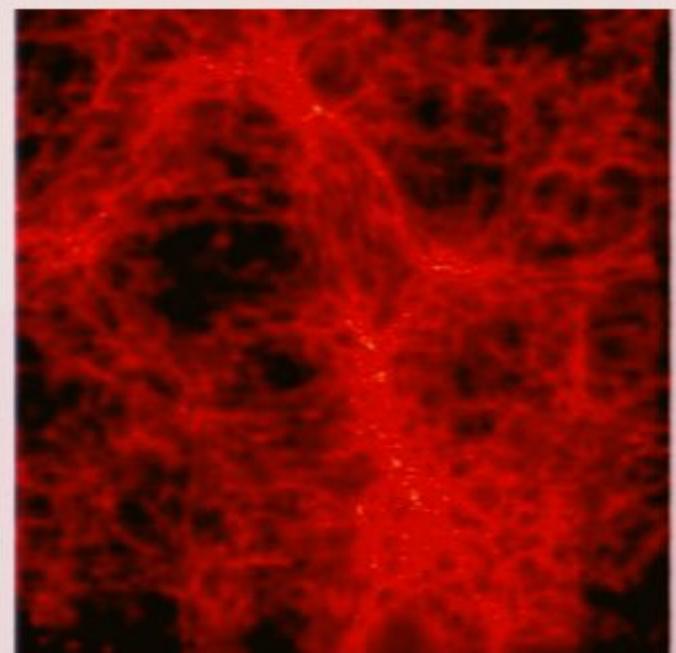
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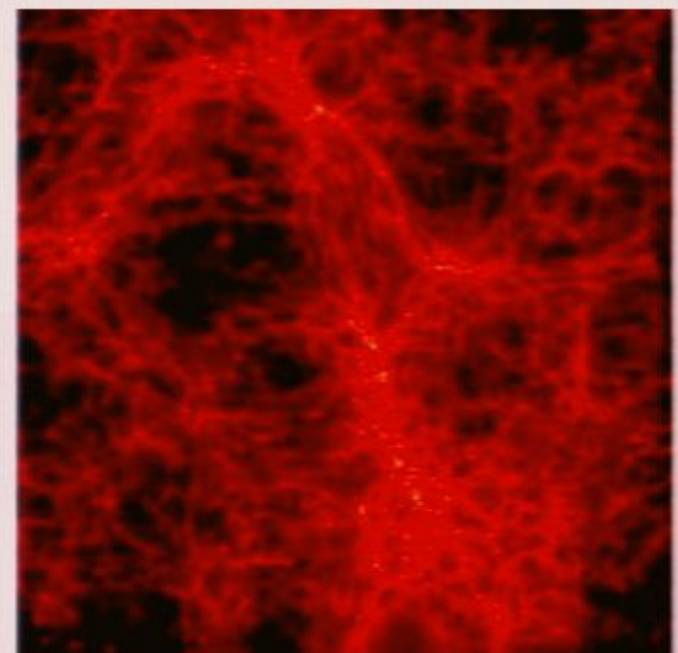
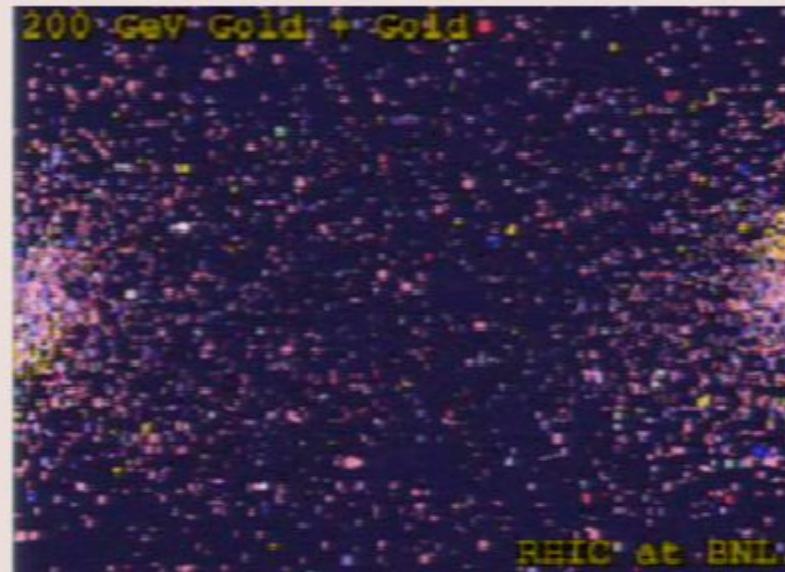
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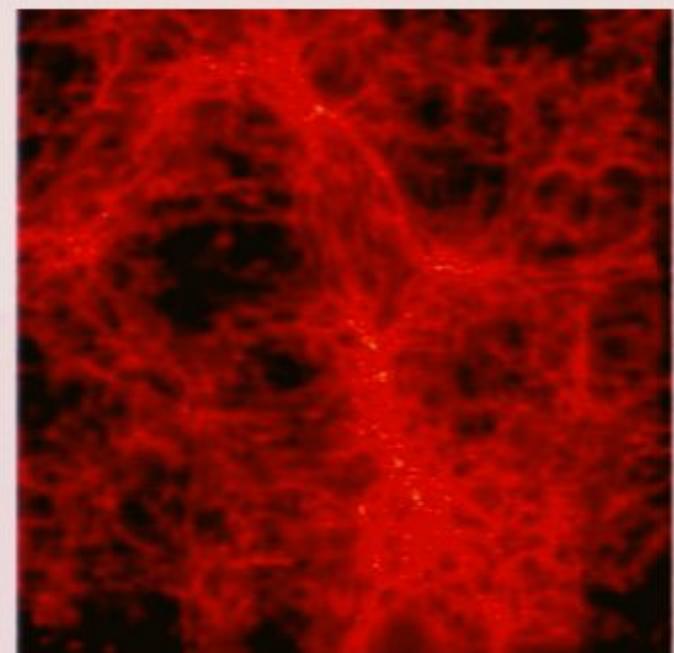
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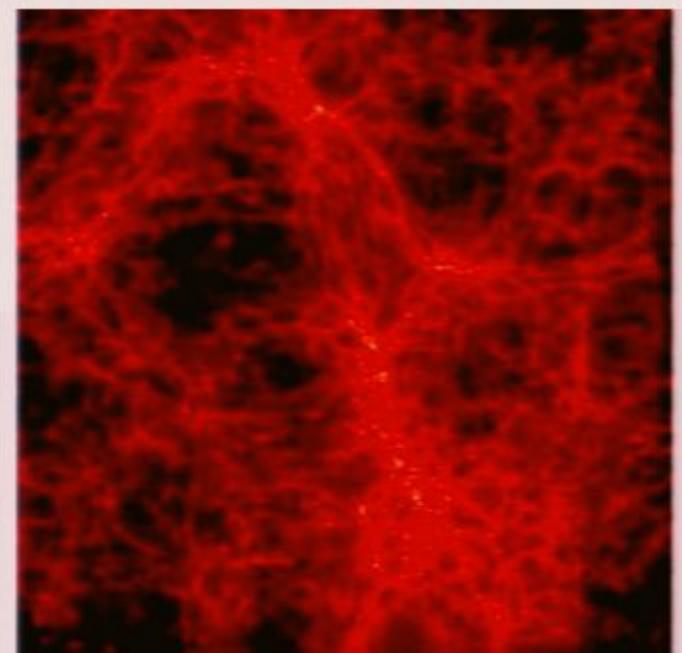
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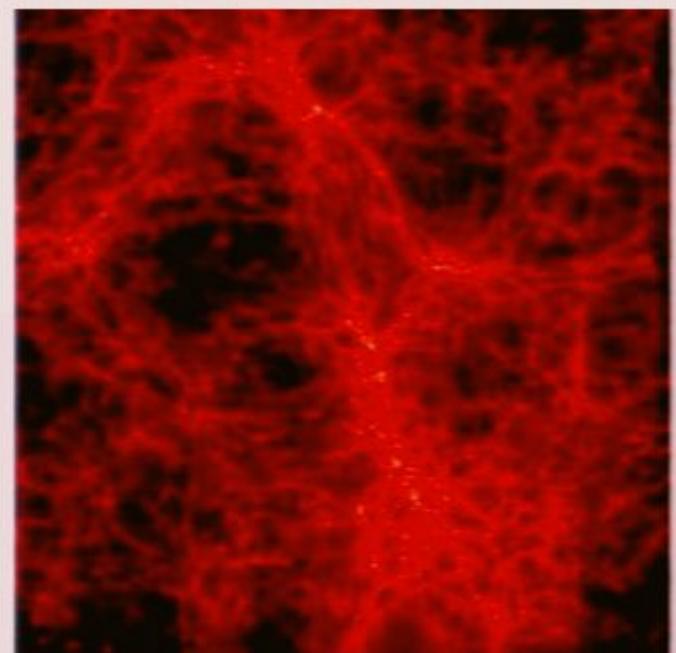
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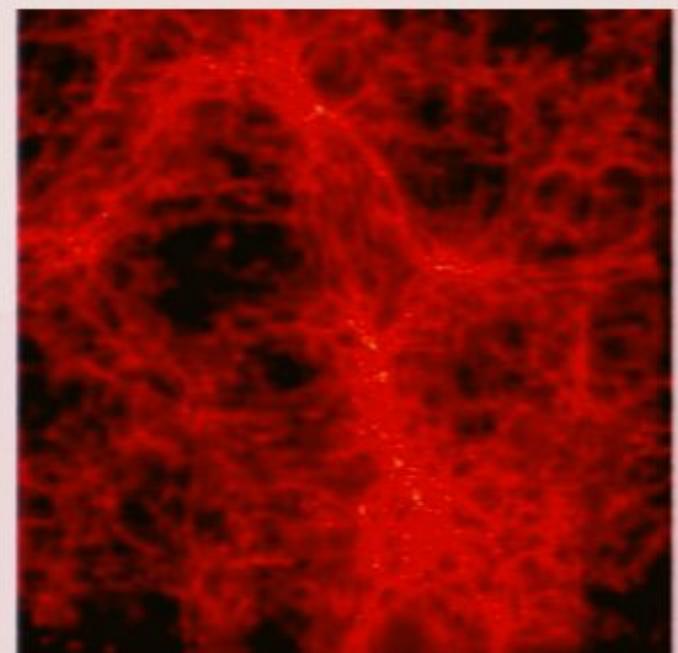
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Gauge/gravity duality provides simple tools to study **some strongly-coupled** gauge theories, e.g.,

Type IIB strings
on $\text{AdS}_5 \times S^5$
with RR flux N_c



$D=4$ $n=4$ $U(N_c)$
super-Yang-Mills

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limited to: large N_c and large 't Hooft coupling

QCD

confinement,
discrete spectrum,
scattering,

$n=4$ SYM

conformal,
continuous spectrum,
no S-matrix, SUSY,

very different !!

QCD

$T=0$

confinement,
discrete spectrum,
scattering,

$n=4$ SYM

conformal,
continuous spectrum,
no S-matrix, SUSY,

very different !!

$T > T_c$

strongly-coupled plasma
of gluons & **fundamental** matter
deconfined, screening,
finite corr. lengths, . . .

strongly-coupled plasma
of gluons & **adjoint** matter
deconfined, screening,
finite corr. lengths, . . .

very similar !!

QCD

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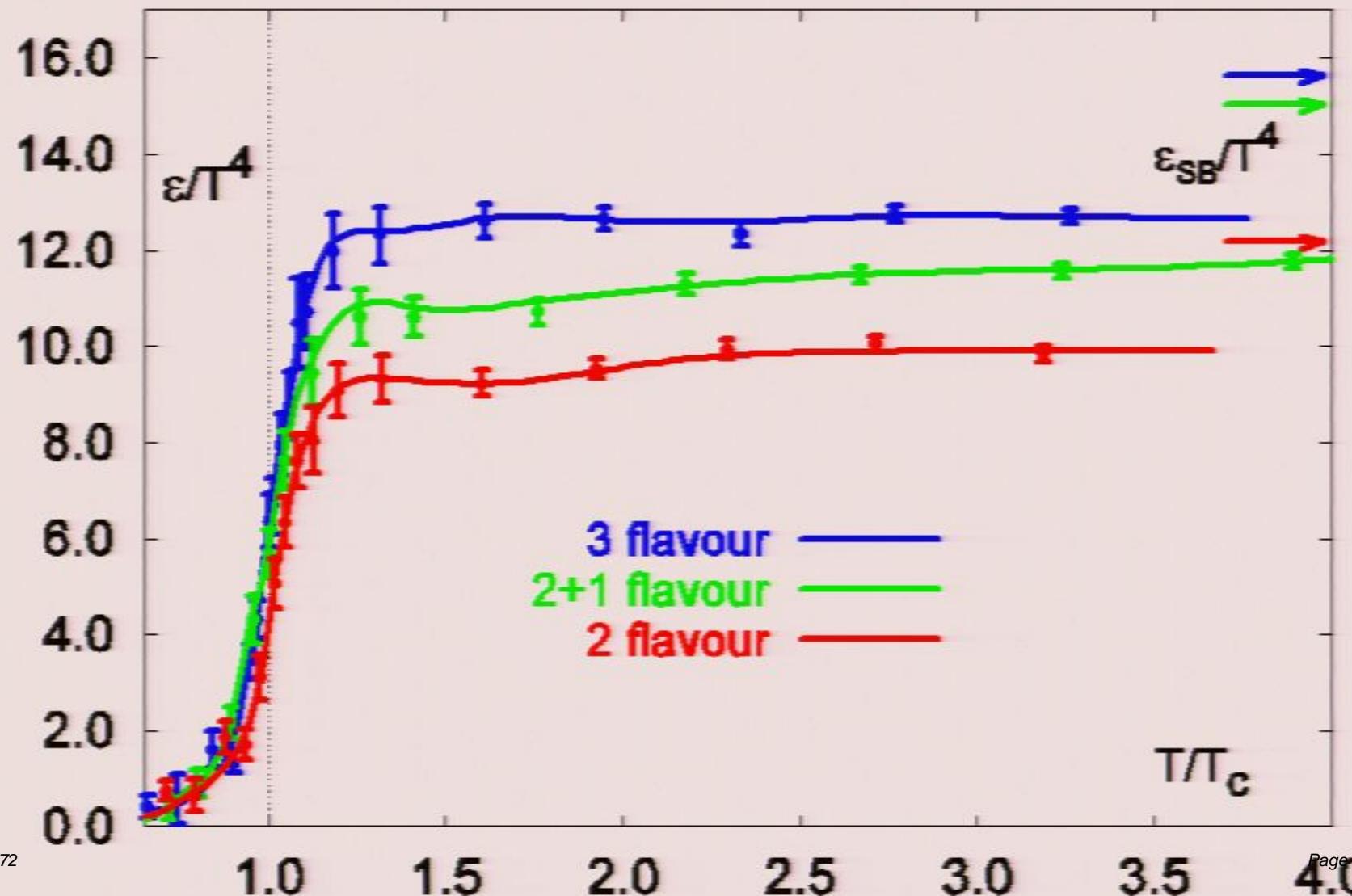
runs to weak coupling

remains strongly-coupled

very different !!

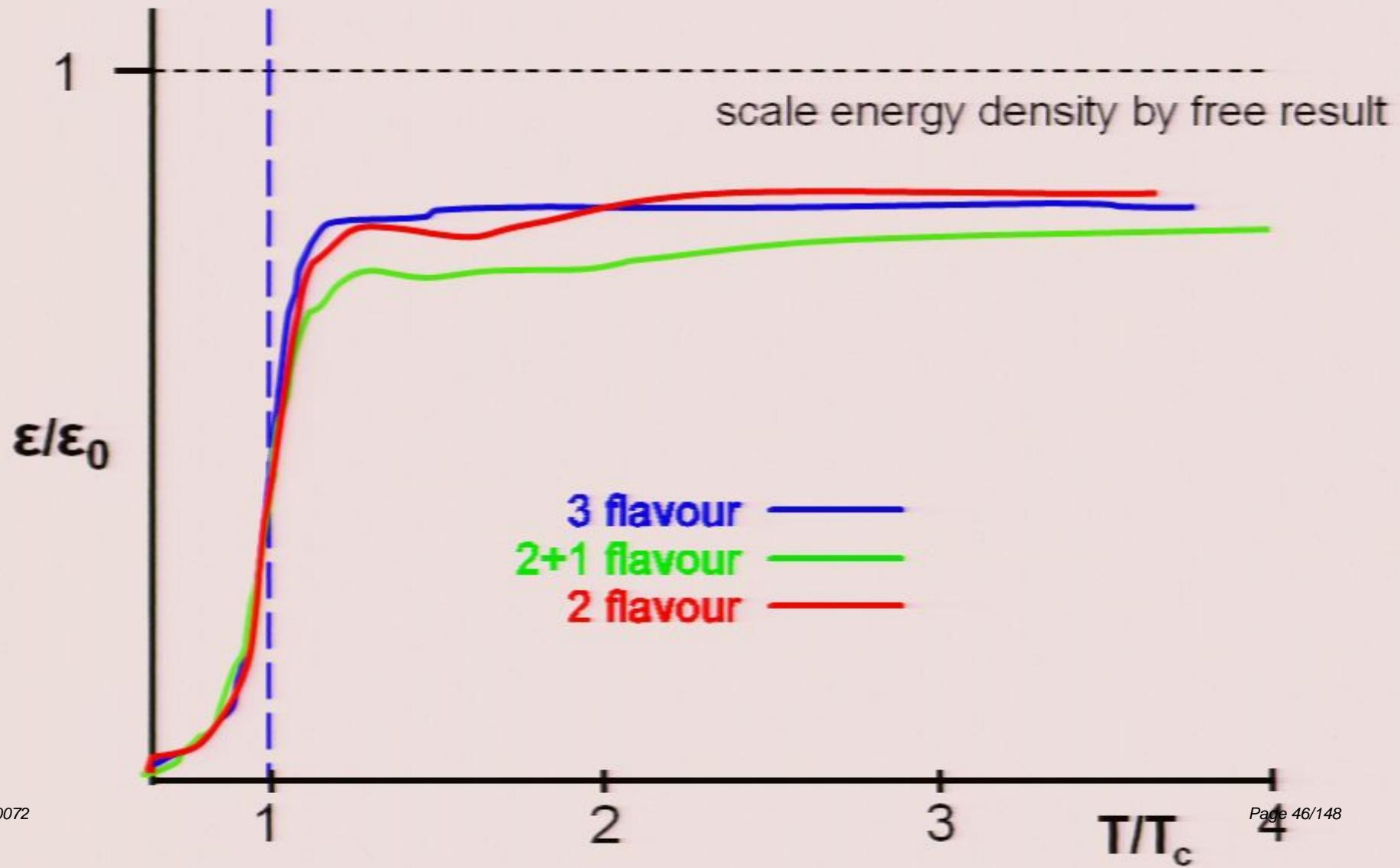
Reality check? Is this more than hot air?

Karsch (hep-lat/0106019)



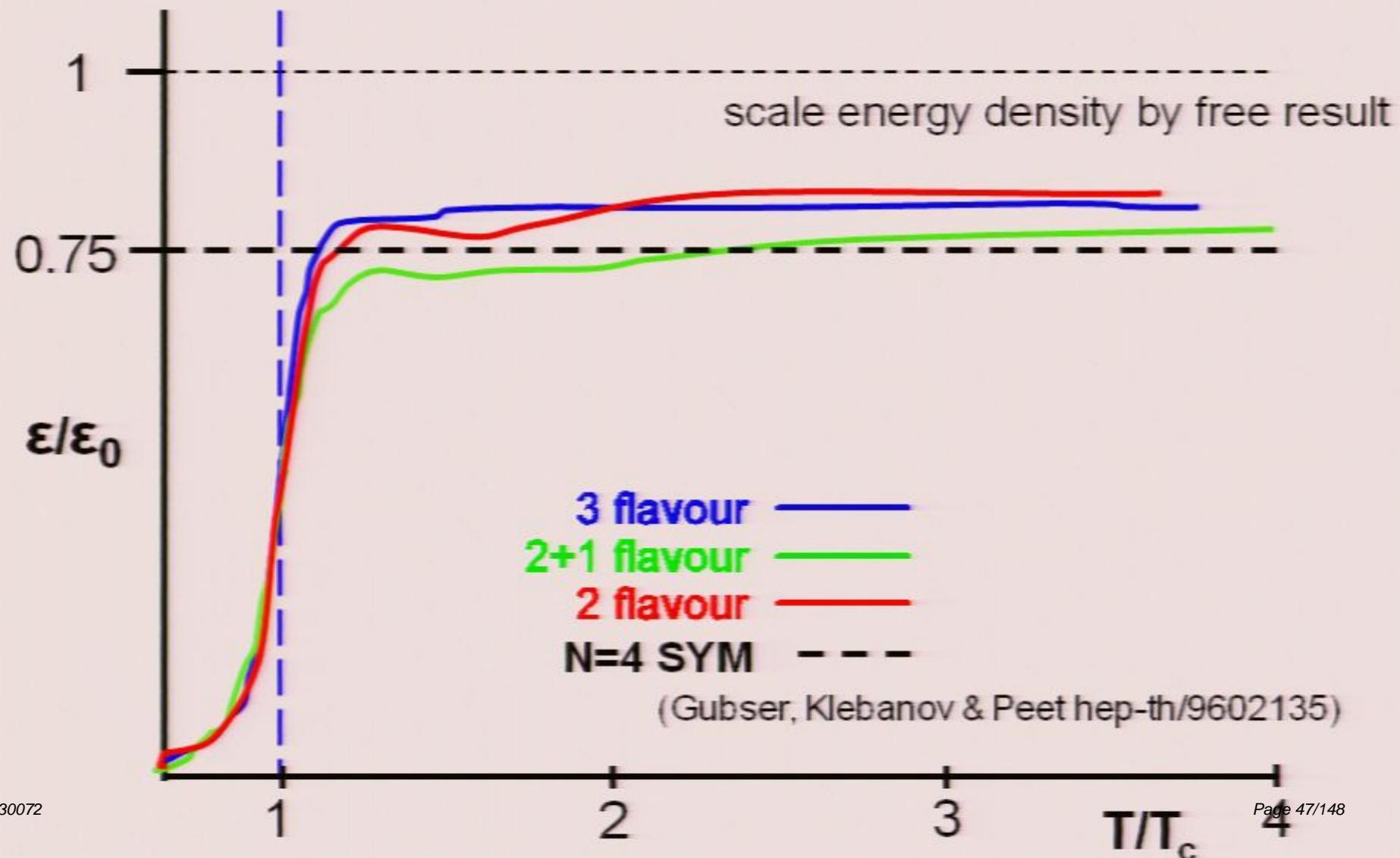
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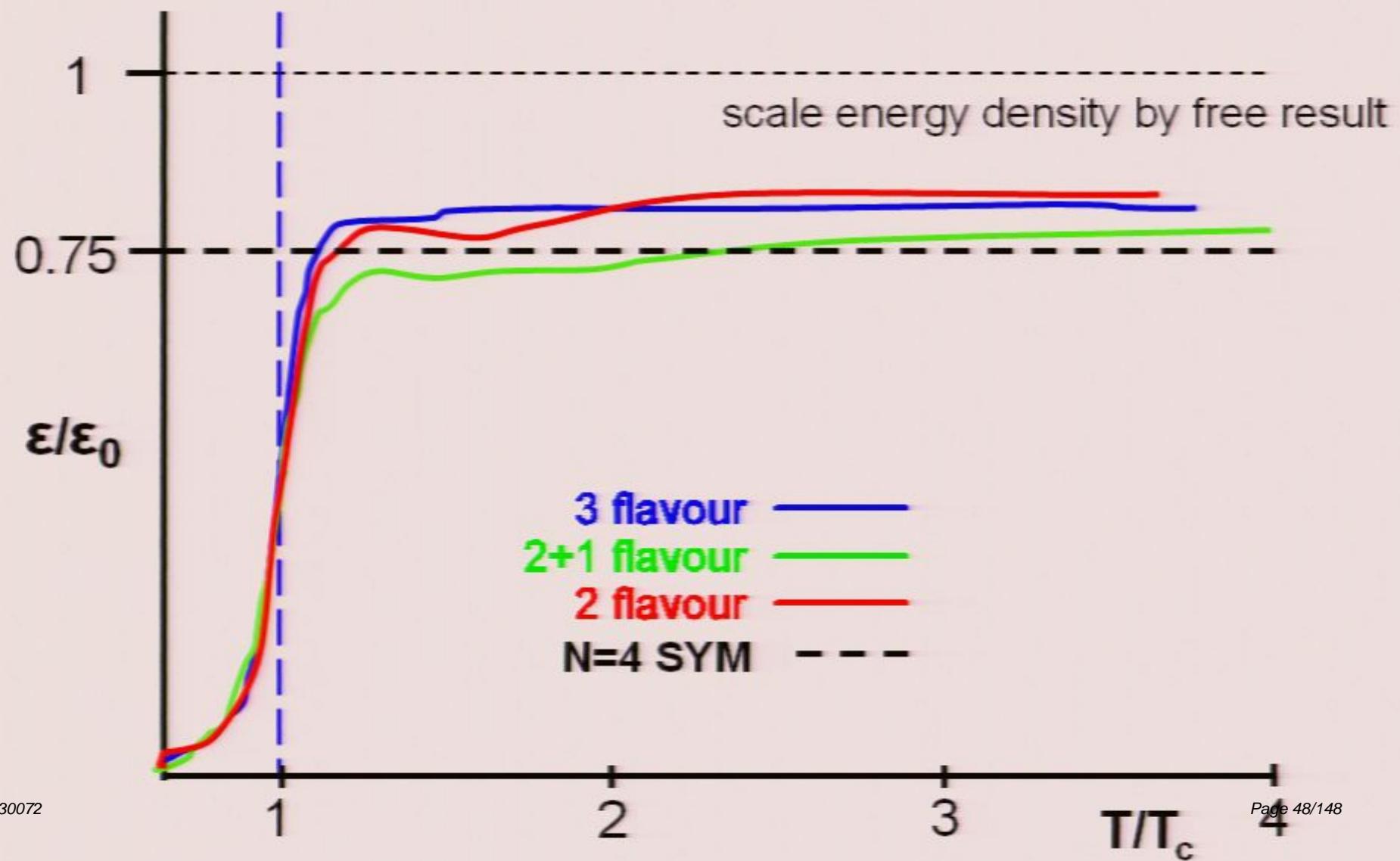
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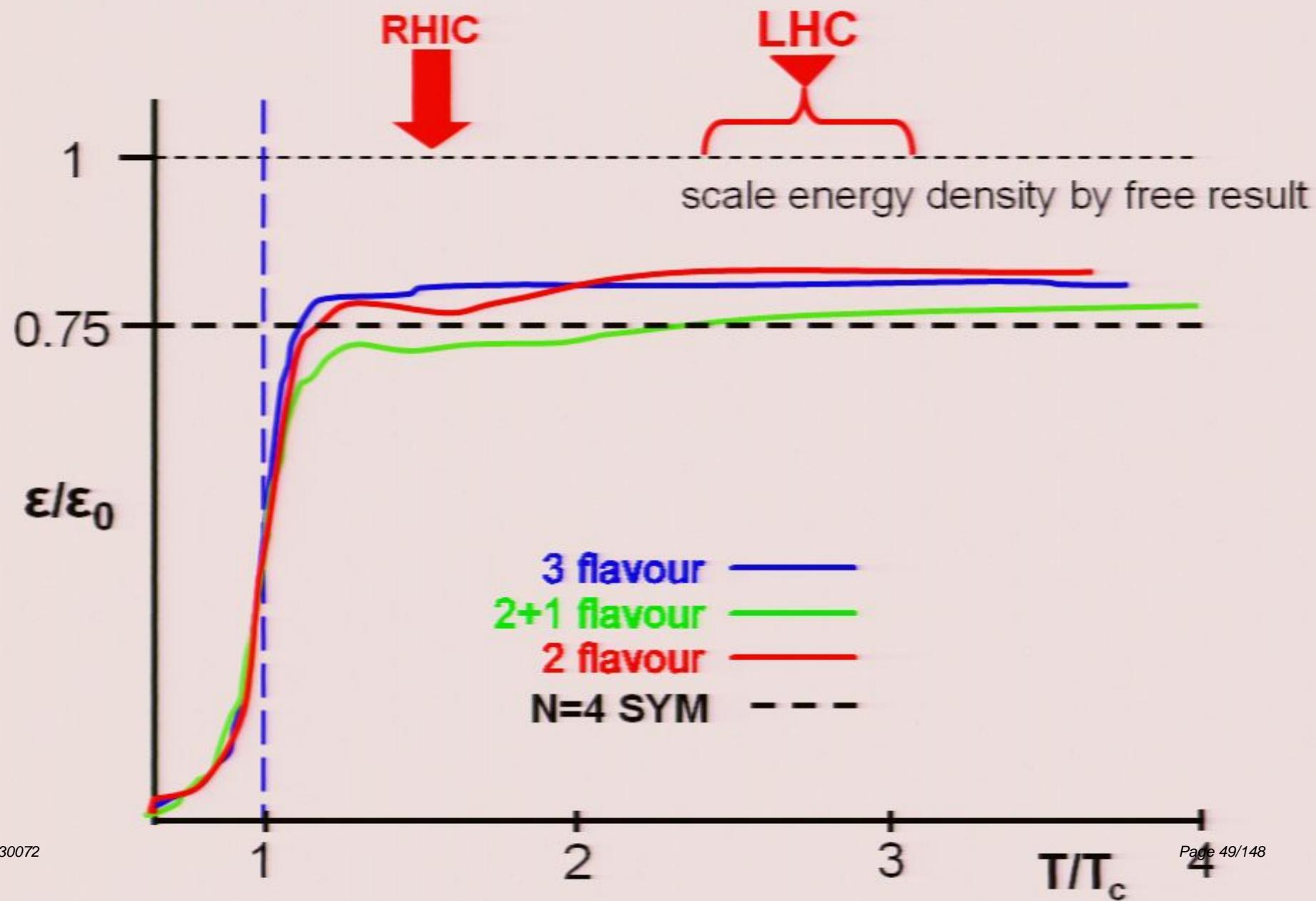
“80% is closer to 75% than 100%”

Strongly coupled QGP seems to be “conformal”, just above T_c

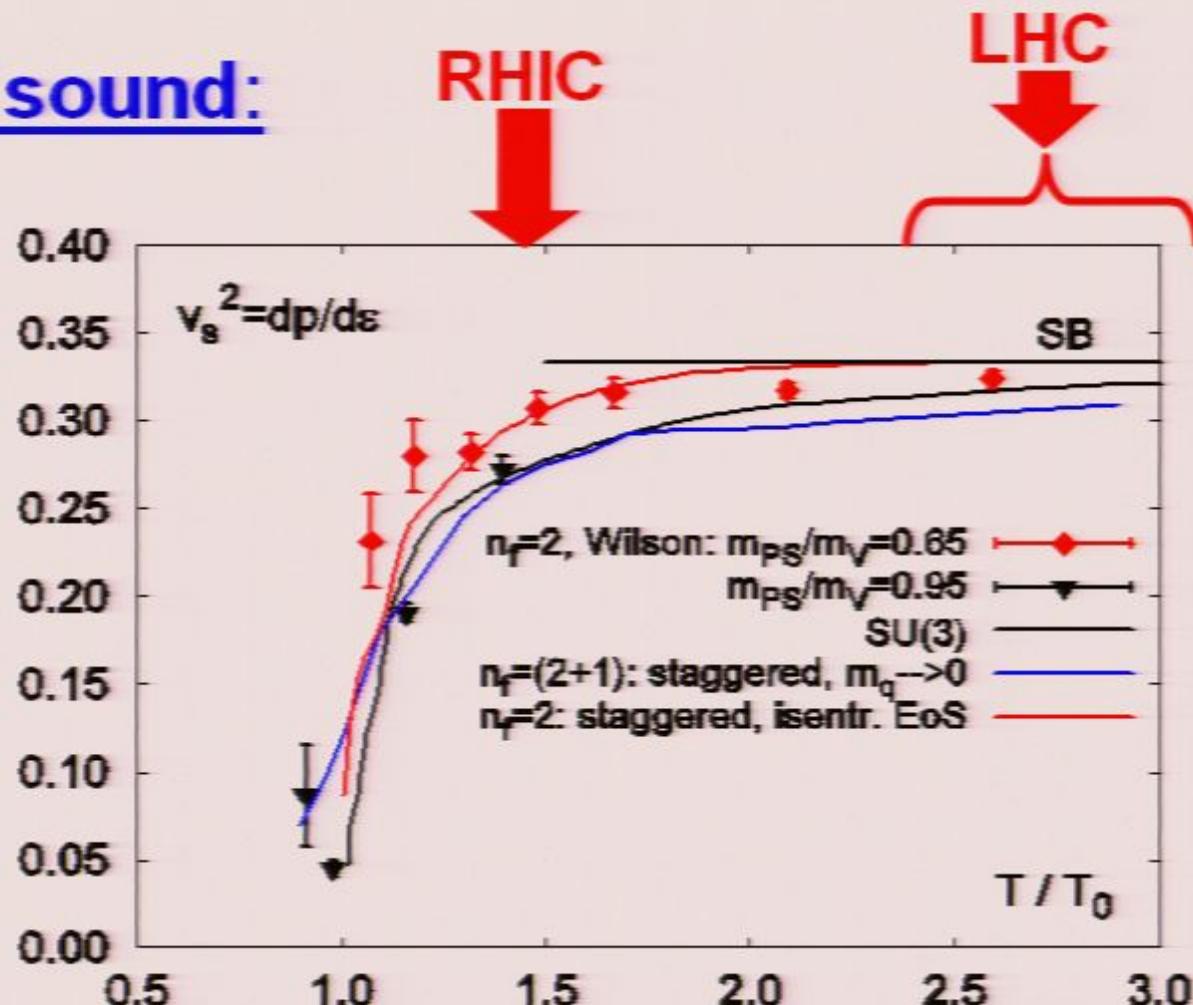


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Speed of sound:

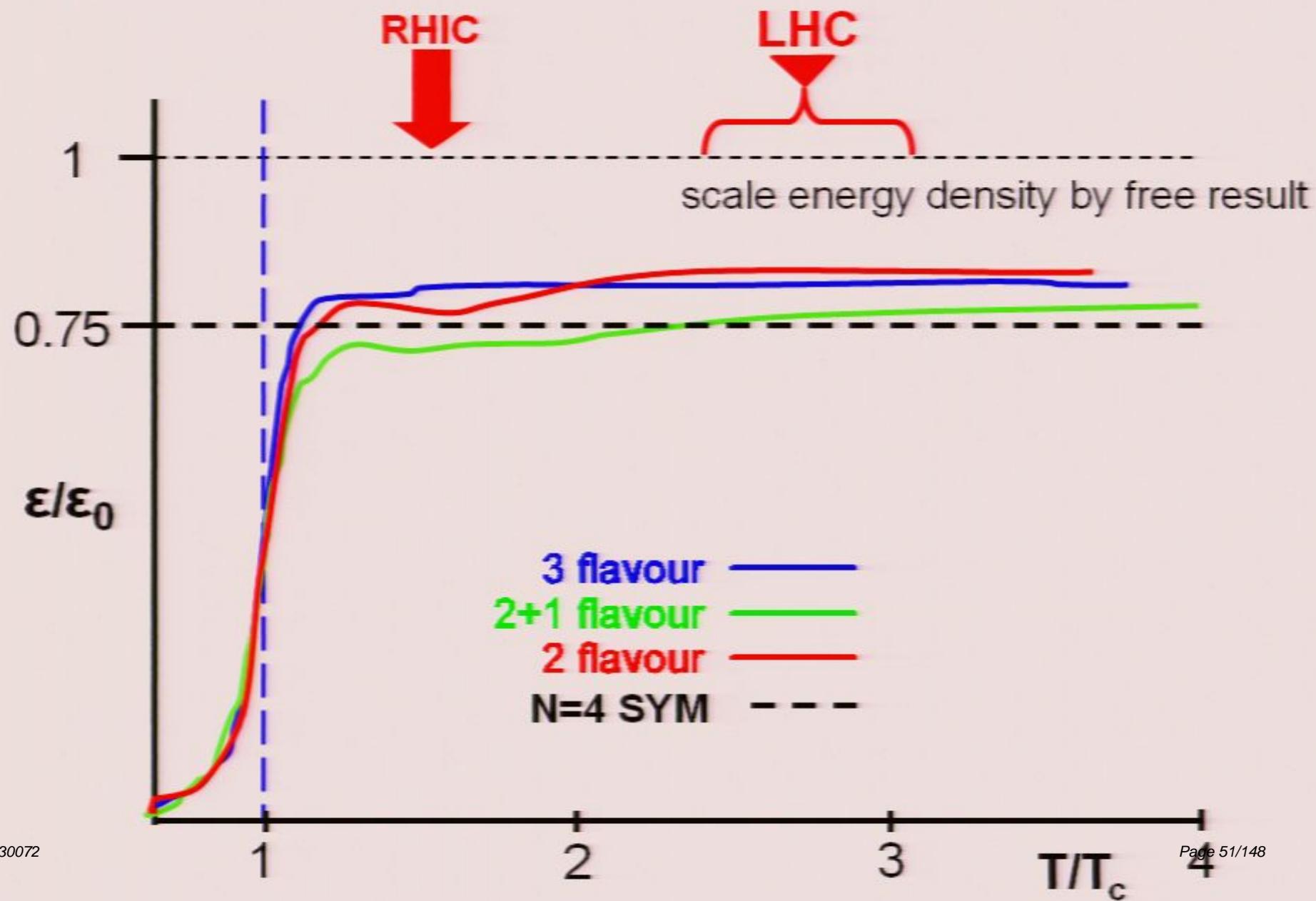


- lattice studies show v_s^2 rapidly approaches $1/3$
→ ideal gas or **conformal** value

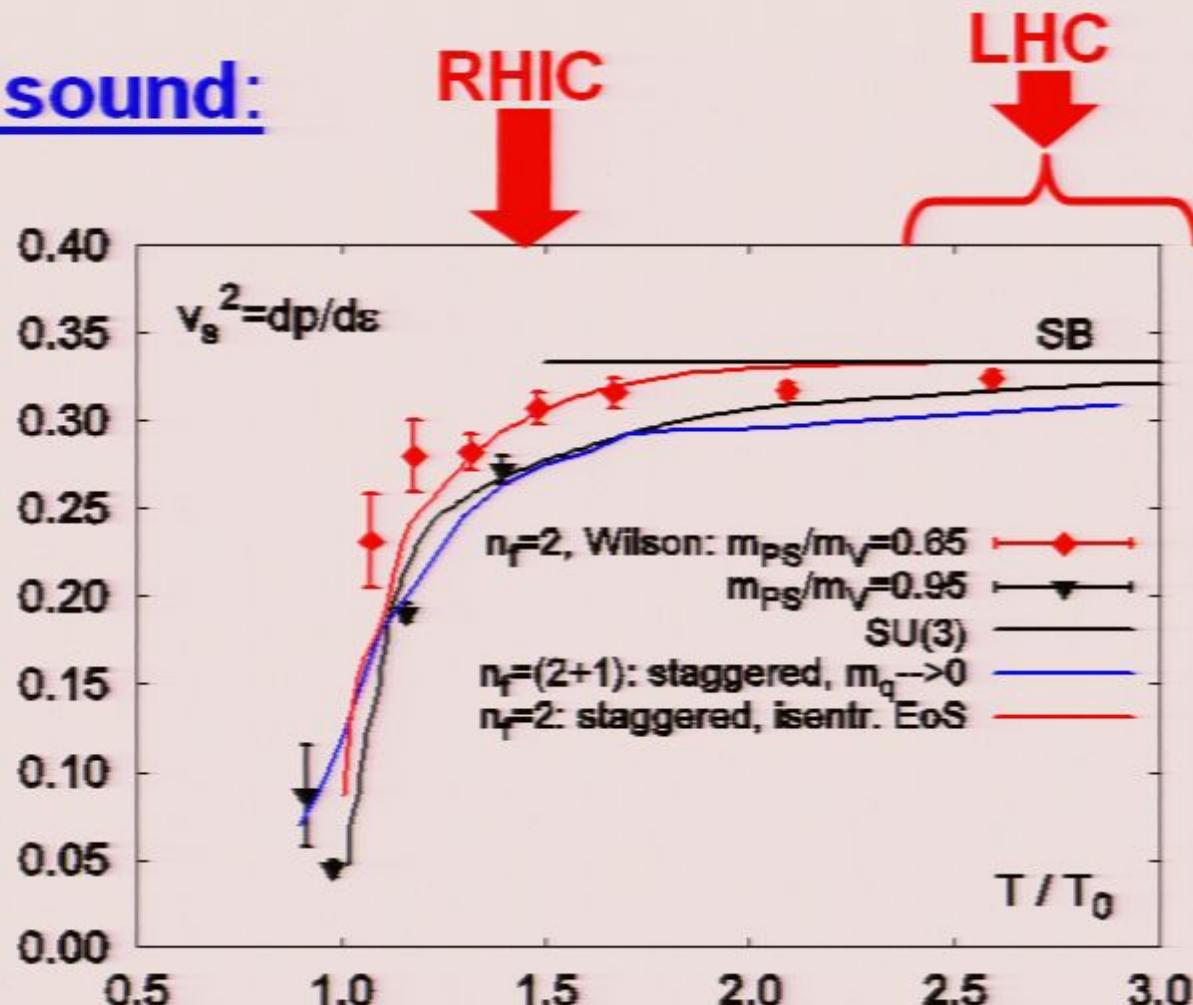
$$v_s^2 \simeq \frac{1}{3} \left(1 - 1.2 \frac{1 + \frac{2}{3}\epsilon/\epsilon_0}{(1 + \epsilon/\epsilon_0)^2} \right) \text{ with } \epsilon_0 \simeq 0.5 \text{ GeV/fm}^3$$

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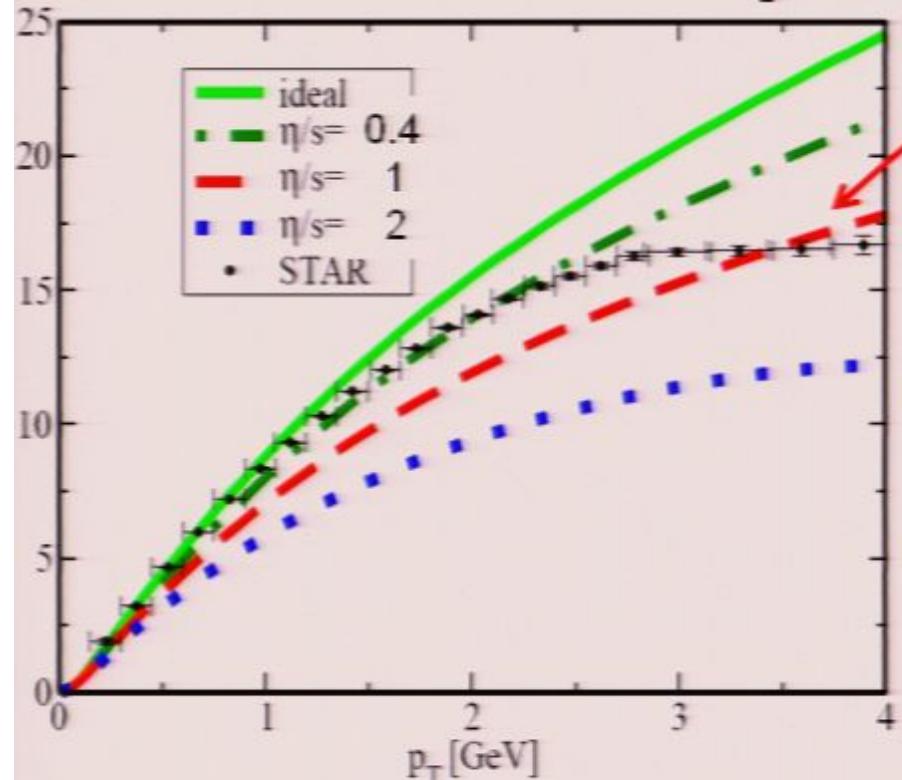
Elliptic flow: inferred from RHIC data

assumes Shear Viscosity η is very small!

Romatschke & Romatschke,

arXiv:0706.1522 [nucl-th])

seems to need: $4\pi \eta/s \sim 1$



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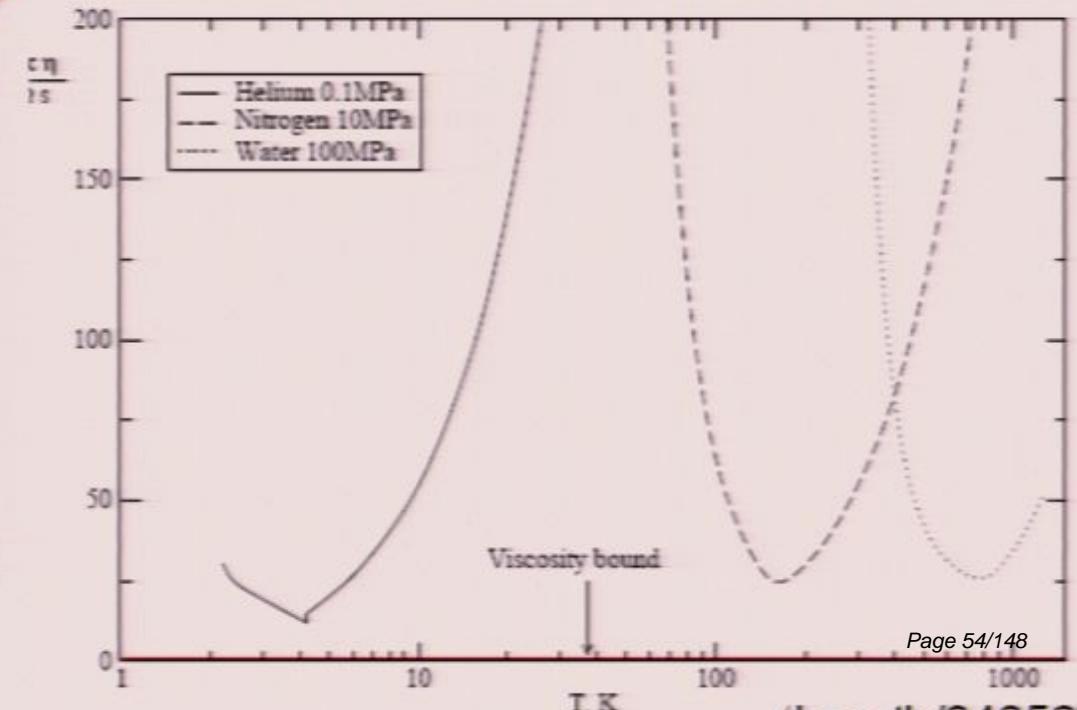
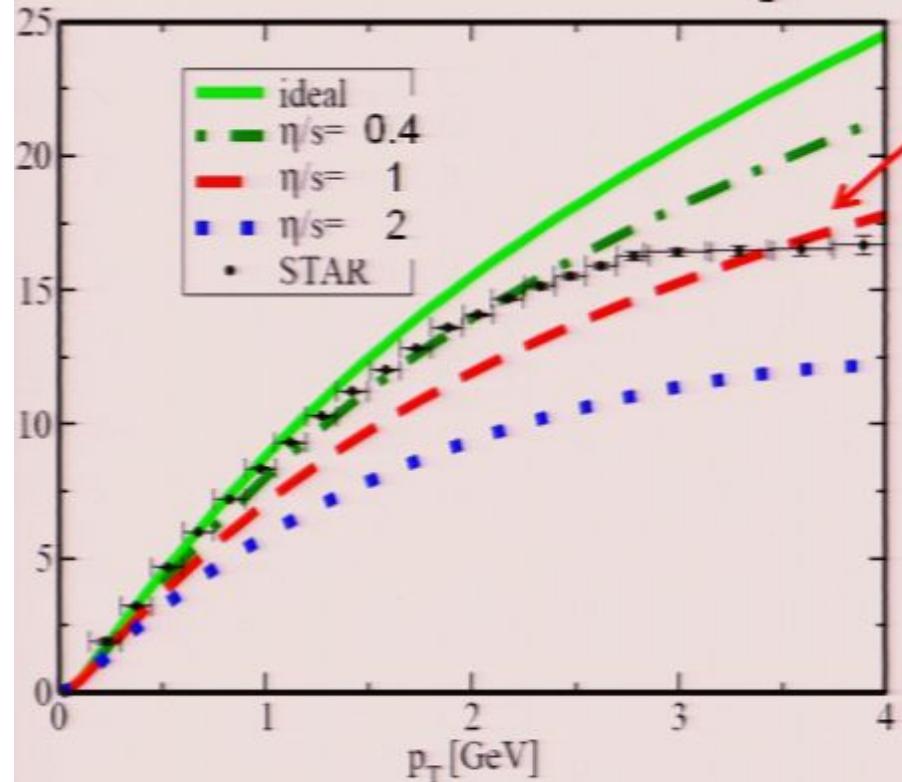
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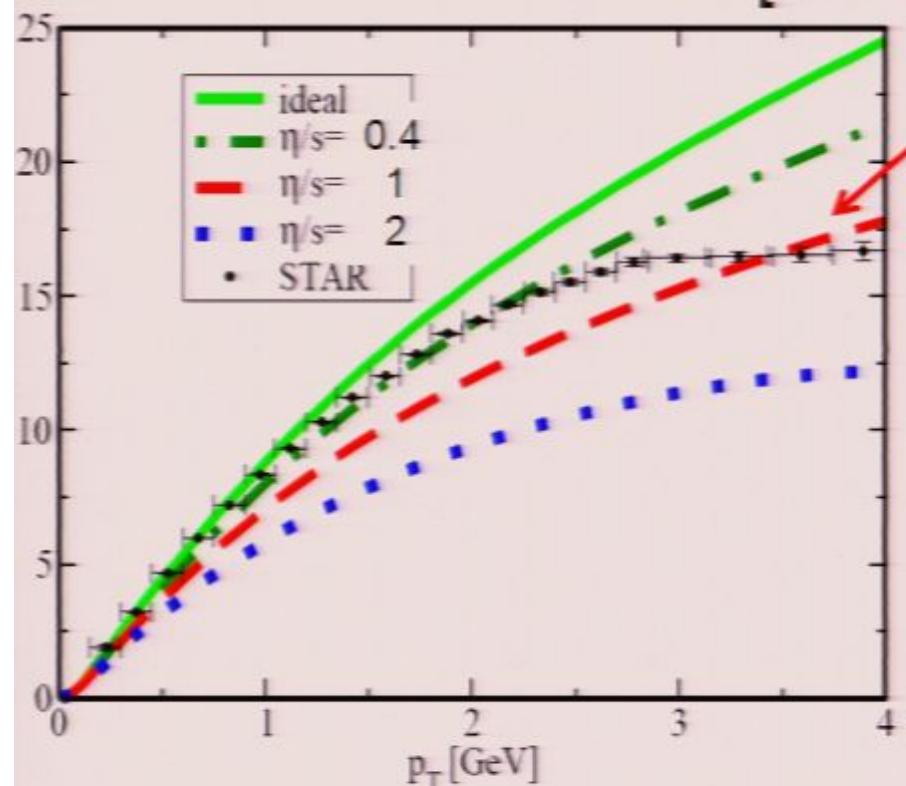


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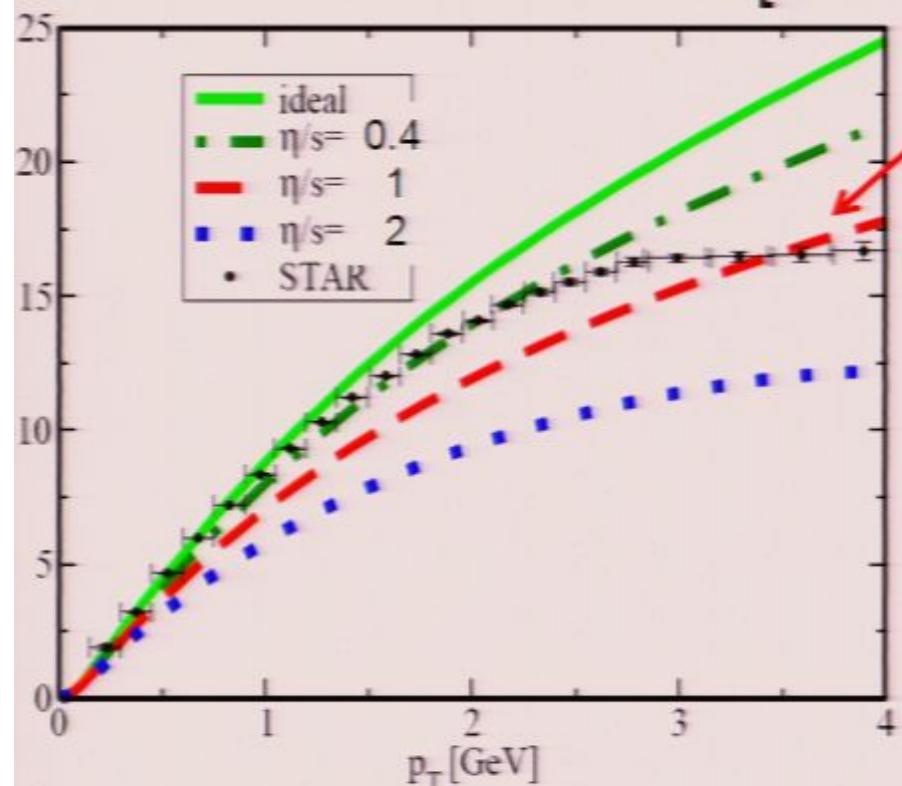
Theoretical challenge:
both perturbative analytic
and computer techniques
fail for strong-coupling dynamics!

Elliptic flow: inferred from RHIC data

assumes Shear Viscosity η is very small!

Romatschke & Romatschke,

arXiv:0706.1522 [nucl-th])



seems to need: $4\pi \eta/s \sim 1$

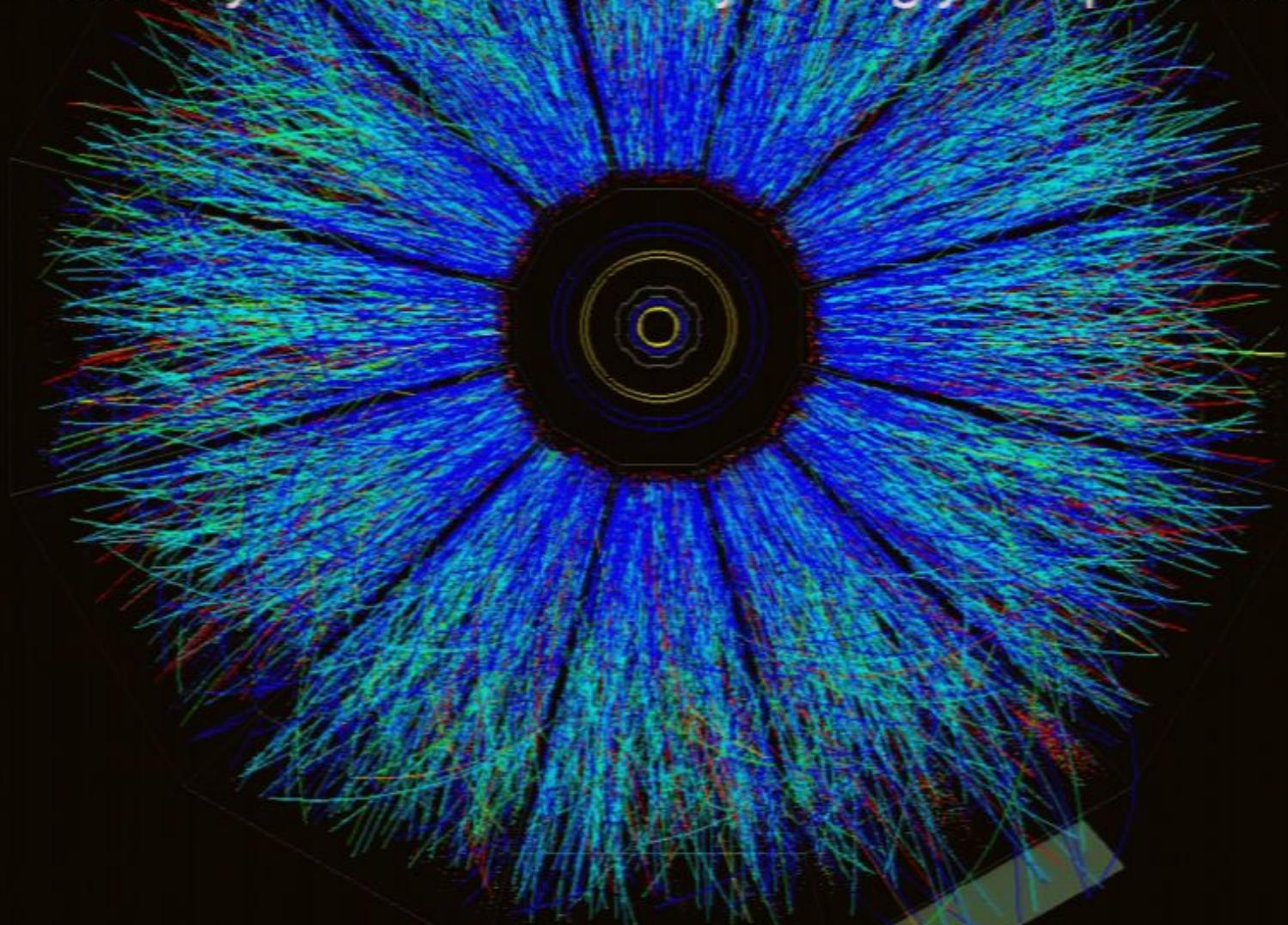
universal result for all known theories with gravity dual:

$$4\pi \eta/s = 1 !!$$

Kotvun, Son & Starinets; Buchel & Liu; . . .

Motivation: “Quark Soup al dente”

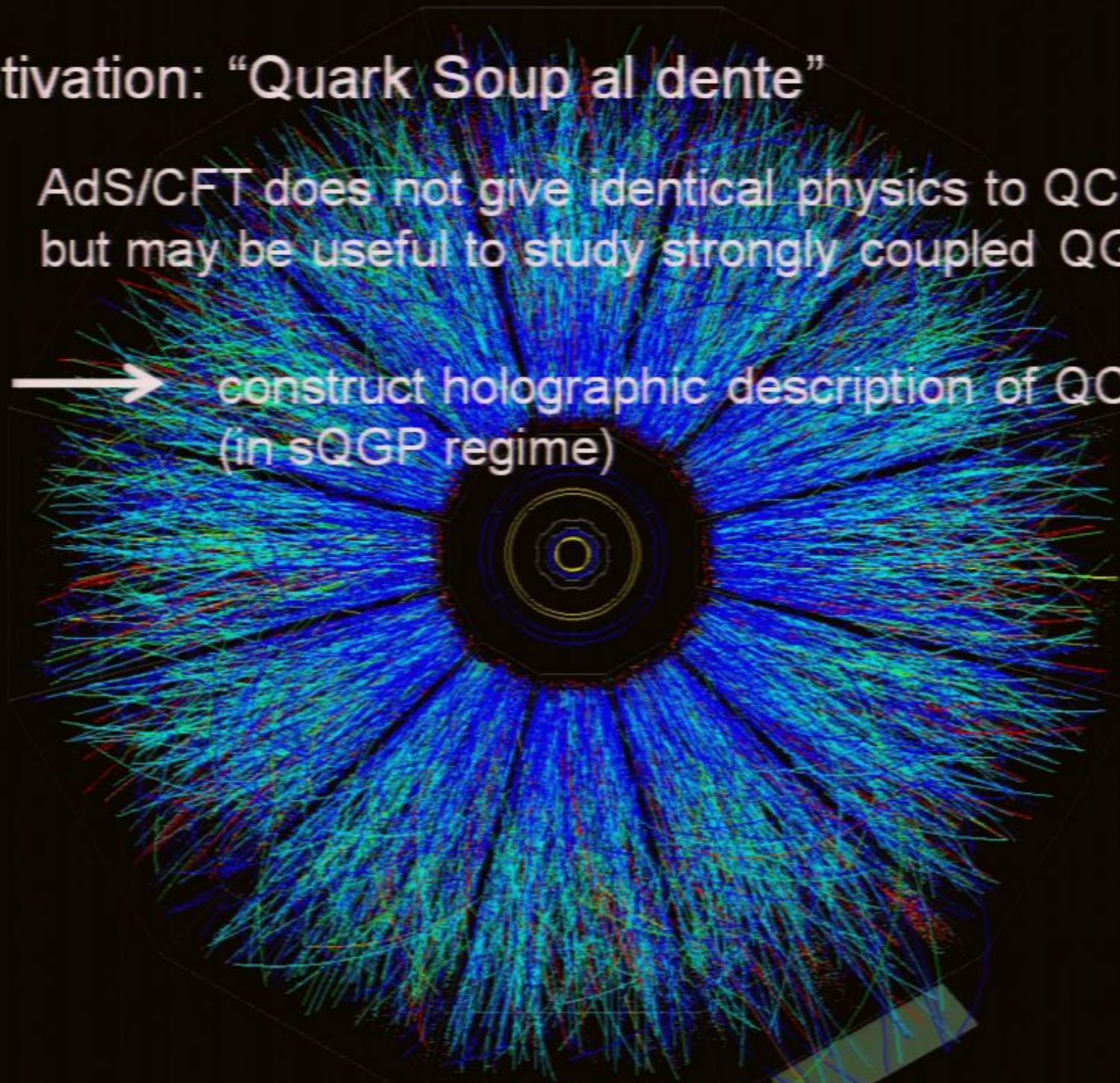
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Present explorations fall firmly in latter class
with objective of adding fundamental matter

Field theory overview:

$N=2$ $SU(N_c)$ 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: $(\phi_{1,2})^a{}_b, (\psi_{3,4})^a{}_b$

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

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

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

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} 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:

$$\begin{array}{lll} \text{free quarks} & \sim & m_q \\ \text{"mesons"} (f\bar{f} \text{ bound states}) & \sim & m_q/\sqrt{\lambda} \end{array}$$

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- low temperatures:

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Adding flavour to AdS/CFT



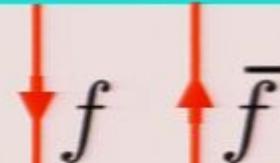
add N_f probe D7-branes

$= \infty$

AdS₅ boundary

D7

$= L$

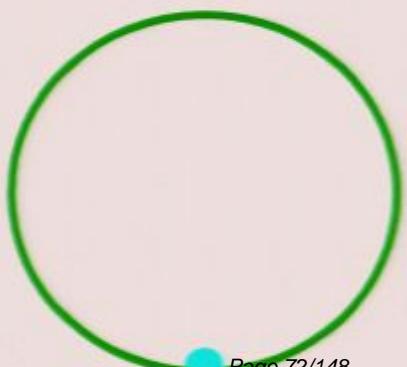
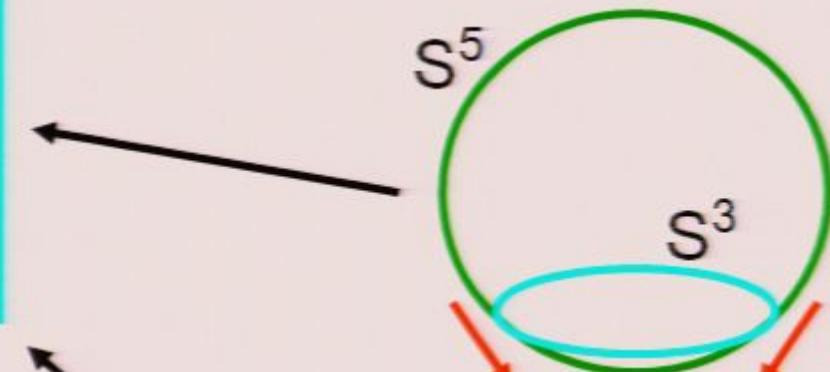
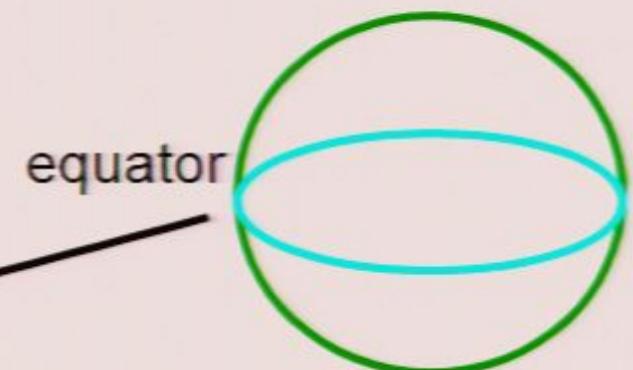


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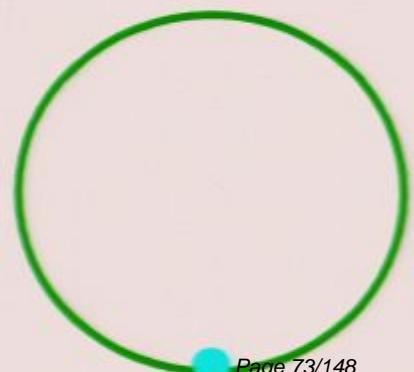
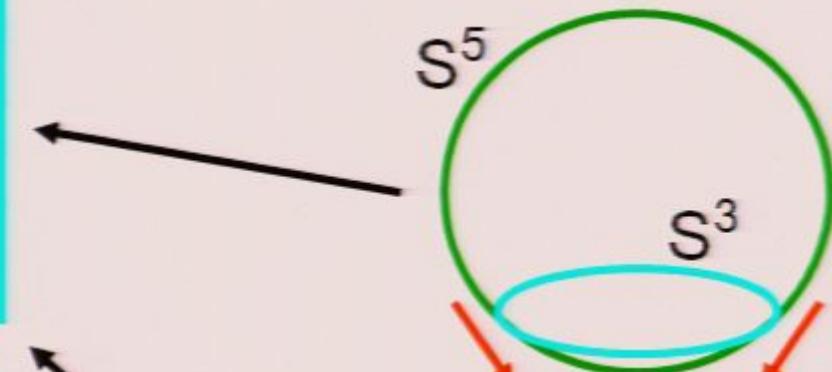
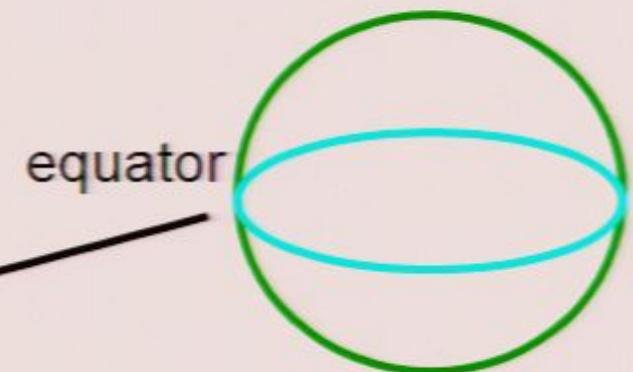
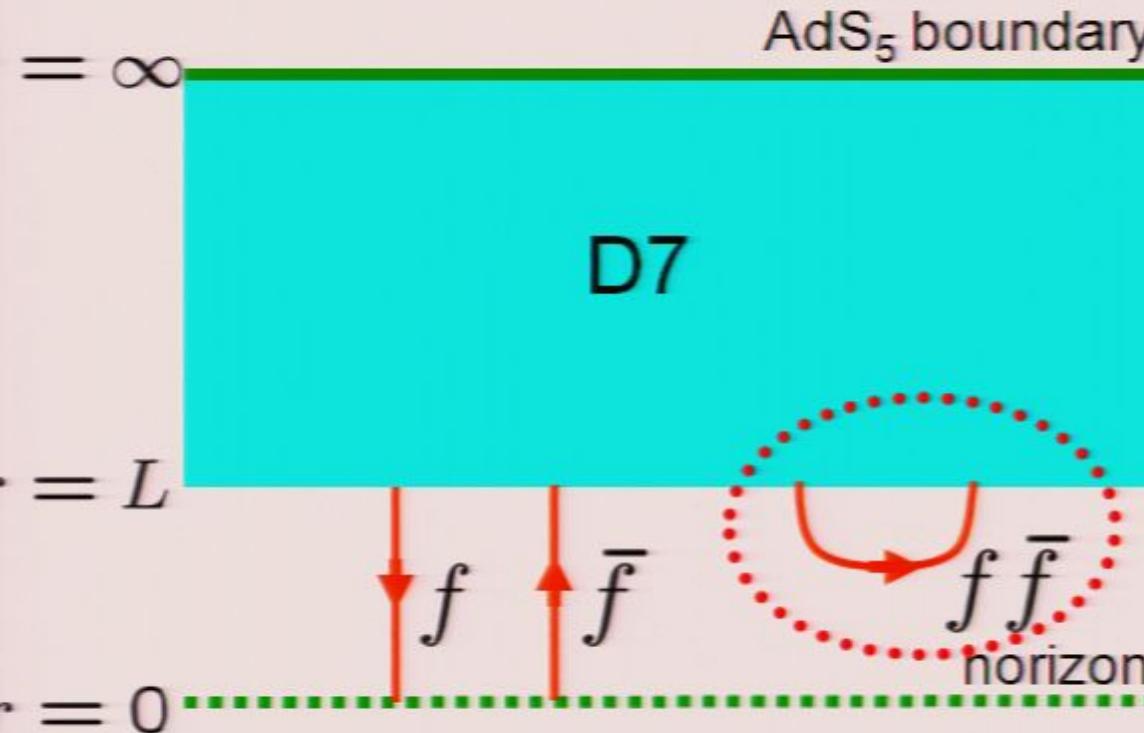
horizon

Free quarks appear with mass:

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



Adding flavour to AdS/CFT

add N_f probe D7-branes

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

Gauge/gravity dictionary:

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

D7-brane modes:

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

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Probe approximation: $N_f / N_c \rightarrow 0$

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

→ considering large- N_c limit with N_f fixed

(see, however: Burrington et al; Kirsch & Vaman;
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Mesons:

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

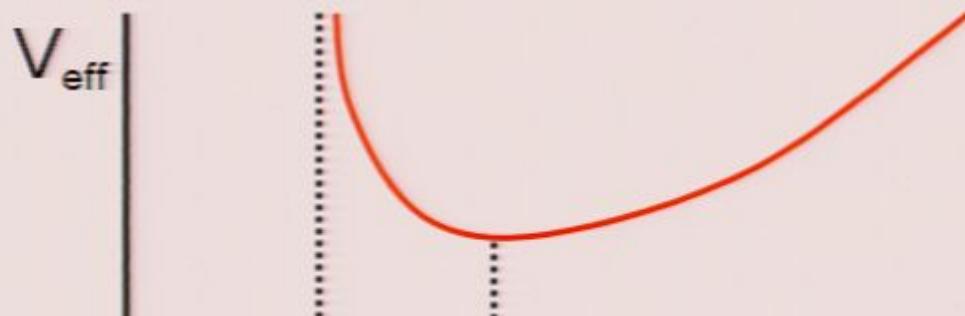
→ their dynamics is governed by usual worldvolume action:

$$S_{D7} = -\frac{1}{(2\pi)^7 g_s \alpha'^4} \int d^8 \xi \sqrt{-\det(P[G]_{ab} + 2\pi\alpha' F_{ab})} \\ + \frac{1}{2(2\pi)^5 g_s \alpha'^2} \int P[C^{(4)}] \wedge F \wedge F$$

free spectrum:

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

discrete
spectrum



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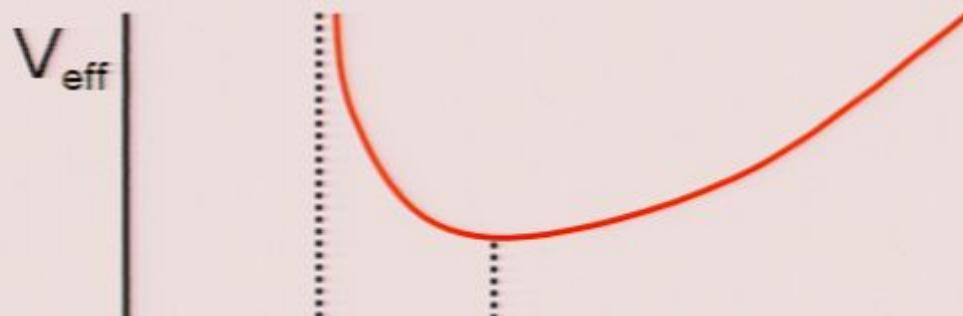
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Meson spectrum:

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

n = radial AdS quantum #

ℓ = angular quantum # on S^3 = R-charge

massive supermultiplets with $8(\ell + 1)$ bosons and fermions

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

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Meson interactions:

Continue expansion of D7-brane action beyond 2nd order

- substitute $\Phi = \phi(x)\psi_{n,\ell}(r)Y_\ell(\Omega)$ and integrate out r and S^3

$$\text{e.g., } \mathcal{L}_{eff} \simeq -\frac{1}{2} [(\partial\phi)^2 + M^2\phi^2] + \frac{2\pi\alpha'}{L} \underbrace{\frac{1}{\sqrt{N_c}} \phi (\partial\phi)^2}_{\text{red bracket}} + \dots$$

agrees with
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Pirsa: 08030072

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Mesons stable

$$\Gamma \sim 1/N_c$$

Page 83/148

Gauge/Gravity thermodynamics:

Gauge theory thermodynamics = Black hole thermodynamics

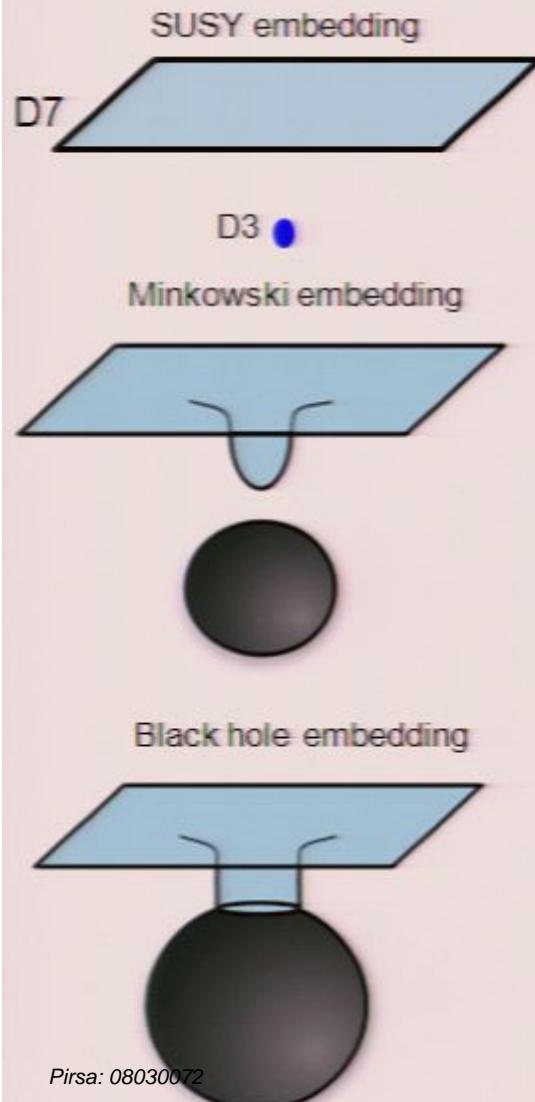
- Replace SUSY D3-throat with throat of black D3-brane
- Wick rotate and use euclidean path integral techniques
-

Here 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”

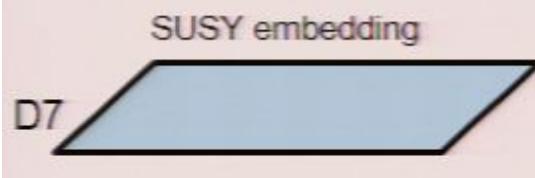
raise T : horizon expands and increased gravity
pulls brane towards BH horizon

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

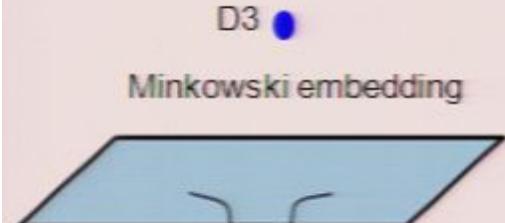
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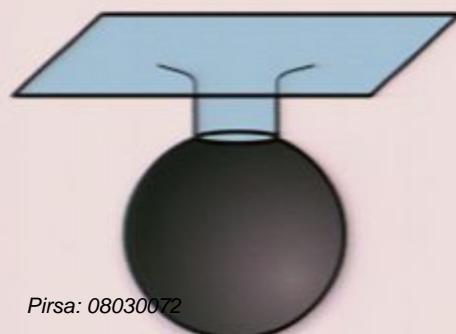
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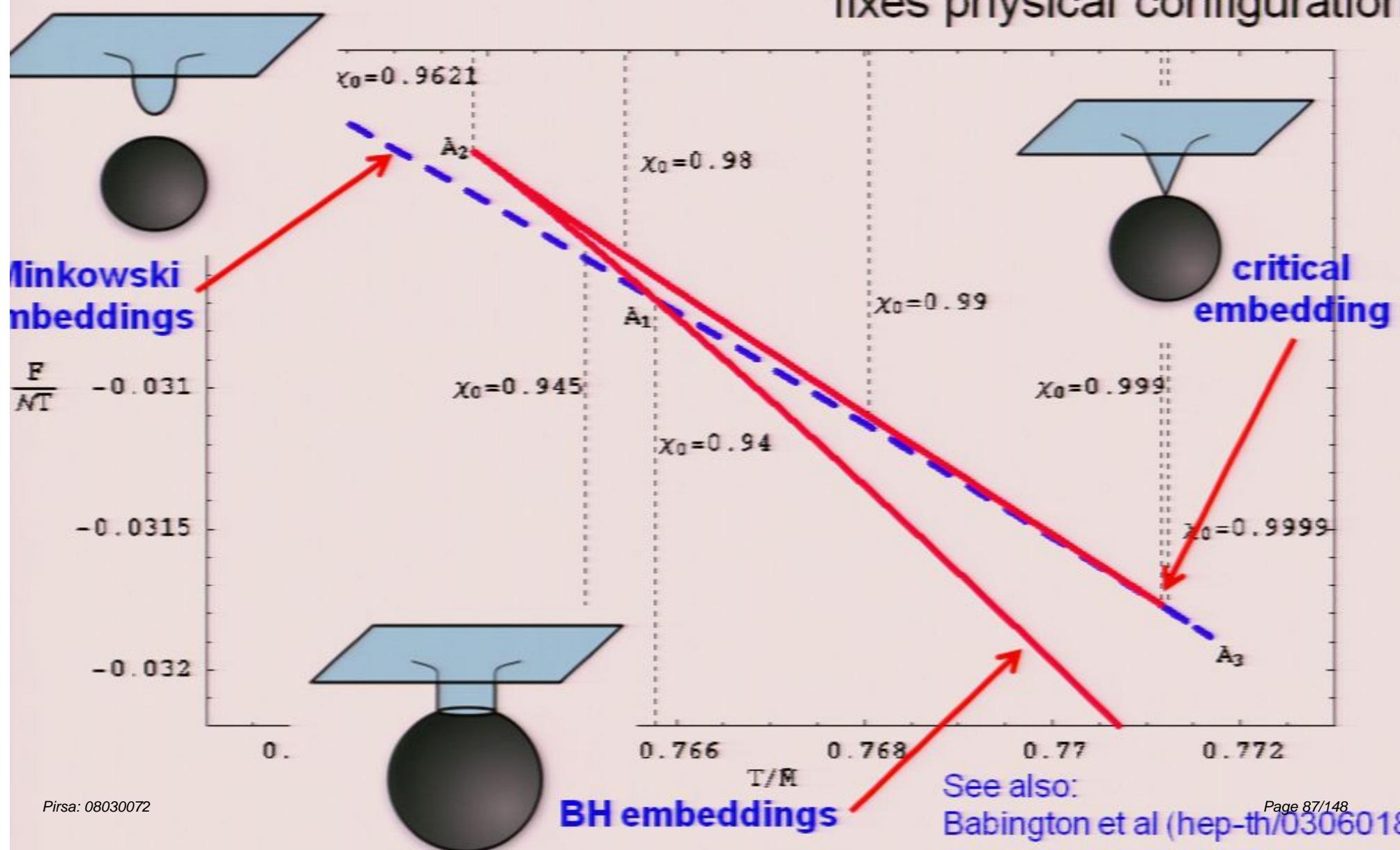
Phase transition[†]



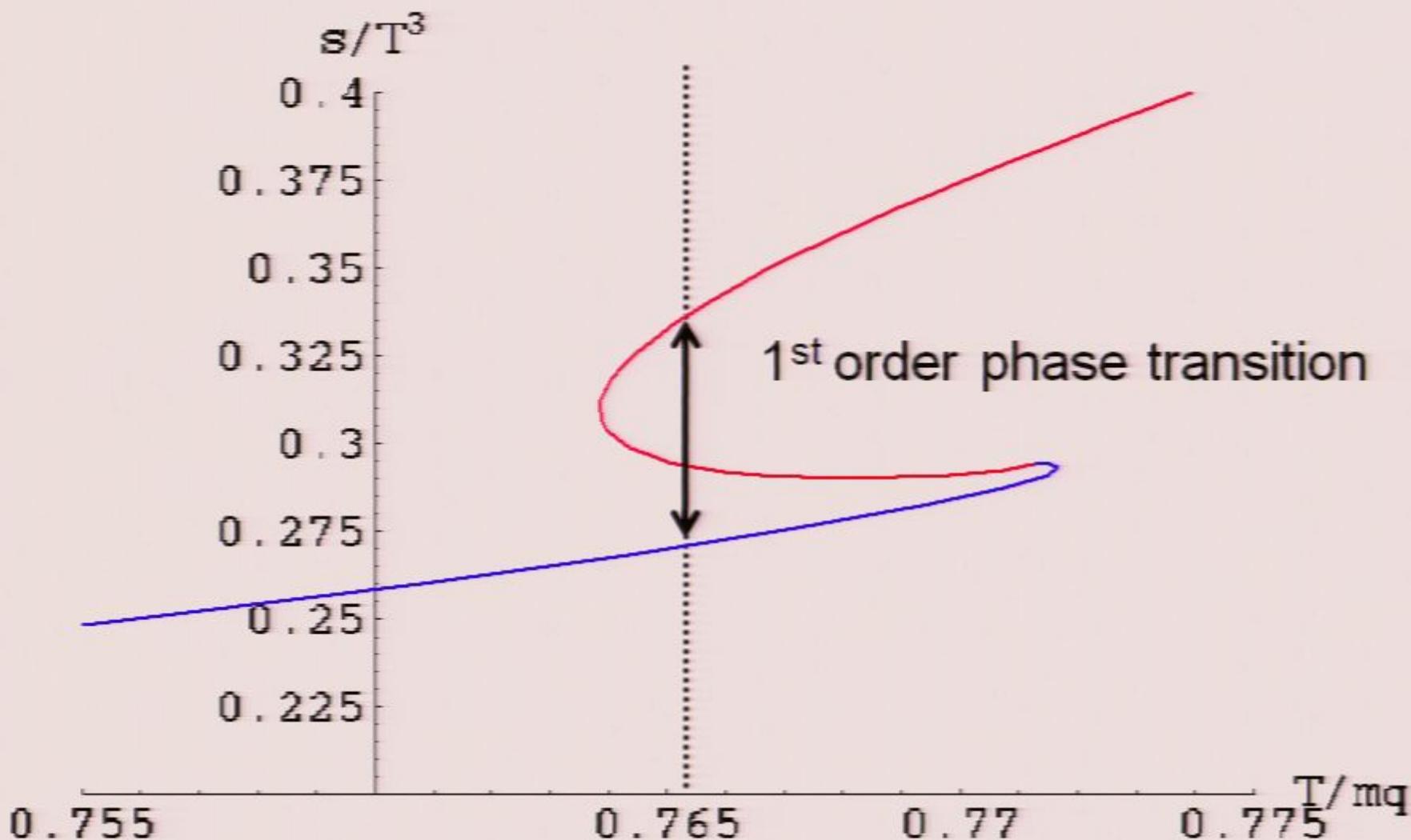
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physical properties of thermal system are multi-valued

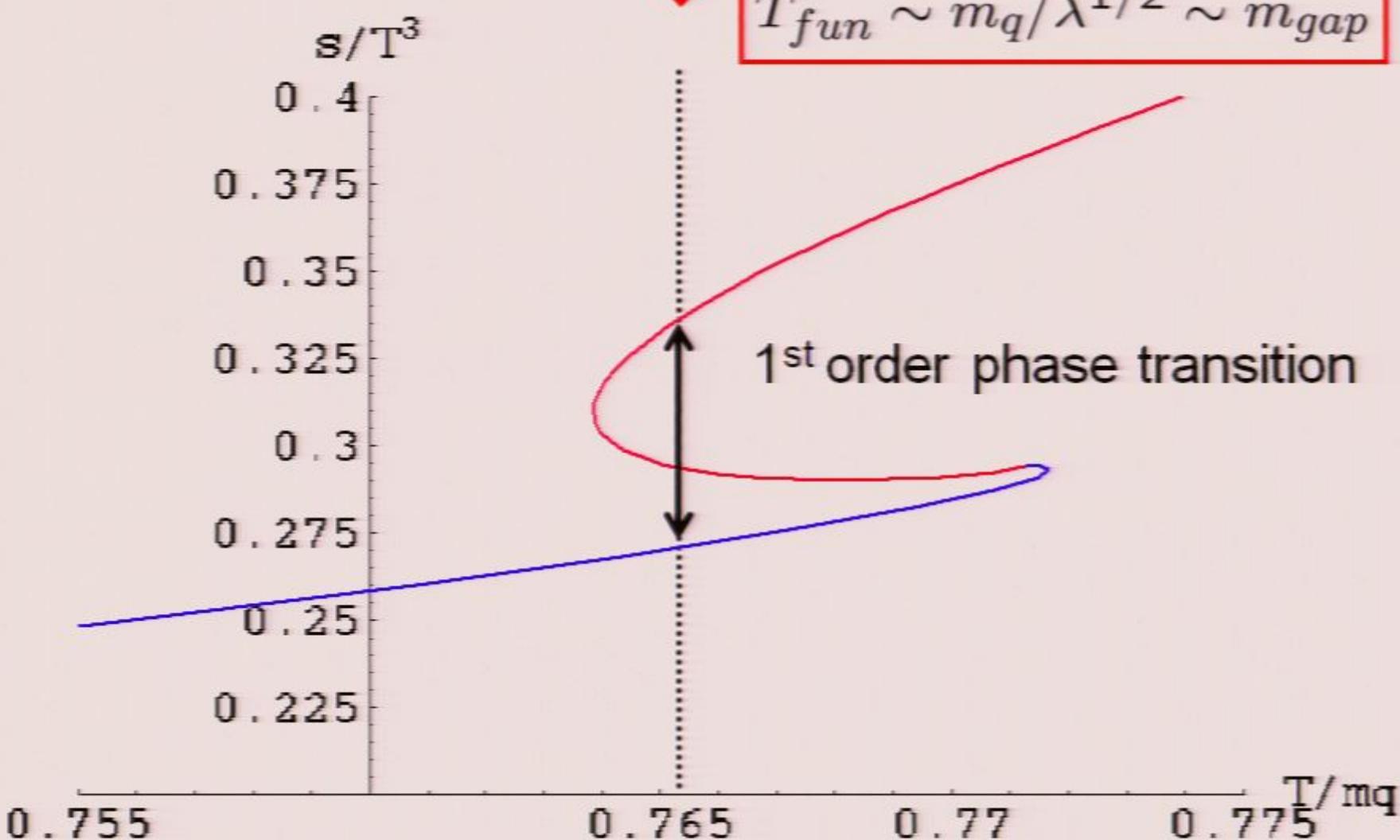
→ minimizing free energy (euclidean brane action) fixes physical configuration



Brane entropy:

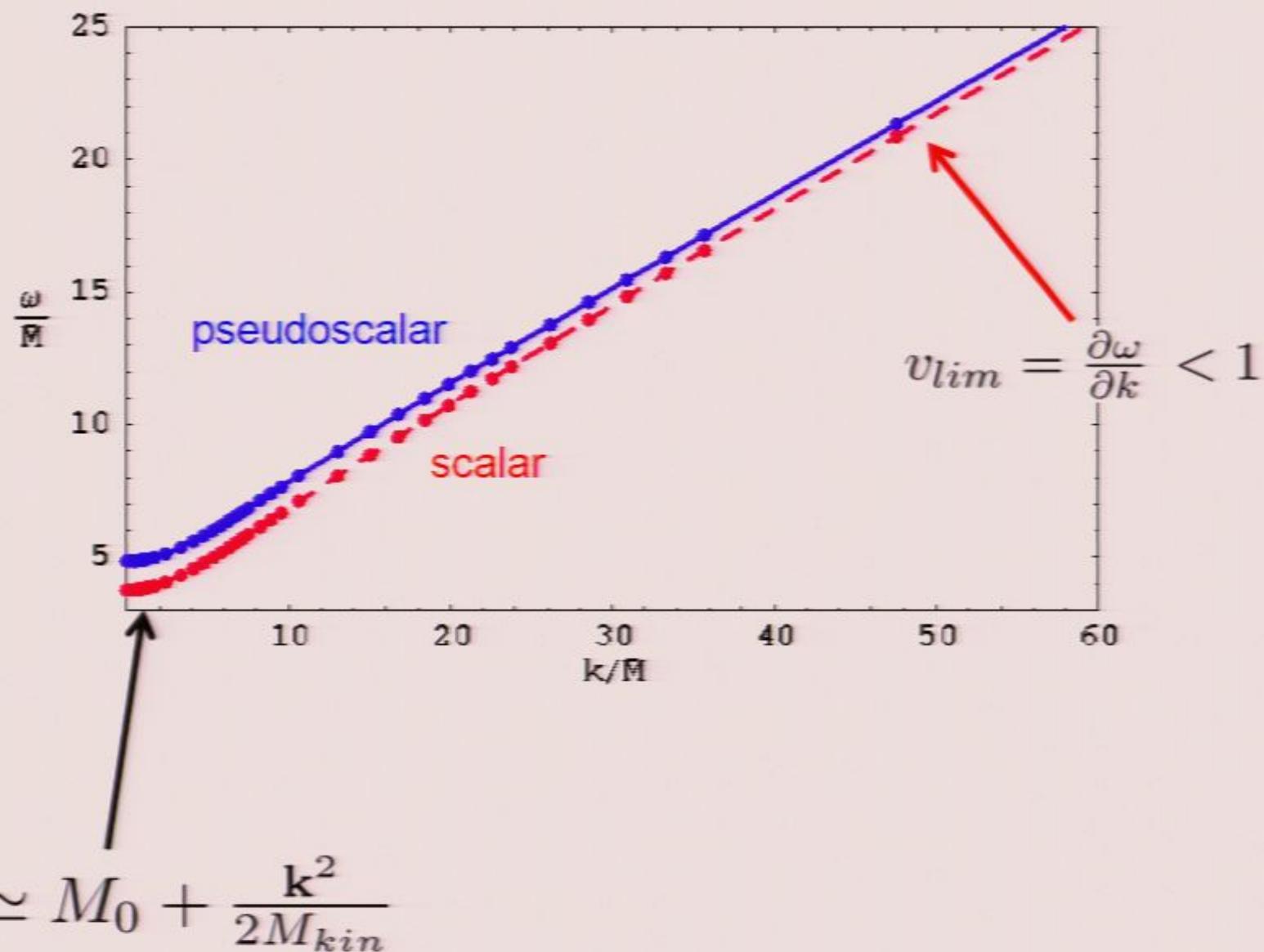


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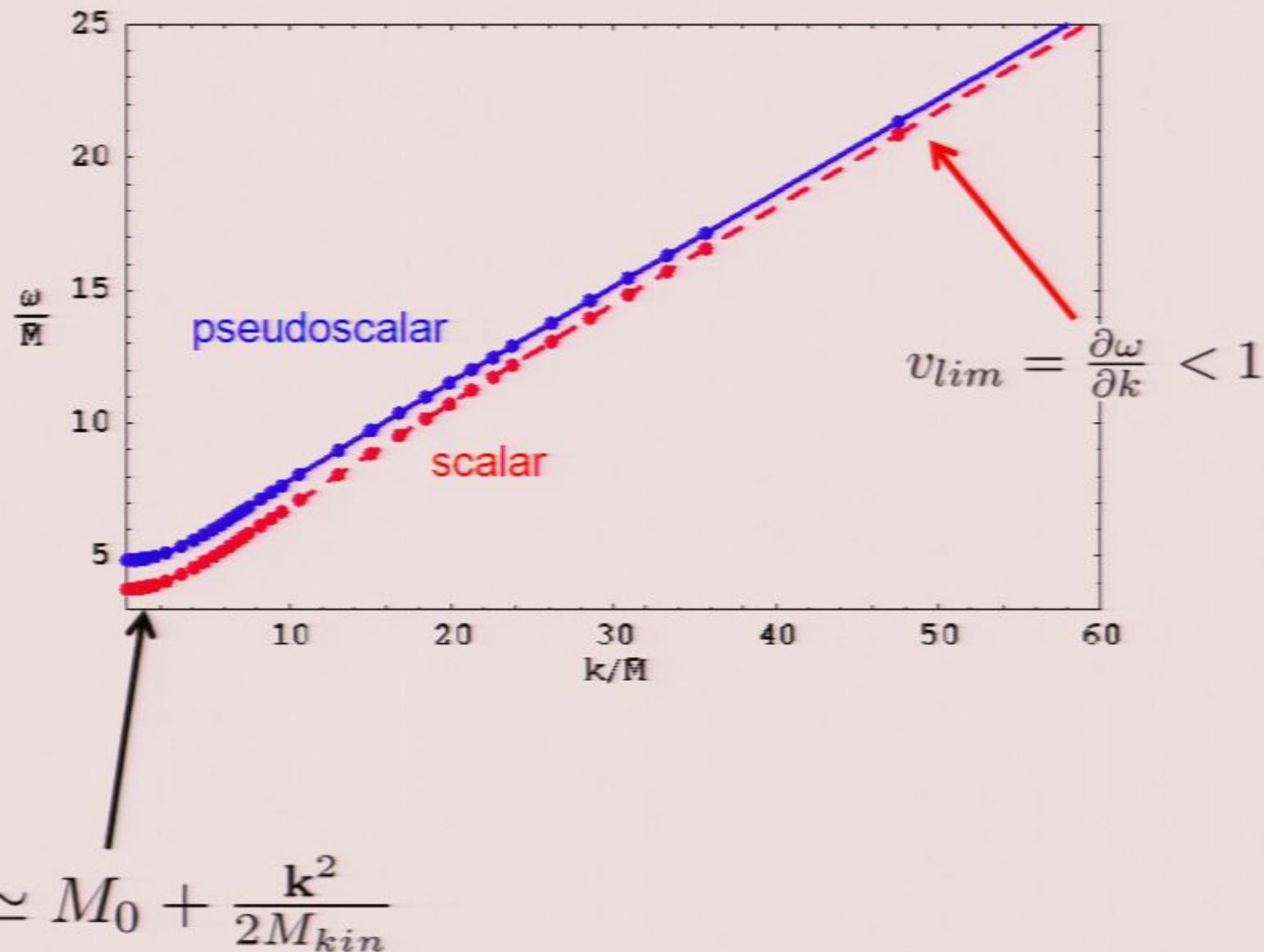
Mesons in Motion:

Mateos, RCM & Thomson [hep-th/0701132]
Ejaz, Faulkner, Liu, Rajagopal & Wiedemann [arXiv:0712.0590]



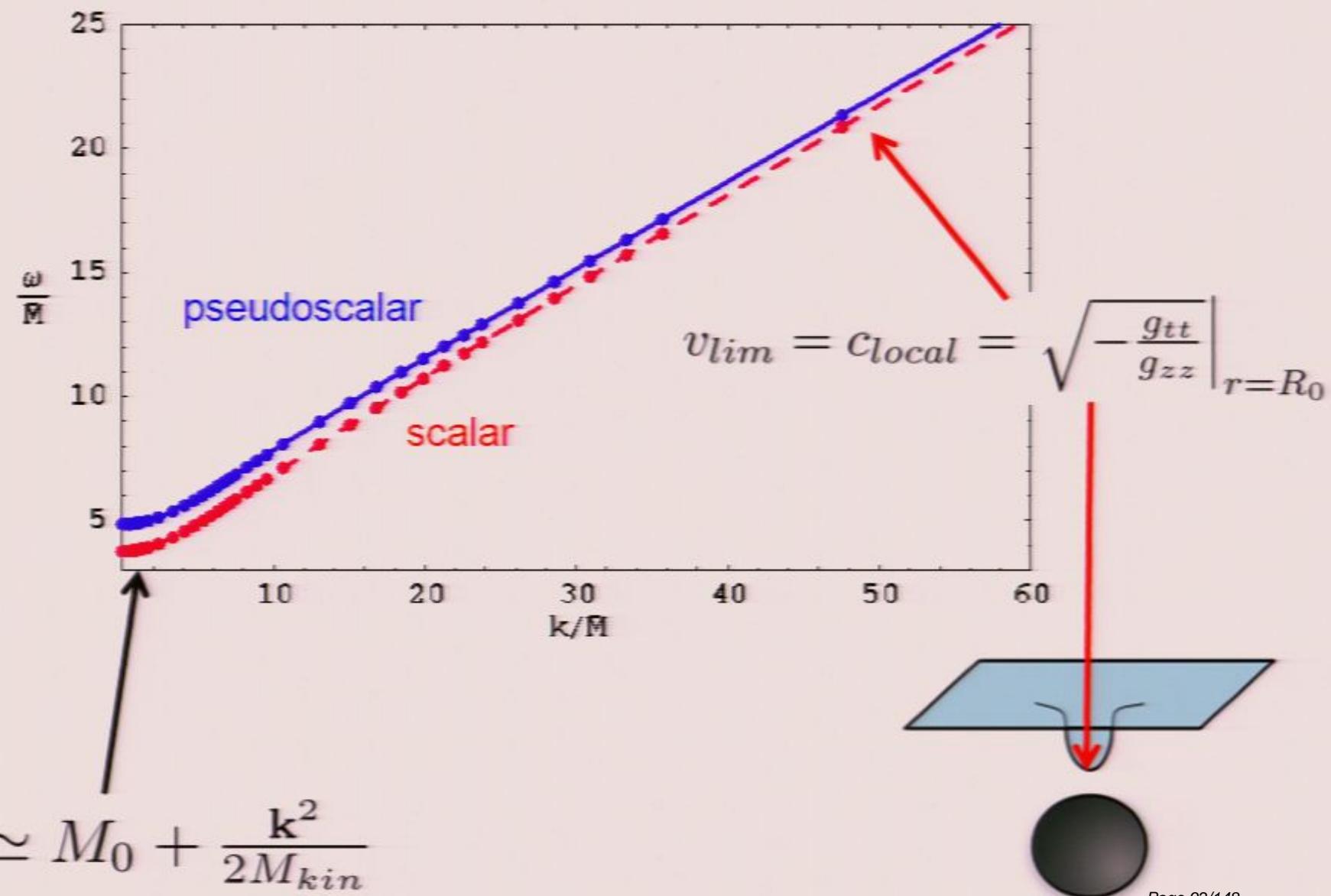
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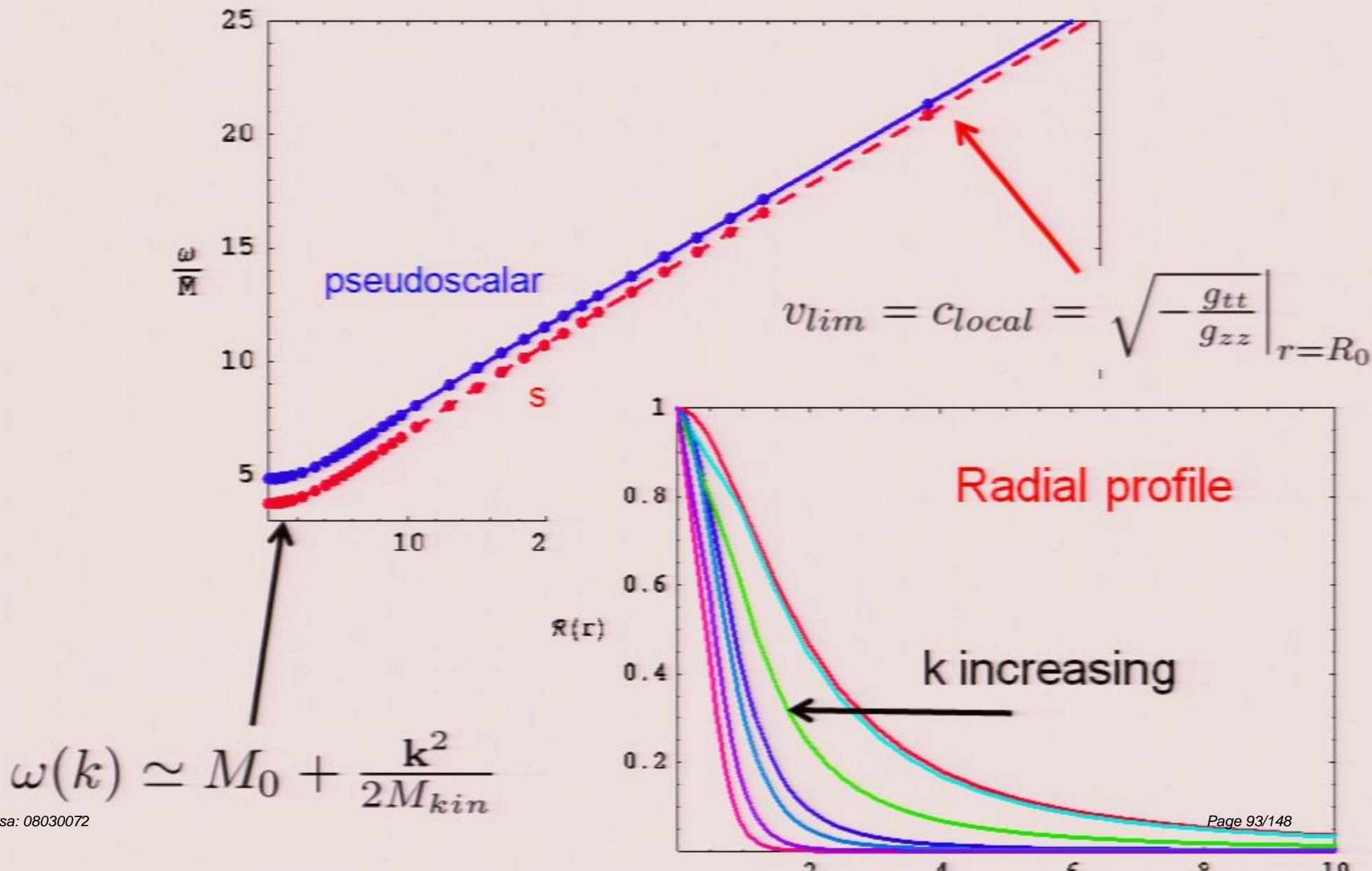
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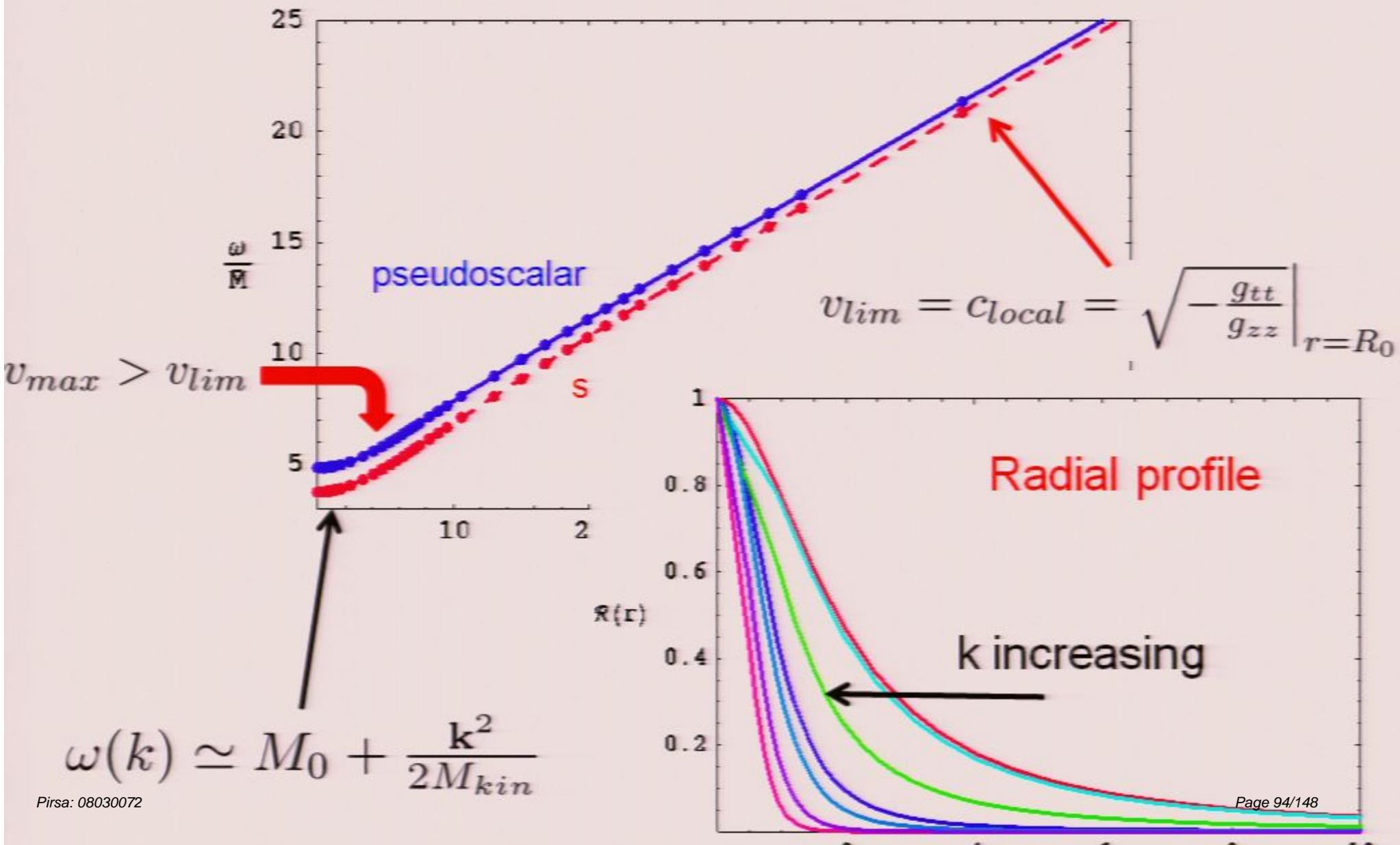
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- lattice QCD indicates heavy quark bound states persist above T_c

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

Asakawa & Hatsuda [hep-lat/0308034]

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

In experiments (eg, RHIC or LHC), these bound states are created with finite (possibly large) momenta.

Does “speed limit” apply to heavy quark states in QCD?

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

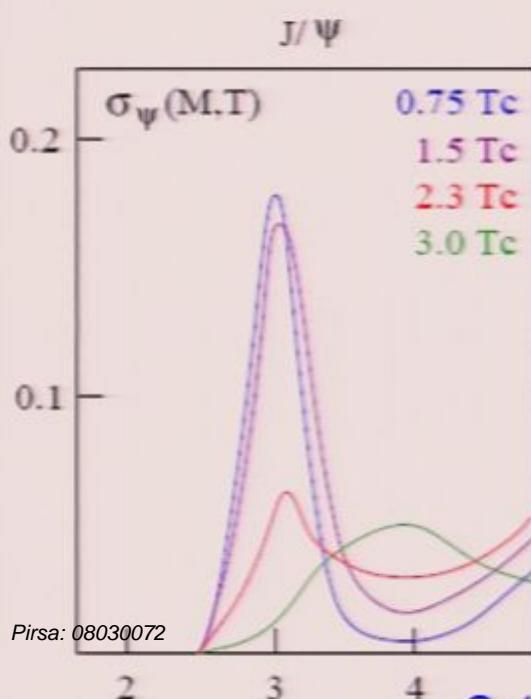
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J/ψ 's have finite width!

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”

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

- simple poles in retarded correlator:

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

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

“quasi-particle” if $\Gamma \ll \Omega$

- characteristic high “frequency” tail:

$$\lim_{(t^2 - \mathbf{x}^2) \rightarrow 0} \langle \mathcal{O}(t, \mathbf{x}) \mathcal{O}(0) \rangle = \frac{\mathcal{A}}{|t^2 - \mathbf{x}^2|^\Delta} + \dots \xrightarrow{\text{red arrow}} \chi \sim \mathcal{A} (\omega^2 - k^2)^{\Delta-2}$$

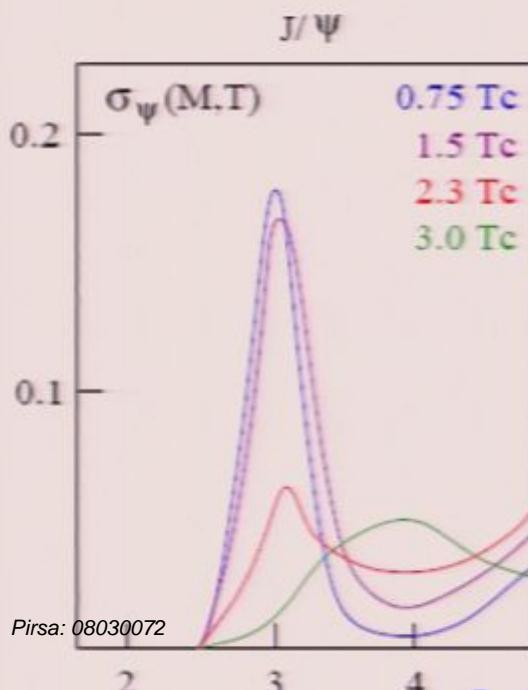
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$$\Upsilon (\bar{b}b) : T_{dissoc} \simeq 3.6 T_c$$

Asakawa & Hatsuda [hep-lat/0308034]

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



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”

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

- simple poles in retarded correlator:

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

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

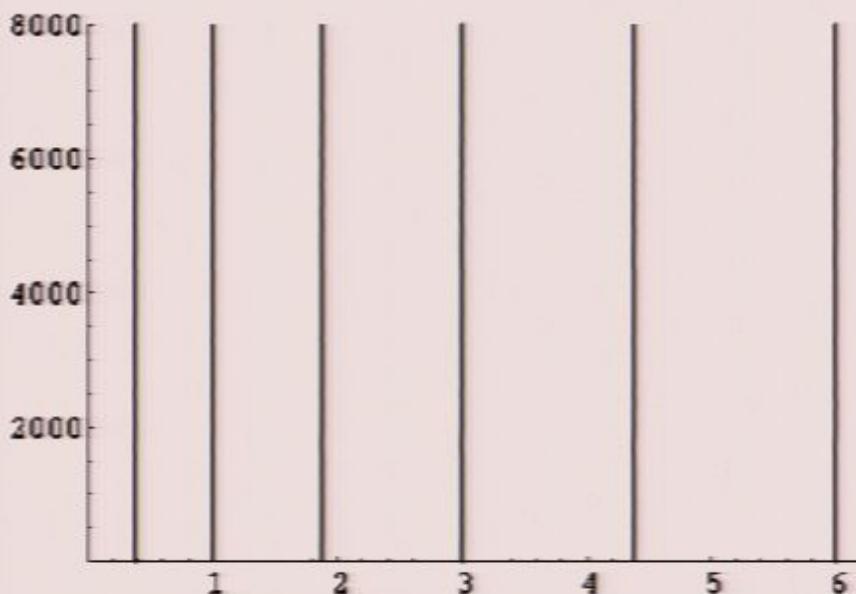
“quasi-particle” if $\Gamma \ll \Omega$

- characteristic high “frequency” tail:

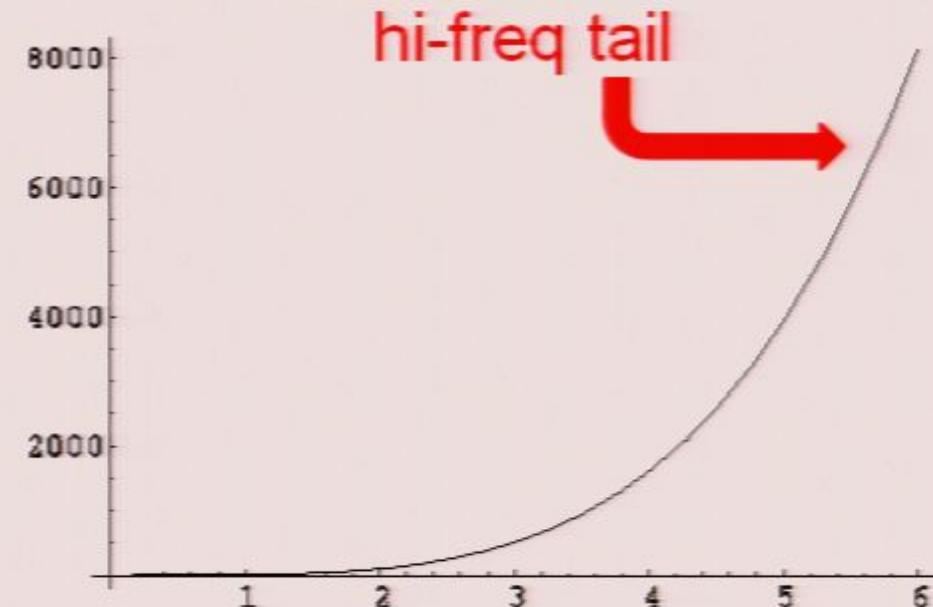
$$\lim_{(t^2 - \mathbf{x}^2) \rightarrow 0} \langle \mathcal{O}(t, \mathbf{x}) \mathcal{O}(0) \rangle = \frac{\mathcal{A}}{|t^2 - \mathbf{x}^2|^\Delta} + \dots \xrightarrow{\text{red arrow}} \chi \sim \mathcal{A} (\omega^2 - k^2)^{\Delta-2}$$

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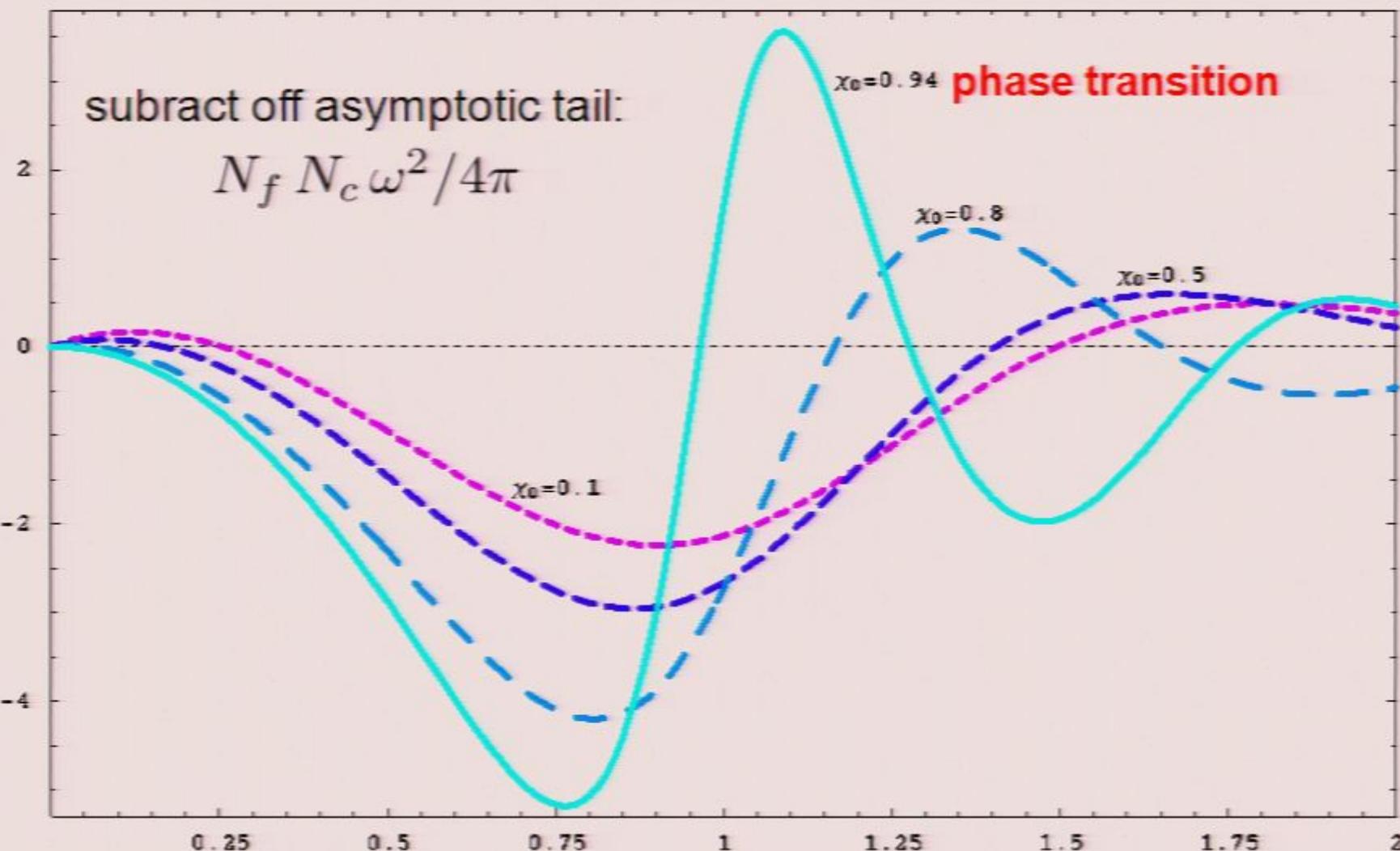


discrete spectrum;
low temperature Mink. phase



continuous spectrum;
high temperature BH phase

Thermal spectral function:

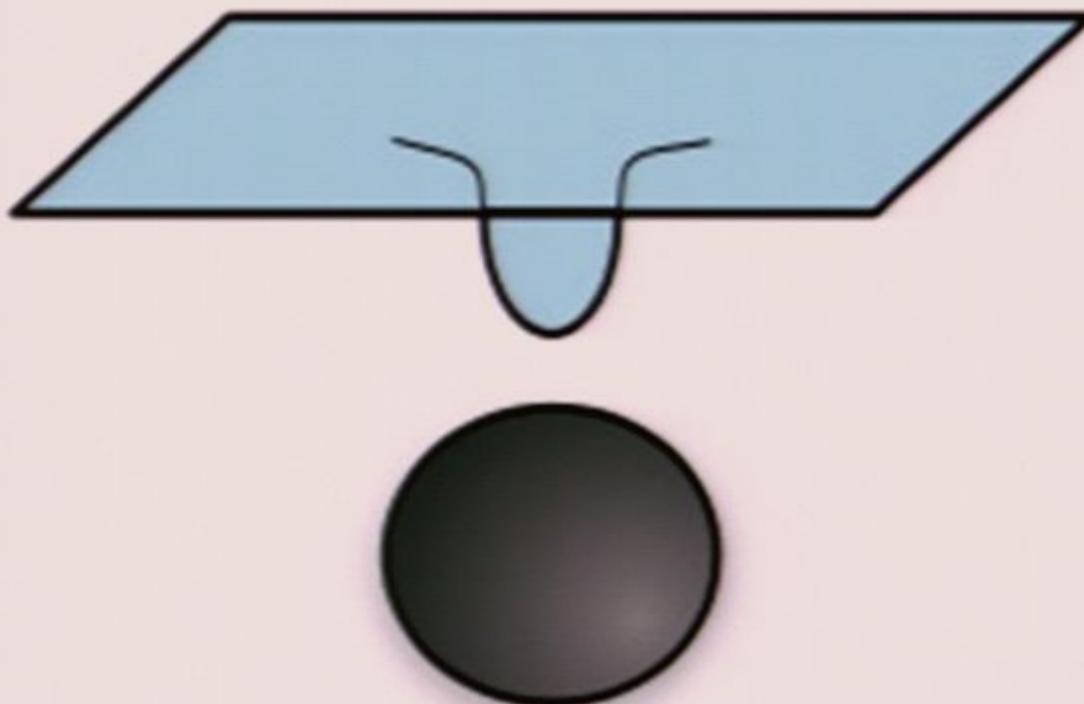


- approaching phase transition, structure builds
→ quasinormal frequencies approach real axis

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: $A_\mu \leftrightarrow J_\mu \simeq [\bar{\psi} \gamma_\mu \psi + \Phi D_\mu \Phi]$



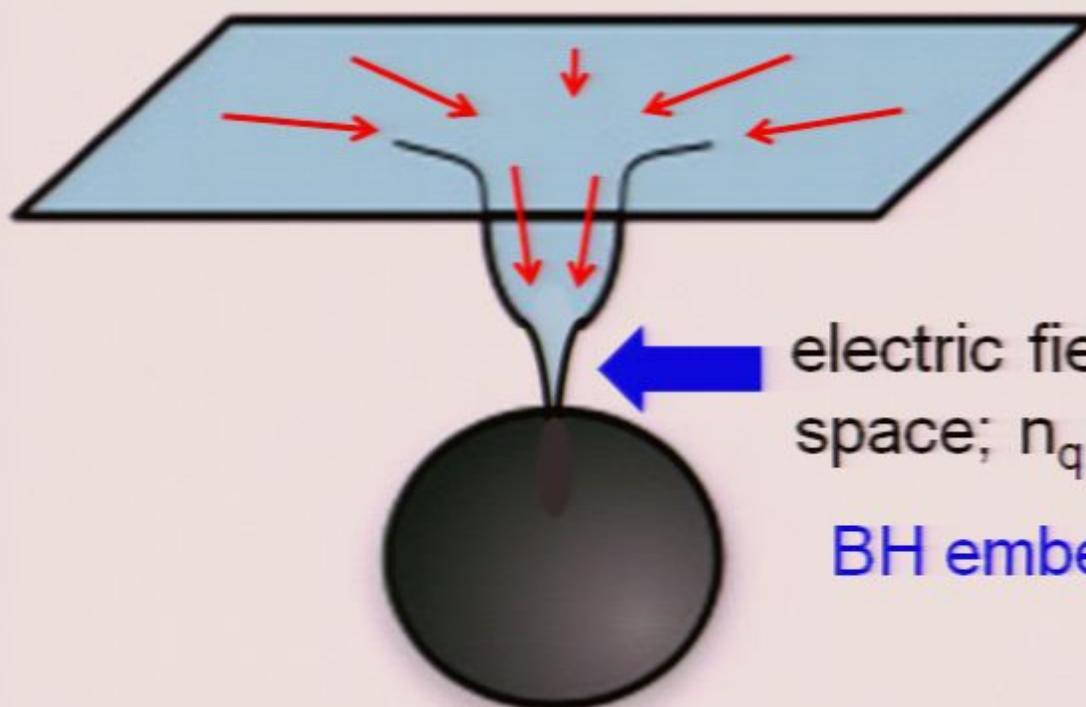
asymptotically ($\rho \rightarrow \infty$):

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

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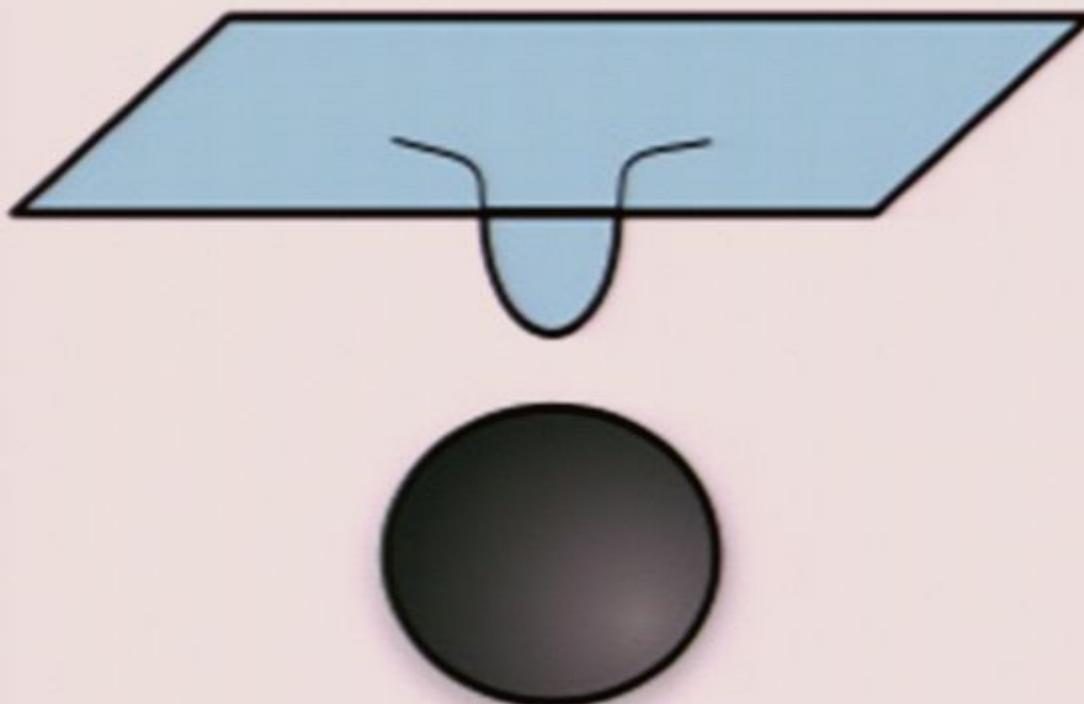
electric field lines can't end in empty space; n_q produces neck

BH embedding with tunable horizon

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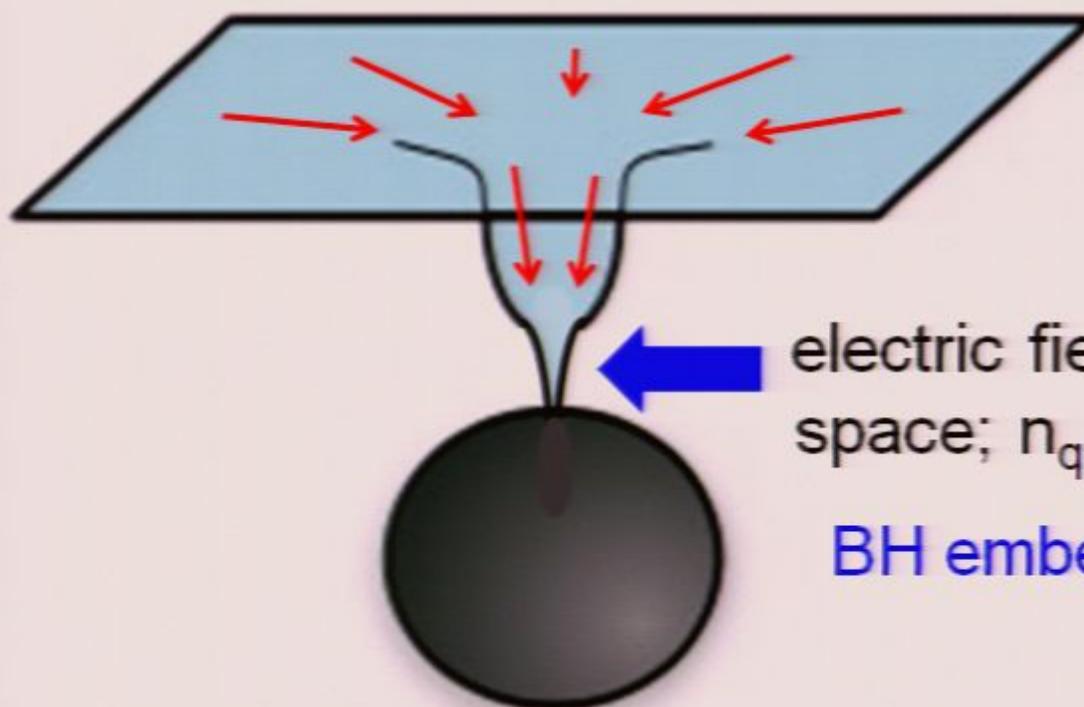
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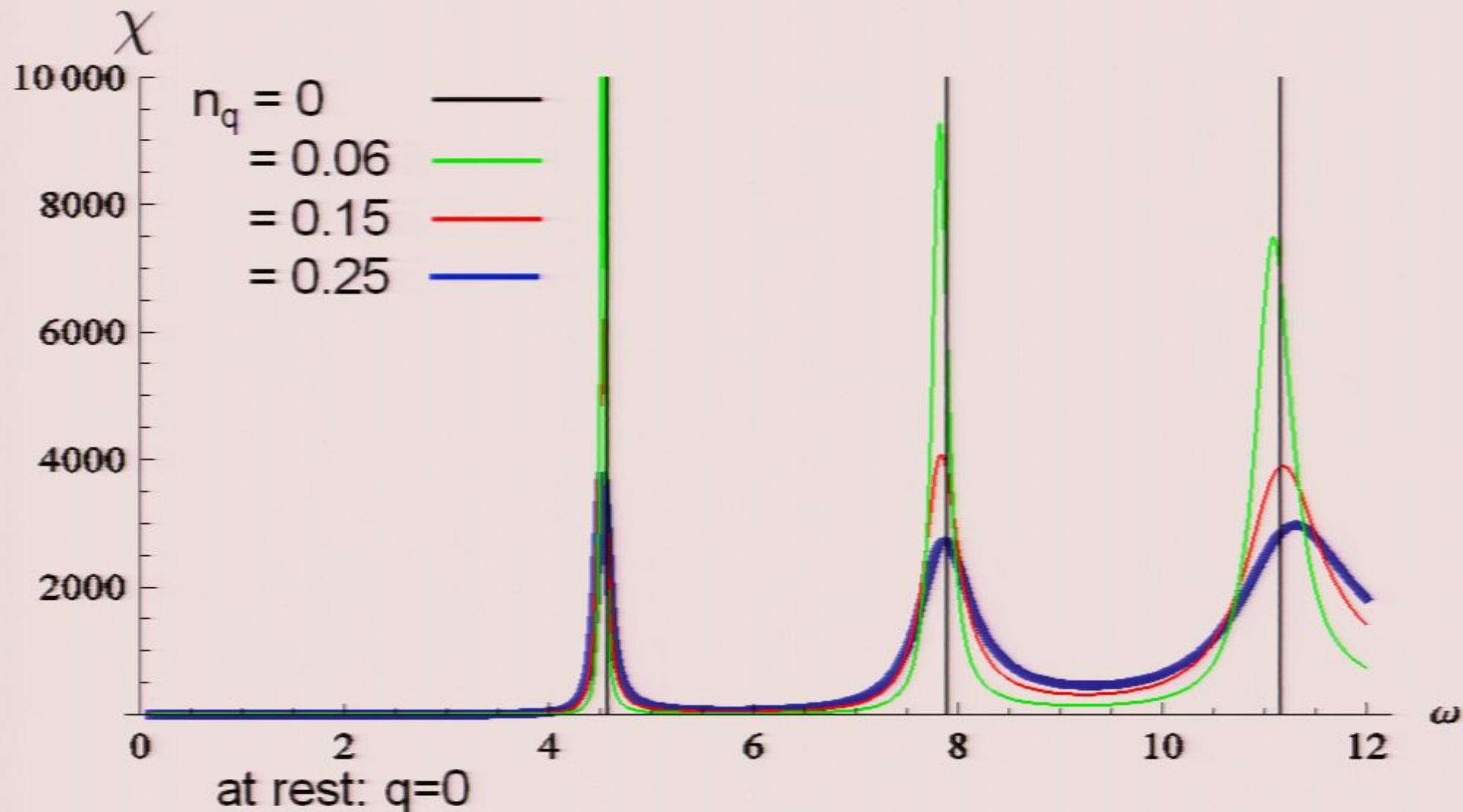
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Spectral functions:

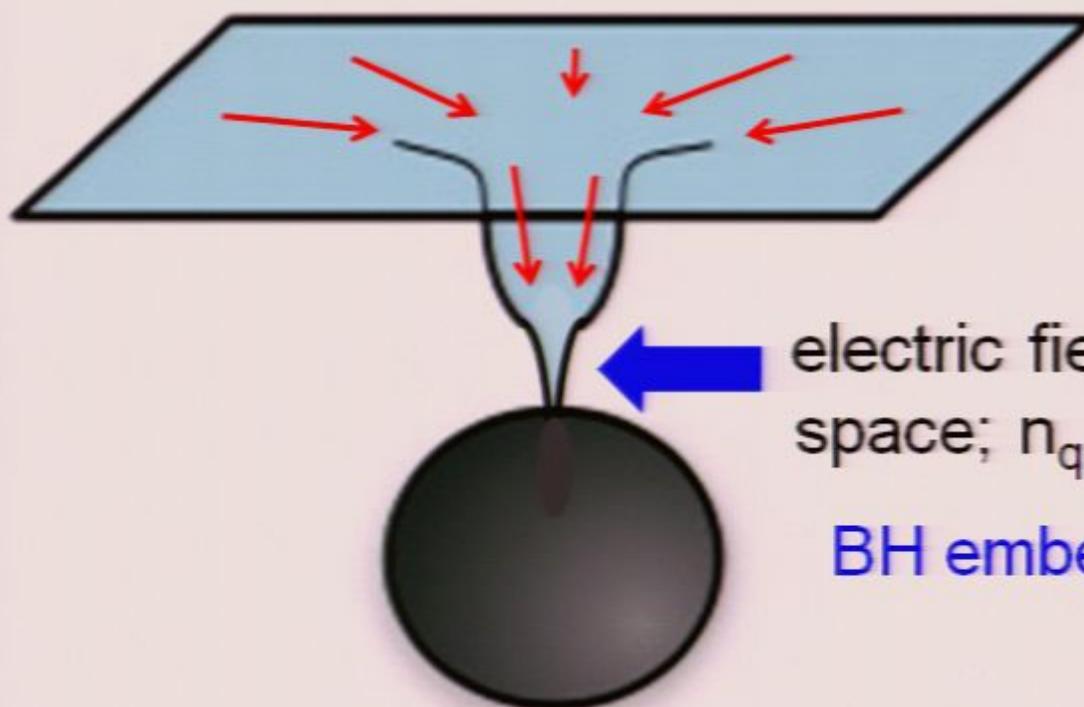
Increasing n_q , increases width of meson states



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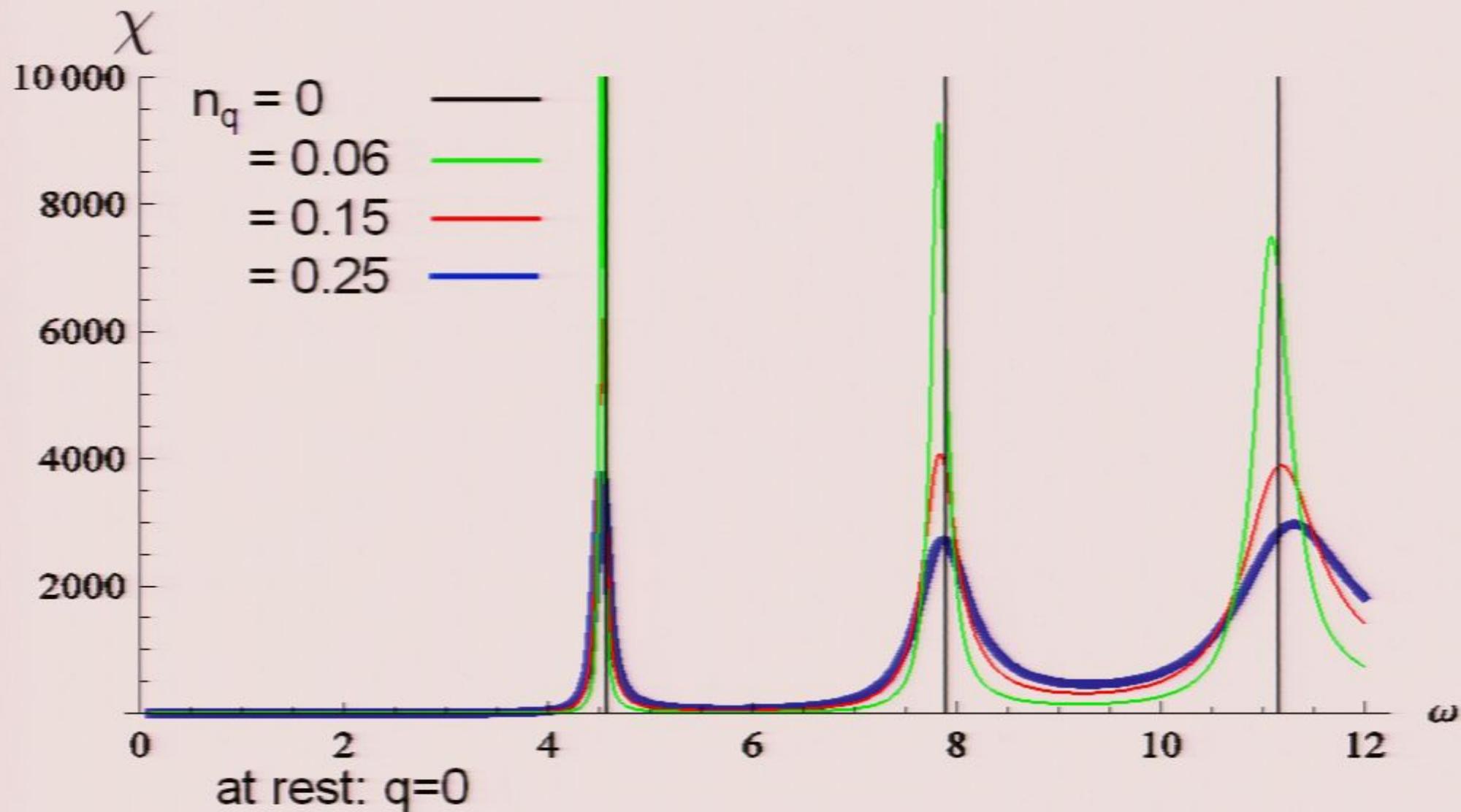
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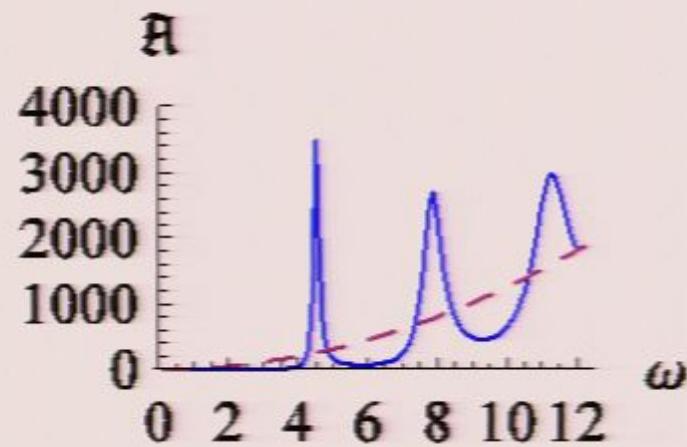


Spectral functions:

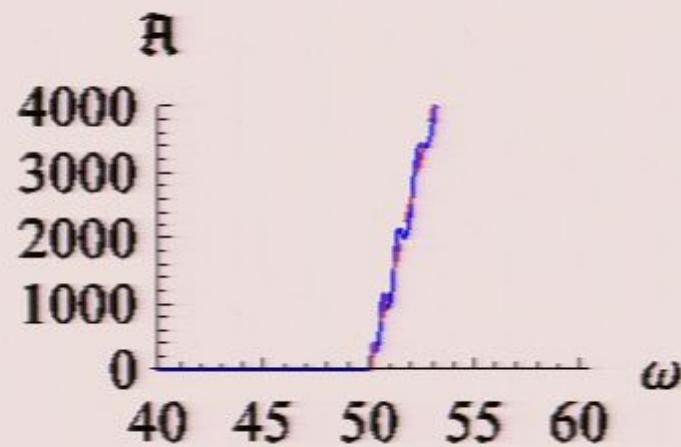
($n_q = 0.25$)

introduce nonvanishing momentum

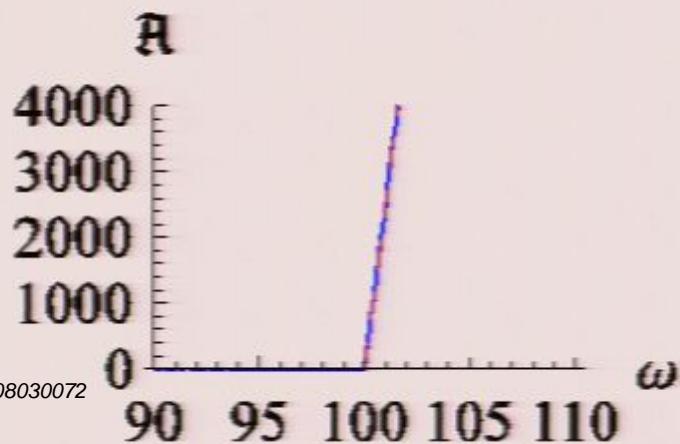
$q=0$



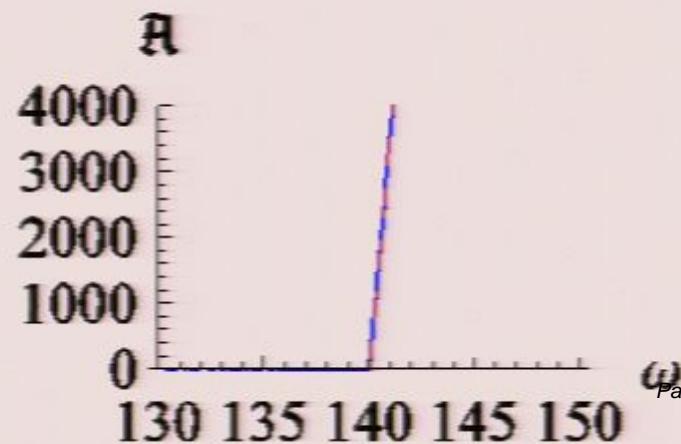
$q=50$



$q=100$



$q=140$

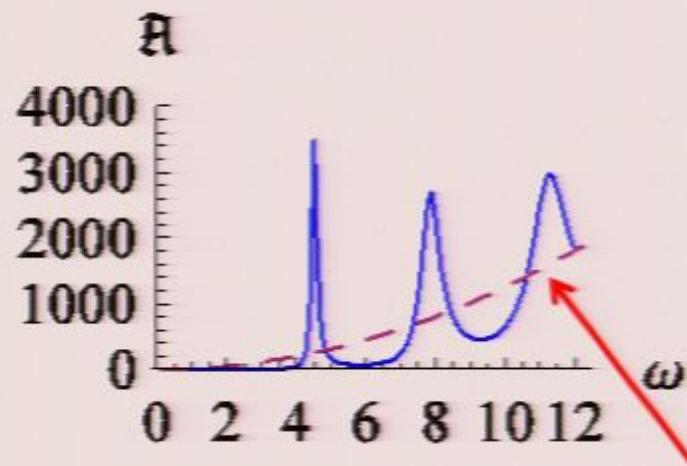


Spectral functions:

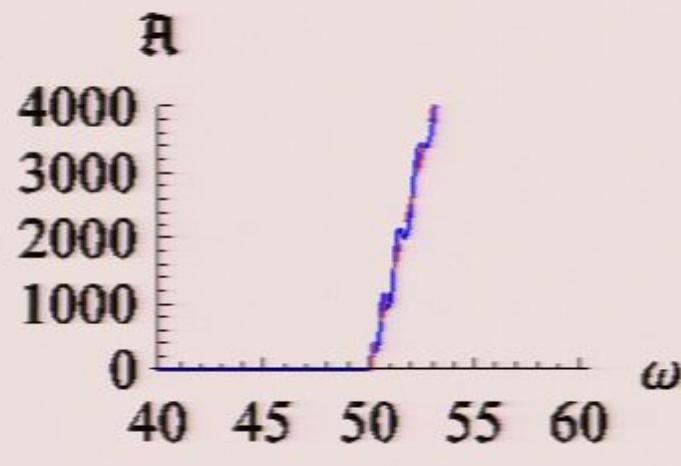
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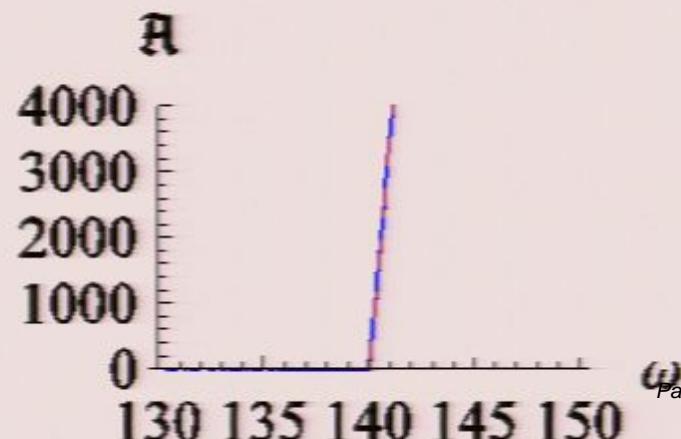
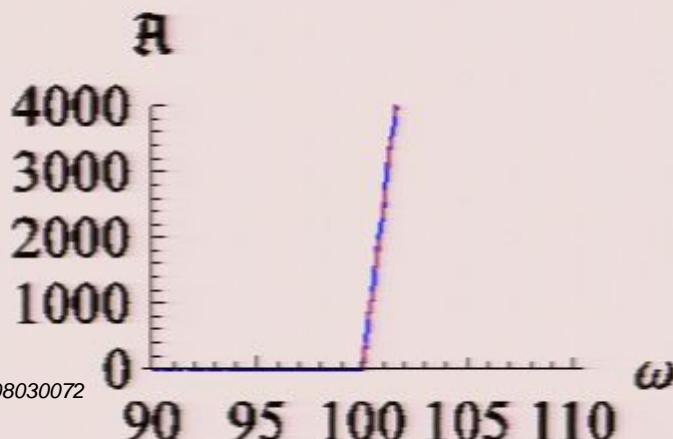
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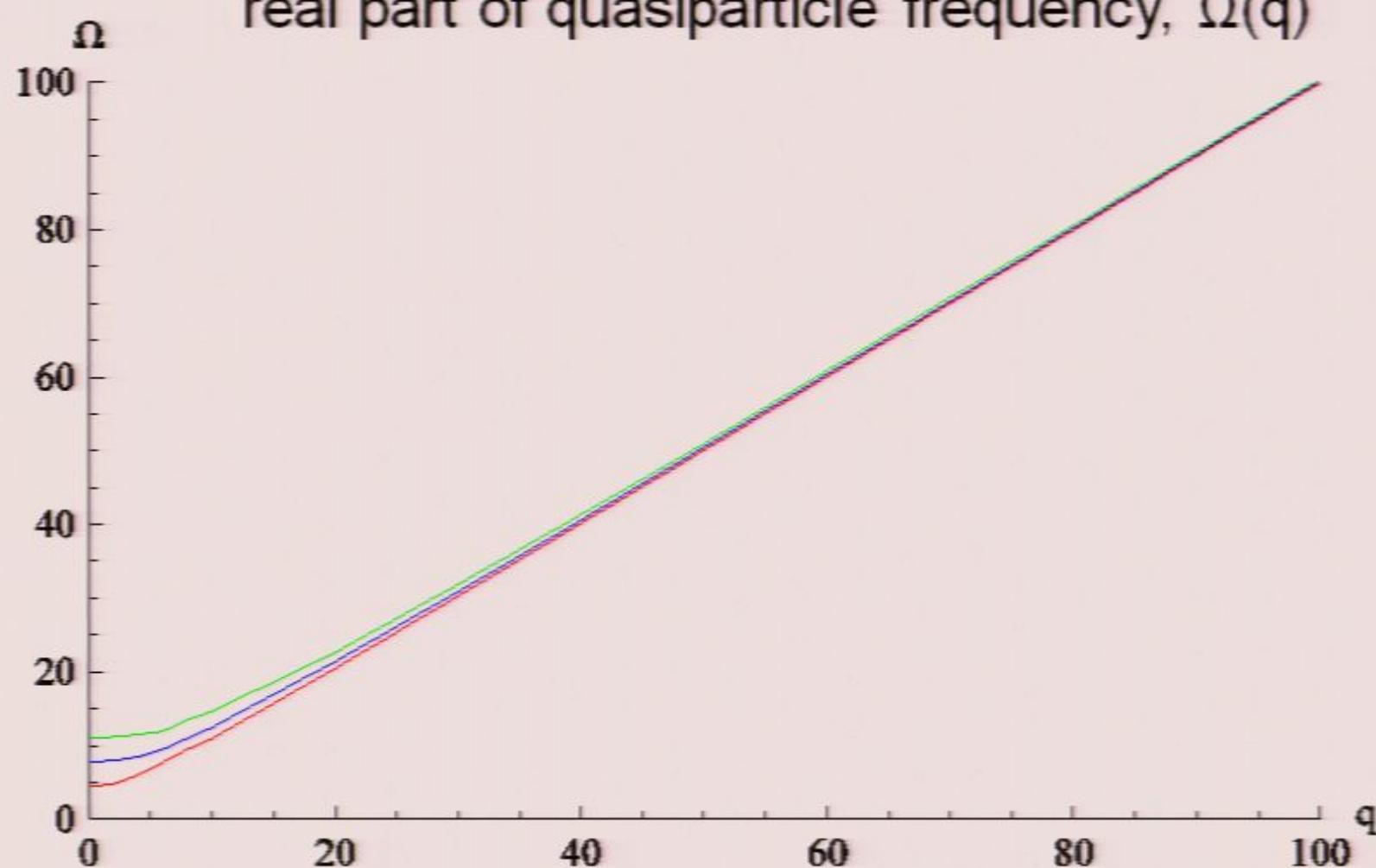


Spectral functions:

($n_q = 0.25$)

follow positions of peaks →

real part of quasiparticle frequency, $\Omega(q)$

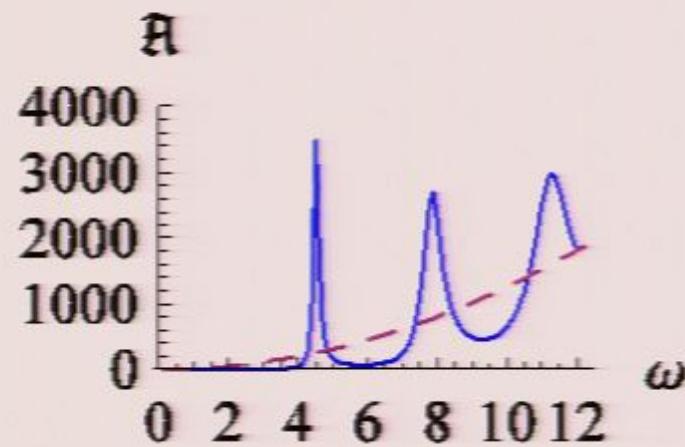


Spectral functions:

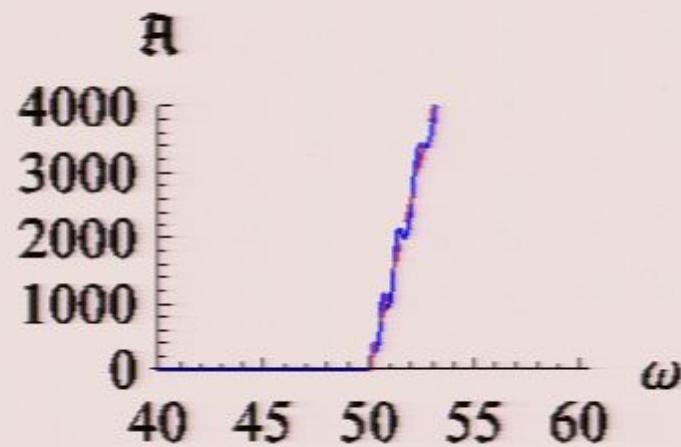
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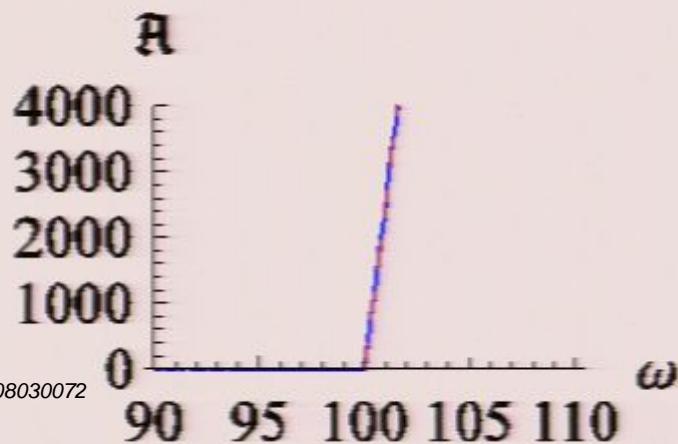
$q=0$



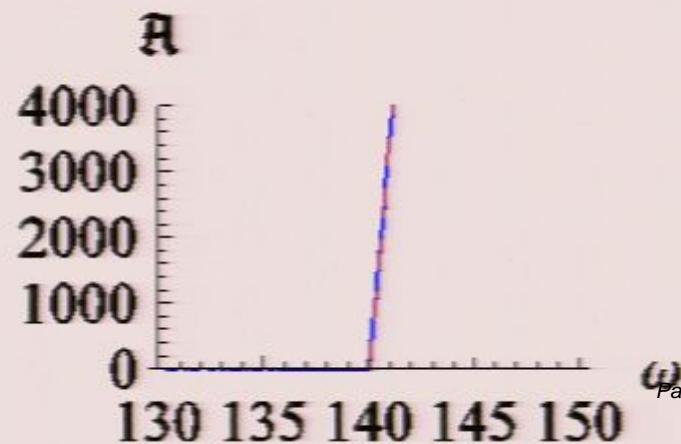
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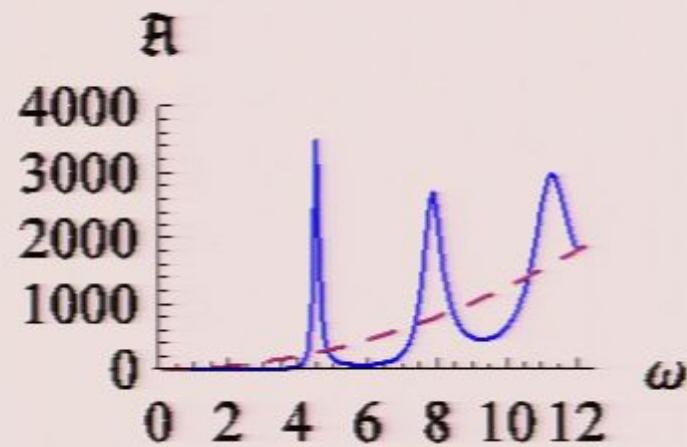


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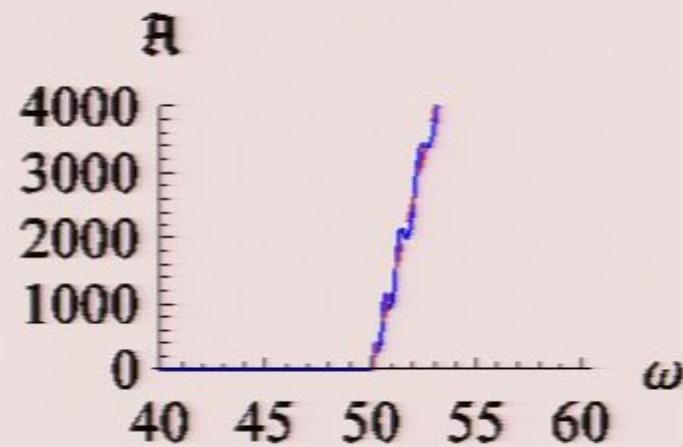
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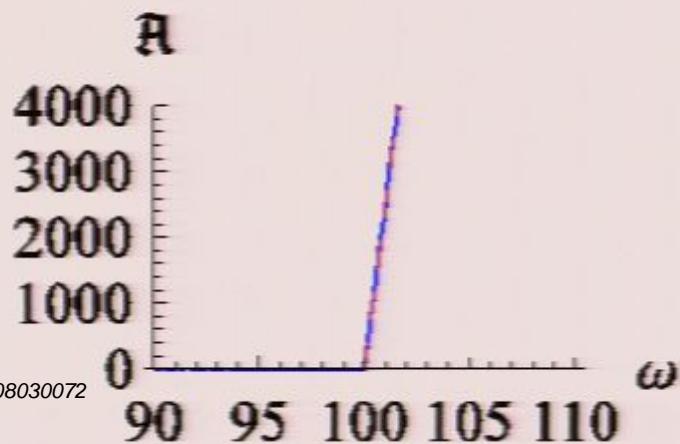
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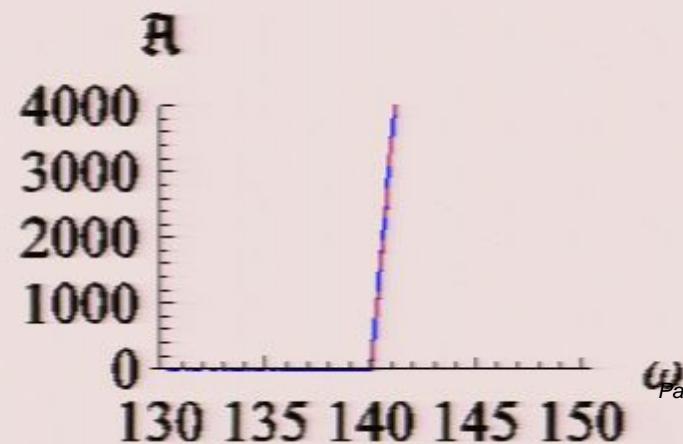
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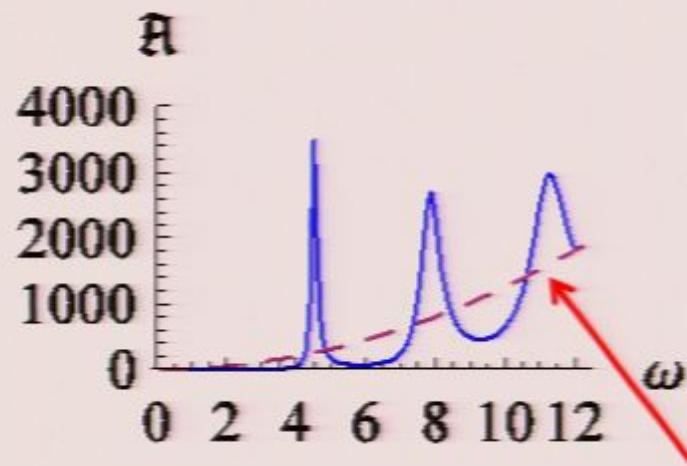


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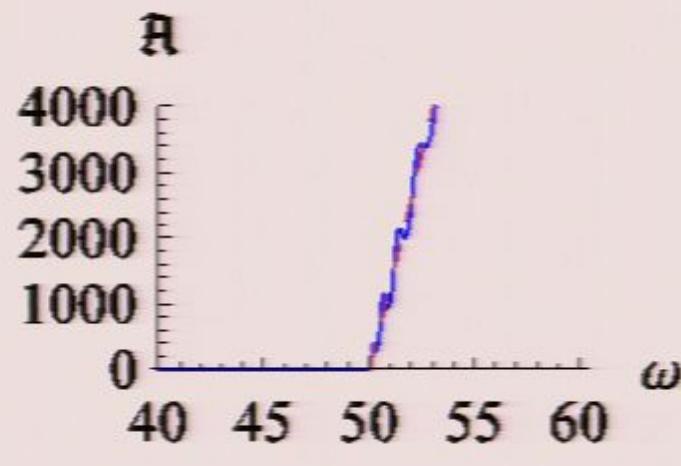
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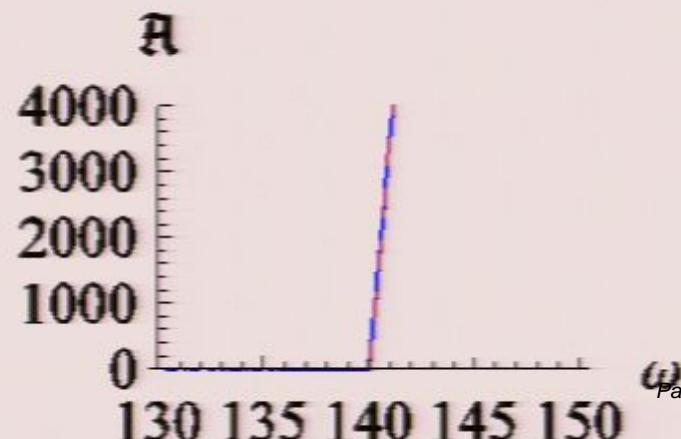
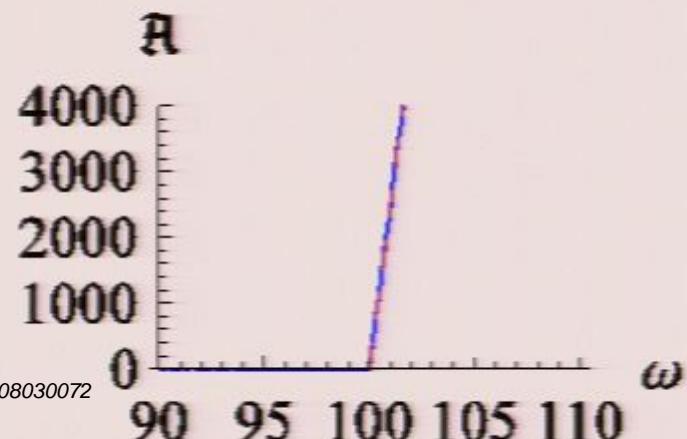
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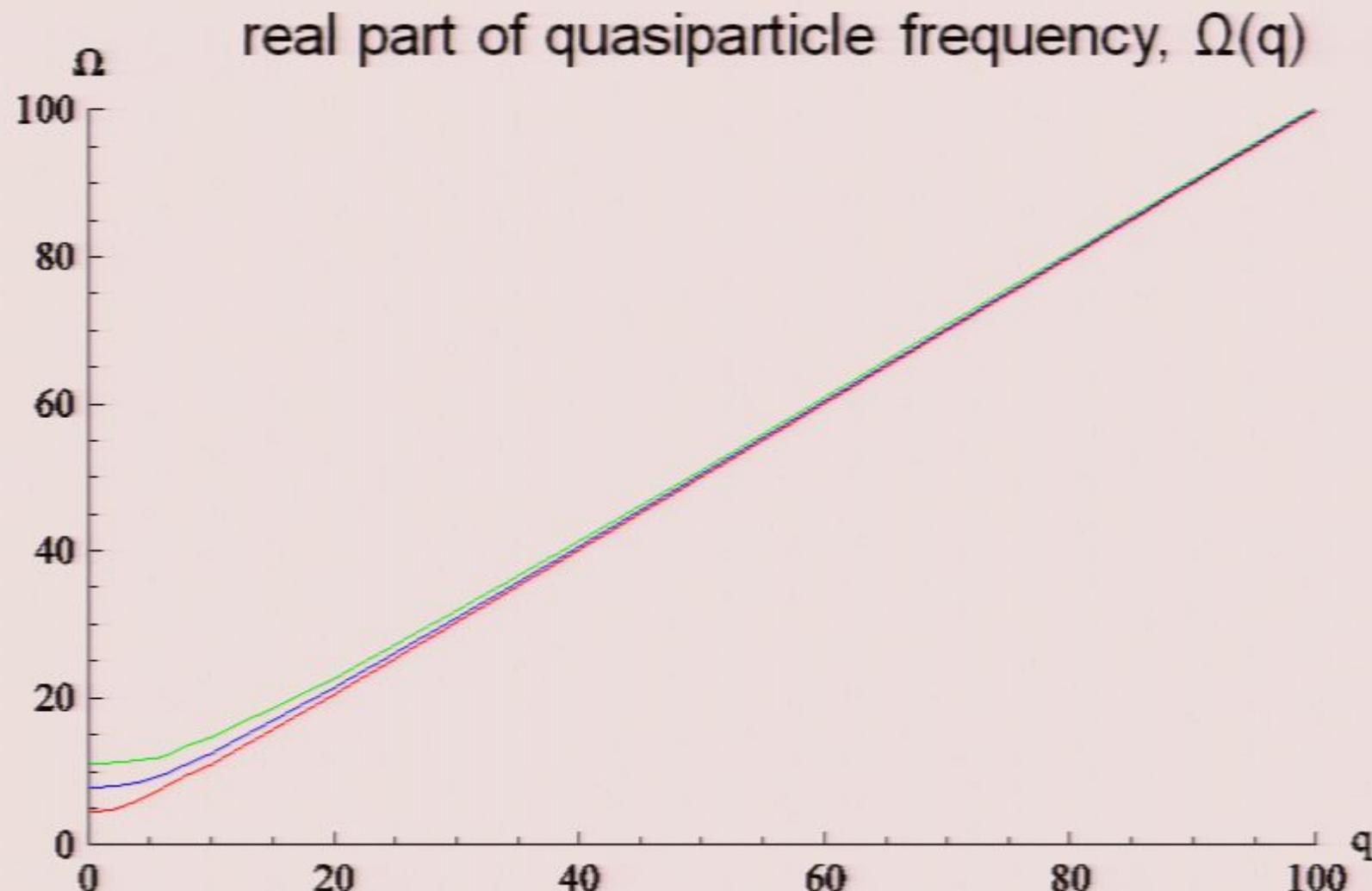
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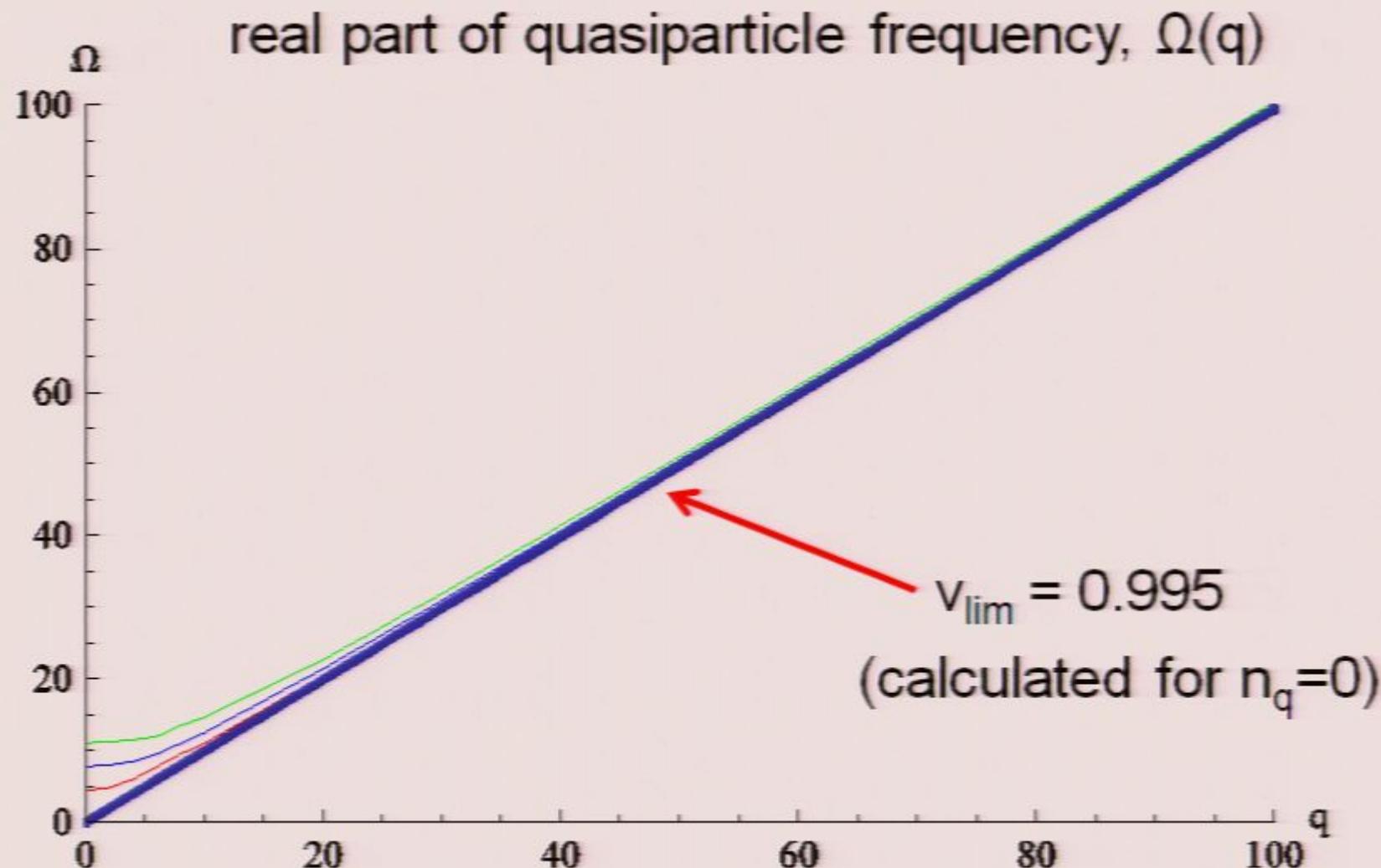
follow positions of peaks \longrightarrow



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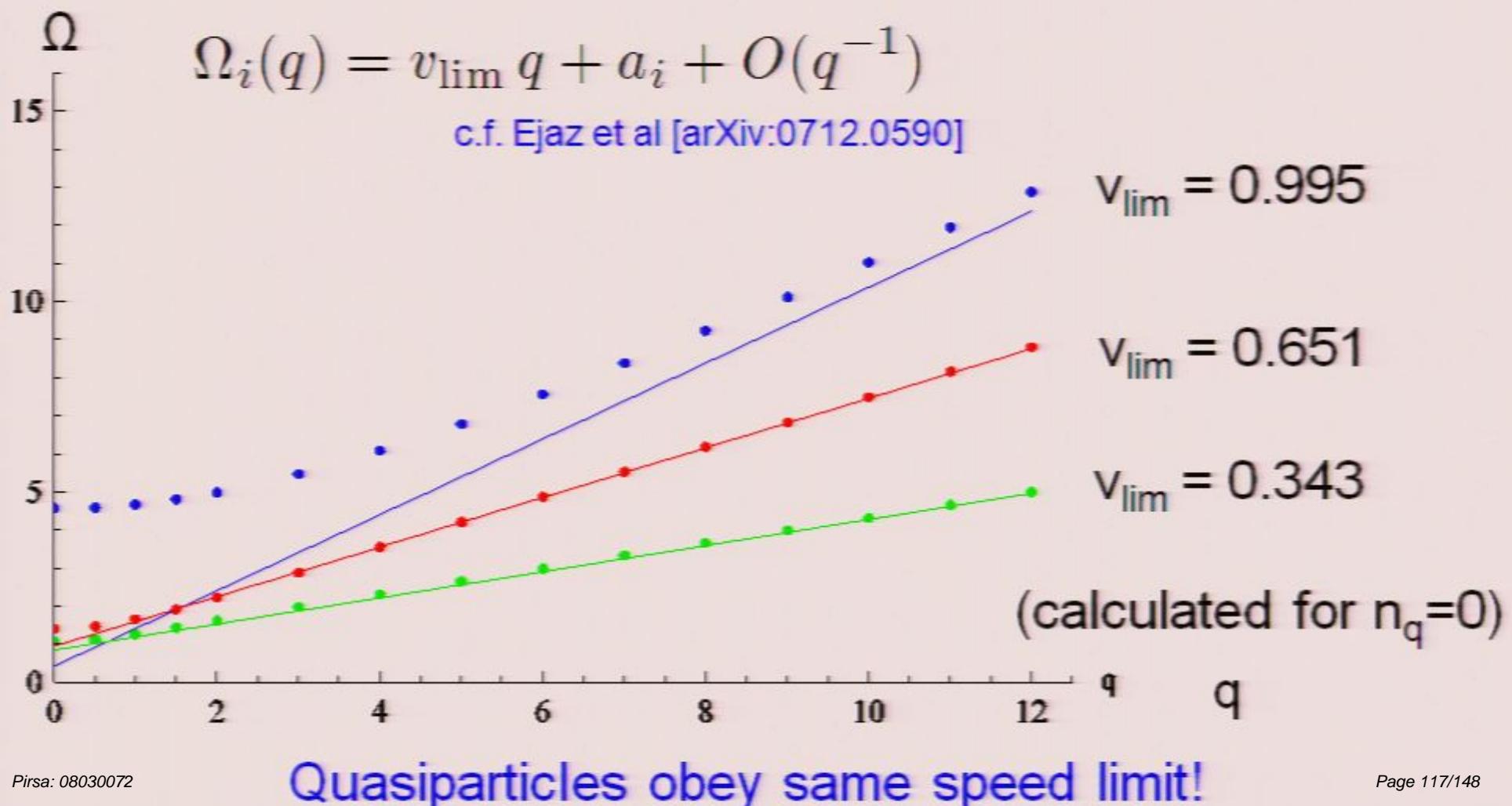
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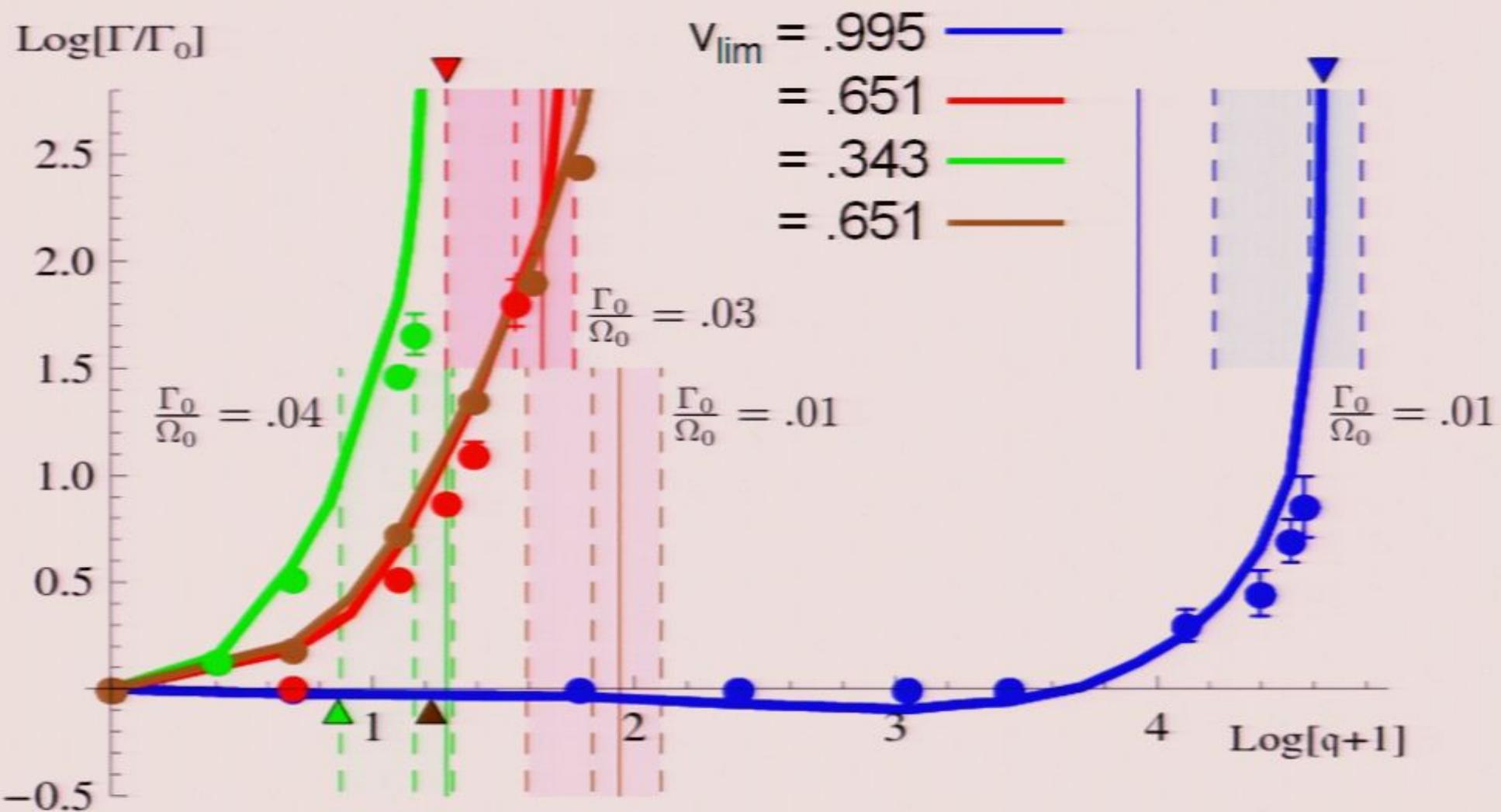
follow positions of peaks \longrightarrow

real part of quasiparticle frequency, $\Omega(q)$



follow widths of peaks →

imaginary part of quasiparticle frequency, $\Gamma(q)$



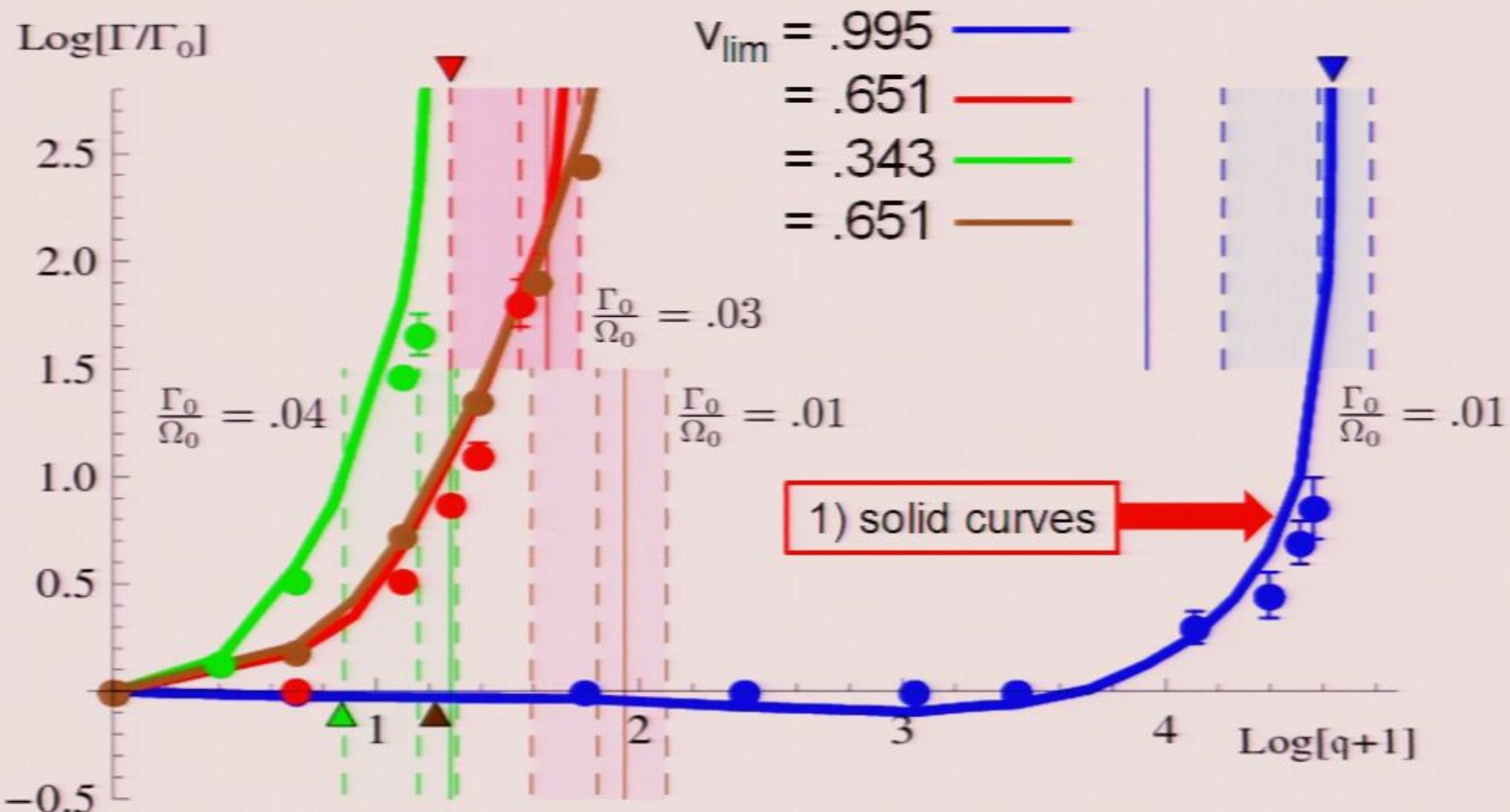
Estimate widths:

$$1) \quad \chi(\omega) \sim \frac{2A\Gamma}{(\omega - \Omega)^2 + \Gamma^2} \quad \rightarrow \quad \Gamma \sim \sqrt{-2 \frac{\chi}{\chi''}} \Big|_{\omega=\Omega}$$

follow widths of peaks



imaginary part of quasiparticle frequency, $\Gamma(q)$



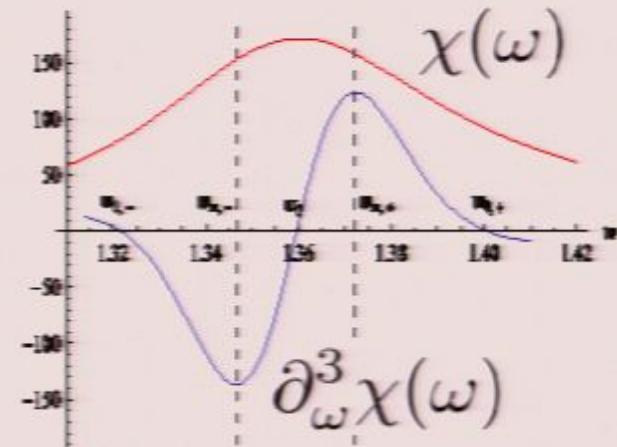
Estimate widths:

$$1) \quad \chi(\omega) \sim \frac{2A\Gamma}{(\omega - \Omega)^2 + \Gamma^2} \quad \xrightarrow{\hspace{1cm}} \quad \Gamma \sim \sqrt{-2 \frac{\chi}{\chi''}} \Big|_{\omega=\Omega}$$

$$2) \quad \chi(\omega) \sim \frac{2A\Gamma}{(\omega - \Omega)^2 + \Gamma^2} + 4\pi(\omega^2 - q^2) \quad \xrightarrow{\hspace{1cm}}$$

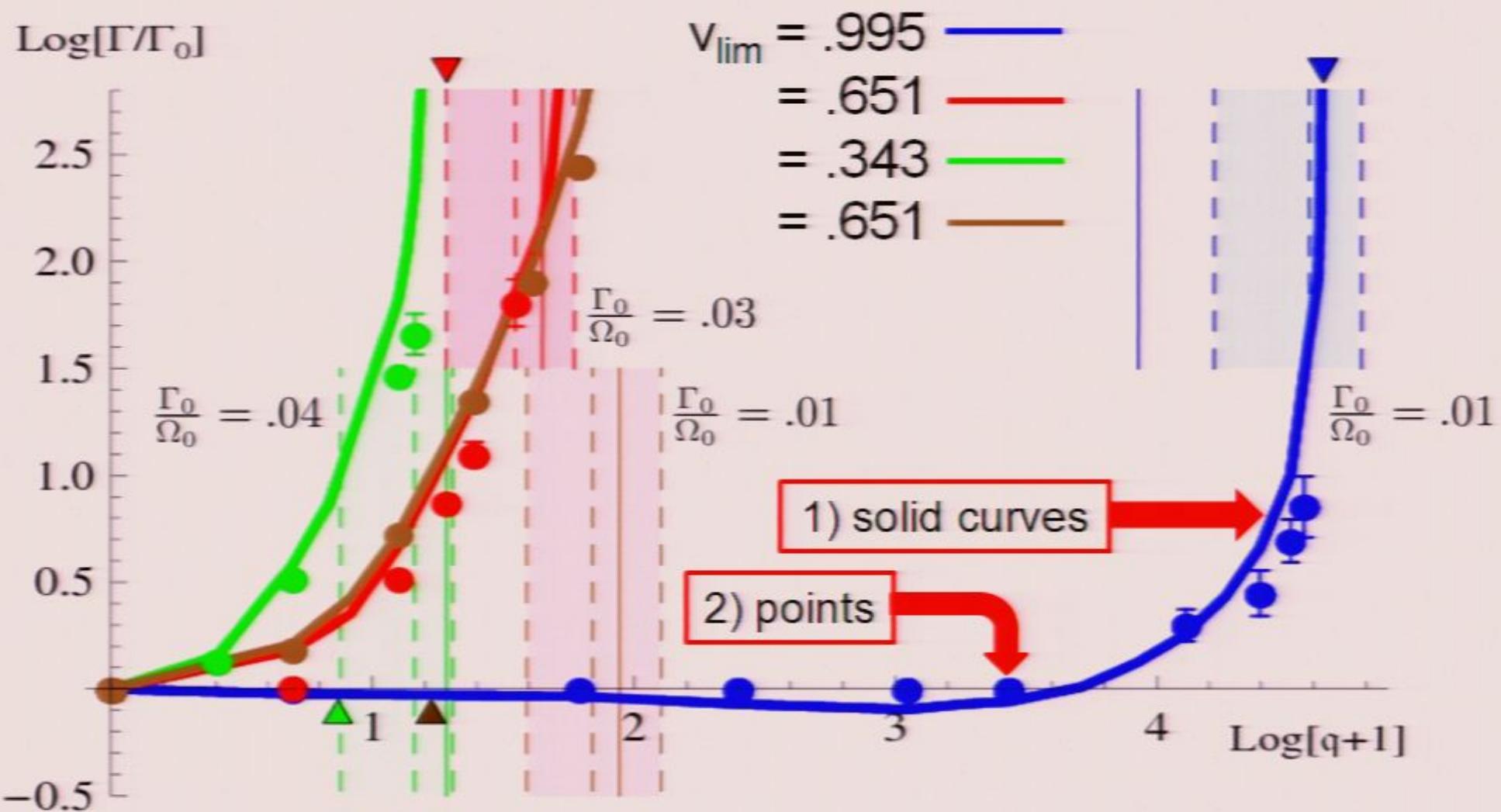
$$\omega_{m,\pm} = \Omega \pm \delta \Gamma \quad \delta = \left(1 - \frac{2}{\sqrt{5}}\right)^{\frac{1}{2}} \simeq 0.3249$$

$$\bar{\Gamma} = \frac{\omega_{m,+} - \omega_{m,-}}{2\delta}$$



follow widths of peaks \longrightarrow

imaginary part of quasiparticle frequency, $\Gamma(q)$



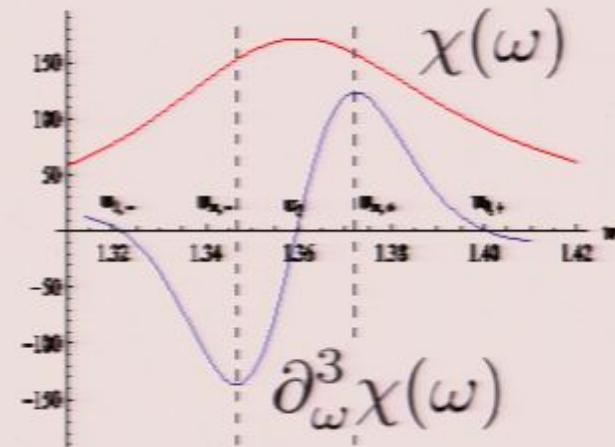
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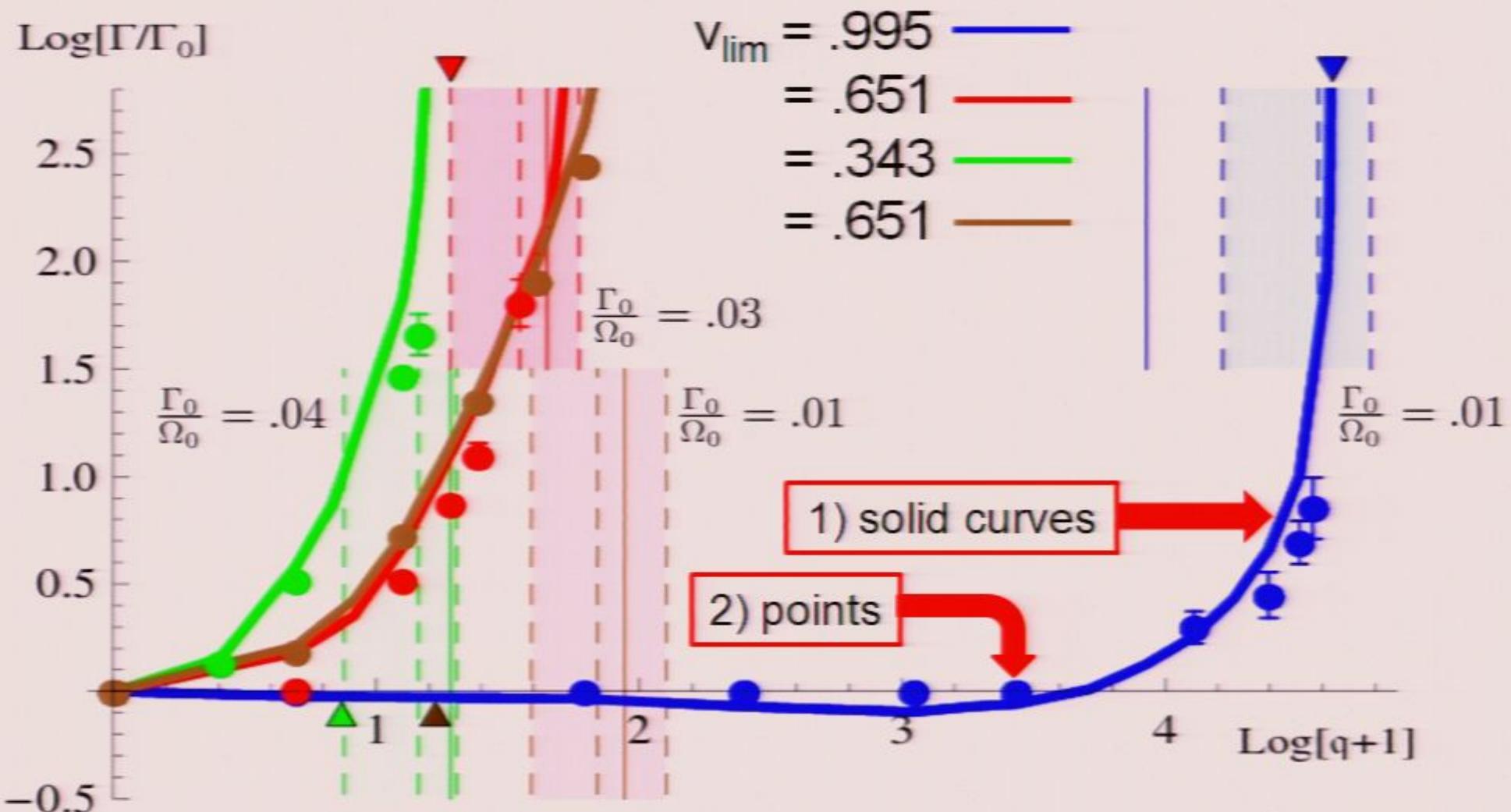
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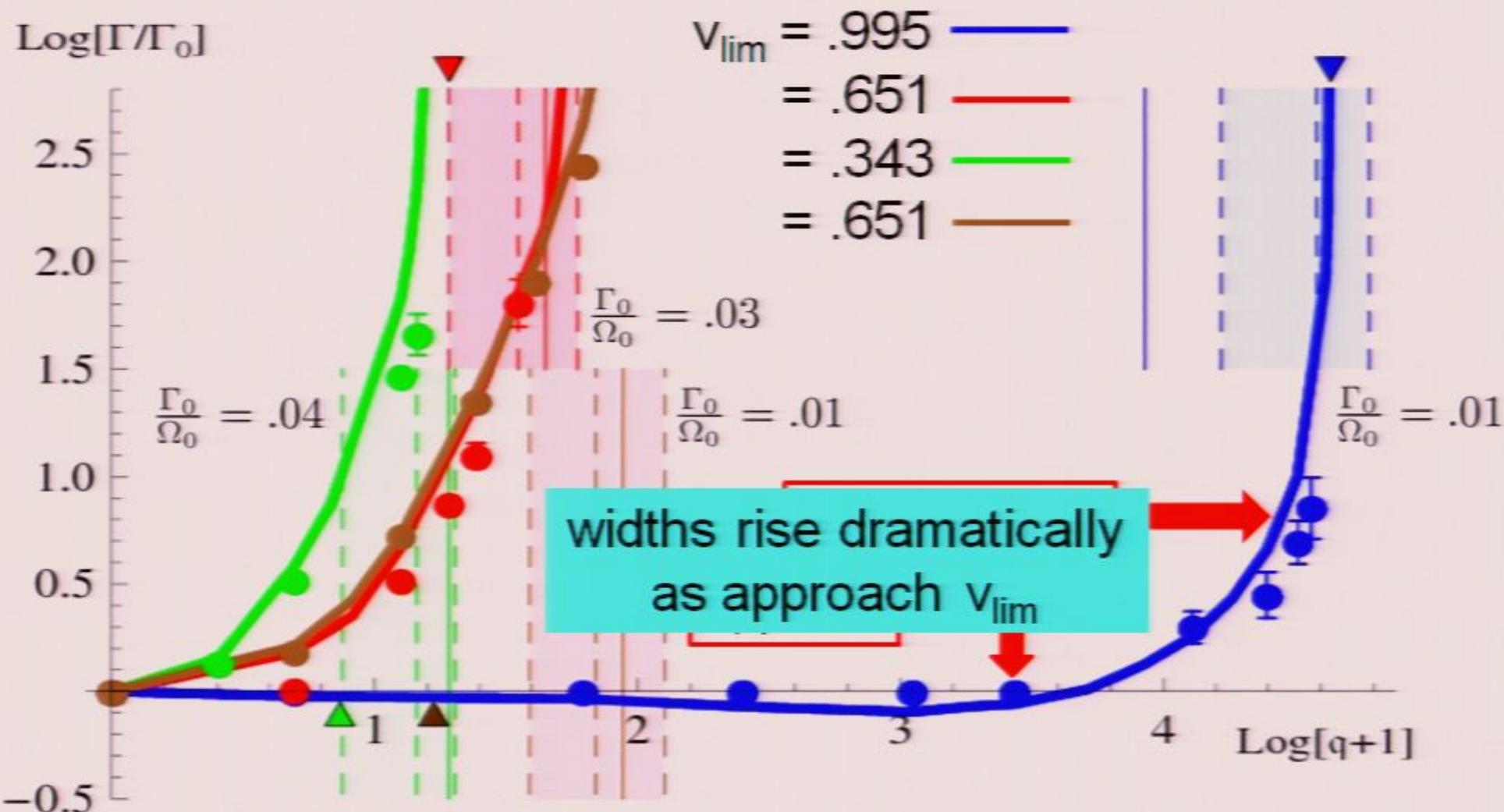


imaginary part of quasiparticle frequency, $\Gamma(q)$

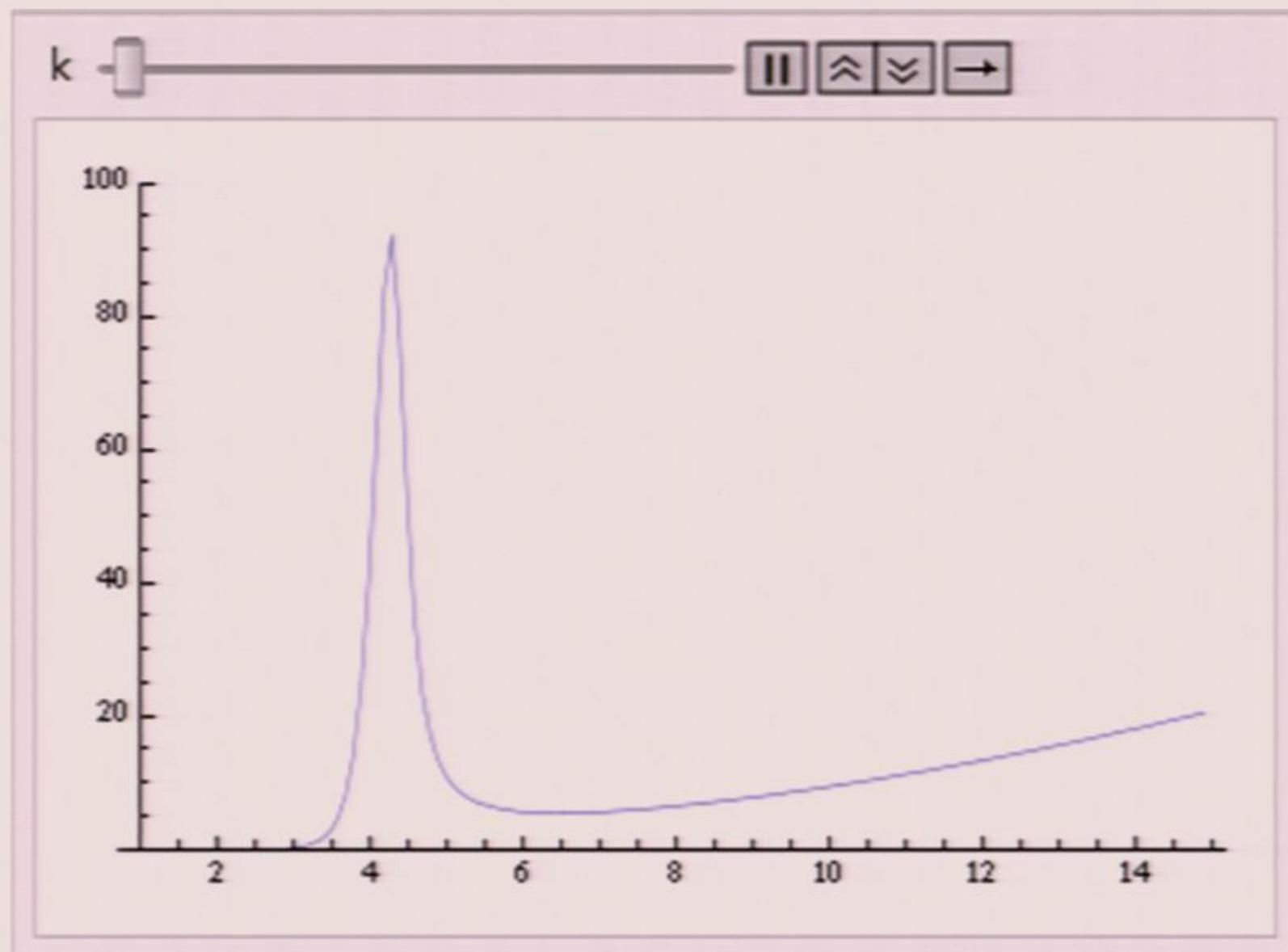


follow widths of peaks \longrightarrow

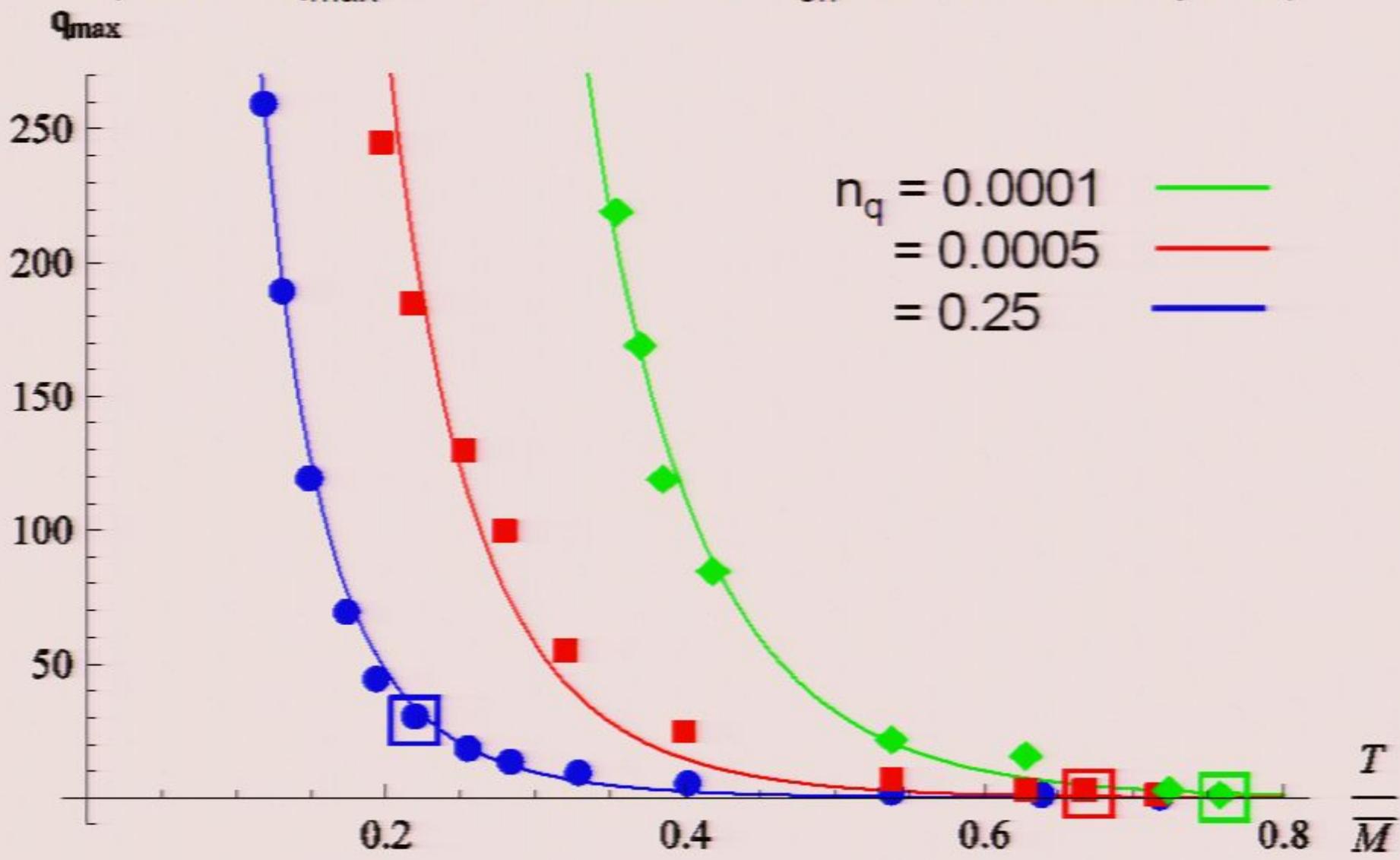
imaginary part of quasiparticle frequency, $\Gamma(q)$



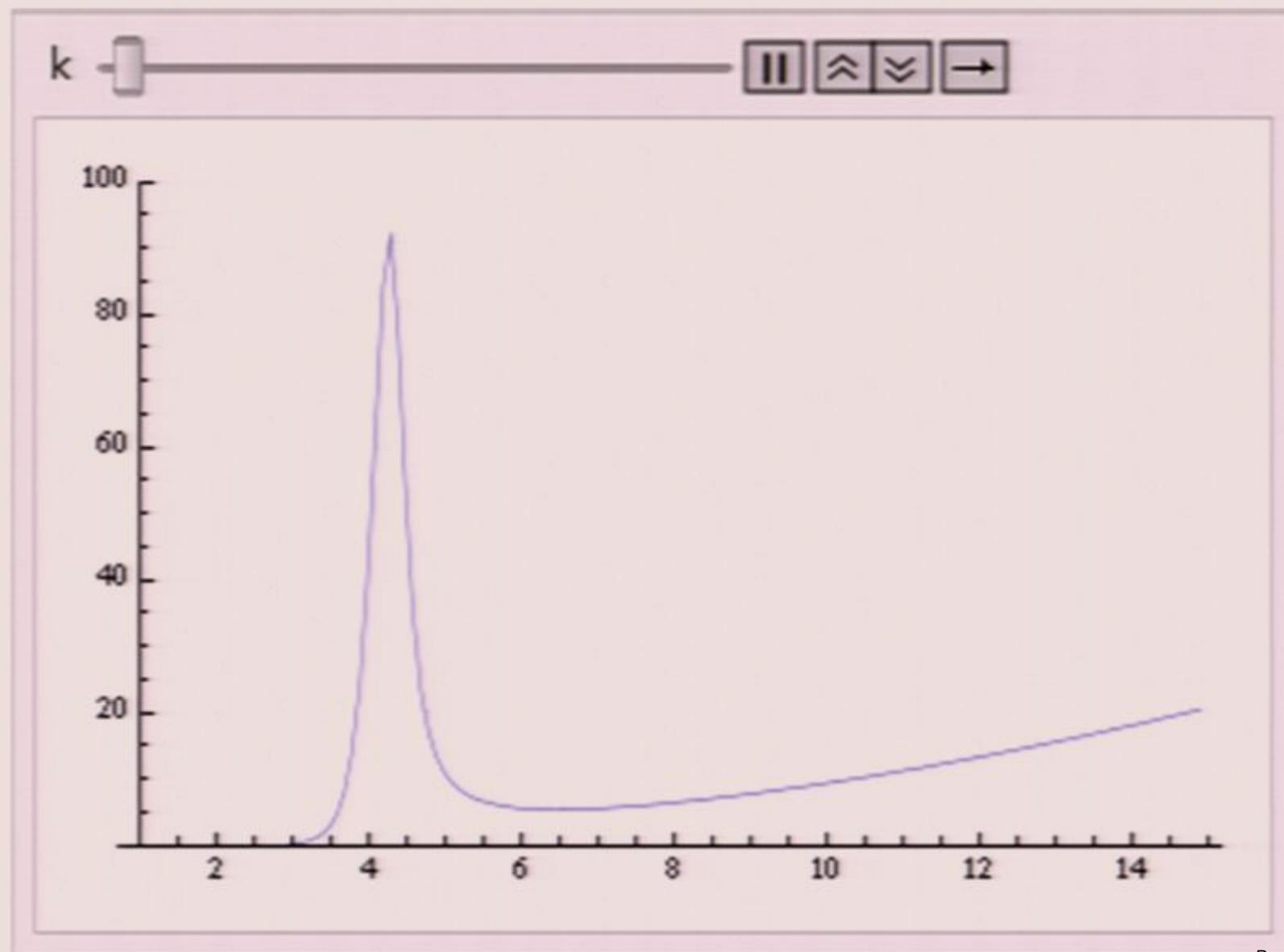
examine Schrodinger potential for quasinormal modes



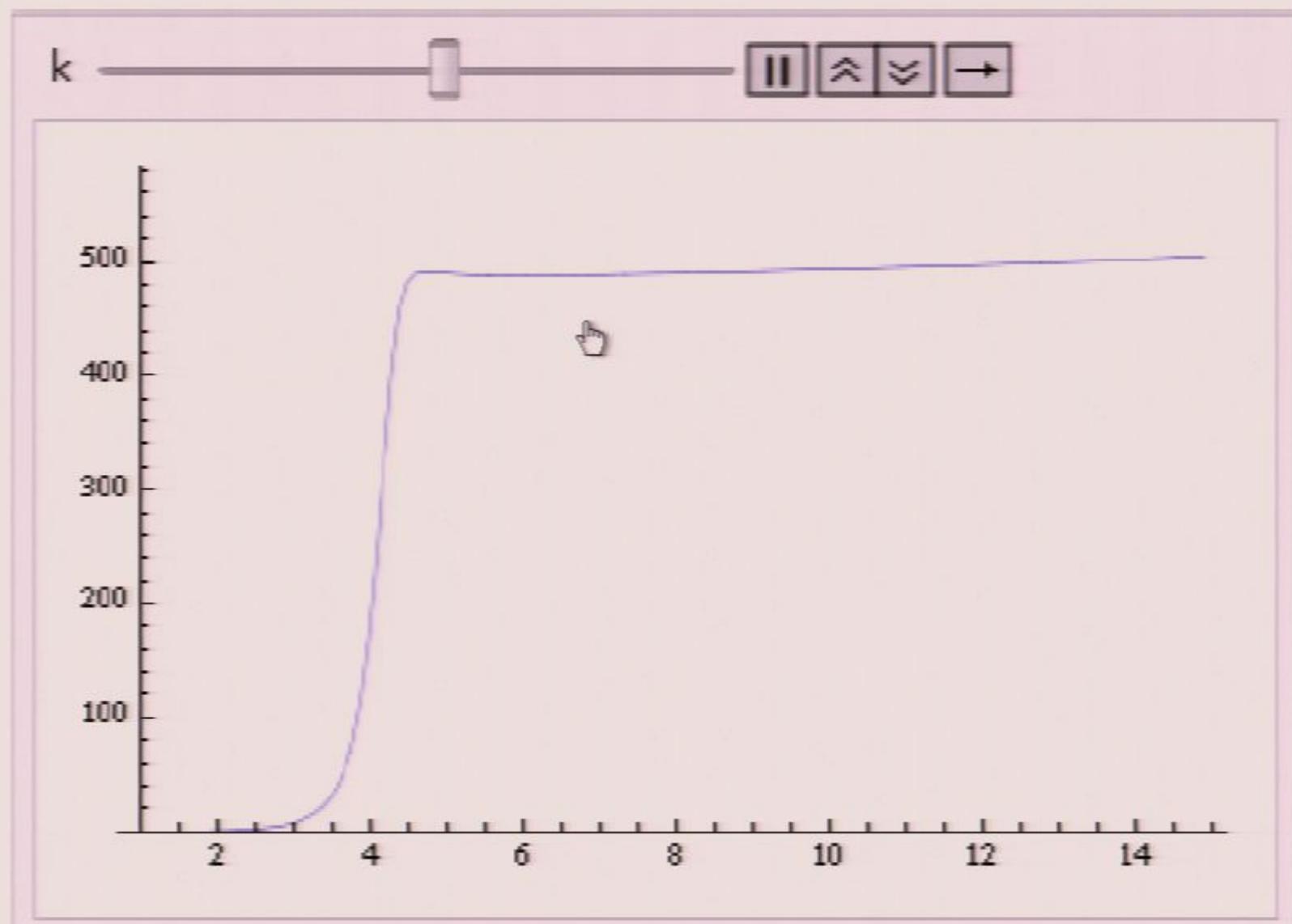
Quasiparticles limited to maximum momentum q_{\max}
 (define q_{\max} as value where V_{eff} has inflection point)



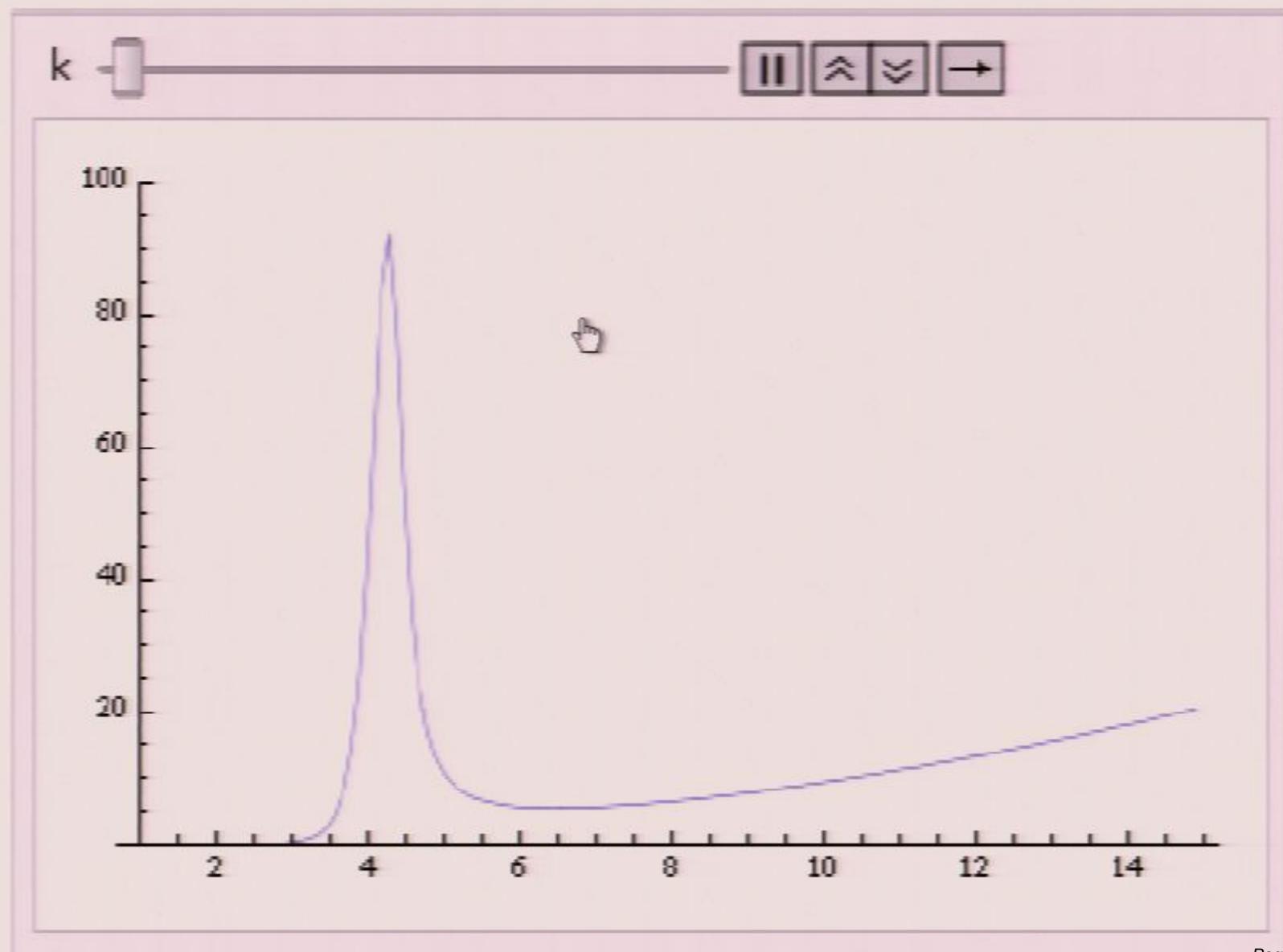
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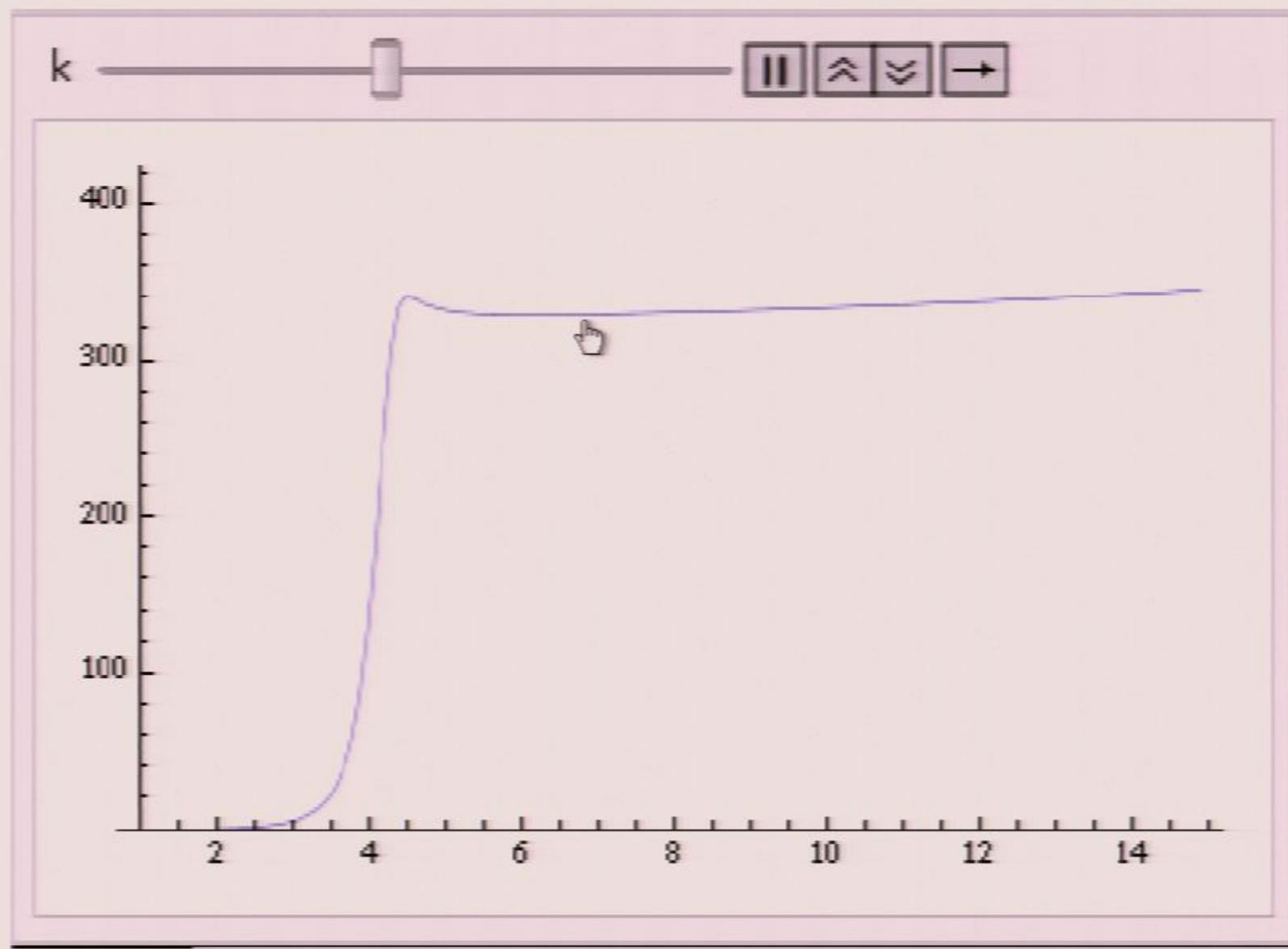
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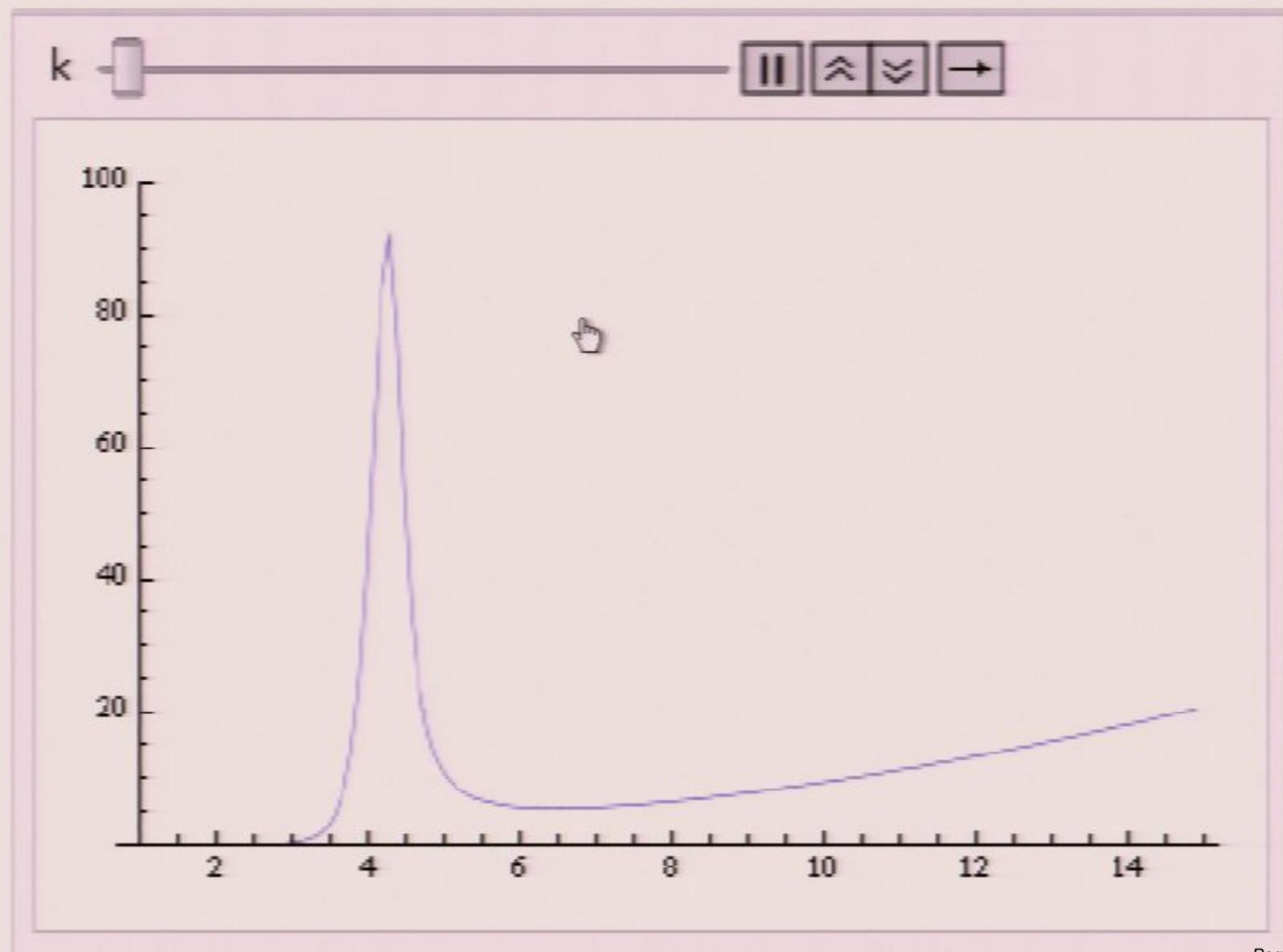
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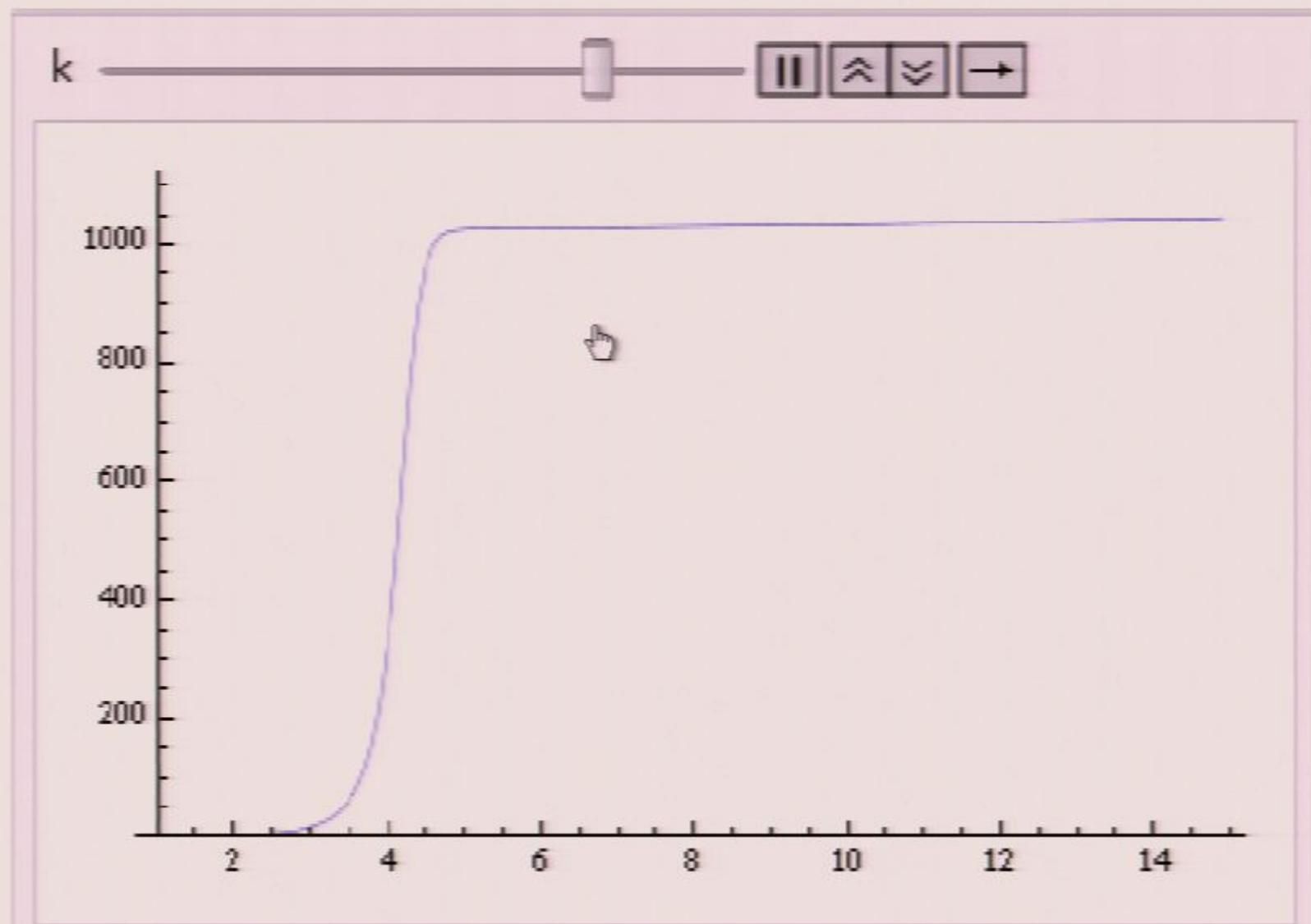
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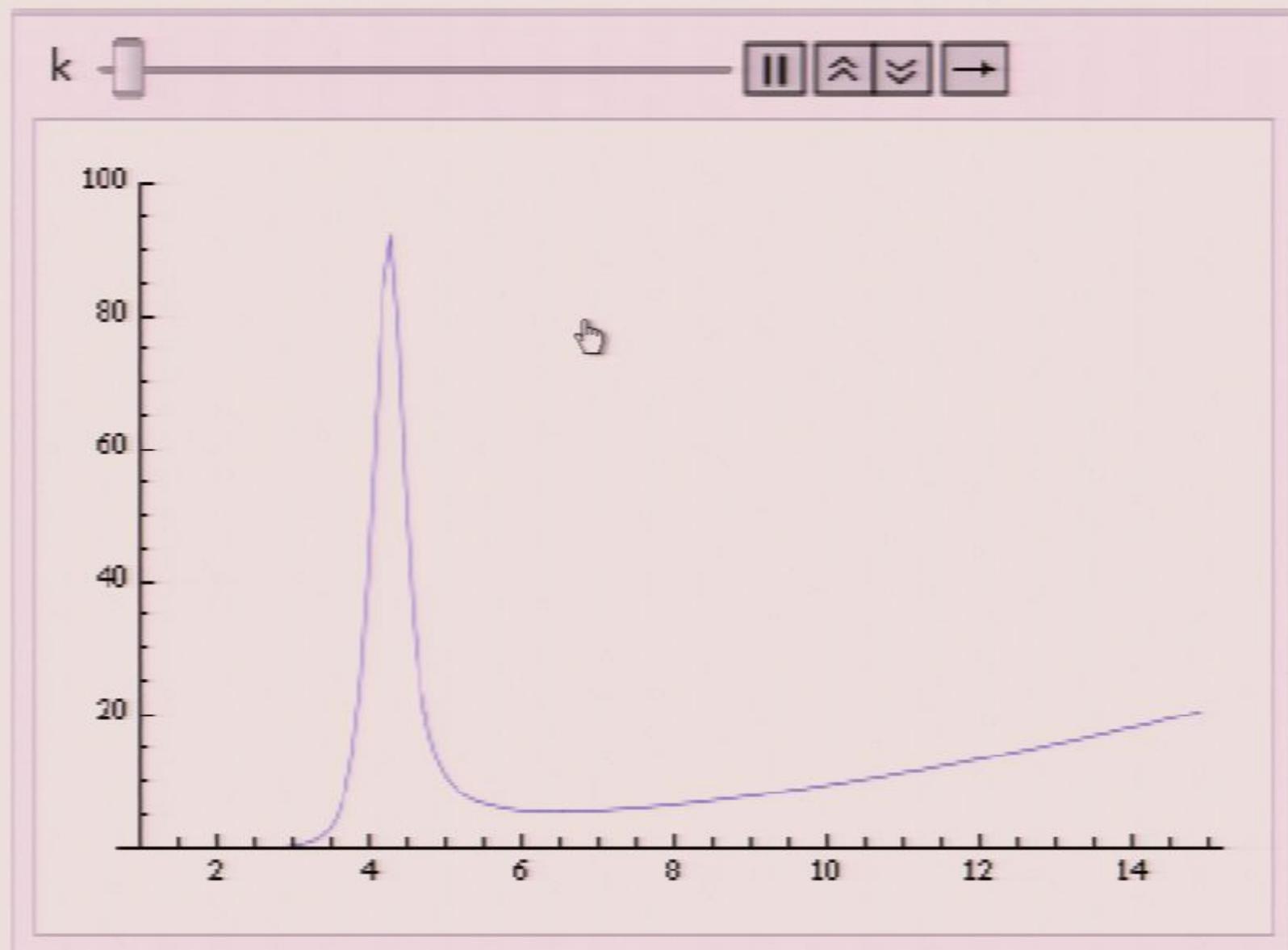
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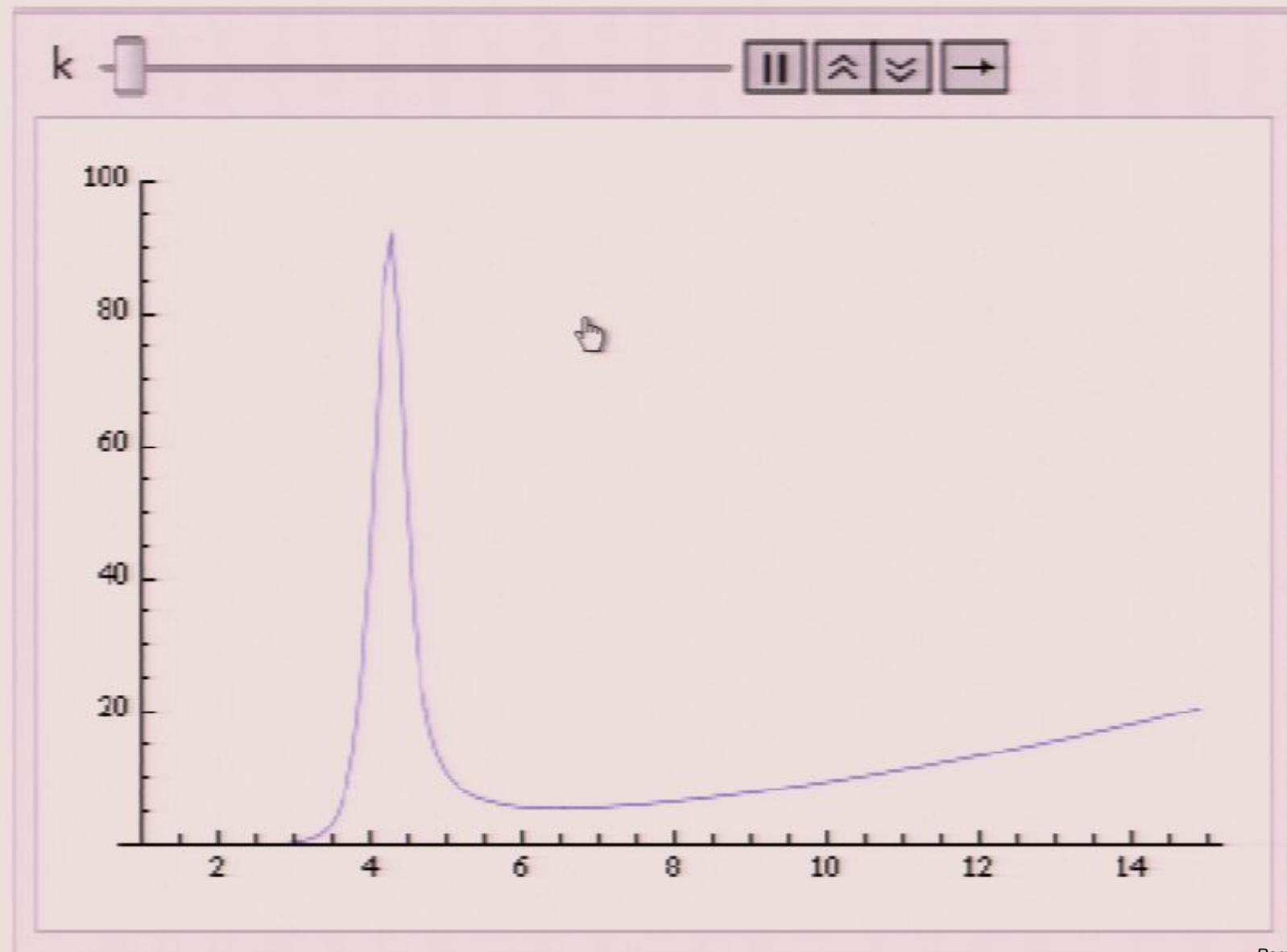
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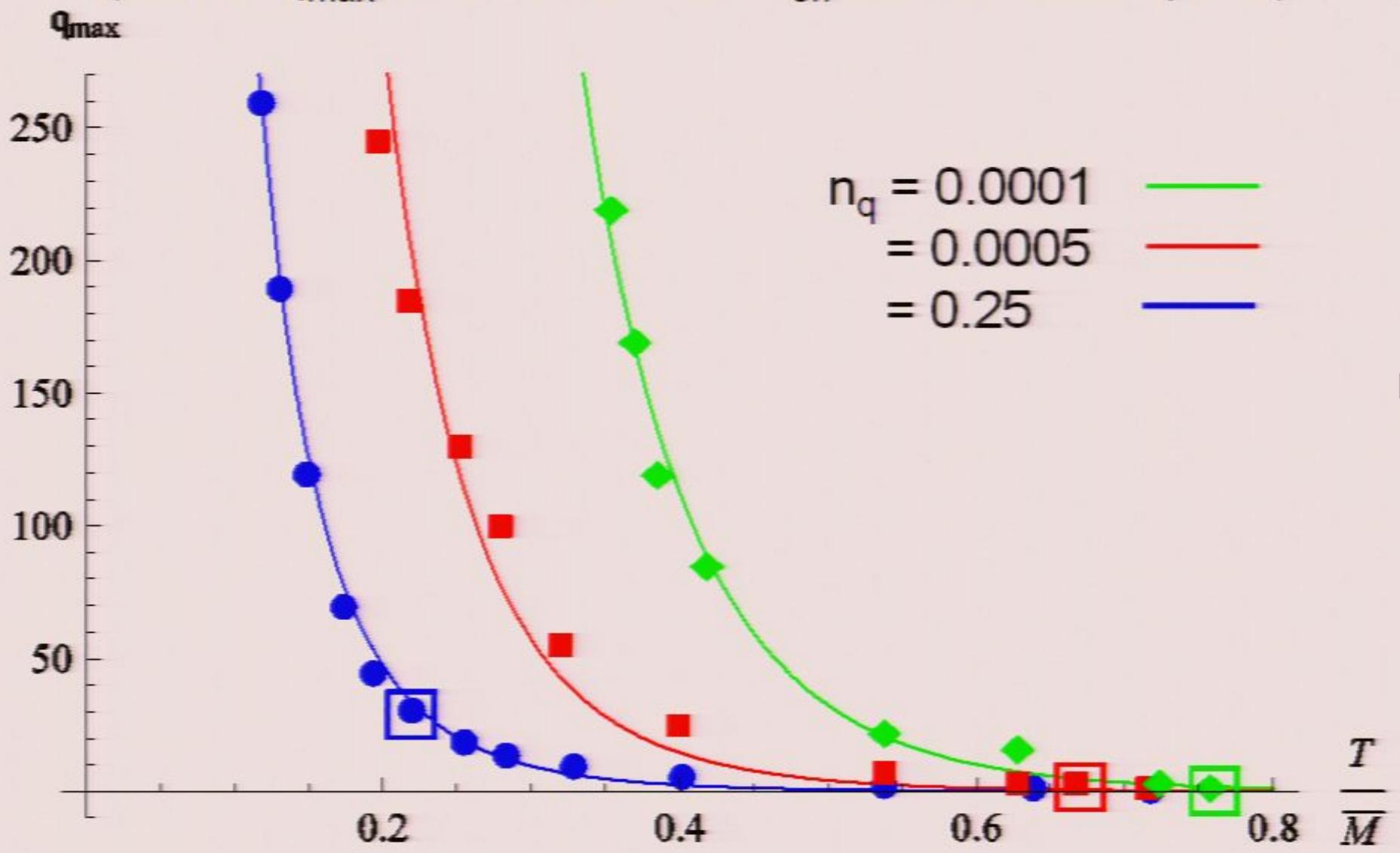
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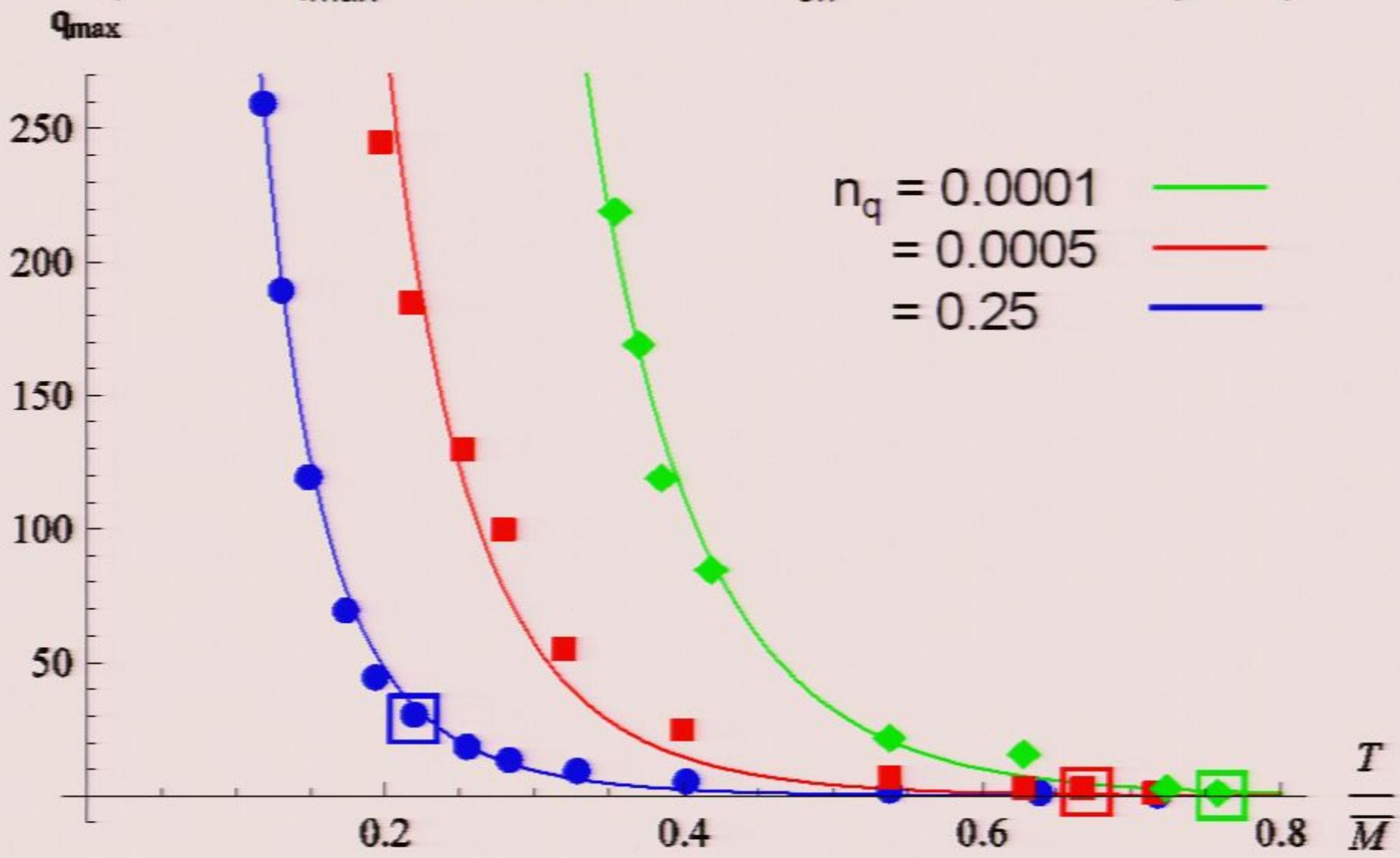
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Flattening spectral functions with increasing momentum:

- 1) widths grow

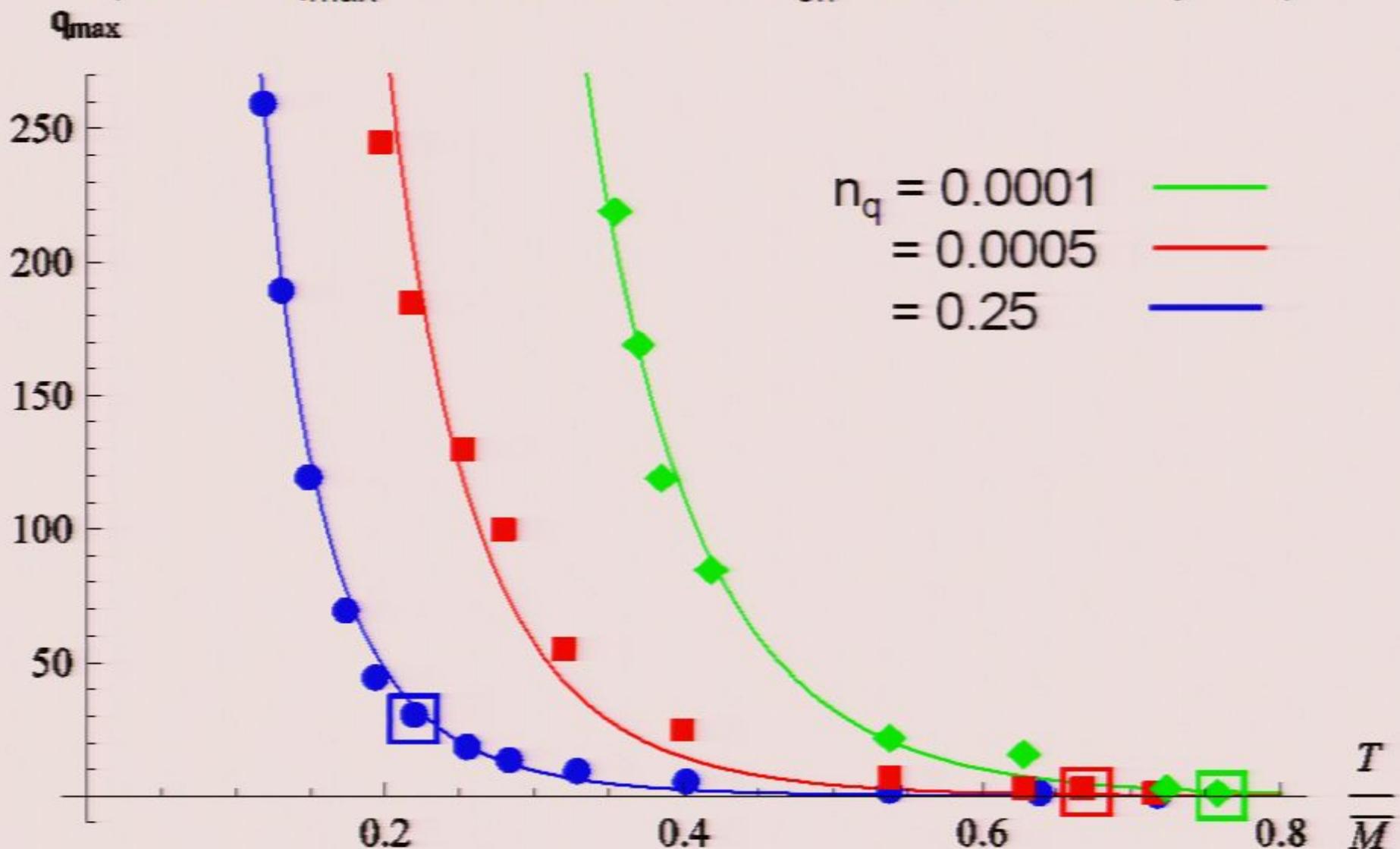
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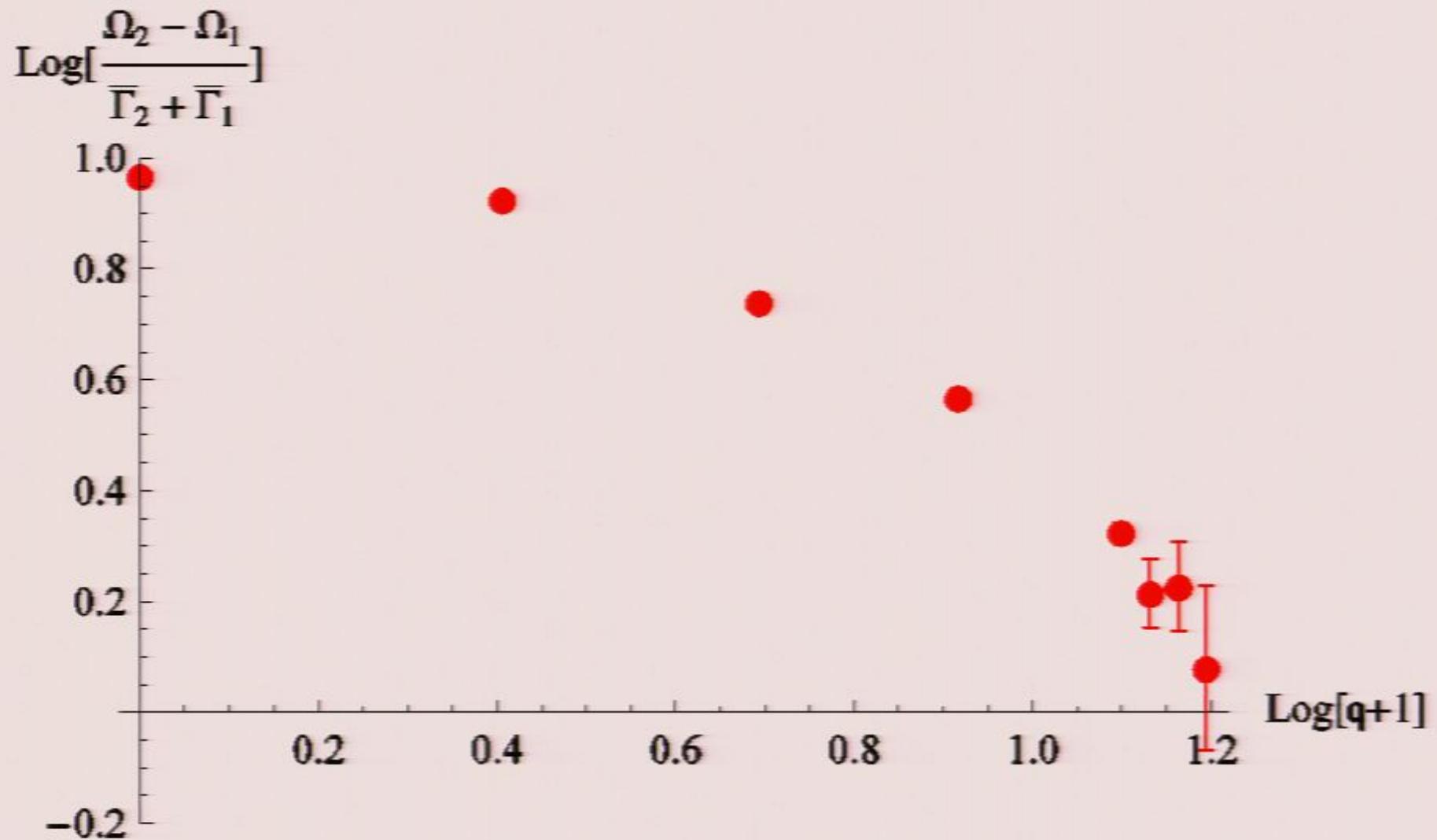


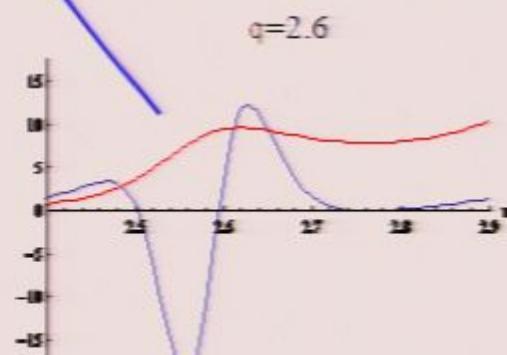
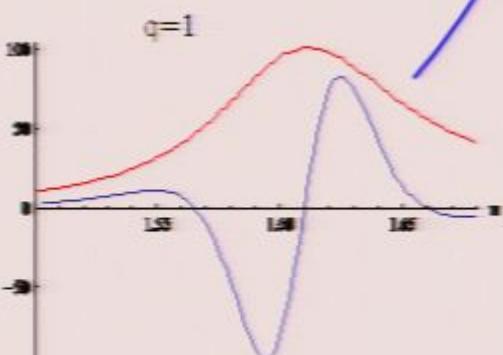
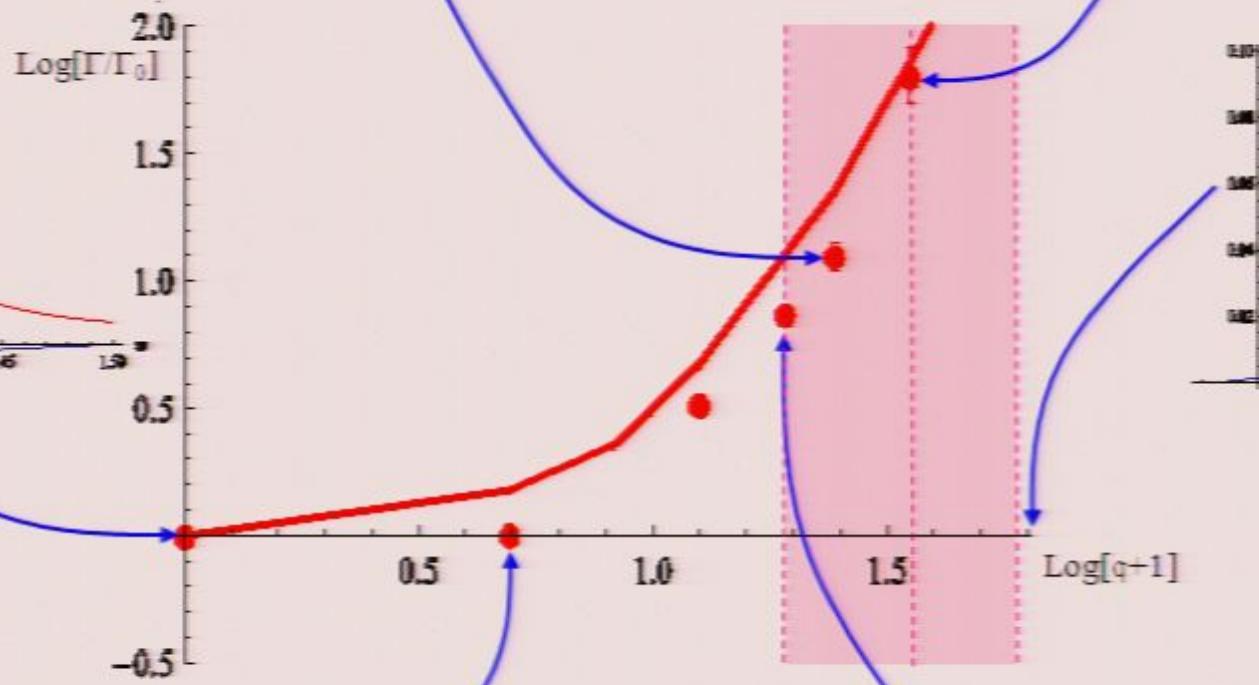
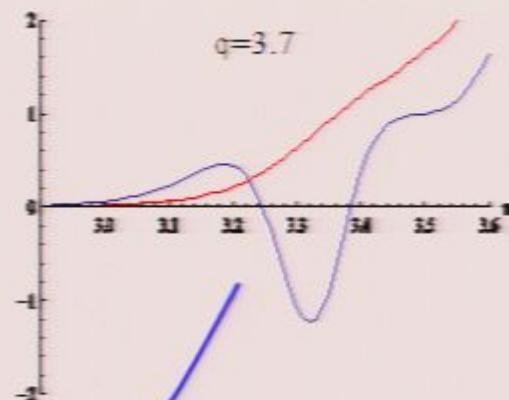
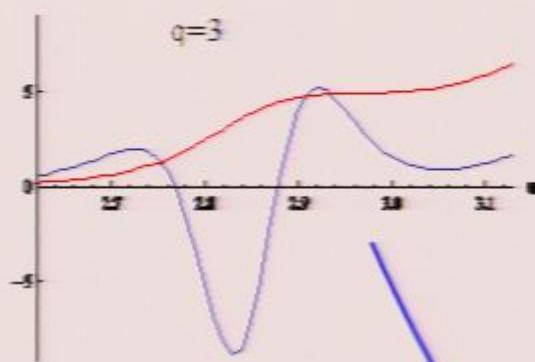
Flattening spectral functions with increasing momentum:

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Flattening spectral functions with increasing momentum:

- 1) widths grow
- 2) poles are crowding in on each other

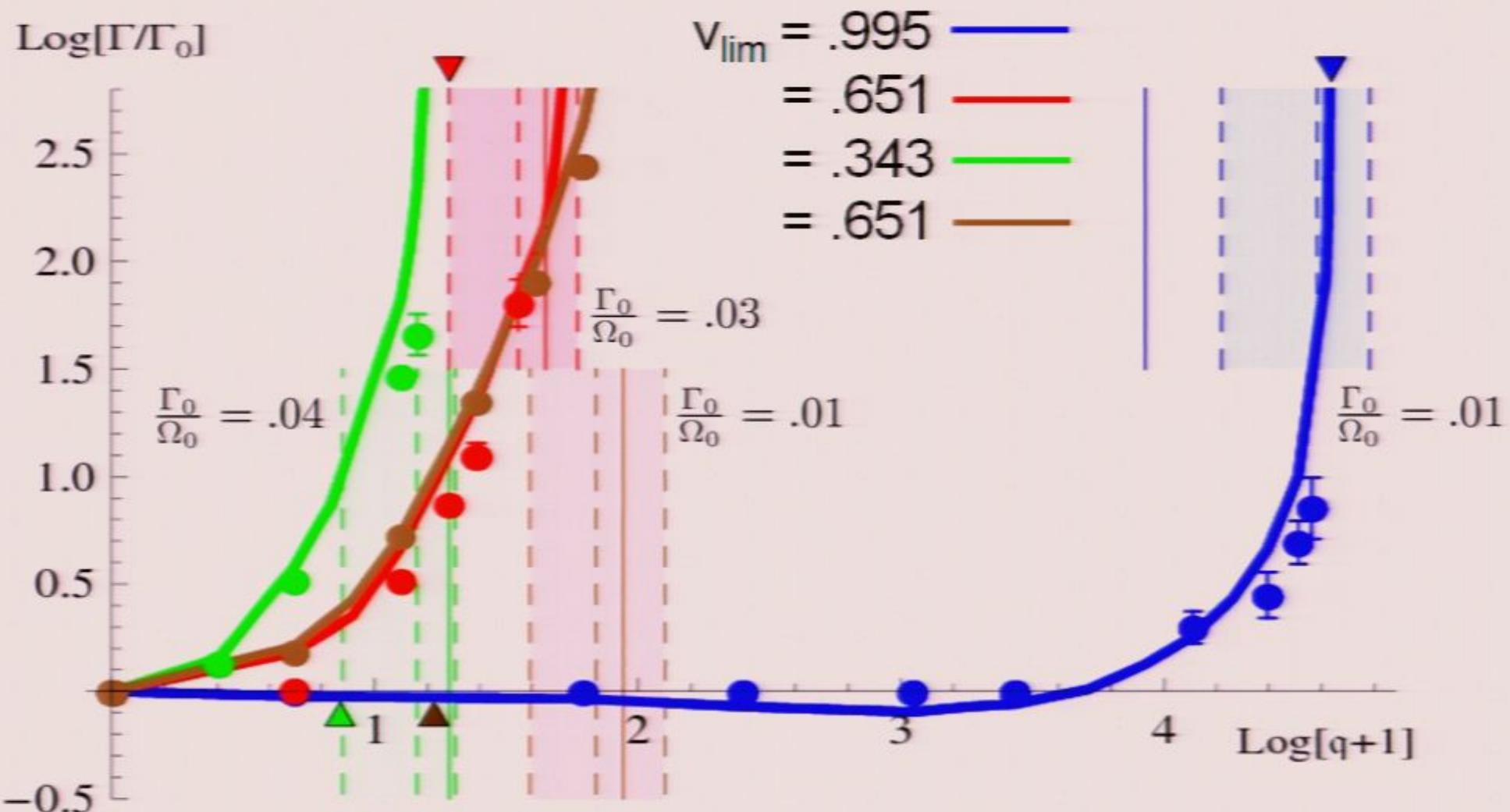




follow widths of peaks



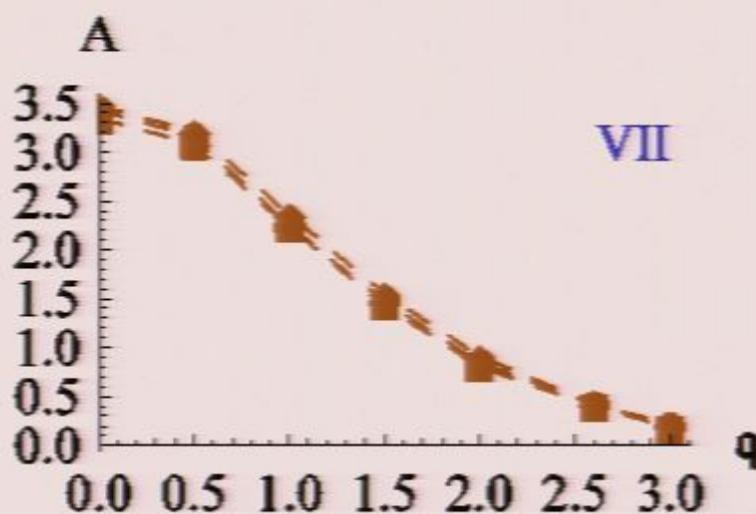
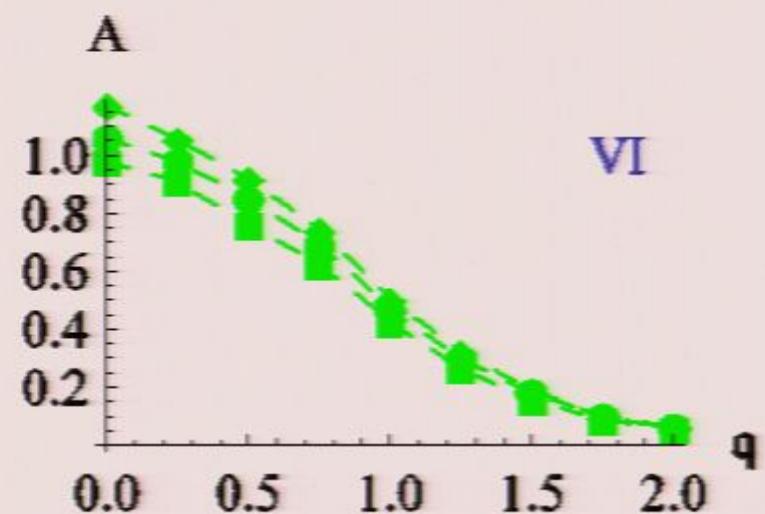
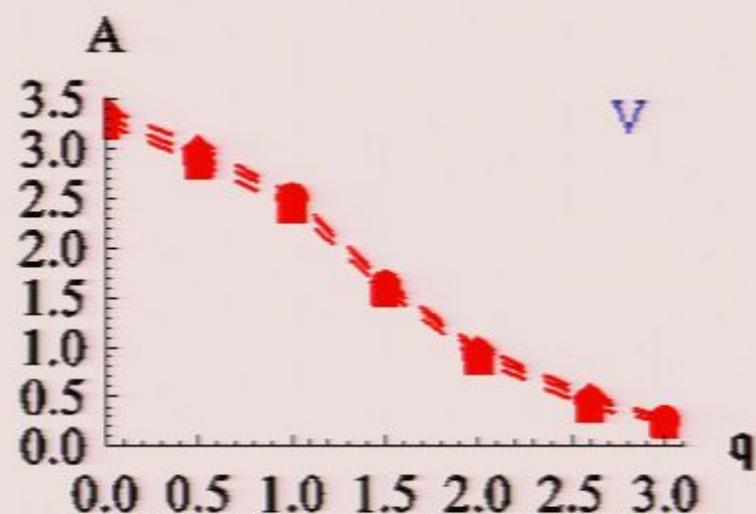
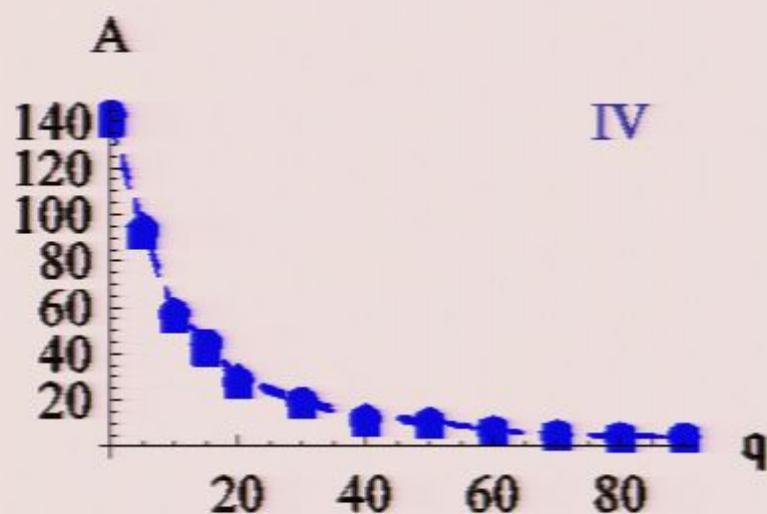
imaginary part of quasiparticle frequency, $\Gamma(q)$



Flattening spectral functions with increasing momentum:

- 1) widths grow
- 2) poles are crowding in on each other
- 3) residues decrease

$$\chi(\omega) \sim \frac{2A\Gamma}{(\omega - \Omega)^2 + \Gamma^2}$$



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_{max} in present holographic model
 - universal behaviour? real world effect? **(INVESTIGATING)**