

# Decoding the Path Integral: Resurgence and Non-Perturbative Physics



Gerald Dunne  
University of Connecticut

Galileo Galilei Institute Colloquium, December 1, 2021



## Physical Motivation

*the Feynman path integral is both conceptually  
and computationally powerful ... but*

*... some important physics computations are still challenging*

- finite density: e.g. the “sign problem”
- non-equilibrium physics at strong-coupling
- real time evolution
- quantum systems in extreme background fields

*standard computational methods from path integrals*

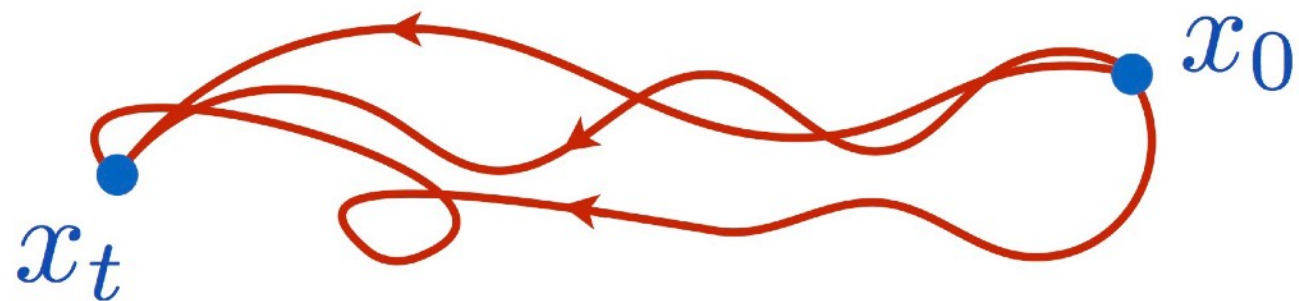
- perturbation theory
- non-perturbative numerical methods: Monte Carlo
- non-perturbative semi-classical methods: “instantons”
- asymptotics

“resurgence”: seeks to unify these approaches

technical problem: how to actually compute a quantum path integral?

# The Feynman Path Integral

$$\langle x_t | e^{-i\hat{H}t/\hbar} | x_0 \rangle =$$



$$\text{QM: } \int \mathcal{D}x(t) \exp \left[ \frac{i}{\hbar} S[x(t)] \right]$$

$$\text{QFT: } \int \mathcal{D}A(x^\mu) \exp \left[ \frac{i}{g^2} S[A(x^\mu)] \right]$$

- stationary phase approximation: classical physics
- bridge from classical to quantum field theory
- quantum perturbation theory: fluctuations about trivial saddle point
- other saddle points: non-perturbative physics
- resurgence: saddle points are related by analytic continuation, so perturbative and non-perturbative physics are *unified*



# Resurgence in Classical Optics: the original “sign problem”

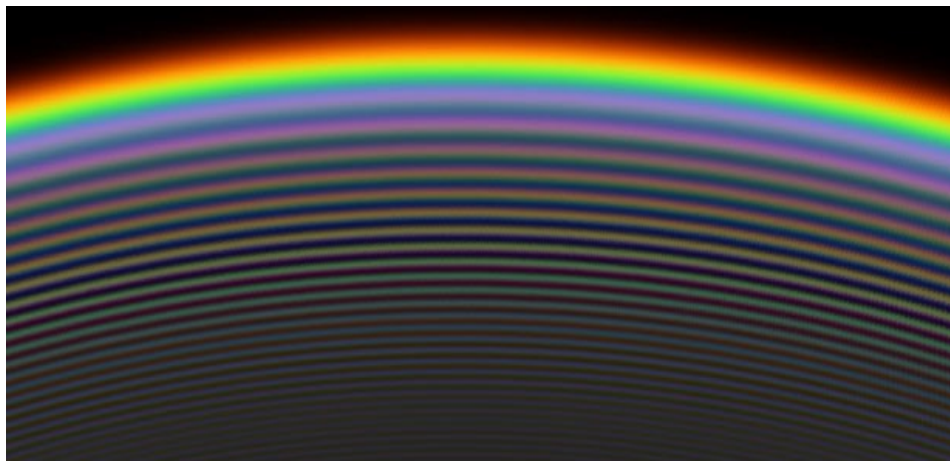
## Airy, Stokes and *spurious/supernumerary* rainbows



Airy 1838: “On the intensity of light in the neighbourhood of a caustic”



Stokes 1850: “On the numerical calculation of a class of definite integrals and infinite series”



W. Miller 1841:  
“On Spurious Rainbows”

“Stokes, by mathematical supersubtlety transformed Airy’s integral into a form by which the light at any point of any of those thirty bands could be calculated with but little effort ...”

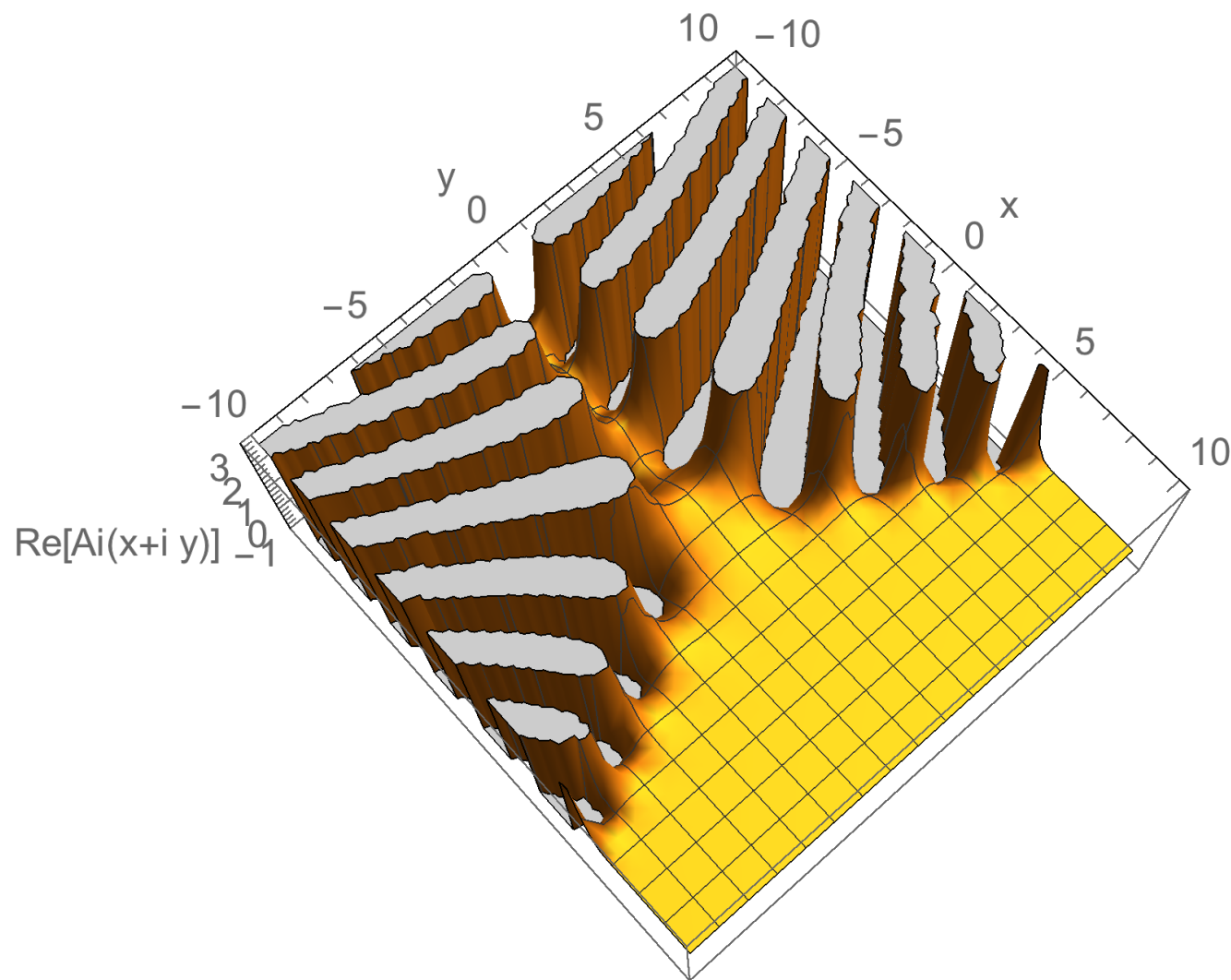
Lord Kelvin (Stokes obituary, 1903)



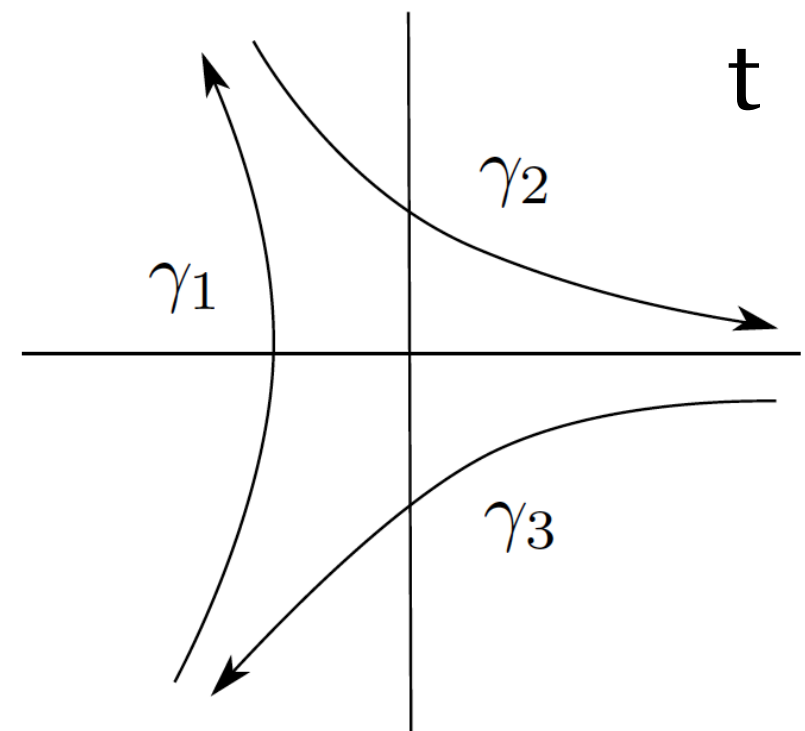
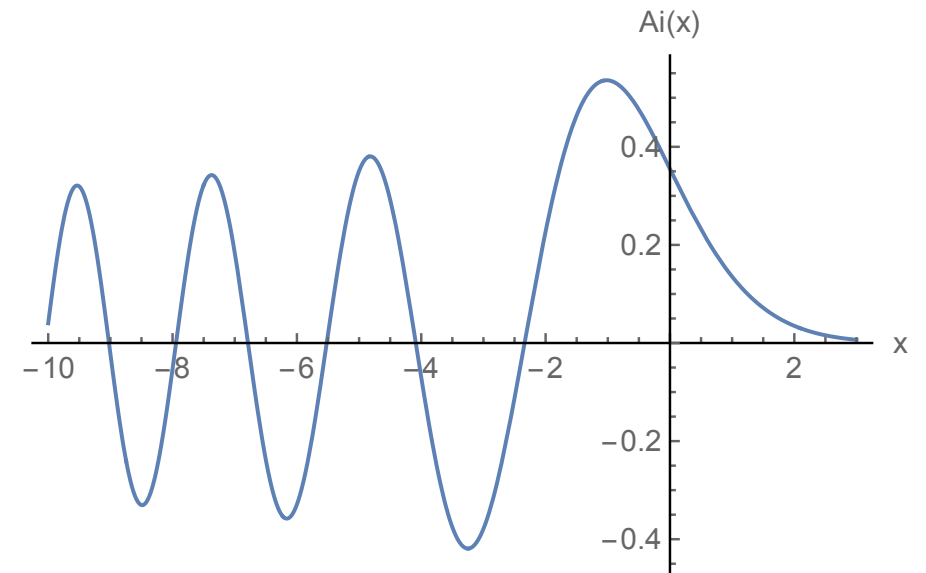
# The Stokes Phenomenon

$$\text{Ai}(x) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} dt e^{i\left(\frac{1}{3}t^3 + xt\right)}$$

Stokes transitions occur in the complex  $x$  plane



Stokes 1857: “On the discontinuity of arbitrary constants which appear in divergent developments”



non-perturbative connection  
formulae connect sectors

$$\text{Bi}(x) = 2e^{\pm \frac{\pi i}{6}} \text{Ai}\left(e^{\mp \frac{2\pi i}{3}} x\right) \mp i \text{Ai}(x)$$

## Analytic Continuation of Path Integrals

since we need complex analysis and contour deformation to make sense of oscillatory exponential integrals, it is natural to explore similar methods for (infinite dimensional) path integrals

$$\int \mathcal{D}x(t) \exp \left[ \frac{i}{\hbar} S[x(t)] \right] \longleftrightarrow \int \mathcal{D}x(t) \exp \left[ -\frac{1}{\hbar} S[x(t)] \right]$$

goal: a satisfactory formulation of the functional integral should be able to describe Stokes transitions

idea: seek a computationally viable constructive definition of the path integral using ideas from resurgent trans-series

# Resurgent Trans-Series

Ecalte 1980s  
Dingle 1960s  
Stokes 1850s

resurgence: new-ish idea in mathematics

perturbative series  $\longrightarrow$  “trans-series”

physics applications: “semiclassical trans-series”

$$f(\hbar) = \sum_p c_{[p]} \hbar^p \longrightarrow f(\hbar) = \sum_k \sum_p \sum_l c_{[kpl]} e^{-\frac{k}{\hbar}} \hbar^p (\ln \hbar)^l$$

- trans-series is well-defined under analytic continuation
- well understood for differential/difference/integral equations & exponential integrals: “natural problems”
- expansions about different saddles are related
- exponentially improved asymptotics

physics: necessarily unifies perturbative and non-perturbative physics



## Resurgent Functions

“resurgent functions display at each of their singular points a behaviour closely related to their behaviour at the origin. Loosely speaking, these functions resurrect, or surge up - in a slightly different guise, as it were - at their singularities”

J. Ecalle, 1980



physical implication: fluctuations about different sectors are related

conjecture: this structure is general

# Dingle: Demystifying and Decoding Divergent Series

*Before Dingle, almost every scientist who encountered a divergent series regarded it as meaningful only up to an inherent vagueness. Dingle ... regarded a divergent series as an exact coding of the function it represents. Decoding ('interpreting') such series is exact in principle, and in practice can lead to vastly improved approximations.*

Robert Dingle obituary, 2010, Michael Berry and John Cornwell



## Asymptotic Expansions: Their Derivation and Interpretation

R. B. DINGLE

*Department of Theoretical Physics,  
University of St. Andrews,  
Fife, Scotland*

1973



ACADEMIC PRESS

LONDON AND NEW YORK

*A Subsidiary of Harcourt Brace Jovanovich, Publishers*

# Resurgence in Exponential Integrals

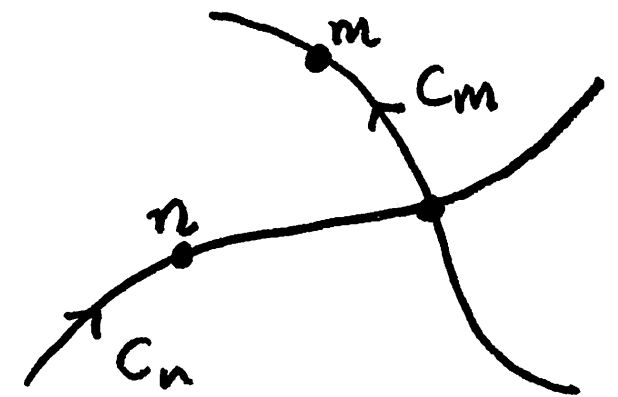
Dingle 1960s;  
Berry & Howls 1991:  
“Hyperasymptotics for  
Integrals with Saddles”

steepest descent integral through saddle point “n”:

$$I^{(n)}(\hbar) = \int_{C_n} dx e^{\frac{i}{\hbar} f(x)} = \frac{1}{\sqrt{1/\hbar}} e^{\frac{i}{\hbar} f_n} T^{(n)}(\hbar)$$

all fluctuations beyond the Gaussian approximation:

$$T^{(n)}(\hbar) \sim \sum_{r=0}^{\infty} T_r^{(n)} \hbar^r$$



straightforward complex analysis implies:

universal large orders of fluctuation coefficients:  $(F_{nm} \equiv f_m - f_n)$

$$T_r^{(n)} \sim \frac{(r-1)!}{2\pi i} \sum_m \frac{(\pm 1)}{(F_{nm})^r} \left[ T_0^{(m)} + \frac{F_{nm}}{(r-1)} T_1^{(m)} + \frac{(F_{nm})^2}{(r-1)(r-2)} T_2^{(m)} + \dots \right]$$

fluctuations about different saddles are quantitatively related



# Resurgence in Exponential Integrals

canonical example: Airy function integral has 2 saddle points

$$T_r^\pm = (\pm 1)^r \frac{\Gamma\left(r + \frac{1}{6}\right) \Gamma\left(r + \frac{5}{6}\right)}{(2\pi) \left(\frac{4}{3}\right)^r r!} = \left\{ 1, \pm \frac{5}{48}, \frac{385}{4608}, \pm \frac{85085}{663552}, \dots \right\}$$

large orders of fluctuation coefficients:

$$T_r^+ \sim \frac{(r-1)!}{(2\pi) \left(\frac{4}{3}\right)^r} \left( 1 - \left(\frac{4}{3}\right) \frac{5}{48} \frac{1}{(r-1)} + \left(\frac{4}{3}\right)^2 \frac{385}{4608} \frac{1}{(r-1)(r-2)} - \dots \right)$$

generic “large-order/low-order” resurgence relation

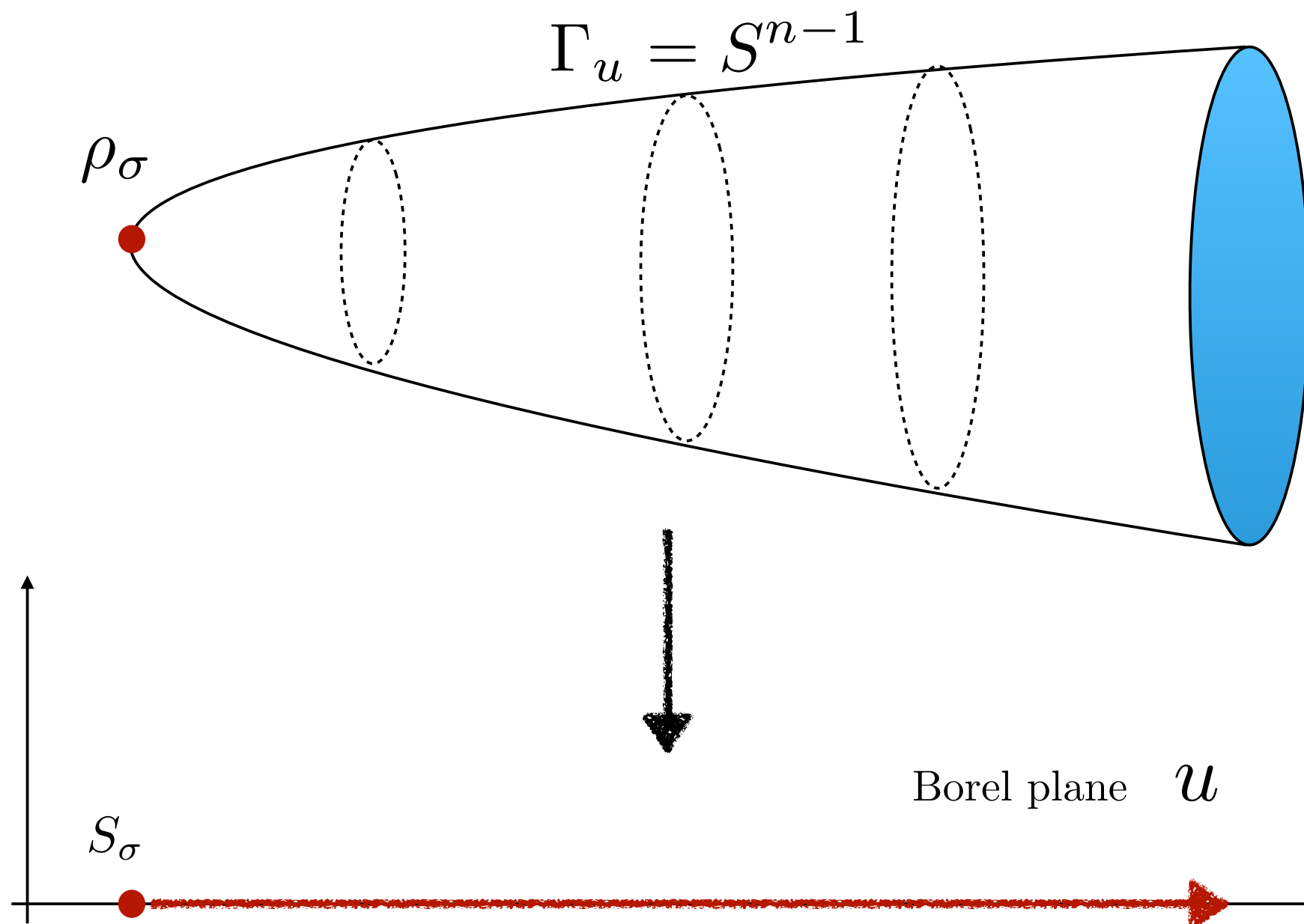
remarkable fact: this resurgent large-order/low-order behavior has been found in matrix models, QM, QFT, string theory, ...

**the natural way to explain this is via analytic  
continuation of functional integrals**

# Lefschetz Thimbles

even the generalization to more than 1 complex dimension is interesting

Pham 1967;  
Howls 1997, ...

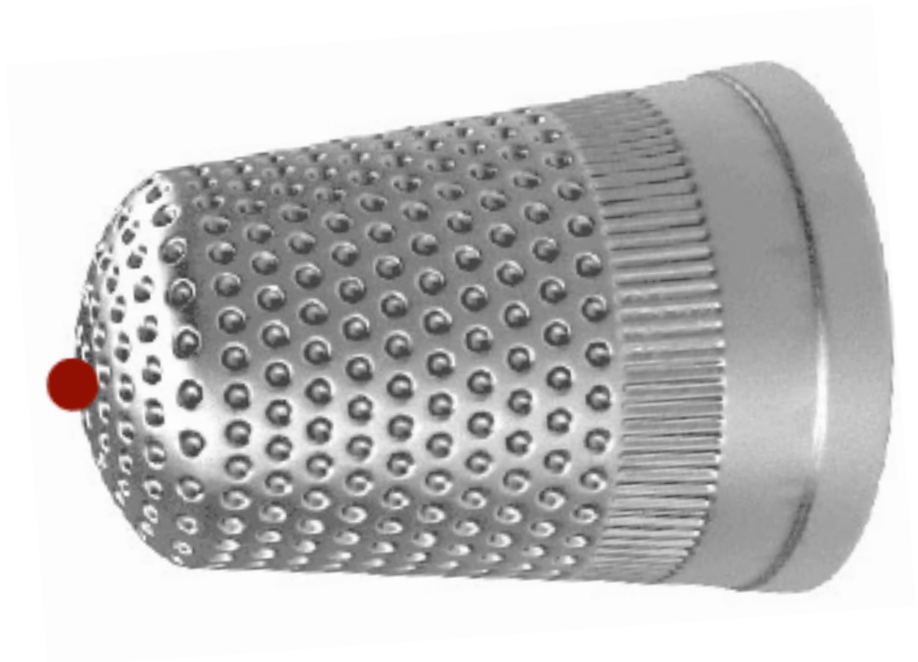


# Analytic Continuation of Path Integrals: “Lefschetz Thimbles”

$$Z(\hbar) = \int \mathcal{D}A \exp \left( \frac{i}{\hbar} S[A] \right) \stackrel{?}{=} \sum_{\text{thimble}} \mathcal{N}_{\text{th}} e^{i \phi_{\text{th}}} \int_{\text{th}} \mathcal{D}A \times (\mathcal{J}_{\text{th}}) \times \exp \left( \mathcal{R}e \left[ \frac{i}{\hbar} S[A] \right] \right)$$

Lefschetz thimble = “functional steepest descents contour”

- in principle, on a thimble, the path integral becomes well-defined and computable
- complexified gradient flow:

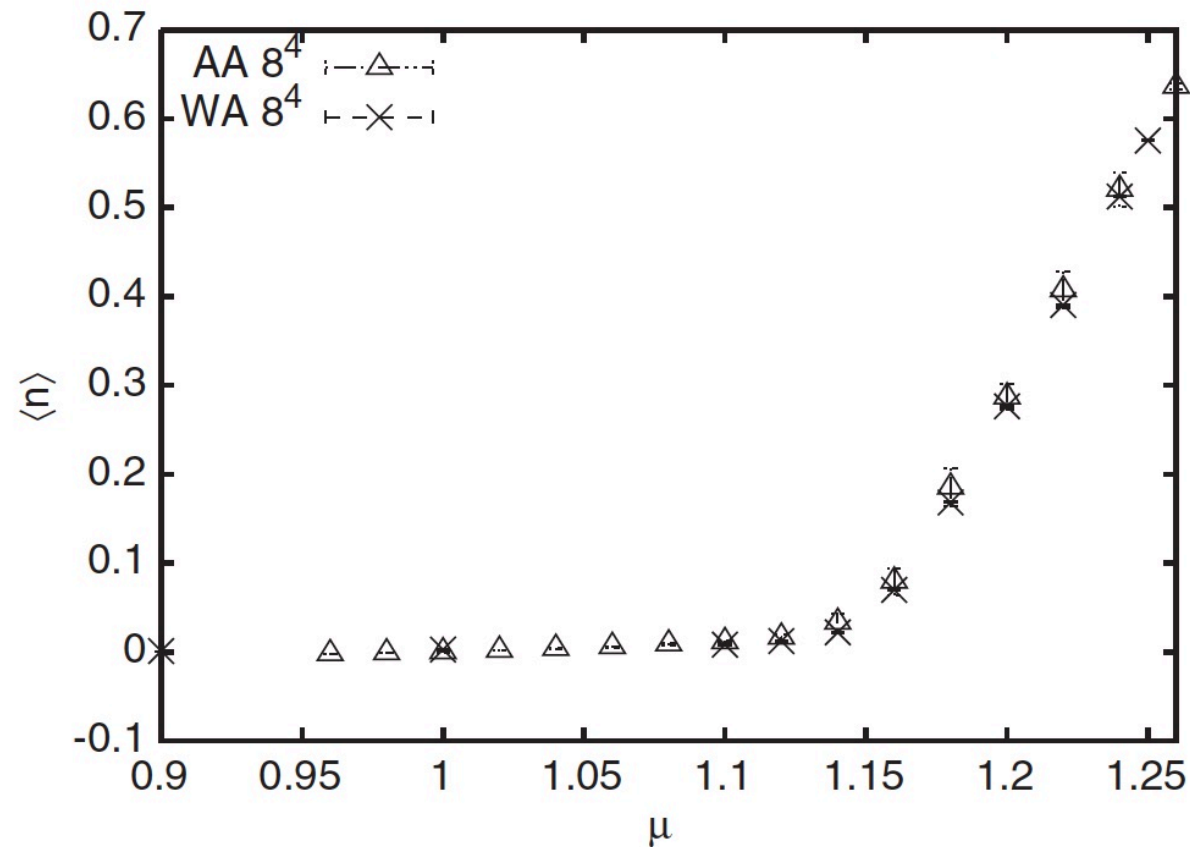


$$\frac{\partial}{\partial \tau} A(x; \tau) = - \overline{\frac{\delta S}{\delta A(x; \tau)}}$$



# Analytic Continuation of Path Integrals: “Lefschetz Thimbles”

CRISTOFORETTI *et al.* (2013)



Fujii et al (2013)

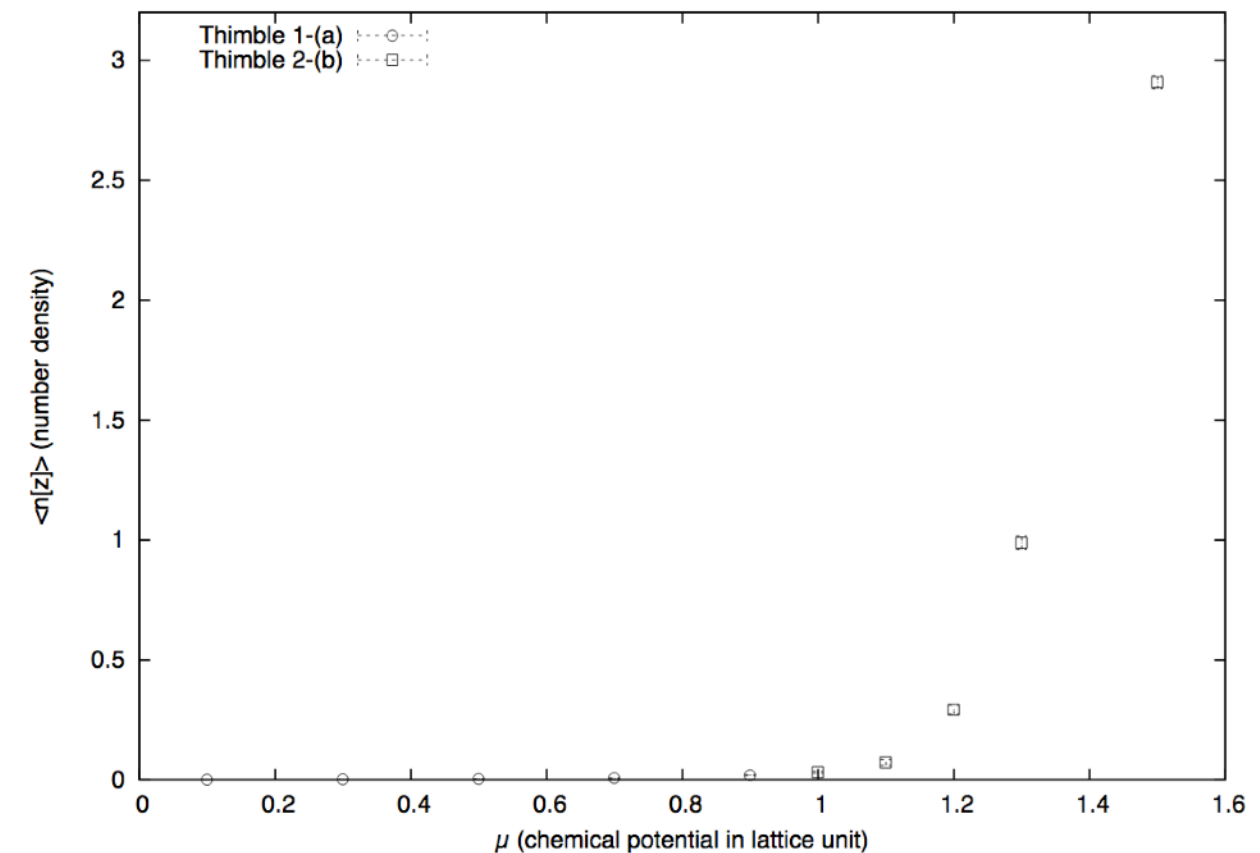


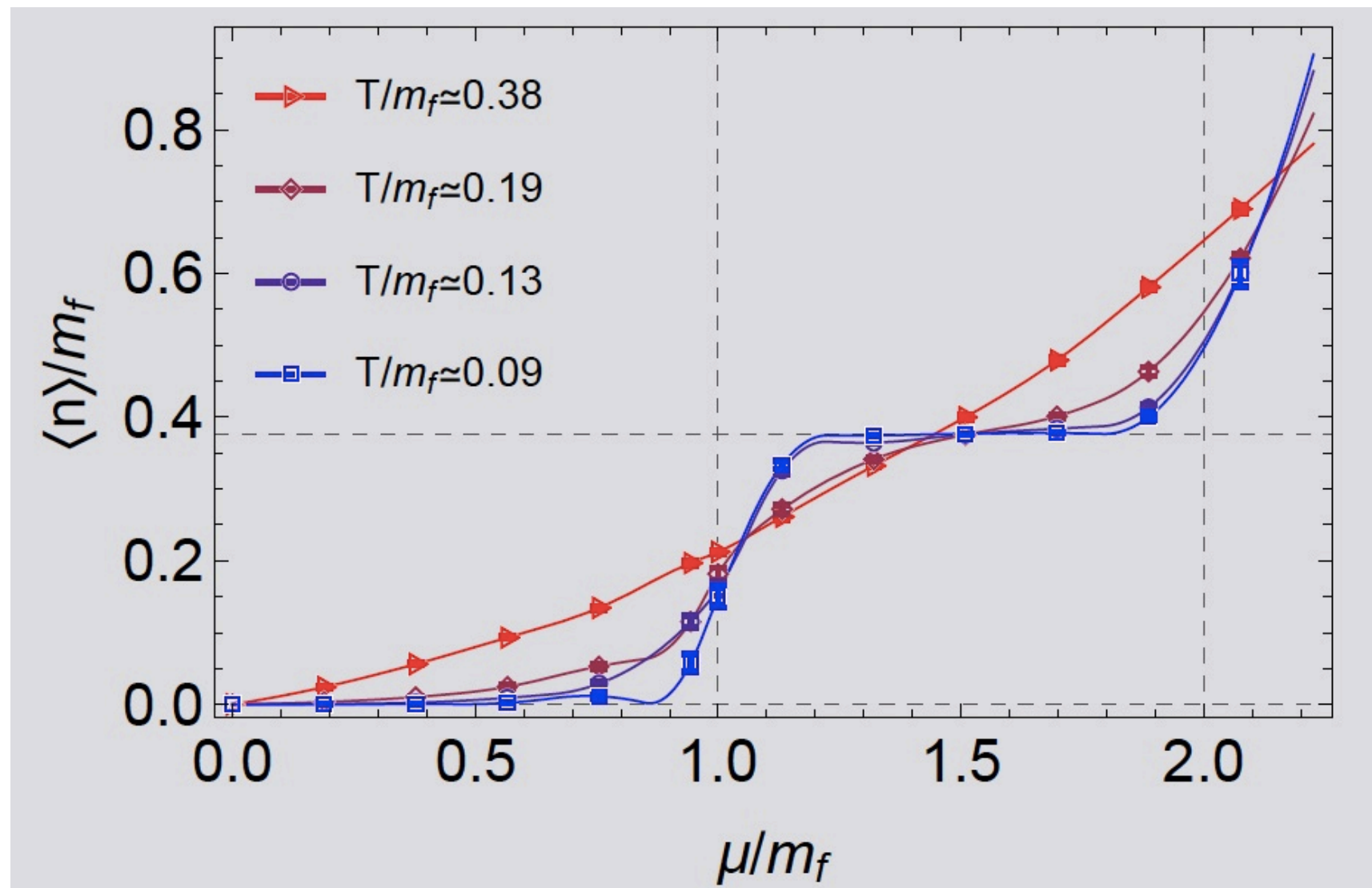
FIG. 3. Comparison of the average density  $\langle n \rangle$  obtained with the worm algorithm (WA) [22] with the Aurora algorithm (AA)

- 4d relativistic Bose gas: complex scalar field theory
- Monte Carlo on thimble softens the sign problem
- results comparable to “worm algorithm”

$$\mathcal{L} = \bar{\psi}^a (\gamma_\nu \partial_\nu + m + \mu \gamma_0) \psi^a + \frac{g^2}{2N_f} (\bar{\psi}^a \gamma_\nu \psi^a) (\bar{\psi}^b \gamma_\nu \psi^b)$$

- chain of interacting fermions: asymptotically free
- sign problem at nonzero density
- generalized thimble method: balance flow cost with sign problem cost

Monte Carlo taming of  
the sign problem and  
demonstration of the  
“Silver Blaze” phenomenon



## Resurgence in QM or QFT Path Integrals?

- perturbation theory works, but it is generically divergent, and it is only part of the story
- resurgence: perturbation theory encodes non-perturbative information

path integral  $\rightarrow$  perturbation theory  $\rightarrow$  Borel  $\rightarrow$  trans-series

path integral  $\rightarrow$  saddle expansion  $\rightarrow$  asymptotics  $\rightarrow$  trans-series

path integral  $\rightarrow$  Lefschetz thimbles/Monte Carlo  $\rightarrow$  trans-series

main conjecture: these should all be the same thing, and resurgence should connect them, as well as connecting different saddles



# Divergence of Perturbation Theory in Quantum Electrodynamics

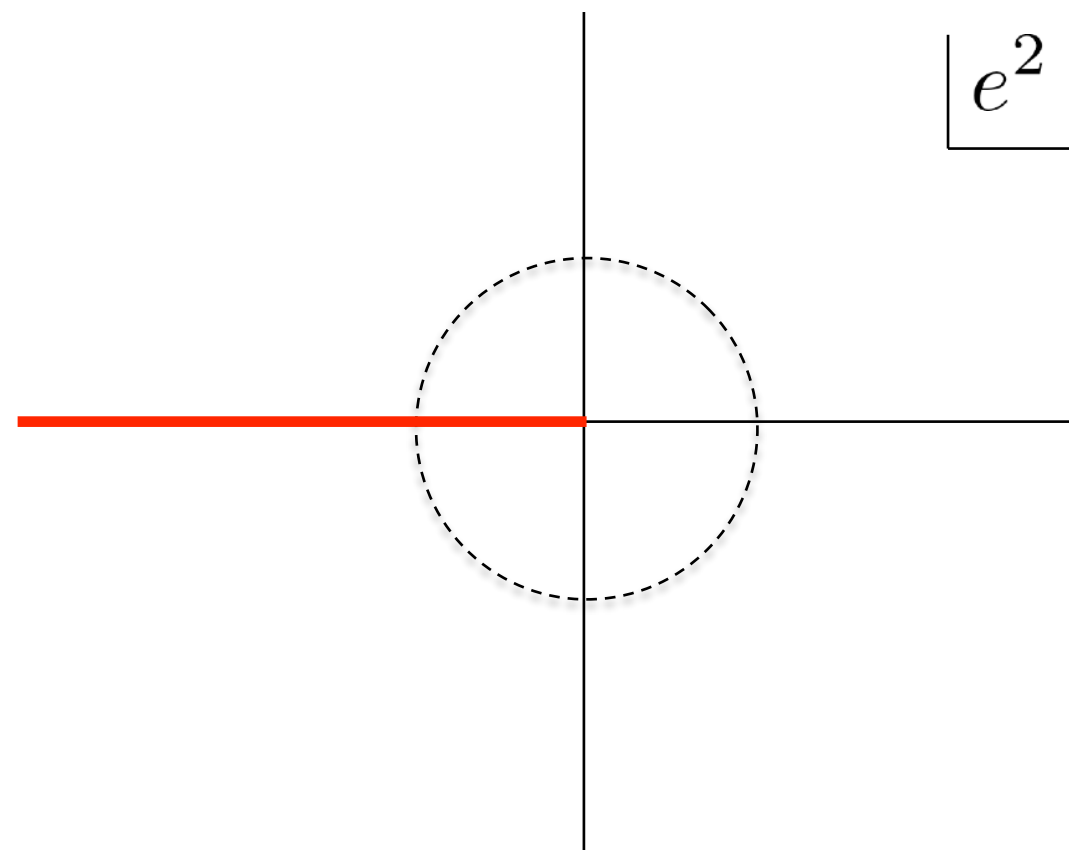
F. J. DYSON

*Laboratory of Nuclear Studies, Cornell University, Ithaca, New York*

(Received November 5, 1951)

An argument is presented which leads tentatively to the conclusion that all the power-series expansions currently in use in quantum electrodynamics are divergent after the renormalization of mass and charge. The divergence in no way restricts the accuracy of practical calculations that can be made with the theory, but raises important questions of principle concerning the nature of the physical concepts upon which the theory is built.

$$F = a_0 + a_1 e^2 + a_2 e^4 + a_3 e^6 + \dots$$



$$e^2 < 0$$

unstable

# Borel Summation: Physical Regularization of Divergent Series

Borel transform of a divergent series with  $c_n \sim n!$

$$f(g) \sim \sum_{n=0}^{\infty} c_n g^n \quad \rightarrow \quad \mathcal{B}[f](t) = \sum_{n=0}^{\infty} \frac{c_n}{n!} t^n$$

Borel sum of the divergent series:

$$\mathcal{S}[f](g) = \frac{1}{g} \int_0^{\infty} dt e^{-t/g} \mathcal{B}[f](t)$$

- the singularities of  $\mathbf{B}[f](t)$  provide a physical encoding of the global asymptotic behavior of  $f(g)$
- singularities of Borel transform  $\longleftrightarrow$  non-perturbative physics
- singularities on positive Borel  $t$  axis: exponentially small imaginary part

# QM Perturbation Theory: Zeeman & Stark Effects

**Zeeman** : divergent, alternating, asymptotic series

$$a_n \sim (-1)^n (2n)!$$

Borel singularities on the negative Borel axis.

physics: Magnetic field causes (real) energy level shifts

**Stark** : divergent, non-alternating, asymptotic series

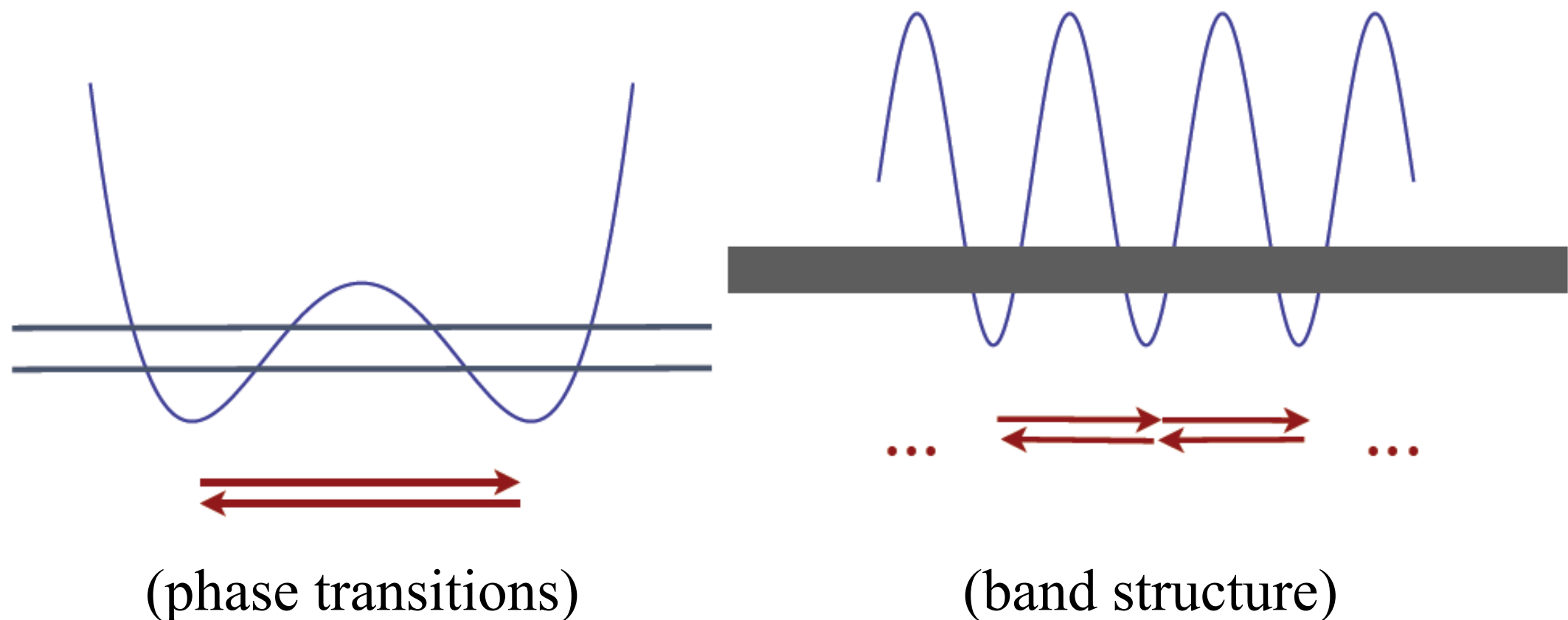
$$a_n \sim (2n)!$$

Borel singularities on the positive Borel axis.

physics: Electric field causes (real) energy level shifts

and ionization (imaginary, exponentially small)

# Instantons and Non-Perturbative Physics



- exponentially small non-perturbative splitting due to tunneling
- Yang-Mills theory and QCD have aspects of both systems

less familiar: perturbation theory is non-alternating divergent

but these systems are stable ???

- resolution: trans-series encodes cancellations between imaginary terms



# 1/R Expansion for $H_2^+$ : Analyticity, Summability, Asymptotics, and Calculation of Exponentially Small Terms

Robert J. Damburg and Rafail Kh. Propin

*Institute of Physics, Latvian Academy of Sciences, Riga, Salaspils, U.S.S.R.*

and

Sandro Graffi

*Dipartimento di Matematica, Università di Bologna, 40127 Bologna, Italy*

and

Vincenzo Grecchi

*Dipartimento di Matematica, Università di Modena, 41100 Modena, Italy*

and

Evans M. Harrell, II

*Department of Mathematics, Georgia Institute of Technology, Atlanta, Georgia 30332*

and

Jiří Čížek and Josef Paldus

*Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada*

and

Harris J. Silverstone

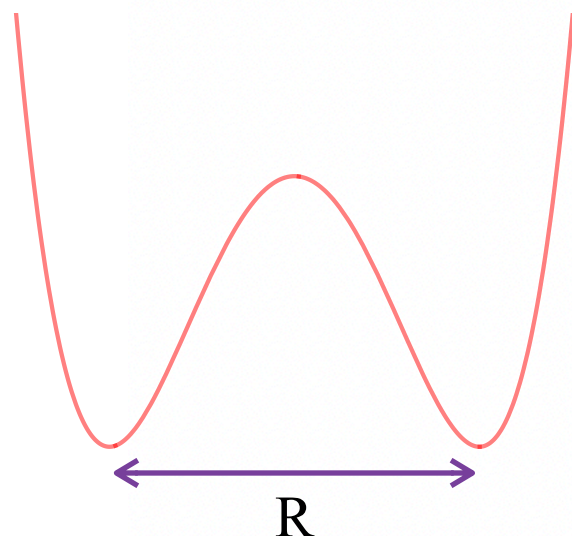
*Department of Chemistry, The Johns Hopkins University, Baltimore, Maryland 21218*

(Received 8 November 1983)

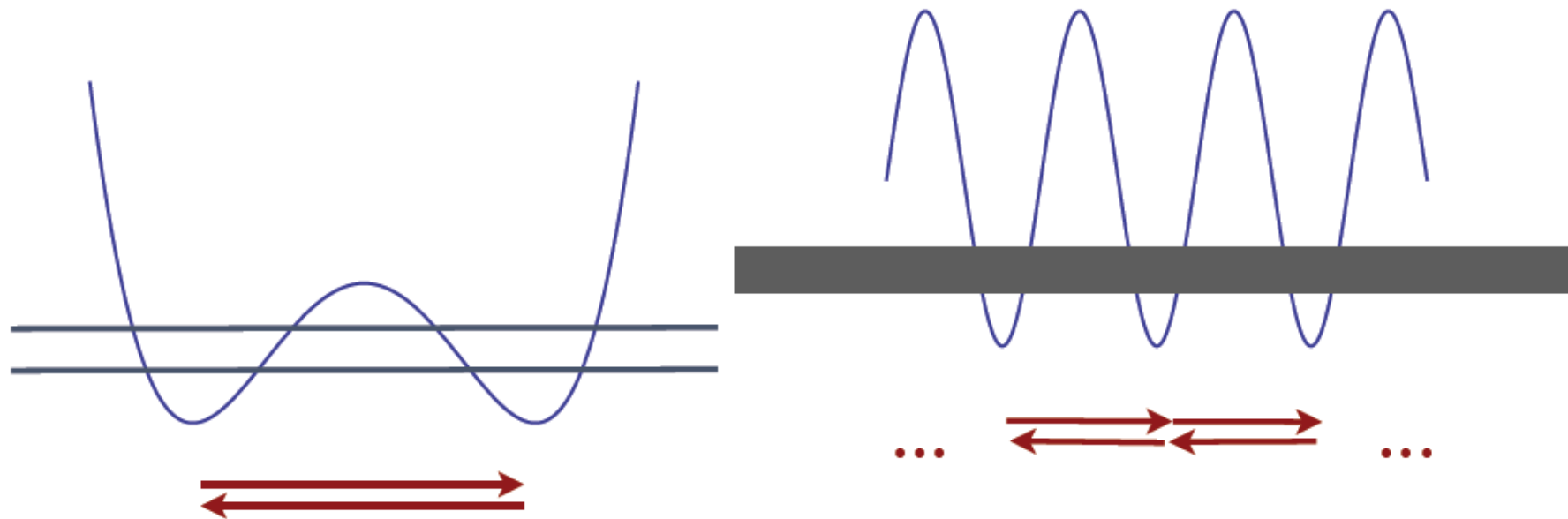
The  $1/R$  perturbation series for  $H_2^+$  has a complex Borel sum whose imaginary part determines the asymptotics of the perturbed energy coefficients  $E^{(N)}$ . The full asymptotic expansion for the energy includes complex, exponentially small terms:

$$E(R) \sim \sum E^{(N)}(2R)^{-N} + e^{-R/n} \sum a^{(N)}(2R)^{-N} \\ + e^{-2R/n} [\sum d^{(N)}(2R)^{-N} + \log R \text{ terms}] \pm i e^{-2R/n} \sum c^{(N)}(2R)^{-N} + \dots$$

The explicit imaginary terms cancel the implicit imaginary part of the Borel sum. An exact relation between the double-well gap series,  $\exp(-R/n) \sum a^{(N)}(2R)^{-N}$ , and the  $i \exp(-2R/n)$  series is derived.



# Resurgence in Quantum Mechanical Instanton Models



- trans-series for energy, including non-perturbative splitting:

$$E_{\pm}(\hbar, N) = E_{\text{pert}}(\hbar, N) \pm \frac{\hbar}{\sqrt{2\pi}} \frac{1}{N!} \left( \frac{32}{\hbar} \right)^{N+\frac{1}{2}} \exp \left[ -\frac{8}{\hbar} \right] \mathcal{P}_{\text{inst}}(\hbar, N) + \dots$$

- fluctuations about first non-trivial saddle:

$$\mathcal{P}_{\text{inst}}(\hbar, N) = \frac{\partial E_{\text{pert}}(\hbar, N)}{\partial N} \exp \left[ S \int_0^{\hbar} \frac{d\hbar}{\hbar^3} \left( \frac{\partial E_{\text{pert}}(\hbar, N)}{\partial N} - \hbar + \frac{(N + \frac{1}{2}) \hbar^2}{S} \right) \right]$$

perturbation theory encodes everything ... to all orders ... in all regions

# Resurgence in QM



resurgent relations in QM path integrals with an infinite number of saddles



# Resurgence and Phase Transitions: Multi-Parameter Trans-Series

$$Z(\hbar) = \int \mathcal{D}A \exp \left( \frac{i}{\hbar} S[A] \right)$$

- in general, we are interested in many parameters

$$Z(\hbar) \rightarrow Z(\hbar, \text{masses, couplings}, \mu, T, B, \dots)$$

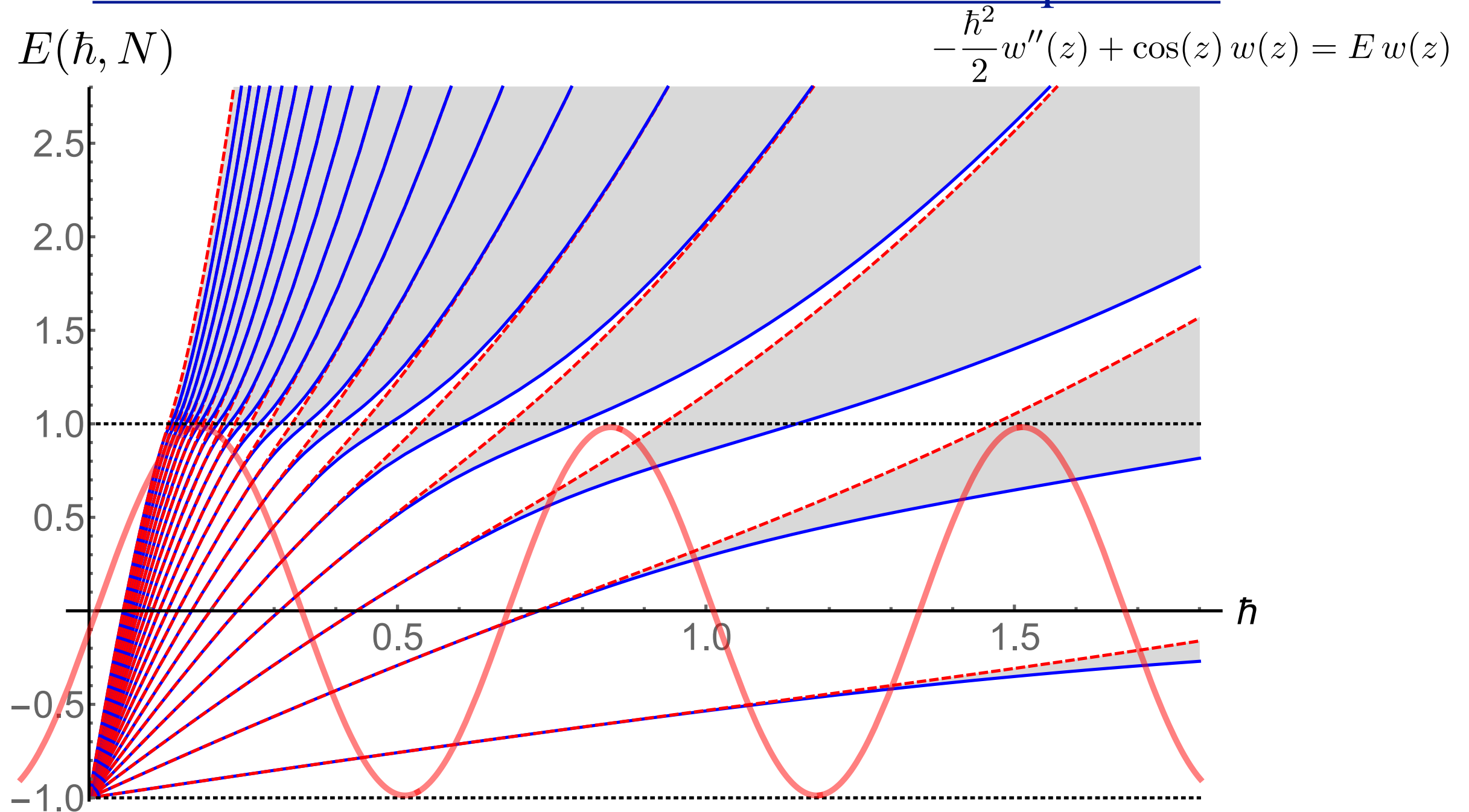
- e.g., for a phase transition: large  $N$  “thermodynamic limit”

$$Z(\hbar) \rightarrow Z(\hbar, N), \text{ and } N \rightarrow \infty$$

- multiple parameters: different limits are possible
- “uniform” ’t Hooft limit:  $N \rightarrow \infty$ ,  $\hbar \rightarrow 0$  :  $\hbar N = \text{fixed}$
- **trans-series transmutes into different form** in the large  $N$  limit
- hallmark of a Stokes transition



# Phase Transition in the Periodic Potential Spectrum



- $N$  = band/gap label;  $\hbar$  = coupling
- phase transition: narrow bands vs. narrow gaps:  $\hbar N = \frac{8}{\pi}$
- real instantons vs. complex instantons
- phase transition = “instanton condensation”
- universal Stokes transition

# Resurgence in QFT: Euler-Heisenberg Effective Action

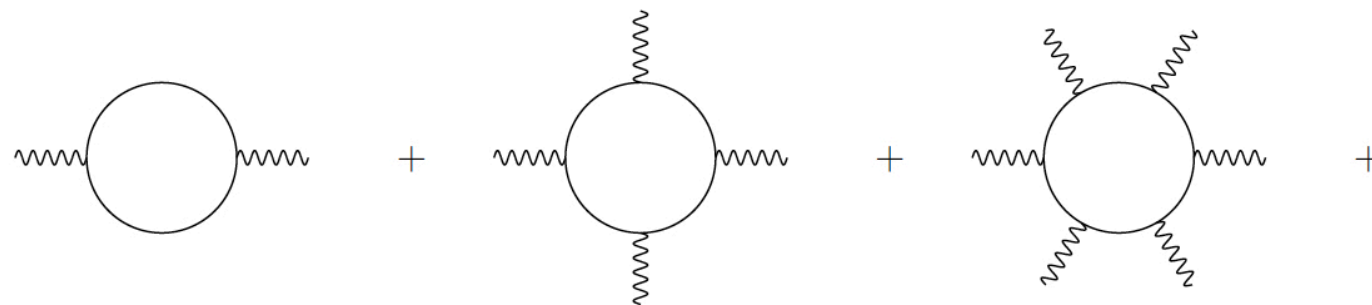
## **Folgerungen aus der Diracschen Theorie des Positrons.**

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwell'schen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2} (\mathfrak{E}^2 - \mathfrak{B}^2) + \frac{e^2}{hc} \int_0^\infty e^{-\eta} \frac{d\eta}{\eta^3} \left\{ i\eta^2 (\mathfrak{E} \mathfrak{B}) \cdot \frac{\cos \left( \frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E} \mathfrak{B})} \right) + \text{konj}}{\cos \left( \frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E} \mathfrak{B})} \right) - \text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3} (\mathfrak{B}^2 - \mathfrak{E}^2) \right\}.$$



- paradigm of effective field theory
- integral representation = Borel sum
- analogue of Stark effect ionization and Dyson's argument

$$\text{Im}[\mathcal{L}] \sim e^{-m^2 \pi / (e\mathcal{E})}$$

## Stokes Phase Transition in QFT

- “Schwinger effect” with *monochromatic* E field:  $E(t) = \mathcal{E} \cos(\omega t)$
- Keldysh adiabaticity parameter:  $\gamma \equiv \frac{m c \omega}{e \mathcal{E}}$
- WKB:  $\Gamma_{\text{QED}} \sim \exp \left[ -\pi \frac{m^2 c^3}{e \hbar \mathcal{E}} g(\gamma) \right]$

Keldysh, 1964;  
Brezin/Itzykson, 1970;  
Popov, 1971

$$\Gamma_{\text{QED}} \sim \begin{cases} \exp \left[ -\pi \frac{m^2 c^3}{e \hbar \mathcal{E}} \right] & , \quad \gamma \ll 1 \quad (\text{tunneling}) \\ \left( \frac{e \mathcal{E}}{m c \omega} \right)^{4 m c^2 / \hbar \omega} & , \quad \gamma \gg 1 \quad (\text{multiphoton}) \end{cases}$$

- phase transition: tunneling vs. multi-photon “ionization”
- phase transition: **real vs. complex instantons** (GD, Dumlu, [1004.2509](#), [1102.2899](#))
- similar to the transition for the QM cosine potential
- Borel transform is no longer meromorphic
- **SLAC** ([Snowmass LoI](#)) & **DESY** experiments aim to probe the transition region

# World-line Instantons for Intense Field Physics

Feynman worldline representation for one-loop effective action Feynman 1949, 1951

$$\Gamma[A] = - \int_0^\infty \frac{dT}{T} e^{-m^2 T} \int \mathcal{D}x(\tau) e^{-\int_0^T d\tau (\dot{x}_\mu^2 + A_\mu(x) \dot{x}_\mu)}$$

Alvarez/Affleck/Manton;  
GD, Schubert

- double saddle-point approximation (cf. Gutzwiller)

$$\ddot{x}_\mu = F_{\mu\nu}(x) \dot{x}_\nu \quad \longrightarrow \quad \text{closed loop with action} = S(T, \text{params})$$

$$\frac{\partial S(T, \text{params})}{\partial T} = -m^2 \quad \longrightarrow \quad T \text{ saddle action} = S(m^2, \text{params})$$

- localized intense fields involve complex saddles of the path integral
- **particle production = Stokes phenomenon**
- interference effects can lead to substantial (exponential) enhancement
- efficient approach to the quantum control problem
- improved semiclassical methods for scattering processes in intense fields



# Resurgence and Large N Phase Transitions in Matrix Models

3rd order phase transition in Gross-Witten-Wadia unitary matrix model

$$Z(t, N) = \int_{U(N)} DU \exp \left[ \frac{N}{t} \text{tr} (U + U^\dagger) \right]$$

Gross-Witten, 1980  
Wadia, 1980  
Marino, 2008

Z depends on two parameters: 't Hooft coupling t, and matrix size N

$$Z(t, N) = \det \left[ I_{j-k} \left( \frac{N}{t} \right) \right]_{j,k=1,\dots,N}$$

phase transition in the  
“thermodynamic” large N limit

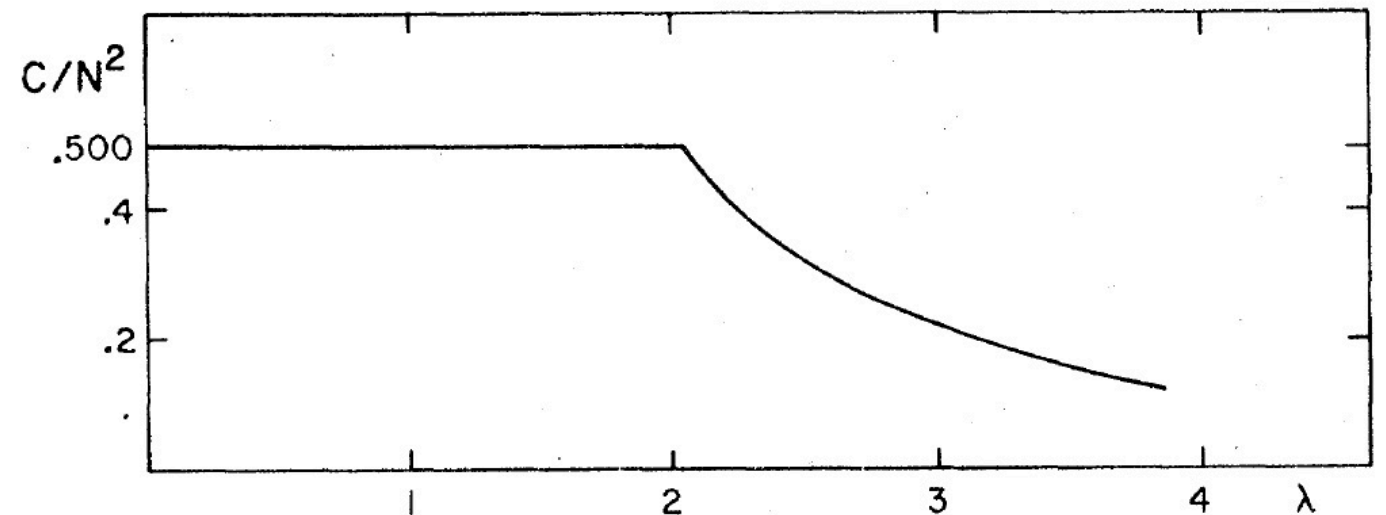


FIG. 2. The specific heat per degree of freedom,  $C/N^2$ , as a function of  $\lambda$  (temperature).

“order parameter”  $\Delta(t, N) \equiv \langle \det U \rangle$

$$t^2 \Delta'' + t \Delta' + \frac{N^2 \Delta}{t^2} (1 - \Delta^2) = \frac{\Delta}{1 - \Delta^2} \left( N^2 - t^2 (\Delta')^2 \right)$$

P. Rossi 1982

# Resurgence in Weak Coupling Large N Trans-Series

ODE  $\Rightarrow$  large N weak coupling trans-series:

Ahmed, GD, 2017

$$\Delta(t, N) \sim \sqrt{1-t} \sum_{n=0}^{\infty} \frac{d_n^{(0)}(t)}{N^{2n}} + \frac{\sigma_{\text{weak}} e^{-N S_{\text{weak}}(t)}}{\sqrt{4\pi N S'_{\text{weak}}(t)}} \sum_{n=0}^{\infty} \frac{d_n^{(1)}(t)}{N^n} + \dots$$

weak coupling large N action:

$$S_{\text{weak}}(t) = \frac{2\sqrt{1-t}}{t} - 2 \operatorname{arctanh}(\sqrt{1-t})$$

“one-instanton” fluctuations: coefficients are functions of  $t$

$$\sum_{n=0}^{\infty} \frac{d_n^{(1)}(t)}{N^n} = 1 + \frac{(3t^2 - 12t - 8)}{96(1-t)^{3/2}} \frac{1}{N} + \dots$$

resurgence: large-order growth of “perturbative coefficients”:

$$d_n^{(0)}(t) \sim \frac{-1}{\sqrt{2}(1-t)^{3/4}\pi^{3/2}} \frac{\Gamma(2n - \frac{5}{2})}{(S_{\text{weak}}(t))^{2n - \frac{5}{2}}} \left[ 1 + \frac{(3t^2 - 12t - 8)}{96(1-t)^{3/2}} \frac{S_{\text{weak}}(t)}{(2n - \frac{7}{2})} + \dots \right]$$

# Resurgence in Strong Coupling Large N Trans-Series

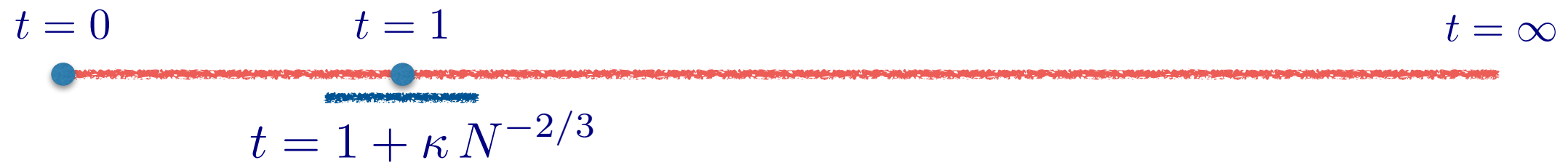
- large N strong-coupling:  $\Delta(t, N) \approx \sigma J_N \left( \frac{N}{t} \right)$
- Debye expansion: completely different trans-series

$$\Delta(t, N) \sim \frac{t e^{-N S_{\text{strong}}(t)}}{\sqrt{2\pi N |S'_{\text{strong}}(t)|}} \sum_{n=0}^{\infty} \frac{U_n^{(0)}(t)}{N^n} + \frac{1}{4(t^2 - 1)} \left( \frac{t e^{-N S_{\text{strong}}(t)}}{\sqrt{2\pi N |S'_{\text{strong}}(t)|}} \right)^3 \sum_{n=0}^{\infty} \frac{U_n^{(1)}(t)}{N^n} + \dots$$

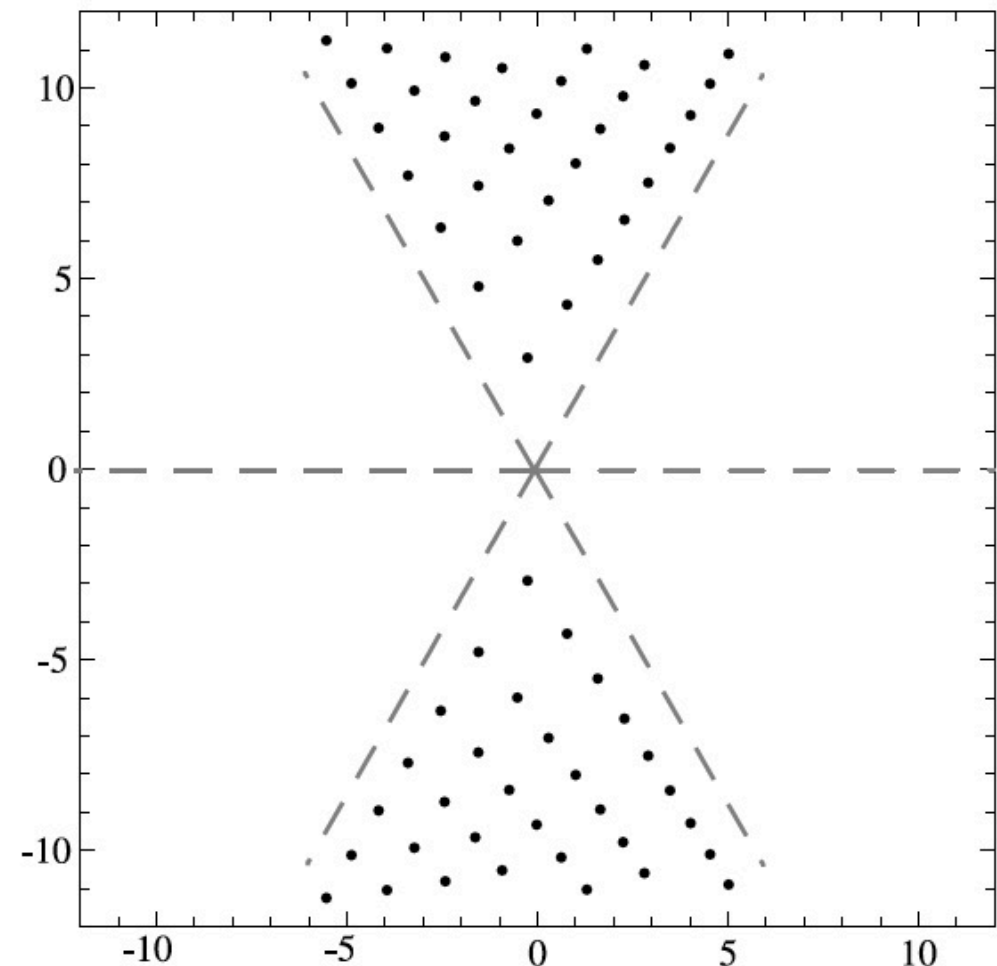
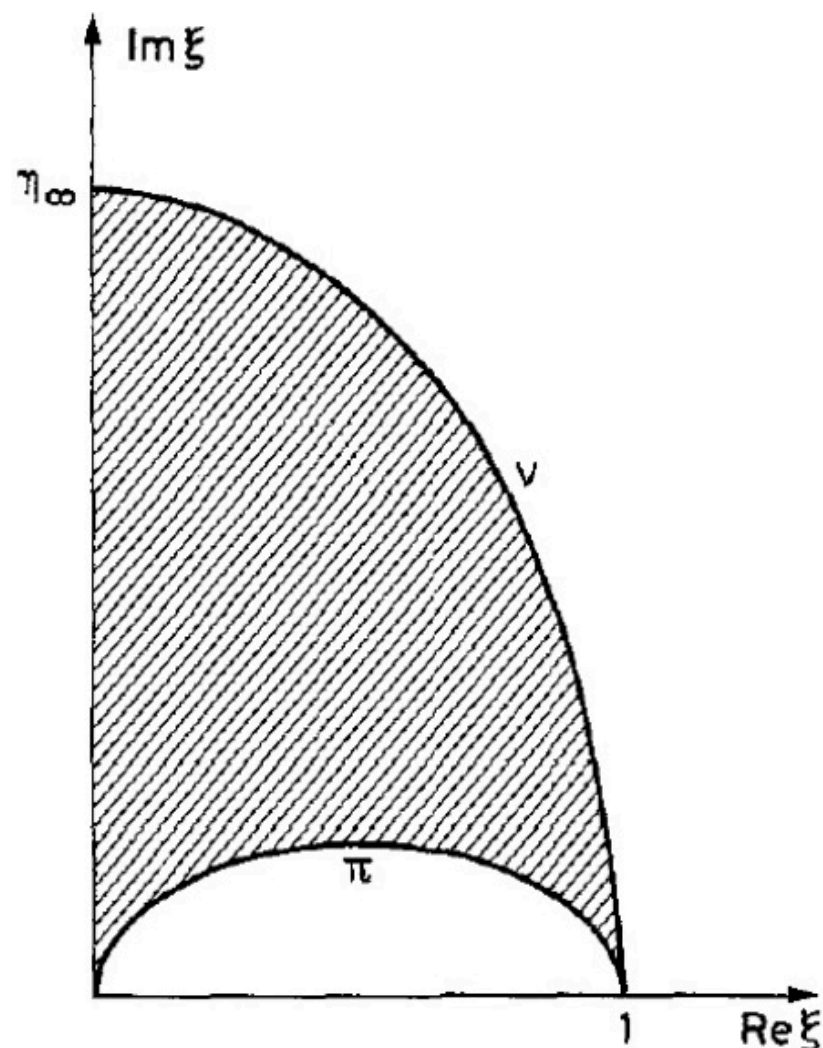
- large N strong-coupling action:  $S_{\text{strong}}(t) = \text{arccosh}(t) - \sqrt{1 - \frac{1}{t^2}}$
- low-order/large-order resurgence relation (for all  $t$ ):

$$U_n(t) \sim \frac{(-1)^n (n-1)!}{2\pi (2S_{\text{strong}}(t))^n} \left( 1 + U_1(t) \frac{(2S_{\text{strong}}(t))}{(n-1)} + U_2(t) \frac{(2S_{\text{strong}}(t))^2}{(n-1)(n-2)} + \dots \right)$$

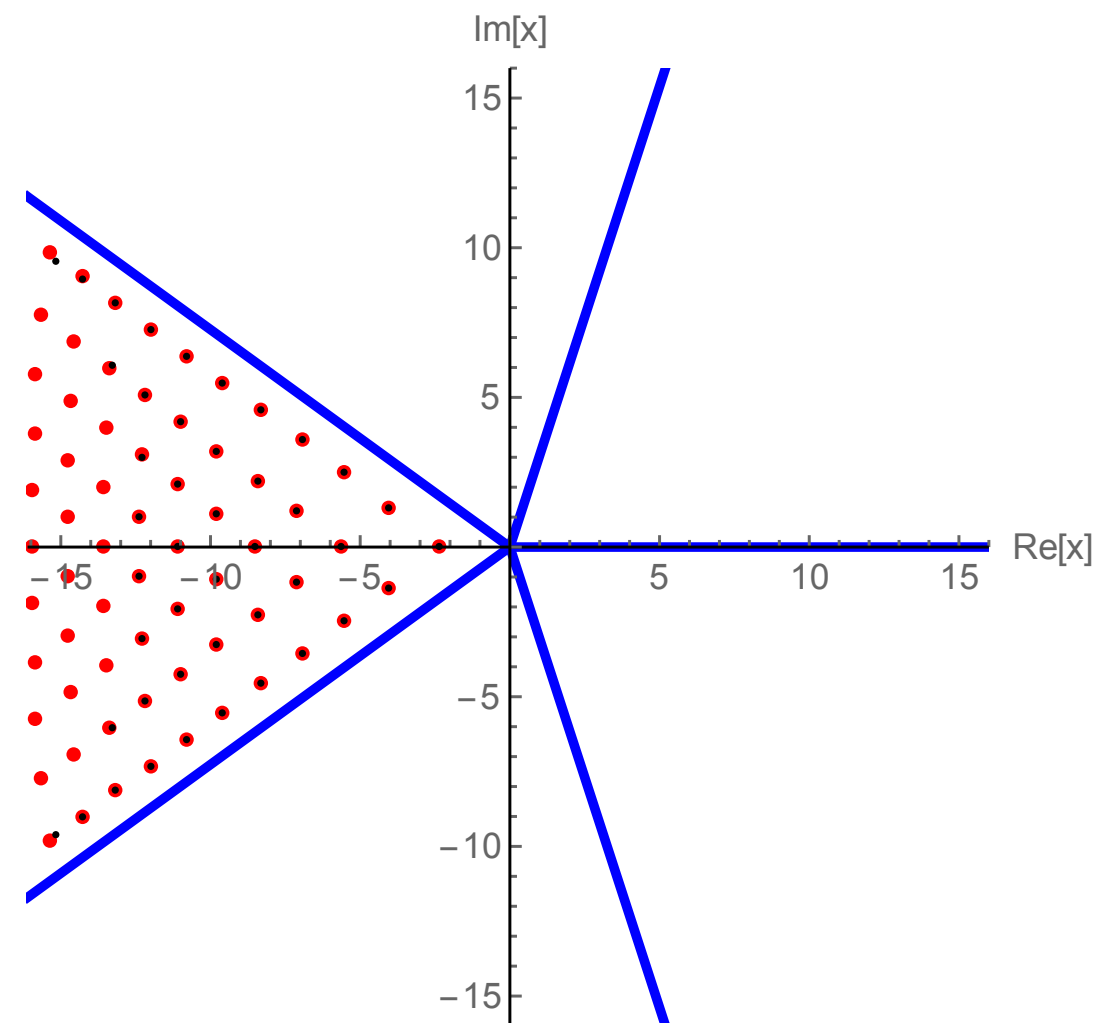
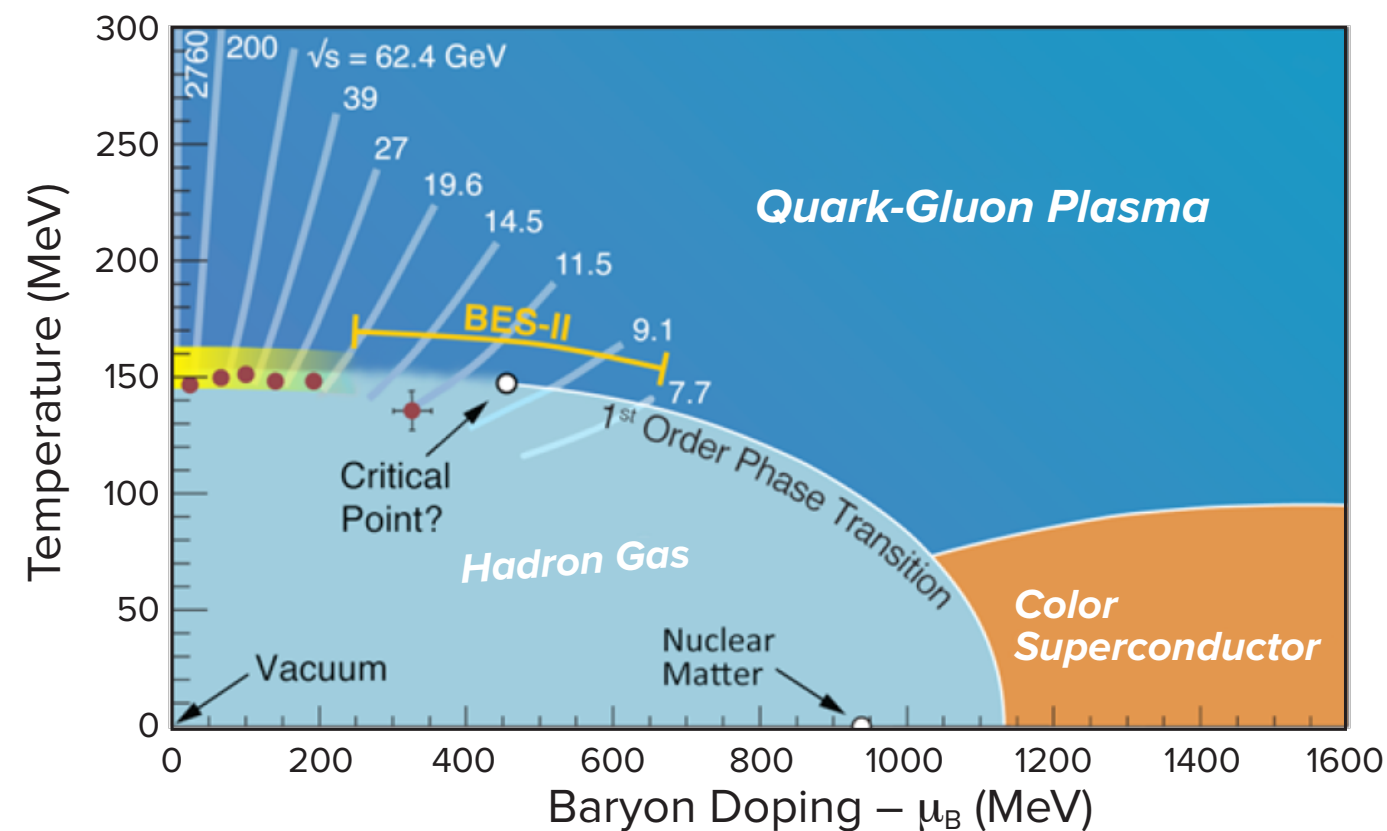
# Lee-Yang view of Large N Phase Transitions in Matrix Models



- double-scaling limit region: bridge between trans-series (nonlinear Airy)
- Lee-Yang: complex zeros of  $Z(t, N)$  pinch the real  $t$  axis at the phase transition, in the thermodynamic (large  $N$ ) limit



- sometimes perturbation theory/asymptotics is the ONLY thing we can do
- question: how much global non-perturbative information can be decoded from a FINITE number of perturbative coefficients ?



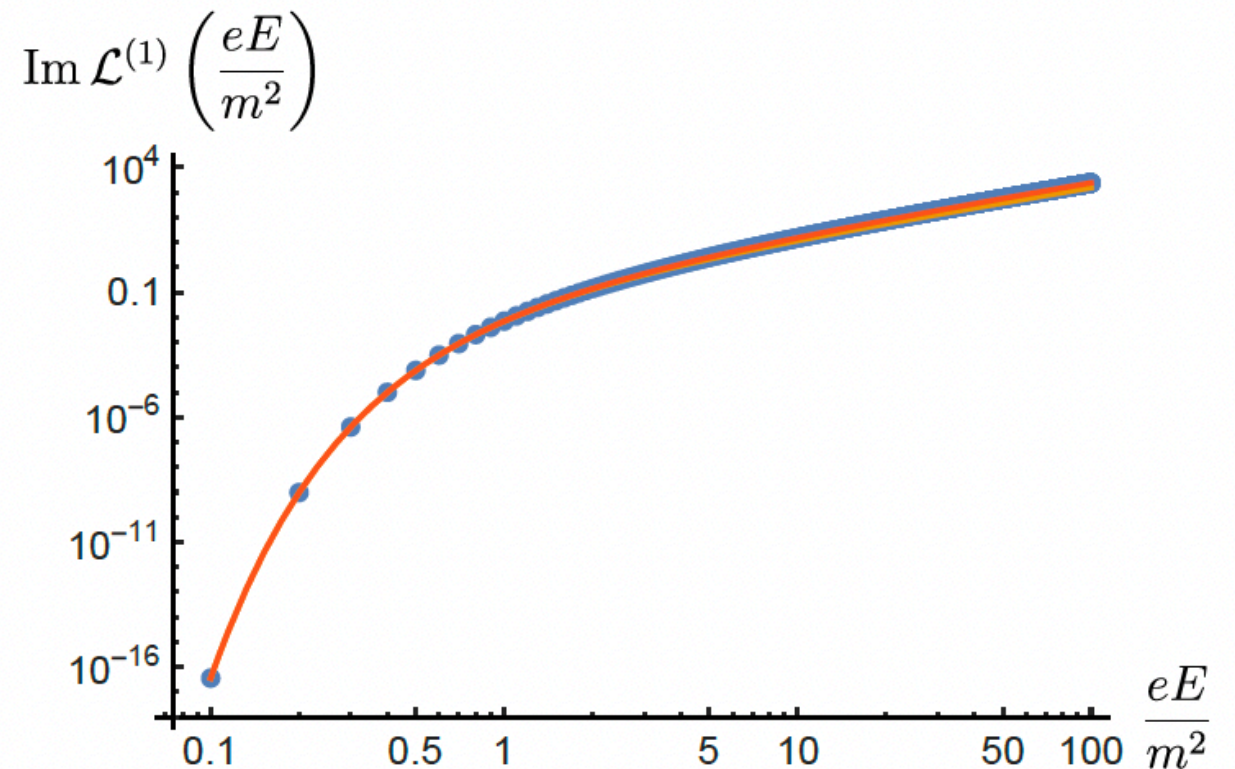
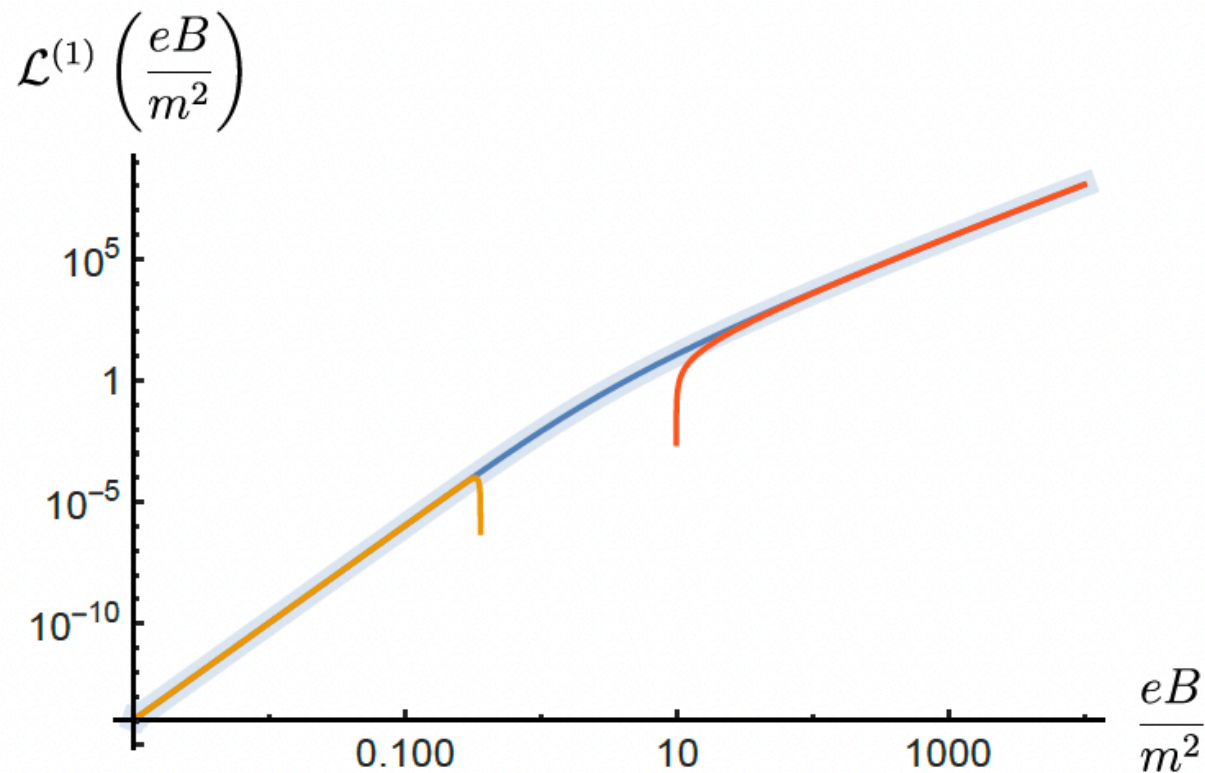
*tritronquee of Painleve I eqn.*



# Resurgent Extrapolation: Euler-Heisenberg at 1-loop

$$\begin{aligned}
 \mathcal{L}^{(1)}\left(\frac{eB}{m^2}\right) &= -\frac{B^2}{2} \int_0^\infty \frac{dt}{t^2} \left( \coth t - \frac{1}{t} - \frac{t}{3} \right) e^{-m^2 t/(eB)} \\
 &\sim \frac{B^2}{\pi^2} \left(\frac{eB}{m^2}\right)^2 \sum_{n=0}^\infty (-1)^n \frac{\Gamma(2n+2)}{\pi^{2n+2}} \zeta(2n+4) \left(\frac{eB}{m^2}\right)^{2n}, \quad eB \ll m^2 \\
 &\sim \frac{1}{3} \cdot \frac{B^2}{2} \left( \ln\left(\frac{eB}{\pi m^2}\right) - \gamma + \frac{6}{\pi^2} \zeta'(2) \right) + \dots, \quad eB \gg m^2
 \end{aligned}$$

- weak to strong  $B$  field extrapolation
- $B$  field to  $E$  field analytic continuation



- accurate over many orders of magnitude (from just 10 input terms!)

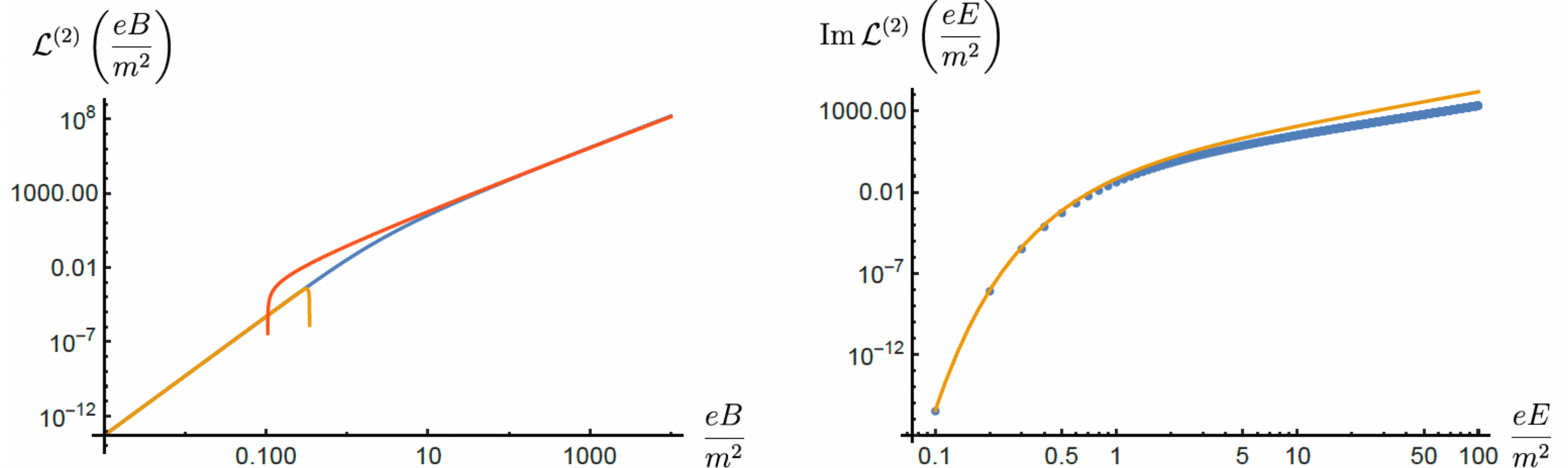
# Resurgent Extrapolation: Euler-Heisenberg at 2-loop

- 2 loop: Ritus double-integral representation

$$\mathcal{L}^{(2)}\left(\frac{eB}{m^2}\right) \sim \frac{B^2}{\pi^2} \left(\frac{eB}{m^2}\right)^2 \sum_{n=0}^{\infty} a_n^{(2)} \left(\frac{eB}{m^2}\right)^{2n}, \quad eB \ll m^2$$

$$\sim \frac{1}{4} \cdot \frac{B^2}{2} \left( \ln\left(\frac{eB}{\pi m^2}\right) - \gamma - \frac{5}{6} + 4\zeta(3) \right) + \dots, \quad eB \gg m^2$$

- weak to strong  $B$  field extrapolation
- $B$  field to  $E$  field analytic continuation



- accurate over many orders of magnitude (from just 10 input terms!)

## Conclusions

- “resurgence” is based on a new and improved form of asymptotics
- deep(er) connections between perturbative and non-perturbative physics
- recent applications to differential eqs, QM, QFT, string theory, ...
- resurgent extrapolation: high-precision extraction of physical information from finite order expansions
- outlook: computational access to strongly-coupled systems, finite density, phase transitions, particle production, far-from-equilibrium physics, ...

Further topics not covered today ....

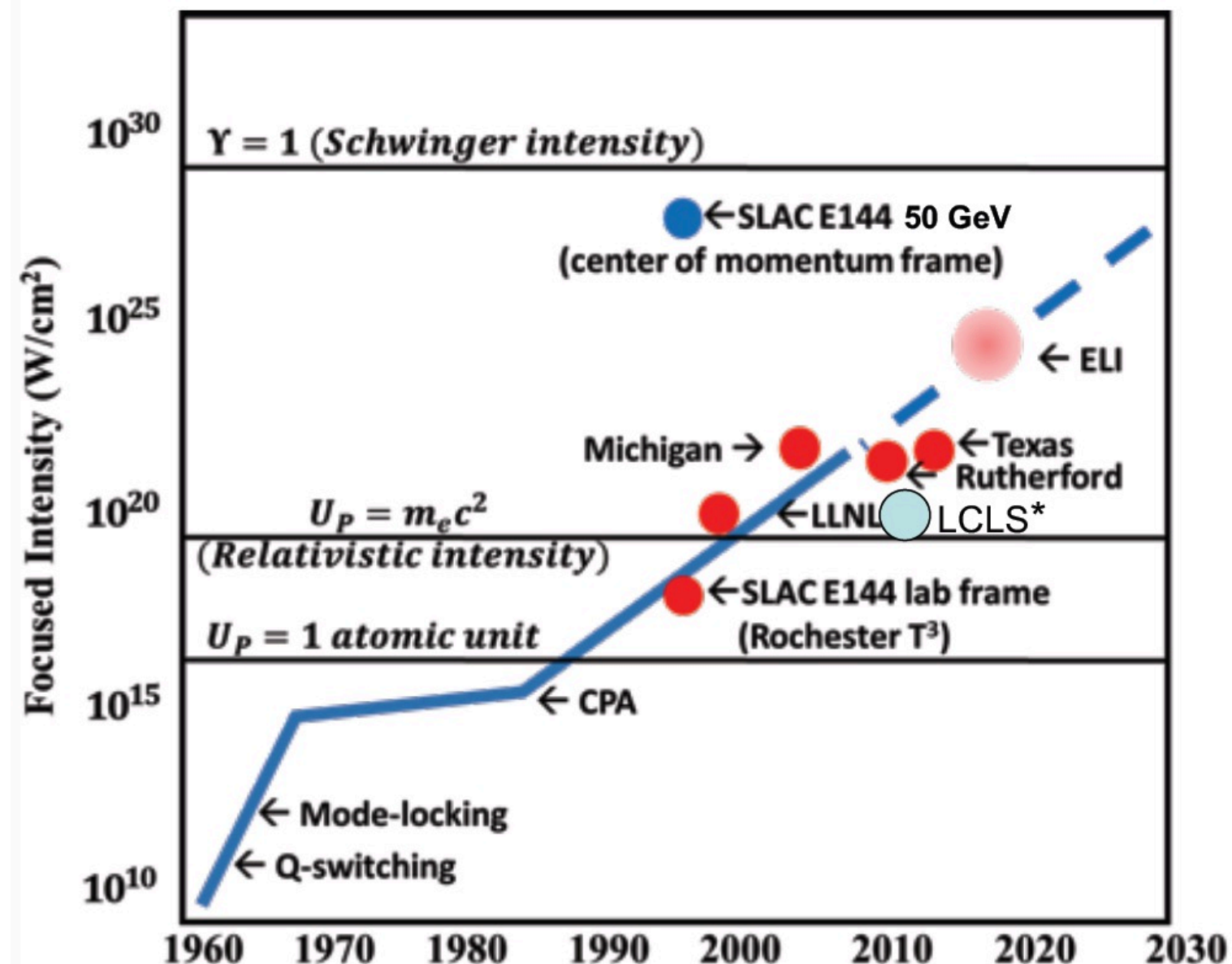
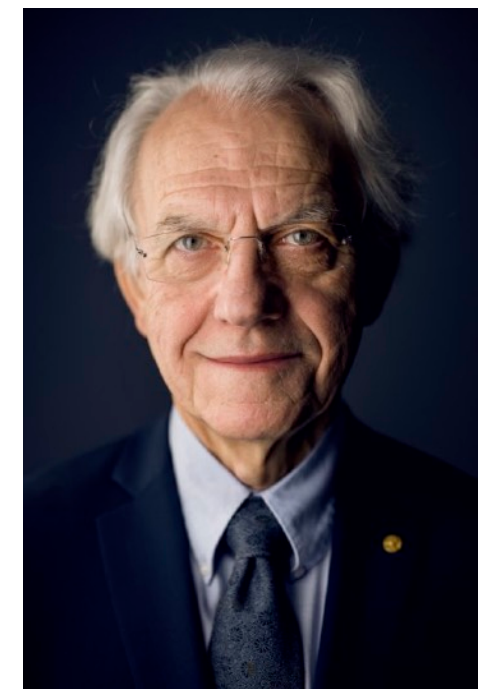
- Lefschetz thimbles and bions
- “Exact WKB”
- Chern-Simons theory
- Yang-Mills & QCD
- Dualities and Modularity
- Integrability and large N
- Renormalons and the OPE
- Hopf algebraic renormalization
- Numerical Stochastic Perturbation Theory



# QFT at Extreme Intensities

- Current experimental proposals: laser-laser; laser-lepton; lepton-lepton; highly-charged ions; astrophysics; ...
- Important theoretical puzzles remain
- Semiclassical computations?
- Non-equilibrium physics?
- Ultra-fast dynamics?
- Snowmass LOI

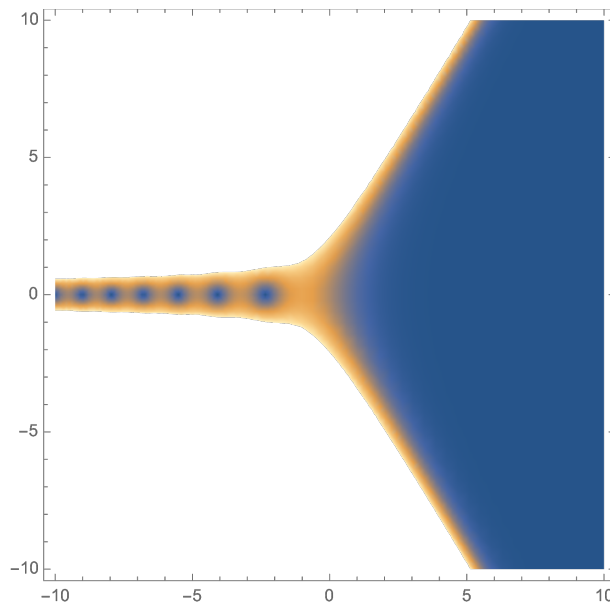
Strickland  
& Mourou  
Nobel Prize 2018



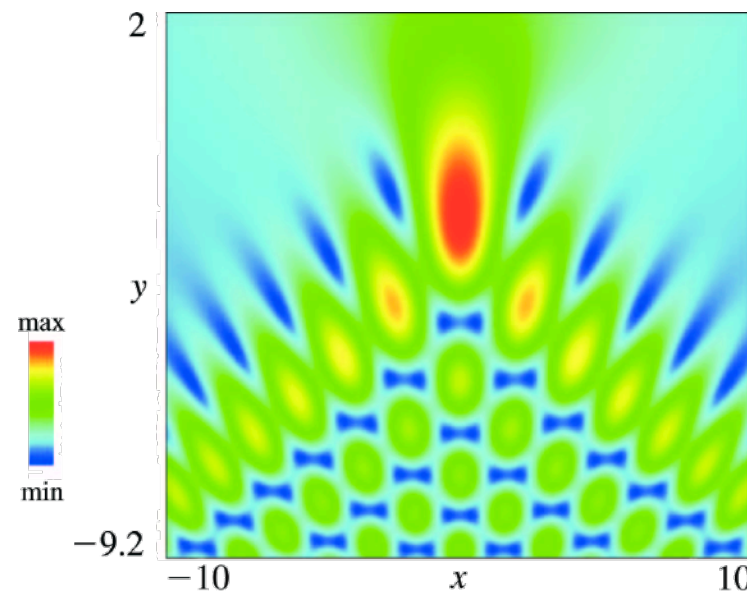
Reviews: Di Piazza et al, 2012;  
US National Academies, 2018

canonical catastrophe integrals:  $\Psi_K(\vec{x}) = \int_{-\infty}^{\infty} du \exp [i \Phi(u; \vec{x})]$

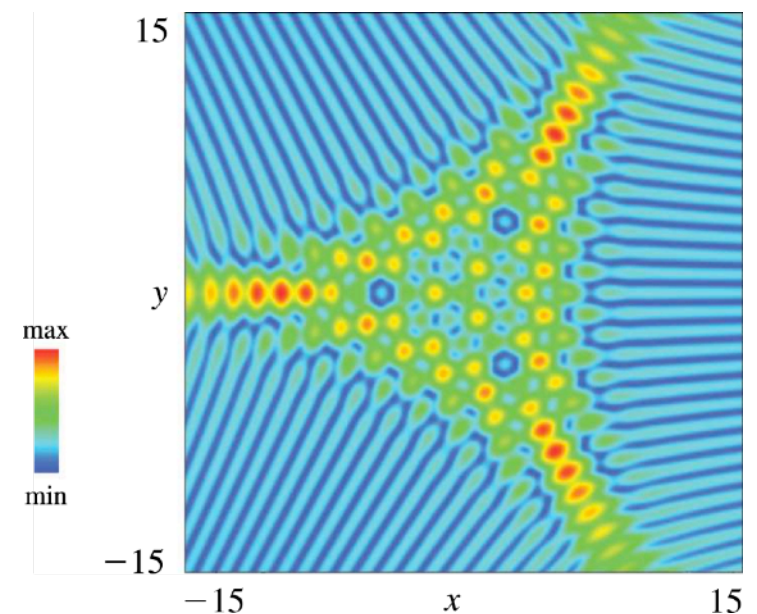
Arnold, ...



fold (P-I)



cusp (P-II)



elliptic umbilic (P-IV)

$$\Psi^{(E)}(t, x, y) = 2\sqrt{\frac{\pi}{3}} \exp \left[ i \left( \frac{4}{27}t^3 + \frac{1}{3}xt - \frac{1}{4}\pi \right) \right] \int_{\infty \exp(-7\pi i/12)}^{\infty \exp(\pi i/12)} \exp \left[ i \left( u^6 + 2tu^4 + (t^2 + x)u^2 + \frac{y^2}{12u^2} \right) \right] du$$

Newton-Calogero form of Painleve equations:  $\ddot{u} = -\partial_u V(u, t)$

Painleve tau functions: resurgent conformal block expansions

N=2 SUSY QFT in 4d: Nekrasov dual partition function & RG interpretation

basic “skeleton” upgraded from exponential integrals to QM and to QFT  
path integrals, with resurgence results at each level