Holography and some phenomenological aspects of QCD

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The Myriad Colourful Ways of Understanding Extreme QCD Matter
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Outline

QCD: The Burning Questions

phase structure, magnetic environment, non-vanishing density

Holography: The Approach & The Ingredients

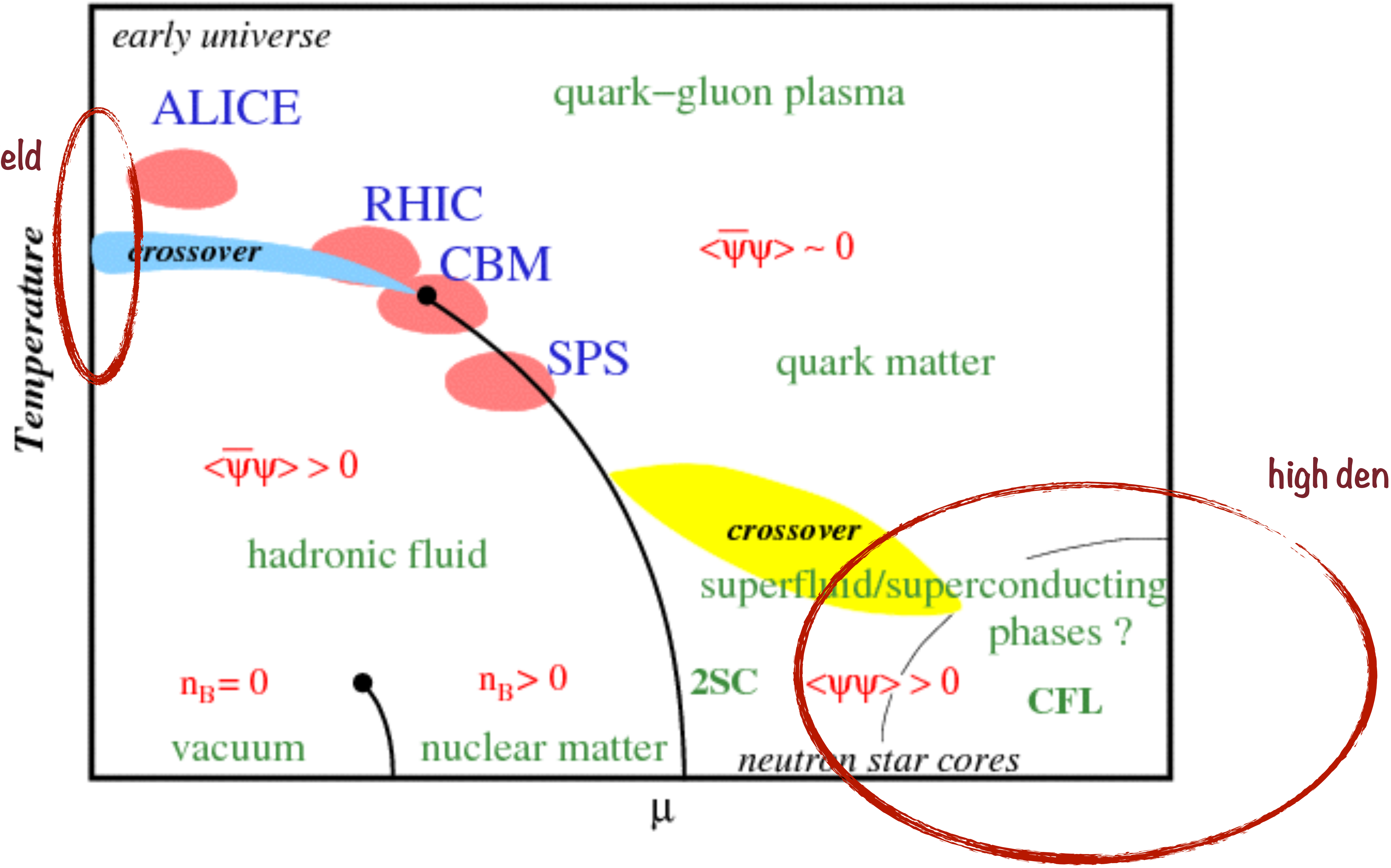
a brief account & comparison

Holographic Tools for QCD-like Phenomenology

some specific examples,
conclusions,
outlook

QCD: The Burning Questions

QCD Phase Diagram: Given a theory, can we determine its phases from first principle?



high magnetic field

high density

picture courtesy: Schaefer & Wagner

QCD: High Magnetic Field

Large magnetic field created in ultra-relativistic heavy-ion collisions at RHIC & LHC

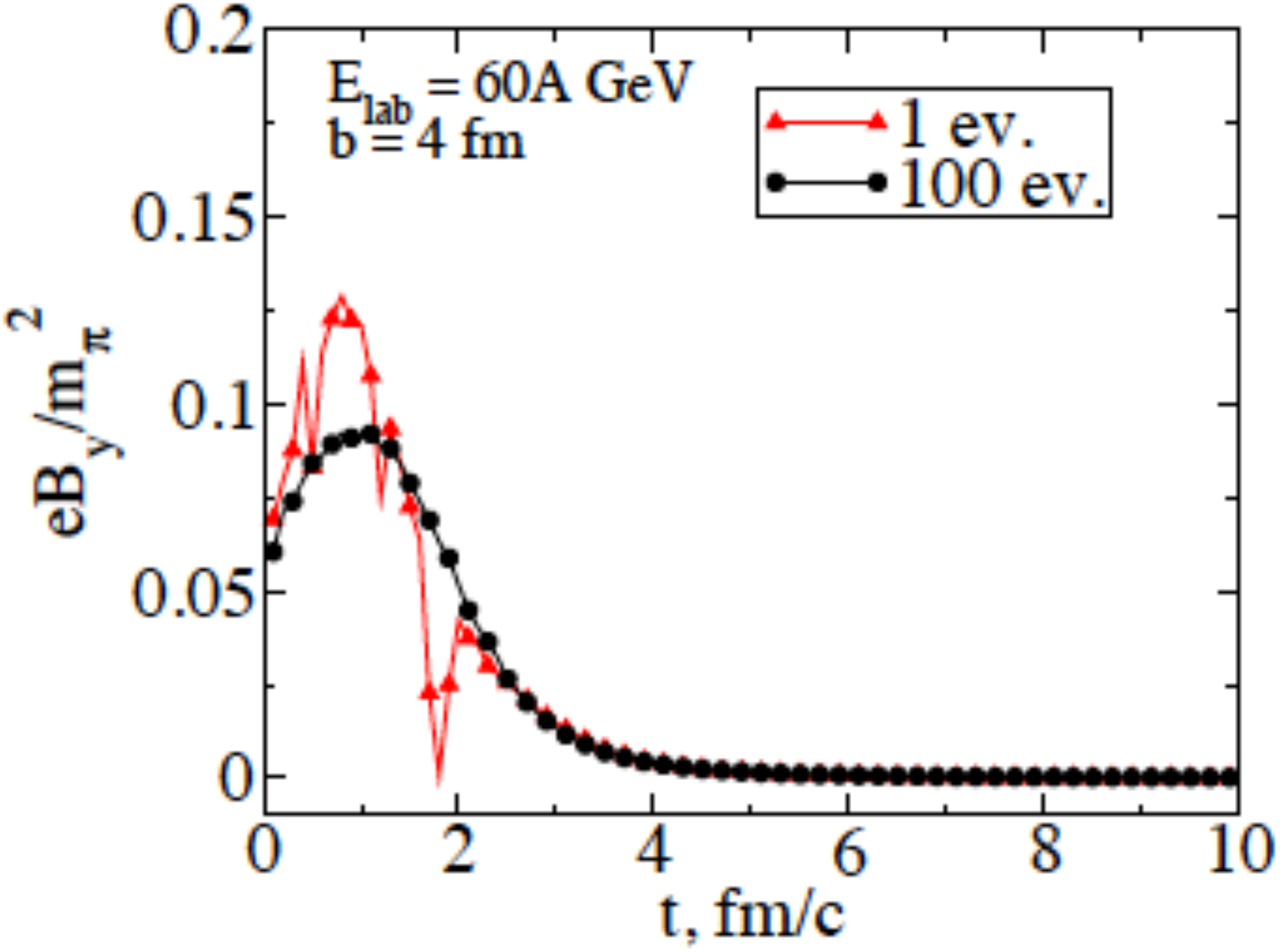
Large magnetic fields may have been present in the early universe: relevant for early Universe cosmology

Core of Neutron stars & magnetars have large magnetic field

magnetic strength $\sim \Lambda^2_{\mathrm{QCD}}$

QCD: High Magnetic Field

Magnetic profile in ultra-relativistic heavy-ion collision: Highly time-dependent



picture courtesy: Skokov, Illarionov, Toneev

QCD: High Density

Complete phase diagram of QCD @ finite density

specially, color-flavour locked (CFL) phase

Alford et. al.

Ground state of strongly interacting system @ finite density

a generic issue in QFT

Technical limitations exist

e.g. Lattice calculations suffer from the "sign" problem

Representative soluble models

Holography as a framework for analyzing QFT

Holography: Basic Ingredients

A QFT question ⟶ a classical General Relativity question, in one dimension higher

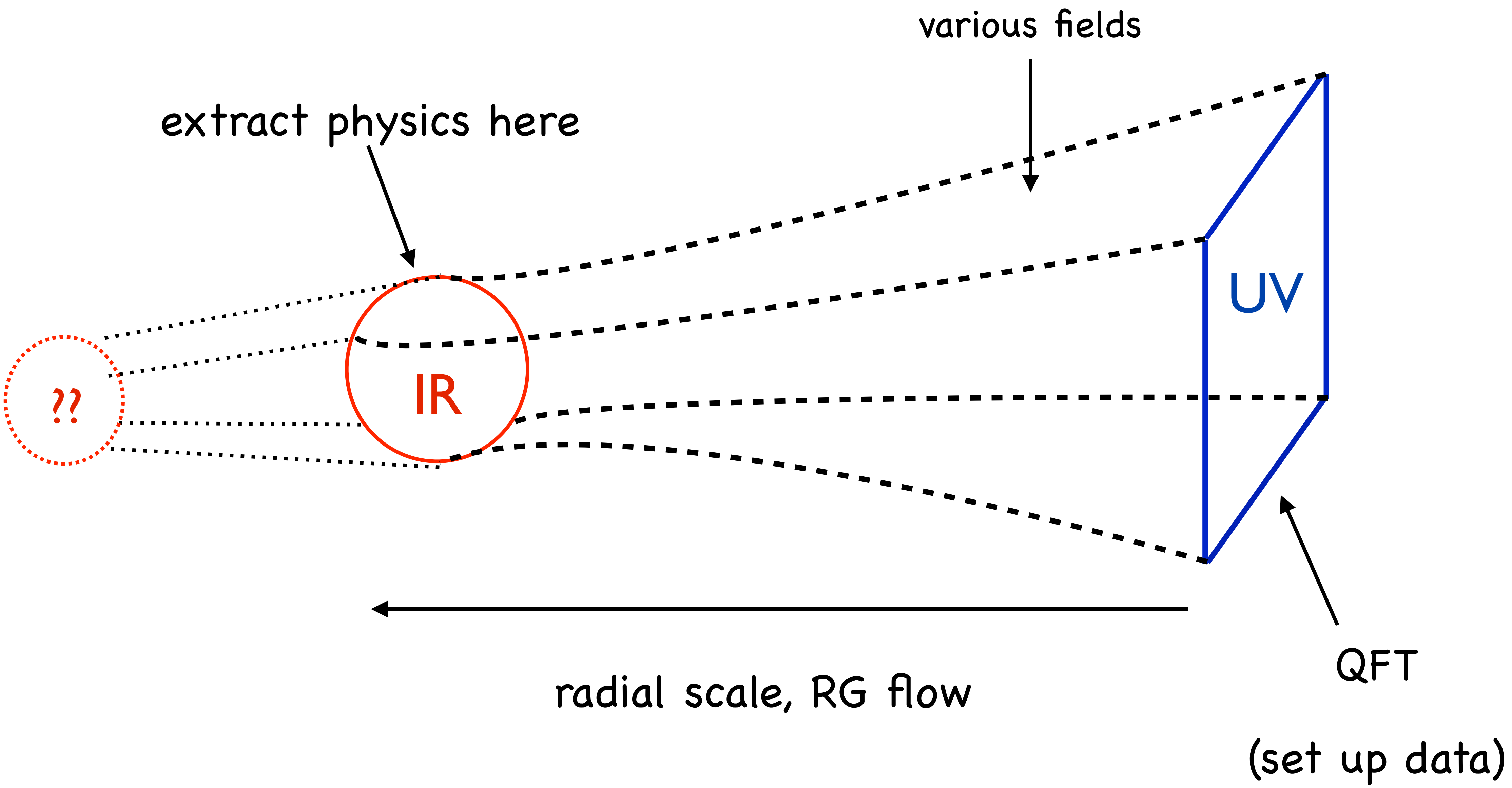
Only large N SU(N) QFTs, at strong ’t Hooft coupling

The GR description has a geometry with a preferred radial scale
This becomes the RG energy-scale of the QFT

The geometry has a (conformal) boundary, where the QFT resides

Various fields propagate in this geometry, their near boundary behaviour determine the QFT interaction term(s)

Holography: Pictorial



QCD is free in the UV: perhaps this is a natural framework

Holography: Various Approaches

Basic philosophy: View this as a tool to address Quantum Field Theory questions, at *large N*, strong coupling

Two Approaches:

Top Down	Bottom Up
Potentially, UV-complete	Wilsonian EFT
Everything is well-defined, constrained	Many free parameters
Hard, in general	Easier, in general
Less scope of phenomenology	Richer scope of phenomenology

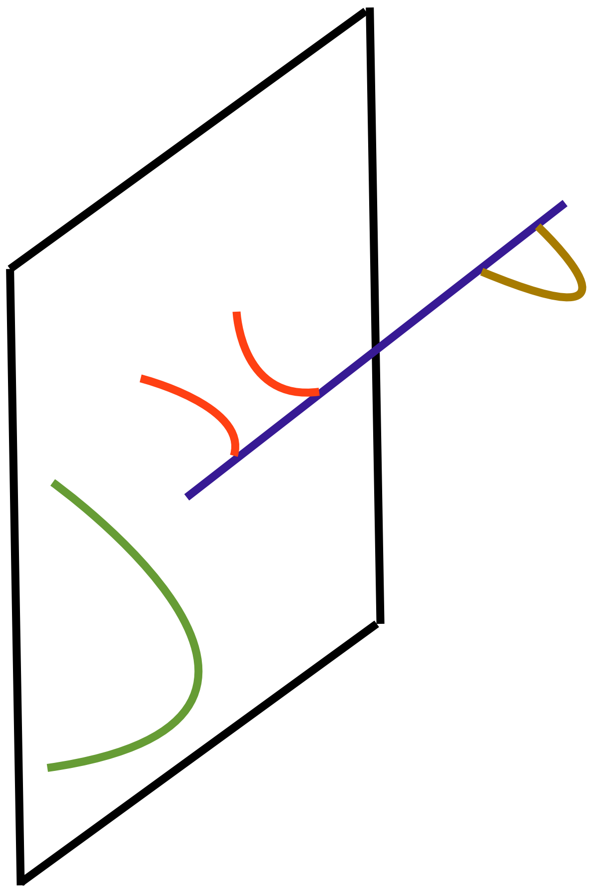
The Holographic Ingredients

Top-down approach: Strings and D-Branes

Two kinds of d.o.f: Adjoint matter & Fundamental matter

Background geometry is made of N $\mathrm{D3}$ -branes

Add N_f $\mathrm{D7}$-branes



3-3 strings: adjoint sector

3-7 strings: fundamental matter

7-7 strings: global symmetry

$U(N_f)$

Karch & Katz

Bottom-up approach: Gravity with generic Matter

Dynamics of QCD Matter

3-3 strings yield an AdS-background: {metric, scalar, other fields}

3-7 strings are probes in this background

The governing action:

$$S_{\text{brane}} = -\underset{\substack{\uparrow \\ \text{brane tension}}}{T_{Dp}} \int d^{p+1}x\, e^{\underset{\substack{\uparrow \\ \text{dilaton}}}{-\phi}} \sqrt{-\det\left[\underset{\substack{\uparrow \\ \text{induced metric}}}{g_{ab}} + (2\pi\alpha' \underset{\substack{\uparrow \\ \text{flux on the brane}}}{F_{ab}})\right]} + S_{\text{topological}}$$

Dynamics of QCD Matter

A typical configuration, summarized:

	$\mathbb{R}^{1,3}$	r	S^3	$\mathbb{R}^2$
$D3$	$-$	$\bullet$	$\bullet$	$\bullet$
$D7$	$-$	$-$	$-$	$\bullet$

3-7 strings can be separated here $\sim m_q$

The near-boundary data: $$L \sim m_q + \frac{c}{r^2} + \ldots$$

condensate: $$\langle \bar{\psi}\psi \rangle \sim c$$

The Magnetic Field

Simple to excite a magnetic flux: $F = H dx^1 \wedge dx^2$

U(1) flux on the brane

In this model, regular UV-data determines: $c\,(m_q)$

No magnetic field: $c(0) = 0$

Any non-vanishing H $\Longrightarrow$ $c(0) \neq 0$

spontaneous breaking of symmetry/mass generation, mediated by the magnetic field

Filev et. al.

Universality(?)

Magnetic catalysis in symmetry breaking: chiral symmetry breaking is facilitated, chiral condensate enhanced

Other Holographic models: similar phenomena observed

more conventional realisation of chiral symmetry breaking:

$$U(N_f)_{\rm L} \times U(N_f)_{\rm R} \rightarrow U(N_f)_{\rm diag}$$

A generic QFT phenomena

Simple reasons!

A large class of QFT models (QCD-like, low energy effective description): exhibits a similar catalysis phenomena

Simple QFT reasons: decoupling of the lowest Landau level

$$E_n = \sqrt{m^2 + |eB|\,n + p_{\parallel}^2}\;, \qquad n = 0, 1, 2, \ldots$$

decoupling limit: $|eB| \gg m^2, p_{\parallel}^2 \qquad \Longrightarrow \qquad \underbrace{E_0 = \sqrt{m^2 + p_{\parallel}^2}}$

decoupled IR-dynamics: (1+1)-dim QFT

(1+1)-dim dynamics is stronger than (3+1)-dim dynamics

condensation!

Miransky et. al.

Simple Holographic reasons!

In Holography, there is only Geometry & Fluxes

To see the simple reason, need to consider back-reaction by the magnetic flux

The flux breaks: $SO(3,1) \rightarrow SO(1,1) \times SO(2)$

$$\underbrace{\mathrm{UV} : \mathrm{AdS}_5 \rightarrow \mathrm{IR} : \mathrm{AdS}_3 \times \mathbb{R}^2}$$

This is a dynamical feature of Einstein's equations

Completely universal: $D \rightarrow D - p$ reduction with an F_p flux

Banerjee et. al.

Interim Summary

The ubiquity of Magnetic Catalysis in QFT, including QCD

QCD is never that simple: Inverse magnetic catalysis! an unsettled issue

QCD Matter: High Density

Holography works at large N

colour-flavour locking is suppressed,
chiral density wave

Deryagin et. al.

High-density, perturbative "QCD": CFL happens if $\frac{N_f}{N} \geq 10^{-3}$

back-reaction is important

Schuster & Son

Veneziano Limit: $N \to \infty \ , \quad N_f \to \infty \ , \quad \frac{N_f}{N} = \text{fixed}$

Veneziano

QCD Matter: High Density

Excite a $\mathrm{U}(1)$-field on the "flavour"-brane $F_2 = A_t'(r)\, dt \wedge dr$

Mateos et. al.

$$A_t = \mu + \frac{n_q}{r^2} + \dots$$

chemical potential

charge density

"Large charge" limit: $S_{\text{brane}} \Longrightarrow S_{\text{string}}$

(non-dynamical external quarks)

Replace the "flavour brane + flux" by an explicit external "String-sources"

An Example

Consider the background: $\mathrm{AdS}_5 \times S^5$

D3-branes yield this geometry

Introduce a bunch of strings here, they back-react and change the geometry

The UV-corrections: $g_{\mu\nu} = g_{\mu\nu}^{\mathrm{AdS}} + \mathrm{sub} - \mathrm{leading}$

The IR-geometry:

$$ds^2 = -r^{2z} dt^2 + r^2 d\vec{x}^2 + \frac{dr^2}{r^2} \ ,$$

$$e^{\phi} = \left(\frac{N^2}{n_q}\right)^2 r^6$$

non-perturbative in back-reaction

Faedo et. al.

Salient Features: Summary

The IR-physics is Lifshitz-symmetric: scale-invariance, non-relativistic

Invariance under scaling: $t \to \Lambda^z t \ , \quad \vec{x} \to \Lambda \vec{x}$

$$s \propto T^{3/z} \ , \quad z = 7$$

fundamentally different from the UV

This structure is generic in Holographic models, with scale-covariance

$$s \propto T^{(p-\theta)/z} \ , \qquad p = \text{number of spatial directions}$$

Such geometries have various instabilities

does it lead to a condensation?

Faedo et. al.

Summary

Holography can provide qualitative landmarks

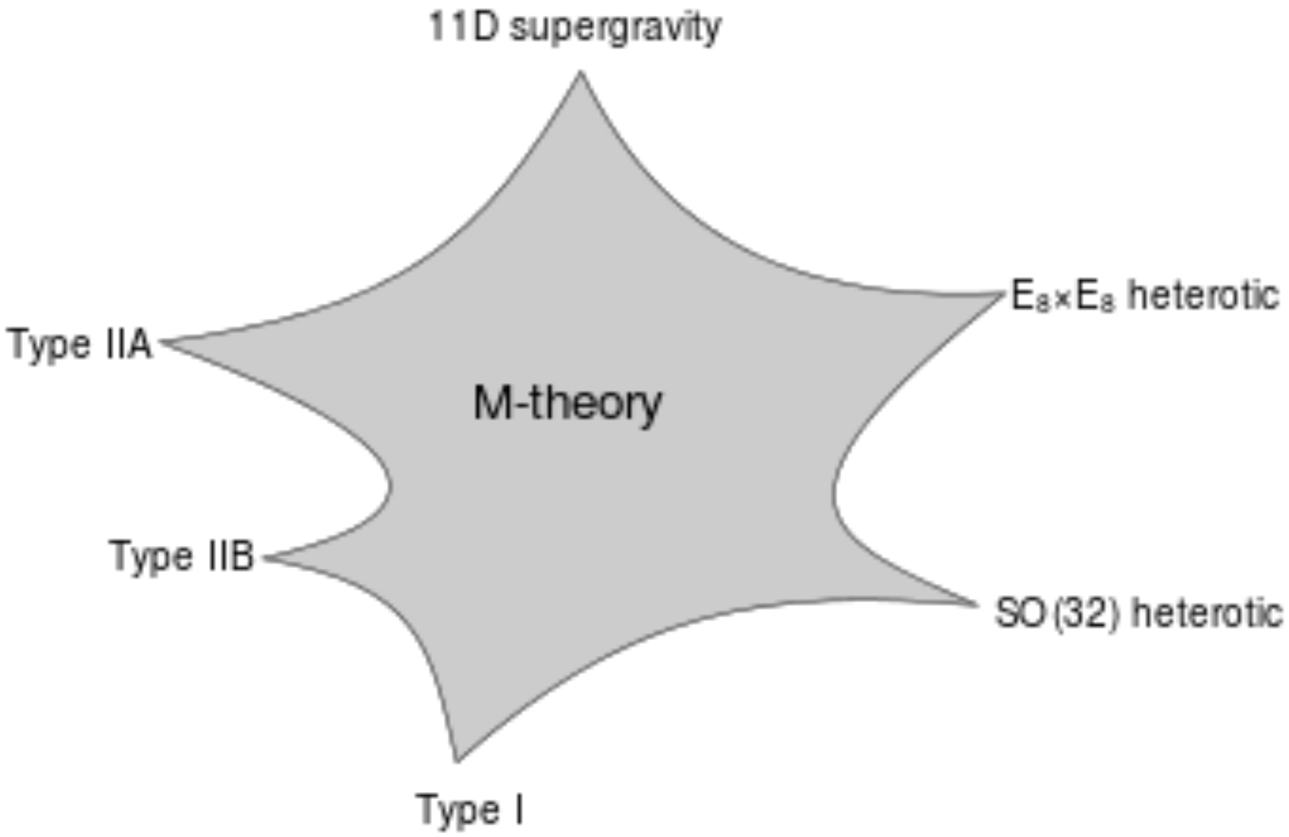
some known and some unknown results

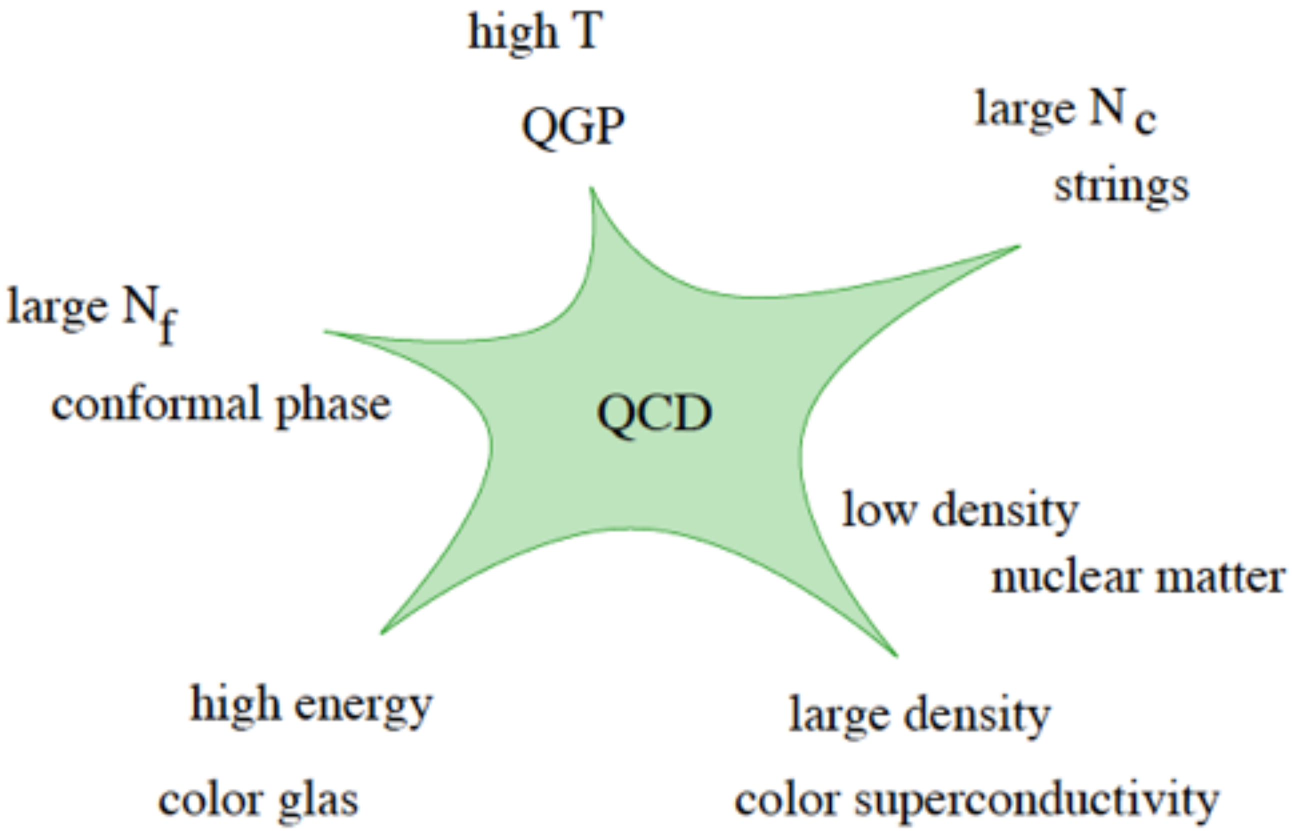
magnetic catalysis, dense phase at the IR

QCD is more than landmarks

A ripe time for cross-talks,
marriage of complementary approaches

How do we determine the phases?





Thank You!