Quantum Many-Body Systems

from high-energy nuclear physics to quantum computing

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March 17, 2023

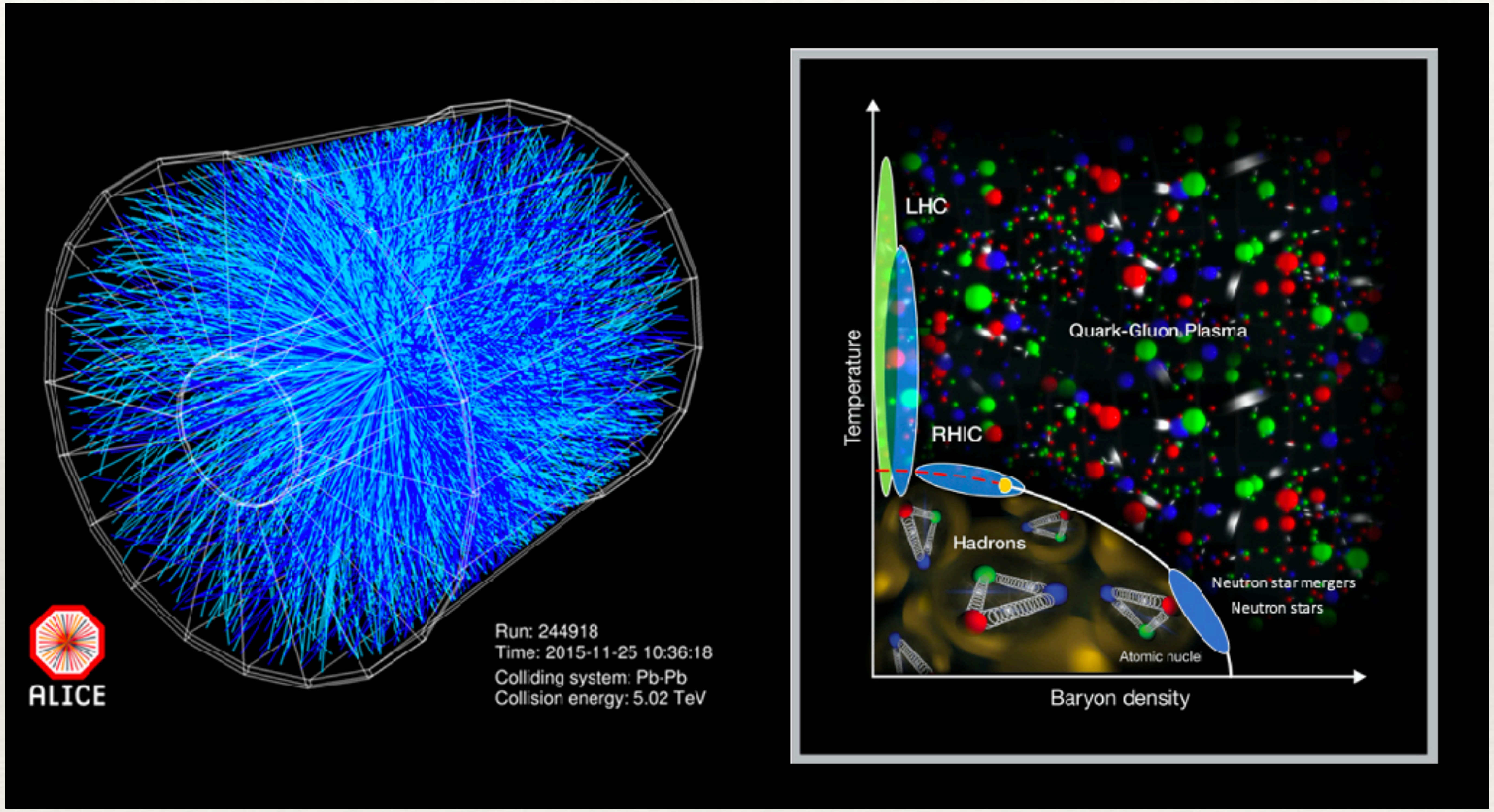
Quantum many-body systems

- Quantum many-body systems are very challenging, e.g. quark-gluon plasma, high-T_c superconductors
    - Quantum effects: wave-particle duality, uncertainty principle, spins (bosons, fermions), etc
    - Statistical effects: screenings, collective excitations, quasiparticles, etc
    - Emergent phenomena: phenomena that bear little resemblance of the underlying elementary laws
- The focus of this talk
    - High-energy nuclear physics: quark-gluon plasma
    - Quantum computing: many-qubit system

High-energy nuclear physics

Heavy-ion collisions and quark-gluon plasma

- Quark-gluon plasma (QGP)
  - Theory: weakly coupled gas
  - Experiment: strongly coupled liquid(!)
- Yang-Mills mass gap / color confinement
  - Clay Millennium Problems
- How to tackle it with thermal quantum field theory?
- What can deep learning do?



https://www.innovationnewsnetwork.com/exploring-matter-after-the-big-bang/8120/

Hard-thermal-loop perturbation theory (HTLpt)

Andersen, Braaten & Strickland, 99

- Quantum Chromodynamics (QCD): massless quarks and gluons — inappropriate d.o.f. at high T

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}] + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi$$

- HTLpt: a resummation method of thermal QCD [see NS, Int. J. Mod. Phys. A, 30, 1530025 (2015) for a review]

$$\mathscr{L}_{\mathrm{HTLpt}} = \left(\mathscr{L}_{\mathrm{QCD}} + \mathscr{L}_{\mathrm{HTL}} - \delta\mathscr{L}_{\mathrm{HTL}}\right)\Big|_{g\to\sqrt{\delta}g}$$

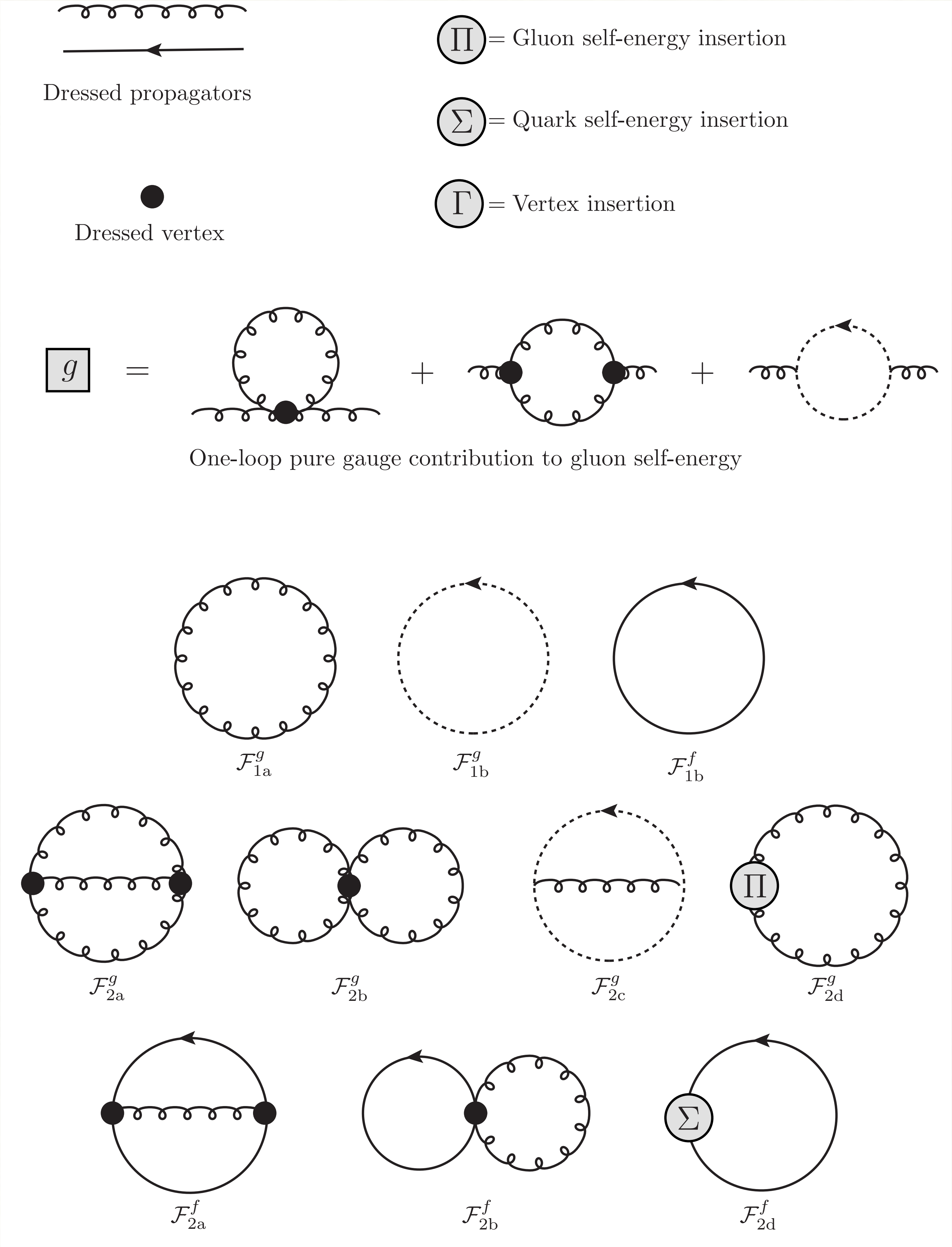
- Hard-thermal-loop effective action: contributions from the (chromo)electric scale gT [Braaten & Pisarski, 92]

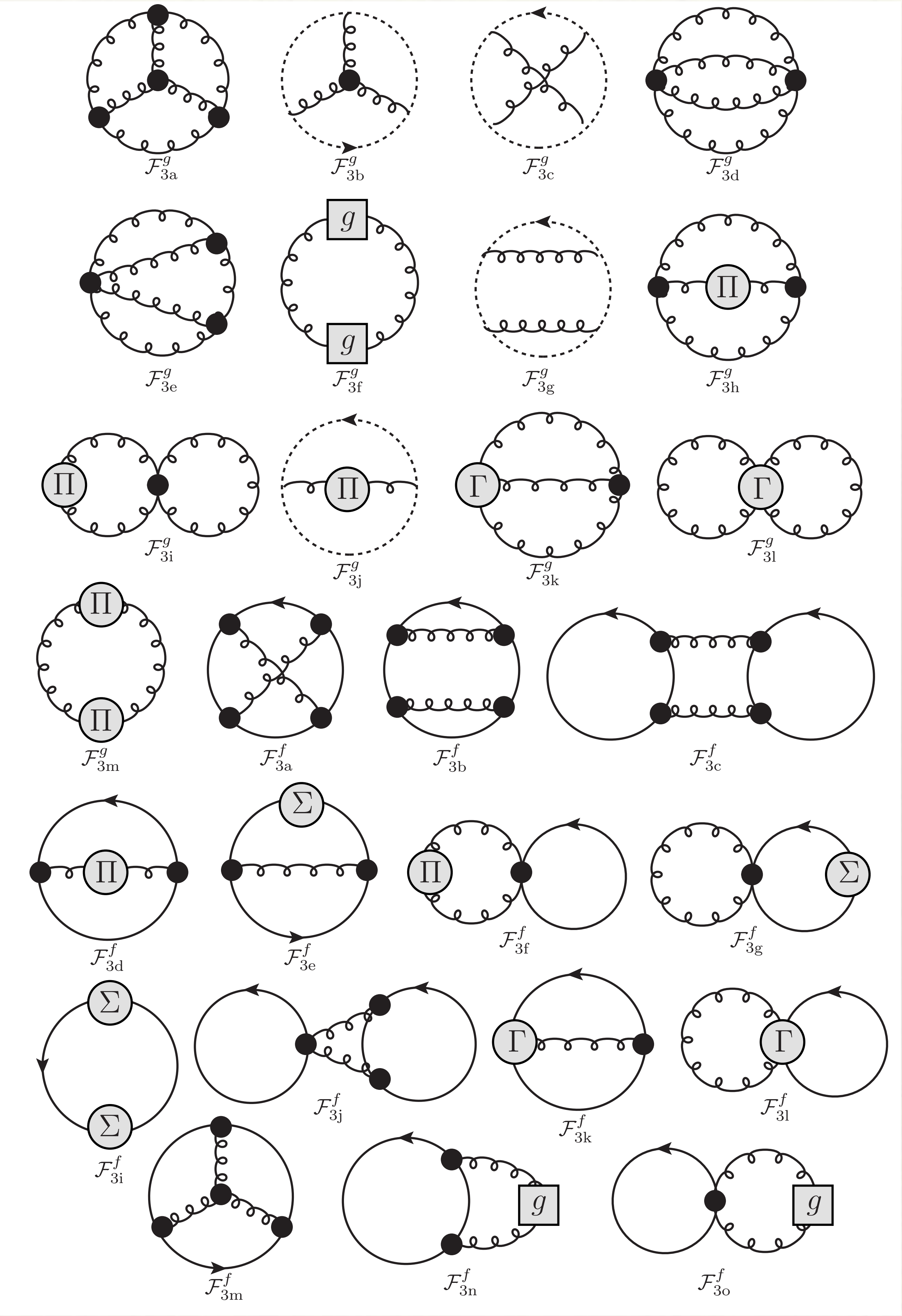
$$\mathscr{L}_{\mathrm{HTL}} = -\frac{1}{2}m_D^2\mathrm{Tr}\left(G_{\mu\alpha}\left\langle\frac{y^{\alpha}y^{\beta}}{(y\cdot D)^2}\right\rangle_y G^{\mu}{}_{\beta}\right)$$

- Adding $\mathscr{L}_{\mathrm{HTL}}$ SHIFTS expansion to an ideal gas of massive (Debye) quasiparticles — appropriate d.o.f. at high T
- EQCD from dimensional reduction — another resummation method for the electric scale gT [Braaten & Nieto, 95]

HTLpt: QCD thermodynamic potential Ω through NNLO/3 loops (46 diagrams)

Andersen, Leganger, Strickland, NS, JHEP 08, 053 (2011)





HTLpt: $\Omega_{\rm NNLO}$ at finite T & μ for general N_c & N_f — analytic!

Haque, Bandyopadhyay, Andersen, Mustafa, Strickland and NS, JHEP 05, 027 (2014)

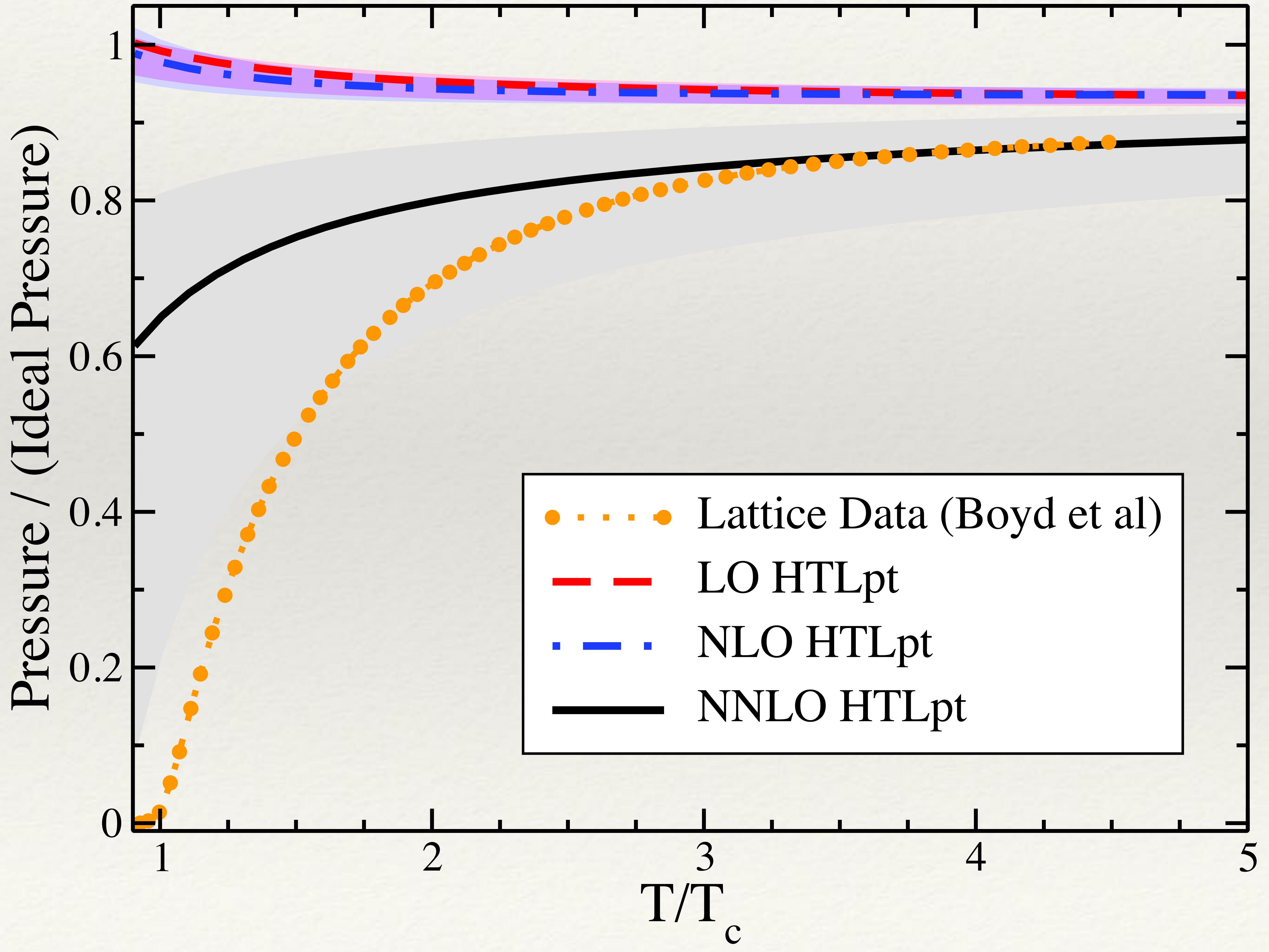
$\Omega_0 \equiv -d_A \pi^2 T^4/45$, $\hat{x} \equiv x/2\pi T$, $\Omega^{\rm YM}_{\rm NNLO}$ taken from Andersen, Strickland, NS, PRL 104, 122003 (2010)

$$
\begin{aligned}
\frac{\Omega_{\rm NNLO}}{\Omega_0} = {} & \frac{7}{4}\frac{d_F}{d_A}\frac{1}{N_f}\sum_f\left(1+\frac{120}{7}\hat\mu_f^2+\frac{240}{7}\hat\mu_f^4\right)-\frac{s_F\alpha_s}{\pi}\frac{1}{N_f}\sum_f\bigg[\frac{5}{8}\left(1+12\hat\mu_f^2\right)\left(5+12\hat\mu_f^2\right)-\frac{15}{2}\left(1+12\hat\mu_f^2\right)\hat m_D \\
& -\frac{15}{2}\bigg(2\ln\frac{\hat\Lambda}{2}-1-\aleph(z_f)\bigg)\hat m_D^3+90\hat m_q^2\hat m_D\bigg]+\frac{s_{2F}}{N_f}\left(\frac{\alpha_s}{\pi}\right)^2\sum_f\bigg[\frac{15}{64}\bigg\{35-32\left(1-12\hat\mu_f^2\right)\frac{\zeta'(-1)}{\zeta(-1)}+472\hat\mu_f^2 \\
& +1328\hat\mu_f^4+64\Big(-36i\hat\mu_f\aleph(2,z_f)+6(1+8\hat\mu_f^2)\aleph(1,z_f)+3i\hat\mu_f(1+4\hat\mu_f^2)\aleph(0,z_f)\Big)\bigg\}-\frac{45}{2}\hat m_D\left(1+12\hat\mu_f^2\right)\bigg] \\
& +\left(\frac{s_F\alpha_s}{\pi}\right)^2\frac{1}{N_f}\sum_f\frac{5}{16}\bigg[96\left(1+12\hat\mu_f^2\right)\frac{\hat m_q^2}{\hat m_D}+\frac{4}{3}\left(1+12\hat\mu_f^2\right)\left(5+12\hat\mu_f^2\right)\ln\frac{\hat\Lambda}{2}+\frac{1}{3}+4\gamma_E+8(7+12\gamma_E)\hat\mu_f^2 \\
& +112\mu_f^4-\frac{64}{15}\frac{\zeta'(-3)}{\zeta(-3)}-\frac{32}{3}(1+12\hat\mu_f^2)\frac{\zeta'(-1)}{\zeta(-1)}-96\Big\{8\aleph(3,z_f)+12i\hat\mu_f\aleph(2,z_f)-2(1+2\hat\mu_f^2)\aleph(1,z_f)-i\hat\mu_f\aleph(0,z_f)\Big\}\bigg] \\
& +\left(\frac{s_F\alpha_s}{\pi}\right)^2\frac{1}{N_f^2}\sum_{f,g}\bigg[\frac{5}{4\hat m_D}\left(1+12\hat\mu_f^2\right)\left(1+12\hat\mu_g^2\right)+90\bigg\{2\left(1+\gamma_E\right)\hat\mu_f^2\hat\mu_g^2-\Big\{\aleph(3,z_f+z_g)+\aleph(3,z_f+z_g^*) \\
& +4i\hat\mu_f\left[\aleph(2,z_f+z_g)+\aleph(2,z_f+z_g^*)\right]-4\hat\mu_g^2\aleph(1,z_f)-(\hat\mu_f+\hat\mu_g)^2\aleph(1,z_f+z_g)-(\hat\mu_f-\hat\mu_g)^2\aleph(1,z_f+z_g^*) \\
& -4i\hat\mu_f\hat\mu_g^2\aleph(0,z_f)\Big\}\bigg\}-\frac{15}{2}\left(1+12\hat\mu_f^2\right)\left(2-1-\aleph(z_g)\right)\hat m_D\bigg]+\left(\frac{c_A\alpha_s}{3\pi}\right)\left(\frac{s_F\alpha_s}{\pi N_f}\right)\sum_f\bigg[\frac{15}{2\hat m_D}\left(1+12\hat\mu_f^2\right) \\
& -\frac{235}{16}\bigg\{\left(1+\frac{792}{47}\hat\mu_f^2+\frac{1584}{47}\hat\mu_f^4\right)\ln\frac{\hat\Lambda}{2}-\frac{144}{47}\left(1+12\hat\mu_f^2\right)\ln\hat m_D+\frac{319}{940}\left(1+\frac{2040}{319}\hat\mu_f^2+\frac{38640}{319}\hat\mu_f^4\right)-\frac{24\gamma_E}{47}\left(1+12\hat\mu_f^2\right) \\
& -\frac{44}{47}\left(1+\frac{156}{11}\hat\mu_f^2\right)\frac{\zeta'(-1)}{\zeta(-1)}-\frac{268}{235}\frac{\zeta'(-3)}{\zeta(-3)}-\frac{72}{47}\Big[4i\hat\mu_f\aleph(0,z_f)+\left(5-92\hat\mu_f^2\right)\aleph(1,z_f)+144i\hat\mu_f\aleph(2,z_f)+52\aleph(3,z_f)\Big]\bigg\} \\
& +90\frac{\hat m_q^2}{\hat m_D}+\frac{315}{4}\bigg\{\left(1+\frac{132}{7}\hat\mu_f^2\right)+\frac{11}{7}\left(1+12\hat\mu_f^2\right)\gamma_E+\frac{9}{14}\left(1+\frac{132}{9}\hat\mu_f^2\right)+\frac{2}{7}\aleph(z_f)\bigg\}\hat m_D\bigg]+\frac{\Omega^{\rm YM}_{\rm NNLO}}{\Omega_0}
\end{aligned}
$$

HTLpt: NNLO free energy / pressure for pure Yang-Mills at finite T

YM: Andersen, Strickland & NS, PRL 104, 122003 (2010); JHEP 08, 113 (2010)

HTLpt with the electric scale gT incorporated works down to $T \sim 3T_c$

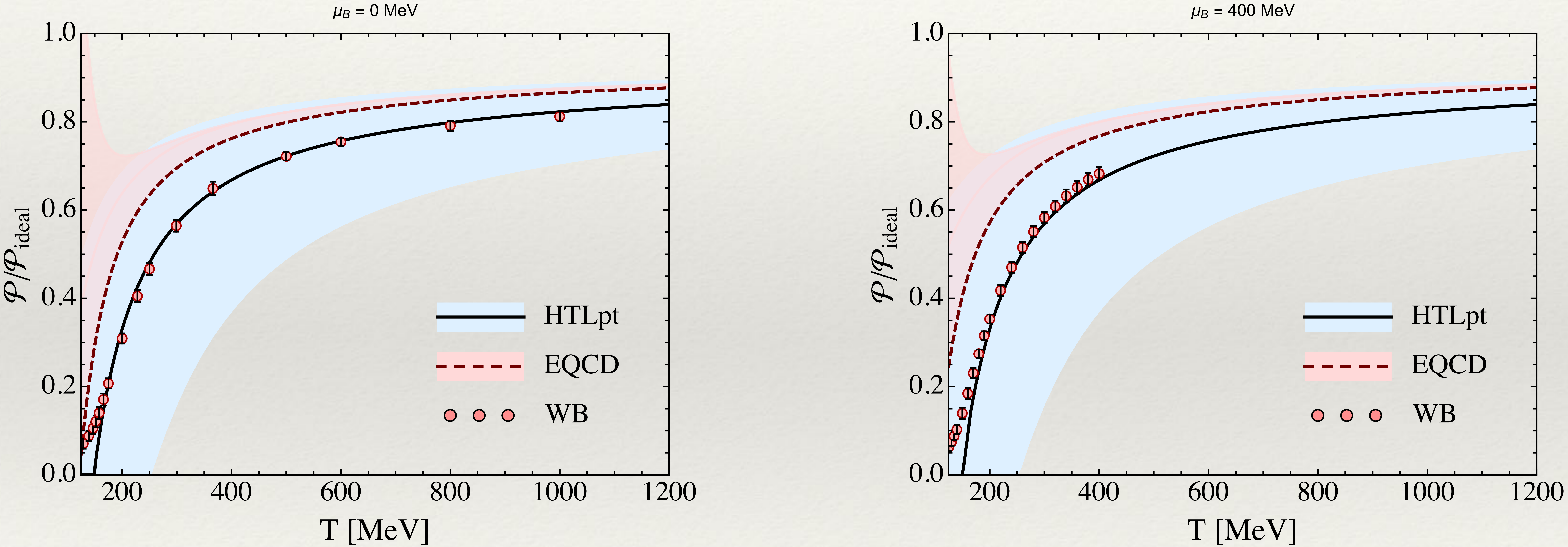


Universality class
of
Yang-Mills / SU(N)
phase transition:
Z(N)

Z(2) → Ising model
Quantum annealing(!)

HTLpt: NNLO free energy / pressure for QCD at finite T & μ

HTLpt: Andersen, Leganger, Strickland & NS, PLB 696, 468-472 (2011); JHEP 08, 053 (2011) Haque, Bandyopadhyay, Andersen, Mustafa, Strickland & NS, JHEP 05, 027 (2014)
EQCD: Mogliacci, Andersen, Strickland, NS & Vuorinen, JHEP 12, 055 (2013)



Collective excitations of hot plasmas — challenges!

- Collective excitations of quarks and gluons are crucial in studying the QGP
  - Debye screening → massive quasiparticles $m_D \sim gT$ (electric scale)
  - Confining (chromo)magnetic scale g^2T not included due to the Linde problem
  - QED and QCD (collective excitations / modes) are INDISTINGUISHABLE(!) in conventional thermal-field methods → weakly coupled gas
  - HOW TO DISTINGUISH? (key in generating long-range correlations!)

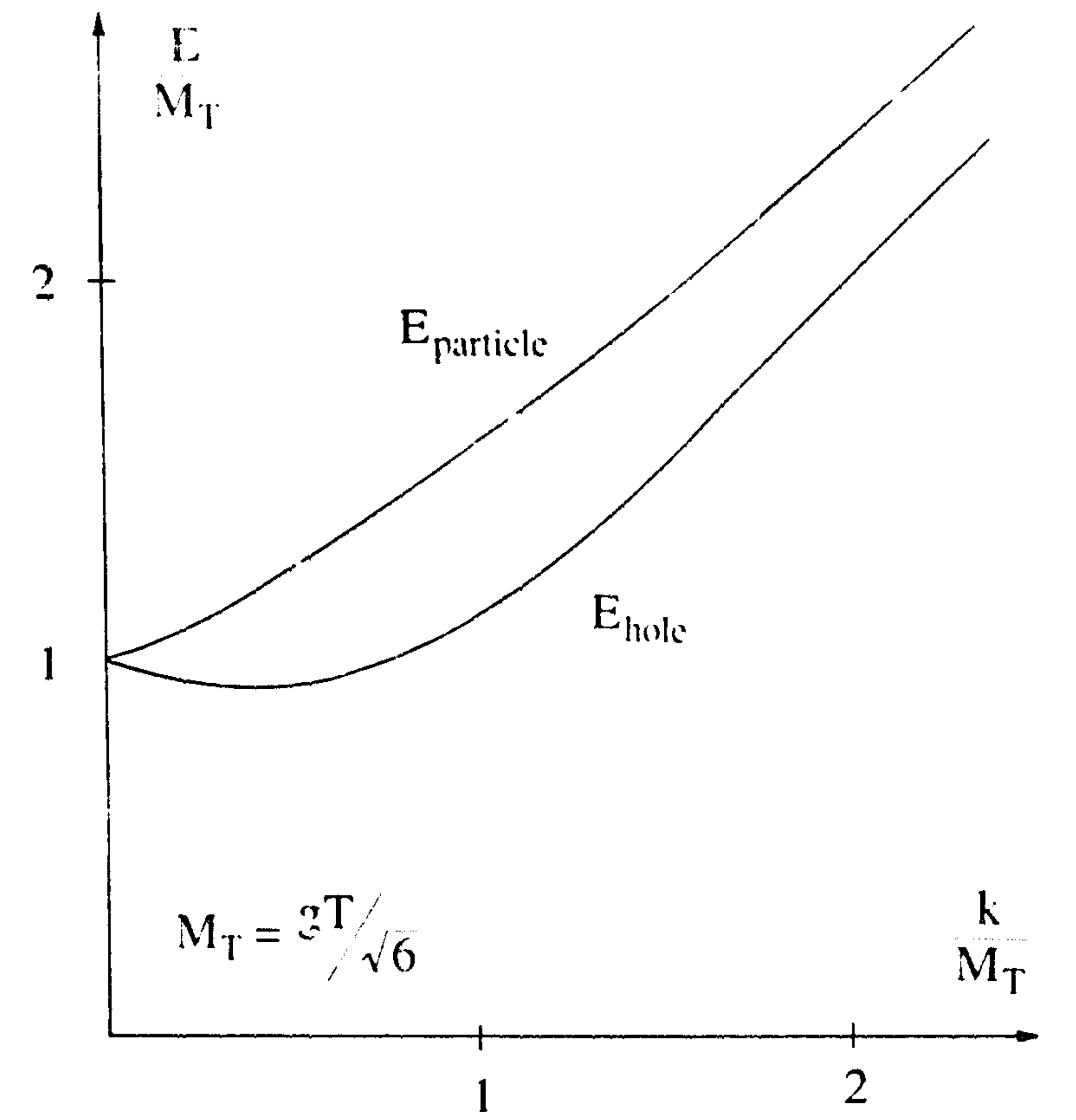
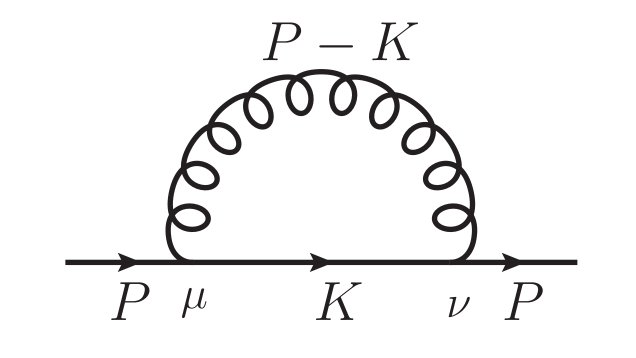


Fig. 1. Dispersion relation for particles and holes.

Gribov-Zwanziger (GZ) quantization: quark thermal self-energy

- Crucial measure of collective behaviors: screening masses, dispersion relations, spectral functions



$$\Sigma(P) = (ig)^2 C_F \sum\!\!\!\!\!\!\int_{\{K\}} \gamma^\mu S(K) \gamma^\nu D^{\mu\nu}(P-K)$$

- At high T ($g \ll 1$), Gribov-Zwanziger action [Gribov 78; Zwanziger 89] provides a renormalizable framework to study confinement effects at the magnetic scale g^2T — improvement over Faddeev-Popov action in the IR

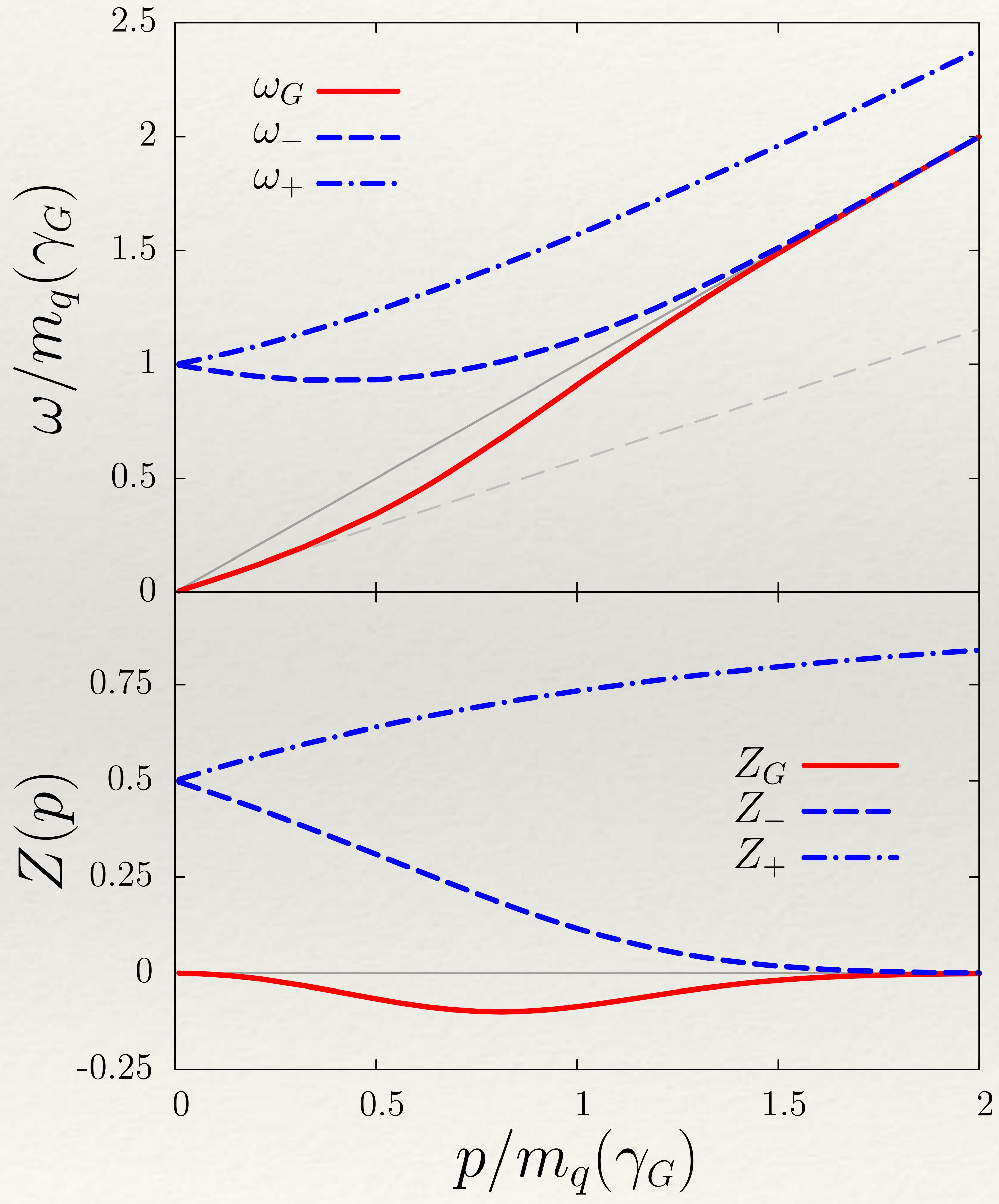
  - Faddeev-Popov: $D^{\mu\nu}_{\rm FP}(P) = \dfrac{1}{P^2}\left(\delta_{\mu\nu} - \dfrac{P_\mu P_\nu}{P^2}\right) \to$ IR divergent(!)

  - Gribov-Zwanziger: $D^{\mu\nu}_{\rm GZ}(P) = \dfrac{P^2}{P^4+\gamma_G^4}\left(\delta_{\mu\nu} - \dfrac{P_\mu P_\nu}{P^2}\right) \to$ IR regular

  with $\gamma_G = \dfrac{d}{d+1}\dfrac{N_c}{4\sqrt{2}\pi} g^2 T$ [Zwanziger, PRD 76, 125014 (2007); Fukushima, NS, PRD 88, 076008 (2013)]

GZ: thermal quark dispersion relations & residues of poles

NS & Tywoniuk, PRL 114, 161601 (2015)

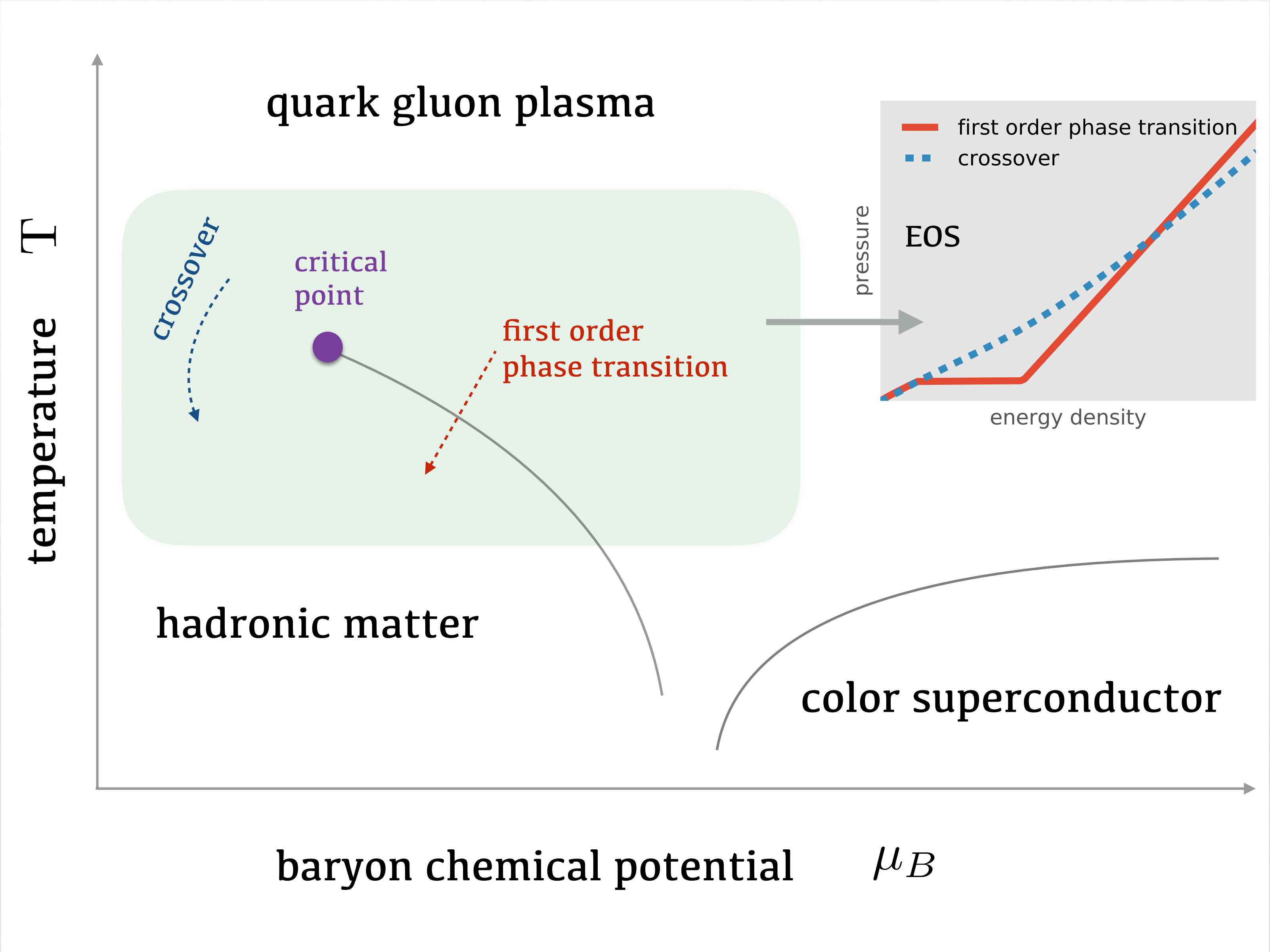


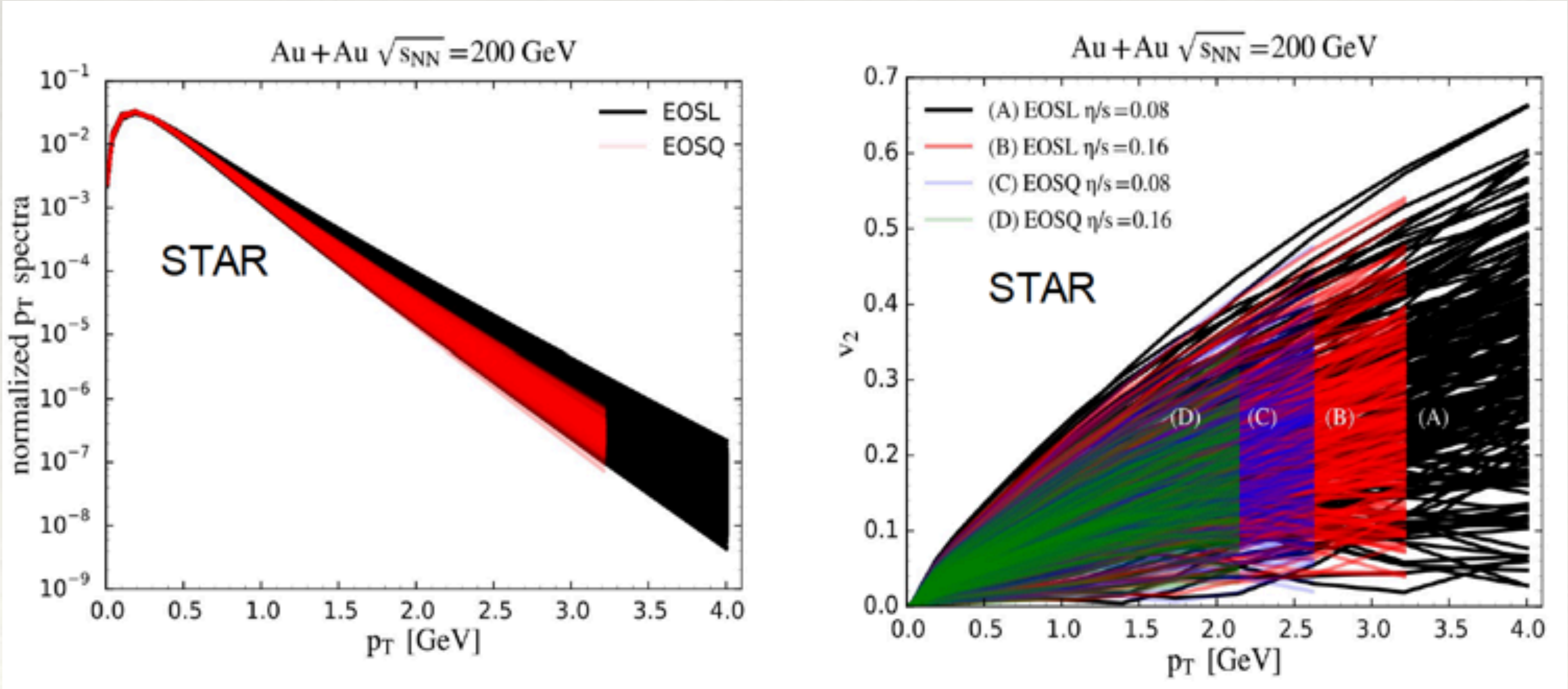
- Quasiparticles recovered — time-like; novel massless mode(!) — space-like
- Sound wave at small p: $\omega \sim v_s p$ with $v_s = 1/\sqrt{3}$
  - Hydrodynamic-like behaviors → long-range correlations incorporated
- Crucial for heavy-ion phenomenology at RHIC and LHC energies
  - Viscosities: $\dfrac{\zeta}{\eta} \propto \left(\dfrac{1}{3} - c_s^2\right)$, strongly coupled liquid(!)

    [Florkowski, Ryblewski, NS & Tywoniuk, Acta Phys. Polon. B 47, 1833 (2016); PRC 94, 044904 (2016)]
- 1st evidence of positivity violation for thermal quarks/collective mode
  - Genuine feature of non-Abelian theories, distinctive from QED(!)
  - Confinement ($\gamma_G \sim g^2 T$) indispensable for thermal QCD even at $T \to \infty$(!)
- Thermal spectral sum rule: $\displaystyle\int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\rho(\omega, p) = 1$, math(!) [Du, NS, Tywoniuk, preliminary]

Extracting physical info from heavy-ion measurements — challenge!

- Heavy-ion measurements $\rho(p_T, \Phi)$ — highly complex
- $\rho(p_T, \Phi) \xrightarrow{?}$ bulk properties, e.g. equation of state (EoS)
  - No direct link
  - Conventional observables — model dependent



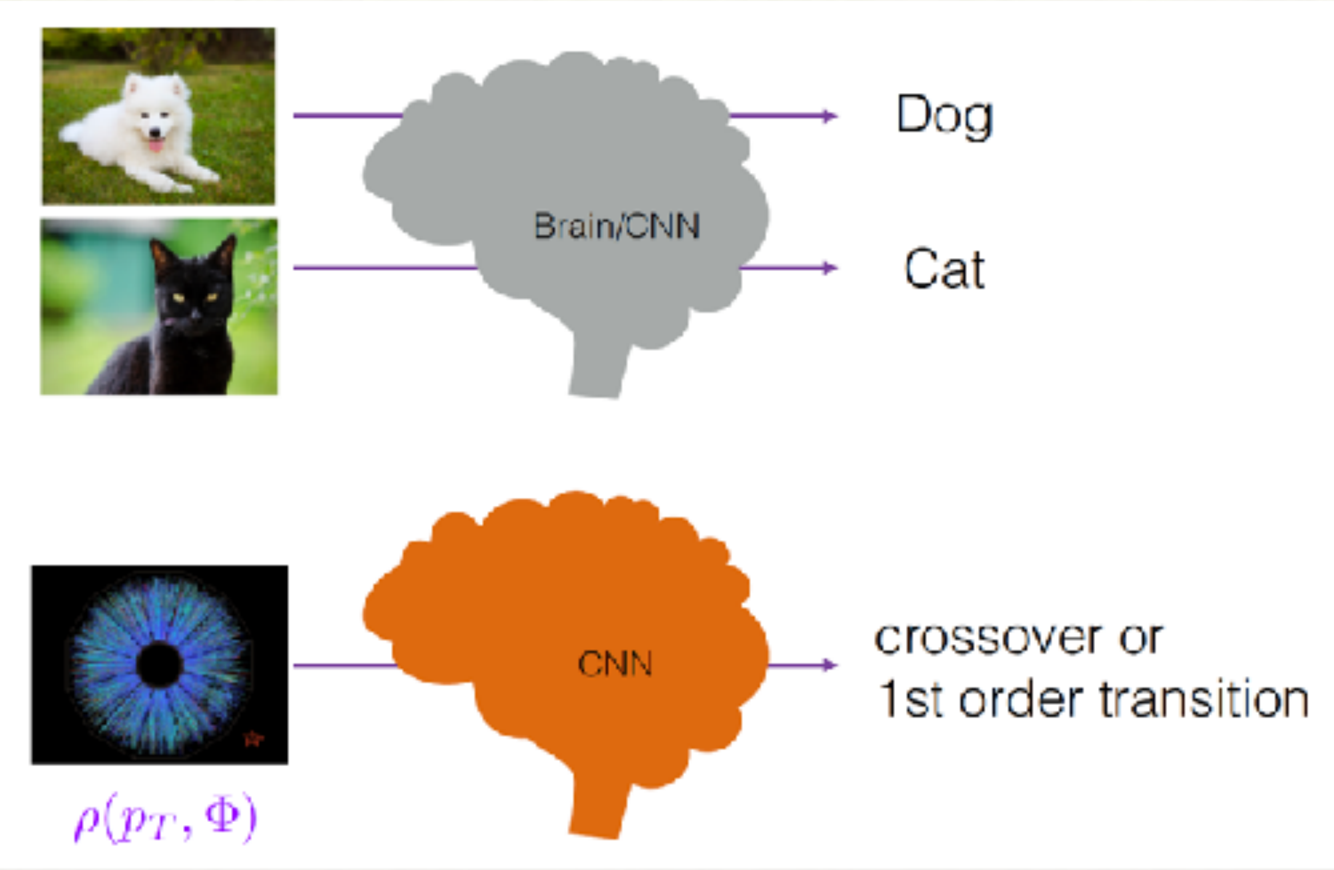


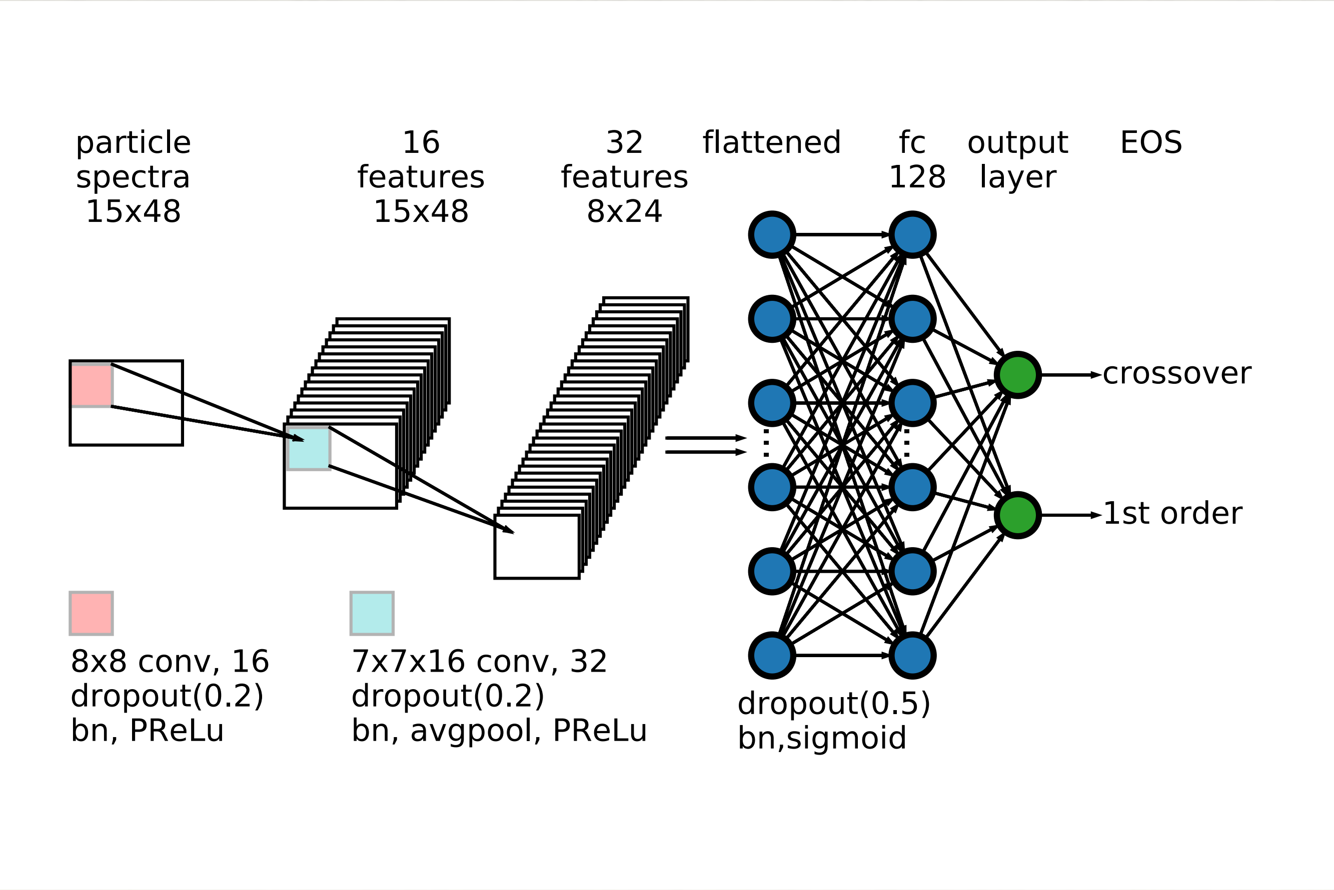
An EoS-meter of QCD transition from deep learning

Pang, Zhou, NS, Peterson, Stöcker & Wang, Nat. Commun. 9, 210 (2018)

- Conventional neural networks (CNN) & hydrodynamic simulations
- An EoS-meter of QCD transition from CNN
    - Direct map between $\rho(p_T, \Phi)$ and the type of EoS — model independent
    - 1st application of deep learning to high-energy nuclear physics
    - 2018 Nat. Commun. "Top 50: Physics"; SAMSON AI Grant

TESTING DATA	GROUP 0	GROUP 1	GROUP 2
Number of events	4000	7343	10953
Accuracy	$99.88 \pm 0.04\%$	$93.46 \pm 1.35\%$	$93.91 \pm 3.92\%$





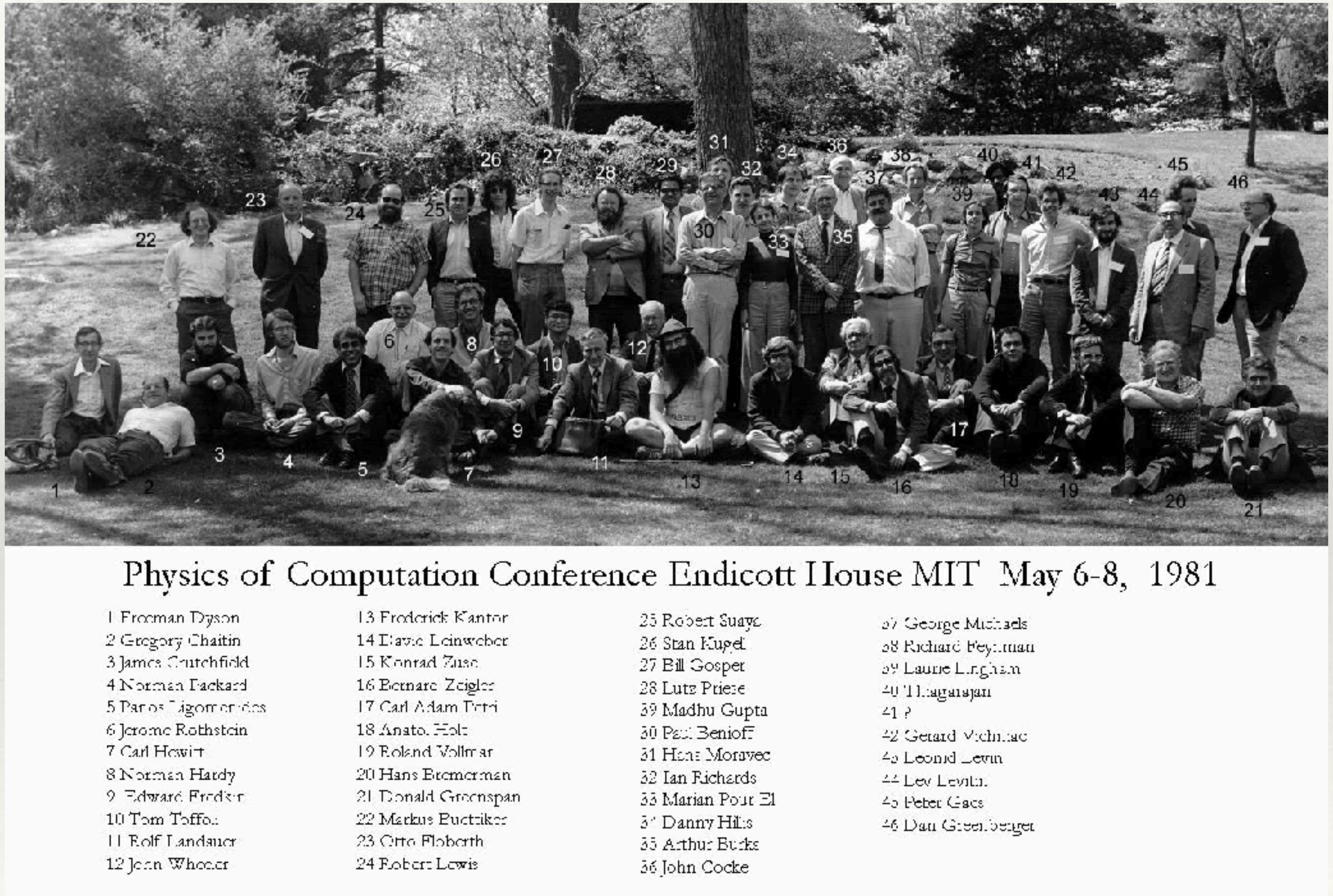
Quantum computing

Computing power of high performance computing (HPC) — challenge!

- 2022 Nobel Prize in Physics: Alain Aspect, John F. Clauser and Anton Zeilinger
  - "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"
- Saturation of conventional HPC's computing power — bottleneck to many applications, e.g.
  - Condensed matter physics — geometrical frustration: very time & power consuming
  - Telecommunication — network routing: very power consuming, low efficiency
  - Materials design — optimal formulation: extremely time & power consuming, suboptimal solutions
  - Intelligent transportation — entire network navigation: beyond the scope of conventional HPC
- Quantum computing as a next generation HPC technology — potentially efficient solutions

Birth of quantum computing

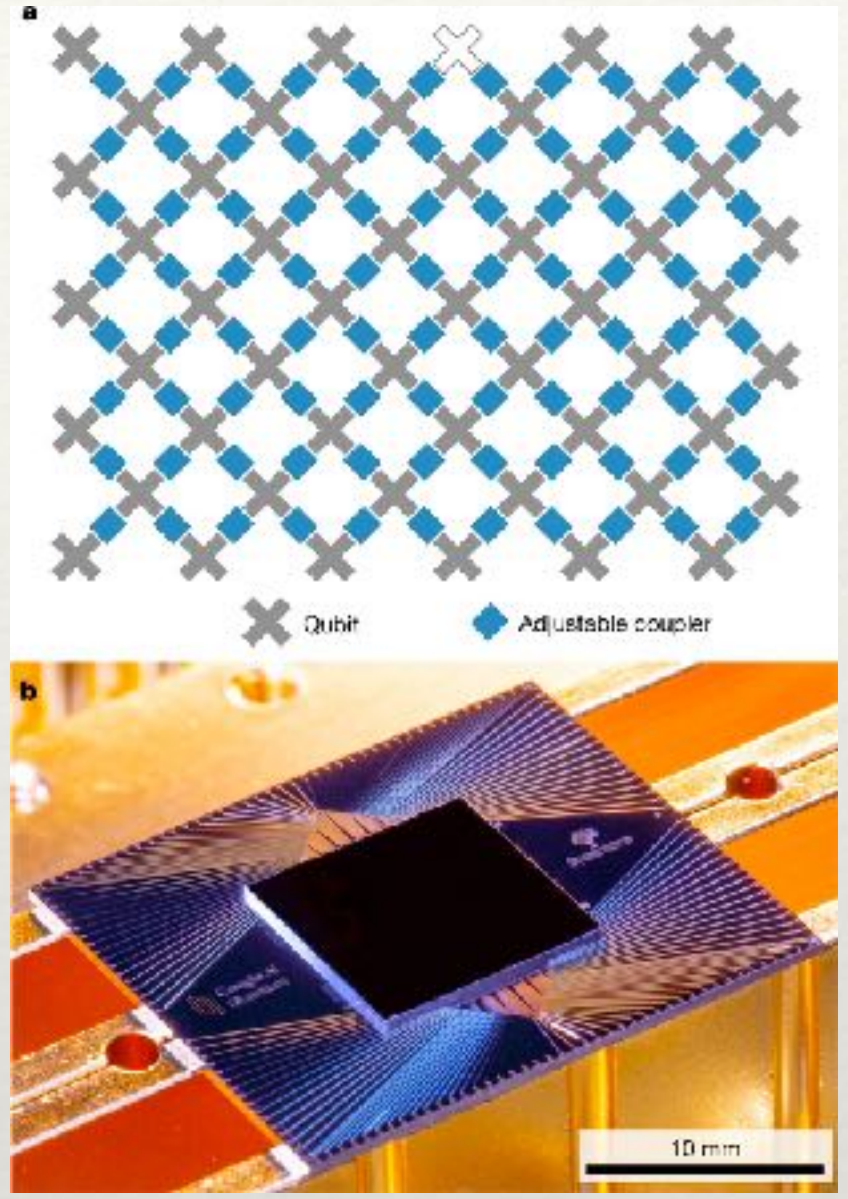
- Physics of Computation Conference, MIT & IBM, May 6-8, 1981
- Richard Feynman: “Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical…”
- Quantum characteristics: superposition, entanglement, tunneling, etc



Quantum advantage

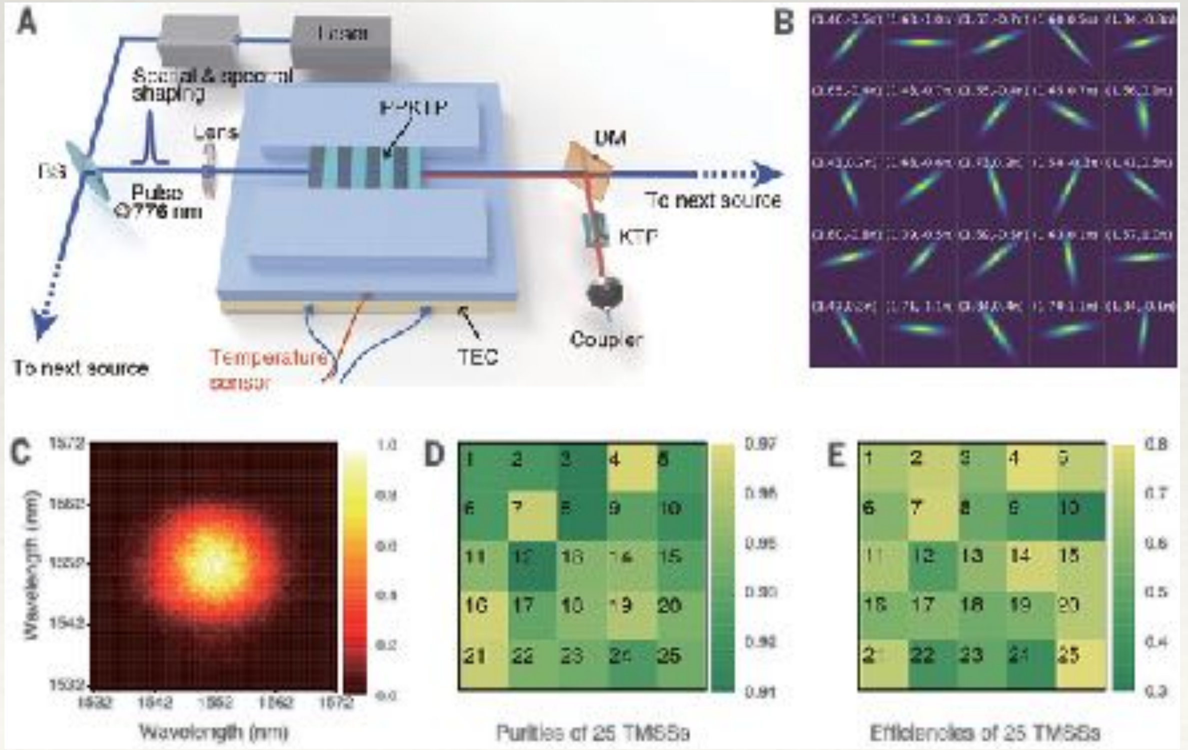
Google Quantum AI (2019)

- "Quantum supremacy using a programmable superconducting processor" [Nature 574, 505 (2019)]
  - 53 superconducting qubits Sycamore processor
  - 200 seconds random sampling — 10,000 years for HPC
  - Can be tackled by HPC within days by IBM Watson [arXiv:1910.09534] & NSC Wuxi [arXiv:2111.01066]
  - Can be tackled by HPC within hours by ITP CAS [PRL 129, 090502 (2022)]



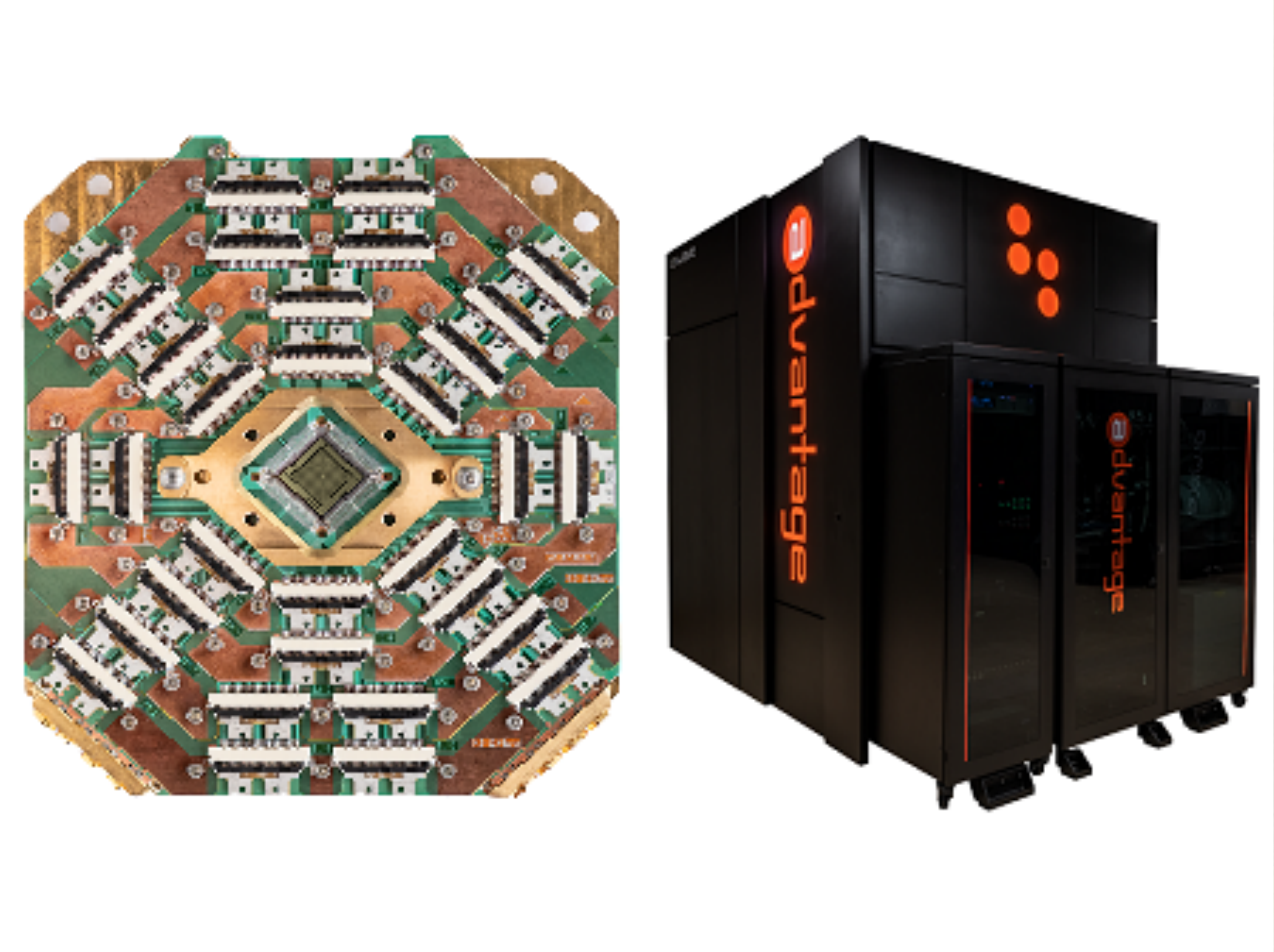
University of Science and Technology of China (2020)

- "Quantum computational advantage using photons" [Science 370, 1460 (2020)]
  - 76 photonics qubits Jiuzhang quantum computer
  - 1st time Boson sampling: 10^{14} faster than HPC (1 second Jiuzhang ~ 3M years HPC)
  - Jiuzhang 2.0 — 113 qubits, 10^{24} faster than HPC [PRL 127, 180502 (2021)]



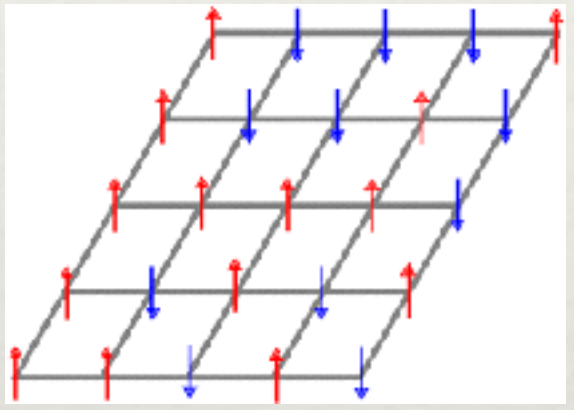
Quantum annealer

- Gate-model universal QC limited in size and error correction
- QC hardware implementation based on quantum annealing, specific computer for combinatorial optimization problems
- Combinatorial optimization: find an optimal object from a finite set of objects, e.g. traveling salesman problem — NP-hard(!)
- January 17, 2022, Jülich Supercomputing Center, D-Wave Advantage System, 5,000+ qubits
- QA emulator: Fujitsu Digital Annealer (~10,000 times faster than HPC), 4rd generation (May 18, 2022), emulating 100,000 qubits
- Ready for practical applications

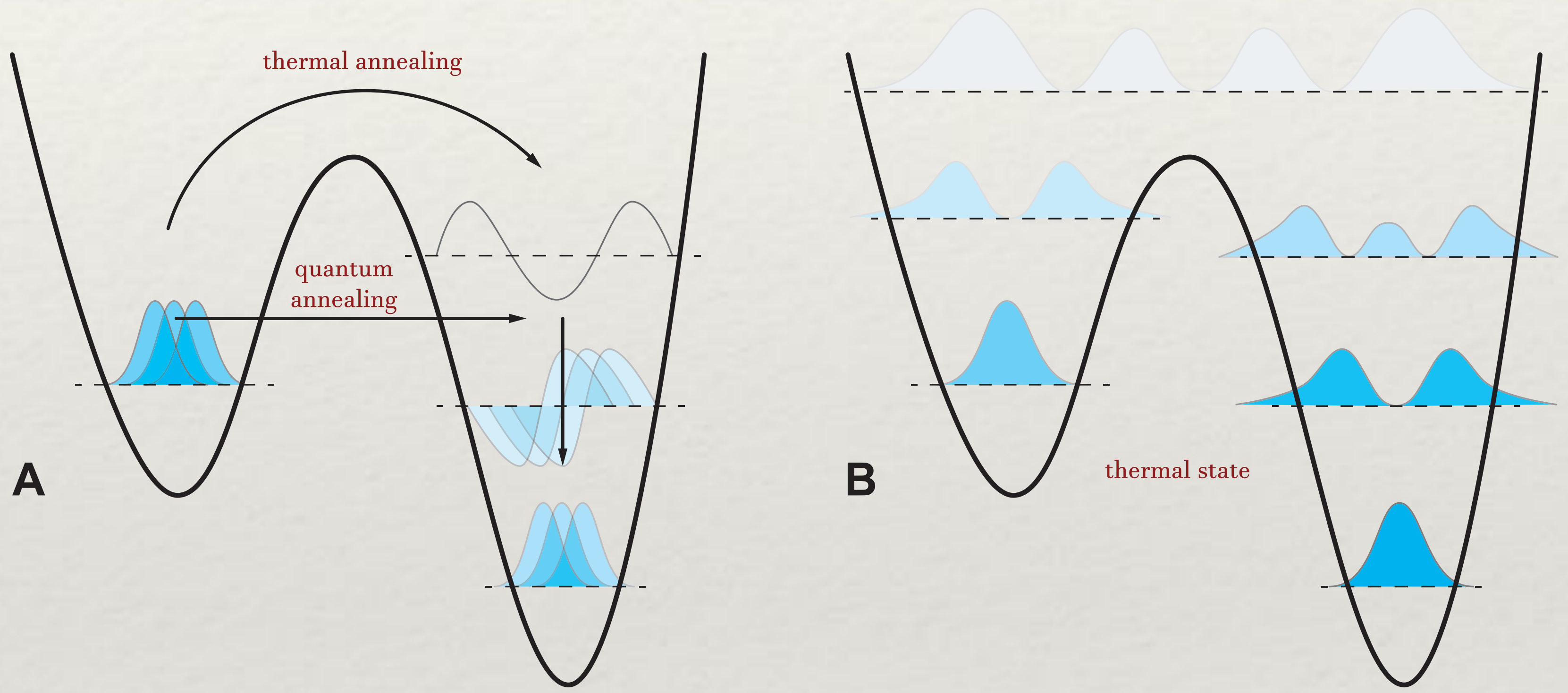


Quantum annealing in a nutshell

- Combinatorial optimization: finding global minimum of Ising Problem



$$\min \left(\sum_i \sum_{j>i} J_{ij}\sigma_i\sigma_j + \sum_i h_i\sigma_i \right), \text{ with } \sigma_i \in \{-1,1\}$$

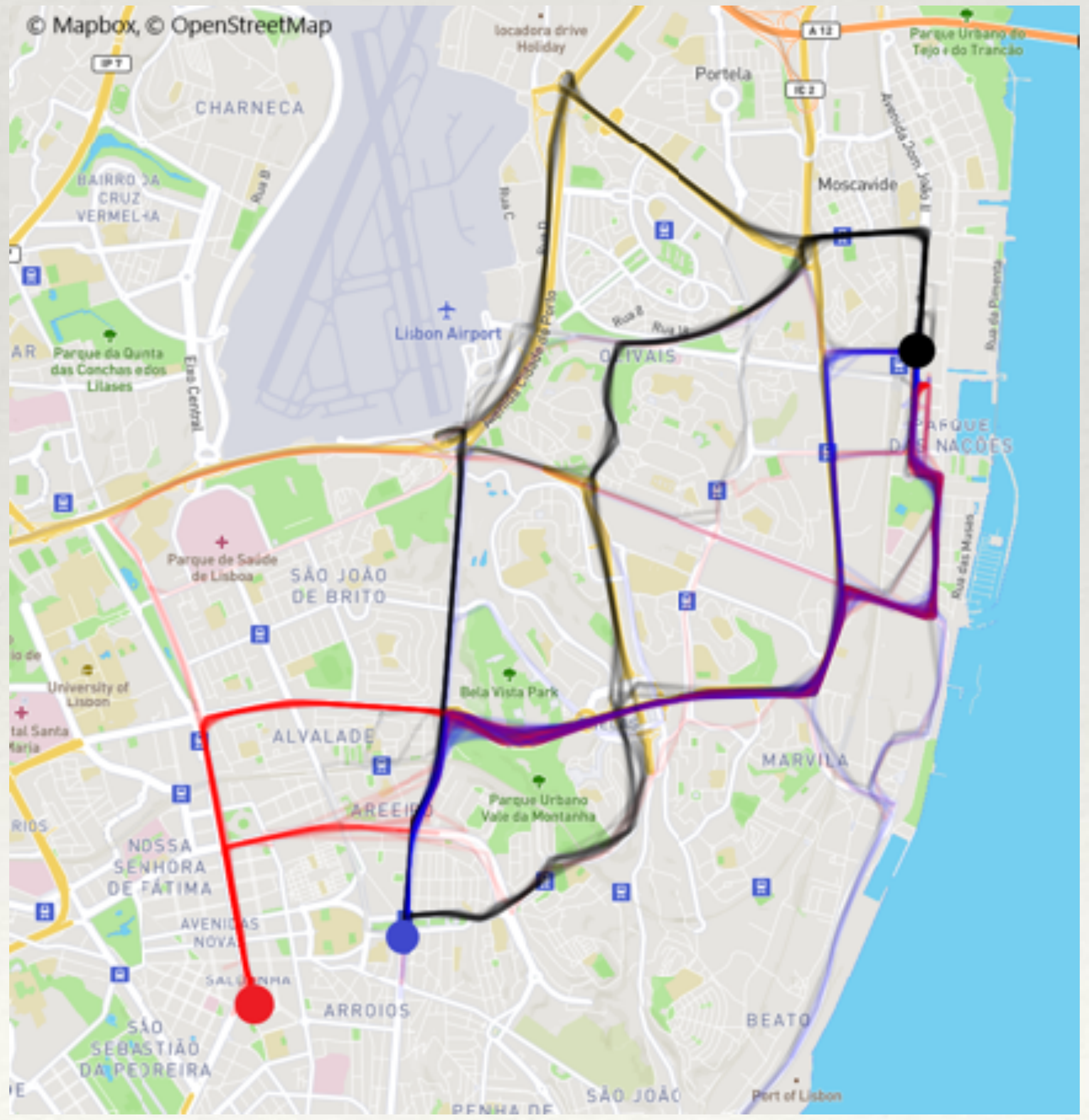


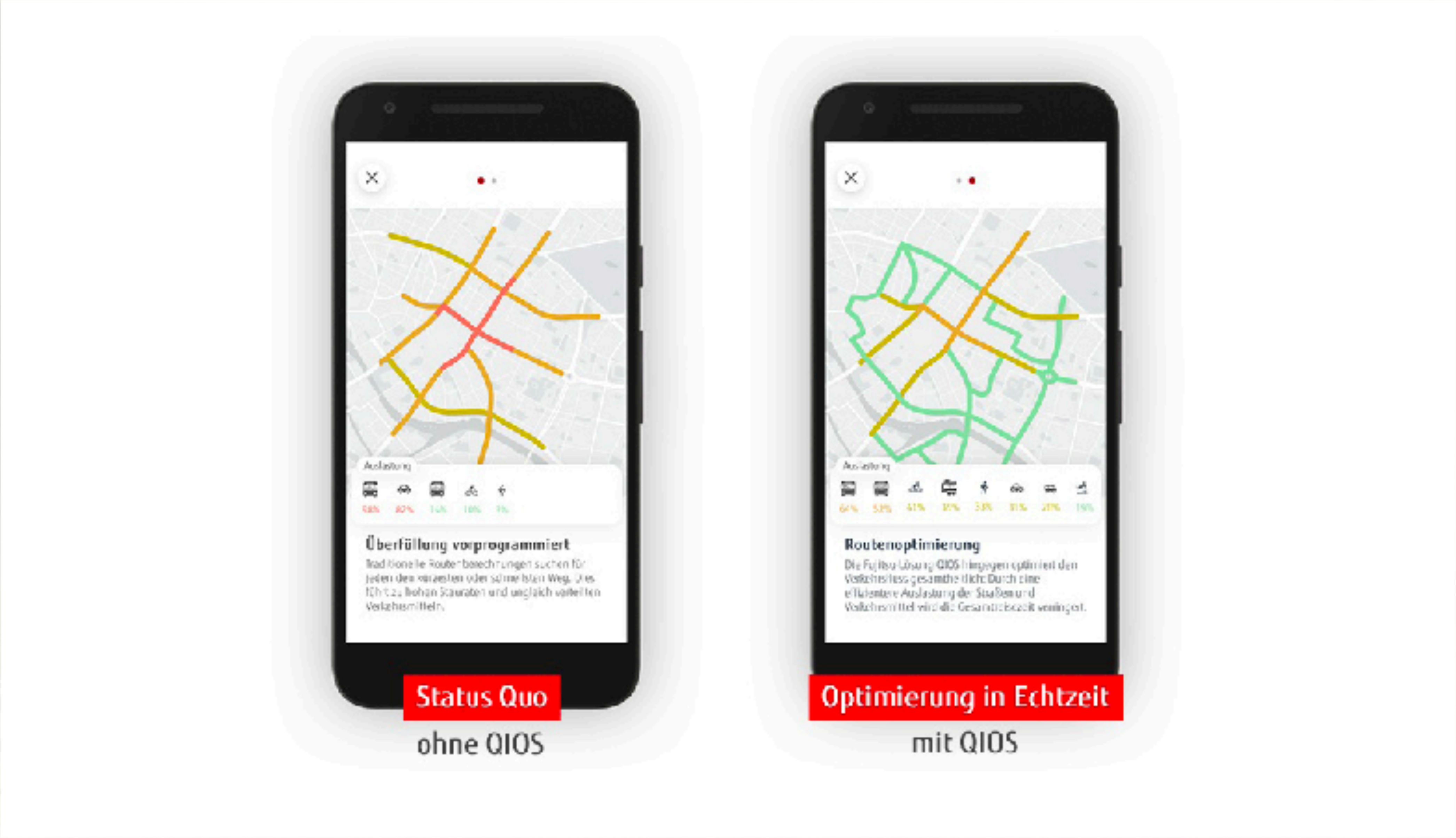
- Quantum annealing: quantum version of simulated annealing
    - Application of quantum many-body theory
- D-Wave: $T_{\text{anneal}} = 20\mu s$, 25kW

Application: entire network navigation

S. Yarkoni *et al.*, *Quantum Shuttle: Traffic Navigation with Quantum Computing*, arXiv:2006.14162
https://www.fujitsu.com/de/microsite/its-world-congress/mozart/index.html

- Quantum Shuttle: Volkswagen, Hexad (2019); MOZART-Projekt: Fujitsu, Hamburg Port Authority, TU Graz (2021)
- Quantum navigation boosts the efficiency of the entire network: saving time, traffic, emission
  - Much more optimized results than HPC, ability of entire network coordination

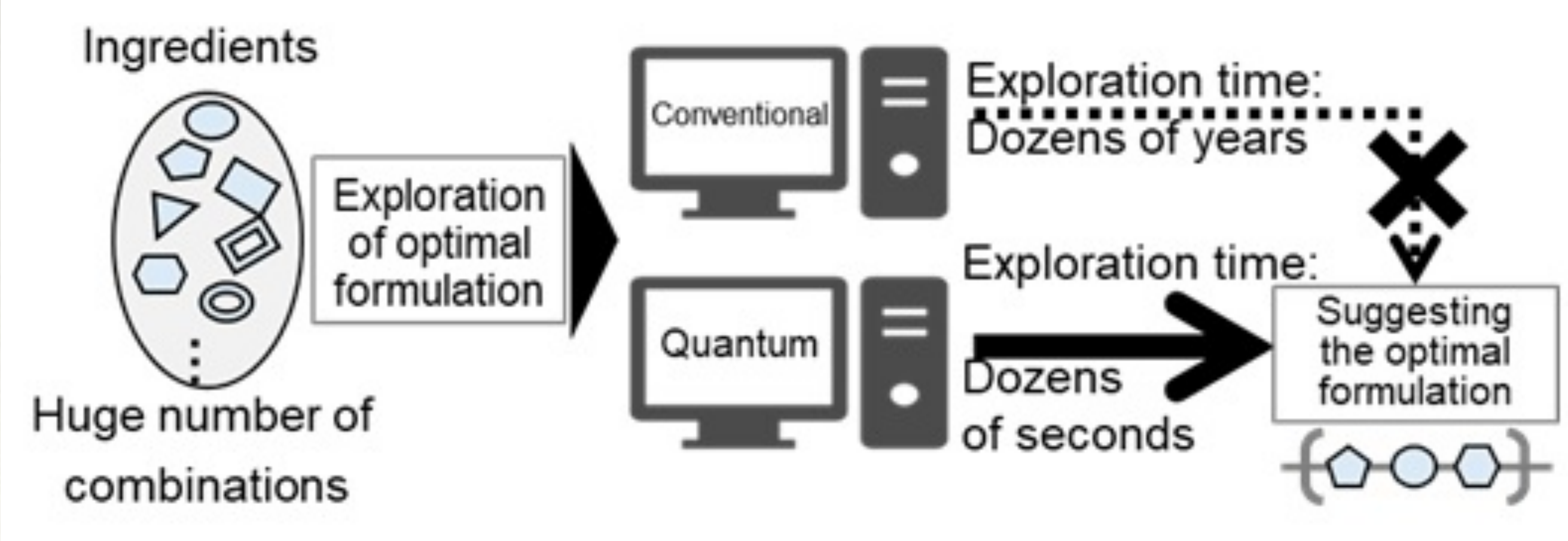




Application: materials design

https://www.sdk.co.jp/english/news/2022/41713.html

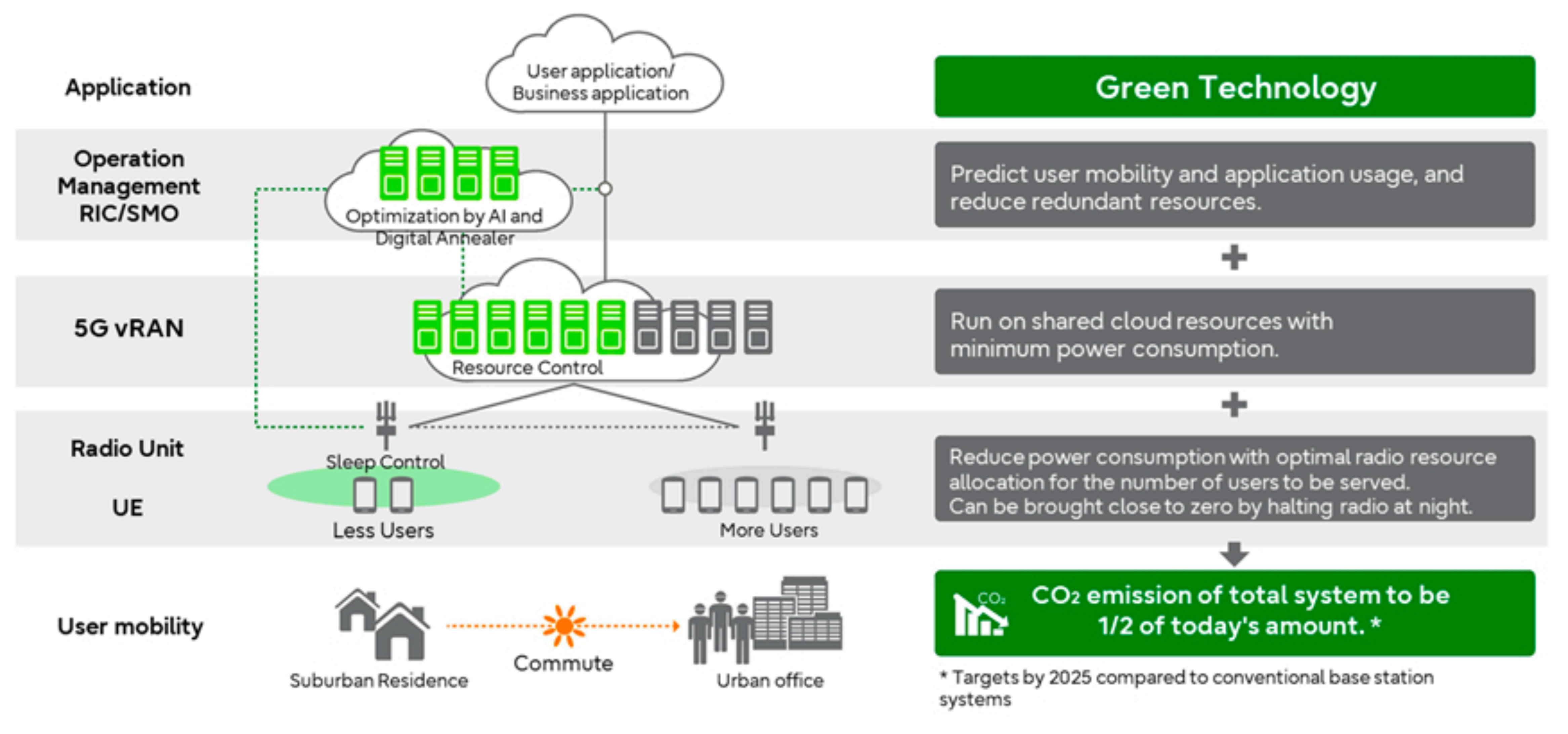
- The theoretical combinations of ingredients and mixing ratios in semiconductor materials design are more than 10^{50}
  - Conventional AI computation takes dozens of years, so only part of all the combinations was analyzed (suboptimal)
- February 2022: Showa Denko
  - Performing such AI analysis with Fujitsu's Digital Annealer only takes dozens of seconds, 72,000 times faster than conventional AI (with limited combinations explored)
  - Obtained semiconductor from optimal formulation is expected to have 30% higher performance than the one from conventional AI



Application: 5G wireless network power & emission reduction

https://www.fujitsu.com/global/about/resources/news/press-releases/2022/0224-01.html

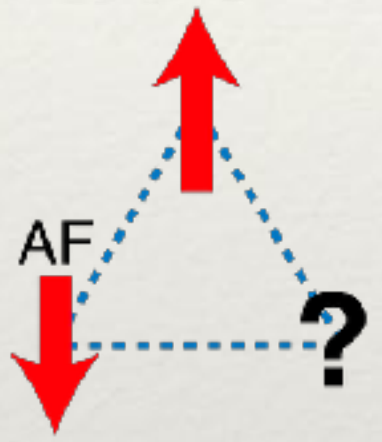
- February 2022: Fujitsu
  - New virtualized radio access network (vRAN) software technology leveraging Fujitsu's AI and Digital Annealer technologies to optimize computing resources of the entire 5G wireless network
  - Estimation of reducing overall system CO2 emissions by 50% or more comparing to conventional base station systems by 2025



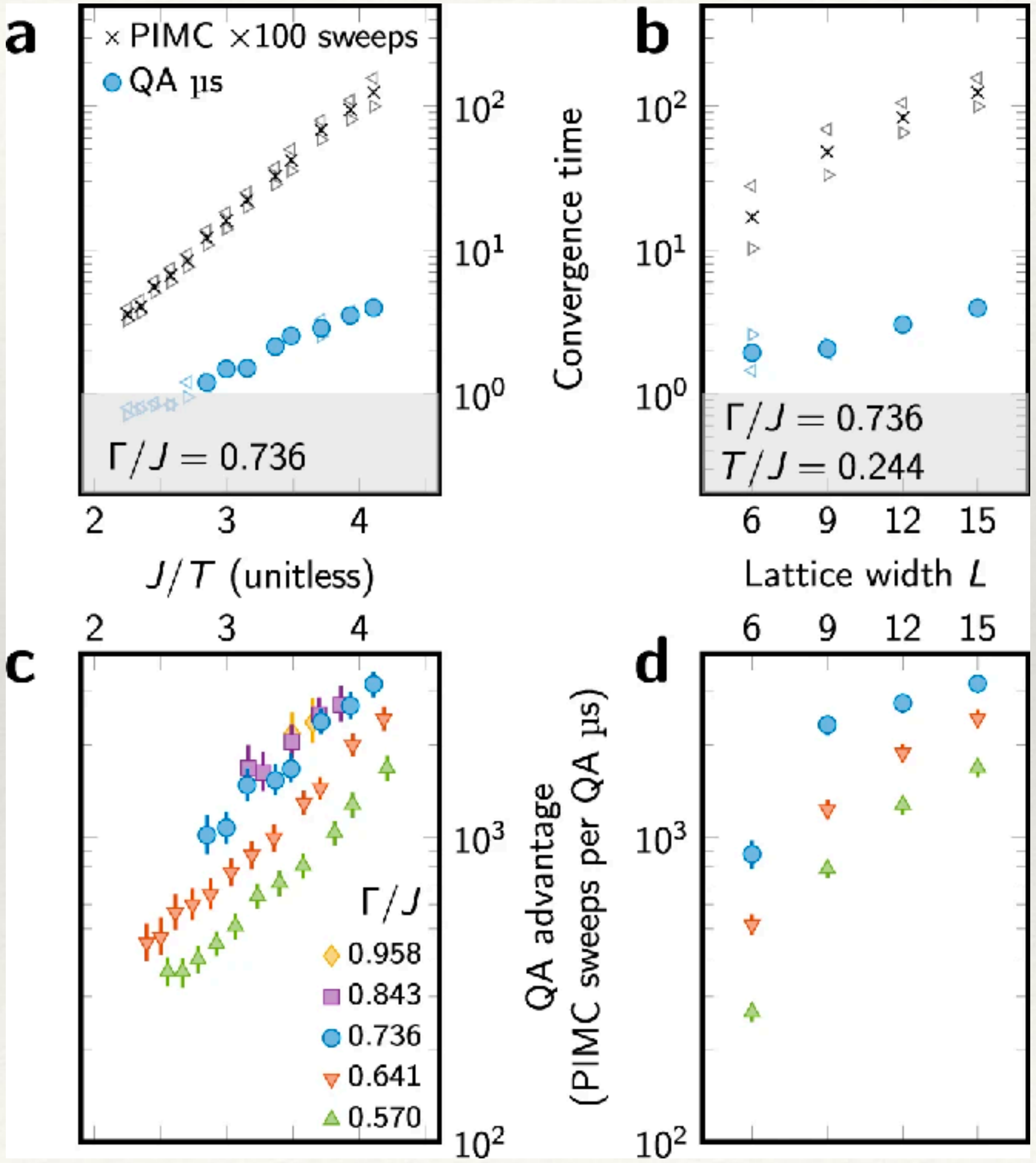
Application: quantum simulation of geometrically frustrated magnets

King, Raymond, Lanting *et al.*, Nat Commun. 12, 1113 (2021)

- D-Wave
  - Geometrical frustration — challenging!



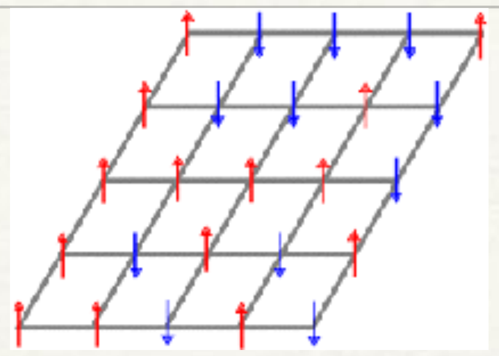
  - “Scaling advantage over path-integral Monte Carlo in quantum simulation of geometrically frustrated magnets”
  - QA equilibration is 3 million times faster than PIMC on a CPU



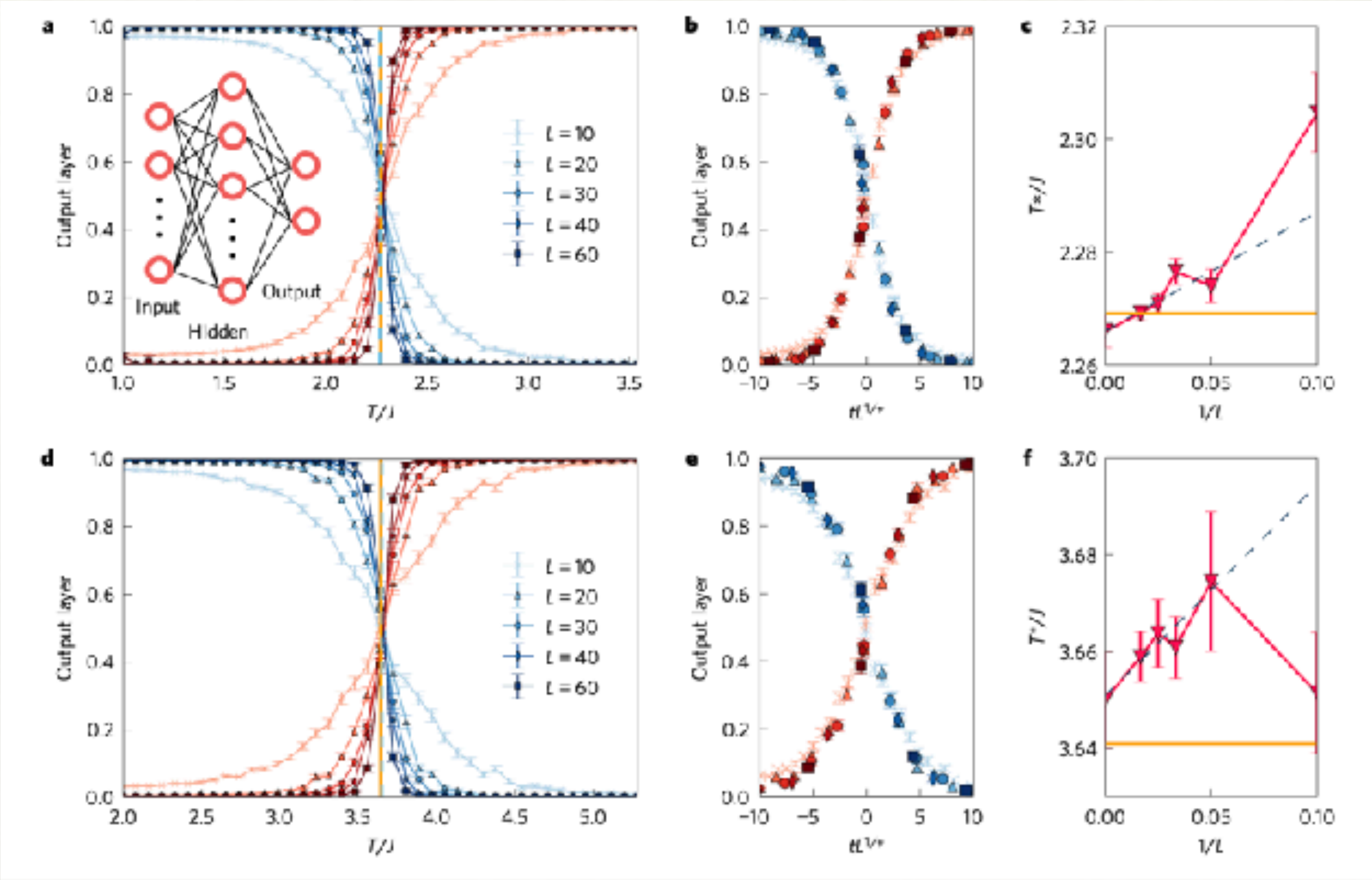
On the generalizability of artificial neural networks in spin models

Yau, NS, SciPost Phys. Core, 5 032 (2022)

- Ising model: $\mathscr{H} = -J\sum_{\langle i,j\rangle} \sigma_i\sigma_j$, where $\sigma \in \{-1,1\}$



- "Machine learning phases of matter" [Carrasquilla & Melko, Nat. Phys. 13, 431 (2017)]
  - Supervised learning, big data training: critical exponent $\nu = 1.0 \pm 0.2$



- Exponential reduction of training data state space
  - $2^N \rightarrow 3$, with N the number of spins, typically $\mathcal{O}(10^2) \sim \mathcal{O}(10^6)$
  - $\{-1,\ldots,-1\}$ & $\{1,\ldots,1\}$ for ordered phase; $\{0,\ldots,0\}$ for disordered phase
  - Critical exponent $\nu = 1.01 \pm 0.11$
- QAML outperforms conventional ML in few data training [Mott *et al.*, Nature 550, 375 (2017)]
  - Training strategy for spin model related problems, e.g. condensed matter physics, materials science, complex networks, etc

Conclusions and outlook

Conclusions and outlook

- Quantum many-body systems offer promising opportunities
- Thermal quantum field theory: incorporation of confinement to thermal QCD for a proper understanding of strong force
  - QCD collective excitations: full analysis
  - Improved HTL effective theory incorporating both electric and magnetic scales (heavy ions, astrophysics, cosmology, etc)
  - Strongly coupled systems in condensed matter physics, e.g. quantum spin liquids
- Quantum computing: applications of quantum many-body theories
  - Lattice simulation: high energy physics, condensed matter physics
  - Telecommunication: wireless and optical network optimizations
  - Energy & sustainability: energy network optimizations, trading strategies

Shandong Institute of Advanced Technology (SDIAT)

- Established in November 2019
- Honorary Director: Prof. Samuel Chao Chung Ting
- 150,000 m2 campus to support 1,200 staffs
    - Particle Physics Research Center
    - Thermal Science Research Center
    - AMS Data Center
    - Material Science Research Center
- Faculty positions at all ranks
    - Competitive salaries & starting supports