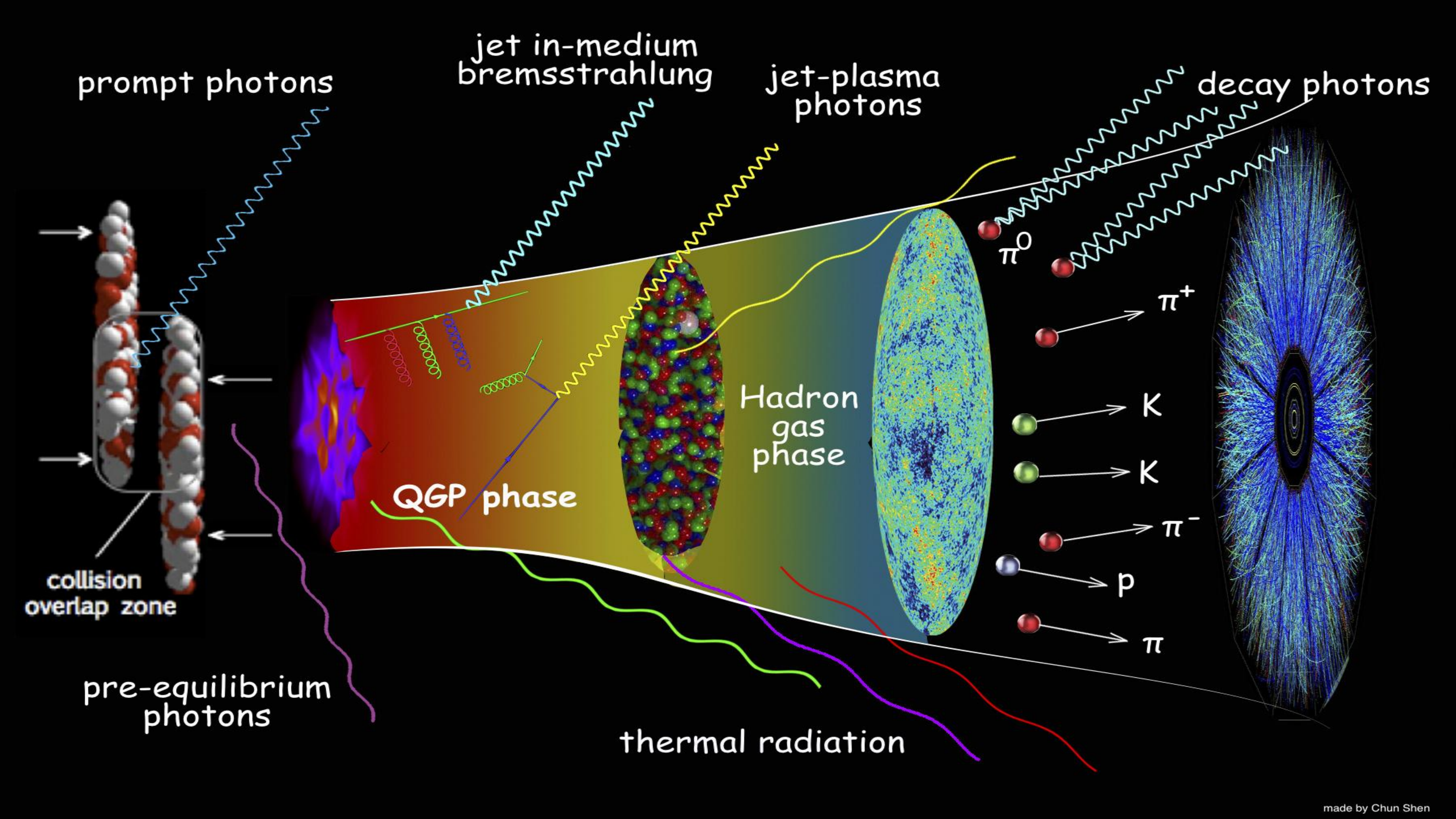
CLVisc Agent for relativistic hydrodynamics

Long-Gang Pang 庞龙刚

Central China Normal University

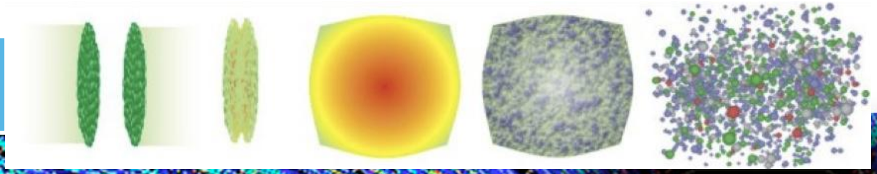
ShangHai，FuDan Univ，2026-7-4

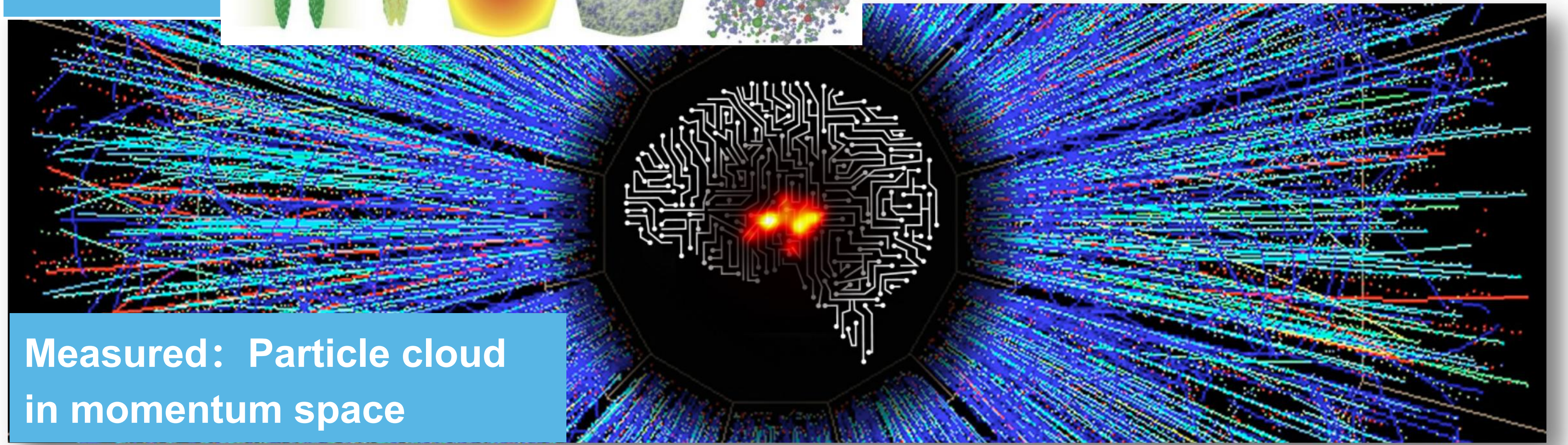

prompt photons
jet in-medium
bremsstrahlung
jet-plasma
photons
decay photons
π^0
π^+
K
K
π^-
p
π
Hadron
gas
phase
QGP phase
collision
overlap zone
pre-equilibrium
photons
thermal radiation
made by Chun Shen

HIC： Typical inverse problem

QGP Lifetime： $10^{-23}s$

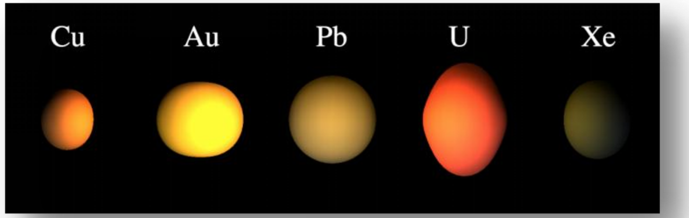
Forward

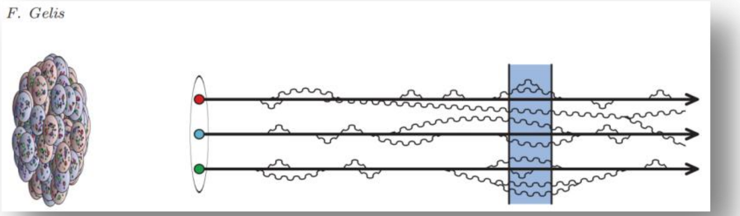


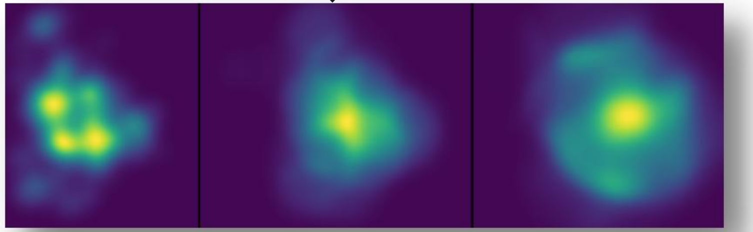


Measured： Particle cloud in momentum space

Inverse





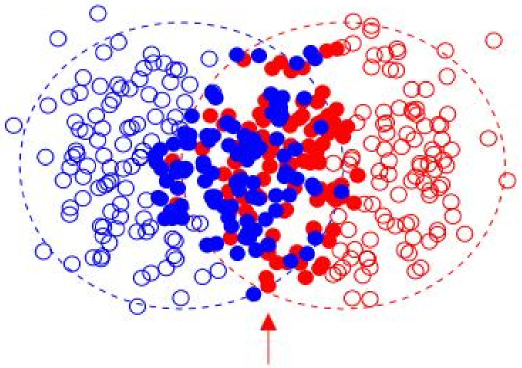


(1) Nuclear Structure

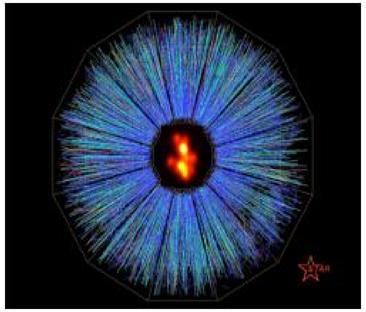
(2) Initial Parton Distribution

(3) QGP properties and EoS

Foward process: relativistic hydrodynamics



$$\nabla_\mu T^{\mu\nu} = 0$$



$$T^{\mu\nu} = (\varepsilon + P + \Pi)u^\mu u^\nu - (P + \Pi)g^{\mu\nu} + \pi^{\mu\nu}$$

Initial condition EoS Bulk Viscosity Shear Viscosity

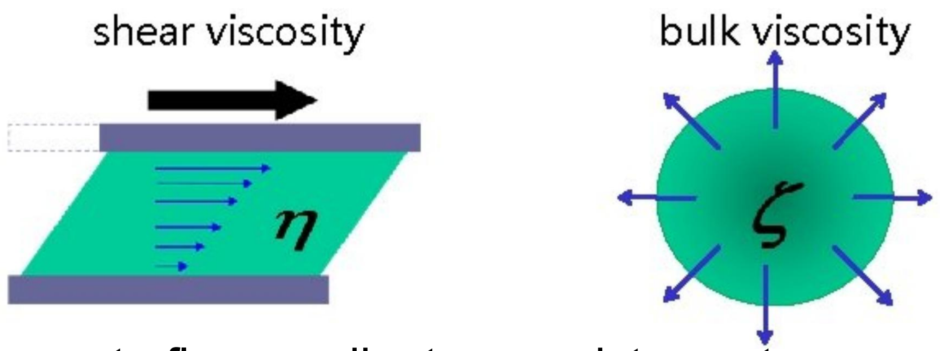
CLVisc:

1. CCNU-LBNL Viscous Hydro, CCNU = Central China Normal University
2. A 3+1D viscous hydro parallized on GPU using OpenCL

Purpose: Describe the non-equilibrium space-time evolution of hot QCD matter
Feature: **100 times faster** than using a single core CPU.

L.G. Pang, Q. Wang and X. N. Wang, PRC 86 (2012) 024911
L.G. Pang, B.W. Xiao, Y. Hatta, X.N.Wang, PRD 2015
L.G. Pang， H.Petersen, XN Wang, PRC97(2018)no.6,064918

Dissipation



resistance to flow gradients   resistance to expansion

credit：HuiChao Song

First order：acausal

$$\Pi = -\zeta\theta - \tau_\Pi \left[u^\lambda \nabla_\lambda \Pi + \frac{4}{3}\Pi\theta \right]$$

$$\pi^{\mu\nu} = \eta_v \sigma^{\mu\nu} - \tau_\pi \left[\Delta^\mu_\alpha \Delta^\nu_\beta u^\lambda \nabla_\lambda \pi^{\alpha\beta} + \frac{4}{3}\pi^{\mu\nu}\theta \right]$$

$$-\lambda_1 \pi^{\langle\mu}_\lambda \pi^{\nu\rangle\lambda} - \lambda_2 \pi^{\langle\mu}_\lambda \Omega^{\nu\rangle\lambda} - \lambda_3 \Omega^{\langle\mu}_\lambda \Omega^{\nu\rangle\lambda},$$

Expansion rate: $\theta \equiv \nabla_\mu u^\mu,$

Shear viscous tensor: $\sigma^{\mu\nu} \equiv 2\nabla^{\langle\mu} u^{\nu\rangle} \equiv 2\Delta^{\mu\nu\alpha\beta}\nabla_\alpha u_\beta,$

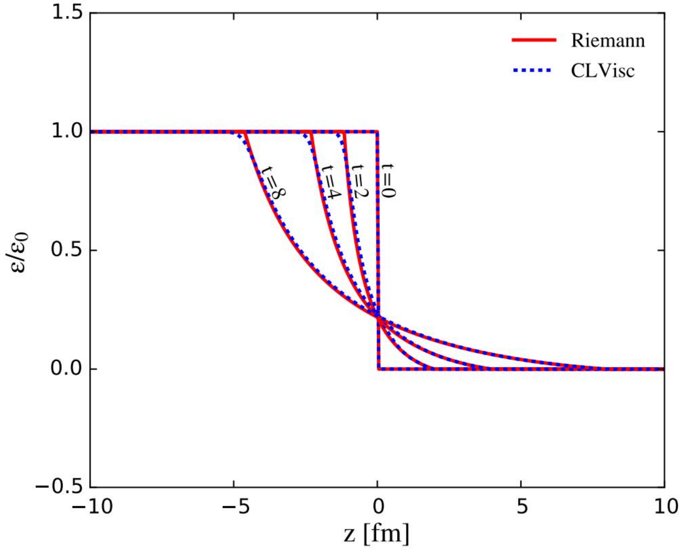
Vorticity tensor: $\Omega^{\mu\nu} \equiv \frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta}(\nabla_\alpha u_\beta - \nabla_\beta u_\alpha),$

Double projection operator: $\Delta^{\mu\nu\alpha\beta} \equiv \frac{1}{2}(\Delta^{\mu\alpha}\Delta^{\nu\beta} + \Delta^{\mu\beta}\Delta^{\nu\alpha}) - \frac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta},$

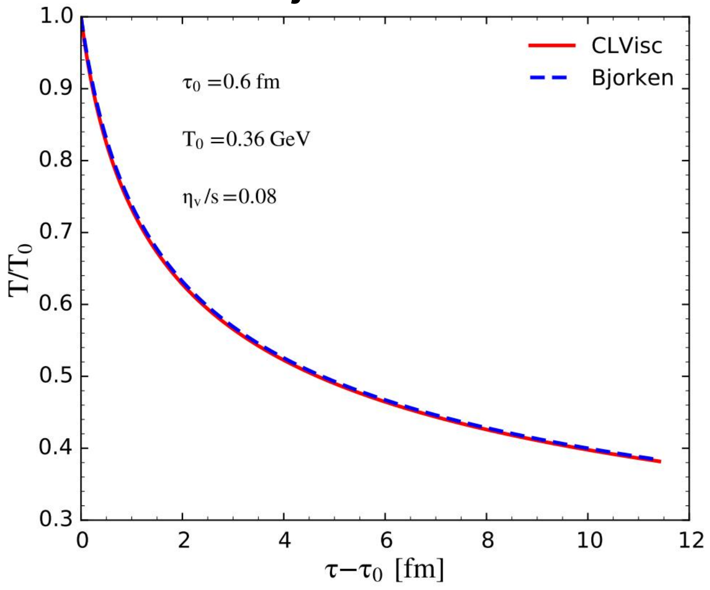
Projection operator: $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

Numerical vs Analytical solutions

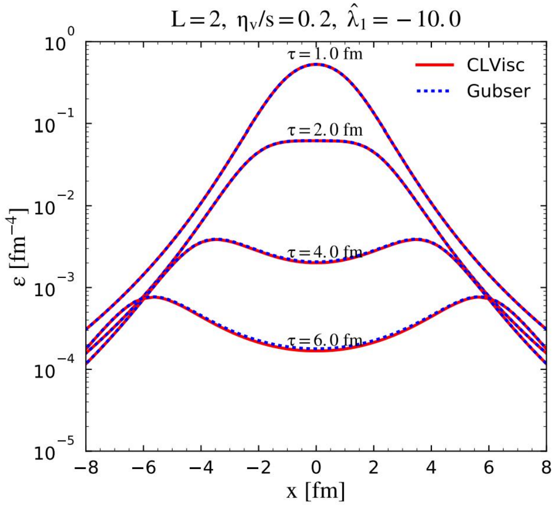
Riemann Solution

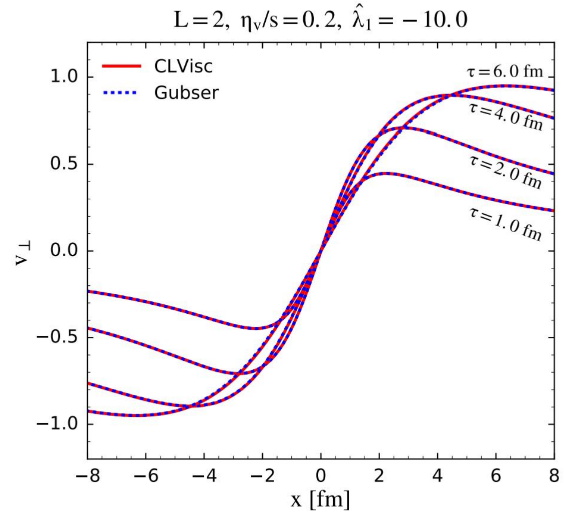


Bjorken Solution



Viscous Gubser Sol.





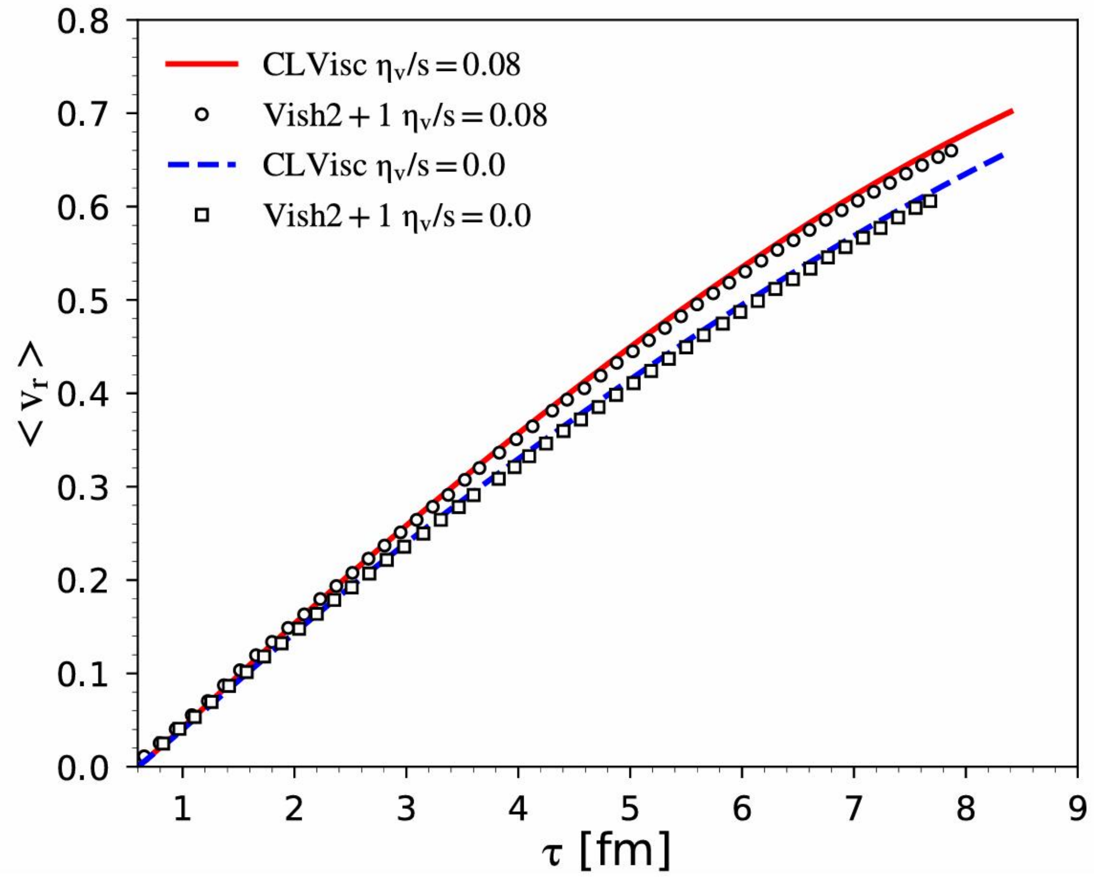
Constructing Analytical Solutions:

- **Select a specific spacetime metric.**
- **Make symmetry assumptions:** Assume a homogeneous energy density distribution.
- **Obtain the flow velocity:** This yields u^μ = (1, 0, 0, 0) in the chosen coordinates.
- **Transform back to flat spacetime:** This results in a non-zero flow velocity profile.

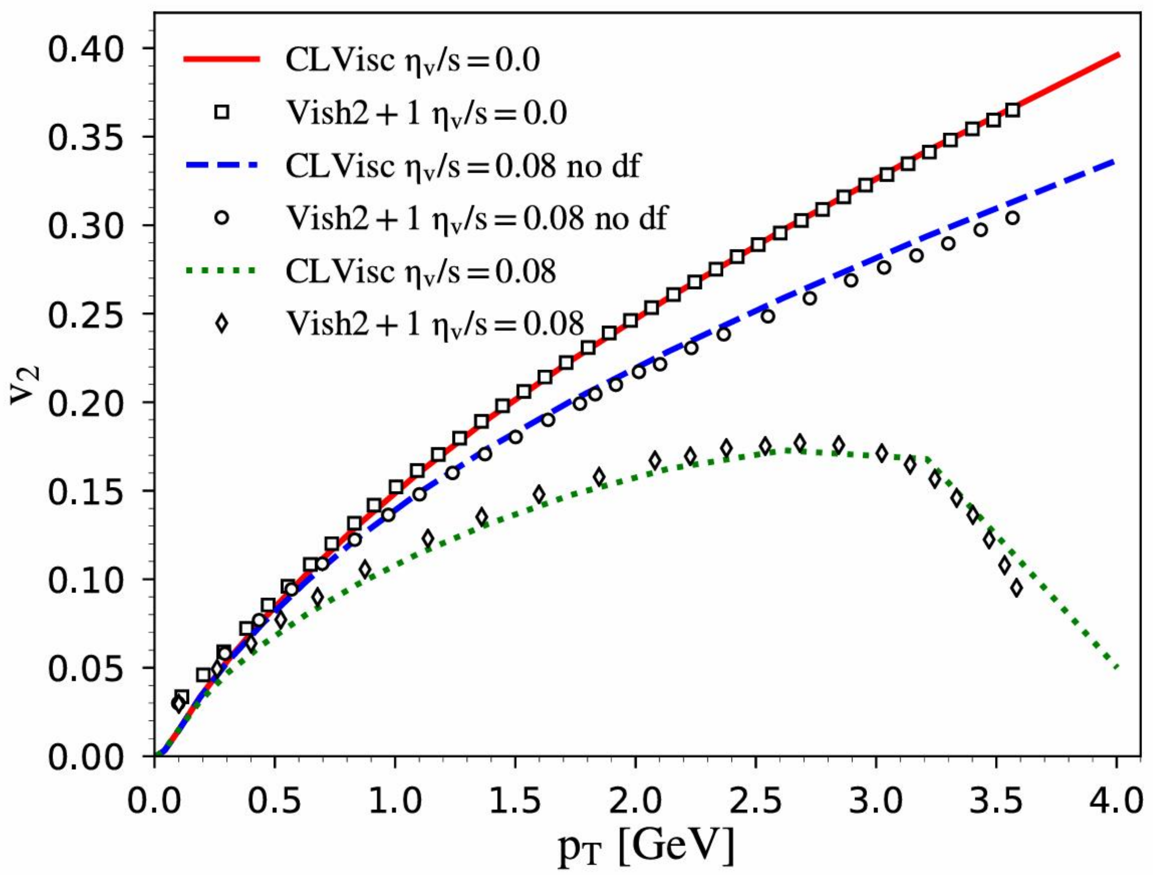
L.G. Pang, H.Petersen, XN Wang, PRC97(2018)no.6,064918

Relativistic fluid from different groups

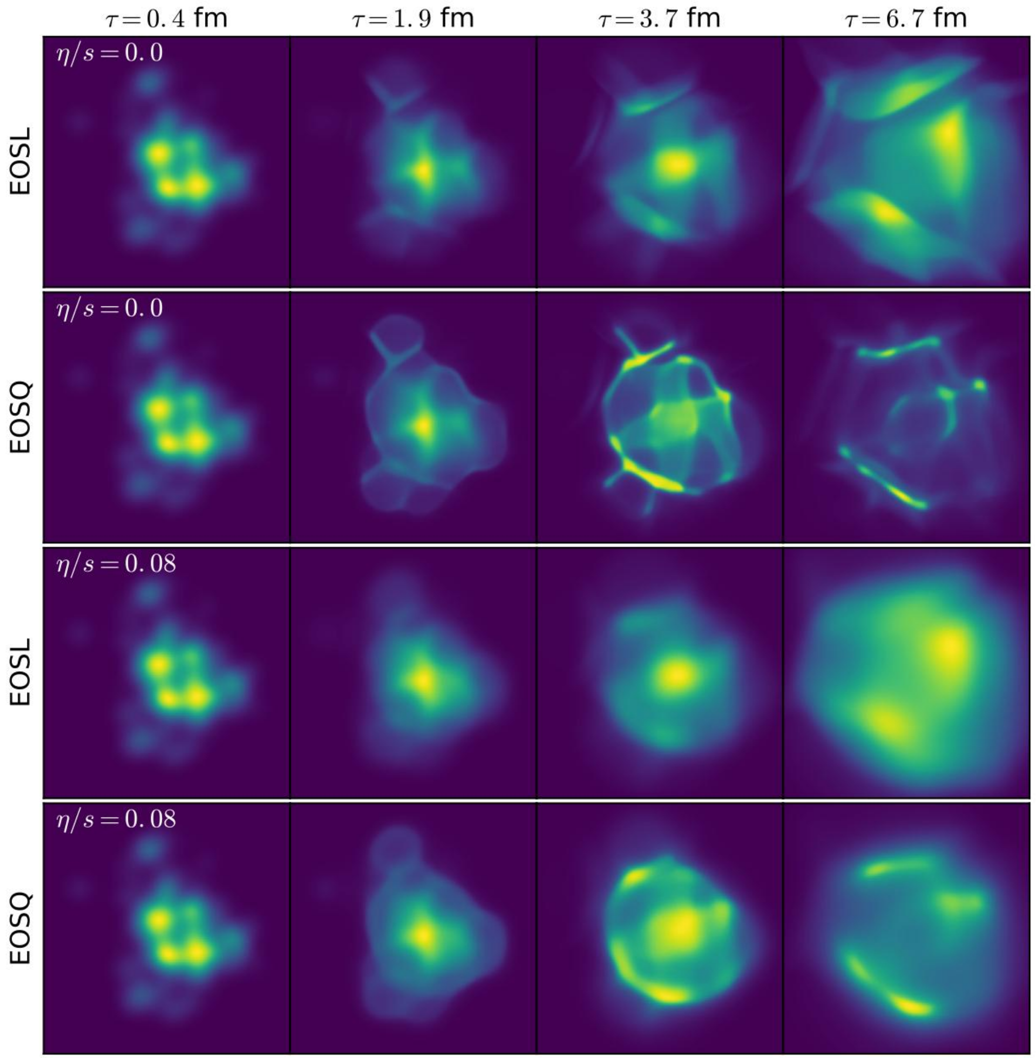
Mean transverse velocity



Elliptic flow



CLVisc for different EoS and η/s



η/s = 0 (shear viscosity over entropy density)
Lattice QCD EoS (smooth cross over)

η/s = 0 (ideal hydro)
First order phase transition

η/s = 0.08 (viscous hydro)
Lattice QCD EoS (smooth cross over)

η/s = 0.08
First order phase transition

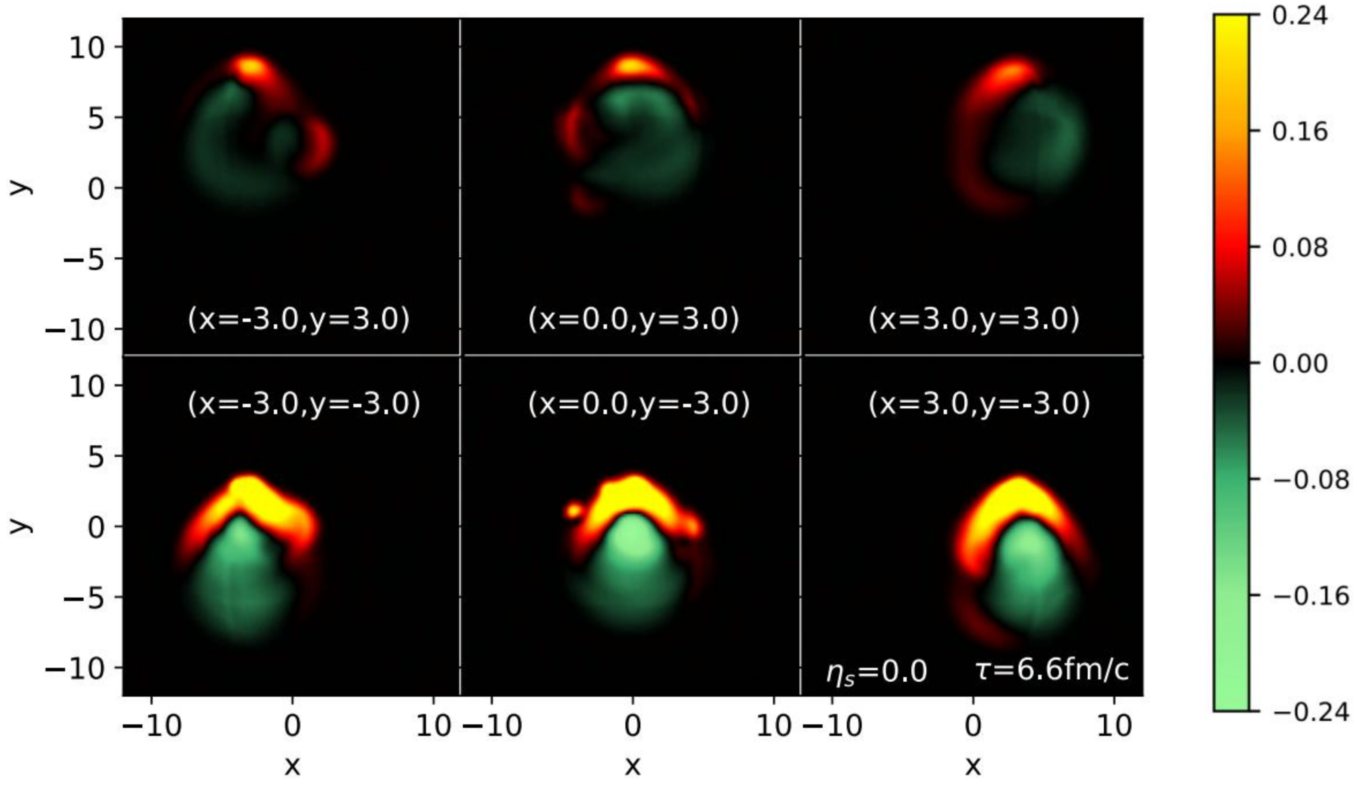
Nature Comm. 2018, **LG. Pang**, K.Zhou, N.Su, H.Petersen, H. Stoecker, XN. Wang.

Medium response for nuclear EoS

$$p\partial f(p) = -C(p) \quad (p\cdot u > p^0_{cut})$$

$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x-x_i)\theta(p^0_{cut} - p\cdot u)$$



LBT: YY He, T Luo, XN Wang, Y Zhu,
PRC 91 (2015) 054908, PRC 97 (2018) 1, 019902

CLVisc:
LG Pang, Q Wang, XN Wang, PRC 86 (2012) 024911
LG Pang, H Petersen, XN Wang, PRC 97 (2018) 6, 064918
XY Wu, GY Qin, LG Pang, XN Wang,PRC 105 (2022) 3, 034909

CoLBT:

W Chen, T Luo, SS Cao, LG Pang, XN Wang,
PLB 777 (2018) 86-90

Review articles on DL for nuclear physics

nature reviews physics https://doi.org/10.1038/s42254-024-00798-x

Nature Review Physics (2025)

Perspective Check for updates

Physics-driven learning for inverse problems in quantum chromodynamics

Gert Aarts[1], Kenji Fukushima[2], Tetsuo Hatsuda[3], Andreas Ipp[4], Shuzhe Shi[5], Lingxiao Wang[3] & Kai Zhou[6,7]

Abstract

The integration of deep learning techniques and physics-driven designs is reforming the way we address inverse problems, in which accurate physical properties are extracted from complex observations. This is particularly relevant for quantum chromodynamics (QCD) – the theory of strong interactions – with its inherent challenges in interpreting

Sections

Introduction

Physics-driven learning

QCD physics

Conclusions and outlook

Review Of Modern Physics (2022)

Colloquium: Machine learning in nuclear physics

Amber Boehnlein, Markus Diefenthaler, Nobuo Sato, Malachi Schram, Veronique Ziegler, Cristiano Fan… Morten Hjorth-Jensen, Tanja Horn, Michelle P. Kuchera, Dean Lee, Witold Nazarewicz, Peter Ostroumo… Orginos, Alan Poon, Xin-Nian Wang, Alexander Scheinker, Michael S. Smith, and Long-Gang Pang

Rev. Mod. Phys. 94, 031003 – Published 8 September 2022

Progress in Particle and Nuclear Physics 135 (2024) 104084

Prog. Part. Nucl. Phys. 135 (2024) 104084

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

Exploring QCD matter in extreme conditions with Machine Learning

Kai Zhou[a,b,*], Lingxiao Wang[a,*], Long-Gang Pang[c,*], Shuzhe Shi[d,e,*]

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[b] School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen 518172, China
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https://doi.org/10.1007/s41365-023-01233-z

REVIEW ARTICLE

Nucl. Sci. Tech. 34 (2023) 6, 88

High-energy nuclear physics meets machine learning

Wan-Bing He[1,2] · Yu-Gang Ma[1,2] · Long-Gang Pang[3] · Hui-Chao Song[4] · Kai Zhou[5]

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Abstract

Science China Physics, Mechanics & Astronomy

Machine learning in nuclear physics at low and intermediate energies

Wanbing He,[1,2,*] Qingfeng Li,[3,4,†] Yugang Ma,[1,2,‡] Zhongming Niu,[5,§] Junchen Pei,[6,7,¶] and Yingxun Zhang[8,9,**] DeepLearning.AI

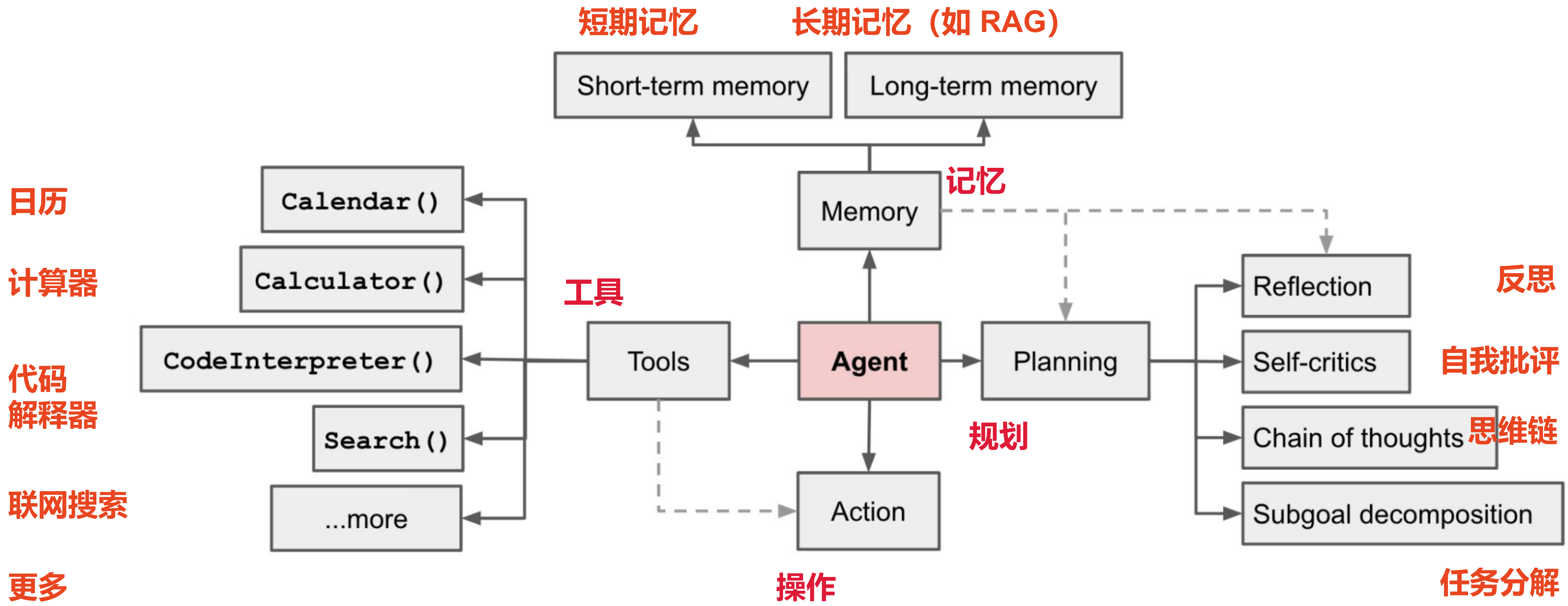
THE BATCH 人工智能大佬吴恩达写给大家的一封信 2024年3月

Dear friends,

I think AI agent workflows will drive massive AI progress this year — perhaps even more than the next generation of foundation models. This is an important trend, and I urge everyone who works in AI to pay attention to it.

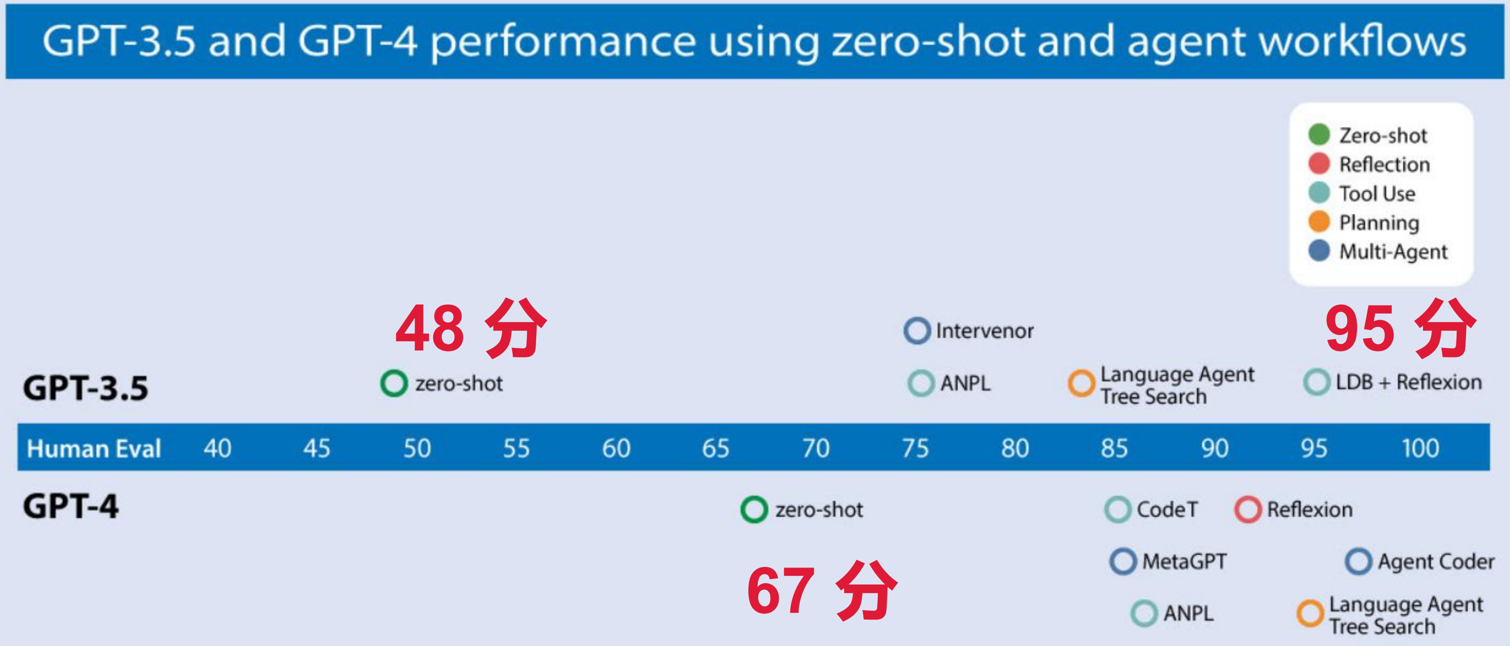
Today, we mostly use LLMs in zero-shot mode, prompting a model to generate final output token by token without revising its work. This is akin to asking someone to compose an essay from start to finish, typing straight through with no backspacing allowed, and expecting a high-quality result. Despite the difficulty, LLMs do amazingly well at this task!

大语言模型 Agent



Lilian Weng，《LLM Powered Autonomous Agents》，2023年6月

大语言模型 Agent 写代码的能力



Performance of GPT-3.5 and GPT-4 (zero-shot) on HumanEval, along with algorithms that use agent workflows on top of GPT-3.5 or GPT-4. Thanks to Joaquin Dominguez and John Santerre for help with this analysis.

对于一次成型代码，人类的评估打分为，

- GPT-3.5： **48 分**
- GPT-4： **67 分**

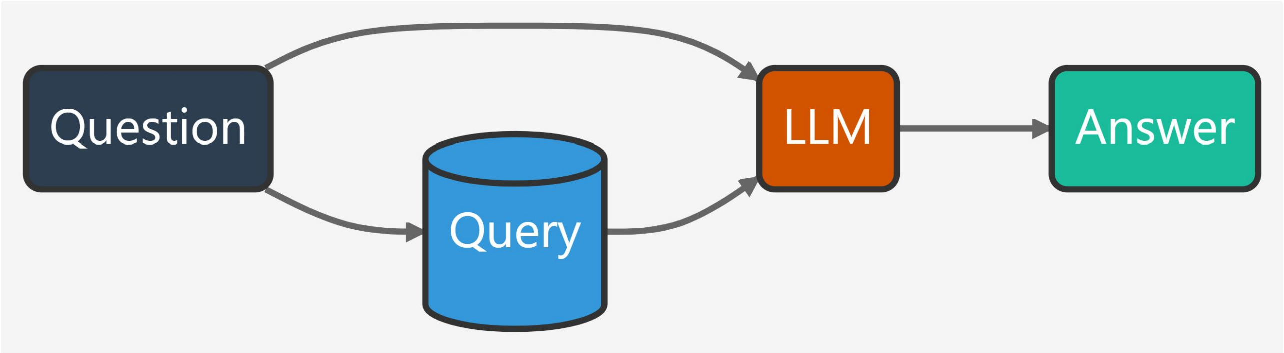
Agent 的引入，允许大型语言模型进行**自我反思与程序调试**，使得 GPT-3.5 编写的代码质量大幅提升，人类评分一跃至 95 分!

早期尝试：RAG与向量数据库

RAG : Retrieval Augmented Generation（检索增强生成）

kimi.moonshot.cn

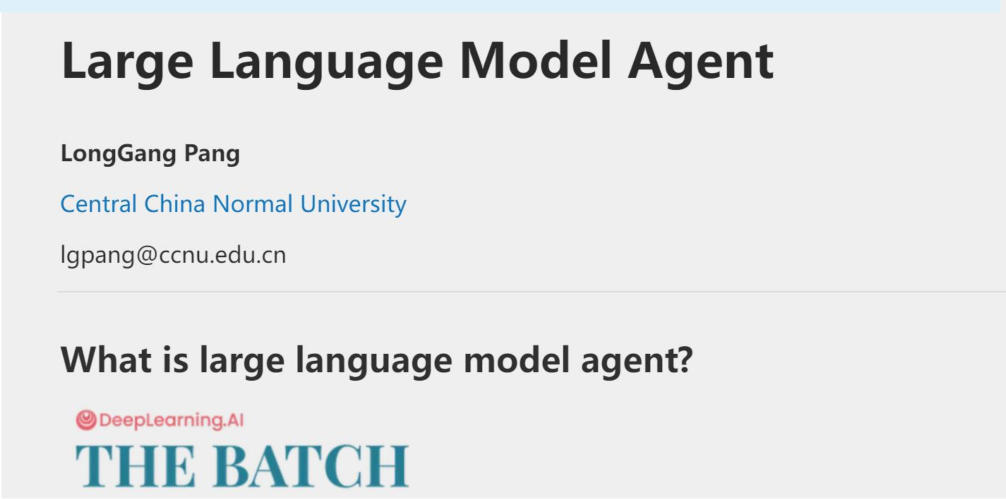
RAG: query documents



2024年7月，西湖大学举办 “AI&Physics” 暑期学校；我受邀授课内容：**大语言模型智能体**

介绍如何使用 Deepseek API，构建 LLM Agent，复现“反思、RAG、调用工具”等功能。课件网址：

https://www.wolai.com/awgzU3pWM7MfZY8kqdZ55b



应用场景：266万篇文献的向量数据库

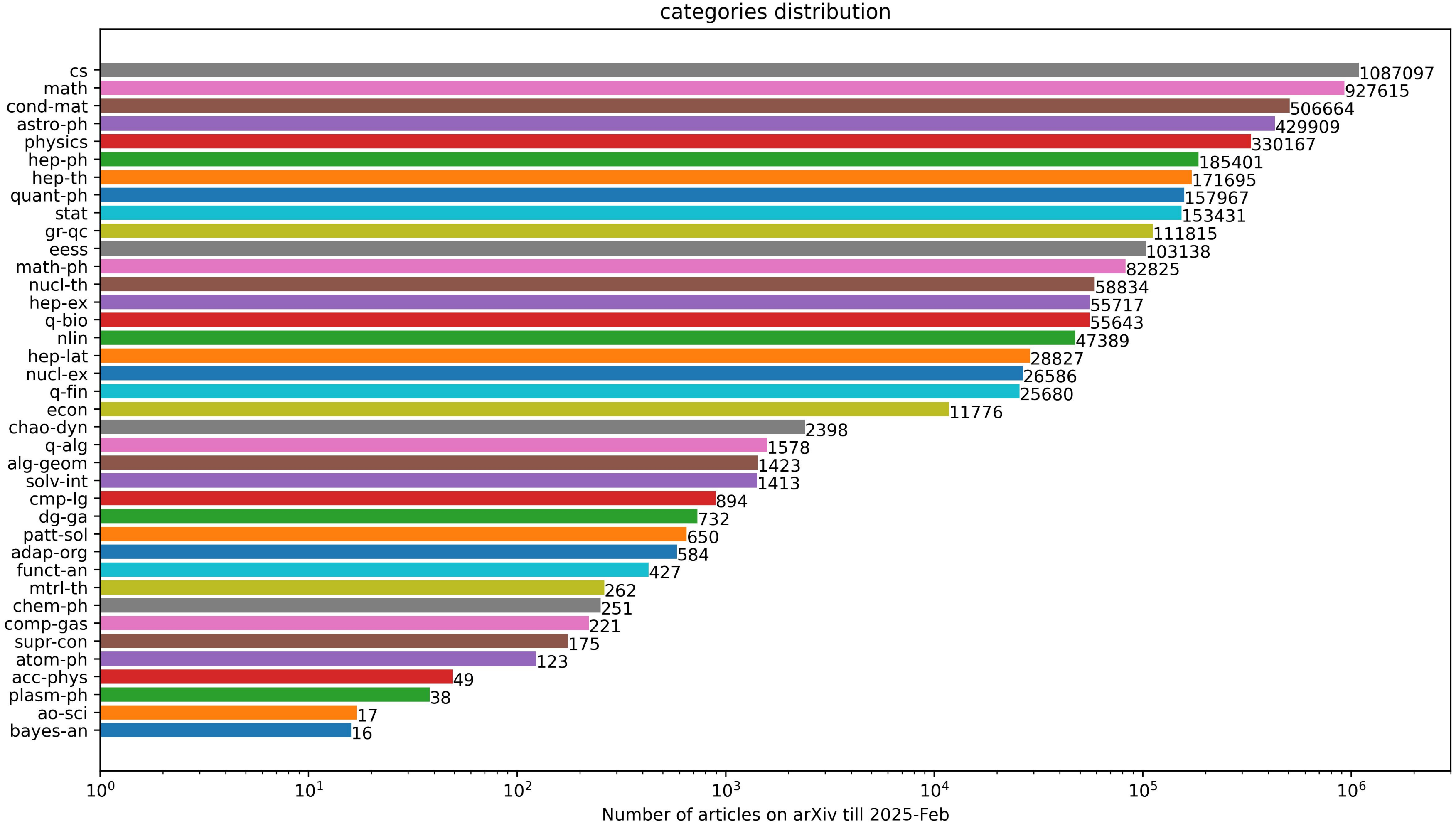
康奈尔大学开源了Arxiv数据集，收录了自然科学领域截止2025年2月的266.6万篇科研论文（仍在更新）

核理论: **58,834** articles

核实验: **26,586** articles

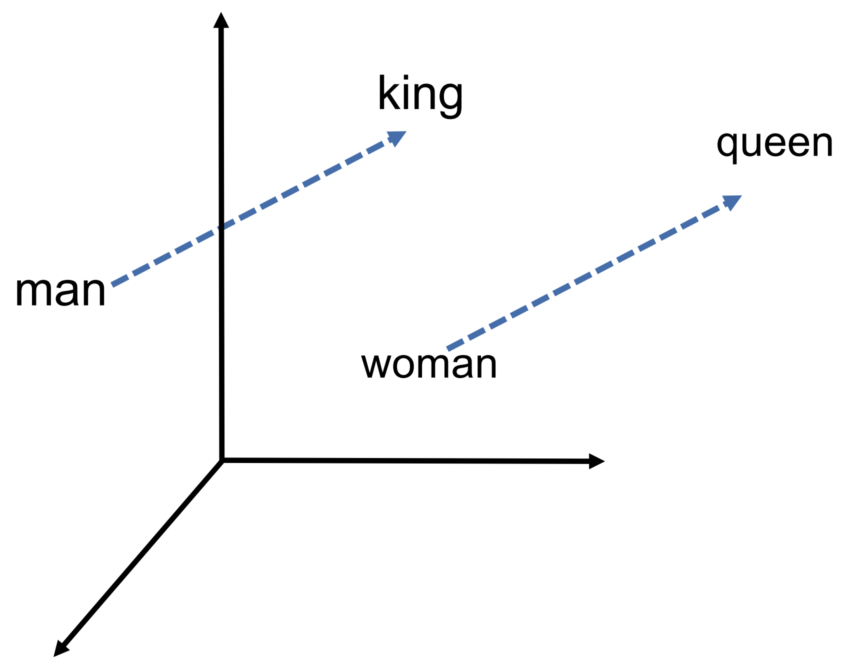
高能唯像: **185,401** articles

高能理论: **171,695** articles



困难：1. 科研人员很难找到相关文献　2. 大语言模型记不住所有知识

ArXiv 向量知识库



词向量 → 段落向量

关键词搜索 ----》基于向量相似度的语义检索

第 48 卷 第 5 期 核 技 术 NUCLEAR TECHNIQUES Vol.48, No.5
2025 年 5 月 www.hjs.sinap.ac.cn May 2025

核物理 AI 研究助手与 arXiv 向量数据库

庞龙刚[1,2]

1（华中师范大学 夸克与轻子教育部重点实验室 武汉 430079）

2（华中师范大学 人工智能与计算物理研究中心 武汉 430079）

我们构建并开源了 Arxiv 向量数据库

https://gitee.com/lgpang/arxiv_vectordb.git

266.6 万篇文章的标题 + 摘要

266.6 万个向量（每个向量1024个元素）

占用硬盘空间：30 GB

通过向量相似度进行语义检索

额外功能：基于 Deepseek 的 LLM agents

- 计算检索结果与原始问题的相关程度
- 下载完整文章的pdf 文件并阅读
- 从文章的 discussion 部分寻找未来研究方向

CLVisc Agent: Motivations

1. Smarter Configuration —— 不再因不恰当参数组合而崩溃，系统自动鲁棒适配。
2. Effortless Usability —— 无需深读多页文档，新手也能快速上手（安装、运行）。
3. Plug-and-Play Connectivity —— 告别“胶水代码”，与上下游模块无缝对接。
4. AI-Augmented Coding —— 精通 CLVisc 物理与操作性知识，可靠编排。
5. Autonomous Discovery —— 超越人为预设，让Agent尝试自主知识发现。

CLVisc Agent for autonomous relativistic hydrodynamics. Q Wang, L-G Pang, S Pu, X-N Wang, in prepare

How do we develop the CLVisc Agent

```
Welcome to Kimi Code CLI!
Send /help for help information.

Model: K2.7 Code
```

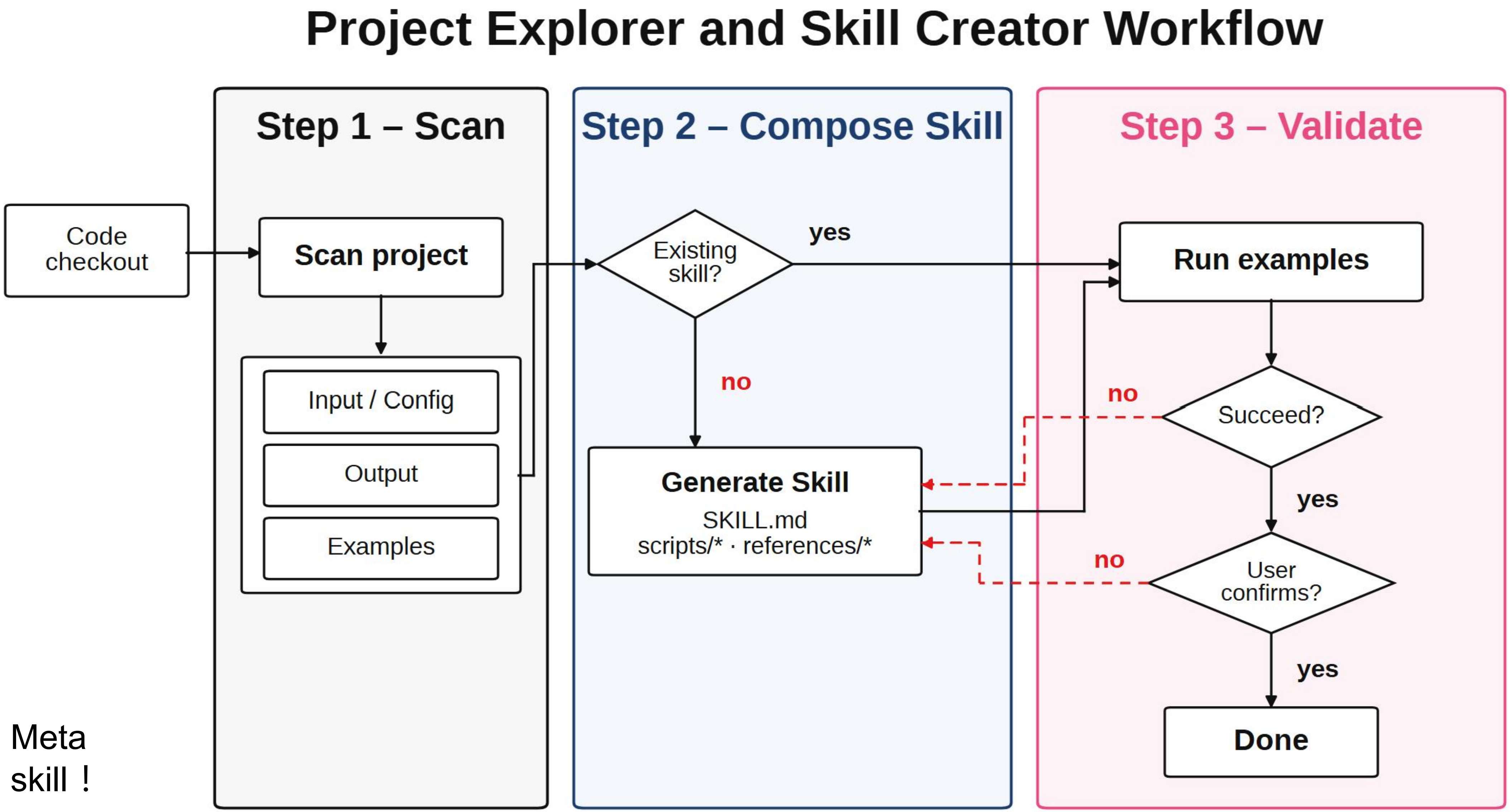
```
moonshot@KimiCode 🚀 introduce yourself
```

```
introduce yourself
```

- *The user is asking me to introduce myself. This is a simple greeting/question that operations or tool usage. I should simply respond directly in a friendly, concise*
- Hello! I'm Kimi Code CLI, an AI-powered coding assistant developed by Moonshot AI.

Kimi Code CLI 国产 AI, 其他国产替代 Opencode + Deepseek 或 Claude + GLM

How do we develop the CLVisc Agent

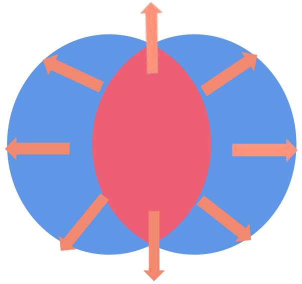


Meta
skill！

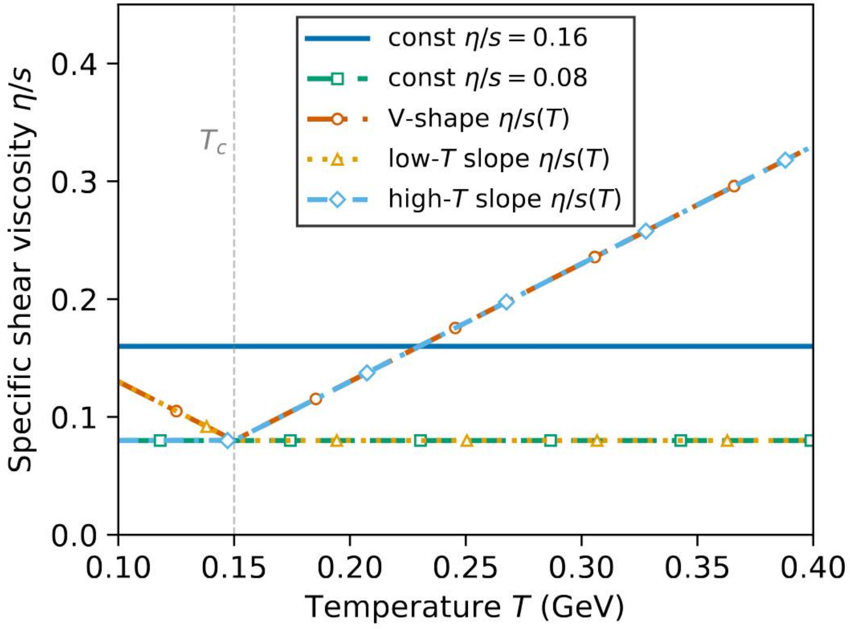
From Skill to Agent

层级	名称	核心定义
LV.1	**CLVisc Skill**	**“即插即用的专家外挂”** 一个标准化的操作流程（SOP）+ 工具集 + 说明文档。任意通用Agent挂载此Skill后，均可在短时间内蜕变为CLVisc专家。（存在上下文长度约束）
LV.2	**LGPang Agent**	**“开发者的数字孪生”** 精准继承开发者在漫长开发与调试中踩过的所有“坑”（报错陷阱、收敛失败、参数死区），具备人类的避错直觉。
LV.3	**CLVisc Agent**	**“超越造物主的物理直觉”** 不仅通晓全部代码与物理内核，其知识广度与深度甚至超越开发者，拥有高能核物理、相对论流体力学更广泛的领域知识，能自主推演未知关联。 优点：构建 CLVisc 子智能体，隔离主智能体的上下文

CLVisc Agent 自动化科研 （1）

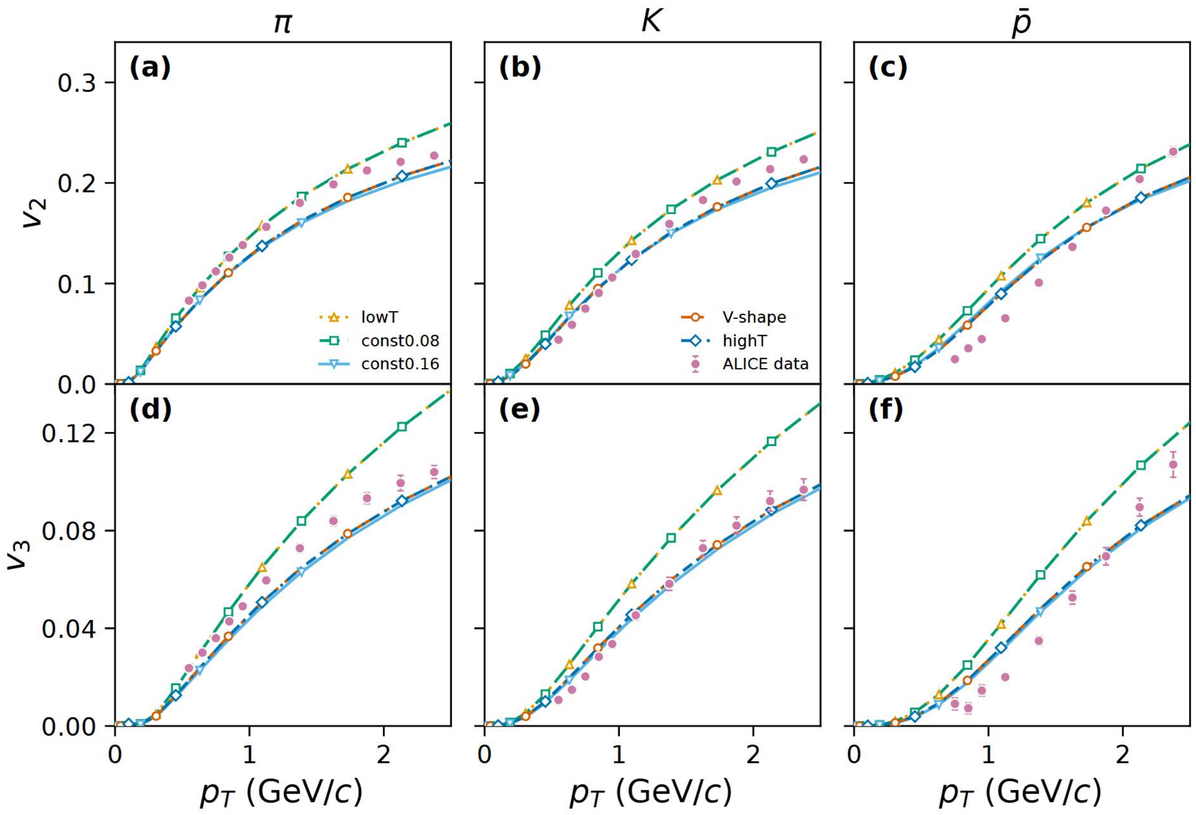


流体力学膨胀将几何各向异性转化为动量空间各向异性，剪切粘滞压低各向异性流



温度依赖的输运系数

各向异性流的简并现象

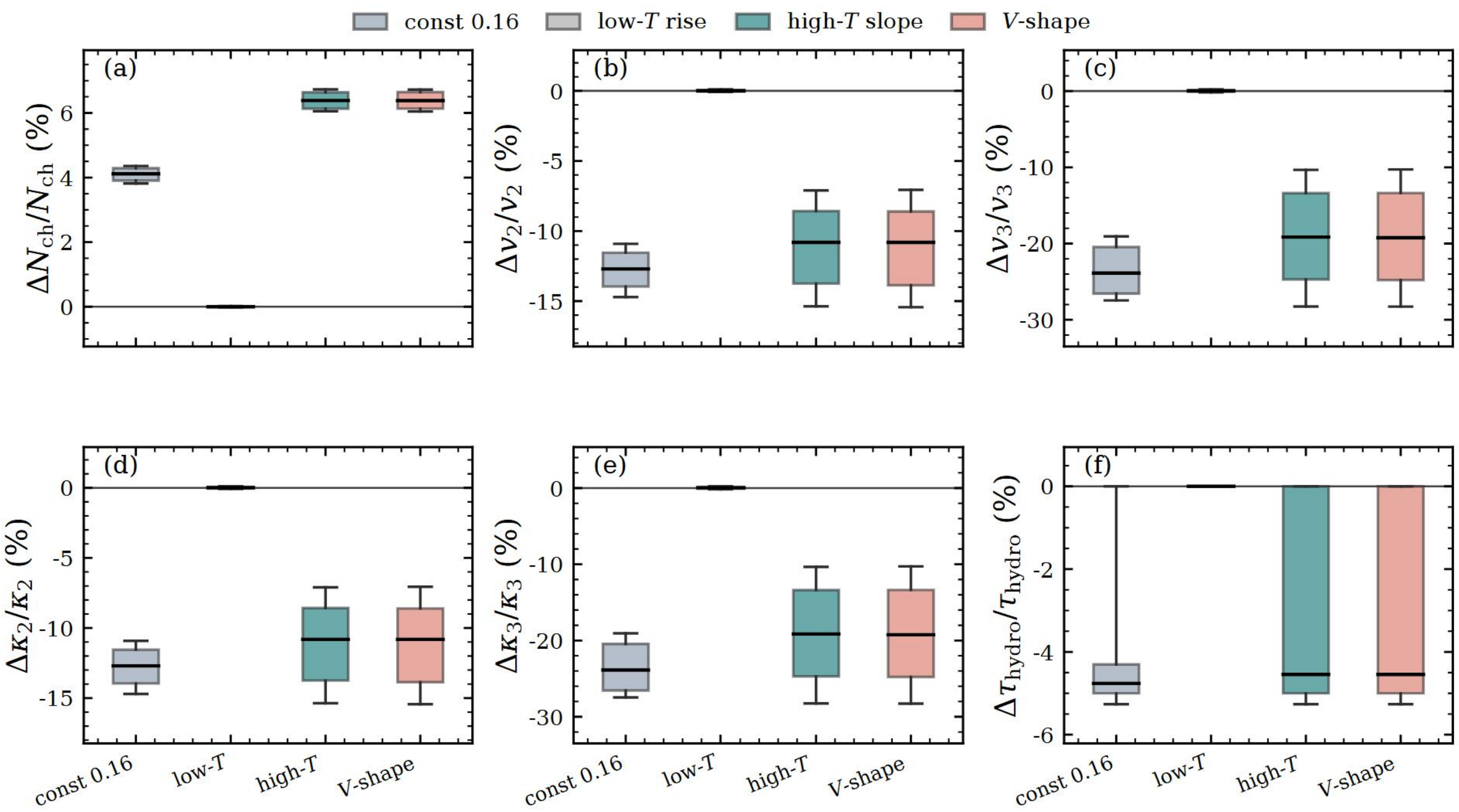


Agent 自己定义的“观测量”

$$\frac{\Delta X}{X} = \frac{X(\text{profile}) - X(\text{const}\,0.08)}{X(\text{const}\,0.08)},$$

验证简并现象：

AI 自己定义的以 eta/s=0.08 为参考的 200 个事件的成对对比图。



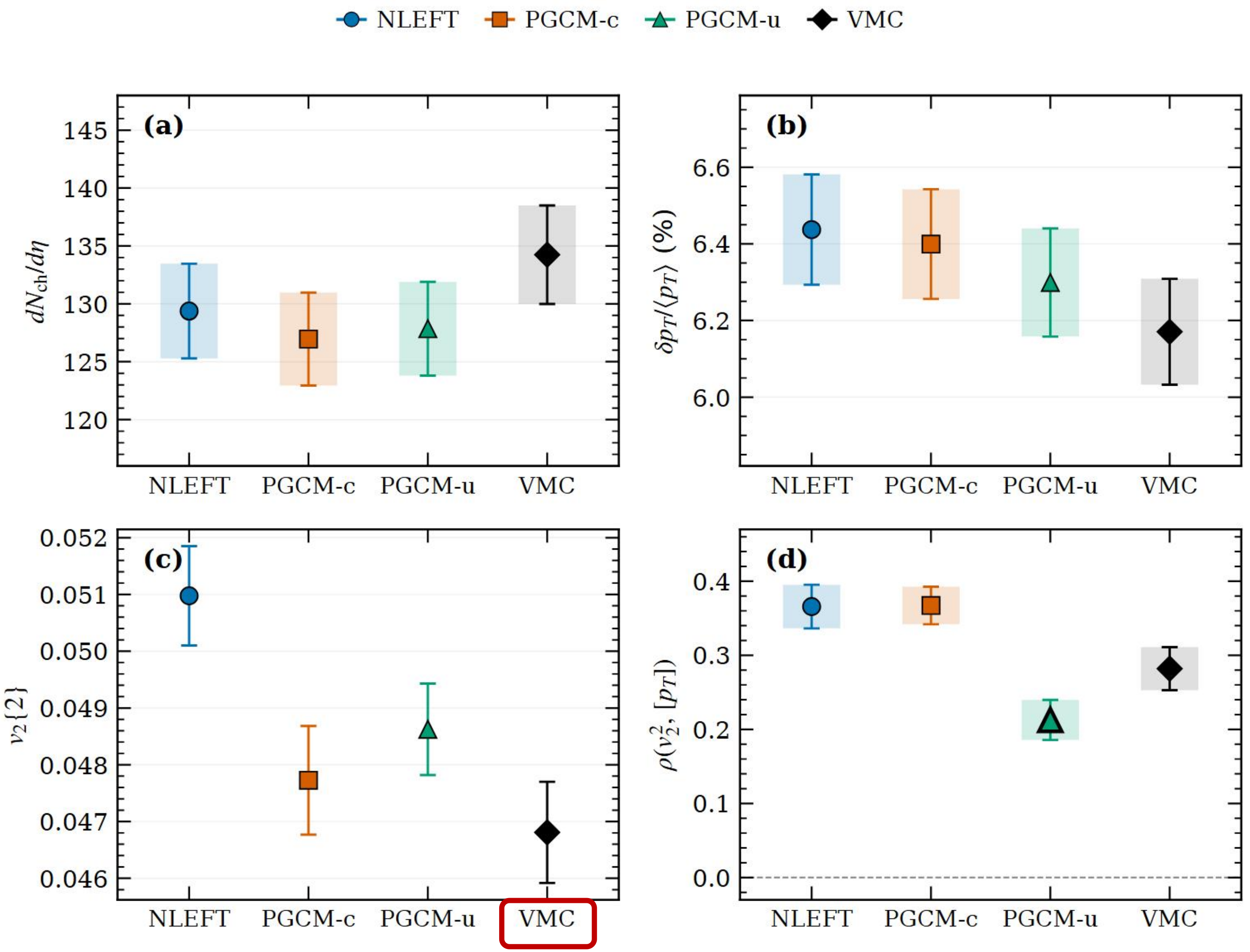
CLVisc 自动化科研 （2）

验证核结构对核碰撞的影响：

1. 提供了4种 O16 核结构

2. CLVisc Agent 使用这四种核结构进行相对论流体力学计算、末态可观测量设计与计算、科研绘图

3. 尝试提供一些物理解释（启发性：比如为何 VMC 结构的椭圆流最小？）



举例：Agent 自己定义物理量解释v2差异来源

标准 Bohr–Mottelson 约定：

$$\beta_2 = \sqrt{\frac{5\pi}{9}\frac{\lambda_{\max}}{AR_0^2}}, \qquad Q_{ij} = \sum_{k=1}^{A}\left(3r_{ki}r_{kj} - r_k^2\delta_{ij}\right)$$

参数说明：

- Q_{ij}：核子坐标的**无迹四极张量**
- $\lambda_{\max}$：Q_{ij} 的**最大本征值**
- $R_0 = 1.2A^{1/3}$，且 $A = 16$

Obs.	NLEFT	PGCM-c	PGCM-u	VMC
$\langle\varepsilon_2\rangle$	0.35	0.33	0.34	0.31
$\rho(\varepsilon_2^2, d_{\text{area}})$	+0.079	+0.117	−0.006	+0.115
$\varepsilon_2\{4\}/\varepsilon_2\{2\}$	0.76	0.74	0.74	0.69
$\langle\beta_2\rangle$	0.60	0.57	0.61	0.44
$\sigma(\beta_2)/\langle\beta_2\rangle$	0.50	0.46	0.45	0.39
$\text{corr}(\beta_2, \varepsilon_2)$	0.62	0.61	0.60	0.60

Shift from solving to learning

GPU isn't the silver bullet.
Relativistic hydro + transport model remain the bottleneck for event-by-event simulations & Bayesian analysis.

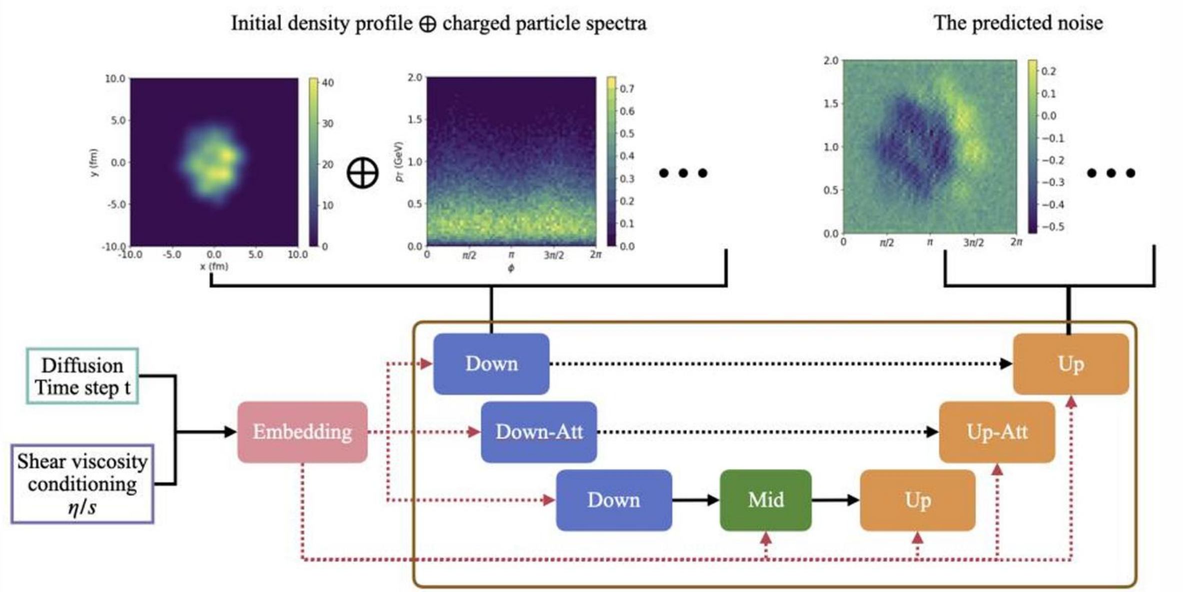
Solution:
Generative models — learn the distribution, skip the solver.

Generative model for HICs

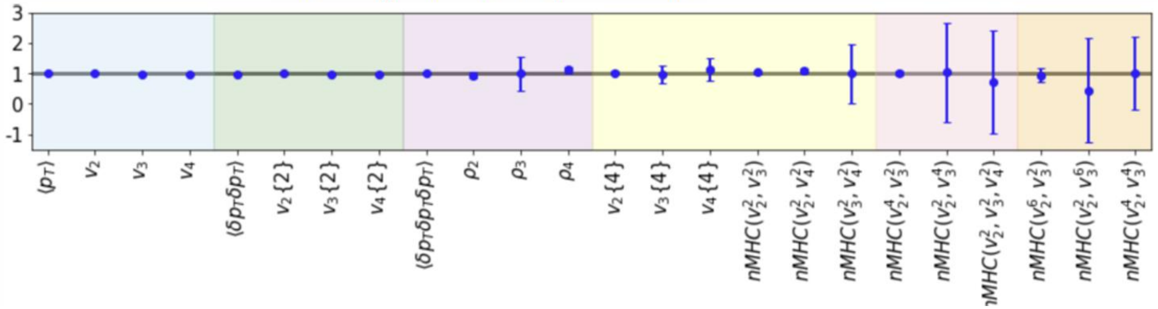
An end-to-end generative diffusion model for heavy-ion collisions

Jing-An Sun,[1,2] Li Yan,[1,3] Charles Gale,[2] and Sangyong Jeon[2]

arXiv:2410.13069



$$S_t = \sqrt{\bar{\alpha}_t} S_0 + \sqrt{1-\bar{\alpha}_t}\,\varepsilon$$



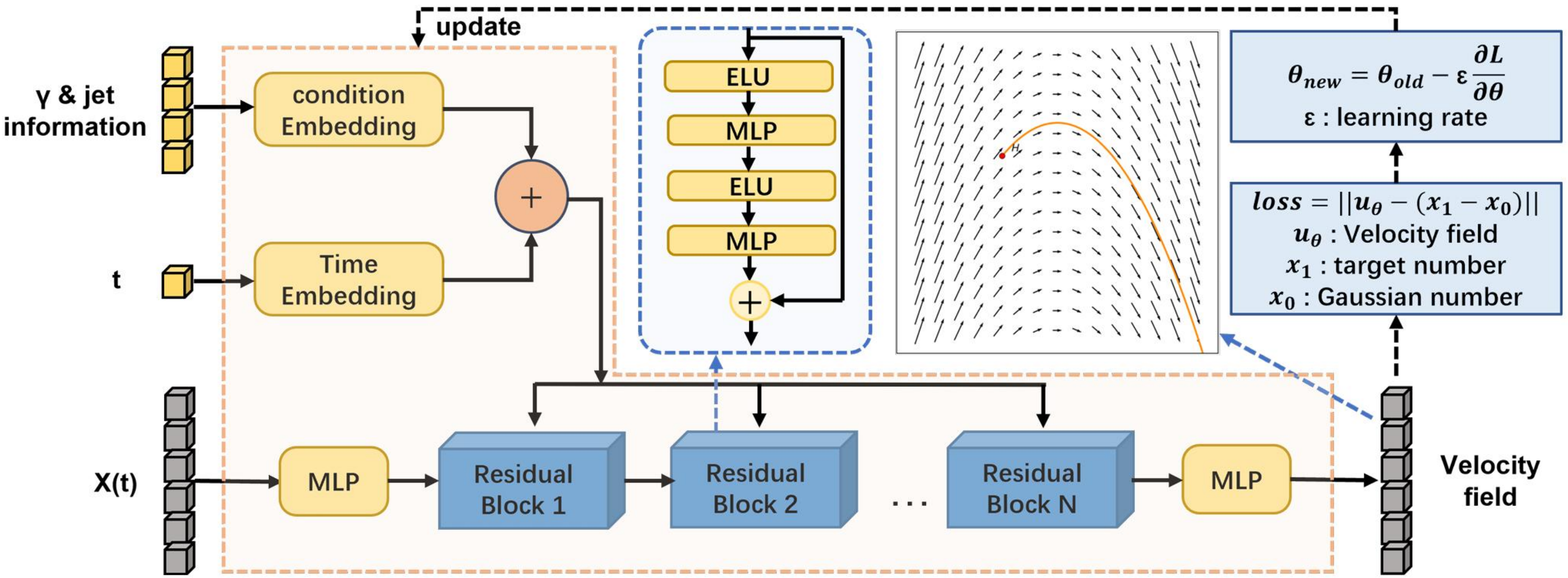
tor. We carried out (2+1)D minimum bias simulations of Pb-Pb collisions at 5.02 TeV, choosing the shear viscosity η/s to be one of three distinct values: 0.0, 0.1, and 0.2. For each value of η/s, we generate 12,000 pairs of initial entropy density profiles and final particle spectra corresponding to 12,000 simulated events, as the training dataset. 70% of the total events are used for training and the rest are used for validation.

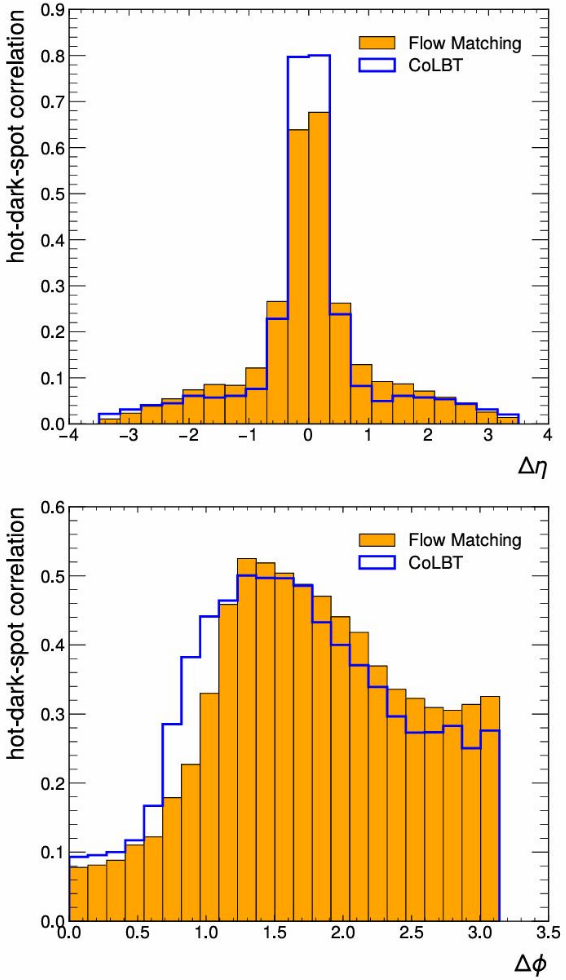
Considering that the spectra $\boldsymbol{S}_0$ depend on the initial entropy density profiles $\boldsymbol{I}$ and the shear viscosity η/s, we train a conditional reverse diffusion process $p(\boldsymbol{S}_0|\boldsymbol{I},\eta/s)$ without modifying the forward process.

one single central collision event in just 10^{-1} seconds on a GeForce GTX 4090 GPU.

ble precision, as the traditional numerical simulation of hydrodynamics for one central event typically takes approximately 120 minutes (10^4 seconds) on a single CPU.

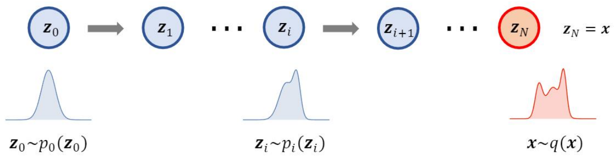
Generative Model For Physical Simulation





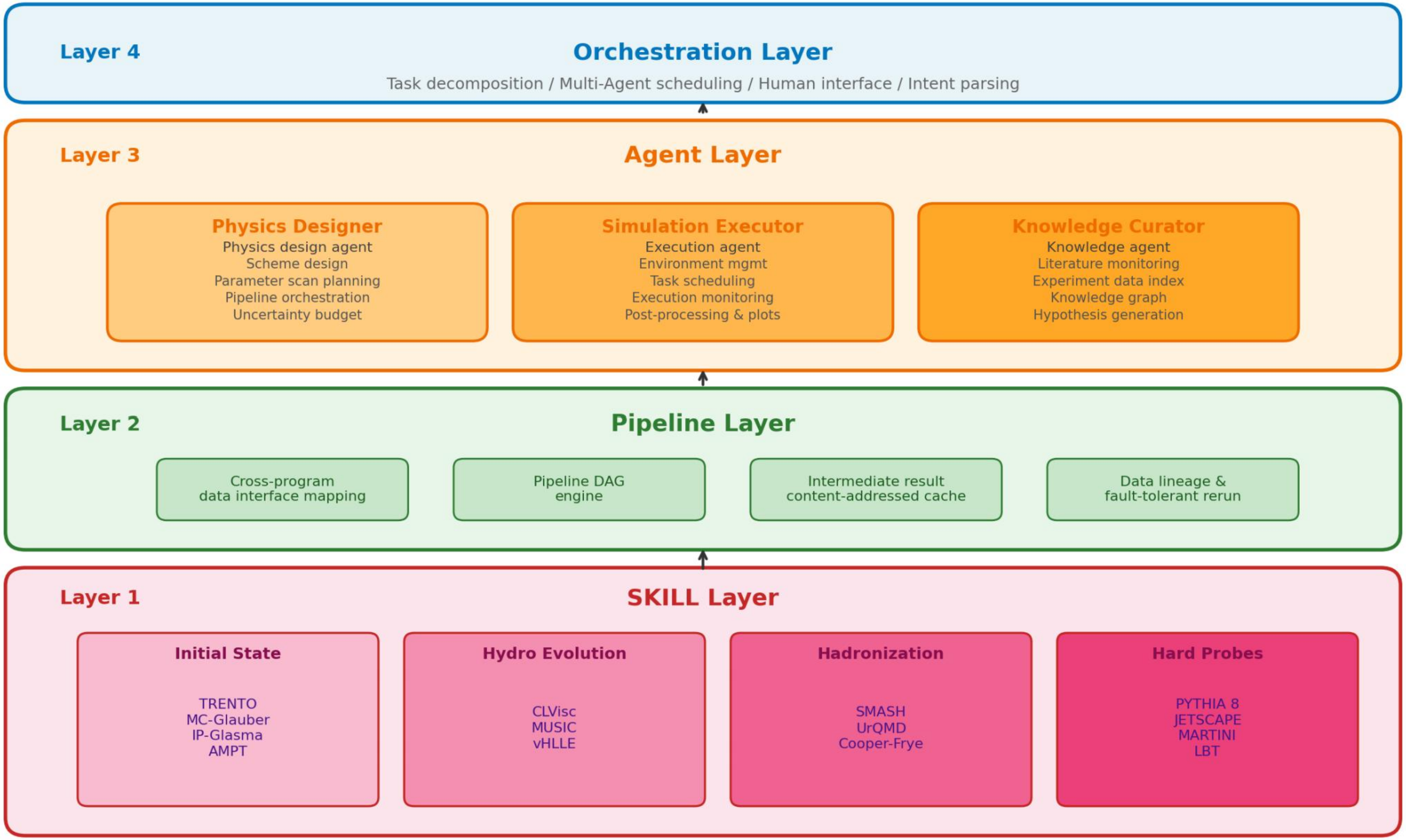
- ✓ **Flow matching generative model for jet-induced medium response simulations**
- ✓ **Model: CoLBT(CLVisc + LBT)**
- ➢ **Speed Up: $\times 10^6$ times**

$$\frac{\mathrm{d}x}{\mathrm{d}t} = u_\theta(x, t)$$



KY Wu, Z Yang, LG Pang, XN Wang, arxiv: 2605.17511

Outlook： Generative Agent for Nuclear Physics Studies



Xin-Nian Wang Suggested, developing in IOPP, CCNU