

基本粒子物理与超算

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上海交通大学

第十一届科学计算研讨会

A person stands on a rock in the foreground, silhouetted against a vast night sky filled with stars and the Milky Way galaxy. The galaxy's light is visible as a vertical band of purple and white stars stretching across the center of the image. The overall scene is dark and atmospheric, with a focus on the cosmic scale of the universe.

面对人类最重要的科学问题为核心，从事**物理和天文**方面的最前沿的科学研究，**寻找宇宙中极大和极小间的关联，探索自然界最基本和最深刻的相互作用规律**

---李政道

人类的好奇心

--仰望星空

宏观大尺度的物理规律

爱因斯坦广义相对论 (1915)

爱因斯坦狭义相对论 (1905)

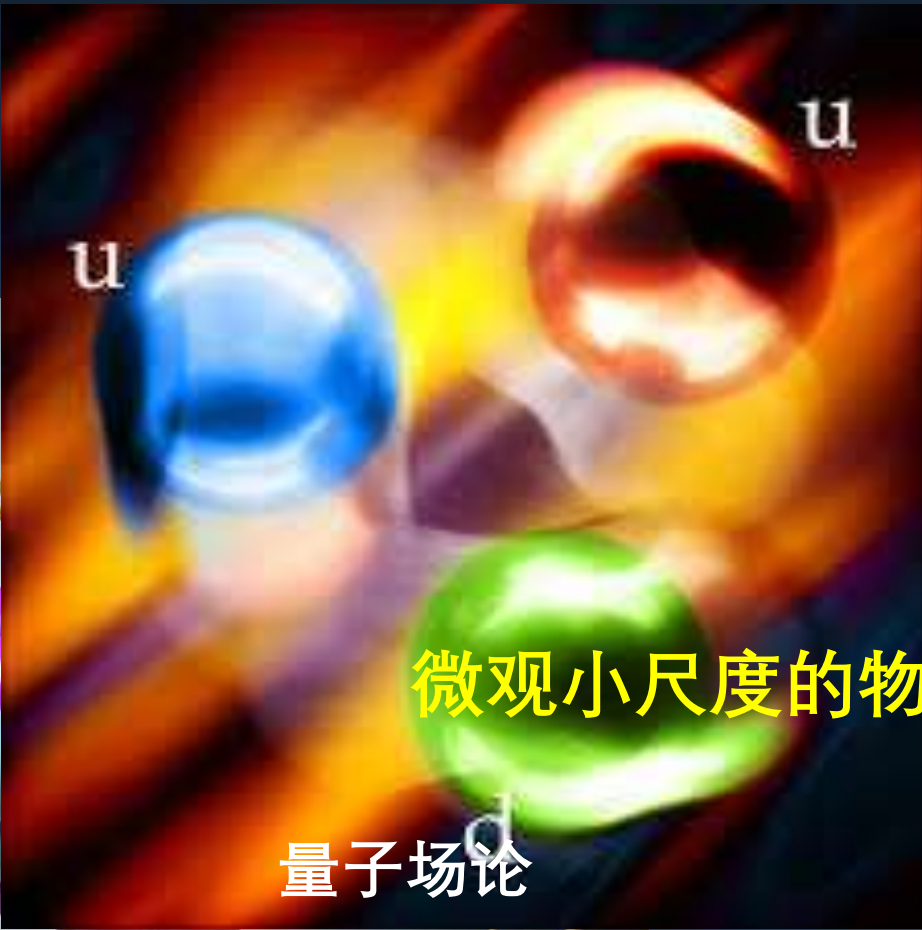
牛顿万有引力 (1687)

人类的好奇心

--探微入粒

量子力学

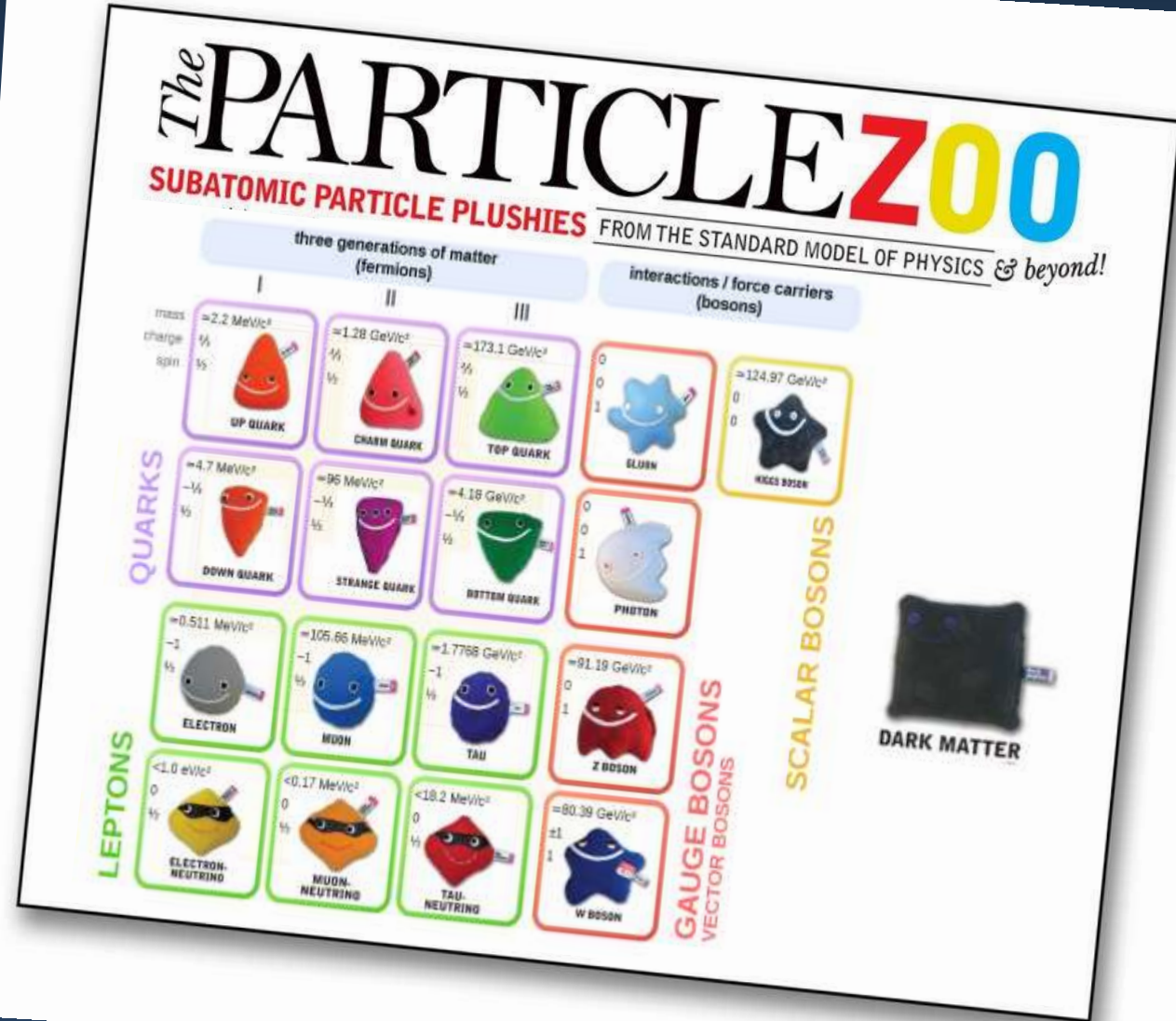
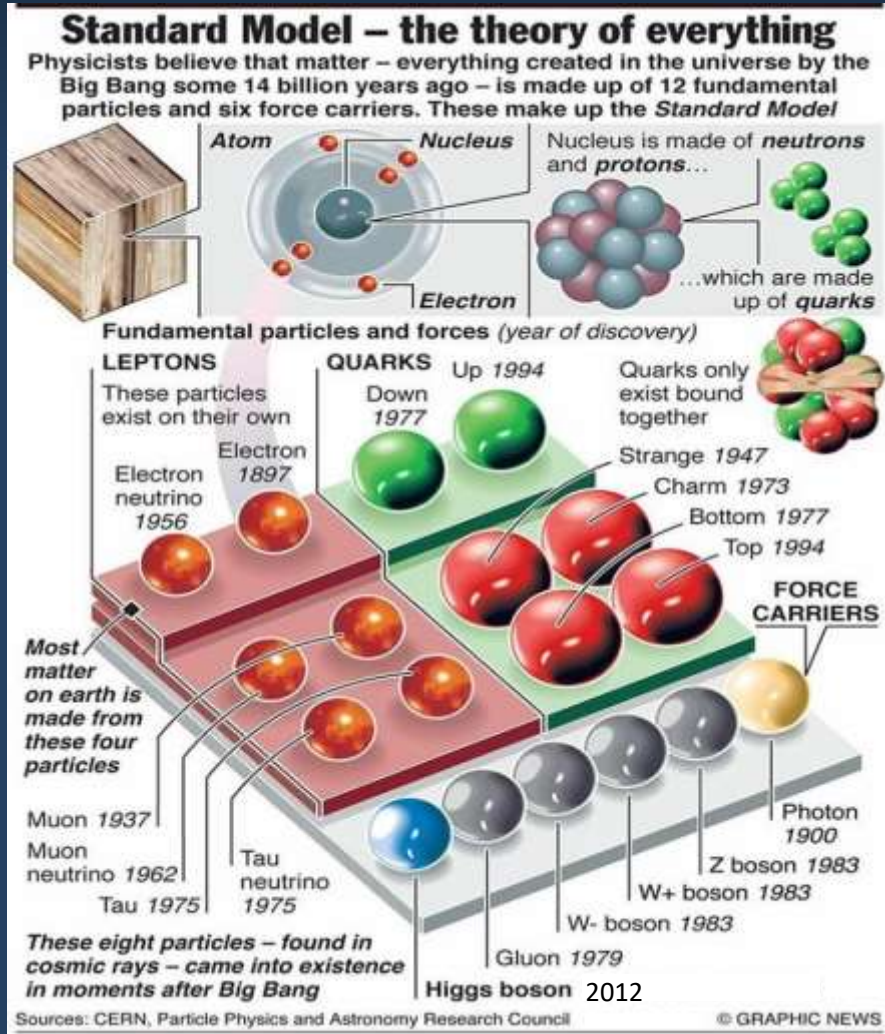
量子场论



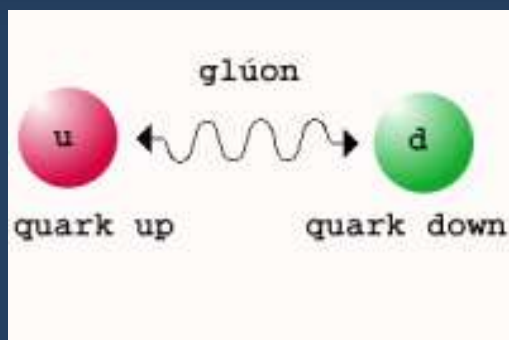
微观小尺度的物理结构



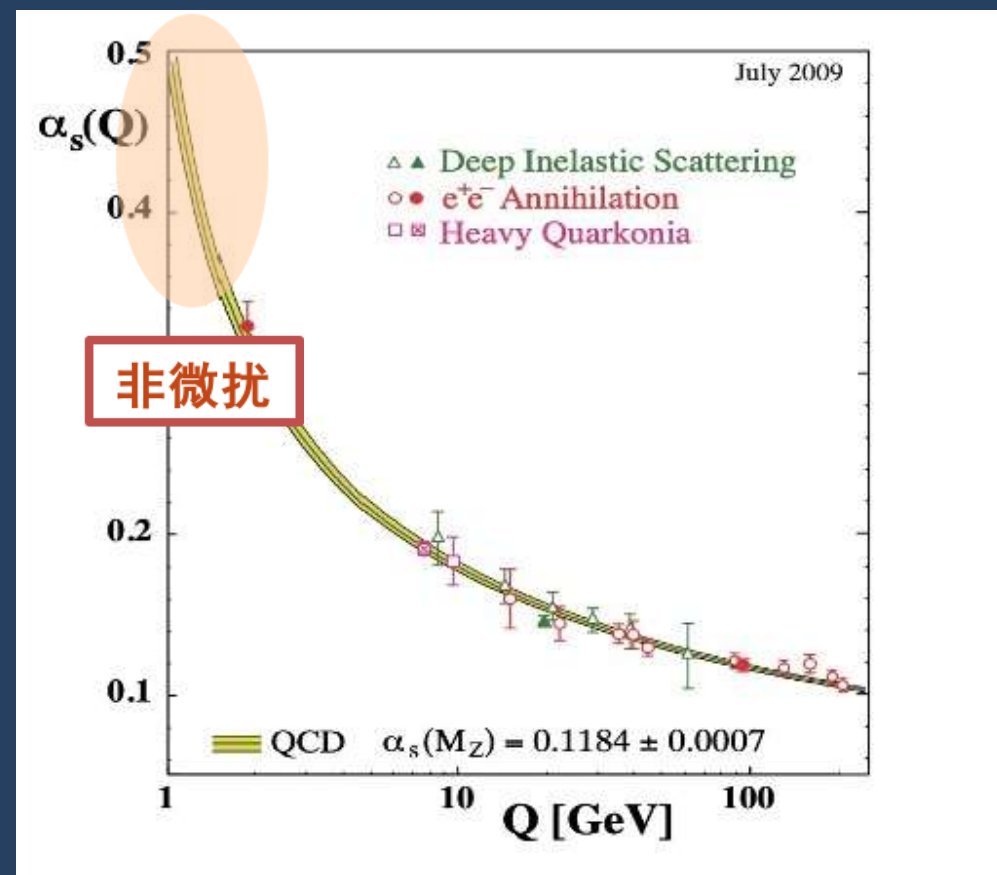
粒子标准模型完美吗？



色紧闭：千禧年问题



- 描述强相互作用的理论被称为量子色动力学 QCD
- 当能标降低时，相互作用增强，量子色动力学进入到非微扰区域

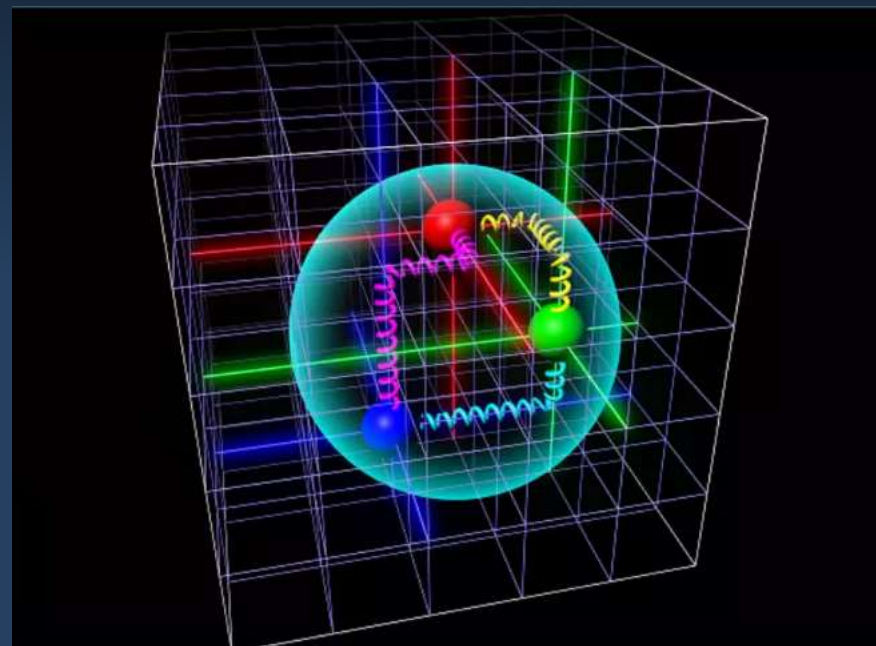
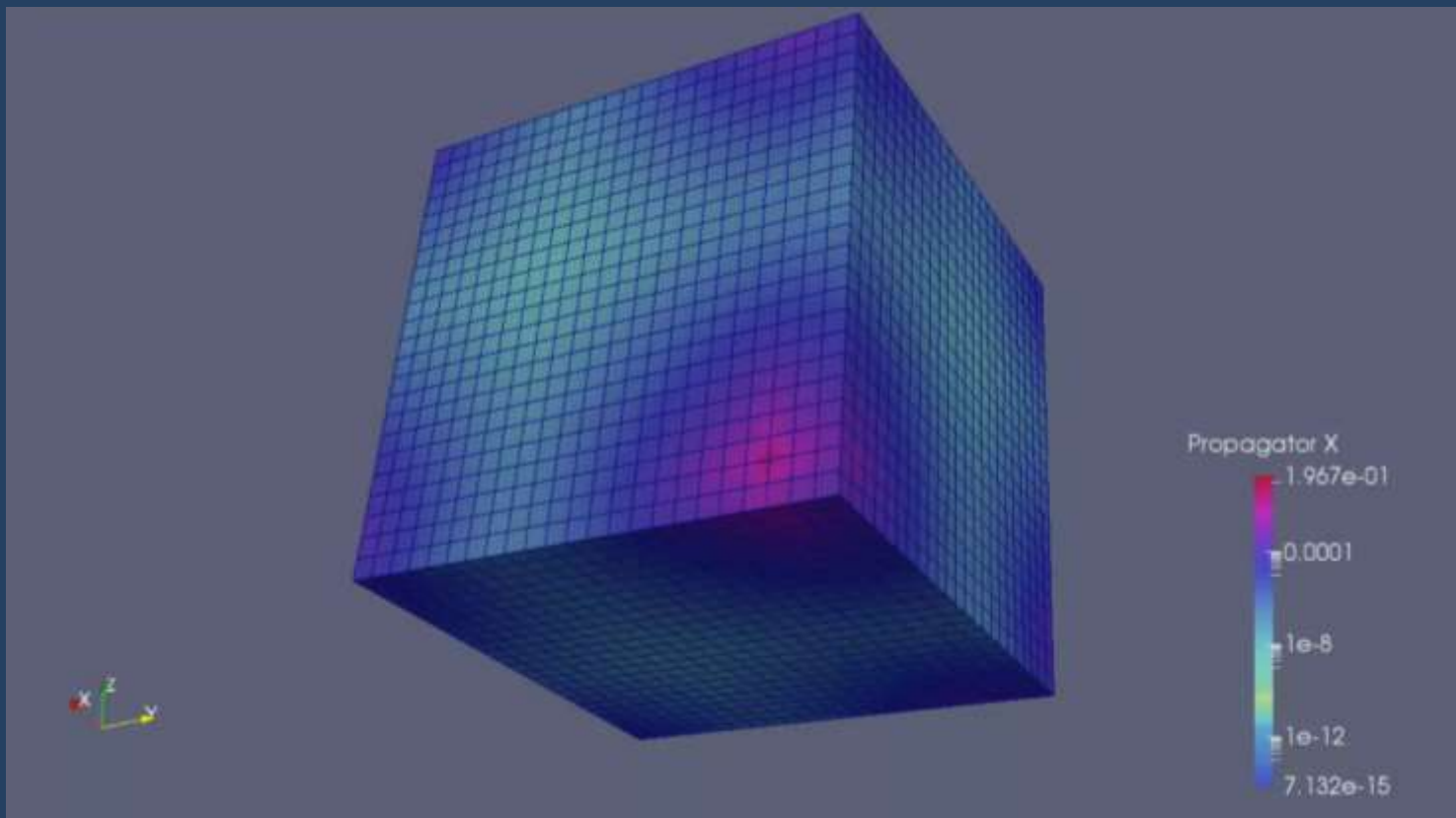


格点规范理论



Ken Wilson: 1936–2013

格点规范理论

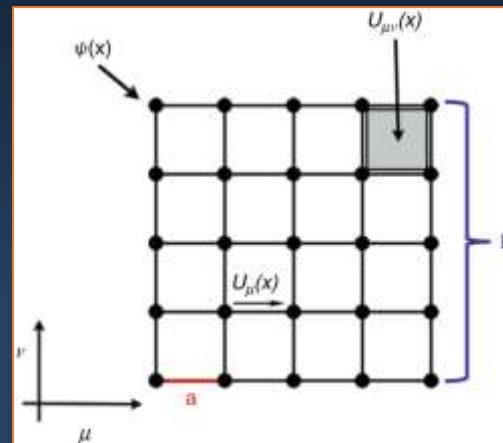


格点规范理论

格点
规范
场构
型

Wilson 作
用量

场构型分
布



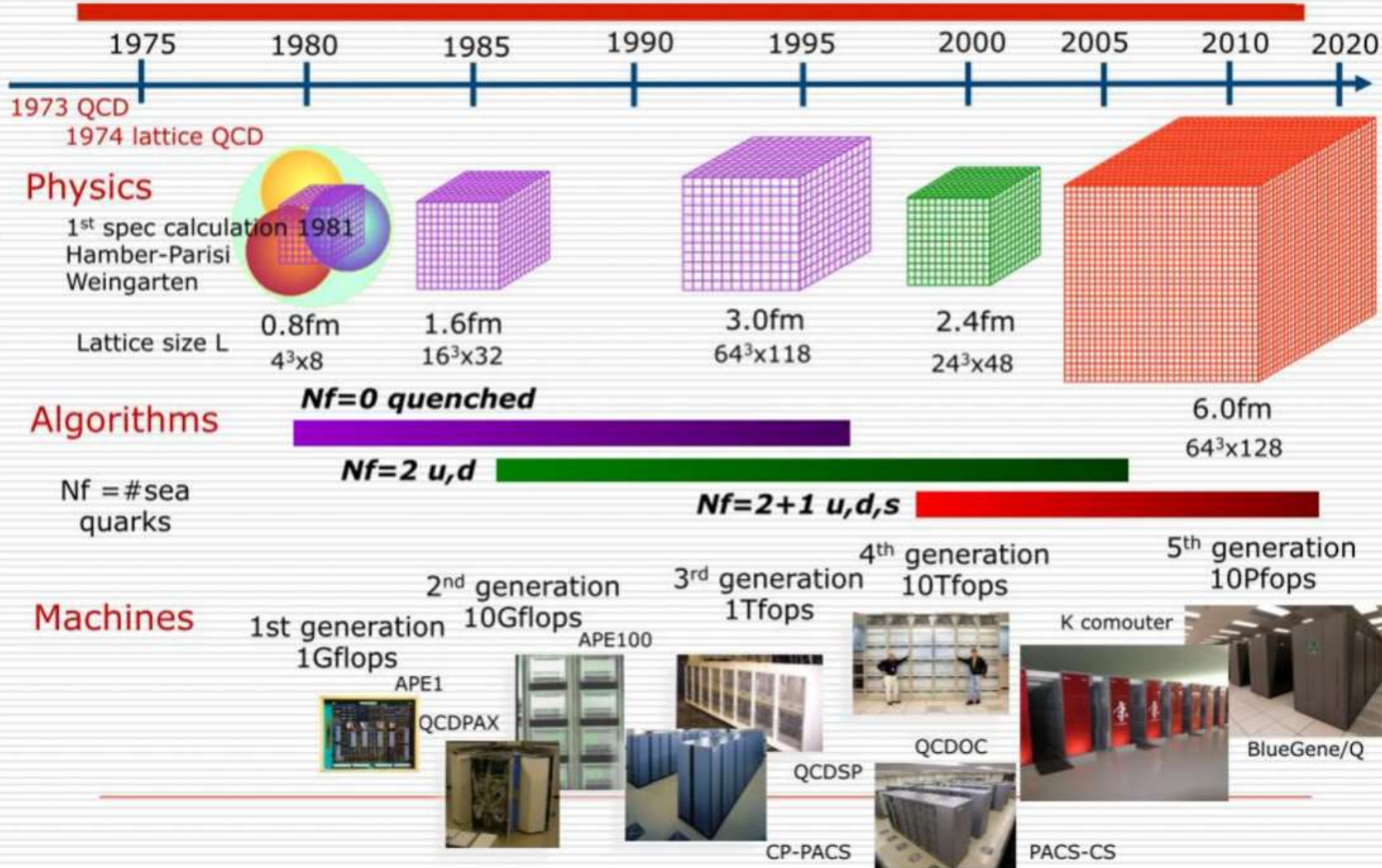
$$S[U] = \frac{\beta}{N} \sum_x \sum_{\mu < \nu} \text{Re Tr}(1 - U_{\mu\nu}(x))$$

$$\langle O \rangle = \frac{1}{Z} \int \mathcal{D}[U] e^{-S_G[U]} O[U]$$

$$dP[U] = \frac{1}{Z} e^{-S[U]} dU$$
$$Z = \int dU e^{-S[U]}$$

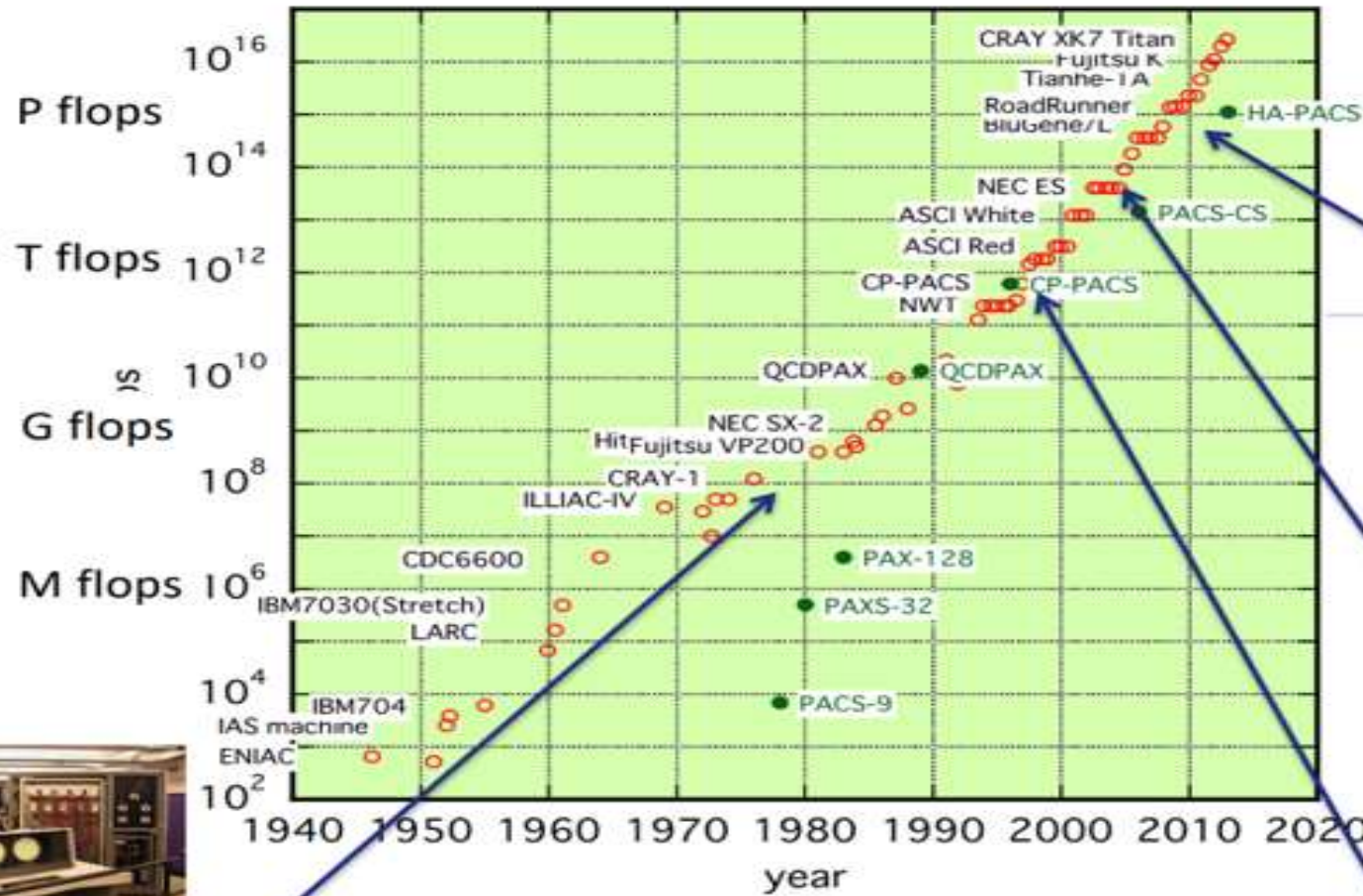


Four decades of Lattice QCD



pictures : BNL machines

computer speed



QCDCQ 0.7 P flops 2012



QCDOC 20 T flops 2005



12 racks (1024 DB per rack) ~ 600GFlops © BNL

QCDCQ 0.6T flops 1998



CDC 6600/7600 40 M flops 1970s

[A. Ukawa]

格点量子色动力学在中国

从事格点QCD研究的人员分布：

北京大学

南开大学

中国科学院高能物理研究所

上海交通大学

华中师范大学

四川大学

浙江大学

中国科学院大学

北京航空航天大学

华南师范大学

湖南师范大学

西北工业大学

中国科学院近代物理研究所

中国科学院理论物理研究所

等

可用于格点QCD研究的计算平台：

神威太湖之光 无锡

天河二号 广州

天河一号 天津

天河三号 天津

神威 济南

Pi2.0/思源1号 上海

曙光 昆山 419 郑州

北京超算中心 北京

华中师范大学计算平台 (武汉)

南方核科学中心(广州)

等

格点量子色动力学在中国

PHYSICAL REVIEW D **101**, 034020 (2020)

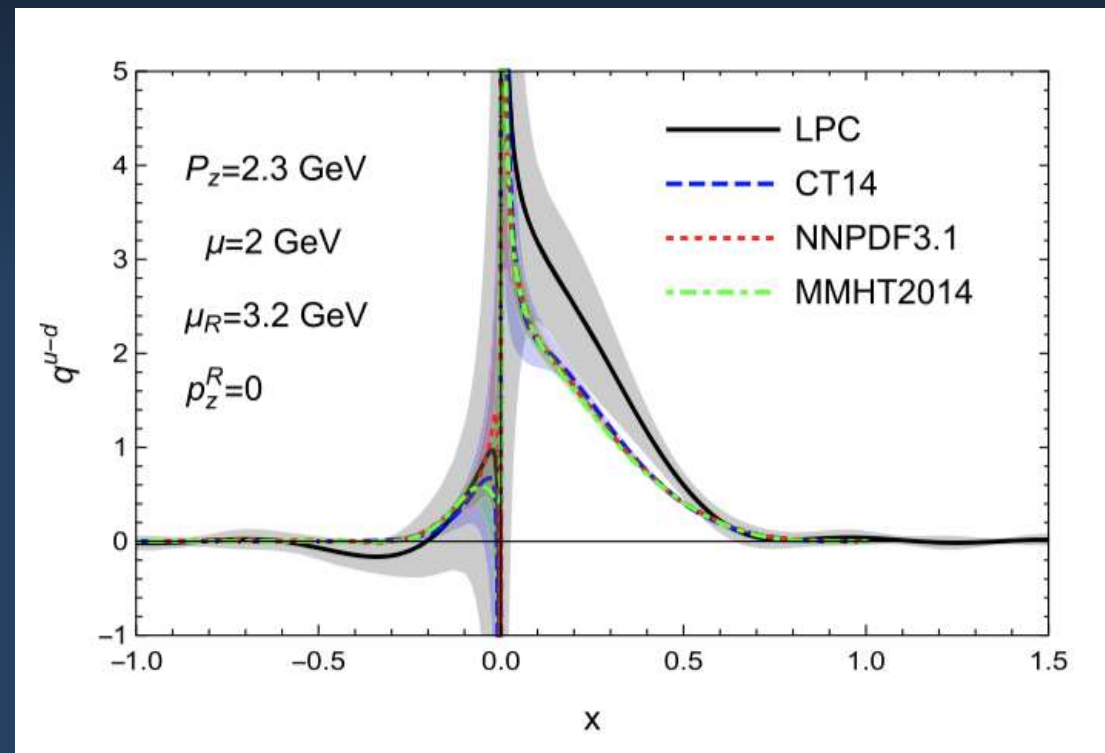
Unpolarized isovector quark distribution function from lattice QCD: A systematic analysis of renormalization and matching

Yu-Sheng Liu,¹ Jiunn-Wei Chen,^{2,3} Yi-Kai Huo,^{4,5} Luchang Jin,^{6,7} Maximilian Schlemmer,⁸ Andreas Schäfer,⁸
Peng Sun,^{9,*} Wei Wang,^{4,7} Yi-Bo Yang,^{10,11} Jian-Hui Zhang,^{8,12} Qi-An Zhang,¹
Kuan Zhang,^{13,11} and Yong Zhao^{3,14}

(Lattice Parton Collaboration)

and Y.-B. Y. thanks Huey-Wen Lin for the discussion on part of the simulation setup. The numerical calculation is supported by the Center for HPC of Shanghai Jiao Tong University, HPC Cluster of ITP-CAS, Jiangsu Key Lab for NSLSCS, and Strategic Priority Research Program of Chinese Academy of Sciences Grant No. XDC01040100.

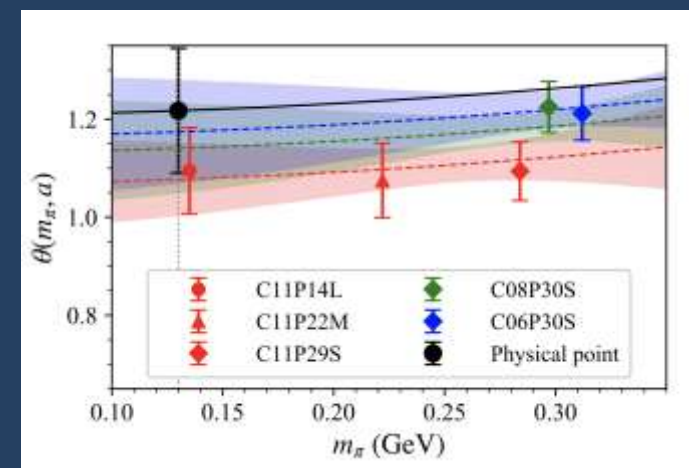
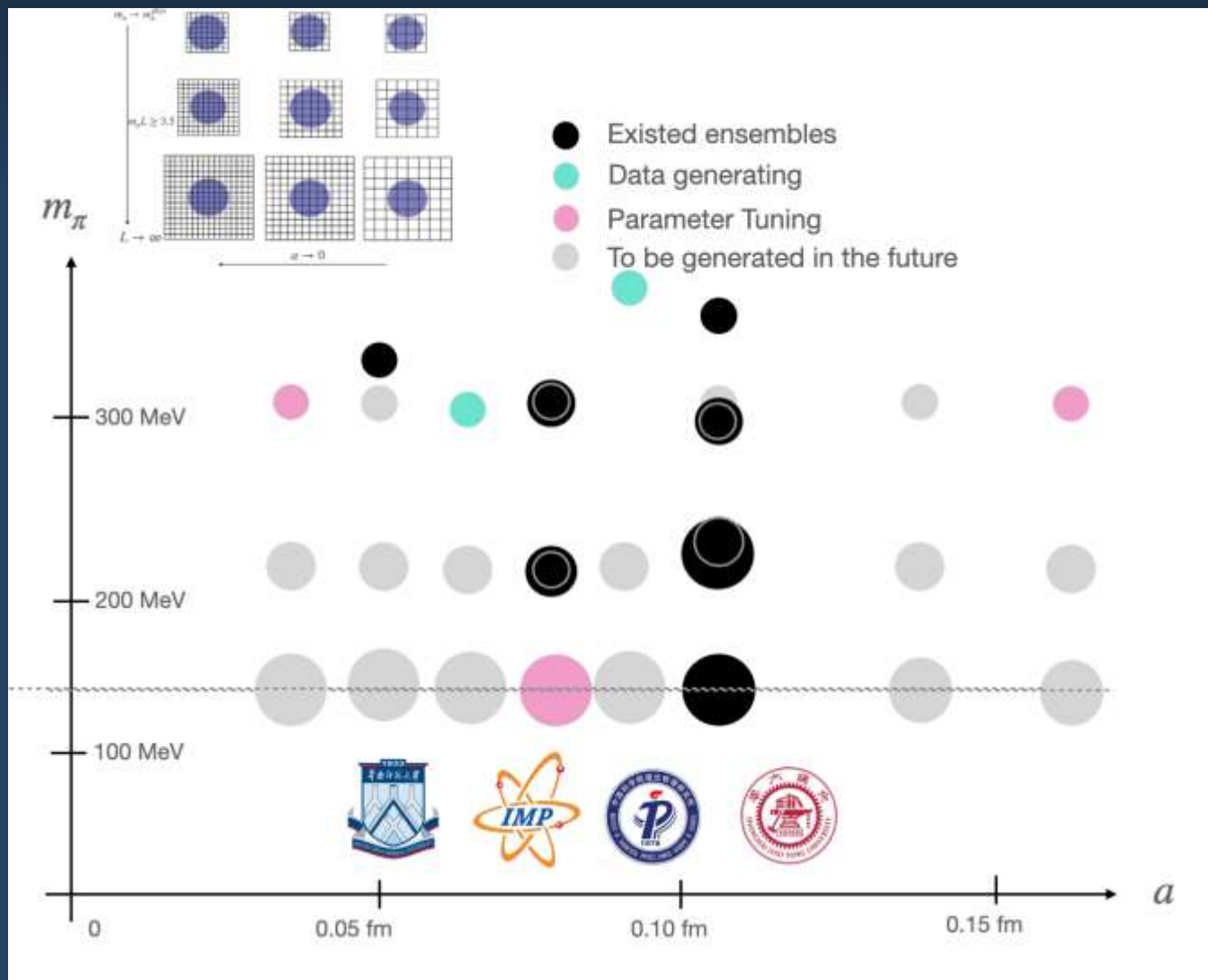
中国极化电子-离子对撞机白皮书[FoP16,64701 (2021)]



come [386]; and as shown in Fig. 2.31, several lattice QCD attempts at computation of the soft function have been carried out [387, 388]. This opens a path to prediction of TMD-related quantities using lattice QCD.

[388] PRL125, 192001(2020), 共同通讯作者

中国格点与组态产生



核子相互作用

Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A 1 H Hydrogen 1.008	2 IIA 2A 4 He Helium 4.002																															
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180															
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B 21 Sc Scandium 44.956	4 IVB 4B 22 Ti Titanium 47.88	5 VB 5B 23 V Vanadium 50.942	6 VIB 6B 24 Cr Chromium 51.996	7 VIIB 7B 25 Mn Manganese 54.938	8 VIII 8 26 Fe Iron 55.933	9 VIII 8 27 Co Cobalt 58.933	10 VIII 8 28 Ni Nickel 58.693	11 IB 1B 29 Cu Copper 63.546	12 IIB 2B 30 Zn Zinc 65.38	13 IIIA 3A 31 Al Aluminum 26.982	14 IVA 4A 32 Si Silicon 28.086	15 VA 5A 33 P Phosphorus 30.974	16 VIA 6A 34 S Sulfur 32.06	17 VIIA 7A 35 Cl Chlorine 35.453	18 VIIIA 8A 36 Ar Argon 39.948															
19 K Potassium 39.098	20 Ca Calcium 40.078	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29															
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium (209)	85 At Astatine 209	86 Rn Radon 222.018															
55 Cs Cesium 132.905	56 Ba Barium 137.327	89-103 Actinide Series	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (268)	111 Rg Roentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium unknown	114 Fl Flerovium 289	115 Uup Ununpentium unknown	116 Lv Livermorium 293	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown															
87 Fr Francium 223.028	88 Ra Radium 226.025																															
																		57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
																		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.083	99 Es Einsteinium (252)	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium (260)

Alkali Metal Alkaline Earth Transition Metal Basic Metal Semimetal Nonmetal Halogen Noble Gas Lanthanide Actinide

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www.ck12.org

STANDARD MODEL OF ELE

QUARKS

UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 u	CHARM 1,275 GeV/c ² 2/3 1/2 c	TOP 173,07 GeV/c ² 2/3 1/2 t
DOWN 4,8 MeV/c ² -1/3 1/2 d	STRANGE 95 MeV/c ² -1/3 1/2 s	BOTTOM 4,18 GeV/c ² -1/3 1/2 b

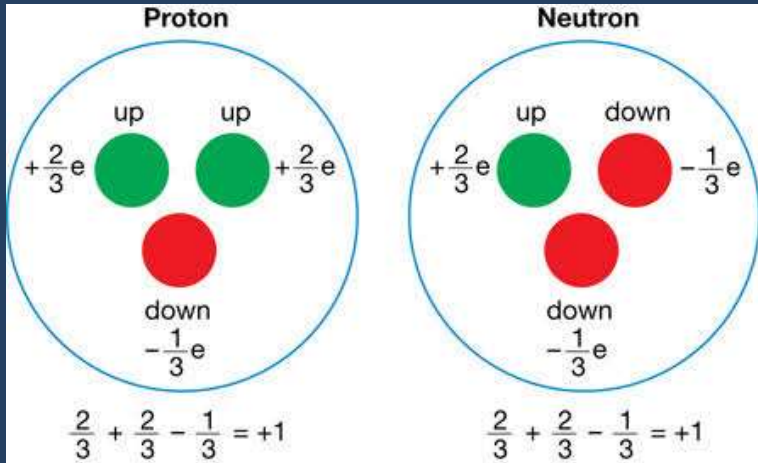
LEPTONS

ELECTRON 0,511 MeV/c ² -1 1/2 e	MUON 105,7 MeV/c ² -1 1/2 μ	TAU 1,777 GeV/c ² -1 1/2 τ
ELECTRON NEUTRINO <2,2 eV/c ² 0 1/2 ν _e	MUON NEUTRINO <0,17 MeV/c ² 0 1/2 ν _μ	TAU NEUTRINO <1,8 MeV/c ² 0 1/2 ν _τ

BOSONS

W BOSON 80,4 GeV/c ² ±1 1 W

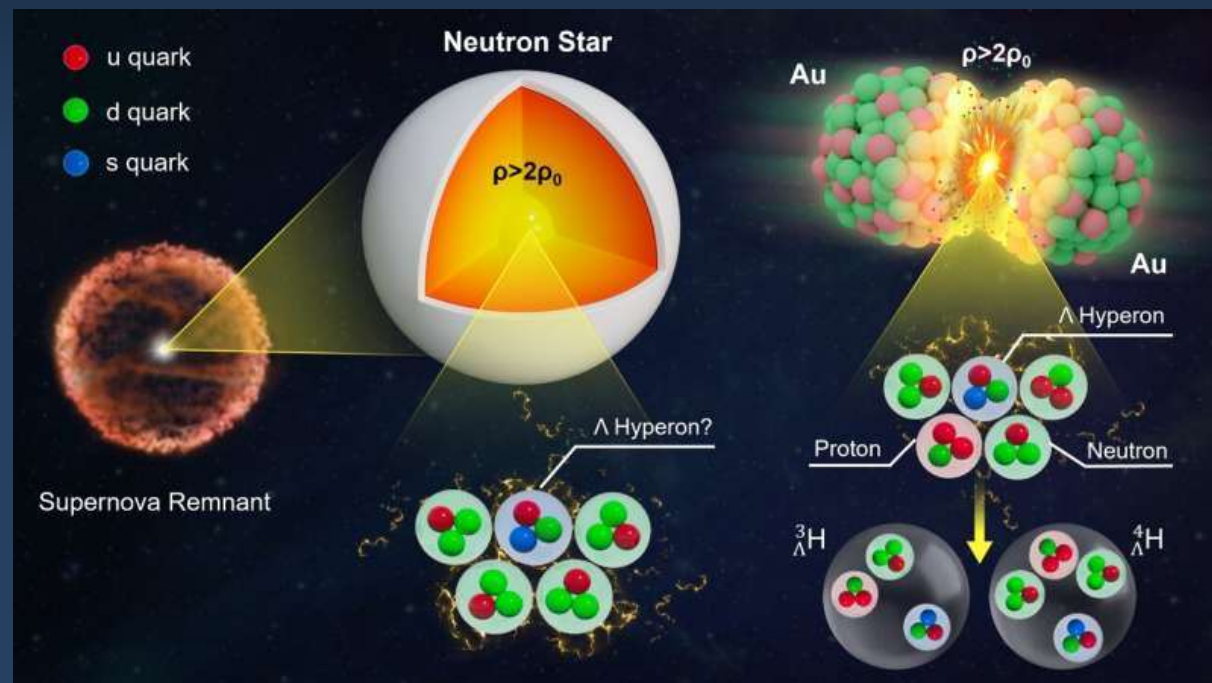
核子相互作用



- ✓ 多夸克态?
- ✓ 多核子?

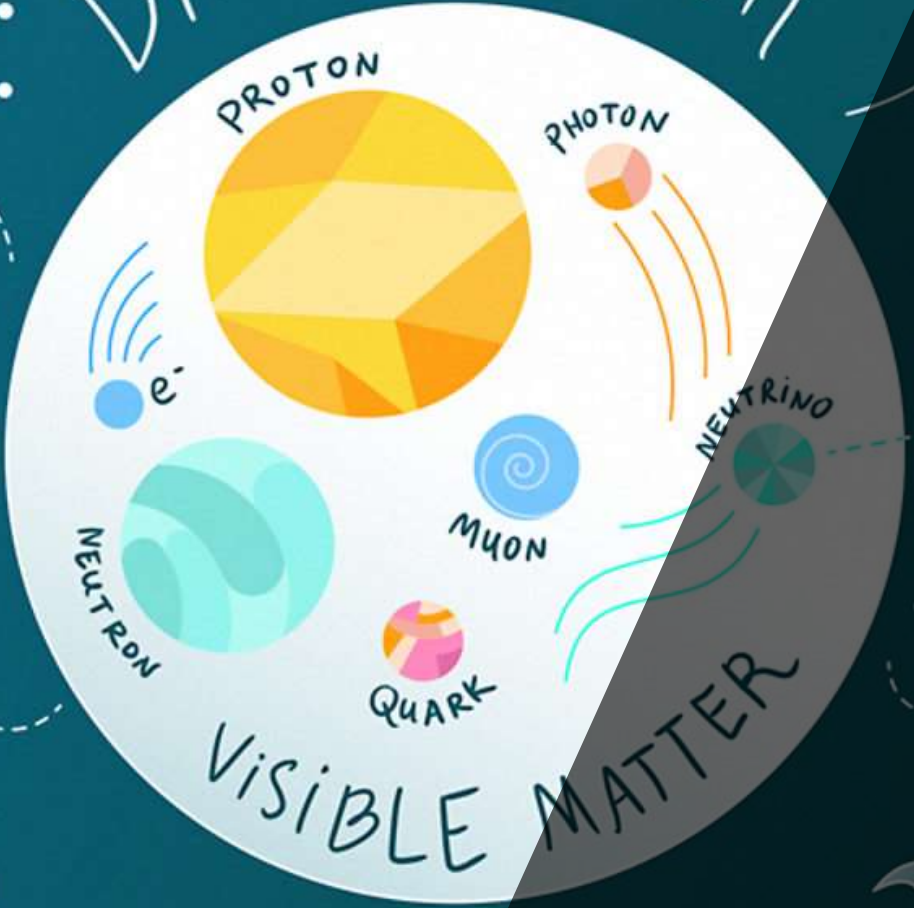
核子相互作用

- 超核相互作用的研究有助于揭示中子星的内部结构和演化过程
- 有助于解释早期宇宙物质如重元素和奇异物质的形成过程
- 有助于理解奇异夸克在强相互作用中的角色



超核相互作用在核物理中是一个非常重要的课题

DARK MATTER



NEUTRALINO

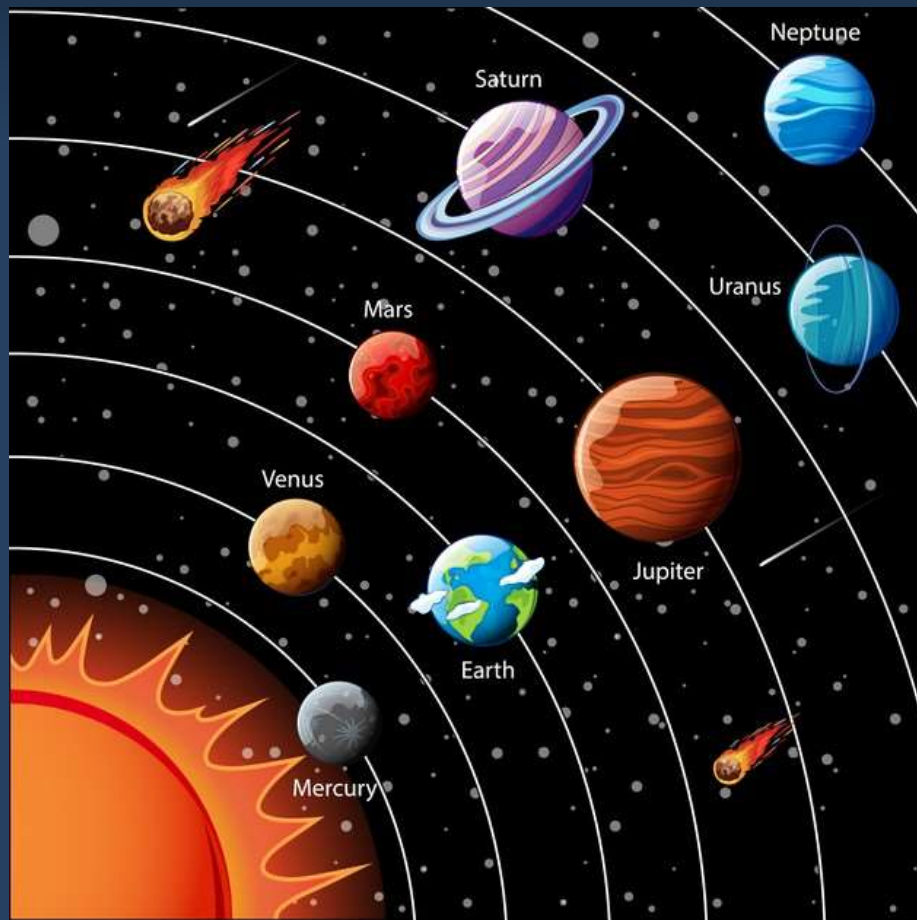
AXION

AXION

GRAVITINO

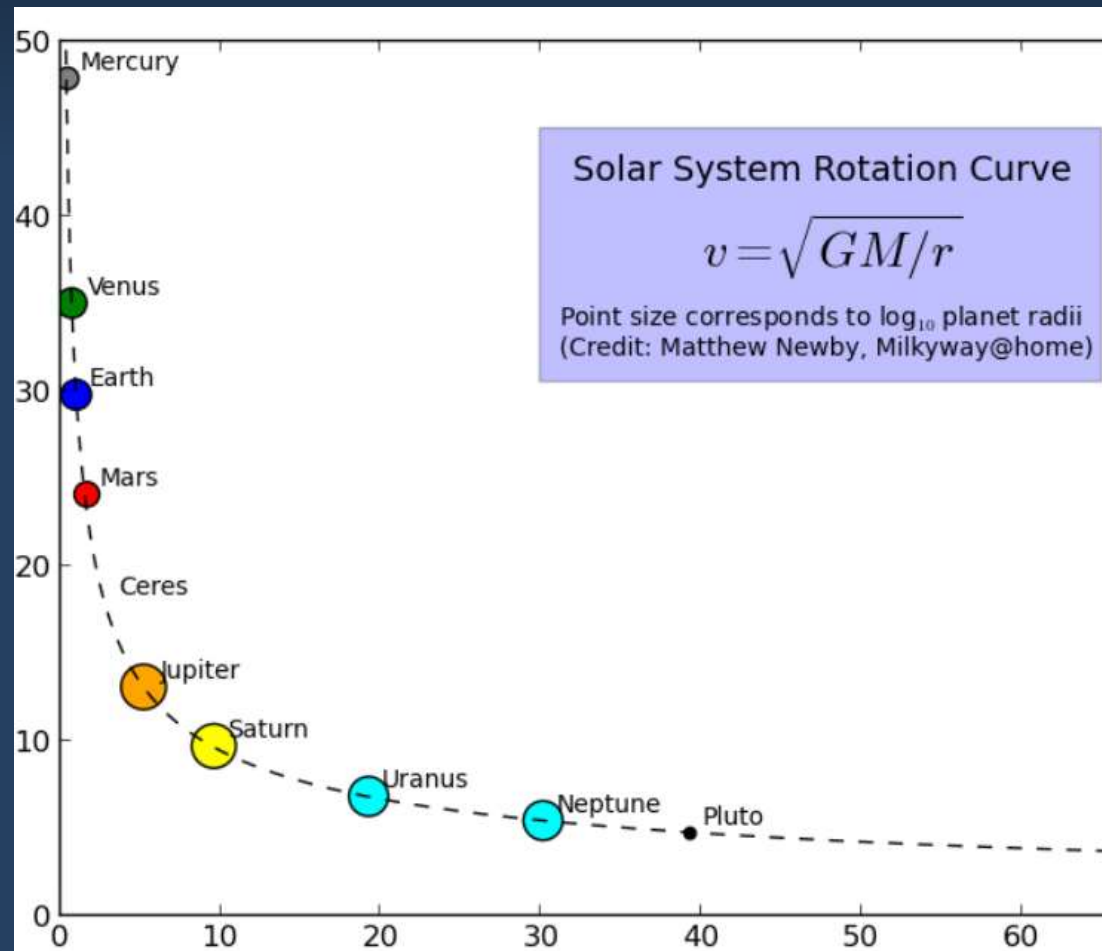
暗物质 Dark Matter

暗物质



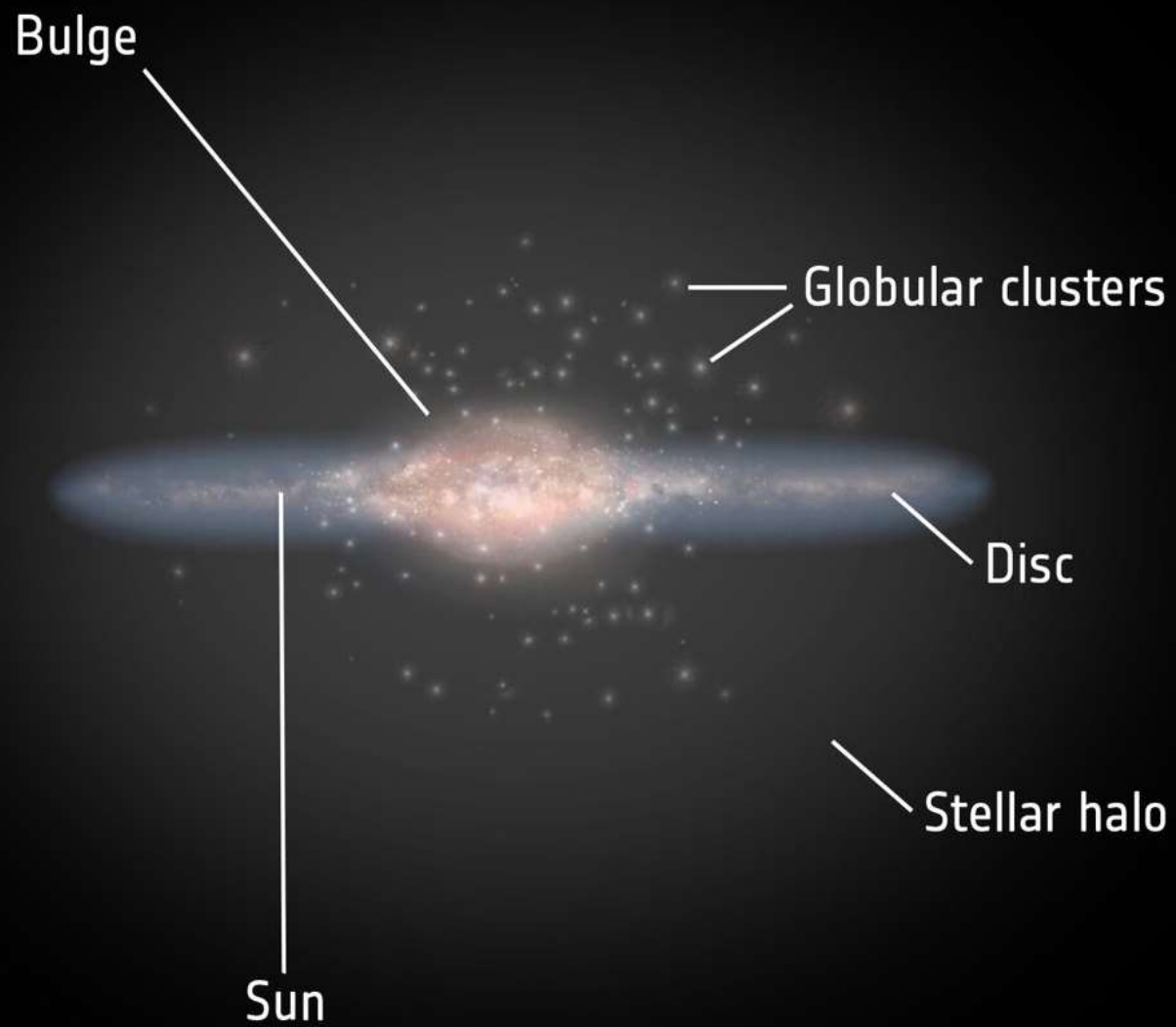
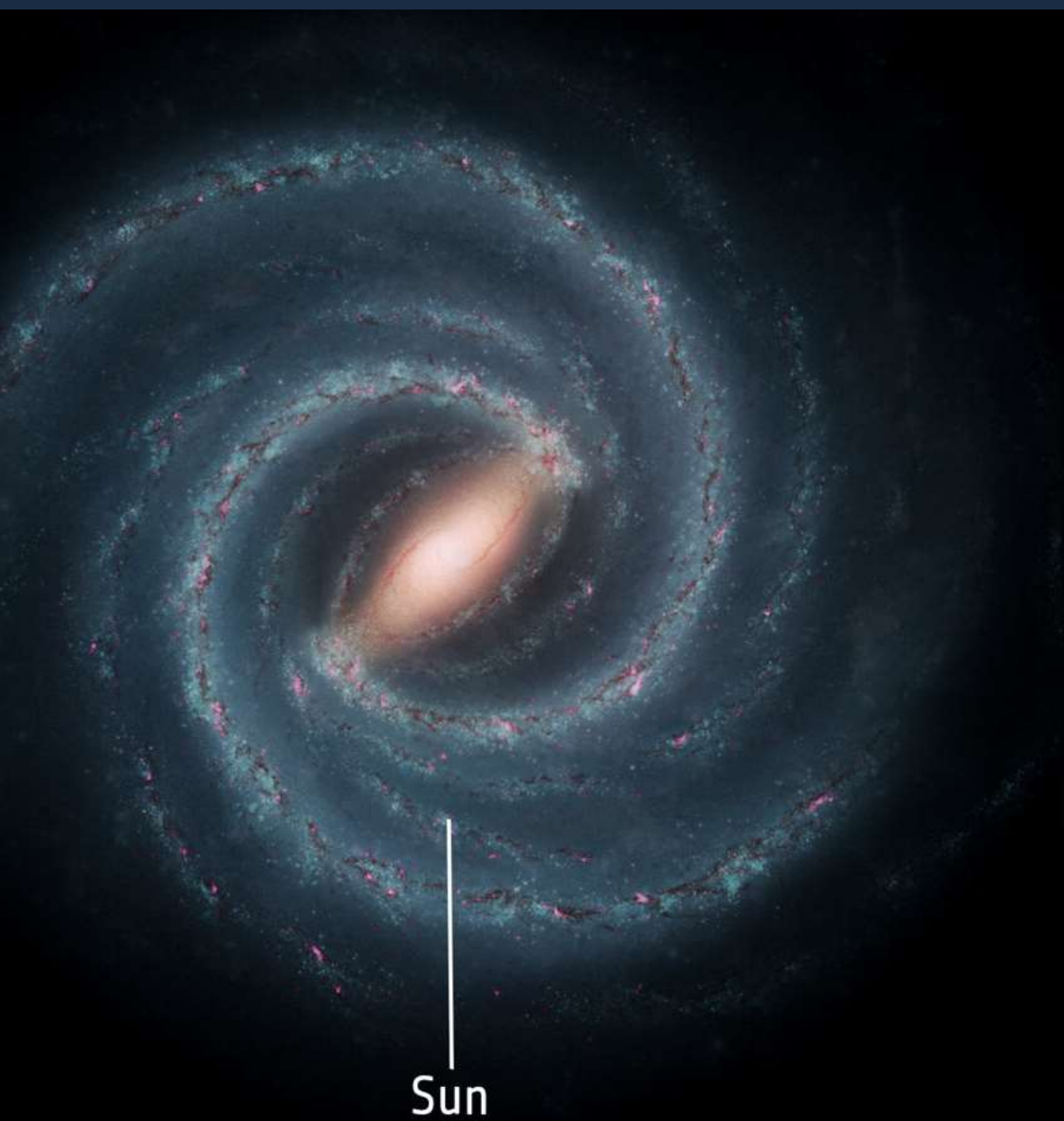
太阳系

行星速度 (公里/秒)

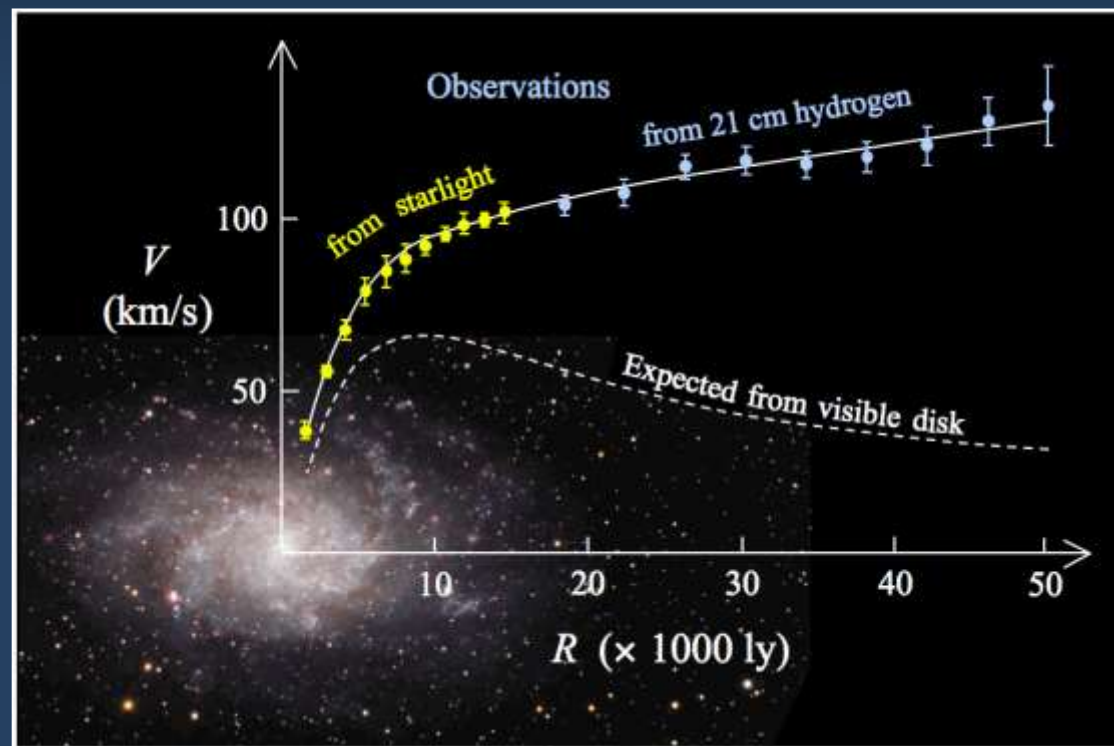
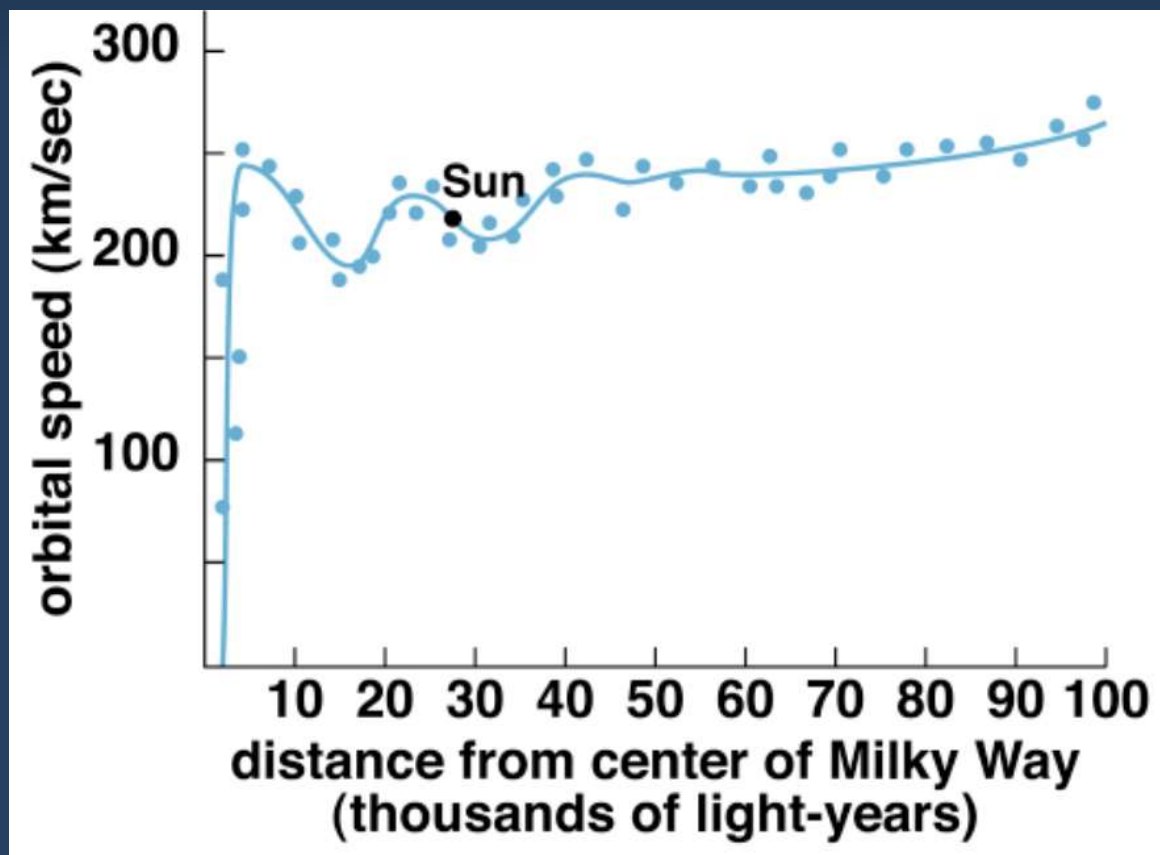


距太阳中心距离 (天文单位 ~ 0.15亿公里)

暗物质

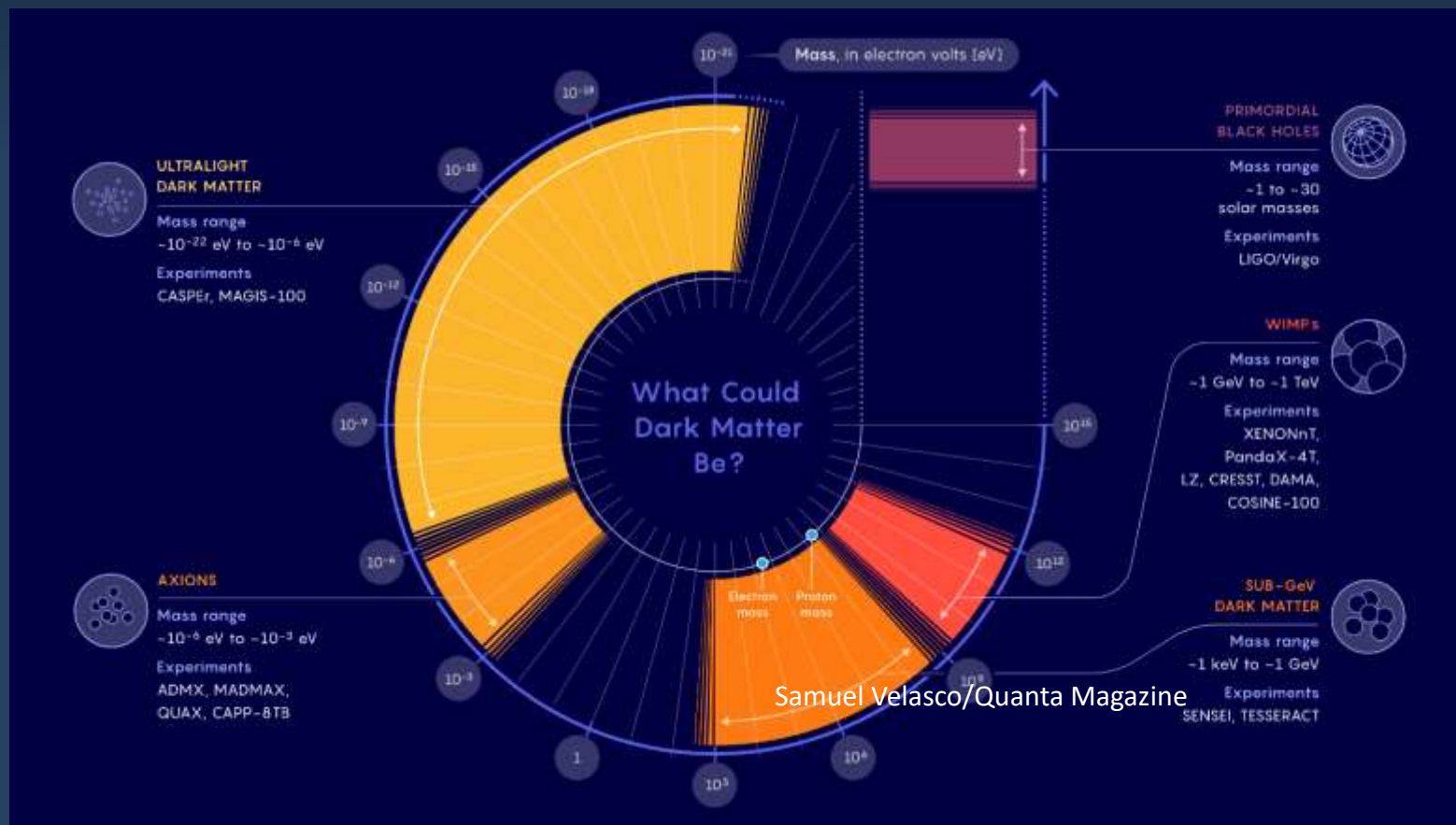


暗物质



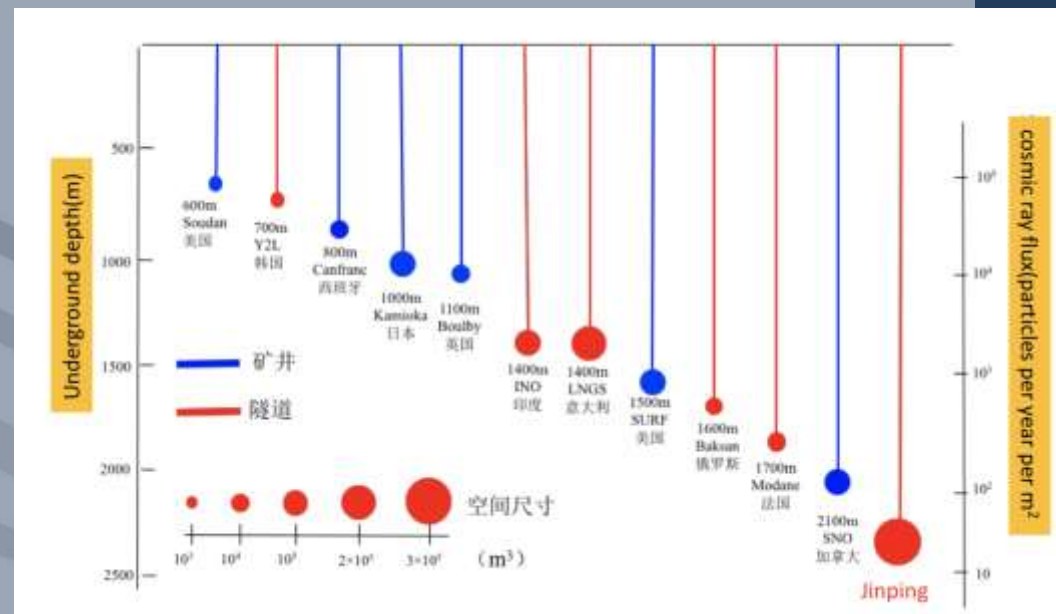
M33星系旋转曲线

暗物质



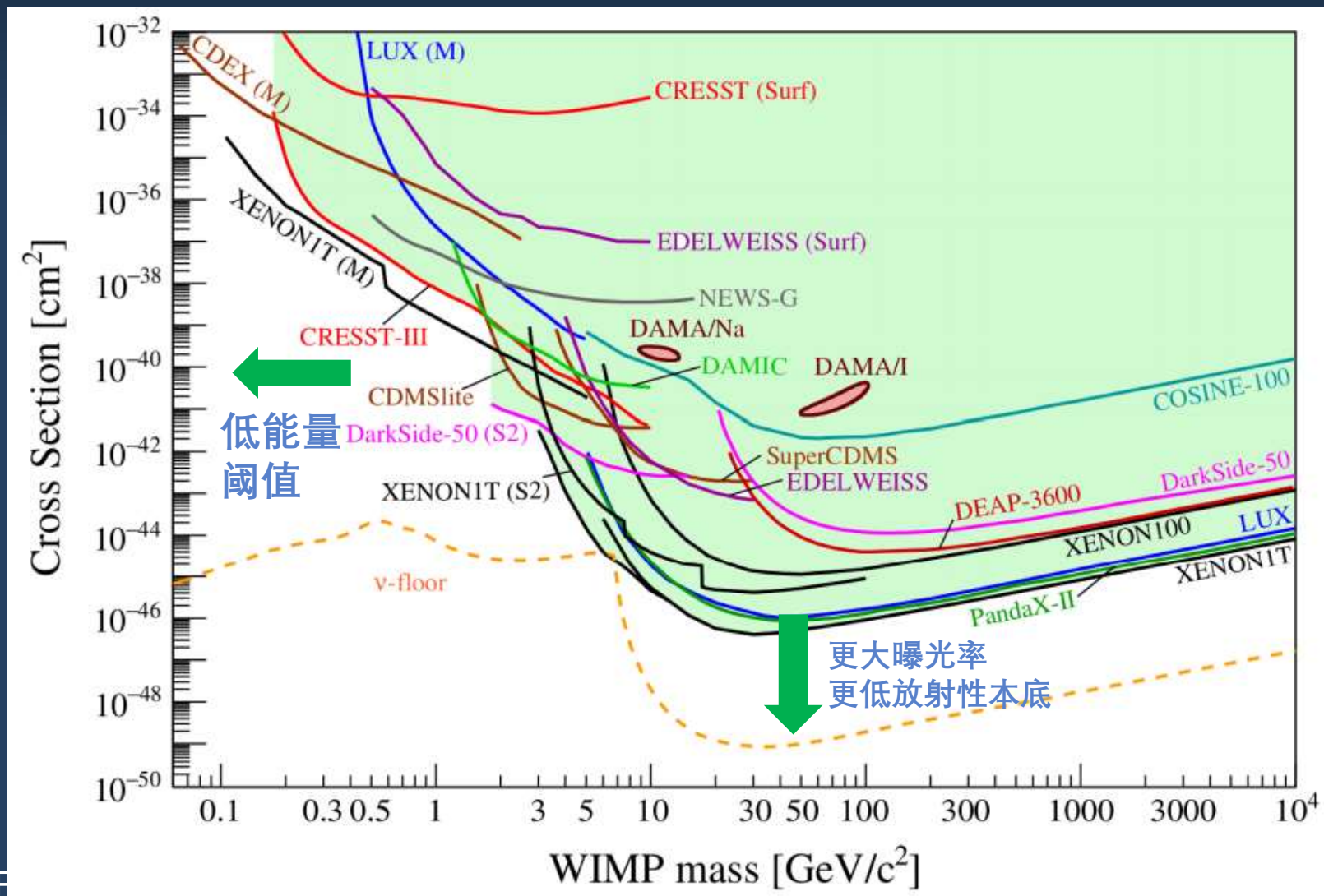
暗物质的候选模型

弱相互作用暗物质的探测：深地实验室



暗物质：冷暗物质模型 (Λ CDM) : WIMP

暗物质与普通物质散射截面



冷暗物质模型的困难

CDM模型模拟相悖的观测

Core-cusp problem

CDM: 晕密度cusp
观测结果: core

Diversity problem

CDM: 自相似密度剖面
观测: 相似星系内部差异

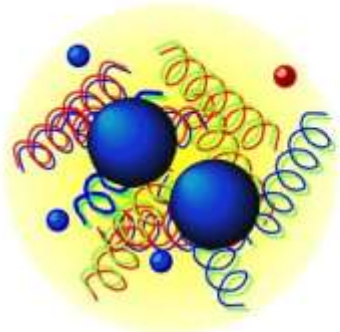
Missing satellites problem

CDM: 成百上千个亚晕
只有10个被发现

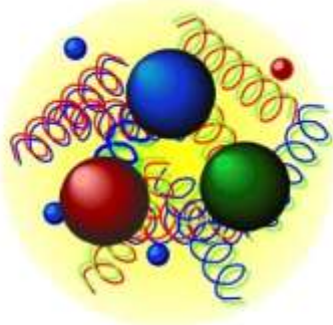
Too-big-to-fail problem

CDM: 亚晕中心密度
观测的恒星动力学

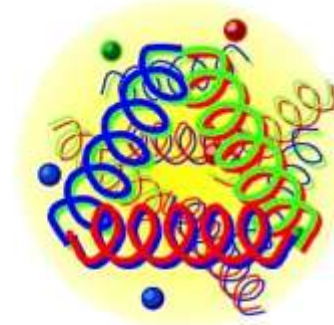
胶球暗物质：



meson




baryon



glueball?

A comparative lattice analysis of $SU(2)$ dark glueballs*

Min-Huan Chu (楚旻寰)^{1,2} Jun-Hui Lai (赖俊辉)^{1†} Wei Wang (王伟)^{1,3‡}  Jialu Zhang (张家璐)¹

Qianteng Zhu (朱潜腾)¹

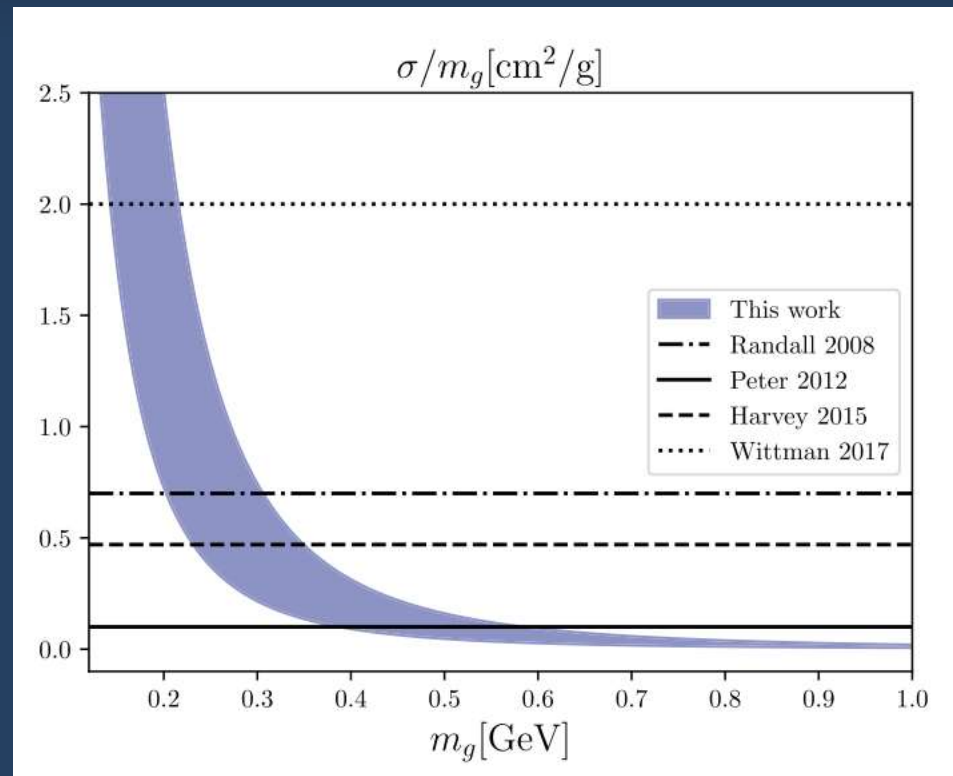
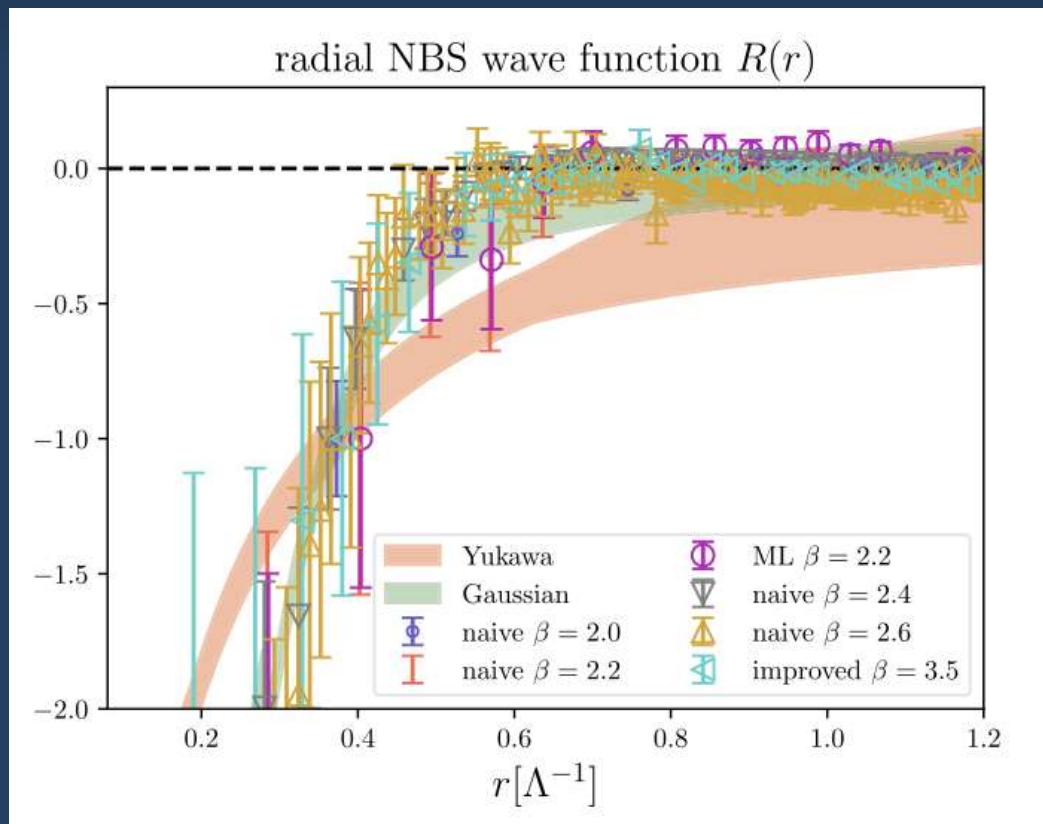
¹INPAC, Key Laboratory for Particle Astrophysics and Cosmology (MOE), Shanghai Key Laboratory for Particle Physics and Cosmology, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

²Yang Yuanqing Scientific Computing Center, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China

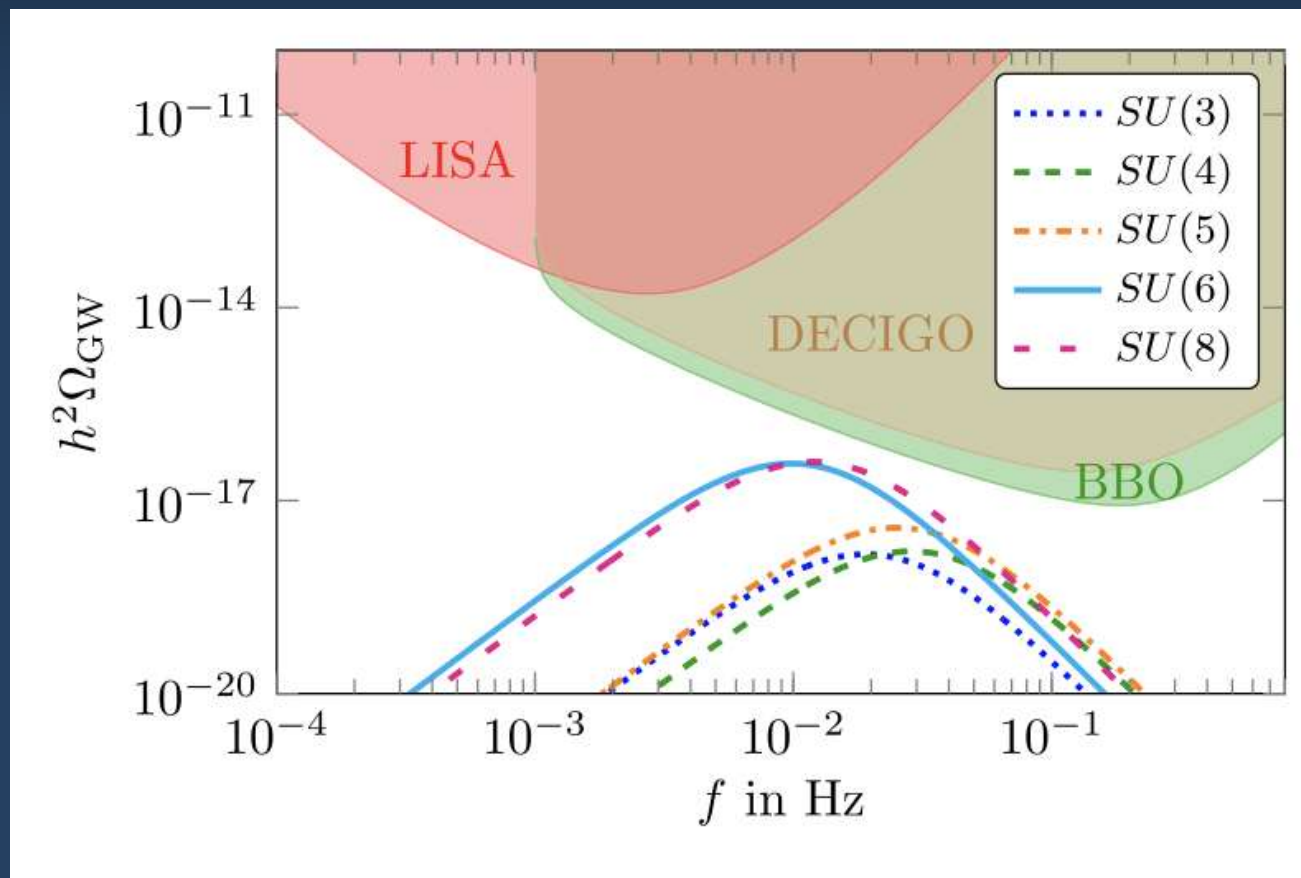
³Southern Center for Nuclear-Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences, Huizhou 516000, China

将强相互作用的方法推广至暗物质

胶球暗物质:



胶球暗物质:



Wei-Chih Huang, et.al, PRD104, 035005 (2021)

机器学习：传统方法生成组态



初始化

冷起点/热起点

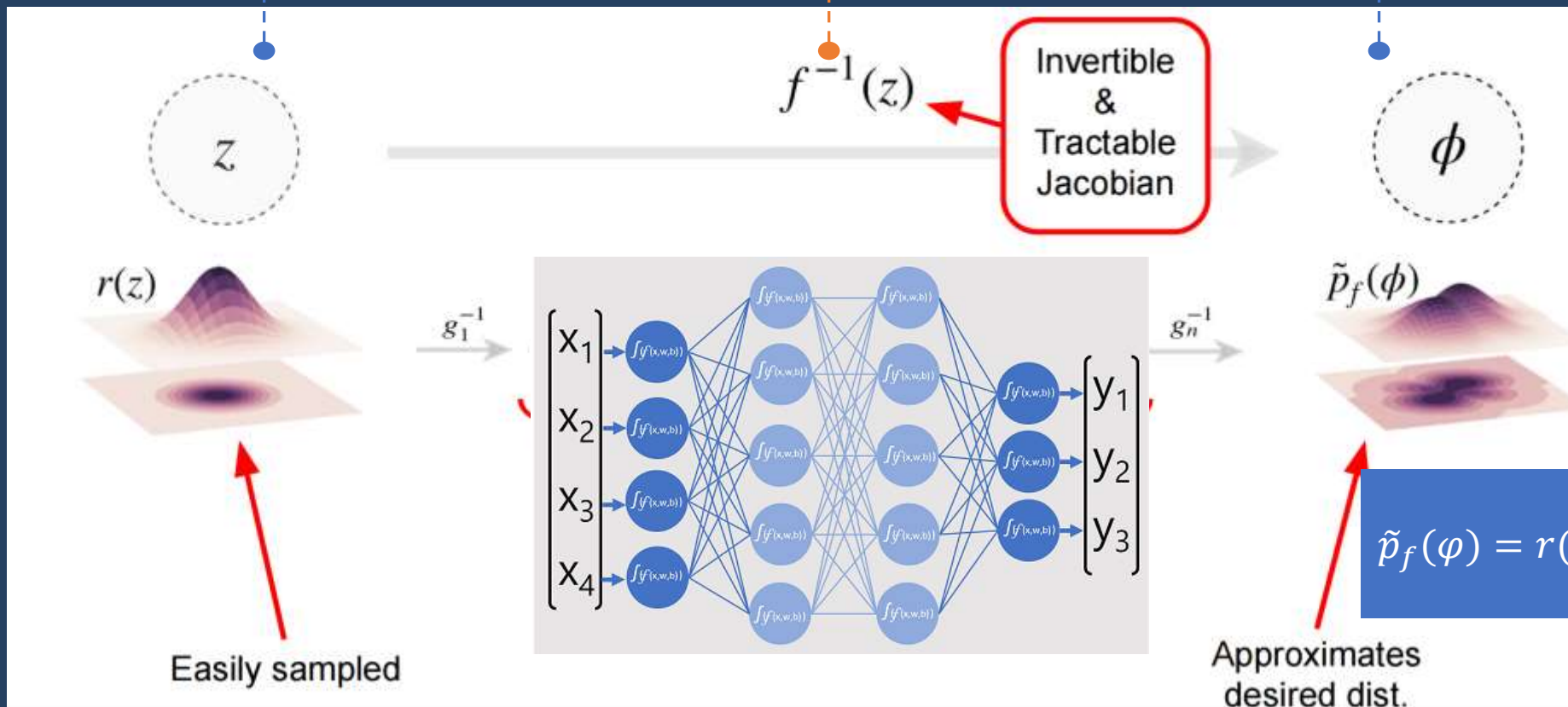
产生组态

更新link,
概率接收

计算物理量

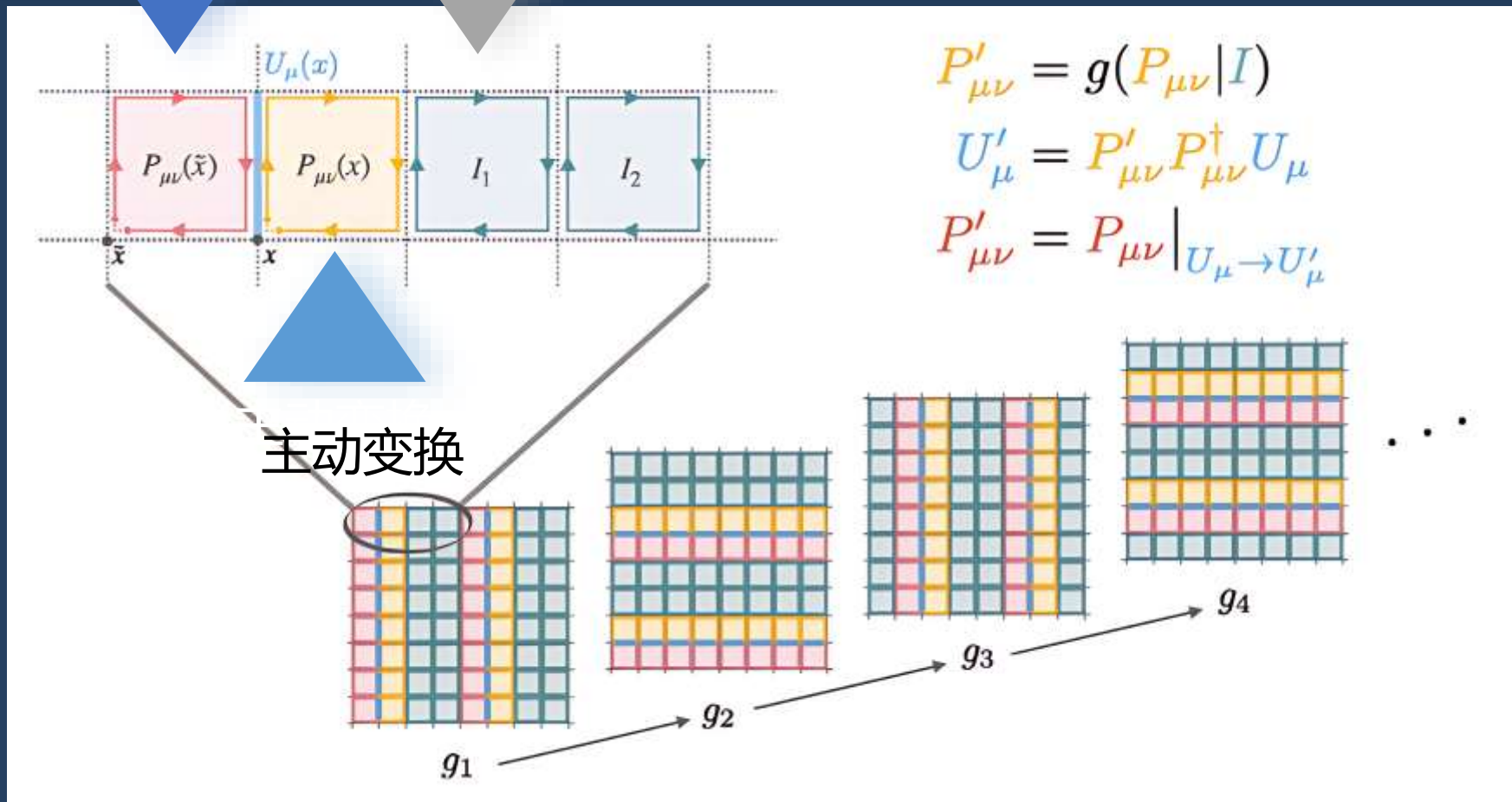
$$P(i \rightarrow j) = \min\left(1, \frac{T(j \rightarrow i)e^{-S[j]}}{T(i \rightarrow j)e^{-S[i]}}\right)$$

组态生成：Flow-Based Model



组态生成: Flow-Based Model

被动变换 冻结 (不变)





传统方法

机器学习方法

- 用于检验
- 制作benchmark
- 能算大格子

- 运算速度慢
- 组态有关联

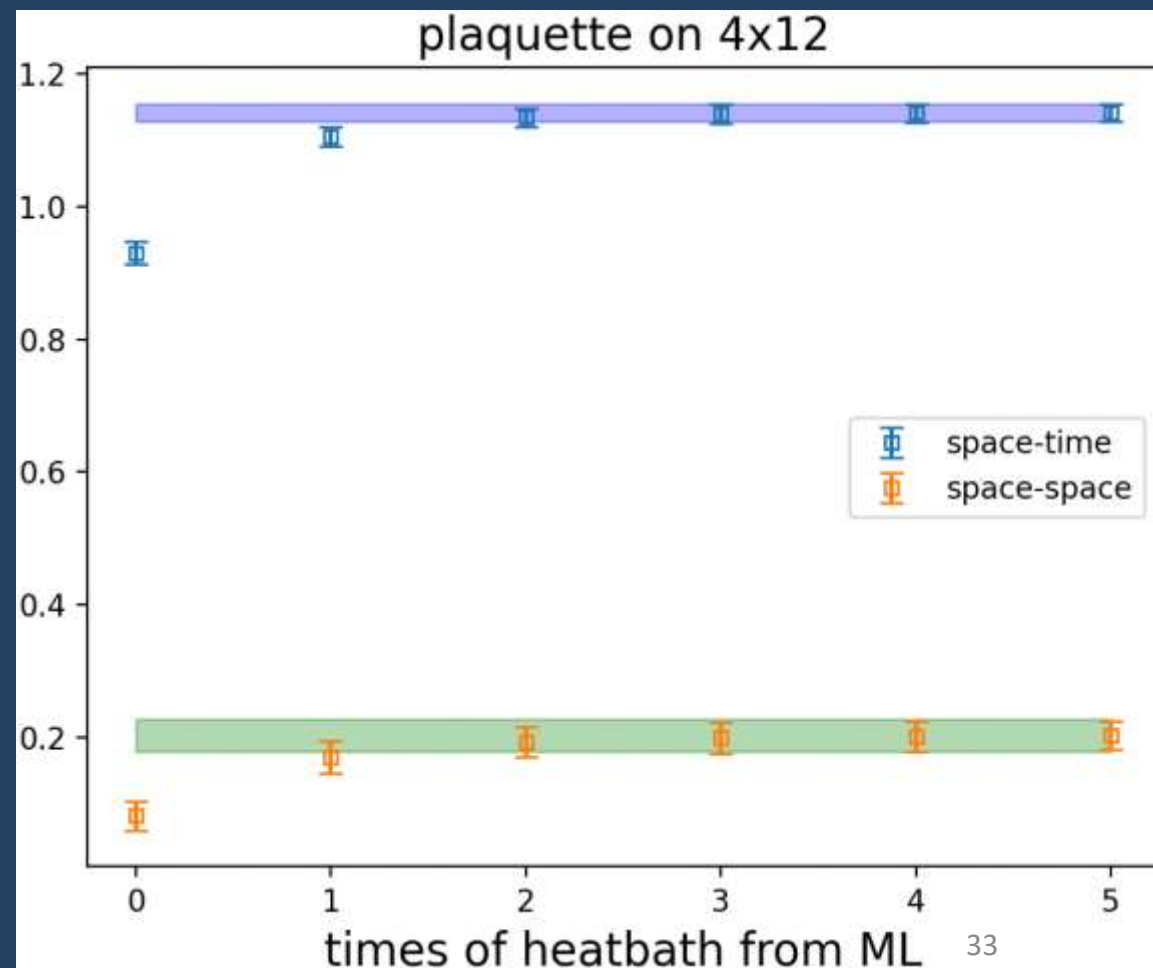
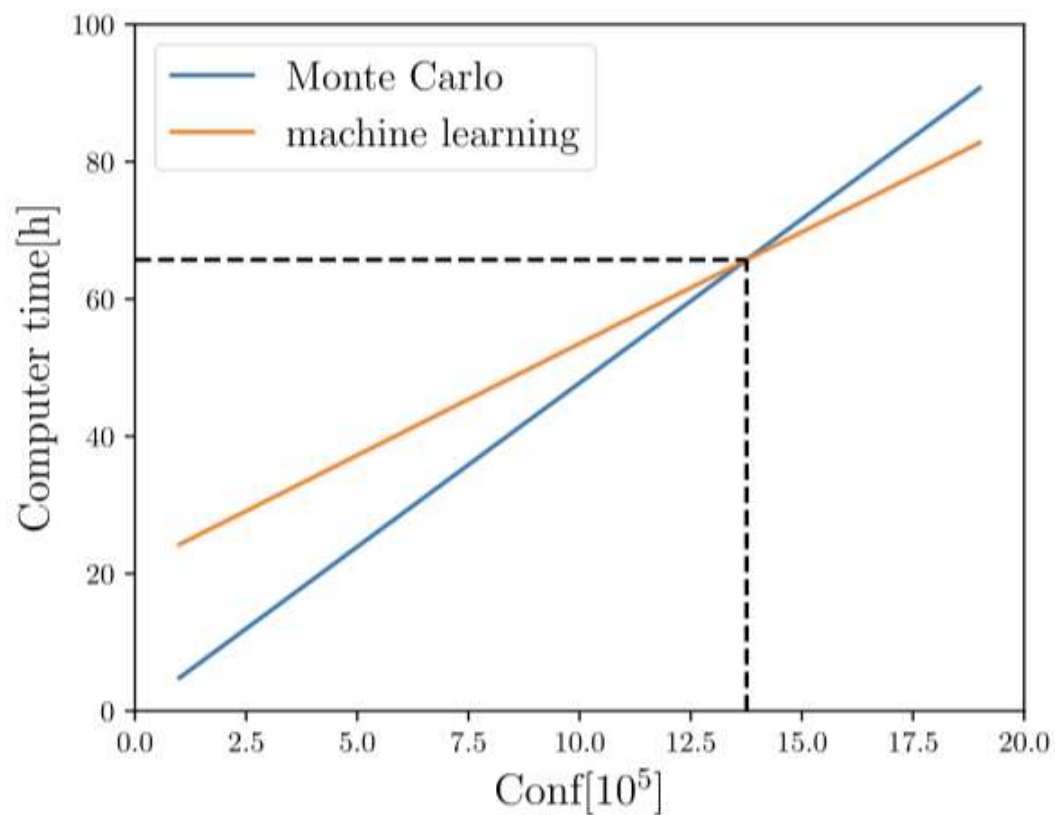
- 组态无关联
- 批量产生
- 误差小

- 大格子占内存
- 组态需要完善

传统方法和机器学习的比较

产生组态的效率

产生组态的准确性



结束语

- 粒子物理是研究物质组成的基本理论，强相互作用只能借助于格点规范场论
- 在各超算平台和同仁的帮助下，我们已经取得了一些成就
- 现在正在研究的问题：
 - 多核子
 - 新对象：暗物质
- 人工智能/机器学习或许能够提供新的视野

衷心地感谢各超算平台和公司对我们的支持!

组态生成：Flow-Based Model

KL散度



样本的分布与目标分布的接近程度

$$D_{KL}(f|g) = \int dx f(x) \ln \frac{f(x)}{g(x)} \geq 0$$



损失函数



用样本平均值估算KL散度

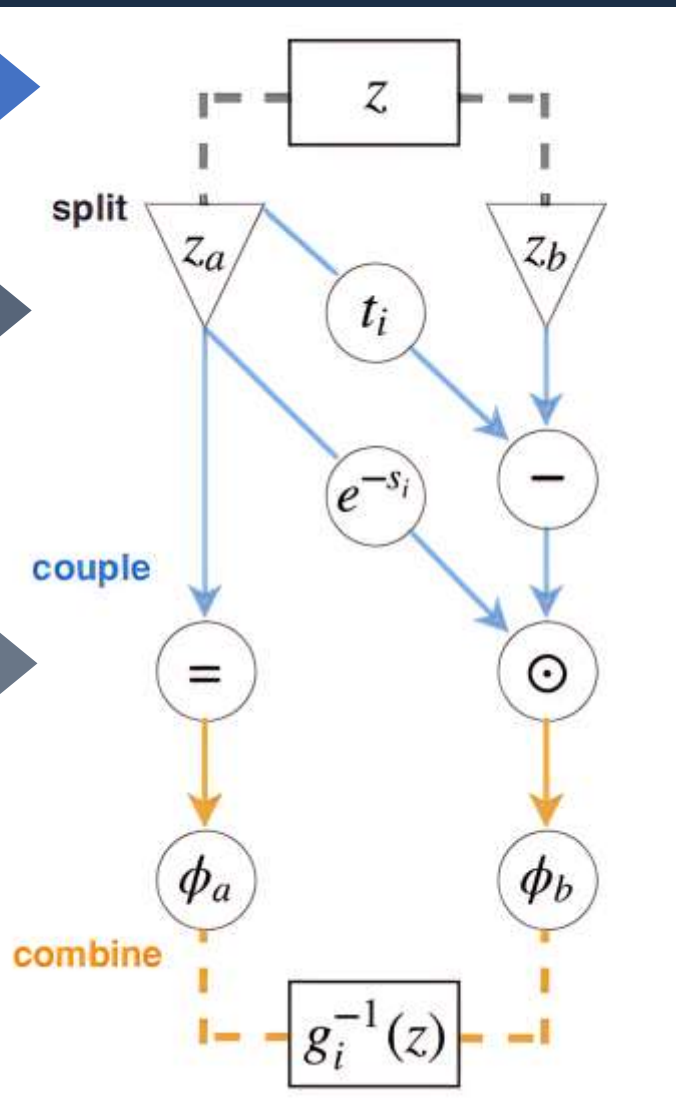
$$\begin{aligned} loss &= D_{KL} \left(\tilde{p}(\varphi) \left| \frac{e^{-S[\varphi]}}{Z} \right. \right) \\ &\approx \frac{1}{N} \sum_{i=1}^N \ln \frac{\tilde{p}(\varphi_i)}{e^{-S[\varphi_i]} / Z} \end{aligned}$$

组态生成：Flow-Based Model

多维样本

分成两类

进行变换



$$\begin{pmatrix} e^{[s(x_2)]_1} & & & \cdot & \cdot & \cdot \\ & e^{[s(x_2)]_2} & & \cdot & \cdot & \cdot \\ & & \ddots & \cdot & \cdot & \cdot \\ \hline & & & 1 & & \\ & 0 & & & 1 & \\ & & & & & \ddots \end{pmatrix}$$

雅可比形式简单

$$\left| \det \frac{\partial g_i(\phi)}{\partial \phi} \right| = \prod_{j=1}^{D/2} e^{[s_i(\phi_a)]_j}$$

$$g_i(\phi) := \begin{cases} z_a = \phi_a \\ z_b = \phi_b \odot e^{s_i(\phi_a)} + t_i(\phi_a) \end{cases}$$

$$g_i^{-1}(z) := \begin{cases} \phi_a = z_a \\ \phi_b = (z_b - t_i(z_a)) \odot e^{-s_i(z_a)}. \end{cases}$$