

中国物理学会高能物理分会第十届全国会员代表大会暨学术年会

Gravitational Clustering of
Relic Neutrinos from the Big Bang
in the Milky Way

背景中微子在银河系中的引力聚集

张珏

北京大学高能物理研究中心

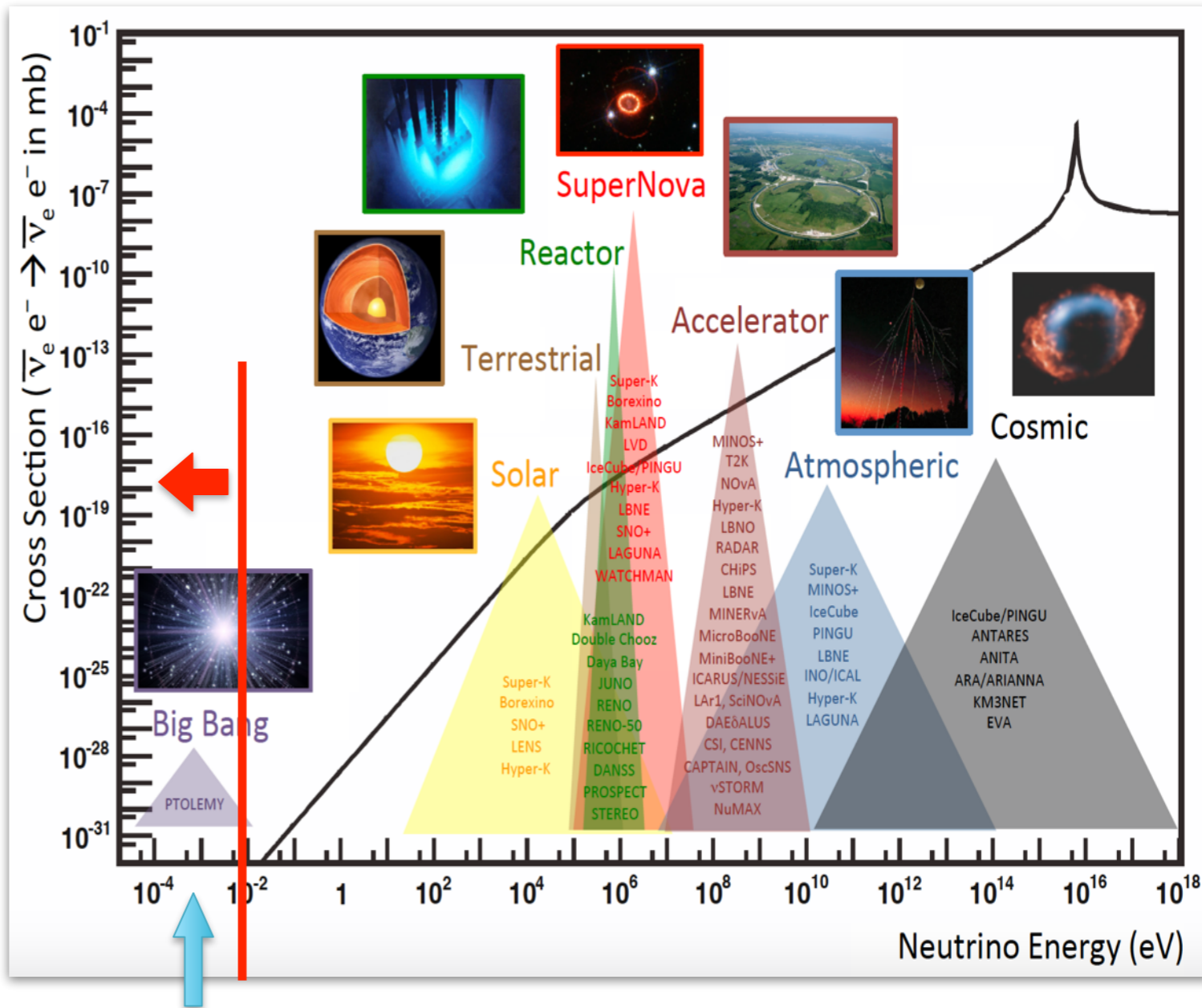
6/22/18

特别的而又无处不在的中微子

夸克轻子“视力表”



上	粲	顶
下	奇异	底
电子	缪子	陶子
1	2	3



宇宙遗迹中微子
 $T_\nu \sim 1.95K \sim 0.2 \text{ meV}$

至少有两代**非相对论性**
 宇宙遗迹中微子!

$$\sqrt{7.5 \times 10^{-5} \text{ eV}^2} \sim 8.7 \text{ meV}$$

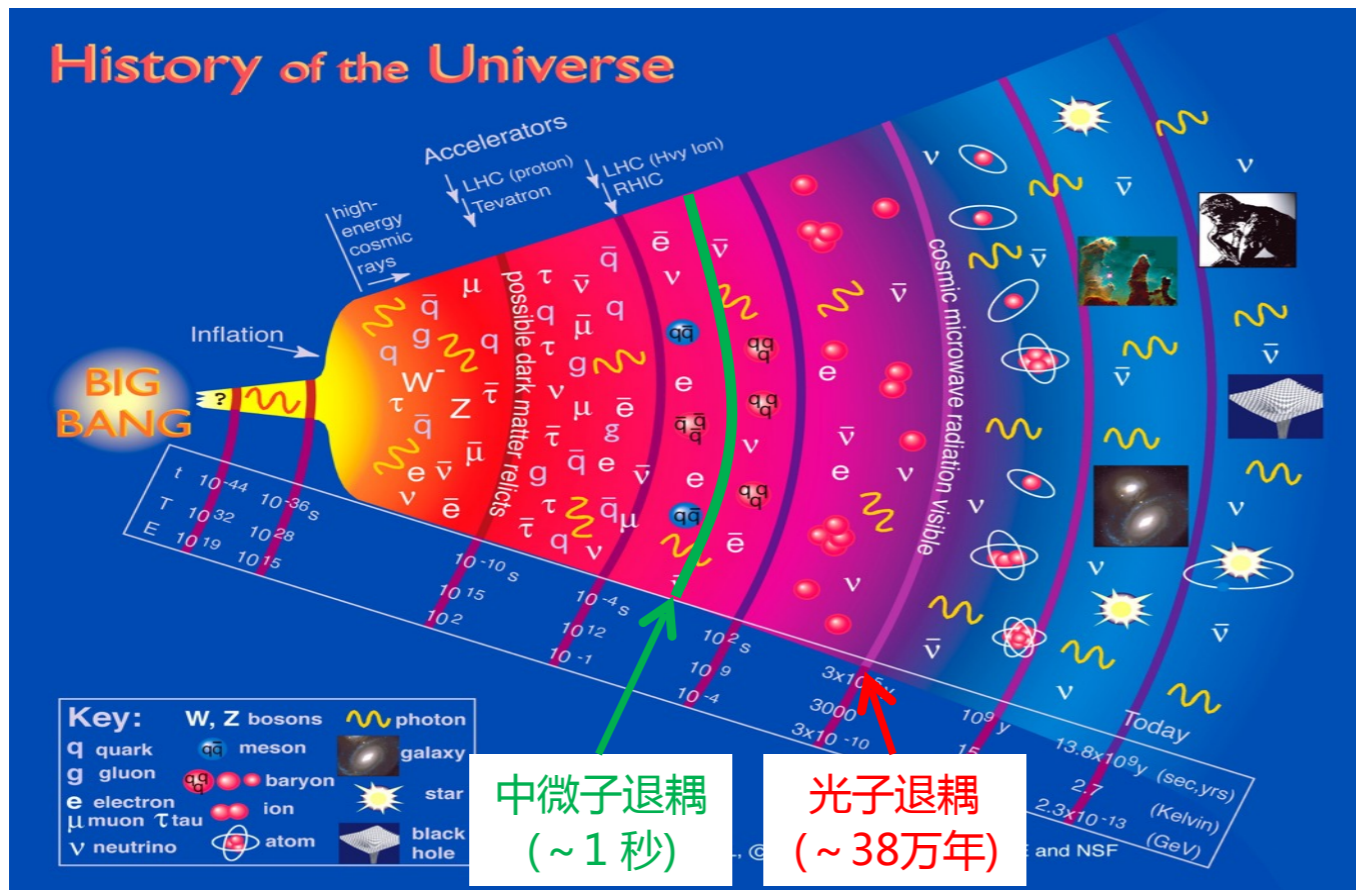
$$\sqrt{2.5 \times 10^{-3} \text{ eV}^2} \sim 50 \text{ meV}$$

$$\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{31}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$$

中微子振荡实验

中微子退耦(粒子物理标准模型 + 标准宇宙学)



粒子物理标准模型

1. 只有左手中微子(右手反中微子)
2. 参与弱相互作用
3. 无质量!

$$e^+ e^- \leftrightarrow \nu + \bar{\nu} \Rightarrow \Gamma_\nu \sim G_F^2 T^5$$

$$H \sim \frac{\sqrt{g_*} T^2}{M_{pl}}$$

$$\Rightarrow T_{fr} \sim \left(\frac{\sqrt{g_*}}{G_F^2 M_{pl}} \right)^{1/3} \sim 1 \text{ MeV} \quad (\sim 1 \text{ 秒})$$

光子再加热

$$e^+ e^- \rightarrow \gamma\gamma$$

加热前 0.5 MeV 加热后

当下

$$T_\nu = T_\gamma$$

$$T_\nu < T_\gamma$$

$$e^+ e^-$$

$$\gamma$$

熵守恒

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11} \right)^{1/3} \approx 0.7$$

$$T_\nu \approx 1.95 \text{ K} \approx 0.2 \text{ meV}$$

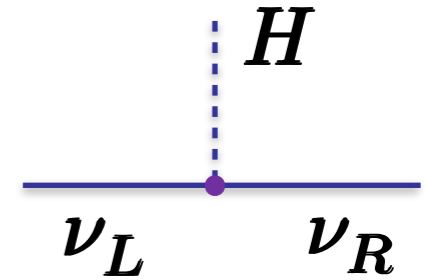
(至少有两代非相对论性的背景中微子)

$$n_\nu \approx 336 \text{ cm}^{-3}$$

新物理1: 狄拉克中微子(右手分量热产生)

标准狄拉克
中微子质量

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \left[\overline{\ell}_{\alpha\text{L}} \underbrace{(Y_\nu)_{\alpha\beta}}_{\sim 10^{-12}} \underbrace{\tilde{H} \nu_{\beta\text{R}}}_{\text{右手分量}} + \text{h.c.} \right]$$



标准狄拉克中微子右手分量
无法在宇宙演化中大量产生!

$\sim 10^{-12}$

右手分量

右手分量可能参与
额外的相互作用?



右手分量能够在宇宙演化中大量产生?

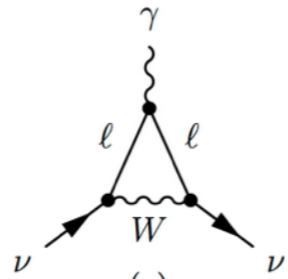
• 原初磁场 (Primordial Magnetic Fields)

Giunti, Li, Studenikin, Zhou, et al, 2015

狄拉克中微子磁矩

$$\overline{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu}$$

$$\mu_{\nu_i} \approx 3 \times 10^{-20} \left(\frac{m_i}{0.1 \text{ eV}} \right) \mu_B$$



• Secret ν_R interactions

van den Aarssen, Bringmann, Pfrommer, 2012

Ahlgren, Ohlsson and Zhou, 2013

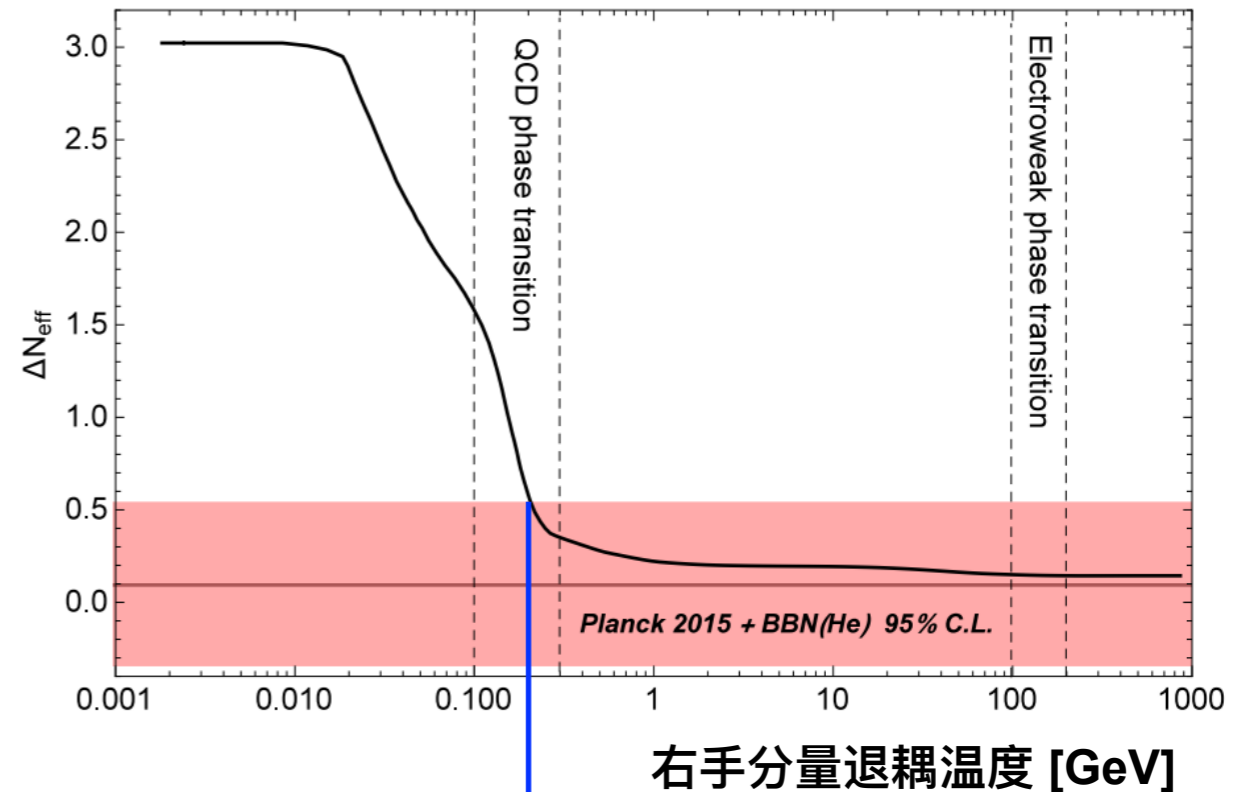
Huang and Zhou, 2017

• Spacetime Deformation Effect

Horvat, Trampetic and You, 2017

宇宙学限制:

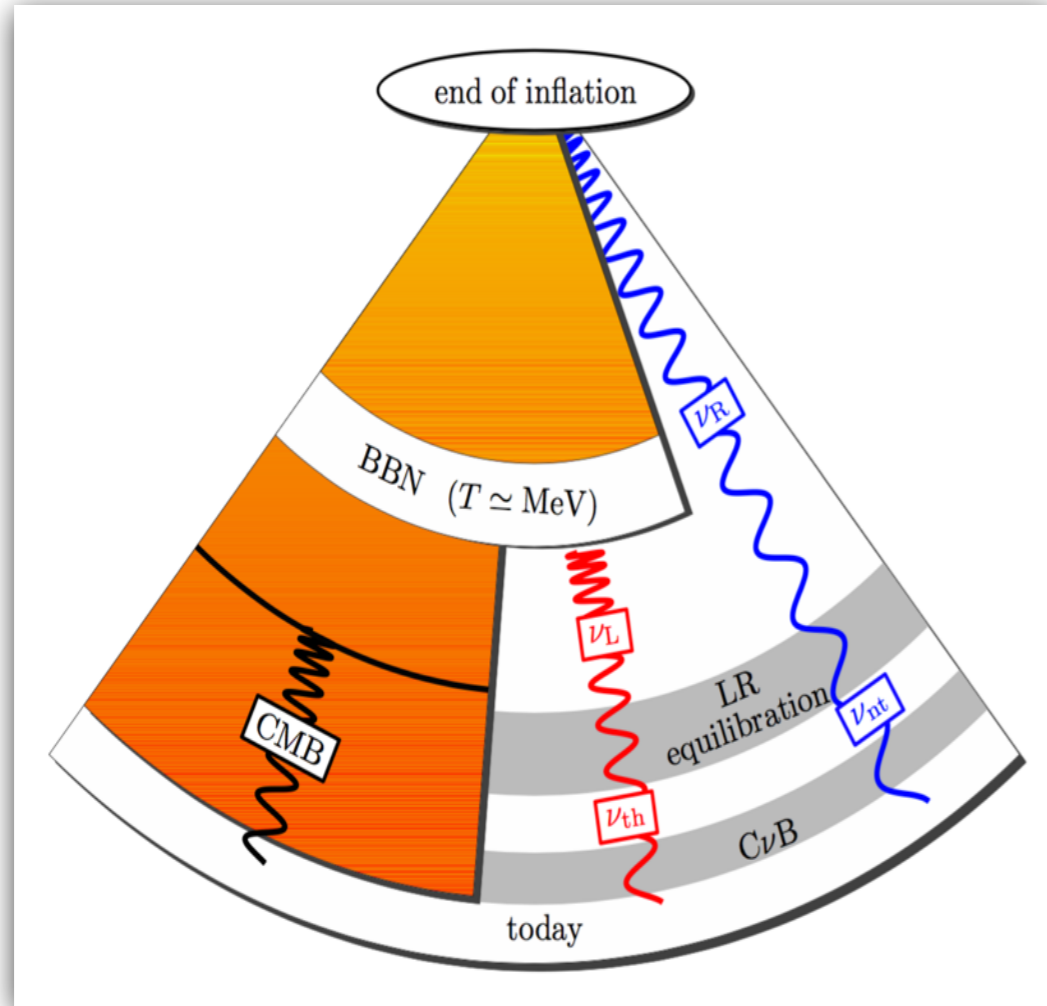
额外有效中微子代数



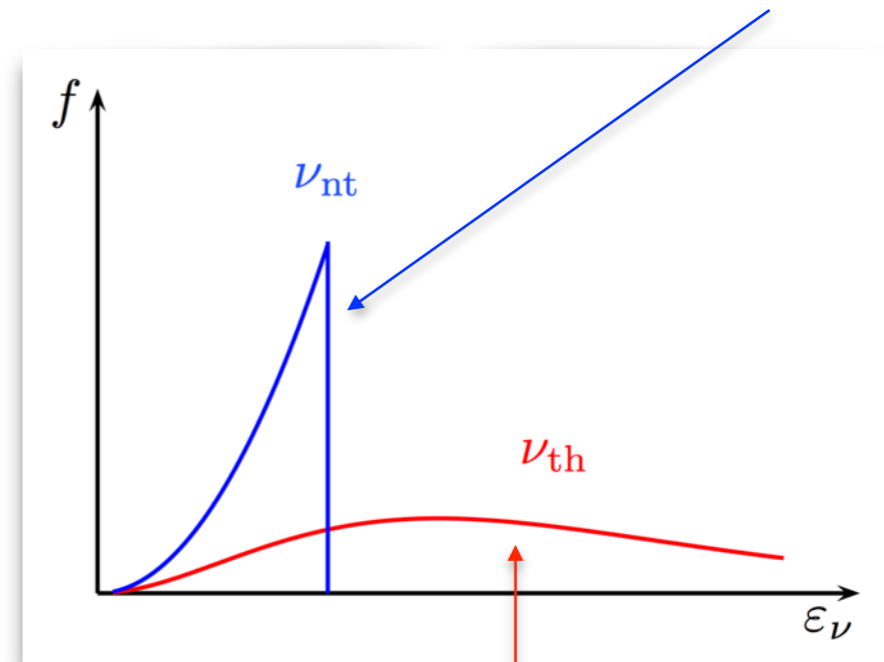
当下允许的最大比值: $\frac{n_{\nu_R}}{n_{\nu_L}} \approx 0.28$

新物理2: 狄拉克中微子(右手分量**非热产生**)

Chen, Ratz and Trautner, 2015



- 右手分量完全与热浴退耦
- 右手分量能量分布函数(f)取决于暴涨模型
- 极限情况: 右手分量形成**简并(Deg)**费米气体

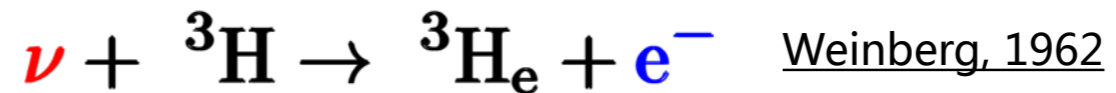


费米-狄拉克(FD)分布

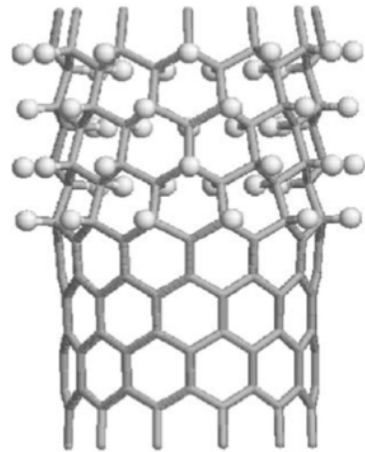
	左手中微子(ν_L)	右手中微子(ν_R) (Dirac)
标准狄拉克中微子	(n_0 , FD)	0
新物理1	(n_0 , FD)	($0.28*n_0$, FD)
新物理2	(n_0 , FD)	($0.56*n_0$, Deg)

宇宙背景中微子探测

贝塔衰变核素俘获:

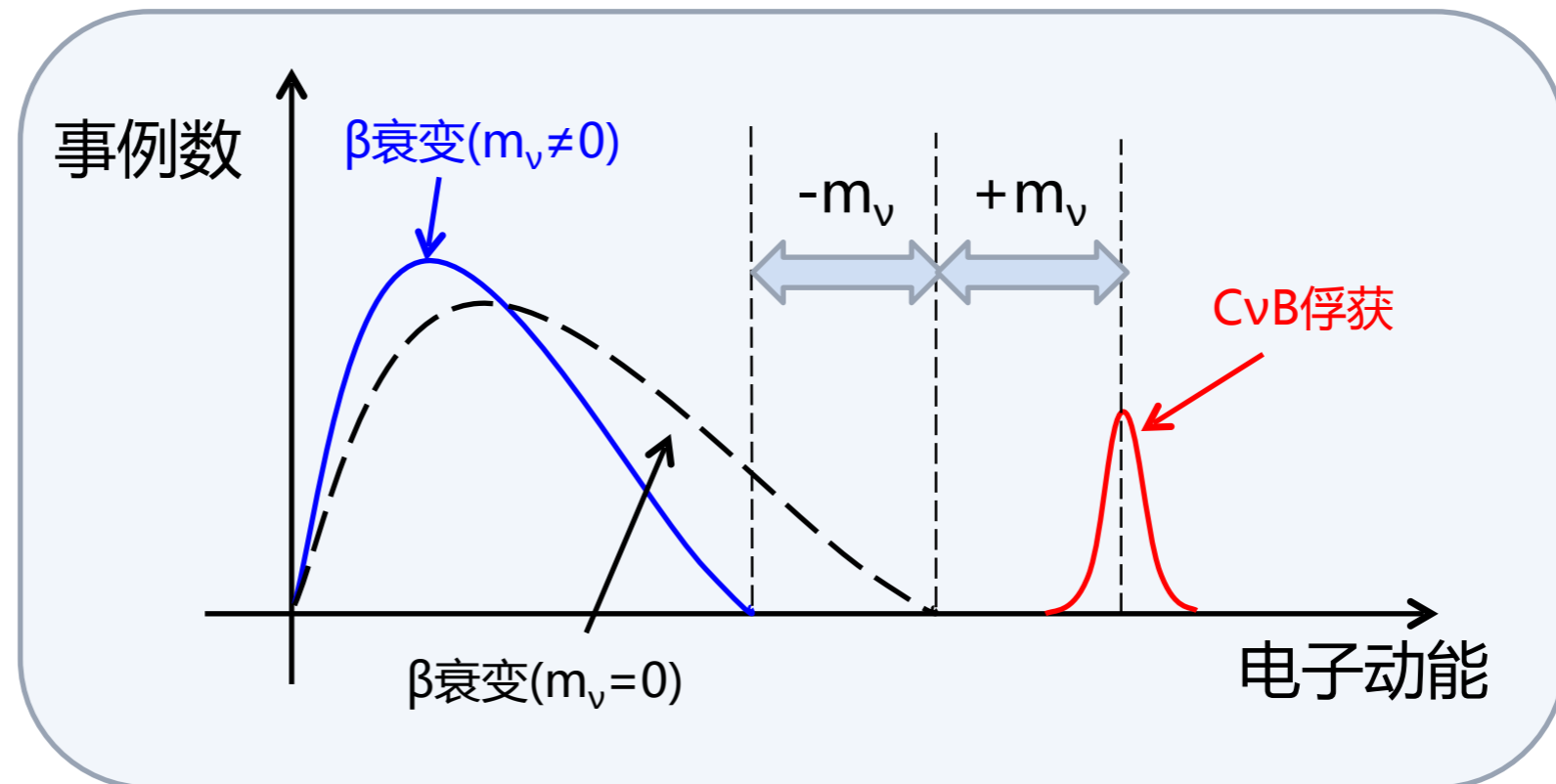


PTOLEMY实验: P on T ecorvo O bservatory for L ight, E arly-Universe, M assive-Neutrino Y ield



100克氦,
能量分辨率~0.15 eV

Betts et al., arXiv: 1307.4738



要求非常
好的能量
分辨率!

Kick-off meeting of the PTOLEMY Project (11-12 December 2017)


iCal export More Europe/Rome Eng

Kick-off meeting of the PTOLEMY Project

chaired by Marcello Messina (Columbia University), Alfredo Giuseppe Cocco (Napoli University & INFN), Christopher Tully (Princeton University, USA)

from Monday, 11 December 2017 at 10:00 to Tuesday, 12 December 2017 at 19:00 (Europe/Rome)
at **Laboratori Nazionali del Gran Sasso ("E. Majorana" conference room)**
Via G. Acitelli, 22 - 67100 Assergi (Italy)

Description

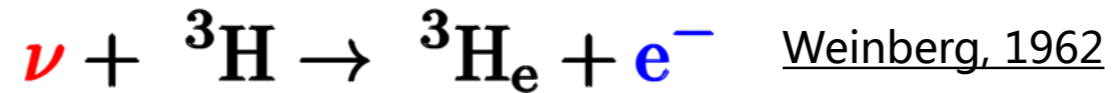


P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

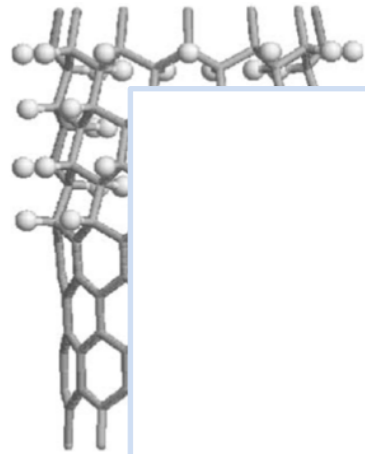
The aim is to promote discussion on the experimental

宇宙背景中微子探测

贝塔衰变核素俘获:



PTOLEMY实验: P on T ecorvo O bservatory for L ight, E arly-Universe, M assive-Neutrino Y ield



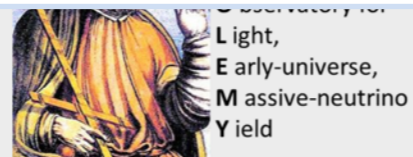
10

能量分辨

Betts et al.,

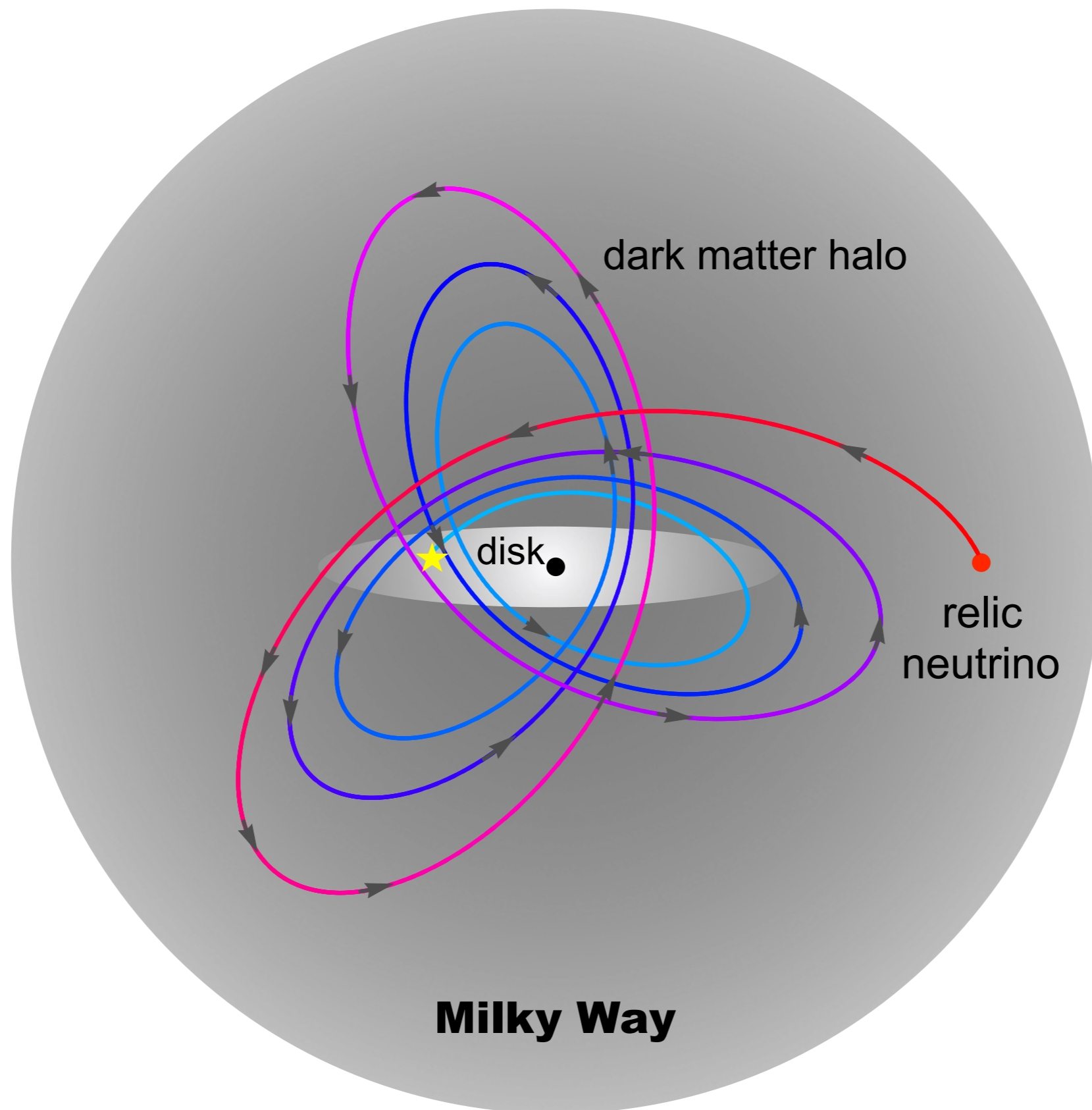
问题: 地球附近到底有多少背景中微子?

要求非常
好的能量
分辨率!



The aim is to promote discussion on the experimental

宇宙背景中微子的引力聚集

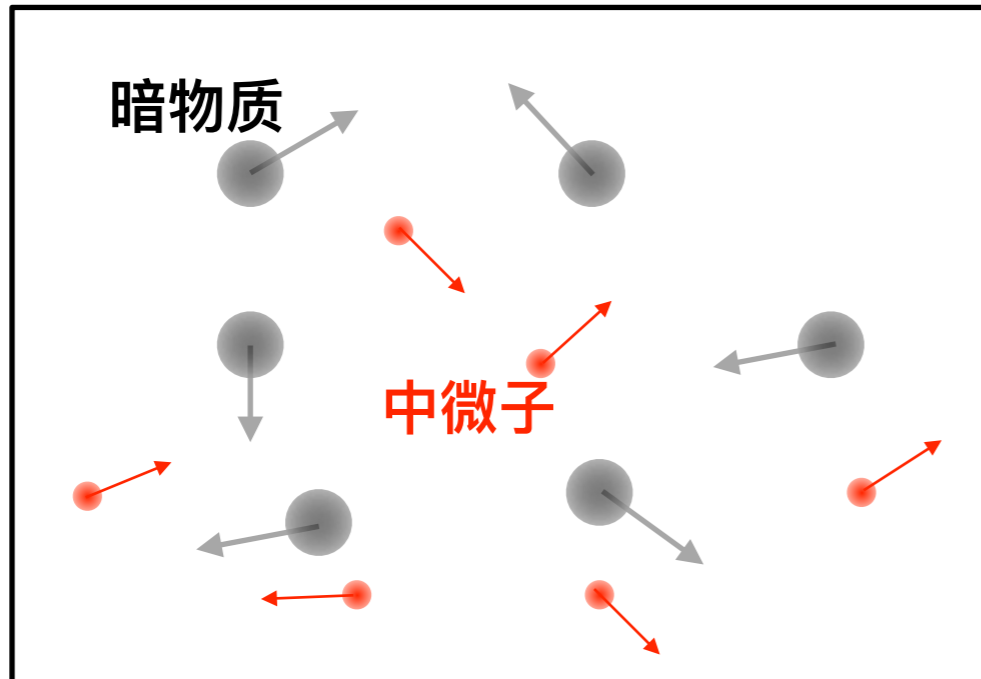


N体模拟 vs. N单体模拟

N体模拟

暗物质:
 $5 < z < 100$

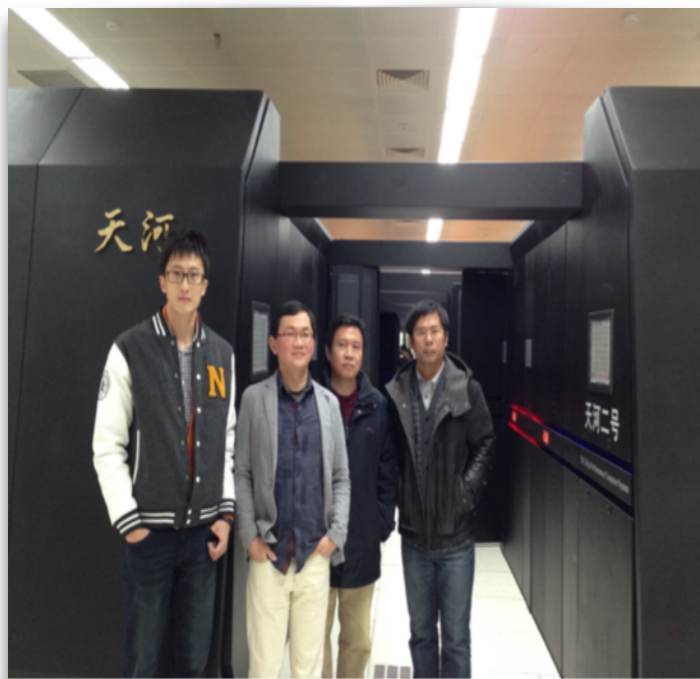
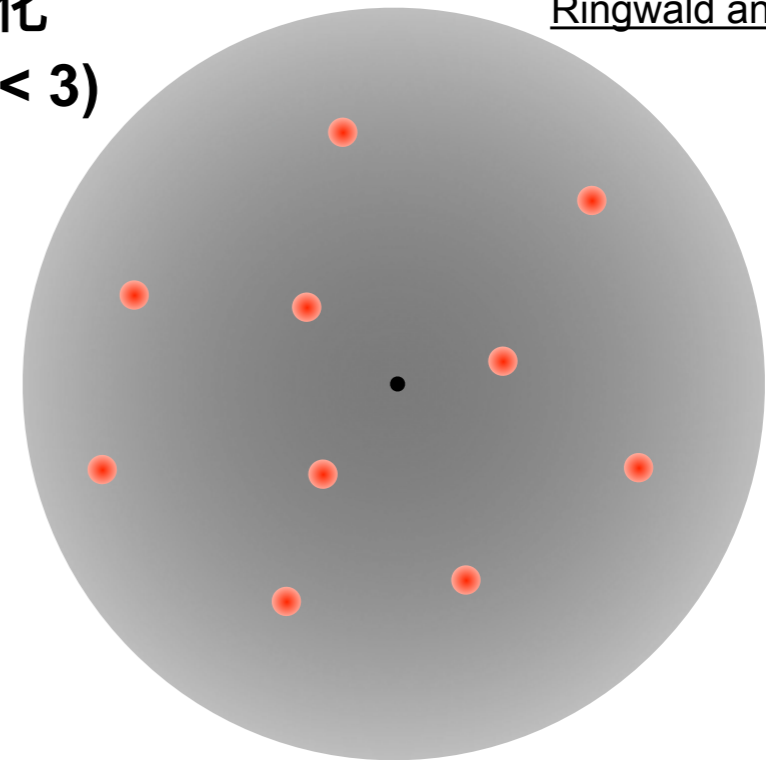
暗物质 +
中微子:
 $z < 5$



N单体模拟

宇宙演化
后期($z < 3$)

Ringwald and Wong, 2014



TianNu Simulation:

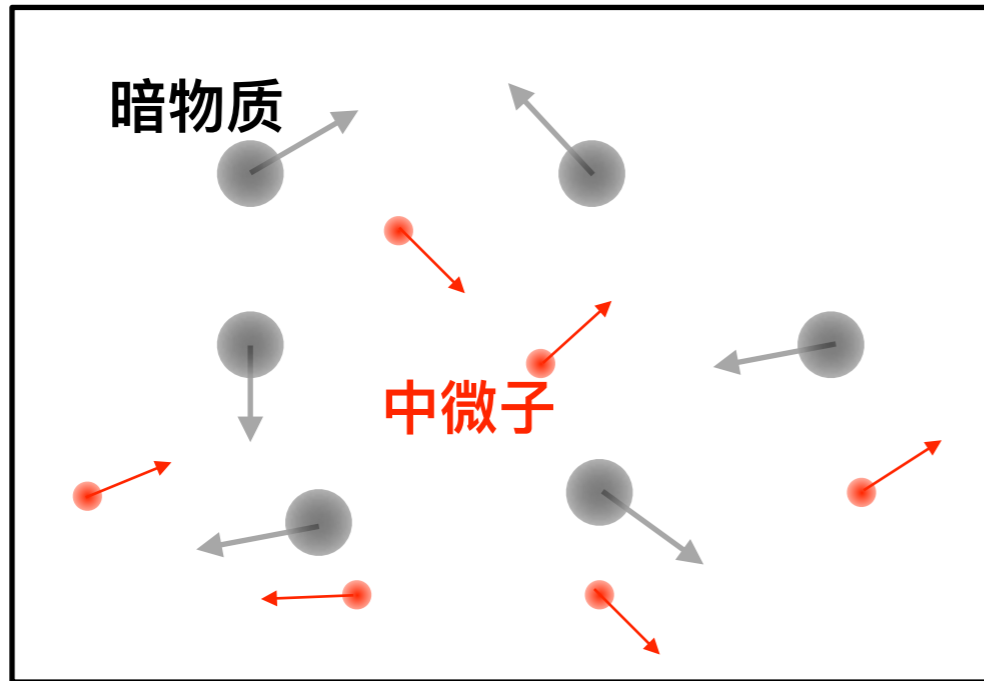
- ▶ 13824 computer nodes
- ▶ 6912^3 CDM particles
- ▶ 13824^3 neutrinos
- ▶ Cubic vol. of $1200 h^{-1} \text{Mpc}$
- ▶ Total: $2.97 \cdot 10^{12}$ particles
- ▶ Largest N-body sim.
- ▶ ~52 hours

N体模拟 vs. N单体模拟

N体模拟

暗物质:
 $5 < z < 100$

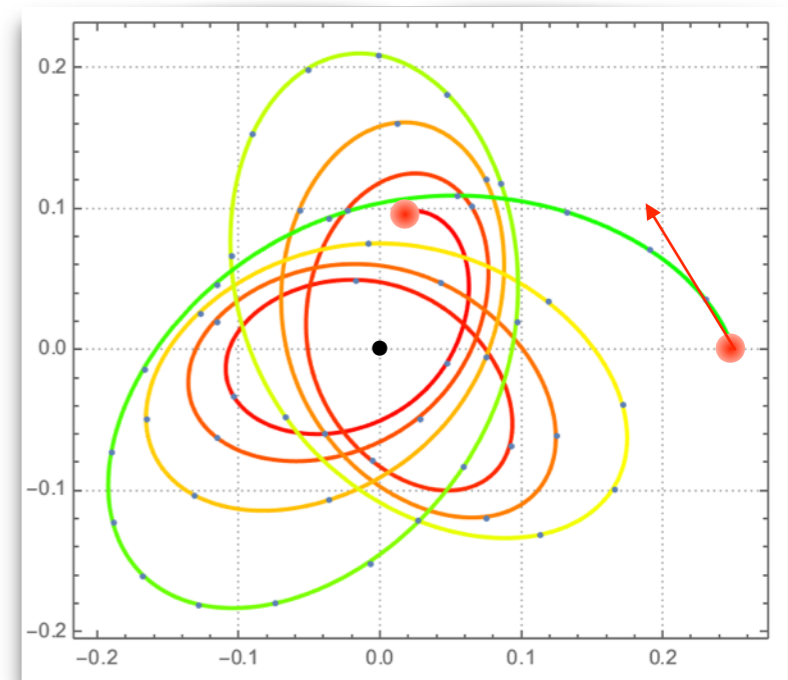
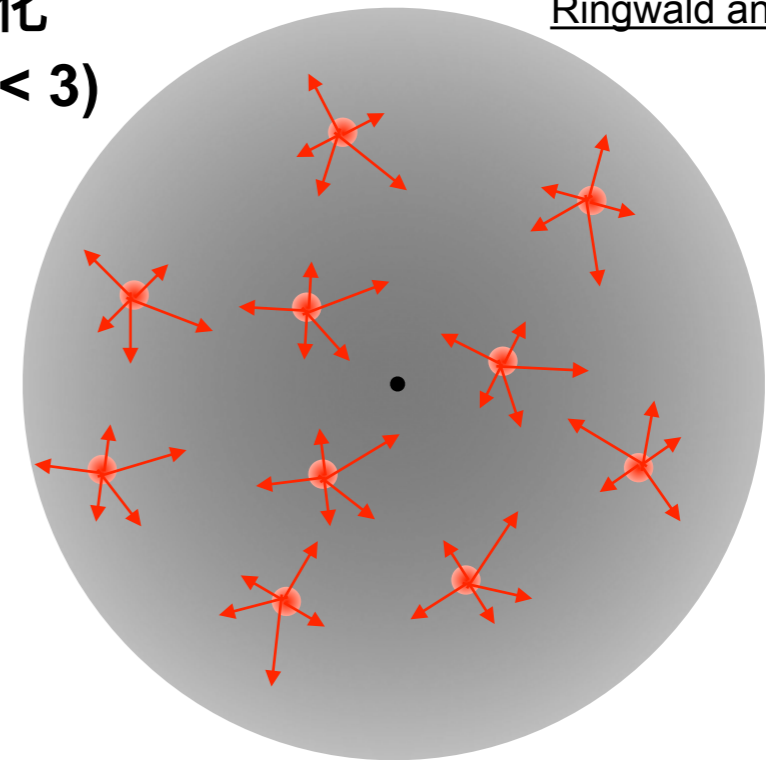
暗物质 +
中微子:
 $z < 5$



N单体模拟

宇宙演化
后期($z < 3$)

Ringwald and Wong, 2014



TianNu Simulation:

- ▶ 13824 computer nodes
- ▶ 6912^3 CDM particles
- ▶ 13824^3 neutrinos
- ▶ Cubic vol. of $1200 h^{-1} \text{Mpc}$
- ▶ Total: $2.97 \cdot 10^{12}$ particles
- ▶ Largest N-body sim.
- ▶ ~52 hours

“Cosmological neutrino simulations at extreme scale”, 1611.01545

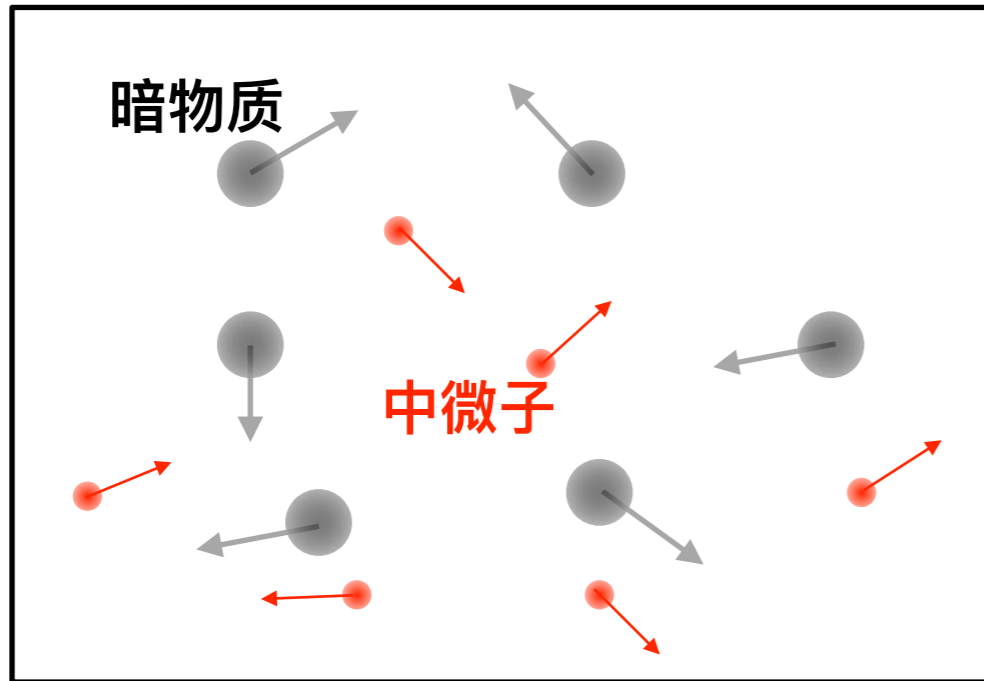
单体有心力场运动

N体模拟 vs. N单体模拟

N体模拟

暗物质:
 $5 < z < 100$

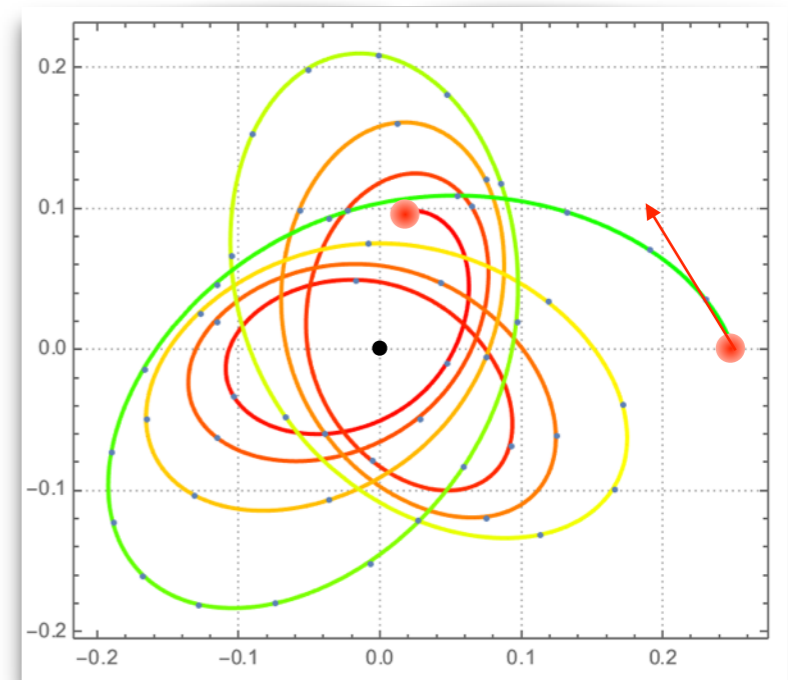
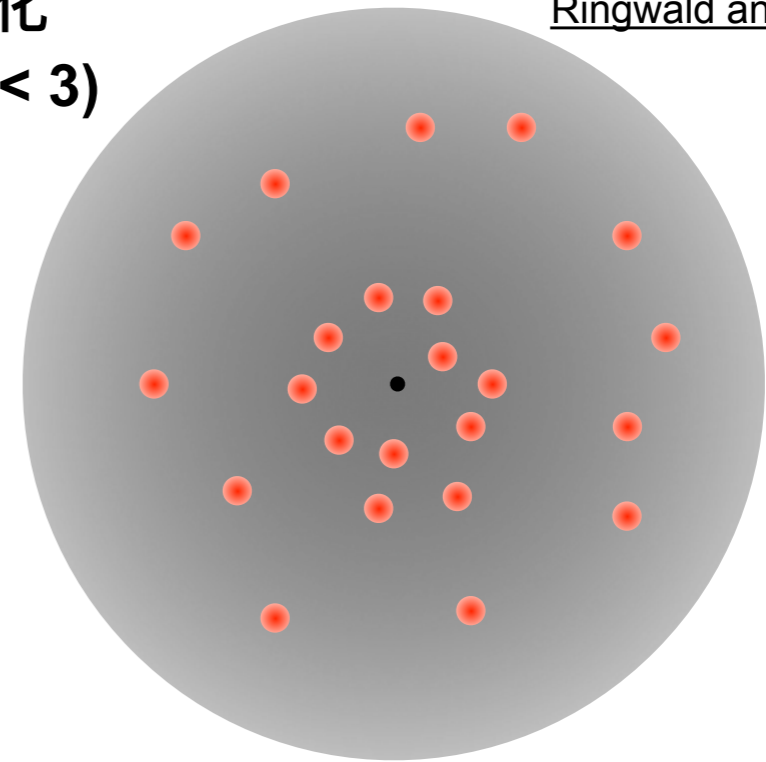
暗物质 +
中微子:
 $z < 5$



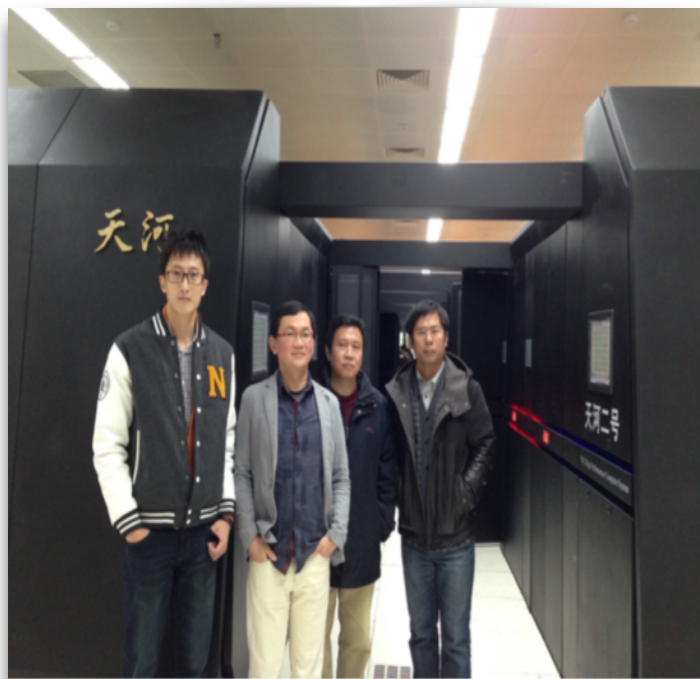
N单体模拟

宇宙演化
后期($z < 3$)

Ringwald and Wong, 2014



单体有心力场运动



TianNu Simulation:

- ▶ 13824 computer nodes
- ▶ 6912^3 CDM particles
- ▶ 13824^3 neutrinos
- ▶ Cubic vol. of $1200 h^{-1} \text{Mpc}$
- ▶ Total: $2.97 \cdot 10^{12}$ particles
- ▶ Largest N-body sim.
- ▶ ~52 hours

“Cosmological neutrino simulations at extreme scale”, 1611.01545

N单体模拟

1. 单粒子(归一化)哈密顿方程:

(假设: 引力势含有球对称性)

$$(r, u_r, u_\theta)$$

↑ ↑
演化量 守恒量

与质量无关!

$$\frac{dr}{dz} = -\frac{u_r}{da/dt}$$

$$\frac{du_r}{dz} = -\frac{1}{da/dt} \left(\frac{u_\theta^2}{r^3} - a^2 \frac{\partial \phi}{\partial r} \right)$$

r — 径向距离
 u_r — 径向速度
 u_θ — 角向速度
 ϕ — 引力势

Ringwald and Wong, 2014

2. 单粒子含有权重:

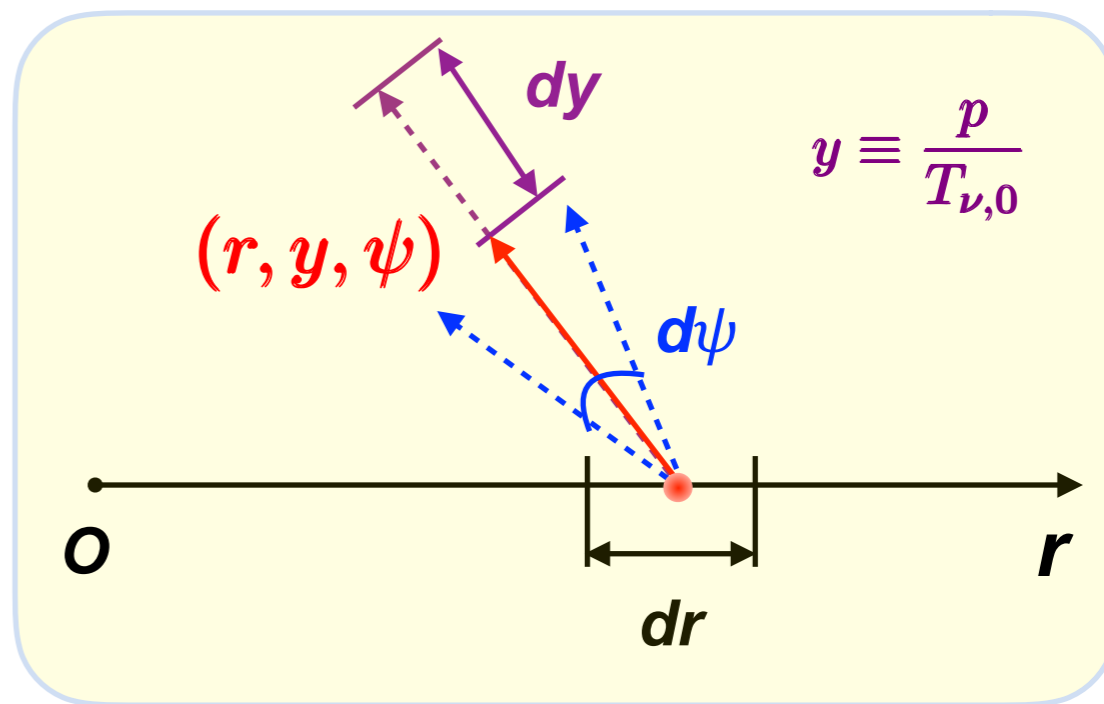
$$dw \propto \int_{r_a}^{r_b} r^2 dr \int_{y_a}^{y_b} f(y) y^2 dy \int_{\psi_a}^{\psi_b} \sin \psi d\psi$$

$$(r, y, \psi) \longrightarrow (r, u_r, u_\theta)$$

$$u_r = \frac{p \cos \psi}{m_\nu} = \frac{y \cos \psi T_{\nu,0}}{m_\nu}$$

$$u_\theta = \frac{p \sin \psi}{m_\nu} = \frac{y \sin \psi T_{\nu,0}}{m_\nu}$$

与质量有关!



3. 粒子分布重构:

$$n(r) = \sum_{i=1}^N \frac{w_i}{h^3} \tilde{K}(r, r_i, h)$$

$$\tilde{K}(r, r_i, h) = \frac{1}{2(2\pi)^{3/2}} \frac{h^2}{rr_i} \left[e^{-(r-r_i)^2/2h^2} - e^{-(r+r_i)^2/2h^2} \right]$$

reweight方法

$$\begin{aligned}
 & \left(r, u_r, u_\theta \right) \xrightarrow{m_{\nu,1} = 0.15 \text{ eV}} (r, y_1, \psi) + dw \propto \int_{r_a}^{r_b} r^2 dr \int_{y_{a,1}}^{y_{b,1}} f(y_1) y_1^2 dy_1 \int_{\psi_a}^{\psi_b} \sin \psi d\psi \\
 & \left(r, u_r, u_\theta \right) \xrightarrow{m_{\nu,2} = 0.06 \text{ eV}} (r, y_2, \psi) + dw \propto \int_{r_a}^{r_b} r^2 dr \int_{y_{a,2}}^{y_{b,2}} f(y_2) y_2^2 dy_2 \int_{\psi_a}^{\psi_b} \sin \psi d\psi
 \end{aligned}$$

$$u_r = \frac{p \cos \psi}{m_\nu} = \frac{y \cos \psi T_{\nu,0}}{m_\nu}$$

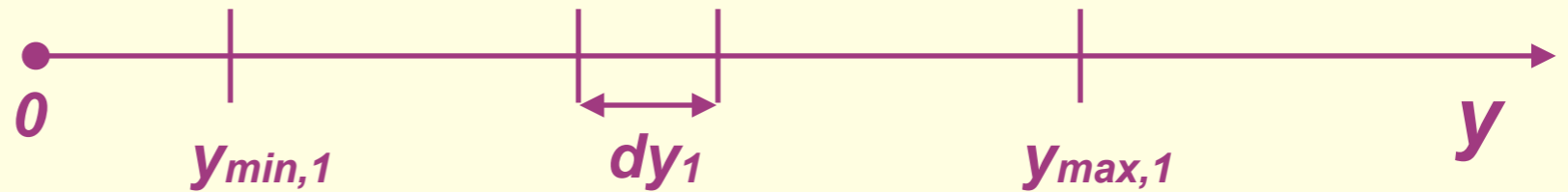
$$u_\theta = \frac{p \sin \psi}{m_\nu} = \frac{y \sin \psi T_{\nu,0}}{m_\nu}$$

JZ and Xin Zhang, 2018

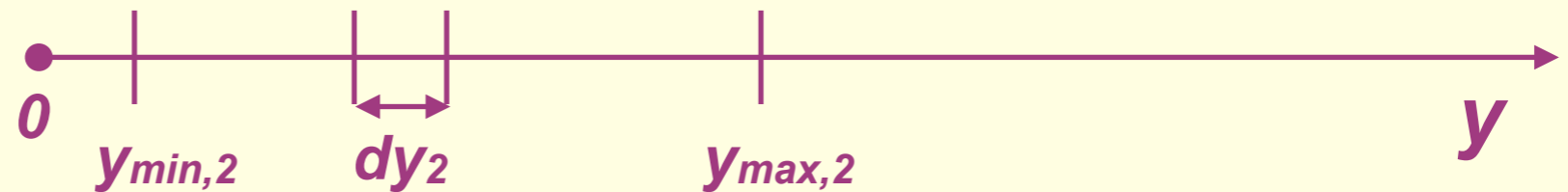
单次N单体模拟



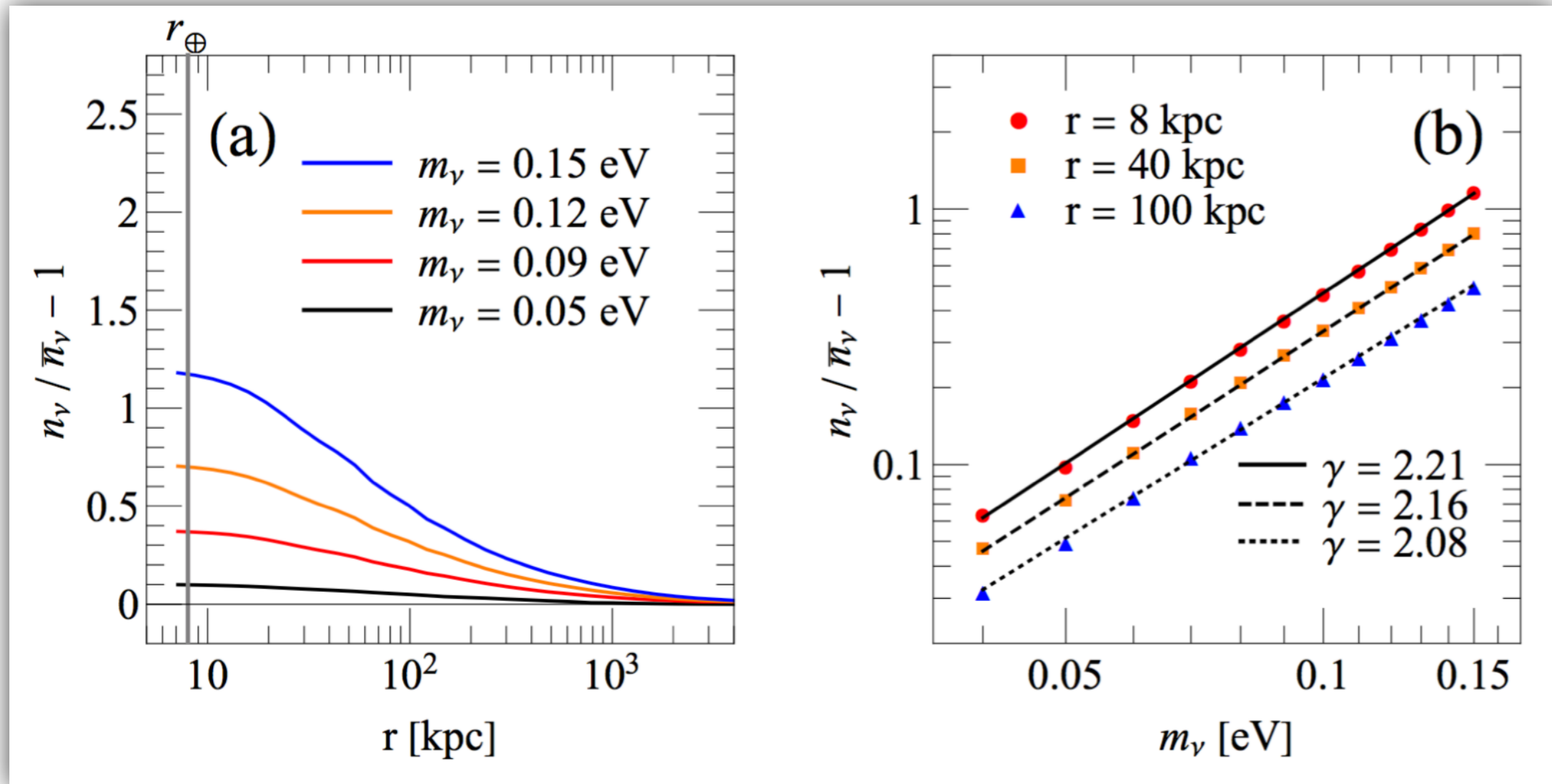
不同中微子质量
&不同相空间分布下
的中微子聚积情况



$$y_2 = \frac{m_{\nu,2}}{m_{\nu,1}} y_1$$



中微子聚集 vs. 中微子质量 (Fermi-Dirac分布)



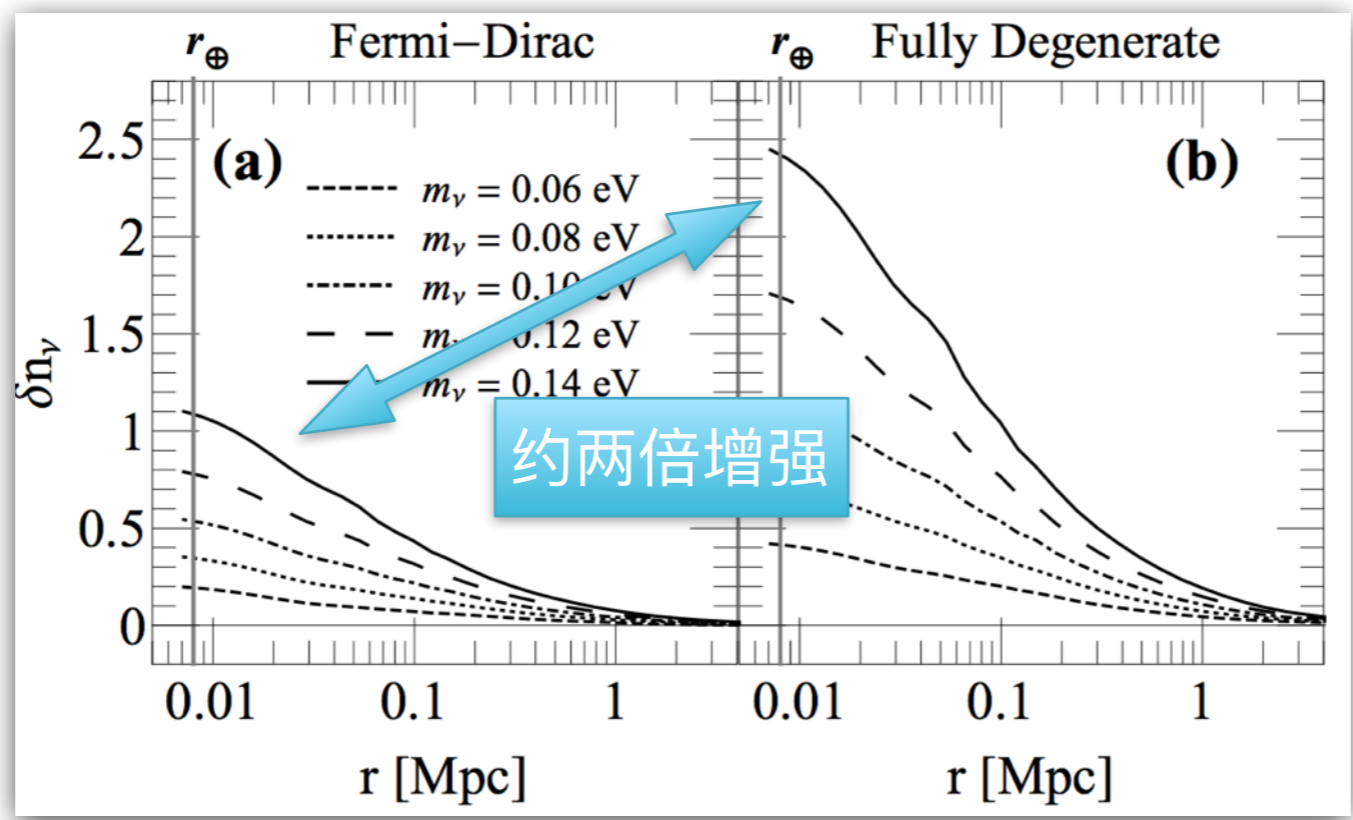
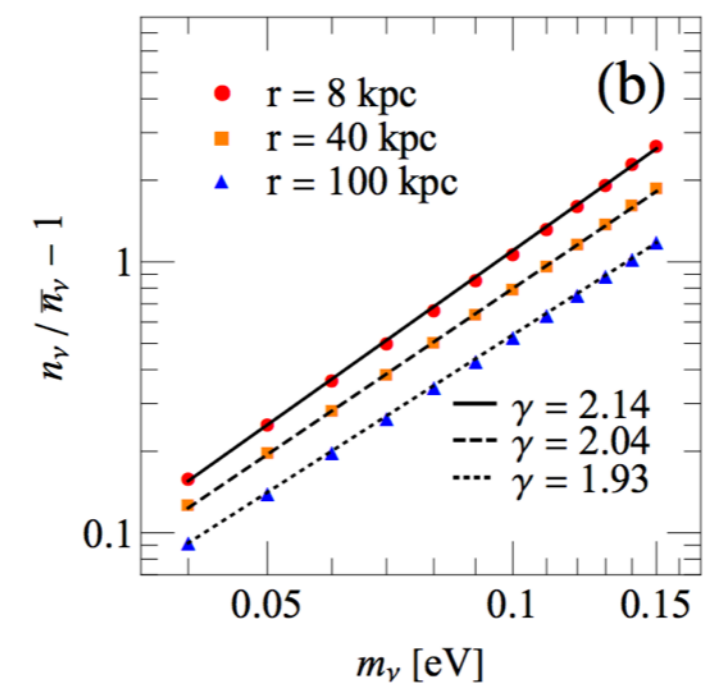
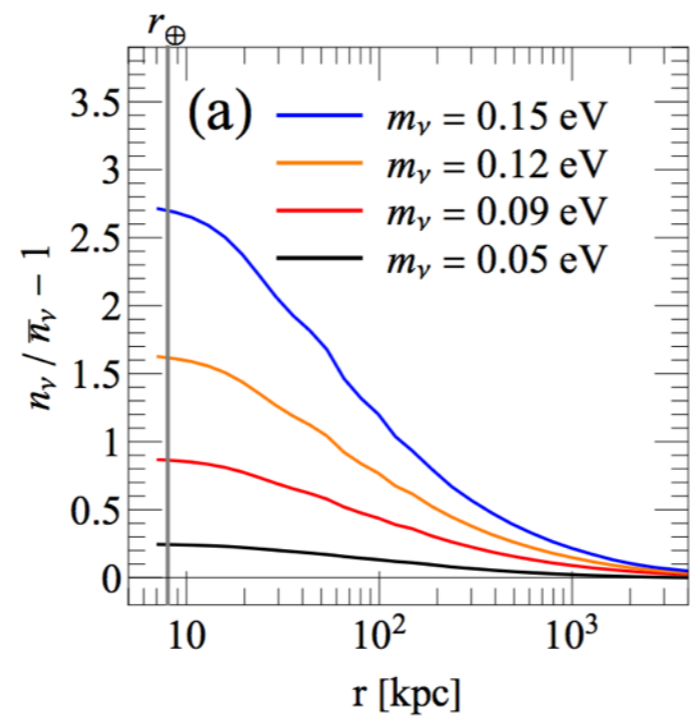
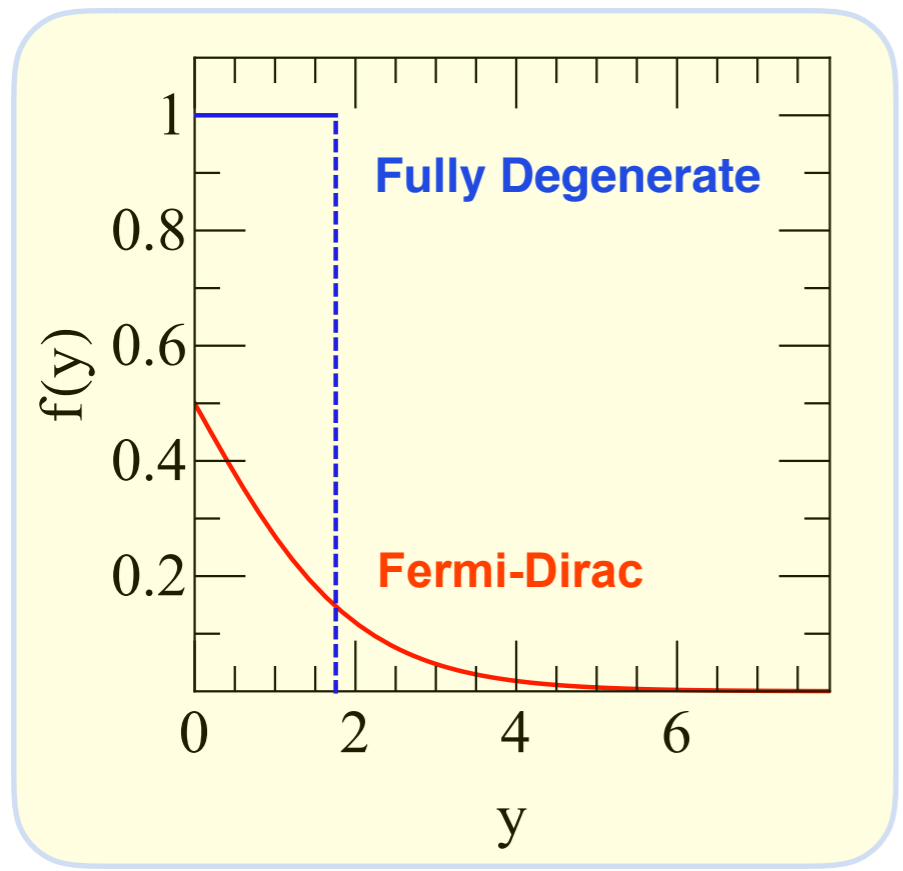
neutrino density contrast:

$$\delta n_\nu \equiv \frac{n_\nu}{\bar{n}_\nu} - 1$$



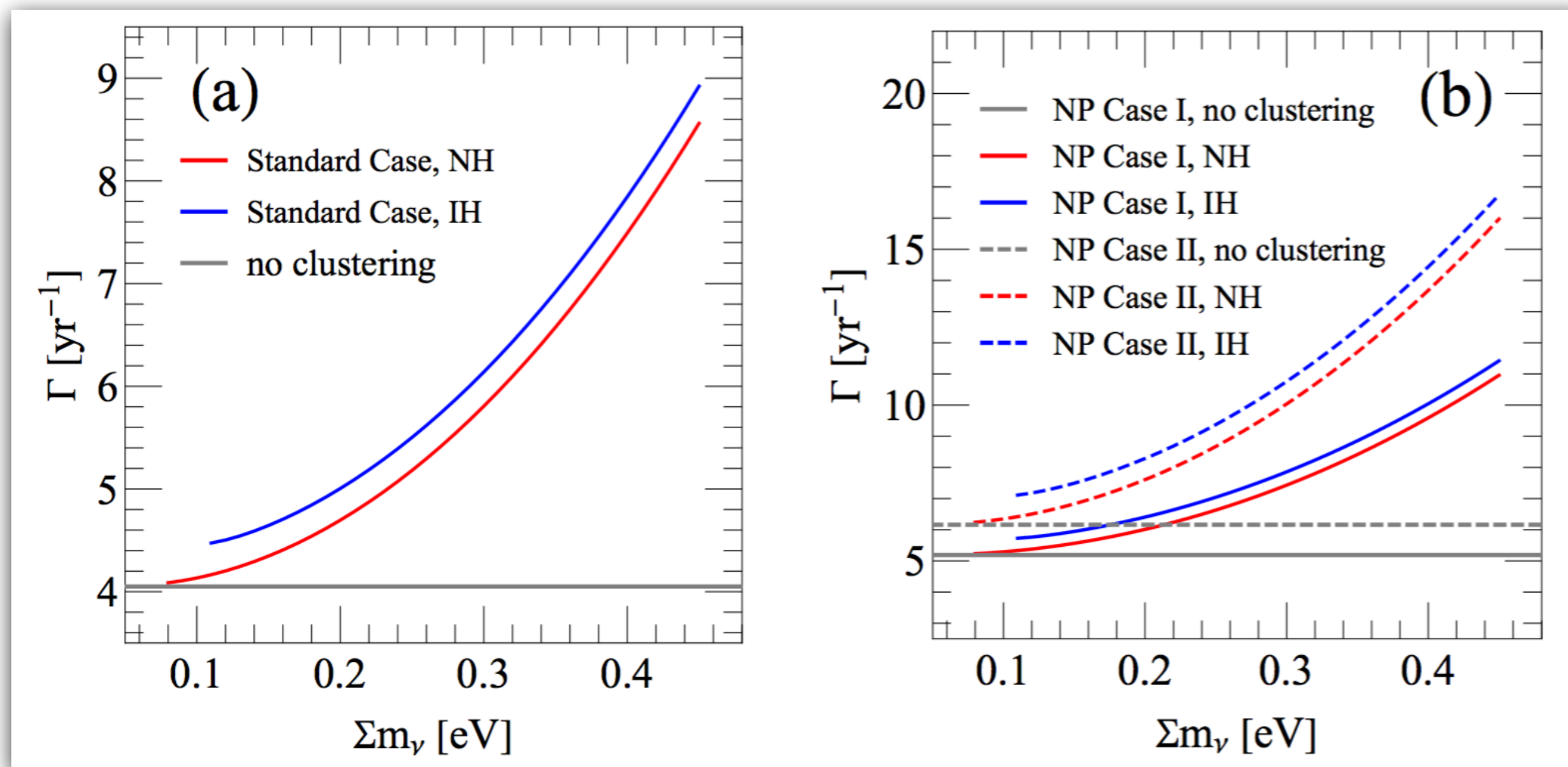
$$\delta n_\nu \propto m_\nu^2$$

不同相空间分布: Fermi-Dirac vs. Fully Degenerate



JZ and Xin Zhang, 2018

俘获率 @ PTOLEMY



	左手中微子(ν_L)	右手中微子(ν_R) (Dirac)
标准狄拉克中微子	(n_0 , FD)	0
新物理1	(n_0 , FD)	($0.28*n_0$, FD)
新物理2	(n_0 , FD)	($0.56*n_0$, Deg)

总结

◆ 背景中微子探测对中微子物理和宇宙学至关重要

- 贝塔衰变核素俘获(**PTOLEMY**)

◆ 背景中微子的引力聚集

- N单体模拟

- **reweight**方法

- 中微子聚集 vs. 中微子质量

$$\delta n_\nu \propto m_\nu^2$$

- 中微子聚集 vs. 相空间分布

总结

◆ 背景中微子探测对中微子物理和宇宙学至关重要

- 贝塔衰变核素俘获(**PTOLEMY**)

◆ 背景中微子的引力聚集

- N单体模拟

- **reweight**方法

- 中微子聚集 vs. 中微子质量 $\delta n_\nu \propto m_\nu^2$

- 中微子聚集 vs. 相空间分布

谢谢大家!

