Degenerate Oscillation in Neutron Star

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Fu, **SFG**, Guo & Wang [arXiv:2405.08591]

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

July 21, 2024
New Opportunities

李政道研究所 Tsung-Dao Lee Institute

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Outline

- **Degenerate Oscillation**
- **Neutron-Antineutron Oscillation in NS**
- **Neutron Star Cooling & GUT**

Neutrino Oscillation

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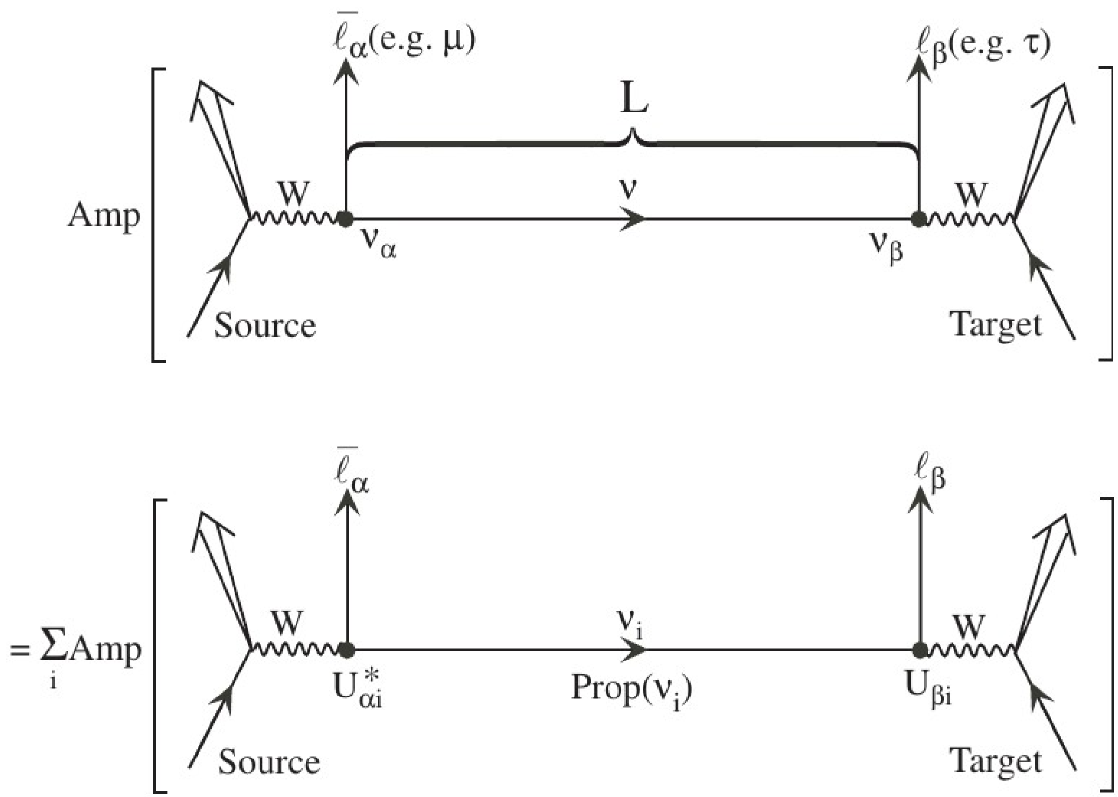


[Kayser, https://arxiv.org/abs/hep-ph/0506165]

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \rightarrow \boxed{\sum_i U_{\alpha i} e^{i(E_i t - \vec{P}_i \cdot \vec{x})} \nu_i} = \boxed{\sum_i U_{\alpha i} P_i U^\dagger_{\beta i} \nu_\beta} \equiv \sum_\beta A_{\alpha\beta} \nu_\beta$$

ν Oscillation in Matter

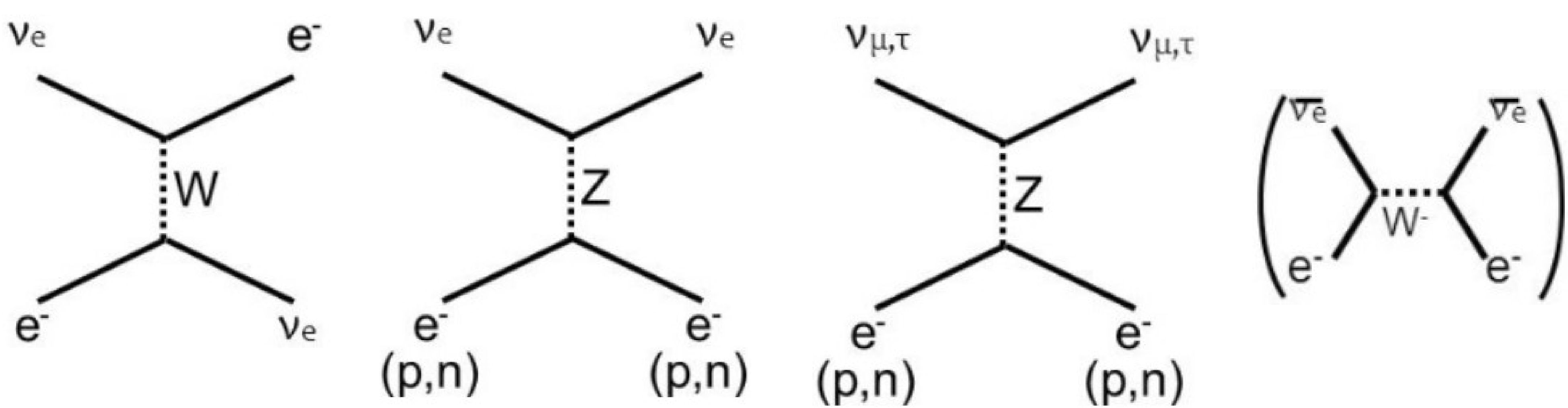
PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{H} = \frac{\mathbf{MM}^\dagger}{2E_\nu} \pm \mathbf{V}$$



Collective Neutrino Oscillation

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$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}x}\psi = \mathsf{H}\psi$$

$$\mathsf{H} = \frac{\Delta m^2}{2E}\mathsf{B} + \lambda\mathsf{L} + \mathsf{H}_{\nu\nu}$$

$$\mathsf{B} = \mathsf{U}\left(\frac{1}{2}\mathrm{diag}[-1,\,1]\right)\mathsf{U}^\dagger = \frac{1}{2}\begin{bmatrix} -\cos 2\theta_\mathrm{v} & \sin 2\theta_\mathrm{v} \\ \sin 2\theta_\mathrm{v} & \cos 2\theta_\mathrm{v} \end{bmatrix}$$

$$= \frac{\Delta m^2}{2E}\mathsf{B} + \sqrt{2}G_\mathrm{F} n_e \mathsf{L} + \sqrt{2}G_\mathrm{F}\int \mathrm{d}^3\mathbf{p}'(1 - \hat{\mathbf{p}}\cdot\hat{\mathbf{p}}')(\rho_{\mathbf{p}'} - \bar{\rho}_{\mathbf{p}'})$$

$$[\rho_{\mathbf{p}'}(t,\mathbf{x})]_{\alpha\beta} = \sum_{\nu'} n_{\nu',\mathbf{p}'}(t,\mathbf{x})\langle\nu_\alpha|\psi_{\nu',\mathbf{p}'}(t,\mathbf{x})\rangle\langle\psi_{\nu',\mathbf{p}'}(t,\mathbf{x})|\nu_\beta\rangle,$$

$$[\bar{\rho}_{\mathbf{p}'}(t,\mathbf{x})]_{\beta\alpha} = \sum_{\bar{\nu}'} n_{\bar{\nu}',\mathbf{p}'}(t,\mathbf{x})\langle\bar{\nu}_\alpha|\psi_{\bar{\nu}',\mathbf{p}'}(t,\mathbf{x})\rangle\langle\psi_{\bar{\nu}',\mathbf{p}'}(t,\mathbf{x})|\bar{\nu}_\beta\rangle,$$

Duan, Fuller & Qian [arXiv:1001.2799]

Degeneracy with Boltzmann Eq.

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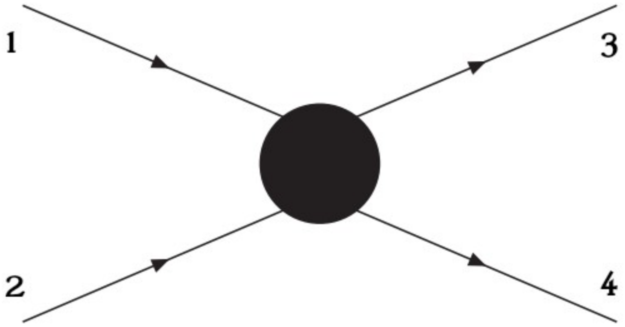
Boltzmann Equation:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}}\frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{p}}\frac{d\mathbf{p}}{dt} = \mathbb{C}[f]$$



$$\mathbb{C}[f] = \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4)$$

$$|\mathcal{M}|^2 \{ f_1 f_2 [1 \pm f_3][1 \pm f_4] - f_3 f_4 [1 \pm f_1][1 \pm f_2] \}$$

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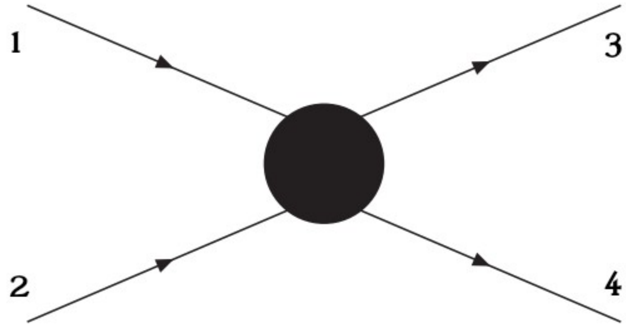

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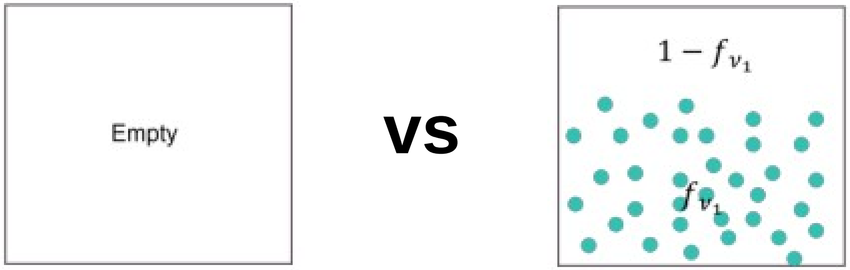
$$|\mathcal{M}|^2 \{ f_1 f_2 [1 \pm f_3][1 \pm f_4] - f_3 f_4 [1 \pm f_1][1 \pm f_2] \}$$

Degeneracy is described by phase space factors: $1 \pm f$

Description with 2nd Quantization



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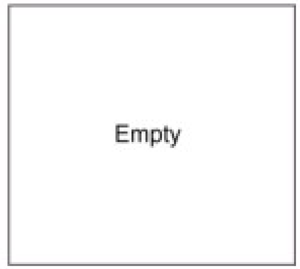

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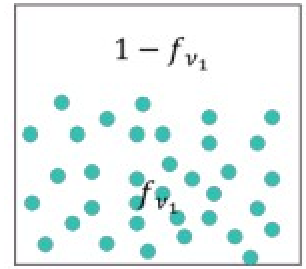
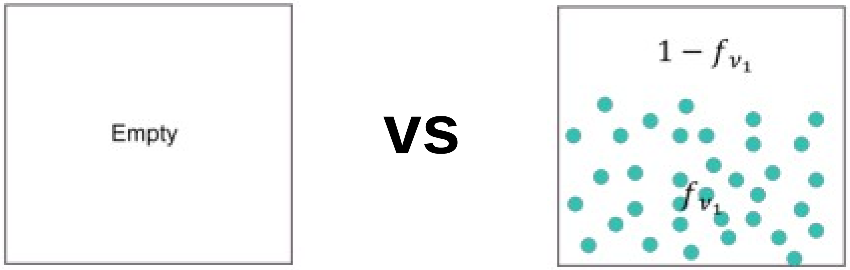


$$|N\rangle \equiv \frac{(a^\dagger)^N}{\sqrt{N!}}|0\rangle$$

Description with 2nd Quantization



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Description with 2nd Quantization

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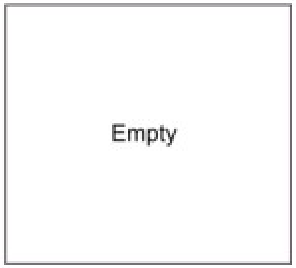

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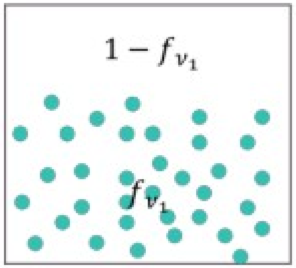

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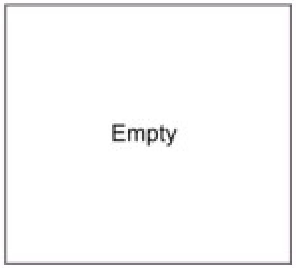

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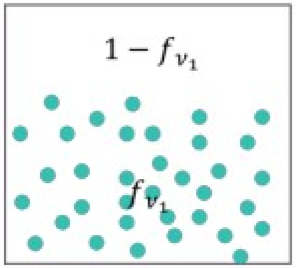

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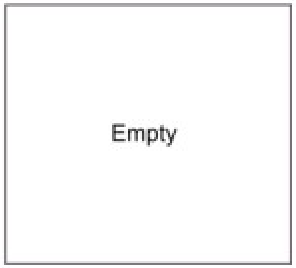

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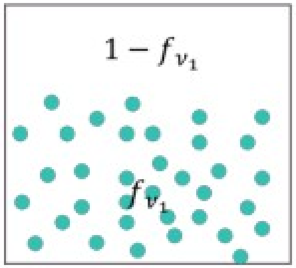

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$|\Omega\rangle$ $\quad f(\mathbf{x}, \mathbf{p})$

Description with 2nd Quantization

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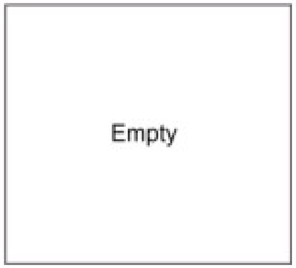

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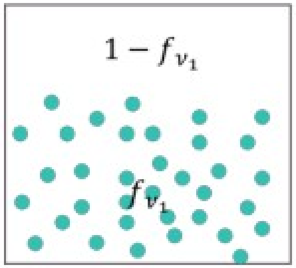

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$$N \equiv \int f(\mathbf{x},\mathbf{p}) d^3\mathbf{x} d^3\mathbf{p}$$

Description with 2nd Quantization

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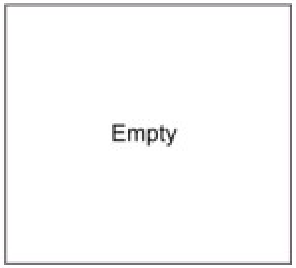

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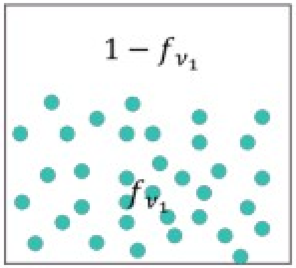

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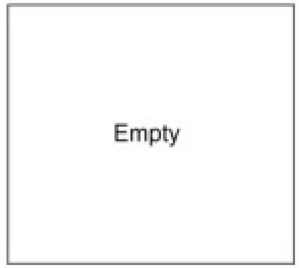

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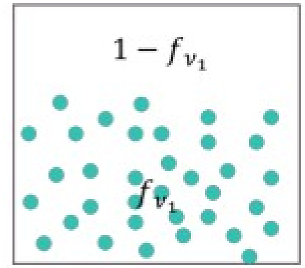

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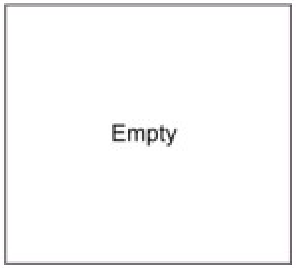

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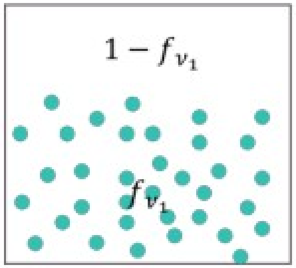

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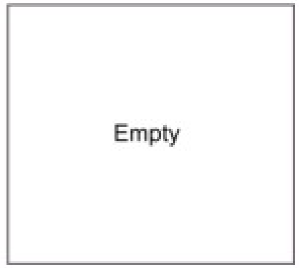

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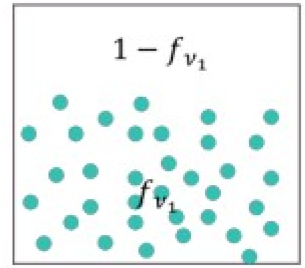

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Description with 2nd Quantization

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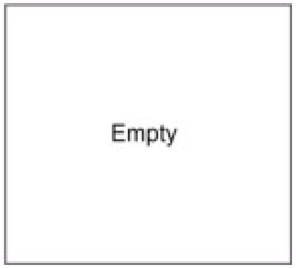

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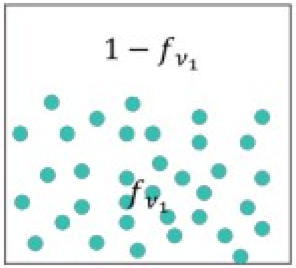

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$$a^\dagger_{\mathbf{p}} a_{\mathbf{p}}|\Omega\rangle = \int d^3\mathbf{x} f(\mathbf{x}, \mathbf{p})|\Omega\rangle$$

$$a_{\mathbf{p}} a^\dagger_{\mathbf{p}}|\Omega\rangle = \int d^3\mathbf{x}[1 \pm f(\mathbf{x}, \mathbf{p})]|\Omega\rangle$$

Degeneracy with External State

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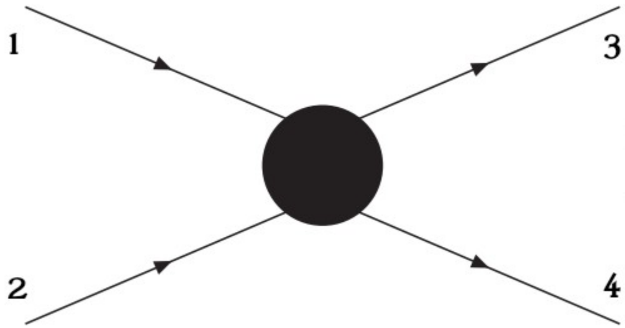

$$|\mathcal{M}|^2\{f_1 f_2[1 \pm f_3][1 \pm f_4] - f_3 f_4[1 \pm f_1][1 \pm f_2]\}$$

Degeneracy with External State

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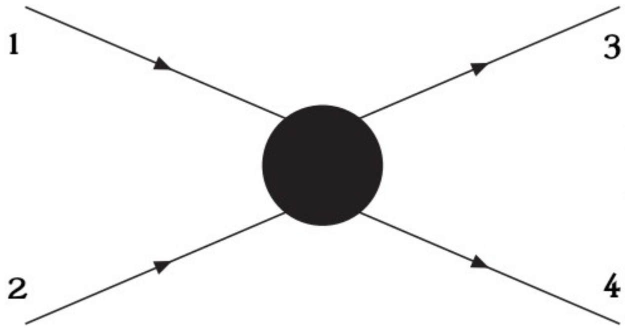

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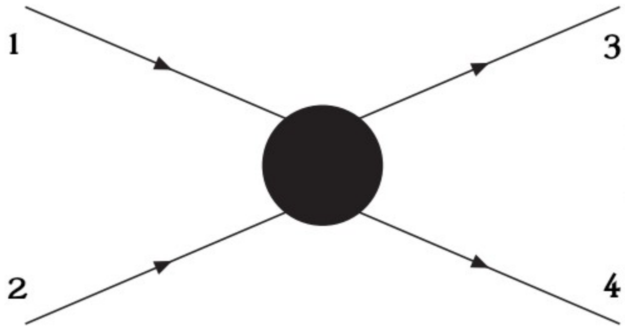
Initial State:

$$\mathcal{M} \sim \langle \Omega + f | \cdots a | i + \Omega \rangle$$

Degeneracy with External State



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$$|\mathcal{M}|^2 \sim \mathcal{M}^* \mathcal{M}$$

Degeneracy with External State

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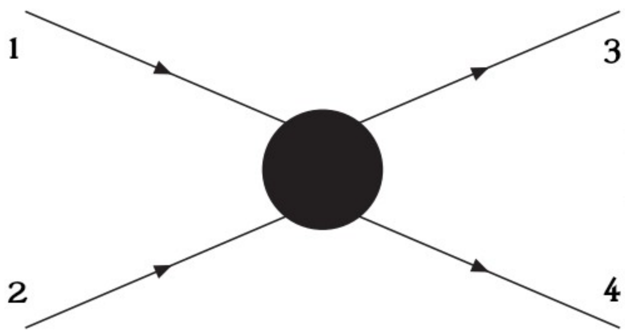

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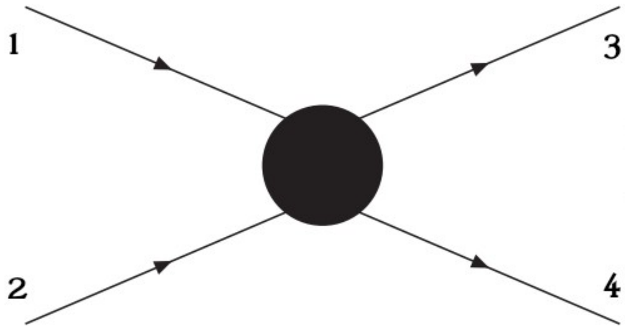
Degeneracy with External State



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$$\downarrow$$

$$f$$

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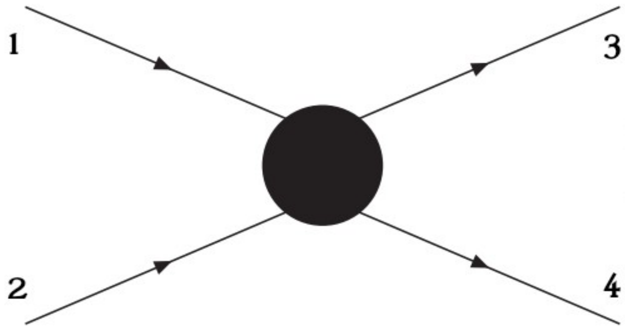

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$\downarrow$

$$f$$

Final State:

$$\mathcal{M} \sim \langle \Omega + f | a^\dagger \cdots | i + \Omega\rangle$$

Degeneracy with External State

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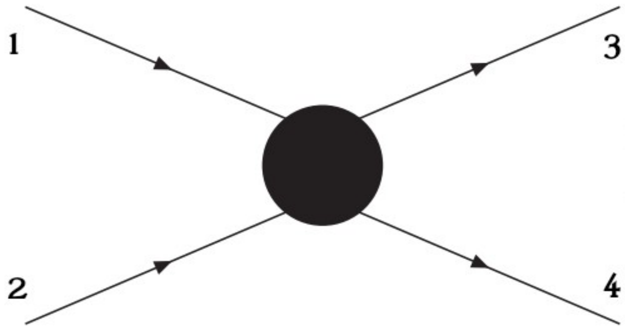

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↓

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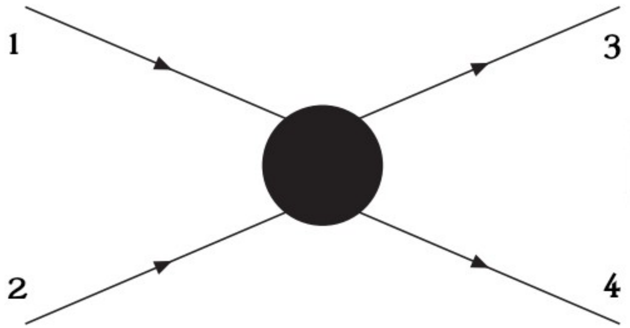
$$|\mathcal{M}|^2 \sim \mathcal{M}^* \mathcal{M}$$

Degeneracy with External State



$$|\mathcal{M}|^2\{f_1 f_2[1\pm f_3][1\pm f_4] - f_3 f_4[1\pm f_1][1\pm f_2]\}$$

Initial State:

$$\mathcal{M} \sim \langle \Omega + f| \cdots a | i + \Omega\rangle$$

$$\begin{aligned} |\mathcal{M}|^2 &\sim \mathcal{M}^*\mathcal{M} \\ &= \langle i + \Omega| \cdots a^\dagger a | i + \Omega\rangle \end{aligned}$$

$$\downarrow$$

$$f$$

Final State:

$$\mathcal{M} \sim \langle \Omega + f| a^\dagger \cdots | i + \Omega\rangle$$

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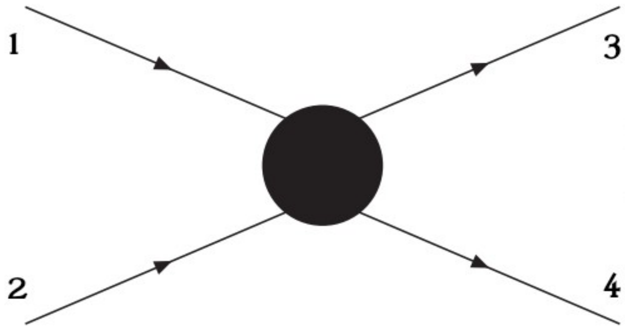

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$$= \langle i + \Omega | \cdots a^\dagger a | i + \Omega \rangle$$

$$\Downarrow$$

$$f$$

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$$\mathcal{M} \sim \langle \Omega + f | a^\dagger \cdots | i + \Omega \rangle$$

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$$1 \pm f$$

Degenerate Oscillation

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Degenerate Oscillation

Tsung-Dao Lee Institute

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SFG, Chui-Fan Kong, Pedro Pasquini [2310.04077]

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Fermion oscillation needs to involve 3 parts:

$$\mathcal{M}_{\beta\alpha} \equiv \mathcal{M}_d \left[\sum_i U_{\beta i} U^*_{\alpha i} e^{i p_i \cdot (x-y)} \langle \Omega | a_{\boldsymbol{p} i} a^\dagger_{\boldsymbol{p} i} | \Omega \rangle \right] \mathcal{M}_p$$

Spinors u & v combined into M_p & M_d

Degenerate Oscillation

Tsung-Dao Lee Institute

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$$\langle \Omega | a_{\boldsymbol{p}i} a^\dagger_{\boldsymbol{p}i} | \Omega \rangle \;\Downarrow\; 1 - f_i$$

Degenerate Oscillation

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Spinors u & v combined into M_p & M_d

$$1 - f_i$$

Pauli blocking factor already appears in amplitude!

Degenerate Oscillation in QFT

Tsung-Dao Lee Institute

$$\mathcal{M}_{\beta\alpha} = \mathcal{M}_d \left[\sum_i U_{\beta i} U^*_{\alpha i} e^{i p_i \cdot (x-y)} (1 - f_i) \right] \mathcal{M}_p$$

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Tsung-Dao Lee Institute

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$$N_\alpha(x = y) \propto \sum_\beta \left| \sum_i U_{\beta i} U^*_{\alpha i} (1 - f_i) \right|^2$$

Degenerate Oscillation in QFT

Tsung-Dao Lee Institute

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Degenerate Oscillation in QFT

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Fraction of events in β flavor

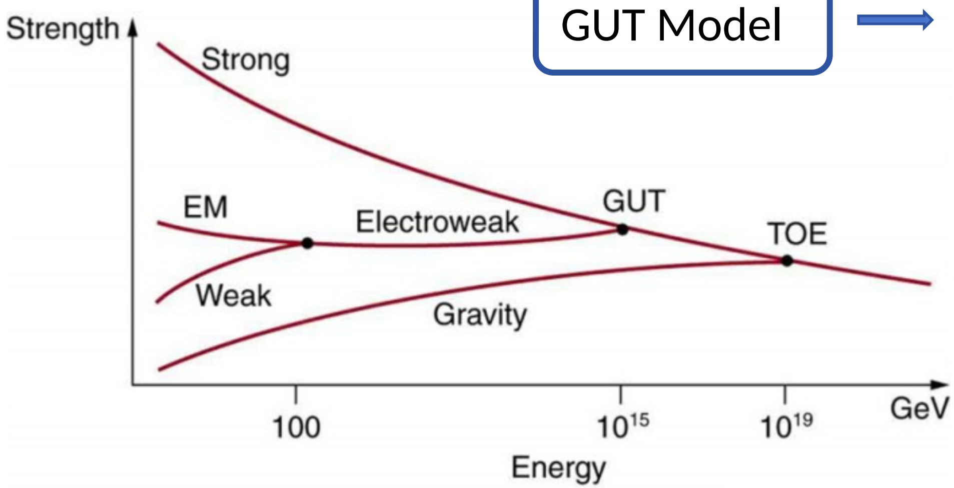
$$P_{\alpha\beta}(x - y) \equiv N_{\alpha \to \beta}(x - y) / N_\alpha(x = y)$$

Outline

李政道研究所
Tsung-Dao Lee Institute

- **Degenerate Oscillation**
- **Neutron-Antineutron Oscillation in NS**
- **Neutron Star Cooling & GUT**

GUT & Baryon Number Violation



GUT Model → Baryon Number Violation → { Proton Decay / Neutron-Antineutron Oscillation }

Table 1

GUT model	Is $N-\bar{N}$ observable?	Implications
(NON SUSY)		
$SU(5)$	No	$\Delta(B-L)=0$
$SU(2)_L \times SU(2)_R \times SU(4)_c$	Yes	$M_c \simeq 10^5$ GeV
Minimal SO(10)	No	
E_6	No	
(SUSY GUT)		
$[SU(3)]^3$	Yes	Induced breaking of R-parity
$SO(10)$	No	

Table Caption: This table summarizes the observability of neutron-anti-neutron oscillation in various GUT models.

Degenerate n-nbar Oscillation

Tsung-Dao Lee Institute

Being neutral, neutron can have Majorana mass term:

$$\mathrm{H} \approx \begin{pmatrix} H_{11} & \delta m \\ \delta m & H_{22} \end{pmatrix}$$

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$$\begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = \mathrm{U} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad \mathrm{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad \tan 2\theta = \frac{2\delta m}{H_{22} - H_{11}}$$

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Neutron-antineutron oscillation!

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$$P_{n\bar{n}} = \frac{c^2 s^2 (1 - f_1)^2 + c^2 s^2 (1 - f_2)^2}{c^2 (1 - f_1)^2 + s^2 (1 - f_2)^2}$$

$$- \frac{2(1 - f_1)(1 - f_2) c^2 s^2 \cos(\Delta E t)}{c^2 (1 - f_1)^2 + s^2 (1 - f_2)^2}$$

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李政道研究所 Tsung-Dao Lee Institute

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Tsung-Dao Lee Institute

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$s \ll 1 - f_1 \ll 1$ $\quad P_{n\bar{n}} \to \dfrac{s^2}{(1-f_1)^2} \ll 1$

Degenerate n-nbar Oscillation

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Zero Distance Limit

$$P_{n\bar{n}} \approx \frac{s^2}{(1-f_1)^2} \qquad P_{nn} \approx c^2$$

The degeneracy effect already appears at zero distance!

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Zero Distance Limit

Tsung-Dao Lee Institute

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Zero Distance Limit

Tsung-Dao Lee Institute

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$$f_1(\mathbf{p}) = \frac{1}{e^{\frac{\varepsilon_n(\mathbf{p})-\mu}{T}} + 1} \approx f_n$$

$$R(\mathbf{p}) \equiv \frac{f_{\bar{n}}}{f_n} = \frac{P_{n\bar{n}}}{P_{nn}} \approx \frac{\tan^2\theta}{[1-f_1(\mathbf{p})]^2}$$

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Note that only neutron is in thermal equilibrium!

Outline

李政道研究所 Tsung-Dao Lee Institute

- **Degenerate Oscillation**
- **Neutron-Antineutron Oscillation in NS**
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Neutron Degeneracy in NS

$$f_1(\mathbf{p}) = \frac{1}{e^{\frac{\varepsilon_n(\mathbf{p})-\mu}{T}} + 1} \qquad \varepsilon_n(\mathbf{p}) = \sqrt{\mathbf{p}^2 + m^2}$$

Fu, **SFG**, Guo & Wang [arXiv:2405.08591]

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Tsung-Dao Lee Institute

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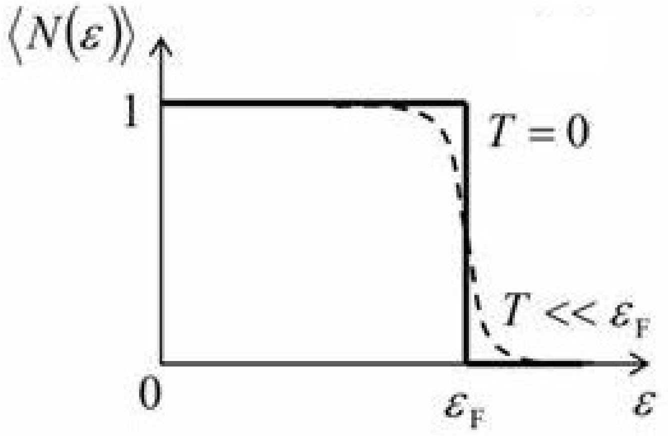
Degenerate fermi gas:

$$k_F = (3\pi^2 n_n)^{1/3}$$



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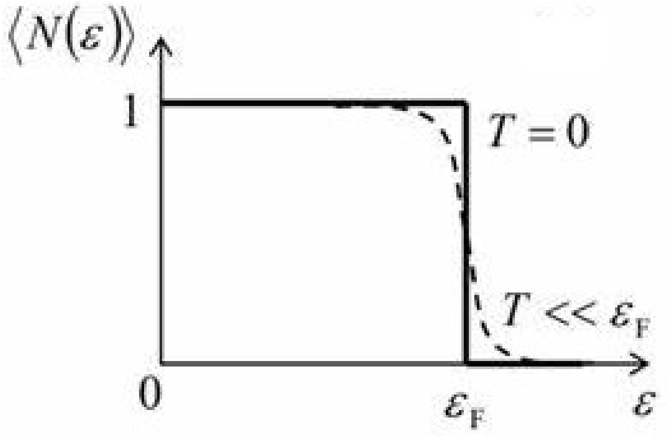

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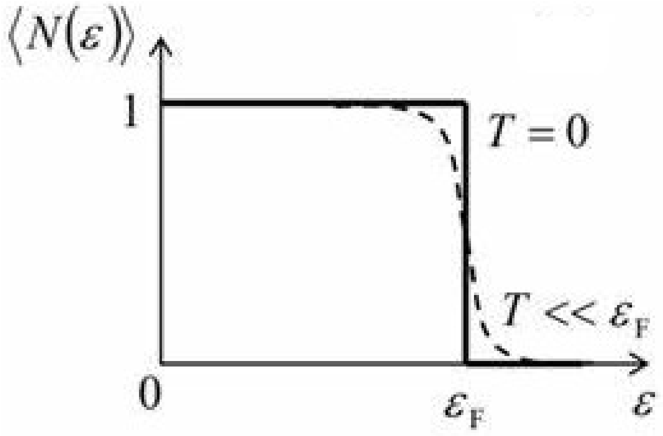

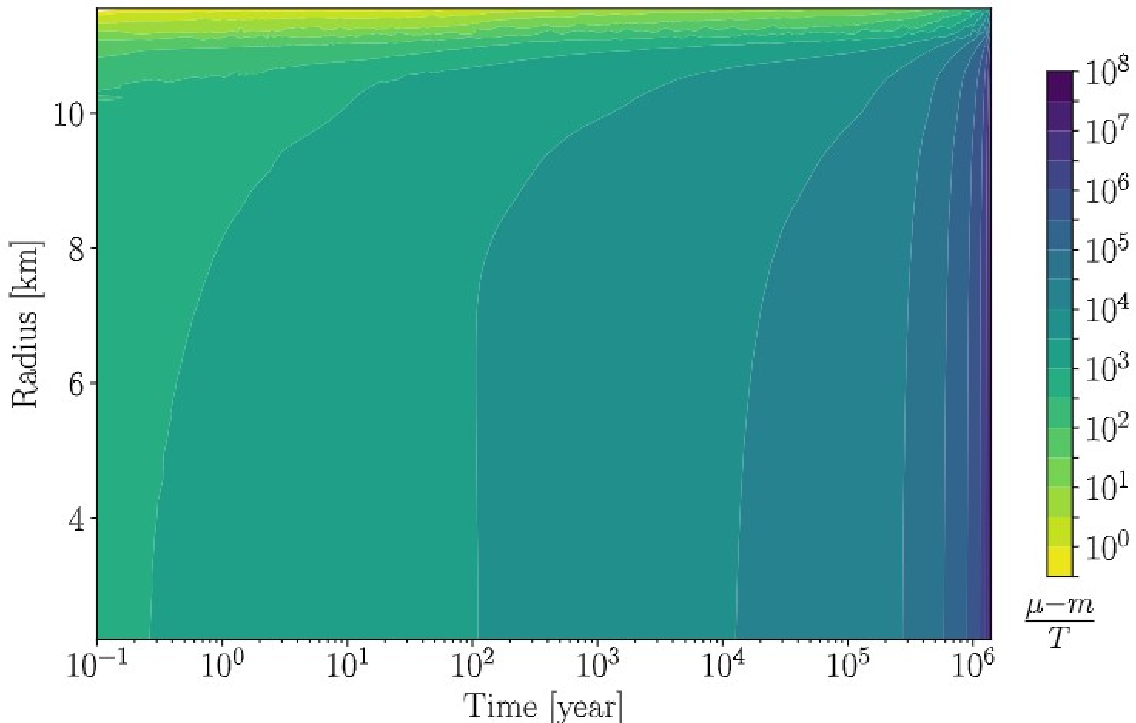

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Antineutron Distribution

$$f_{\bar{n}} \approx \frac{s^2}{[1 - f_1(p)]^2} f_1$$

$$n_{\bar{n}} = \frac{m^2 T}{2\pi^2} e^{\frac{\mu}{T}} \left[2K_2\left(\frac{m}{T}\right) + e^{\frac{\mu}{T}} K_2\left(\frac{2m}{T}\right) \right] s^2$$

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$$\frac{\mu - m}{T} \sim \mathcal{O}(10^4)$$

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Huge enhancement

$$\frac{\mu - m}{T} \sim \mathcal{O}(10^4) \quad \Rightarrow \quad e^{\frac{\mu - m}{T}} \sim 10^{\mathcal{O}(1000)}$$

Antineutron Annihilation

During a single annihilation, nucleon number reduces by 2

$$\mathrm{d}N = -2\langle\sigma v\rangle n_n n_{\bar{n}} \mathrm{d}t\mathrm{d}V$$

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Tsung-Dao Lee Institute

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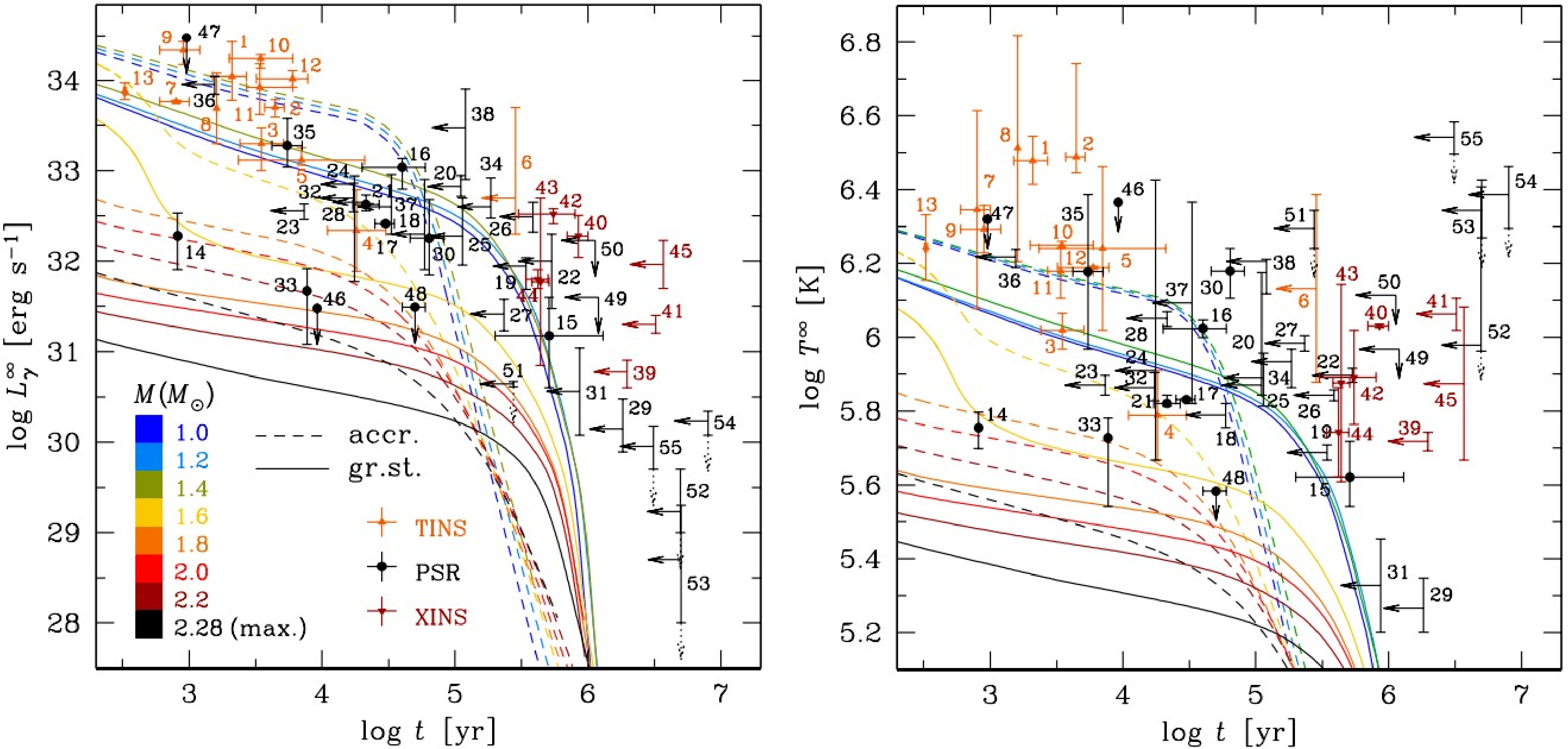
NS lifetime > 10^6 yrs ⇒ $$R \approx \frac{s^2}{[1 - f_1(\mathbf{p})]^2} \lesssim 10^{-37}$$

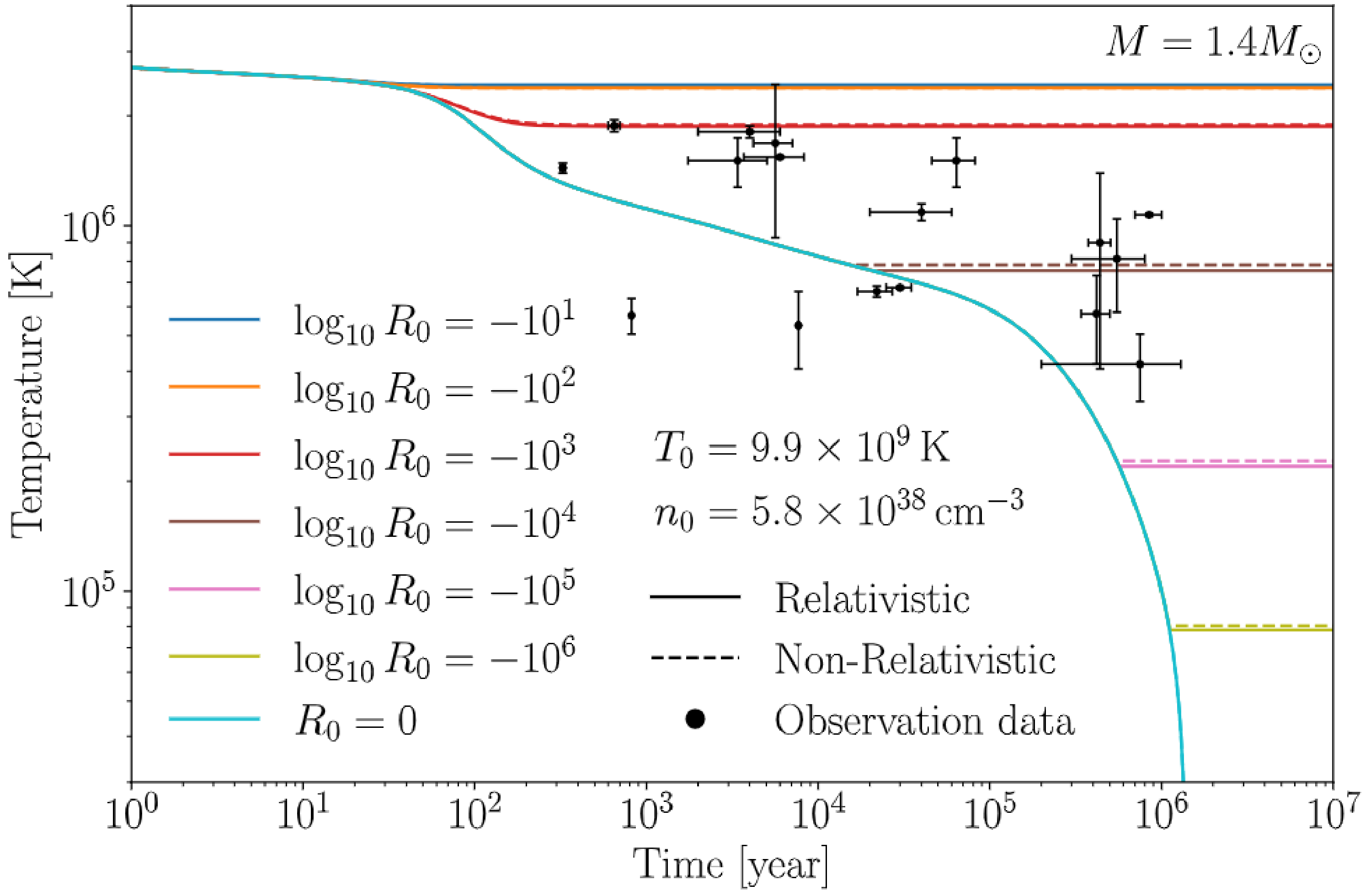
NS Cooling Data

Tsung-Dao Lee Institute

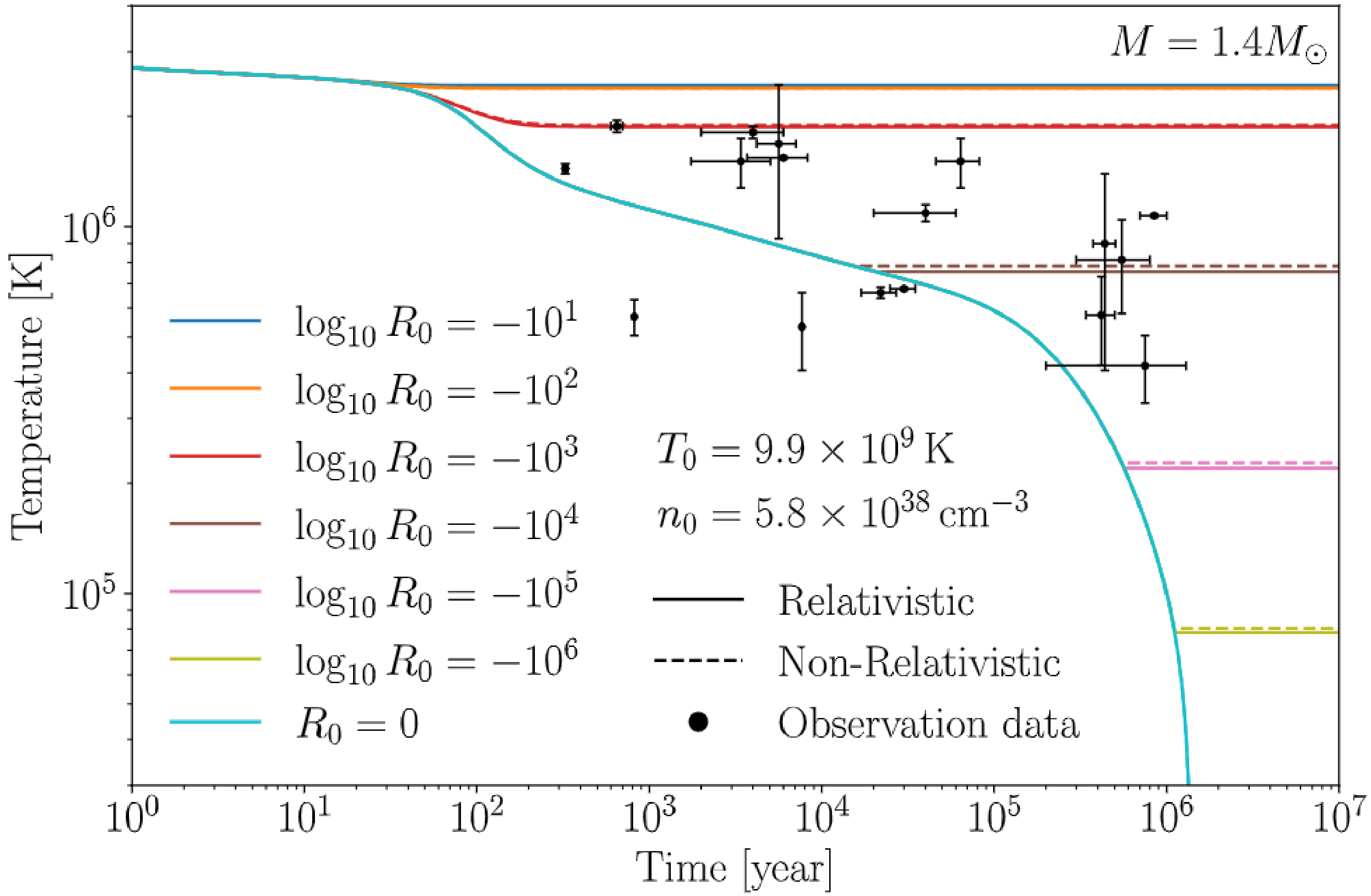


Potekhin, Zyuzin, Yakovlev, Beznogov & Shibanov
MNRAS 496, 5052-5071 (2020) [arXiv:2006.15004]

NS Cooling



$M = 1.4 M_\odot$
$\log_{10} R_0 = -10^1$
$\log_{10} R_0 = -10^2$
$\log_{10} R_0 = -10^3$
$\log_{10} R_0 = -10^4$
$\log_{10} R_0 = -10^5$
$\log_{10} R_0 = -10^6$
$R_0 = 0$
$T_0 = 9.9 \times 10^9$ K
$n_0 = 5.8 \times 10^{38}$ cm^{-3}
Relativistic
Non-Relativistic
Observation data
Temperature [K]
Time [year]
10^6
10^5
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7



$$R \approx \left(\frac{T}{T_0}\right)^{\frac{3}{2}} e^{\frac{2(\mu - m)}{T} - \frac{2(\mu_0 - m)}{T_0}} R_0$$

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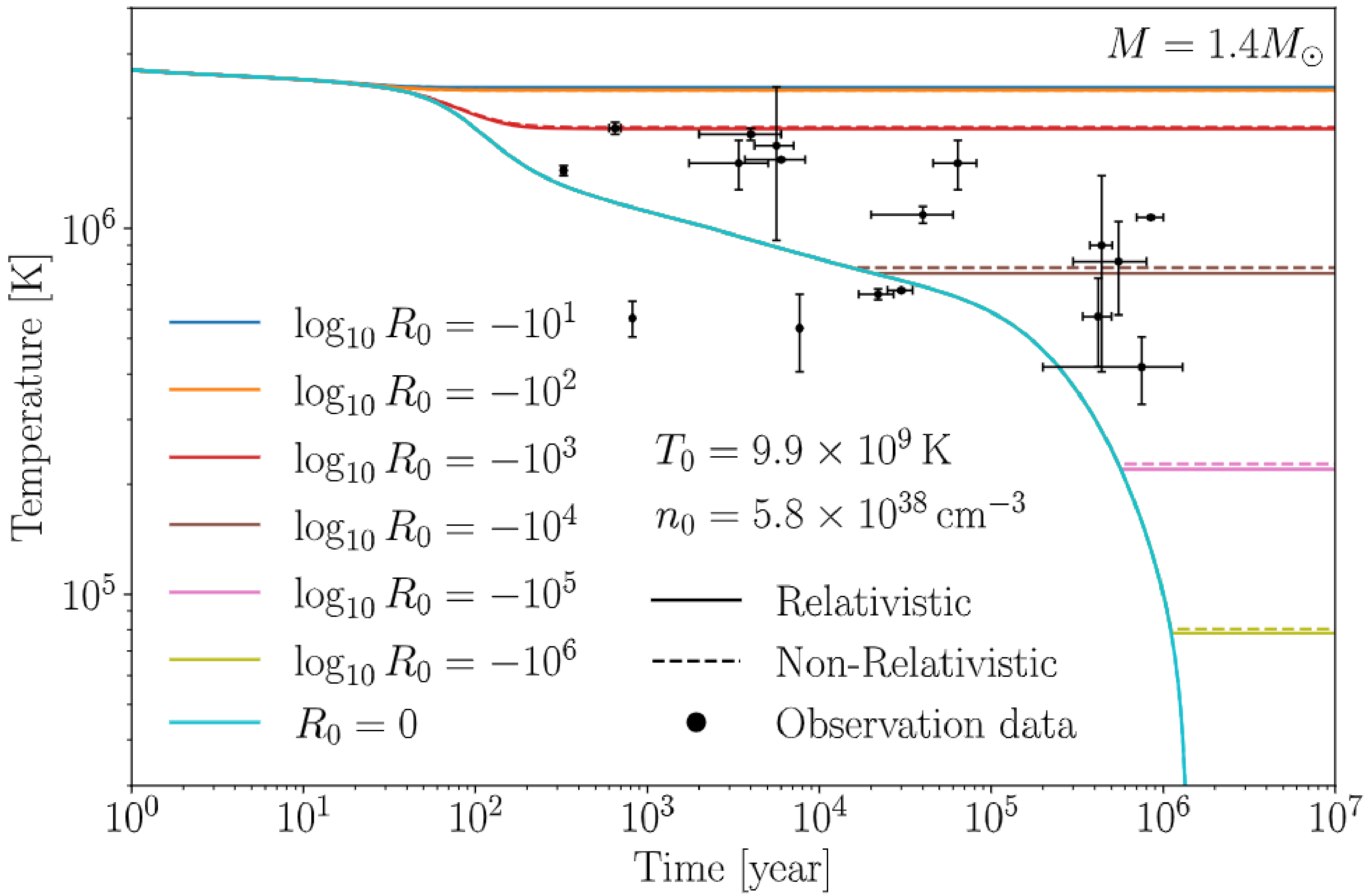

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Cooling power

$$4\pi R^2 \sigma T^4 \sim 10^{21} \, \mathrm{W}$$

Constraints on GUT

$$\text{H} \approx \begin{pmatrix} H_{11} & \delta m \\ \delta m & H_{22} \end{pmatrix} \qquad\qquad s \sim \frac{\delta m}{\Delta H}$$

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which is far beyond the Planck scale!

Summary

- **Degenerate Oscillation**

    1. Consistent picture of degeneracy in external & intermediate state

- **Neutron-Antineutron Oscillation in NS**

    1. Concrete realization with n-nbar oscillation
    2. Standing fraction of antineutron

- **Neutron Star Cooling & GUT**

    1. Degeneracy enhancement
    2. Very strong constraint

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Thank You

Superfluidity in NS