QUANTUM GRAVITY EFFECT ON NEUTRINO OSCILLATION

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INTRODUCTION

- Neutrinos are ideal probes of distant 'laboratories' as they interact only via the weak and gravitational forces.
- 3 of 4 forces can be described in QFT, 1 (Gravity) is missing (and exp. evidence):
  - quasi-classical theory is the best understood
  - graviton interactions suppressed by 10^{38} GeV^2
- Many sources of astrophysical neutrinos (SNe, GRB, ..)
- Neutrino states during propagation are different from neutrino states during (weak) interactions

CLASSICAL NEUTRINO

- Neutrino Oscillation observed due to Interaction (weak) - Propagation (Inertia) - Interaction (weak)
- Neutrinos propagates as superposition of mass states.

$$|\nu_f\,(t)>=\sum_a V_{fa}e^{-iE_at}|\nu_a>$$

$$P_{\nu_f\rightarrow\nu_{f'}}\,(E,L)=\sum_{j,k}V_{f'j}V_{f'k}e^{-i\frac{m_j^2}{2E_\nu}L}e^{i\frac{m_k^2}{2E_\nu}L}V^*_{fj}V^*_{fk}$$

MATTER EFFECT

- neutrinos interact due to flavor (via W/Z) with particles (leptons, quarks) as flavor eigenstates
- MSW effect: neutrinos passing through matter change oscillation characteristics due to change in electroweak potential
- effects electron neutrino component of mass states only, due to electrons in normal matter
- neutrino may be in mass eigenstate after MSW effect: resonance
- Expectation of asymmetry for earth MSW effect in Solar neutrinos is ~3%

GRAVITON INTERACTION

- Neutrinos interact due to mass (via gravitons) with particles (solar mass) as mass eigenstates.
- Propagating neutrino is 'observed' by graviton, has definitive mass, propagates in a mass eigenstate.
- Neutrino in definitive mass state due to Interaction (weak) - Propagation (inertia) - Graviton Interaction (gravitation) - Propagation (inertia) - Interaction (weak)
- Neutrino ceases to demonstrate oscillation phenomena or effects depending on being in a superposition of mass states.

$$\Psi_{\nu_f \to \nu_a} = e^{-i \frac{m_a^2}{2E_\nu} L} V_{af}$$

NEUTRINO DETECTION

- Probability for initial electron neutrino to be in mass eigenstate depends on PMNS matrix element.
  - independent of energy, distance travelled, phase.
- Flavor measurement depends on P_G, The probability for neutrino to have interacted with graviton

$$P_{e\to 1} = \cos^2\theta_{12}\cos^2\theta_{13}$$

$$P_{e\to 2} = \cos^2\theta_{13}\sin^2\theta_{12}$$

$$P_{e\to 3} = \sin^2\theta_{13}$$

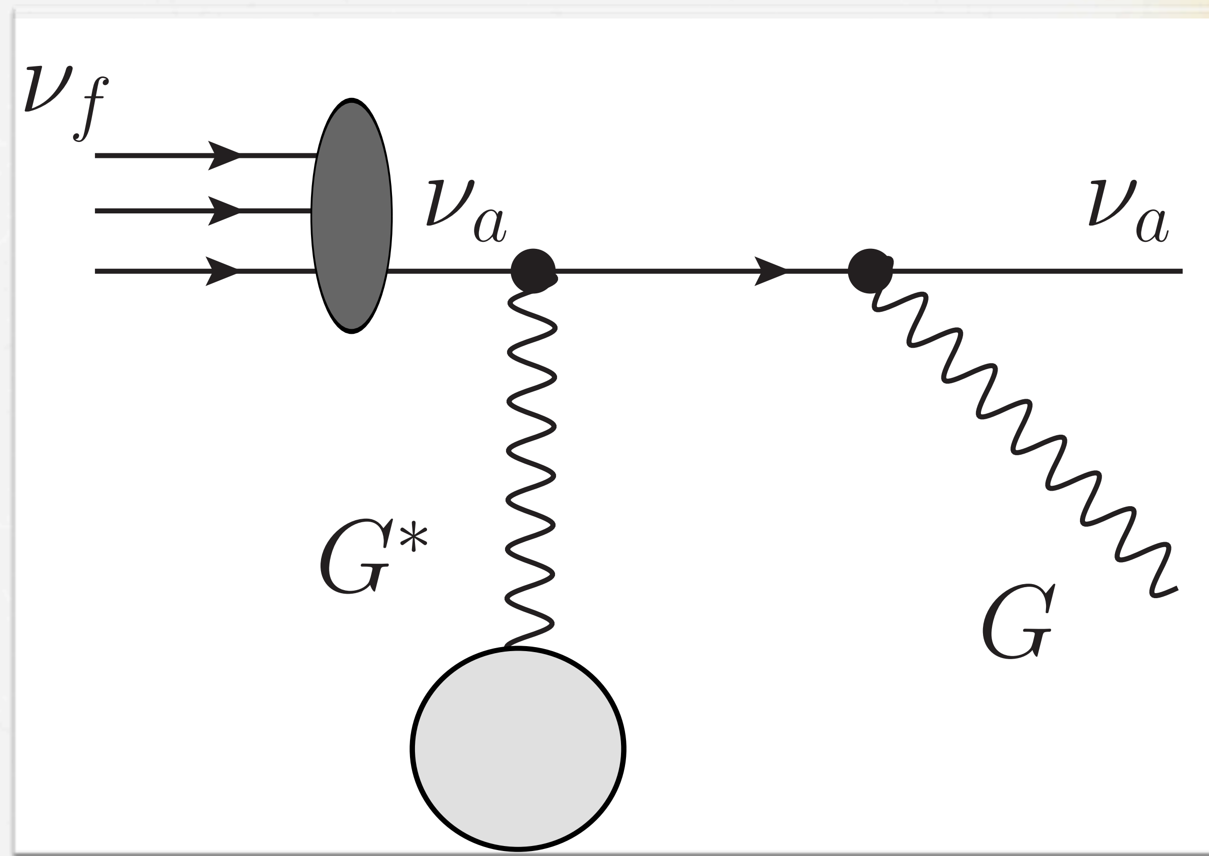
$$\frac{N_{\mathrm{e,det}}}{N_{\mathrm{e,init}}} = P_{\mathrm{ee}}^{\mathrm{vac}}(1 - P_G) +$$

$$P_G \sum_{i=1,2,3} V_{ei}V_{ie}^{*}V_{ei}V_{ie}^{*}$$

GRAVITON BREMSSTRAHLUNG

NEUTRINO-MASSIVE SOURCE SCATTERING

Analogical to Photon Bremsstrahlung on Nucleus



B. M. Barker, S. N. Gupta, J. Kaskas, Phys. Rev. 182 (1969) 1391-1396.

GRAVITON BREMSSTRAHLUNG

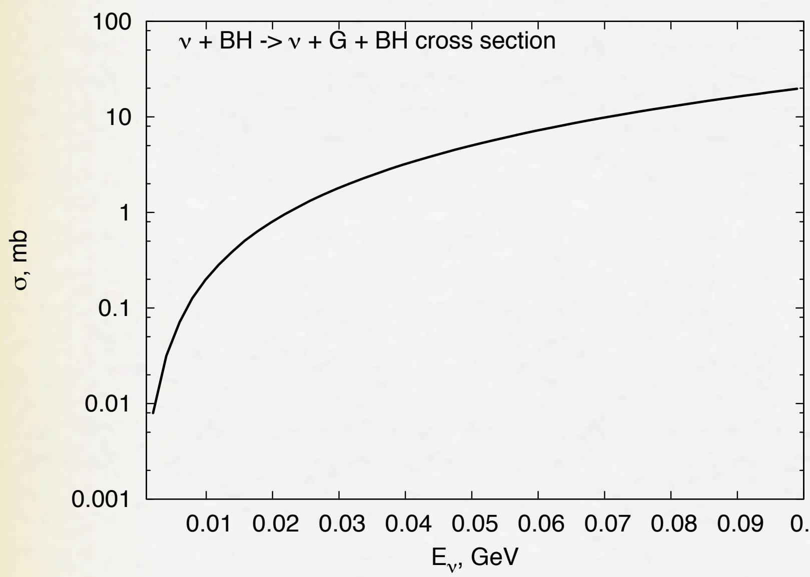
$$\frac{d\sigma}{dk_0 d\Omega_k d\Omega_{p'}} = \frac{\kappa^6 M^2}{(4\pi)^5} \frac{|\mathbf{p}'|}{|\mathbf{p}|} \frac{k_0 \left(I\left(\mathbf{p}, \mathbf{k}, \mathbf{p}'\right)\right)^2}{\left(\mathbf{k} + \mathbf{p}' - \mathbf{p}\right)^4}$$

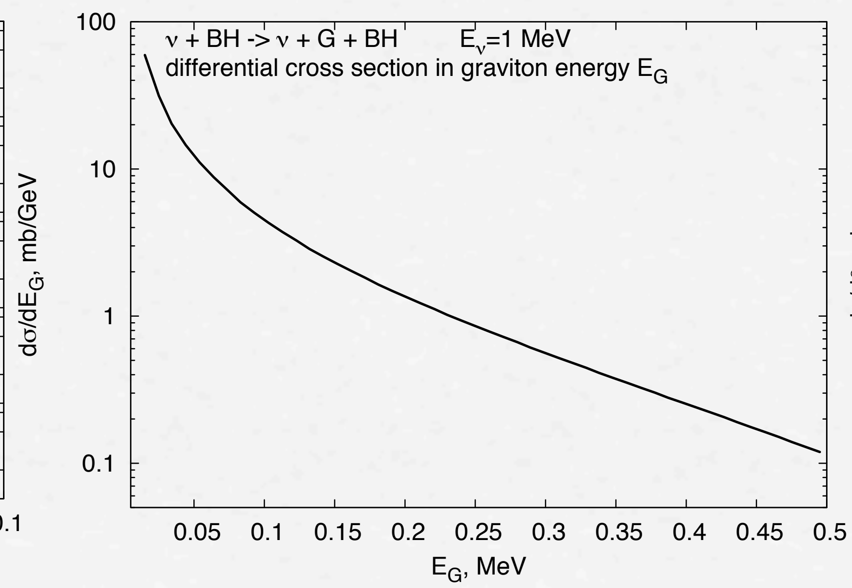
- scattering of small mass (m) off large mass (M)
- more correct then considering external field
- spinless approximation, result after summation over polarization

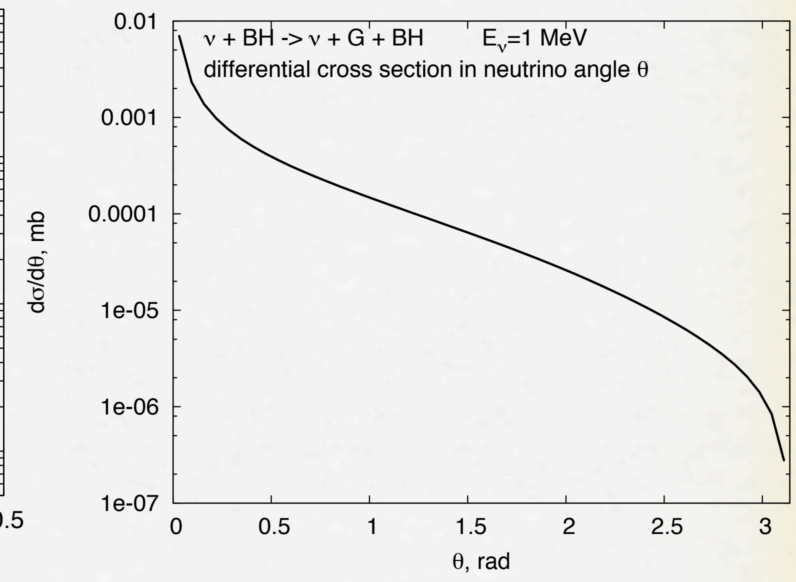
$$\sigma_{\mathrm{GBH}} \sim \frac{M^2 E_\nu^2}{M_{Pl}^6}, \quad M \gg E_\nu \gg m_\nu$$

$$M \sim 10^{57}\ \mathrm{GeV}\ \text{gives}\ M^2/M_{Pl}^6 \sim 1\ \mathrm{GeV}^{-4}$$

GRAVITON BREMSSTRAHLUNG





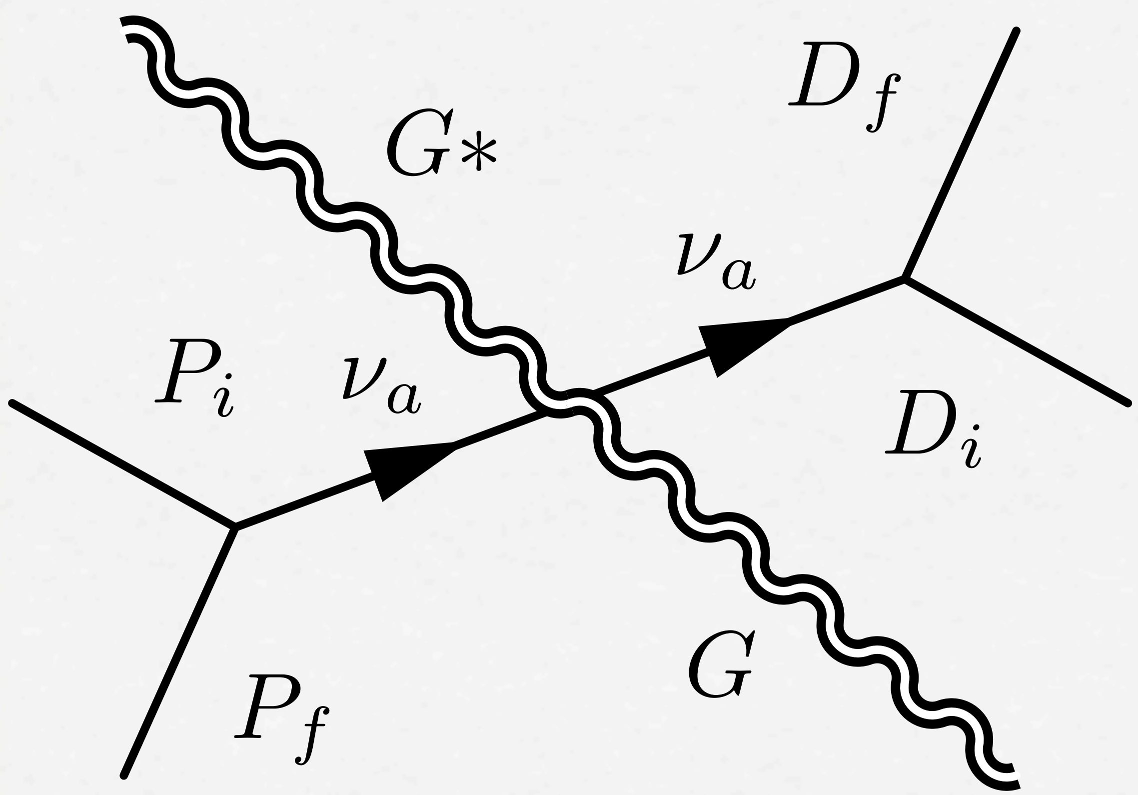


The bulk of the cross section comes form soft graviton emission in forward limit.

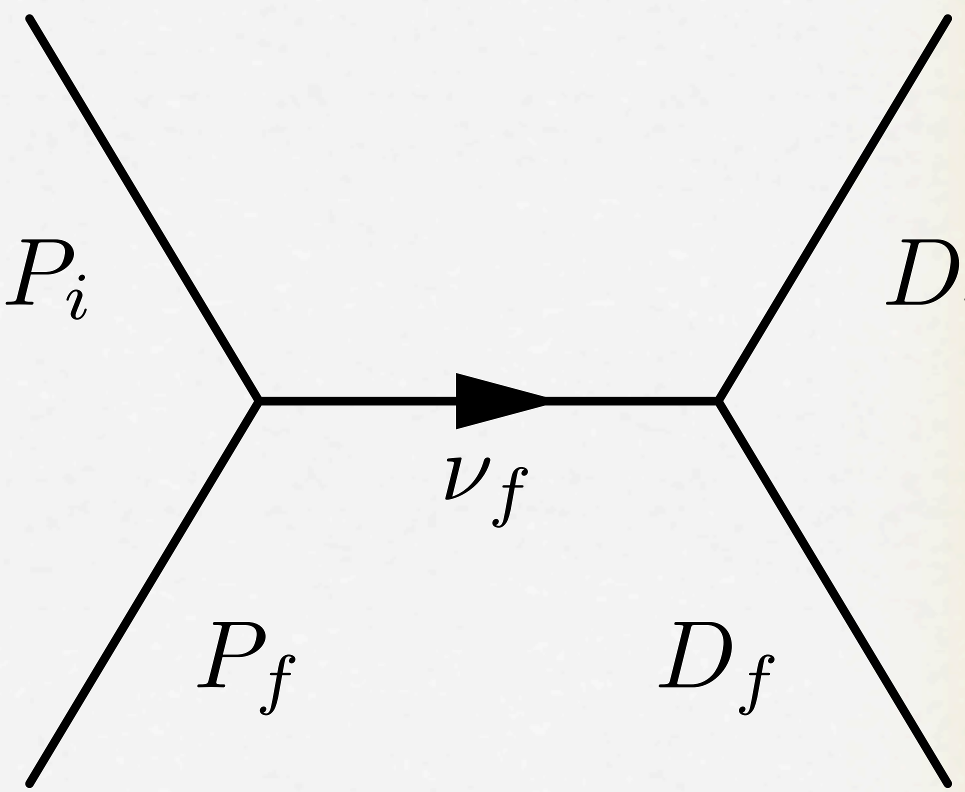
The cross section is larger than electron-neutrino cross section by 16-18 order of magnitudes.

Real, hard gravitons may be produced, Quantum Gravity!

NEUTRINO PROPAGATION



Neutrino produced and detected in detector in flavor state, exists as a definite mass state (due to graviton 'observation'), decoherence due to only single neutrino state propagating.

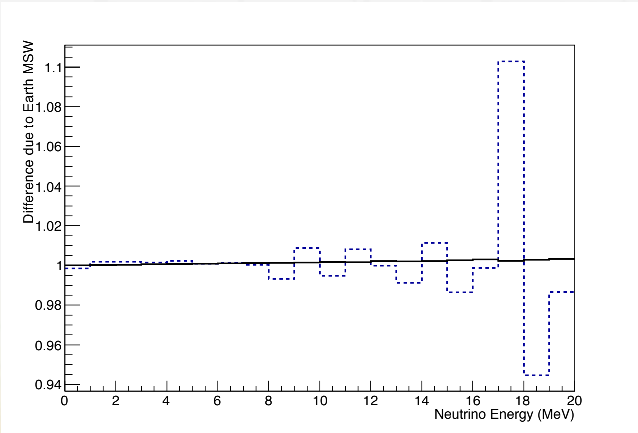


Neutrino produced and detected in flavor state, exists in superposition of mass states, decoherence caused by separation of mass states.

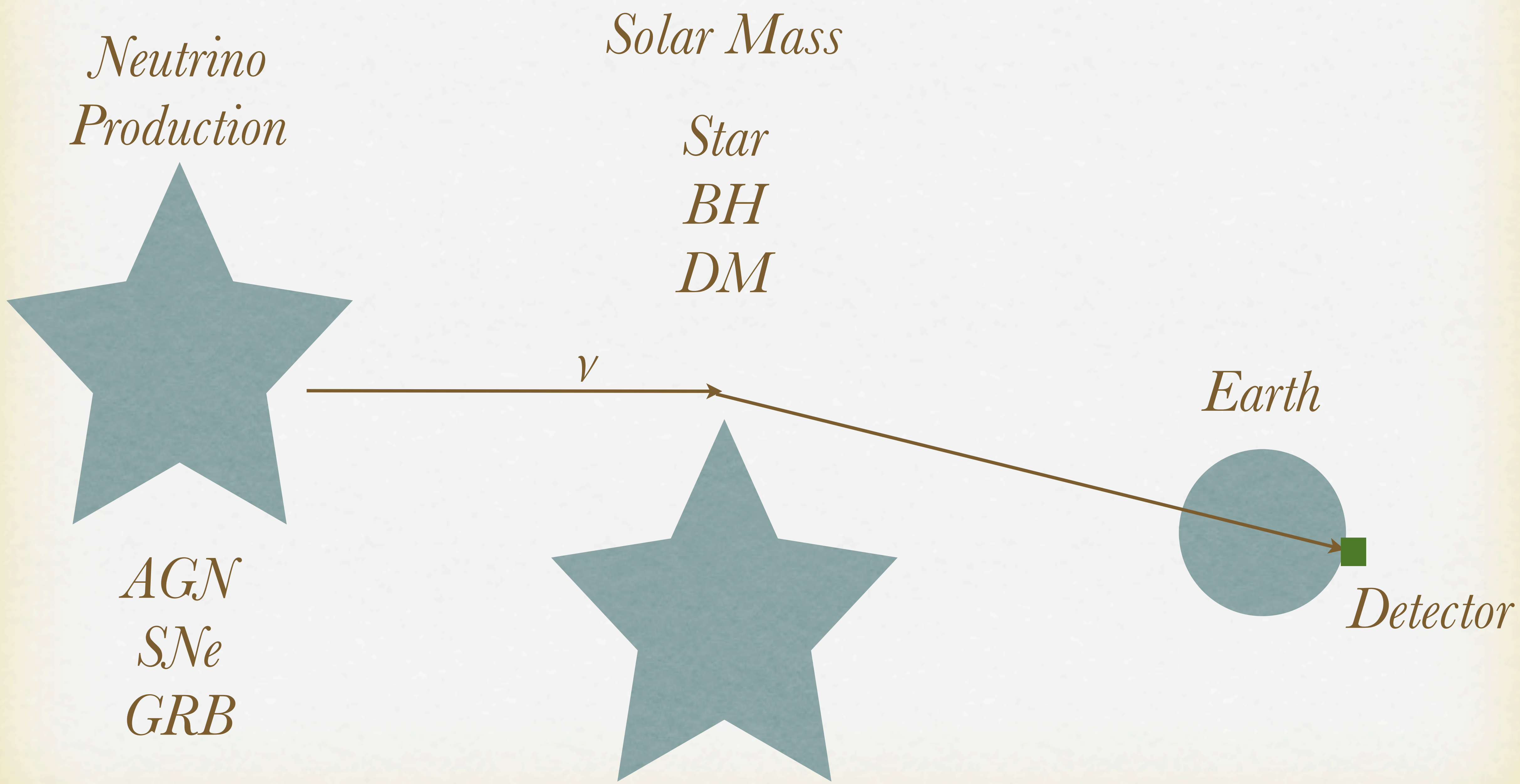
DETECTION: EARTH MSW

- Neutrinos which are decoherent due to propagation exist as a decoherent superposition of mass eigenstates.
- Neutrinos which are decoherent due to quantum gravity exist as a single mass eigenstate.
- For low energies, the single mass eigenstates do not demonstrate regeneration while superpositions do.
- Expect an (energy and location dependent) ~10% effect for neutrinos which have not had an interaction with a graviton, ~0% for neutrinos which have.

Simulation based on s-matrix formulation and initial uniform flux of e-type neutrinos. (flux independent)



CARTOON


Neutrino
Production
Solar Mass
Star
BH
DM
ν
Earth
AGN
SNe
GRB
Detector

CONCLUSIONS

- Quantum gravity interactions, due to hard graviton emission, have reasonably high cross-section.
- Neutrino oscillation behavior can be used as an observable to measure this cross-section.
- Due to the difference between quantum gravity induced decoherence and decoherence due to propagation, existing in a single mass eigenstate versus a decoherent superposition of mass eigenstates, measuring the Earth MSW effect can provide an energy dependent 10% difference in expectations.
- **Quantum Gravity can be measured!** For astrophysical neutrinos a point source is required (SNe/GRB/AGN) and large, low energy (?) neutrino detectors at multiple points around the world (Chile, Japan, North America, Europe, Antarctica) to differentiate the quantum gravity induced decoherence from other sources of decoherence.

NEUTRINO OBSERVATORIES

NEUTRINO OBSERVATORIES

Observatory	Size + Type	Location	near SNe #
Super-K	32 kT (Water)	Japan - Now	7000
Borexino	0.3 kT (Scint)	Italy - Now	100
SNO+	0.8 kT (Scint)	Canada-Now*	300
LBNE(1)	10 kT (Argon)	USA-201X	1000
LBNE(2)	Mixed	USA-202X?	40000+
LENA**	50 kT (Scint)	Europe - 202X	15000
ANDES	3 kT (Scint)	Chile - 202X	1000
Hyper-K	530 kT (Water)	Japan -202X?	110000
Beyond DC	1 MT (Ice)	Antarctica-203X?	??

CONCLUSIONS 2

- A neutrino observatory at the ANDES laboratory increases the possibility of measuring the Earth MSW effect for astrophysical neutrino point sources.
- Other observatories which come online in 202X/203X are intended to be relevant for ~50 years and see 10k+ astrophysical neutrinos from a nearby point source (10 kpc SNe).
  - Neutrino observatory in ANDES should be leveraged to do most interesting physics (Scintillator).
  - Laboratory should be relevant on ~50 year timetable.
  - Final neutrino observatory should see ~10k astrophysical neutrinos from nearby point source (modular design?).