Particle Physics with a Space Neutrino Detector

Beach Conference 6-11 June 2022, Krakow Poland

Dr. Nickolas Solomey (PI), Prof. of Physics at Wichita State Univ. and NASA Fellow

In cooperation with colleagues from:

M. Christl, NASA MSFC; R. McTaggart, South Dakota State Univ.;

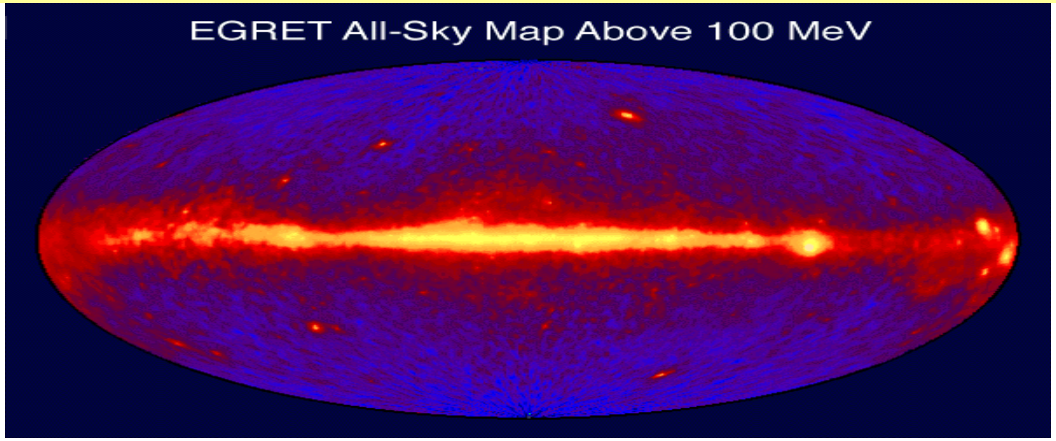
G. Pawloski, Univ. of Minnesota; B. Sutin NASA's JPL/Caltech; and

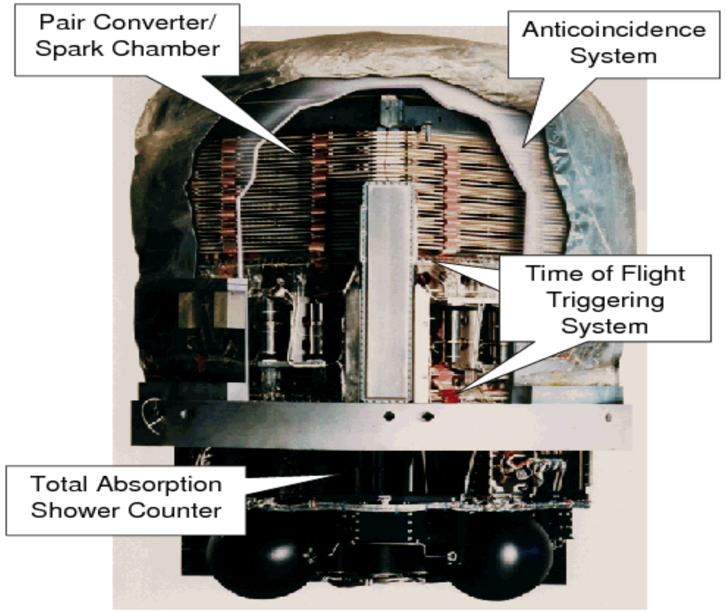
H. Meyer, A. Dutta, J. Folkerts, B. Doty, K. Messick, S. Tripathi, T. English, H. Kwon, J. Novak and M.L. Buchele; Wichita State Univ.

Background:

- Experimental Particle Physicists are starting since 1990s to get involved with NASA Astrophysics experiment developments.
- Take something simple, put it into someplace where NASA or ESA can bring it to do new unique science that cannot be done on Earth.
- However, there are possibilities for unique Particle Physics studies!
- Past Example: High Energy Gamma Rays

Using a small spark-chamber particle detector in 1992 NASA launched the EGRET spacecraft, which opened our eyes to high-energy Gamma-ray Astronomy. Now a large amount of gamma ray astronomy like this is done with the Fermi Satellite.





Question:

- If we can operate a neutrino detector in Space What new Science can be done?
  - On Earth a few hundred solar neutrinos have been detector from the Sun's core. By going closer to the Sun the $1/r^2$ dependence would let us get a solar neutrino flux up to 45,000x.
  - A detector with 25 kg active target is equal to 25 T on Earth at 7 Solar Radii.
  - A detector with 25 kg active target is equal to 1/4 kT on Earth at 3 Solar Radii.
  - Close to the Sun a collection of neutrino events would permit the internal radius structure of neutrino emitting core to be studied 900x better, so each event is equal to 900 events on earth, for internal structure.

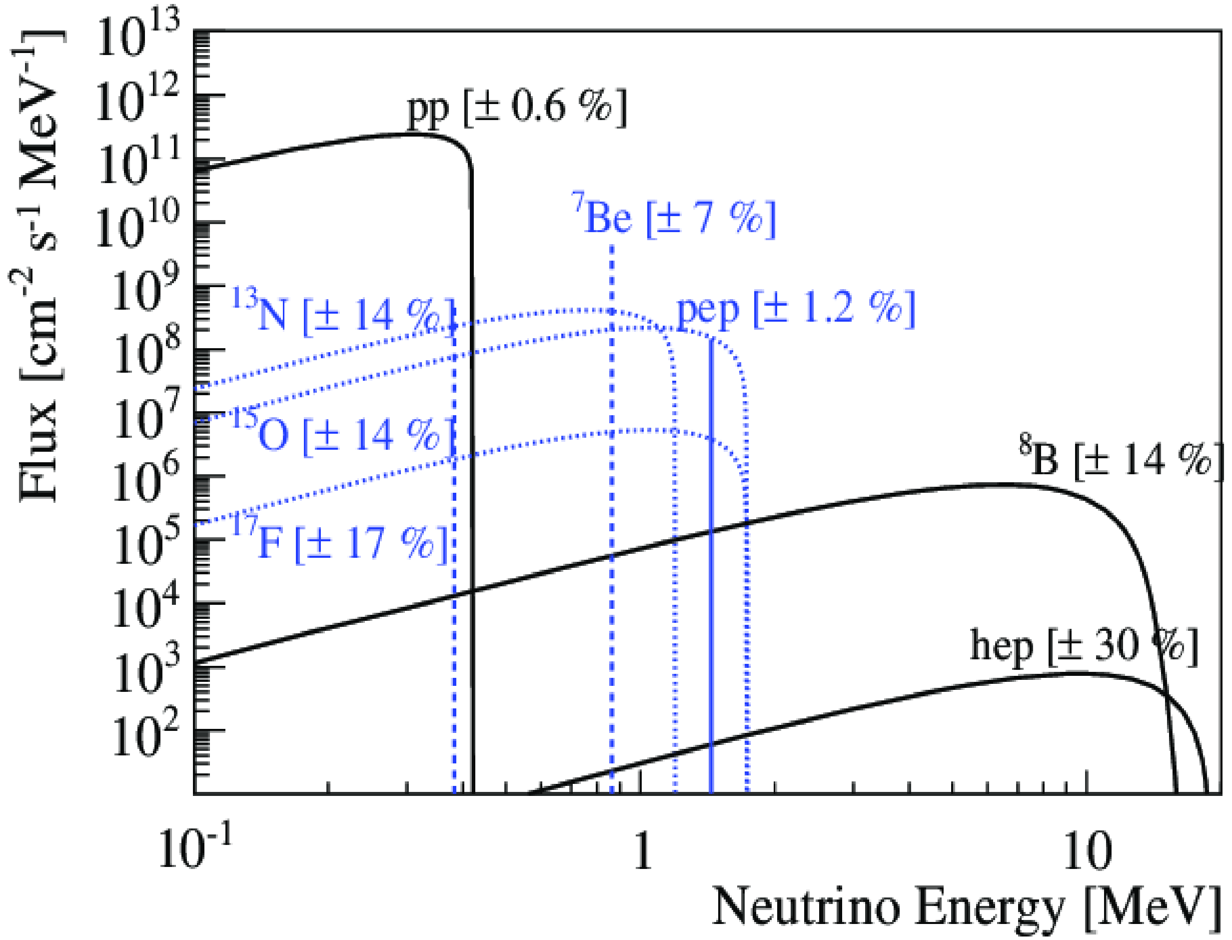
Table 1: Intensity of solar neutrinos at various distances from the Sun.

Distance from Sun	Solar Neutrino intensity relative to Earth
696342 km	46400
1500000 km (~3 Sun R)	10000
4700000 km (~7 Sun R)	1000
15000000 km	100
47434000 km	10
Mercury	6.7
Venus	1.9
Earth	1
Mars	0.4
Astroid belt	0.1
Jupiter	0.037
Saturn	0.011
Uranus	0.0027
Neptune	0.00111
Pluto	0.00064
KBP	0.0002
Voyager 1 probe 2015	0.00006

- Dark Matter searches would be 10x less solar neutrino backgrounds in an asteroid, 100x less at Saturn and 1000x less at Neptune.

Study Solar Nuclear Core:

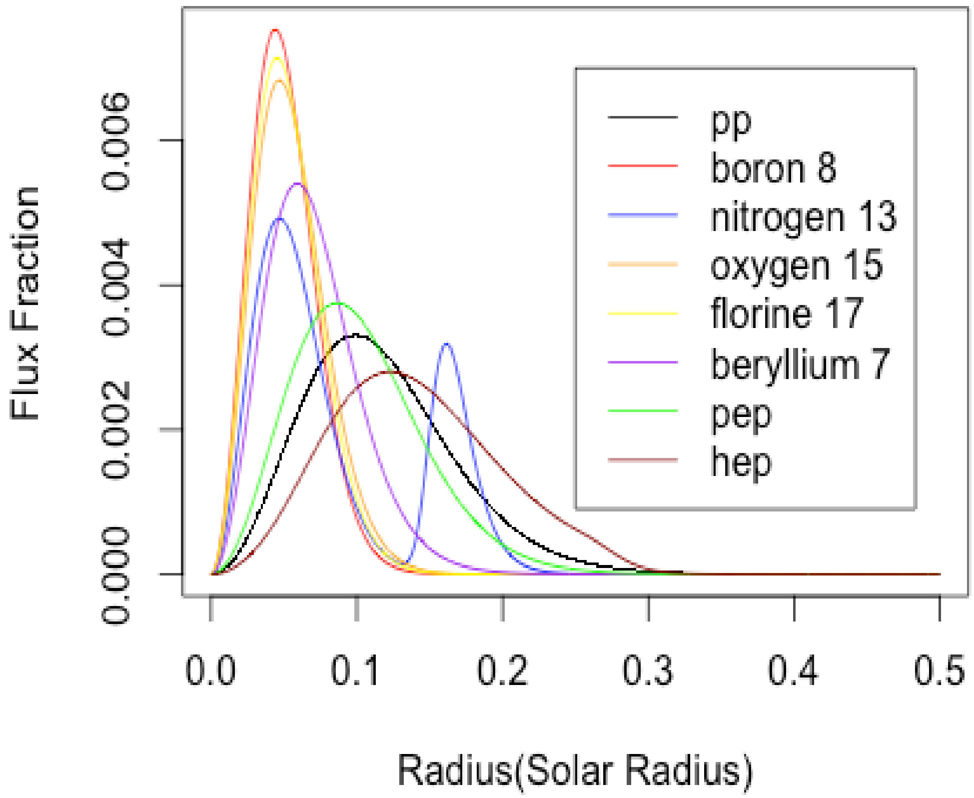
- By going close to the Sun it not only increases the neutrino flux and improves the signal to noise ratio, but allows a platform for new Science:
  - A spacecraft in orbit could change distance and go off the axis of the ecliptic.
  - At Earth, the neutrino oscillations are coherent, but closer than 35 solar radii solar neutrino flavors are incoherent, changing their ratio to each other with distance from the sources
- Rare neutrino fusion and better understanding of currently observed fusion neutrino processes.



Study Solar Nuclear Core:

- By going close to the Sun it not only increases the neutrino flux and improves the signal to noise ratio, but allows a platform for new Science:
  - A spacecraft in Solar orbit could change distance and go off the axis of the ecliptic.
  - At Earth the neutrino oscillations are coherent, but closer than 35 solar radii solar neutrino flavors are incoherent, changing their ratio to each other with distance from the sources

- Science:
  - Image the fusion reactor core of the Sun.

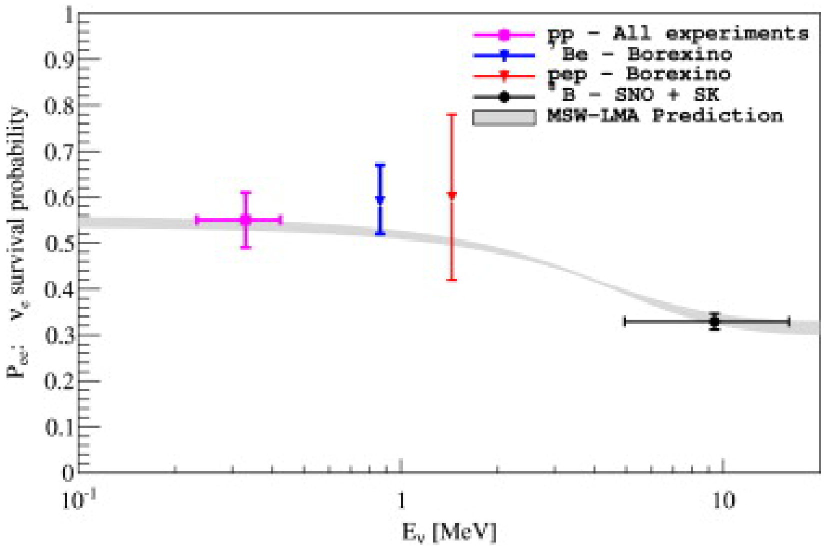


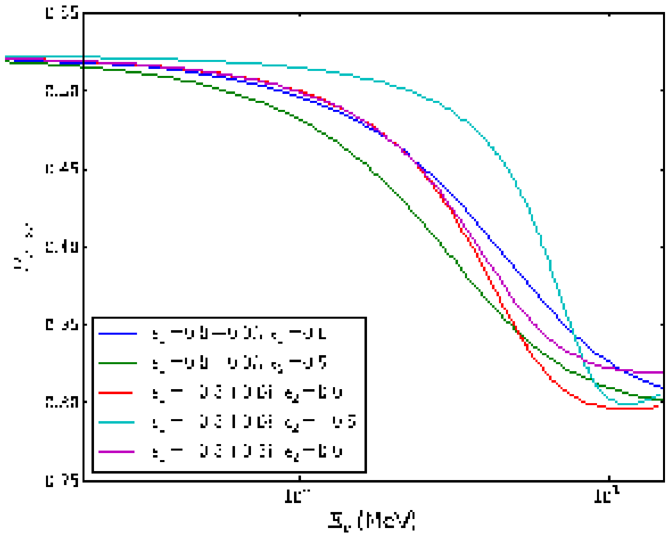
Study Solar Nuclear Core:

- By going close to the Sun it not only increases the neutrino flux and improves the signal to noise ratio, but allows a platform for new Science.

- Science:
  - Rare neutrino fusion and better understand of current fusion neutrino processes.
  - At Earth the neutrino oscillations are coherent, but closer than 35 solar radii solar neutrino flavors are incoherent, changing their ratio to each other with distance from the sources

Neutrino Energy (MeV)	Oscillation length (km)	Coherence Length (km)	?$_x$ (cm)
1	34	$2.44x10^5$	$3.15x10^{-9}$
5	170	$6.10x10^6$	$3.15x10^{-9}$
10	340	$2.44x10^7$	$3.15x10^{-9}$





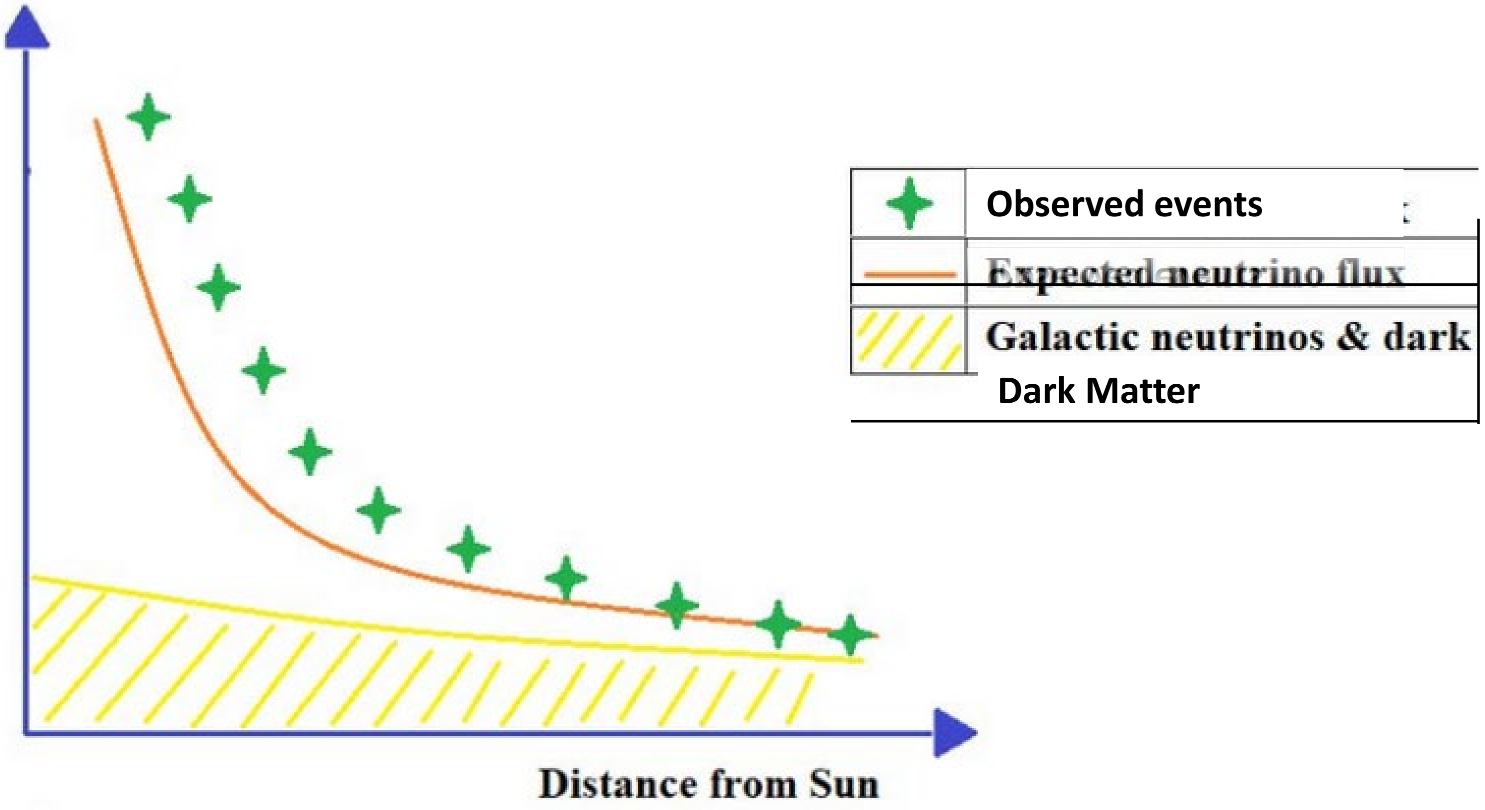
Dark Matter Search in Space, proposing a joint Wichita State & JPL

Wichita State in cooperation with JPL is developing a Dark Matter Search Mission to be deployed on an asteroid that changes distance from Sun.

We started at WSU a Physics simulation study of neutrino emissions from a spherical shell source like the Sun and a Dark Matter distributions trapped around the Sun due to gravity.

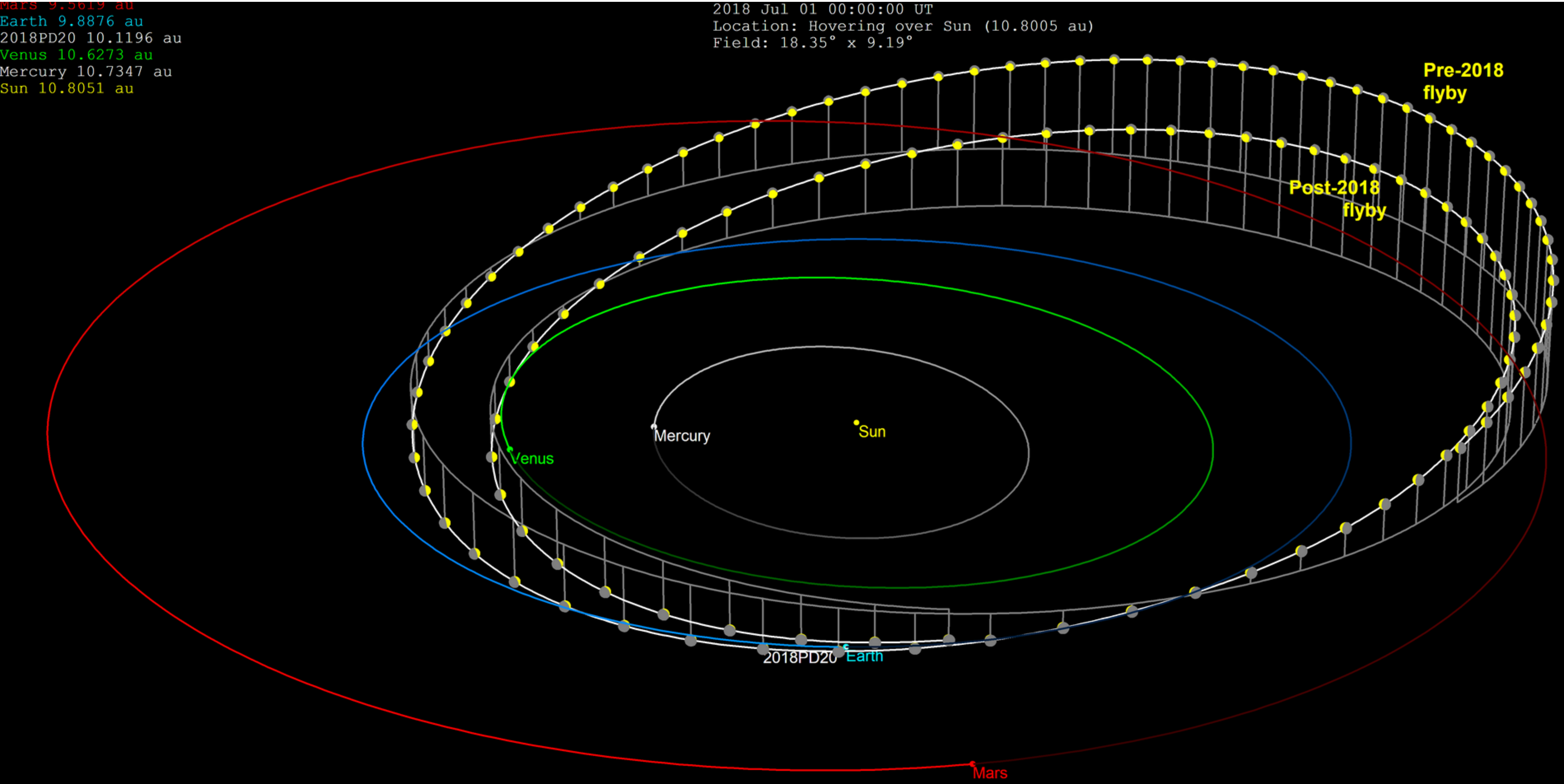
JPL would design the mission concepts, engineering and system ideas to get inside the asteroid.

Shrey Tripathi, Monti Carlo Study of a Space-Based Dark Matter Detector, Physics Master's Thesis, April 2021, Wichita State University



Idea is that if solar neutrinos and dark matter cannot be distinguished in a detector, but the solar neutrino emission fall off from its source is well predictable and if the dark matter trapped around the Sun distorts this then by having a detector that changes distance from Sun the Sun's contributions can be removed leaving the dark matter candidates and its flux distribution measured.

Dark Matter Detector inside an Asteroid that changes distance from Sun



Why this Dark Matter Search project and Why now.

Science

Dark Matter in the Universe is one of the most important questions in the NASA Astrophysics division. Ways to search for it on Earth based experiments are becoming limited due to solar neutrino background. Finding new ways to search and study it are important and this project would do a new exciting way to explore Dark Matter in our local space.

Other Impacts to aid NASA programs

Near Earth asteroids are a danger to Life on Earth. The NASA planetary defense program could gain a lot of information about ways to breakup or move an asteroid by knowing more about their interior. This project would be a first to provide such information

A New Neutrino Detection Technique for Space

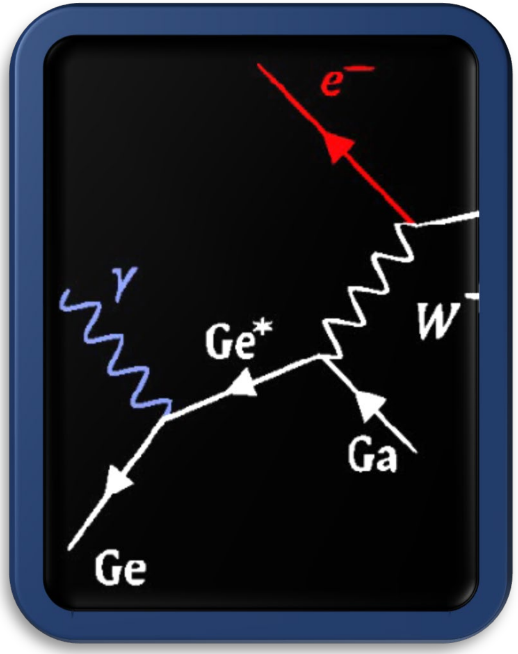
Ray Davis Homestakes Solar neutrino observatory technique

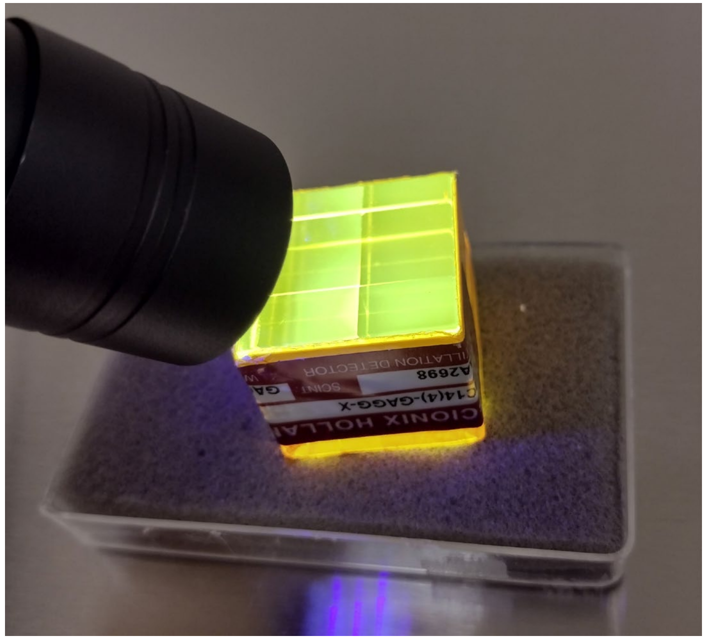
$$\nu_e + {}^{37}Cl \mapsto {}^{37}Ar + e^-$$

Double timing pulse

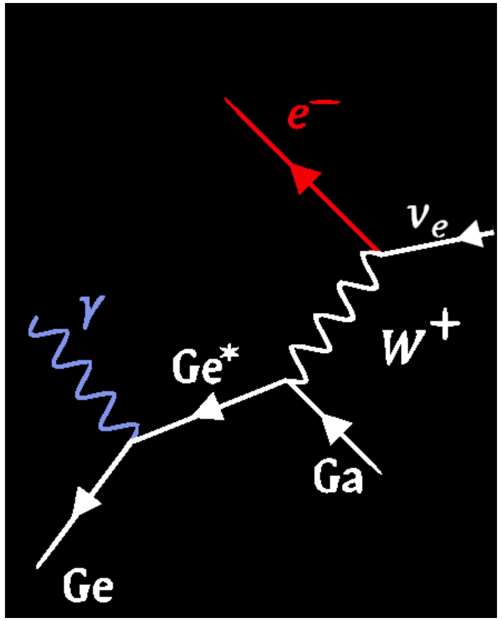
$^{69}Ga + \nu$ into e- ^{69}Ge m1 or m2	^{69}Ge m1 decays X-ray	5 us	86 keV
	^{69}Ge m2 decay gamma	2.8 us	397 keV
$^{71}Ga + \nu$ into e- ^{71}Ge m1	^{71}Ge m1 decay gama	20 ms	175 keV

GAGG Crystal with 20% Ga, large and fast light yield:





Study of Double Delayed Coincidence

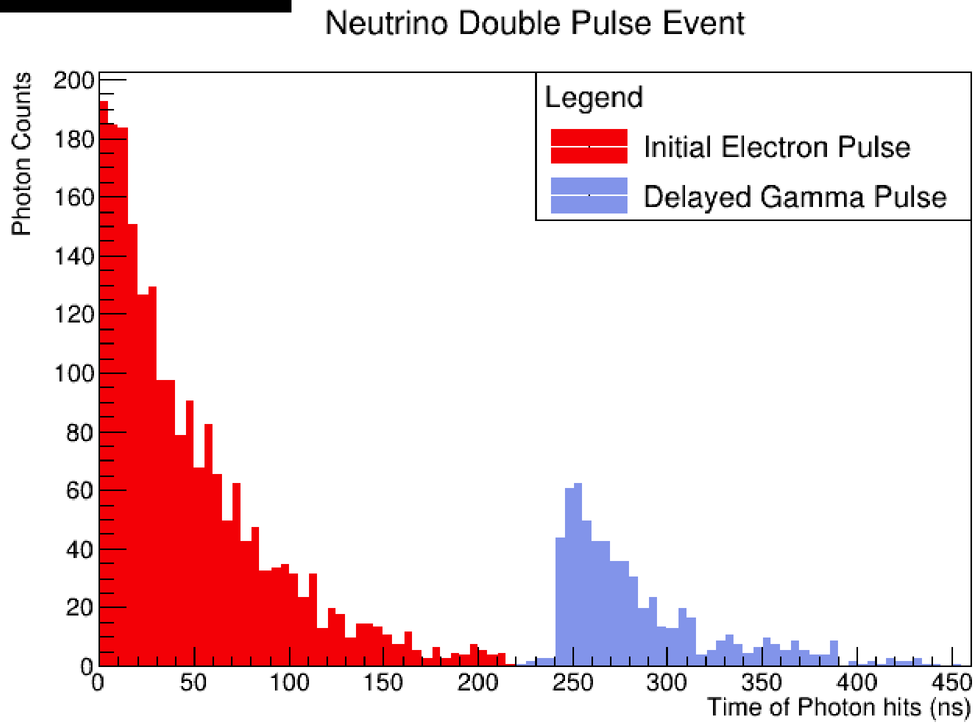


Interaction

Neutrino interactions with Gallium will produce 66% of the time a double event

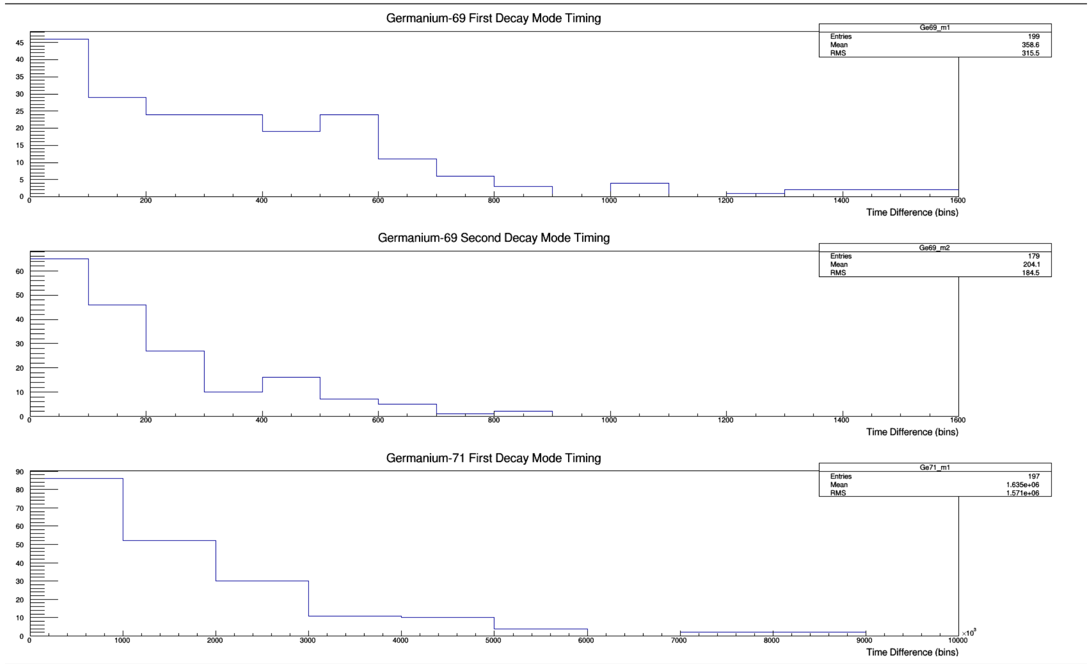
Primary conversion electron creates first signal like our beta decay lab signal

Look for secondary pulse having the characteristic gamma peak that appears some time after, out to maybe 10 half-lives



Reconstructing double timing events

- The three double timing events reconstructed with proper amount of Galactic and Solar backgrounds added from Cosmic Rays, Gamma rays and low energy solar emission particles.



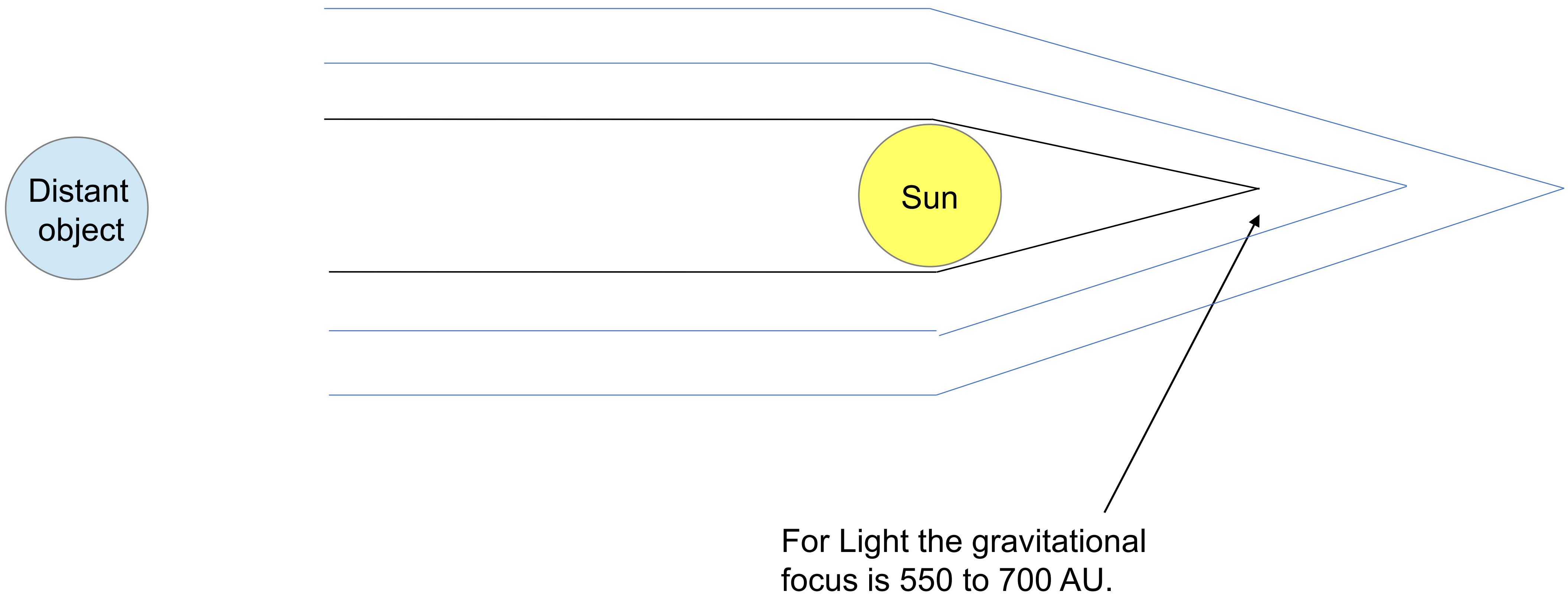
Ways to increase neutrino flux:

Although going closer to the Sun can increase the flux of solar neutrinos 3 or 4 orders of magnitude.

And going away from the Sun can decrease the solar neutrino flux by 6 orders of magnitude

- There is another 3rd way to change the neutrino flux and that is to go to the neutrino gravitational focus of the Sun.
- This can increase the stellar fusion neutrinos 4 or 5 orders of magnitude.
- There is also the possibility for high energy neutrino from accretion disks.

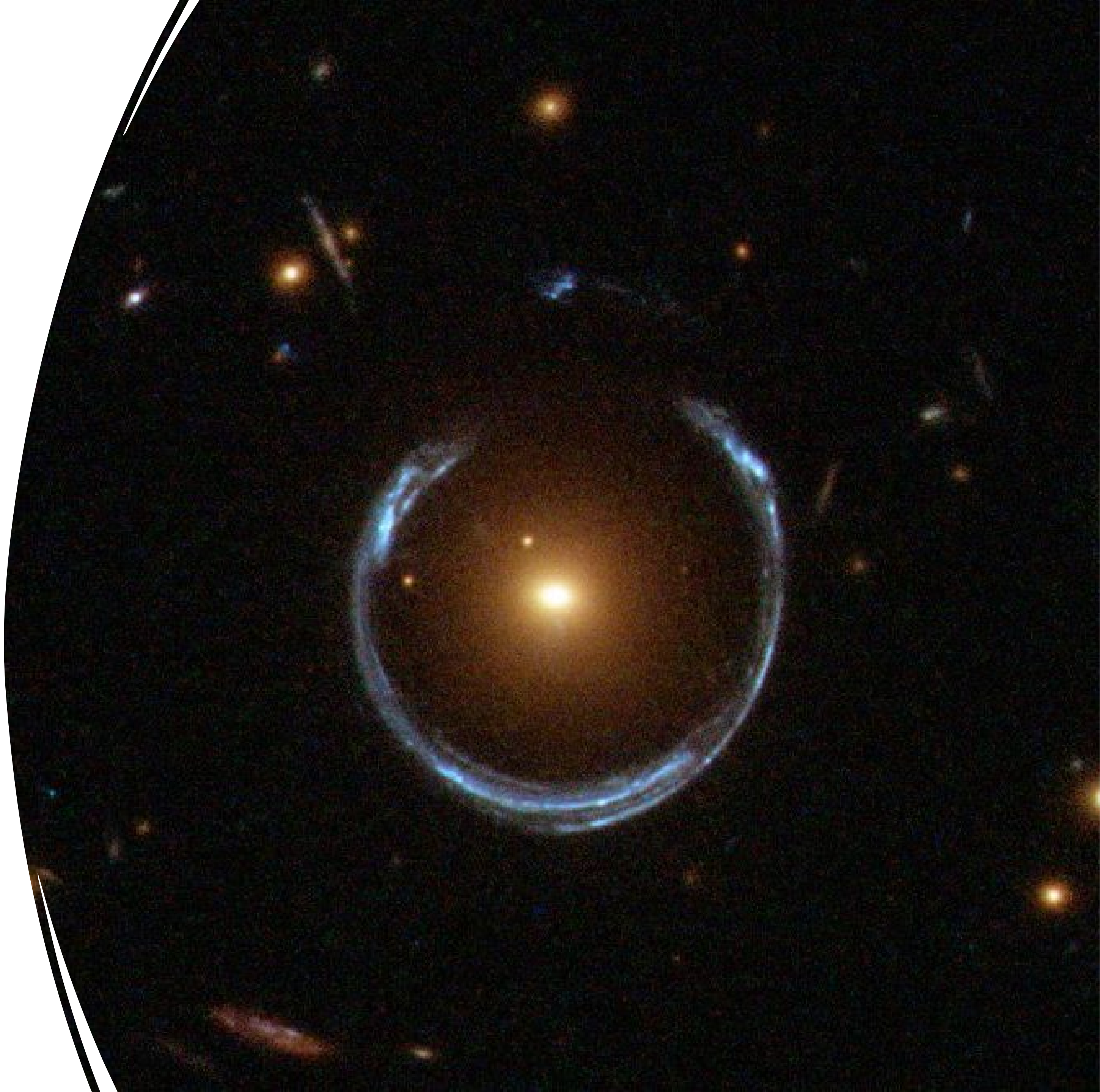
Gravitational Lensing



[1] A. Einstein, Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field, Science, Vol. 84 (1936), p. 506.
[2] G.A. Landis, Mission to the Gravitational Focus of the Sun: A Critical Analysis, 23 April 2016, arXiv:1604.06351v2 [astro-ph.EP].
[3] S.G. Turyshev and B-G. Andersson, “The 550-AU Mission: a critical discussion”, Mon. Not. R. Astron. Soc. 341, pp. 577-582 (2003).

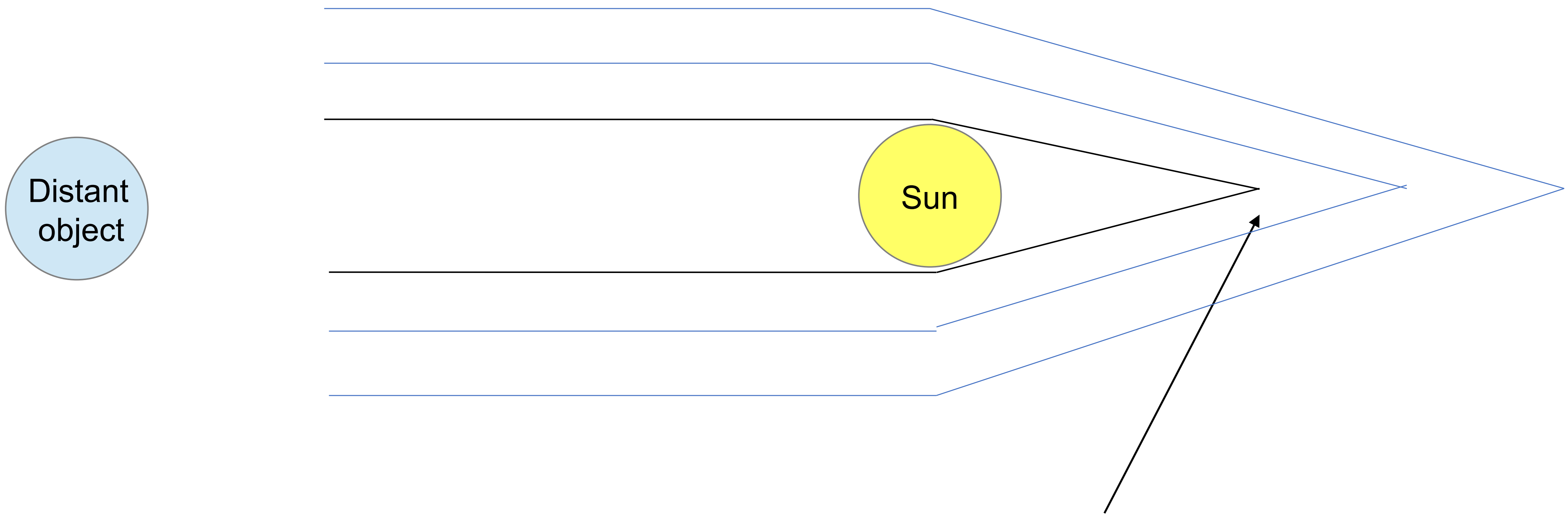
Hubble has some nice images of accidental alignment:

- This is an example of off axis imaging. The small blue galaxy at the top is the direct light and the ring is the gravitational image. The ring is much brighter showing the enormous light collection power of a gravitational lens.



[1] M. J. Dulude et al., WFC3 HST STSI Instrument Science Report, 2011-04, Feb. 2011.

Gravitational Lensing



Neutrinos have mass so their Neutrino Gravitational Focus is much closer, 20 to 45 AU.

[1] Y. Demkov and A. Puchkov, Gravitational focusing of cosmic neutrinos by the solar interior, Phys. Rev. D v61, 083001.

Initial Estimates of fusion neutrinos from Galactic Core Stars

- Used model of stars in galactic core and their distribution by Kent (S.M. Kent et al. Luminosity model of Milky Way, APJ v378, p131, 1991)
- Estimate used absolute magnitude of stars to figure the number of neutrinos compared to our Sun, this is certainly wrong, but it is to low.
- Corrected for the distance to the Galactic core at 25,000 l.y.
- Used "Light" collecting power of Gravitational Lens at 10^{12}.
- Used off axis stars with "light" reduction out to 1 degree.
- Assumed a 4 m diameter 8 m long detector volume, i.e. size of space craft upper stage.

- Get that the number of galactic neutrinos is 800 to 8000 times more stellar fusion neutrinos than at the surface of the Earth directly from our own Sun.

- Mary Lynn Buchele (senior thesis) and N. Solomey (adviser), Galactic Neutrinos Lensed by the Sun: an Initial Estimate, Wichita State University 2018.

- A. Bains (senior Physics major project) and N. Solomey (adviser), high energy neutrinos from accretion disks in the galactic core, Wichita State University is currently ongoing.

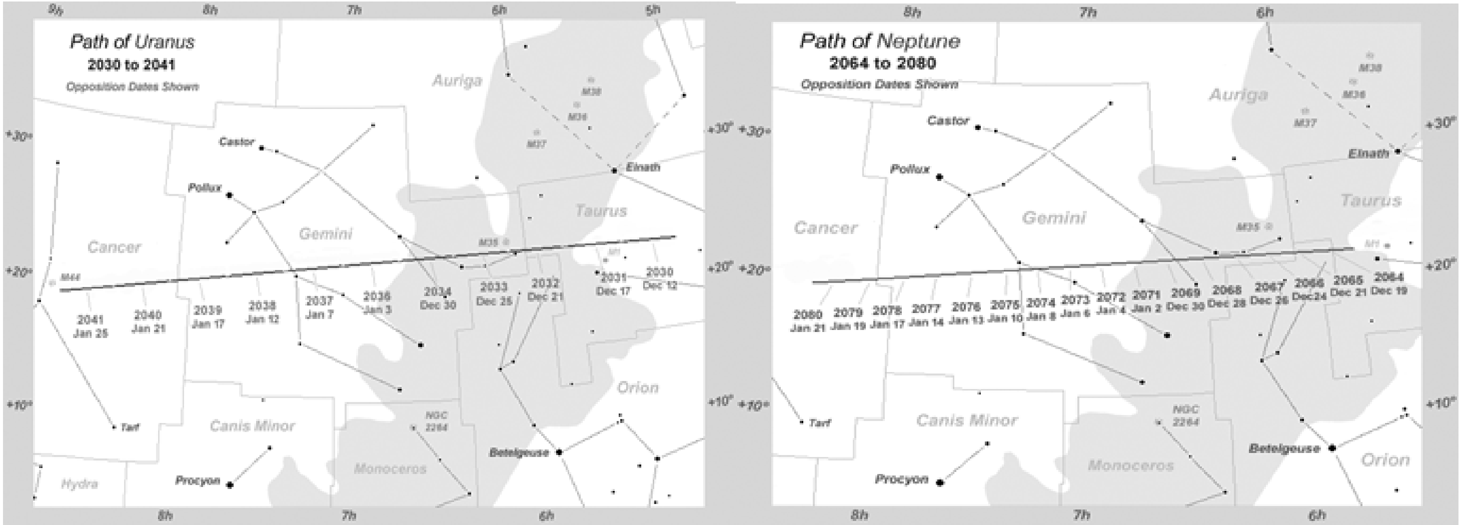
High Energy neutrinos from Galactic Core

Chandra X-ray telescope has shown that the galactic core has 1000 to 10,000 accretion disks of neutron stars and black holes.

As matter falls into these objects the protons and electrons make neutrons and neutrinos are isotopically emitted.

These would produce higher energy neutrinos that can convert into muon tracks.

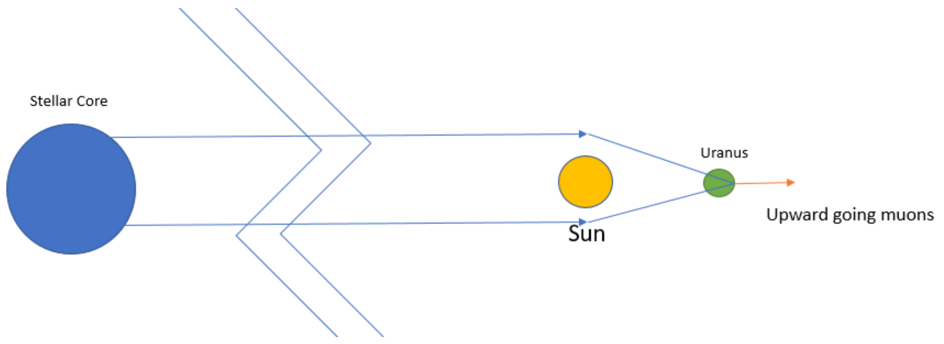
Uranus and Neptune will soon be passing through Neutrino Gravitational Focus of Galactic Core formed by our Sun.



Left is the track of Uranus through the night sky and on the right is the track of Neptune [13]; as can be seen from extending these graphs the two planets will be opposite the Sun from the galactic core in 2037-2038 and 2065-2067 and will provide an opportunity for using them as a large target for galactic core neutrinos being gravitationally focused by our Sun.

Could an orbiter's imaging camera on the dark side of Uranus or Neptune image muon tracks?

- How much light would there be
- What optics imaging system: filters or enhanced light collection needed
- How close to the gas giant would the spacecraft have to get

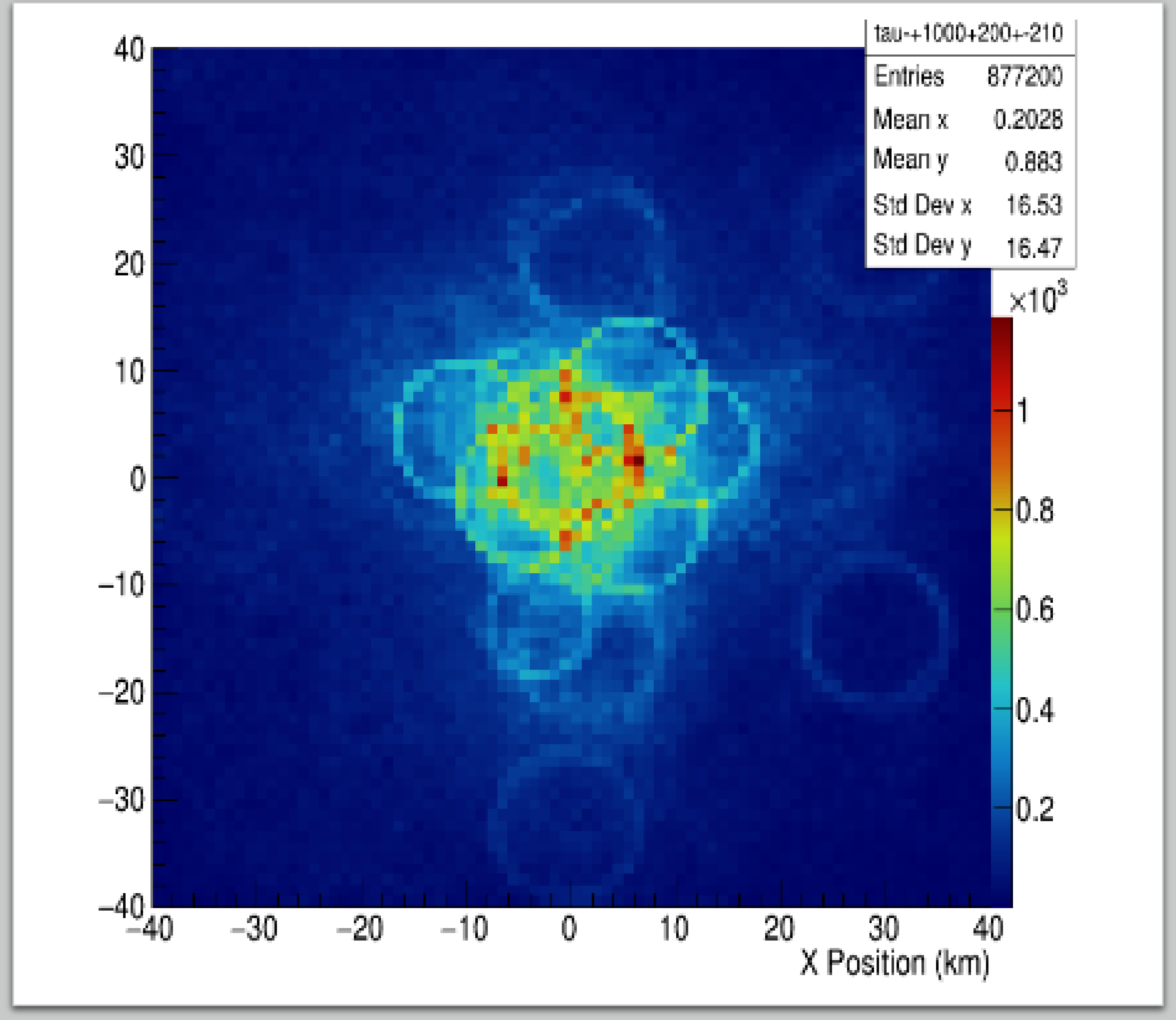


- All these questions will be studied in our coming planned one-year study.

Imaging high energy neutrinos from Galactic Core

- Science from high energy neutrinos focused by Sun:
  - Astrophysics study of galactic core
  - Planetary interior study using neutrino tomography

Trent English, Concept Study for Observing Galactic Neutrinos in Neptune's Atmosphere, Physics Master's Thesis, April 2022, Wichita State University

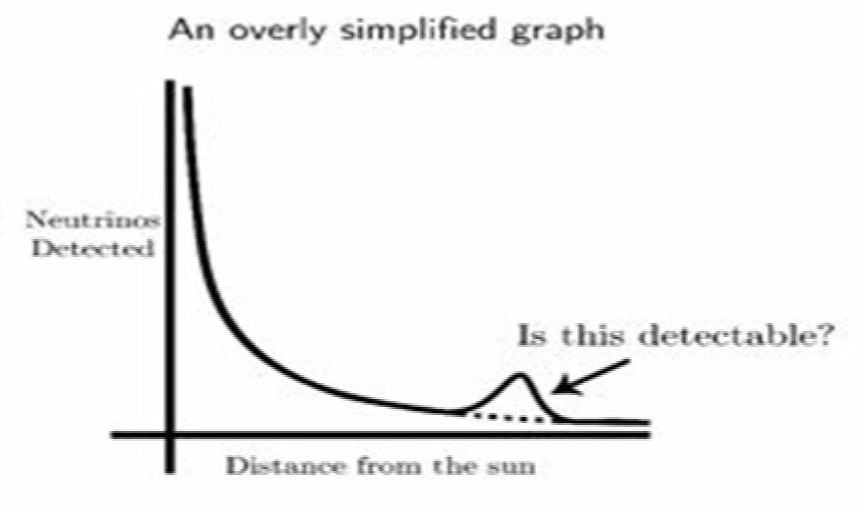


Science possible:

Elementary Particle Physics:

Can we measure Mass of Neutrino

- From location of neutrino gravitational focus from the Sun.



Astrophysics:

- Measure neutrino intensity of point sources like Crab and Geminga Pulsar.
- Measure number of Galactic Core Accretion disks
- Image Galactic Core Structure

Planetary Science:

Study the interior structure of a Gas or Ice Giant using neutrino tomography

Developments:

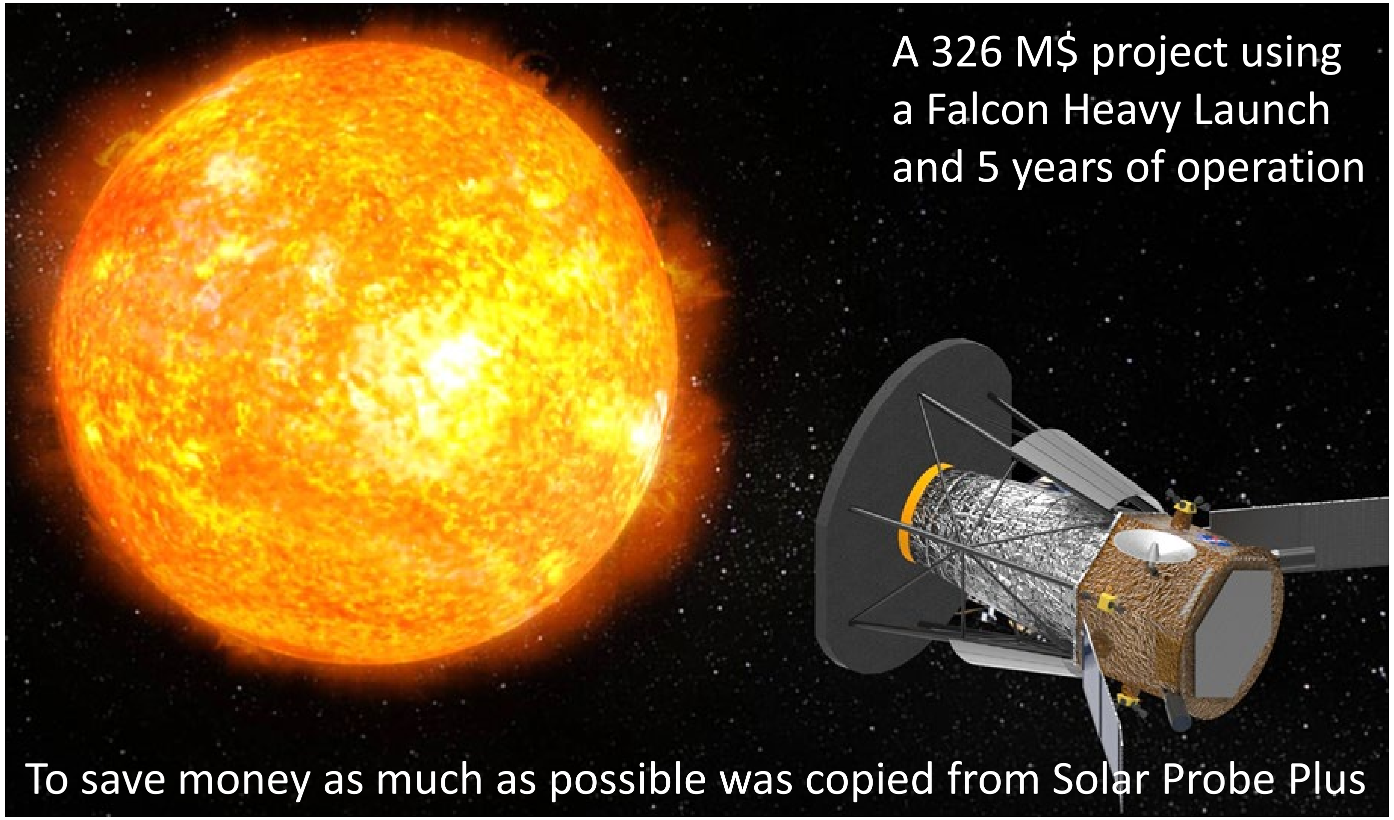
What was presented here were ideas and some initial calculations and simulations from my funded NASA development project.

We will improve the simulations, answers more questions and determine how feasible these ideas are! Some studies with more Lab test & a detector LEO flight test CubeSat.

Future work could be instrumentation development to tests these ideas close to the Sun while we preform this initial demonstrator mission investigations.

Conclusion:

- Detector R&D on Space Based Neutrino Detector:
  - NASA funding started in 2016
  - Current NASA funding 2 M$/year
  - Building 3U CubeSat detector to be tested in space.
  - Launch, Operations, Communications and Data Analysis Fall of 2024 through Summer of 2026
- A future mission, called neutrino Solar Orbiting Lab (νSOL), close to Sun is in development and budgeting.
- Mission to Neutrino Gravitational Focus are running simulations and hope to have funding for further lab studies.



[1] N. Solomey, Studying the Sun's Nuclear Furnace with a Neutrino Detector Spacecraft in Close Solar Orbit, AAS/ Solar Physics Division, Abstracts# 47 Presentation and poster P7-26, Boulder Colorado June 2016.

[2] N. Solomey (PI), NASA Innovation and Advanced Concept Phase-1 2018 Grant "Astrophysics and Technical Study of a Solar Neutrino Spacecraft", May 15, 2018 ot Feb. 14 2019 80NSSC18K0868, and NASA Innovation and Advanced Concept Phase-2 2019-2021 Grant, Astrophysics and Technical Lab Studies of a Solar Neutrino Spacecraft Detector, 80NSSC19M0971.

[3] N. Solomey (PI), CubeSat test of a space neutrino detector, NIAC Phase-3 grant, Oct. 1, 2021 through Sept. 30, 2023, 80NSSC21K1900.