Yu-Dai Tsai
University of California, Irvine
with Bramante, Linden
arXiv:1706.00001 (PRD18)
with Palmese, Profumo, Jeltema
arXiv:2007.03686 (JCAP21)

Multi-messenger Signatures of Dark Matter from Compact Objects

Crab Nebula, NASA, ESA, J. Hester and A. Loll (Arizona State University)

yt444@cornell.edu & yudait1@uci.edu
https://arxiv.org/a/tsai_y_1.html

New Model Independent Constraints on Dark Matter and Cosmic Neutrinos (while Protecting the Earth)

Yu-Dai Tsai

University of California, Irvine

with Josh Eby, Jason Arakawa, Marianna Safronova & Davide Farnocchia (NASA)

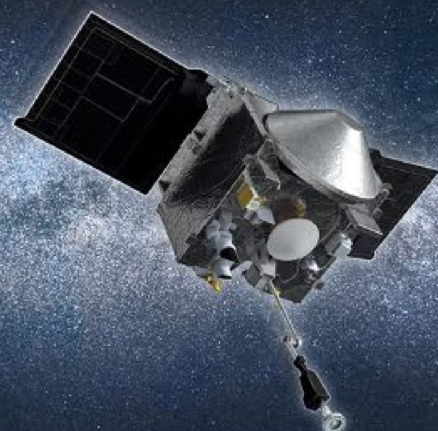
To appear on arXiv next week!

- **https://arxiv.org/abs/2112.07674**

To appear on Nature Astronomy!

- **https://arxiv.org/abs/2107.04038**

Under review by Nature Astronomy



*"There is always a possibility that **dark matter effects can modify the trajectory of an asteroid**, which could wipe out all life on this planet. The only way these people can get on with their happy lives is that **they do not know about it**."* – An agent warned me about giving this talk.

NASA's OSIRIS-REx mission readies itself to touch the surface of asteroid Bennu.
Credits: NASA/Goddard/University of Arizona

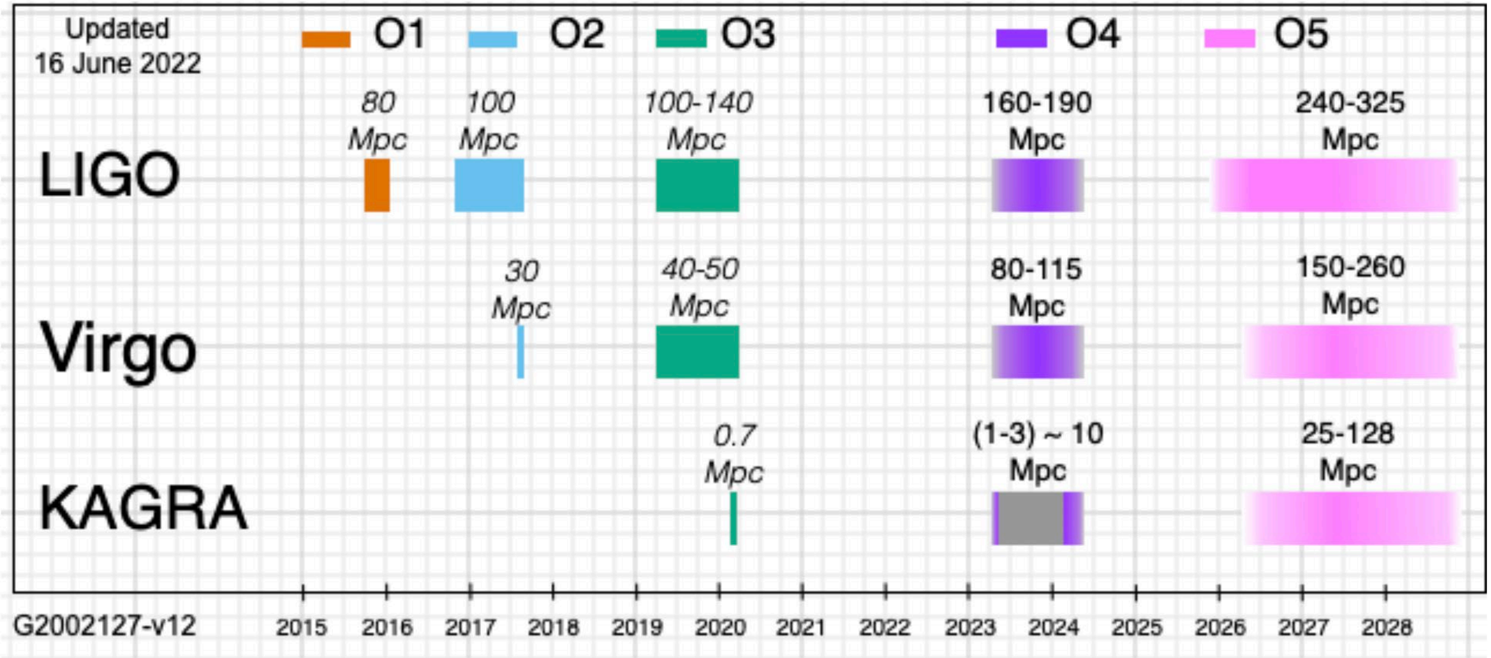
Notes

- **Apologies:** due to my father's health condition &
  a job interview, I have not gone through a complete
  reference update.
  Please let me know if your relevant works are not mentioned.
- **This talk will have a bit of an informal flavor**
- See the relevant talks form **Gustavo Marques Tavares**, **Volodymyr Takhistov, Huangyu Xiao, Dake Zhou, Violetta Sagun, Michael Fedderke, and more** in https://www.int.washington.edu/program/schedule/1055/4

Outline

- Dark matter (DM) and Astrophysical Motivations
- DM-induced Neutron Star (NS) Implosions: Mechanism
- Signatures & Constraints; Why Multi-messenger?
- Primordial Black Holes: GW170817 as a case study
- Outlook: A Lot More to Come!
- Bridging Planetary Defense, Quantum Technology & Fundamental Physics

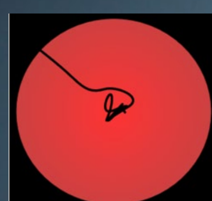
LIGO-Virgo-Kagra (LVK) Observing Runs



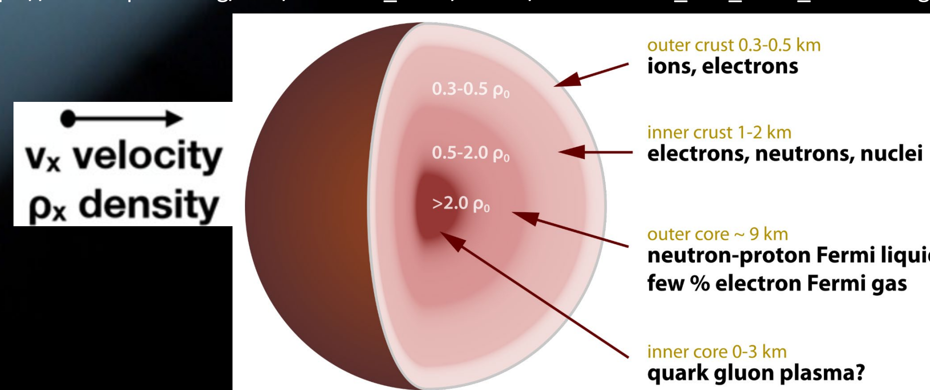
- https://observing.docs.ligo.org/plan/, expressed in terms of Binary Neutron Star (BNS) range.
- **New Lampposts for New Physics Studies**
- Sky- and orientation-averaged distance up to which one can detect a BNS merger with a signal-to-noise ratio (SNR) of 8.
- Update O4 plan? See Ryan Foley's letter: https://tinyurl.com/O4positive

Topic today: the **capture of dark matter** and implosion of neutron star (and other compact objects)

- DM Scattering with SM particles! Replacing the detector with a compact objects
- Allow to go much beyond the direct-detection limits and projections!



https://en.wikipedia.org/wiki/Neutron_star#/media/File:Neutron_star_cross_section.svg



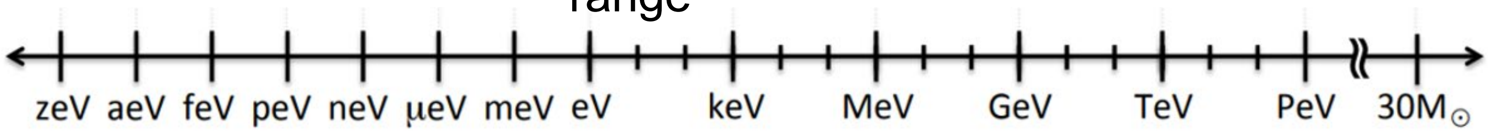
Going Beyond Direct Detection!

Dark Sector Candidates, Anomalies, and Search Techniques

Bramante, Linden, **Tsai**, 1706.00001

PeV - EeV

Can be extended to wider mass range



- Astrophysical observations is the **natural habitats** for the DM signatures!
- New astrophysical observations = new opportunities
- **Extreme astrophysical systems** provides probes that is out of reach for **terrestrial experiments**

Neutron Star & Dark Matter?

- Neutron star (NS) has **high density**: high fiducial mass (event rate) as a DM detector
- The densest stars ~ $\mathbf{10^{17}\ kg/m^3}$ (Earth has a density of around $\mathbf{5\times10^{3}\ kg/m^3}$). Almost a **black hole (BH)**, but the degeneracy pressure is keeping it from collapsing.
- What could **asymmetric DM (ADM)** do to neutron stars? **Implode them.**
- Can gather ADM in a small radius, allowing **collapse/implosion**, to give us various signatures
- **White Dwarf (WD)** $\sim 10^9\ \mathrm{kg/m^3}$ useful as well, see, e.g., Graham, Janish, Narayan, **Rajendran**, Riggins, PRD18

Dark Matter-Induced Neutron Star Implosions

NS Implosion & Asymmetric Dark Matter

- Asymmetric Dark Matter (ADM): dark matter with **particle/anti-particle asymmetry in the dark sector**, often linked to **baryon/lepton asymmetry (well motivated!)**.

- The asymmetry often sets the DM relic abundance.
- see, e.g., reviews from Petraki and Volkas 2013, Zurek 2013 …

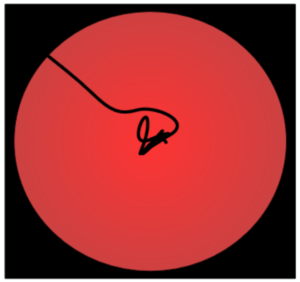
- Dark matter asymmetry allows **efficient collection and collapse** in stars without annihilating to lighter particles
- See, e.g., Goldman and Nussinov 1989, Kouvaris and Tinyakov 2010, Lavallaz and Fairbairn 2010, McDermott, Yu, Zurek 2011, Bell, Melatos, Petraki 2013, Bertoni, Nelson, **Reddy** 2013, …

- Extend to **Topological Defects (GUT)**, **Q-Ball (SUSY)**, etc. (in progress)

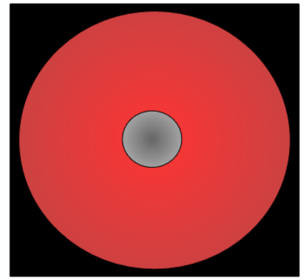
DM-induced NS Implosions

NS capture enough DM to potentially form black hole

1. DM captured



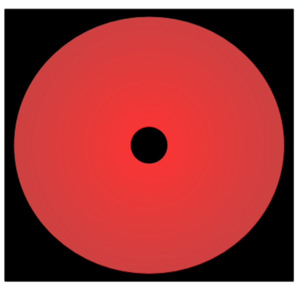
2. DM thermalizes



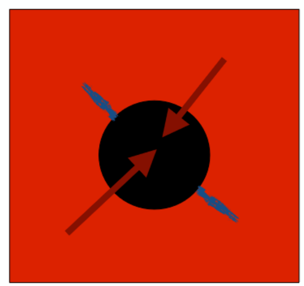
Repeated scattering: DM reach the same temperature and settle at center of neutron star

Collapse into a black hole

3. DM collapses

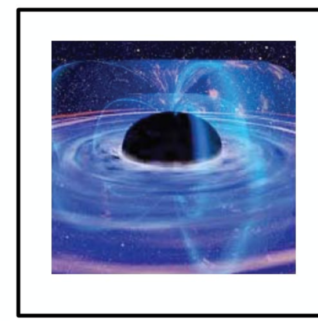


4. BH consumes neutron star



Black hole consumes the neutron star

5. Form solar mass BH



- Consider the implosion using **PeV-EeV (10^6 -10^9 GeV) ADM** as an example.

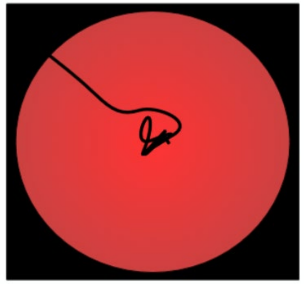
Reference:

- For **super heavy ADM**: see e.g., Bramante, Unwin, '17 & Bramante, Delgado, Martin, '17
- **Other mass ranges**: see e.g., Bramante, Kumar, et al. '13, Bramante, Elahi '15

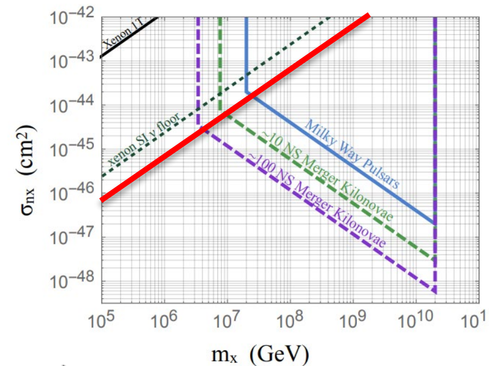
Dark Matter Capture

v_x velocity
ρ_x density
in MW halo

1. DM captured



$\sigma_{\rm nx}$
determines whether DM scatters, gets trapped



DM-nucleon cross section, $\sigma_{nx} \gtrsim 10^{-45}\text{cm}^2\left(\frac{m_x}{\text{PeV}}\right)$,

implies **maximum mass capture rate**, $b_{\max} = \left(\frac{2GMR}{v_x^2}\right)^{1/2}\left(1-\frac{2GM}{R}\right)^{-1/2}$

(DM initial halo kinetic energy scales linearly with m_x)

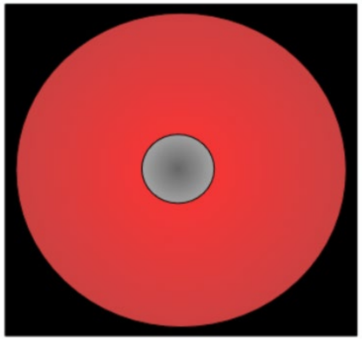
R: NS radius
M: NS mass

$\boldsymbol{t_c}$:= Dark Matter Capture Time:
the time for a critical collapsing mass ($\boldsymbol{M_{crit}}$) to accumulate

$t_c \propto v_x/\rho_x.$ $\left(t_c \propto \frac{v_x}{\rho_x\sigma_{nx}}\text{ for smaller }\sigma_{nx}.\right)$

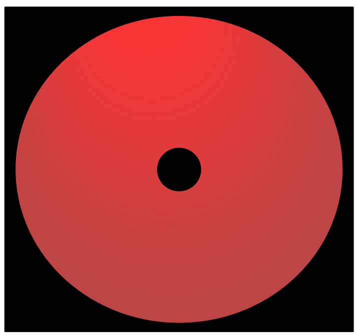
See Bramante, Linden, **YT,** ’17 (1706.00001)
also Bramante, Delgado, Martin, ‘17 (multi-scattering, 1703.04043)

2. DM thermalizes



Repeated scattering results in DM with same temperature and settle at center of neutron star

3. DM collapses



$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$ ($\sim 10^{-14}$ **$M_\odot$ for PeV DM**)

DM will collapse to a black hole if the accumulated mass exceeds its own degeneracy pressure

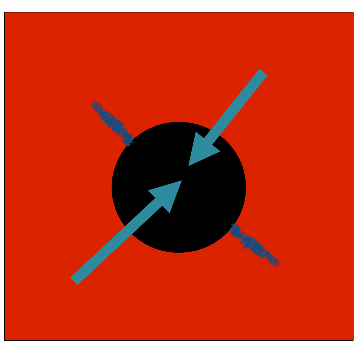
($M_{crit} \gg M_{self-gravitate}$ for PeV-EeV mass DM)

$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

$$M_{crit}^{bos} \simeq \sqrt{\lambda} M_{pl}^3/m_X^2$$

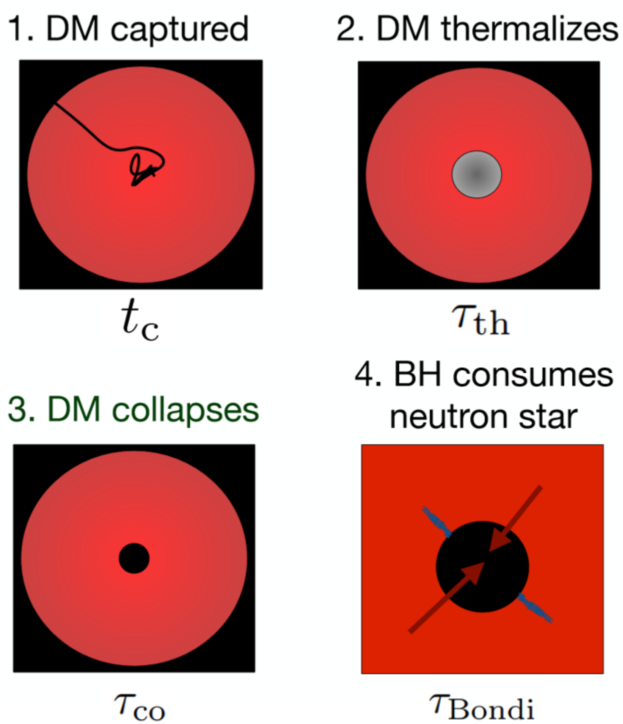
$$V(\phi) = \lambda |\phi|^4$$

4. BH consumes neutron star



Accretion from the black hole consumes the host neutron star

Time scales



For PeV-EeV ADM:

$t_c \sim 10$ Gyrs

$\tau_{\rm th} \sim 8 \times 10^{-3}$ yrs

$\tau_{\rm co} \sim 4 \times 10^{5}$ yrs

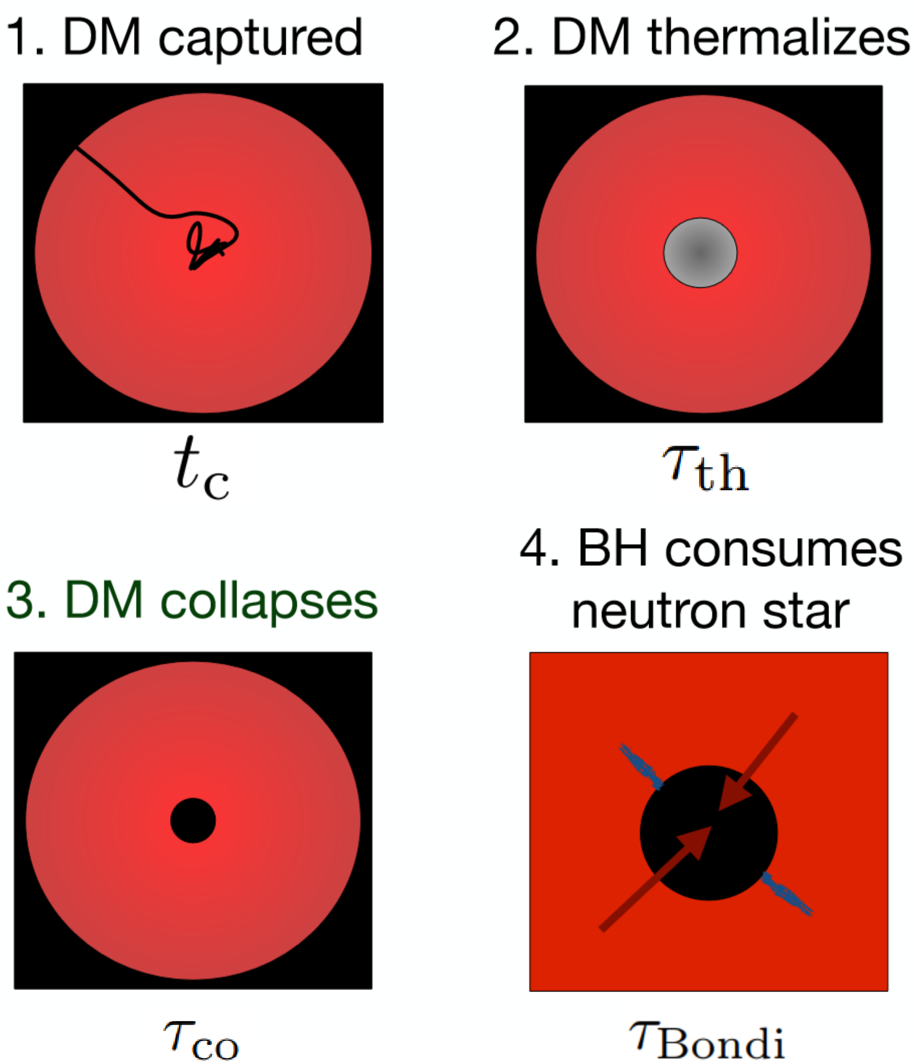
$\tau_{\rm Bondi} \sim 0.1$ yrs

Bramante, Linden, **YT**, 1706.00001

$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

$\sim 10^{-14}$ $M_\odot$ **for PeV DM**

Determining the Implosion Time



For PeV-EeV ADM:

$t_c \gg \tau_{th}, \tau_{co}, \tau_{Bondi}$

- So, the capturing sets the implosion time.
- Easy to parameterize
- We will care most about capture time from now
- **That's part of the reason why we discuss PeV - EeV**
- Appendix of 1706.00001

Thermalization Radius

- Consider DM thermalization radius [see, e.g., Bertoni, Nelson, Reddy, 1309.1721].

- As the DM thermalizes, it collects within a sphere of radius r_{th} given by the virial theorem

$$\frac{GM(r_{th})m_\chi}{r_{th}} \approx \frac{3}{2}T\ , \qquad r_{th} \approx 2.2\ \mathrm{m}\ \left(\frac{T}{10^5\ \mathrm{K}}\right)^{1/2}\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{1/2}\ .$$

- where M(r_{th}) is the mass of the neutron star enclosed within a radius r_{th}: it is stellar density dependent!

- T is the temperature of the neutron star.

- r_{th} is too large and DM density is too small to collapse for heavy but less dense objects, e.g., Sun, white dwarf, etc.

Normalized Implosion Time (NIT)

PeV-EeV ✓

Heavy dark matter, fermionic or bosonic — fewer particles required for collapse.

For $\sigma_{nx} \gtrsim 10^{-45}\mathrm{cm}^2 \left(\frac{m_x}{\mathrm{PeV}}\right)$, saturates the capture rate

$t_c \propto v_x/\rho_x$. We propose this **normalized implosion time**,

$$t_c \frac{\rho_x}{v_x} = \text{Constant} \times \left[\mathrm{Gyr}\ \frac{\mathrm{GeV/cm^3}}{200\ \mathrm{km/s}}\right]$$

Fermion:

$$t_c \frac{\rho_x}{v_x}\bigg|_f = \left(\frac{10\ \mathrm{PeV}}{m_x}\right)^2 15\ \mathrm{Gyr}\ \frac{\mathrm{GeV/cm^3}}{200\ \mathrm{km/s}}$$

Boson:

$$t_c \frac{\rho_x}{v_x}\bigg|_b = \left(\frac{\lambda}{1}\right)^{1/2} \left(\frac{3\ \mathrm{PeV}}{m_x}\right)^2 20\ \mathrm{Gyr}\ \frac{\mathrm{GeV/cm^3}}{200\ \mathrm{km/s}},$$

R=10 km, M=1.4 $M_\odot$

$V(\phi) = \lambda|\phi|^4$

Colpi, Shapiro, and Wasserman, 1986

Some Key References

1. Dark Matter In Extreme Astrophysical Environments, Baryakhtar, … **Tsai**, et al

2. Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO's Second Observing Run, LIGO, PRL 19;
   Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run, LVK, PRL 22

3. Improved Treatment of Dark Matter Capture in Neutron Stars, Bell, Busoni , Robles, Virgato, JCAP 20

4. Test for the Origin of Solar Mass Black Holes, Volodymyr Takhistov, George M. Fuller, Alexander Kusenko, arXivZ:2008.12780

5. Fate of a neutron star with an endoparasitic black hole and implications for dark matter, East, Lehner, arXiv:1909.07968

Astrophysical Motivations for **DM-induced NS Implosions**

Explain Observations/puzzles (fun to speculate!):

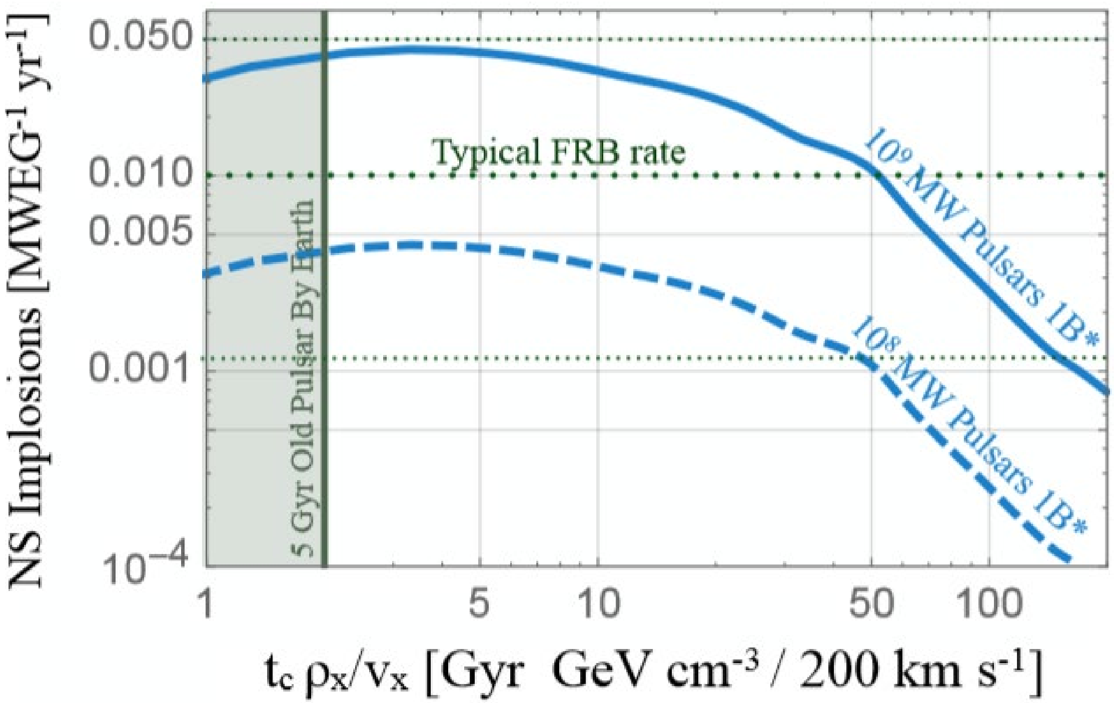
- Missing Pulsar Problem
  Dexter & O'Leary, '13, Bramante, Elahi, '15, see Violetta's talk

- Explain Fast Radio Burst (FRB)
  Fuller & Ott, 2014, Bramante, Linden, **Tsai**, 2017

- Quiet Kilonova & (Early and Diverse) Enrichment of r-process Elements

  DM: Bramante, Linden, 2016, Bramante, Linden, **Tsai,** 1706.00001;
  PBH: Fuller, Kusenko, Takhistov, 2017

Total NS Implosion Rate in terms of $t_c \frac{\rho_x}{v_x}$



MWEG: Milky Way Equivalent Galaxy ~ (4.4 Mpc)^3

Could match **FRB energy/rate!** [Fuller and Ott, 2014].

Incorporates **NS birthrates in Milky Way**, capture rate for position in galaxy [Hopkins and Beacom, 06, Sartore et al, 09]

- Bramante, Linden, **YT**, 2017
- **FRB** rate estimated from surveys [arXiv:1505.00834 and 1612.00896]
- Needs an update after recent FRB observations!!

Potential Signatures

I) NS-mass BHs and their mergers (G-wave)

II) NS merger galactic spatial distribution

(G-wave + Optical Signature)

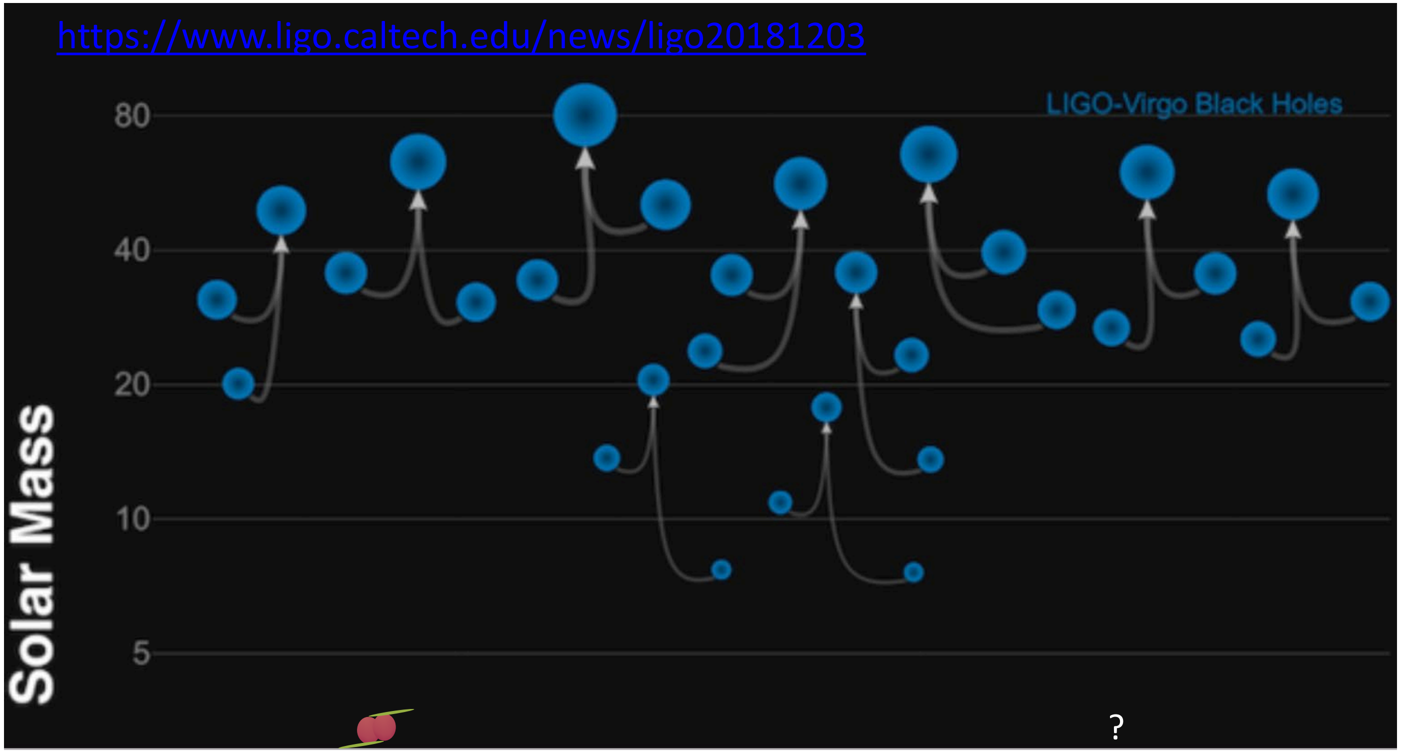
III) Quiet (orphan) kilonova & r-Process abundance

from NS implosions

(I) Light Black Holes and their Mergers

Gravitational-Wave Signature form Converted **BNS** or **NSBH** Merger

“Mass gap” between BH & NS



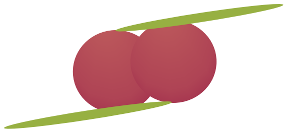
- **There is a postulated mass gap between lightest BH and heaviest NS.**
- Observationally (historically), BH mass (> 3.8 $M_\odot$ or 3.3 $M_\odot$, Thompson et al, ‘19) and BBH mergers are (>18.5 $M_\odot$). Standard Astro processes hard to produce BH with mass < 3$M_\odot$; need updates with current measurements!

Light Mass Black Hole from ADM

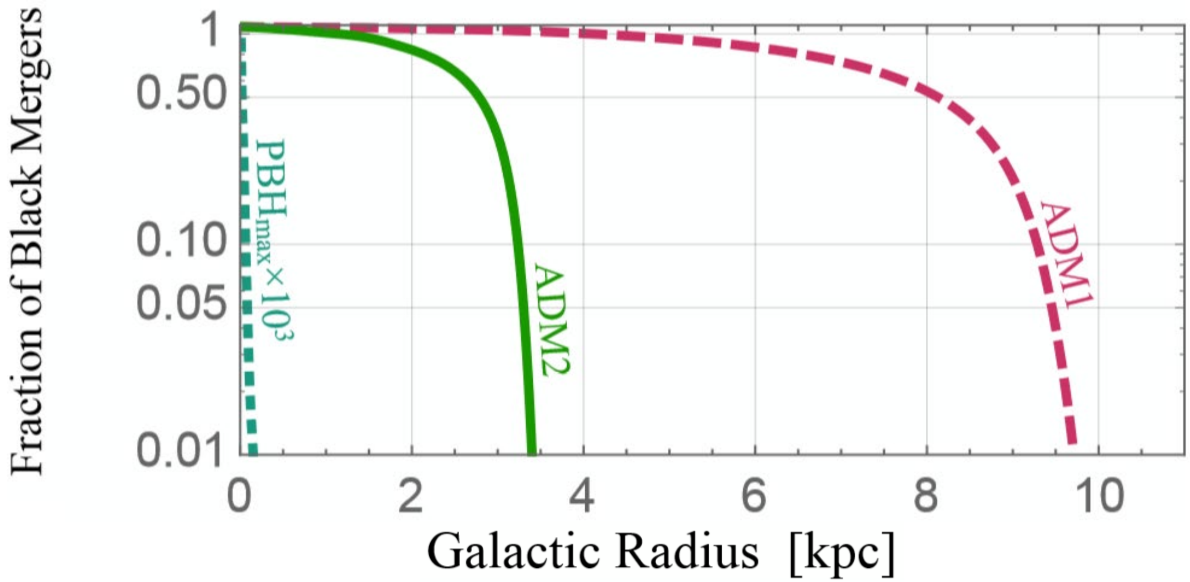
- NS can be converted into BH, through **ADM-induced Implosion**, creating a **m ~ 1 – 2 $M_\odot$ (NS-mass) BH, violating the putative mass gap** and has a **distinctive prediction of mass range**!
- Sharp prediction of the spectrum (comparing to light primordial black hole): tracing neutron star and DM distribution, O(1) fraction of neutron star can be converted. Always ~ **1 – 2 $M_\odot$**
- See e.g., Bramante, Linden, **Tsai**, 2017,

(I-1) G-Wave Signature: Converted BBH Mergers

- BNS can also be converted into BBH, creating **NS-mass BBH mergers**, again violating the putative mass gap.
- These are **NS-mass mergers WITHOUT optical follow-on**, we call them **“Black Mergers”, or “Light Black Hole Mergers”**
- Bramante, Linden, **YT**, 2017



(I-1) G-Wave Signature: Converted BBH Mergers



ADM1: Faster Implosions ($t_c \rho_x / v_x$ = 3 Gyr/cm^3(200 km/s)$^{-1}$)

ADM2: Slower Implosions ($t_c \rho_x / v_x$ = 15 Gyr/cm^3(200 km/s)$^{-1}$)

- Can use **LIGO/Virgo** to see merger signatures, that confirm that they are without optical signatures by, e.g., **DES, BlackGEM** telescopes
- Black Merger rate ~ NS Merger rate for certain model parameter! (Bramante, Linden, **YT,** 2017)

(I-2) Exotic NSBH: NS-mass BH in NSBH

- GW170817 still could be **exotic NSBH!**

  with a BH from NS implosion?
- ADM could implode one of the NS in BNS system, but the rate is small.
- Exotic NSBH can also come from PBH (2nd part of the talk)
- **The exotic NSBH scenario is not fully investigated yet.**

Astrophysical objects and rates:

Light BBH (black merger)	O(1) fraction of normal BNS rate
Light (exotic) NSBH	very rare
One heavy-one light BBH	O(1) of normal NSBH

- Red: converted from normal BNS
- Green: converted from normal NSBH

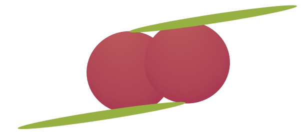
See interesting updates on these searches from LIGO-Virgo-Kagra (LVK)
Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run, LVK collaboration, PRL 22

(II) BNS Merger Spatial Distribution

Use the **depleted BNS merger galactic spatial distribution** to test DM scenarios

Need localization; **Multi-messenger!**

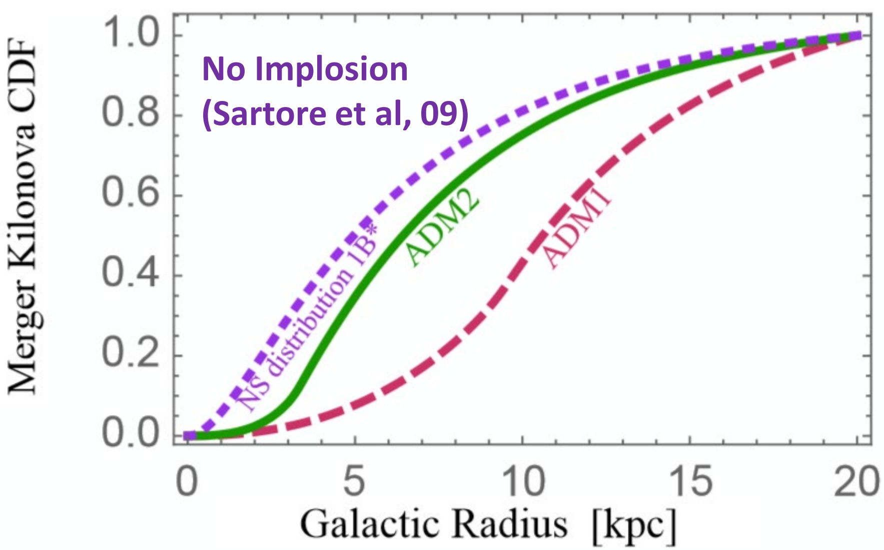
Distribution of NS Mergers

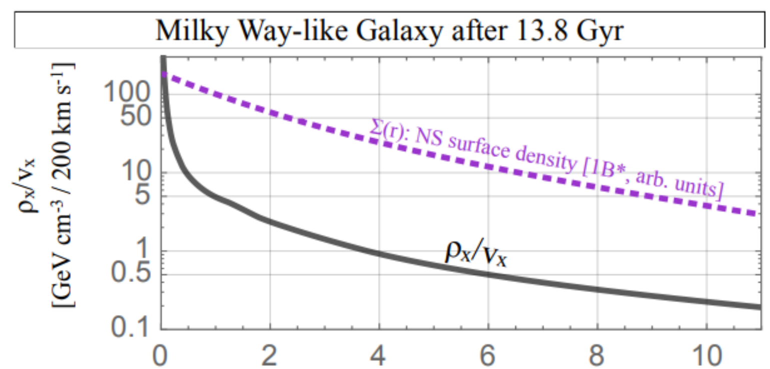


BNS mergers

- In-spiral/merger signatures detectable by LIGO/Virgo
- The associated Kilonova event can be seen by optical telescopes, e.g., DES, BlackGEM, Zwicky Transient Facility (ZTF), …
- Having *Black Mergers* means the usual NS-NS mergers have can the **distribution altered by NS implosions**

CDF of the Merger Kilonova





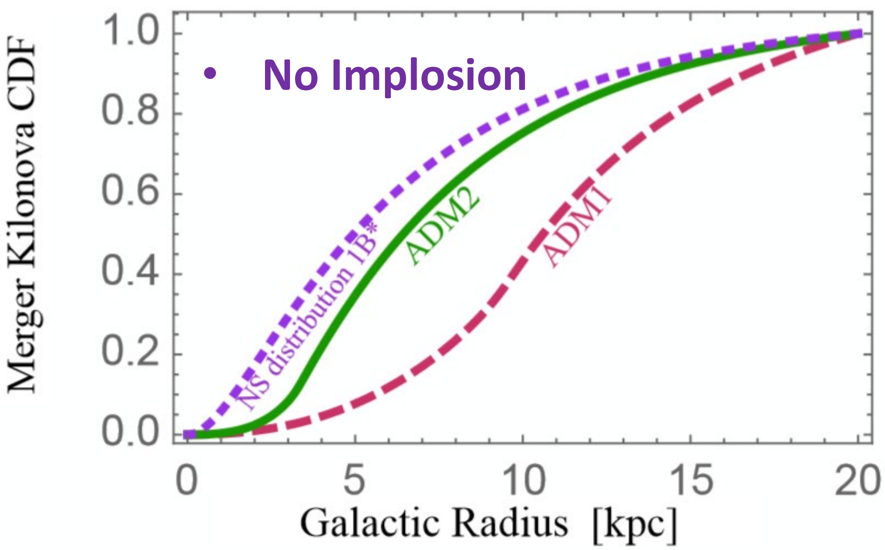
ADM1: Faster Implosions

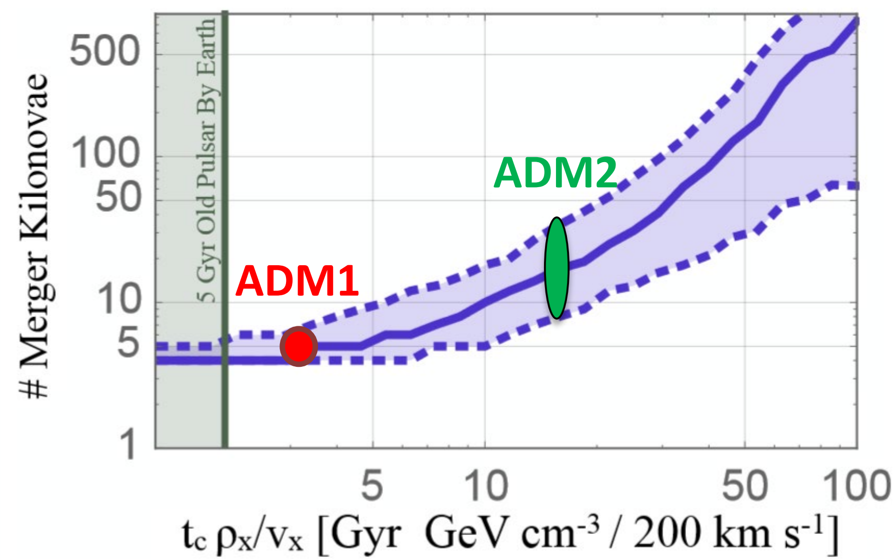
($t_c \rho_x / v_x$ = 3 Gyr/cm^3(200 km/s)$^{-1}$)

ADM2: Slower Implosions

($t_c \rho_x / v_x$ = 15 Gyr/cm^3(200 km/s)$^{-1}$)

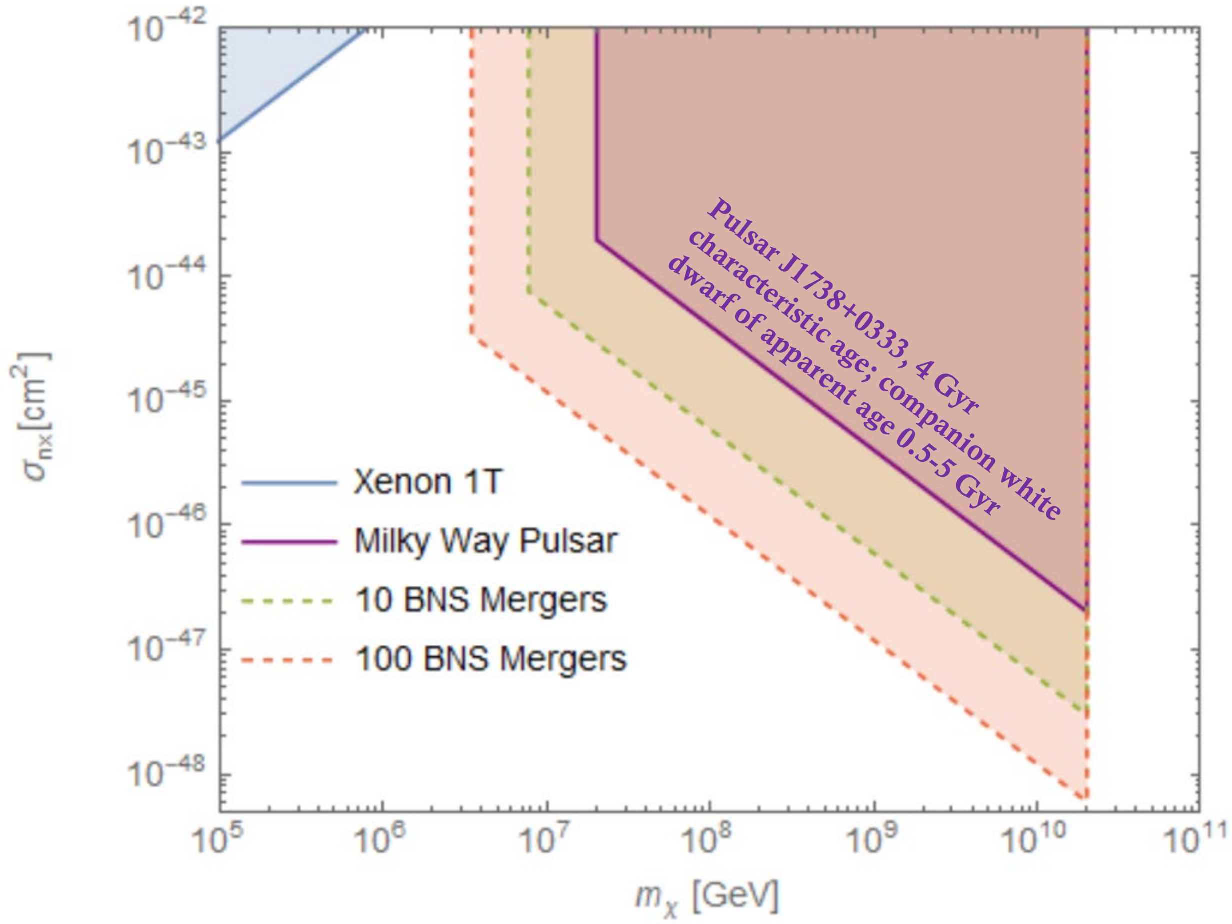
Statistics of Merger Kilonova Events





- Apply **Kolmogorov–Smirnov test** for randomly generated events based on $t_c \rho_x / v_x$
- (Right) **Purple band** indicate number of events needed for **2σ significance** in testing the ADM model parameters
- **Dashed**: upper and lower quartile; **Solid**: the median based on the repeated experiments.
- **Update with realistic NS merger distributions/host galaxies (NGC 4993-like? Elliptical?)**

Beyond Direct Detection

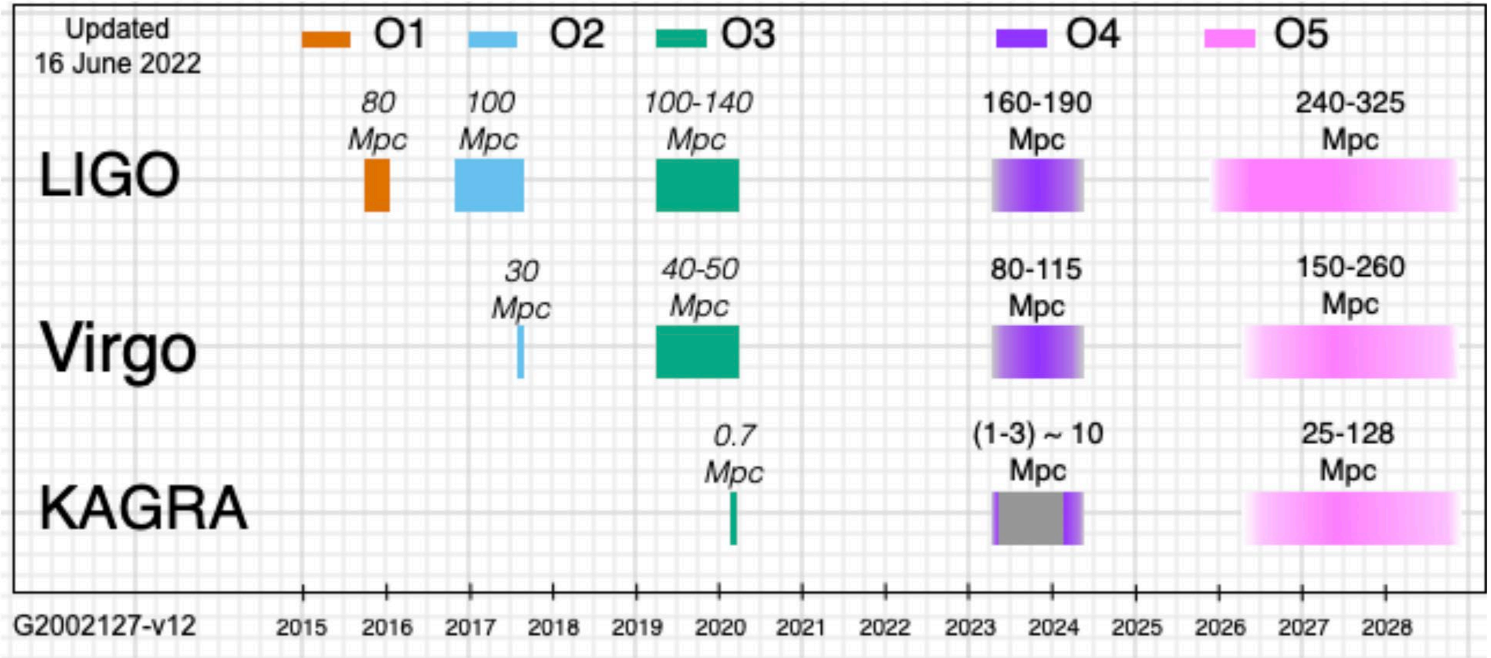


YU-DAI TSAI,
UC IRVINE,
2022

$$M_{cret}^{ferm} \simeq M_{pl}^3/m_X^2,$$
$$E_k \propto m_X v_x^2.$$

- **Left**: black hole not formed yet
- **Right**: Black hole formed would be too small and evaporate

LIGO-Virgo-Kagra (LVK) Observing Runs



- https://observing.docs.ligo.org/plan/, expressed in terms of Binary Neutron Star (BNS) range.
- **New Lampposts for New Physics Studies**
- Sky- and orientation-averaged distance up to which one can detect a BNS merger with a signal-to-noise ratio (SNR) of 8.
- Update O4 plan? See Ryan Foley's letter: https://tinyurl.com/O4positive

Why Multi-messenger?
Localization!

GW170817 is as important as SN1987A
These are just words; I will explain why.

GW170817 & PBH Case Study

Question time

- How far away is the NS merger event, GW170817, from the center of the host galaxy NGC 4993?
- NGC 4993 elliptical galaxy: ? Mpc away from us
- Observation angle: ? arcsec (arcsec = 1/3600 of a degree)
- Answer: ? kpc

NS merger distance from host galaxy

- NGC 4993 elliptical galaxy: 40 Mpc away from us.
- Observation angle: 10.31 ± 0.0100”.
- Answer: 2 kpc !!!
- Really near the center of the galaxy!

  GW170817 has nice localization based on the optical signature
- The environment of GW170817 can be found in arXiv:1710.05444

Can GW170817 be a NSBH Merger?

- The possibility of GW170817 being an NSBH merger is first considered in Hinderer et al., PRD19, which finds a 40% chance for the event
- Further studies show that NSBH can account for the multi-messenger signatures involving AT2017gfo and GRB170817A, Coughlin & Dietrich, PRD19.
- **Can GW170817 be a NS-PBH merger?**

  Tsai, Palmese, Profumo, and Jeltema, JCAP21, arXiv:2007.03686

NGC4993 Environment

NGC 4993 is a nearby (z = 0.009680 ± 0.000150) early–type galaxy with stellar mass $M_\star = (3.8 \pm 0.20) \times 10^{10}\ M_\odot$,

$$M_{\text{halo, NGC4993}} = 194^{+120}_{-70} \times 10^{10} M_\odot$$

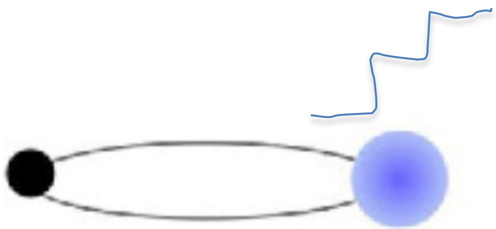
concentration c200 = 7.52+2.17 −2.07. This implies a scale radius Rs = 20.7 kpc, Tsai, Palmese, Profumo, and Jeltema, JCAP21, arXiv:2007.03686, Levan, Lyman, Tanvir, APJ 17

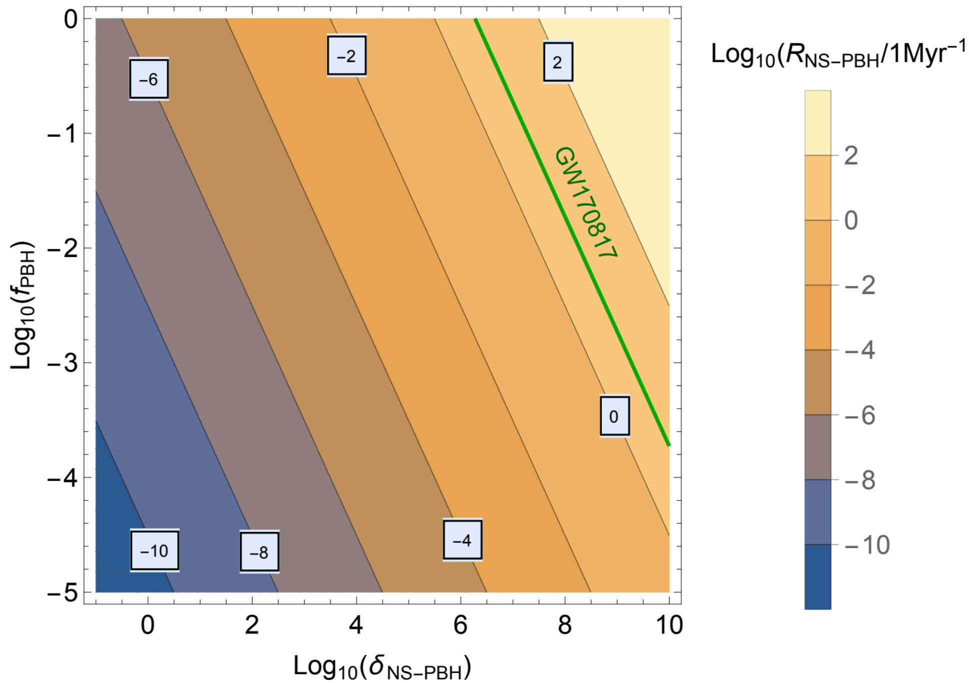
$$\rho_{\text{NS}}(r) = \rho^0_{\text{NS}} \frac{r}{R_0} \exp(-r/R_0),$$

$N_{\text{NS}} = \ 6.7 \times 10^7. \quad R_0 = 4.5\ \text{kpc},$ Paczynski, APJ 1990.

- There is a lot of environmental information one can use for new physics studies

Dynamical Formation of PBH-NS Merger





$$R(m_1, m_2) = 4\pi \int_0^{R_{\rm vir}} r^2 dr \langle \sigma v \rangle (r, m_1, m_2) \frac{\rho_1(r)}{m_1} \frac{\rho_2(r)}{m_2},$$

velocity-averaged cross-section for binary formation

$$R_{\rm NS-PBH} \simeq 3.2 \times 10^{-6} f_{\rm PBH} \delta_{\rm NS-PBH} \ {\rm Myr}^{-1},$$

where ρ_i is the mass density distribution for species i, and R_{vir} is the virial radius.

arXiv:2007.03686 (JCAP21)

Outlook

- **O4 and O5 projections important**! update O4 plan? See Ryan Foley's letter: https://tinyurl.com/O4positive
- Explore other theoretical models that could have signatures in neutron stars & compact mergers

  - New physics studies with GW170817 & other mergers

  - Other new physics to be studied by compact objects & mergers
- **New works alert!** "Why multi-messenger? New Physics and GW170817", **Tsai**, Sathyaprakash +, in preparation.

Studying Dark Matter with Asteroids & Space Quantum Sensor

Yu-Dai Tsai

University of California, Irvine

with Josh Eby, Jason Arakawa, Marianna Safronova

& Davide Farnocchia (NASA)

- Contact: yudait1@uci.edu
  yt444@cornell.edu

To appear on arXiv next week!

- **https://arxiv.org/abs/2112.07674**

To appear on Nature Astronomy!

- **https://arxiv.org/abs/2107.04038**

Under review by Nature Astronomy

INSPIRE: https://inspirehep.net/authors/1274923

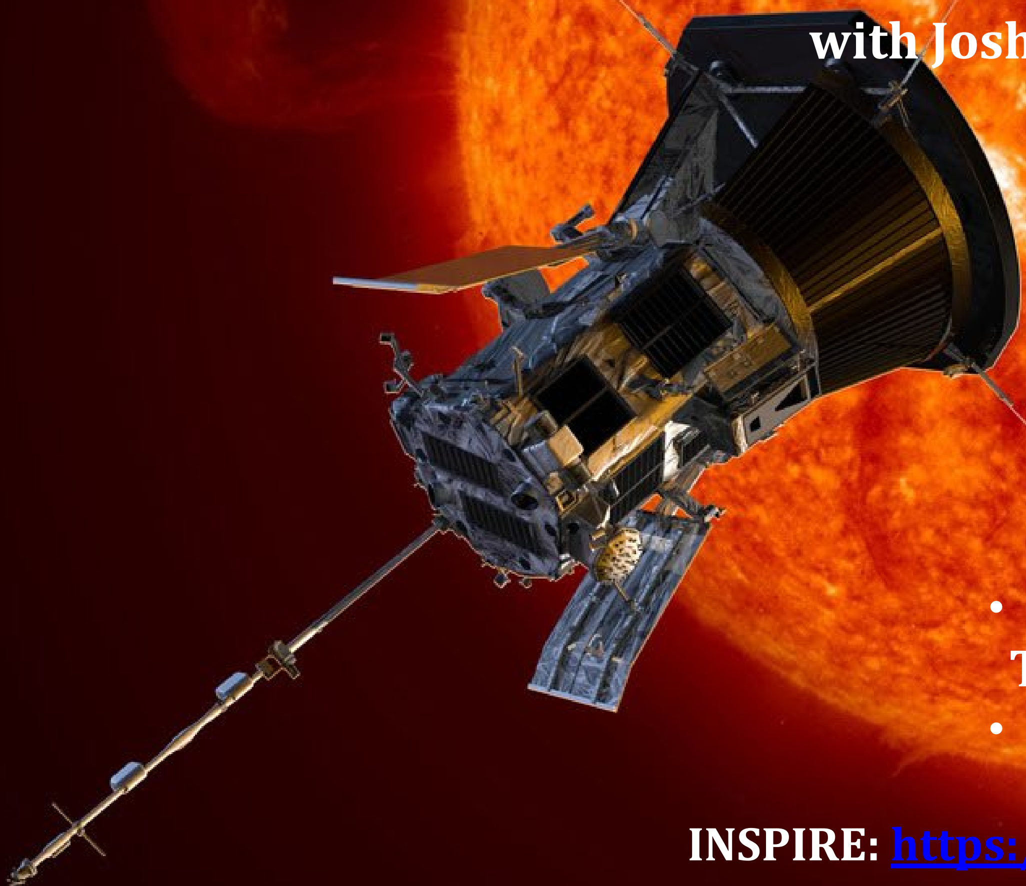


Image: Parker Solar Probe
Credit: NASA/Johns Hopkins APL/Steve Gribben

Big Questions

- Can planetary data set meaningful constraints on
  Dark matter?
  General Relativity?
  5th forces?

- Can we use current or future **Space Quantum Technologies** to study fundamental physics?

- **Warning: a lot of real-life consequences & applications**

Answers

- Can planetary data set meaningful
  dark matter constraints?
  General Relativity?
  5th forces?
  Yes! Many opportunities

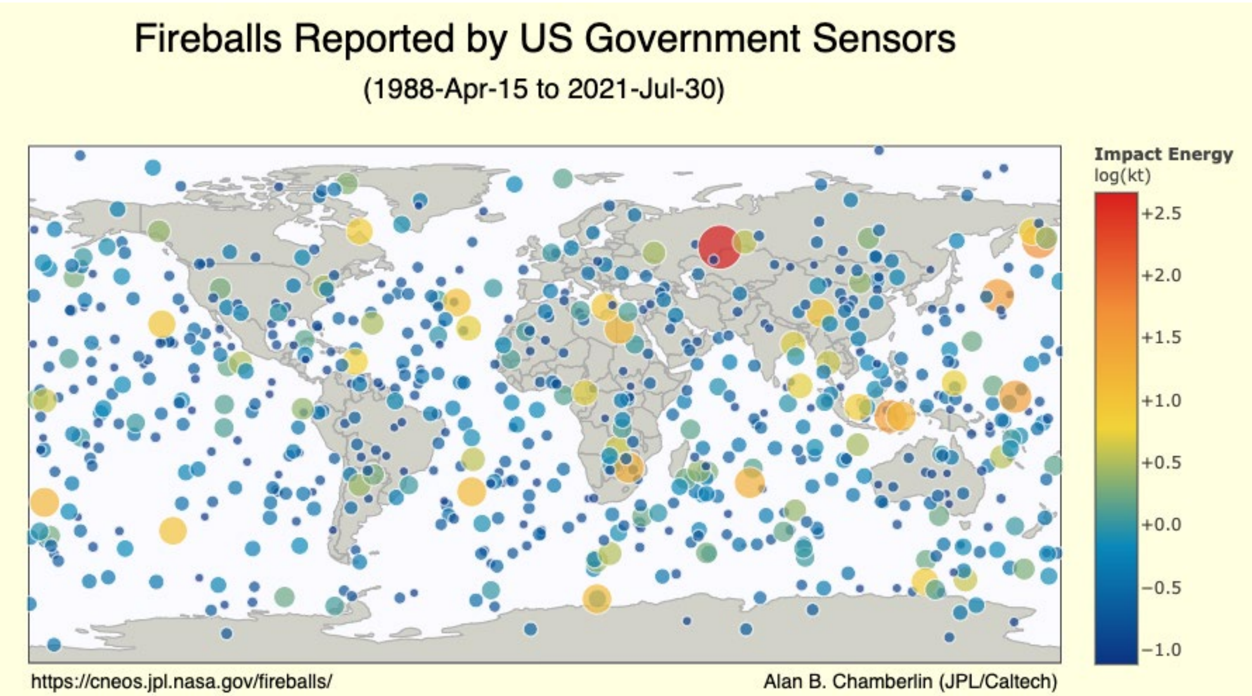
- Can we use current or future space Quantum Technology to study fundamental physics?
  Yes! I will show you an example today.

- **Robust analyses underway utilizing NASA Sentry-II asteroid program & OSIRIS-REx data**

Model-Independent Constraints on Dark Matter

Yu-Dai Tsai, UC Irvine, '22
yudait1@uci.edu

Asteroids hitting the Earth



~~Don’t~~ **Please Look Up**

~ 65 million years ago

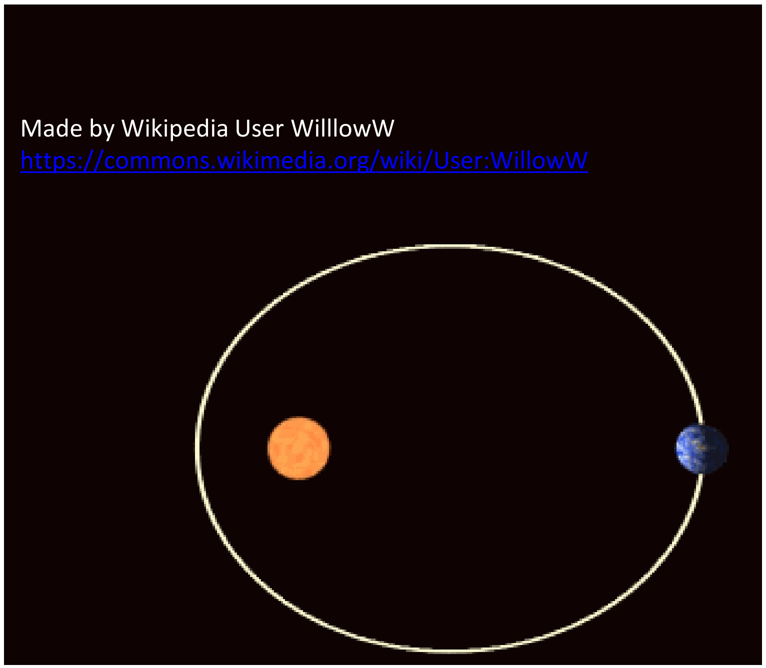
Tracking asteroids is extremely important

e.g., unexpected 2013 Chelyabinsk meteor injured >1500 people

Also, near-Earth asteroid search accidentally found ‘Oumuamua

Perihelion Precession: Einstein’s Success

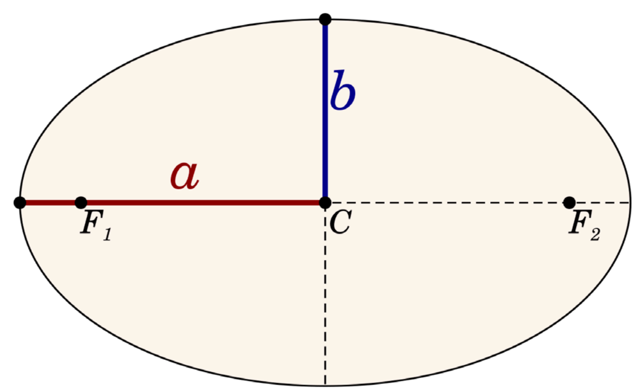
Precession of Mercury's perihelion (closest point to the Sun)



https://en.wikipedia.org/wiki/Apsidal_precession#/media/File:Precessing_Kepler_orbit_280frames_e0.6_smaller.gif under CC BY 3.0

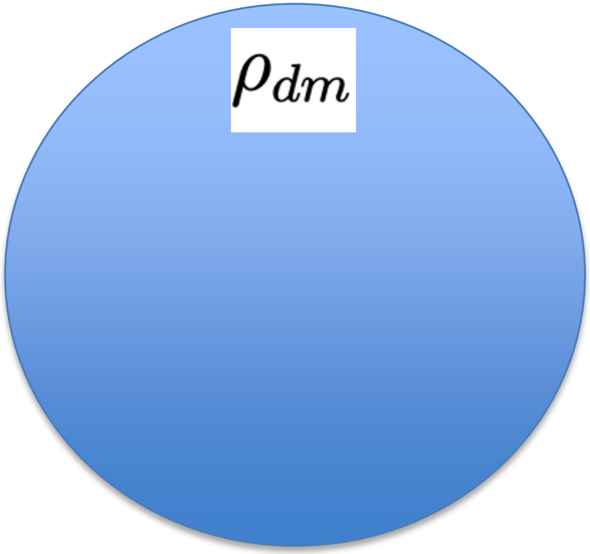
$$\frac{\mathrm{d}^2 u}{\mathrm{d}\varphi^2} + u - \frac{GM_\odot}{L^2} = \boxed{\frac{3GM_\odot}{c^2} u^2.}$$ **(GR)**

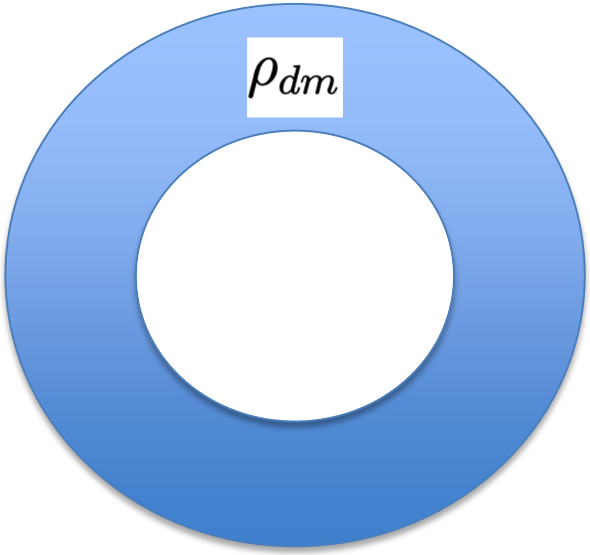
- Consider planar motion and fix θ = π/2.
- Define inverse radius variable u ≡ 1/r = u(φ)
- $a = \frac{L^2}{M_\odot(1-e^2)}$, a is the semi-major axis



M. W. Toews (CC0)

Dark Matter Profile & Planetary Precession





Dark matter

$$F(r) = \frac{2\pi}{3} G m \rho_0 \left(\frac{2r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$

$$\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}}$$

Adding Dark Matter to the Force Model

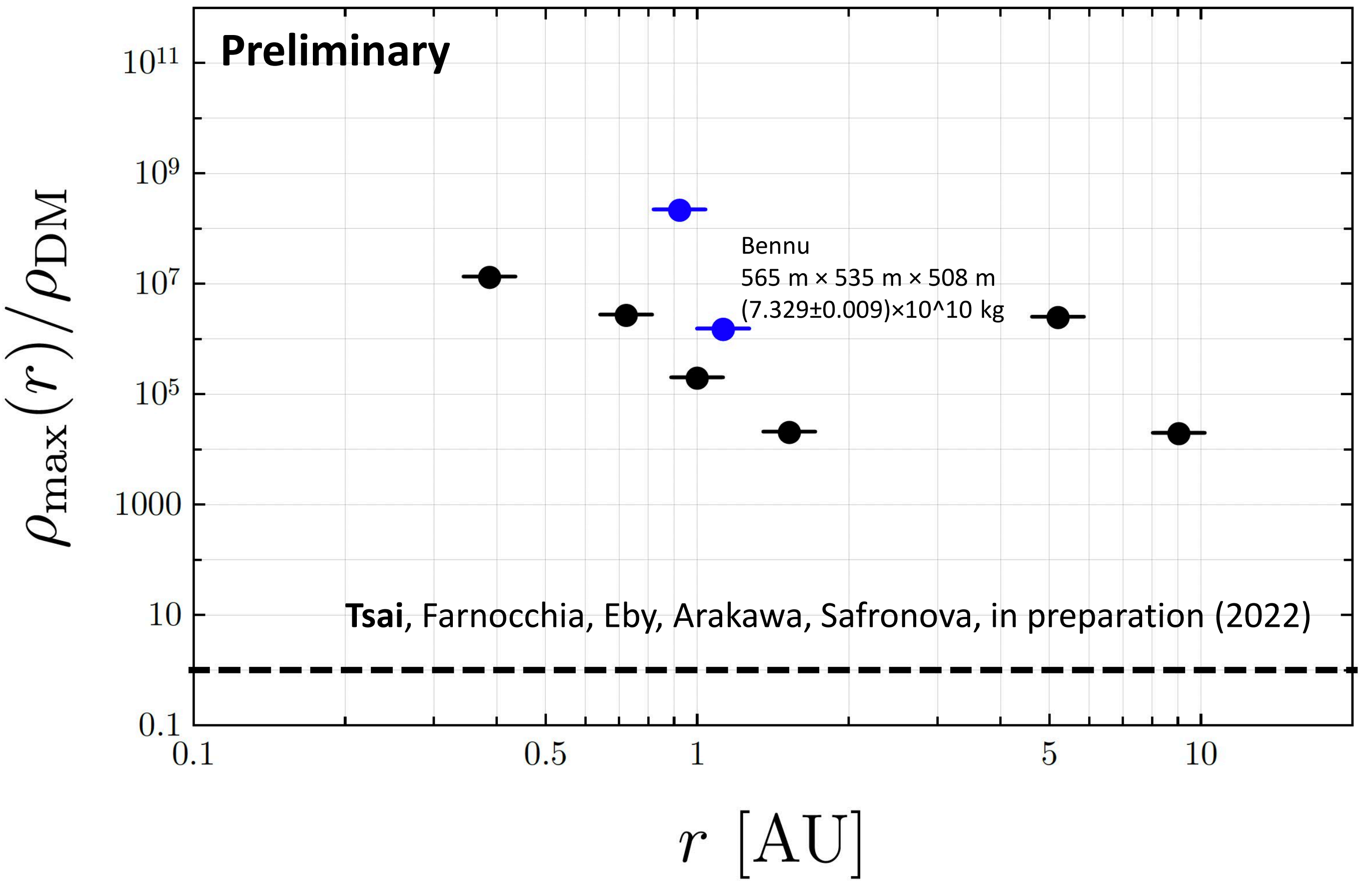
$$
\begin{aligned}
\ddot{\mathbf{r}}_i = \sum_{j\neq i} \frac{\mu_j(\mathbf{r}_j - \mathbf{r}_i)}{r_{ij}^3}\Bigg\{ & 1 - \frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{\mu_l}{r_{il}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
& + \gamma\left(\frac{\dot{s}_i}{c}\right)^2 + (1+\gamma)\left(\frac{\dot{s}_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\cdot\dot{\mathbf{r}}_j \\
& - \frac{3}{2c^2}\left[\frac{(\mathbf{r}_i-\mathbf{r}_j)\cdot\dot{\mathbf{r}}_j}{r_{ij}}\right]^2 + \frac{1}{2c^2}(\mathbf{r}_j-\mathbf{r}_i)\cdot\ddot{\mathbf{r}}_j\Bigg\} \\
& + \frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}^3}\left\{\left[\mathbf{r}_i-\mathbf{r}_j\right]\cdot\left[(2+2\gamma)\,\dot{\mathbf{r}}_i-(1+2\gamma)\,\dot{\mathbf{r}}_j\right]\right\}(\dot{\mathbf{r}}_i-\dot{\mathbf{r}}_j) \\
& + \frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}}
\end{aligned}
$$

From Dr. Davide Farnocchia's (NASA, JPL) slide

Dark matter

$$
\begin{aligned}
F(r) &= \frac{2\pi}{3}Gm\rho_0\left(\frac{2r_0^3}{r^2} - 2r\right)\hat{\mathbf{r}} \\
&\simeq -\frac{4\pi}{3}Gm\rho_0 r\hat{\mathbf{r}}
\end{aligned}
$$

New Project: New Model Independent Constraints!

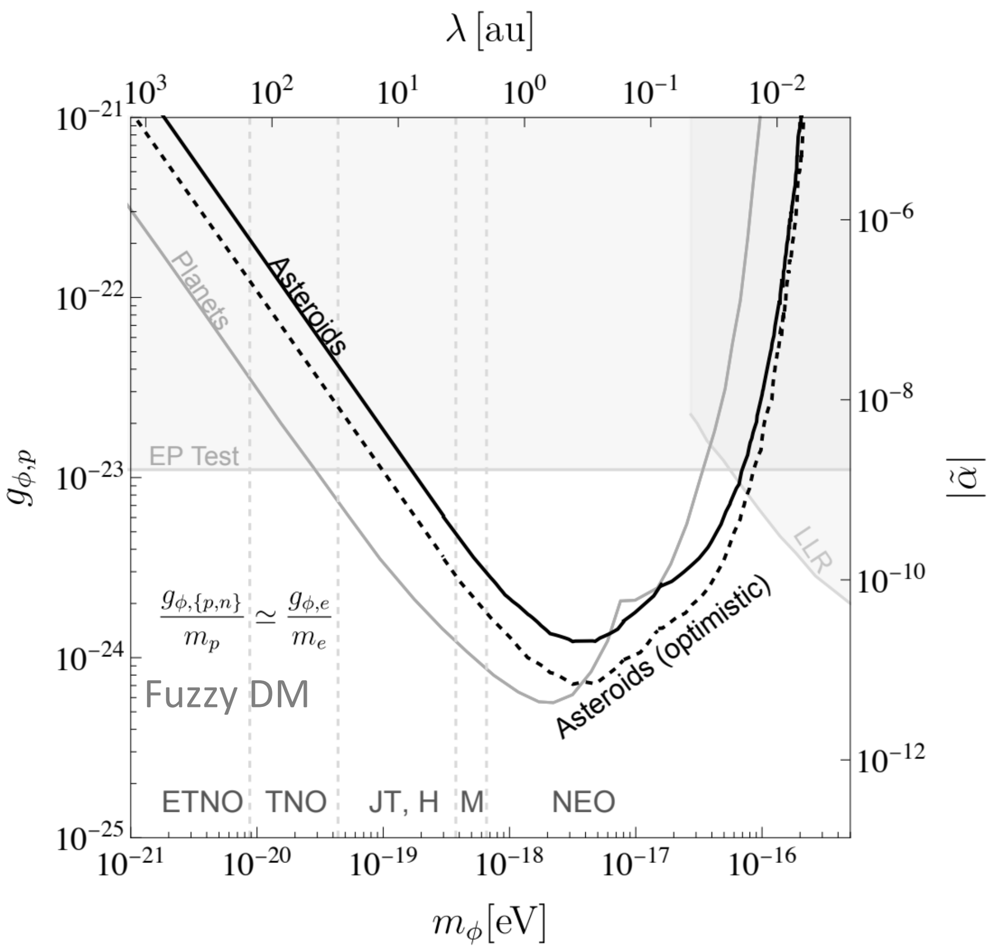


Tsai, Farnocchia, Eby, Arakawa, Safronova, in preparation

Obtained results from NASA JPL Sentry-II code & OSIRIS-Rex+ data

Can be applied to ideas like Solar-Basin & Axion Mini-cluster (more refs in paper)

Asteroid Constrain EP Conserving 5th forces



- **LLR: Lunar Laser Ranging**
  Williams, Turyshev, Boggs, PRL 04
- **Planets:**
  Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**

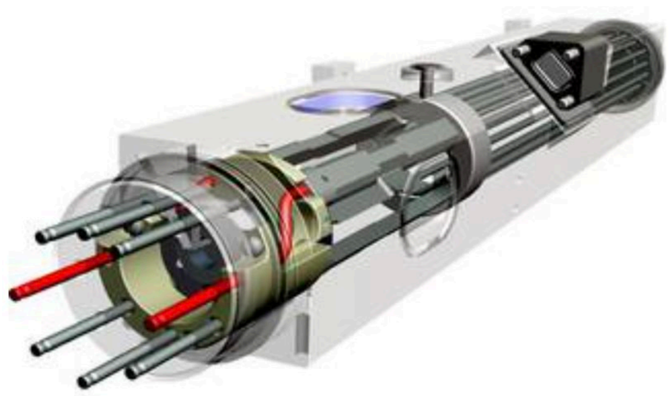
Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

We are conducting a **detailed study** using **MONTE** with people from **JPL & ESA**

Searching for Dark Matter and Test Variation of Fundamental Constants with Space Quantum Sensors

Yu-Dai Tsai, UC Irvine, '22
yudait1@uci.edu

NASA DSAC & Parker Solar Probe



- **Deep Space Atomic Clock loses one second every 10 million years**, as proven in controlled tests on Earth.
- The clock has operated for more than **12 months in space; demonstrated long-term fractional frequency stability of 3×10^{-15}**
  Burt, Prestage, Tjoelker, Enzer, Kuang, Murphy et al., Nature 595 (2021) 43.

- Exceeds previous space clock performance by up to an order of magnitude

(1.0 m × 3.0 m × 2.3 m)

Parker Solar Probe
Kasper, Klein, Lichko, Huang, Chen, Badman et al.,
Parker solar probe enters the magnetically dominated solar corona, Phys. Rev. Lett. (2021)

- **Why don't we put a quantum clock on a solar probe? What can we do with that?**

Scalar DM Halo

Stable solution can be supported by external potential

$$V_{\rm ext} = \begin{cases} -\dfrac{G\,m_\phi\,M_{\rm ext}}{r} & \text{for } R_\star > R_{\rm ext}\,, \\ -\dfrac{3\,G\,m_\phi\,M_{\rm ext}}{2\,R_{\rm ext}}\left[1 - \dfrac{1}{3}\left(\dfrac{r}{R_{\rm ext}}\right)^2\right] & \text{for } R_\star \leq R_{\rm ext}\,, \end{cases}$$

$$\rho(r) \simeq \rho_\star \exp\left(-2r/R_\star\right), \quad \text{for } R_\star > R_{\rm ext}$$

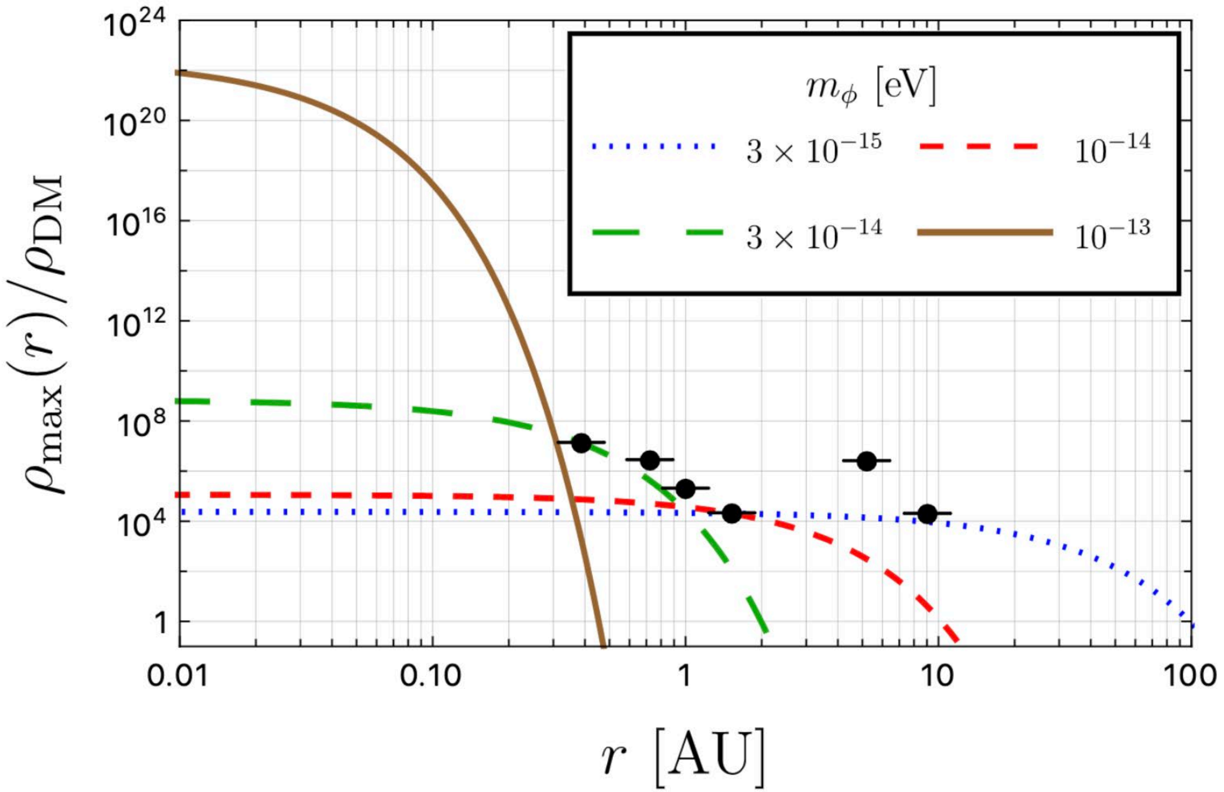
$$R_\star \simeq \frac{M_P^2}{M_{\rm ext}\,m_\phi^2},$$

where $M_{\rm ext} = M_\odot$ is the mass of the external host body; note that $R_\star$ is independent of the total mass in the halo

$$v_\star = (m_\phi\,R_\star)^{-1},$$

Banerjee, Budker, Eby, Flambaum, Kim, Matsedonskyi, and Perez, 1912.04295

Dark matter in solar system? **Planetary constraint!**



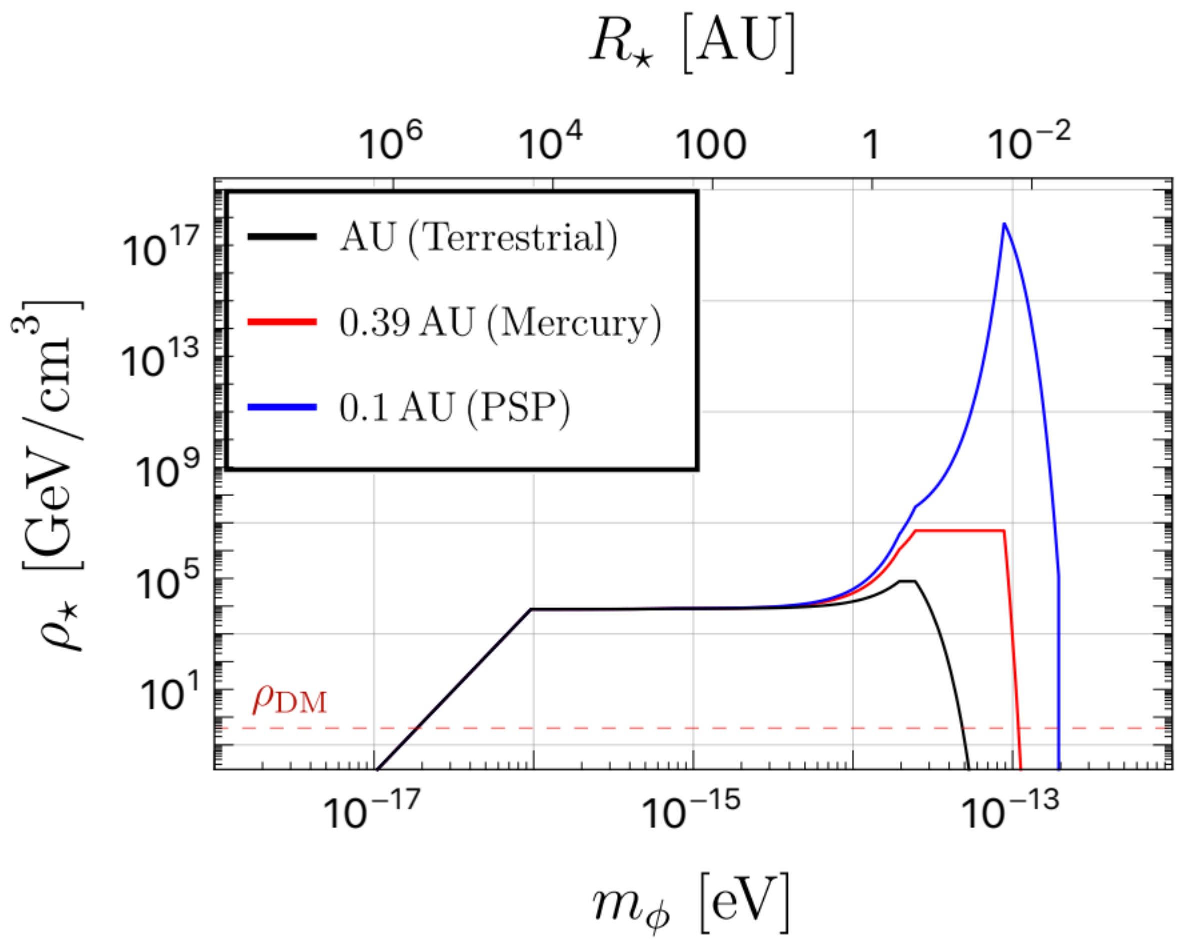
- **Black data points are model-independent constraints!**
- **Dark matter induce precessions to the planets**

Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters ’13

Tsai, Eby, Safronova, 2112.07674

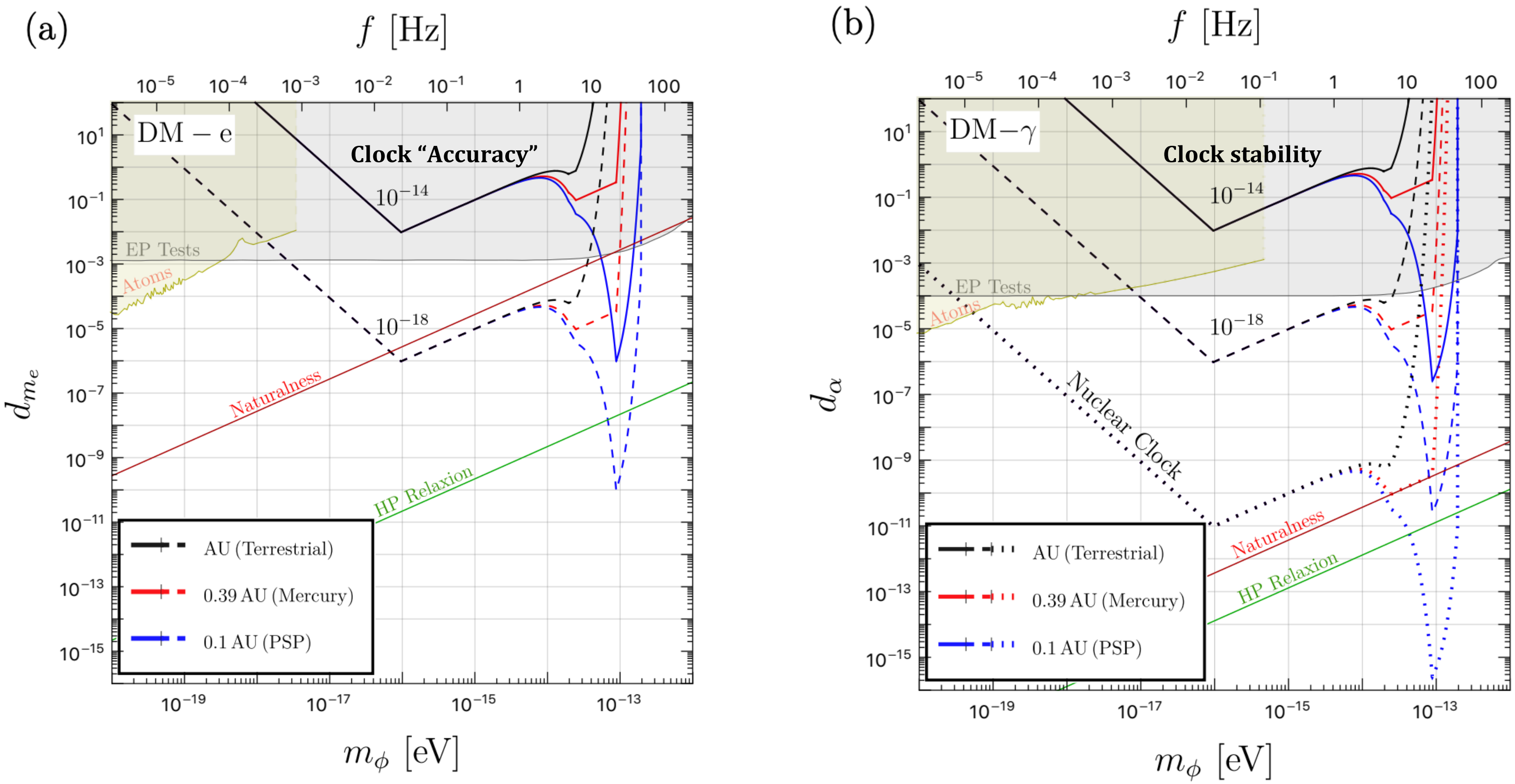
Enhancement of the DM Density



PSP: Parker Solar Probe

Tsai, Eby, Safronova, arXiv:2112.07674

Results



- Motivate **Specific Frequency Region!**
- Motivate **Nuclear Clocks!**
- **Tsai**, Eby, Safronova, arXv:2112.07674

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e} e + \frac{d_\alpha}{4} F_{\mu\nu}F^{\mu\nu} + \frac{d_g\,\beta_3}{2g_s} G^A_{\mu\nu}G^{A\mu\nu} \right), \quad (1)$$

$$\frac{g_e^2 \Lambda^2}{(4\pi)^2} \lesssim m_\phi^2, \quad \Lambda = 4\pi v_{EW} \simeq 3\ \text{TeV}.$$

Naturalness condition

Spatial Variation of Fundamental Constants

$$k_X \equiv c^2 \frac{\delta X}{X\,\delta U}. \quad X = \alpha,\ \mu,\ \text{or}\ m_q/\Lambda_{QCD}.$$

δU: change in gravitational potential .

$\delta U/c^2 \simeq 3.3 \times 10^{-10}$, Earth variation.

$\delta U/c^2 \sim 9 \times 10^{-8}$, from Earth to Solar probe at 0.1 AU.

- Achieve constraints on k_X that are a factor of $\sim$ 300 stronger!

We can also discus & collaborate on …

- Planetary defense/asteroidal astrometry & space quantum sensors (clocks) to study fundamental physics with Safronova et al
- Fixed-target searches for dark matter & long-lived particles (**FerMINI** & LongQuest) with Pospelov et al.
- LHC Forward Experiments: Forward Physics Facility, **FORMOSA** (a millicharge experiment I proposed), with Feng et al.
- Dark matter model building (dark sector QCD, Strongly Self-Interacting Dark Matter, SIMP/ELDER), with Murayama, Slatyer, Perelstein et al.
- Neutrino physics (cosmic neutrino background) & neutrino BSM, with Shoemaker et al.
- Collaborating with **many awesome early-career collaborators.**

Invisible disabilities cultivate diverse abilities

THANK YOU!

Yu-Dai Tsai
UC Irvine

Tim Linden
Stockholm University

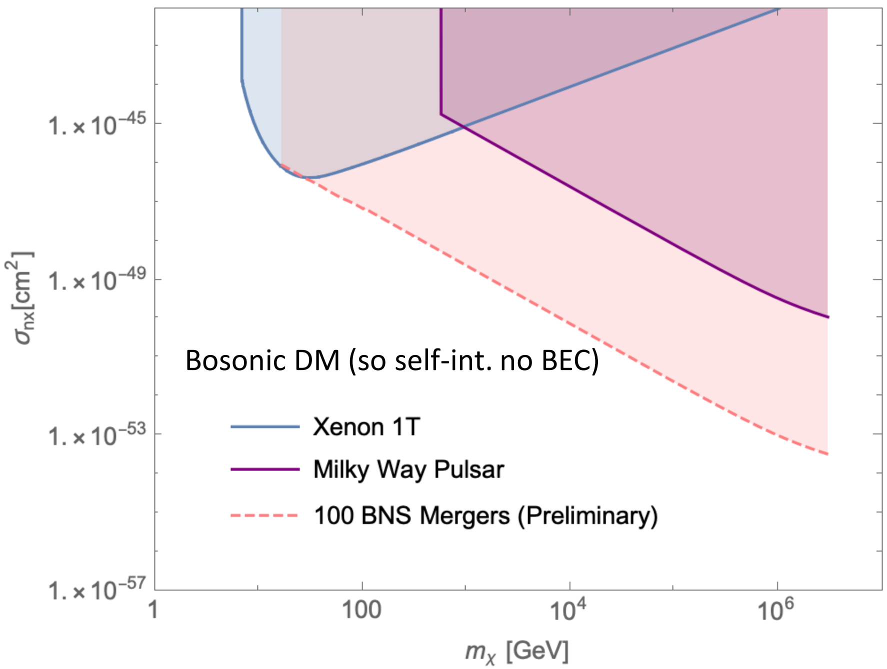
Joe Bramante
Queen's U

Antonella Palmese
UC Berkeley

Stefano Profumo
UCSC

Tesla Jeltema
UCSC

Bosonic DM (Preliminary)



$$\frac{\mathrm{d}M_{BH}}{\mathrm{d}t} = \frac{\mathrm{d}M_{BH}}{\mathrm{d}t}\Big|_{\mathrm{NS}} + \frac{\mathrm{d}M_{BH}}{\mathrm{d}t}\Big|_{\mathrm{DM}} + \frac{\mathrm{d}M_{BH}}{\mathrm{d}t}\Big|_{\mathrm{Hawking}}.$$

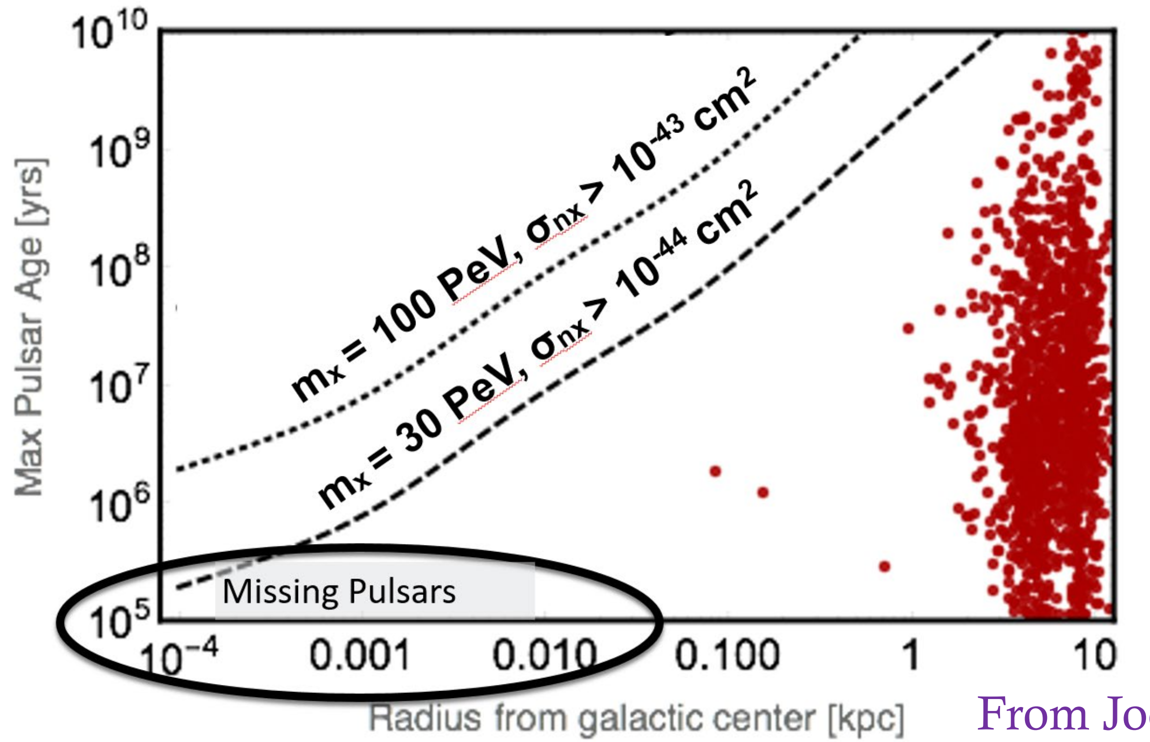
$$\frac{\mathrm{d}M_{BH}}{\mathrm{d}t}\Big|_{\mathrm{Hawking}} = -\frac{1}{15360\pi G^2 M_{BH}^2}.$$

- BHs evaporate too fast when

$$m_\chi \gtrsim 3\times 10^6\,\mathrm{GeV} \quad \text{for bosons with no} - \text{BEC}$$
$$m_\chi \gtrsim 10^{10}\,\mathrm{GeV} \quad \text{for fermions.}$$

- **Left**: black hole not formed yet
- **Right**: Black hole formed would be too small and evaporate

Dark Matter and Maximum Pulsar Age Curves



From Joe Bramante

- **ATNF Pulsar Catalogue Overlaid, ages from pulsar timing**
- Based on the number of GC pulsar progenitor stars, GC radio surveys should have already found O(10) pulsars in the central parsec. However, none have been observed. **Missing Pulsar Problem!** (Only a few ~ 10^4 age young magnetars found so far. Maybe pulses broadened by electron scattering?)
- Milky Way's 1-500 pc center surveyed in the next decade by FAST, SKA.
Worth an updated analysis now!

(III) Quiet Kilonova / NS Implosion Morphology (skip)

... or **"Quilonova Donut"**

Imploding

Imploded

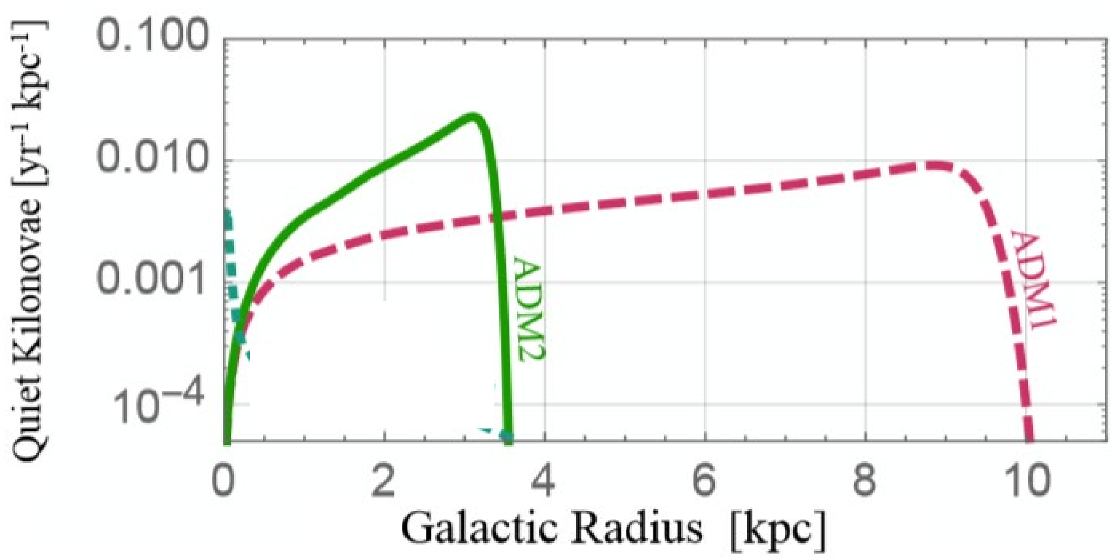
ADM2

Imploding

Imploded

ADM1

- **ADM1 and ADM2 are implosions with two NIT/model parameters**
- **ADM1 implosion faster than ADM2**
- **ADM1 is the larger donut**
- **DM use NFW profile.** Finding them with the assist of **FRB**s?

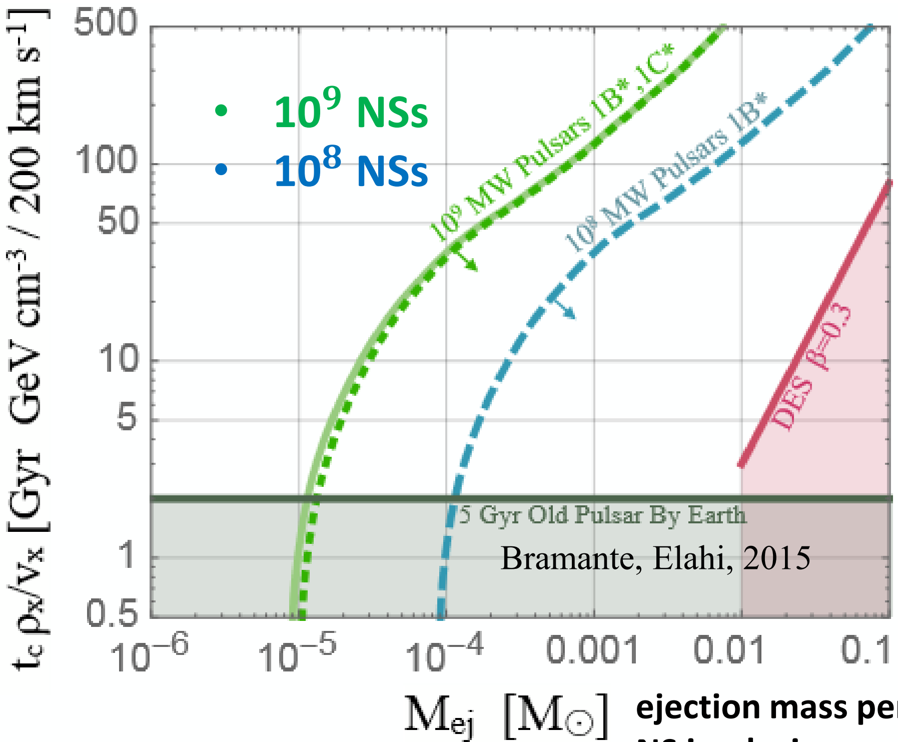


ADM1: $t_c \rho_x / v_x$ = 3 Gyr/cm^3(200 km/s)$^{-1}$

ADM2: $t_c \rho_x / v_x$ = 15 Gyr/cm^3(200 km/s)$^{-1}$

Bramante, Linden, **YT**, 2017

r-Process Abundance Implications



ejection mass per NS implosion

- **x-axis: ejection mass per NS implosion**
- **y-axis: NIT, $t_c \rho_x / v_x$ (related to the rate)**

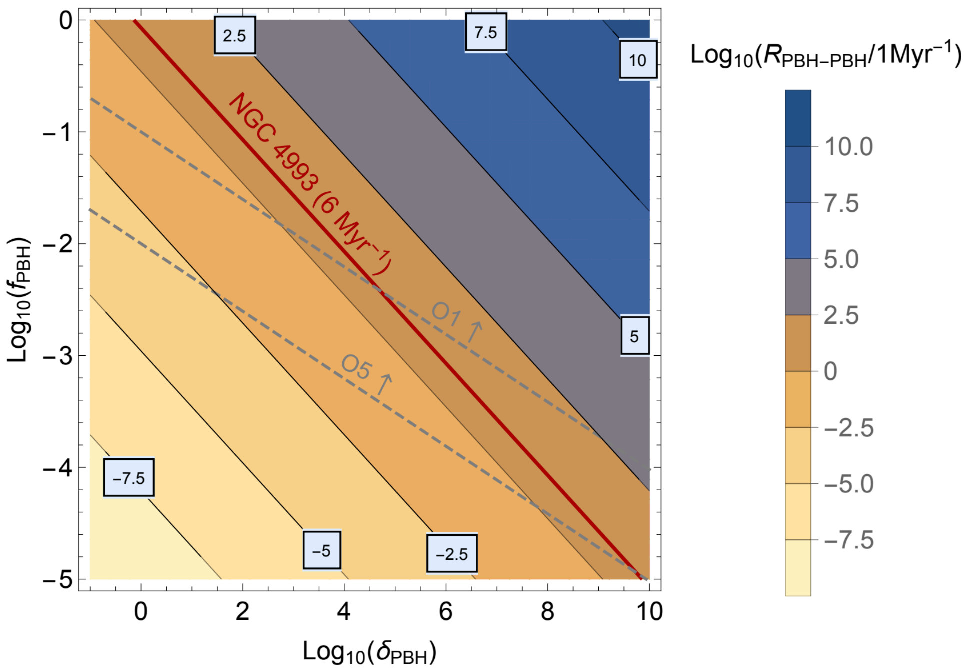
Assuming **NS implosions** are responsible for all the **r-process elements**, get the "matching" curves and constraints from setting **total NS mass ejected to ≤ 10^4 $M_\odot$ in MW.**

- The **constraints are stronger** if NS implosions only partially responsible for all r-process elements

- **Numerical simulation of the NS implosion to determine the mass ejection. (**With the help of D. Siegel**)**

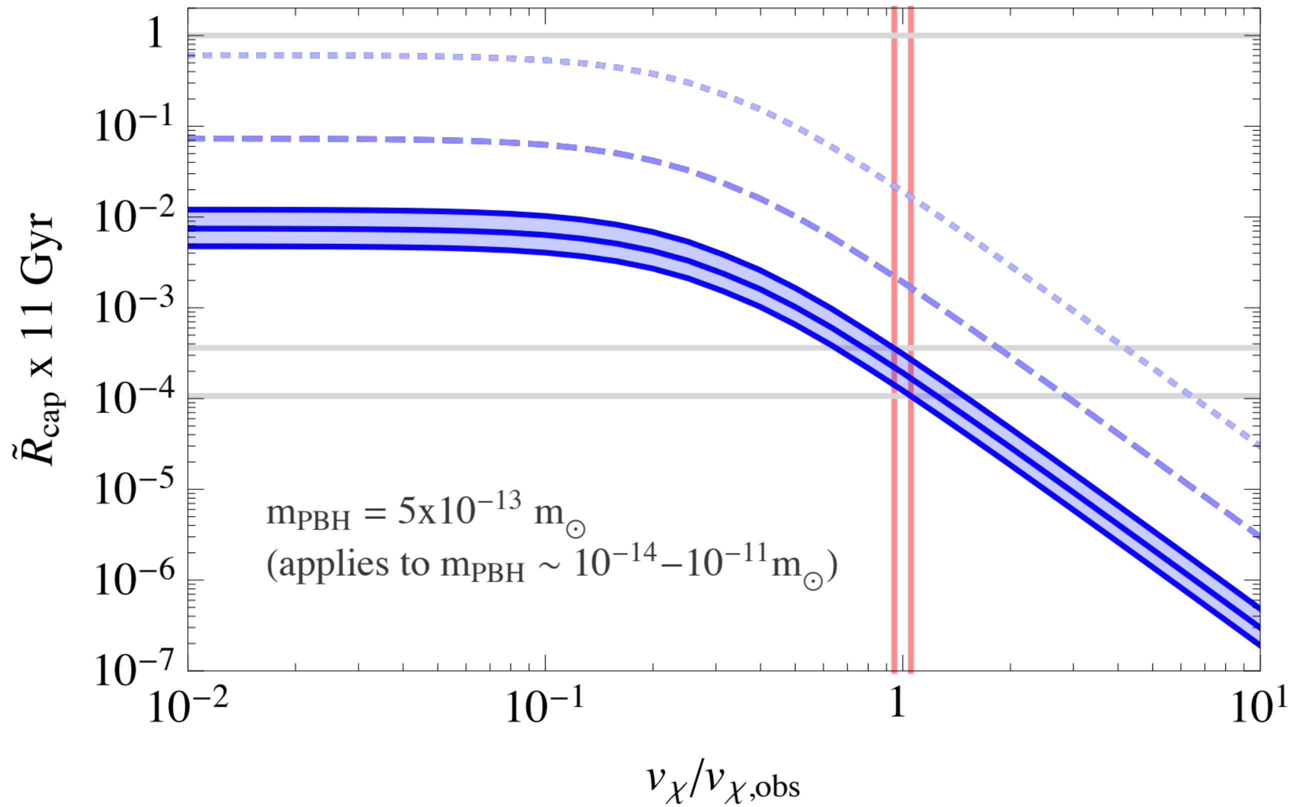
Bramante, Linden, '16 & Bramante, Linden, **YT**, '17

PBH Capture or Implosion



Tsai, Palmese, Profumo, and Jeltema, JCAP21, arXiv:2007.03686,

PBH Imploded One of NS of GW170817?



Tsai, Palmese, Profumo, and Jeltema, JCAP21, arXiv:2007.03686,