Title: Searching for Dark Matter with Neutron Star Mergers and Quiet Kilonovae

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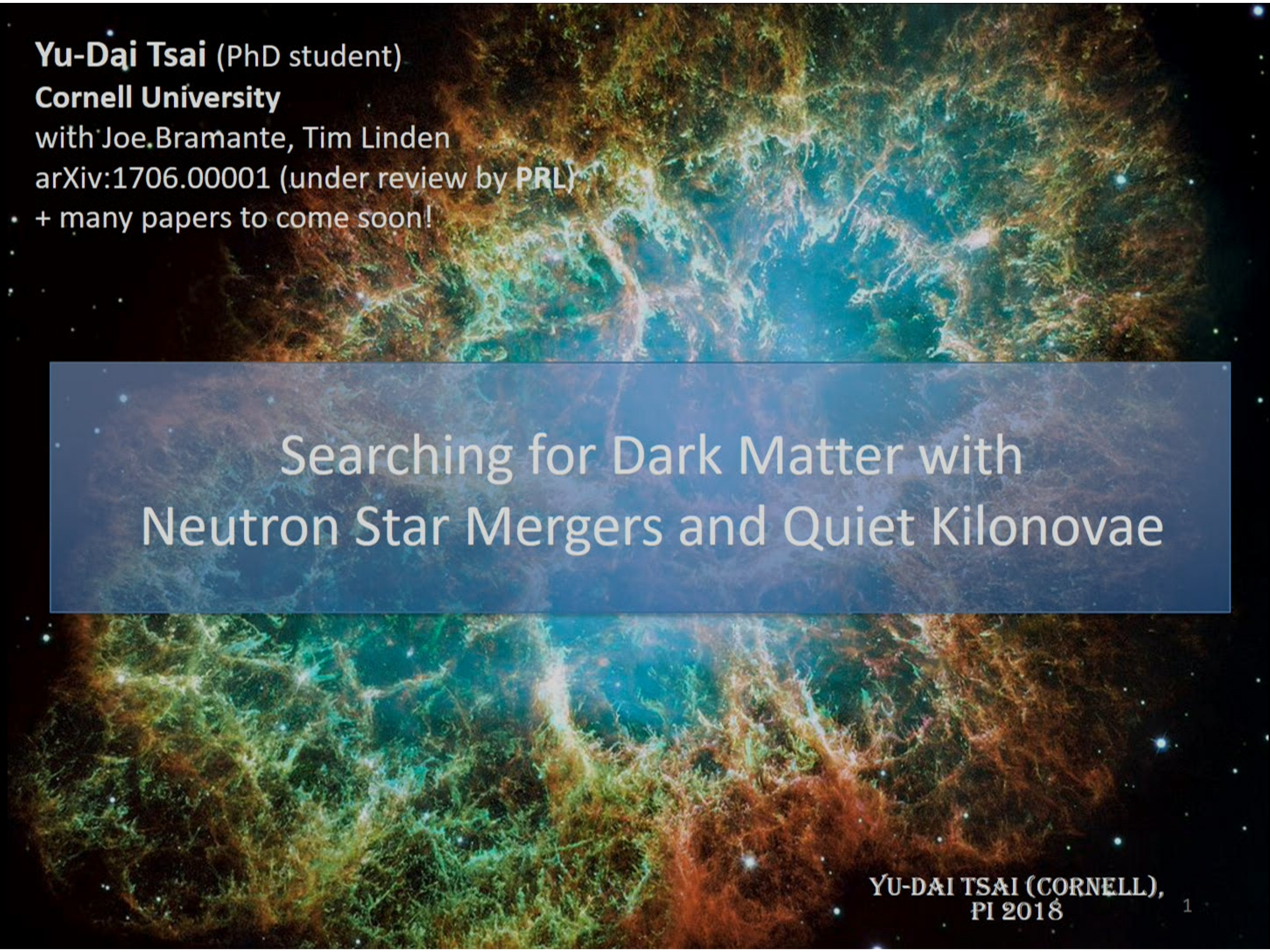
Abstract: <p>TBD.</p>

Yu-Dai Tsai (PhD student)
Cornell University
with Joe Bramante, Tim Linden
arXiv:1706.00001 (under review by **PRL**)
+ many papers to come soon!

Searching for Dark Matter with Neutron Star Mergers and Quiet Kilonovae



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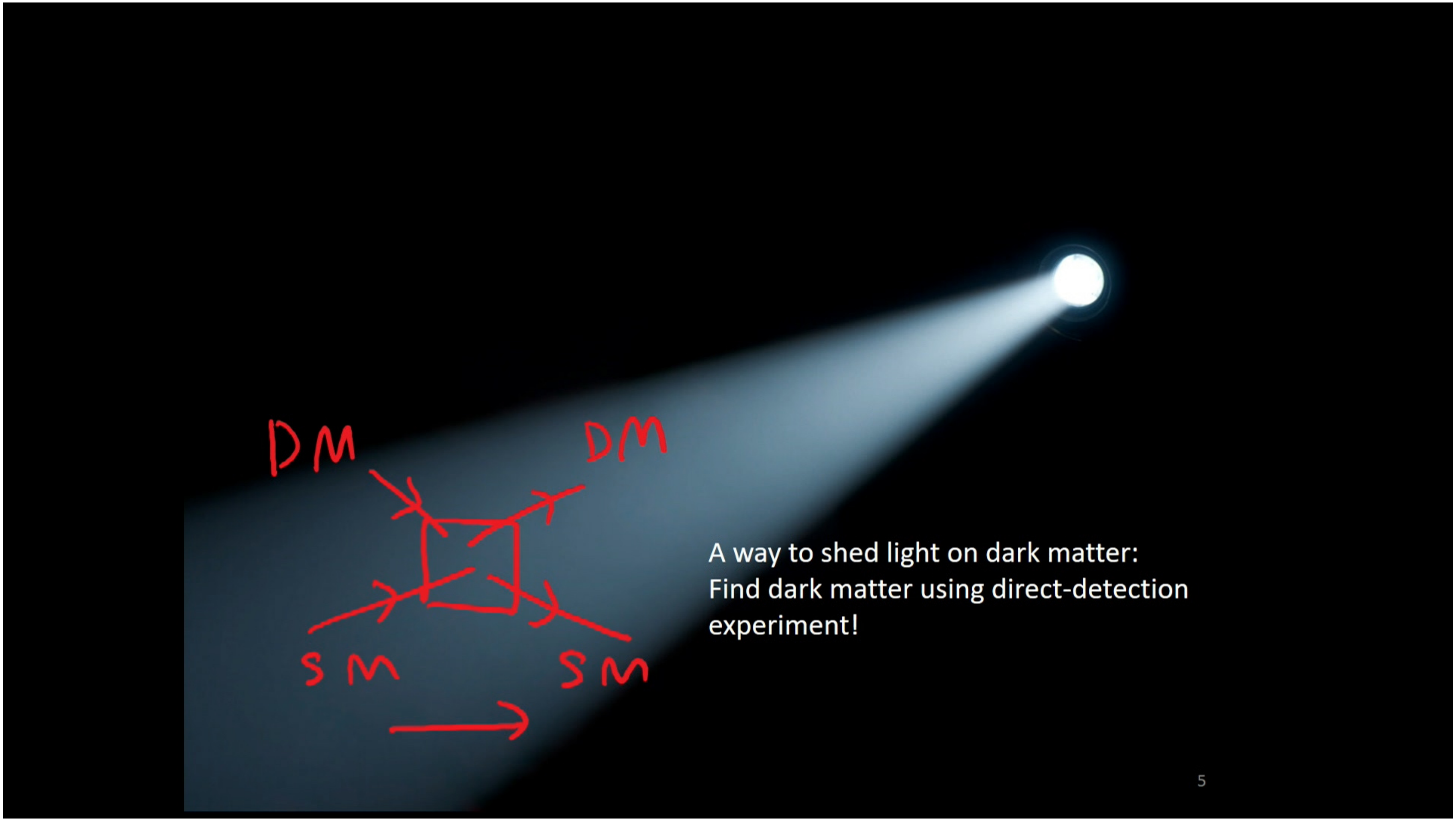
1

The most exciting time: NOW!

- A **neutron star merger** was just observed. We proposed to apply it to test **dark matter scenarios**
- Let me first give a review of our understanding of dark matter

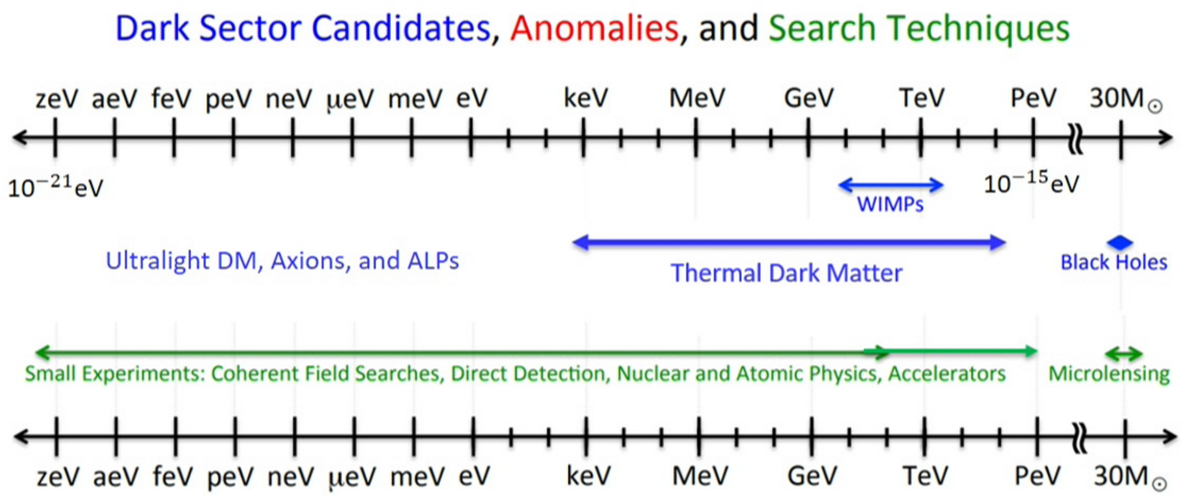
THANK N3AS FOR THE INVITATION!


Overwhelming
Observational
Astrophysical + Cosmological
Evidences
4



DM
DM
SM
SM
A way to shed light on dark matter:
Find dark matter using direct-detection experiment!
5

Dark Matter/Hidden Particles Exploration



US Cosmic Visions 2017

$M_{\odot}=2 \times 10^{30} kg$
$kg = 5.6 \times 10^{35}$ eV
$M_{\odot} = 10^{66}$ eV $= 10^{57}$ GeV

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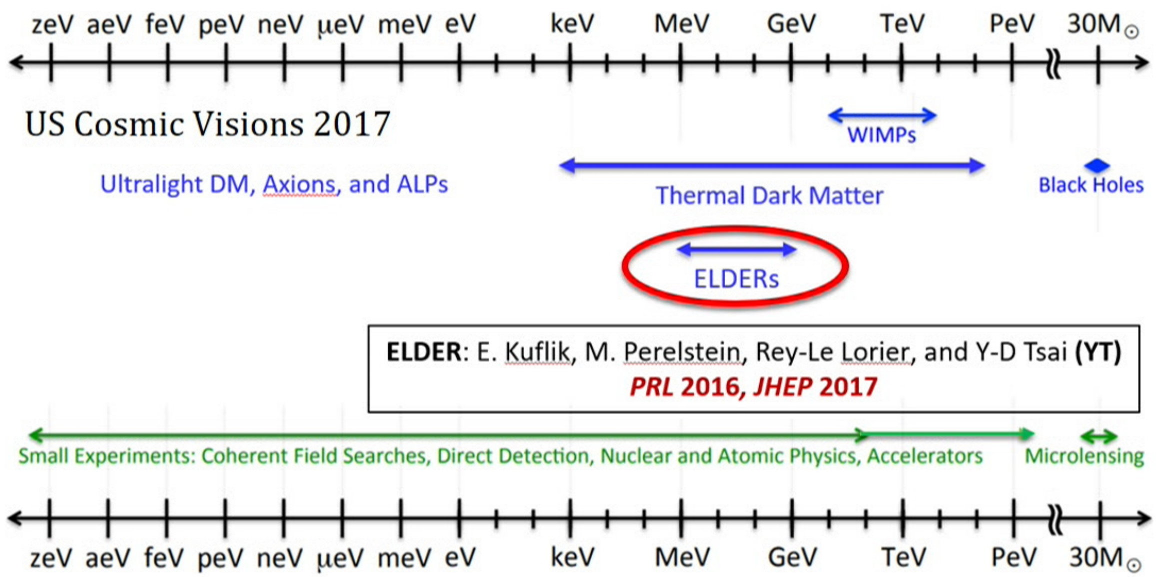
PI 2018

I mostly work on proposing **dark matter models**, considering the **experimental/observational signatures**, and **search methods for DM** & **hidden particles**

6

Dark Matter/Hidden Particles Exploration

Dark Sector Candidates, Anomalies, and Search Techniques



I spent a lot of my time on proposing/studying **Elastically Decoupling Relic (ELDER)** Dark Matter:

- Develop **code for coupled Boltzmann equations**
- **Analytical approach & Thermal averaging**
- **Experimental signatures** & **Astrophysical constraints (SN)**

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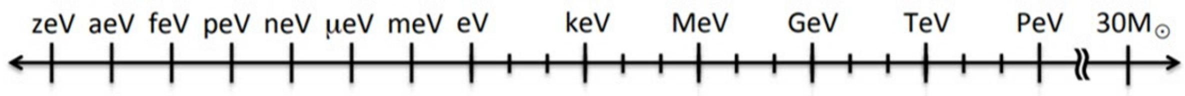
Beyond Direct Detection!

Dark Sector Candidates, Anomalies, and Search Techniques

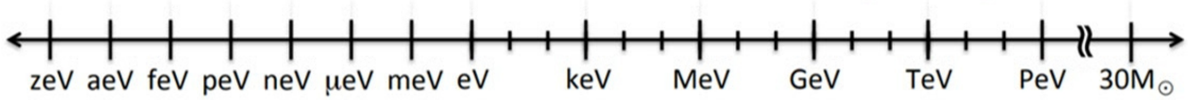


Bramante, Linden, **YT**, 1706.00001 ⟷ **PeV - EeV**

- Phenomenology of **Super-heavy ADM** and **Neutron-Star Implosion**
  Link to NS-NS Mergers!

Bramante, Raj, Baryakhtar, and others + **YT** ⟷ **keV - EeV**

- More General DM with **Neutron-Star Implosion / Neutron-Star Heating**



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Unrelated to ELDER dark matter. But DM self interaction could be interesting to consider

NEW LAMPPOSTS FROM ASTROPHYSICS

Going beyond DM Direct-detection Limits

Outline/Overview

- DM-induced Neutron Star (NS) Implosions
- Astrophysical signatures:
  - **Kilonova Events** and **r-Process Abundance**
  - Implosion optical signature – Quiet Kilonova
    speculative radio signature – Fast Radio Burst
  - Indirect signature – Black Merger
    Gravitational + optical signature – Merger Kilonova: NS merger galactic distribution
- I dreamed for a neutron star merger …

and we have it now!
GW170817 !!!!!

Golden age for neutron star phenomenology
& multi-messenger probes for new physics

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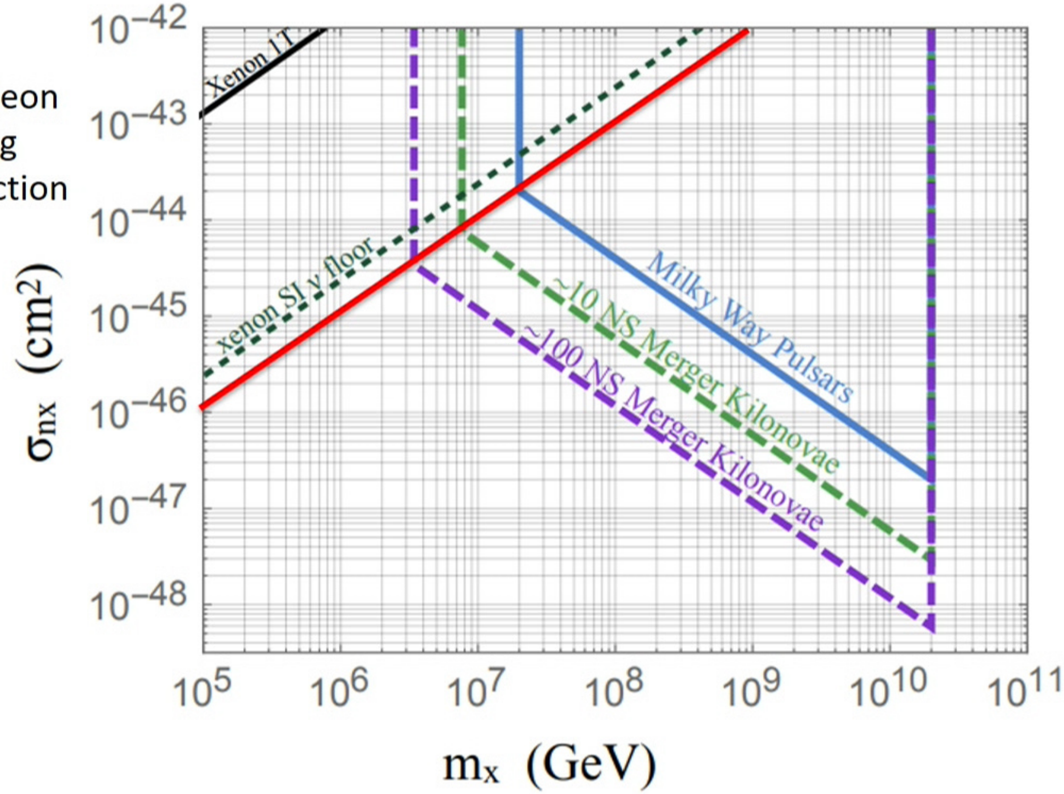
Why Neutron Star?

- Use neutron star as our direct-detection detector? It is because the density of the detector is very important! (event rate)
- The densest stars. They have densities of **10^{17} kg/m^3**
- the Earth has a density of around 5×10^3 kg/m^3 and even white dwarfs have densities over a million times less. A teaspoon of neutron star material would weigh around a billion tons.
- Almost a **black hole (BH)**, but the degeneracy pressure is keeping it from collapsing.

12

Beyond Direct Detection

DM-Nucleon Scattering Cross-section



We will focus on cross-sections above this red curve in this talk

Astrophysical Motivations for DM-induced NS Implosions

Explain Observations/Puzzles:

- Missing Pulsar Problem
  (Bertoni, Nelson, Reddy, 2013 & Bramante, Elahi, 2015)

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

- Enrichment of r-process elements
  (Bramante, Linden, 16 & Bramante, Linden, **YT**, 17, also in progress, considering recent Draco measurement)

New Astrophysical Object:

- Black Merger: NS-mass BH-BH binary merger events (Bramante, Linden, **YT**, 2017)

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.

- 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 (Bramante, **YT**, just started)

- Primordial black hole (different process), see e.g. Fuller, Kusenko, Takhistov, 17

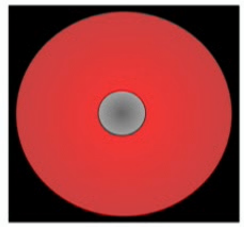
14

DM-induced NS Implosions

NS capture enough DM to potentially form black hole

1. DM captured

2. DM thermalizes

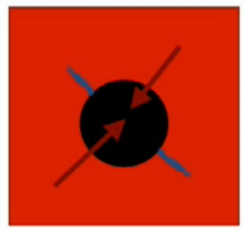


Repeated scattering: DM reach the same temperature and settle at center of neutron star

Collapse into a black hole

3. DM collapses

4. BH consumes neutron star



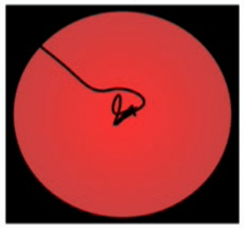
Black hole consumes the neutron star

5. Form solar mass BH

- Consider the implosion using **PeV-EeV (10^6-10^9 GeV) ADM** as an example
- **Super heavy ADM**: see e.g. Bramante, Unwin, 2017
- Other mass ranges: see e.g. Bramante, Kumar, et al. 2013, Bramabte, Elahi 2015

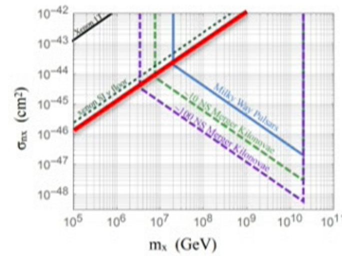
Dark Matter Capture

1. DM captured



v_x velocity
ρ_x density
in MW halo

σ_{nx} determines whether DM scatters, gets trapped



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

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

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

$t_c \propto v_x/\rho_x.$ (assume NFW profile throughout the talk)

See also Bramante, Linden, **YT,** 1706.00001
+ Bramante, Delgado, Martin, 2017 (multi-scattering)

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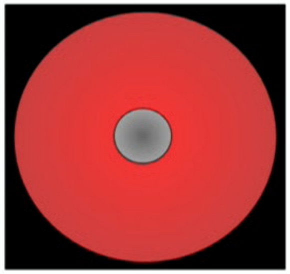
2. DM thermalizes



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

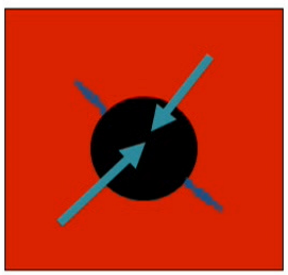
($M_{crit} \gg M_{self-gravitate}$ for PeV-EeV mass DM)

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

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

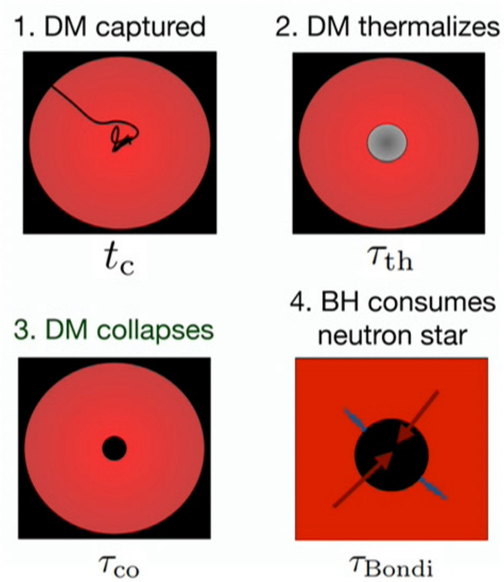
$V(\phi) = \lambda|\phi|^4$

4. BH consumes neutron star



Bondi accretion from the black hole consumes the host neutron star

Time scales



For PeV-EeV ADM:

$t_c \sim 10$ Gyrs

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

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

$\tau_{Bondi} \sim 0.1$ yrs

Bramante, Linden, **YT**, 1706.00001

Normalized Implosion Time (NIT)

PeV-EeV ✓ **Heavy** dark matter, fermionic or bosonic — fewer particles required for collapse.

For $\sigma_{nx} \gtrsim 10^{-45}\text{cm}^2 \left(\frac{m_x}{\text{PeV}}\right)$, $\quad b_{\max} = \left(\frac{2GMR}{v_\text{x}^2}\right)^{1/2} \left(1 - \frac{2GM}{R}\right)^{-1/2}.$

$t_\text{c} \propto v_\text{x}/\rho_\text{x}$. We propose this **normalized implosion time**,

$$t_\text{c}\frac{\rho_\text{x}}{v_\text{x}} = \text{Constant} \times \left[\text{Gyr}\ \frac{\text{GeV/cm}^3}{200\ \text{km/s}}\right]$$

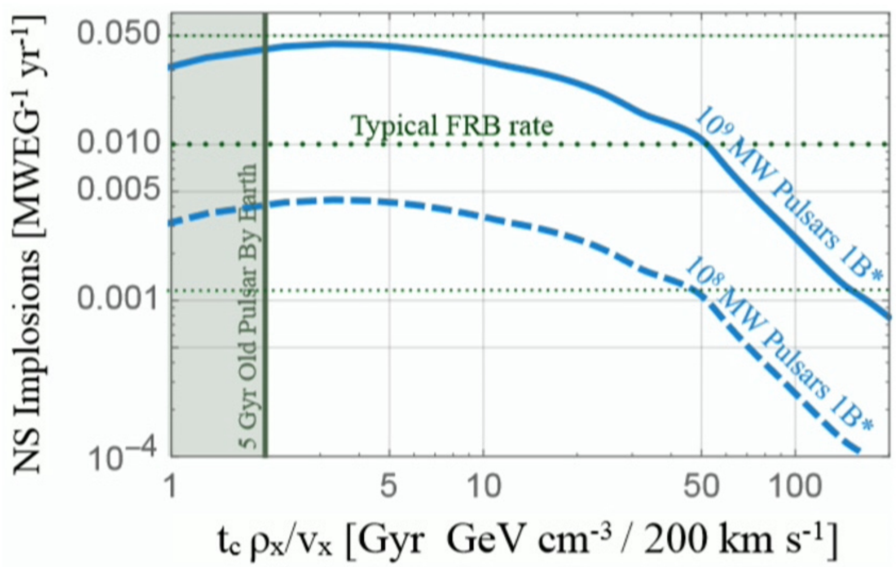
Fermion:
$$t_\text{c}\frac{\rho_\text{x}}{v_\text{x}}\bigg|_\text{f} = \left(\frac{10\ \text{PeV}}{m_\text{x}}\right)^2 15\ \text{Gyr}\ \frac{\text{GeV/cm}^3}{200\ \text{km/s}}$$

Boson:
$$t_\text{c}\frac{\rho_\text{x}}{v_\text{x}}\bigg|_\text{b} = \left(\frac{\lambda}{1}\right)^{1/2} \left(\frac{3\ \text{PeV}}{m_\text{x}}\right)^2 20\ \text{Gyr}\ \frac{\text{GeV/cm}^3}{200\ \text{km/s}},$$

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

Colpi, Shapiro, and Wasserman, 1986 $\quad V(\phi) = \lambda|\phi|^4$

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



Bramante, Linden, **YT**, 2017

MWEG: Milky Way Equivalent Galaxy $\sim (4.4\ \mathrm{Mpc})^3$

Incorporates NS birthrates in Milky Way, capture rate for position in galaxy

Could match **FRB energy/rate (Fuller & Ott, 2014)**

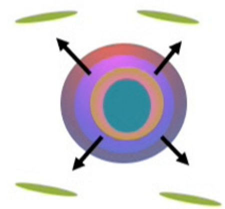
R-PROCESS AND KILONOVA

Preferred/Constrained
NS Implosion Parameter Space

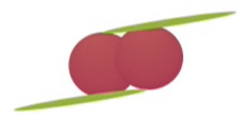
r-Process (Rapid Neutron Capture Process)

<u>Postulated</u> r-process sources:

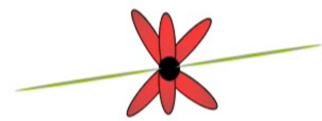
- Core collapse supernovae



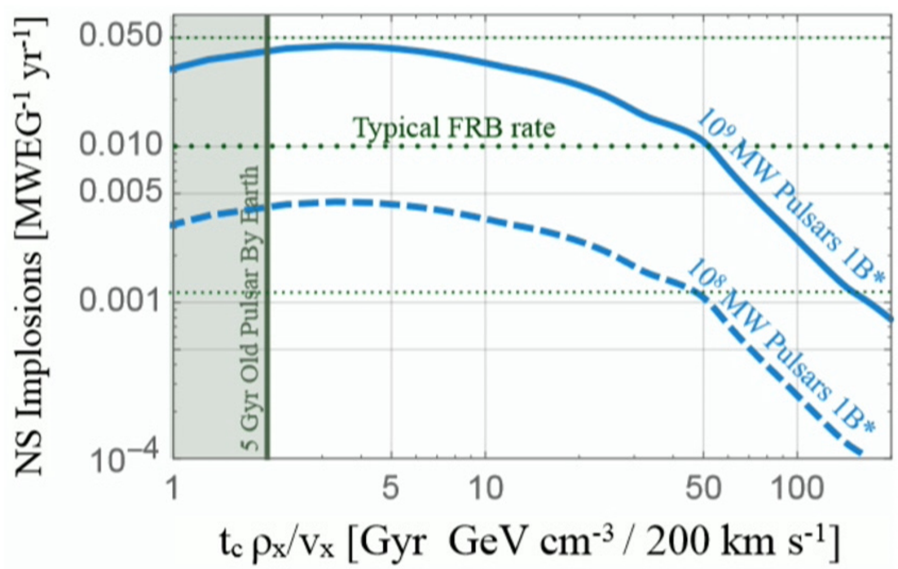
- Merging neutron star binaries



- Neutron star implosion tidally ejects neutron star fluid (rate see e.g. 1706.00001)



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



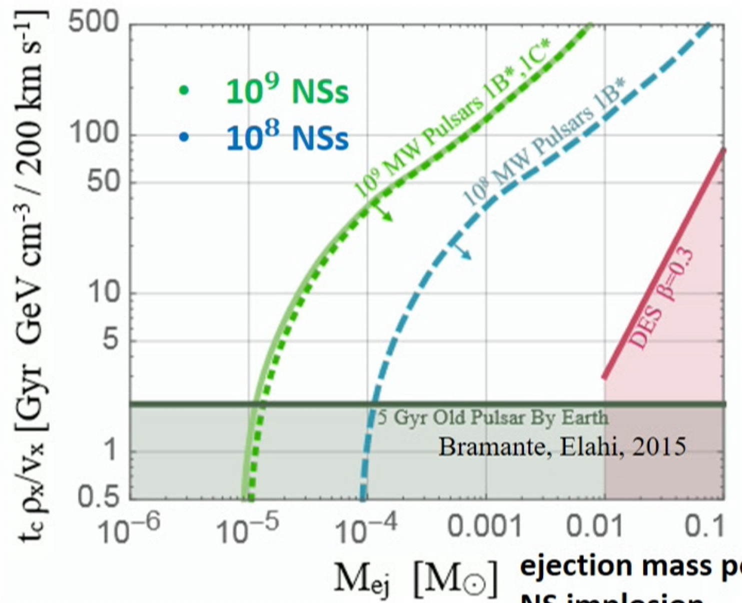
Bramante, Linden, **YT**, 2017

MWEG: Milky Way Equivalent Galaxy $\sim$ (4.4 Mpc)^3

Incorporates NS birthrates in Milky Way, capture rate for position in galaxy

Could match **FRB energy/rate (Fuller & Ott, 2014)**

r-Process Element Abundance & Bounds



ejection mass per NS implosion

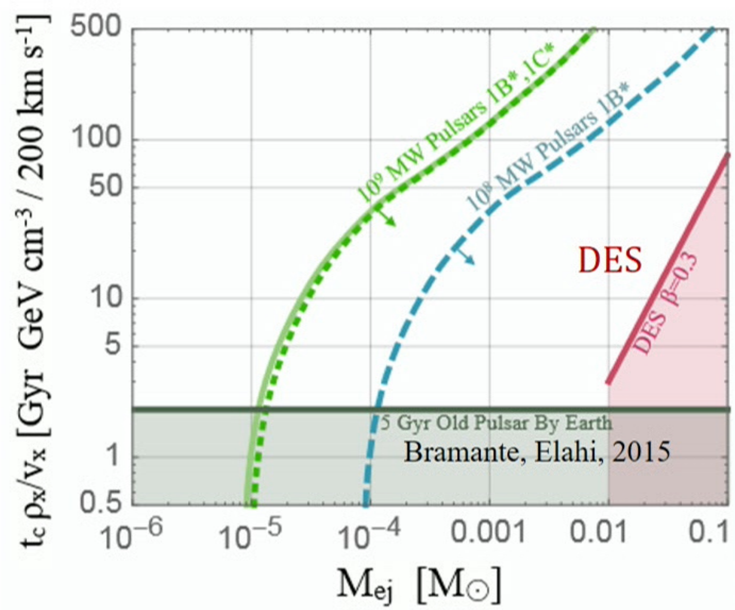
The **constraints are stronger** if NS implosions only partially responsible for all r-process elements

If **NS implosions** are responsible for all the **r-process elements**, we have the "matching" curves and constraints set by requiring **total NS mass ejected to ≤ 10^4 $M_\odot$ in the Milky Way.**

- **x-axis: ejection mass per NS implosion**
- **y-axis: implosion parameter $t_c\rho_x/v_x$**
- **Plan to develop numerical simulation of the NS implosion**

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

Kilonova Bound



x-axis: ejecta mass per NS implosion
y-axis: implosion parameter $t_c \rho_x / v_x$

Bramante, Linden, **YT**, 2017

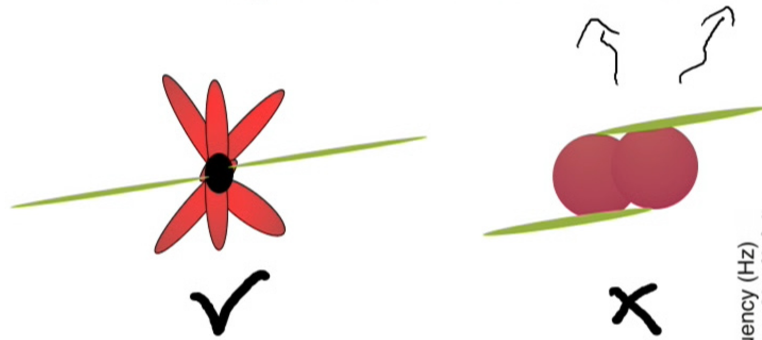
Kilonova light curves depend mainly on the **mass** and **velocity** of NS fluid ejected (Barnes & Kasen, 2013)

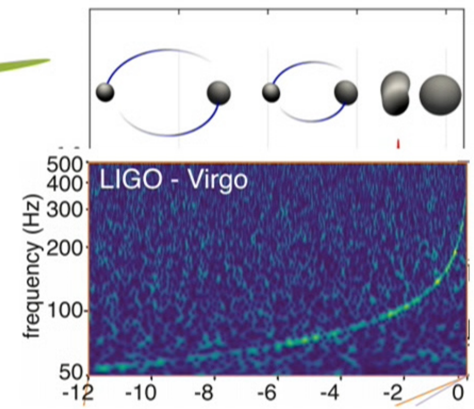
- **Dark Energy Survey (DES)** published a null wide field optical search for kilonovae (Doctor et al., DES, 2017)
- We set **bounds from (not-seeing) kilonova events by DES,** assuming **ejection velocity β = 0.3c**
- **The kilonova bound may eventually exclude the r-process matching curves**

QUIET KILONOVA AND ITS MORPHOLOGY

Optical Signature from NS Implosions

Quiet Kilonova





Abbott et al., LIGO/VIRGO, PRL 2017

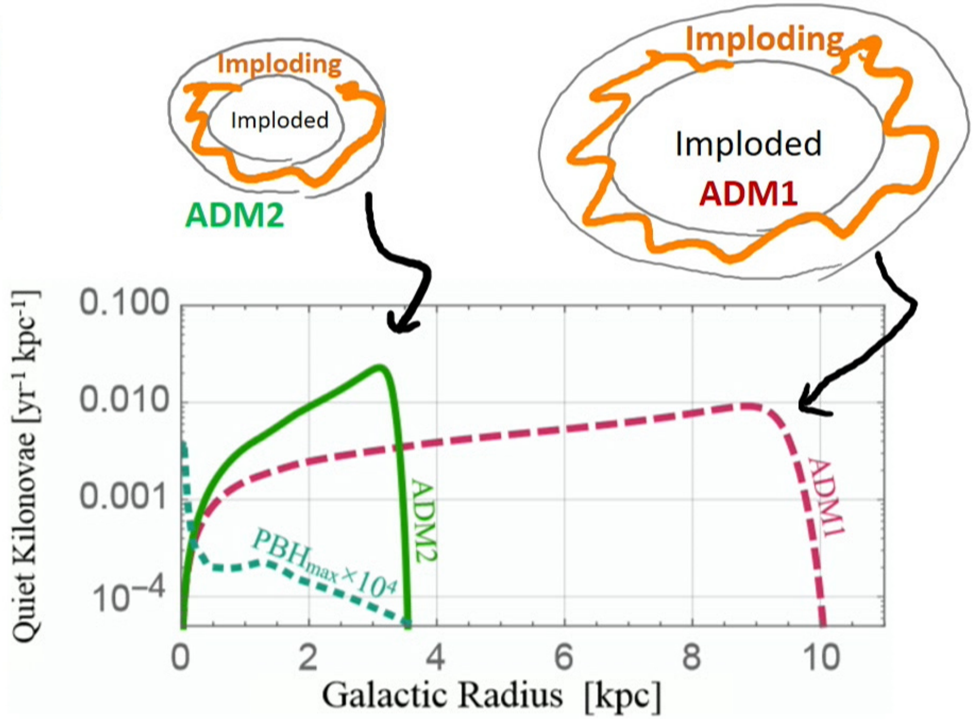
Quiet Kilonova:

- **Kilonova events from NS implosions**, but NOT from the NS-NS or NS-BH mergers.
- **WITHOUT detectable inspiral/merger signatures**, so we call them "Quiet Kilonova" (Bramante, Linden, **YT**, 2017)

Quiet Kilonova/NS Implosion Morphology

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

- **ADM1 implosion faster than ADM2;**
- **ADM1 is the larger donut;**
- **DM use NFW profile.**
- Finding them with the assist of **FRBs** (Fuller and Ott,2014, Bramante, Linden, **YT**, 2017, new work in progress)



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)$^{-1}$

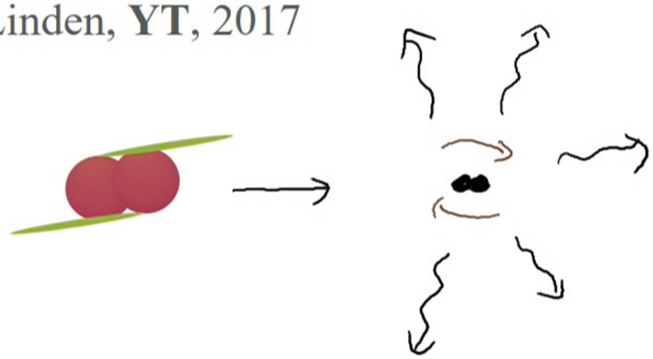
Bramante, Linden, **YT**, 2017

BLACK MERGER

Gravitational-wave Signature form
Converted NS-NS Merger

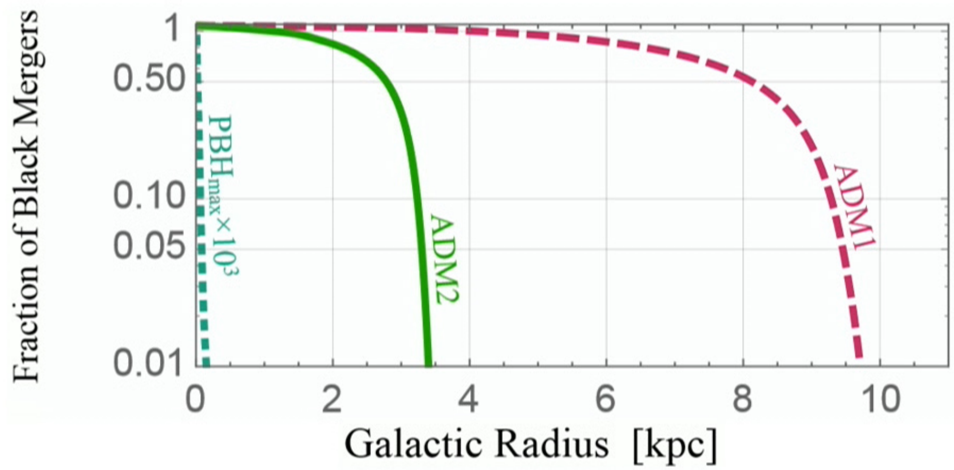
G-Wave Signature: Black Mergers

- **There is a postulated mass gap between lightest BH and heaviest NS (< 3 $M_\odot$)**
- Black Hole (BH) mass: BH (> 8 $M_\odot$) and BH-BH mergers are (>18 $M_\odot$) observationally
- NS-NS mergers are converted into BH-BH mergers, creating **m ~ 2 - 3 $M_\odot$ (neutron-star-mass) BH-BH mergers**, violating the putative mass gap.
- These are **NS-mass** merger events WITHOUT optical follow-on, we call them **"Black Mergers".**
- Bramante, Linden, **YT**, 2017



32

G-Wave Signature: Black Mergers



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

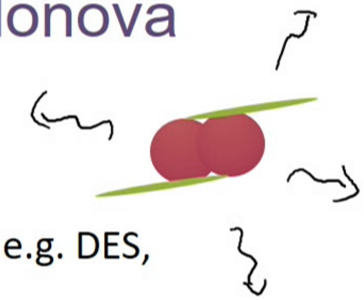
ADM2: $t_c \rho_x / v_x = 15$ Gyr/cm^3(200 km/s)$^{-1}$

- **No NS-NS merger in the Galactic Center**
- Can use **LIGO/Virgo** to see merger signatures, that are without optical signatures by **BlackGEM** telescope
- **Not easy to confirm a black merger**
- Bramante, Linden, **YT**, 2017, Yang, East, Lehner, (PI) 2017

MERGER KILONOVA (NS-NS MERGER DISTRIBUTION)

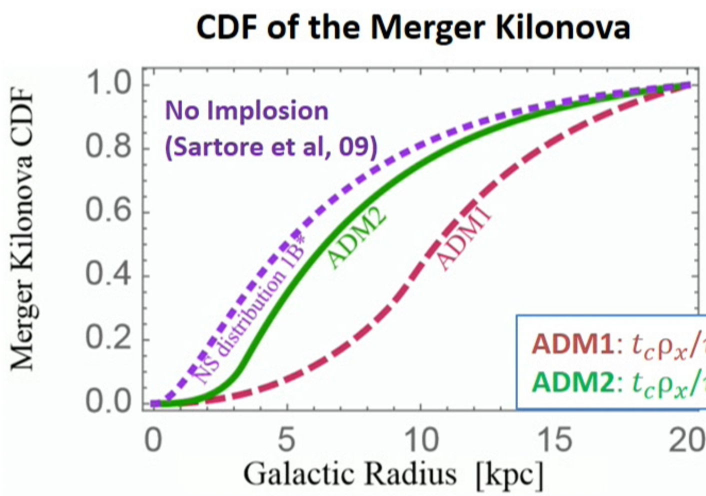
Using the altered NS-NS galactic merger distribution to test DM-induced implosions

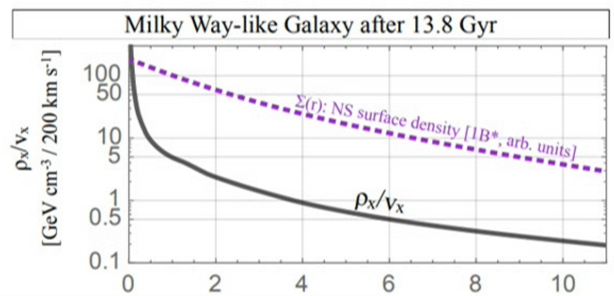
Combined Signature: Merger Kilonova



Merger Kilonova: NS-NS mergers

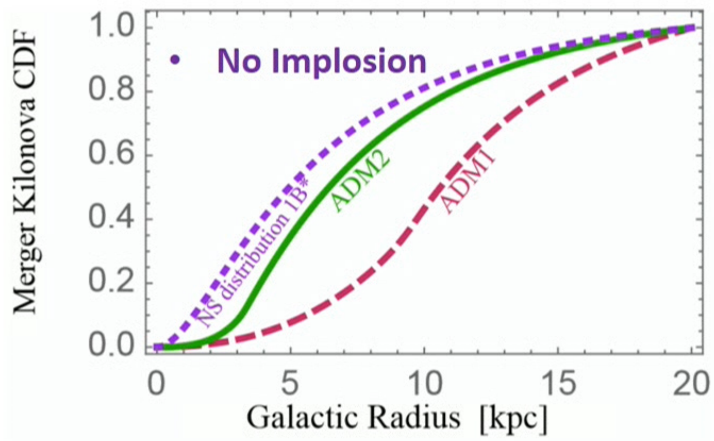
- Merger signatures detectable by LIGO/Virgo
- The associated Kilonova signature can be confirmed by, e.g. DES, BlackGEM, ZTF, …
- Having *Black Mergers* means the usual NS-NS(BH) mergers have the **distributions altered by NS implosions**

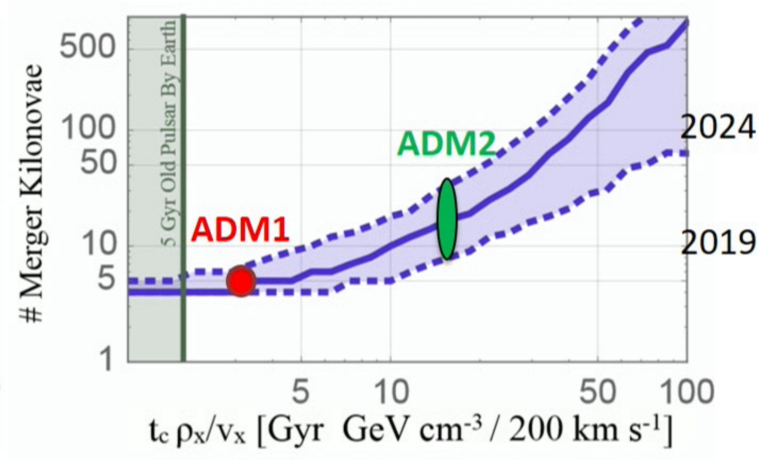




ADM1: $t_c\rho_x/v_x$ = 3 Gyr/cm^3(200 km/s)$^{-1}$
ADM2: $t_c\rho_x/v_x$ = 15 Gyr/cm^3(200 km/s)$^{-1}$

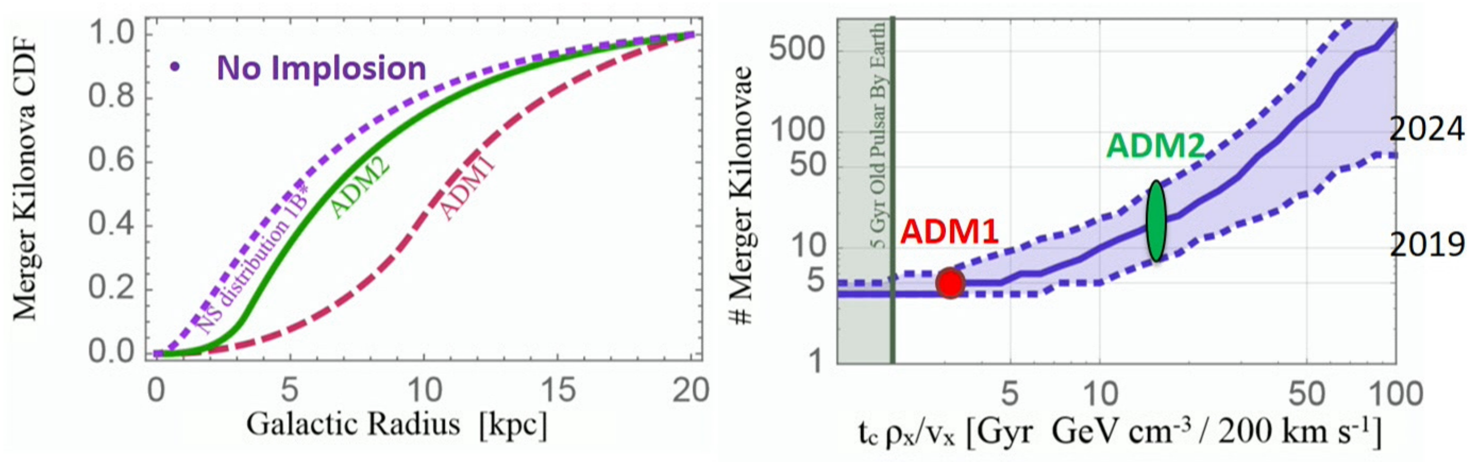
Statistics of Merger Kilonova Events





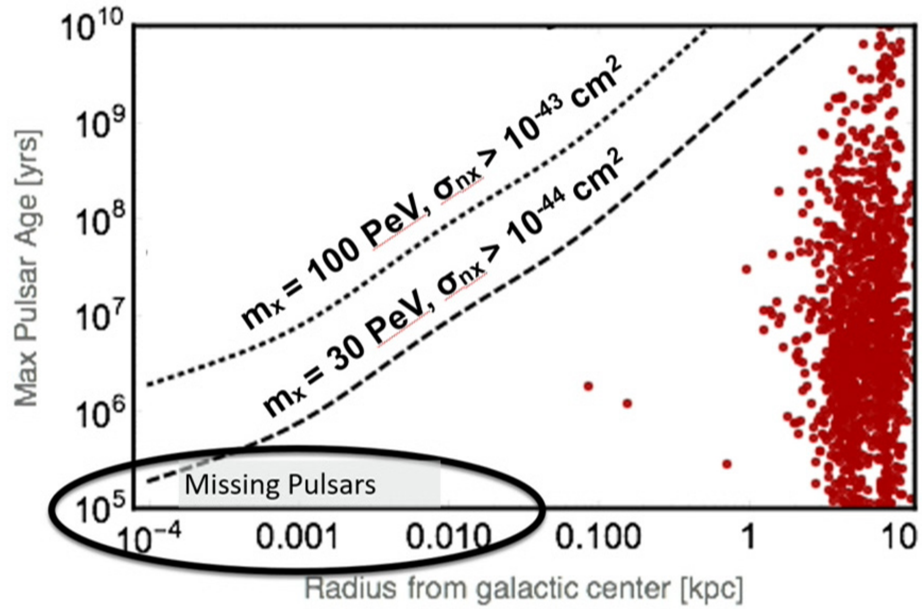
- Apply K-S test for randomly generated events based on the implosion parameter $t_c\rho_x/v_x$
- (Right) **Purple band** indicate number of events needed for **2σ significance** in testing the ADM model parameters
- Dashed: upper and lower quartile; **Solid**: the median based on the repeated experiments.
- **Different NS-distribution models does not change the result much**
- This was done just for MWEG with NFW profile.
- Different galaxy would need modification (e.g. NGC 4993 elliptical galaxy)

Statistics of Merger Kilonova Events



- Apply K-S test for randomly generated events based on the implosion parameter $t_c \rho_x / v_x$
- (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.
- Can use **pulsars** to do the similar analysis, but hard to see near the center. NS implosion consistent with “missing pulsar problem”

Dark Matter and Maximum Pulsar Age Curves

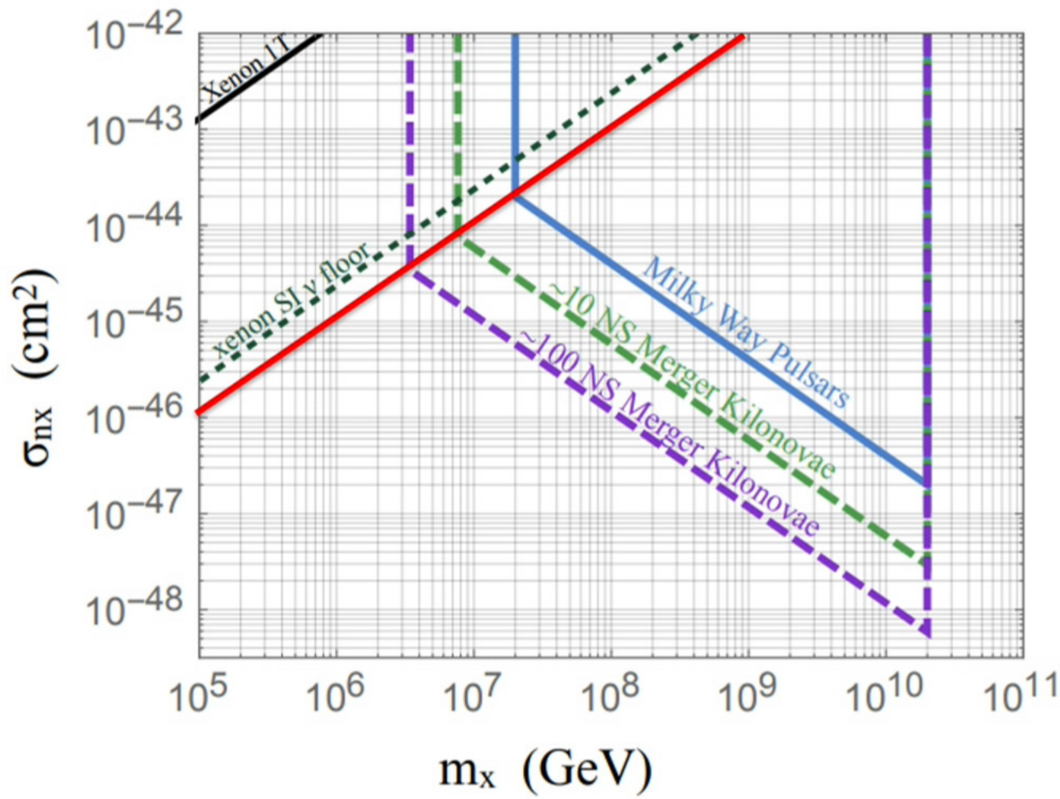


- **ATNF Pulsar Catalogue Overlaid, ages from pulsar timing**

- 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!**

- Milky Way's 1-500 pc center surveyed in the next decade by FAST, SKA.

Beyond Direct Detection



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FAST RADIO BURSTS

A Possible Radio Signature

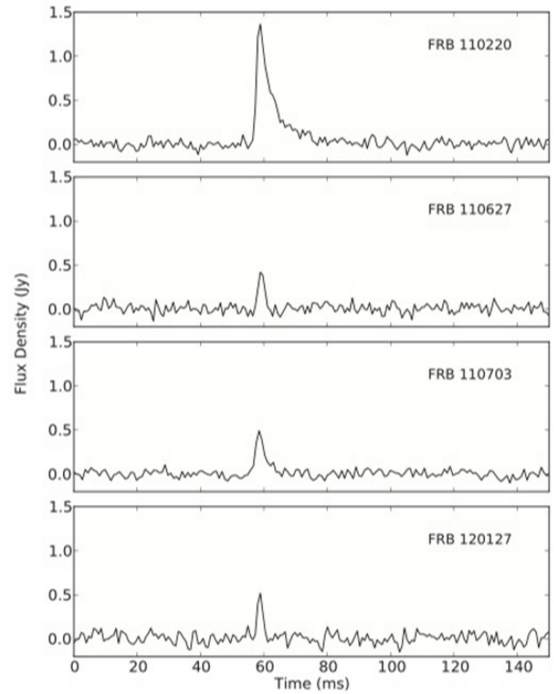
Fast Radio Burst and DM Implosions

Fast radio bursts (FRBs) from DM:

- millisecond-length & $\sim$Ghz radio pulses
- all sky rate $\sim 10^4$/day.
- The source is not determined.

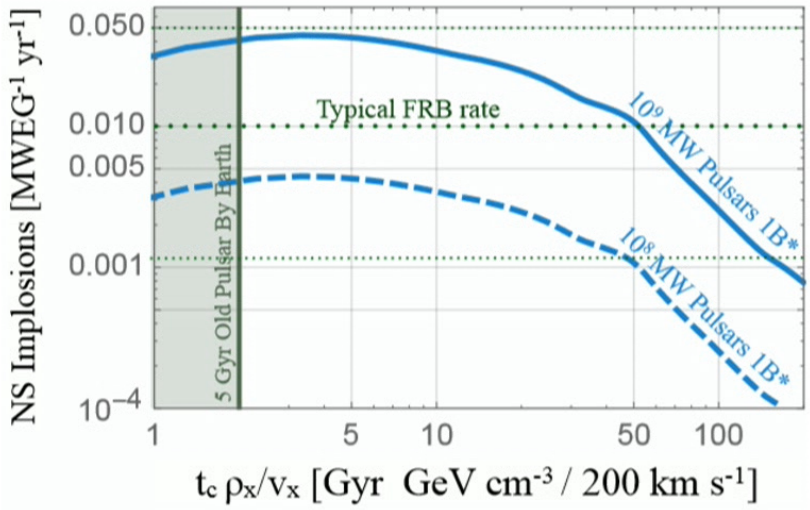
- DM-induced NS implosions may be the source of FRBs.
- The EM energy released by a NS implosion could match what is required for an FRB [Fuller and Ott, 2014].

❖ **We improve on the rate calculations by using a realistic star formation history [Hopkins and Beacom, 06] and NS distribution [Sartore et al, 09]**



- Thornton et al., 2013

Match NS Implosion Rate to the FRB Rate



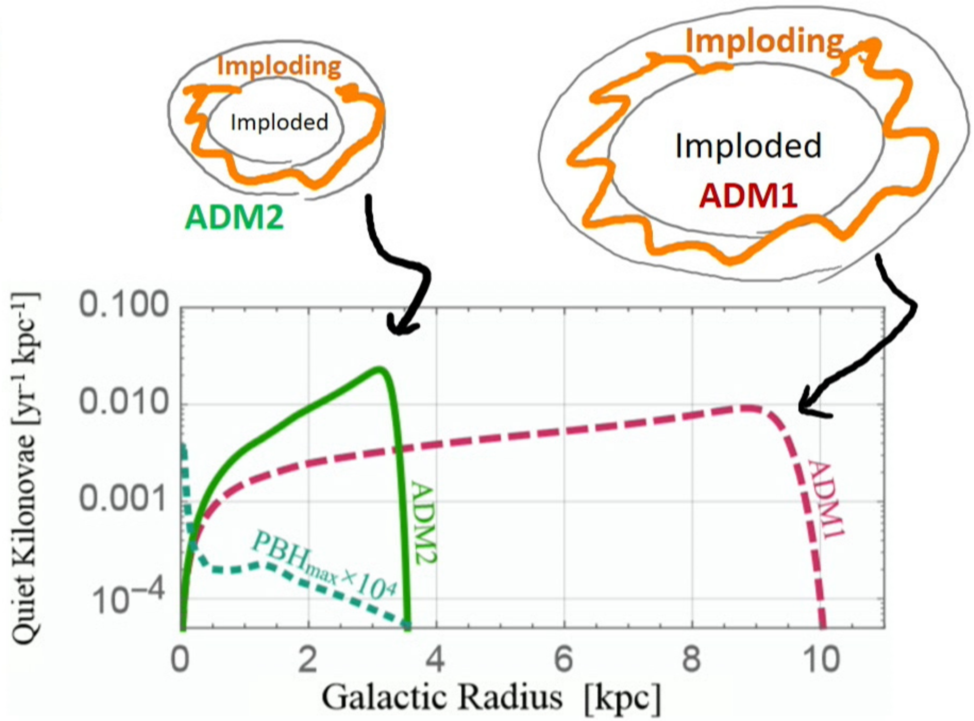
Incorporate **NS birthrates** in Milky Way
& **capture rate** for given position in galaxy

Bramante, Linden, **YT**, 2017

- The dotted lines indicate high, median, and low **FRB** rate estimates from surveys [arXiv: 1505.00834 and 1612.00896].

FRB/NS Implosion Morphology

… or **"FRB Donut"**



- **ADM1 implosion faster than ADM2;**
- **ADM1 is the larger donut;**
- **DM use NFW profile.**
- Finding **Quilonova** with the assist of **FRBs** (Fuller and Ott, 2014, Bramante, Linden, **YT**, 2017, new work in progress)

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

Linking FRBs to NS-Implosions

- The energy contained in the magnetosphere can be estimated as

$$E_M \sim 10^{42}\,\mathrm{erg}\,B_{12}^2,$$

- where B_{12} is the dipole field strength in units of 10^{12} G.
  The radio emission from the NS implosion scenario is similar to that described in Falcke & Rezzolla (2014) (FR14), examining **the collapse of an isolated and magnetized supramassive rotating neutron star (SURON)** to a BH.

- **During the collapse, electrons/positrons bound to field lines generate coherent radiation as the field reconfigures. If $\sim 10^{-3}$ of the field energy is emitted as radiation near GHz frequencies, an FRB can be generated** (Fuller & Ott, 2014)**.**

Linking FRB to NS-Implosions

- To describe the emission, they use a basic relativistic curvature radiation model (Gunn & Ostriker 1971; Ruderman & Sutherland 1975) over radius R (R = r_{10} 10 km its radius)

$$\nu_{\rm curv} = \frac{3c\gamma^3}{4\pi R} \simeq 7.2\,\gamma^3\,r_{10}^{-1}\ \ {\rm kHz}\,.$$

- However, for the radio emission to propagate through the plasma, the radiation has to be above the plasma frequency for a e+ /e − pair plasma:

$$\nu_{\rm p} = \frac{\omega_{\rm p}}{2\pi}\ \sim 40\ {\rm GHz}$$

$$\gamma_{\rm min} \gtrsim 175.3\ .$$

45

Linking FRB to NS-Implosions

- Also, requiring that no more power is radiated than is available in the magnetosphere as discussed in FR14, one need to require that the fraction of relativistic electrons with $\gamma \geq \gamma_{min}$ should not be higher than

$\eta_{e,max} \lesssim 0.3\,\%$ $\gamma_{min} \gtrsim 175.3$

- E.g. if we assume that the **energy distribution of electrons in the shock front** is a power-law of the form

$$dN_e(\gamma)/d\gamma \propto \gamma^{-p},$$

with $1 < \gamma < \infty$,

$$\eta_{e,max} = N(\gamma \geq \gamma_{min})/N(\gamma \geq 1) = \gamma_{min}^{1-p}.$$

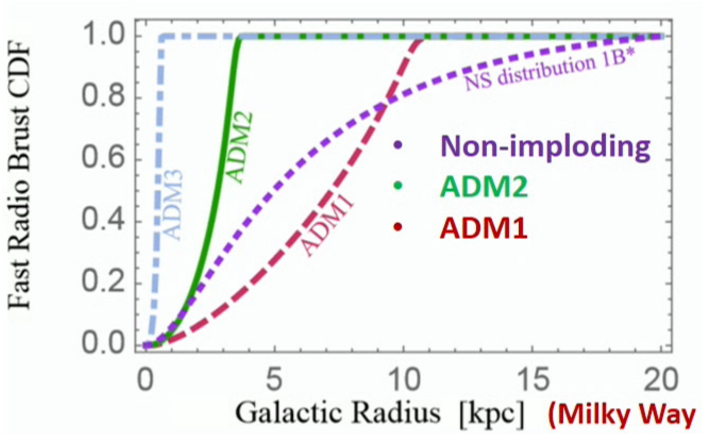
- Hence, after requiring that $\gamma_{min} \geq 175$ and that $\eta_{e,max}$ <0.3%, it was concluded conclude that $p \geq 2.1$ as a electron distribution criterion for the FRB.

46

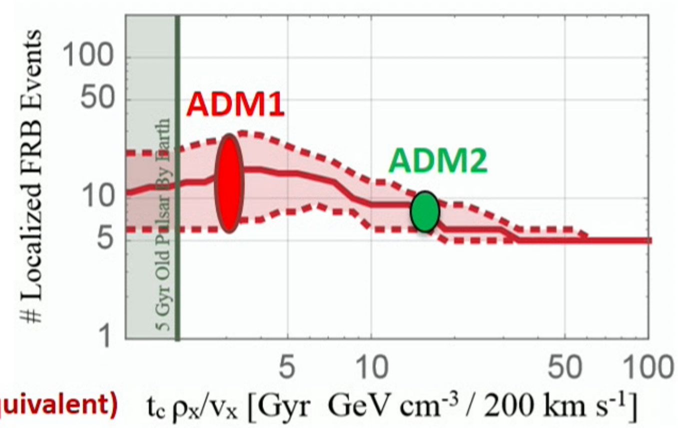
Statistics of Located FRBs (+Quilonova)

- FRB caused by **DM-induced NS-implosions** **vs** FRB come from a **non-imploding population of NSs**, at 2σ significance.
- Need localized to ~ **1 kpc** in a host galaxy
- FRBs could possibly be **located** by

CHIME - The **C**anadian **H**ydrogen **I**ntensity **M**apping **E**xperiment &
HIRAX- The **H**ydrogen **I**ntensity and **R**eal-time **A**nalysis e**X**periment



(Milky Way Equivalent)



Bramante, Linden, **YT**, 2017

FRB donuts

ADM2 ADM1

47

Outlook

- Future astrophysical observations:
  - **Kilonova events** seen by telescopes like **Dark Energy Survey (DES), BlackGEM and ZTF**
  - **Merger signatures** by **LIGO/Virgo**
  - **located FRBs** by radio arrays like CHIME and HIRAX

  can be applied to test the DM implosion scenarios, in the **next few years**.
- **Extend to a wider mass-range and coupling strength.**
- **Many other rich phenomena one could explore!**

Astrophysical Motivations for DM-induced NS Implosions

Explain Observations/Puzzles:

- Missing Pulsar Problem
  (Bertoni, Nelson, Reddy, 2013 & Bramante, Elahi, 2015)

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

- Enrichment of r-process elements
  (Bramante, Linden, 16 & Bramante, Linden, **YT**, 17, also in progress, considering recent Draco measurement)

New Astrophysical Object:

- Black Merger: NS-mass BH-BH binary merger events (Bramante, Linden, **YT**, 2017)

Outlook

- Future astrophysical observations:
  - **Kilonova events** seen by telescopes like **Dark Energy Survey (DES), BlackGEM and ZTF**
  - **Merger signatures** by **LIGO/Virgo**
  - **located FRBs** by radio arrays like CHIME and HIRAX

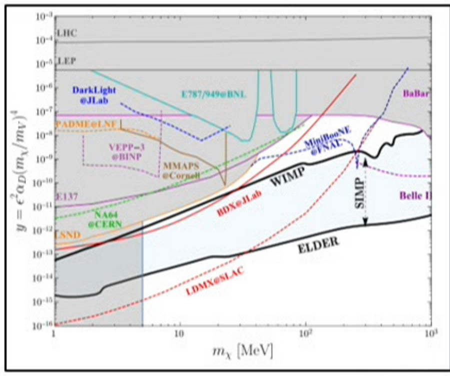
  can be applied to test the DM implosion scenarios,

  in the **next few years**.
- Study **Topological Defects (GUT)**, **Q-ball (SUSY)** models!
- Plan to think about **neutrino signatures**

Outlook

- Understanding **neutron star** and **nuclear physics** better!
- The golden age of **neutron star phenomenology** (no pun intended)
- **Multi-messenger Astrophysical Probes** for **New Physics**: Imagine O(100) SN 1987A
- NS implosion/collapse simulation

The dark photon-DM constraints & forecast, also shown by Prof. Hitlin



Ongoing Research

I'm Yu-Dai Tsai, a 5th year PhD student

1 Sub-GeV Thermal DM

- Perelstein
- Kuflik
- Lorier
- Slatyer
- Xue
- Liu

- **ELDER** / ELDER + **NFDM**
- Experimental /Observational Signatures
  - 1512.04545,1706.05381...

2 ν Hopes for New Physics

- Maxim Pospelov
- Gabriel Magill
- Ryan Plestid

Constraints and signatures of new physics in **neutrino detectors**, including **BoreXino**, **LSND**, SBND, Mini/MicroBooNE, and SHiP

-arXiv: 1706.00424 ...

3 New Lampposts from Astrophysics

- Joseph Bramante
- Tim Linden

Constraints and Probes of **ADM** (and PBH) models through astrophysical observations

- arXiv: 1706.00001 ...

'We are all in the gutter, but some of us
are looking at the stars.'
– Oscar Wilde, on searching for new physics

Thanks you! Special thanks go to Joe and Tim.

Thank Angelika and Luis for the invitation,
and thank everyone for this interview!

NASA/CXC/UMASS/D. WANG ET AL./STSCI/JPL-PI/SSC/S.STOLOVY

YU-DAI TSAI (CORNELL), PI 2018

53