Title: Optical, Gravitational, and Radio Signatures of DM-induced Neutron Star Implosions

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Abstract:

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with Joe Bramante, Tim Linden
arXiv:1706.00001

# Optical, Gravitational, and Radio Signatures of DM-induced NS Implosions

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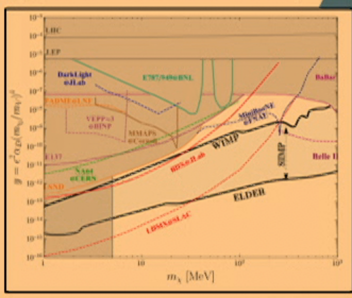
# Ongoing Research

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

The dark photon-DM constraints & forecast (in Adam or Eder's talk)



## 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 ...

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# Outline

- Intro to DM-induced neutron star (NS) implosions
- Astrophysical Signatures:
  - Kilonova Events and r-Process Elements
  - Optical Signature
  - Gravitational Signature
  - Optical + Merger Signature
  - Radio Signature
- Conclusion and Outlook

# NS Implosion & Asymmetric Dark Matter

- Asymmetric Dark Matter (ADM): dark matter with particle/anti-particle asymmetry, often linked to baryon / lepton asymmetry.

- The asymmetry often sets the DM relic abundance.

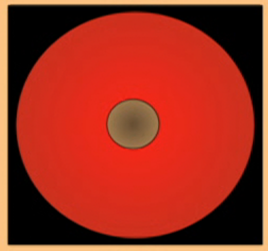
- Dark matter asymmetry allows efficient collection and collapse in stars without annihilating to lighter particles
- See e.g. Goldman and Nussinov 1989, Kouvaris and Tinyakov 2010, Lavallaz and Fairbairn 2010, Kouvaris 2011, …

- Primordial black holes (PBHs) could also implode NSs through a different process, but among the signatures we study they only have negligible effects, details see arXiv:1706.00001.

# DM-induced NS Implosions

1. DM captured

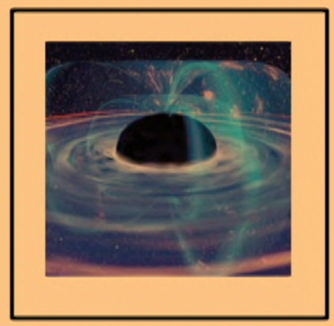
2. DM thermalizes



3. DM collapses

4. BH consumes neutron star

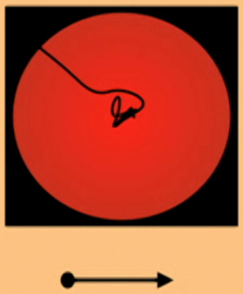
**5. Form solar mass BH**



- Go through the process using **PeV-EeV ($10^{15}$-$10^{18}$eV) DM** as an example
- **Superheavy 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

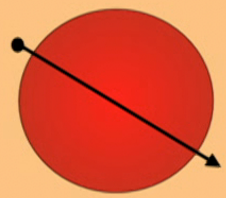


$v_x$ velocity
$\rho_x$ density
in MW halo

For $\sigma_{nx} \gtrsim 10^{-45}\text{cm}^2 \left(\frac{m_x}{\text{PeV}}\right)$, as Chris/Nirmal mentioned,

capture rate $C_X \propto \dfrac{\rho_x \sigma_{nx}}{v_x}$

$= \dfrac{\textbf{DM density} \times \textbf{DM-nucleon cross section}}{\textbf{DM velocity}}$



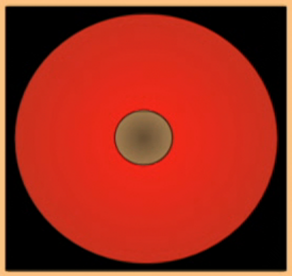
$\sigma_{\rm nx}$
**determines whether DM scatters, gets trapped**

$t_c$ := Dark Matter Capture Time
(from no DM to when the critical mass $M_{crit}$ accumulated)

$t_{\rm c} \propto v_{\rm x}/\rho_{\rm x}.$

See e.g. Bramante, Delgado, Martin, 2017
+ Baryakhtar, Bramante, Li, Linden, Raj, 2017

2. DM thermalizes



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

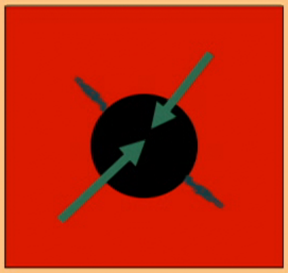
3. DM collapses

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

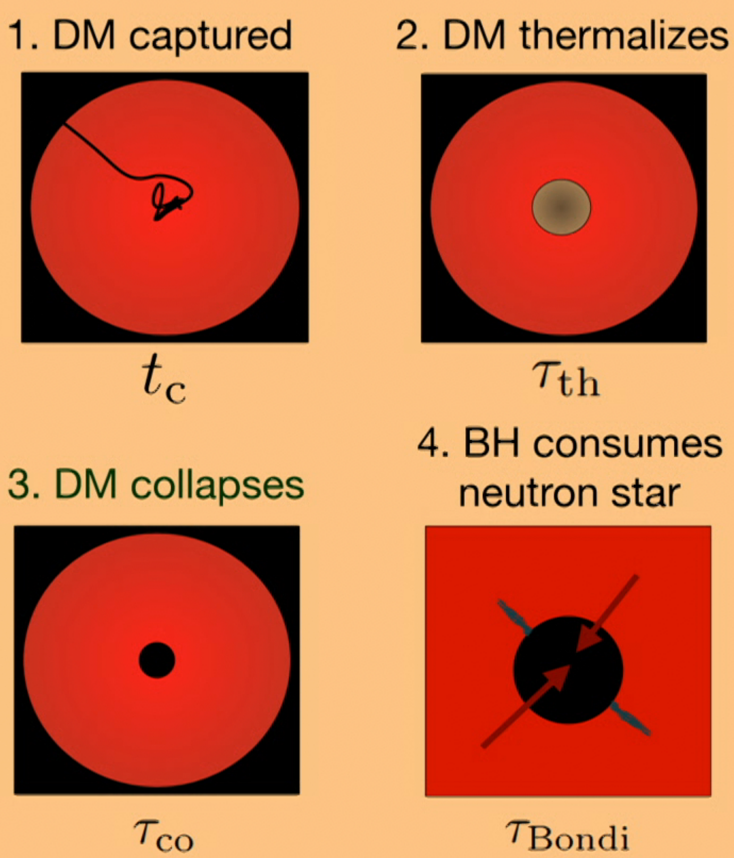
4. BH consumes neutron star



Bondi accretion from the black hole consumes the host neutron star

YU-DAI TSAI, PI 2017

# 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
- Appendix of 1706.00001

# Normalized Implosion Time

**PeV-EeV** ✓

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

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

$$t_c \propto v_x/\rho_x.$$

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

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

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

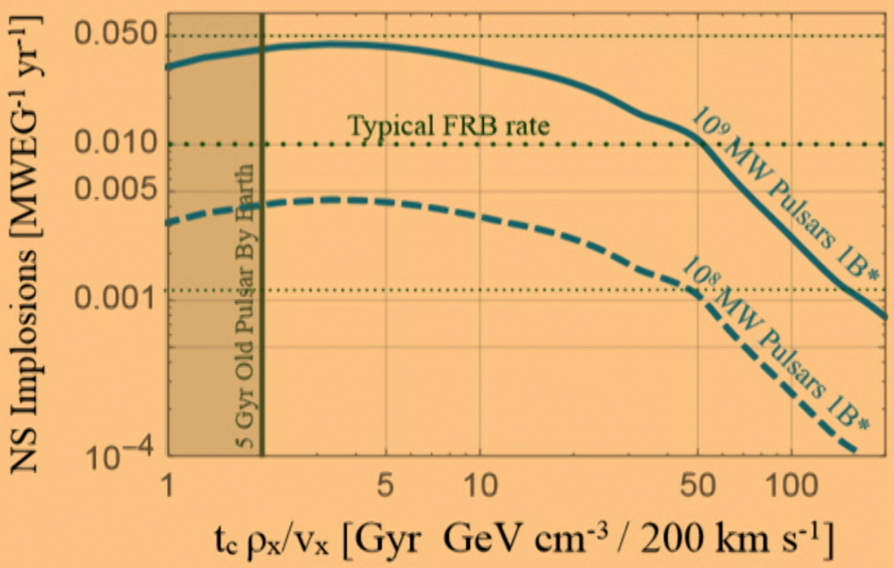
$$V(\phi) = \lambda|\phi|^4$$

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

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

Colpi, Shapiro, and Wasserman, 1986

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




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

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

Bramante, Linden, **YT**, 2017

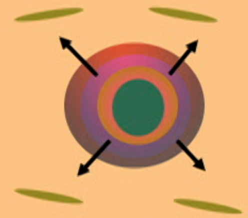
# R-PROCESS AND KILONOVA

Preferred/Constrained DM-implosion
Parameter Space

# r-Process (Rapid Neutron Capture Process) & Kilonova Events

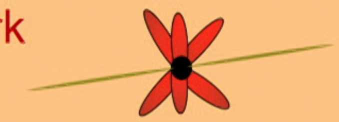
**Possible r-process sources:**

- Neutrons ejected by neutrino wind from core collapse supernovae (frequent, ~1/100 years)



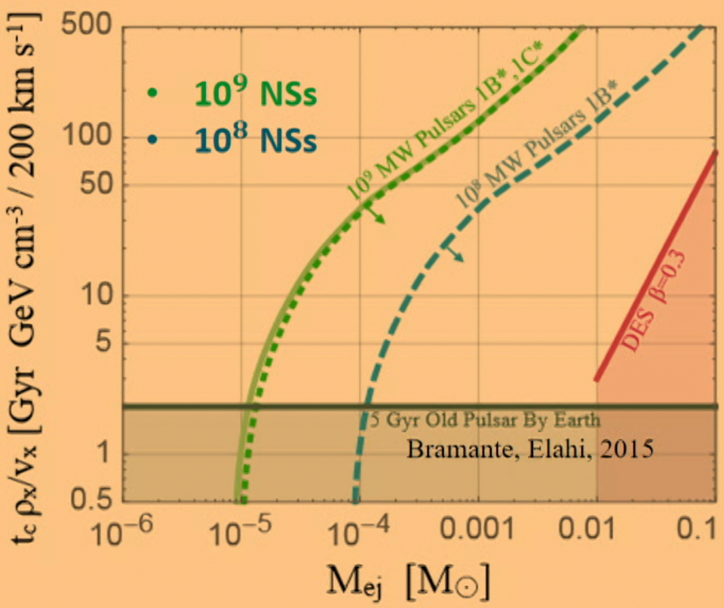
- Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/$10^4$ years)

- Neutron star slurped into a black hole made of dark matter at its core. Implosion tidally spurts neutron star fluid (rate see e.g. 1706.00001)



**Neutron-rich fluid then beta decays, create kilonova events, and forms heavy neutron-rich elements,**
**total $10^4$ $M_\odot$ r-process elements produced in Milky Way**
(see, e.g., Freeke et al, 2014)

# r-Process Element Abundance & Bounds



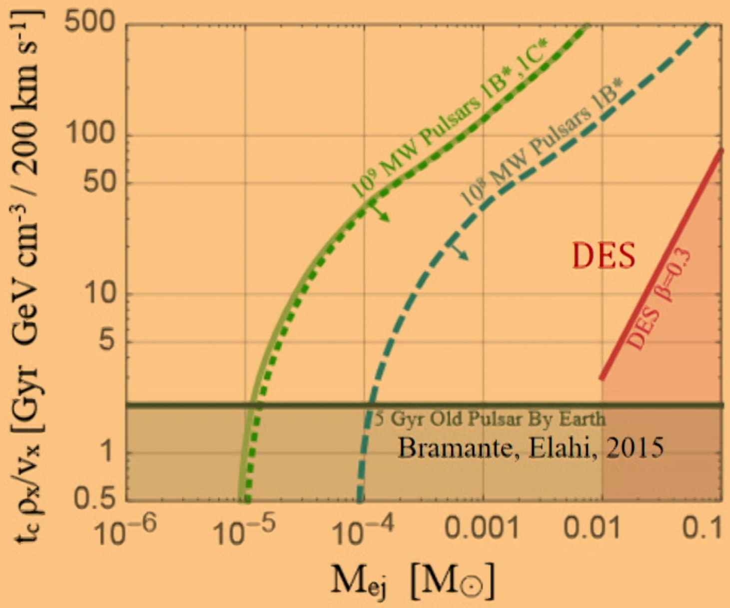

Two matching curves assume different total neutron star numbers

Bramante, Linden, **YT**, 2017

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 $t_c\rho_x/v_x$**
- The constraints are stronger if NS implosions not responsible for all r-process elements
- "Self-detecting" dark matter?

# Kilonova Bound




x-axis: ejecta mass per NS implosion

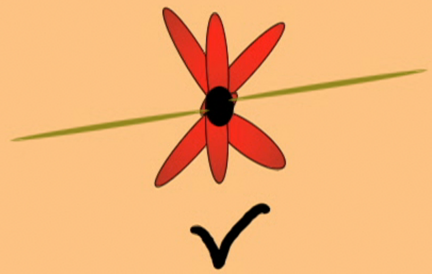
y-axis: implosion parameter $t_c \rho_x / v_x$

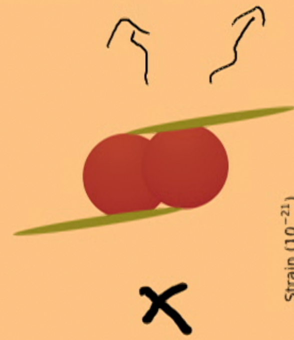
Bramante, Linden, **YT**, 2017

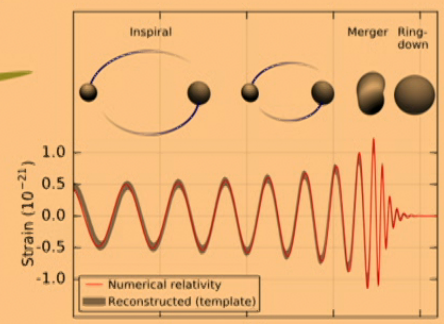
**Kilonova light curves** depend mainly on the **mass** and **velocity** of NS fluid ejected (Kasen et al, 2013)

- **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








**Quiet Kilonova:**

Abbott et al., LIGO/VIRGO, PRL 2016

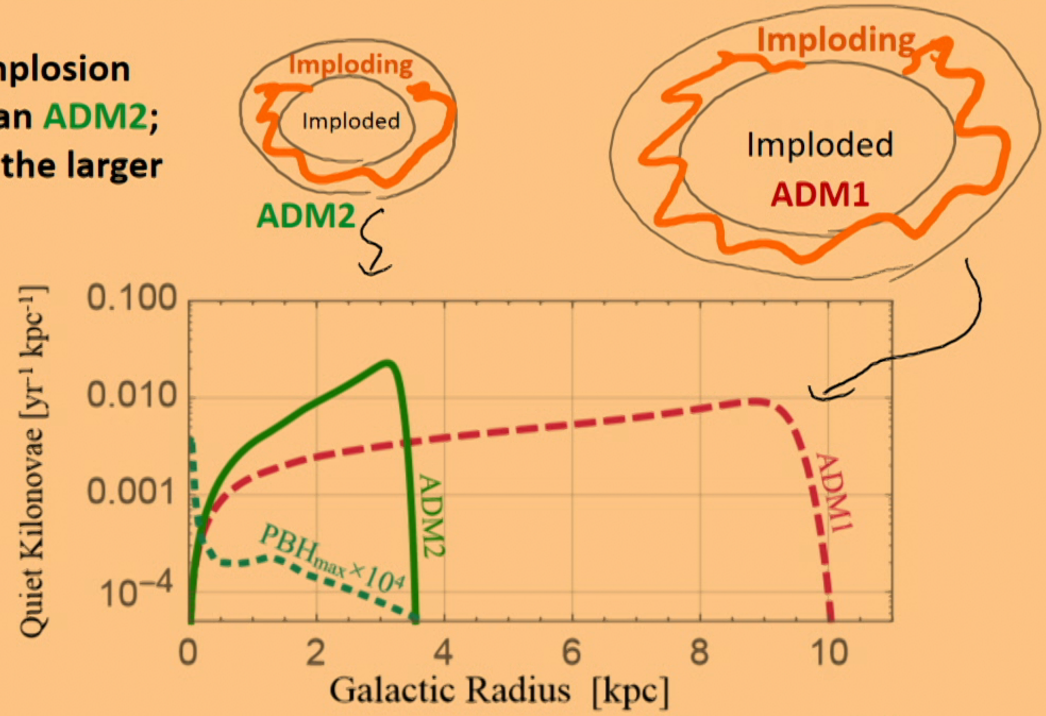
- **Kilonova events from NS implosions**, but NOT from the NS-NS or NS-BH mergers.
- **WITHOUT detectable merger signatures**, so we call them "Quiet Kilonova" (Bramante, Linden, **YT**, 2017)

YU-DAI TSAI, PI 2017

# Quiet Kilonova Morphology

… or **"Gold Donut"**, since its related to r-process that can give you gold

- **ADM1 implosion faster than ADM2;**
- **ADM1 is the larger donut**




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

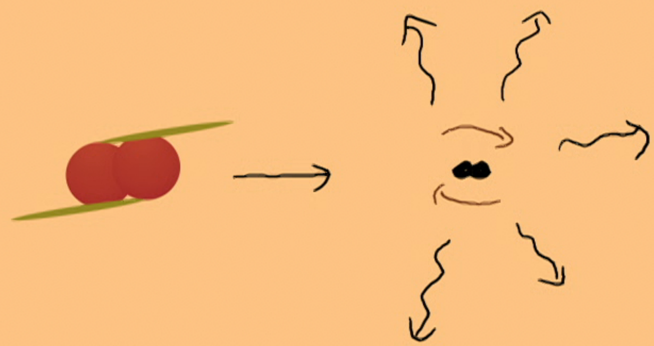
**ADM2**: $t_c \rho_x / v_x = 15$ Gyr/cm$^3$(200 km/s)$^{-1}$

# BLACK MERGER

Gravitational-wave Signature form
Converted NS-NS(BH) Merger

# G-Wave Signature: Black Mergers

- Putative "mass gap" between NSs ($m \leq 3\ M_\odot$) and BHs ($m \geq 5\ M_\odot$)
- NS-NS or NS-BH mergers are converted into BH-BH mergers, creating **$m \leq 3\ M_\odot$ solar-mass BH-BH mergers**, violating the mass gap
- These are merger events WITHOUT optical follow-on, we call them **“Black Mergers”.**



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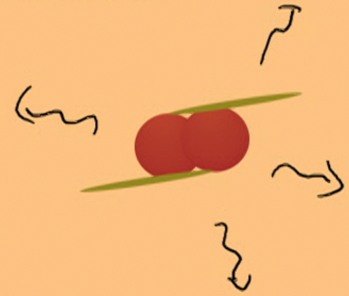
# MERGER KILONOVA (BRIGHT MERGER)

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

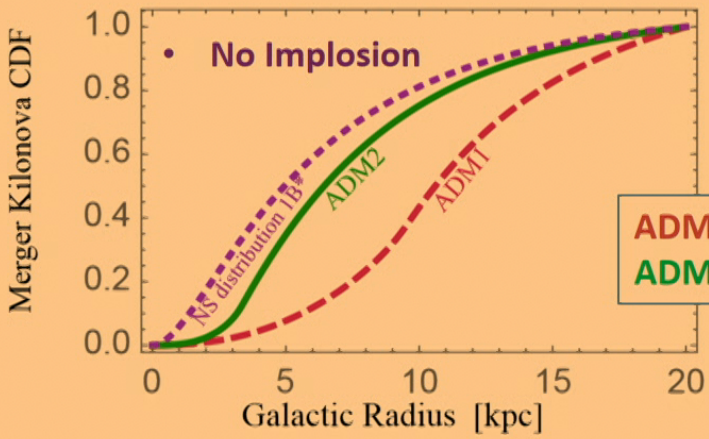
# Combined Signature: Merger Kilonova

Having *Black Mergers* means the usual NS-NS(BH) mergers have the **distributions altered by NS implosions**



**Merger Kilonova**: NS-NS(BH) mergers

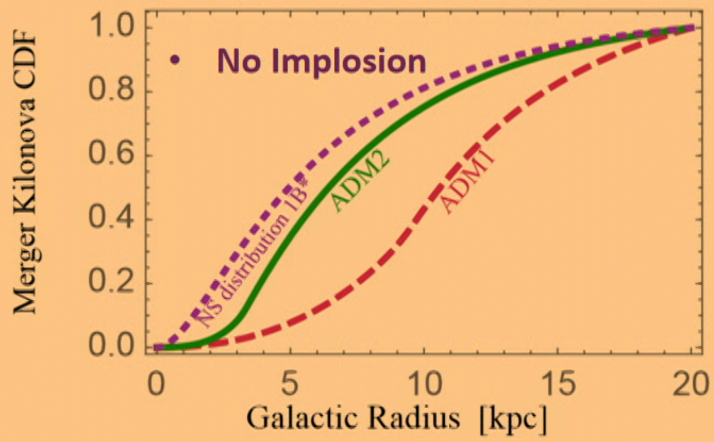
- Merger signatures detectable by LIGO/VIRGO
- The associated Kilonova signature can be confirmed by BlackGEM

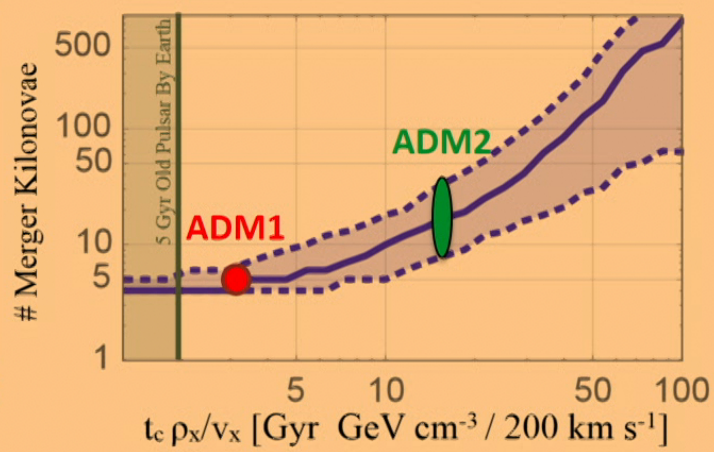



- **CDF(Cumulative distribution function) of the Merger Kilonova**
- **Sartore et al, 09**

**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

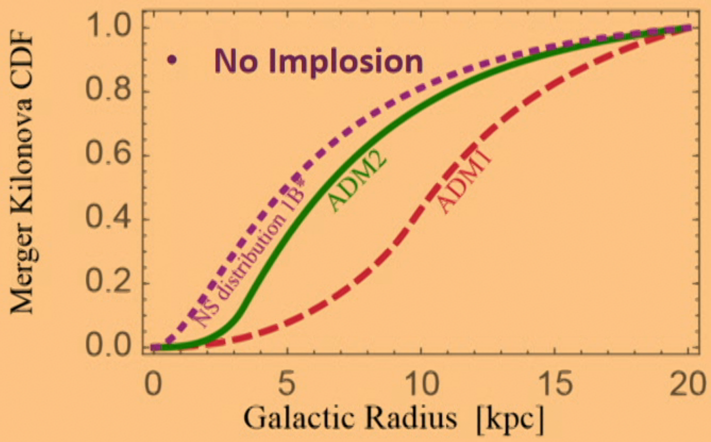


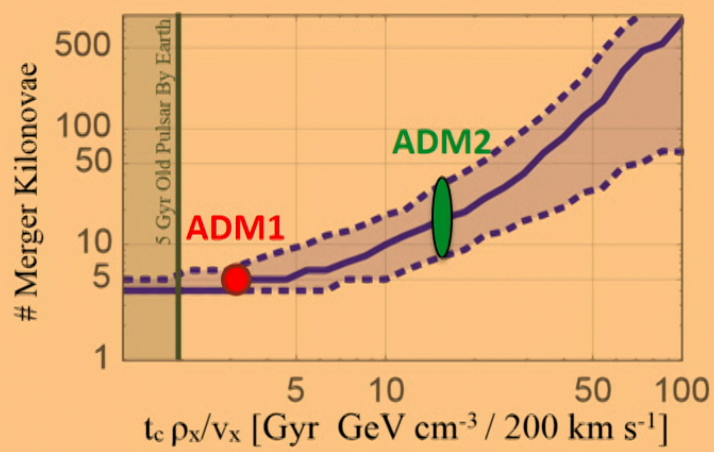




- Apply K-S test for randomly generated events based on the implosion parameter $t_c \rho_x / v_x$
- (Right) **Purple band** indicate number of events needed for **2σ significance** in testing the ADM model parameters
- Dashed: upper and lower quartile; **Solid**: the median based on the repeated experiments.
- **Different NS-distribution models does not change the result much**

YU-DAI TSAI, PI 2017

# Statistics of Merger Kilonova Events

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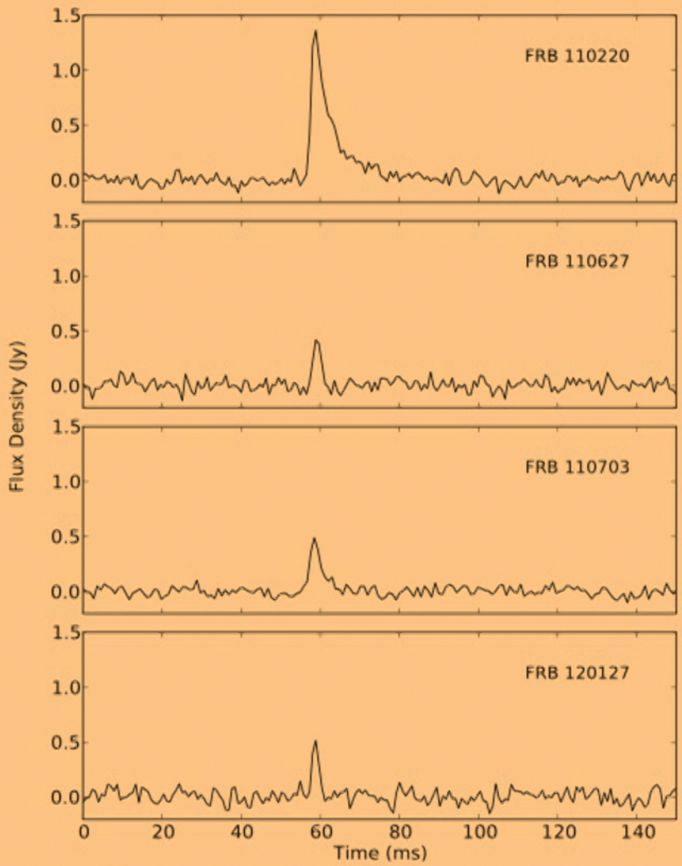
# Radio Signatures: Fast Radio Bursts




- Unexplained ~ ms long radio pulses (spanning a large range of radio frequencies)
- First identified in 2007, in archived 2001 data recorded by the Parkes Observatory
- ~ 20 detected so far
- figure from Thornton et al., 2013

The jansky (symbol jy)= $10^{-26}$ watts per square metre per hertz.

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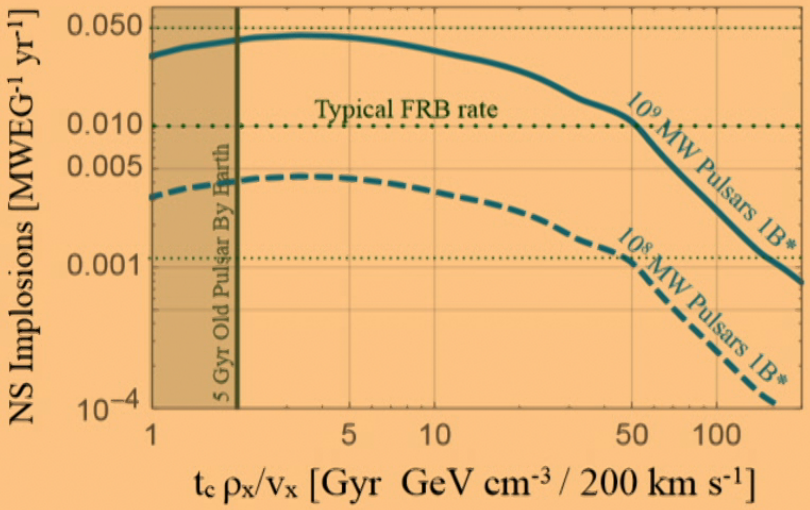
# Fast Radio Burst and DM Implosions

**Fast radio bursts (FRBs) from DM:**
FRBs: millisecond-length & $\sim$Ghz radio pulses, found to distances of 2 Gpc with an all sky rate $\sim$ 10^4/day. The source is not fully determined.

DM-induced NS implosions may be the source of FRBs. The EM energy released by a NS implosion matches 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]**

# Match NS Implosion Rate to the FRB Rate




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

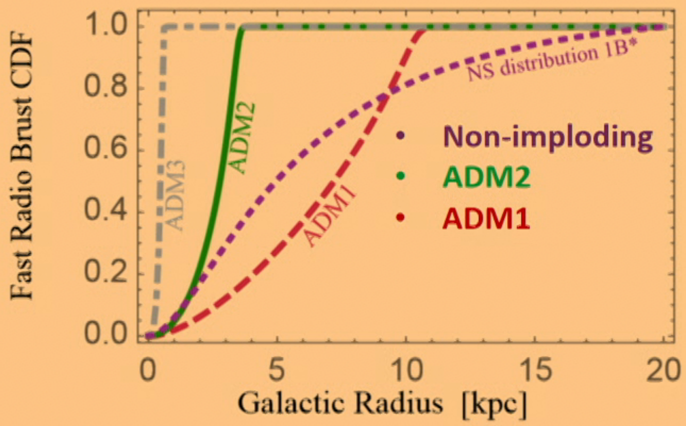
Bramante, Linden, **YT**, 2017

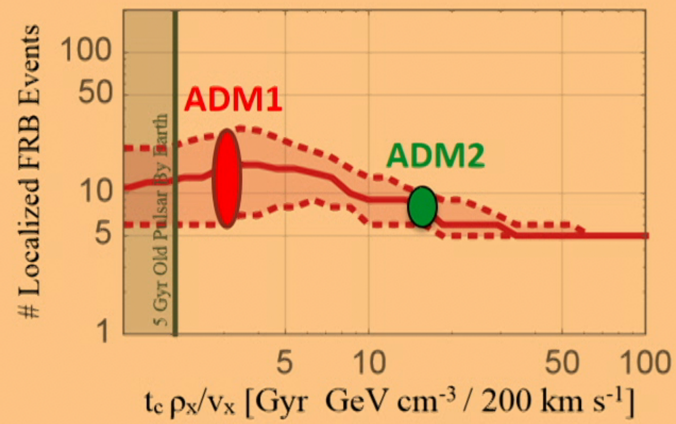
- The dotted lines indicate high, median, and low **FRB** rate estimates from surveys [arXiv: 1505.00834 and 1612.00896].

# Statistics of Located FRBs

- 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




Bramante, Linden, **YT**, 2017

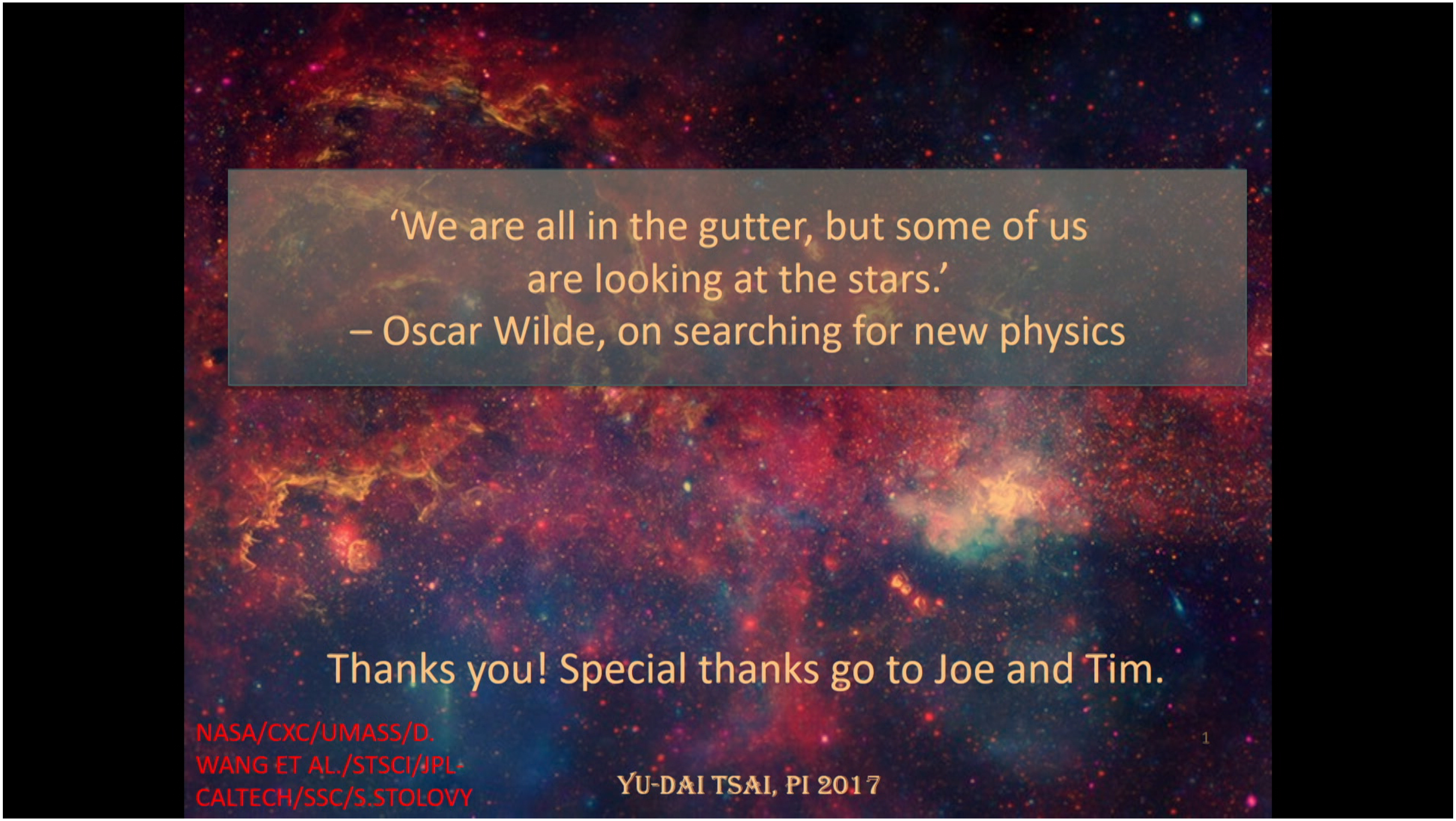
**FRB donuts**

# Conclusion and Outlook

- (Asymmetric) Dark Matter implodes neutron stars and give novel astrophysical signatures.
  - **Kilonova events** seen by telescopes like Dark Energy Survey (DES) and BlackGEM
  - **Merger signatures** by LIGO/VIRGO
  - **located FRBs** by radio arrays like CHIME and HIRAX

  can be applied to test the DM implosion scenarios.

- Explore similar/different models for NS-implosions and conduct more detailed analysis


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