Yu-Dai Tsai (PhD student)
Cornell University

with Joe Bramante, Tim Linden

arXiv:1706.00001
+ many papers to come soon!

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

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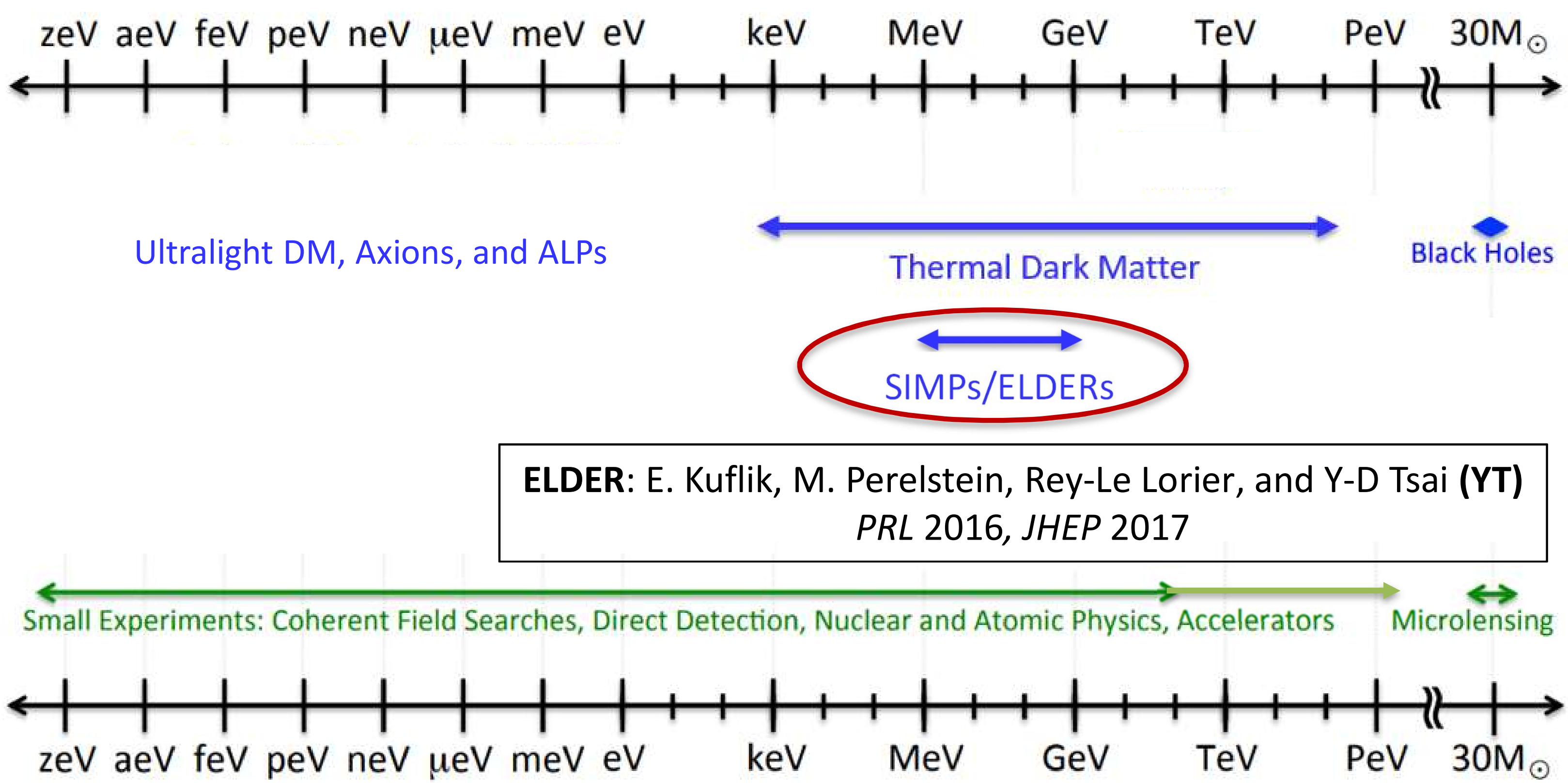
arXiv:1706.00001
+ many papers to come soon!

Or, Self-detecting Dark Matter (I will explain)

Also allow me to take some questions afterward since I have a lot to say

Beyond WIMP/CDM!

Dark Sector Candidates, Anomalies, and Search Techniques



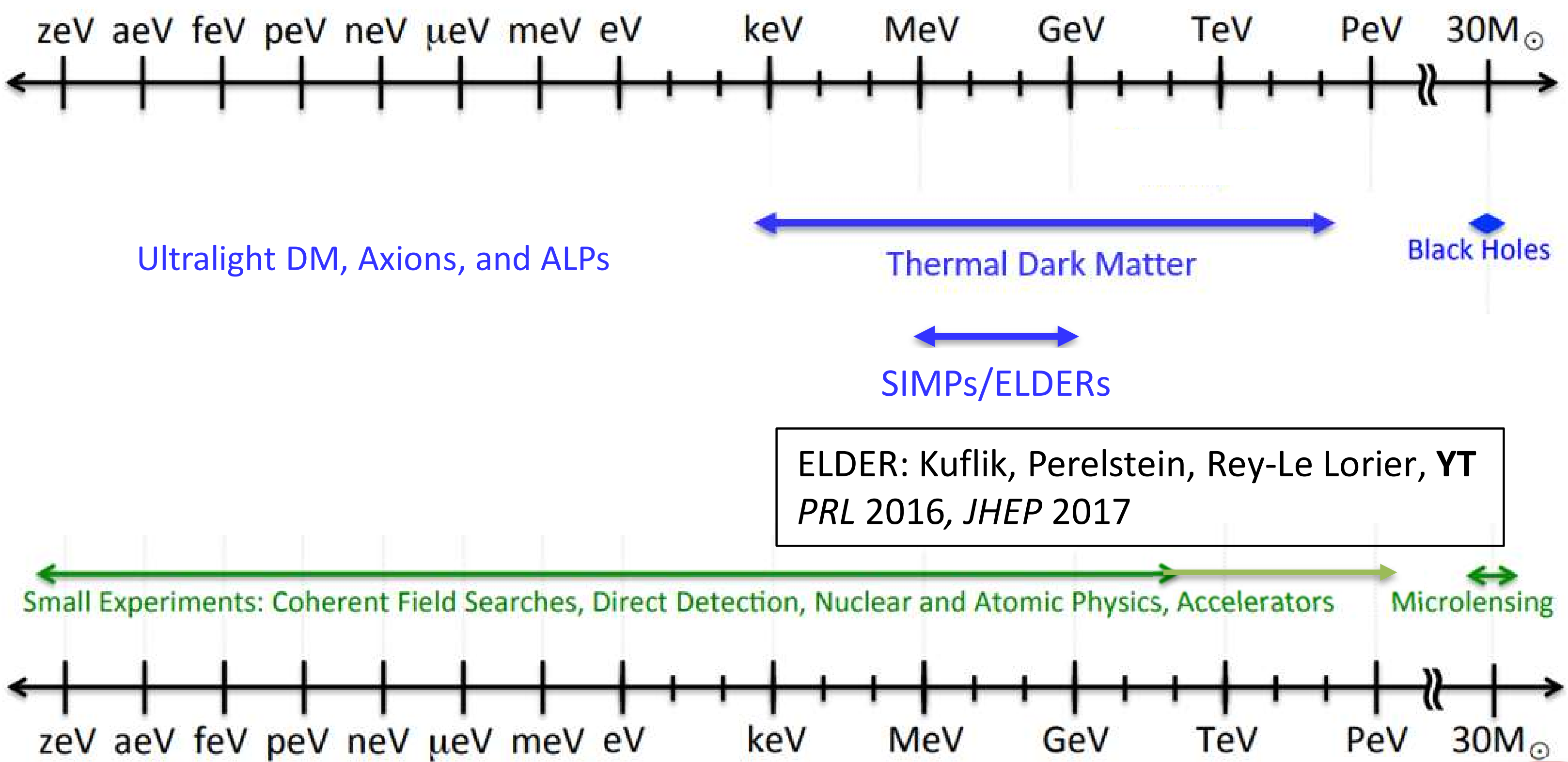
ELDER: E. Kuflik, M. Perelstein, Rey-Le Lorier, and Y-D Tsai **(YT)**
PRL 2016, *JHEP* 2017

US Cosmic Visions 2017

I am super excited about dark matter direct detections (especially sub-GeV),
and hidden particle searches (e.g. LDMX talk by Porf. Hitlin)

Yu-Dai Tsai,
BNL 2017

Beyond Direct Detection!



ELDER: Kuflik, Perelstein, Rey-Le Lorier, **YT**
PRL 2016, *JHEP* 2017

Bramante, Linden, **YT**, 1706.00001

PeV - EeV

Phenomenology of Super-heavy ADM and Neutron-Star Implosion

NS-NS Merger Alert!

Bramante, Raj, Baryakhtar, and others + **YT**

keV - EeV

Neutron-Star Implosion / Neutron-Star Heating

Yu-Dai Tsai,
BNL 2017

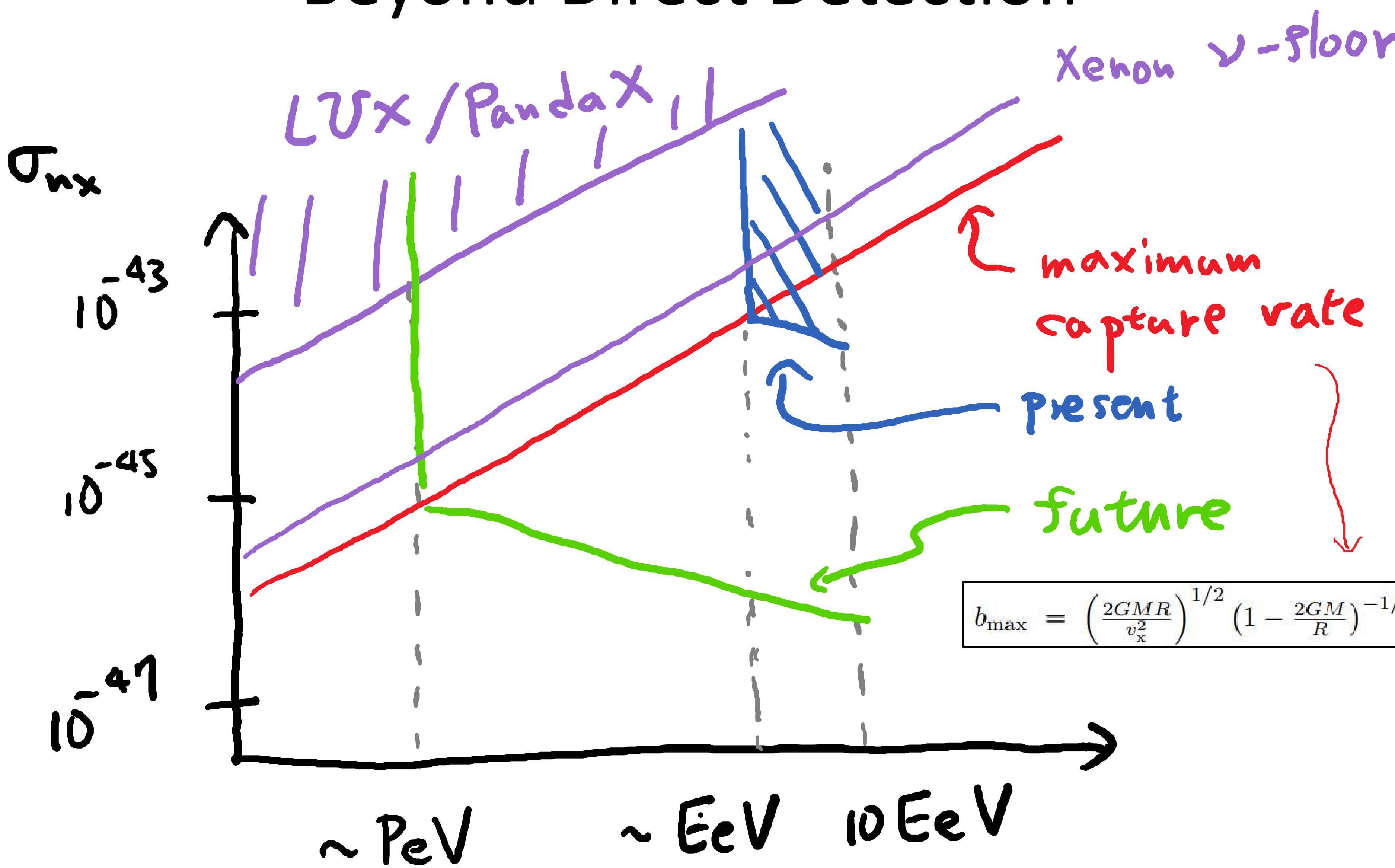
New Lampposts from Astrophysics

Going beyond Direct-detection Limits

Why Neutron Star?

- As we just learned from Yue, the density of the detector is very important!
- 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) meaning that a teaspoon of neutron star material would weigh around a billion tons.
- Almost a **Black Hole**, but the degeneracy pressure is keeping it from collapsing.

Beyond Direct Detection



$$b_{\rm max} = \left(\frac{2GMR}{v_x^2}\right)^{1/2}\left(1-\frac{2GM}{R}\right)^{-1/2}$$

VERY PRELIMINARY!

Outline

- Intro to DM-induced neutron star (NS) implosions
- Astrophysical Signatures:
  - Kilonova Events and r-Process Elements
  - Optical Signature – Quiet Kilonova
  - Gravitational Signature – Black Merger
  - Optical + Gravitational Signature – Merger Kilonova
  - Possible Radio Signature – Fast Radio Bursts

    (may skip the radio signature due to time limit)
- Conclusion and Outlook

NS Implosion & Asymmetric Dark Matter

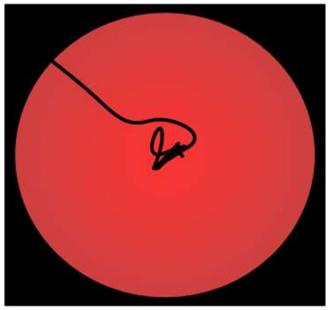
- Asymmetric Dark Matter (ADM): dark matter with particle/anti-particle asymmetry in the dark sector, often linked to baryon/lepton asymmetry.

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

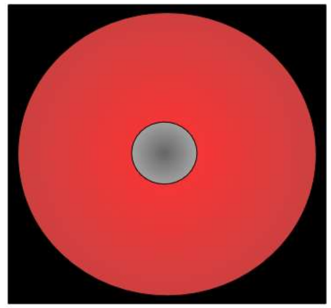
- Dark matter asymmetry allows efficient collection and collapse in stars without annihilating to lighter particles
- See e.g. Goldman and Nussinov 1989, Kouvaris and Tinyakov 2010, Lavallaz and Fairbairn 2010, McDermott, Yu, Zurek 2011, Bell, Melatos, Petraki 2013 …

DM-induced NS Implosions

1. DM captured

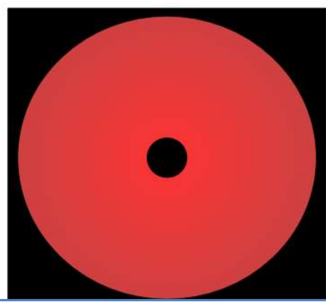


2. DM thermalizes



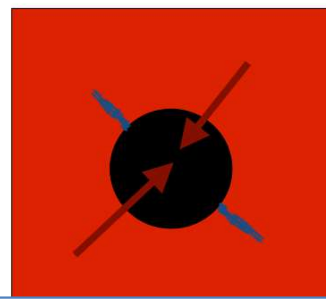
Repeated scattering: DM reach the same temperature and settle at center of neutron star

3. DM collapses



Collapse into a black hole once reach critical mass

4. BH consumes neutron star

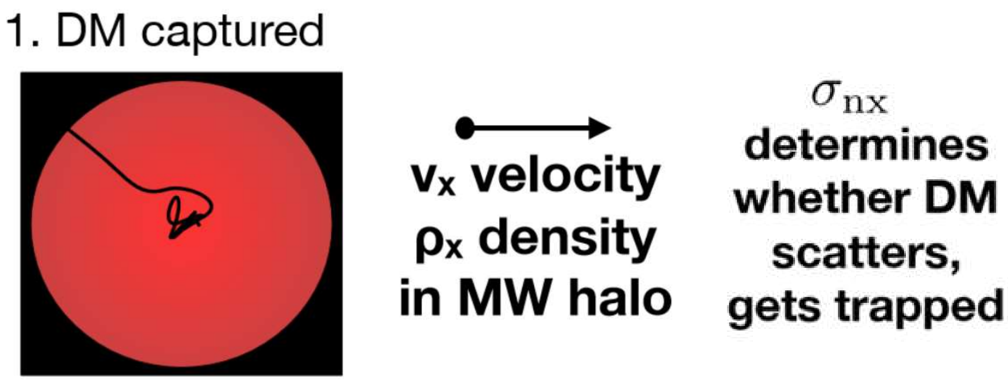


Black hole Bondi accretes inside the neutron star

5. Form solar mass BH

- Consider the implosion using **PeV-EeV (10^6-10^9 GeV) DM** 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



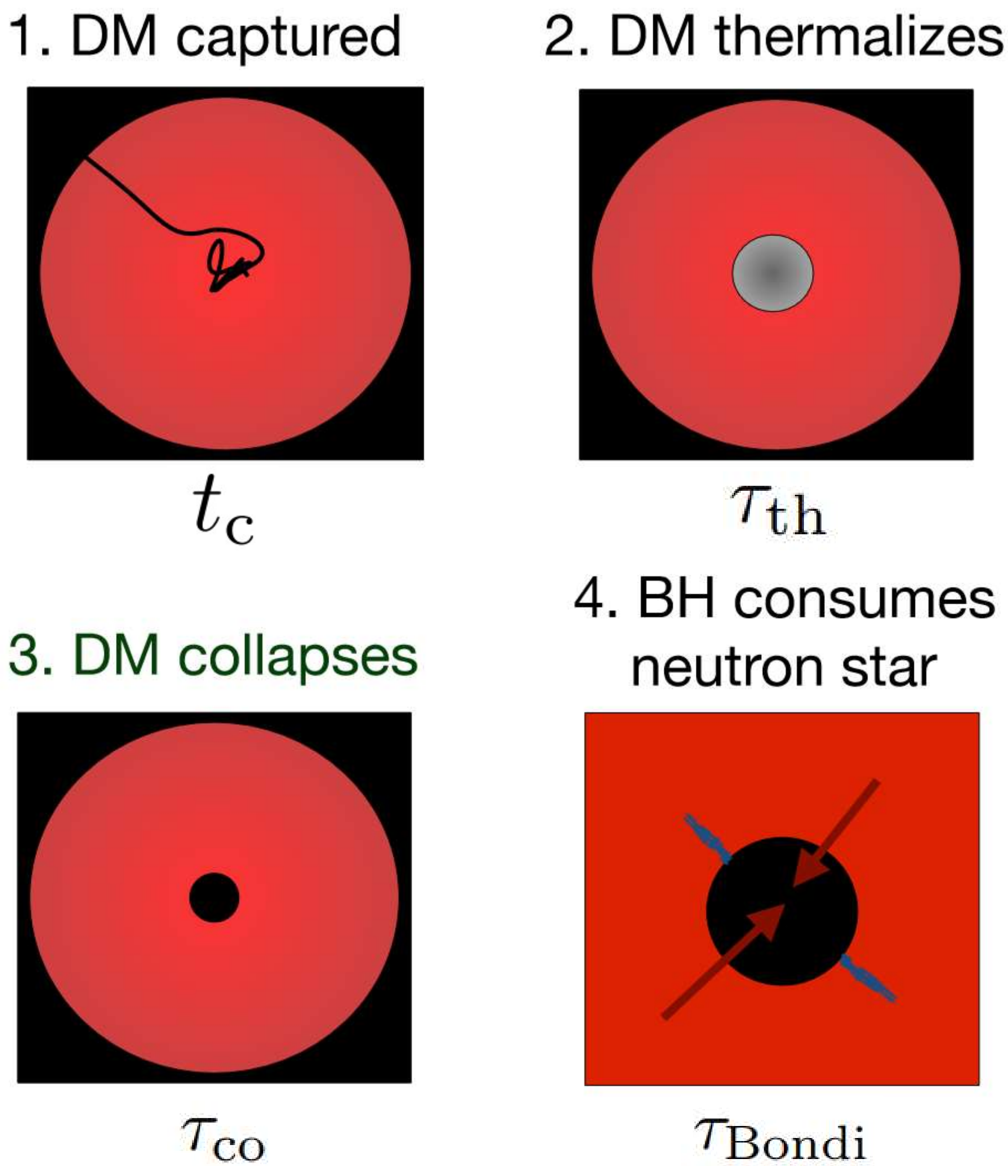
DM-nucleon cross section, $\sigma_{nx} \gtrsim 10^{-45}\text{cm}^2 \left(\frac{m_x}{\text{PeV}}\right)$,
implies maximum mass capture rate, since DM initial halo kinetic energy scales linearly with m_x

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

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

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

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.

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

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

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

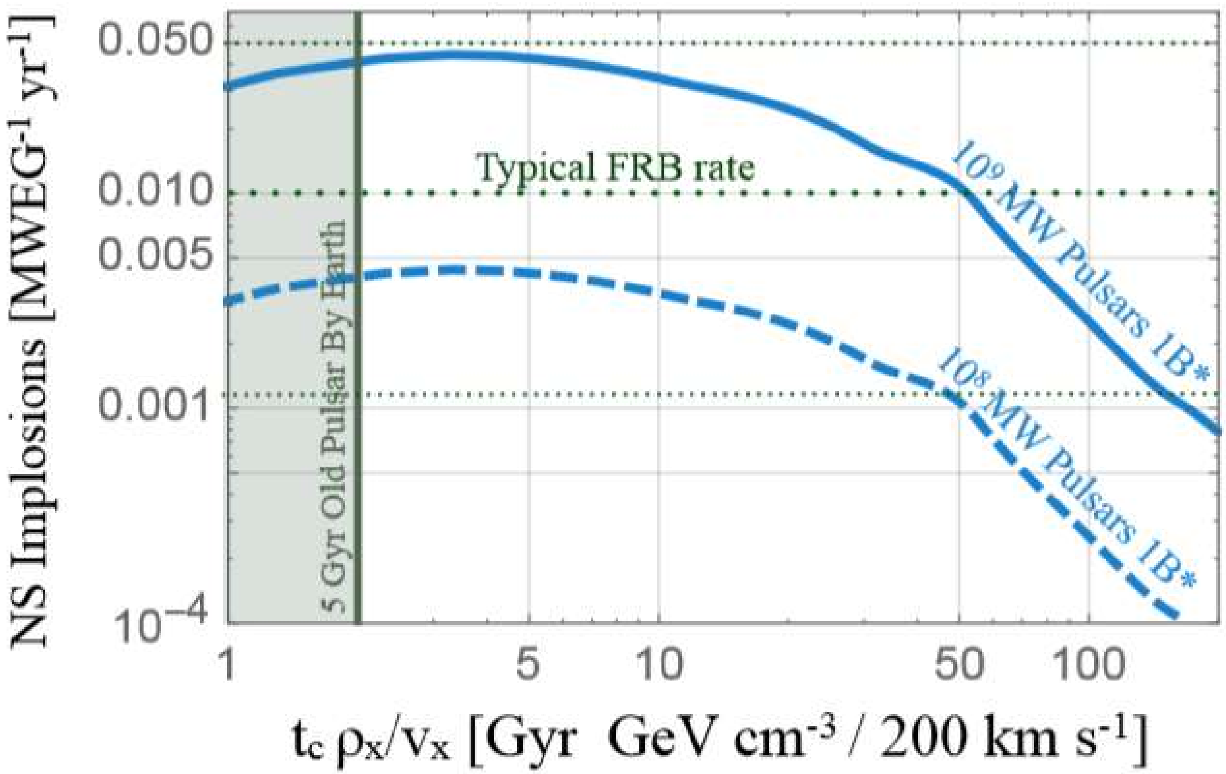
$$t_c \frac{\rho_x}{v_x}\bigg|_f = \left(\frac{10\ \mathrm{PeV}}{m_x}\right)^2 15\ \mathrm{Gyr}\ \frac{\mathrm{GeV/cm^3}}{200\ \mathrm{km/s}}$$

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

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

Colpi, Shapiro, and Wasserman, 1986

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



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

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

Bramante, Linden, **YT**, 2017

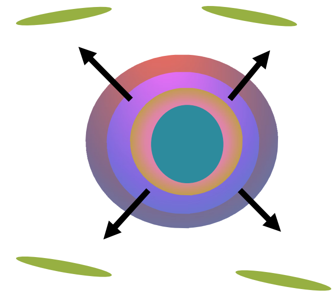
R-Process and Kilonova

Preferred/Constrained DM-implosion
Parameter Space

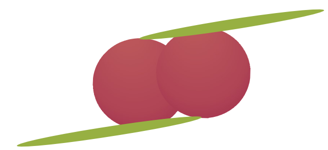
r-Process (Rapid Neutron Capture Process) & Kilonova Events

Postulated r-process sources:

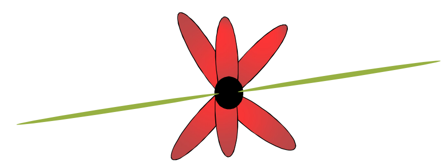
- Core collapse supernovae (frequent, ~1/100 years)



- Merging neutron star binaries (rare, ~1/10^4 years)

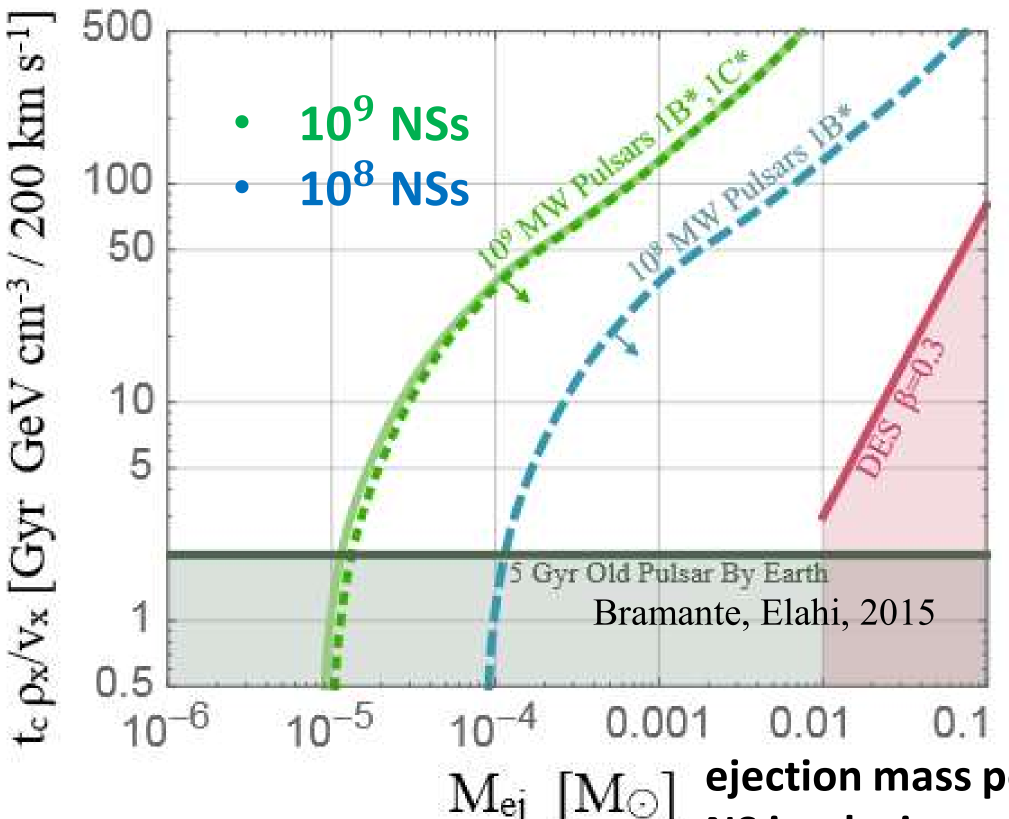


- Neutron star implosion tidally ejects neutron star fluid (rate see e.g. 1706.00001)



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
(e.g. Gold, Xenon, Germanium, and Uranium)
(see, e.g., Freeke et al, 2014)

r-Process Element Abundance & Bounds



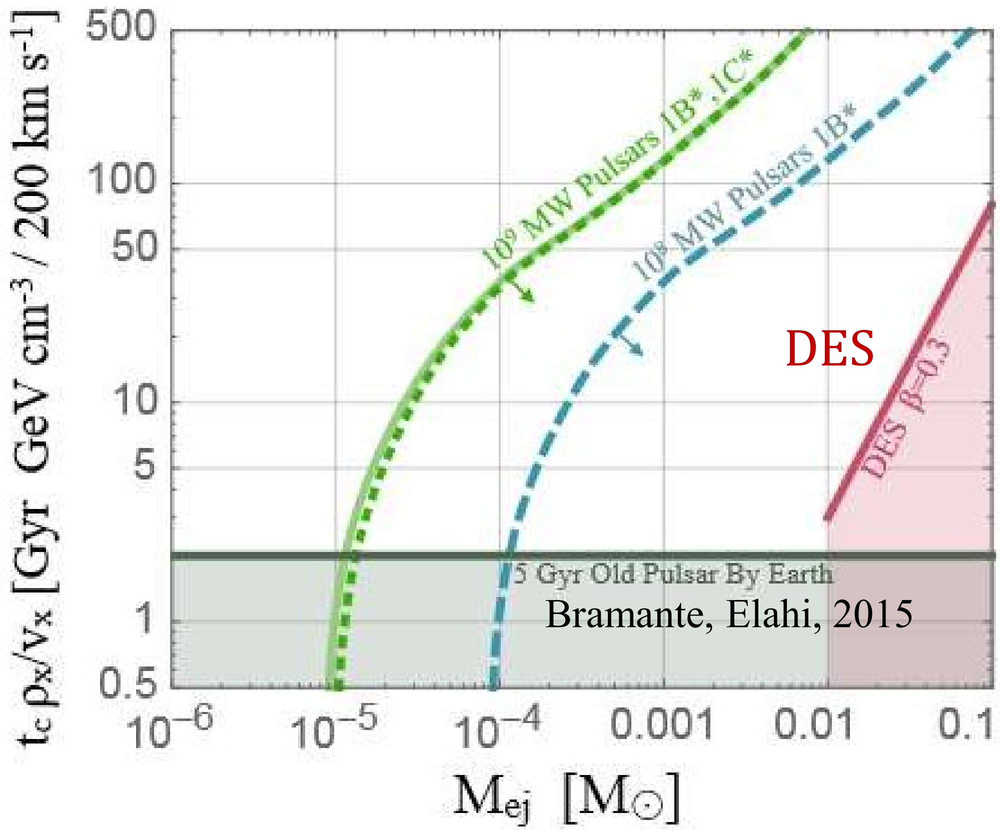
ejection mass per NS implosion

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

Kilonova Bound



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

Bramante, Linden, **YT**, 2017

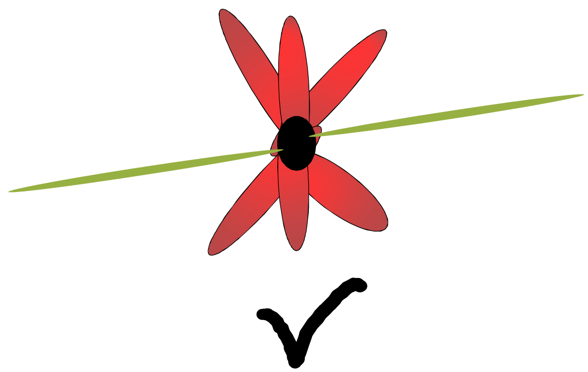
Kilonova light curves depend mainly on the **mass** and **velocity** of NS fluid ejected (Kasen et al, 2013)

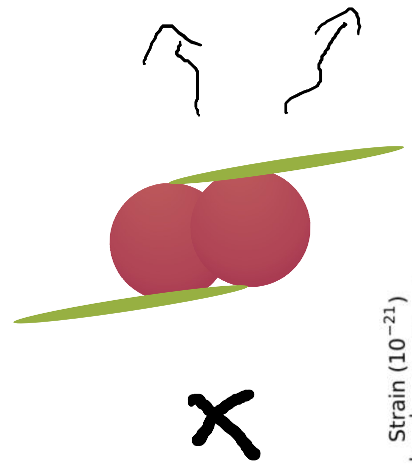
- **Dark Energy Survey (DES)** published a null wide field optical search for kilonovae (**Doctor** et al., DES, 2017)
- We set **bounds from (not-seeing) kilonova events by DES,** assuming **ejection velocity β = 0.3c**
- **The kilonova bound may eventually exclude the r-process matching curves**

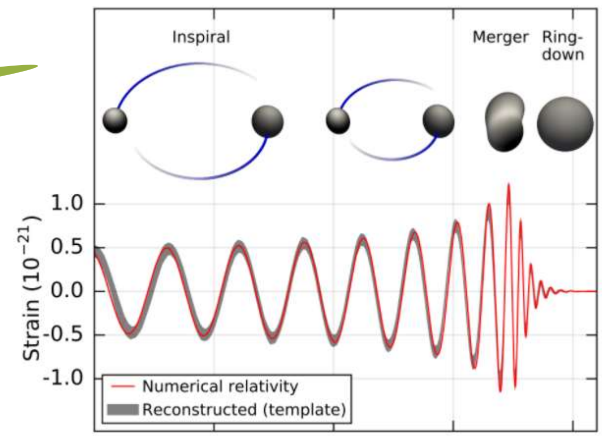
QUIET KILONOVA AND ITS MORPHOLOGY

Optical Signature from NS Implosions

Quiet Kilonova







Quiet Kilonova:

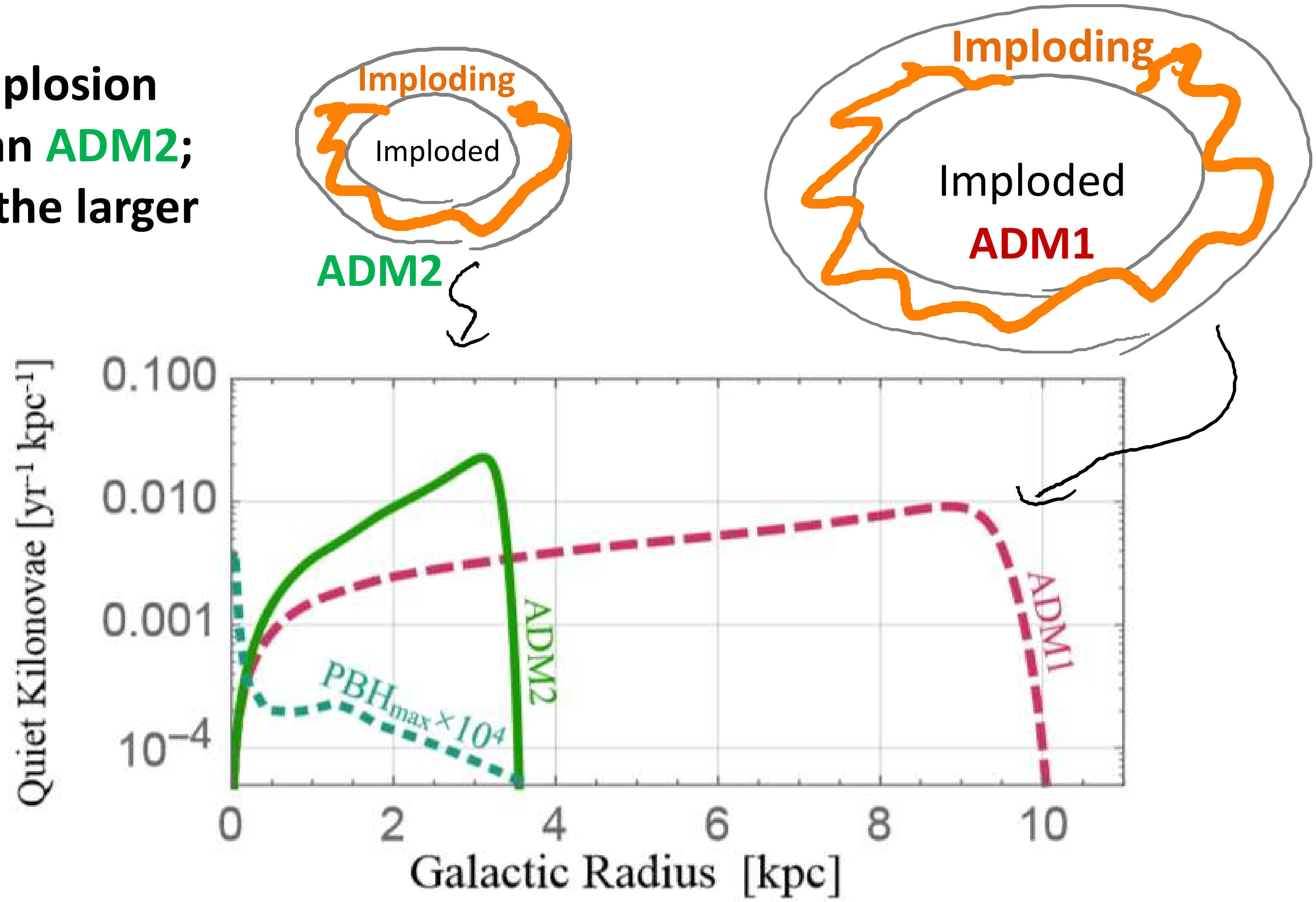
Abbott et al., LIGO/VIRGO, PRL 2016

- **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)

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)$^{-1}$

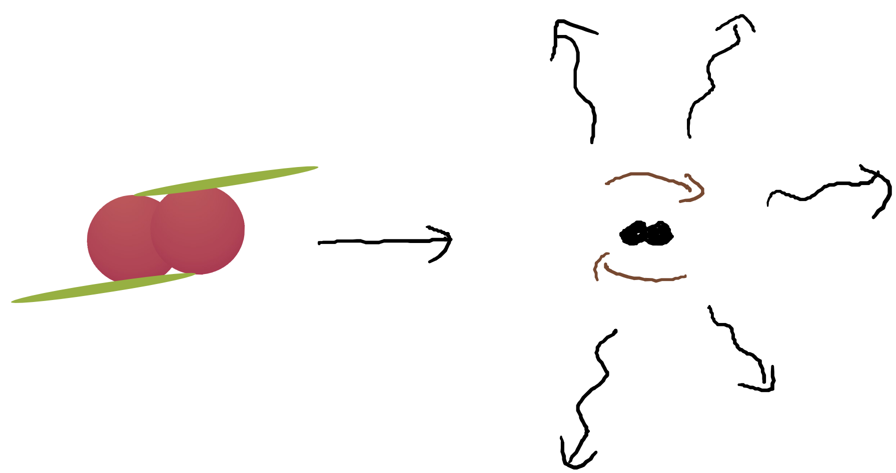
ADM2: $t_c \rho_x / v_x$ = 15 Gyr/cm^3(200 km/s)$^{-1}$

BLACK MERGER

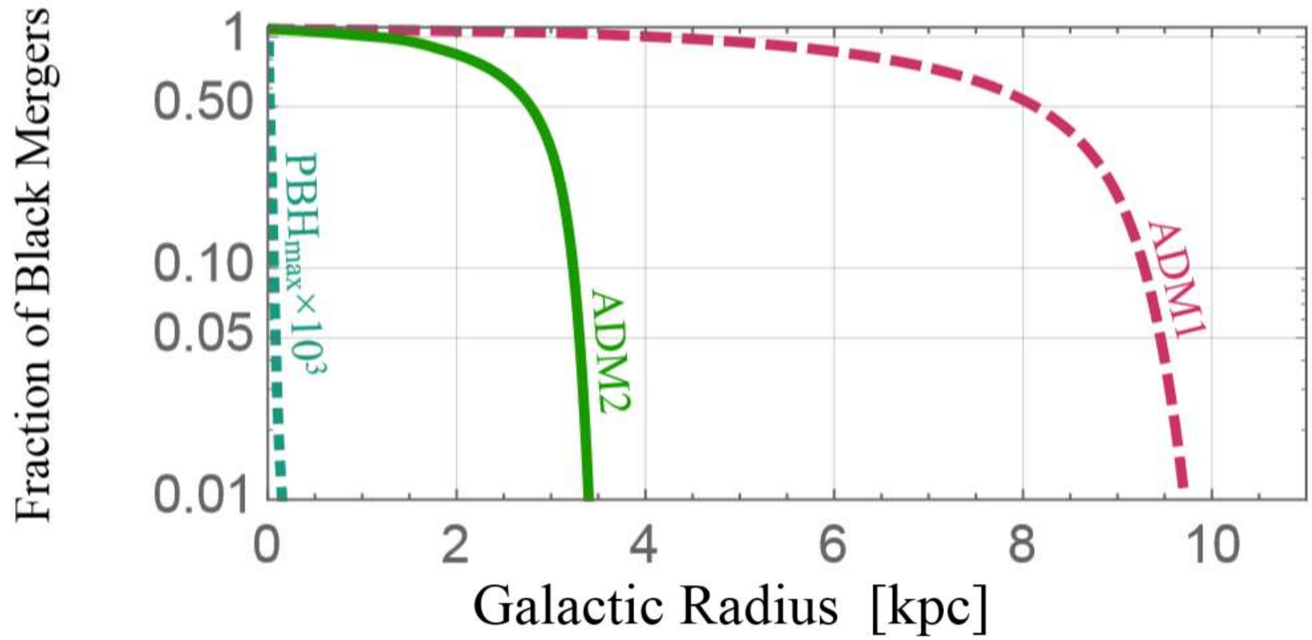
Gravitational-wave Signature form
Converted NS-NS(BH) Merger

G-Wave Signature: Black Mergers

- As we heard from Prof. Mavalvala, BH (> 8 $M_\odot$) and BH mergers are (>30 $M_\odot$)
- 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”.**



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)$^{-1}$

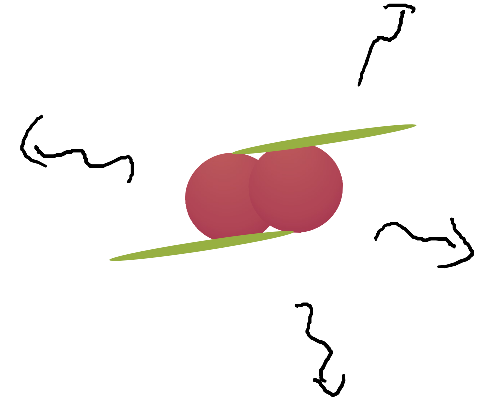
- **No NS-NS merger in the Galactic Center**
- Can use **LIGO/VIRGO** to see merger signatures, that are without optical signatures by **BlackGEM** telescope
- **Not easy to confirm a black merger**

Merger Kilonova (Bright Merger)

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

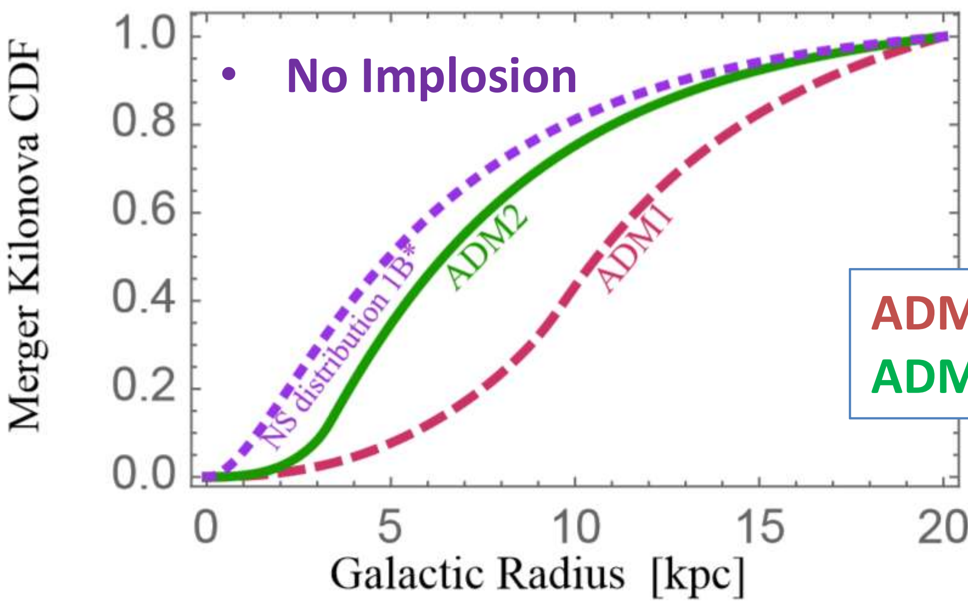
Combined Signature: Merger Kilonova

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



Merger Kilonova: NS-NS(BH) mergers

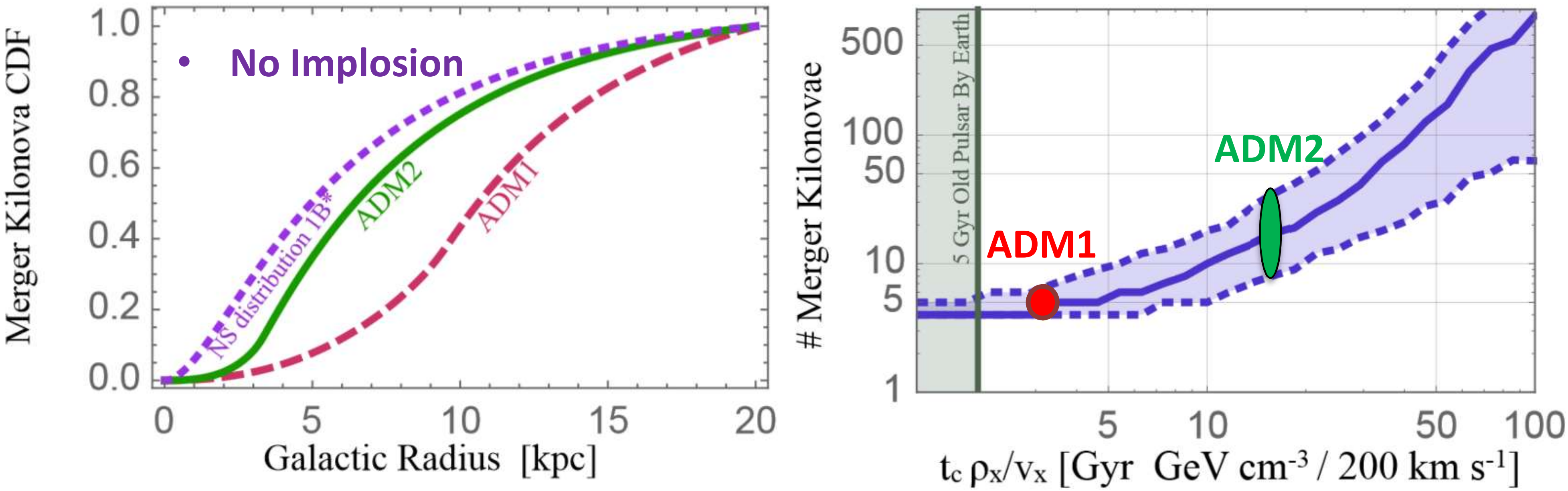
- Merger signatures detectable by LIGO/VIRGO
- The associated Kilonova signature can be confirmed by BlackGEM



- **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**

Neutron-star Merger Alert?

- LIGO/Virgo, optical telescopes, and gamma-ray telescopes altogether could make this possible soon!
- Thanks Professor Mavalvala for the great talk yesterday!
- Will we have our **first robust data point** next Monday?
- Next ten years will be the golden age of neutron-star physics (phenomenology)!

(no pun intended)

FAST RADIO BURSTS

A Possible Radio Signature

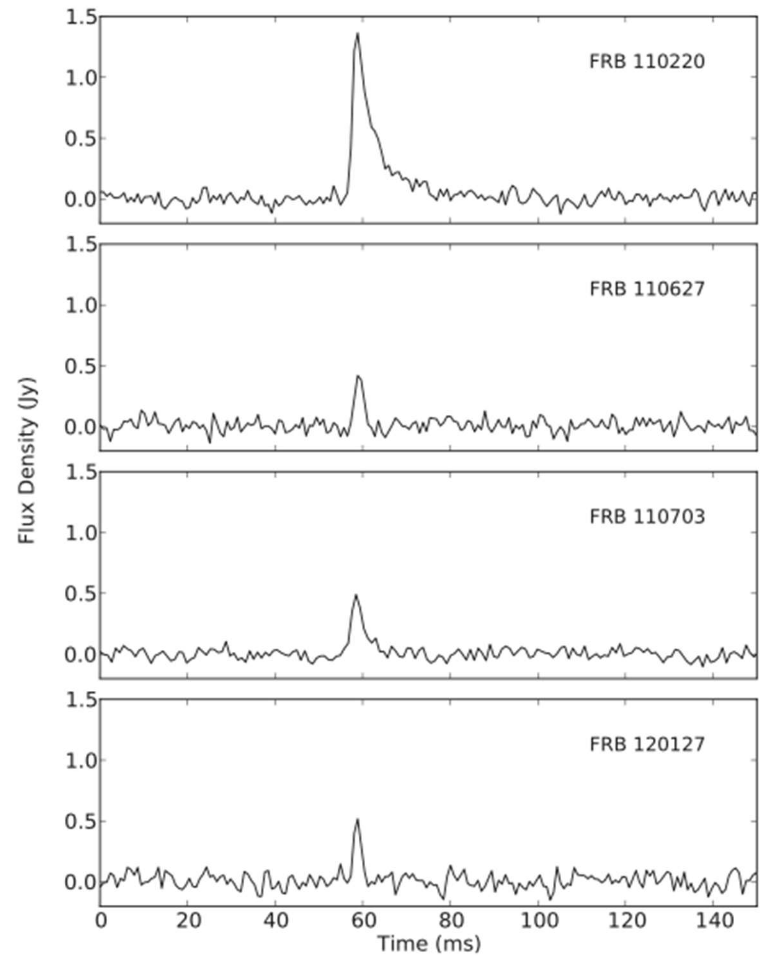
Fast Radio Burst and DM Implosions

Fast radio bursts (FRBs) from DM:

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

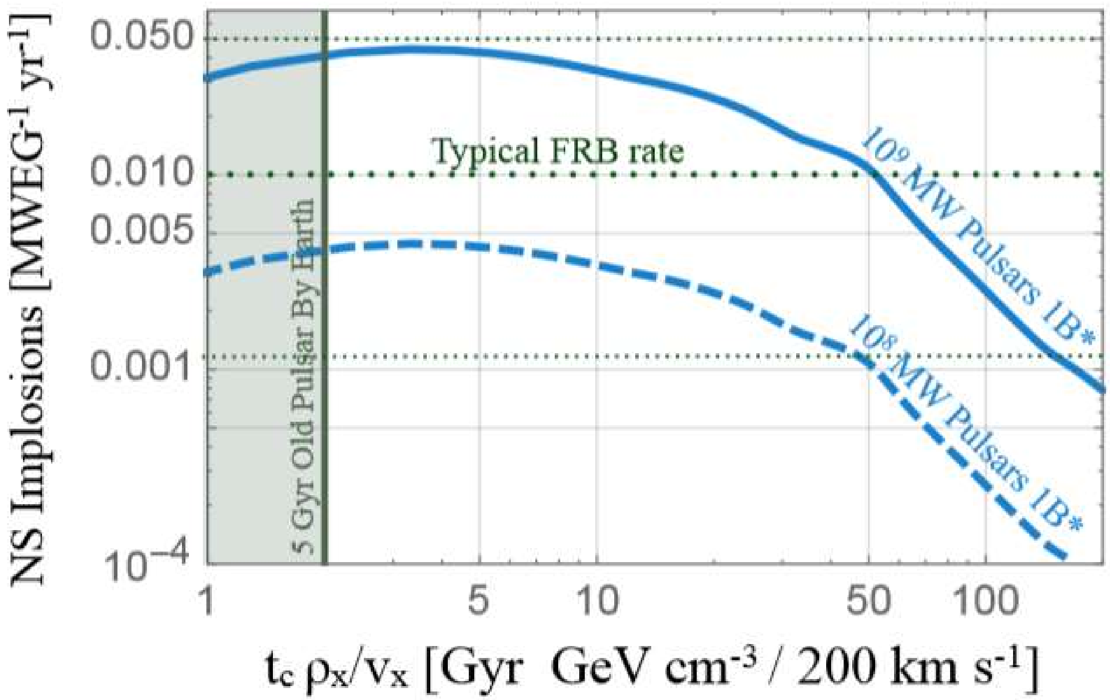
- DM-induced NS implosions may be the source of FRBs.
- The EM energy released by a NS implosion matches what is required for an FRB [Fuller and Ott, 2014].

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



- 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

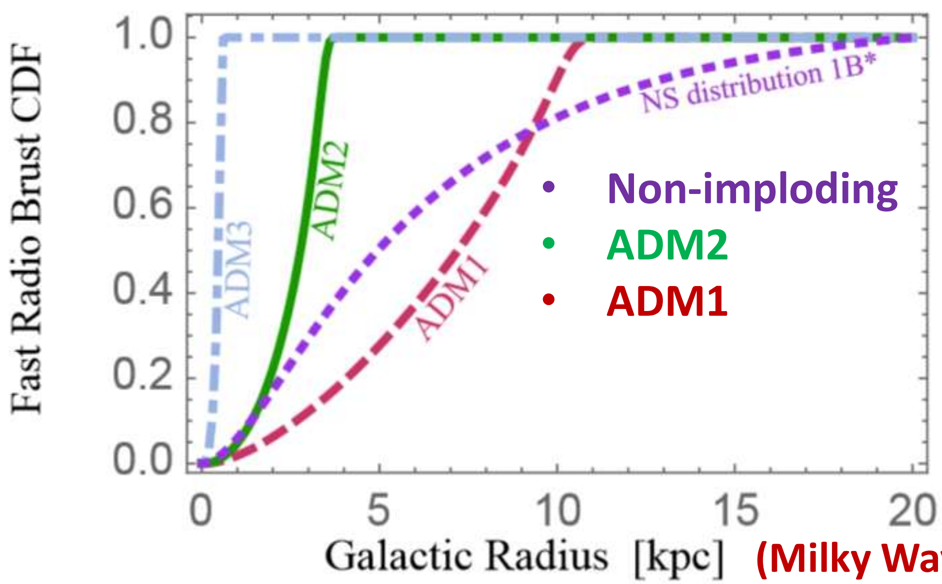
Bramante, Linden, **YT**, 2017

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

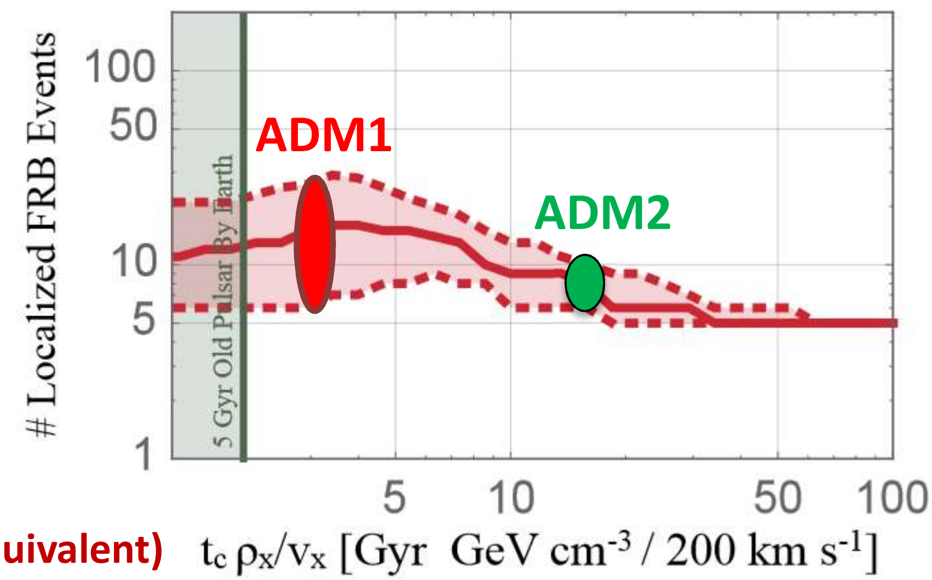
Statistics of Located FRBs

- 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



(Milky Way Equivalent)



Bramante, Linden, **YT**, 2017

FRB donuts

ADM2 ADM1

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

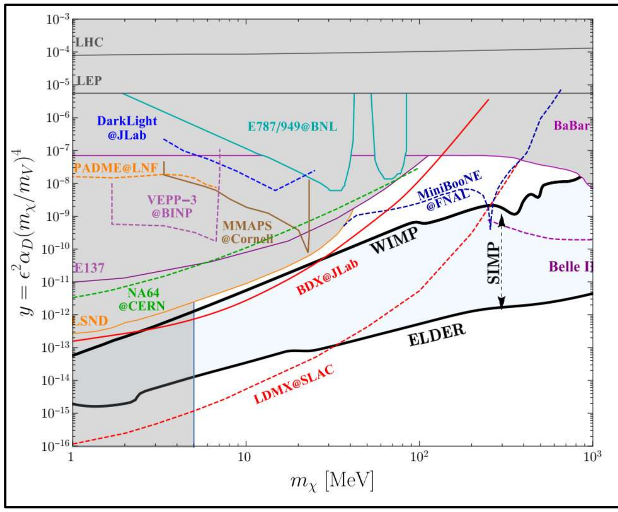
  can be applied to test the DM implosion scenarios.

- Explore similar/different models, extend to other mass ranges for NS-implosions and conduct more detailed analysis

Ongoing Research

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

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



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

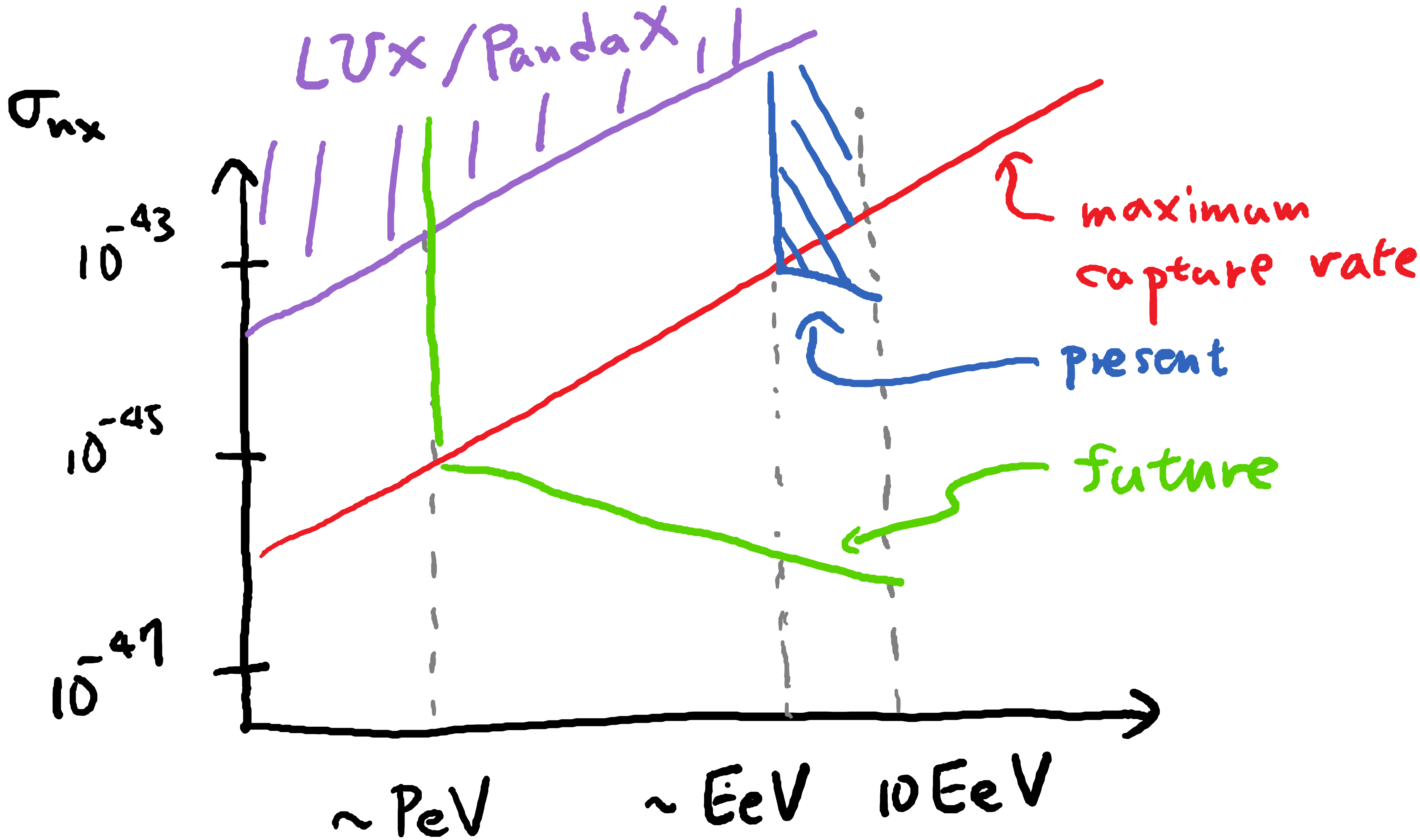
- arXiv: 1706.00001 …

‘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.

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

Beyond Direct Detection



VERY PRELIMINARY!

Yu-Dai Tsai (Cornell), BNL 2017

Kilonova and Supernova

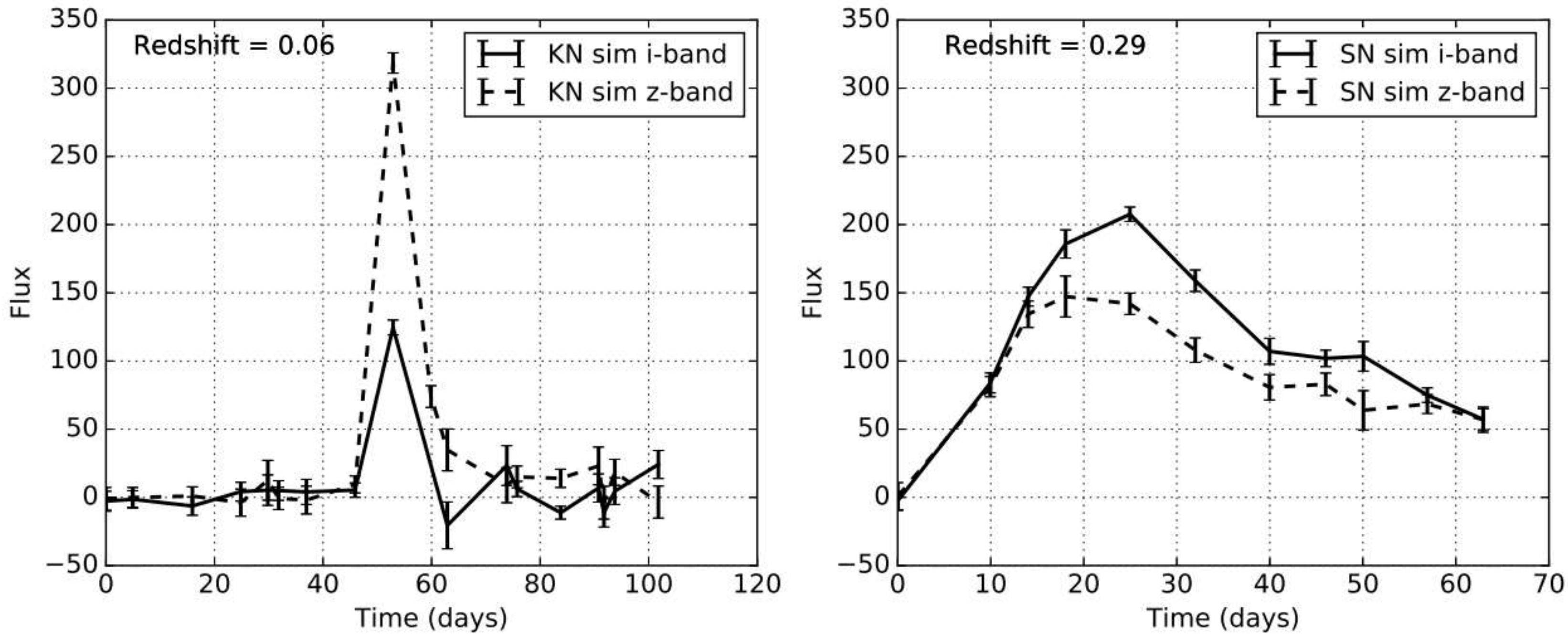


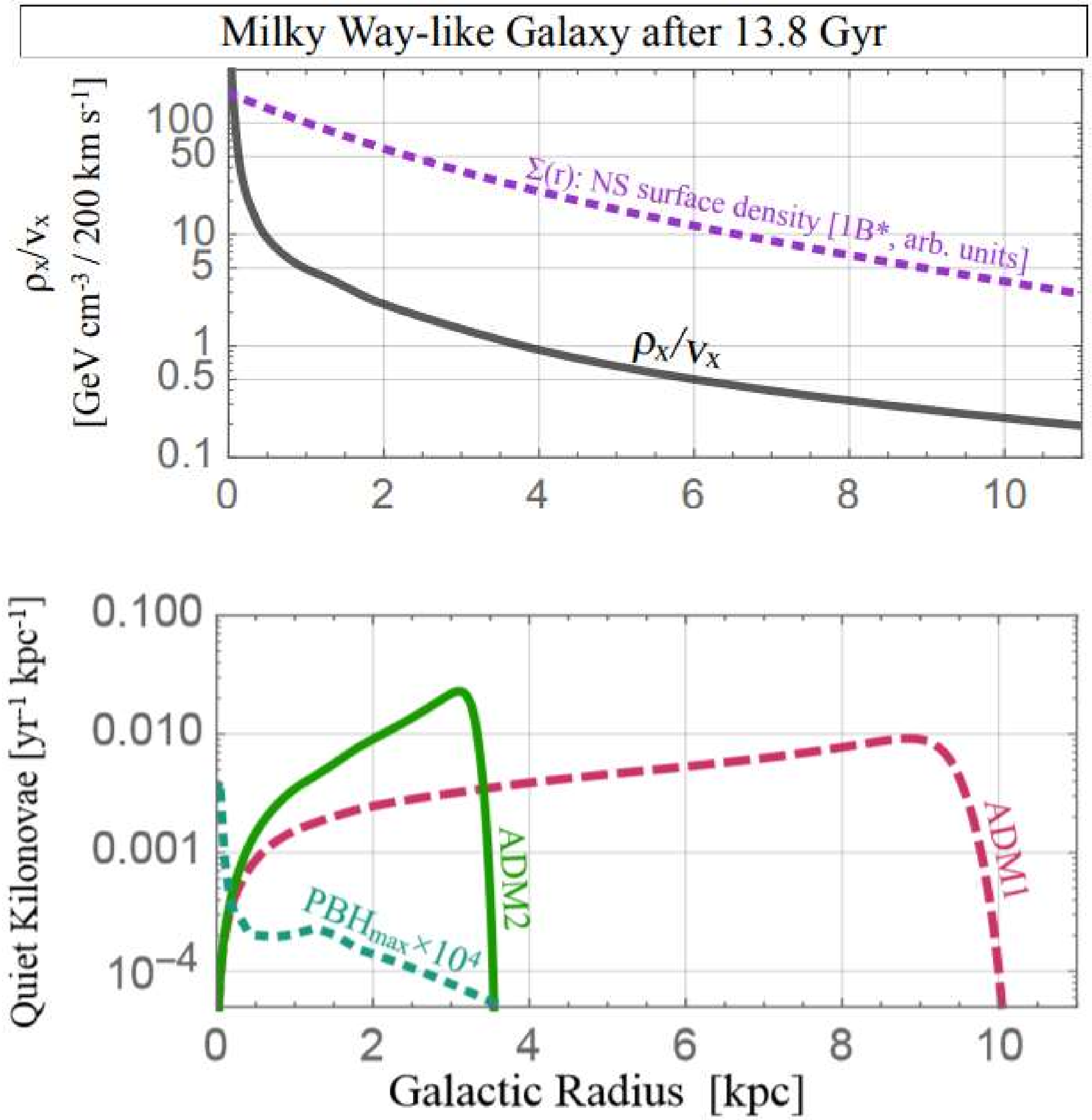
Figure 2. Observed KN and SN light curves in the i and z filters, as simulated with SNANA. The KN is based on the BK13 model with $\beta = 0.3$, $M = 0.1 M_\odot$ and redshift $z = 0.06$. The SNIa is simulated with SALT-II color $c = 0.03$, stretch parameter $x_1 = -0.75$, and redshift $z = 0.29$. Magnitudes are given by $27.5 - 2.5 \log_{10}(\mathrm{Flux})$; e.g., the shallow-field detection limit of mag=23.5 corresponds to Flux=40. The error bars show the simulated flux and uncertainties for each observation; the lines connect these simulated points to guide the eye.

- For DES-SN, the telescopes were used to make repeated observations of ten 3 deg^2 fields.
- Each field was observed in **griz** bands with central wavelengths of 4830, 6430, 7830, 9180 ˚A, respectively.

- Study done on NS mergers: BK13 (Barnes, Kasen, APJ 2013)
- ejecta masses ~10^{-3} - 10^{-1} M_{sun}
- ejecta velocities ~0.1 - 0.3 c.

Directly from *Doctor et al., DES, APJ 2017, 1611.08052*

NS Distribution



Neutron Star Wiki

Neutron Star temperature:

- The temperature inside a newly formed neutron star is from around 10^{11} to 10^{12} kelvin.[16] However, the huge number of neutrinos it emits carry away so much energy that the temperature of an isolated neutron star falls within a few years to around 10^{6} kelvin.[16]
- At this lower temperature, most of the light generated by a neutron star is in X-rays.

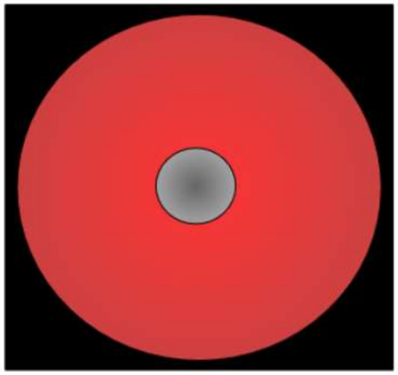
Neutron Star density

- 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) meaning that a teaspoon of neutron star material would weigh around a billion tons.

Neutron Star age

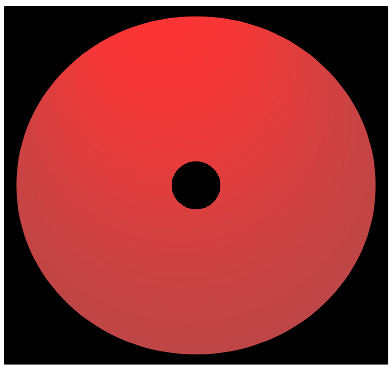
- Billions of years old. Age determination difficult. Oldest ~ 5 Gyr

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

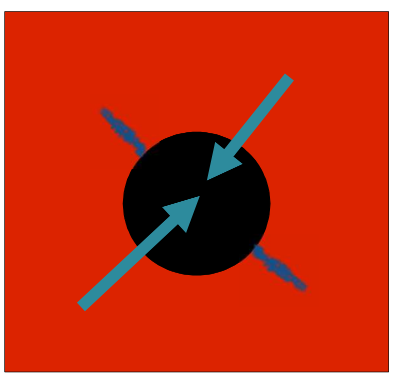
($M_{crit} \gg M_{self-gravit}$ for PeV-EeV mass DM)

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

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

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

4. BH consumes neutron star



Bondi accretion from the black hole consumes the host neutron star