Probing the millisecond pulsar interpretation of the Galactic Center gamma-ray excess

A binary population synthesis study

by
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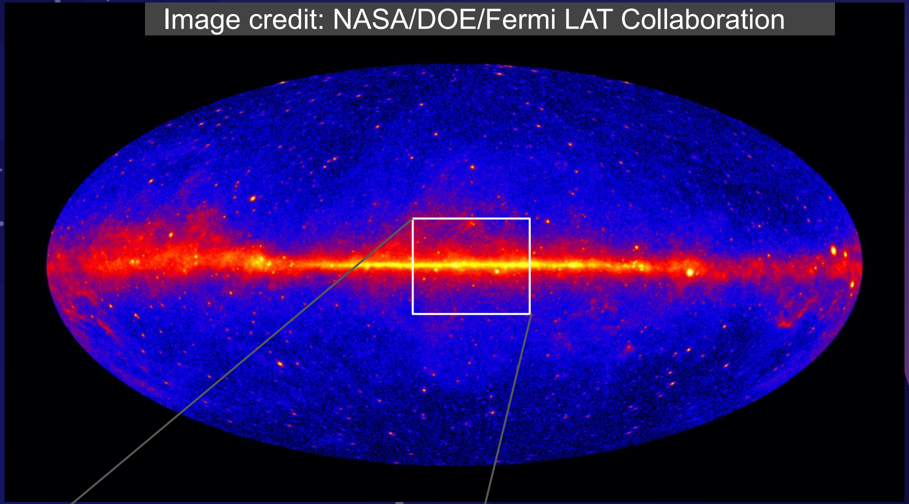
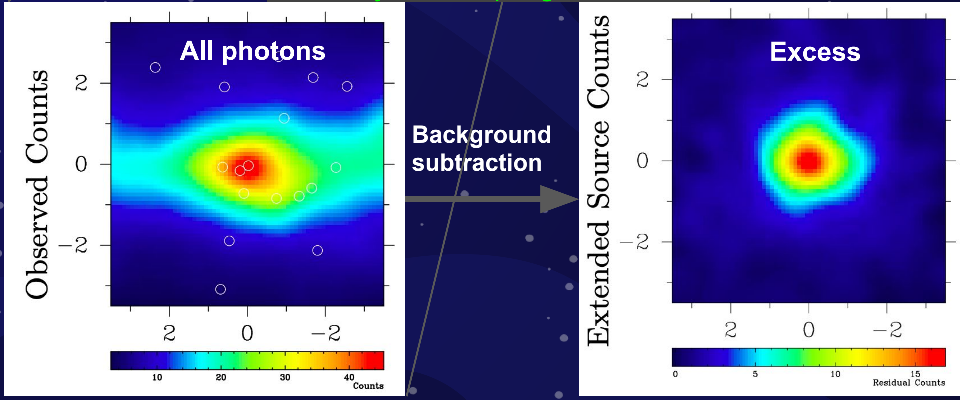
The Galactic Center GeV Excess

- Data from the Fermi-Large Area Telescope reveals prominent, unexplained, diffuse, non-thermal emission coincident with the Galactic bulge.
- Initial discovery in ‘09 by Goodenough & Hooper, in the Galactic Center (GC)
- Discovered to extend beyond the GC, into the inner galaxy, by Hooper & TRS ‘13.
- Confirmed by Fermi collaboration, in analysis of Ajello et. al ‘16
- The Galactic Center gamma-ray excess (GCE) peaks at ~2 GeV with an approximately spherical ($r^{-2.4}$) intensity profile.
- Possible sources include dark matter annihilation and emission from thousands of millisecond pulsars (MSPs).



Abazajian & Kaplinghat ‘12



Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

Arguments in favour of the MSP interpretation of the GCE:

- Typical MSP spectra have both the power law index and the energy cut-off intriguingly similar to those of the GCE.
- Recent point source analyses conclude that the photon count distribution of the GCE is more consistent with arising from a population of faint point sources rather than being truly diffuse.

Arguments against the MSP interpretation of the GCE:

- Based on the number of MSPs observed locally, it has been claimed that Fermi should detect many more bright MSPs from the vicinity of the GC/bulge, whereas it detects none.

  Countering this, we note that while the last active star formation in the Galactic bulge happened ~10 Gyrs ago, while the Galactic disk environment has experienced star formation up to the present day.

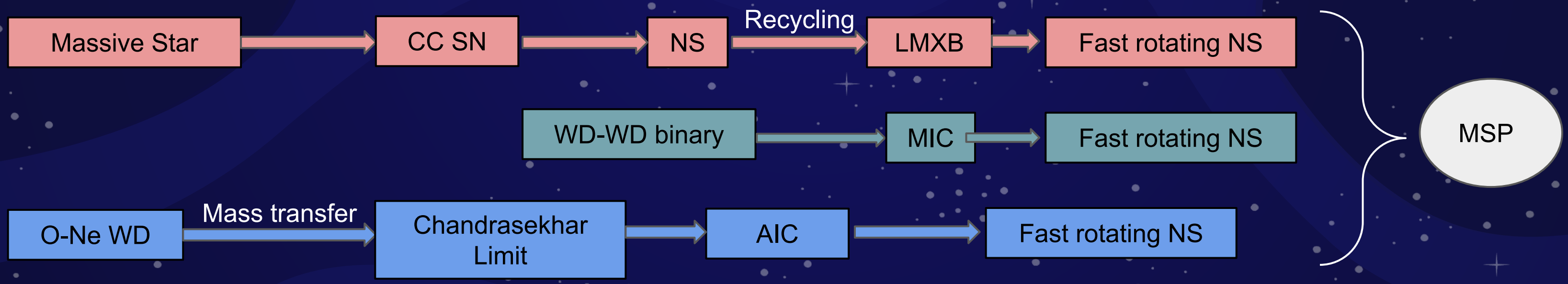
- The number of LMXBs observed in the bulge is considerably smaller than is expected. (42 LMXBs, and 46 additional LMXB candidates, were observed within 10 degree radius around the Galactic Center)

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

Alternate MSP formation channels:

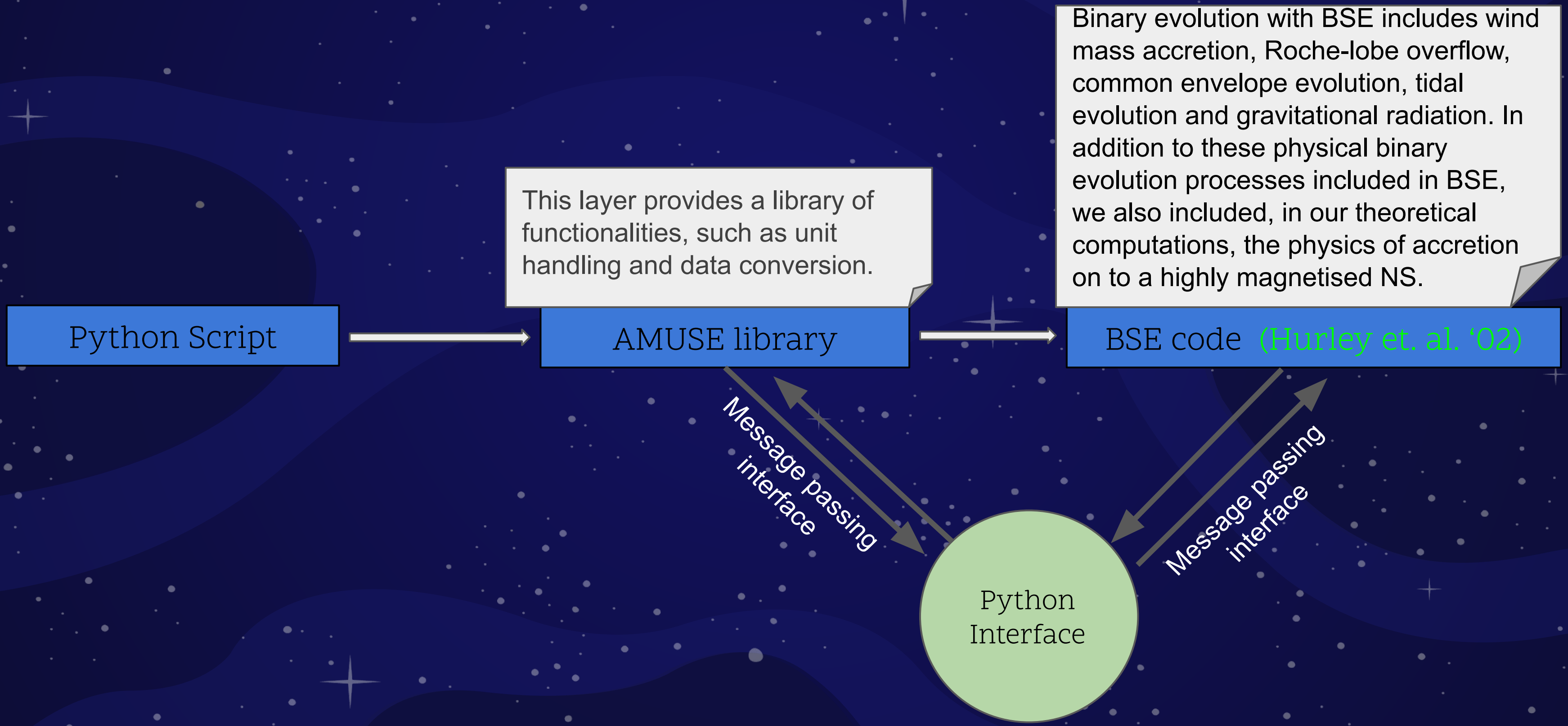
- **MIC**: A binary pair of white dwarfs may eventually merge due to gravitational wave radiation in a merger induced collapse (MIC), with conservation of angular momentum allowing millisecond periods. MIC channel would produce isolated MSPs which means that no subsequent LMXB phase would be possible.

- **AIC**: An Oxygen-Neon (ONe) white dwarf near the Chandrasekhar limit (~1.44 $M_\odot$) that is accreting from a low mass companion can undergo AIC. The resulting neutron star is now significantly more compact than the progenitor white dwarf, so angular momentum conservation results in approximately millisecond period rotation. No LMXB phase is necessary before the MSP emerges in this scenario.



Binary Simulation Model

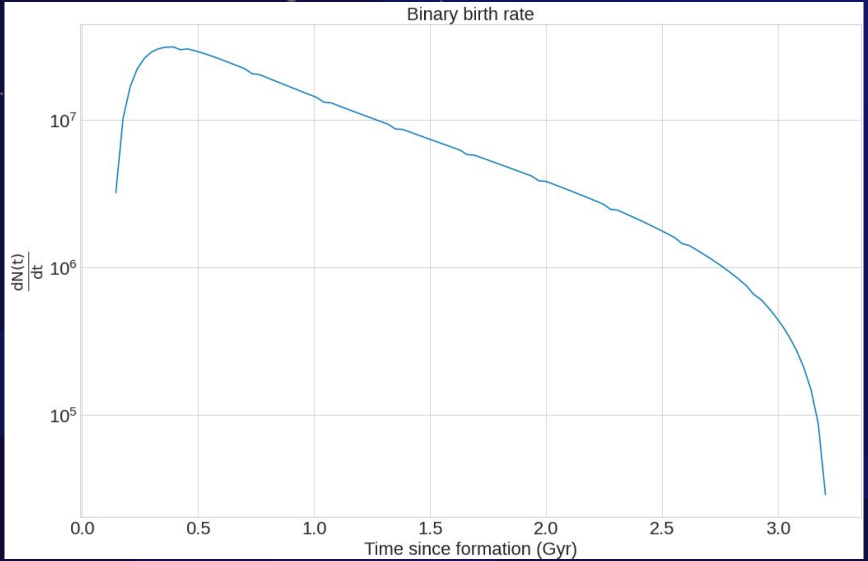
Binary evolution is performed using the community supported binary-star evolution (BSE) code module of the Astrophysical Multipurpose Software Environment (AMUSE).

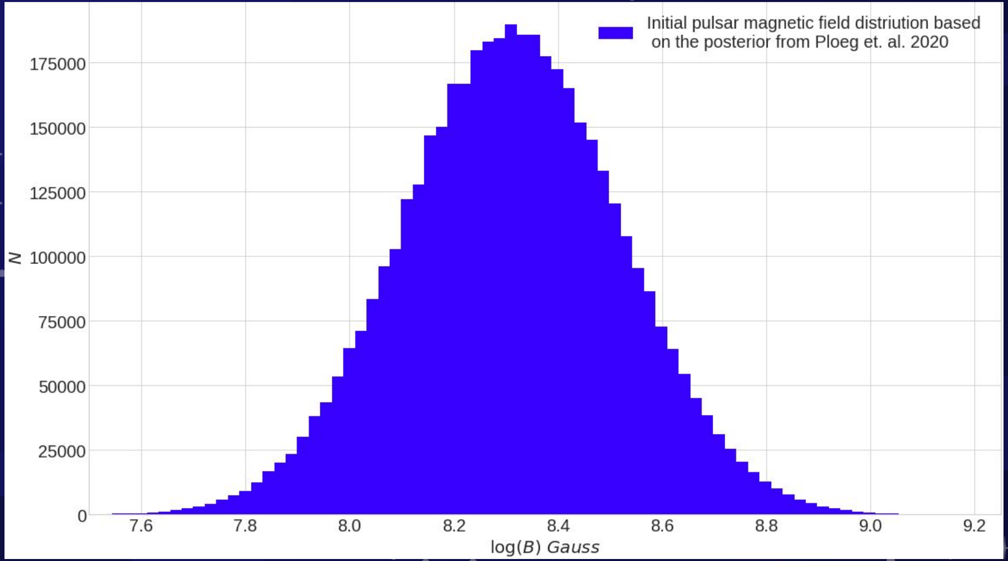


Binary Simulation Model

- We initialise the binary systems in our population with a birth-time that is sampled from a distribution based on the bulge star formation rates (SFRs) which is adopted from Crocker et. al. (2017).

- During the AIC collapse event, an ONe WDs with magnetic field of the order 10^3-10^5G collapses to become a rapidly rotating NS with fields of the order 10^8-10^{10}G, owing to the conservation of magnetic flux. We assign magnetic fields to the AIC NSs through random sampling from a magnetic field distribution based on the magnetic field posterior from Ploeg et. al. 2020. The magnetic field distribution is log-normal with a median of $10^{8.21}$G and a standard deviation of 0.21.





Accretion on to degenerate objects

The variation in spin is related to the torque exerted on to the star by the standard expression

$$\tau = -\frac{2\pi I \dot{P}}{P^2}$$

where I is the stellar moment of inertia.

For an accreting WD, the accreted material comes from the inner edge of an accretion disk, which is assumed to be at the WD's surface. The torque due to accretion is given by

$$\tau_{acc} = \dot{M}\ r^2\ \Omega_K(r) = \dot{M}\sqrt{GMr}$$

where $\Omega_K(r)$ is the Keplerian angular velocity at radius r.

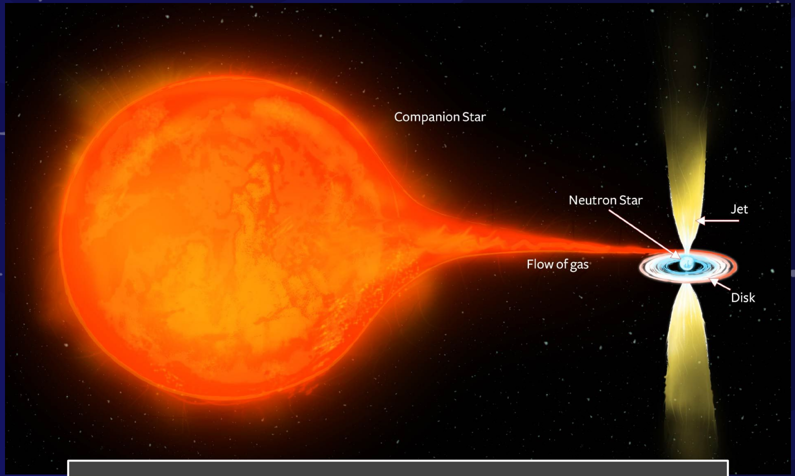


Image and video credits: NASA Goddard

Accretion-torque model

Given this donated gas has some large enough specific angular momentum, it cannot be transferred directly to the surface of the NS and instead forms a circumstellar accretion disk around it. The gas from the accretion disk is channelled on to the magnetic poles of the NS along the magnetic-field lines. This channelling occurs at what is known as the *magnetosphere radius*,

$$r_m = \xi r_A = \xi \left(\frac{\mu^4}{2GM\dot{M}^2} \right)^{1/7}$$

the steeply rising magnetic field threads the gas flow, enforcing corotation. This coupling between the field lines and the disk results in a torque acting on the star that can spin it up or down depending on the relative difference between r_m and the co-rotation radius,

$$r_c = \left(\frac{GM}{\Omega^2} \right)^{1/3}$$

which is the location of a Keplerian disk that rotates with the same frequency of the NS, where G is the gravitational constant, M is the mass of the NS, $\Omega = 2\pi/P$ is its angular frequency.

NSs in low-mass binaries (LMBs) may experience the phase of ejector, accretor, or propeller.

Ejector phase: NS braking results from the loss of magneto-dipole radiation as in an ordinary pulsar. This phase remains active until matter penetrates right to the NS magnetosphere.

$$\dot{P} = 3.15 \times 10^{-16} \frac{\mu_{26}^2}{P} \text{ s yr}^{-1}$$

Accretion-torque model

Propeller phase: If $r_m > r_c$, the NS spins faster than the accretion disk, thus acting to spin the NS down by ejecting the matter far out from the magnetosphere.

Accretor phase: If $r_m > r_c$, the NS spins slower than the accretion disk and so the gas that is channelled on to the NS has greater specific angular momentum than the NS, thus acting to spin it up.

The torque from this accretion disk-magnetic field coupling and outflow model predicts,

$$\dot{P} \approx -8.1 \times 10^{-5}\ \xi^{1/2}\ M_{1.4}^{3/7}\ I_{45}^{-1}\ \mu_{30}^{2/7} \left[\left(\frac{P}{1s} \right) \dot{M}_{-9}^{3/7} \right]^2 (1 - \omega_s)\ \ \mathrm{s\ yr^{-1}}$$

where, ω_s is the *fastness parameter* is defined as the ratio of the NS spin frequency to the Keplerian orbital frequency at the magnetospheric boundary,

$$\omega_s = \frac{\Omega}{\Omega_K(r_m)}$$

The sign of ω_s dictates whether the NS accretes the gas and spins up (the "slow rotator" regime, $\omega_s < 1$) or ejects the gas and spins down (the "fast rotator" regime, $\omega_s > 1$).

MSPs gamma-ray emission mechanism

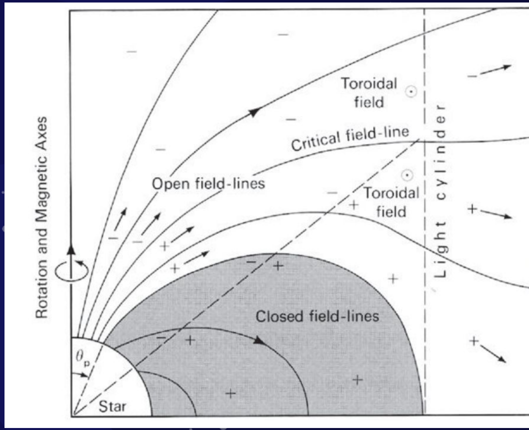
For pulsar gamma-ray luminosity, we use a Two Pole Caustic Slot Gap (TPC) gamma-ray emission model.

- The radiating region is confined to the surface of the last closed magnetic field lines, and it extends from the polar cap to the light cylinder. The light cylinder is defined as a hypothetical cylinder, centered on the pulsar and aligned with the rotation axis, with radius at which the rotational speed of the co-rotating particles is equal to the speed of light. The radiating gap region is where particle acceleration takes place as well as where high-energy photons originate.

- Particles attached to closed magnetic field lines co-rotate with the star and form a co-rotating magnetosphere. Charged particles stream out along the open field lines. Electrons may be dragged from the surface of the neutron star, but the protons are very tightly bound to the NS crust. As a result, rather than a neutral stream, a flux of electrons is dragged from the surface of the polar cap along open field lines and are accelerated by the intense induced electric fields just above the polar caps.

- The accelerated particles very rapidly lose any velocity component perpendicular to the magnetic field lines by synchrotron radiation, but, as they stream out along the curved magnetic field lines, they radiate curvature radiation. In the strong magnetic fields close to the pulsar, the high energy photons produced by the curvature radiation interact with the transverse component of the magnetic field to produce electron–positron pairs.

- In turn, these electrons and positrons radiate synchrotron photons and produce a second generation of pairs. Such a $e^{\pm}$-photon cascade cascade will continue until the synchrotron photons fail to meet the energetic requirements to pair produce and can escape to contribute to the high-energy pulsar emission.



We use an empirical gamma gamma-ray luminosity model for TPC gamma-ray emission, presented by Gonthier et. al. (2018), with the form

$$L_\gamma = 6.8172 \times 10^{35} f P_{-3}^{\alpha} \dot{P}_{-20}^{\beta} \text{ erg . s}^{-1}$$

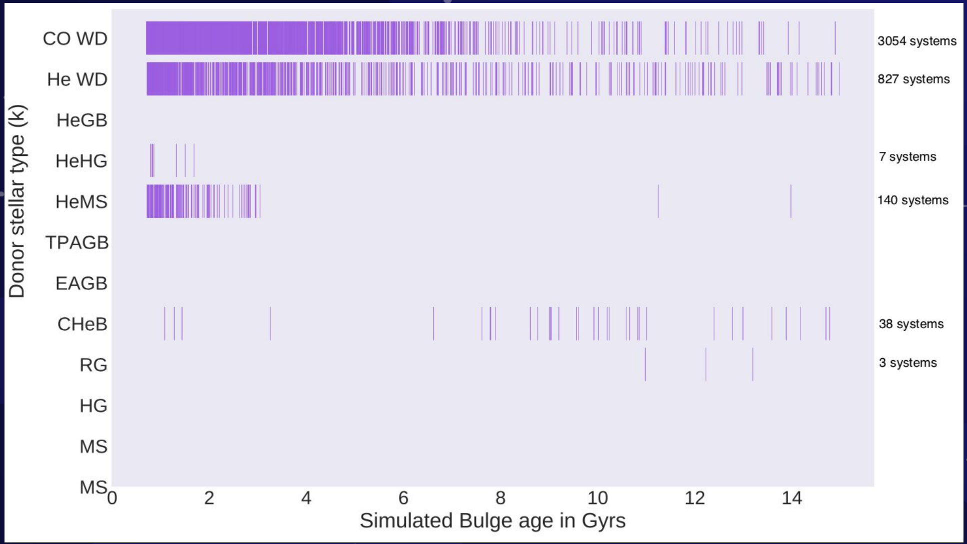
where *f* is the overall multiplicative factor of the gamma-ray luminosity, and *α* and *β* are the period and period derivative exponents, respectively. For the Two Pole Caustic Slot Gap (TPC) gamma-ray emission model, we use f=0.0122, *α* = -2.12 and *β* = 0.82 (from Gonthier et. al. (2018) MCMC free parameter fitting).

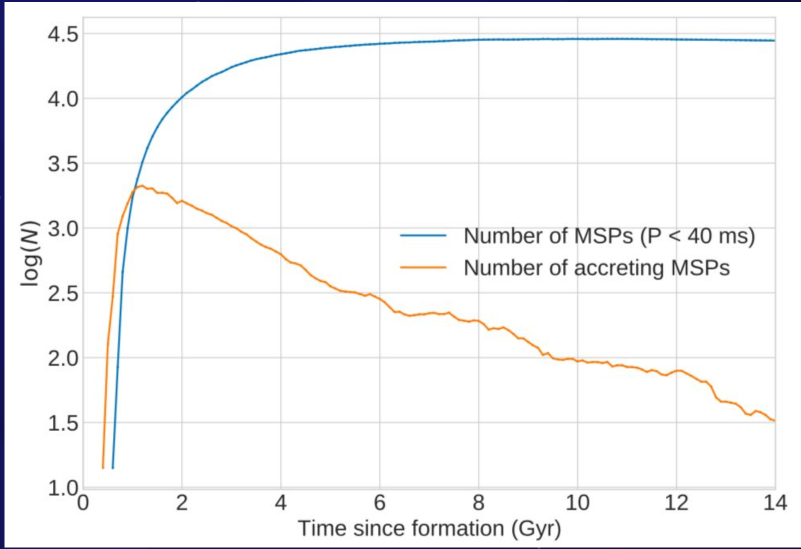
Results: The Simulated Bulge MSP and LMXB population

- **AIC donor types:** Donors can be giants, Core Helium Burning (CHeB) stars, He MS stars, stripped-helium burning stars or WDs. Systems with CO WD, He WD and He-MS donors dominate the AIC progenitor population.

- We start seeing AIC events when the population is ~1 Gyr old and the rate of AIC events decreases as we move forward in time.
- $L_X > 10^{36}$ erg/s ---> observable LMXB

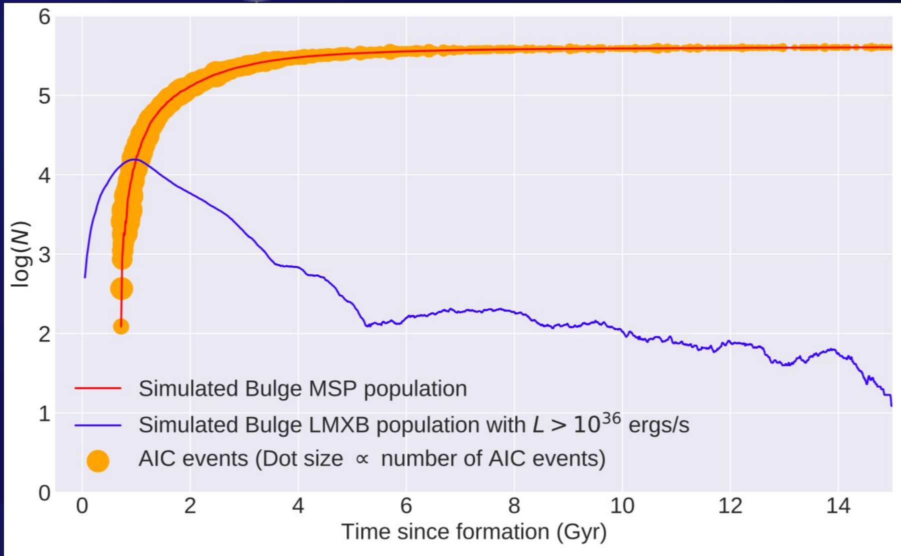
- Haggard et. al. (2017) estimated 42 LMXBs (and 46 additional LMXB candidates) within 10° radius around the Galactic Center.
- My population synthesis gives an estimate ~40 LMXBS. While at the same time predicting about 1.7×10^4 MSPs with periods less than 40 ms in the Galactic bulge.



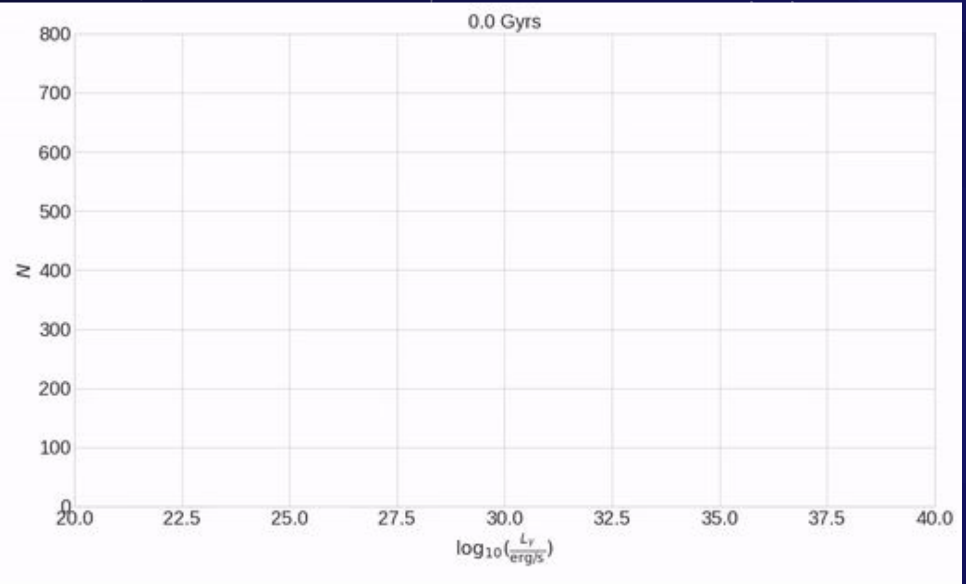


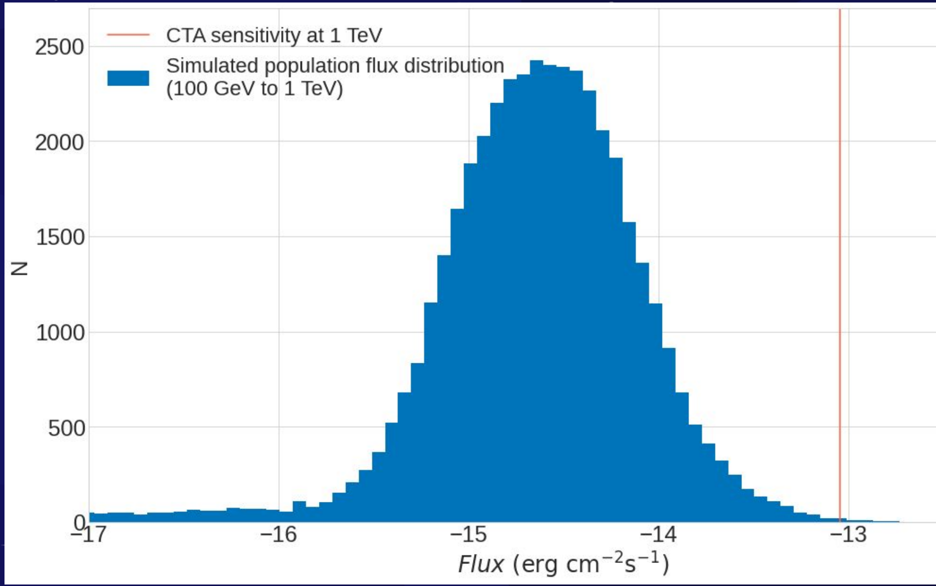
Results: The Simulated Bulge MSP and LMXB population

- Our synthesis of the MW Bulge indicates that the dominant NS population is old and that most NS were formed earlier than a delay time of ~8 Gyrs from the beginning of star formation in the Bulge.
- In the synthesised population, we start seeing AIC events when the population is ~1 Gyr old and the rate of AIC events decreases as we move forward in time.
- Most MSPs in our simulated population are born early in the life span of the Bulge.
- Accreting NS are potential LMXB sources. We classify any low mass binary that has X-ray luminosity higher than 10^{36} erg/s as an observable LMXB. (Based on Haggard et. al. 2017, where they consider a given LMXB in the Inner Galaxy to be detectable by INTEGRAL if it has X-ray luminosity exceeding 10^{36} erg/s.)
- Haggard et. al. (2017) estimated 42 LMXBs (and 46 additional LMXB candidates) within 10° radius around the Galactic Center using the INTEGRAL General Reference Catalogue. We estimate ~60 LMXBS at time t=13.7 Gyrs after the beginning of star formation in the Galactic bulge. At the same time (t=13.7 Gyrs), our synthetic population predicts 3.9 x 10^{5} MSPs in the Galactic bulge.



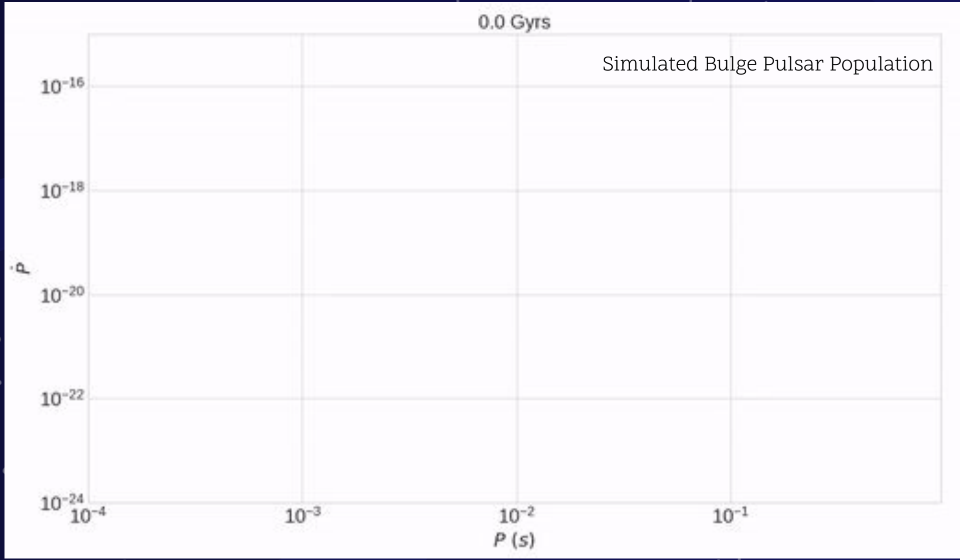
Luminosity and Flux distribution of the simulated Bulge MSP population

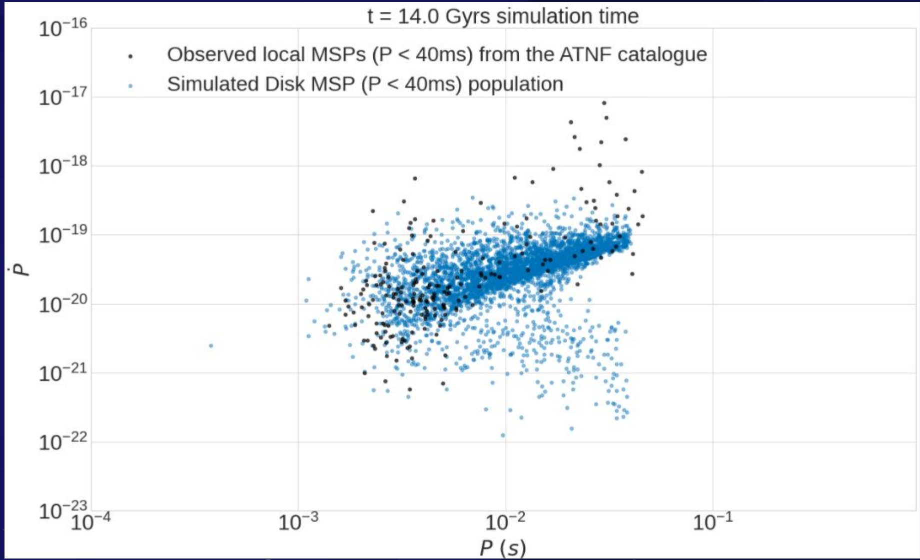




This model predicts ~300 MSPs in the MW Bulge above the point source sensitivity of the Cherenkov Telescope Array (CTA South 50h) at 1 TeV.

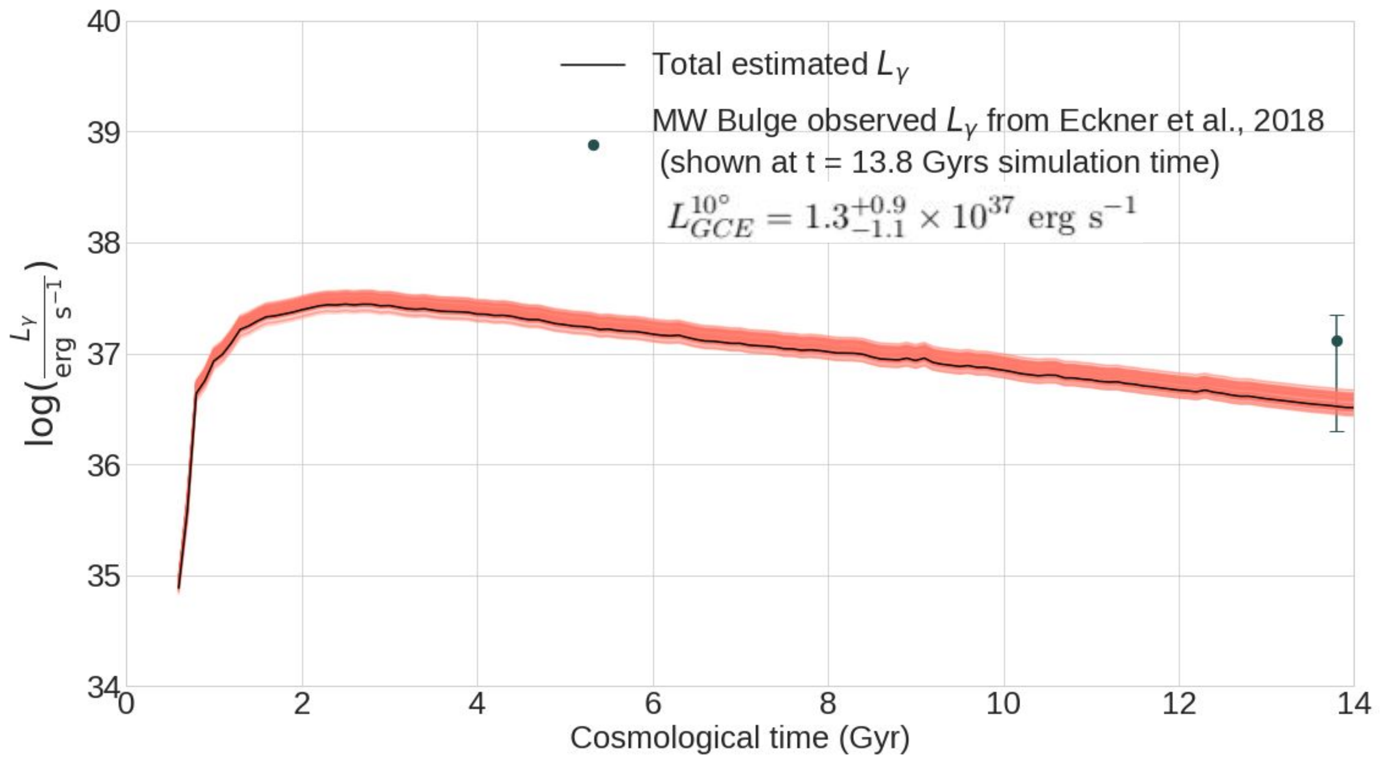
Period evolution of the simulated Bulge MSP population





The P-P_dot evolution of NSs formed via AIC as compared to the NSs catalogued in the ATNF pulsar database. We find that the P-P_dot of fast spinning NSs from our population somewhat resembles that of the observed NSs.

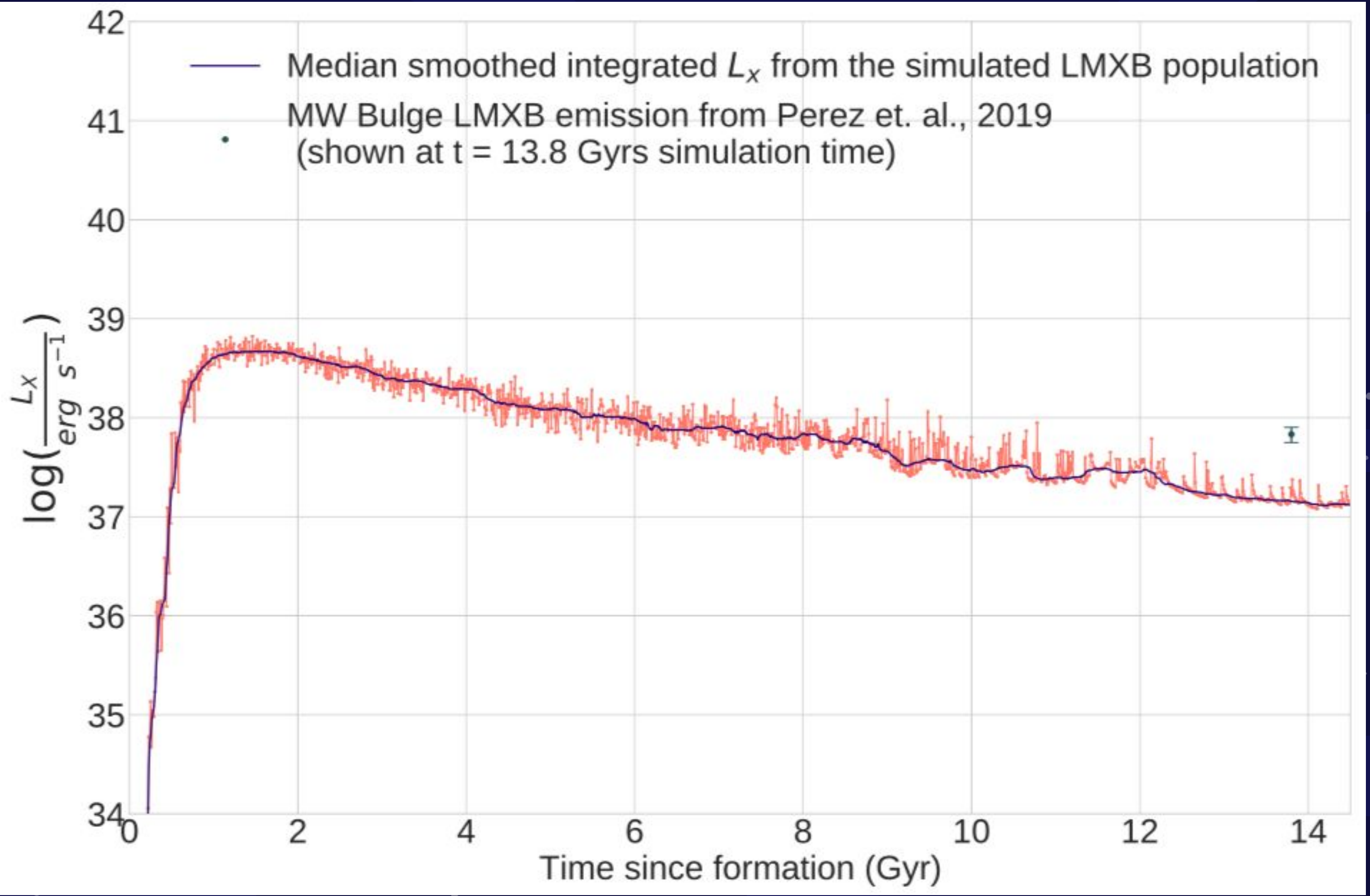
Total gamma-ray luminosity of simulated Bulge MSP population



Gamma-ray luminosity of each pulsar in our population is calculated using an empiricalγ-ray luminosity model for TPC γ-ray emission, presented by Gonthier et al. 2018.

$$L_\gamma = 6.8172 \times 10^{35} f P_{-3}^{\alpha} \dot{P}_{-20}^{\beta} \ \mathrm{erg\ .\ s^{-1}}$$

Total X-ray luminosity of simulated Bulge accreting pulsar population



Summary

- Based on the simulation data, we find that a population of MSPs in the bulge can naturally explain the gamma-ray excess and also overcome all arguments raised against MSP explanations for the GCE.
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- Drawing a parallel between the MW bulge γ-ray excess observations and our simulated population, we predict that a population of Accretion Induced Collapse MIllisecond Pulsars in the MW Bulge, formed in-situ, would have a mean γ-ray luminosity of the order~9×10^31 erg/s and would contribute considerably to the GCE and might even completely explain it. Furthermore, such a population would be more than 10 Gyrs old with the total number of MSPs of the order 30,000.

- It should be pointed out that any other astrophysical populations with similar spectral, luminosity and spatial characteristics as the MSPs could also contribute to the origin of the excess. However, MSPS are the most natural sources to satisfy these constraints.

- In the near future, an improvement in the local MSP luminosity function determination, together with improved observational studies of the non-thermal activity of sources in the MW bulge will narrow down the current spectrum of possibilities.

THANKS!