Constraining Axion Mass through Gamma-Ray Observations of Pulsars

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Synopsis

- Axions - properties , detection and production from pulsars
- We use a model from Berenji et al (2016) to set limits on axion mass using gamma-ray observations of 18 pulsars
- We consider effect of lower pulsar core temperatures on that model
- Consider an energy loss rate method to determine UL axion mass m_a
- Conclusion and future work

Axion Properties

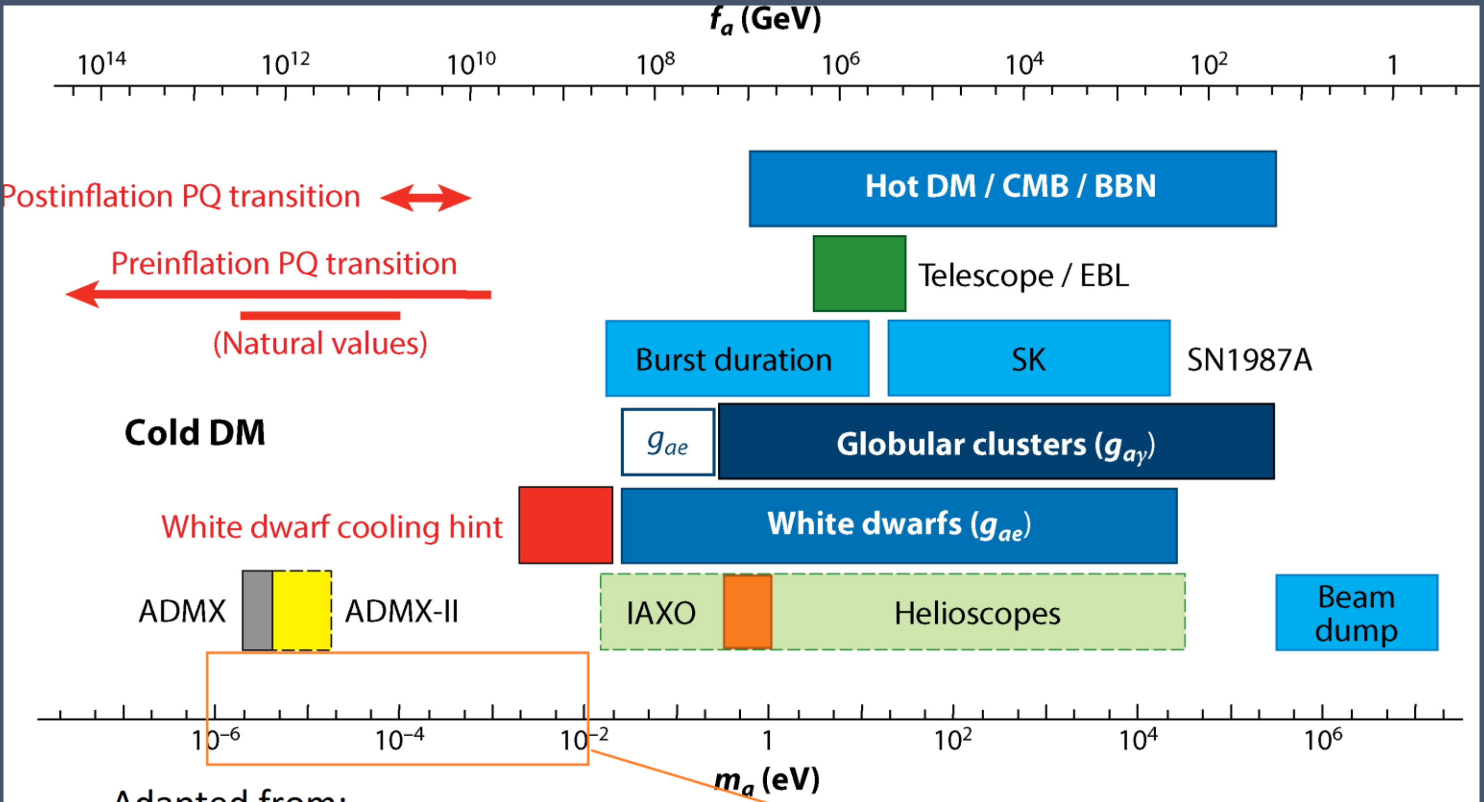
- Axions are a dark matter candidate – long lived, weakly interacting
- The axion can acquire a mass m_a through interactions with neutral pions given by :

$$m_a = \frac{6.0 \text{ eV}}{f_a/10^6 \text{ GeV}} \qquad \text{Eqn 1}$$

f_a is the axion decay constant or Peccei-Quinn Scale

- Photons and axions can interconvert in B and E fields $\Rightarrow$ direct detection experiments e.g. CAST – Solar axions converting to X-rays, probes $m_a < 0.02$ eV and ADMX – Galactic halo axions converting to microwaves 1.9 - 3.5 μeV

Axion Detection Search Space



Adapted from:

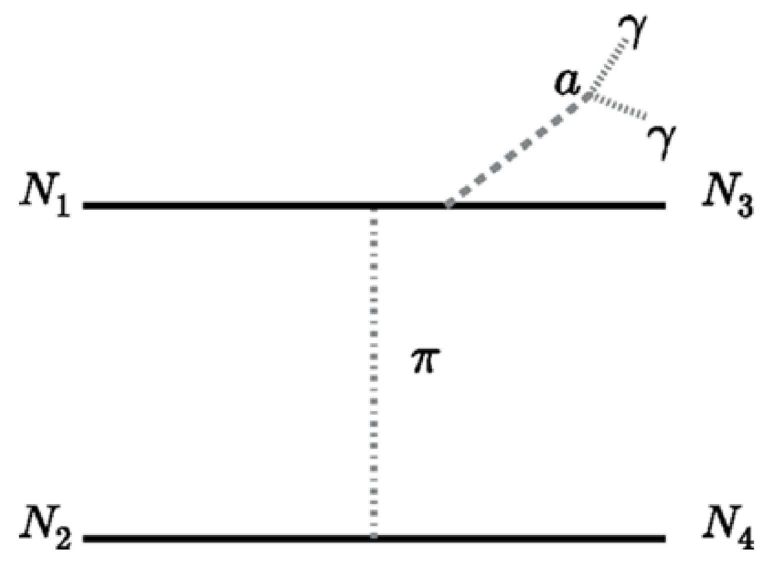
Graham PW, et al. 2015.
Annu. Rev. Nucl. Part. Sci. 65:485–514

Axion Mass Search Window

10^{-6} eV - 10^{-2} eV

Axion Emission from Pulsars

Mechanism - Nucleon nucleon Bremsstrahlung, one pion exchange, axion *a* decays to 2 gamma-ray photons



PSR Axion Emissivity (Hanhart et al 2001)

A Spin structure function Sσ(ω) allows for balanced energy and momentum transfer of nucleons via Bremsstrahlung:

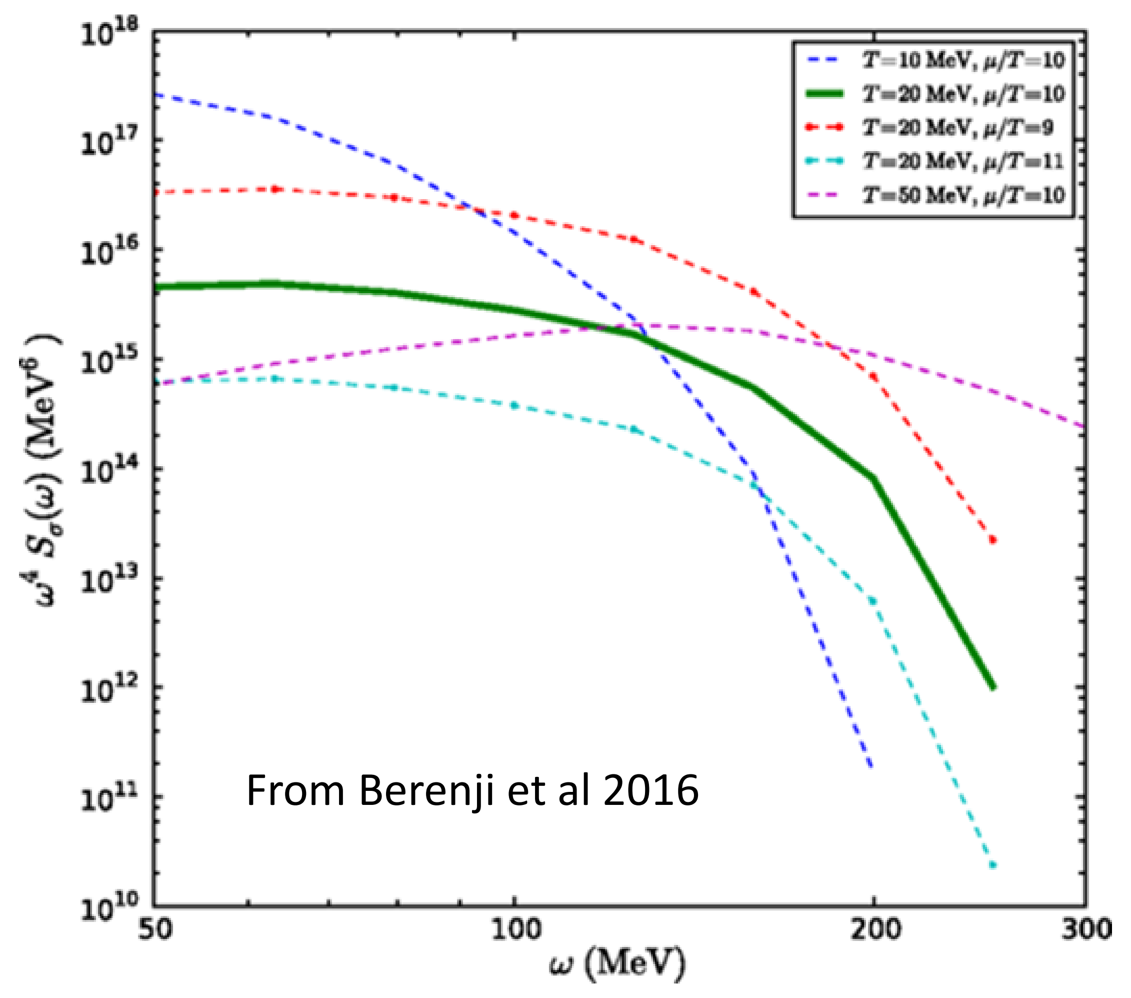
$$S_\sigma(\omega) = \int \left[\prod_{i=1,\ldots,4} \frac{d^3 p_i}{(2\pi)^3} \right] (2\pi)^4 \delta^3\left(\mathbf{p_1} + \mathbf{p_2} - \mathbf{p_3} - \mathbf{p_4}\right) \times \delta(E_1 + E_2 - E_3 - E_4 - \omega) \mathcal{F} \frac{1}{s} \mathcal{H}_{ii} \qquad \text{Eqn 2}$$

($H_{ii} \approx 10/\omega^2$, F is product of thermodynamic functions)

Axion emissivity ε_a is analogous to neutrino emissivity where ω is the axion energy, M is nucleon mass and g_{ann} is axion-nucleon coupling (10^{-8} (m_a/eV):

$$\mathcal{E}_a = \frac{g_{\mathrm{ann}}^2}{16\pi^2 M^2} \frac{1}{3} \int d\omega \, \omega^4 \, S_\sigma(\omega) \qquad \text{Eqn 3}$$

Axion Emissivity vs Energy

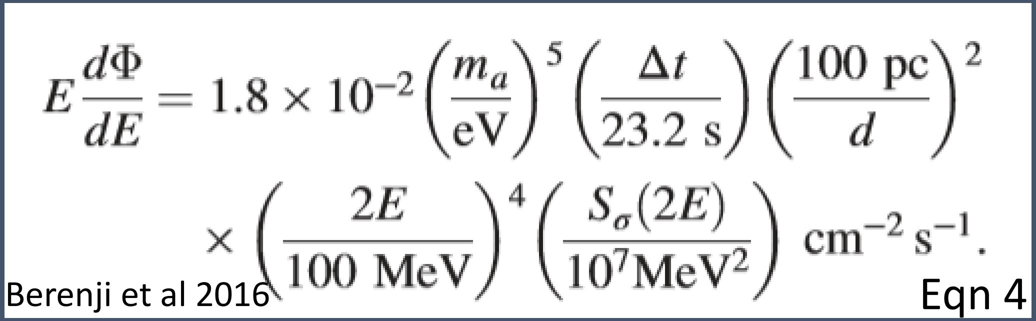


From Berenji et al 2016

- Berenji et al (2016) uses analytic simplification (Hannestad and Raffelt 1998) to numerically evaluate phase space integral
- Higher NS temperatures increase emission of higher energy axions and γ γ
- Berenji et al choose green line for their analysis, PSR core Temp = 20 MeV

Determine Axion Mass using PSRs

- Berenji et al formulate an astrophysical gamma-ray flux model based on axion emission rate / decay:



$$E\frac{d\Phi}{dE} = 1.8 \times 10^{-2}\left(\frac{m_a}{\mathrm{eV}}\right)^5\left(\frac{\Delta t}{23.2\ \mathrm{s}}\right)\left(\frac{100\ \mathrm{pc}}{d}\right)^2 \times \left(\frac{2E}{100\ \mathrm{MeV}}\right)^4\left(\frac{S_\sigma(2E)}{10^7\mathrm{MeV}^2}\right)\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}.$$

Berenji et al 2016

Eqn 4

- Model is then used predict spectral energy distribution (SED) of expected differential photon flux

- They use Fermi-LAT observations of 4 nearby gamma-ray dark pulsars to get a normalisation of this SED model and from normalisation to power 1/5 obtain UL m_a= 0.079 eV

Our Refined *Fermi*-LAT Analysis

Berenj 2016:

- Fermi-LAT Pass 7 data release
- 2 FGL Catalogue
- 4 pulsars <0.4 kpc
- 5 years of event data
- Unbinned analysis
- Free sources within 10^o
- Use own MINOS calculation of pulsar flux 95 % flux upper limits

Our analysis:

- Pass 8 (Improves PSF / 60 MeV)
- 3FGL Catalogue + Source Detection
- 18 gamma-dark PSRs <0.5 kpc
- 9 years of event data
- Binned analysis 4 bins / decade
- Free sources within 13^o
- Use fermipy source attribute flux_UL95, the 95 % confidence limit on photon flux integrated over analysis range
- Conservative for low energy as used in Lloyd et al 2018 for Globular Cluster analysis

Our calculation of UL Axion Mass

We re-arrange the Berenji model to get UL axion mass m_a in terms of upper limit photon flux and spin structure functions (Eqn 5)

$$m_a = \left[flux\_UL95 \times 55.5 \times \left(\frac{d}{100\ pc}\right)^2 \left(\frac{100\ MeV}{2E}\right)^4 \left(\frac{10^7\ MeV}{S\sigma(2E)}\right) \right]^{\frac{1}{3}}$$

- We consider two axion energies 100 MeV and 200 MeV
- Lookup Sσ(ω) from axion emissivity plot for these axion energies
- Then determine a UL axion mass from UL photon fluxes for our pulsars

UL Axion Mass m_a for ω=100 MeV

PSR Sample and Count	**UL Axion Mass /eV**
All pulsars (18)	0.0098
Omit >3σ Possible Detections (13)	0.0086
Berenji Pulsars Only (4)	0.0098

8 to 9 fold improvement on Berenji $m_a < 0.079$ eV

UL Axion Mass m_a for ω=200 MeV

PSR Sample and Count	UL Axion Mass /eV
All pulsars (18)	0.0326
Omit >3σ Possible Detections (13)	0.0289
Berenji Pulsars Only (4)	0.0329

More modest twofold improvement on Berenji $m_a < 0.079$ eV

Reconsider PSR Core Temperature

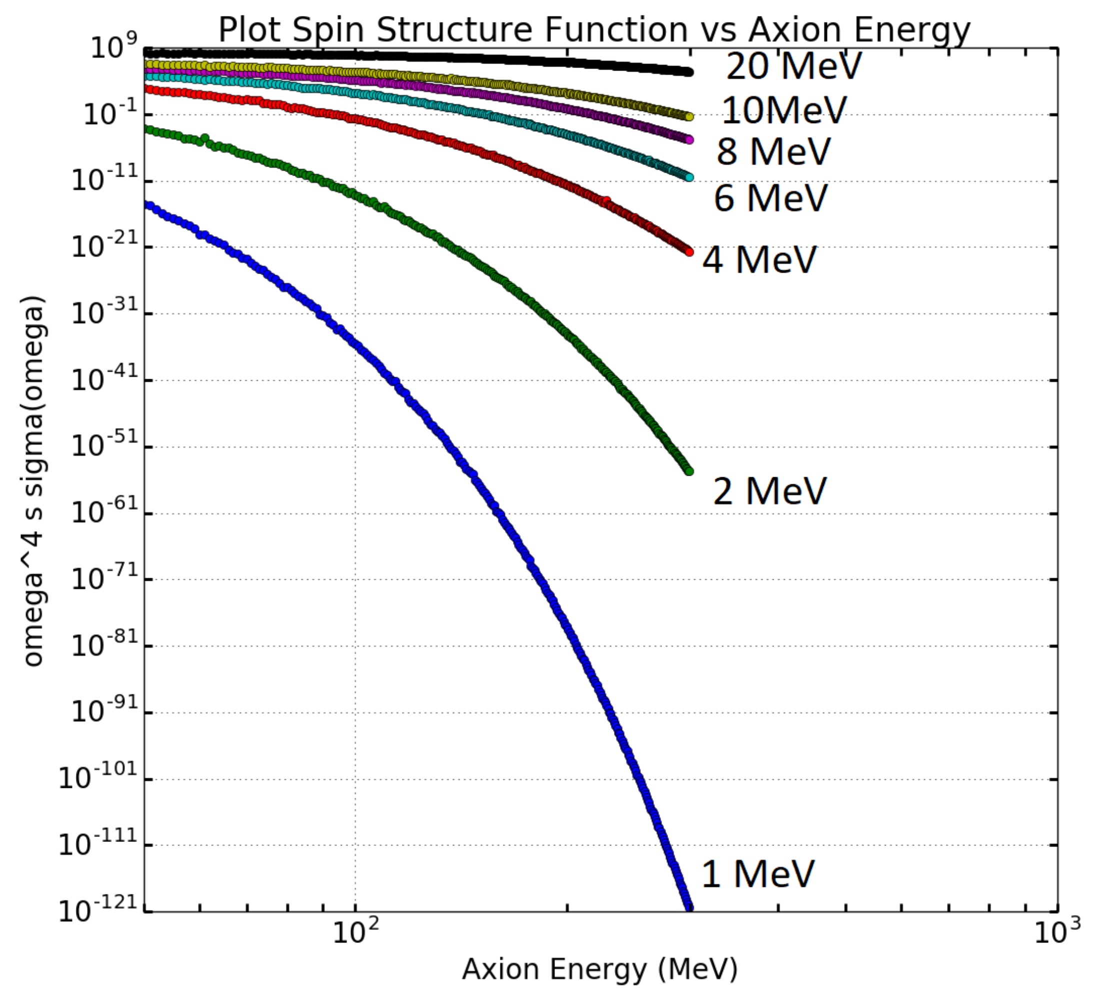
- Axion emission has strong temperature dependence $\approx T^6 \Rightarrow$ leads us to examine more closely the PSR temperature used

- 20 MeV PSR core temperature used by Berenji et al cites phase diagram of quark core hybrid stars (Rüster et al 2005) along with quark core slow cooling (Negreiros et al 2012) and crustal heating due to superfluidity (Larson and Link 1999) along with Akmal et al 1998 (T_F=20 MeV)

- T_c =20 MeV appears a high temperature choice more consistent with cores v. shortly after supernova event (peak T_c 10-30 MeV at 150 ms Sumiyoshi et al 2005)

- PSR core cools to $\approx$ 1-2 MeV in seconds (Pons et al 1999, Nakazato et al 2018 , Zhu et al 2018)

Sσ(ω) **at Lower PSR Core Temperatures**



- Axion emissivity is much reduced with lower PSR core temperature T_c
- Reducing T_c from 20 MeV to 4 MeV lowers ω^4 Sσ(ω) and hence axion emissivity by factor of $\times 10^9$

UL Axion Mass from Energy Loss Rate

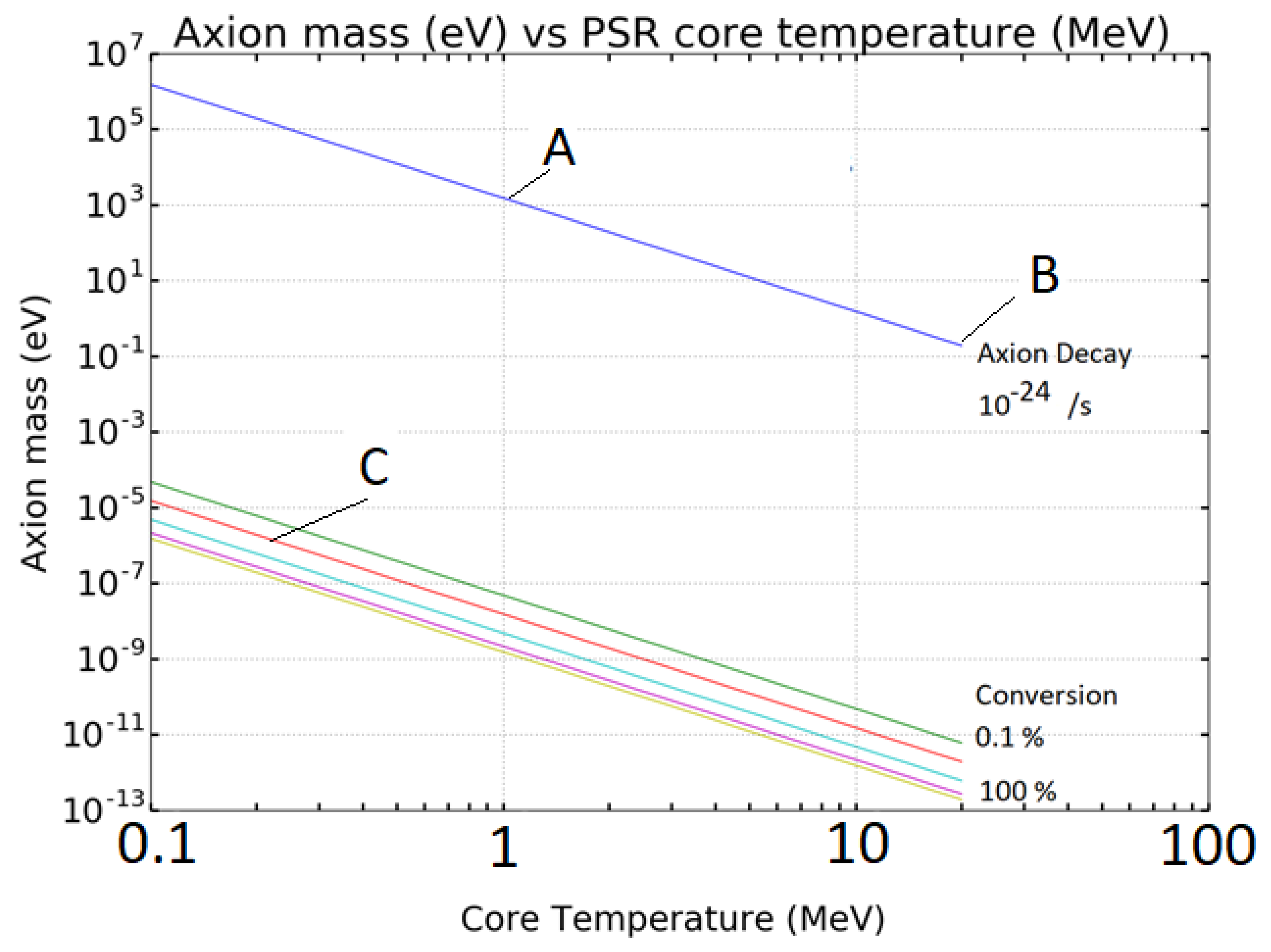
- Axion power equation – Raffelt 1996, from Iwamoto 1984 and Brinkmann and Turner 1988. Can apply canonical NS values, strong temperature dependence

$$\epsilon_a^{\mathrm{D}} = \alpha_a \, 1.74 \times 10^{31} \, \mathrm{erg\,g^{-1}\,s^{-1}} \, \rho_{15}^{-2/3} \, T_{\mathrm{MeV}}^{6}$$

Eqn 6

- Here α_a is axion/nucleon FSC ≡ $(C_N M / f_a)^2 / 4\pi$
- C_N model dependent coupling constant of order unity
- Can derive total luminosity and relate this to UL energy flux eflux_ul95 for our 18 pulsars
- Can obtain f_a and thus determine UL axion mass

Axion Photon Conversion and UL m_a



(A)-Axion decay alone yields too heavy axions

(B)- At T_c = 20 MeV UL m_a = 0.2 eV consistent with Berenji

(C)- Low T_c and/or low conversion needed to keep UL $m_a > 10^{-6}$ eV

Conclusion and Future Work

- We analyse 18 gamma-ray dark pulsars using 9 years of Fermi-LAT pass 8 data

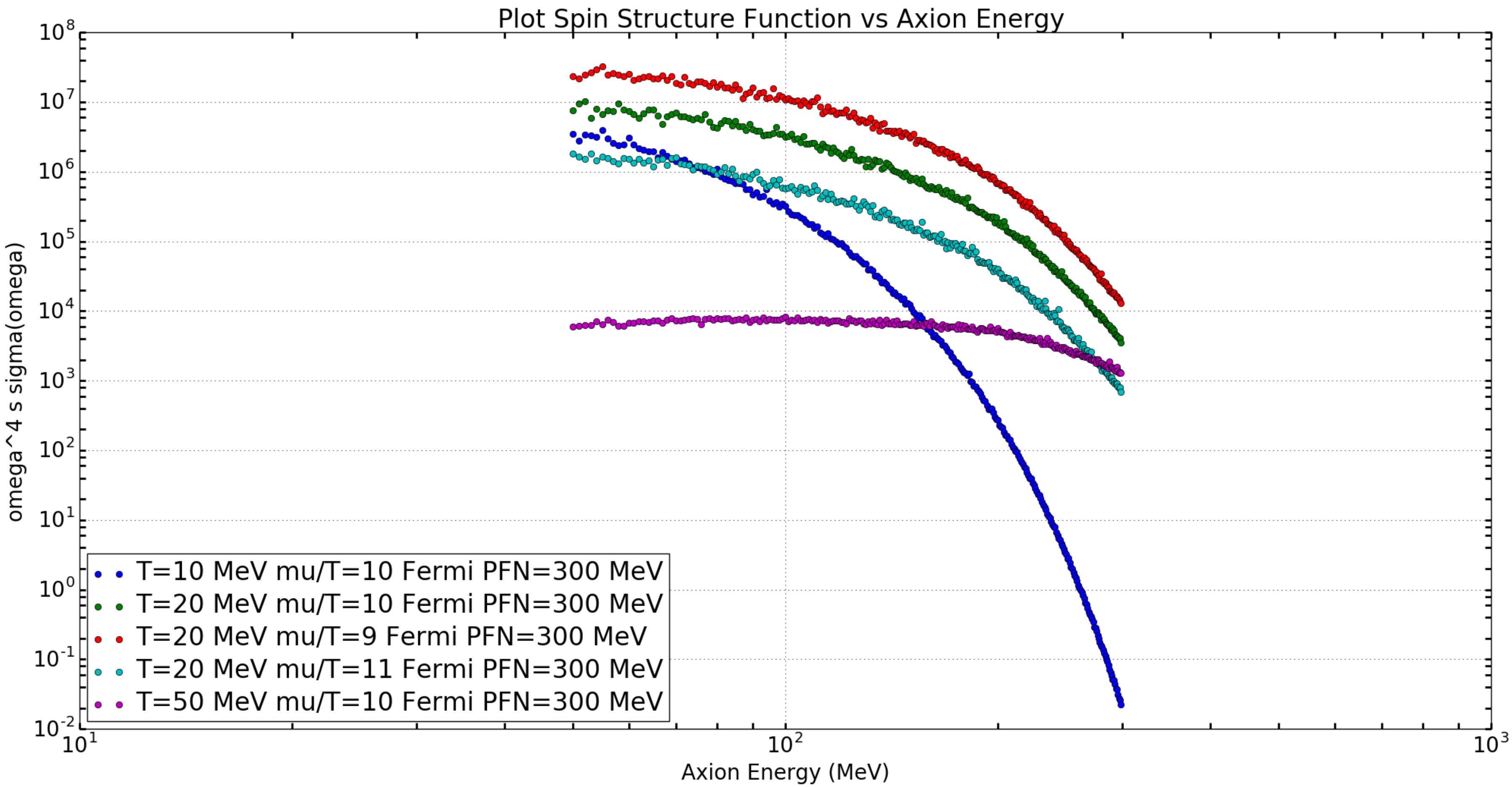
- We use these obs and Berenji et al model to calculate upper limit axion mass of 0.0098 eV for axion energy 100 MeV and 0.0326 eV for axion energy 200 MeV

- We extrapolate spin structure function to realistic PSR core temperatures of 1 MeV and show axion emissivity is much reduced

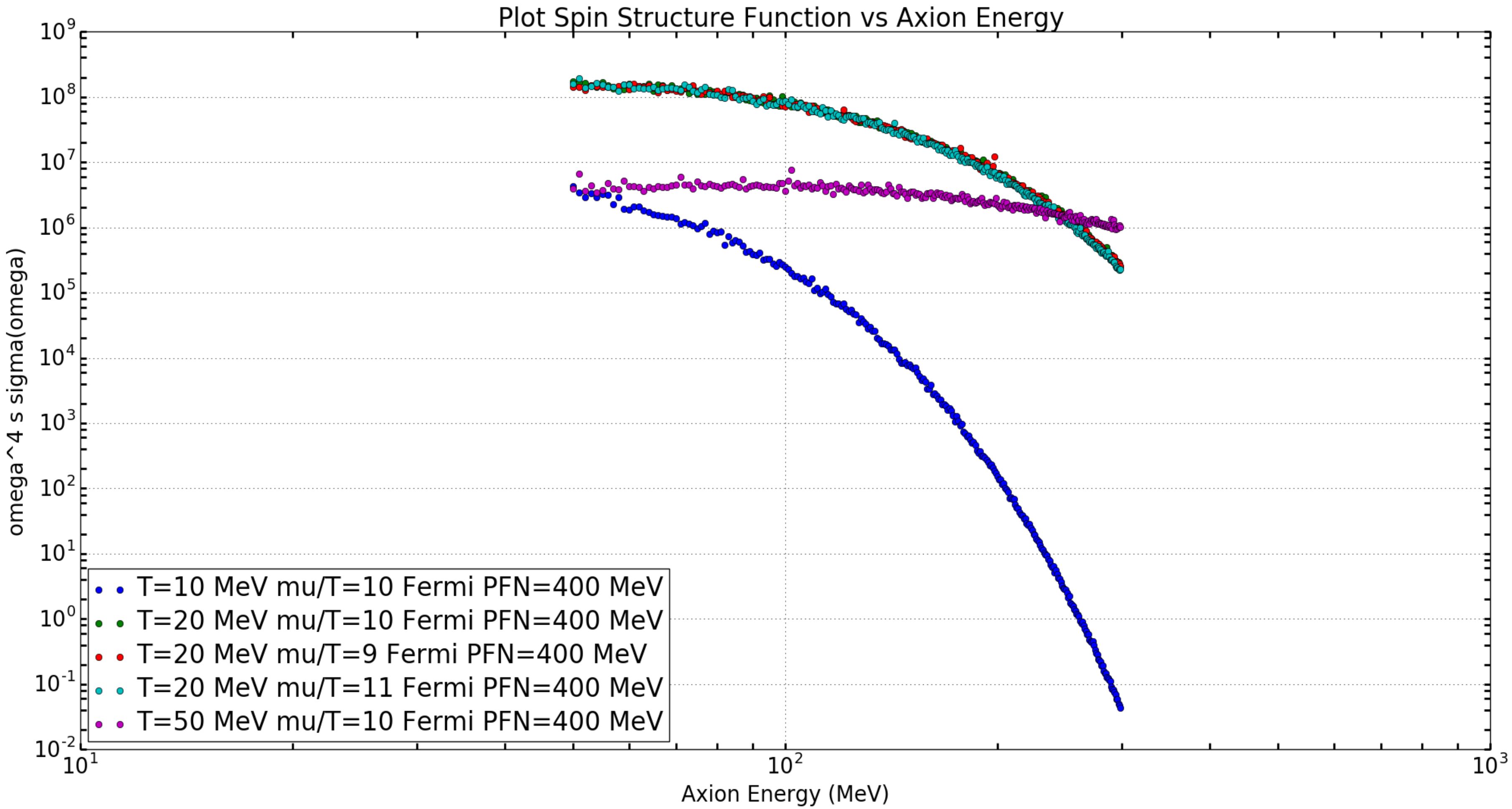
- We derive UL axion masses using the Raffelt axion power equation and show low T_c and low $a\rightarrow\gamma\gamma$ conversion (but greater then conservative decay) needed to obtain plausible m_a

- Our future work will seek to quantify $a\rightarrow\Upsilon\Upsilon$ in PSR B field regime using Fortin and Sinha 2018 modelling work on Magnetars

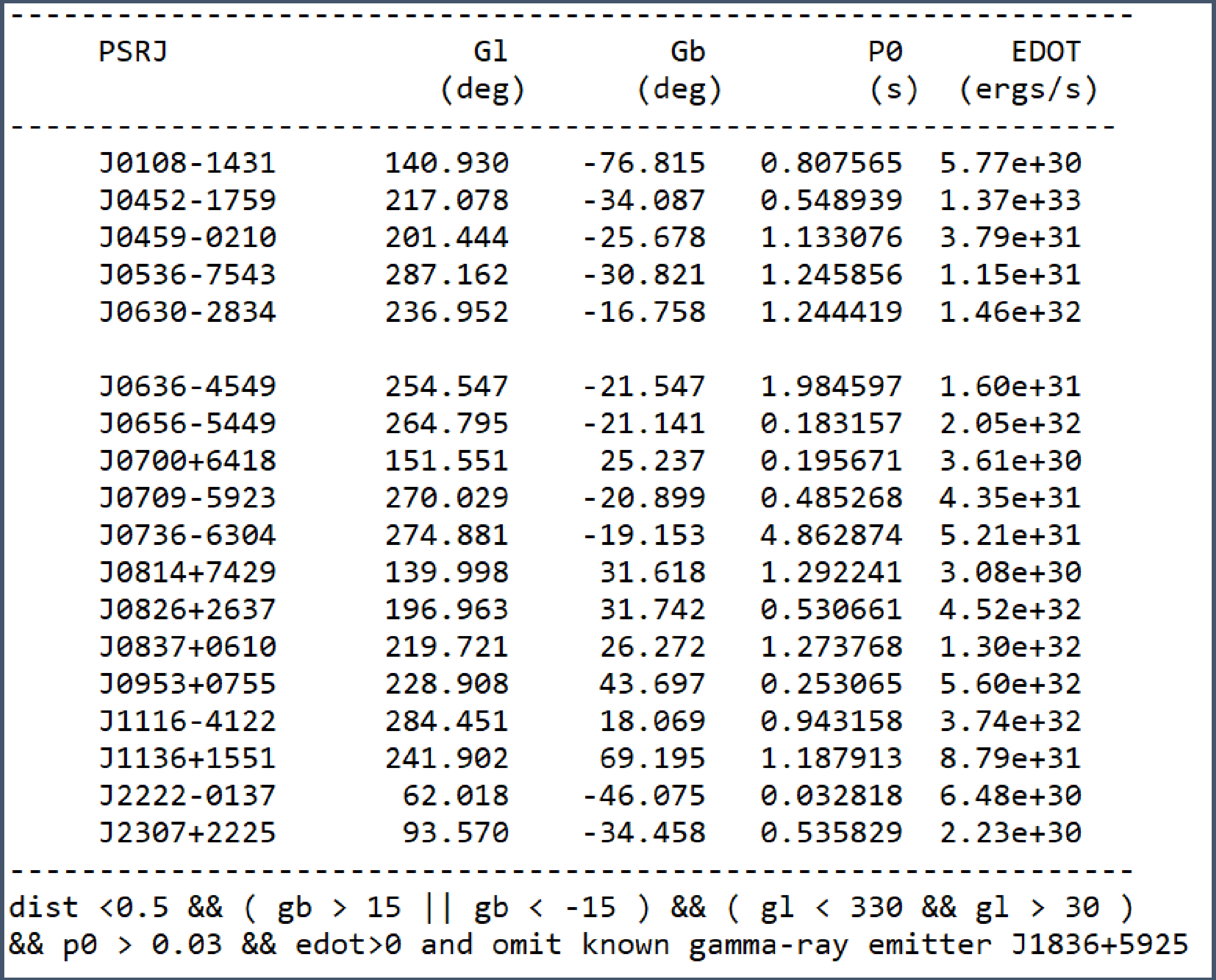
BACKUP – Spin Structure Low PFN



BACKUP – Spin Structure High PFN



BACKUP – PSR Selection ATNF



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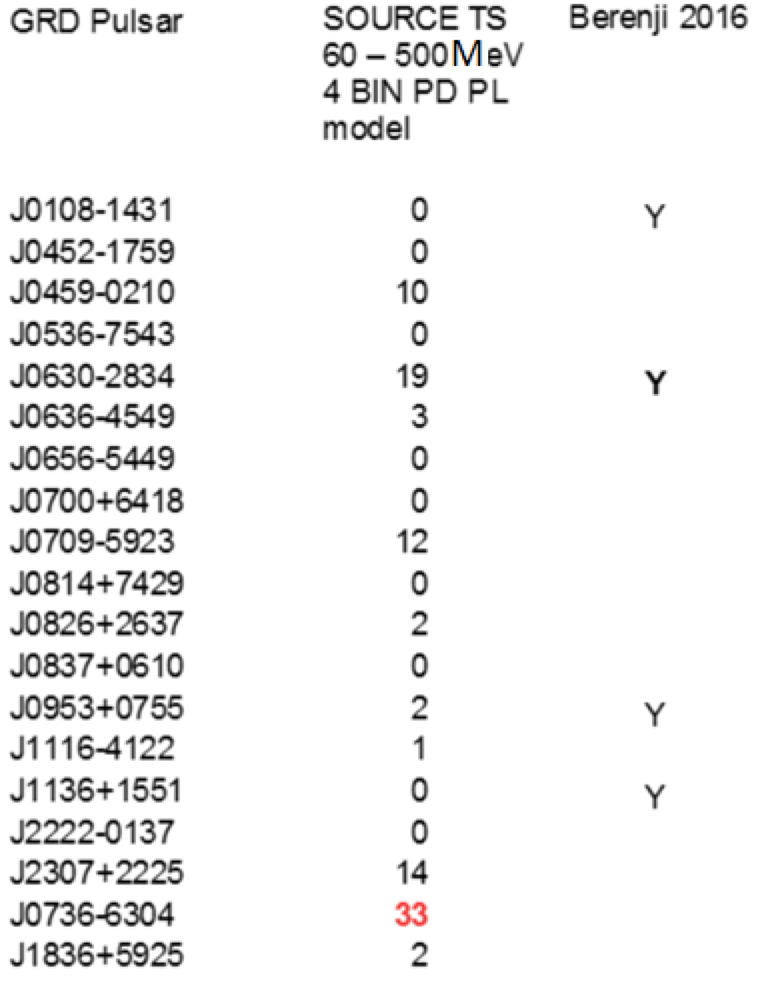
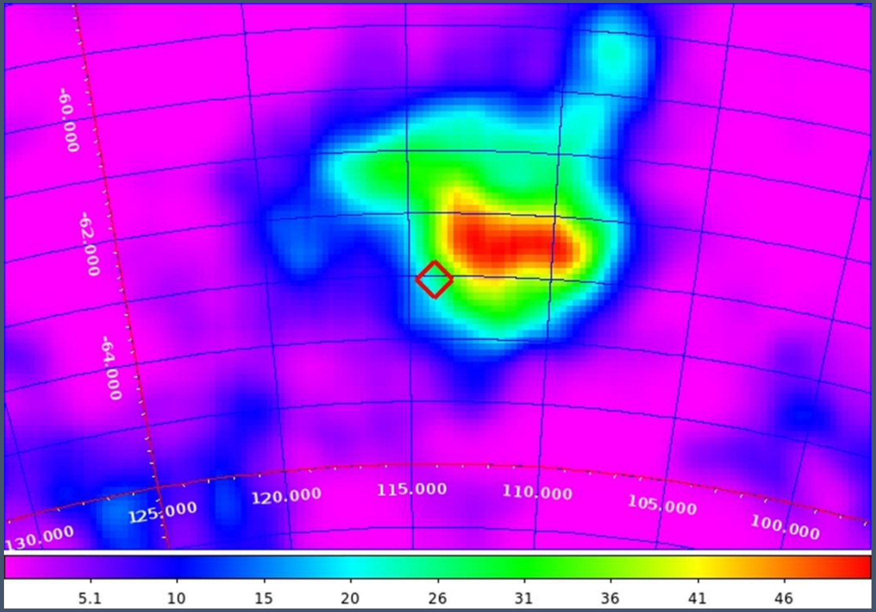
----------------------------------------------------------------
    PSRJ                  Gl          Gb          P0        EDOT
                       (deg)       (deg)         (s)   (ergs/s)
---------------------------------------------------------------
    J0108-1431      140.930     -76.815    0.807565   5.77e+30
    J0452-1759      217.078     -34.087    0.548939   1.37e+33
    J0459-0210      201.444     -25.678    1.133076   3.79e+31
    J0536-7543      287.162     -30.821    1.245856   1.15e+31
    J0630-2834      236.952     -16.758    1.244419   1.46e+32

    J0636-4549      254.547     -21.547    1.984597   1.60e+31
    J0656-5449      264.795     -21.141    0.183157   2.05e+32
    J0700+6418      151.551      25.237    0.195671   3.61e+30
    J0709-5923      270.029     -20.899    0.485268   4.35e+31
    J0736-6304      274.881     -19.153    4.862874   5.21e+31
    J0814+7429      139.998      31.618    1.292241   3.08e+30
    J0826+2637      196.963      31.742    0.530661   4.52e+32
    J0837+0610      219.721      26.272    1.273768   1.30e+32
    J0953+0755      228.908      43.697    0.253065   5.60e+32
    J1116-4122      284.451      18.069    0.943158   3.74e+32
    J1136+1551      241.902      69.195    1.187913   8.79e+31
    J2222-0137       62.018     -46.075    0.032818   6.48e+30
    J2307+2225       93.570     -34.458    0.535829   2.23e+30
----------------------------------------------------------------
dist <0.5 && ( gb > 15 || gb < -15 ) && ( gl < 330 && gl > 30 )
&& p0 > 0.03 && edot>0 and omit known gamma-ray emitter J1836+5925
```

BACKUP – Analysis Results

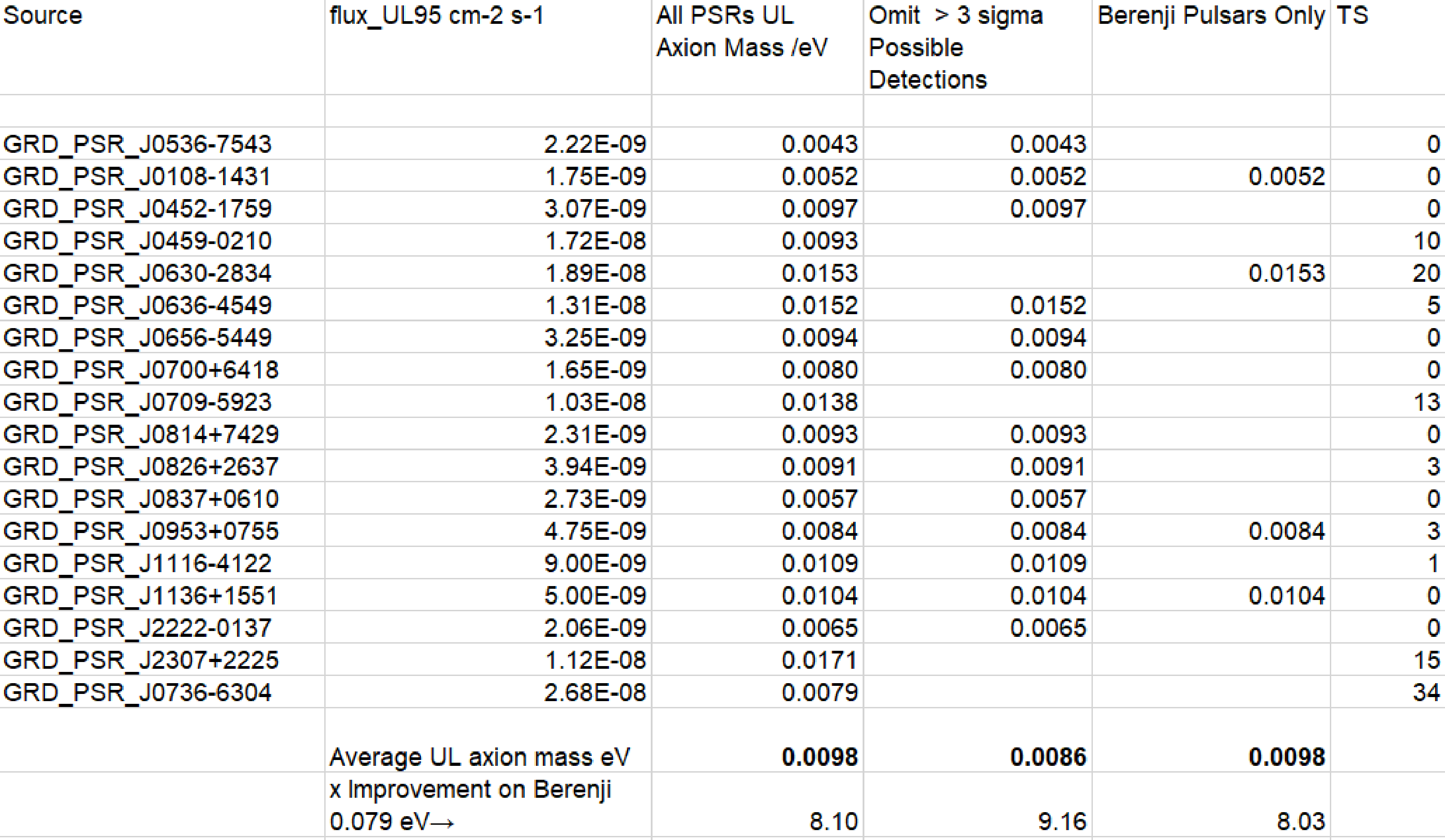


GRD Pulsar	SOURCE TS 60 – 500MeV 4 BIN PD PL model	Berenji 2016
J0108-1431	0	Y
J0452-1759	0	
J0459-0210	10	
J0536-7543	0	
J0630-2834	19	Y
J0636-4549	3	
J0656-5449	0	
J0700+6418	0	
J0709-5923	12	
J0814+7429	0	
J0826+2637	2	
J0837+0610	0	
J0953+0755	2	Y
J1116-4122	1	
J1136+1551	0	Y
J2222-0137	0	
J2307+2225	14	
J0736-6304	33	
J1836+5925	2	



- J0736-6304 TS Map – Not a detection, placing test sources at other positions probes this map
- If we don’t add any test source this feature disappears – an artifact of normalisation of Galactic background

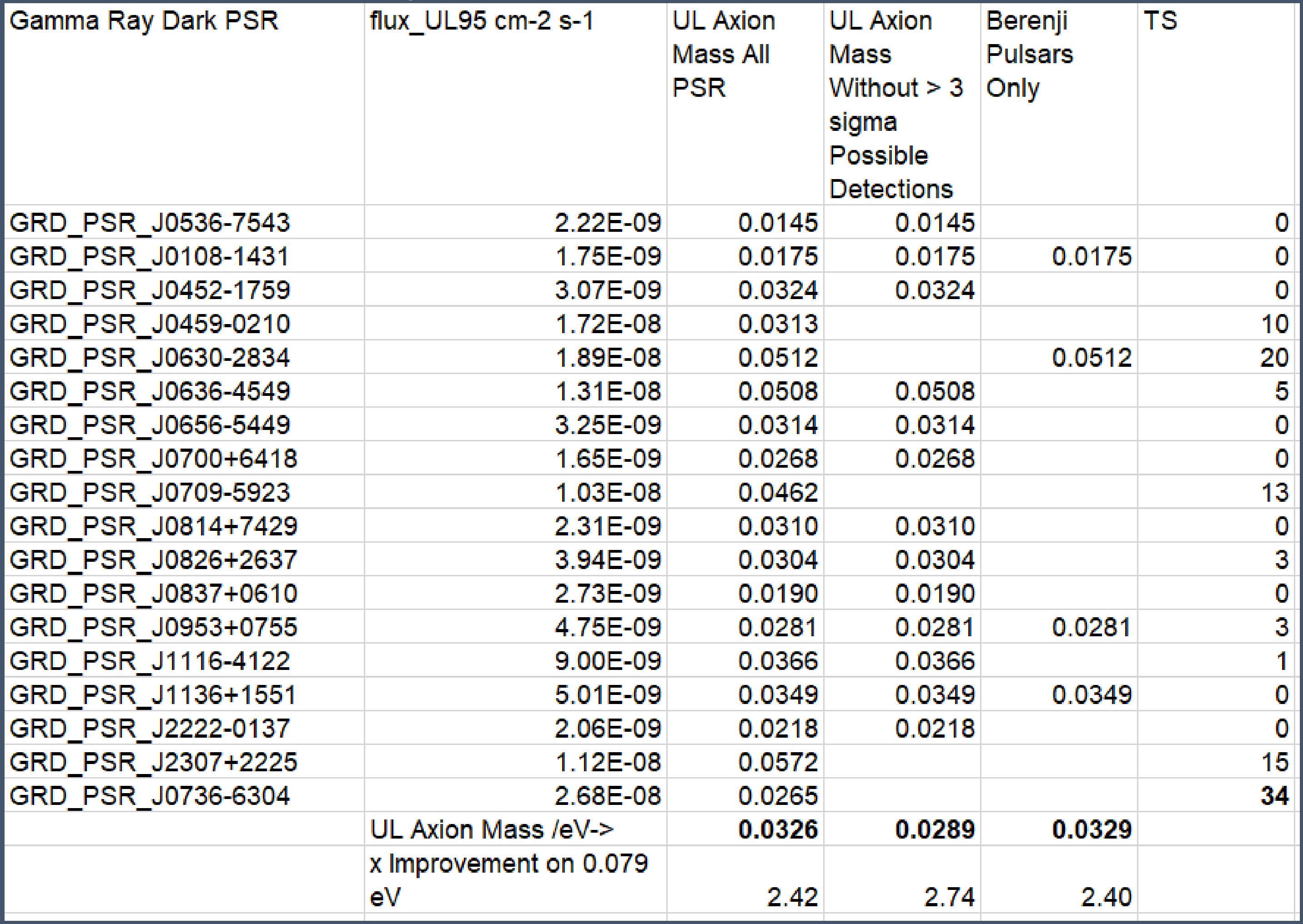
BACKUP m_a Calc ω=100 MeV



Source	flux_UL95 cm-2 s-1	All PSRs UL Axion Mass /eV	Omit > 3 sigma Possible Detections	Berenji Pulsars Only	TS
GRD_PSR_J0536-7543	2.22E-09	0.0043	0.0043		0
GRD_PSR_J0108-1431	1.75E-09	0.0052	0.0052	0.0052	0
GRD_PSR_J0452-1759	3.07E-09	0.0097	0.0097		0
GRD_PSR_J0459-0210	1.72E-08	0.0093			10
GRD_PSR_J0630-2834	1.89E-08	0.0153		0.0153	20
GRD_PSR_J0636-4549	1.31E-08	0.0152	0.0152		5
GRD_PSR_J0656-5449	3.25E-09	0.0094	0.0094		0
GRD_PSR_J0700+6418	1.65E-09	0.0080	0.0080		0
GRD_PSR_J0709-5923	1.03E-08	0.0138			13
GRD_PSR_J0814+7429	2.31E-09	0.0093	0.0093		0
GRD_PSR_J0826+2637	3.94E-09	0.0091	0.0091		3
GRD_PSR_J0837+0610	2.73E-09	0.0057	0.0057		0
GRD_PSR_J0953+0755	4.75E-09	0.0084	0.0084	0.0084	3
GRD_PSR_J1116-4122	9.00E-09	0.0109	0.0109		1
GRD_PSR_J1136+1551	5.00E-09	0.0104	0.0104	0.0104	0
GRD_PSR_J2222-0137	2.06E-09	0.0065	0.0065		0
GRD_PSR_J2307+2225	1.12E-08	0.0171			15
GRD_PSR_J0736-6304	2.68E-08	0.0079			34
	Average UL axion mass eV	**0.0098**	**0.0086**	**0.0098**	
	x Improvement on Berenji 0.079 eV→	8.10	9.16	8.03	

A 7 to 8 fold improvement on 0.079 eV axion mass of Berenji et al

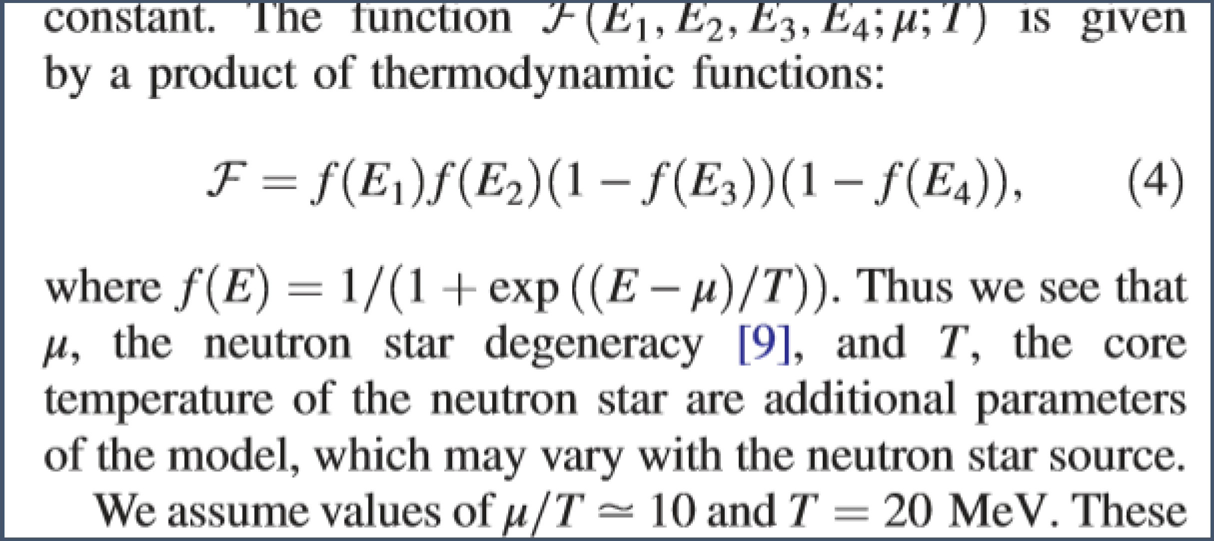
BACKUP m_a Calc ω=200 MeV



Gamma Ray Dark PSR	flux_UL95 cm-2 s-1	UL Axion Mass All PSR	UL Axion Mass Without > 3 sigma Possible Detections	Berenji Pulsars Only	TS
GRD_PSR_J0536-7543	2.22E-09	0.0145	0.0145		0
GRD_PSR_J0108-1431	1.75E-09	0.0175	0.0175	0.0175	0
GRD_PSR_J0452-1759	3.07E-09	0.0324	0.0324		0
GRD_PSR_J0459-0210	1.72E-08	0.0313			10
GRD_PSR_J0630-2834	1.89E-08	0.0512		0.0512	20
GRD_PSR_J0636-4549	1.31E-08	0.0508	0.0508		5
GRD_PSR_J0656-5449	3.25E-09	0.0314	0.0314		0
GRD_PSR_J0700+6418	1.65E-09	0.0268	0.0268		0
GRD_PSR_J0709-5923	1.03E-08	0.0462			13
GRD_PSR_J0814+7429	2.31E-09	0.0310	0.0310		0
GRD_PSR_J0826+2637	3.94E-09	0.0304	0.0304		3
GRD_PSR_J0837+0610	2.73E-09	0.0190	0.0190		0
GRD_PSR_J0953+0755	4.75E-09	0.0281	0.0281	0.0281	3
GRD_PSR_J1116-4122	9.00E-09	0.0366	0.0366		1
GRD_PSR_J1136+1551	5.01E-09	0.0349	0.0349	0.0349	0
GRD_PSR_J2222-0137	2.06E-09	0.0218	0.0218		0
GRD_PSR_J2307+2225	1.12E-08	0.0572			15
GRD_PSR_J0736-6304	2.68E-08	0.0265			**34**
	UL Axion Mass /eV->	**0.0326**	**0.0289**	**0.0329**	
	x Improvement on 0.079 eV	2.42	2.74	2.40	

A more modest 2 fold improvement on 0.079 eV axion mass of Berenji et al

BACKUP THERMODYNAMIC FUNCTIONS



constant. The function $\mathcal{F}(E_1, E_2, E_3, E_4; \mu; T)$ is given by a product of thermodynamic functions:

$$\mathcal{F} = f(E_1)f(E_2)(1 - f(E_3))(1 - f(E_4)), \qquad (4)$$

where $f(E) = 1/(1 + \exp((E - \mu)/T))$. Thus we see that μ, the neutron star degeneracy [9], and T, the core temperature of the neutron star are additional parameters of the model, which may vary with the neutron star source.

We assume values of $\mu/T \simeq 10$ and $T = 20$ MeV. These

From Berenji et al 2016

BACKUP ANALYSIS DESCRIPTION

- Use *Fermipy* and *Fermi Science Tools* (v10R0p5) source photons / front events 60-500 MeV
- Create source maps for 3FGL sources and exposure cube
- Add GRD PSR PL test point source to model with index 2
- Disable energy dispersion on 3FGL and isodiff / galdiff and enable energy dispersion on PSR test source
- Use *optimize* method to perform binned likelihood analysis followed by secondary likelihood analysis with *fit*
- Delete sources from model with TS <=4 and npred <=1
- Free prefactor (normalisation) 3FGL sources within 13^0 of PSR and prefactor/index of test PSR source
- *Optimize* all sources with TS>25 and *fit* again
- Run *Find_sources* and *fit* again