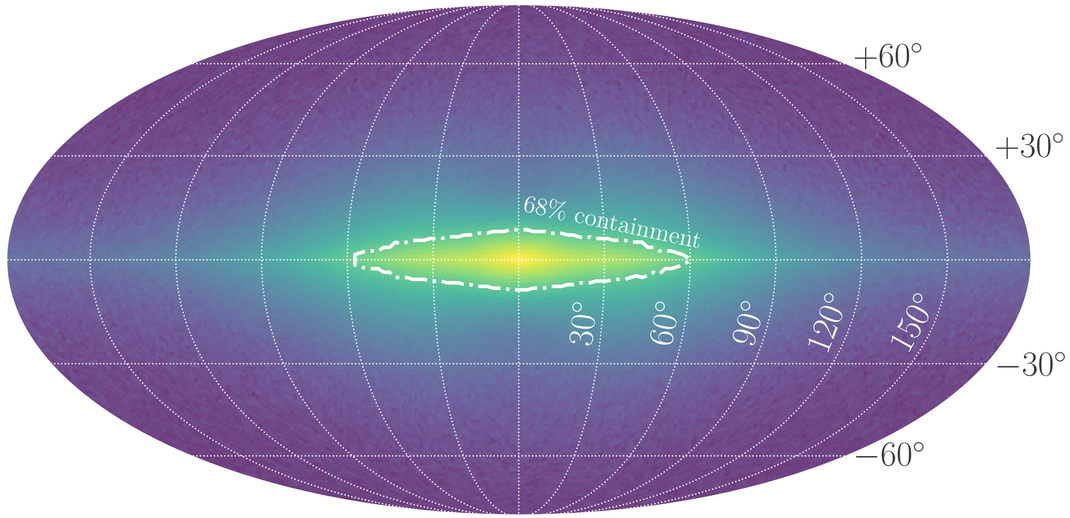
Axion Miniclusters hitting (neutron) stars



Bradley J Kavanagh
Instituto de Física de Cantabria
(CSIC-Universidad de Cantabria)

In collaboration with Tom Edwards, Luca Visinelli & Christoph Weniger

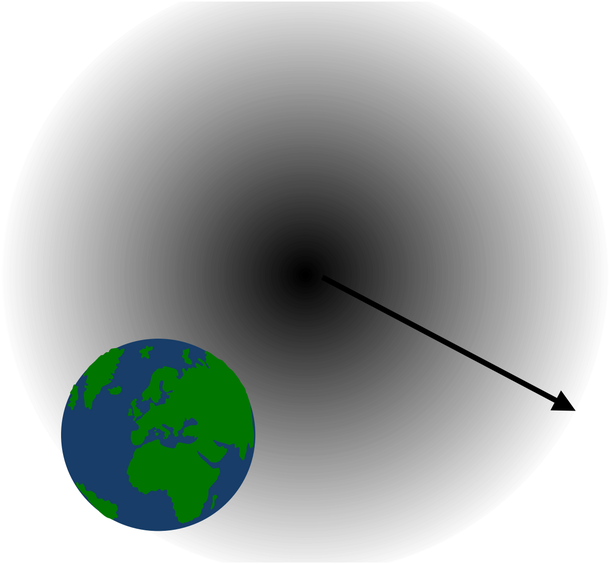
2011.05377, 2011.05378
github.com/bradkav/axion-miniclusters

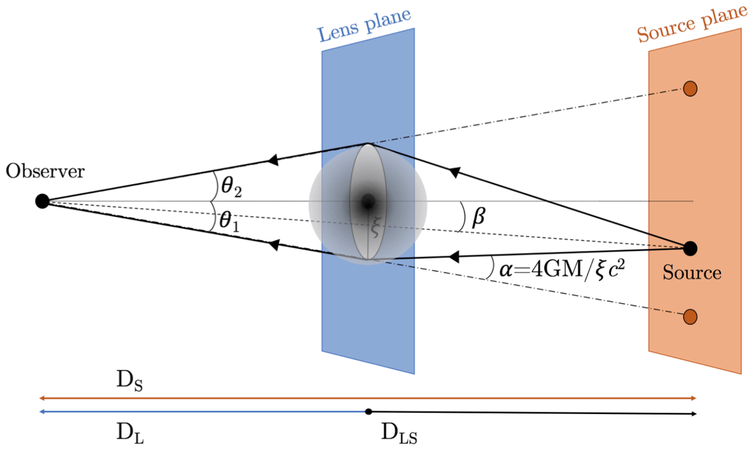
10th December 2020

kavanagh@ifca.unican.es
@BradleyKavanagh

Interesting signatures…

Direct detection of axions through AMC encounters
(or lack thereof)

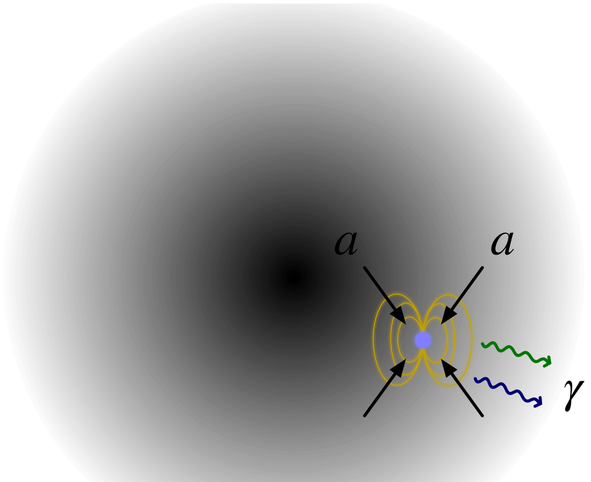




[Croon et al., 2002.08962]

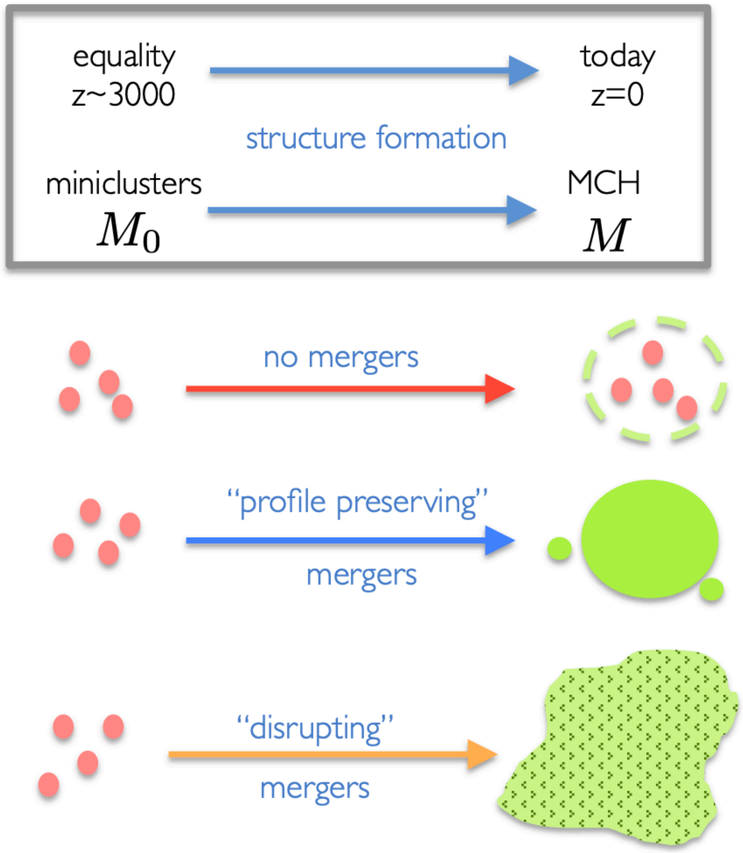
Microlensing (by extended DM substructures)

Axion-photon conversion in NS magnetospheres



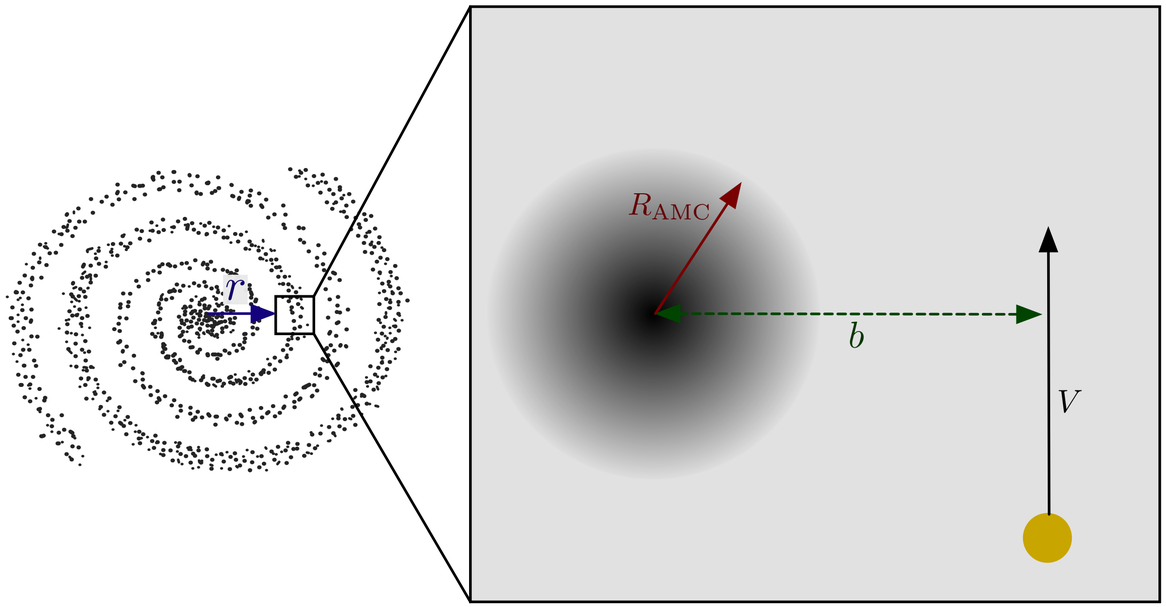
AMC properties?

Over cosmic time?



[Fairbairn et al., 1707.03310]

Today, in the Milky Way?



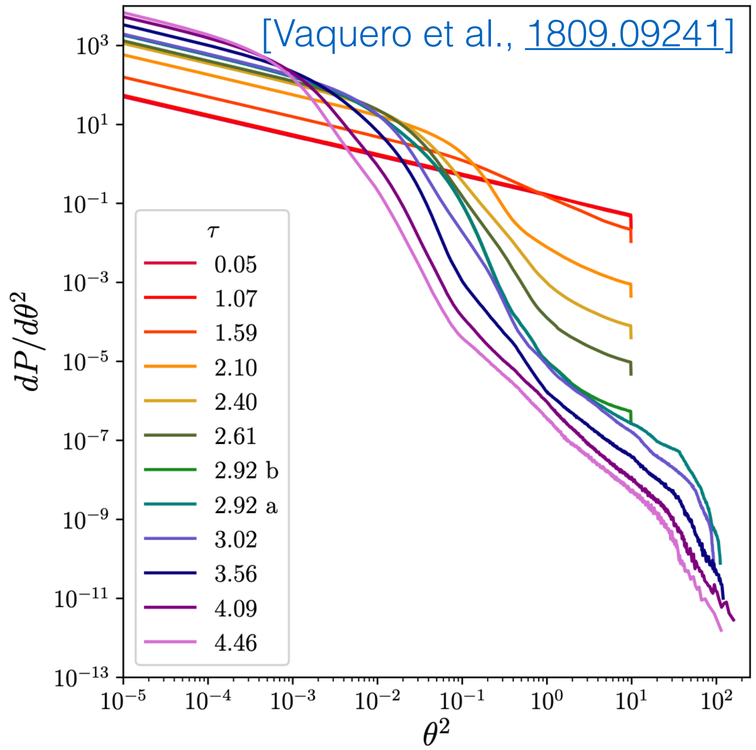
[**BJK**, Edwards, Visinelli, Weniger, 2011.05377]

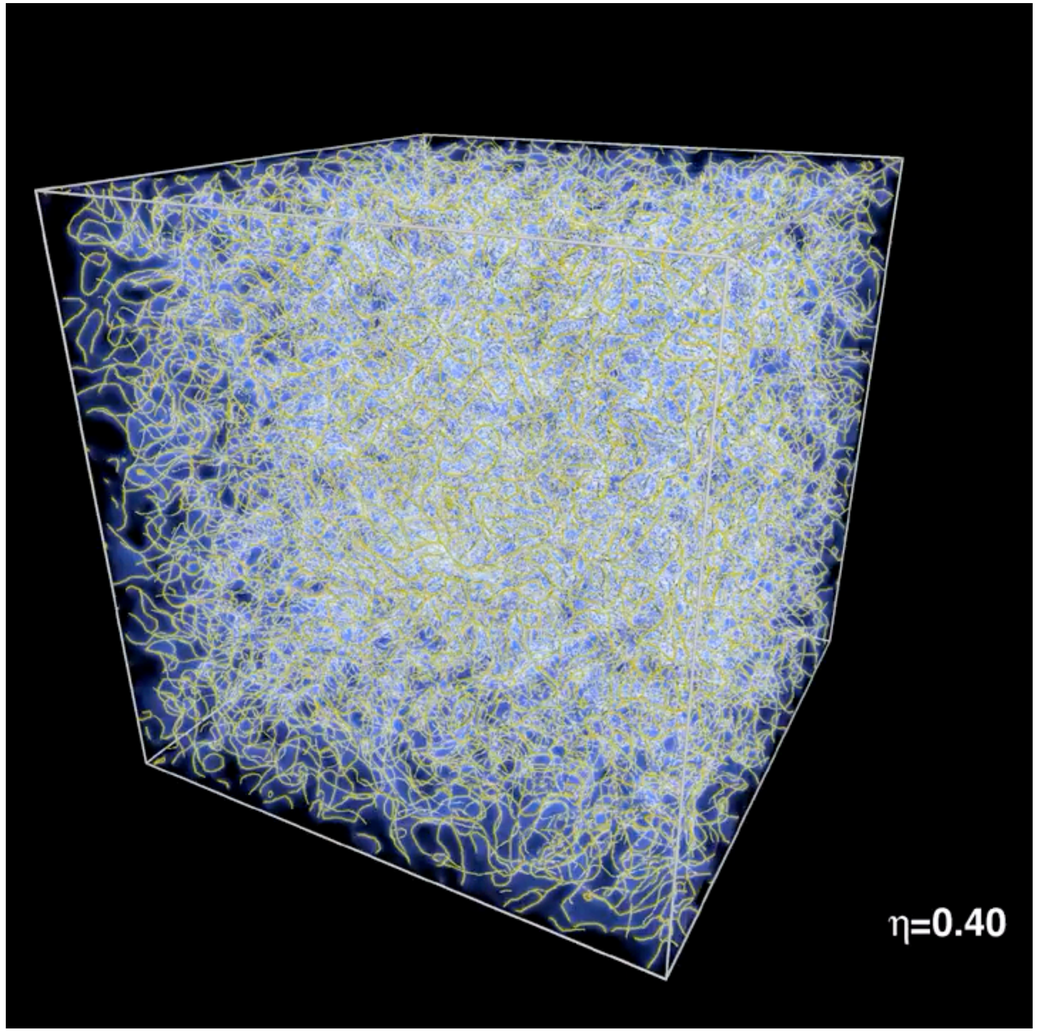
Axion Miniclusters (AMCs)

Post-inflationary axions

Consider Dark Matter QCD axions,
in which the PQ symmetry is broken *after* inflation

Axion field has random initial values in
causally disconnected patches





[Buschmann et al., 1906.00967]

Fix the axion mass to $m_a = 20\mu\mathrm{eV}$, although higher values are possible.

[Gorghetto et al., 2007.04990]

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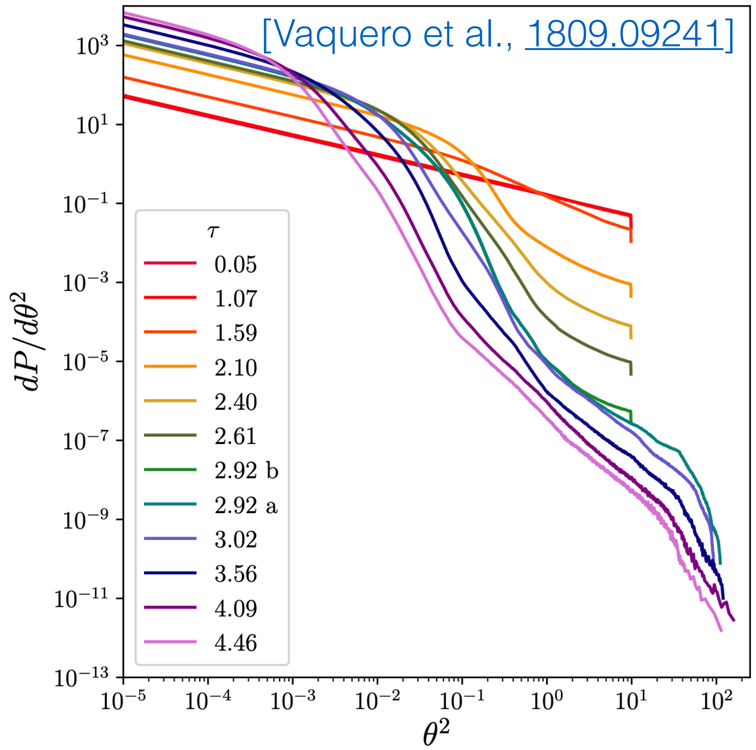
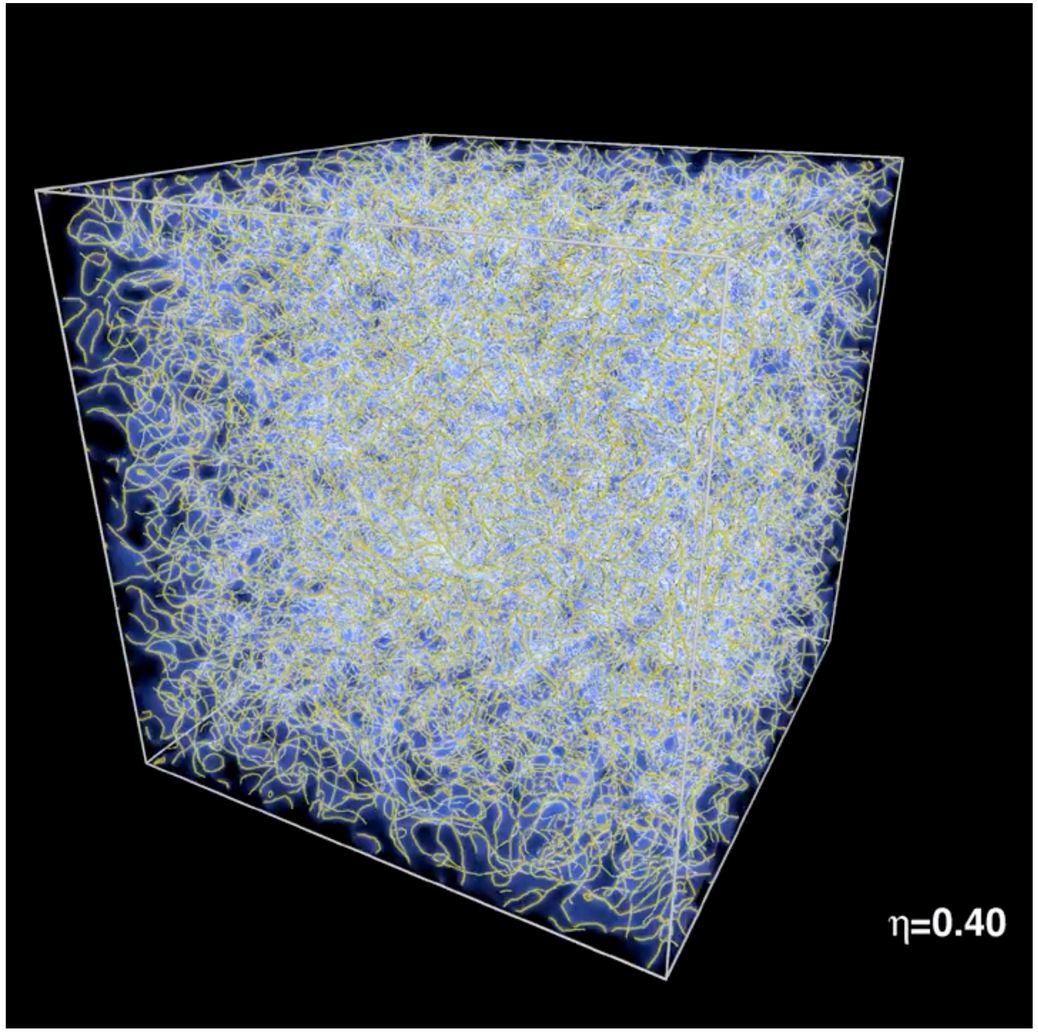




[Buschmann et al., 1906.00967]

Fix the axion mass to $m_a = 20\mu\mathrm{eV}$, although higher values are possible.

[Gorghetto et al., 2007.04990]

AMC Overdensities

Overdensities act as ‘seeds' for bound “axion miniclusters” (**AMCs**)

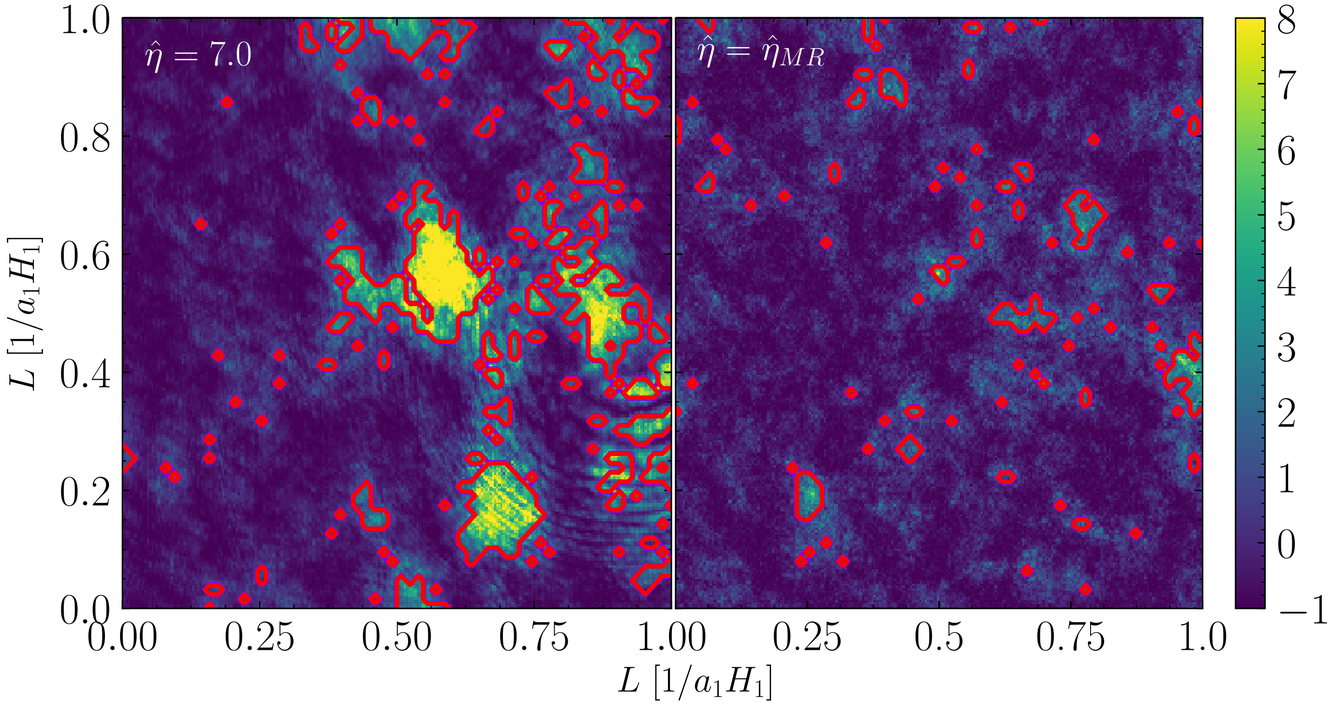
For an overdensity of size $\delta = (\rho - \bar{\rho})/\rho$ the final density is:

$$\rho_{\rm AMC}(\delta) = 140(1+\delta)\delta^3\rho_{\rm eq}$$

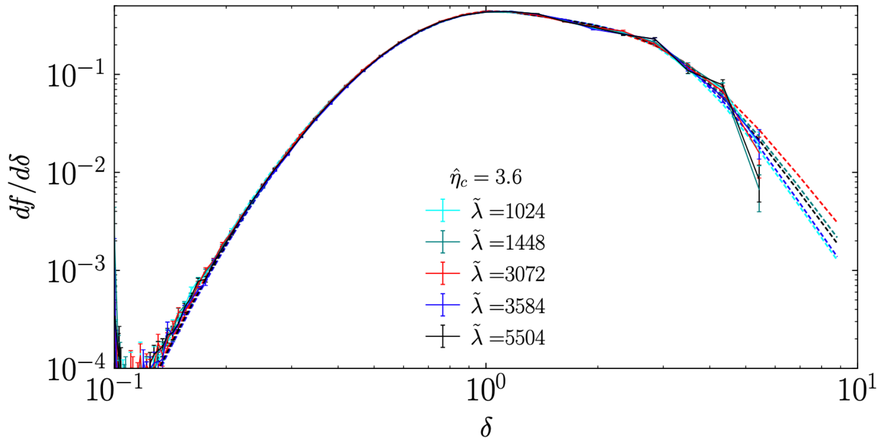
[Kolb & Tkachev, astro-ph/9403011]

Not to be confused with Axion Stars

[See Slide 16]



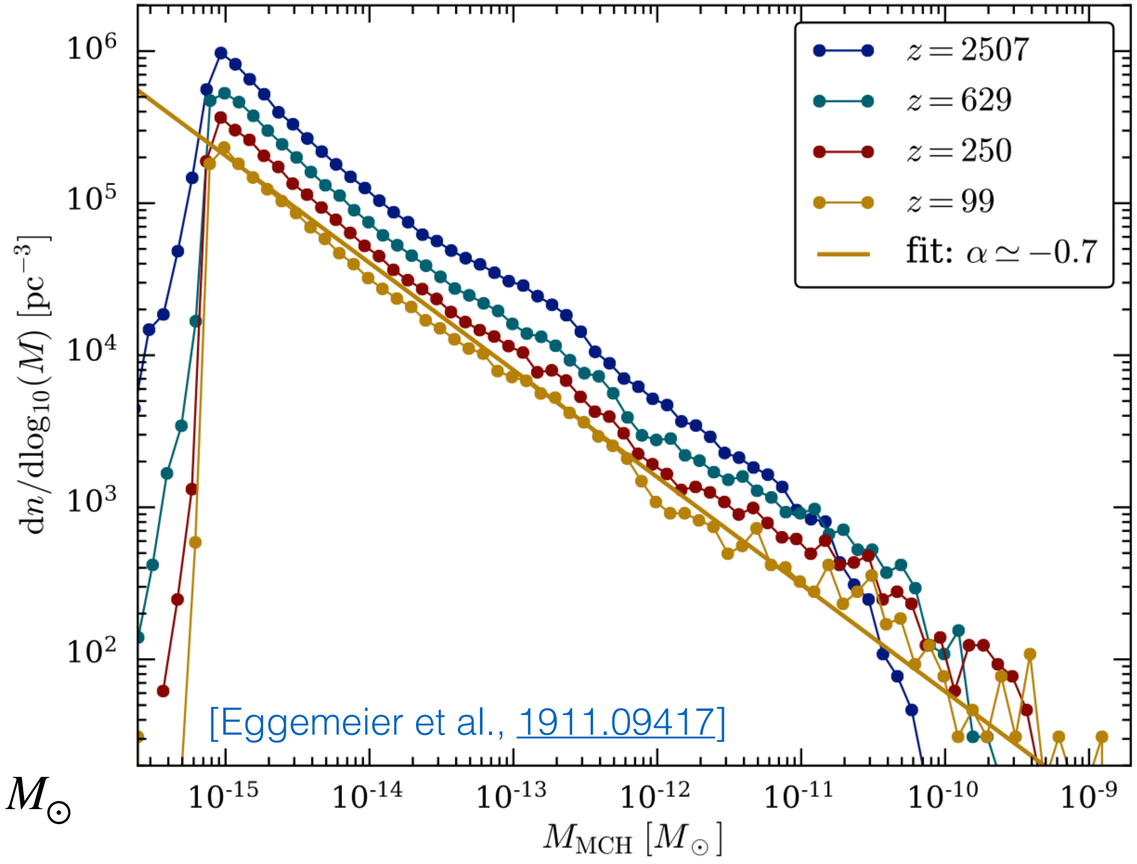
[Buschmann et al., 1906.00967]



[See also Zurek et al., astro-ph/0607341; Vaquero et al., 1809.09241; Eggemeier et al., 1911.09417]

AMC mass function

$$M_0 \approx 10^{-11} M_\odot (1+\delta) \left(\frac{20\mu\text{eV}}{m_a}\right)^{1/2}$$



[Eggemeier et al., 1911.09417]

$$\frac{\mathrm{d}P}{\mathrm{d}\log M_{\mathrm{AMC}}} \sim {M_{\mathrm{AMC}}}^{-0.7}$$

Extend down to $M_{\mathrm{AMC}} \sim 10^{-19}\, M_\odot$

(Set by the Jeans mass for $m_a = 20\,\mu\text{eV}$)

Extend up to $M_{\mathrm{AMC}} \sim 10^{-5}\, M_\odot$

(Growth of hierarchical structure to today)

[Fairbairn et al., 1707.03310]

Everything can be recast for different distributions of $(M_{\mathrm{AMC}}, \delta)$ or equivalently $(M_{\mathrm{AMC}}, \rho_{\mathrm{AMC}})$!

[github.com/bradkav/axion-miniclusters]

AMC density profiles

Power law profile:

$$\rho_{\rm int}^{\rm PL}(R) \propto R^{-9/4}$$

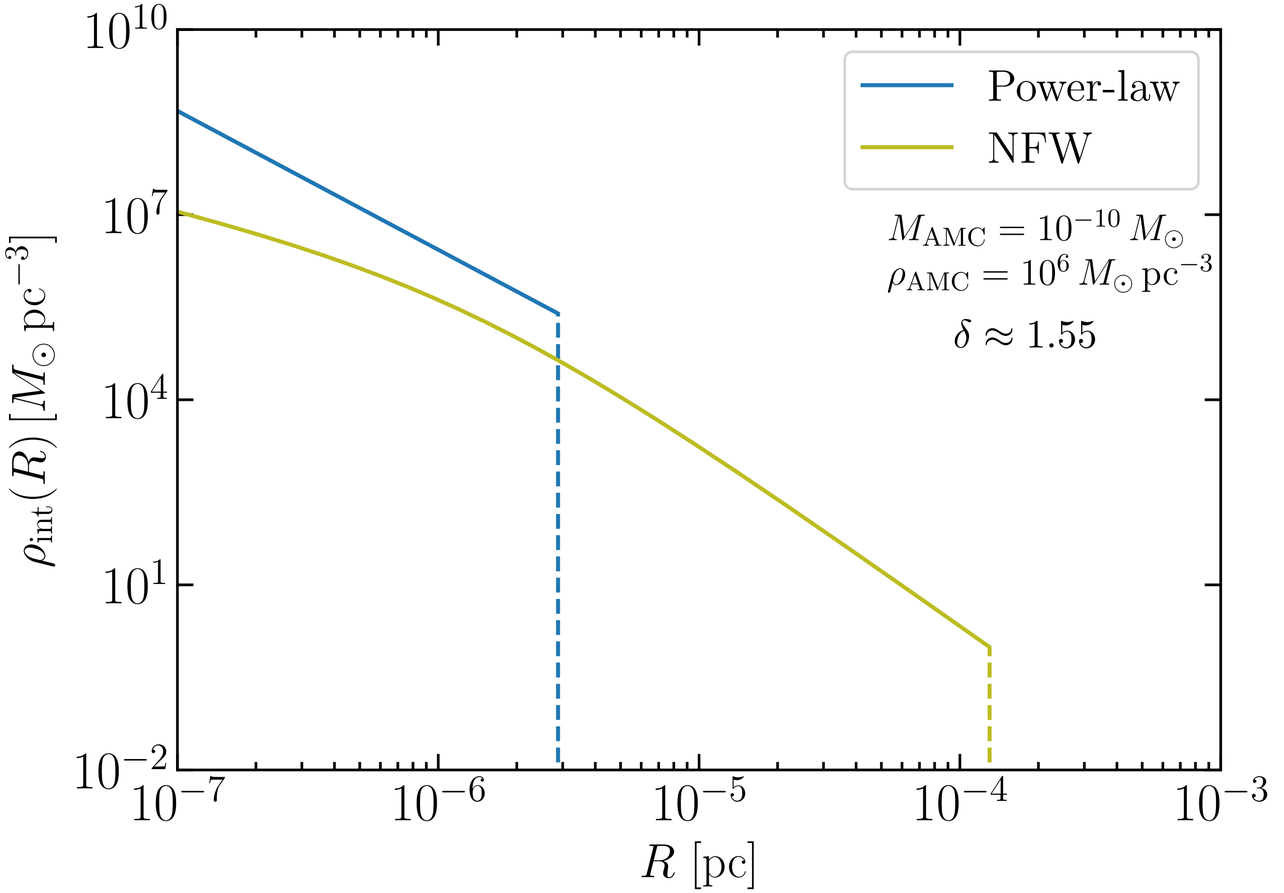
(Fix mean density equal to $\rho_{\rm AMC}(\delta)$)

NFW profile:

$$\rho_{\rm int}^{\rm NFW} = \frac{\rho_s}{(R/R_s)(1+R/R_s)^2}$$

(Fix $\rho_s = \rho_{\rm AMC}(\delta)$ and $c = 100$)

[Fairbairn et al., 1707.03310]



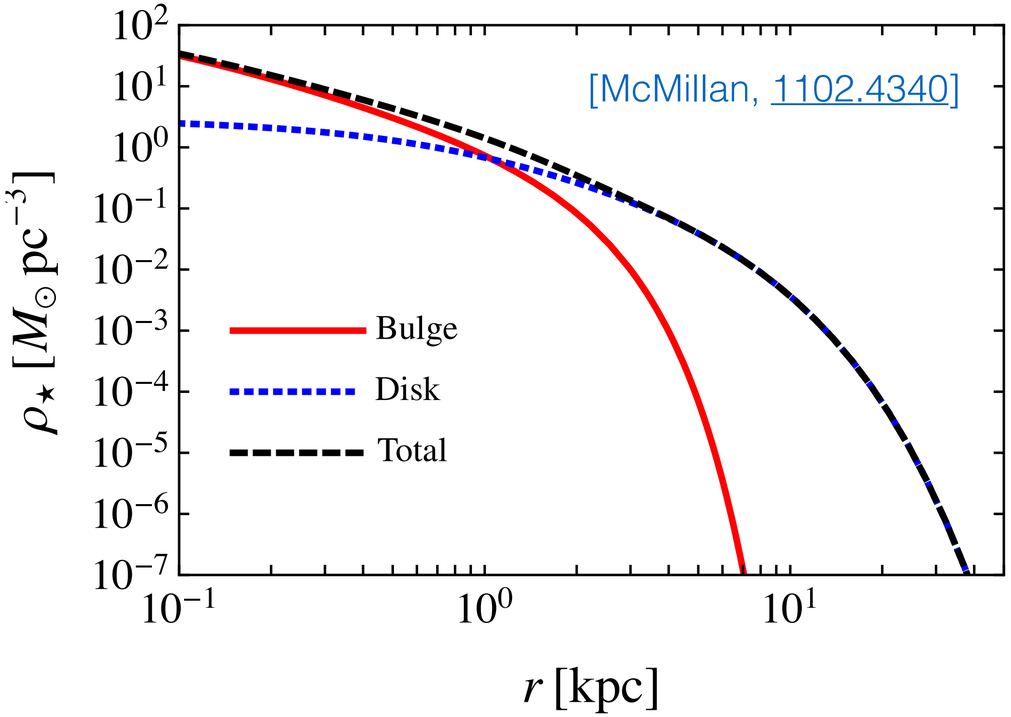
Concentrations today are likely to be much higher (e.g. $c \approx 10^4$), but this doesn't make much sense for substructure in the MW

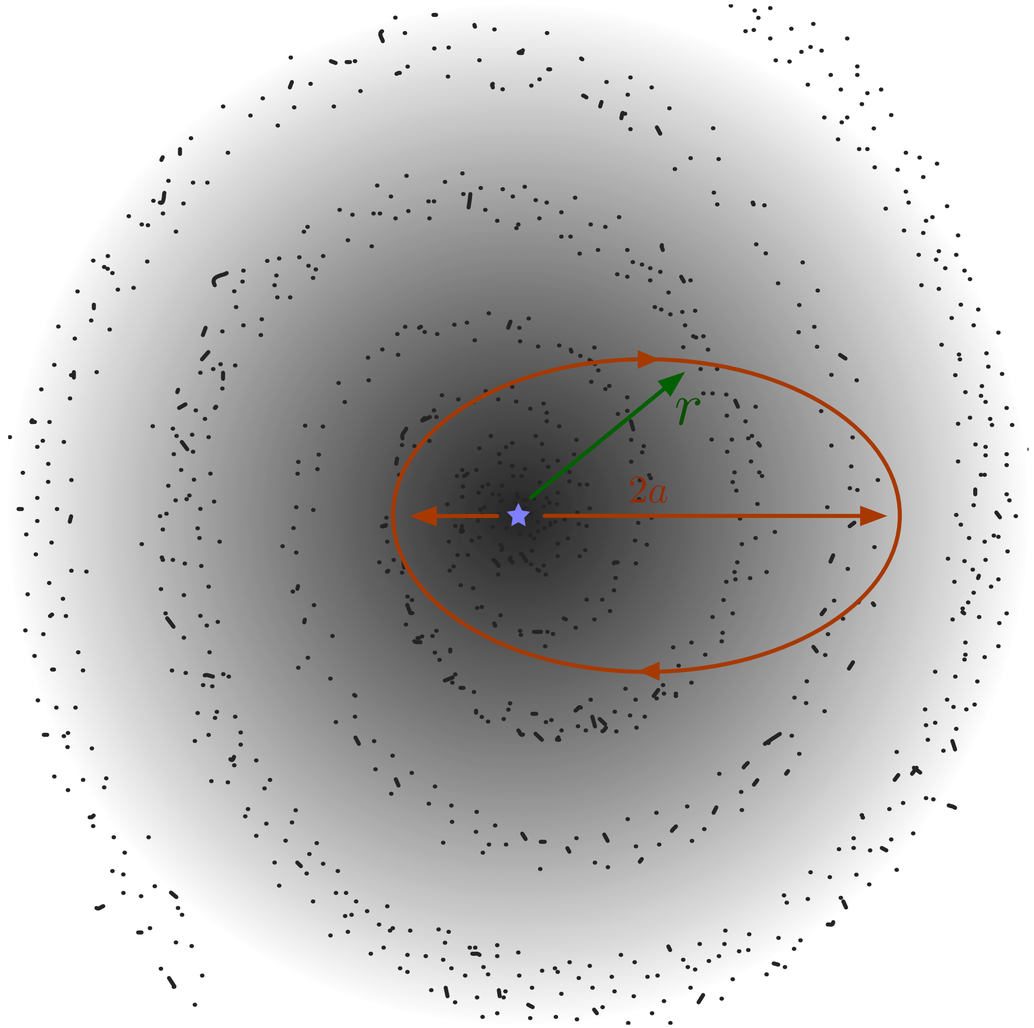
[Ellis et al., 2006.08637]

For fixed $(M_{\rm AMC}, \delta)$, the mean density of our NFW miniclusters is $\sim 10^5$ times lower than the corresponding PL profile

AMCs in the Milky Way

Milky Way Setup





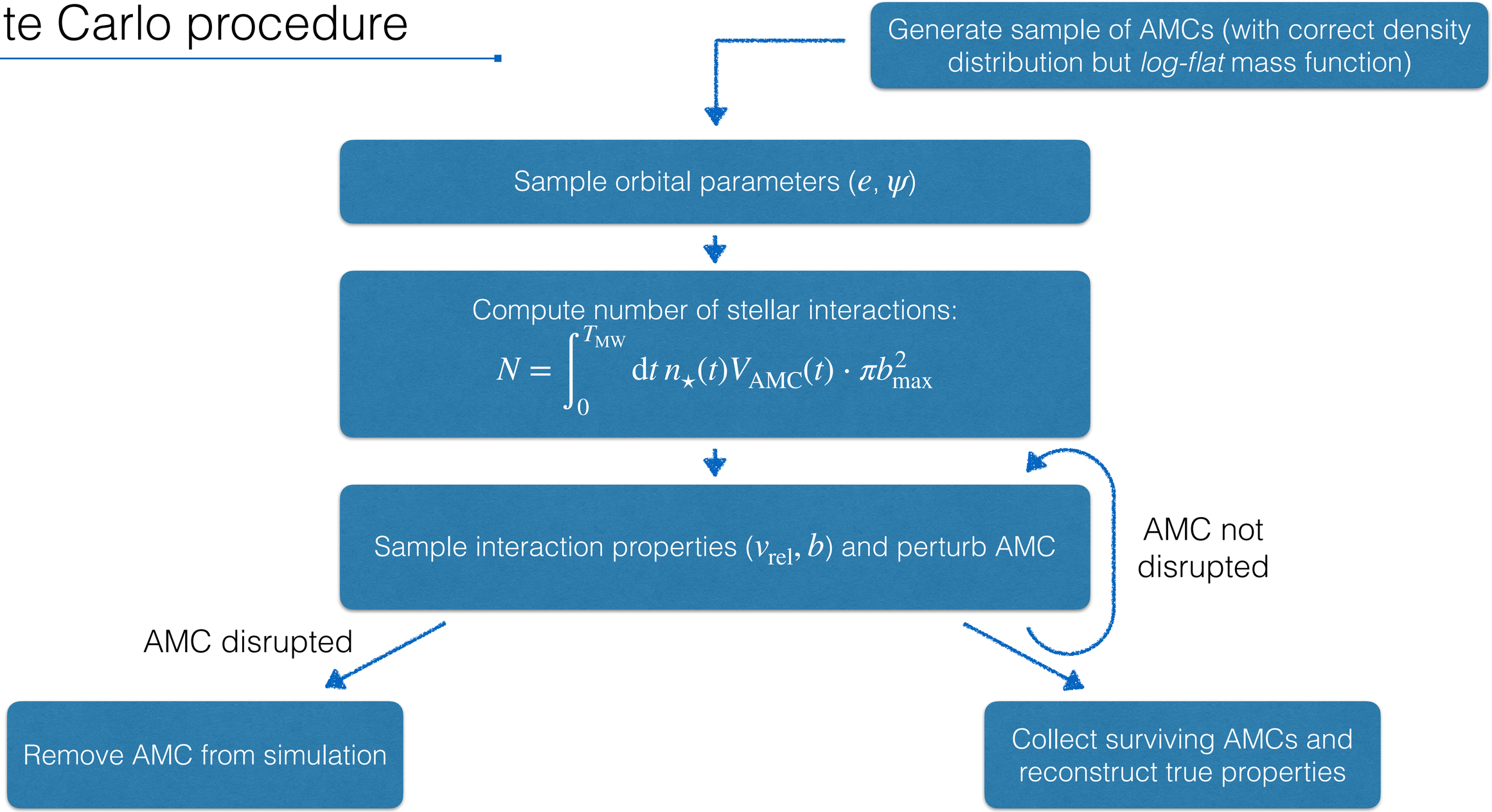
$$n_{\mathrm{AMC}}(r) = f_{\mathrm{AMC}}\,\frac{\rho_{\mathrm{DM}}(r)}{\langle M_{\mathrm{AMC}}\rangle}$$

$$f_{\mathrm{AMC}} \approx 100\%$$

$$\langle M_{\mathrm{AMC}}\rangle \approx 10^{-14}\,M_\odot$$

Caveat: Don't deal with concurrent structure formation, stellar formation & AMC distruption

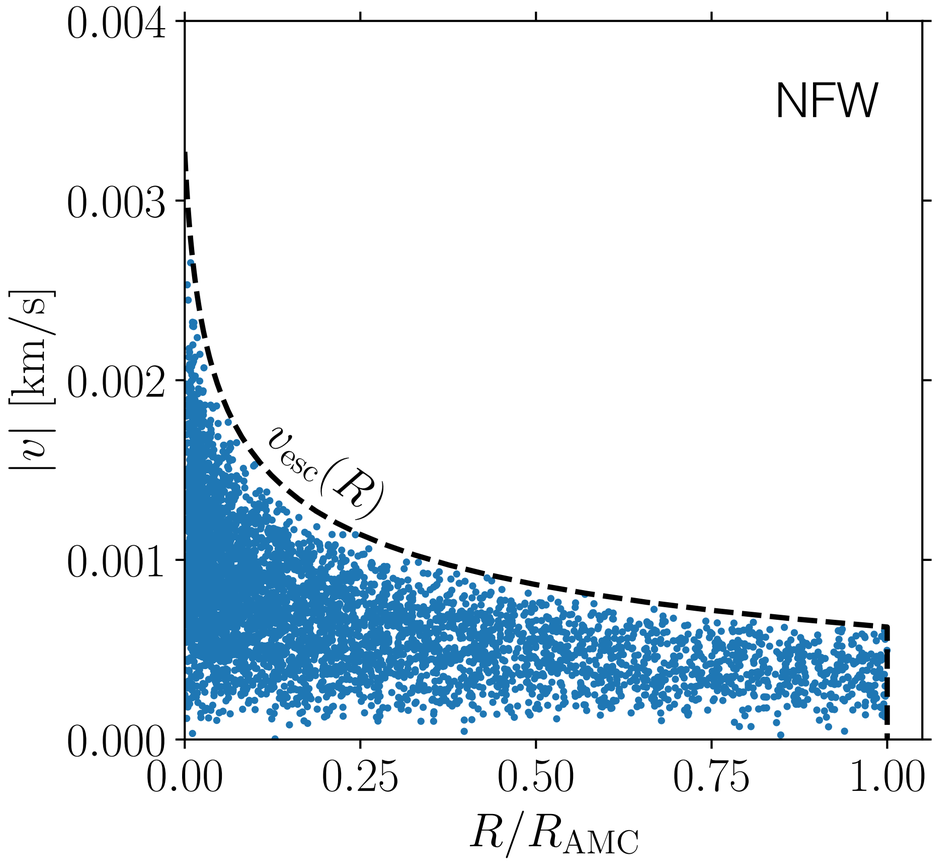
Monte Carlo procedure



But! Need to know the response of an AMC to stellar perturbations…

AMC Distribution functions

Describe the AMC by a self-consistent distribution function $f(\mathscr{E})$ (obtained using Eddington's formula)



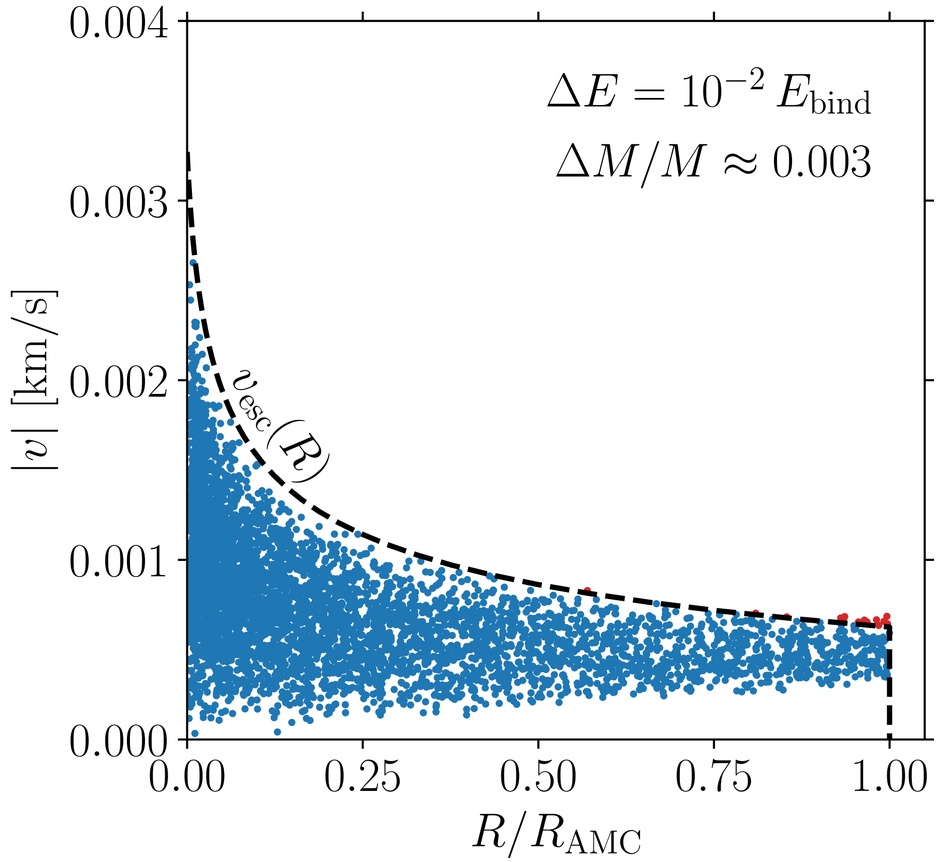
Perturb

$$\Delta\mathcal{E} \sim \Delta\left(\frac{1}{2}v^2\right) \sim \frac{\Delta E}{M_{\rm AMC}}\frac{R^2}{\langle R^2\rangle}$$

'Distant-tide' approximation:

$$\Delta E \approx \left(\frac{2GM_\star}{b^2 v_{\rm rel}}\right)^2 \frac{M_{\rm AMC}\langle R^2\rangle}{3}$$

[Green & Goodwin, astro-ph/0604142]



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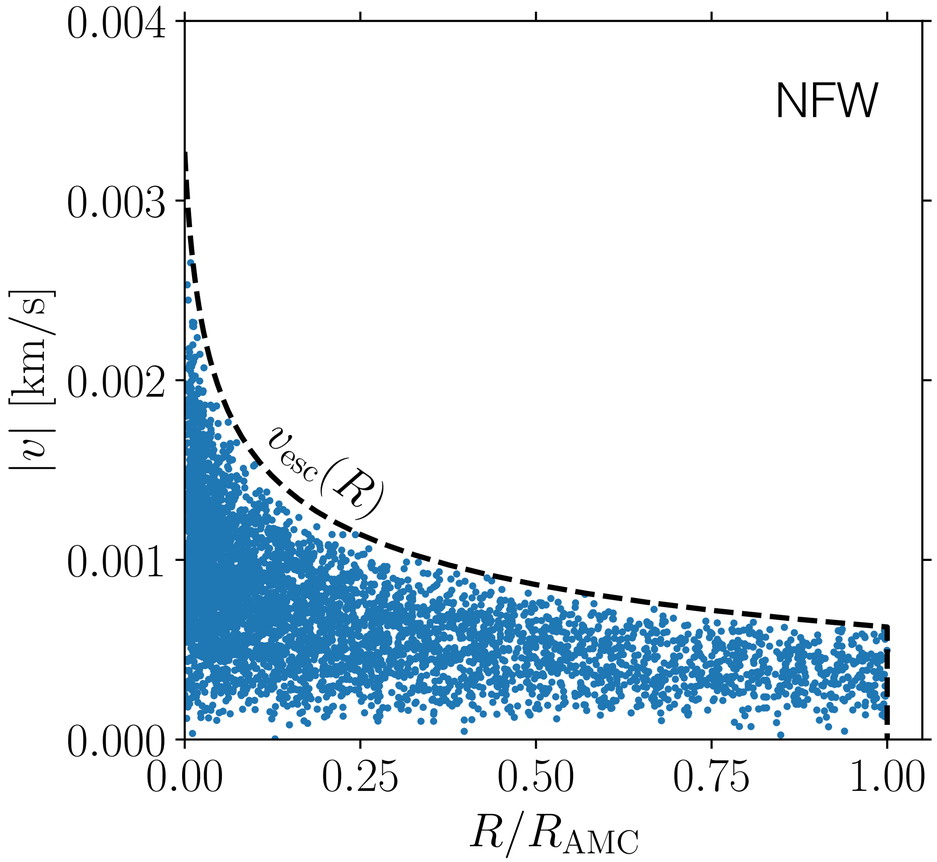

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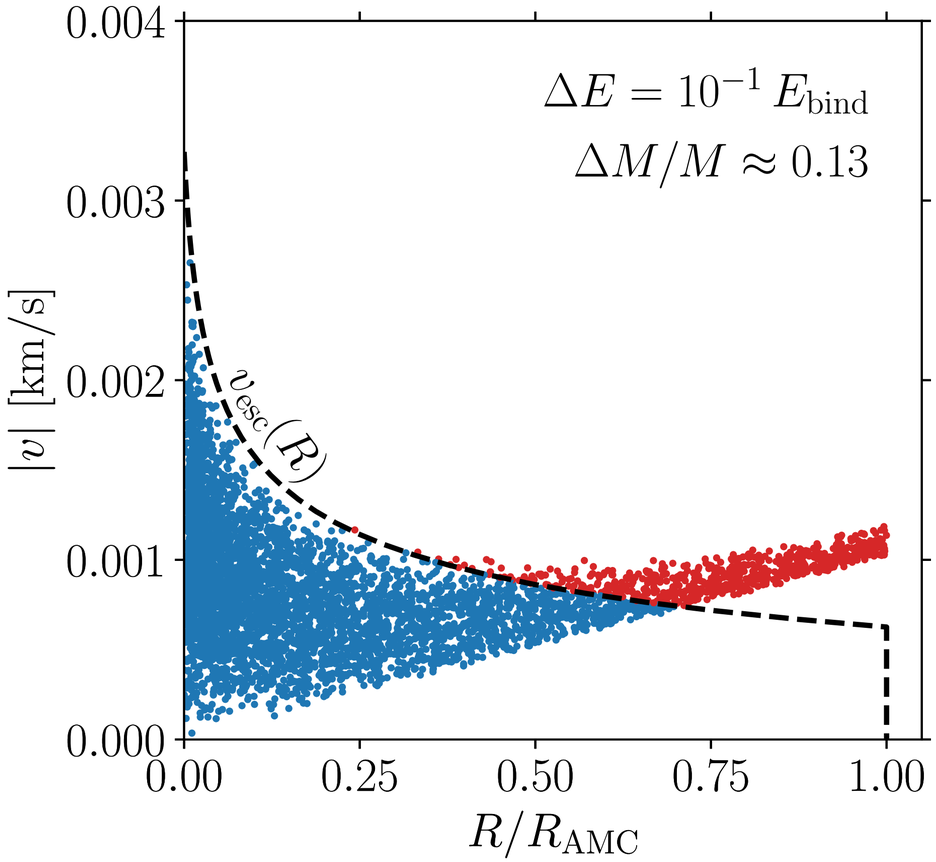

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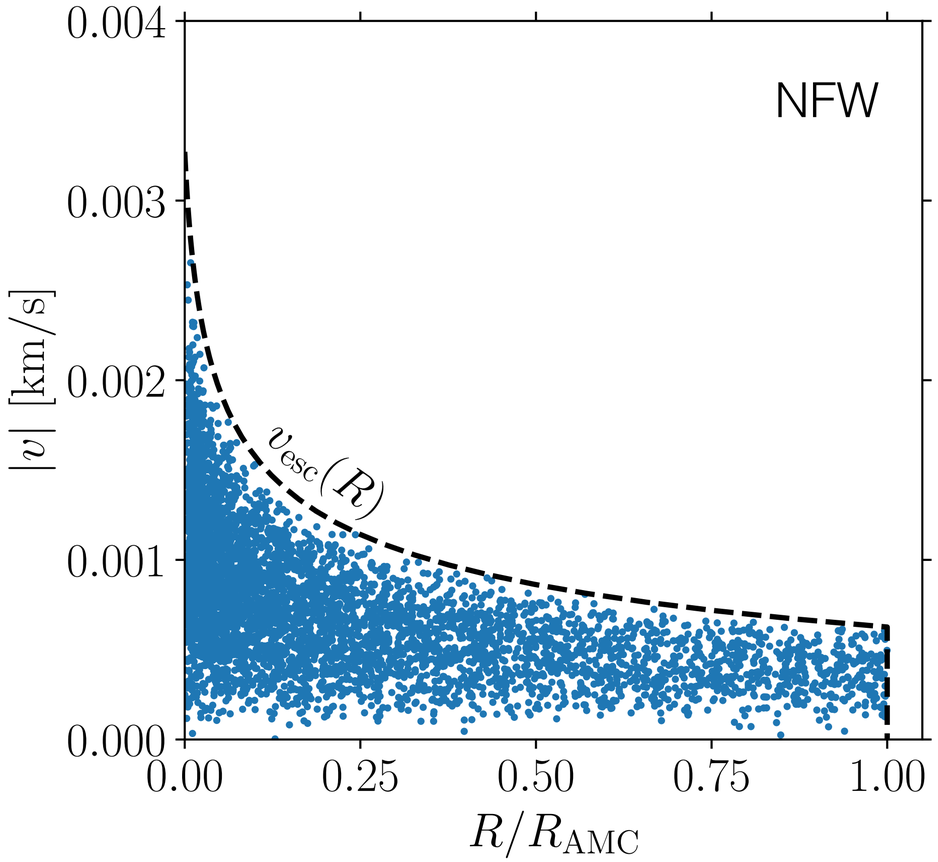

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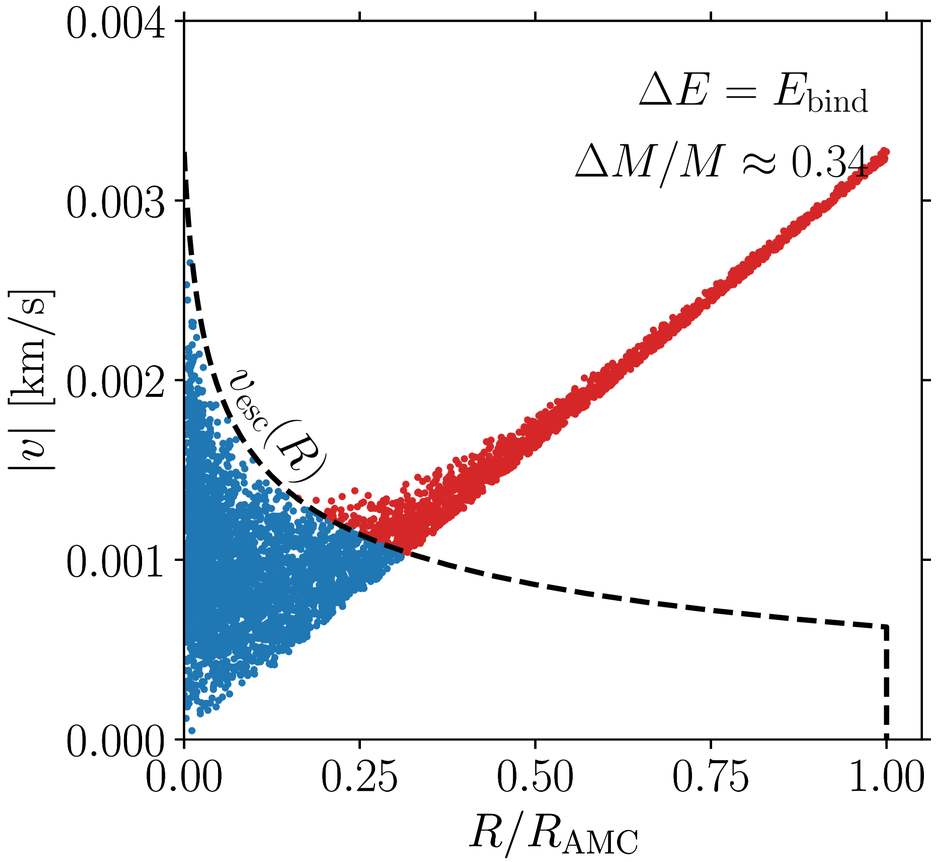
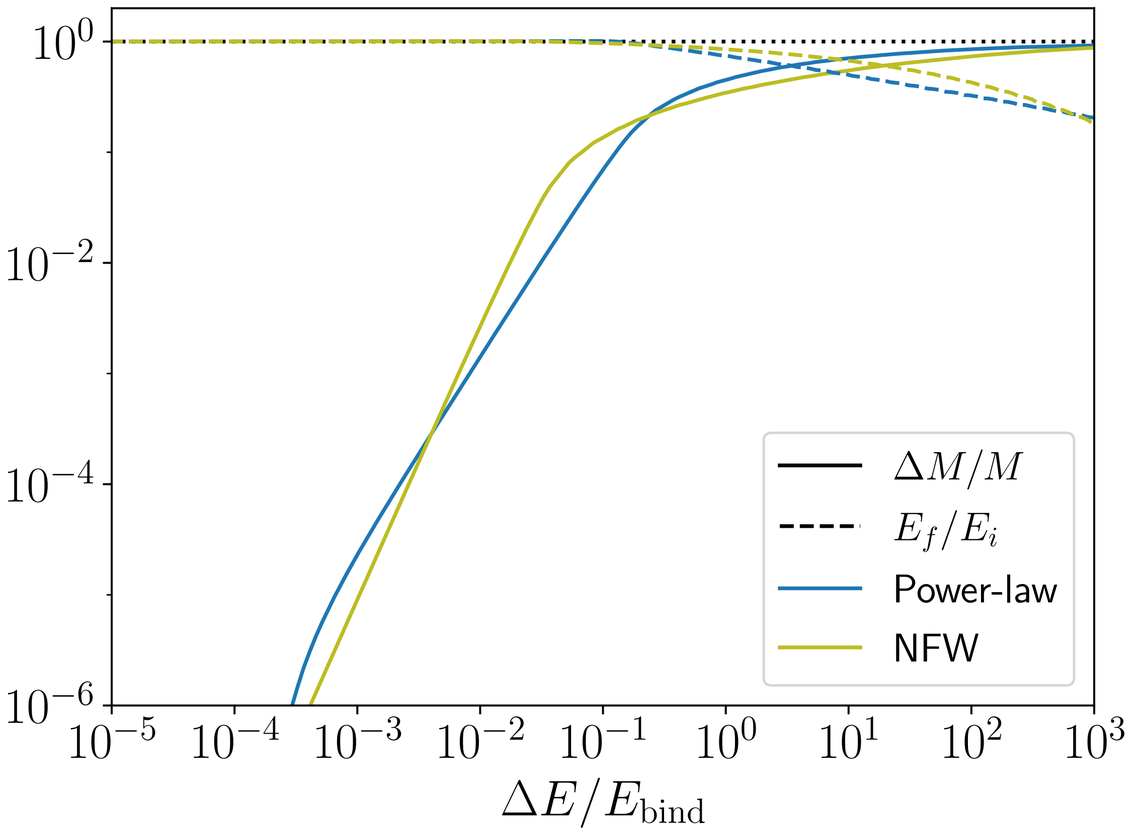
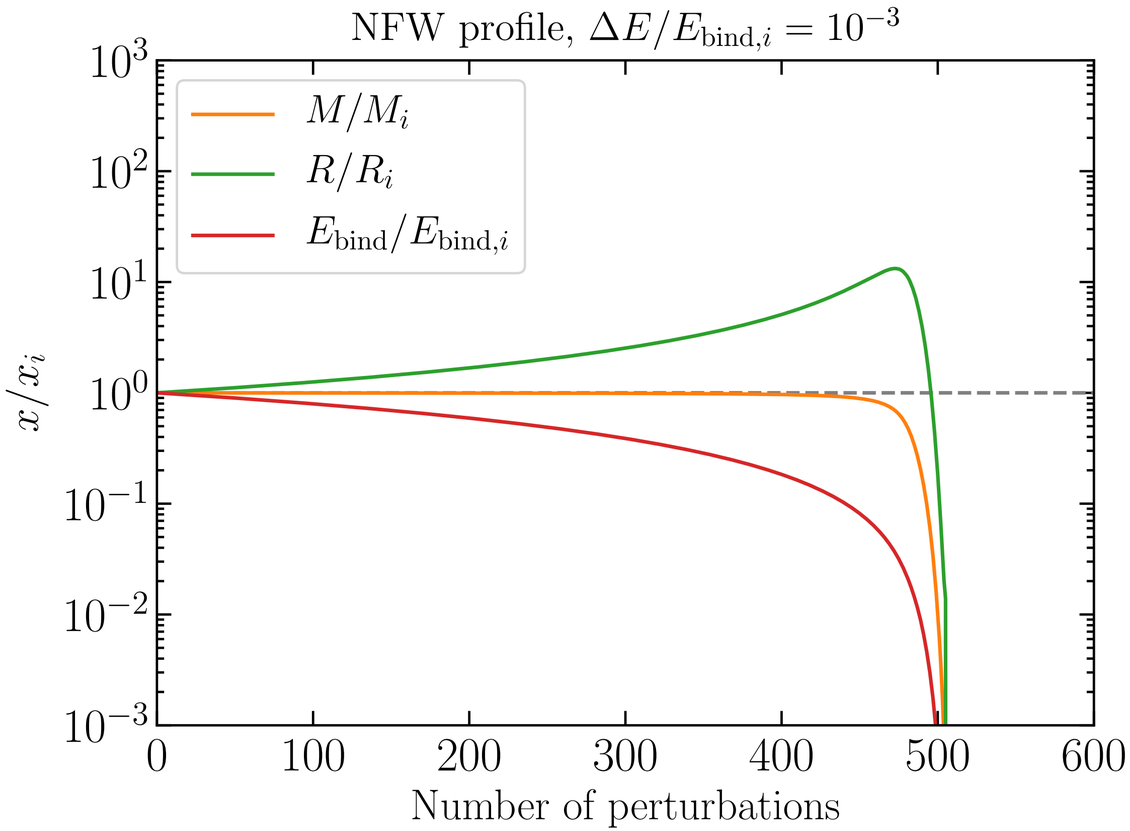


Mass-loss and remnants





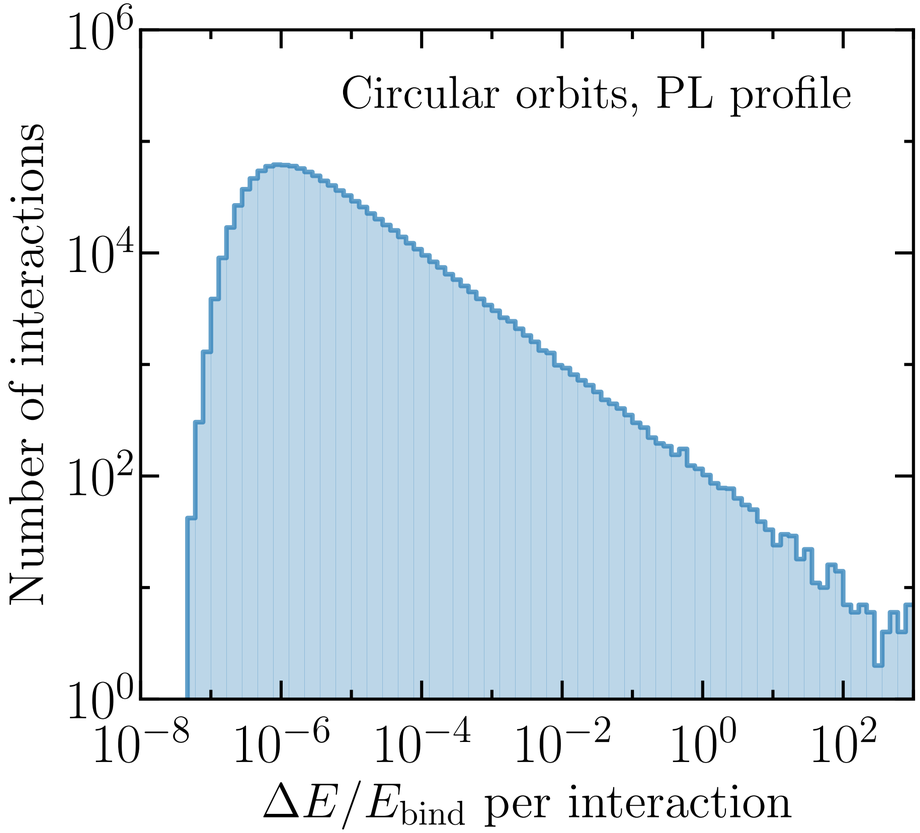
Fractional energy injection depends predominantly on the mean AMC density:

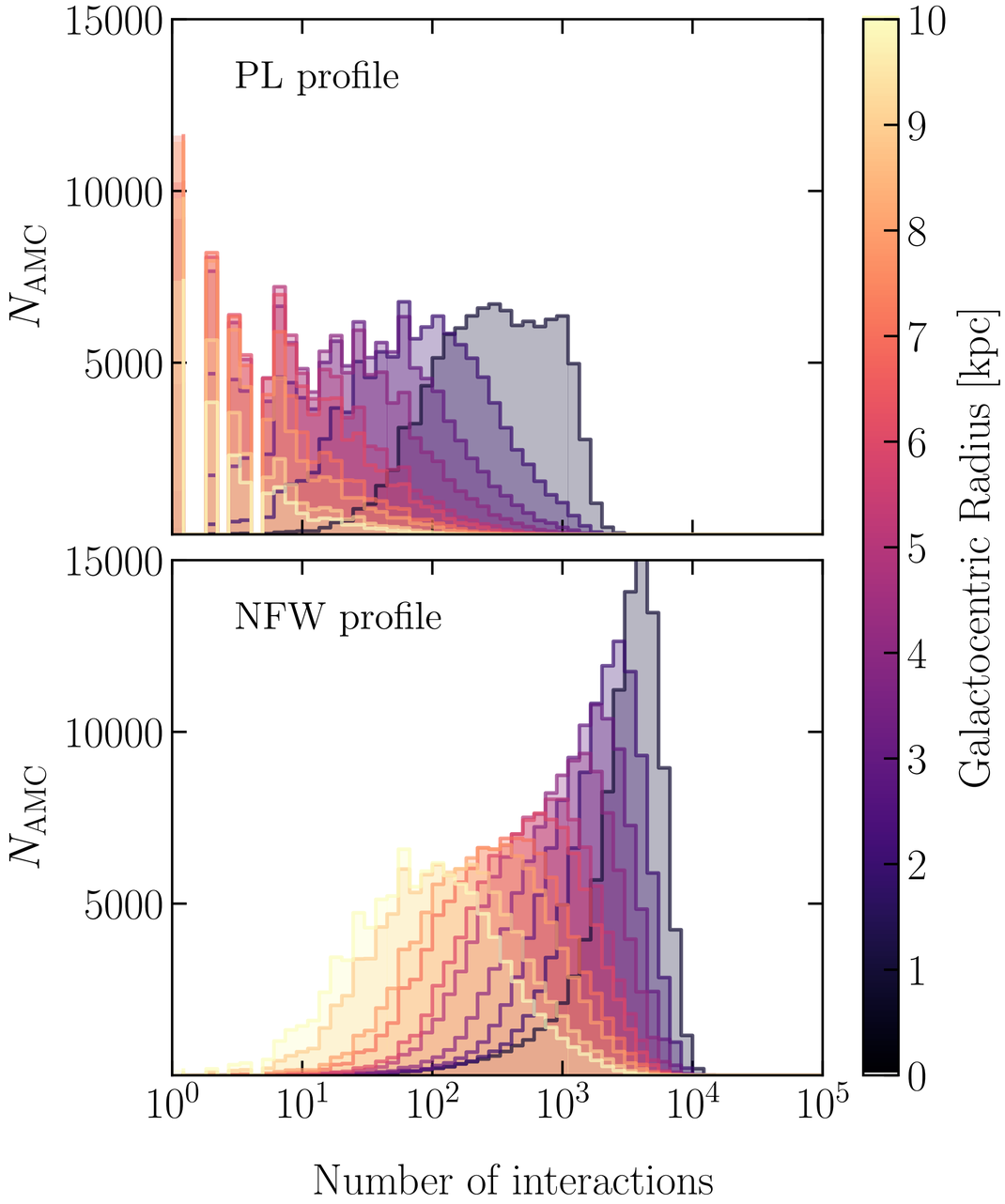
$$\Delta E/E_{\rm bind} \sim 1/\bar{\rho}$$

AMC-Stellar encounters

$$N = \int_0^{T_{\rm MW}} {\rm d}t\, n_\star(t) V_{\rm AMC}(t) \cdot \pi b_{\rm max}^2$$

Fix $b_{\rm max}$ such that $\Delta E(b_{\rm max}) = 10^{-6}\, E_{\rm bind}$ and truncate at $N_{\rm cut} = 10^6$ interactions.





Reconstructing AMC properties

Map from Monte Carlo output (which assumed a log-flat mass function) to ‘true’ distribution.

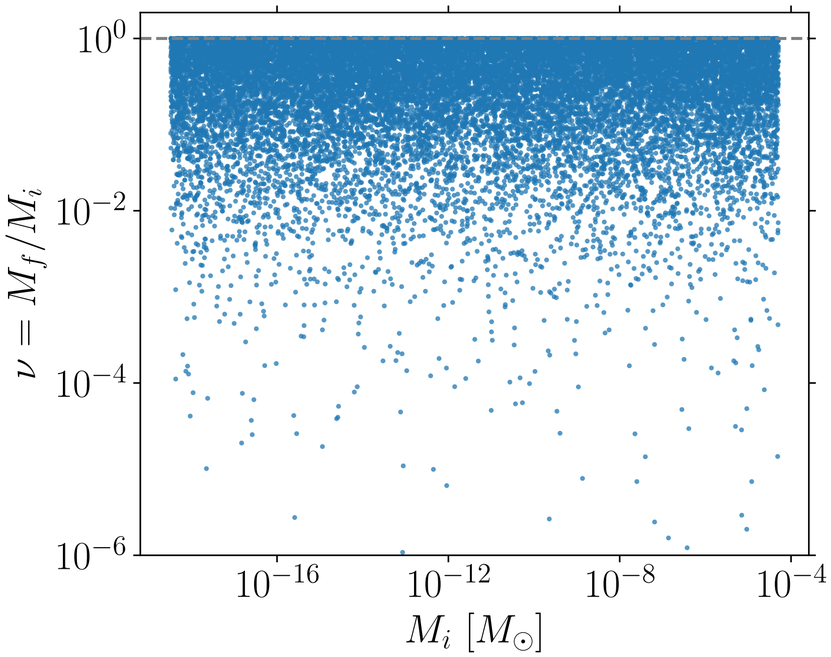
First, need to ‘smear' each AMC by applying a spatial weight:

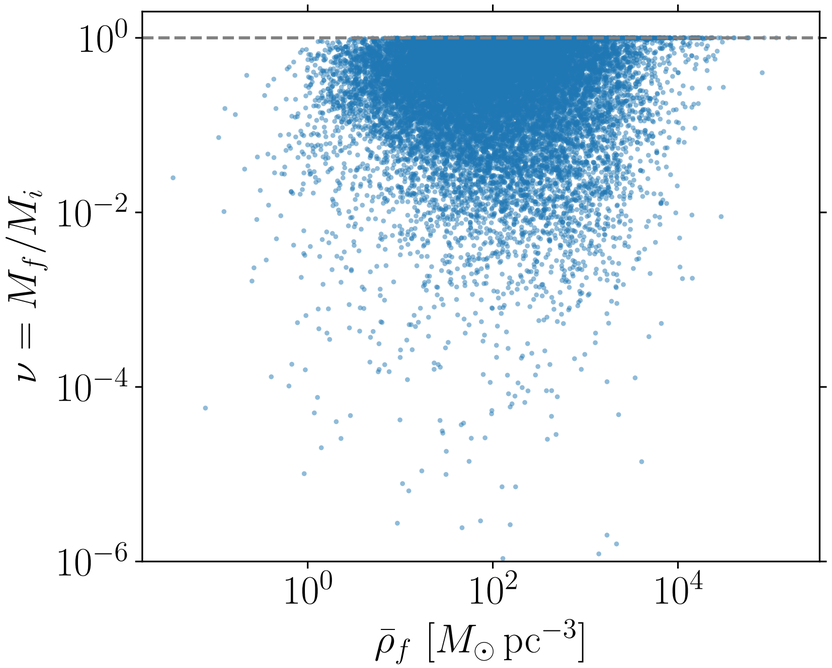
$$w_k \propto P(r|a_k, e_k)$$

Then we can calculate final distributions based on MC samples $\{\nu_k, \rho_k\}$. E.g.:

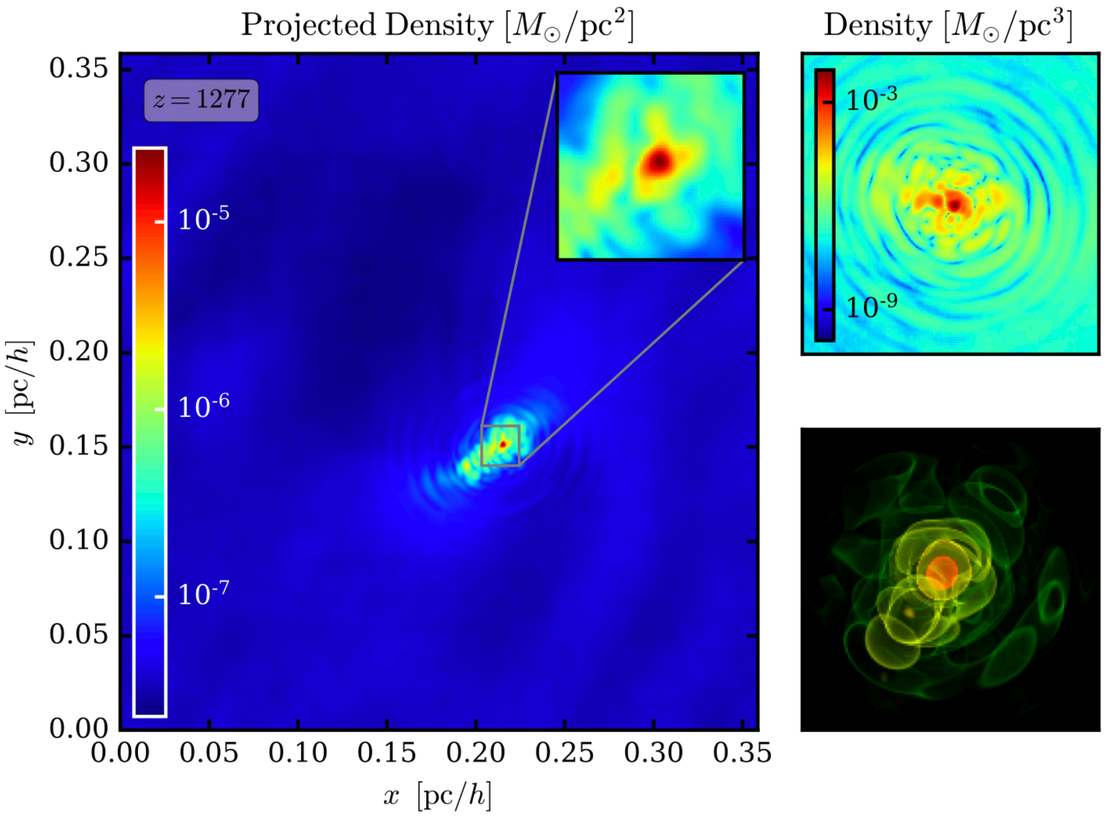
$$P\left(M_f|r\right) = \iint \frac{1}{\nu} P_i\left(M_f/\nu\right) P(\rho, \nu|r) \mathrm{d}\nu \mathrm{d}\rho$$
$$\approx \sum_k \frac{w_k}{\nu_k} P_i\left(M_f/\nu_k\right)$$

Easily recast for different mass-function/cut-offs!

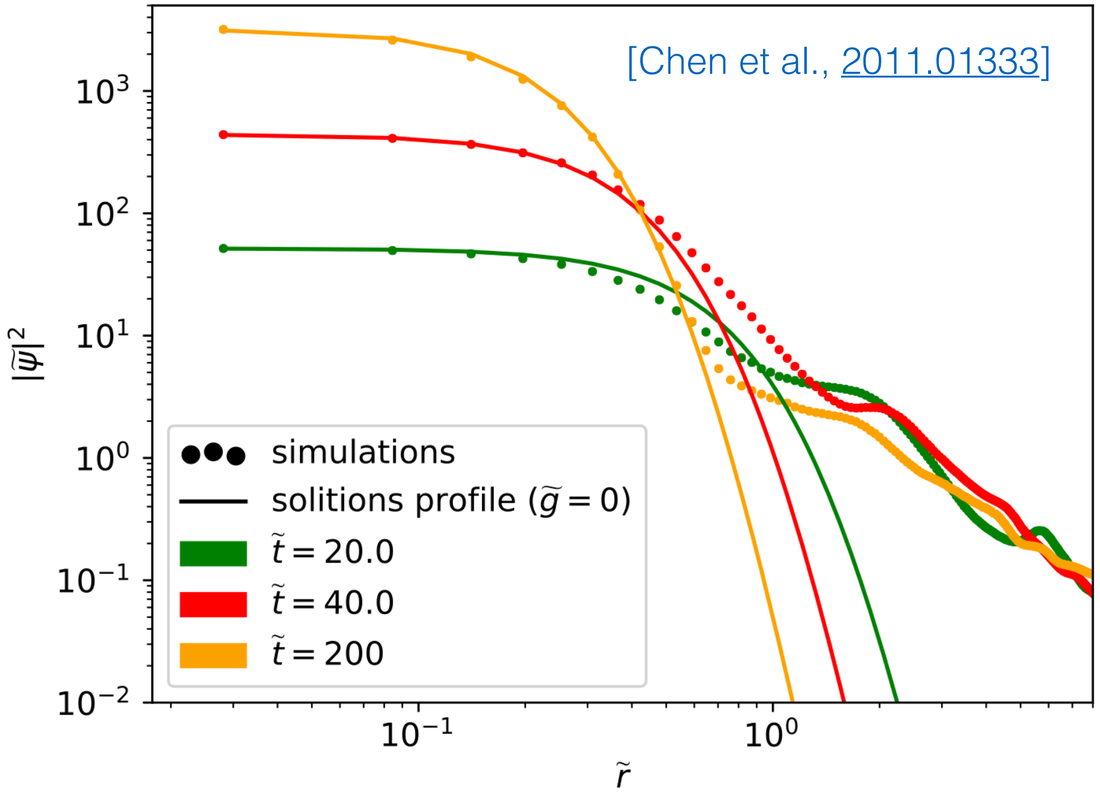




Axion Star cores



[Eggemeier et al., 1906.01348]



$$R_{\mathrm{AS}} = 2.47 \times 10^5 \ \mathrm{m} \left(\frac{20\mu\mathrm{eV}}{m_a}\right) \left(\frac{M_{\mathrm{AMC}}}{1 M_\odot}\right)^{-1/3}$$

[Schive et al., 1407.7762, Visinelli et al., 1710.08910]

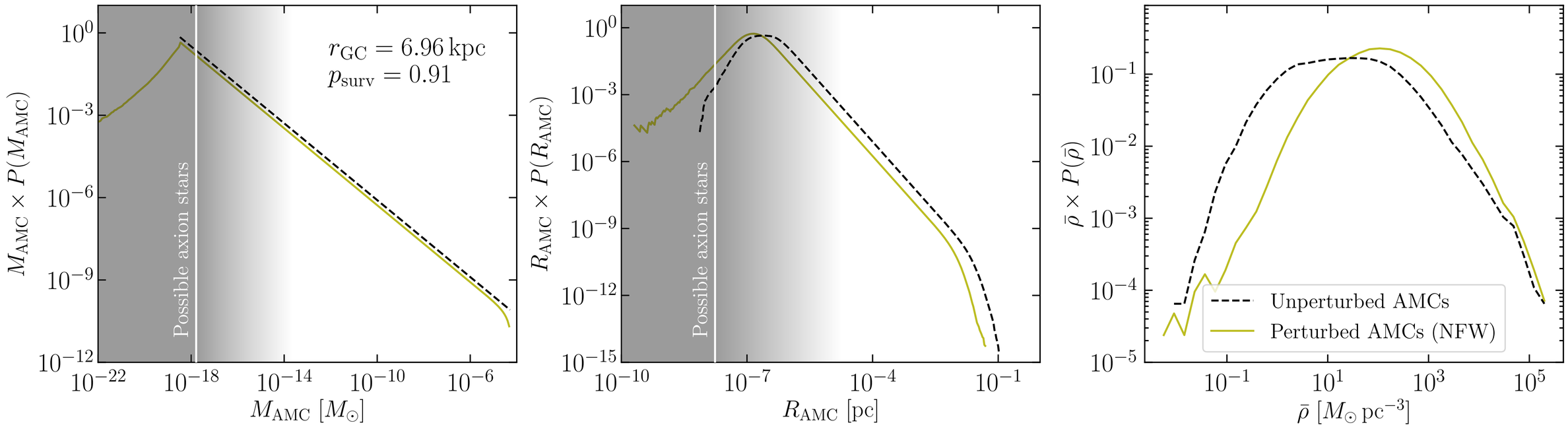
Apply an **AS cut**, by requiring: $R_{\mathrm{AMC}} > R_{\mathrm{AS}}$

AMC Properties Today

$$f_{\rm cut}^{\rm NFW} = 1.5 \times 10^{-2}$$

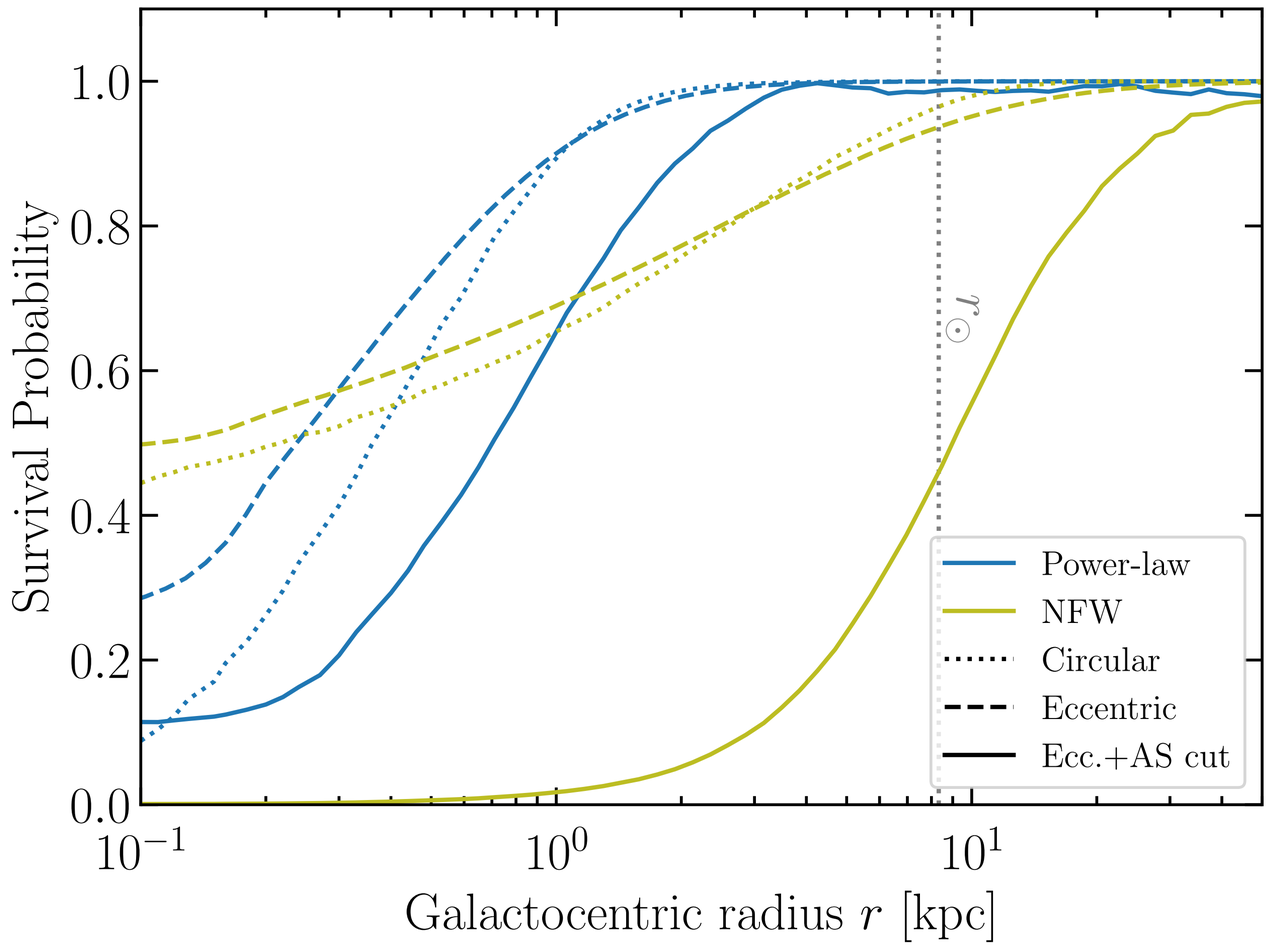
$$f_{\rm cut}^{\rm PL} = 2.7 \times 10^{-4}$$

Example of AMC properties at $r_{\rm GC} \approx 7\,{\rm kpc}$ for NFW internal density profiles:



[Distributions and tools for re-casting available online: github.com/bradkav/axion-miniclusters]

Survival probabilities



Survival probability at Solar circle:
$\mathcal{O}(40\%)$ for NFW profiles
$\mathcal{O}(99\%)$ for PL profiles

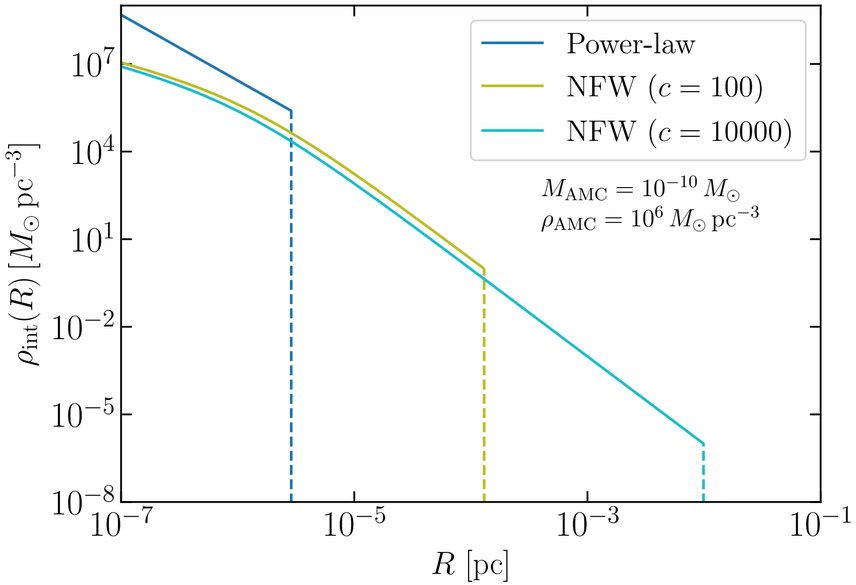
But remember that even ‘surviving' AMCs may be drastically altered.

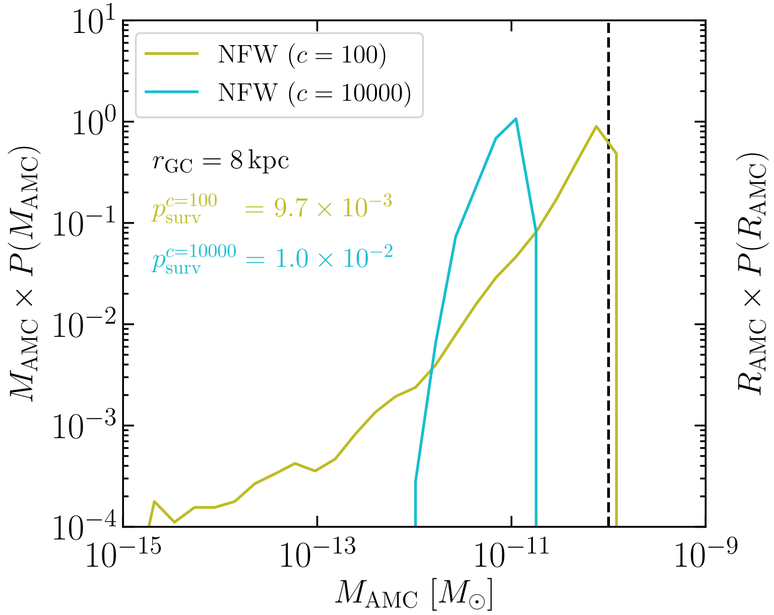
[See also previous work, e.g. Tinyakov et al., 1512.02884; Dokuchaev et al., 1710.09586]

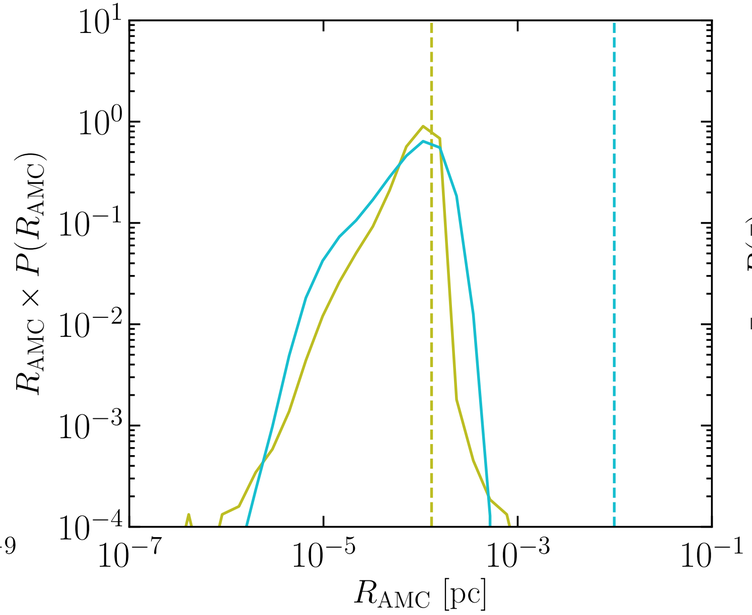
Impact of concentration

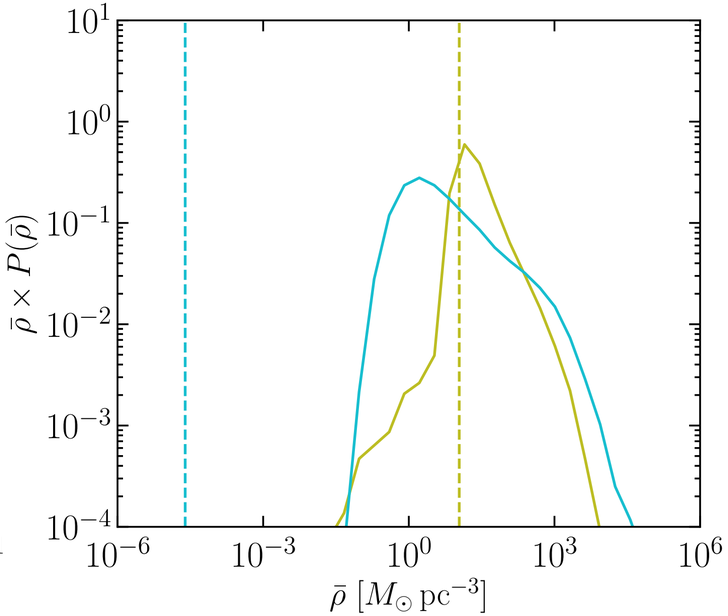
Perform some ‘toy' Monte Carlos using different NFW concentrations.

Fix $M_{\mathrm{AMC},i} = 10^{-10}\,M_\odot$ and $\rho_{\mathrm{AMC},i} = 10^{6}\,M_\odot\,\mathrm{pc}^{-3}$:









[Thanks to Doddy for discussing some of this with us.]

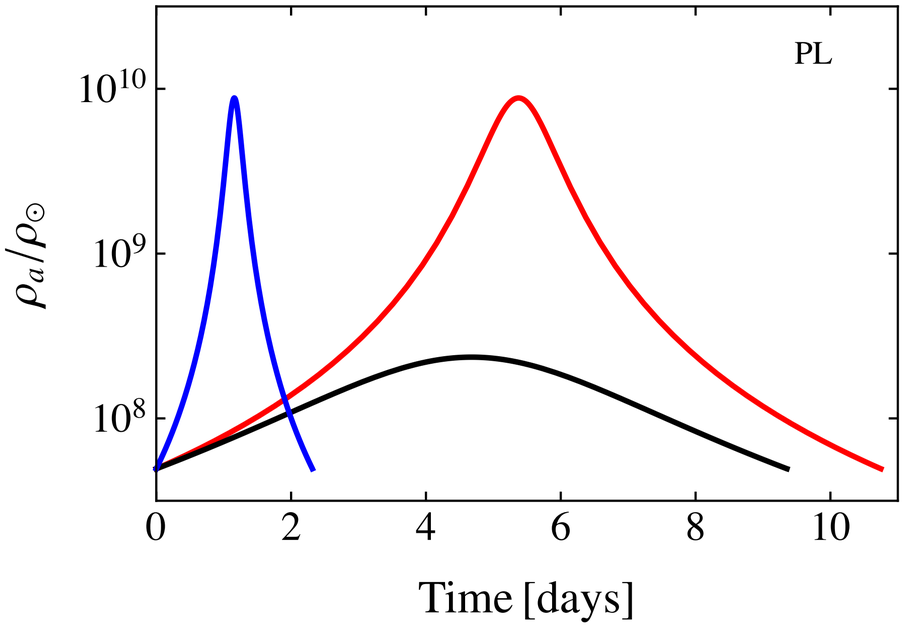
Observational Consequences

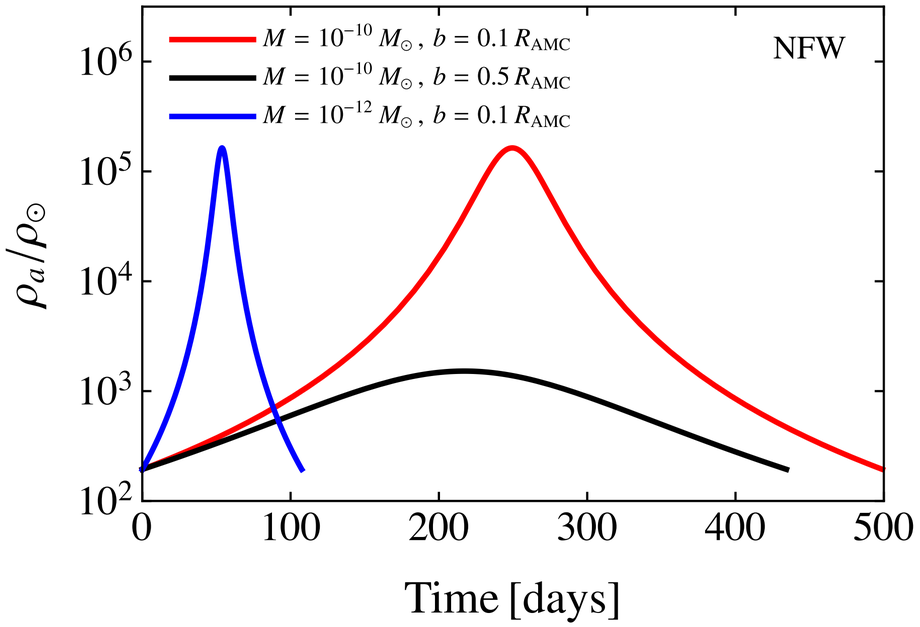
Axion Direct Detection

$$\Gamma_\odot = n_{\rm AMC}\left(r_\odot\right)\overline{\langle\sigma u\rangle}\left(r_\odot\right)$$

$\Gamma_\odot \approx \left(3\times10^6 \text{ years}\right)^{-1}$ for PL profiles

$\Gamma_\odot \approx \left(4\times10^3 \text{ years}\right)^{-1}$ for NFW profiles





[See also Sikivie, astro-ph/0610440]

Minicluster lensing

$$\bar{N}_{\rm ex} \propto \int {\rm d}t \int {\rm d}x \frac{{\rm d}^2\Gamma}{{\rm d}x\ {\rm d}t}$$

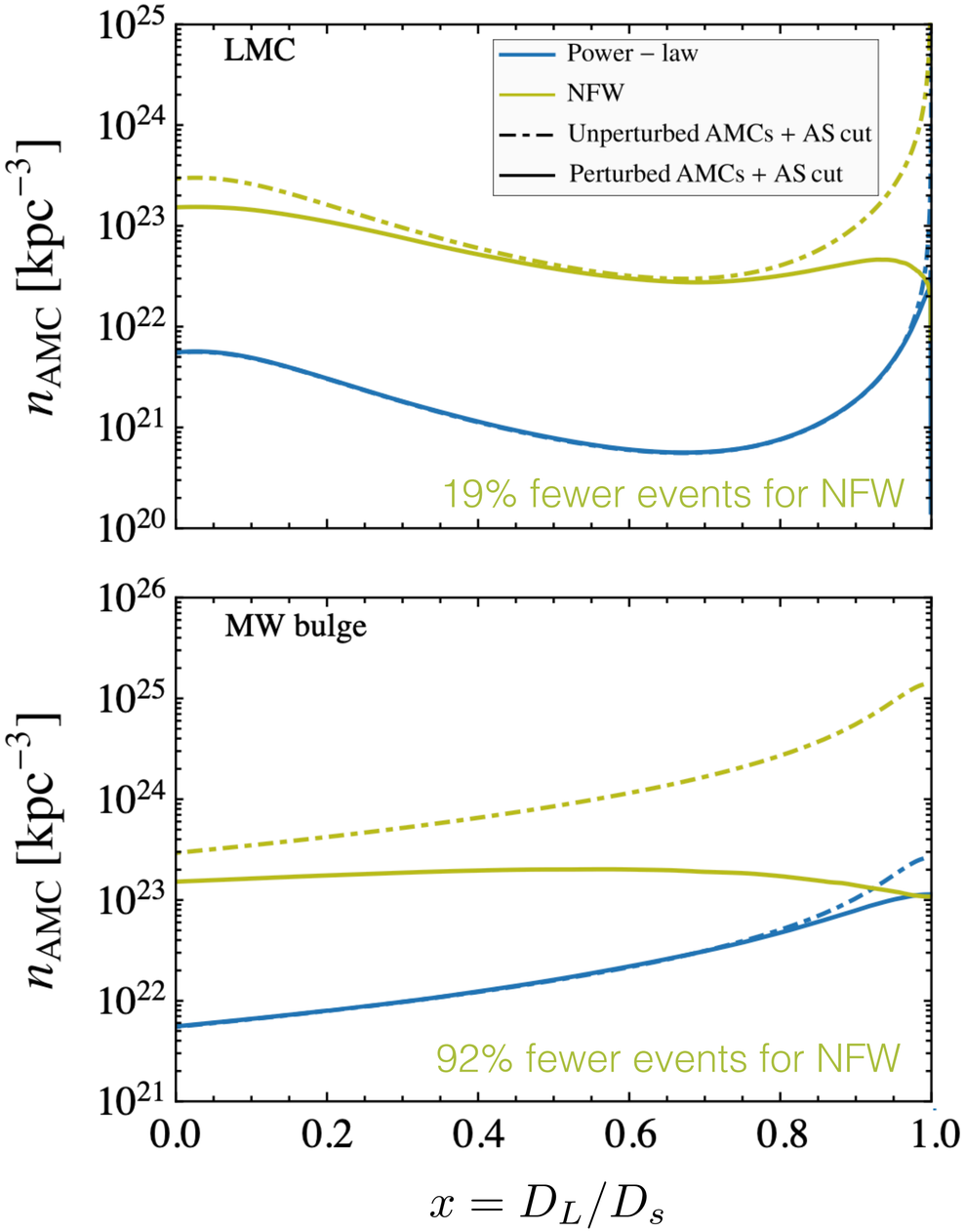
$$\frac{{\rm d}^2\Gamma}{{\rm d}x\ {\rm d}t} \sim n_{\rm AMC}(x)$$

But properties of lensing events would be altered:

$$\langle \hat{t} \rangle \approx (M_{\rm AMC}/{\rm M}_\odot)^{1/2} \times 140\,{\rm days}$$

[MACHO, astro-ph/0001272]

[See e.g. Fairbairn et al., 1701.04787, 1707.03310]



NS-AMC Encounters

Axion-photon Conversion

Assuming a Goldreich-Julian model for the NS magnetosphere, emitted radio power:
[Goldreich & Julian (1969)]

$$\frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega} \sim \frac{\pi}{3}\, g_{a\gamma\gamma}^2 B_0^2\, \frac{{R_{\rm NS}}^6}{{R_c}^3}\, \frac{\rho_c}{m_a}$$

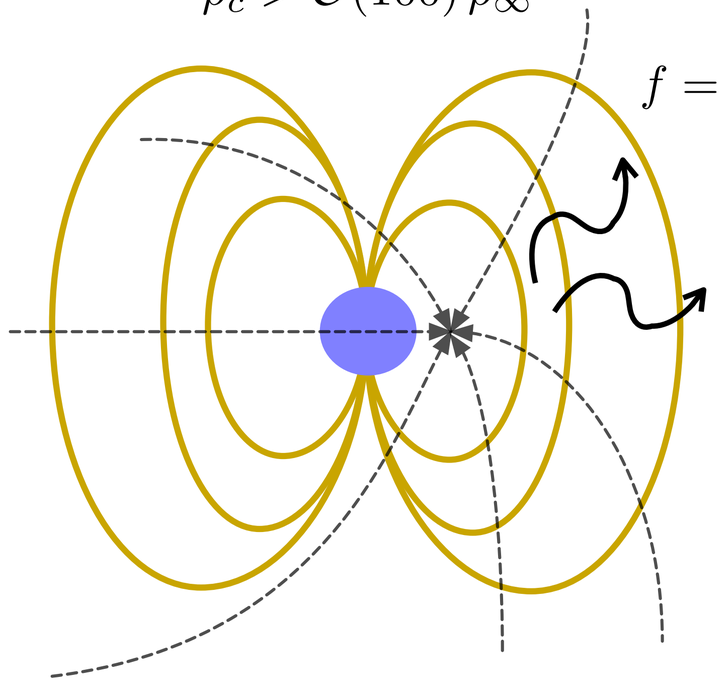
Plenty of uncertainties on magnetosphere properties, conversion probabilities, anisotropy…

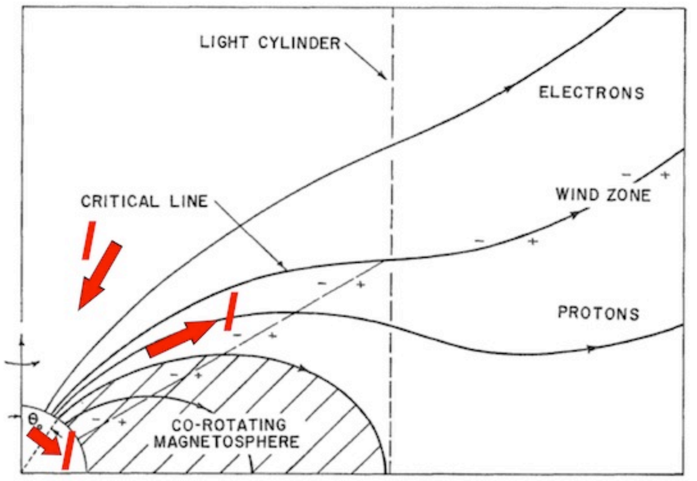
[Battye et al., 1910.11907; Leroy et al., 1912.08815]

Assume isotropic emission and focus on enhancements to ρ_c due to AMC encounters.

$\rho_c > \mathcal{O}(100)\,\rho_\infty$

$f = 4.84\,\mathrm{GHz}$





[Hook et al., 1804.03145; Safdi et al., 1811.01020; Edwards, Chianese, **BJK**, Nissanke, Weniger, 1905.04686; Foster et al., 2004.00011]

Neutron Star Distributions

Assume that the spatial distribution of old NSs follows that of millisecond pulsars in the MW

[As in Safdi et al., 1811.01020]

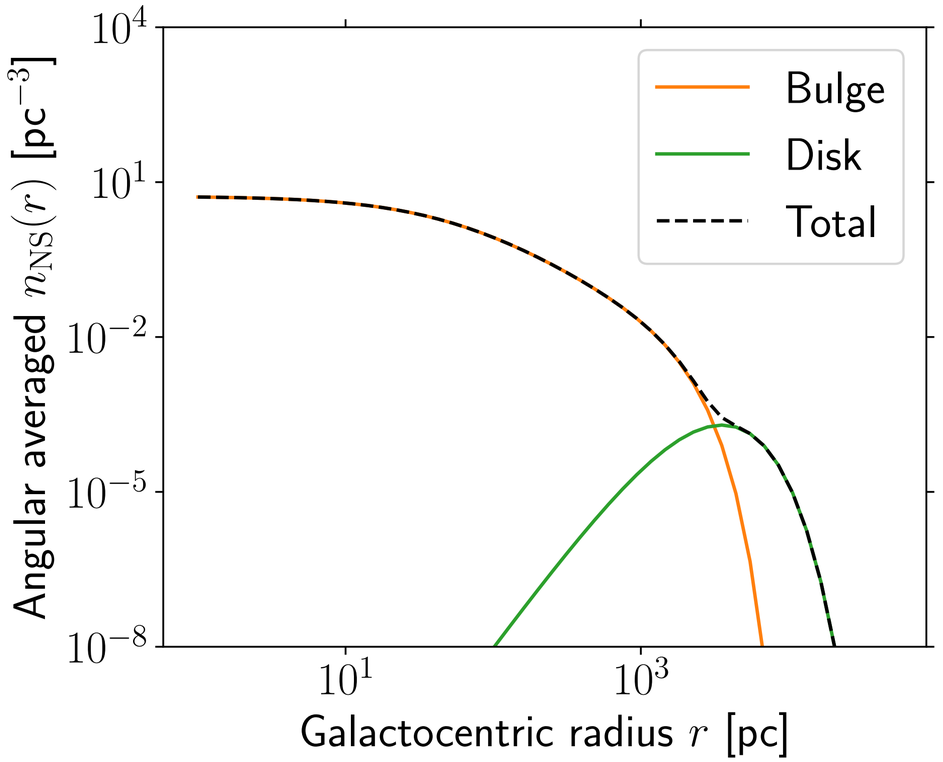
Assume 10^9 NSs born in the MW (60% in the bulge, 40% in the disk).
~20% of these ejected due to Natal kicks.

[Sartore et al., 0908.3182]

Assume log-normal distributions for B-field and Period:

$$\log_{10}(B_0/\mathrm{G}) = 12.65; \quad \sigma_{B_0} = 0.55$$
$$\log_{10}(P/\mathrm{ms}) = 2.7; \quad \sigma_P = 0.34$$

[Lorimer et al., astro-ph/0607640, Bates et al., 1311.3427]

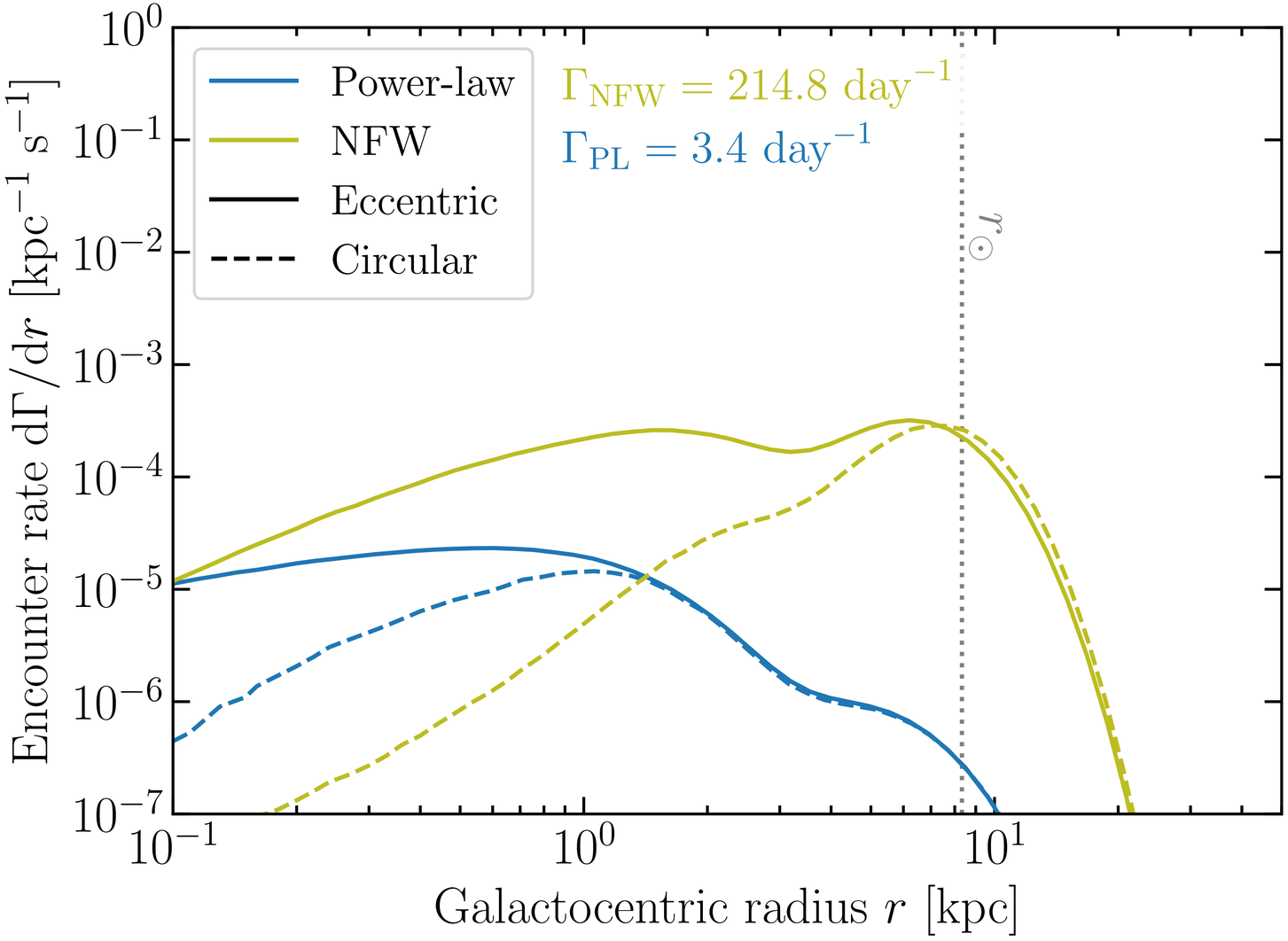


Encounter Rate

$$\Gamma = \int \mathrm{d}^3\mathbf{r} \int \mathrm{d}R \frac{\mathrm{d}n_{\mathrm{AMC}}(r)}{\mathrm{d}R} n_{\mathrm{NS}}(\mathbf{r}) \langle \widetilde{\sigma u} \rangle (r)$$

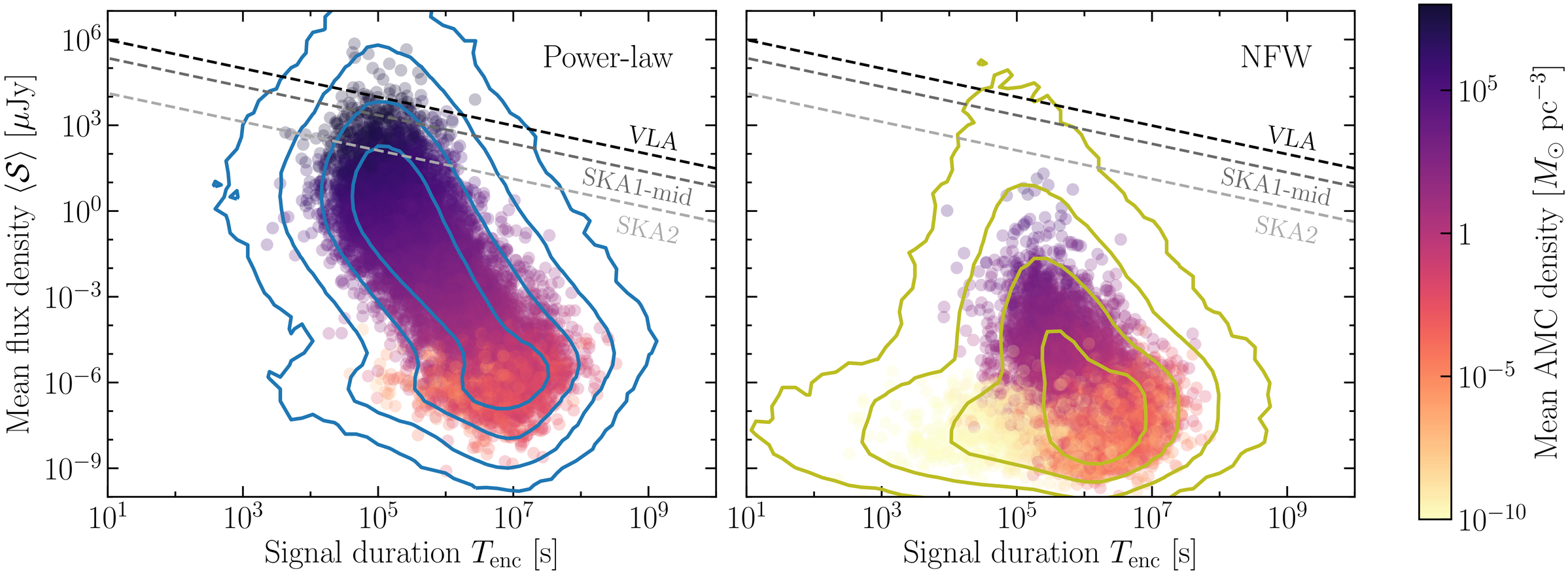
$$\langle \sigma u \rangle (r) \sim \sigma_u R^2$$

Without stellar disruption,
encounter rate would be:
39.3x larger for NFW profiles
1.4x larger for PL profiles



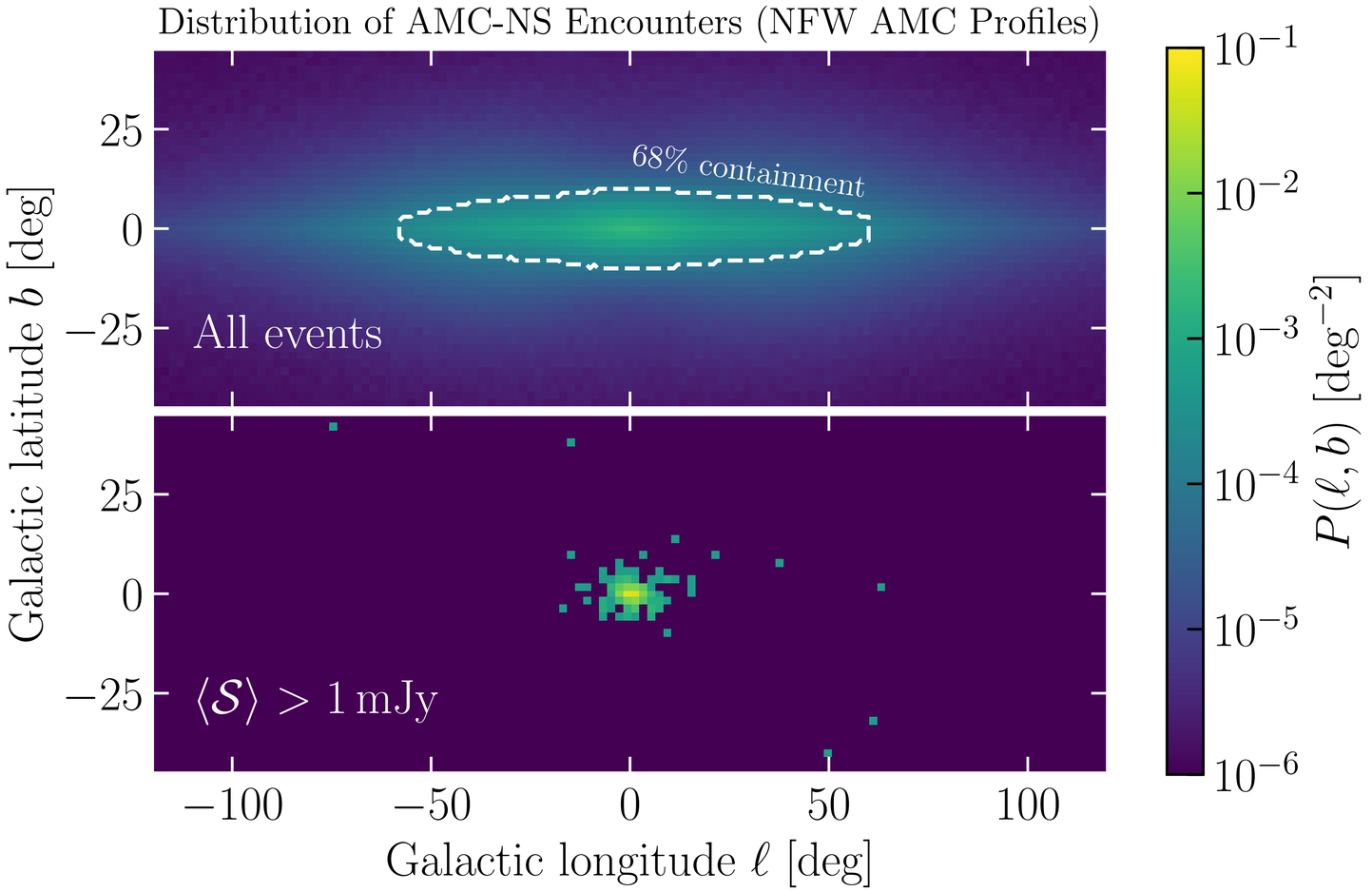
Signal Flux and Duration

$$\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$$



Based on velocity dispersion of AMC, expect an *incredibly narrow line.*
Instead, fix bandwidth BW = 1 kHz (based on telescope resolution).

Sky Distributions



For PL profiles, 68% of events lie with 7 degrees of the GC.

Summary

AMC-NS radio transients

- Lasting days to years
- Within reach of current & future searches
- Expect O(1) bright event on the sky at all times
- Concentrated towards the Galactic Centre

Missing ingredients

- Concurrent structure formation & disruption
- Realistic input to Monte Carlo simulations (e.g. density profiles, $P(M, \delta)$)
- Understanding axion star formation at the low-mass end

Please re-cast the results and re-use the code!

2011.05377, 2011.05378
github.com/bradkav/axion-miniclusters

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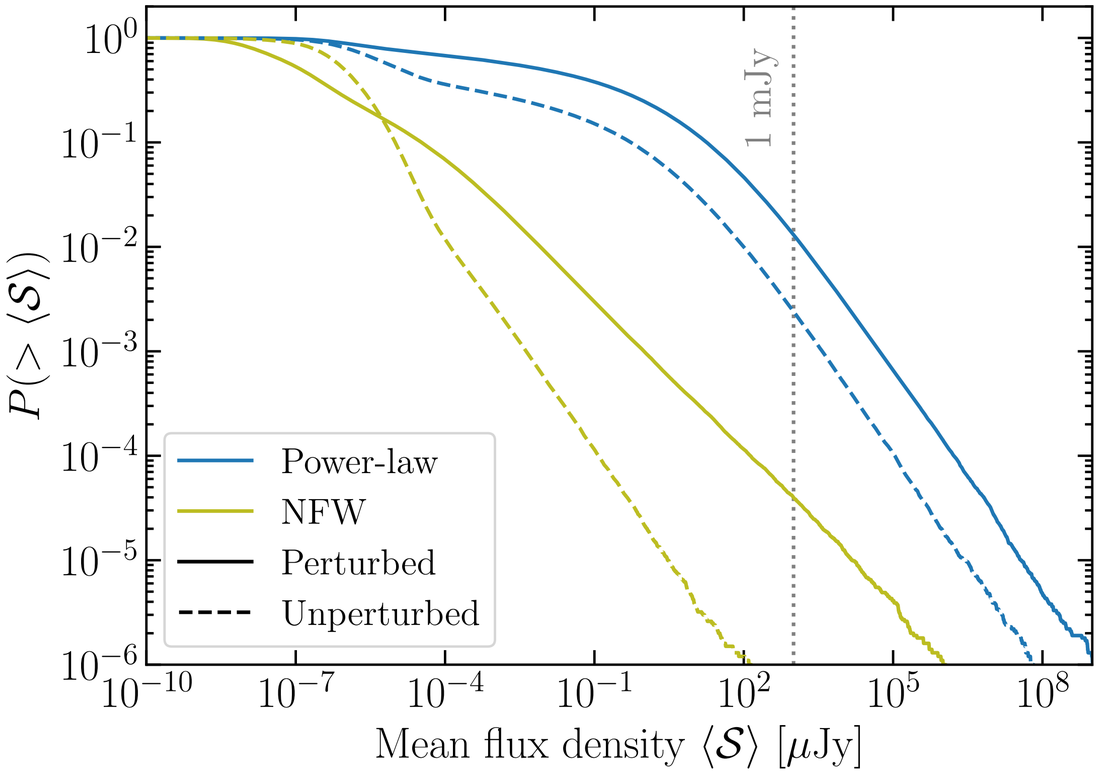
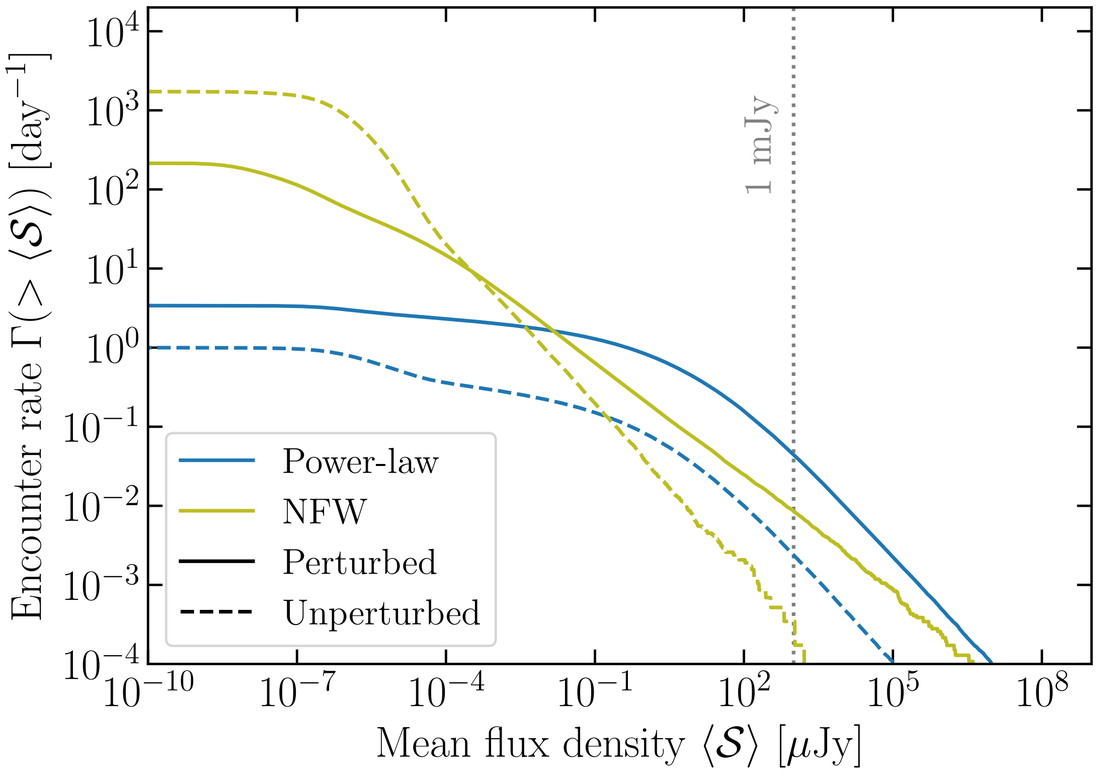
Thank you!

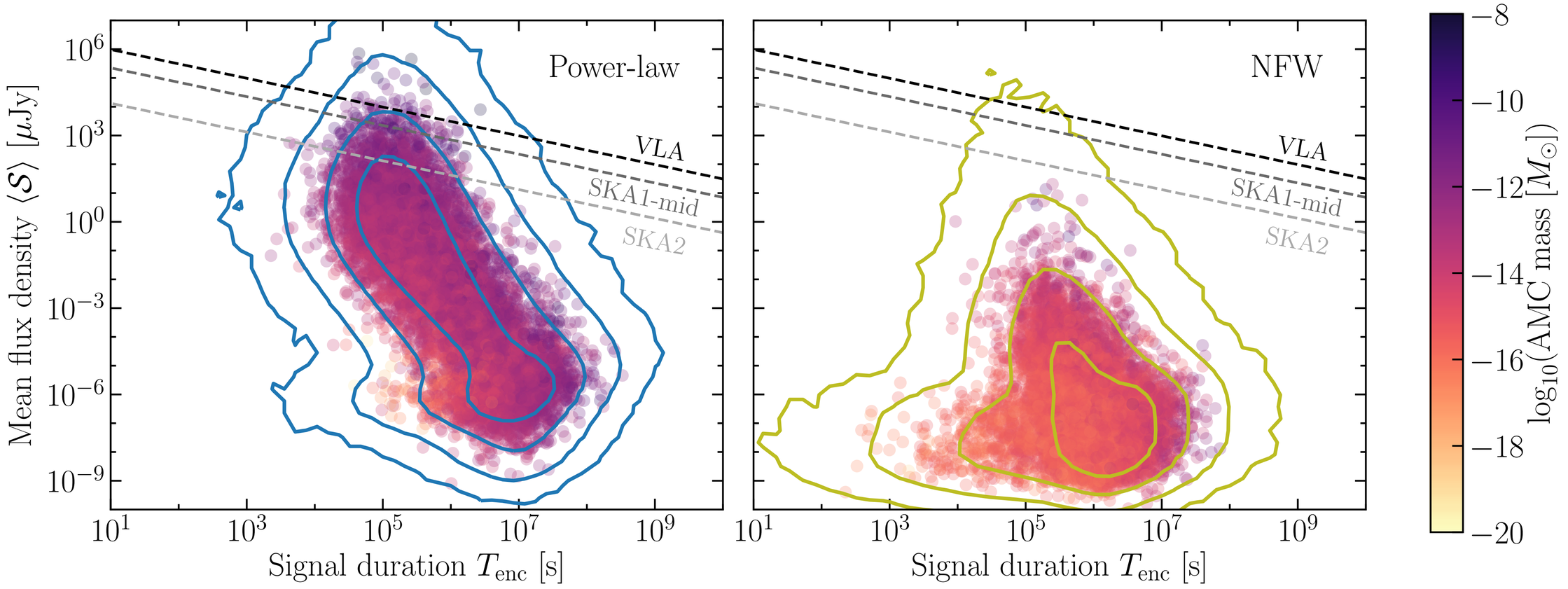
Backup slides

Flux Distribution





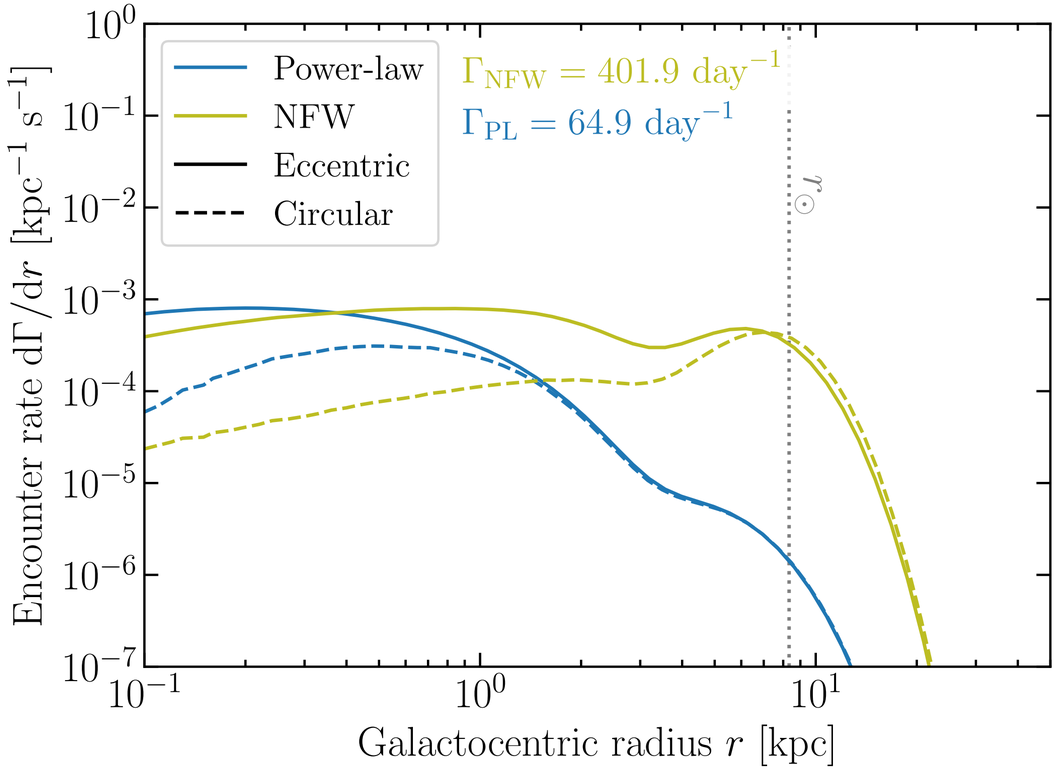
AMC mass dependence



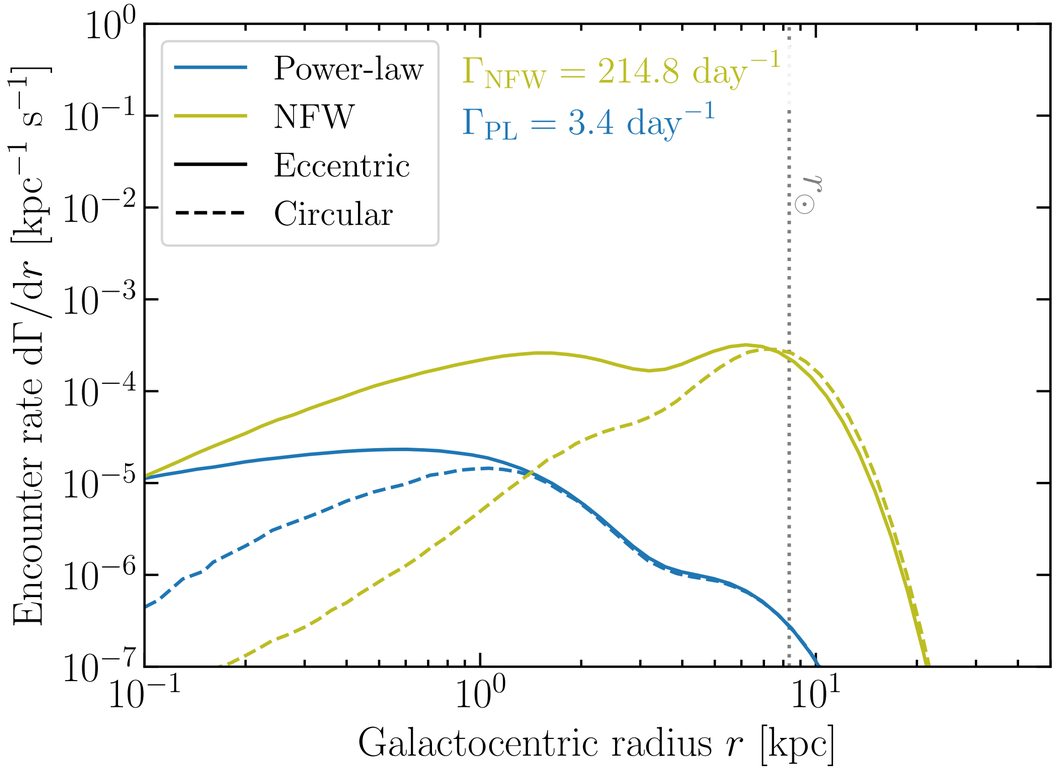
with axion star cut

Impact of the AS cut (1)

Without axion star cut

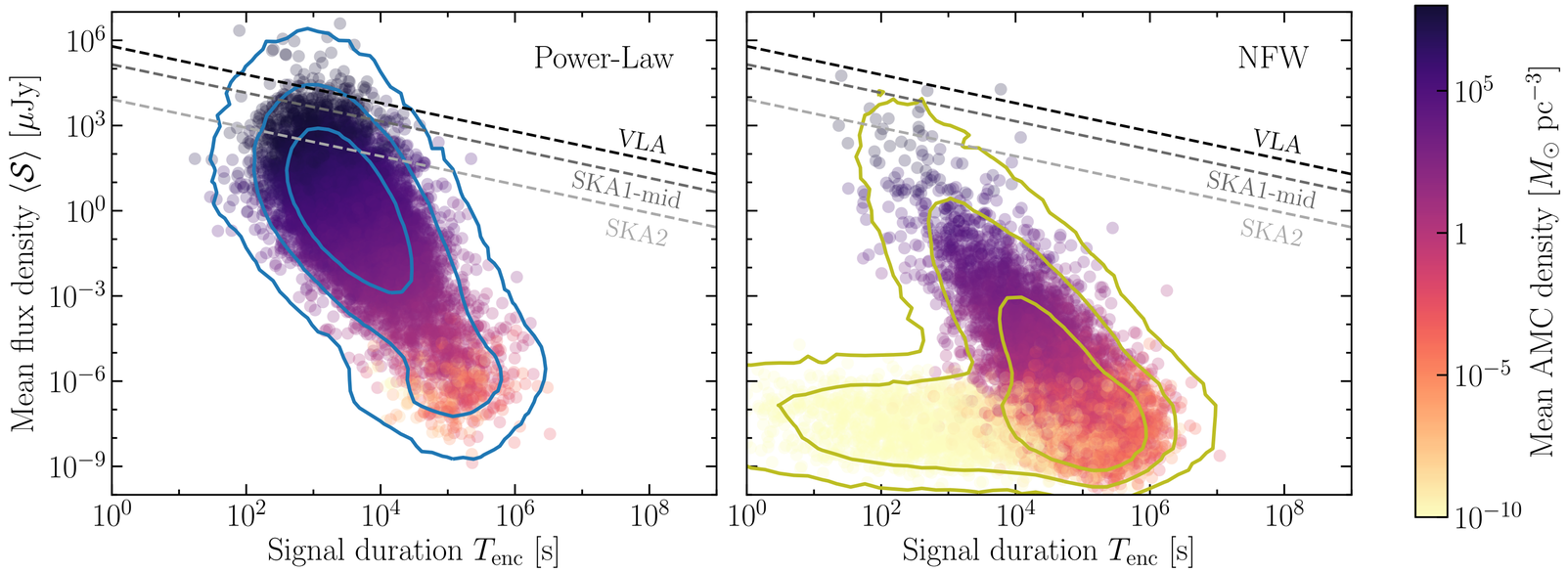


With axion star cut



Impact of the AS cut (2)

Without axion star cut



With axion star cut