Finding the Milky Way's Last Neutron Star Mergers

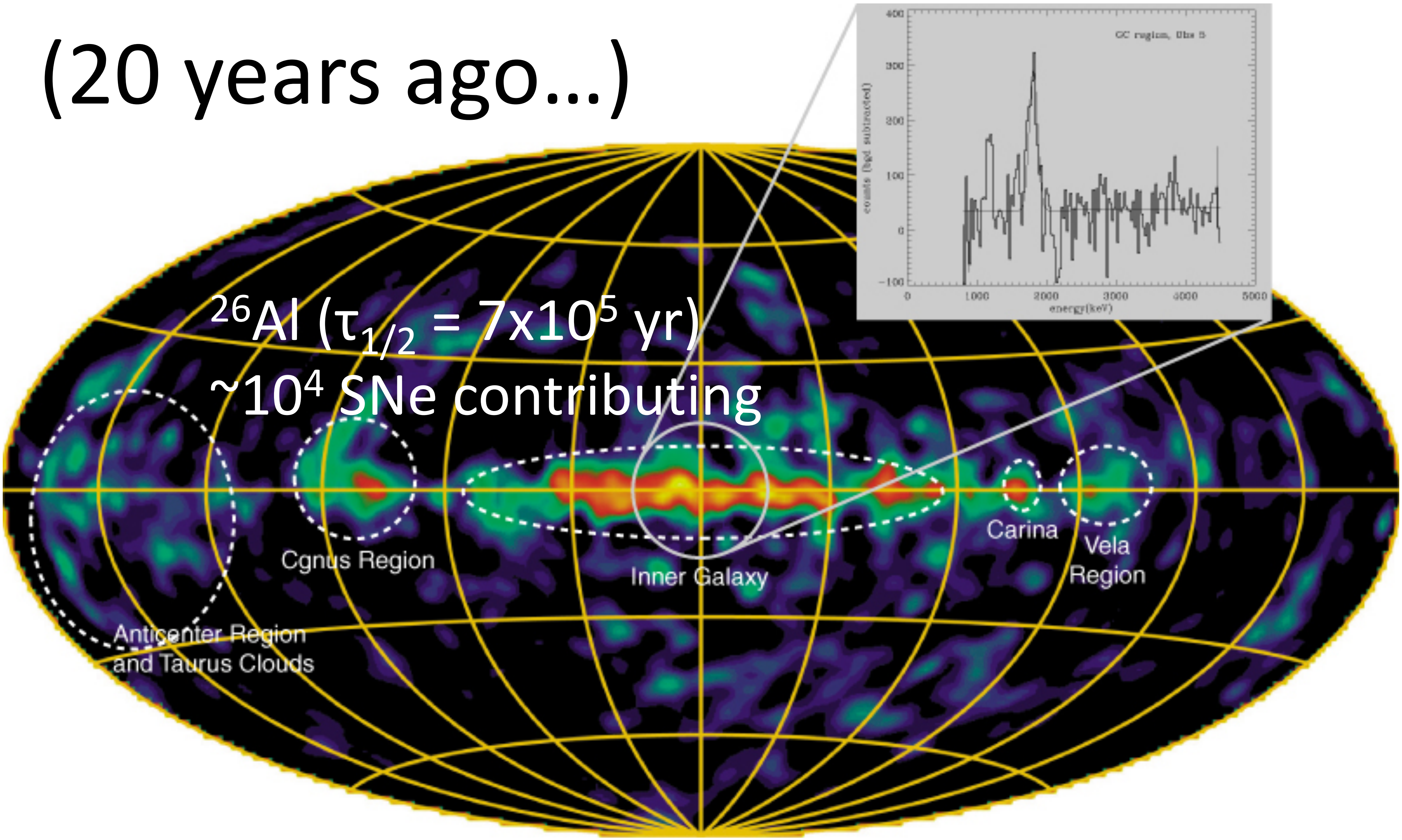
Brian Metzger

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Meng-Ru Wu, Projjwal Banerjee, Gabriel Martinez-Pinedo, Tsuguo Aramaki, Eric Burns, Chuck Hailey, Jennifer Barnes, Georgia Karagiogi

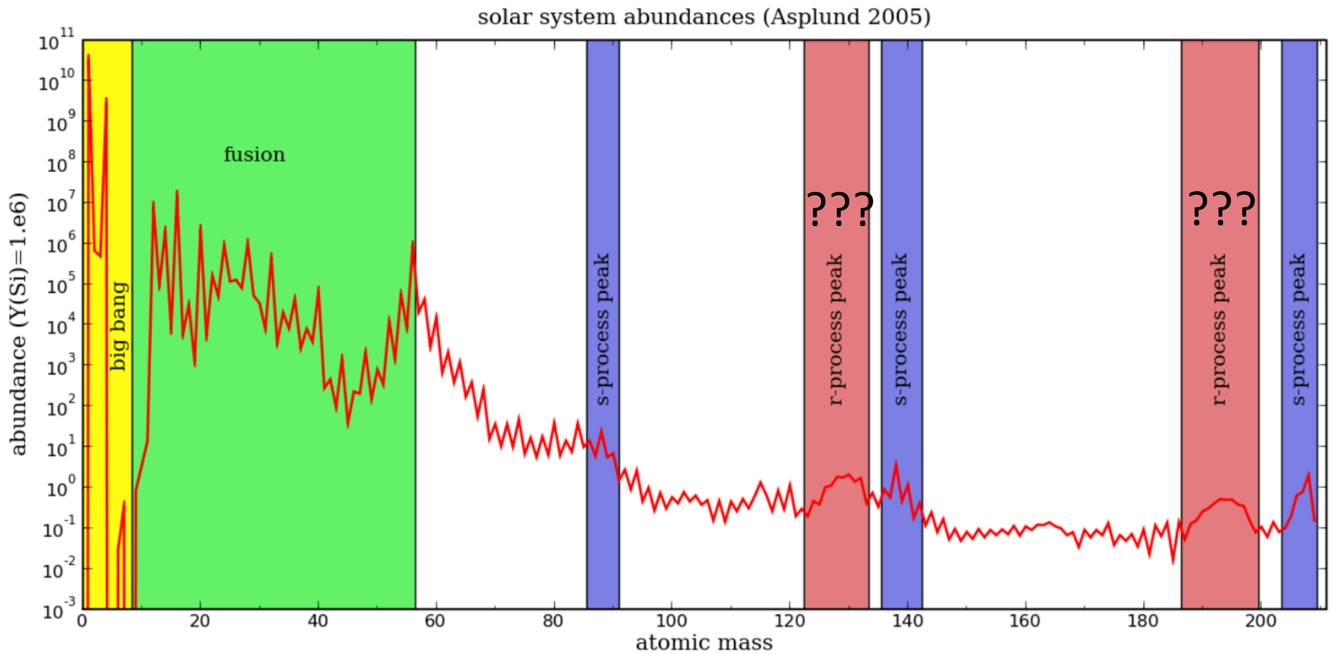
MeV Astronomy: Unlocking the Multi-Messenger Universe

COMPTEL
(20 years ago...)



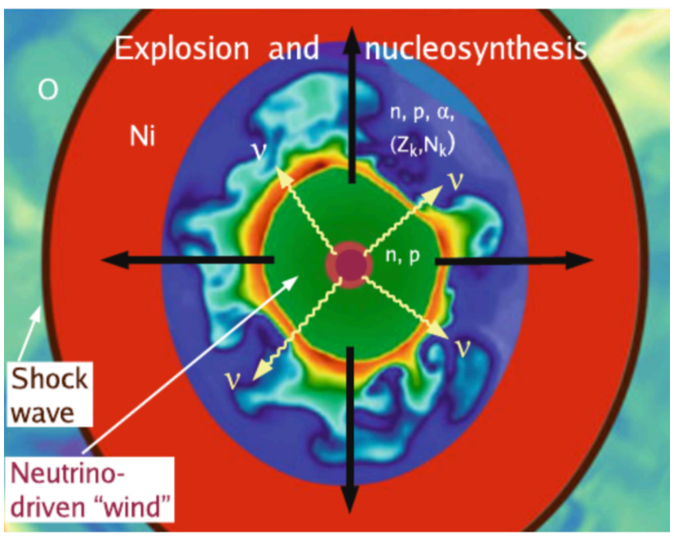
^{26}Al traces the locations of young and massive stars.

Where, oh where, is the r-process?



Supernovae

(e.g. Qian & Woosley 96; Mosta+14)

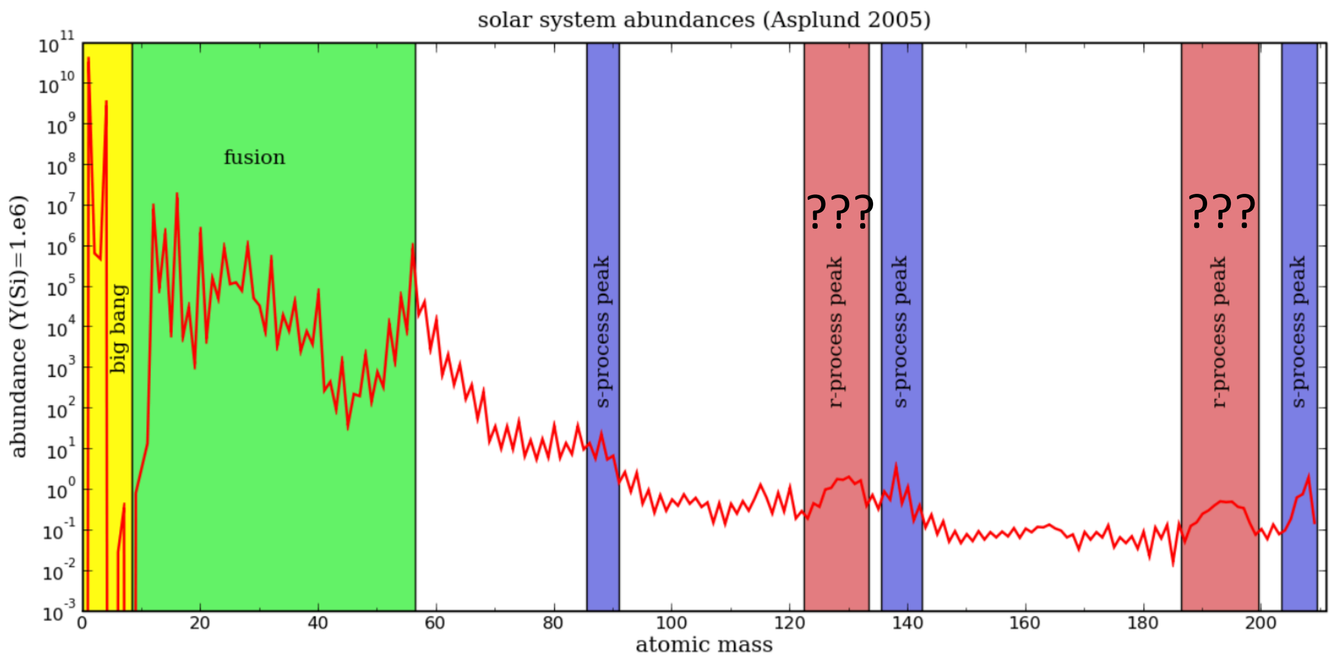


AND/OR

Neutron Star Mergers

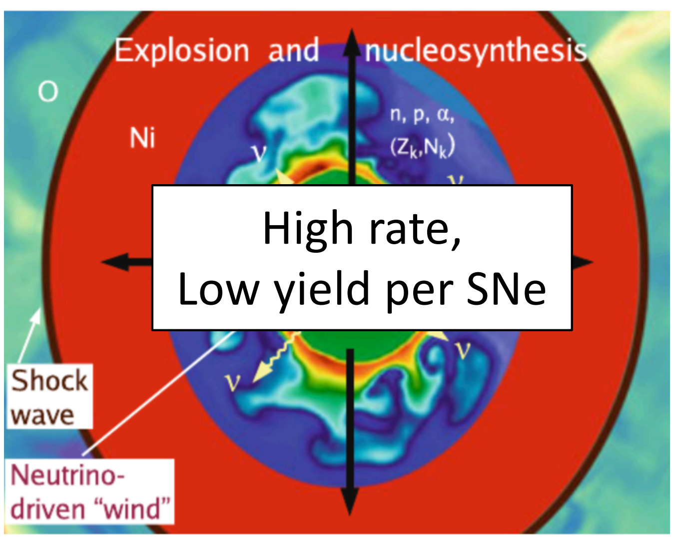
(e.g Lattimer & Schramm 74; Freiburghaus+99)

Where, oh where, is the r-process?



Supernovae

(e.g. Qian & Woosley 96; Mosta+14)



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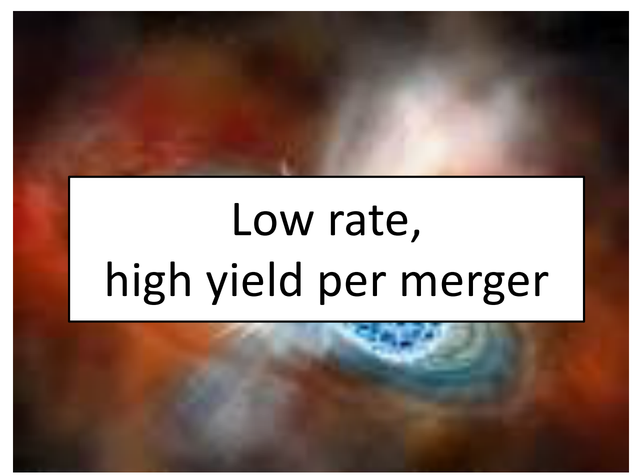
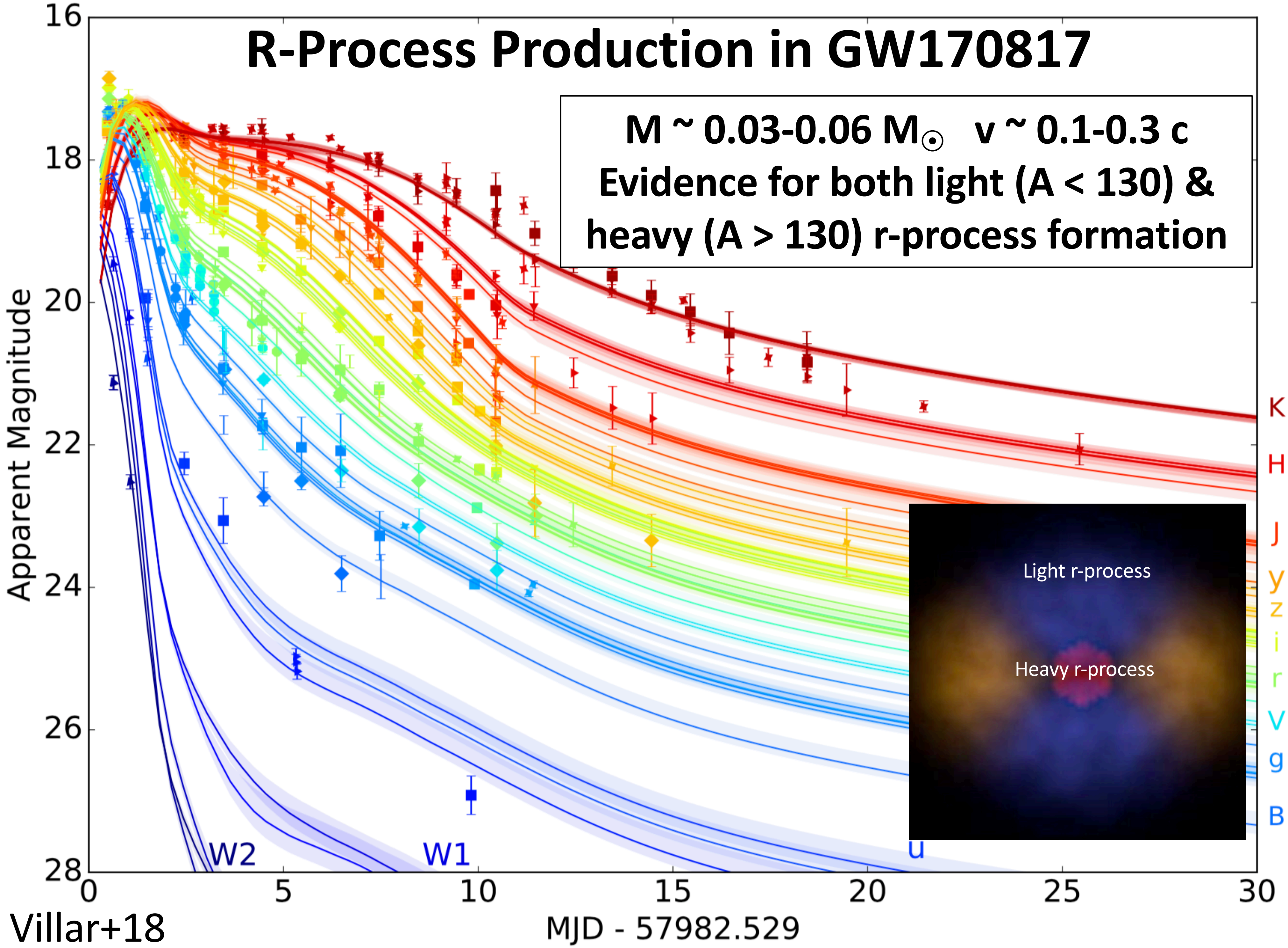
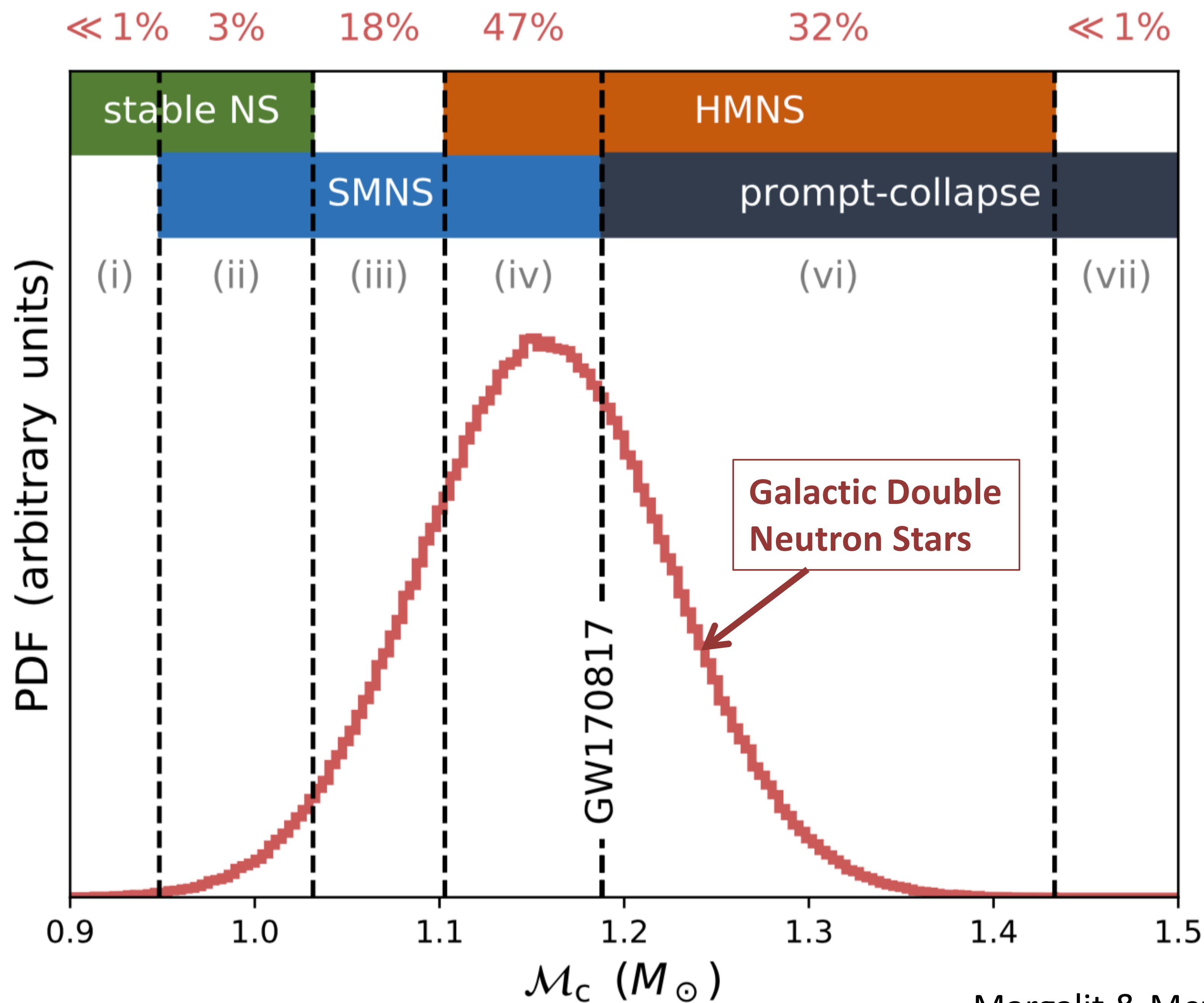



R-Process Production in GW170817
M ~ 0.03-0.06 $M_\odot$ v ~ 0.1-0.3 c
Evidence for both light (A < 130) &
heavy (A > 130) r-process formation
Light r-process
Heavy r-process
Apparent Magnitude
16
18
20
22
24
26
28
0
5
10
15
20
25
30
MJD - 57982.529
K
H
J
y
z
i
r
V
g
B
u
W1
W2
Villar+18

GW170817: Probably Typical in Milky Way



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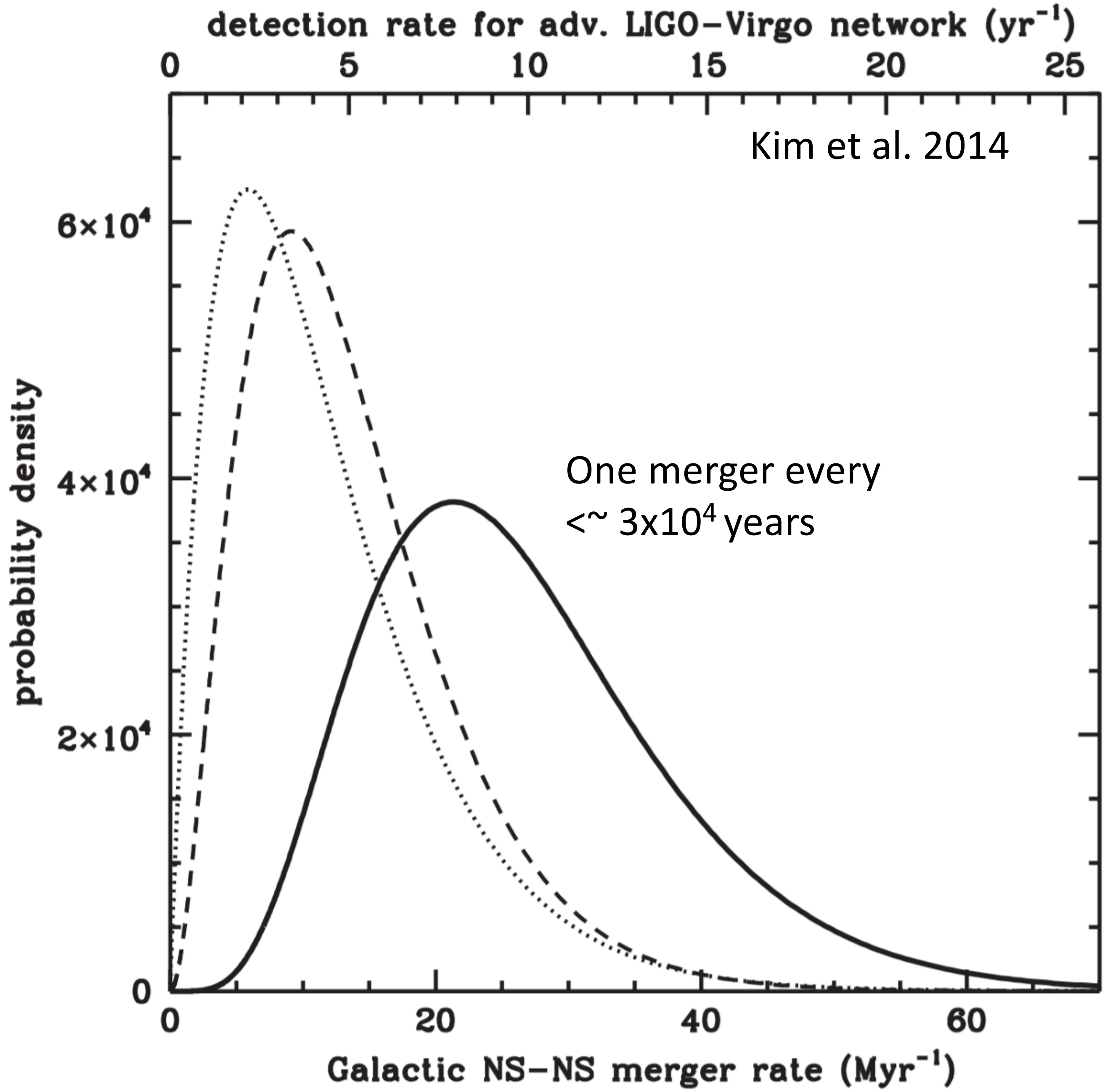
Galactic Neutron Star Merger Rate



Nuclei with X/γ decay lines: 100 yr < $\tau_{1/2}$ < 100 Myr

	Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
rare/short-lived	^{249}Cf	α to ^{245}Cm	0.0035	388	66.0
	^{241}Am	α to ^{237}Np	0.0043	13.9	37.0
				59.5	35.9
	^{251}Cf	α to ^{247}Cm	0.0090	15	53.0
	^{226}Ra	$\alpha\beta$ to ^{206}Pb	0.016	351.9 (^{214}Pb)	35.6
				609.3 (^{214}Bi)	45.5
	^{240}Pu	α to ^{236}U	0.066	13.6	9.6
	^{243}Am	$\alpha\beta$ to ^{239}Pu	0.074	14.3 (^{239}Np)	43.3
				74.66	67.2
	^{229}Th	$\alpha\beta$ to ^{209}Bi	0.079	12.3	80.0
				40.0 (^{225}Ra)	30.0
rare	^{250}Cm	$\alpha\beta$ to ^{246}Cm	0.083	679.2 (^{246}Am)	11.5
	^{245}Cm	$\alpha\beta$ to ^{237}Np	0.084	14.3	53.0
	^{239}Pu	α to ^{235}U	0.24	13.6	4.3
	^{231}Pa	$\alpha\beta$ to ^{207}Pb	0.33	12.7	45.0
	^{230}Th	$\alpha\beta$ to ^{208}Pb	0.75	351.9 (^{214}Pb)	35.6
				609.3 (^{214}Bi)	45.5
	^{233}U	$\alpha\beta$ to ^{209}Bi	1.59	12.3 (^{229}Th)	80.0
				40.0 (^{225}Ra)	30.0
2nd R-Process Peak	^{126}Sn	β to ^{126}Te	2.3	87.6	37.0
				414.7 (^{126}Sb)	98
				666.3 (^{126}Sb)	100
				695.0 (^{126}Sb)	97
rare	^{234}U	α to ^{230}Th	2.46	13.0	10.0
	^{242}Pu	α to ^{238}U	3.73	13.6	8.6
	^{237}Np	$\alpha\beta$ to ^{209}Bi	21.4	12.3 (^{229}Th)	80.0
				13.3	49.3
				40.0 (^{225}Ra)	30.0
				311.9 (^{233}Pa)	38.5
3rd R-Process Peak	^{182}Hf	β to ^{182}W	89	67.7 (^{182}Ta)	42.6
				270.4	79.0
				1121.3 (^{182}Ta)	35.24
rare/ long-lived	^{247}Cm	$\alpha\beta$ to ^{235}U	156	14.3 (^{239}Np)	43.3
				74.66 (^{243}Am)	67.2
				402.4	72.0
	^{129}I	β to ^{129}Xe	157	29.782	36
	^{236}U	α to ^{232}Th	234	13.0	9.0
	^{244}Pu	$\alpha\beta$ to ^{236}U	811	14.3 (^{240}Np)	27.0
				554.6 (^{240}Np)	20.9

Monte Carlo Galactic Merger Remnants

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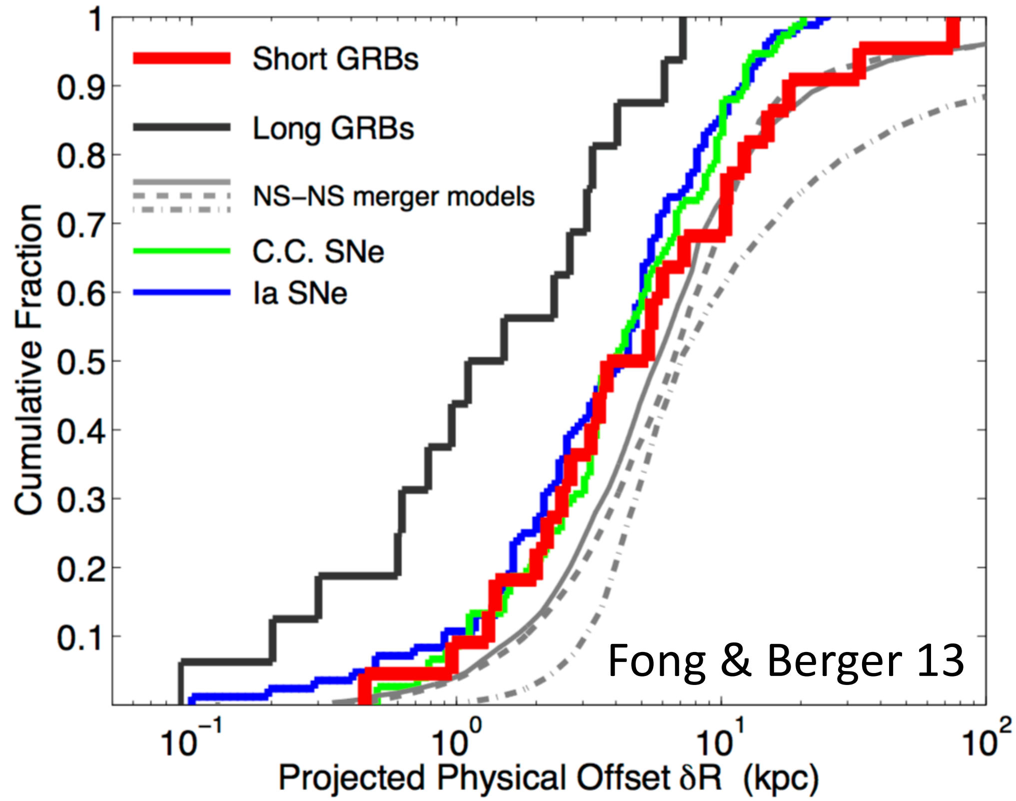
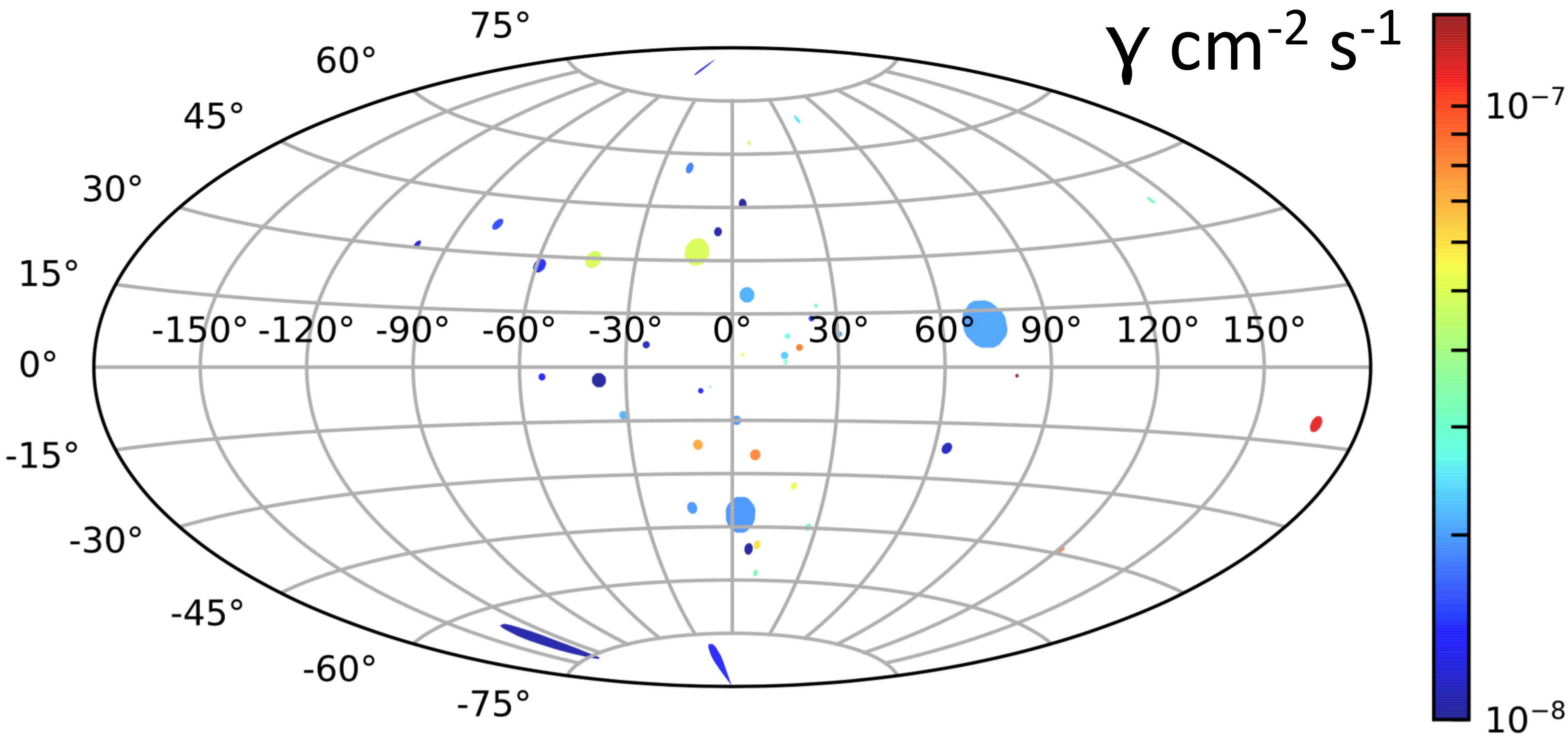


- Populate Milky Way with NS merger remnants
  - traces stellar mass.
  - add "empirical" galaxy offset (account for NS natal kicks).
- Galactic merger rates:
  - optimistic case: R = 100 Myr^{-1}
  - pessimistic case: R = 10 Myr^{-1}
- R-Process abundances
  - each merger assumed to release 0.04 $M_{\odot}$ of r-process ejecta with solar system abundance ratios.
- Measure:
  - distances to mock remnants and their gamma-ray fluxes.
  - present-day physical/angular size and expansion velocity of remnants (remnant blast wave evolution calculated using average ISM density at merger location)

Milky Way's Last Remnants

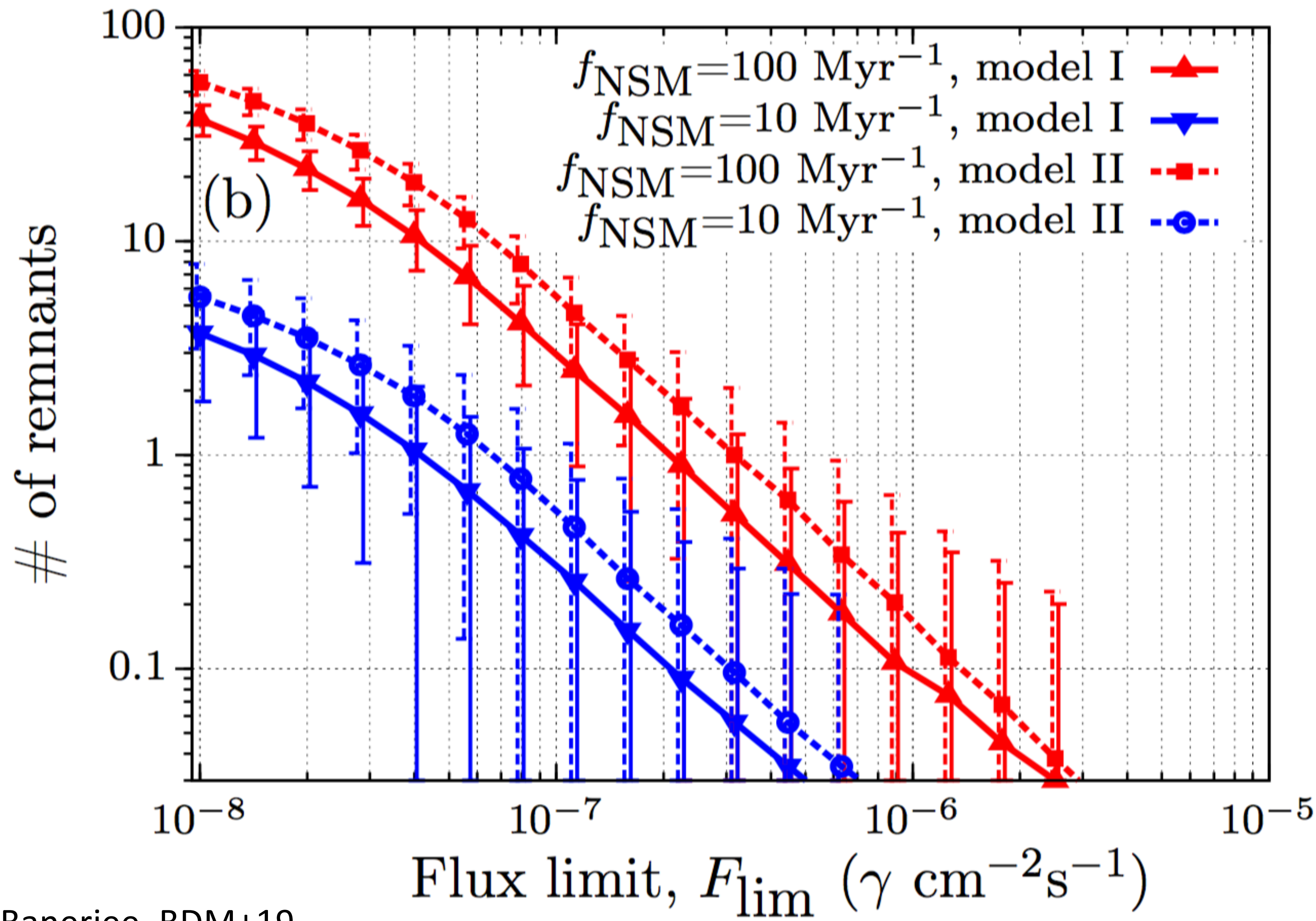
^{126}Sn ($\tau_{1/2}$ = 2x10^5 yr) E_γ ~ 400-700 keV

~10 Mergers Contributing



Many remnants outside Galactic plane

Gamma-Ray Line Flux Distribution



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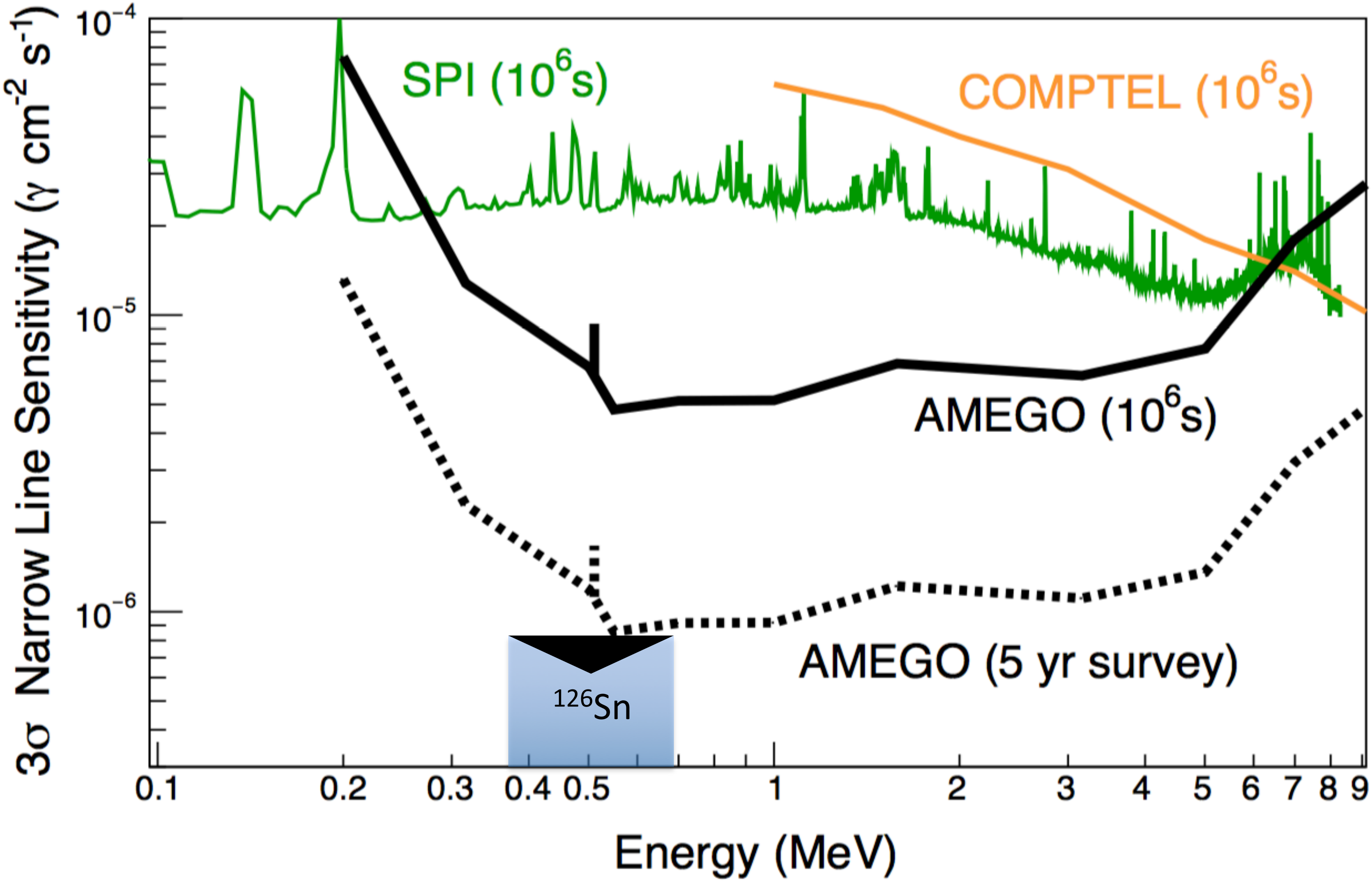
Required: Big Advance in Line Sensitivity

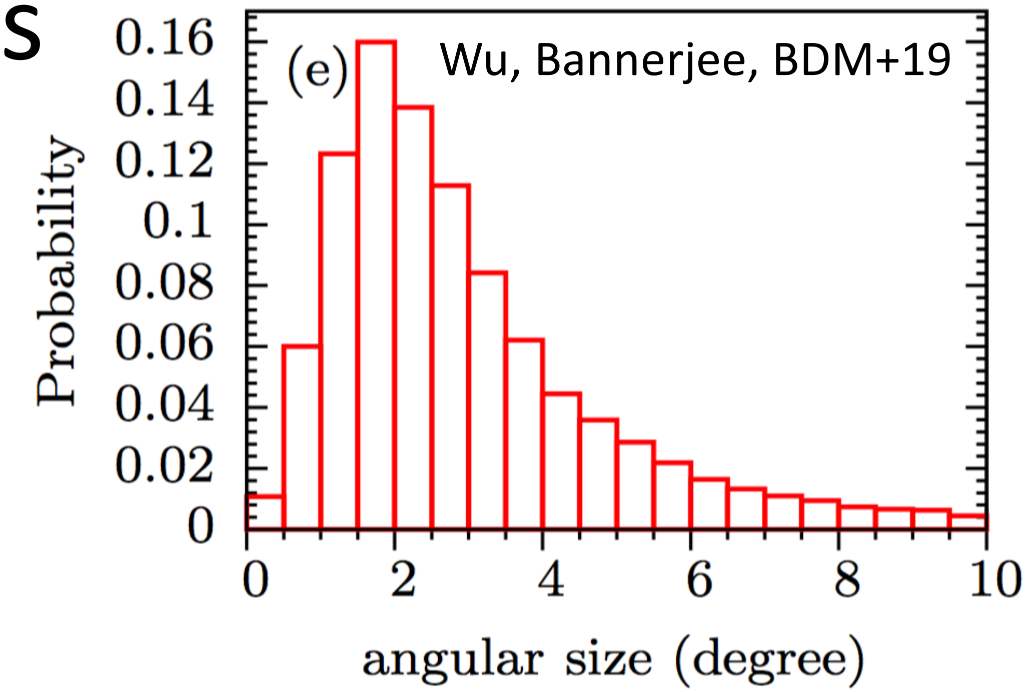


Sensitivity improvement by searching for multiple lines?

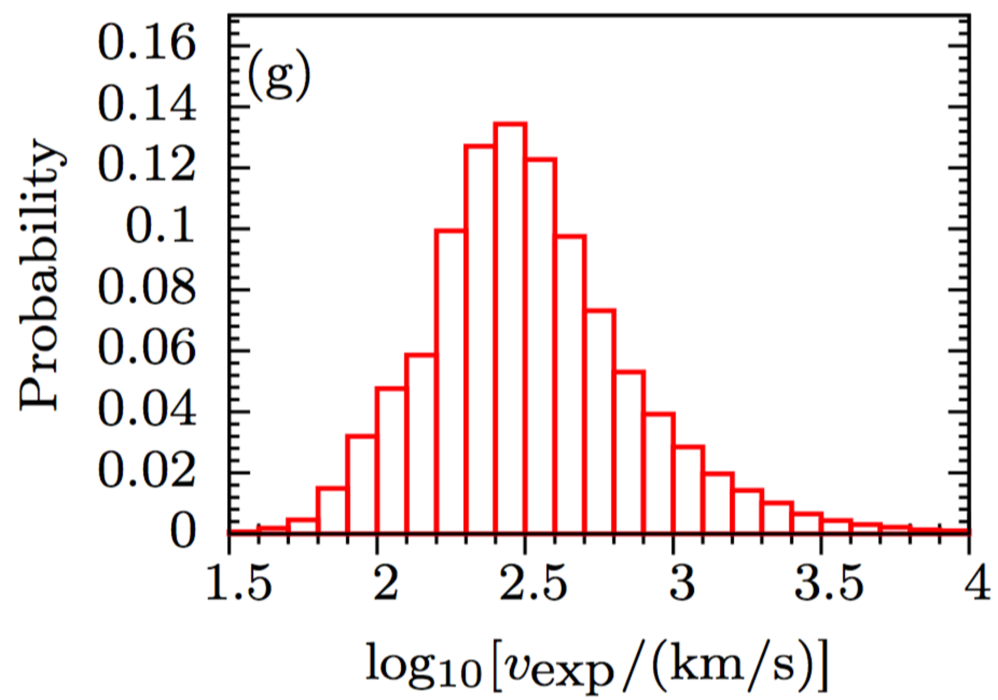
Remnant Properties

(^{126}Sn flux >10^{-8} γ cm^{-2} s^{-1})

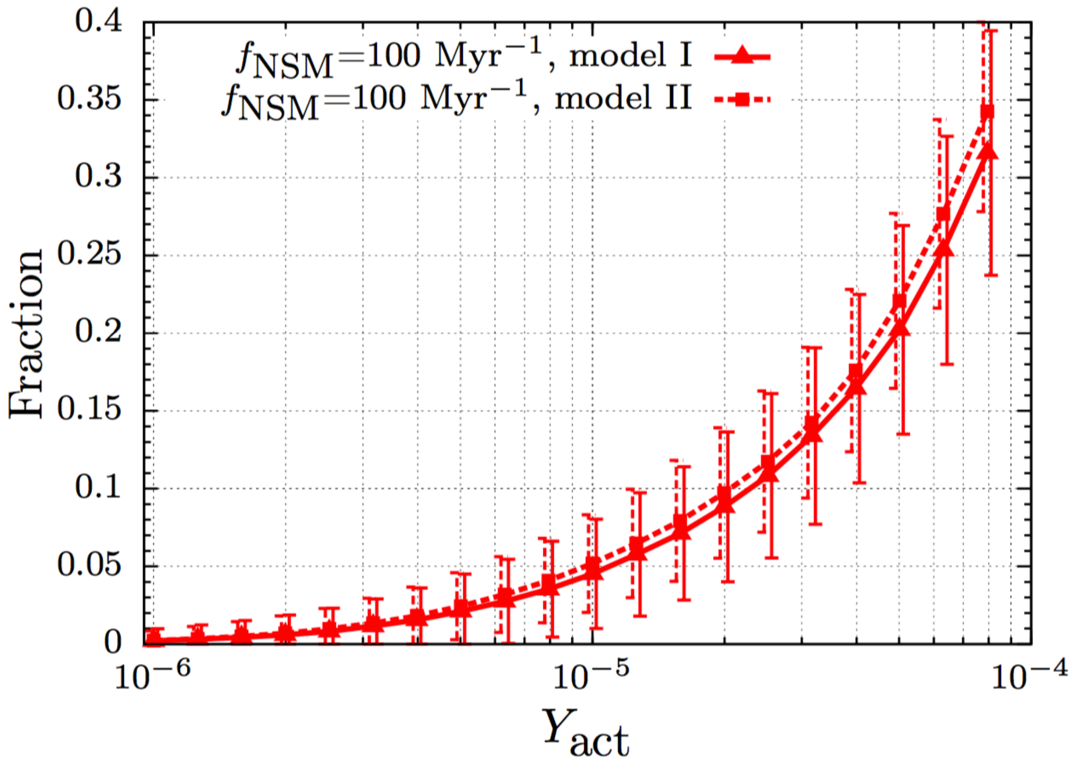
Required:
angular resolution
<~ degrees



Required:
energy resolution
dE/E ~< 10^{-3}



Co-Production of ^{230}Th Probes Actinide Production



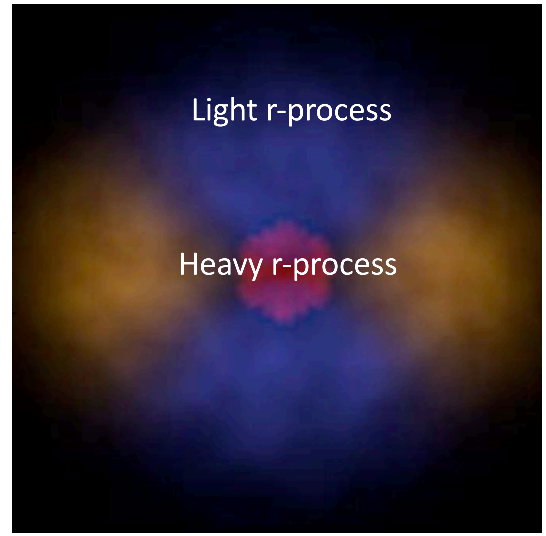


Figure 5. Fraction of NSM remnants that produce γ-line fluxes larger than $F_{\rm lim} = 10^{-8}\ \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$ from *both* the decay of ^{126}Sn and ^{230}Th as a function of the actinide abundance at production, $Y_{\rm act}$, normalized to all remnants with ^{126}Sn fluxes exceeding the same $F_{\rm lim}$. We show results separately for Model I and II, and in each case assume a Galactic merger rate $f_{\rm NSM} = 100\ {\rm Myr}^{-1}$.

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Searching Old Supernova Remnants

1 of every ~300 “SN remnants” could be masqurarding merger

Table 1. Ages, distances, and predicted ^{126}Sn γ-ray line fluxes at 666.3 keV for nearby SN remnants for which the latter range exceeds 10^{-6} γ cm^{-2} s^{-1}. We assume an ejecta mass $M_{ej} = 0.01\ M_{\odot}$ and $Y(^{126}\mathrm{Sn}) = 1.7 \times 10^{-4}$. The final column indicates the possible association of a compact object (P, M, CCO, PWN denote “pulsar”, “magnetar”, “central compact object”, and “pulsar wind nebula”, respectively).

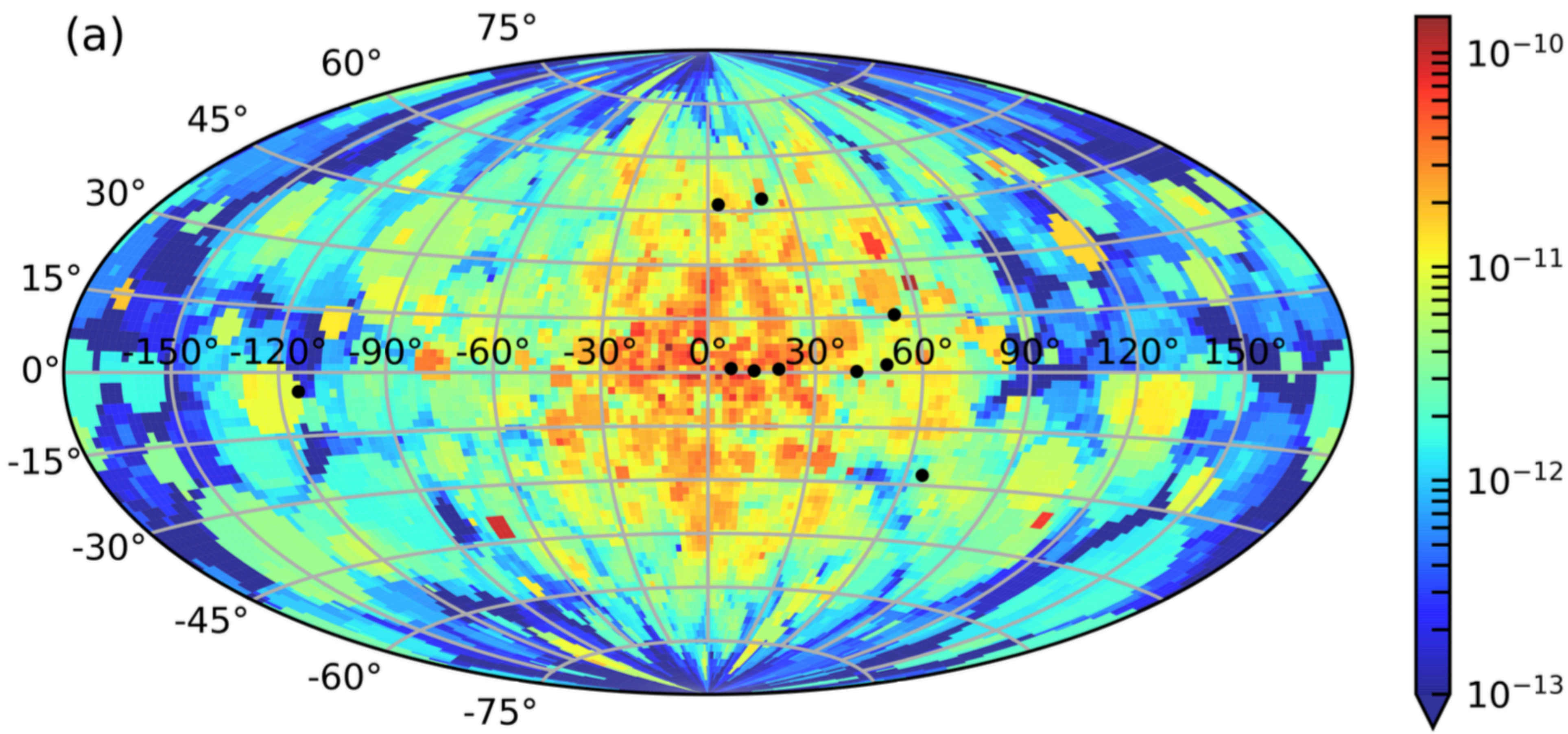
Source	Age (10^3 yr)	Distance (kpc)	Line Flux (10^{-6} γ cm^{-2}s^{-1})	Compact Object or PWN?
Lupus Loop	15–31	0.15–0.5	5.80–67.60	P?
Vela	9–27	0.25–0.3	16.30–24.78	P
Antlia	$(1–6)\times10^3$	0.06–0.34	0-21.75	P? CCO?
HB9	4–7	0.4–1.2	1.08–9.83	M?
Vela Jr	2.4–5.1	0.5–1.0	1.57–6.32	CCO? P?
3FGL J2014.4+3606	11–12	0.5–4	0.10–6.16	–
Cygnus Loop	10–20	0.576–1	1.50–4.65	PWN?
Monoceros Loop	30–150	0.6–1.98	0.26–4.04	?
IC443	3–30	0.7–2	0.36– 3.22	?
2FGL J2333.3+6237	7.7	0.7	3.17	P?
HB21	4.8–15	0.8–2.1	0.34–2.45	–
G65.3+5.7	20	0.8	2.34	P?
RX J1713.7-3946	1-2.1	1	1.58–1.59	CCO?
DA 495	7-155	1–3.6	0.08–1.56	PWN?
G107.5-01.5	3-6	1.1	1.29–1.30	–
CTA 1	13	1.1–1.7	0.53–1.26	P
S147 Sh2-240	26–34	1.1–1.5	0.64–1.22	P
R5	20–30	1.15	1.10–1.13	–

50-Year Dream: Halfnium Background

^{182}Hf ($\tau_{1/2}$ = 9x10^6 yr)

~100-1000 Mergers Contributing

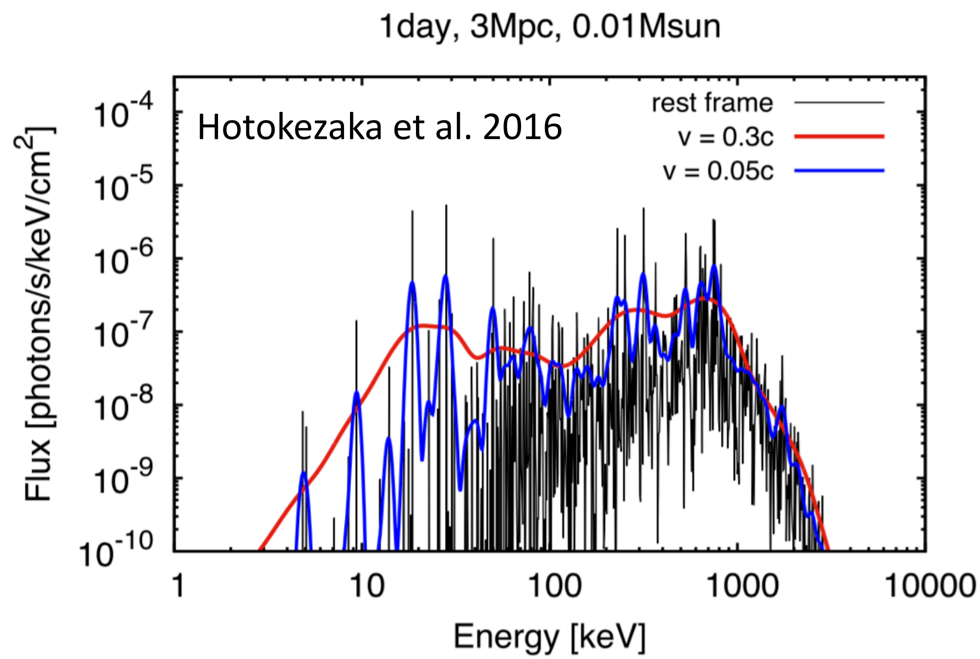
γ cm^{-2} s^{-1} rad^{-1}

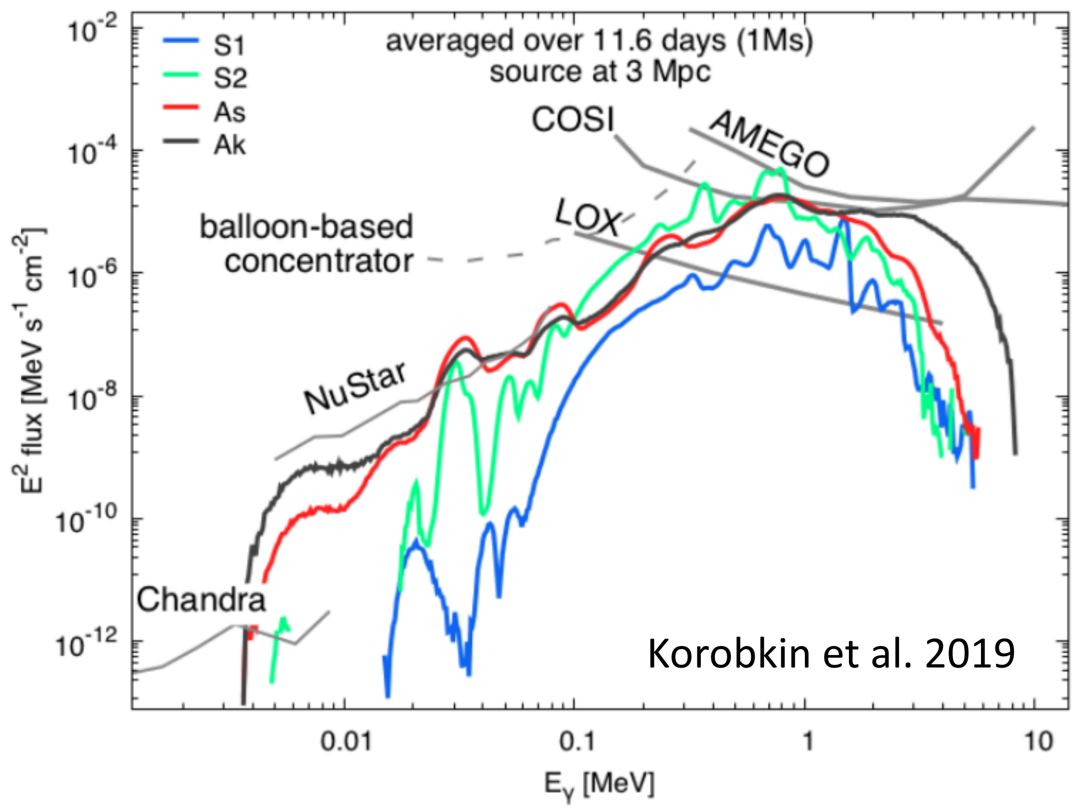


Extragalactic Mergers?

- Requires rapid response <~ hours – days to observe near peak.

- Requires very nearby
< 10 Mpc mergers, which are extremely rare
< 1 per decade—century





Summary

- GW170817 revealed NS mergers can be prodigious sources of r-process nucleosynthesis. However, open questions remain about the ejecta composition.
- The last NS merger in the Milky Way took place ~10^4 years ago. Its remnant could still be visible and its discovery could help answer these questions.
- Gamma-ray decay lines offer a potentially unambiguous signpost to the last mergers and a probe of the r-process.
- The most promising lines are from ^{126}Sn (at 415, 666, 695 keV). At least ~one remnant expected with $F > 10^{-7}$ γ cm^{-2} s^{-1}, though one can hope to get luckier.
- Most promising search strategy is a survey above and below the Galactic plane. Though a long shot, deep integrations on individual SN remnants can proto-type the analysis.
- Joint detection of gamma-lines from ultra-heavies (e.g. ^{230}Th) would confirm third-peak r-process production in NS mergers.