Astrophysical Quests for Neutron Capture Data of Unstable Nuclei

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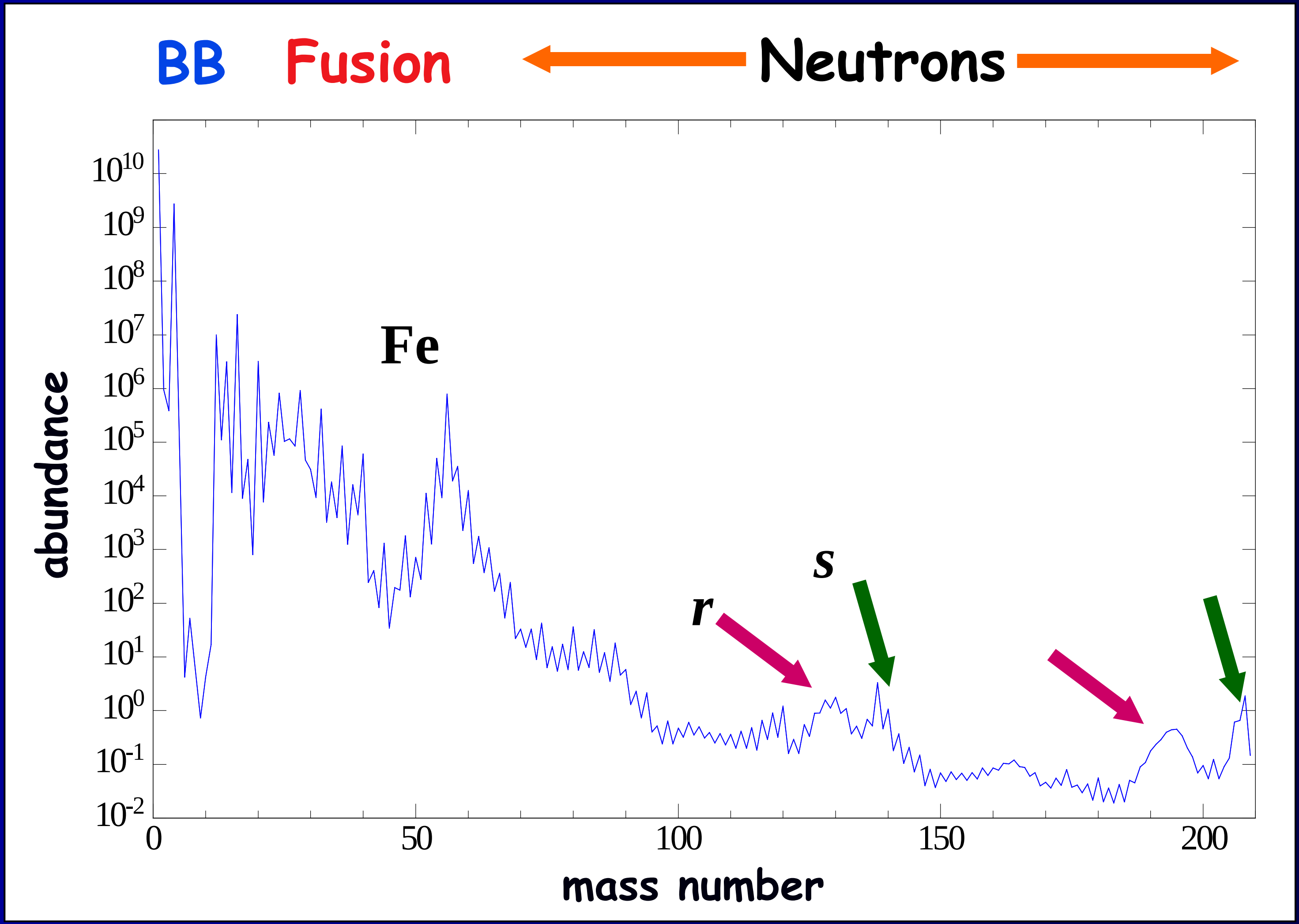
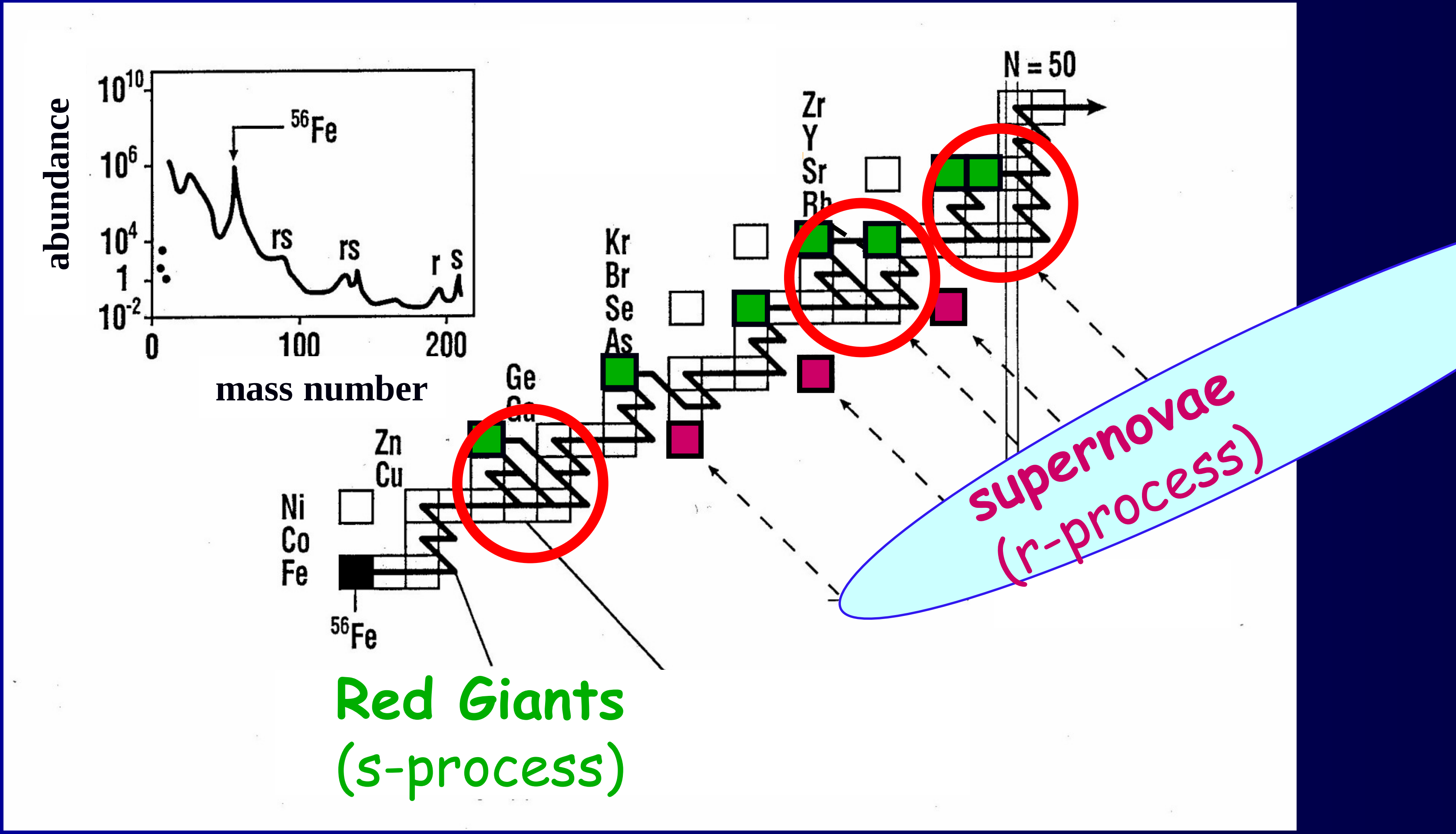
- abundances & production scenarios
- neutron reactions & available data
- laboratory work: activation vs TOF
- opportunities & prospects

Galactic abundances



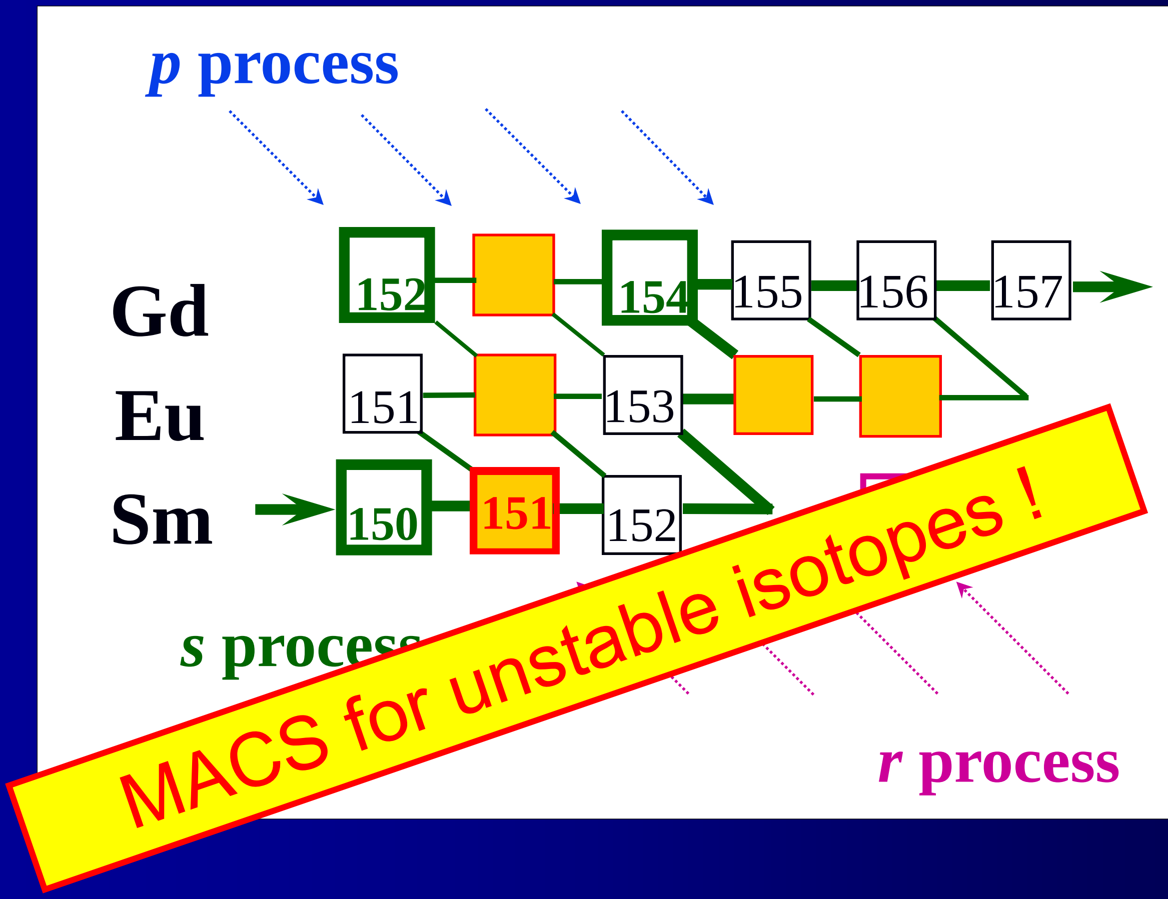
neutrons produce 75% of the stable isotopes, but only 0.005% of total abundances

Fe to U: s- and r-process



s-abundance x cross section = $N_s \sigma$ = constant

s-process branchings



probing neutron density, temperature, pressure, time scales !

Maxwellian averaged cross sections

- $\sigma(E_n)$ measured by TOF for $1 < E_n < 300$ keV, MACS by folding with stellar neutron spectrum

$$\langle\sigma\rangle = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int \sigma(E_n)\, E_n \exp(-E_n/kT)\, dE_n}{\int E_n \exp(-E_n/kT)\, dE_n}$$

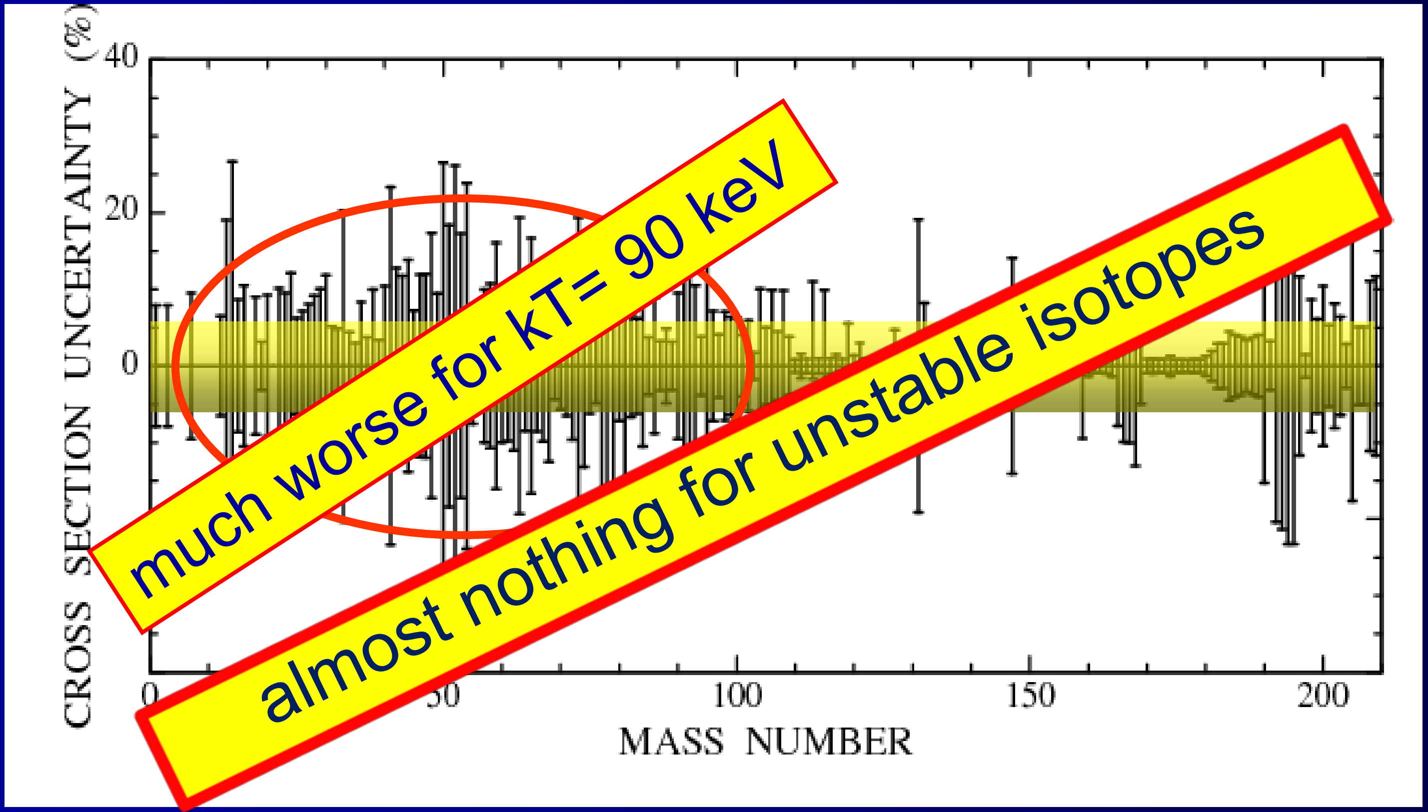
- MACS directly measured via activation

needed

uncertainties between **1** and **5%**

for complete set of isotopes from ^{12}C to ^{210}Po,

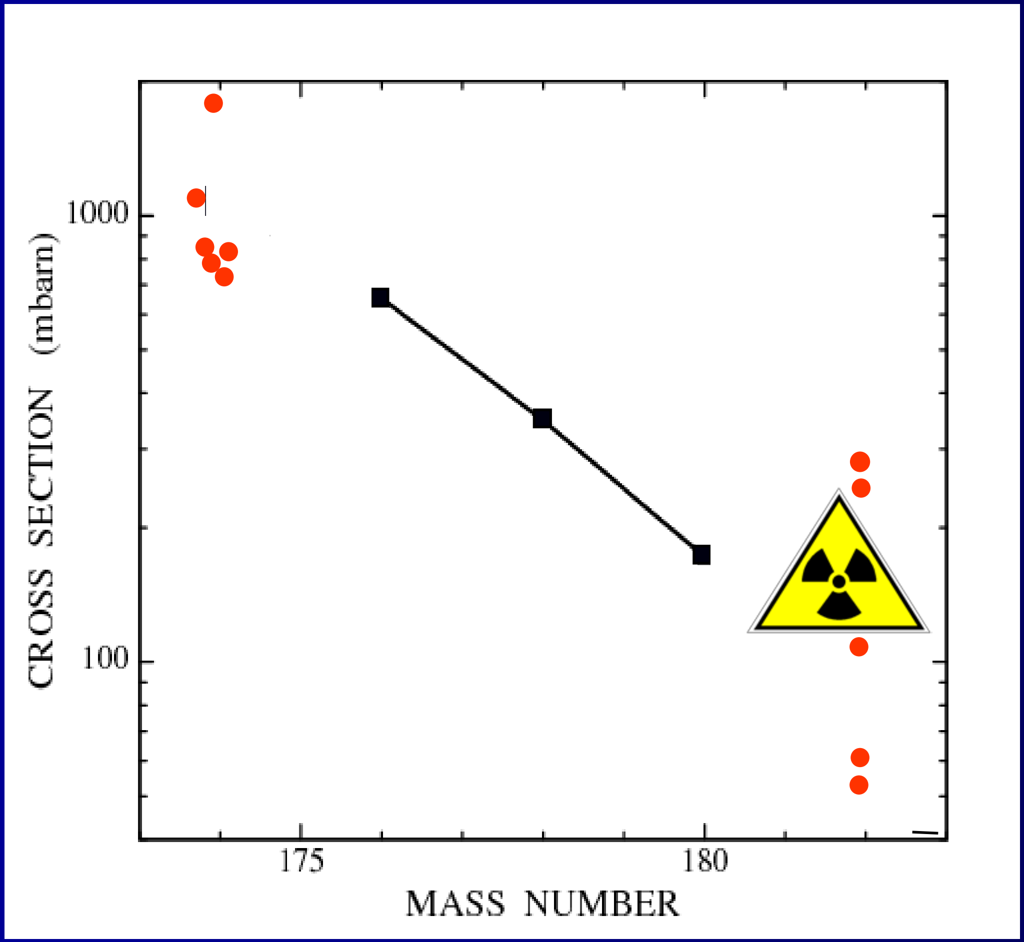
including unstable samples



major *s*-process requests

- **AGB model tests:** **16 *s*-only isotopes ± 1%**
  ~20 unstable isotopes ± 5%
- **massive stars:** **Fe – Kr region ± 3-5%**
- **presolar grains:** **75 isotopes ± 1%**
- **bottle neck nuclei:** **15 n-magic nuclei**
- **neutron poisons:** **C, N, O, Ne, Mg**
- **neutron sources:** **$^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$**
- **thermally excited states:** **el. and inel. scattering**

what about theory?



^{176}Hf, ^{178}Hf, ^{180}Hf:

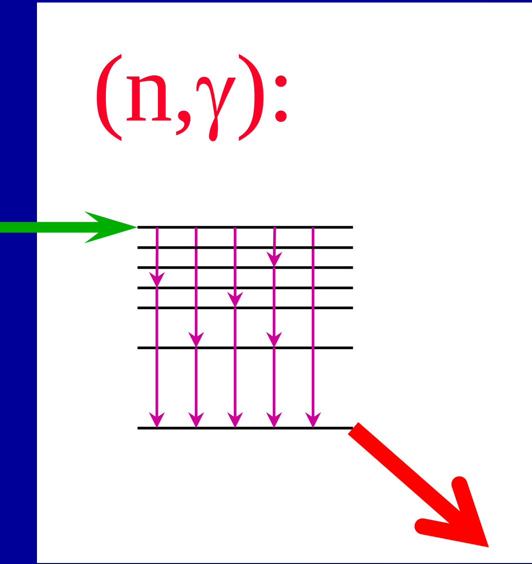
MACS uncertainties

1 - 2%

exercise joined by 6 leading groups:

calculate MACS of ^{174}Hf and ^{182}Hf prior to measurement

detection of neutron capture events



prompt γ-rays + TOF-method

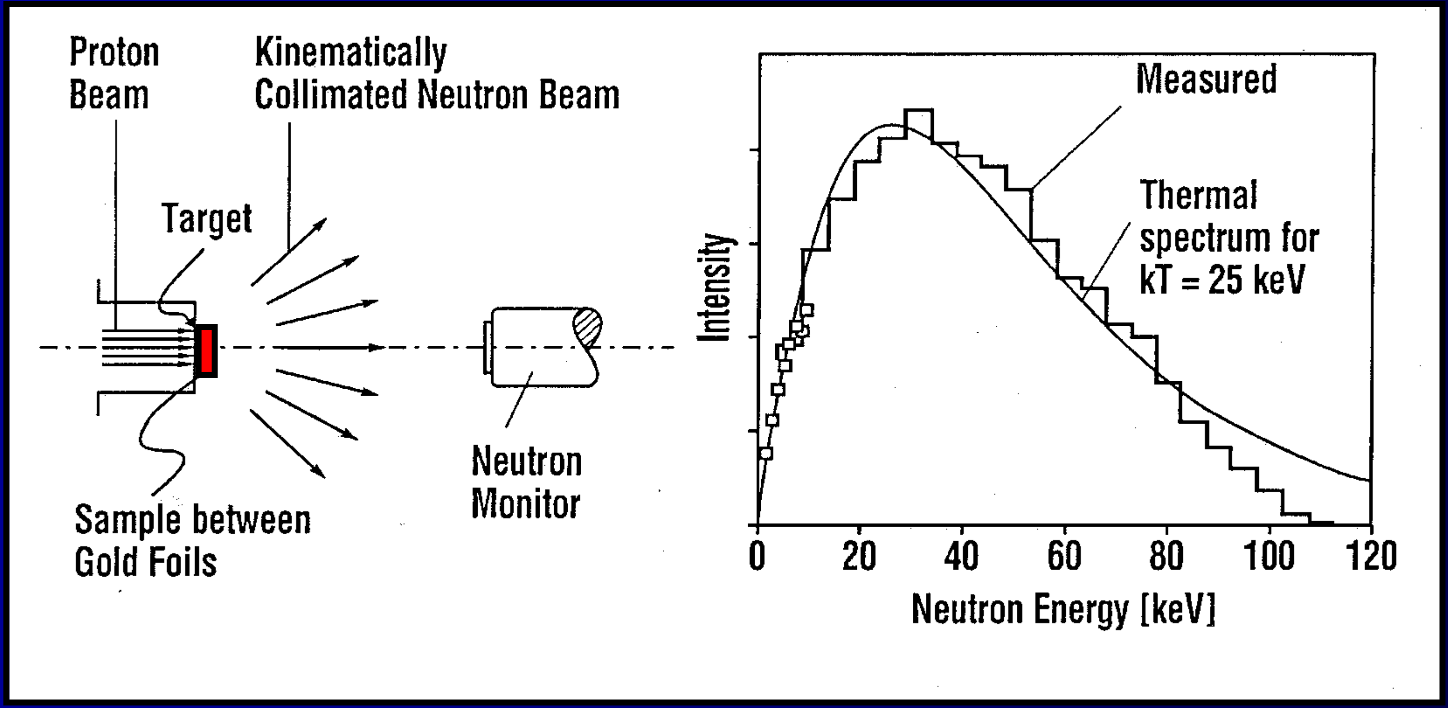
single γ´s	* Moxon-Rae	ε_γ ~ 1%
	* PH-weighting	~ 20%
	* Ge	< 1%
full γ cascade	* 4π BaF_2	~100%

activation in quasi-stellar spectrum

most sensitive	* small cross sections, **10^{14}** atoms sufficient
selective	* natural samples or low enrichment

activation technique at kT=25 keV

- neutron production via $^7Li(p,n)^7Be$ reaction at Van de Graaff
- induced activity measured with HPGe detectors



only possible when product nucleus is radioactive

→ not applicable for most branch-point isotopes

activation: unique sensitivity

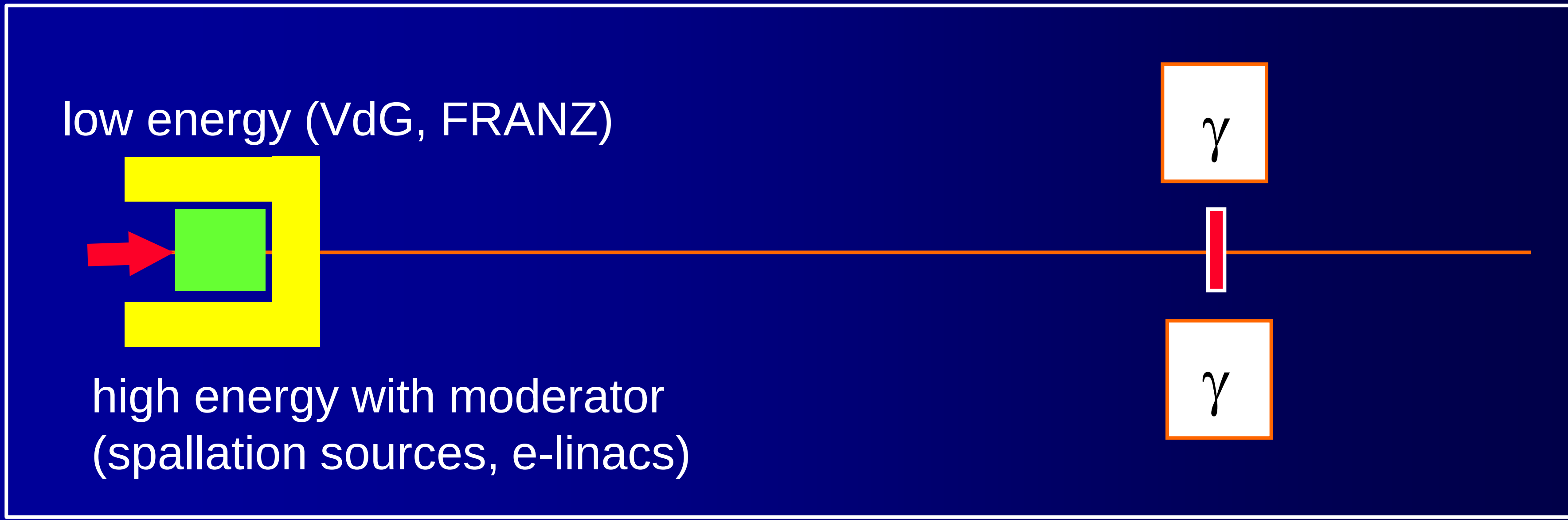
4 - 5 orders of magnitude higher flux than best TOF facilities!

→ measurement of **μbarn** cross sections

→ measurements with **ng** samples,
important for cross sections of unstable isotopes

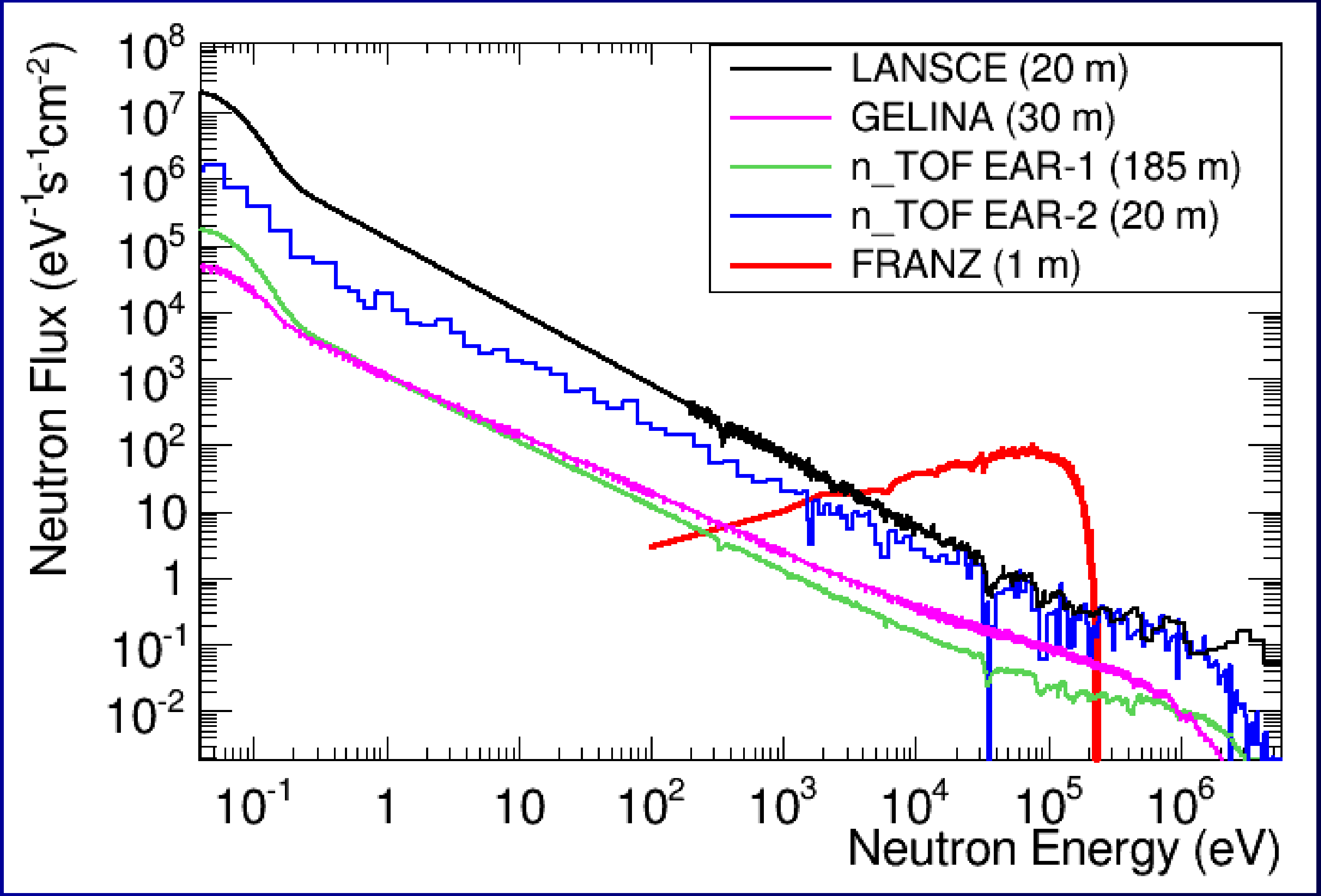
28 ng ^{147}Pm

parameters for TOF experiments



neutron energies:	0.3 – 300 keV
TOF resolution:	important if RRR matters
signal/background:	crucial, many aspects

pulsed neutron sources



Reifarth et al., J Phys G: Nucl.Part.Phys. 41 (2014) 053101

flux and resolution: 10 - 100 keV

Facility	Φ_n (10^4 $cm^{-2}s^{-1}$)	$\Delta E/E$ (‰)
n_TOF EAR1	0.4	1 – 2
GELINA (30 m)	1.4	1.3
n_TOF EAR2	8	10 – 20
LANSCE (20 m)	13	8 – 26
FRANZ	*** in activation mode: $\Phi_n \sim 10^{12}$ ***	

exp. MACS for unstable branch points

TOF data in green

- ^{60}Fe
- ^{63}Ni
- ^{79}Se
- ^{81}Kr
- ^{85}Kr
- ^{147}Nd
- ^{147}Pm
- ^{148}Pm
- ^{151}Sm
- ^{152}Eu

- ^{154}Eu
- ^{155}Eu
- ^{153}Gd
- ^{160}Tb
- ^{163}Ho
- ^{170}Tm
- ^{171}Tm
- ^{179}Ta
- ^{185}W
- ^{204}Tl

☆ n_TOF 2014/15

summary & outlook

MACS for unstable isotopes crucial for understanding stellar scenarios

main branchings
1 – 3 $M_\odot$ stars:
<10^{10} n/cm^3

more work needed for
scenarios with much higher neutron densities:

- massive stars…………………….up to **10^{12}** n/cm^3
- low-metallicity stars…………. **10^{15}**
- Supernovae, *r*-process……… **>10^{20}**

sample aspects: mass & radiation

activation:

now: 30 - 100 ng (10^{14} atoms)

soon: 300 **pg**

limited to special cases

time-of-flight:

typically: 0.5 - 5 **mg** sepa

^{173}Lu, 40 µg = ~10^{17} atoms

→ measurements on radioactive samples