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東京大学大学院理学系研究科附属ビッグバン宇宙国際研究センター
Research Center for the Early Universe

# Enrichment of r-process elements in nearby dSph galaxies, the Milky way, and globular cluster(s)

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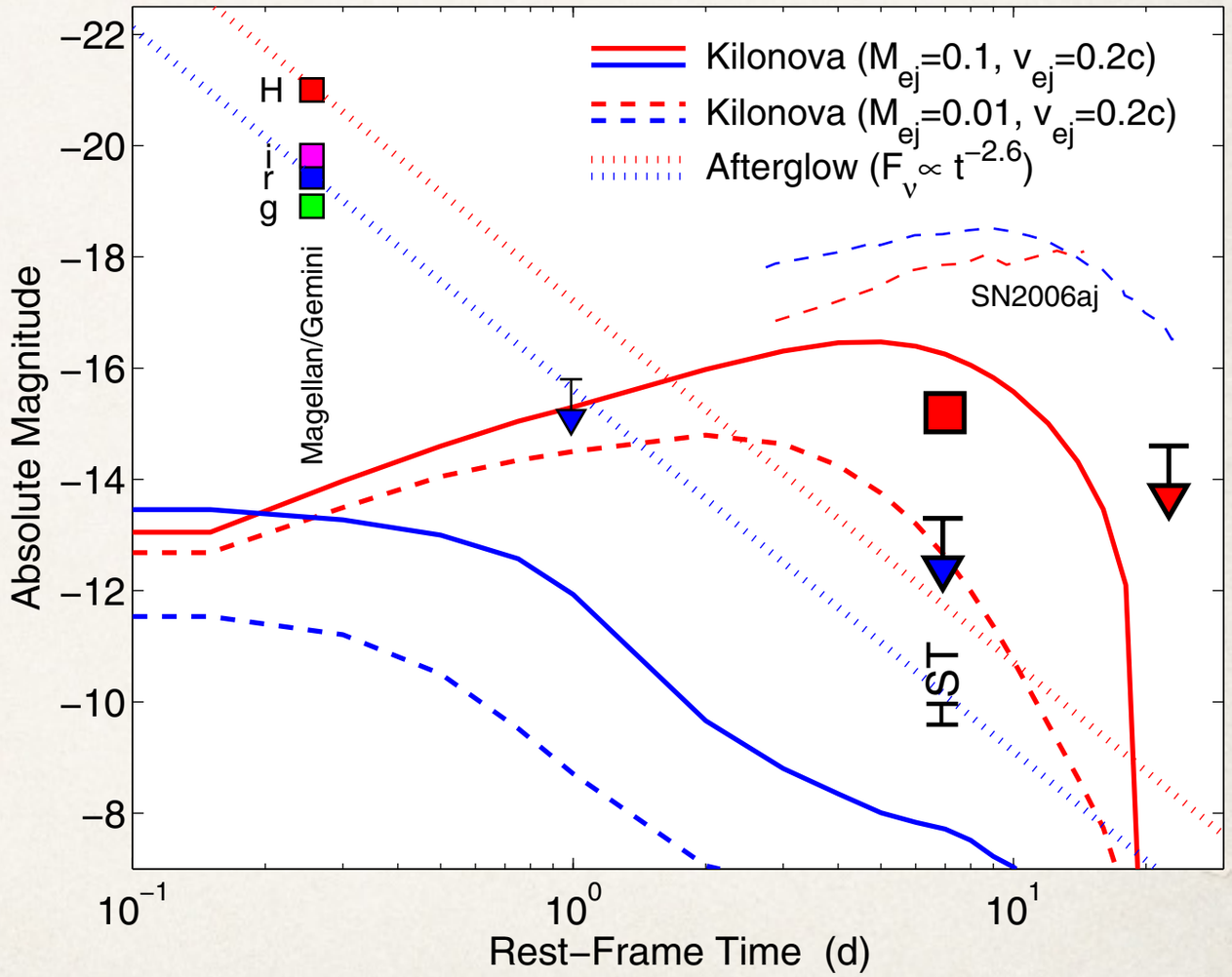
Based on Tsujimoto & TS 2014

# Kilonova

- Afterglow of GRB130603B at day 9
  - Berger+ 13, Tanvir+ 13
  - NIR detection
  - no detection of optical band



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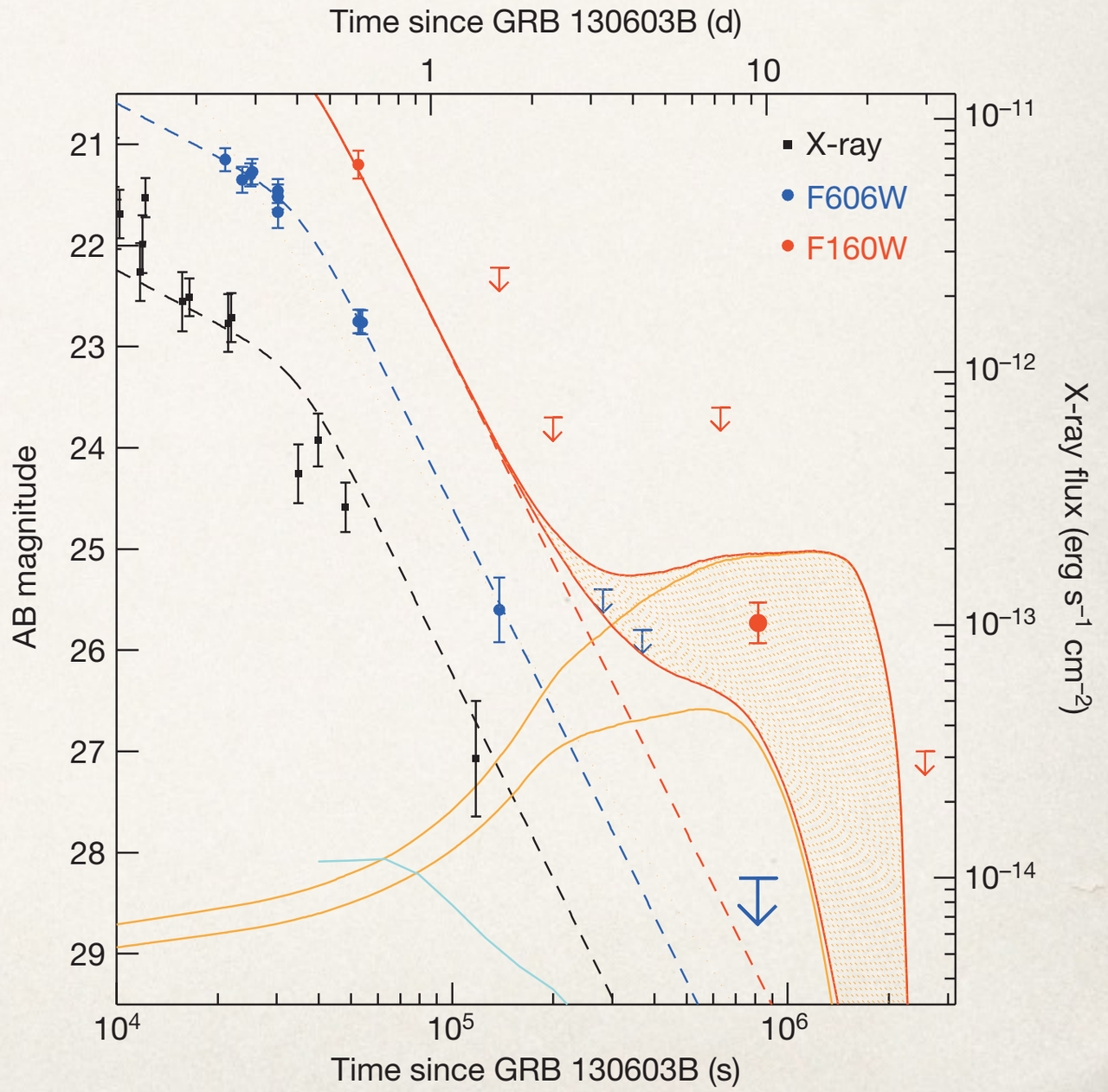


# Summary of Kilonova

- short GRB is a result of neutron star merger (NSM)

  1. ejects r-process rich matter

  2. Mass~0.01 $M_\odot$

  3. speeds~>0.1c

- 1 & 2 motivate us to revisit NSM as a major production site of r-process elements

# Transfer properties

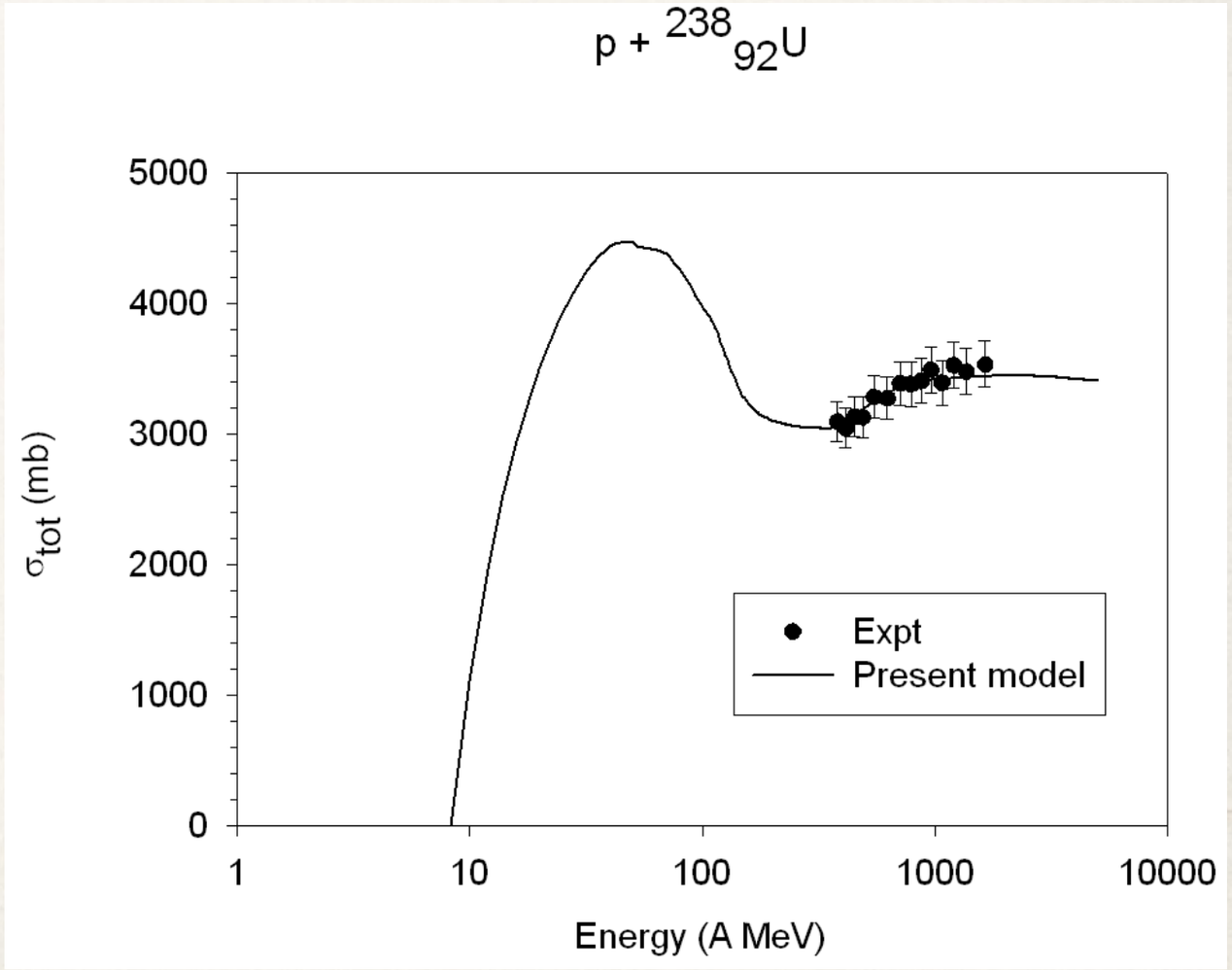
- The speed of ejecta = 0.1-0.3c ($\gamma$=1.010-1.099)
- Stopping length
  - $$l_{\mathrm{S}} \sim 400\ \mathrm{kpc}\left(\frac{v}{0.2c}\right)^{2}\left(\frac{A}{153}\right)\left(\frac{Z_{\mathrm{eff}}}{63}\right)^{-2} n^{-1}$$
    - Fe (from SN): $l_s$~0.1/n kpc
- Most of ejecta escape from a galaxy?

# Effects of magnetic fields

- If B~1 μG
  - $r_g$~2×10$^{15}$ cm<<size of a galaxy
  - r-process elements propagate along **B** fields (kinetic pressure<<magnetic pressure)
    - Structure of **B** decides the dissipation of kinetic energy of r-process elements
    - turbulent **B** may stop r-process elements through ionizations
- r-process elements pervade the entire proto-galactic cloud (with some leakage)

# Transfer properties

- The speed of ejecta = 0.1-0.3c ($\gamma$=1.010-1.099)
- Energy per nucleon $=m_u c^2(\gamma\text{-}1)$=10-100 MeV / A
- If 0.3c, then spallation occurs before traveling through the stopping length
- If 0.1c, then below the threshold energy



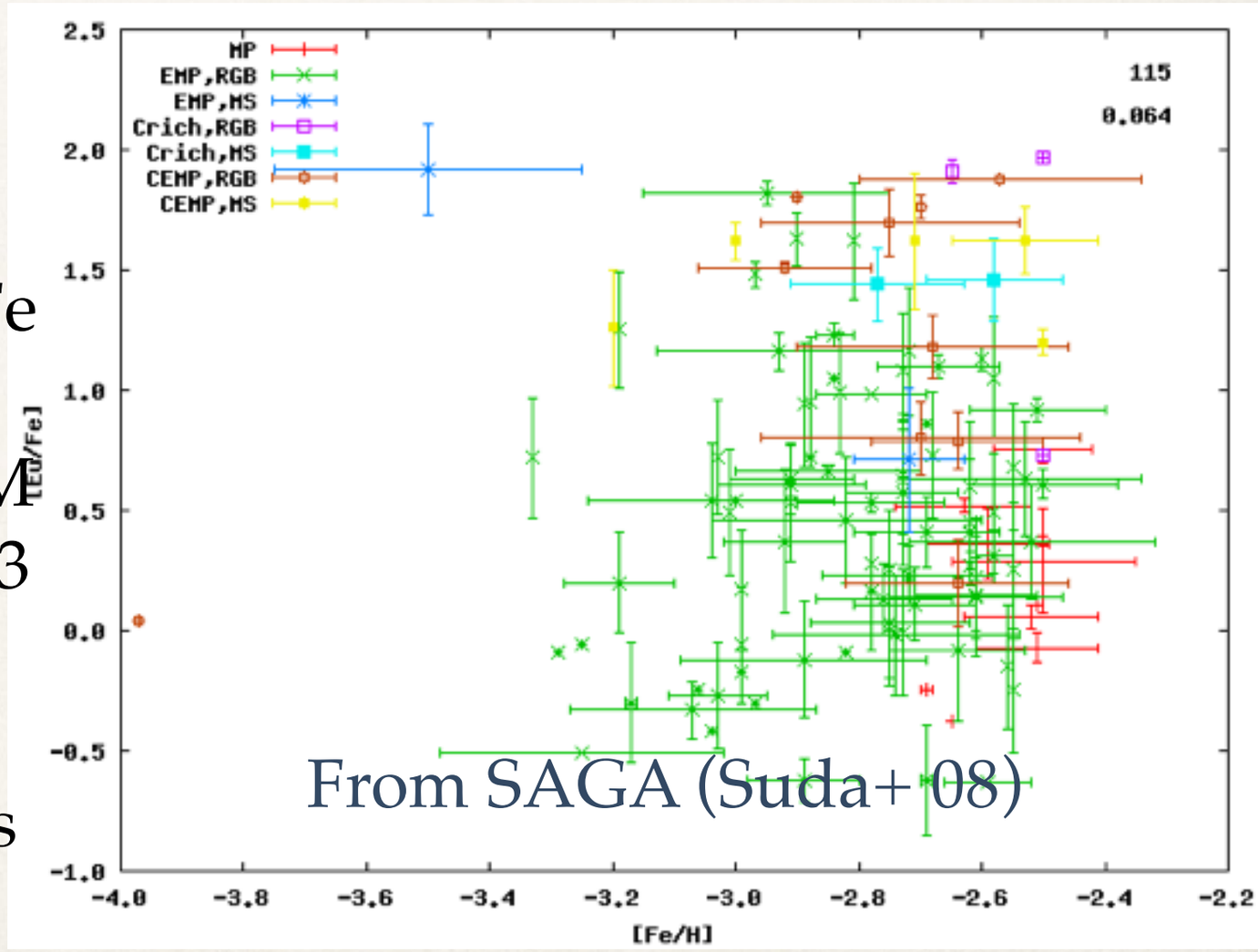
# r-process elements in extremely metal-poor stars(EMP stars) in the Milky Way

- Large dispersion in [Eu/Fe]

- Supernova supplies ~0.1 $M_\odot$Fe

  - SNR sweeps and mixes ISM of mass ~$10^5$ $M_\odot$: [Fe/H]~-3

  - Assume that stars are formed in the swept up gas



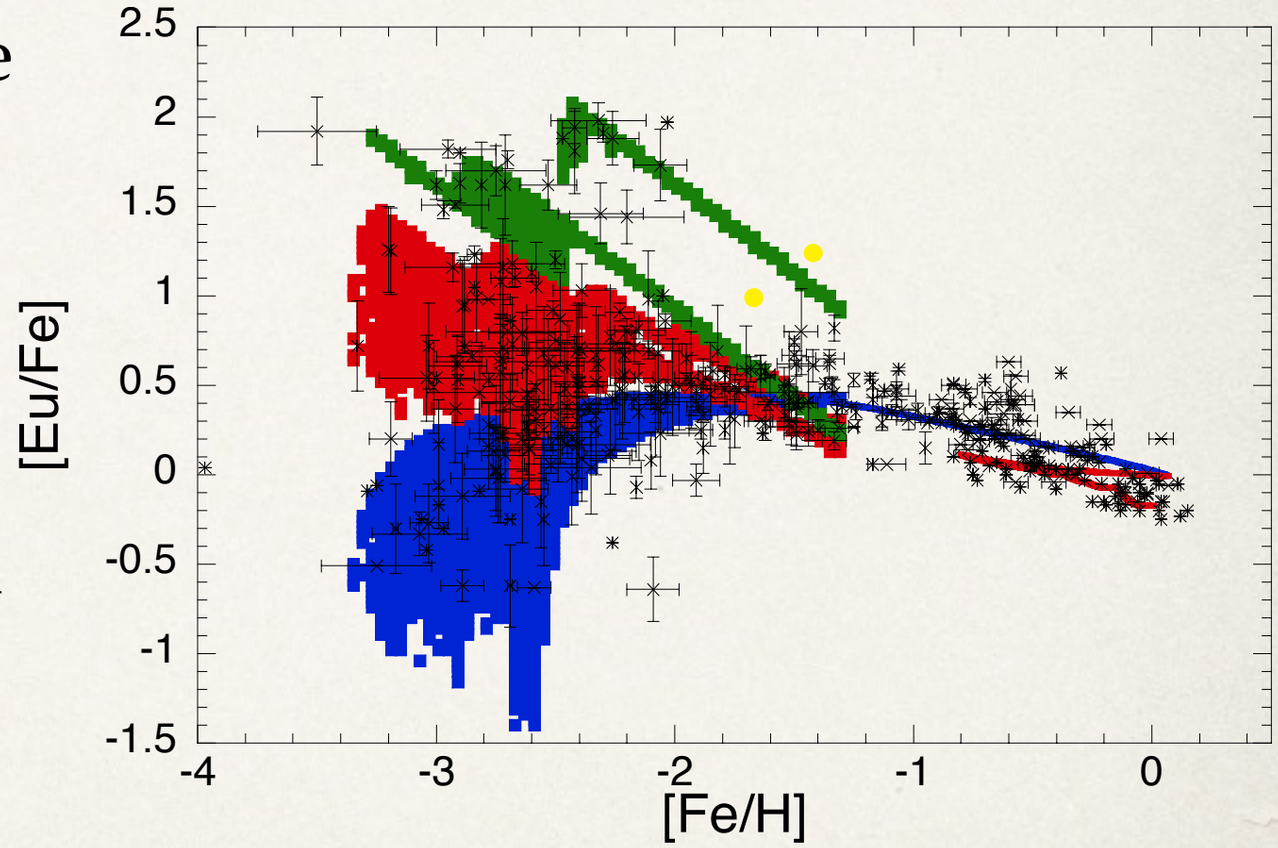

From SAGA (Suda+ 08)

# r-process elements in EMP stars

- in ~7/n Myr after a NS merger
  - r-process elements could be uniformly distributed
    - concentration of r-process elements is determined by the cloud mass
    - How much fraction is trapped inside the cloud is unknown (Assume 100% here)
- High(Low) [r-process/Fe]→low (high) cloud mass
  - EMP stars were formed in gas swept up by individual SNe
    - Fe abundance is determined by the SN+ISM

# Chemical evolution model

- Fe is mixed in a shell swept up by a SNR (the mass~$10^5$ $M_\odot$)
- r-process elements diffuse over the entire proto-galactic cloud.
- NSM rate: Eu/H-Fe/H relation in massive dSphs
- Chemical evolution in clouds with different masses
  - Blue: ~$10^9$ $M_\odot$
  - Red: $10^7$-$2\times10^7$ $M_\odot$
  - Green: $5\times10^5$, $2\times10^6$ $M_\odot$(with a few NSM events)



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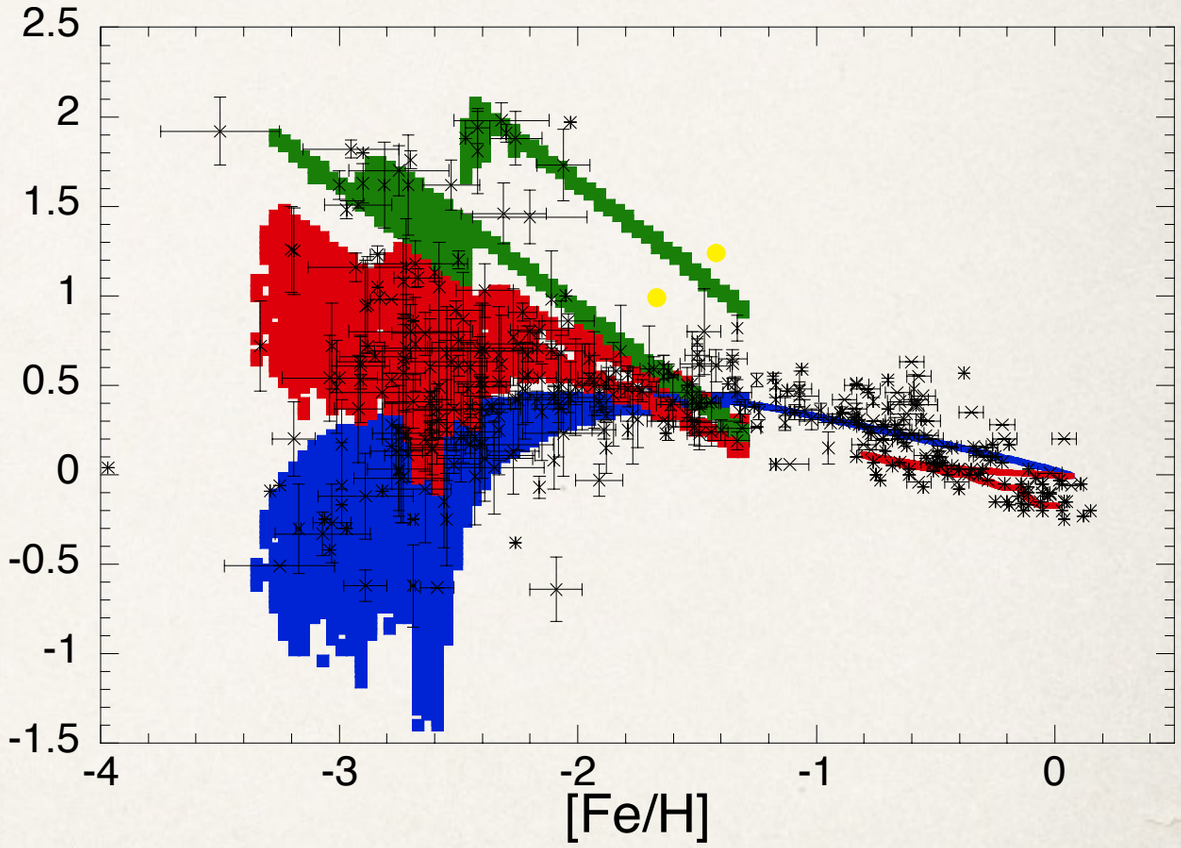
**Cannot rule out NSM as the origin of r-process elements.**

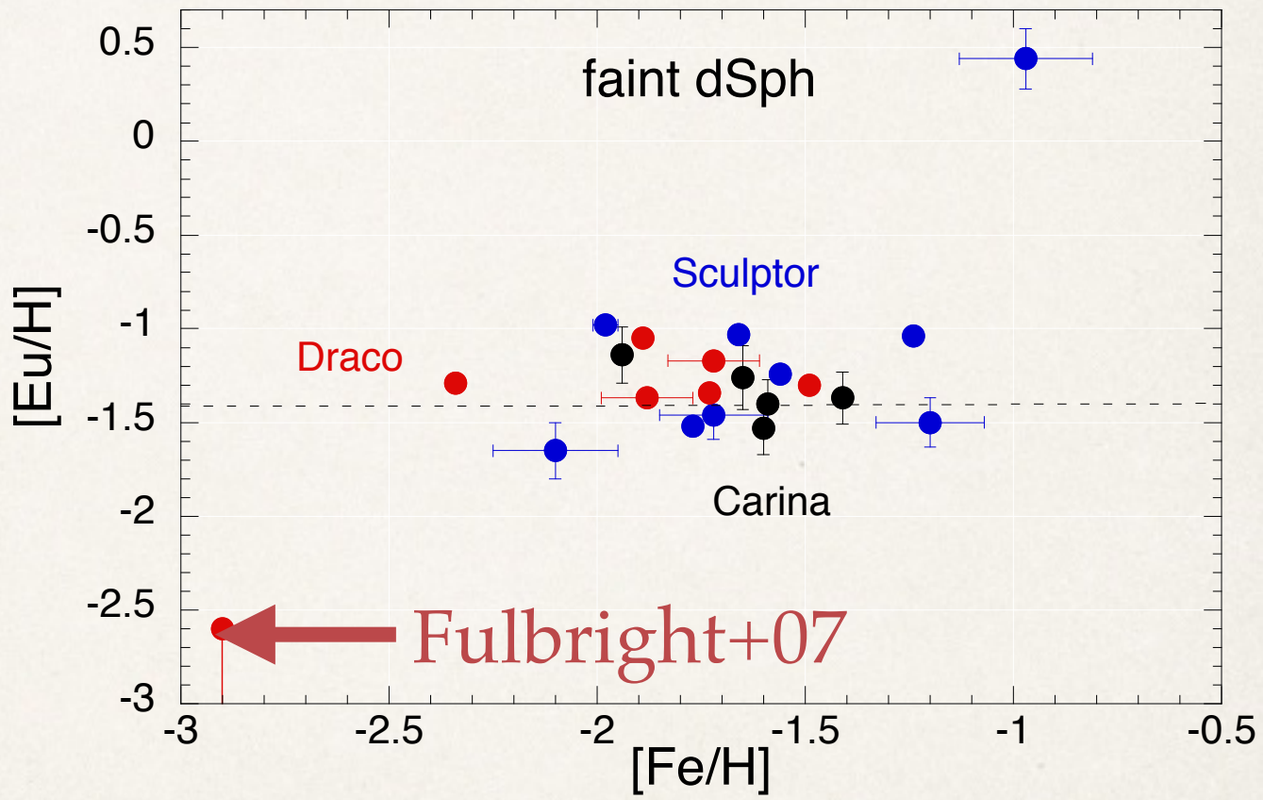


# A few comments on faint dSphs

# r-process elements in dSphs

**Ultra Faint dSphs**

- no evolution or sudden increase of Eu in small mass dSphs
- Eu/H independent of the masses of dSphs
  - dSph masses are small
- Suppose NSM supplies Eu
  - very few NSM events
  - a small fraction of Eu were trapped (High velocity!)

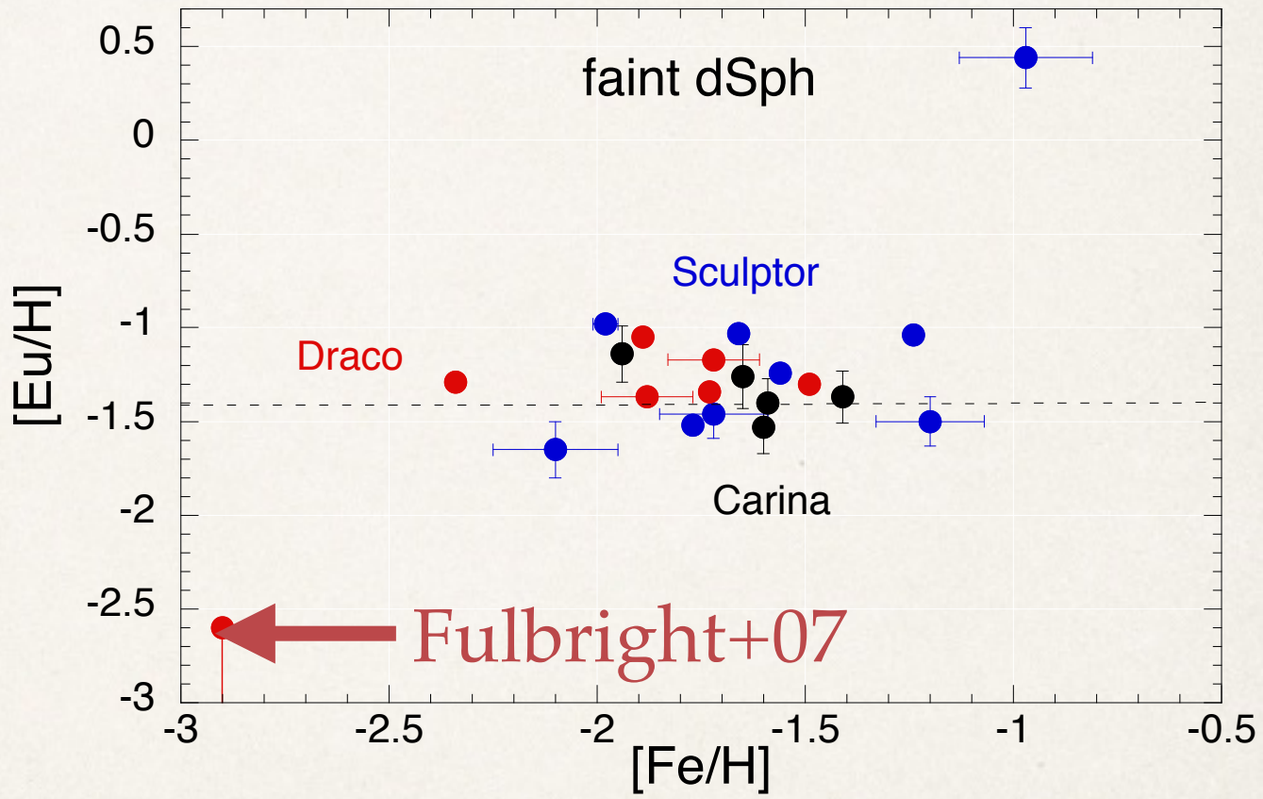



$$\mathrm{Eu/H} \sim \frac{X_{\mathrm{Eu}} M_{\mathrm{ej}}}{X_{\mathrm{H}} M_{\mathrm{cl}}} \left( \frac{R}{l_{\mathrm{S}}} \right) \propto \frac{X_{\mathrm{Eu}} M_{\mathrm{ej}}}{R^2 X_{\mathrm{H}}}$$

# r-process elements in dSphs

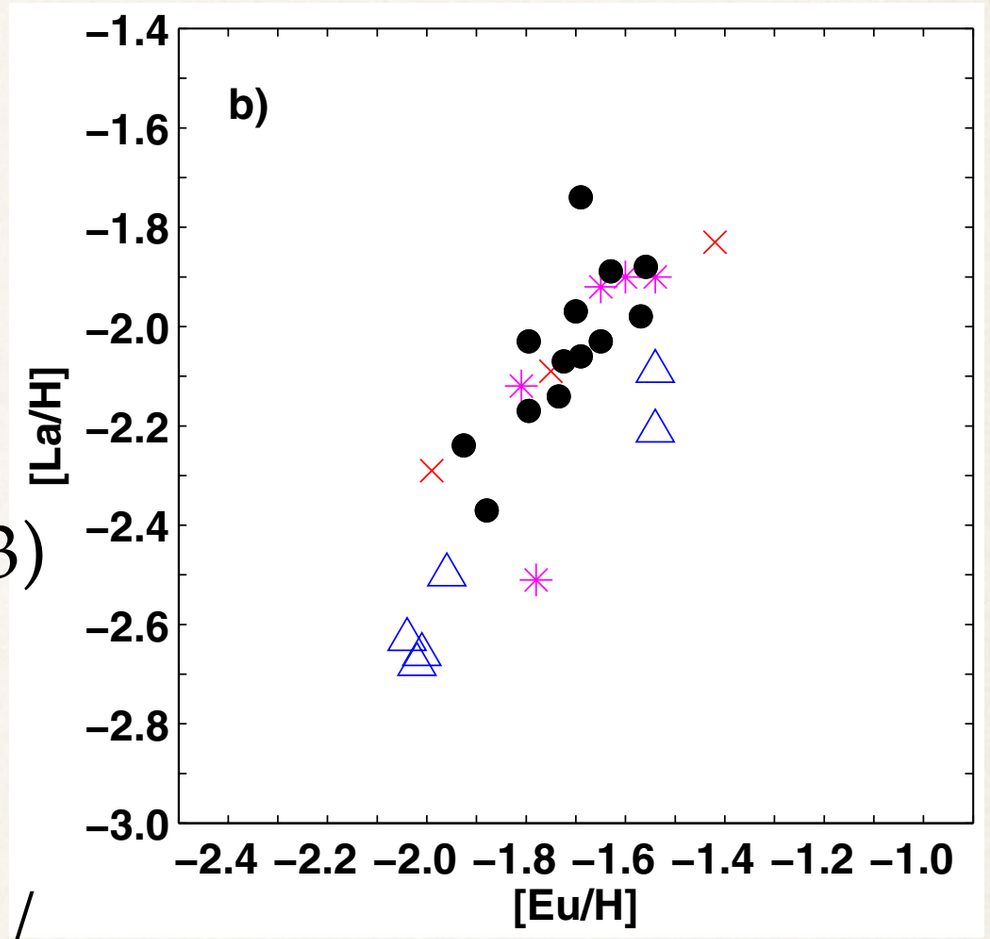
**Ultra Faint dSphs**

- Suppose SNe supply Eu in Draco
  - [Fe/H]=-2.3 requires ~500 SNe
    - The mass of the proto-galactic cloud~$10^7$ $M_\odot$ ($L\sim 2\times10^5$ $L_\odot$)
- No enrichment in Eu/H by the subsequent 2500 SNe
  - disfavors SNe as a source of r-process elements



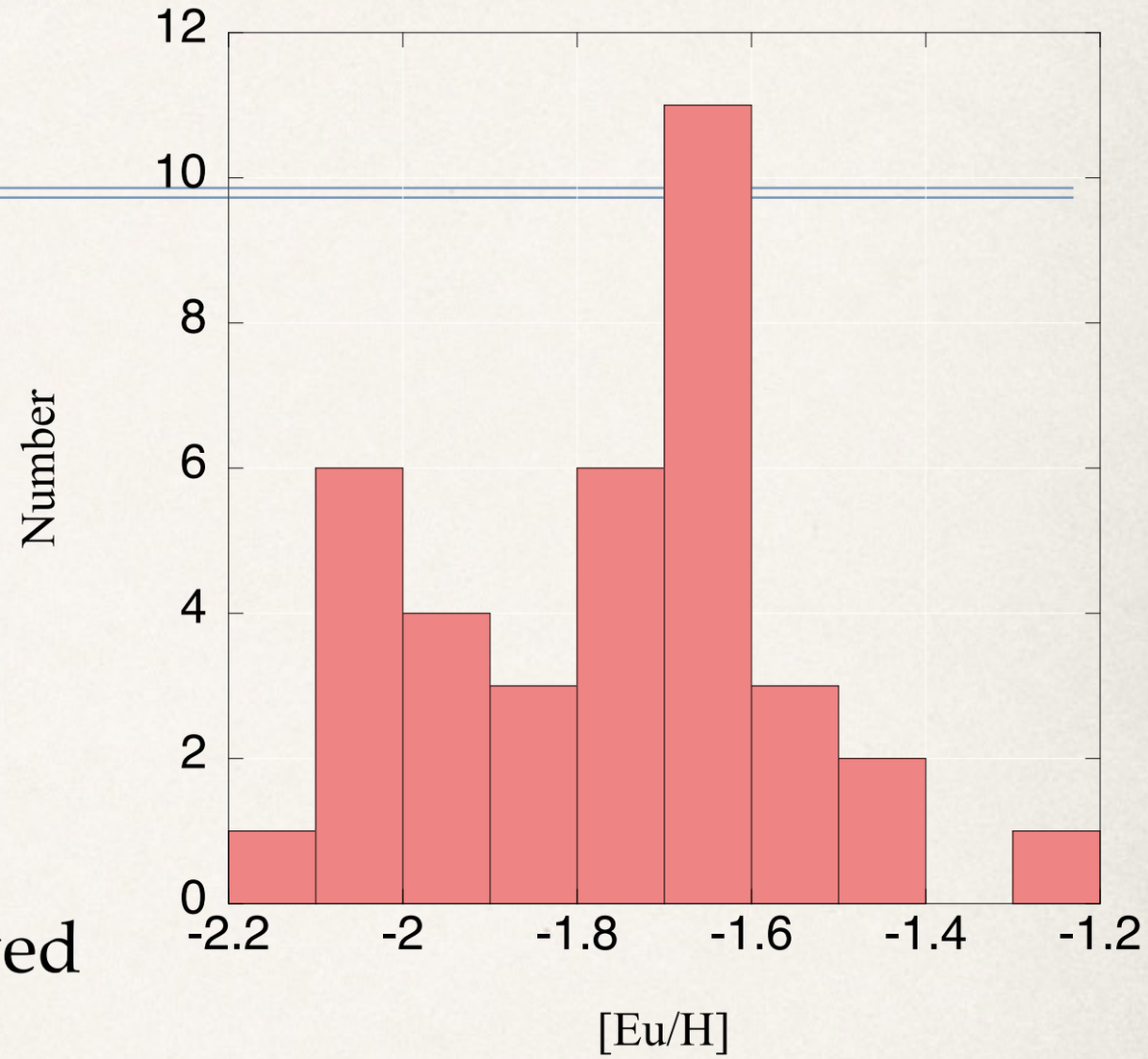
# r-process elements in globular cluster

- M15(Otsuki+ 2011, Roederer 2013, Worley+ 2013)
- massive and metal-poor ([Fe/H]~-2.3)
- hosts some double pulsars
- variation in [Eu/H], [La/H], and [Ba/H]
- ***no significant variation in* [Fe/H]**




Worley+ 2013

# Stellar surface polluted with NSM ejecta?




- Red-giants with r-process excess
  - Possible scenario
    - First star formation event
    - all supernovae went off
      - all the gas component removed
    - less massive stars evolved to AGB and supplied gas
    - NSM enriched the gas with r-process elements
    - still less massive dwarfs have accreted the r-process rich gas

- some dwarfs become extremely r-process rich
- the dwarfs evolved to red-giants to be observed
- The distribution with respect to r-process elements becomes bimodal.

# Summary

- Milky way halo
- mixing of r-process elements different from heavy elements ejected by SNe
- Eu/Fe determined by proto-galactic cloud mass
- Milky way halo composed of stars formed in various proto-clouds with different masses

- dSph galaxies
  - Discrete increases in Eu/H
  - Common plateau of Eu/H with increasing Fe/H prefers NSM but needs early occurrence(~10 Myr)
- Globular cluster M15
  - Stars with different Eu/H ratios with the same Fe/H
    - apparently rule out SNe as the source of r-process
    - SNe that eject r-process elements always eject Fe