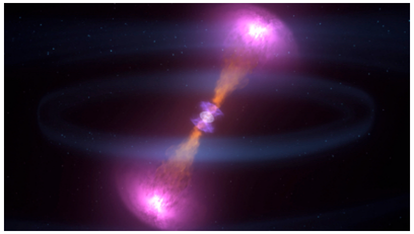
Probing Cosmic Chemical Evolution with MeV Photons

Dieter H. Hartmann
Clemson University

Splinter Meeting

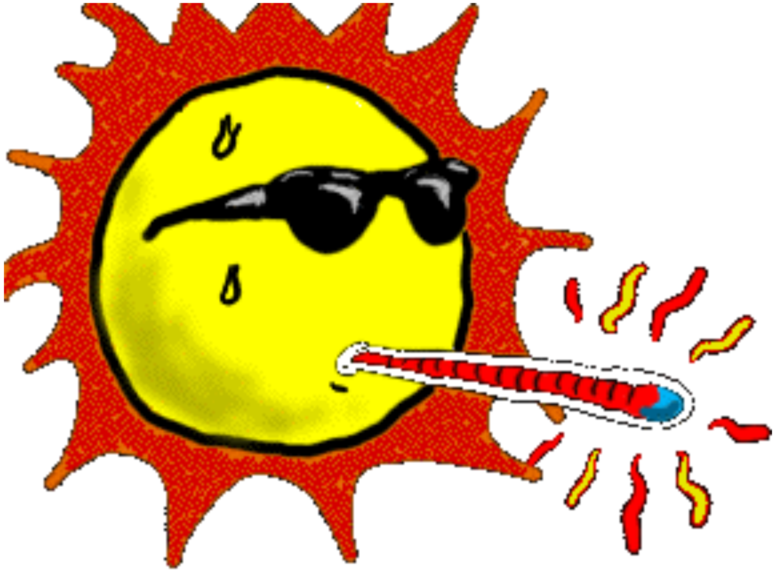


Astrophysical Extremes and Life Cycles of the Elements: Opportunities from the MeV Gamma-ray Sky

Wednesday, January 10, 2018 from 1:00 pm - 4:30 pm

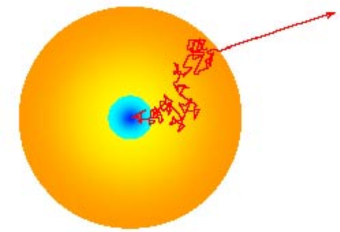
National Harbor 8 at the Gaylord National

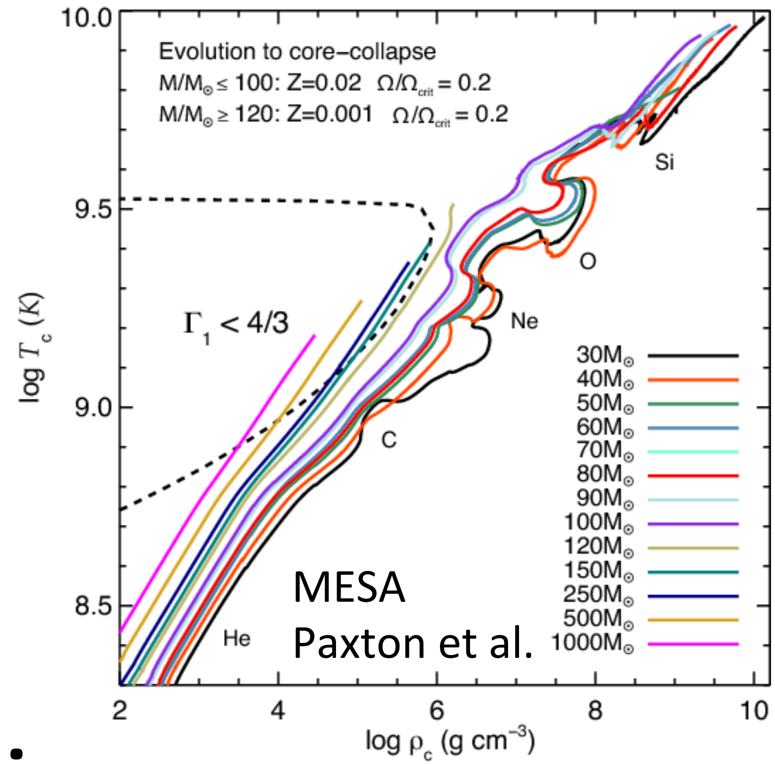
SOC: Fabian Kislat, Andreas Zoglauer, Roopesh Ojha



“Temperature” E (MeV) ~ kT_{10}

Plasma
Gaseous
Fluid
Solid

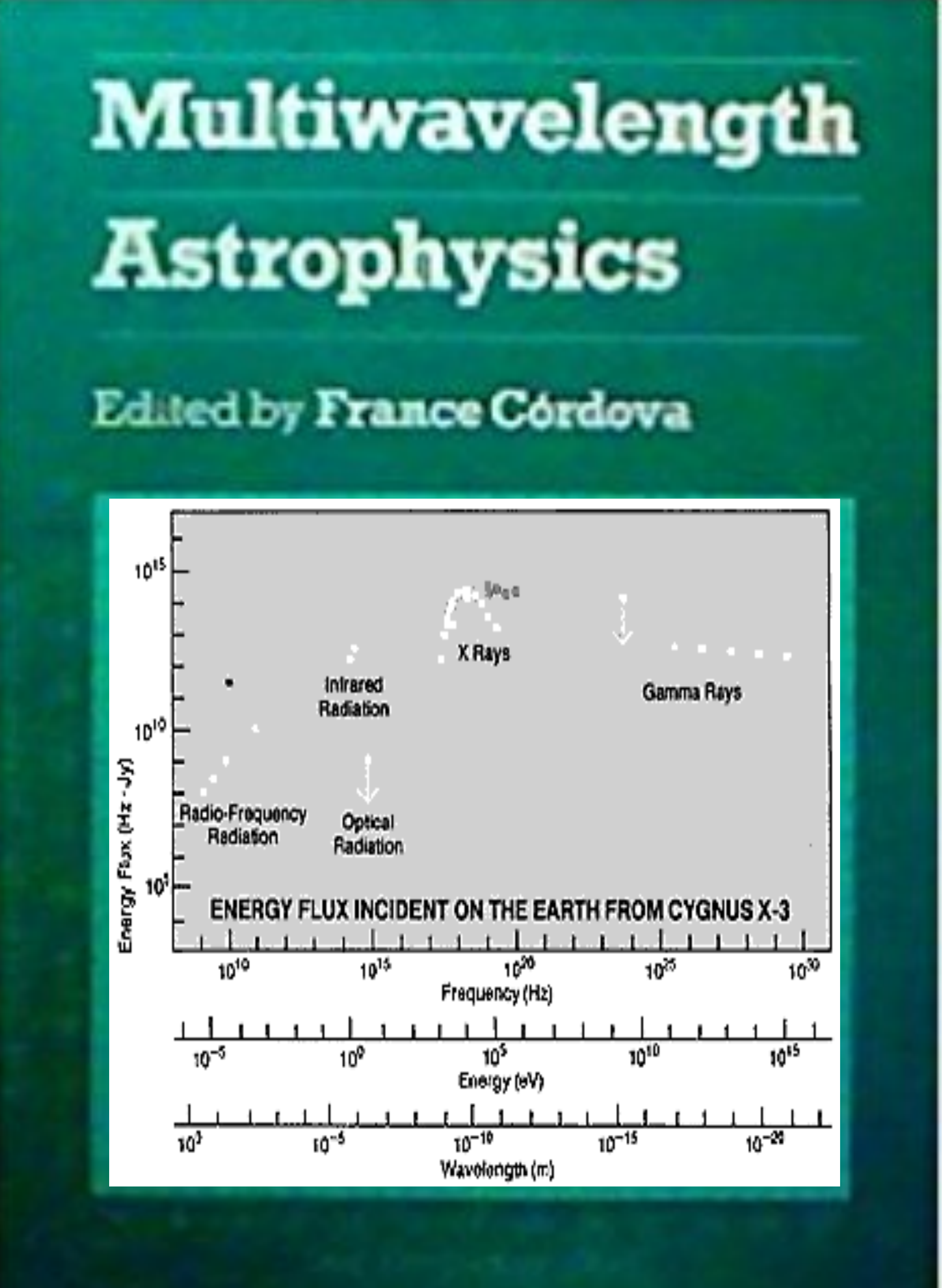




Physics at	E-scale	T-scale
Particle	GeV	10^{13} K
Nuclear	MeV	10^{10} K
Atomic	keV	10^{7} K
Atomic	eV	10^{4} K
Molecular	meV	10 K

non-thermal MeV astrophysics

Nuclear Processes & Particle acceleration

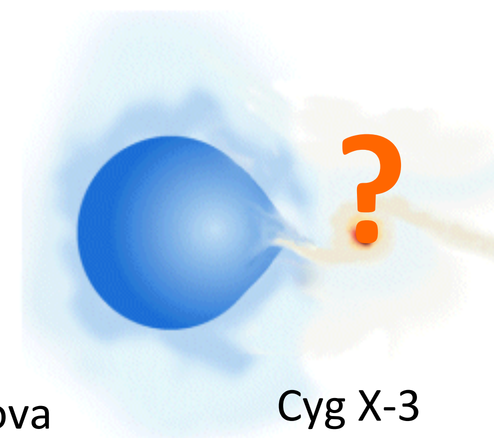


----> **MeV Chauvinism is no good** ☺

TDA: Time Domain Astrophysics

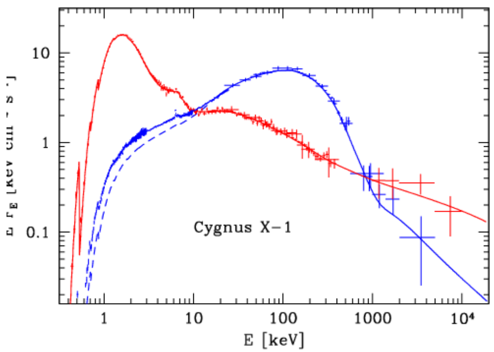
MMA: Multi-Messenger Astrophysics

All Sky Monitoring – Fast Response

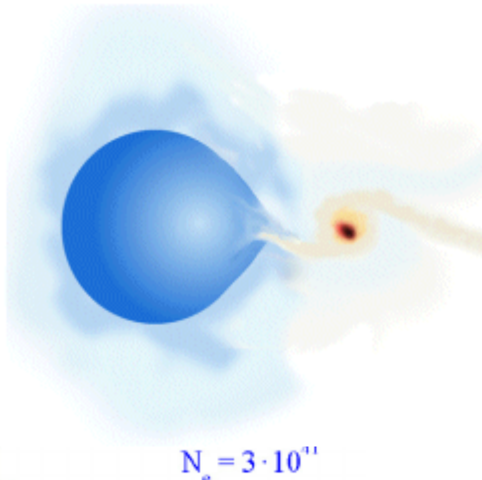


F. Cordova workshop: Taos, NM, August 1987

Cyg X-3
Giacconi et al. 1967
50 years ago! -

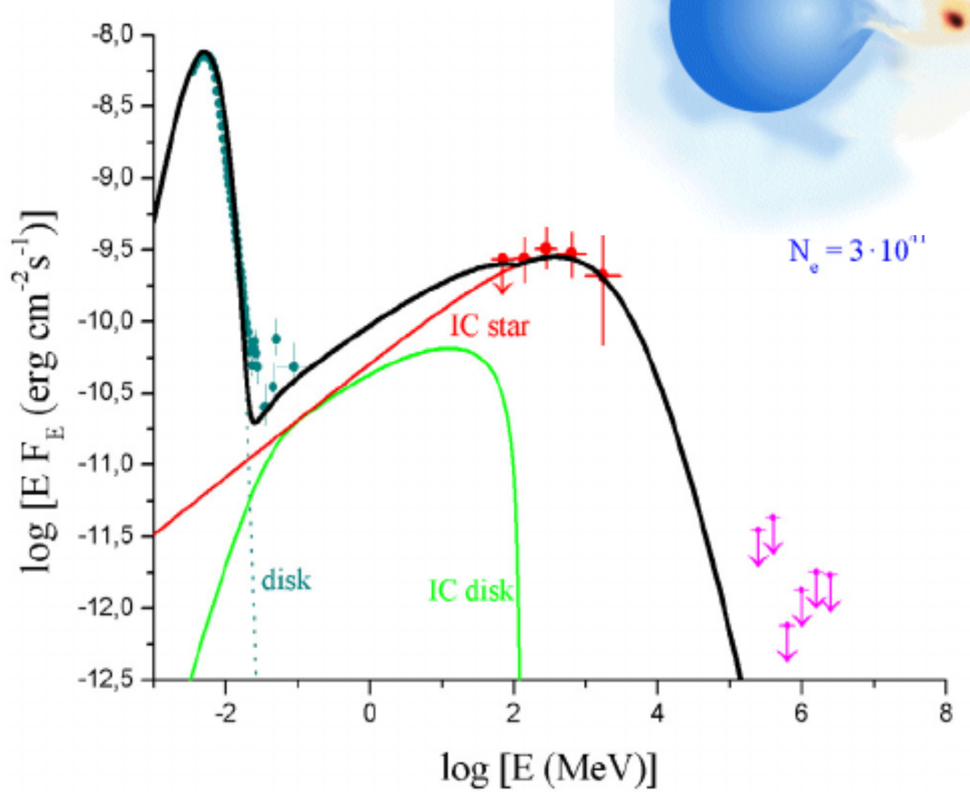


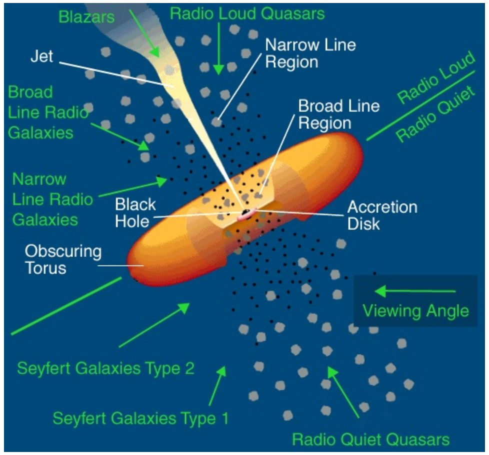
HMXRBs are characterized by two (or more) SED states which exhibit time variability on a variety of time scales



AGILE monitoringof Cyg X-3 (G. Piano,+ 2012 A&A 545
SED during the main γ -ray events (non-sim. data) and the leptonic model. Blue: X-ray average "hypersoft" SED (Koljonen et al. 2010), RXTE-PCA and RXTE-HEXTE data (~ 3 to ~ 150 keV); red: AGILE-GRID (50 MeV to 3 GeV); magenta: MAGIC UL.

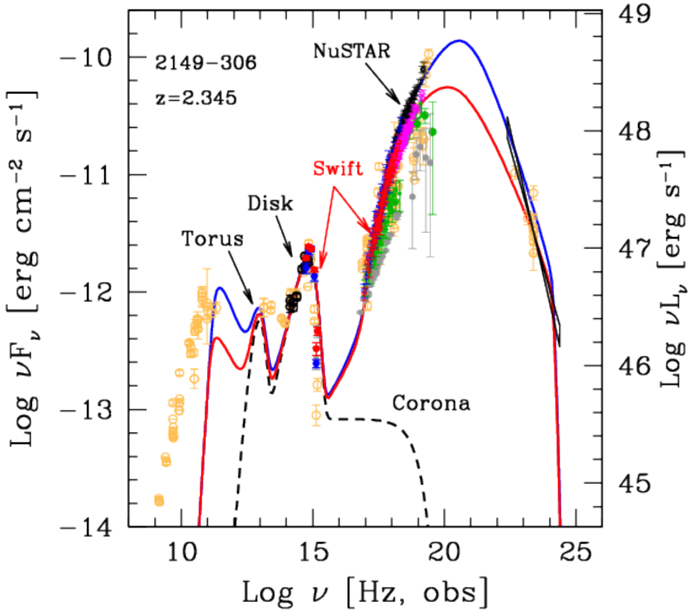
In Outburst ATel 11127: Piano+



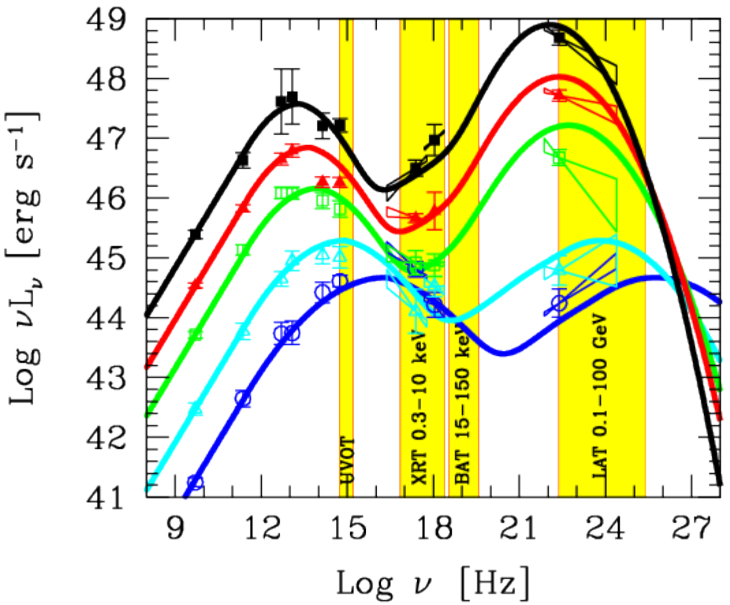


M. Urry and P. Padovani

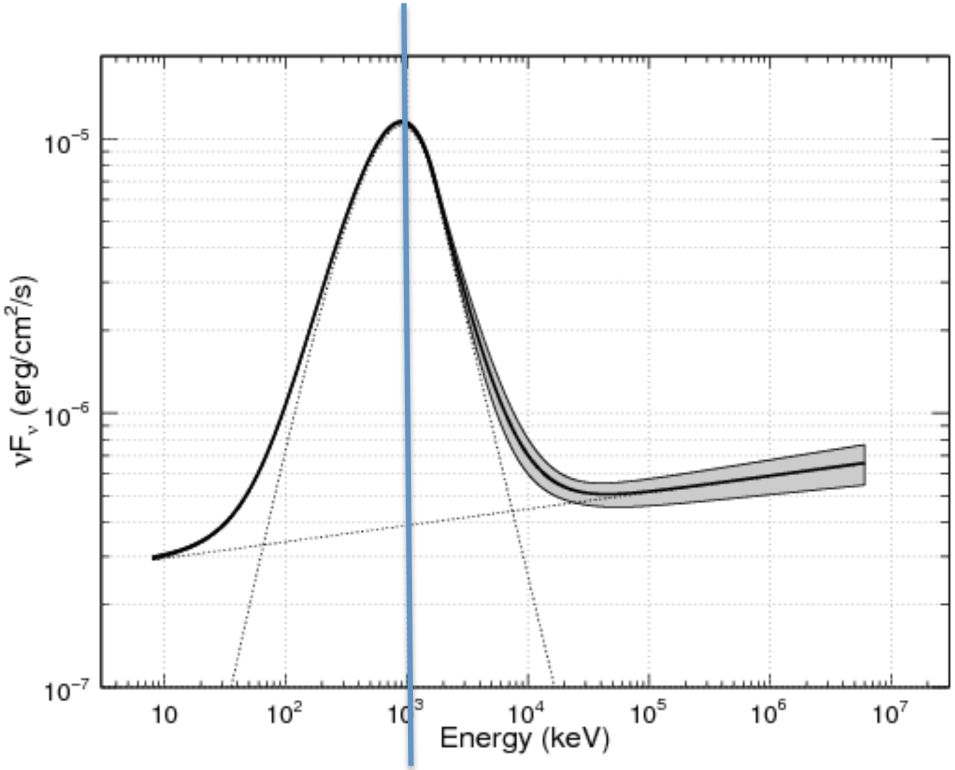
PKS 2149--306, a blazar at z=2.345



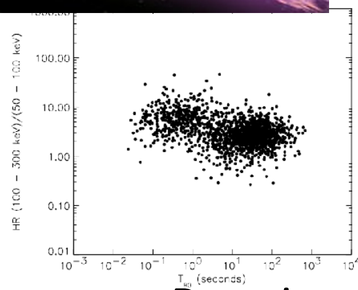
Blazar sequence: SEDs change according to L_{bol}(jet): Ghisellini+ 2015, JHEAp 7



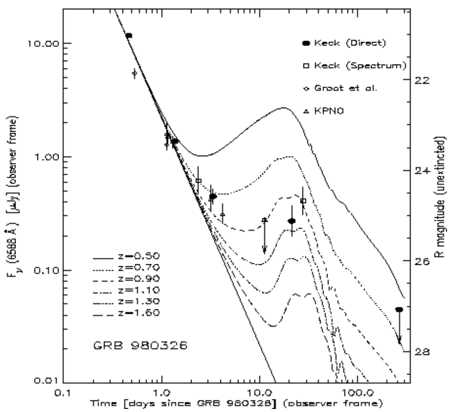
Tagliaferri et al 2015: Swift/XRT - NuSTAR, observing sim., 0.3--70 keV: Opt/UV bump due to the accretion disk, hard X—ray due to beamed jet emission (IC off photons produced by IR torus (hump at ~10^{13} Hz). **Archival data illustrate variabilit**y. **Blazar power mostly around 1 MeV,** and are best found in hard X--ray surveys rather than >100 MeV surveys (of comparable $\nu F\nu$ sensitivities).



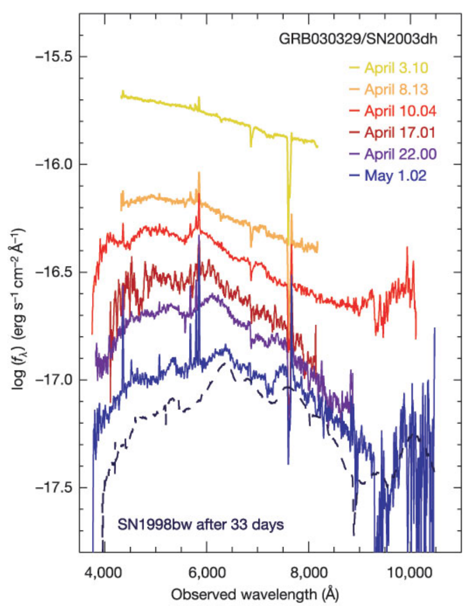
HR



Duration

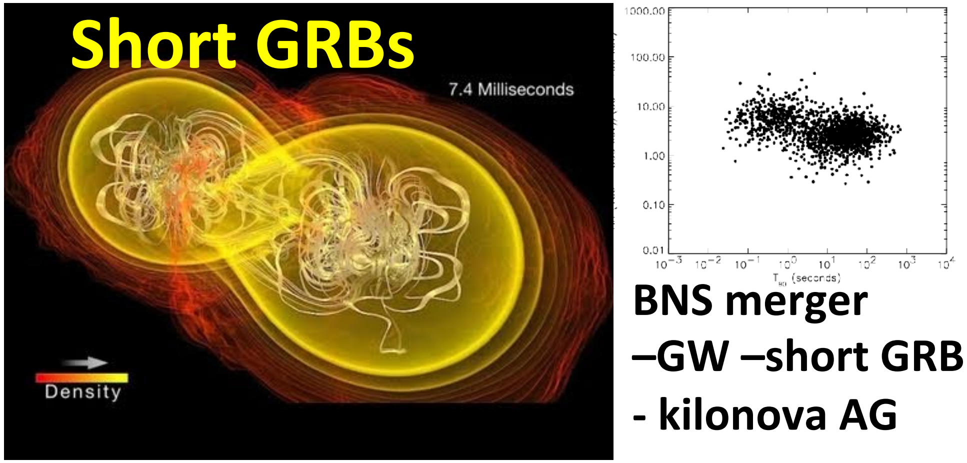


GRB980326: Bloom+99

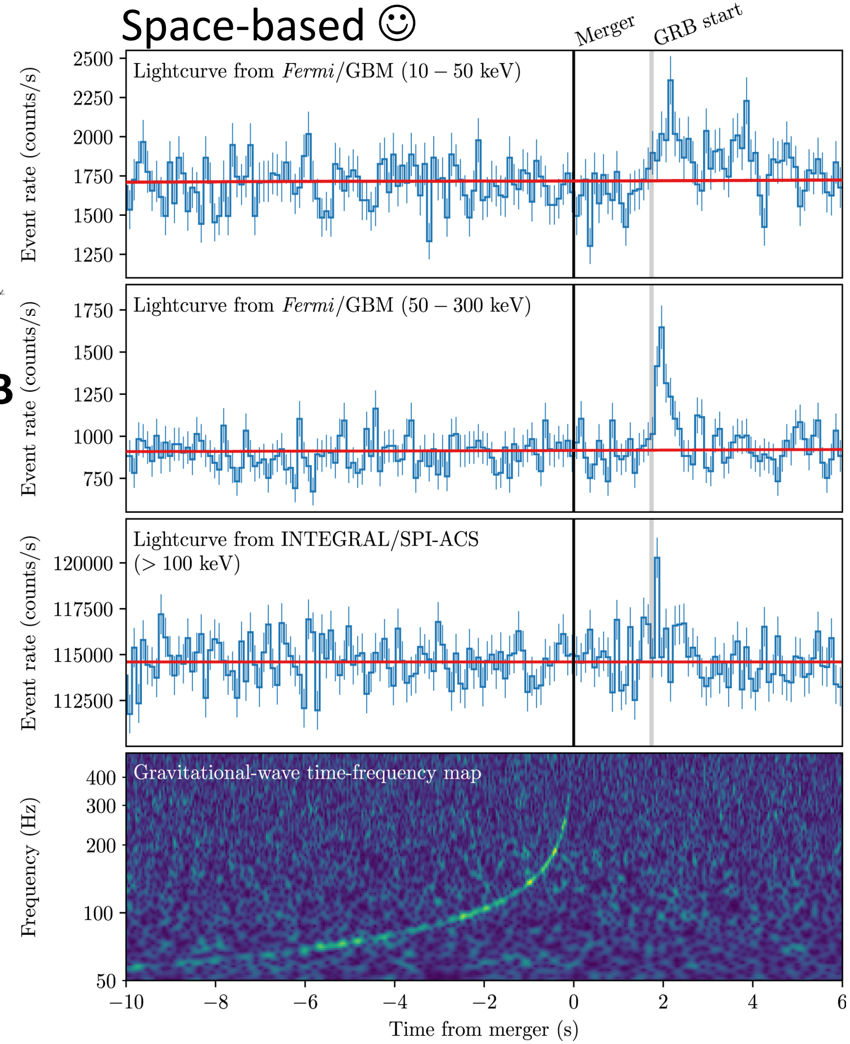


AG Spectroscopy: CCE

1925 - 2013

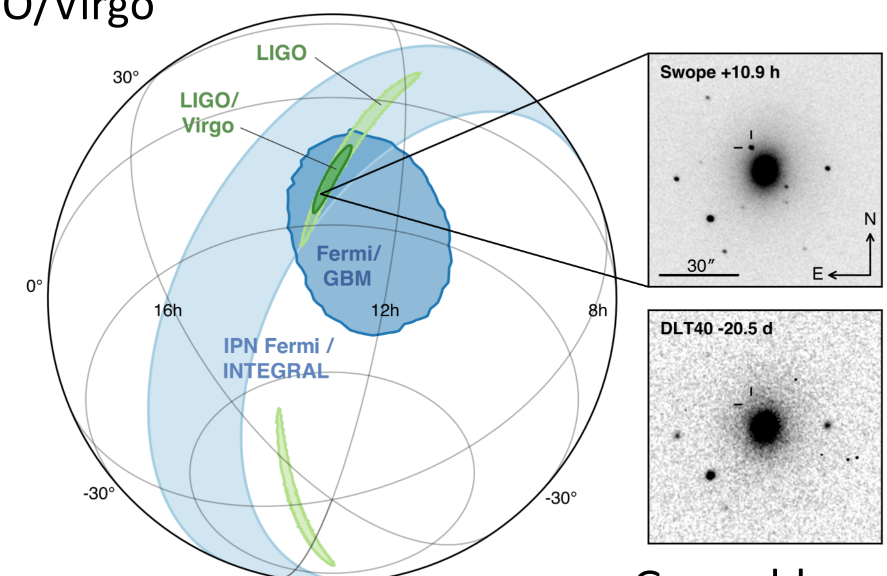


BNS merger –GW –short GRB - kilonova AG



GW170817/GRB170817A

LIGO/Virgo



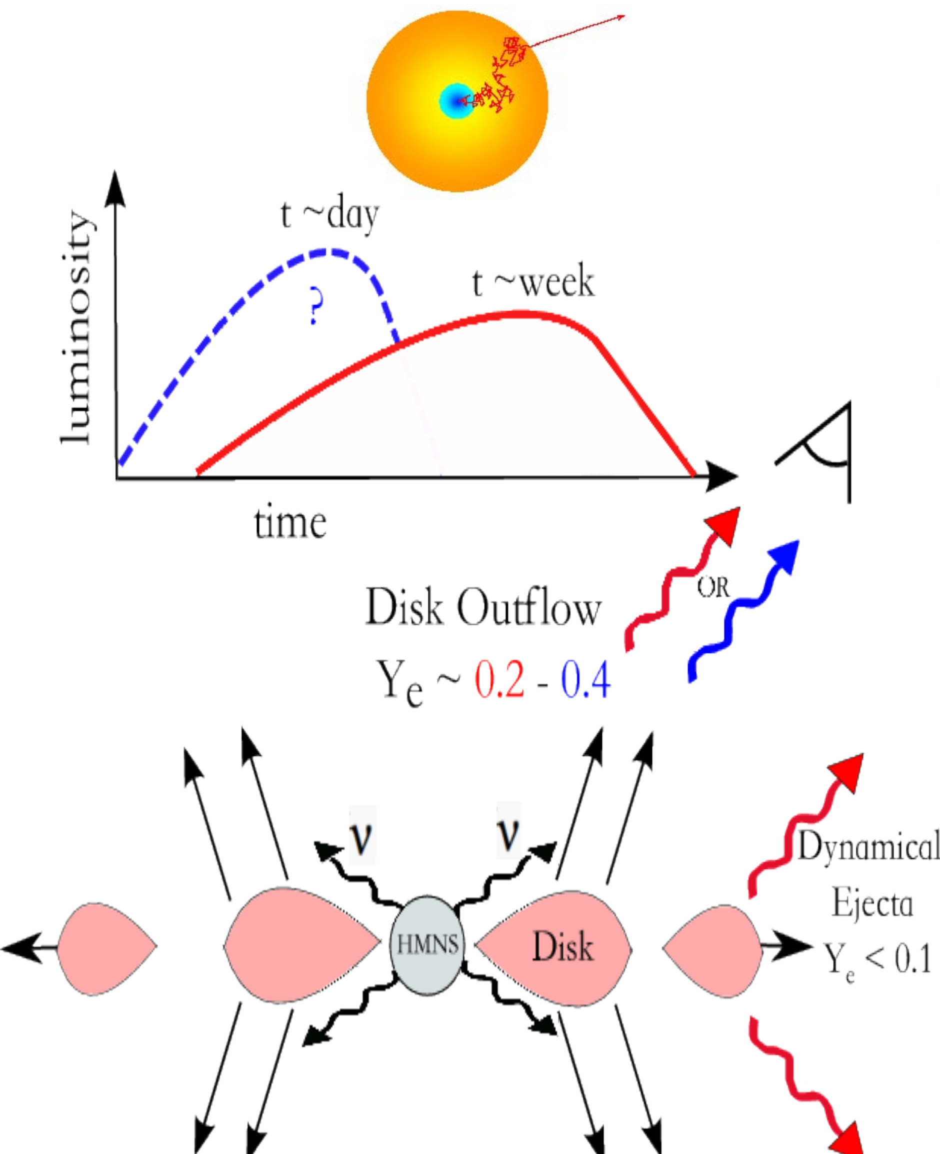
Ground-based ☺

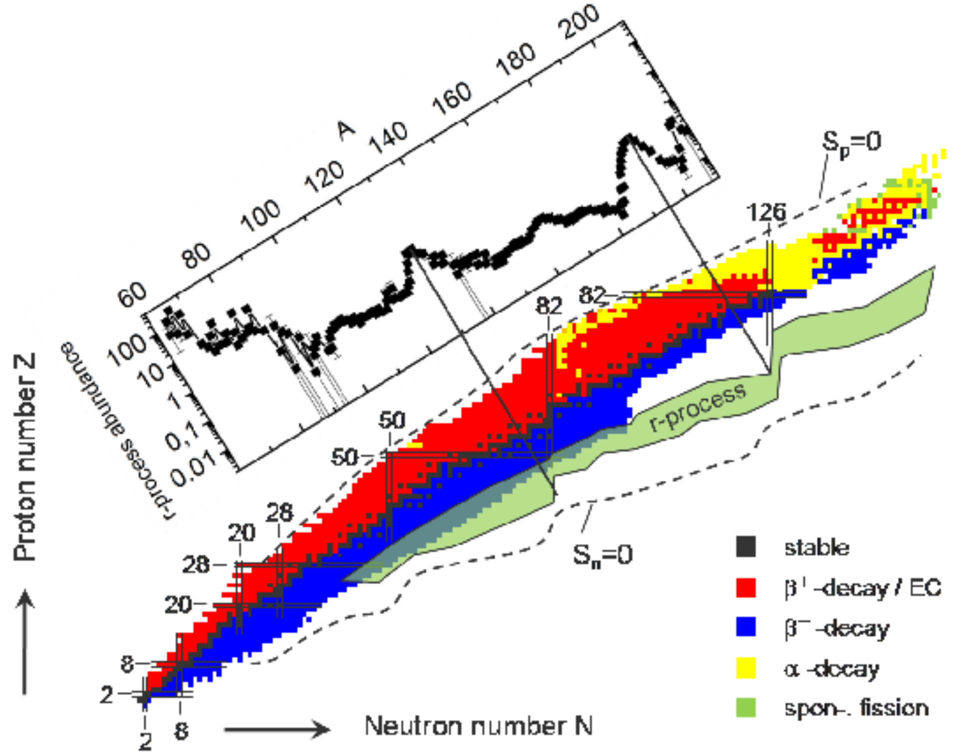
Abbott, B. P., et al. "Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A." 2017, ApJL, [848, L13.]()

> 3,000 authors ☺

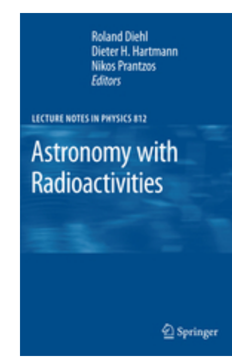
Underground-based: no detection ☹

Kilo-Nova astrophysics





A unique look at r-process nucleosynthesis in action



- Nuclear Statistical Equilibrium (NSE)
  - At T > 0.5 MeV, nuclear forward and backward reactions go into statistical equilibrium -> chemical equilibrium:

$$Z_i \mu_p + N_i \mu_n = \mu_i$$

nuclear species i

$$n = \sum_i n_i A_i$$

Mass conservation

$$\boxed{nY_e = n_p + 2n_\alpha + \sum_i Z_i n_i}$$

Charge conservation

  - Saha-like equations for abundances $Y_i = \frac{n_i}{n}$

nuclear part. fn.

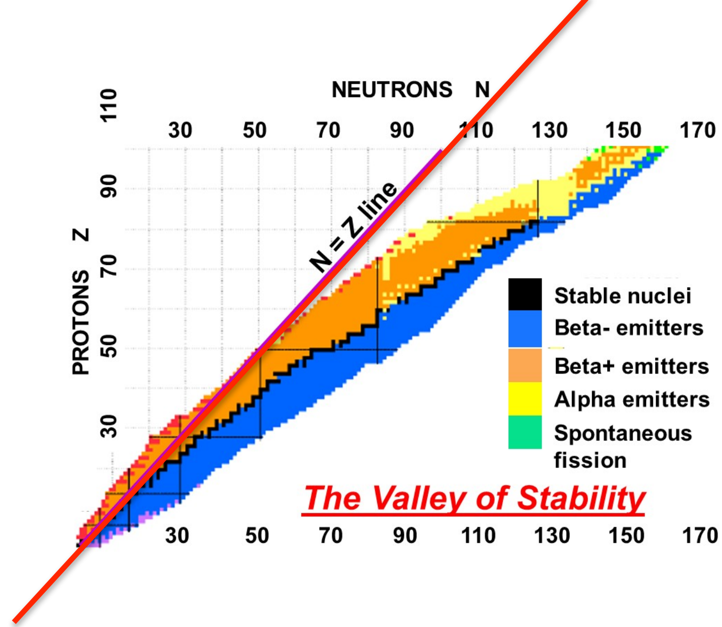
$$Y_{Z_i,A_i} = \frac{G_{Z_i,A_i}}{2^A (m_u kT/(2\pi\hbar)^{(3/2[A-1])}} (\rho N_A)^{A-1} Y_p^Z Y_n^N \exp\left(\frac{Q}{kT}\right)$$

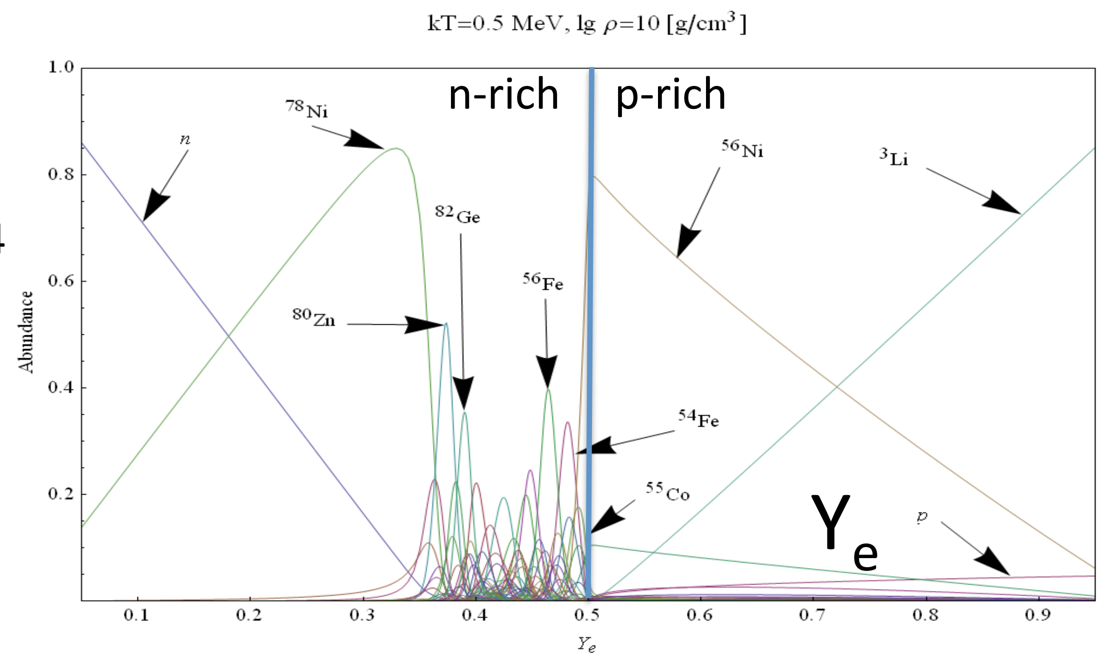
$$Q = Zm_p + Nm_n - M(N,Z) \quad A = N + Z$$

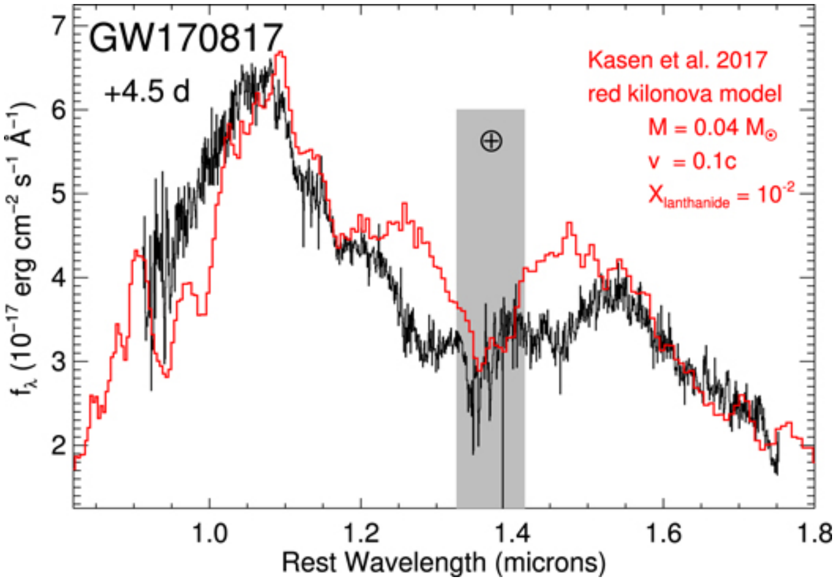
  - Abundances completely determined by ρ, T, Y_e.

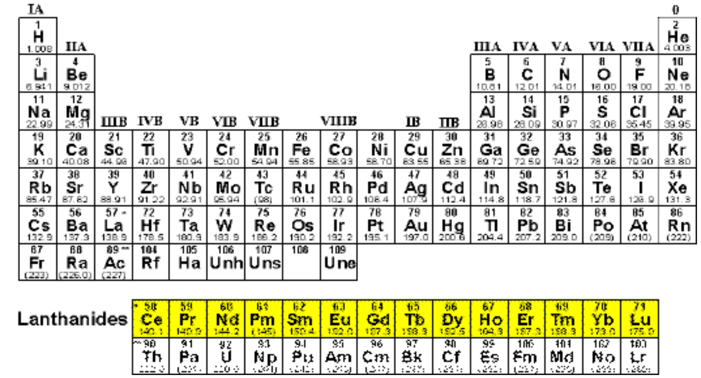
C. D. Ott @ YITP GW School, March 2015

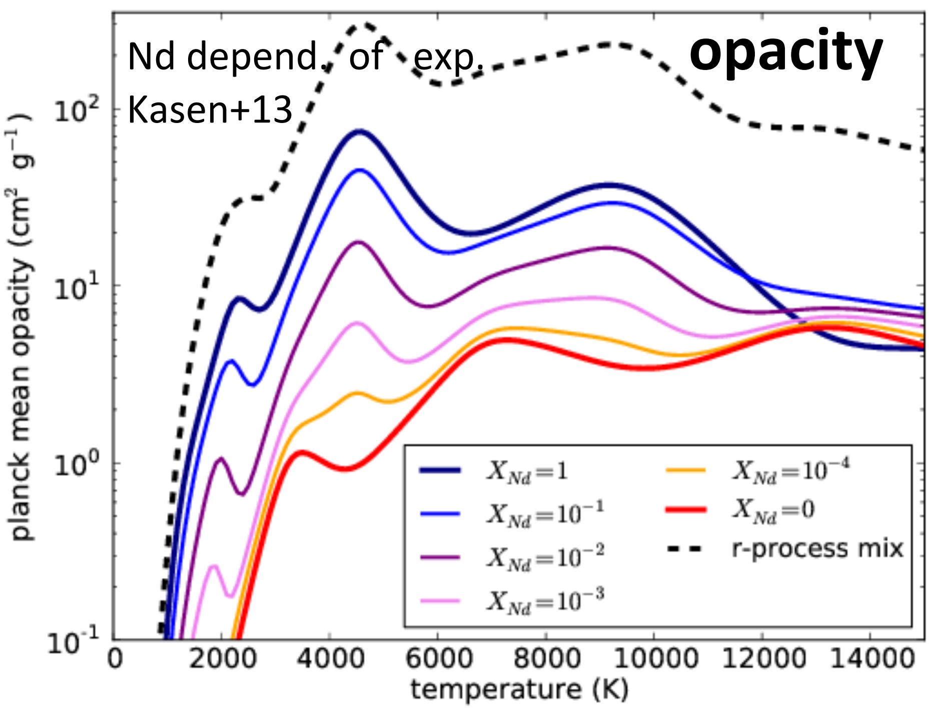
Y_e(Nd) = Z/A = 60 / (60 + 60 + 22) ~ 0.4









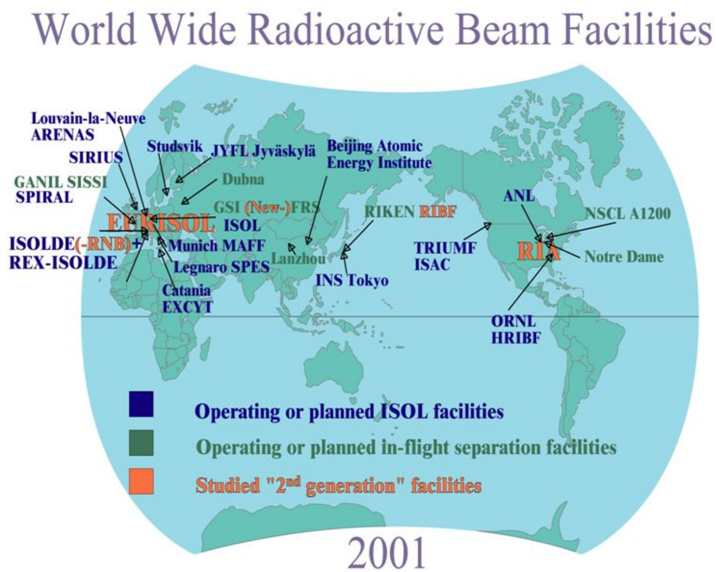


Lanthanides and Actinides offer the largest atomic complexity –> Lines –> Pseudo-continuum opacity

Y_e(Nd) = Z/A = 60/144 ~ 0.4

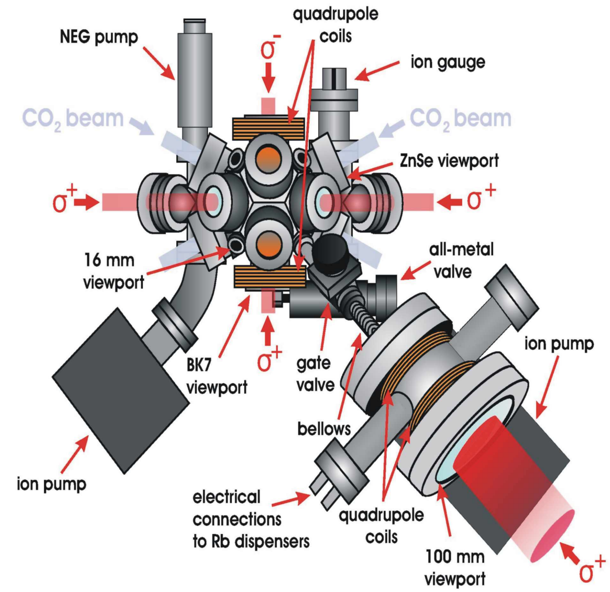
Nucleosynthesis studies need input from

Lab Astro: nuclear masses, lifetimes, etc.:

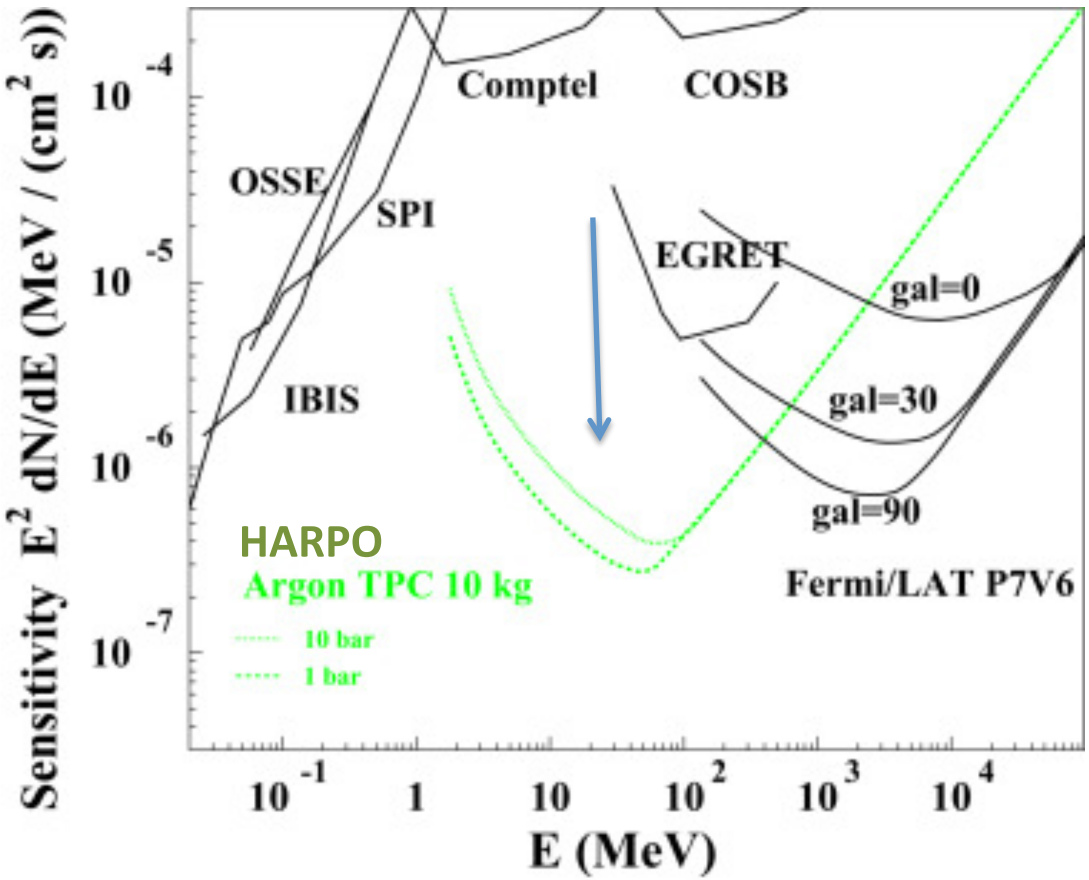


Full use of kN spectroscopy requires input from

Lab Astro: EBITs etc



We have an MeV sensitivity gap



Y. Geerenbaert, et al 2017, NIM 845

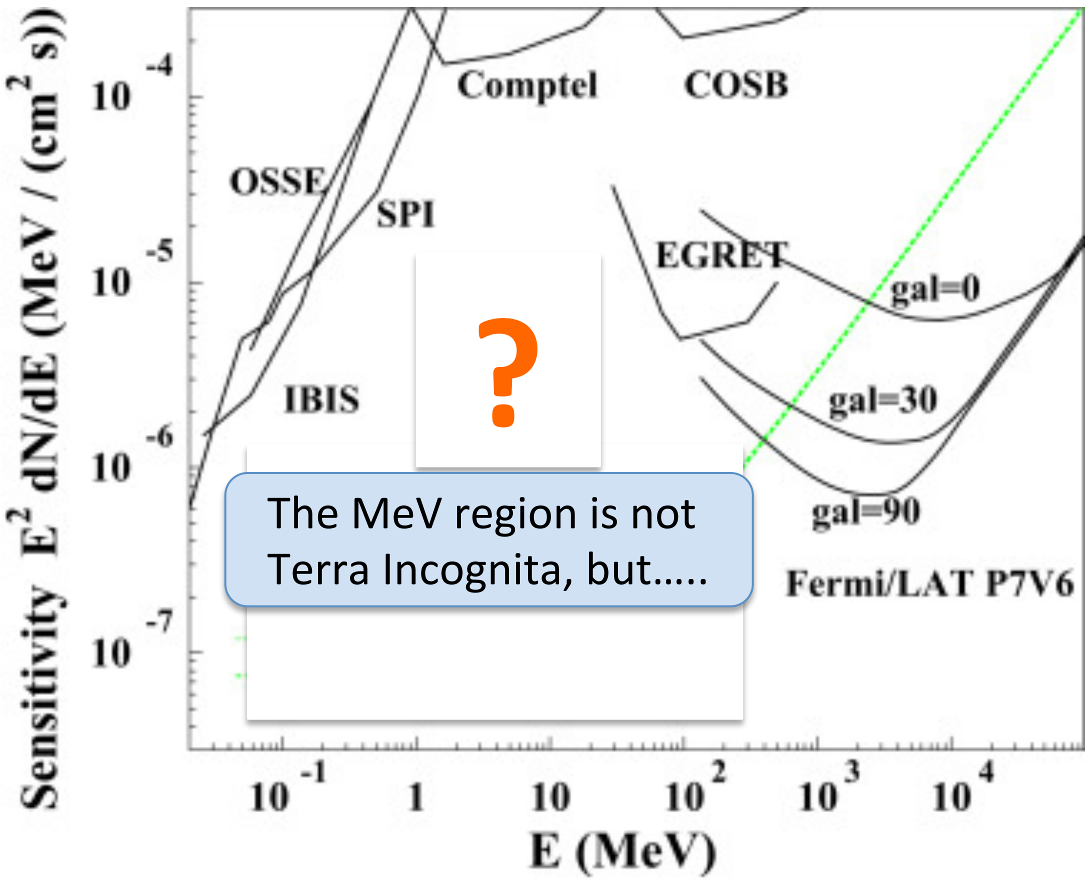
How to close the gap?

Larger Detectors
Smarter Event Analysis
Novel Concepts

See Talks on
eASTROGAM
AMEGO
TAO/TAP
COSI-X
LOX

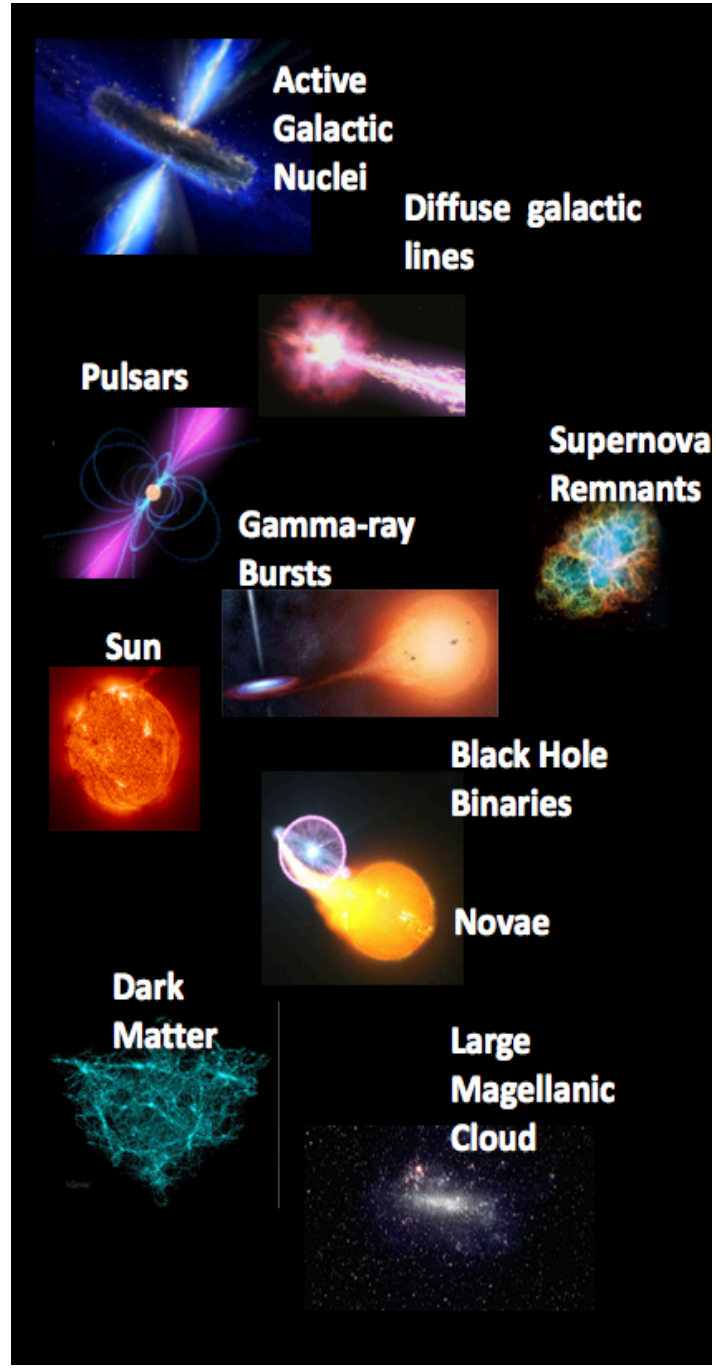
… we have many ideas, and $/photon is high, so let us explore further why the MeV band is so important.

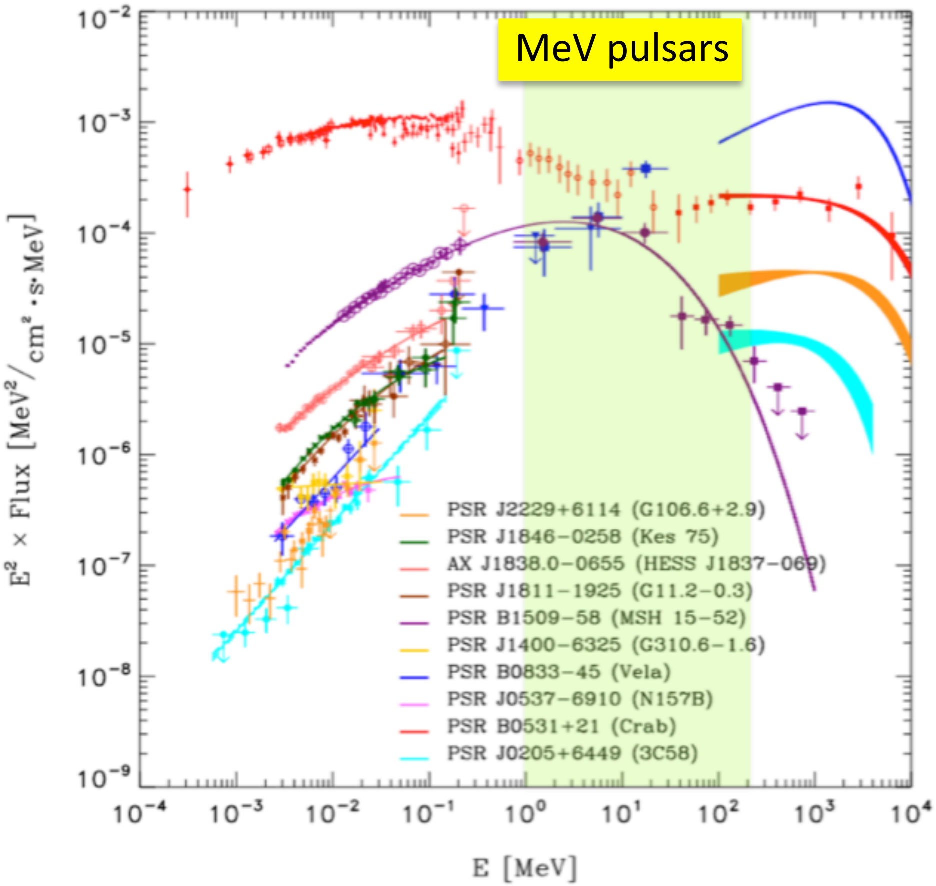
The MeV discovery land



The MeV region is not Terra Incognita, but.....

...it a) contains many sources whose power peaks there, and, b) it probes unique aspects of nuclear astrophysics



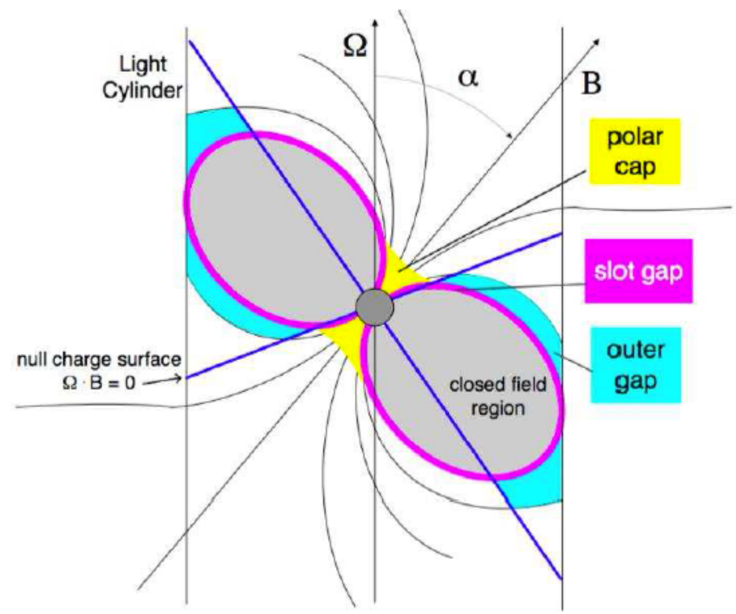


* Pulsars seen in hard X-ray but not by Fermi-LAT, peak in MeV band

* 11 MeV pulsars known

- ○Extreme $E_{dot} > 10^{36}$ erg

- Possible “hidden” population of energetic soft gamma-ray pulsars
- Emission might probe different part of the magnetosphere than GeV

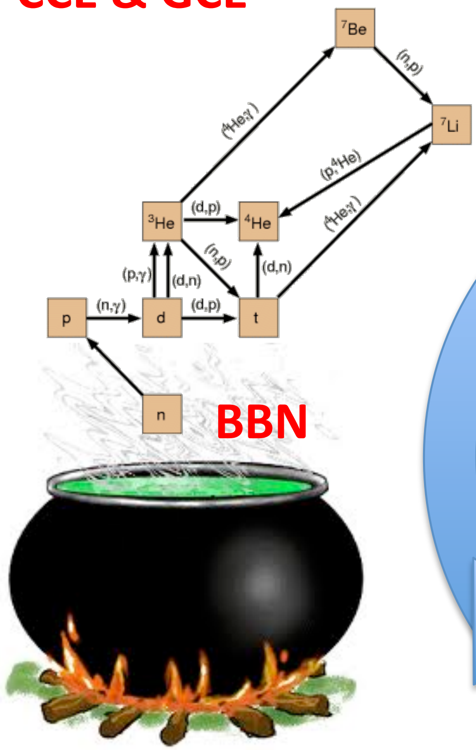


Puzzles:

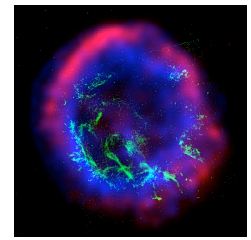
- Why do most have single peaked lightcurves?
- Why are most are radio quiet?
- Why do their SEDs peak near MeV ?

Chemical Evolution
Element Synthesis
CCE & GCE

Production (stars, CR spallation)
& Redistribution SN-SNR-ISM
Star Formation History & IMF

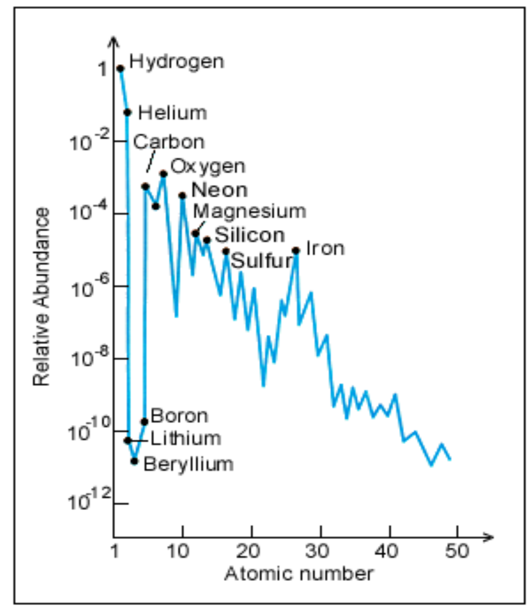


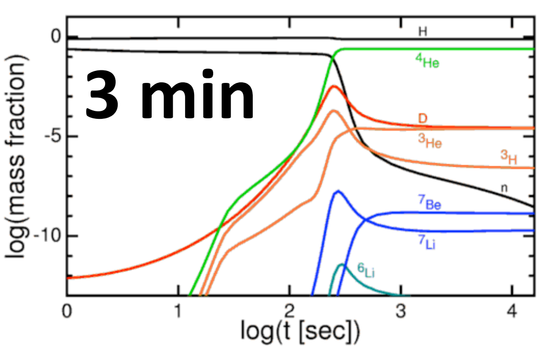
BBN



13.4 Gyrs later

z_{ISM} ~ 2%





Multi-Messenger:
⊙, Stellar atmospheres
ISM gas abundances
Meteorites
Radioactivites, γ-lines

The players:

Sources

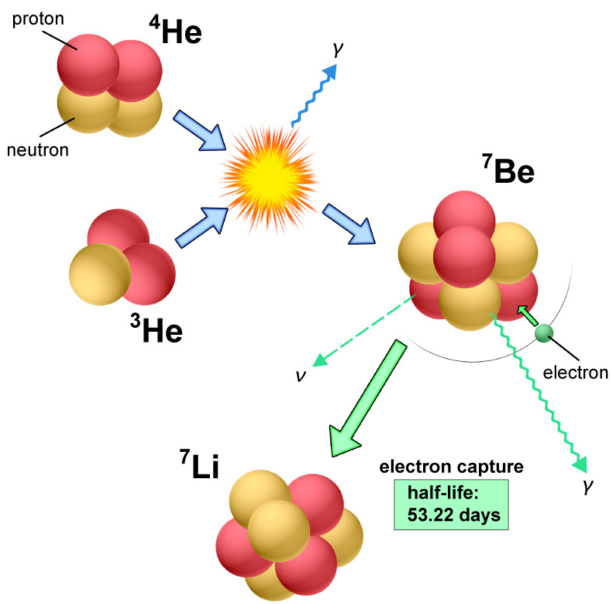
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	$1.04\ 10^6$y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	$2.0\ 10^6$y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma..$	511, <511

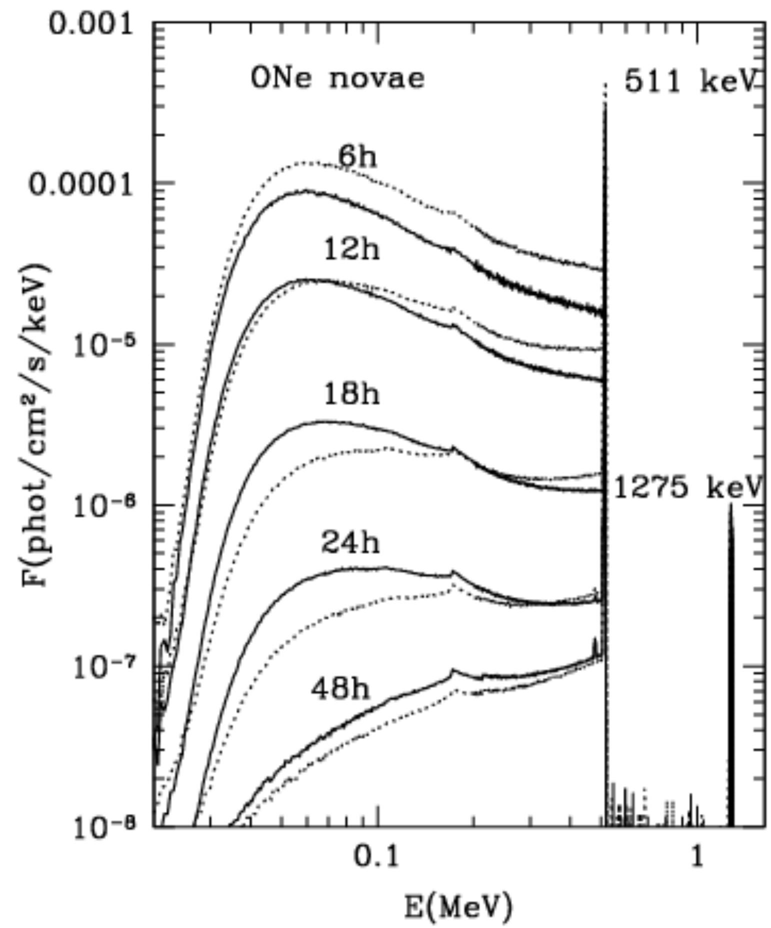
Diffuse

Key: $(M_{ej}/\tau)\ R_{event}\ F_{escape}$

Novae: not yet detected
In the MeV regime:

While Fermi established novae as GeV sources



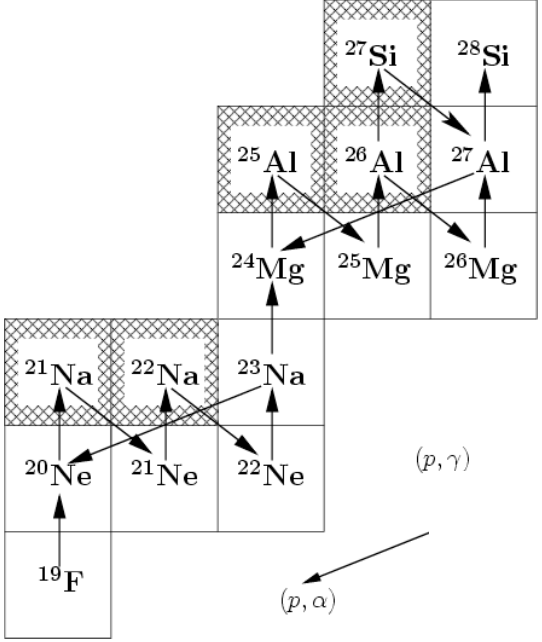


Hernanz 2012

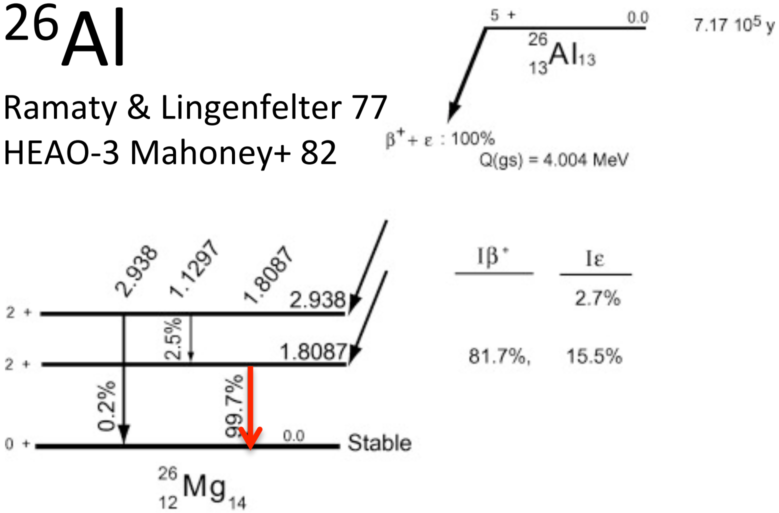
Galactic Rate ~ 40 / yr : Deep monitoring with Next-Gen Instrument could change this situation

We would learn about their dynamic envelope expansion

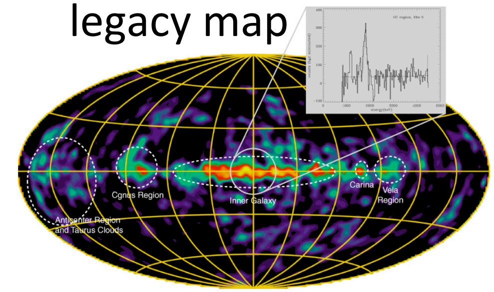
^{26}Al



Ramaty & Lingenfelter 77
HEAO-3 Mahoney+ 82



COMPTEL/CGRO legacy map

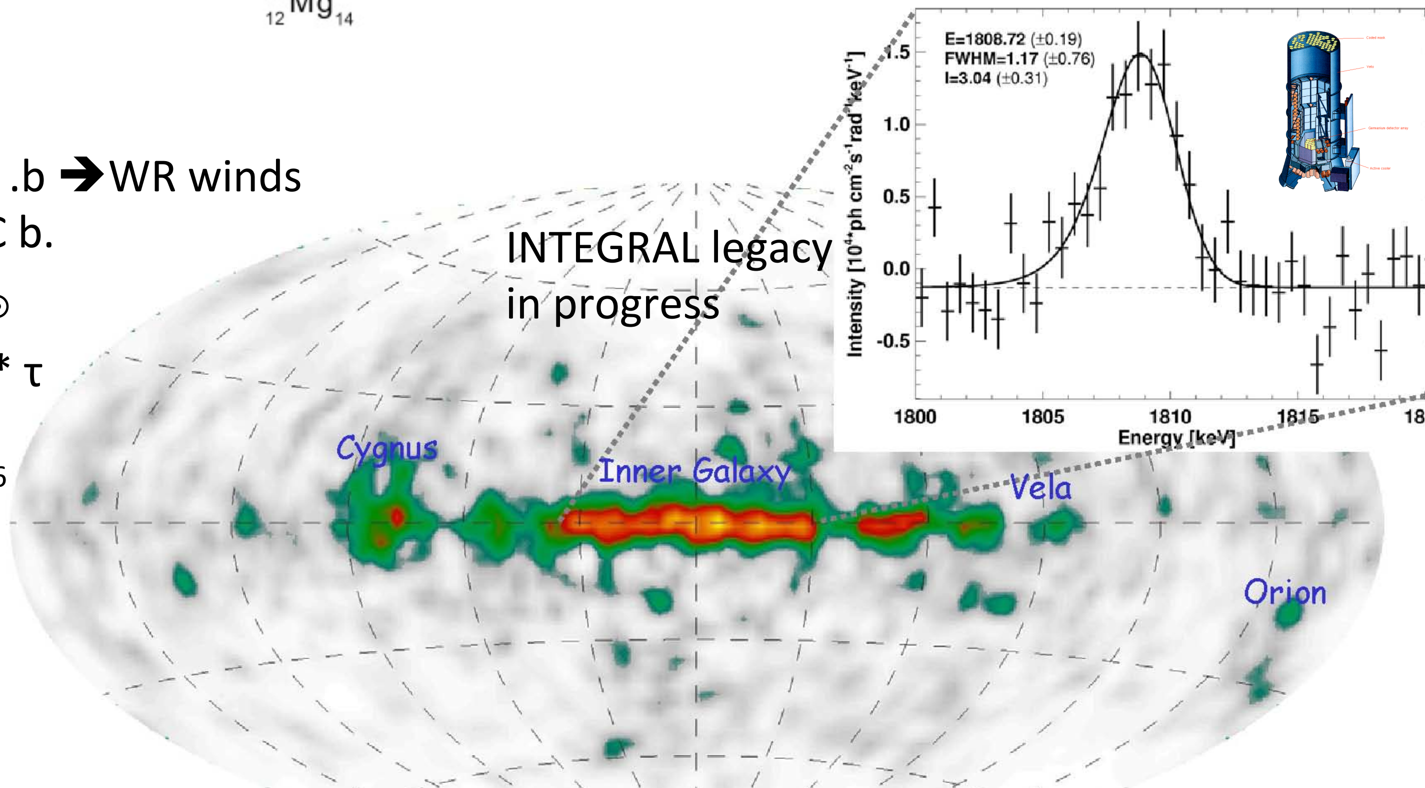


Static H/He-shell .b ➔WR winds
& explosive Ne/C b.
<Yield> ~ 10^{-4} $M_\odot$

M_{ISM} = SNR * M_{ej} * τ

~ 10^{-2} 10^{-4} $M_\odot$ 10^6

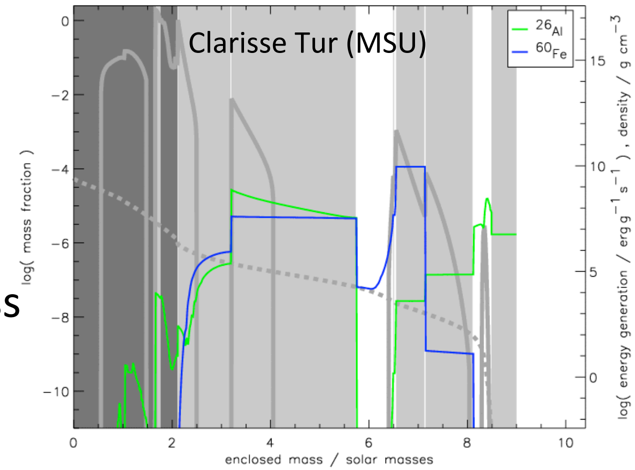
INTEGRAL legacy
in progress

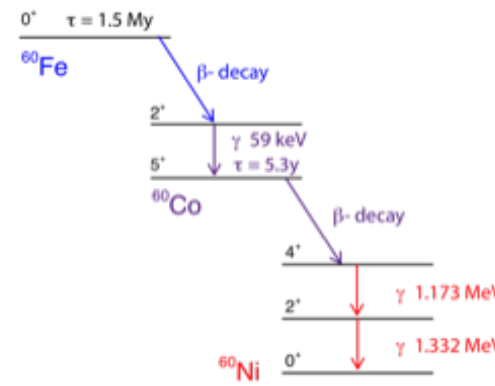


The Global galactic SFR ~ 2-3 $M_\odot$ yr^{-1}

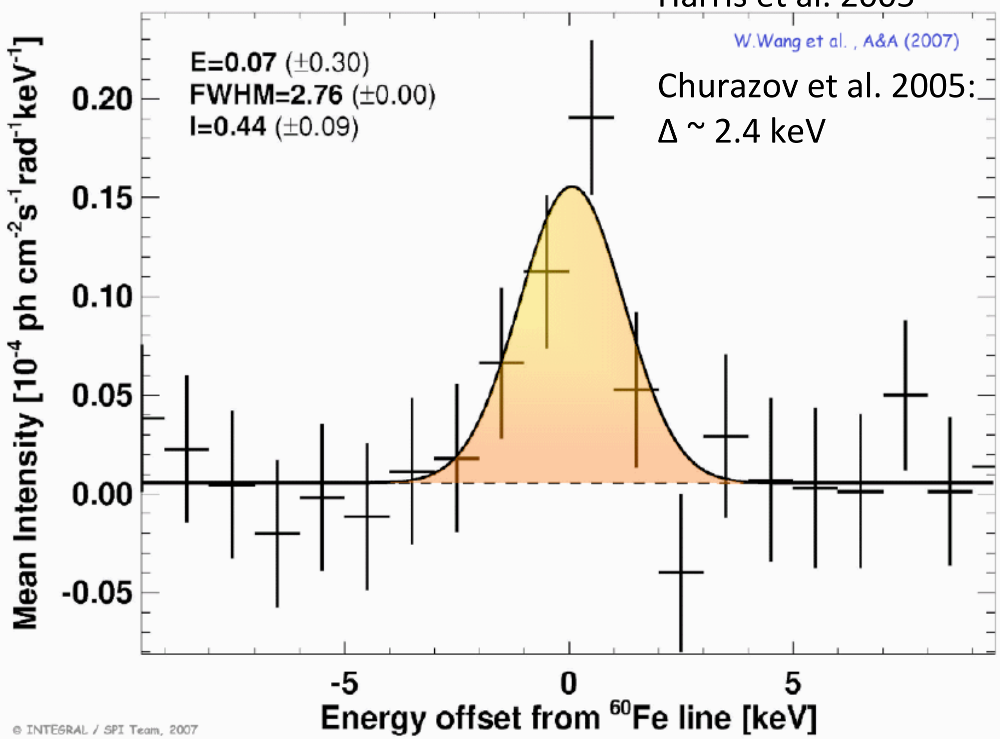
^{26}Al & ^{60}Fe

Coproduced in massive stars:
Static He-shell burning s-process
(the explosion only ejects!)





RHESSI: Smith 2005
INTEGRAL/SPI
Harris et al. 2005

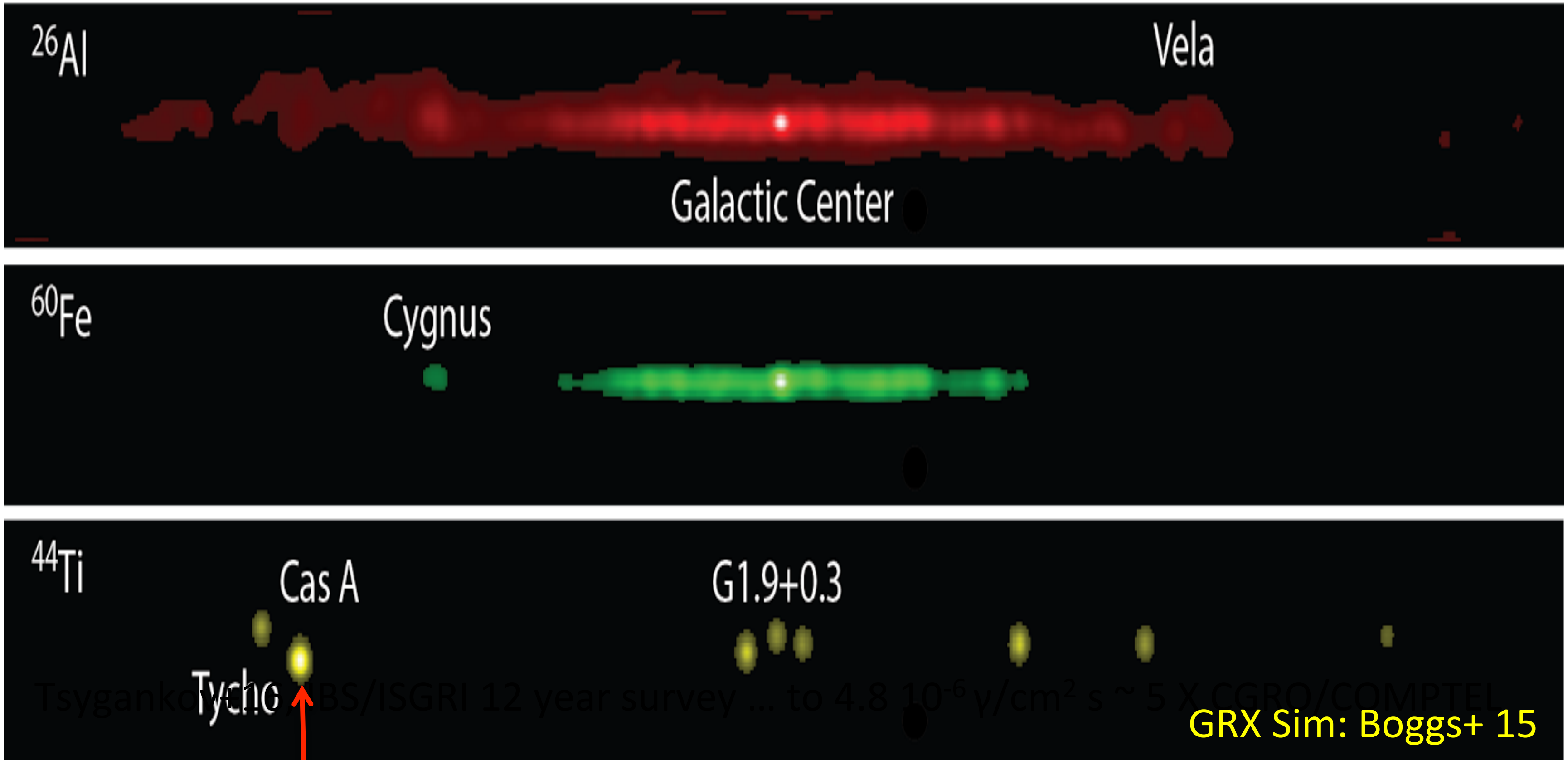


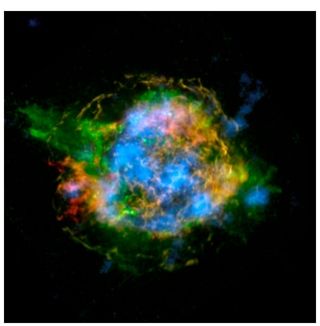
Churazov et al. 2005:
Δ ~ 2.4 keV

^{59}Fe(n,γ)^{60}Fe(n,γ)^{61}Fe
Rate uncertainties
➔ yield uncertainties
Mass loss

^{26}Al/^{60}Fe flux ratio
~ 10-20% ✔

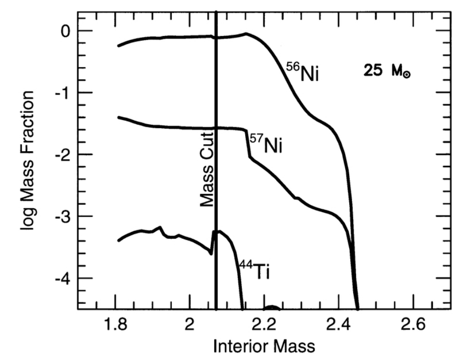
For SNII/Nova decomposition
We need a map





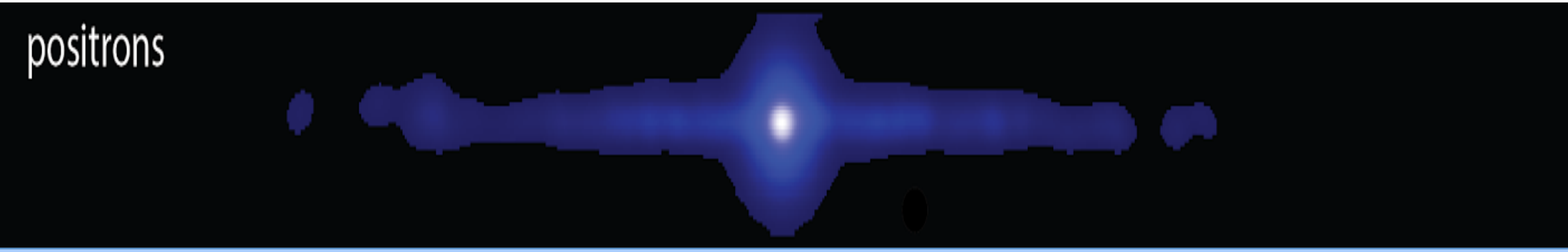
✓ But no other

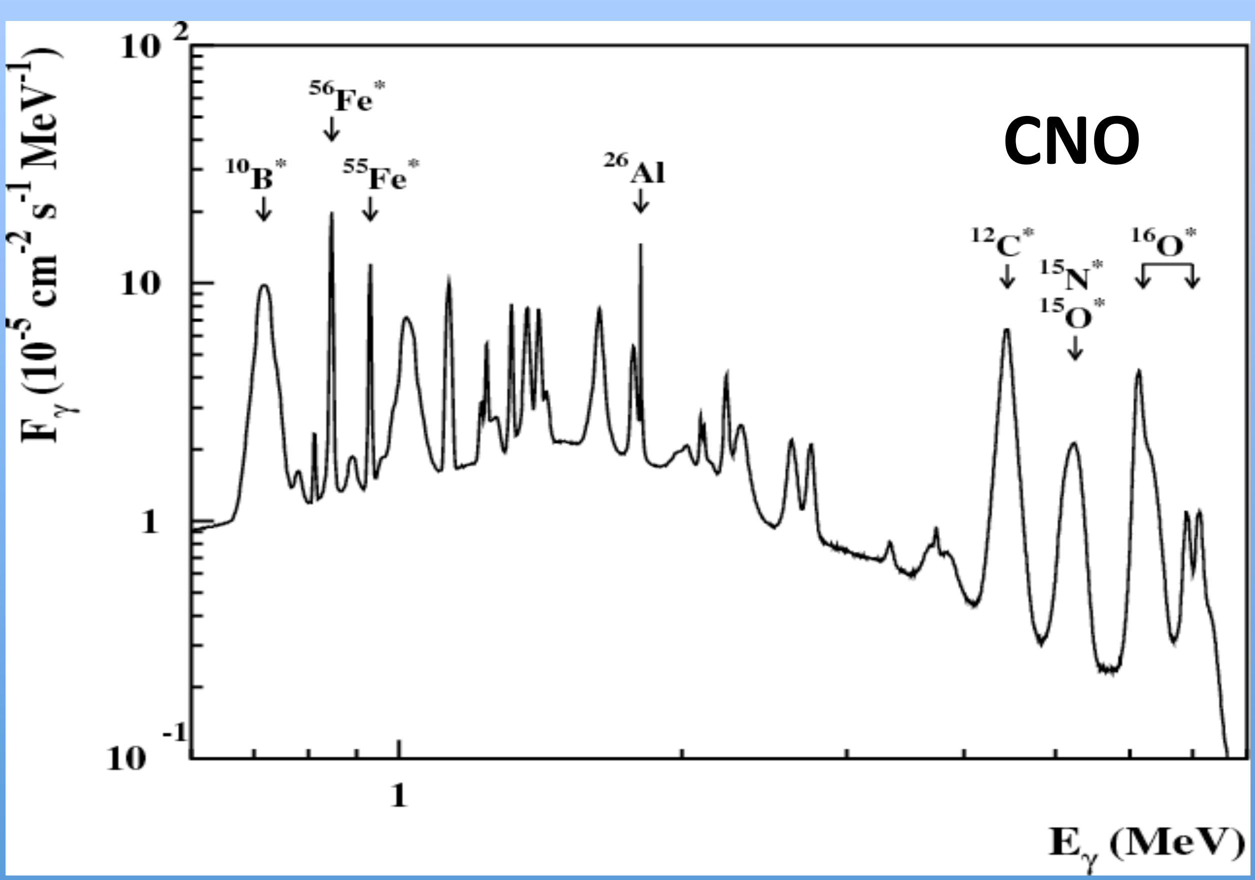
The Y_{44} $(1/4\pi D^2)$ $\exp(-t/\tau)$ challenge for sensitivity



L.-S. The et al. 06: ^{44}Ti sources are rare events

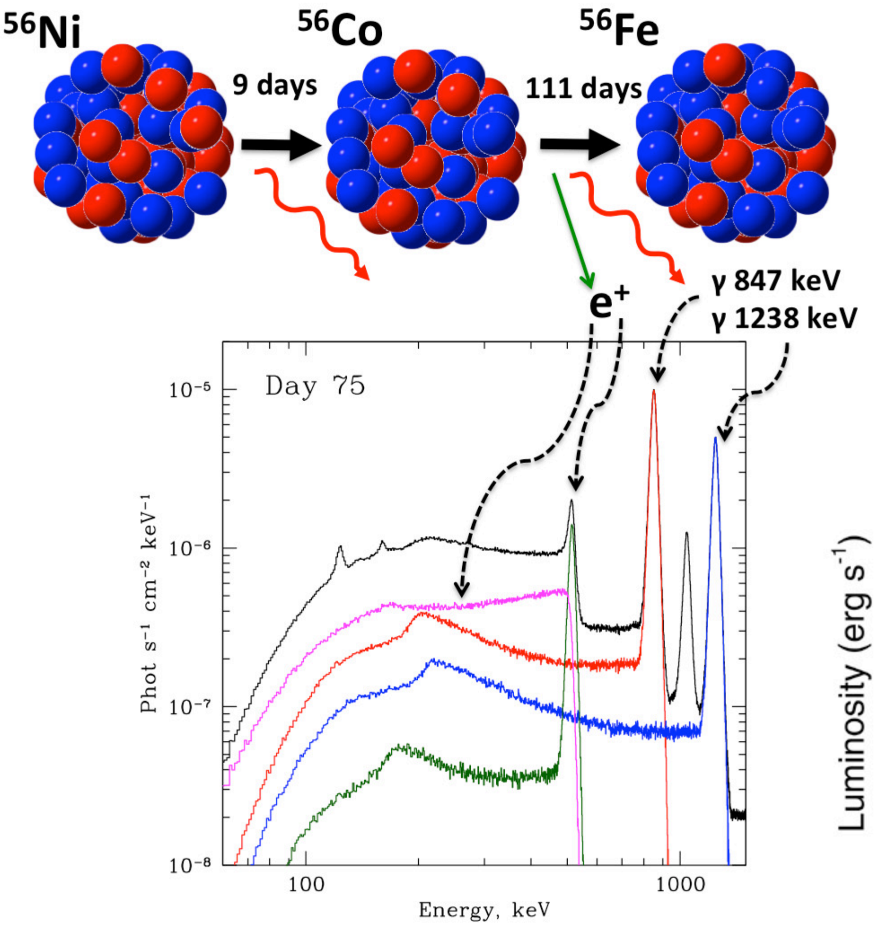
The Galactic positron distribution remains largely unexplored





Nearby SF regions in The MW ISM are guaranteed sources that have yet to be detected

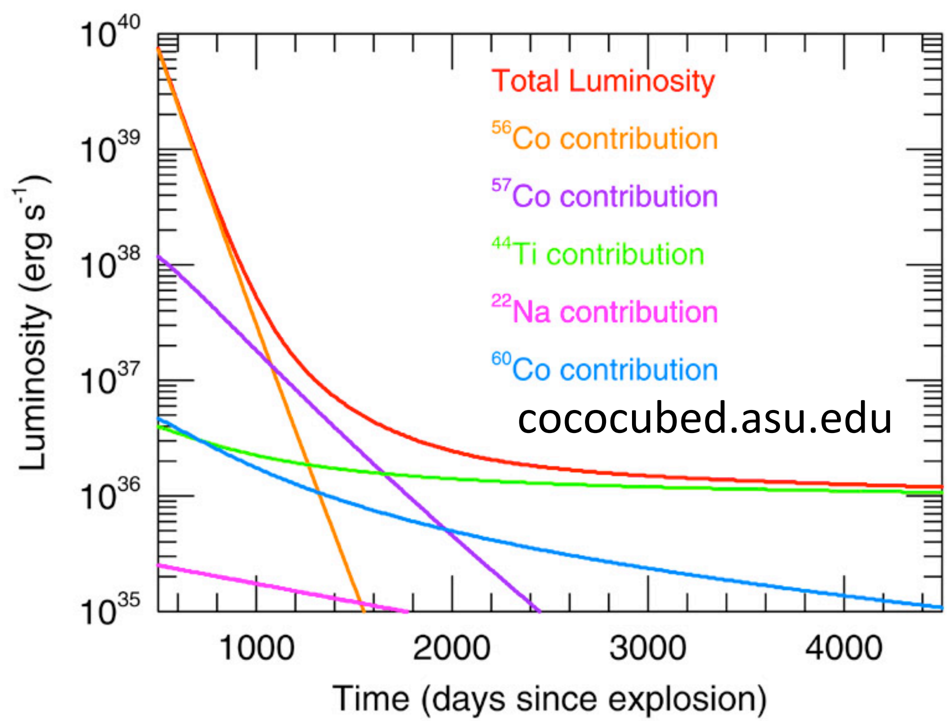
CR astrophysics holds clues to the galactic SFR, which is essential for GCE



Radioactivities

keep the SN lights on !

^{254}Cf (B^{2}FH: 1957) ➔ ^{56}Ni



$L(t) \neq L_{radiogenic}(t)$

Delayed power model (Clayton92)

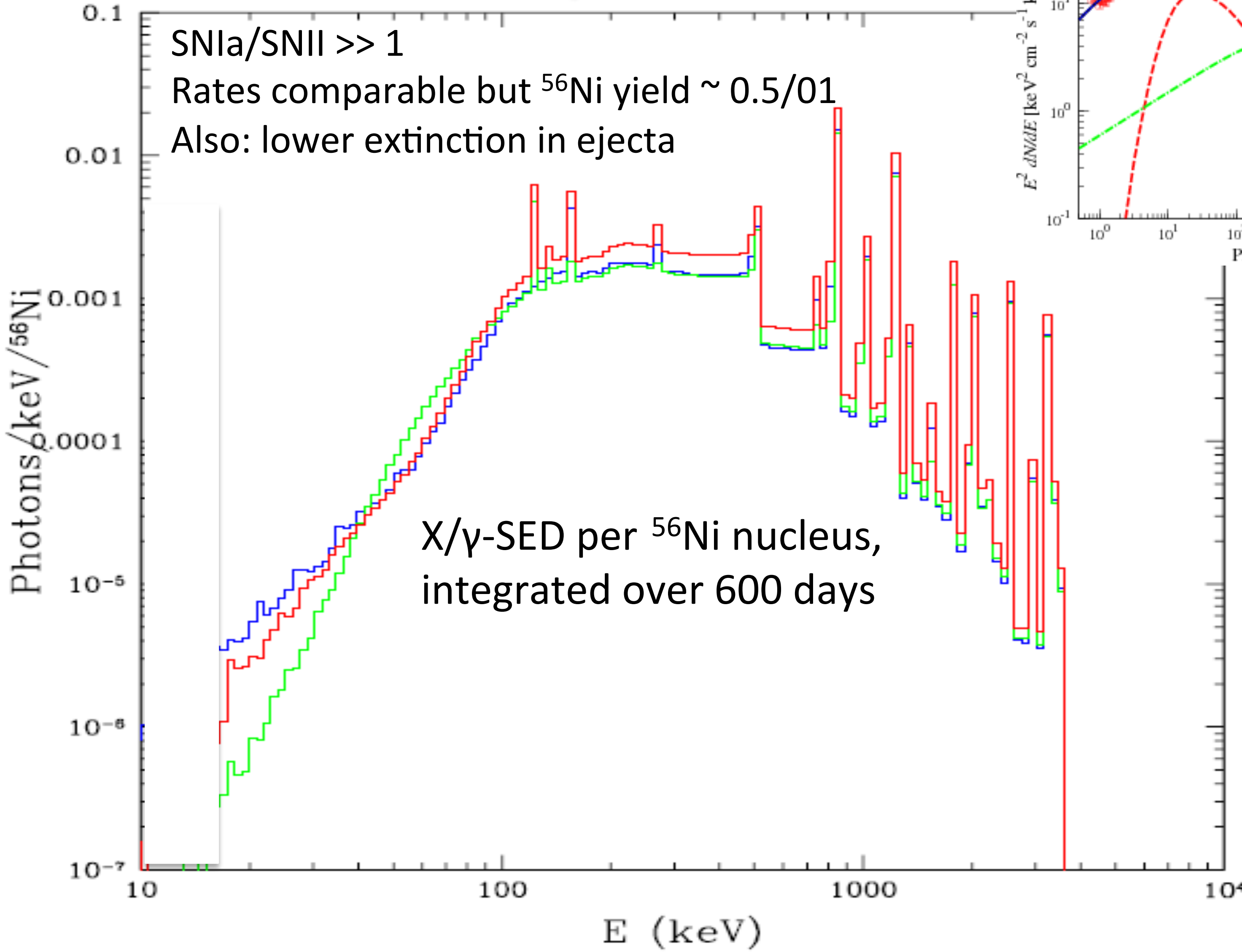
Time-dependent ionization

Time integrated escape SED -> CGB

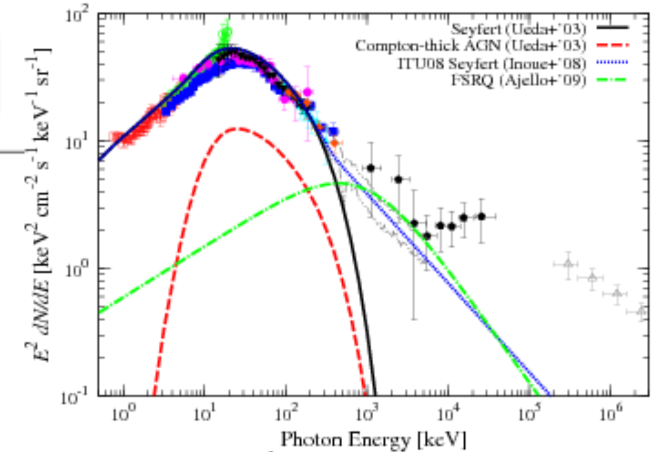
SNIa/SNII >> 1

Rates comparable but ^{56}Ni yield ~ 0.5/01

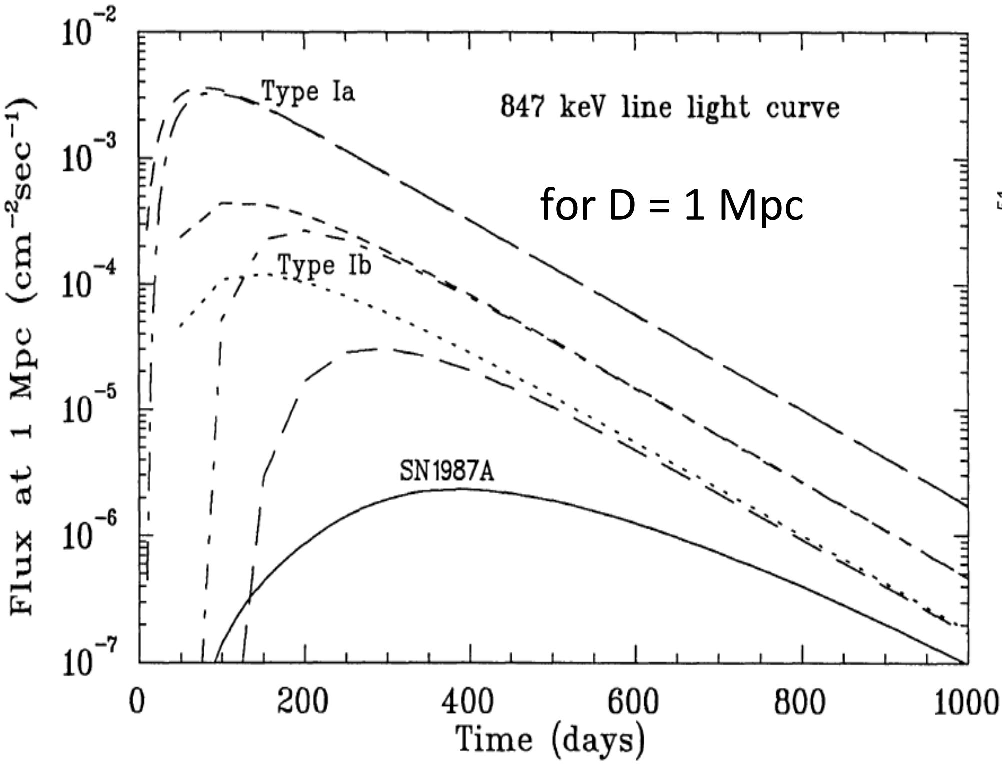
Also: lower extinction in ejecta



X/γ-SED per ^{56}Ni nucleus, integrated over 600 days

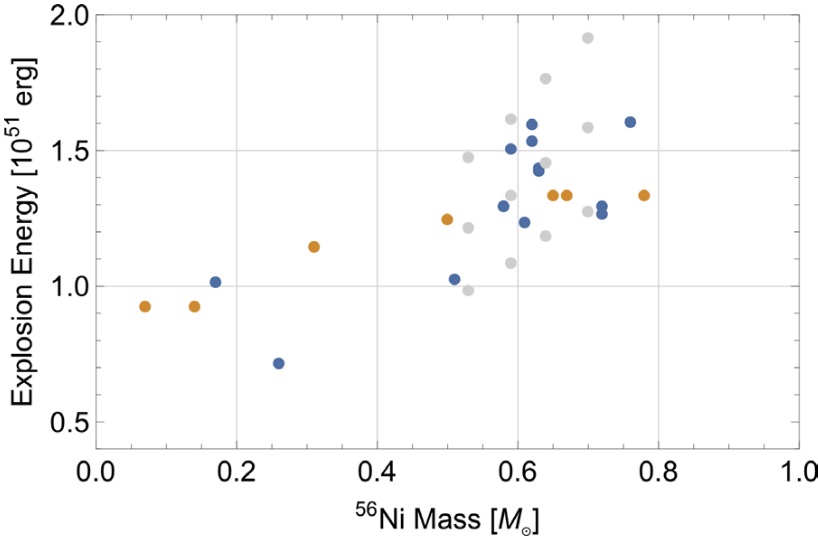


Diagnosing SNIa models
with MC Transport simulations



The, Clayton, Burrows 1991

Parameter space is large, but not a scatter cloud (adapted from the LOX collaboration)

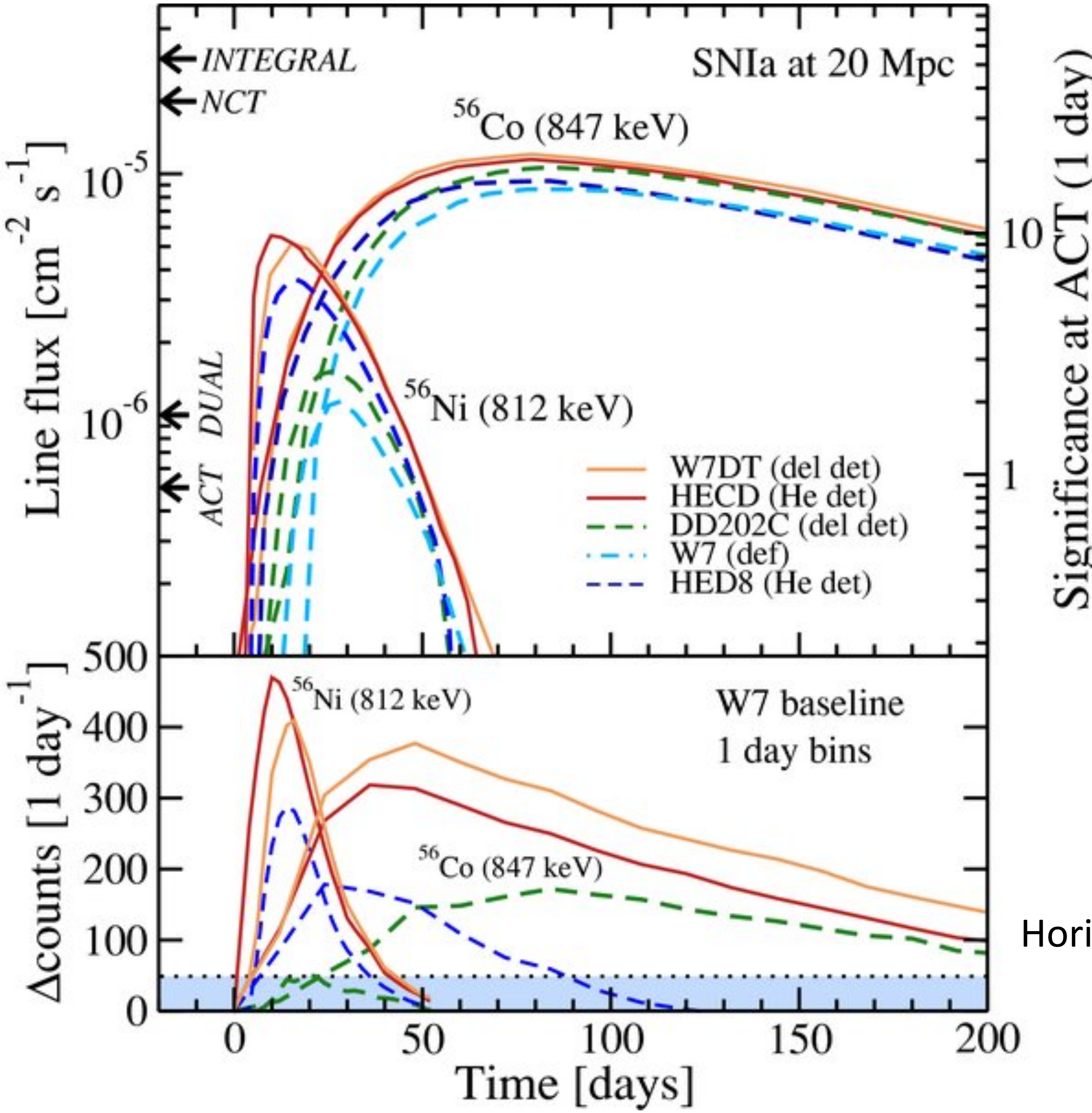


Detection distance must be D_{Ia} > 30 Mpc for reasonable rates.

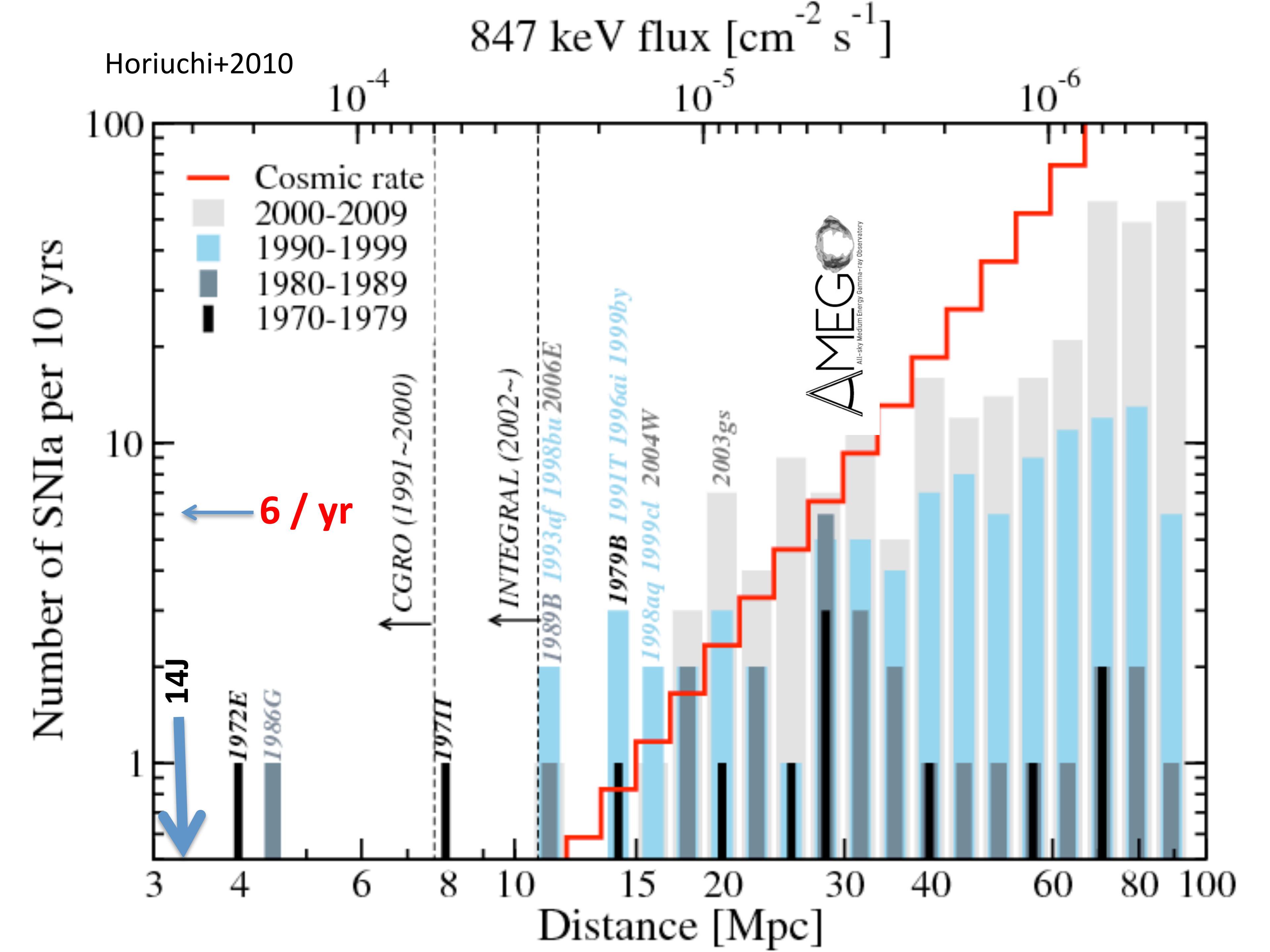
Calibrating SNIa is crucial for their use as standard candles

Diagnosing SNIa models

Ejecta mass Distribution Kinematics



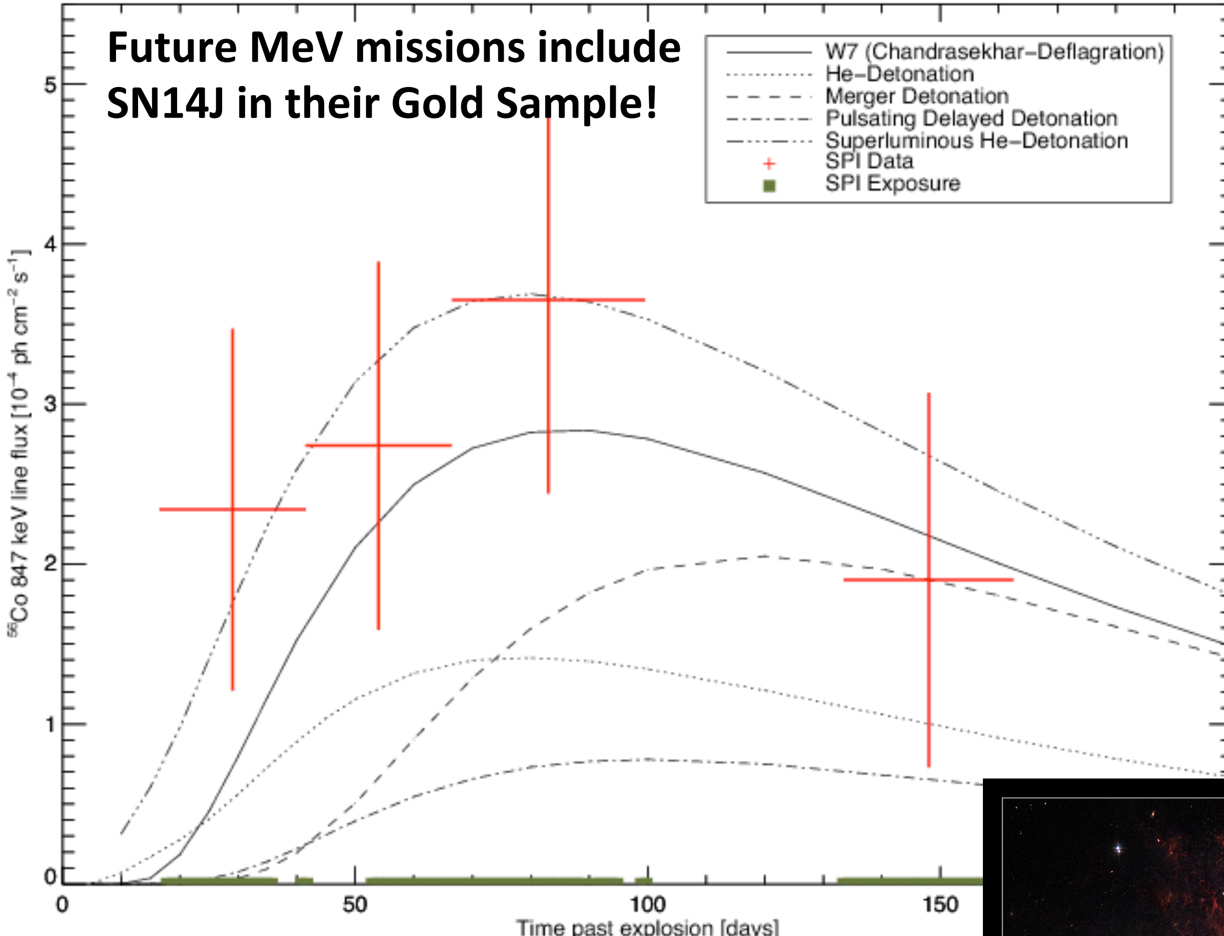
Horiuchi+2010

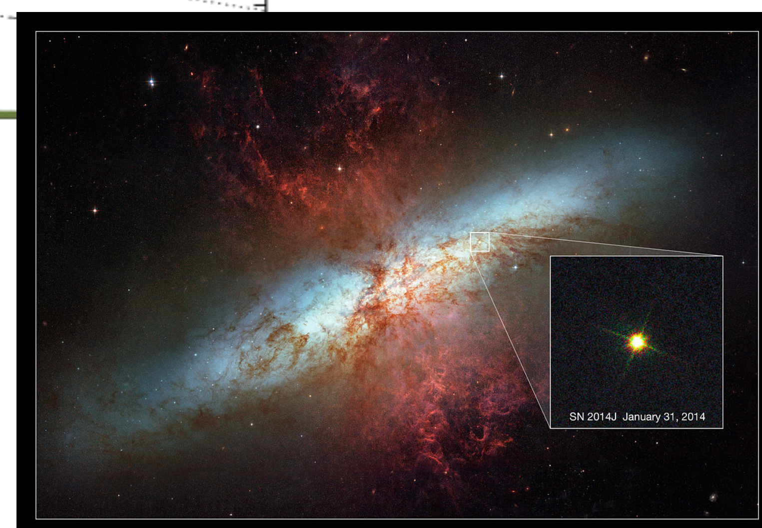


Horiuchi+2010
847 keV flux [cm^{-2} s^{-1}]
Cosmic rate
2000-2009
1990-1999
1980-1989
1970-1979
Number of SNIa per 10 yrs
Distance [Mpc]
6 / yr
14J
1972E
1986G
1971I
CGRO (1991~2000)
INTEGRAL (2002~)
1989B 1993af 1998bu 2006E
1979B 1991T 1996ai 1999by
1998aq 1999cl 2004W
2003gs
AMEGO
All-sky Medium Energy Gamma-ray Observatory

SN2014J at 3.5 Mpc: Diehl et al 2015: INTEGRAL/SPI

Future MeV missions include SN14J in their Gold Sample!

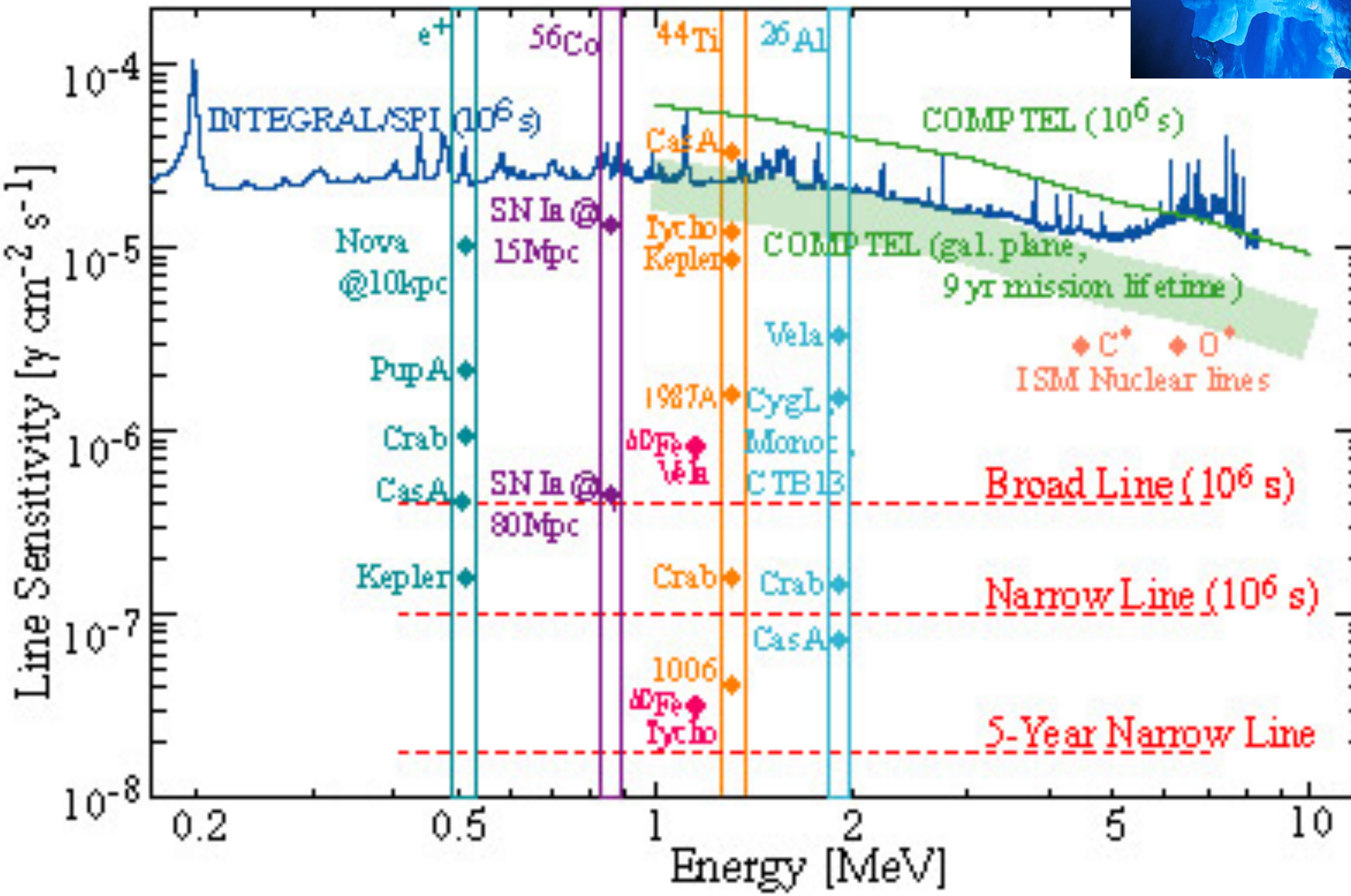




Thank You

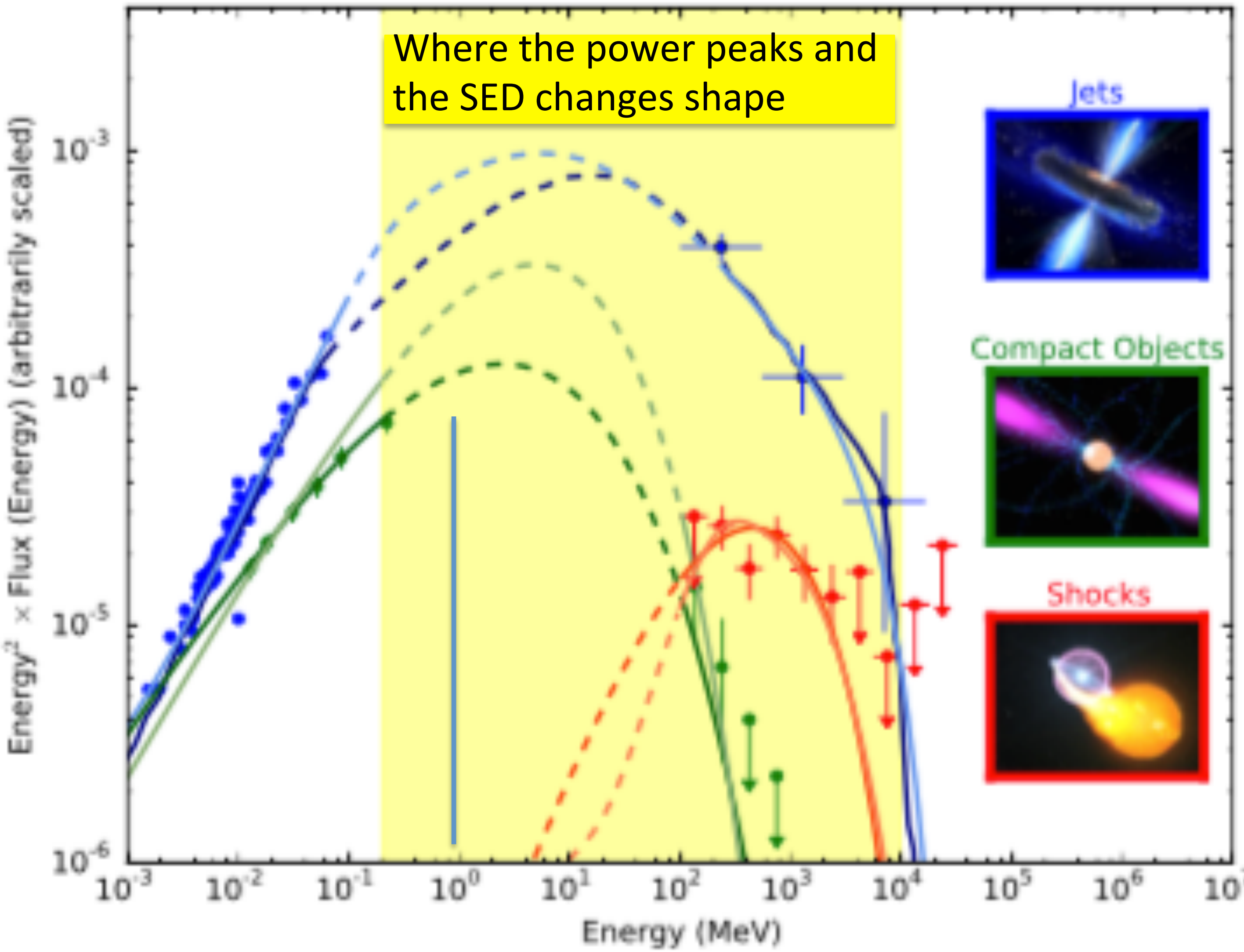
Additional slides (not presented)

The MeV regime is rich, if proper sensitivity can be reached

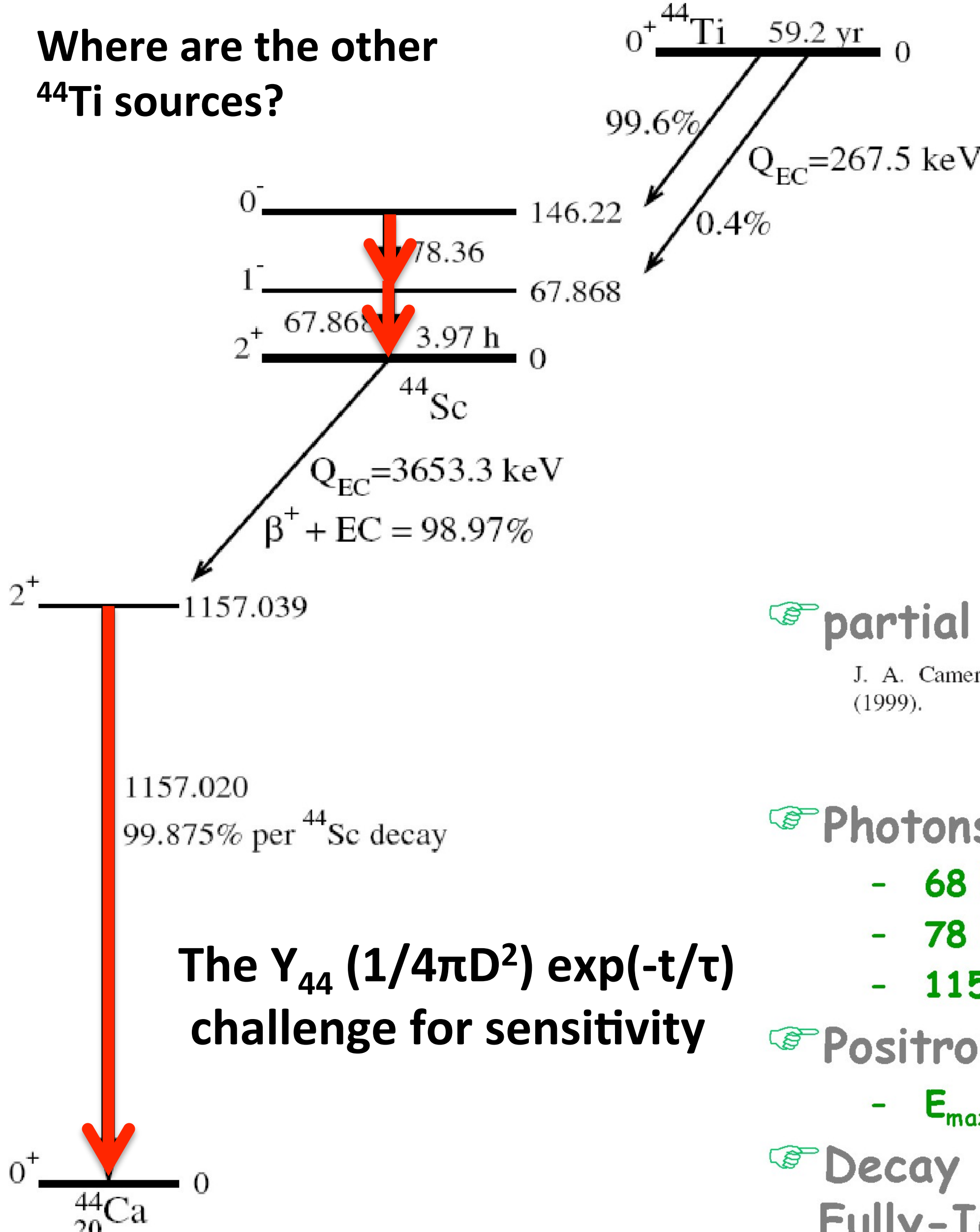


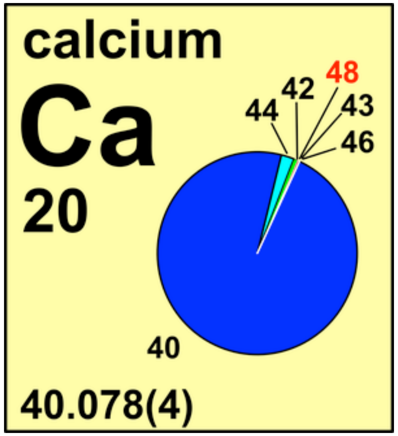
ACT study

Accretion onto compact objects creates ubiquitous disk-jet systems with time-dependent SEDs that exhibit important features in the Mev band that provide critical information.



Where are the other ^{44}Ti sources?



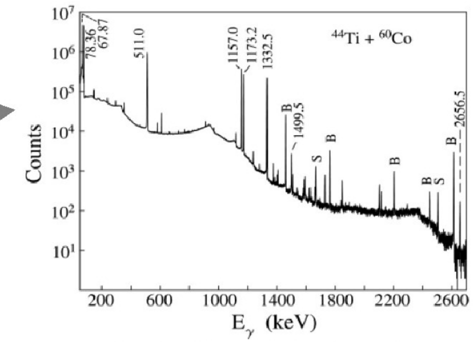


^{44}Ti ➔ ^{44}Sc ➔ ^{44}Ca

The Y_{44} $(1/4\pi D^2)\exp(-t/\tau)$ challenge for sensitivity

☞ partial level schemes and ^{44}Ti decay

J. A. Cameron and B. Singh, Nucl. Data Sheets **88**, 299 (1999).



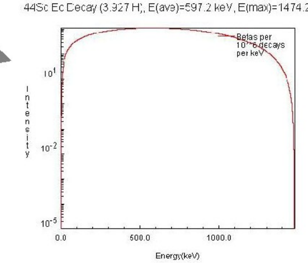
☞ Photons:

- 68 keV 100%
- 78 keV 99.6%
- 1157 keV 99.9%

☞ Positrons

- E_{max}=1.47 MeV 98%

44Sc Ec Decay (3.927 H;, E(ave)=597.2 keV, E(max)=1474.2 keV



☞ Decay Inhibited for Fully-Ionized ^{44}Ti (EC!)

$^{26}Al/^{60}Fe$ flux ratio

~ 10-20% ✔

Diagnostic for SNII/Nova decomposition

We need a map