TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

Proposal for a ½ MW Electron Linac for Rare Isotope and Materials Science

Shane Koscielniak

EPAC08, 24 June 2008

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

Talk Outline

- Motivation for e-linac
- Facility Overview
- Accelerator
- 4th Generation light source technology "testbed"
- Commercial Collaborator
- Photofission
- Nuclear Structure
- Nuclear Astrophysics
- Beta-detected NMR
- Thanks

Multi-Faceted Motivation for e-linac

Science

- High yield of limited number of neutron-rich species but lower isobar contamination
- Neutron-rich rare isotopes niche region complements proton-rich isotope program
- Very few unwanted isotopes produced hence “safer” in our neighbourhood to run @ hi-power – easier licensing
- Expansion of β-NMR essential for unique Canadian facility
- Explore novel medical-isotope production

Technology

- New driver hones skills on a new technology - development of SRF competence makes Canadian industry 1 of 5 in world
- ILC advanced accelerator R&D involvement – work at edge of technology
- Testbed for 4th generation light source technology

Partnerships

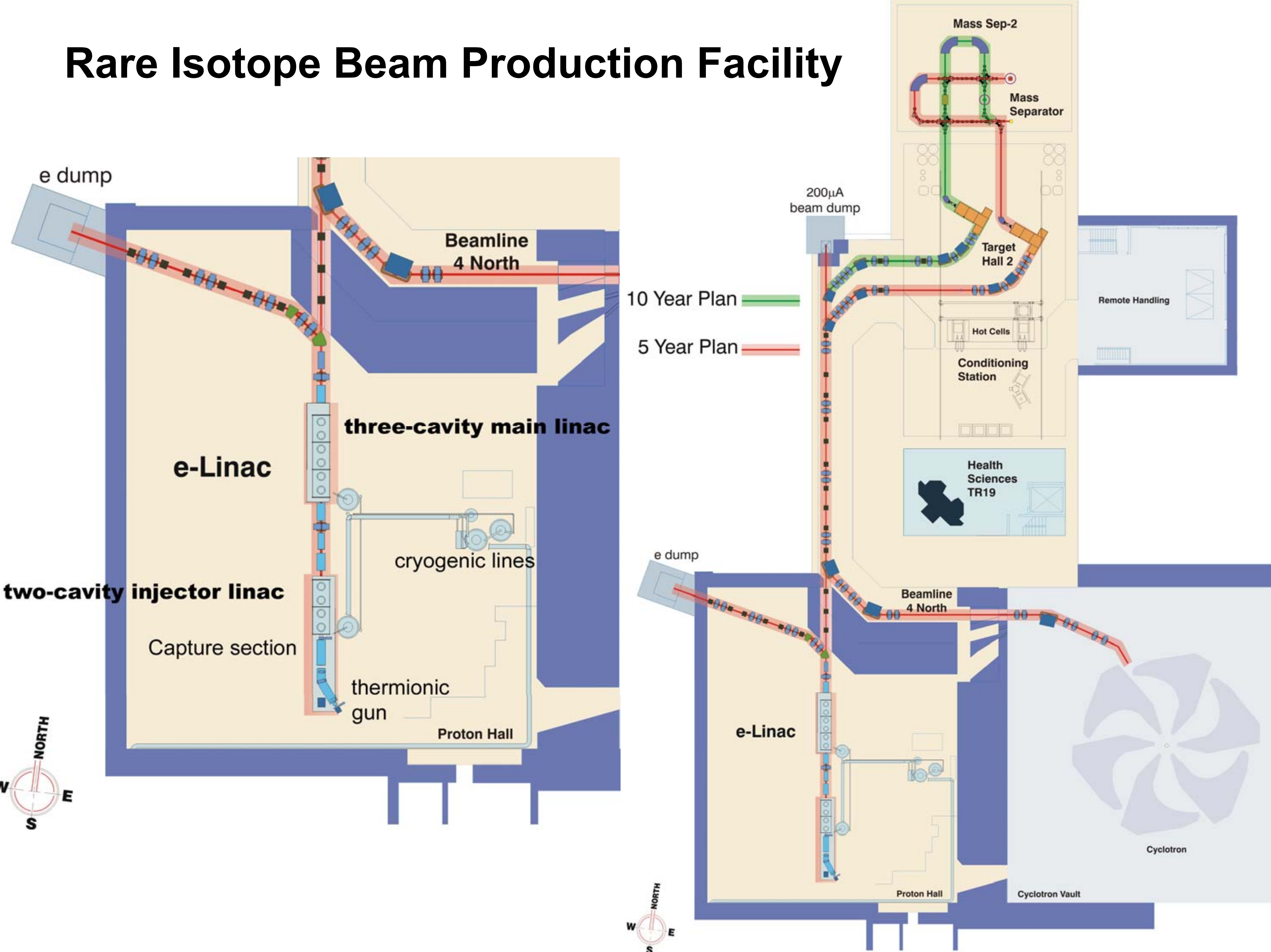
- Connects TRIUMF to Asia: VECC India will co-build & RIKEN photo-fission collaboration
- Building two-way collaboration with local high-tech company, PAVAC, for elliptical cavity fabrication

e-linac & new proton beam line

A 10-Year Plan for ISAC

- ***A Critical Shortage of New Unstable Nuclei Beams at ISAC***
- **All the ISAC programs critically need more rare-isotope beams.**
- **More beam time, more beams delivered, and more science**
- E-linac implements strategy of multiple beams (e, p) to multiple users to accelerate science output
- One electron and one proton beam line in a common tunnel using new common actinide target technology
- Physics Case: nuclear astrophysics (neutron rich r-process, proton rich rp-process, element abundances, supernova explosion neutron density models, neutron star crusts and nuclear structure with actinides (unique in world), Begin fundamental symmetries,
- Allow beta-NMR to triple in running time (study interfaces at 4 nm longitudinal resolution, basic research of material boundaries, unique facility in world – inflight laser spin polarization)
- Opportunity for new radio-tracer development with actinides.

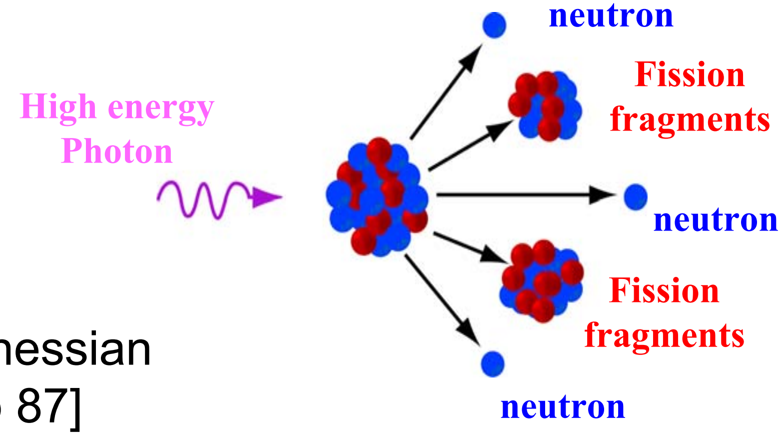
Rare Isotope Beam Production Facility

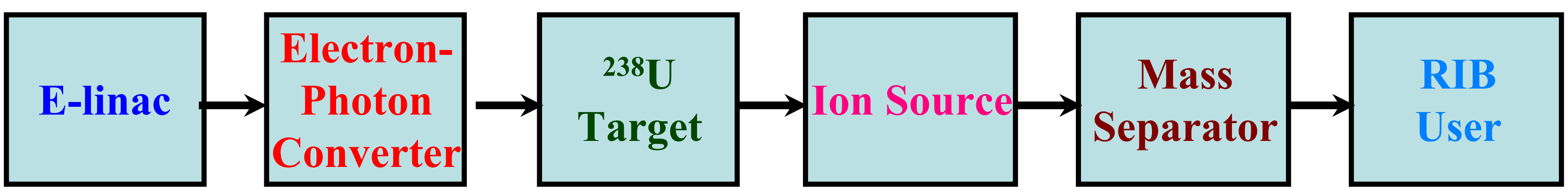


E-linac photofission

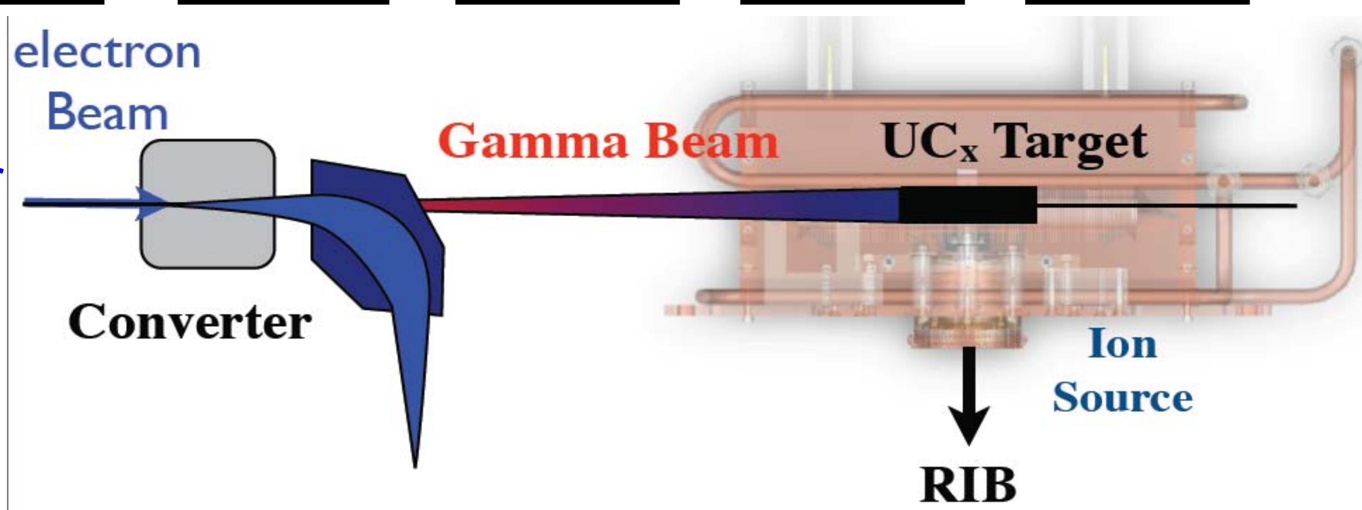
Photofission of ^{238}U has been proposed by W. T. Diamond (Chalk River) in 1999 [NIM, V 432, (1999) p 471] as an alternative production method for RIB.

The idea was taken a little further by Y. T. Oganessian in 2000 [RNB2000, Nucl. Phys. A 701 (2002) p 87]



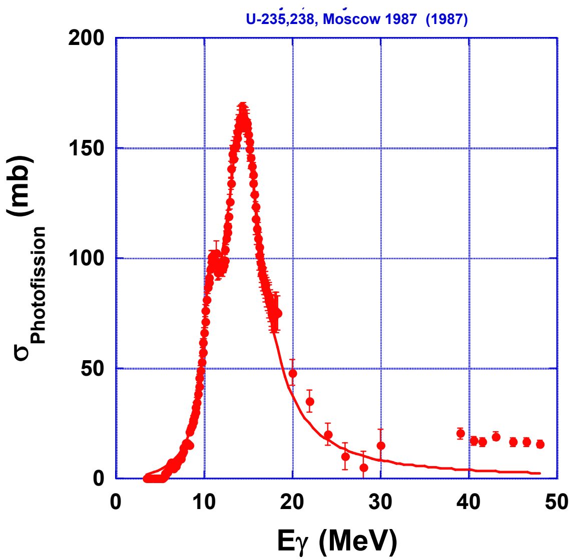


Electron beam power > 25 kW

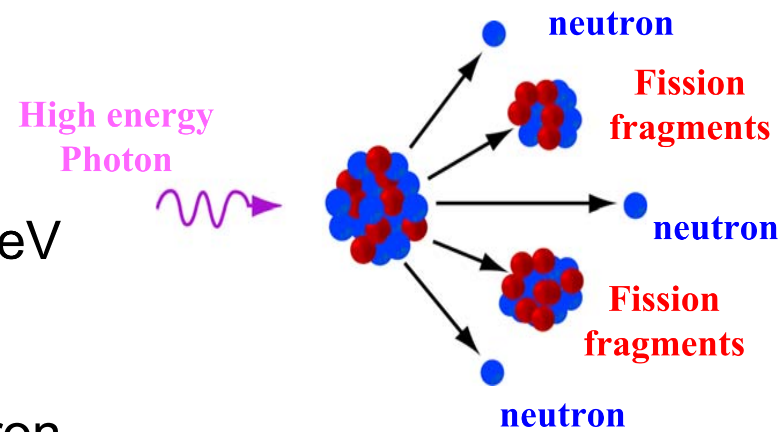


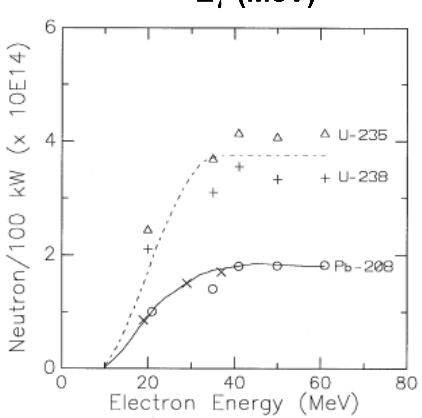
E-linac photofission

The continuous gamma spectrum produce by electron bremm-strahlung is utilized to excite giant dipole resonance (GDR) in ^{238}U.



Photofission cross-section ≈ 160 mb @ 15 MeV photons
Leads to E-3 photofission/electron





Neutron/fission yield saturates above 40 MeV

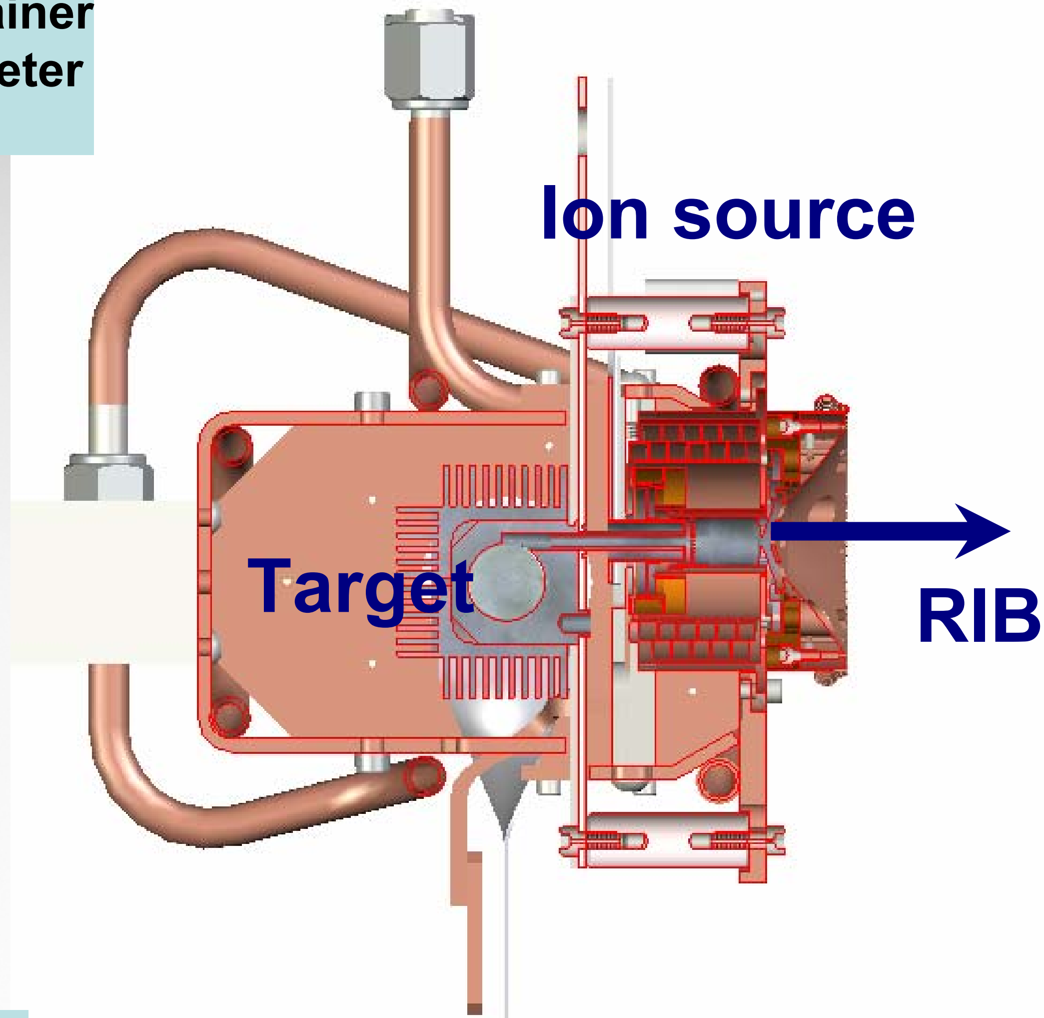
Conclusion: A 50 MeV, 500 kW electron beam could produce 4-7 ×10^{13} fissions/second from a ^{238}U target, leading to copious neutron-rich isotopes.

Adapt existing ISAC Target/Ion Source for 500 MeV 10μA protons

Target container
20 mm diameter
20 cm long

P < 5 kW dissipated in the target by proton beam

High power target can dissipate P ~ 20 kW in target



E-linac Beam Specification

Bunch charge (pC)	16
Bunch repetition rate (GHz)	0.65
Radio frequency (GHz)	1.3
Average current (mA)	10
Kinetic energy (MeV)	50
Beam power (MW)	0.5
Duty Factor	**100%**

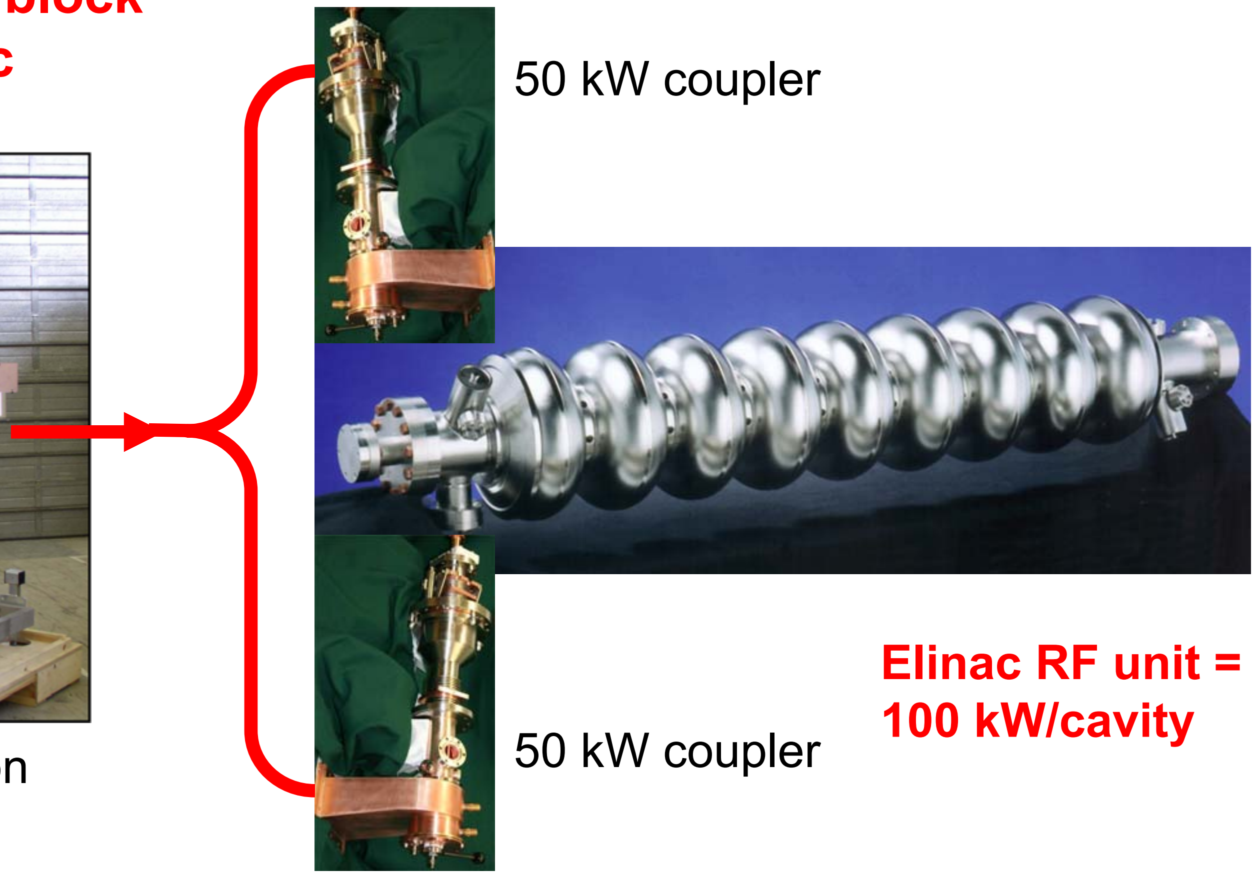
Bunch vital statistics	inject	eject
Normalized emittance (μm)	<30π	<100π
Longitudinal emittance (eV.ns)	<20π	<40π
Bunch length (FW), inject (ps)	<170	>30
Energy spread (FW)		<1%

The requirement: 50 MeV × 10 mA = ½ MW beam power eliminated on target.

- **ILC: gradient-limited**
- **Fission-driver: power limited by input coupler and cryo load**

HLRF building block for E-linac

130 kW klystron

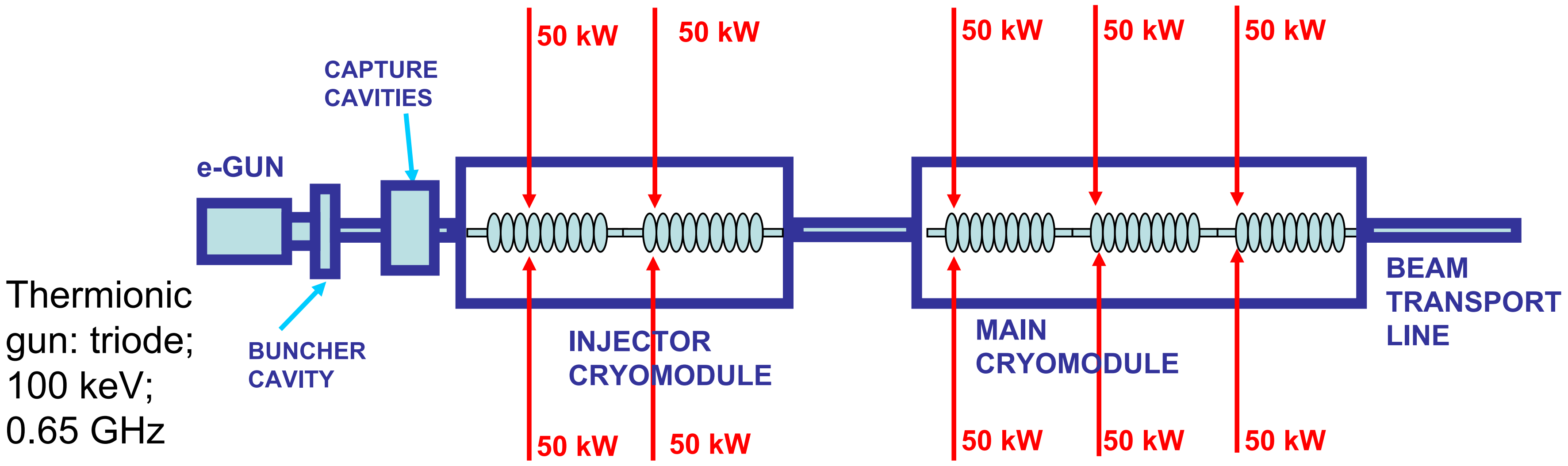


Beam current	Cavity gradient	Quality Factor	# cavities	Beam energy	Beam power
10 mA	10 MV/m	10^{10}	5	50 MeV	500 kW

E-linac power distribution

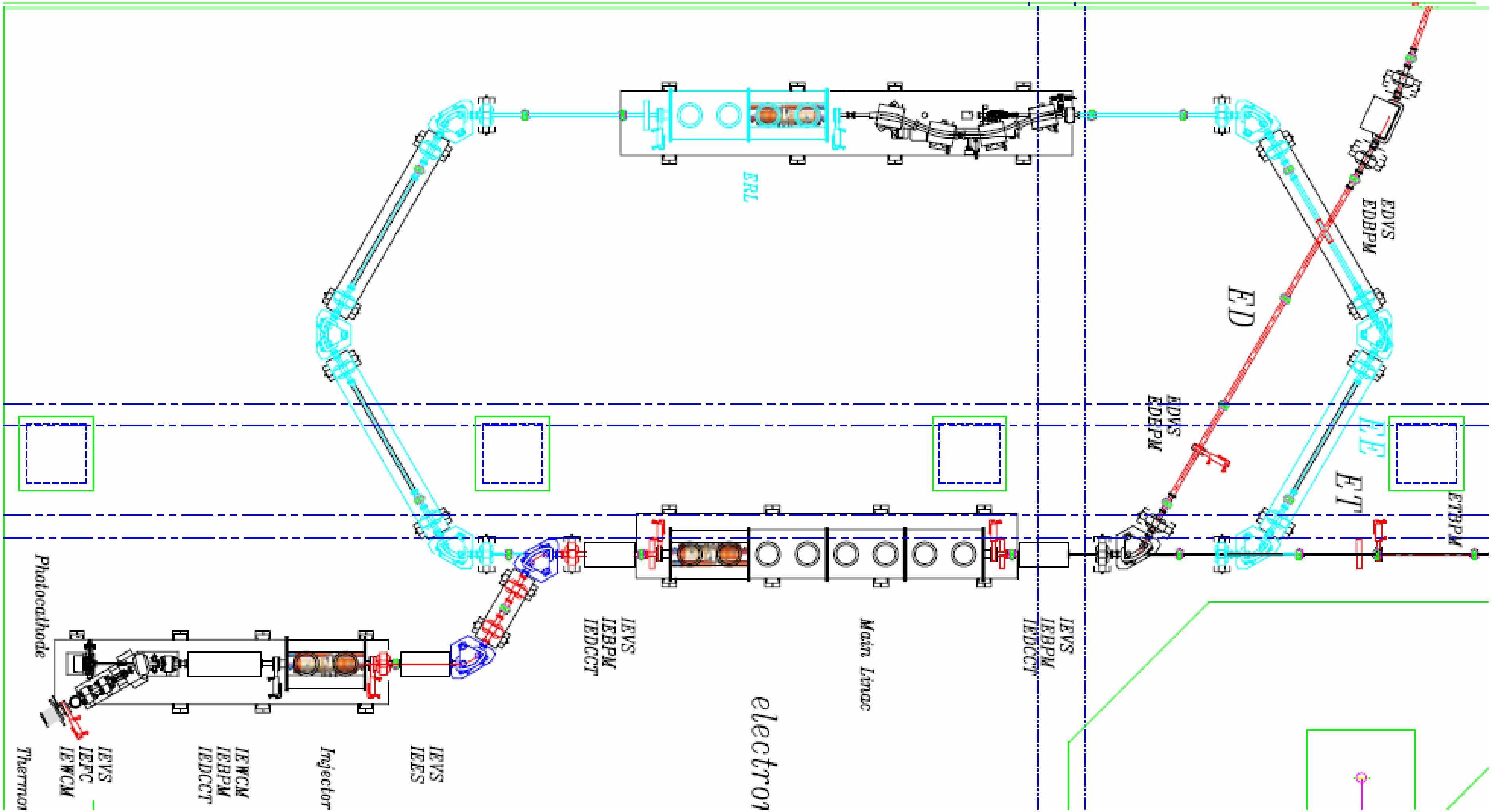
Five 130 kW klystrons

Fission Driver: 500 kW CW RF power has to propagate through input couplers and cavities to beam



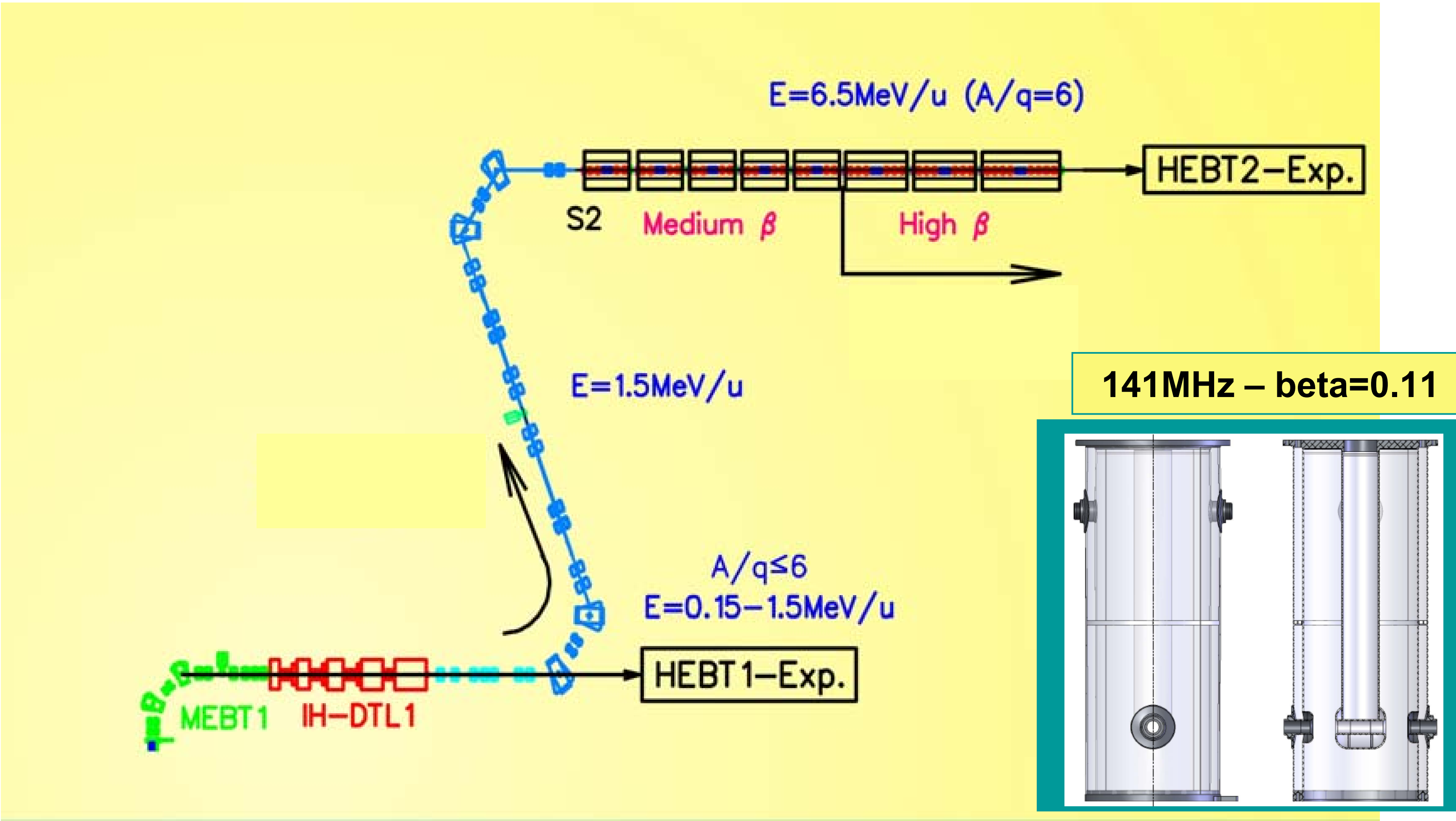
Division into injector & main linacs allows:

- Injector to prototype some components for main linac
- Definite staging: 5 mA, 40 MeV mid-2013; 10 mA, 50 MeV after 2015
- Possible expansion path to test-bed for
  - Energy Recovery Linac (ERL) – e.g. 10 mA, 80 MeV
  - Recirculating Linear Accelerator (RLA) – e.g. 2 mA, 160 MeV



Insertion of return arcs (light blue) could reconfigure E-linac as ERL or RLA – **for demonstrator of 4th generation light source technology**

Partnership with BC-based engineering company on ISAC-II SC Linac-Future



The Phase-II Extension of ISAC-II calls for the addition of 20 `high beta' (β=0.11) quarter wave cavities by the end of 2009

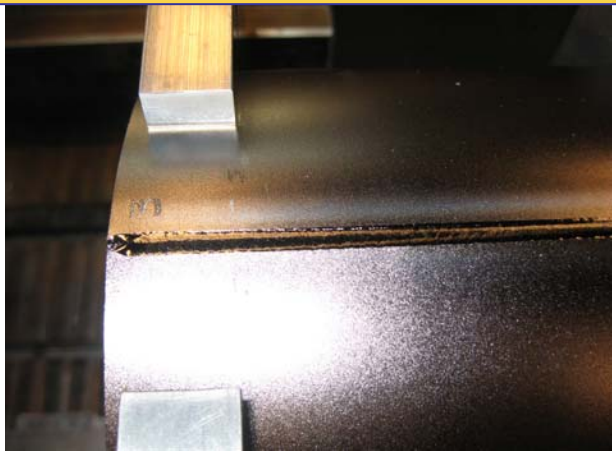
Beta=0.11 cavity prototypes at PAVAC

- Who is PAVAC?
  - A Canadian Company located in Richmond B.C.
- Specializing in
  - Electron Beam Welding
  - Precision machining
  - Pulsed Electron Beam Coating (PEB-PVD)

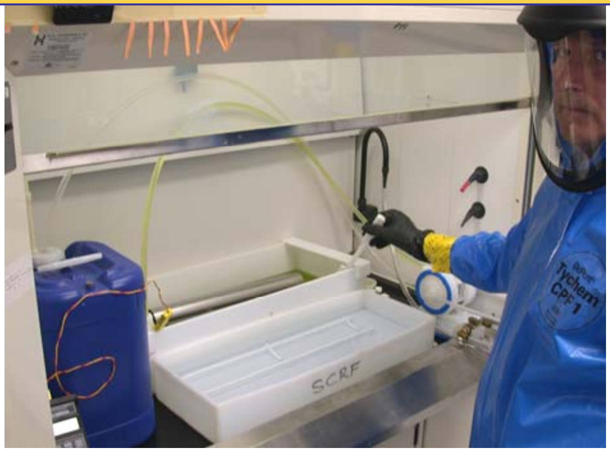
First Frequency Tuning

Forming and Machining

EB Welding



Pre-weld Etching - TRIUMF



Bulk Nb quaterwave cavity

# cavities	When
6	August 2008
6	November 2008
8	Feb. 2009

- The future: fabricate 1.3 GHz elliptical cavities for e-linac: 3 single-cell prototypes, two 9-cell prototypes, two 9-cell for HTF, five 9-cell for elinac.
- Building e-linac cavities could qualify PAVAC for future ILC contracts.
- Interest in industrial applications

The Big Questions in Nuclear Structure

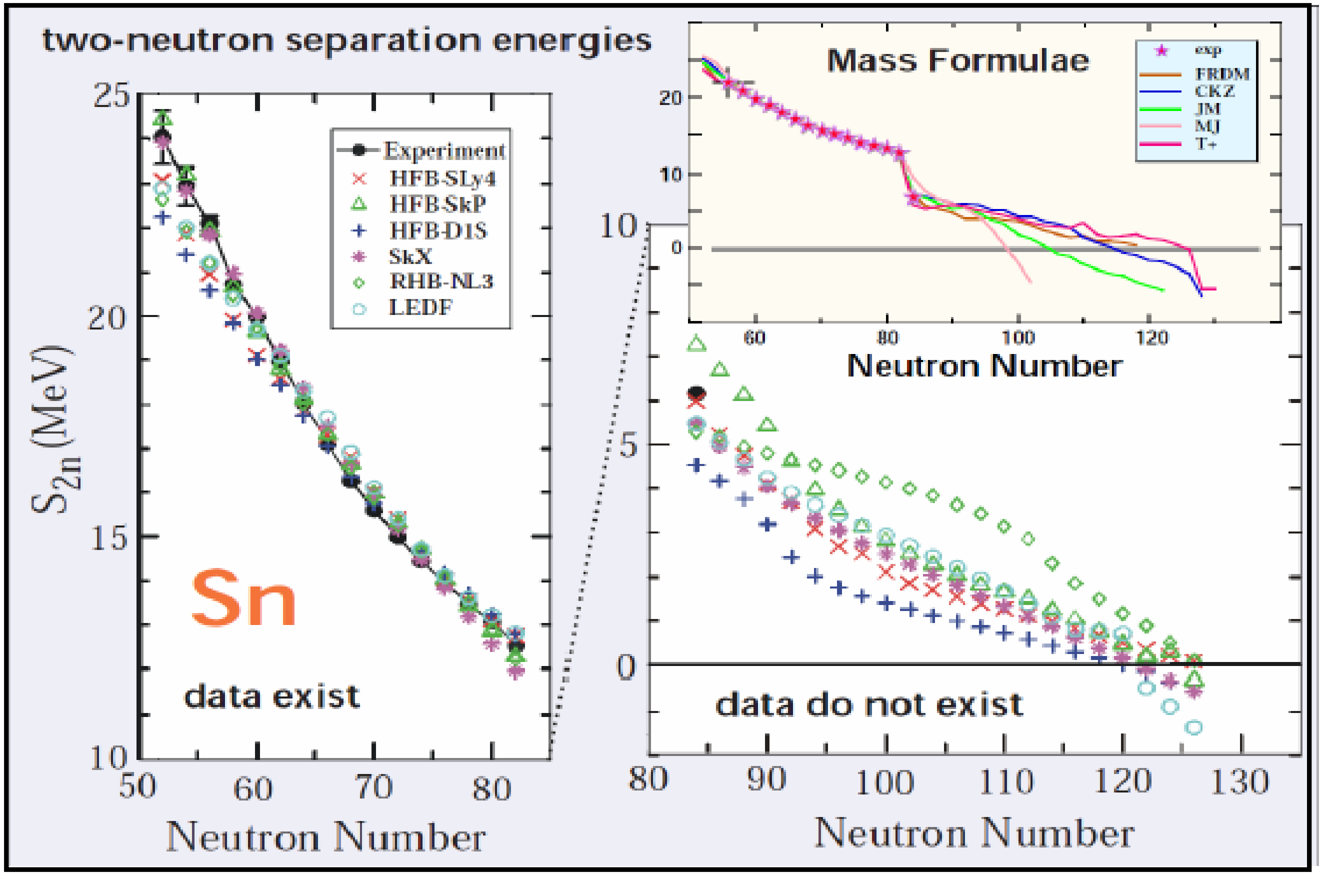
- What is the Structure of Nuclei and Nuclear Matter?
- What are the Limits of Nuclear Existence? (proton/neutron drip lines?)
- What are Nuclear Properties as Function of Neutron-to-Proton Asymmetry?
- Studies of the Evolution of Shell Structure at ISAC
- Nuclear Matrix Elements for Extracting Neutrino Masses

Nuclear theory needs experimental input to refine the models.

- Mass spectrometry is a key field to provide basic and benchmark data for nuclear structure & for theory
- Mass spectroscopy often a discovery tool for new phenomena:
  - Appearance/disappearance of Magic Numbers.
  - Finding of new isomers in unexpected regions.

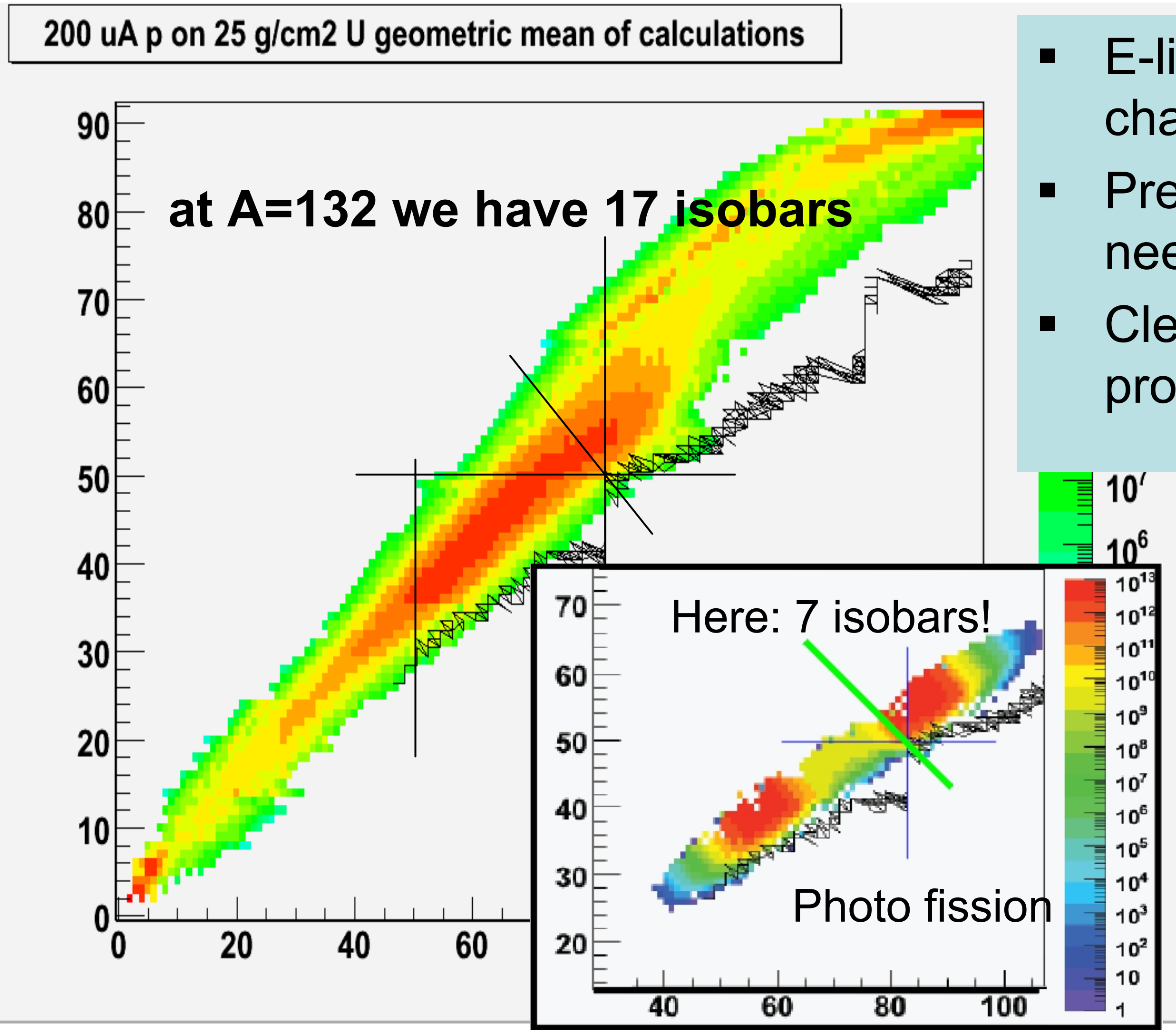
Mass measurements - example

Nuclear structure at neutron-rich heavy (A=132) hot topic to test theory



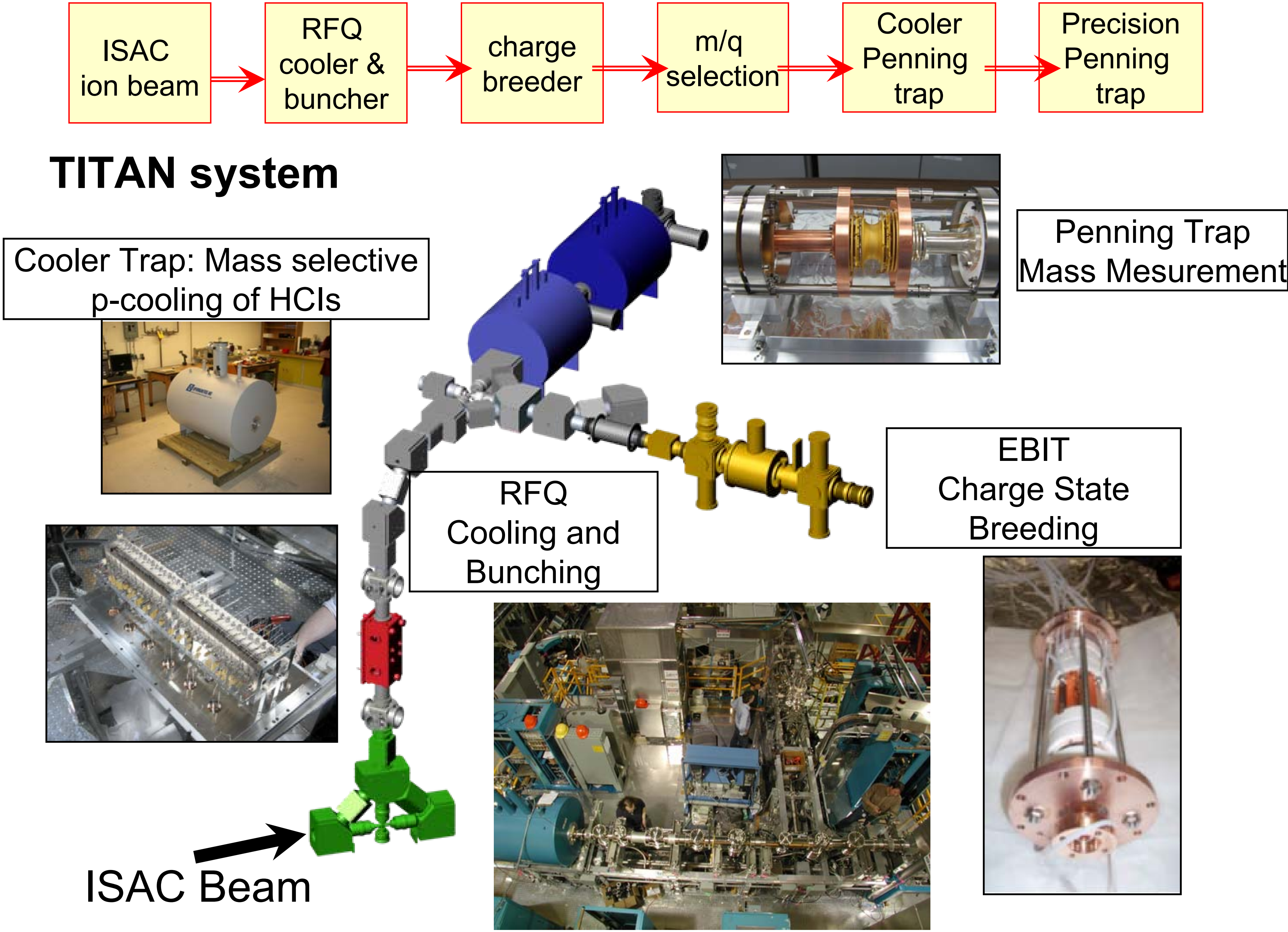
- New mass measurements (Dwarschak et al PRL 2008) removed the proposed shell gap at N=84 and restored N=82 as Magic Number.
- BUT: mass measurements difficult, since yields are low and half-lives short **- plus beam purity is a problem!**

Production in limited area with the photo fission system



- E-linac provides unique area of chart of isotopes.
- Precise and accurate data needed!
- Cleaner beams due to limited production (isobar suppression).

Use photo-production and advanced ionisation capabilities (resonant laser) to provide beams in best quality (low emittance) and very clean (low or zero contamination).


ISAC ion beam
RFQ cooler & buncher
charge breeder
m/q selection
Cooler Penning trap
Precision Penning trap
TITAN system
Cooler Trap: Mass selective p-cooling of HCIs
Penning Trap Mass Mesurement
EBIT Charge State Breeding
RFQ Cooling and Bunching
ISAC Beam

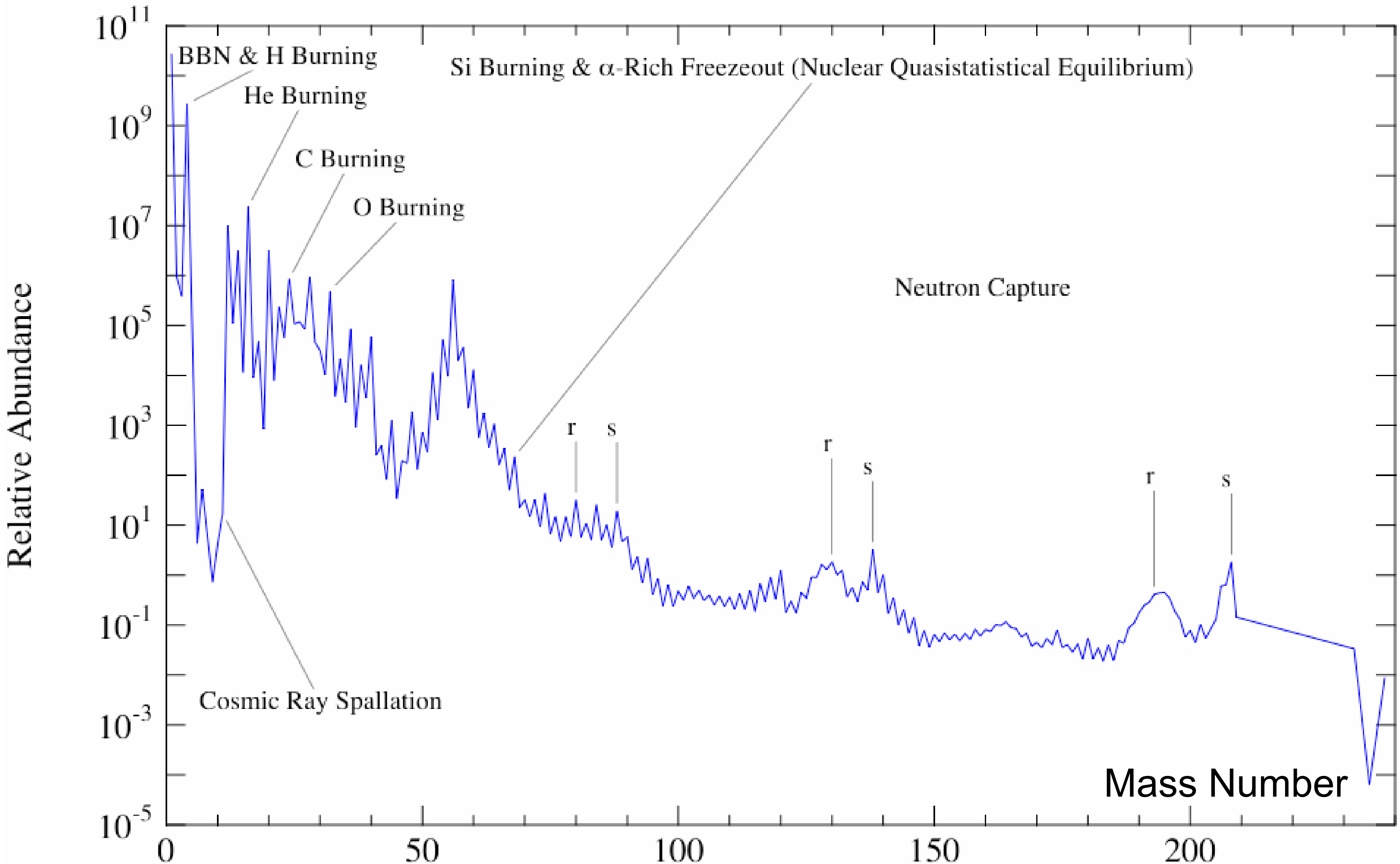
Nuclear Astrophysics- The Big Questions

- **How, when, and where were the chemical elements produced?**
- **What role do nuclei play in the liberation of energy in stars and stellar explosions?**
- How are nuclear properties related to astronomical observables:
  - solar neutrino flux,
  - γ-rays emitted by astrophysical sources,
  - light curves of novae, supernovae,
  - and x-ray bursts of neutron stars/accretion disks?

ISAC will focus on Nuclear Astrophysics with Neutron-Rich Nuclei

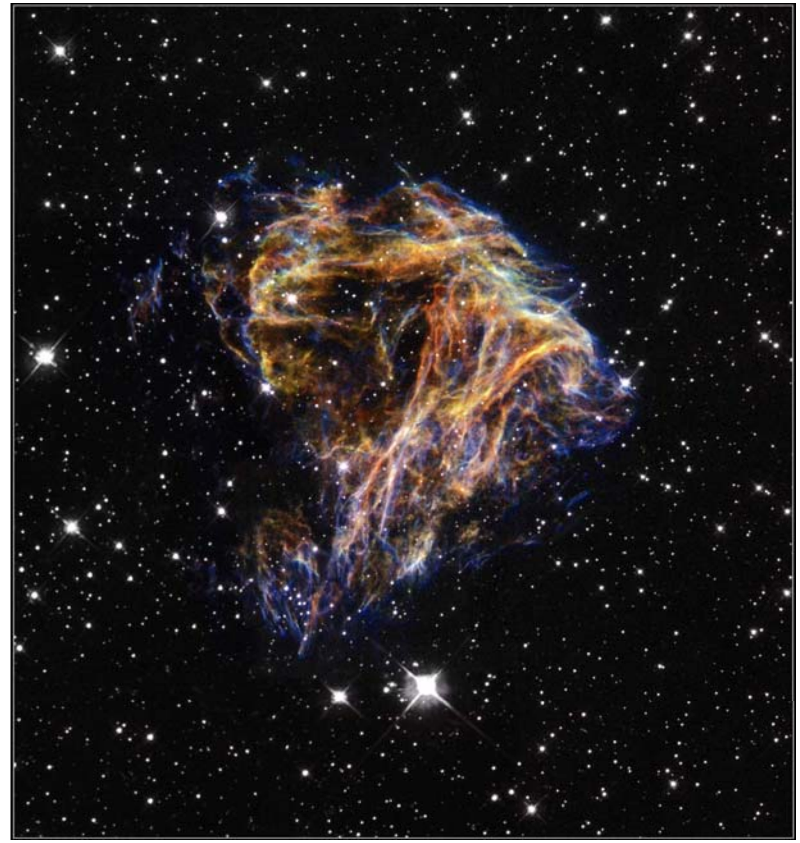
- *r* process: neutron captures on very rapid timescale (~ 1 s) in a hot (GK), dense environment (> 10^{20} neutrons cm^{-3})
- Observational and experimental constraints are crucial

Abundances and Origins of the Chemical Elements



Neutron-rich nuclei are of primary importance in the *r* process, which created roughly half of the nuclei with A > 70

The *r*-Process Site?

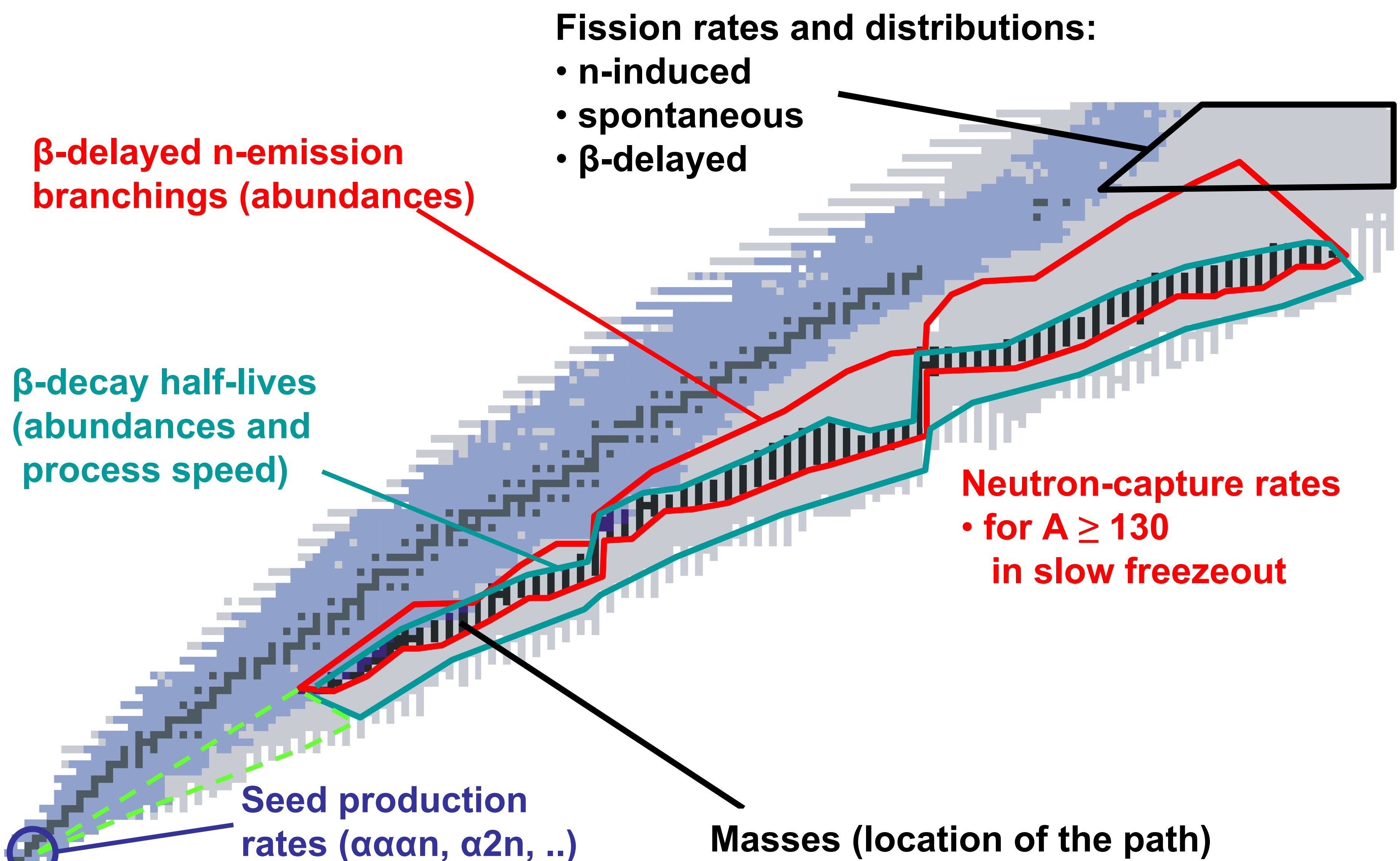


Core-collapse supernovae are the favoured astrophysical site; explosion liberates synthesized elements, distributes throughout interstellar medium.

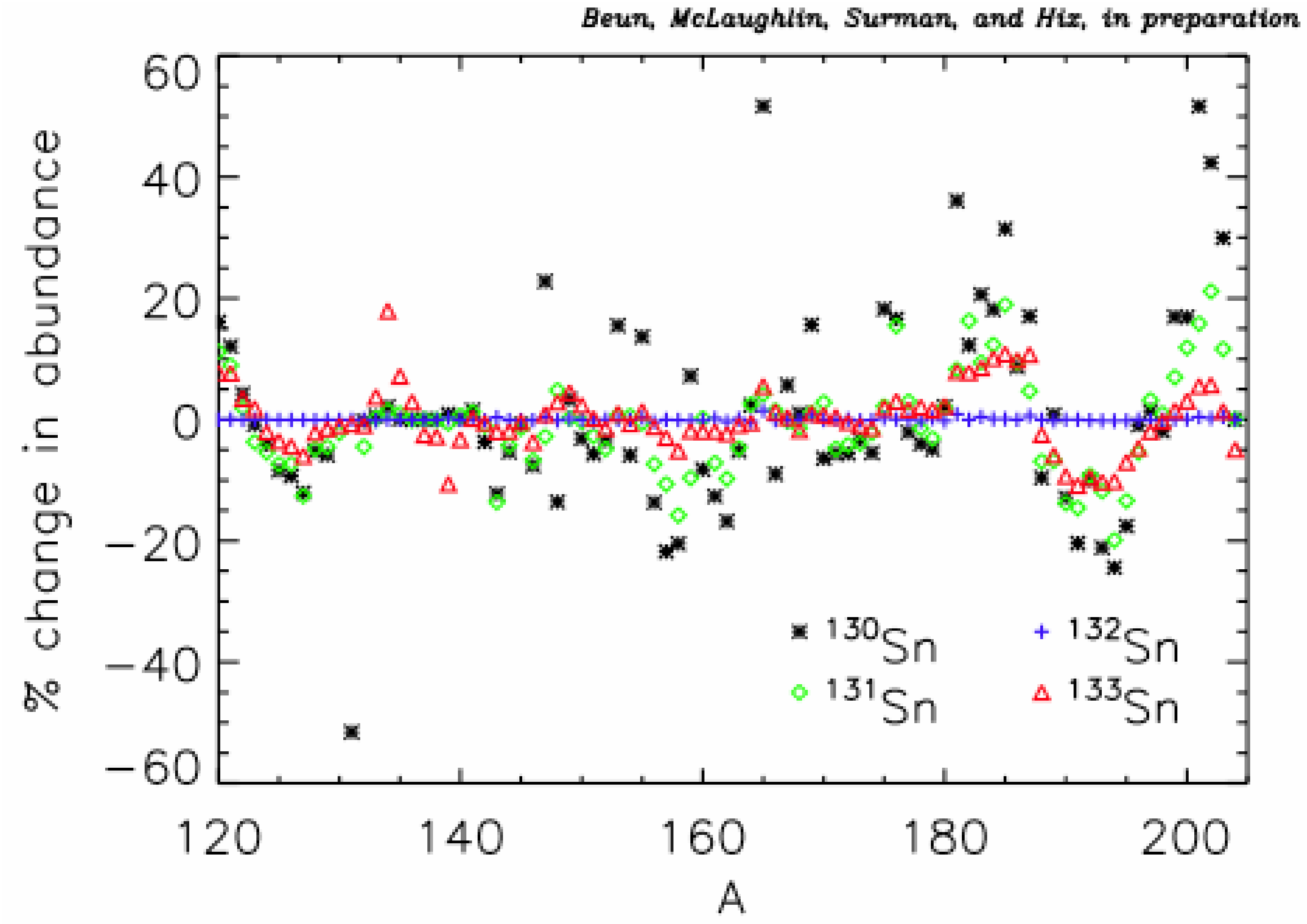
Abundances of *r* process elements in old stars show consistent pattern for $Z > 47$, but variations in elements with $Z \leq 47$, implying ≥ 2 sites

Montes *et al.* 2007

Nuclear Physics of the *r* Process



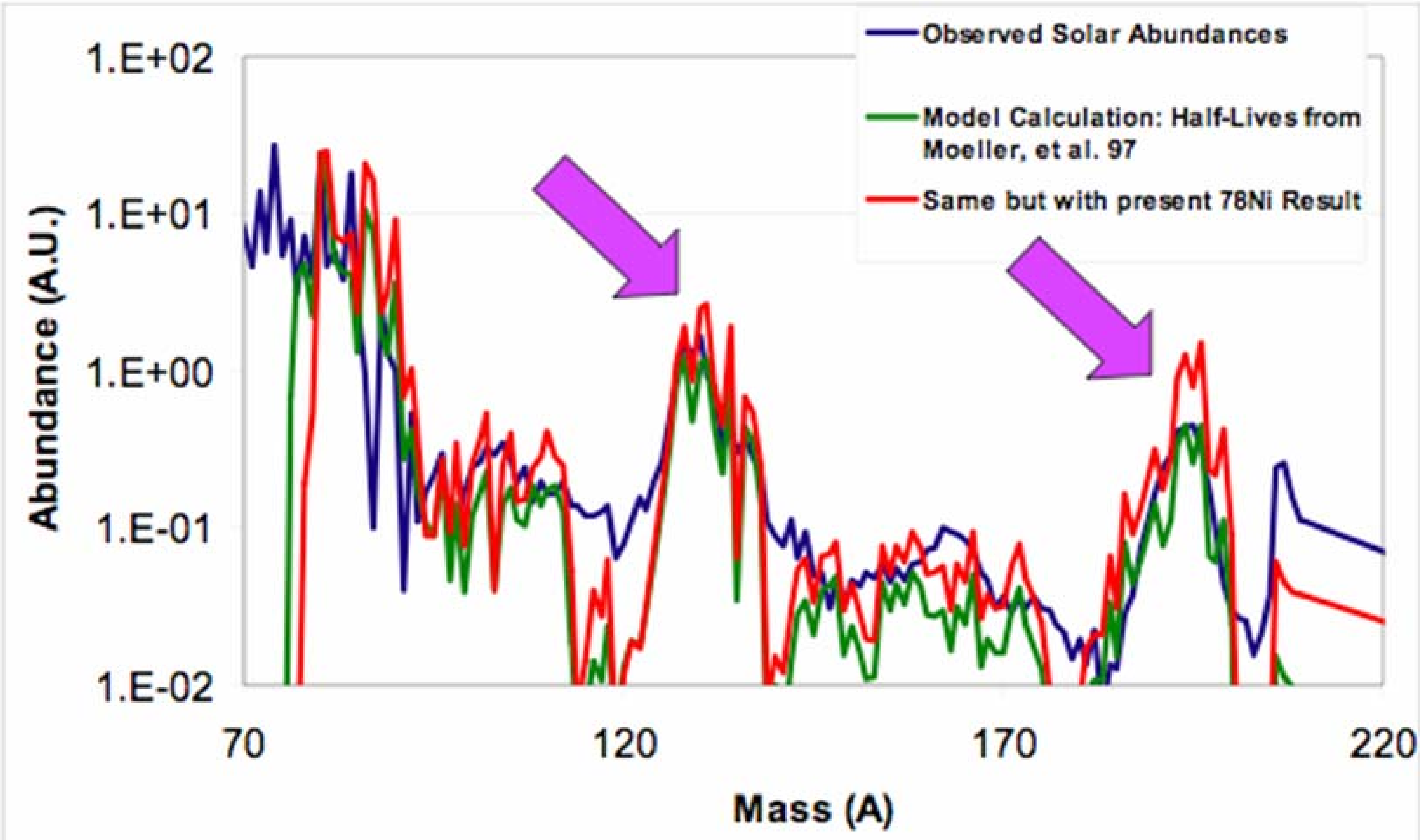
Neutron Capture Rates May "Matter"



n capture rates multiplied by 100 for sensitivity study

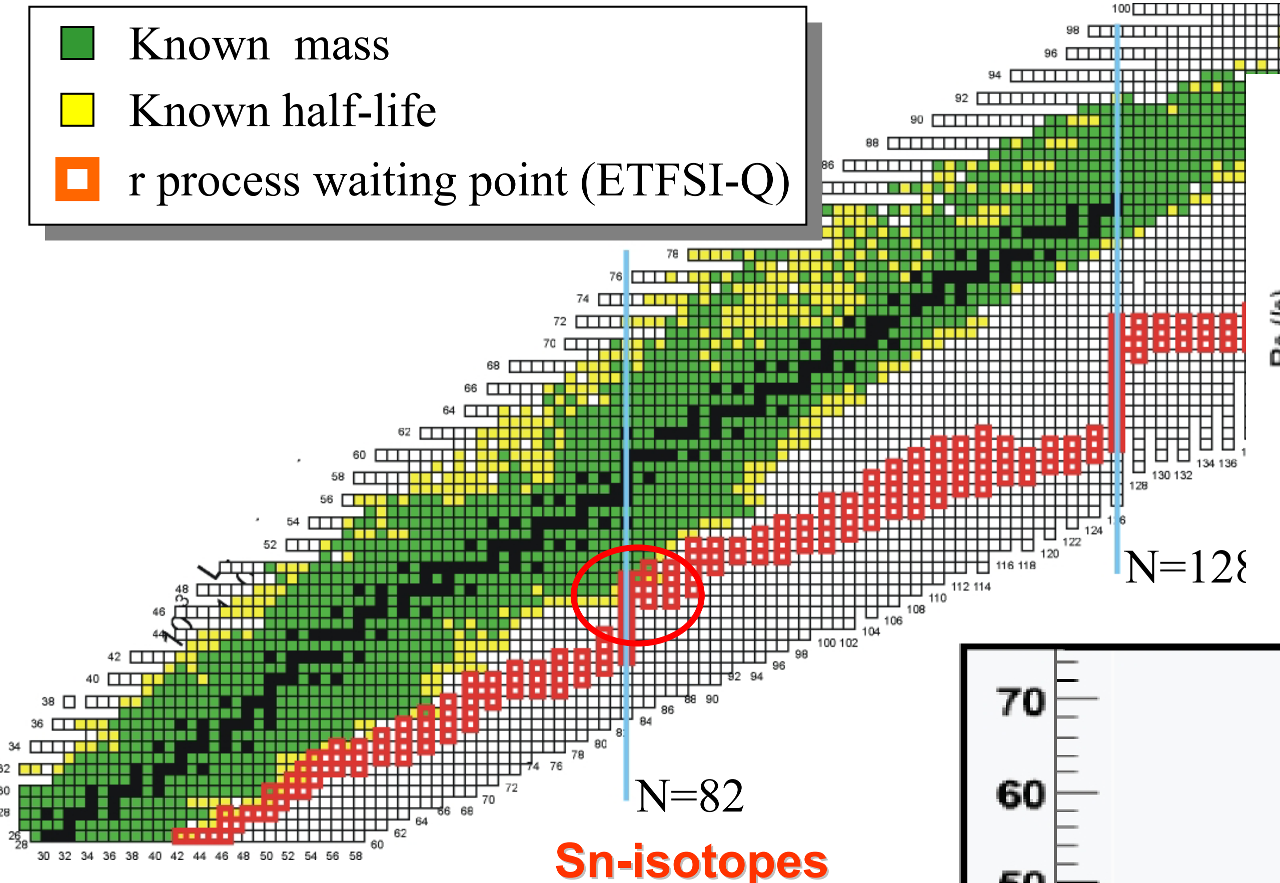
Beun, McLaughlin, Surman, and Hix 2008

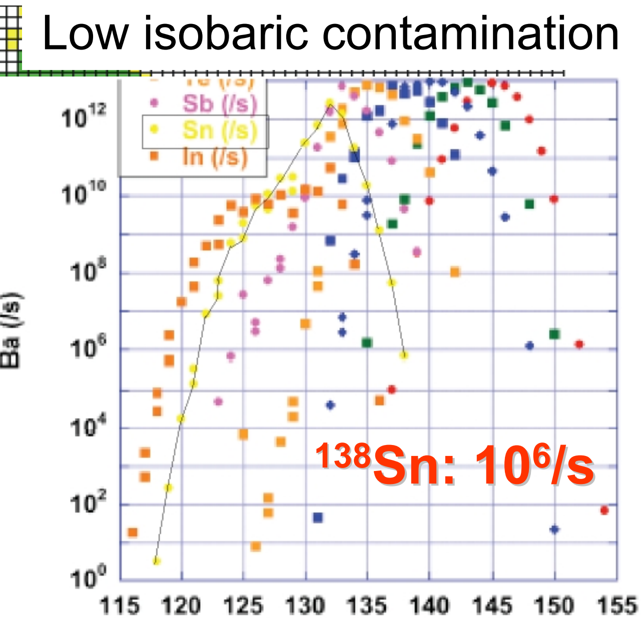
Beta-decay Half-Lives Influence Abundances

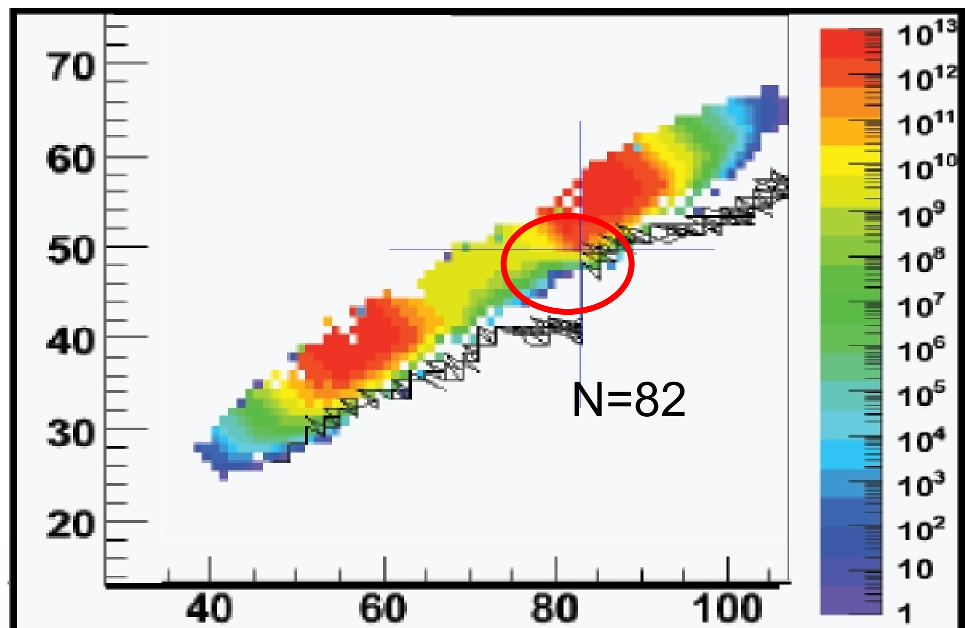


Hosmer, Schatz *et al.* 2005

r-process path: measurements at ISAC



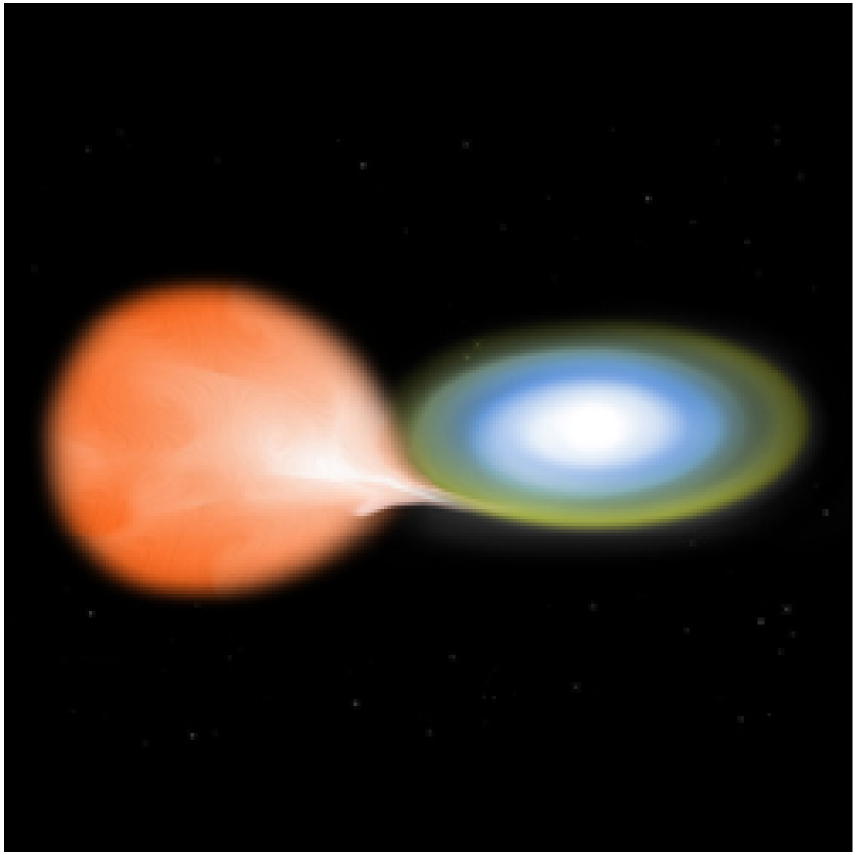




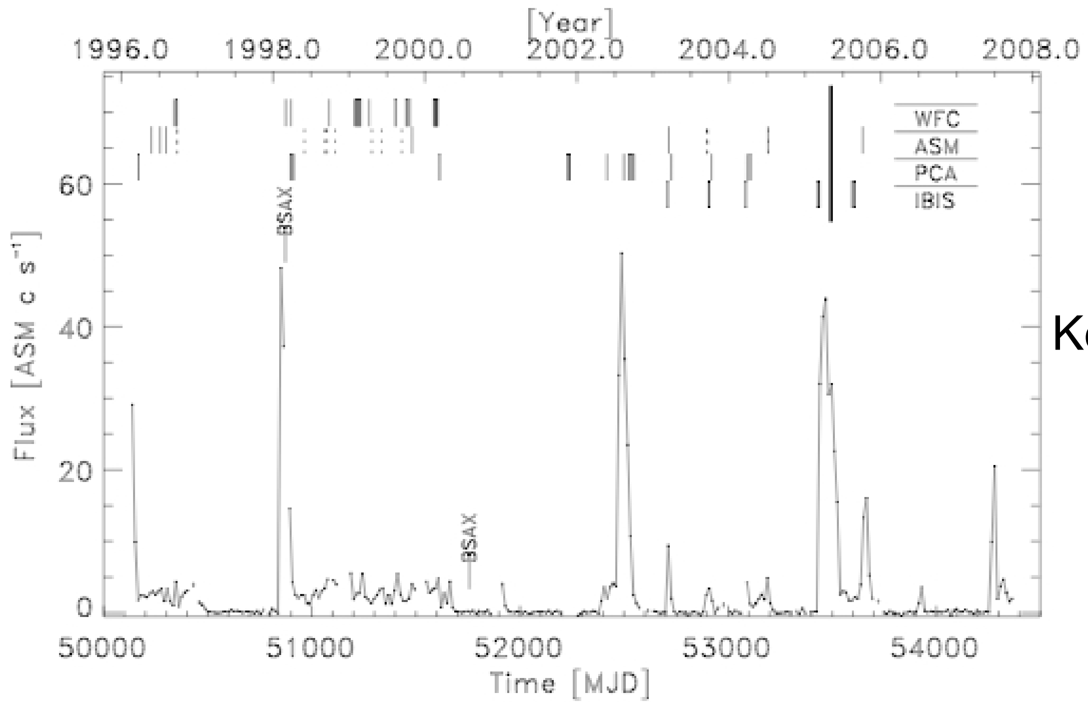
Photofission produces only neutron-rich nuclei with A > 70
Overlaps *r*-process progenitors, notably 50 ≤ N ≤ 62 and 82 ≤ N ≤ 90;
E.g., mass measurements of ^{136}Sn, ^{139}Sb, ^{142}Te

Interacting Binaries: X-Ray Bursts

- Accretion onto neutron stars in binary systems triggers thermonuclear explosions
- X-ray bursts: Huge increases in emitted light, nucleosynthesis
- Explosion confined to thin shell on surface, repeats after further accretion



Accreting Neutron Stars: X-Ray Bursts and Superbursts



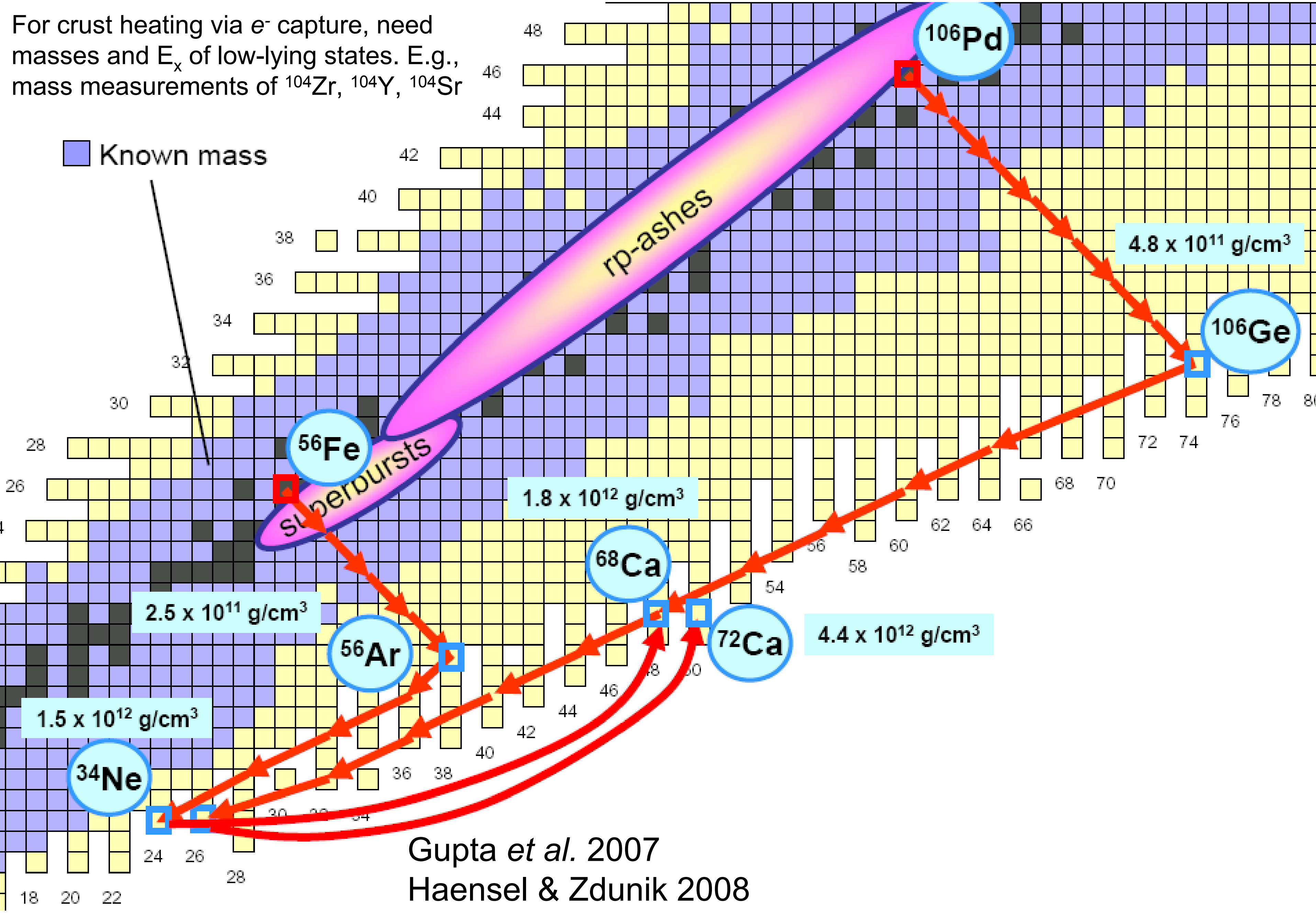
Keek *et al.* 2008

X-ray burst: accreted H and He from low mass companion lands on NS surface, layer builds up; thermonuclear runaway ensues

Superbursts may result from explosive C burning at greater depth, sensitive to thermal properties of crust

Neutron Star Crust Heating – where can we contribute?

For crust heating via e^- capture, need masses and E_x of low-lying states. E.g., mass measurements of ^{104}Zr, ^{104}Y, ^{104}Sr



Gupta *et al.* 2007
Haensel & Zdunik 2008

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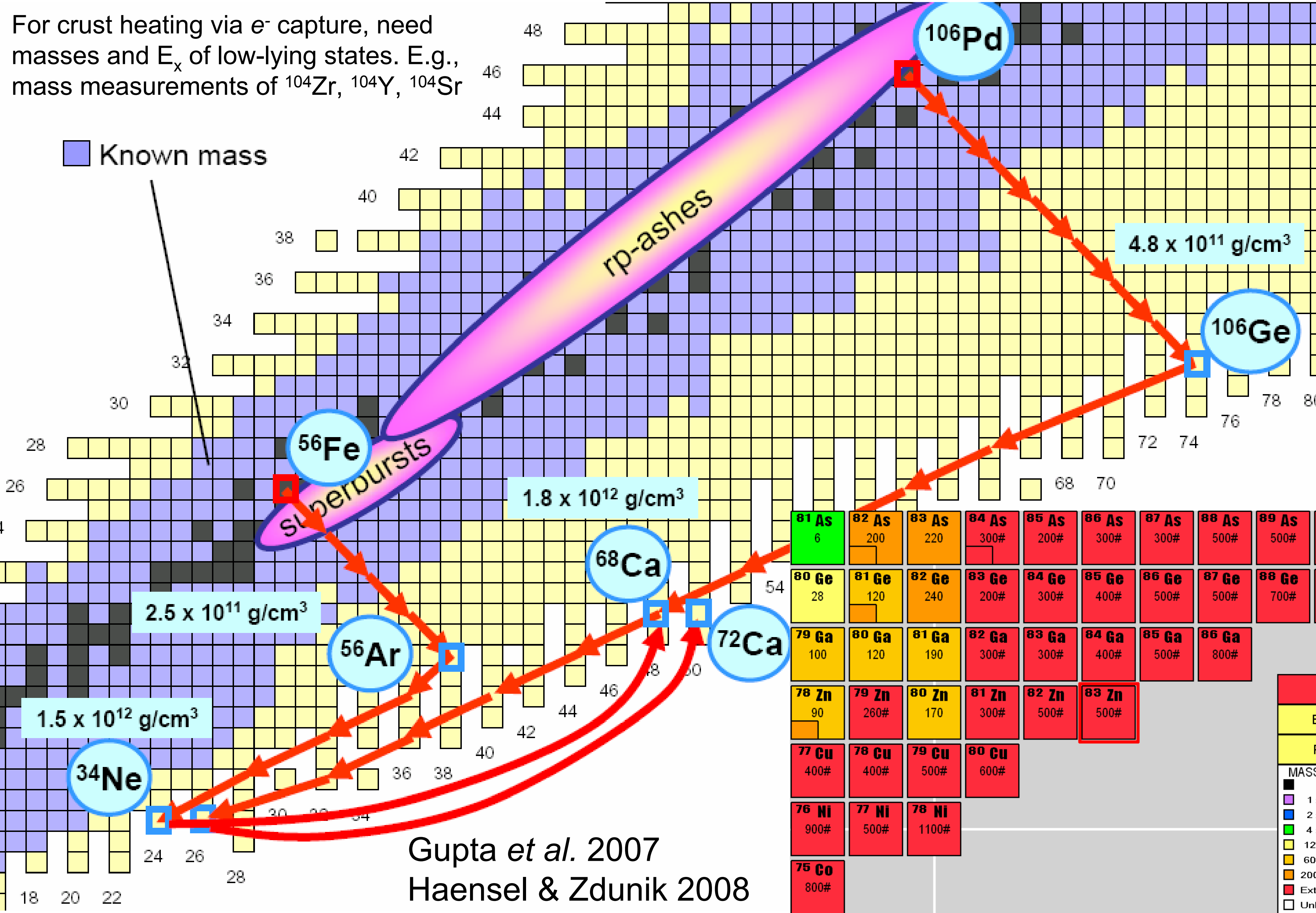
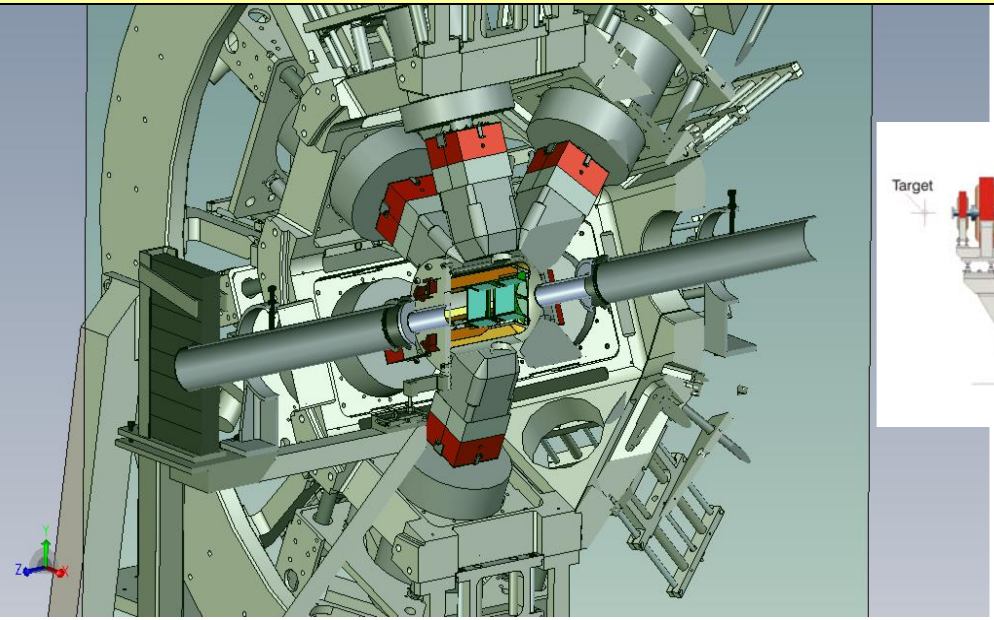


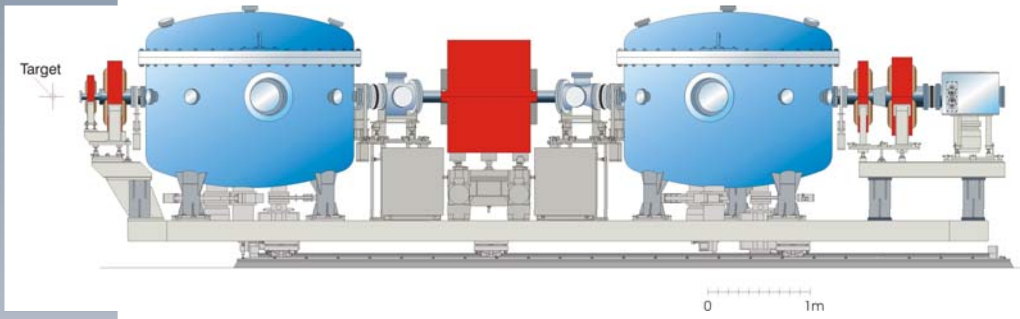
Measurements in Nuclear Astrophysics Enabled by the Proposed Facility

We need systematic measurements of nuclear masses, β-decay lifetimes, β-delayed n emission probabilities, neutron capture rates, and excitation energies to constrain astrophysical models & determine *r* process site(s)

β-decay half-lives: 8π / EMMA + TIGRESS e.g. Zr, Pd, Ag, In, Rh
β-delayed n emission probabilities: DESCANT + EMMA
Masses: TITAN e.g. Pd, Ag, Cd, In, Sn, Sb, Te
(d,p) reactions around N=82, fusion studies: EMMA + SHARC + TIGRESS



TIGRESS + SHARC

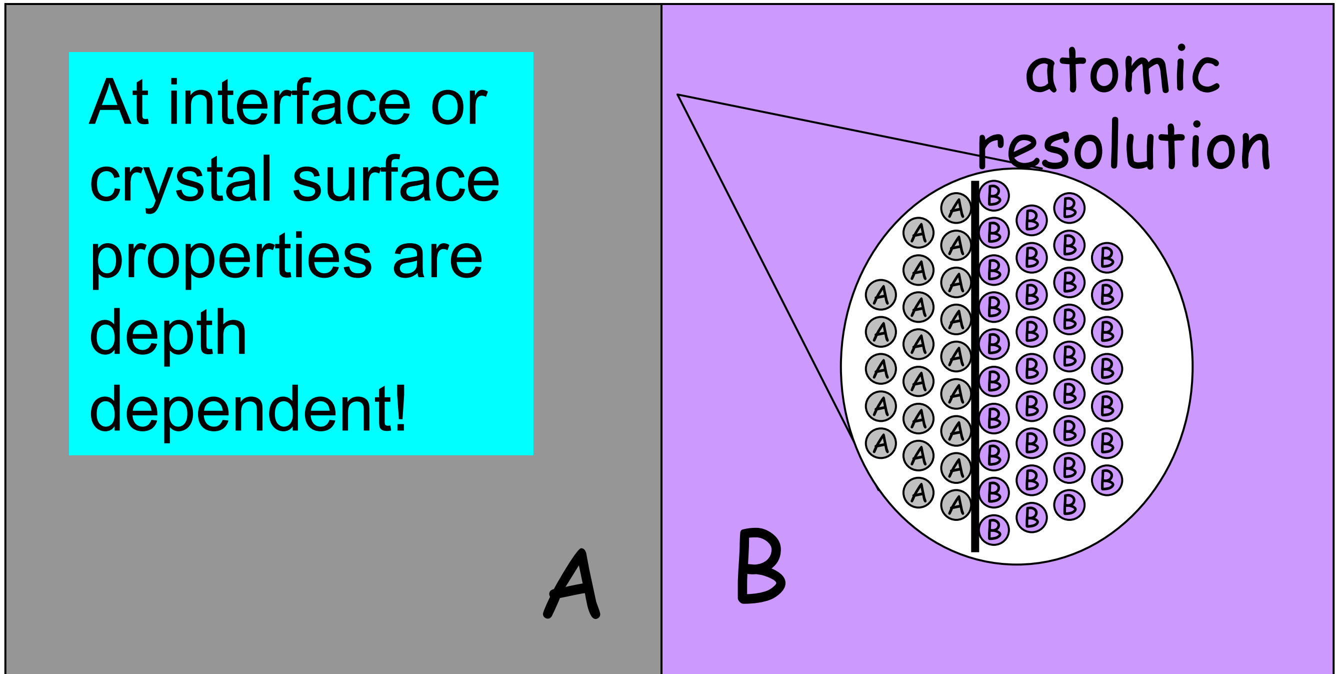


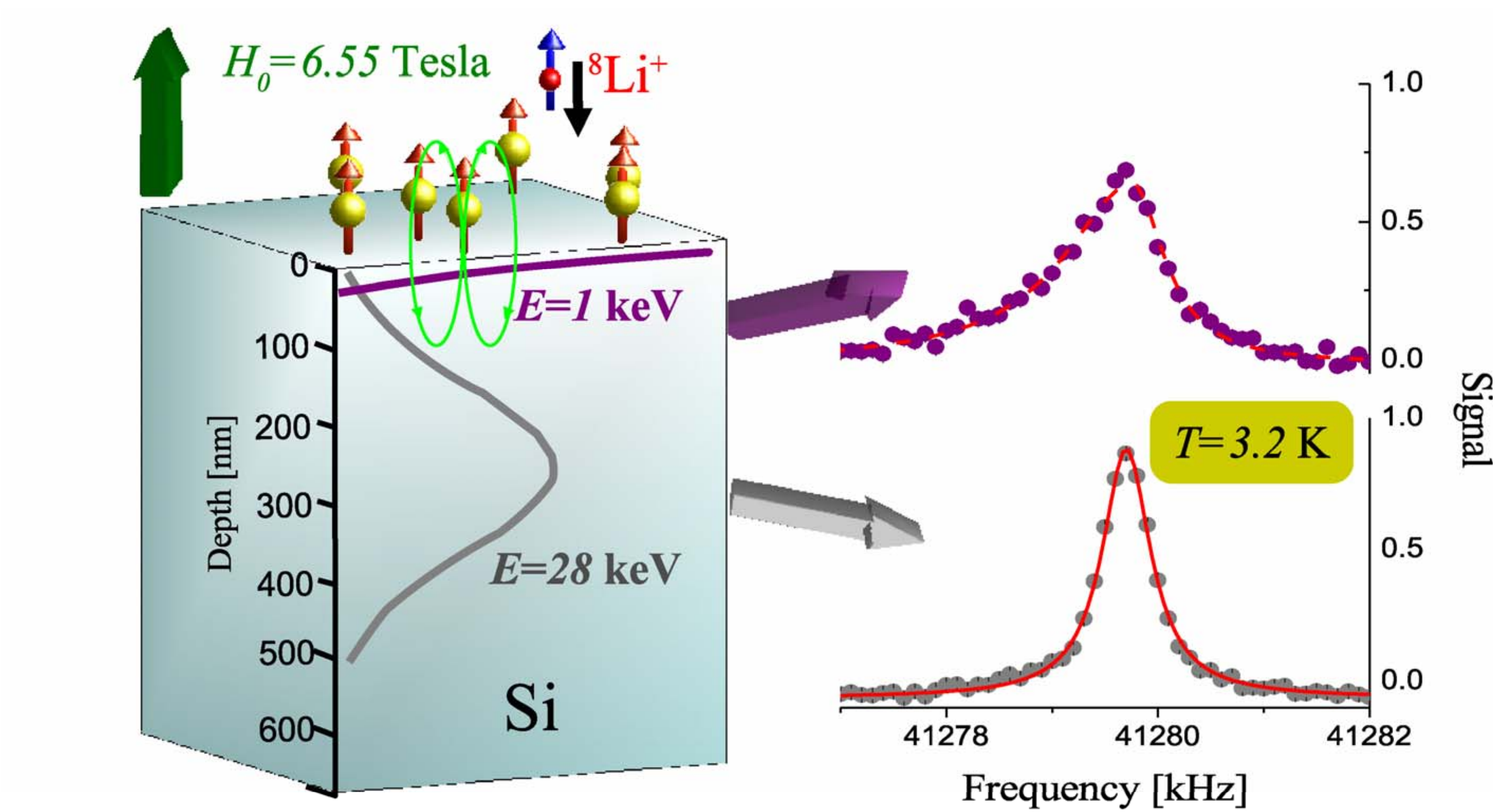
EMMA: ElectroMagnetic Mass Analyser

The Science of ß-NMR: Metamaterials & solid Interfaces

E-linac will produce Light Unstable Nuclei for beta-detected NMR

- **Beta-detected NMR (β-NMR) employs implanted spin-polarized light ions, $^{8}Li^{+}$, that sense their magnetic environment and report this information through their spin-dependent anisotropic beta decay,**
- Provides sensitive magnetic probes for studies of matter at atomic scale.
- ßNMR is a near surface probe ~ 200 nm depth resolved capability, whereas is a bulk probe ~ 0.1 mm
- ßNMR probes much longer lived than μ^{+}, sense different phenomena than μSR



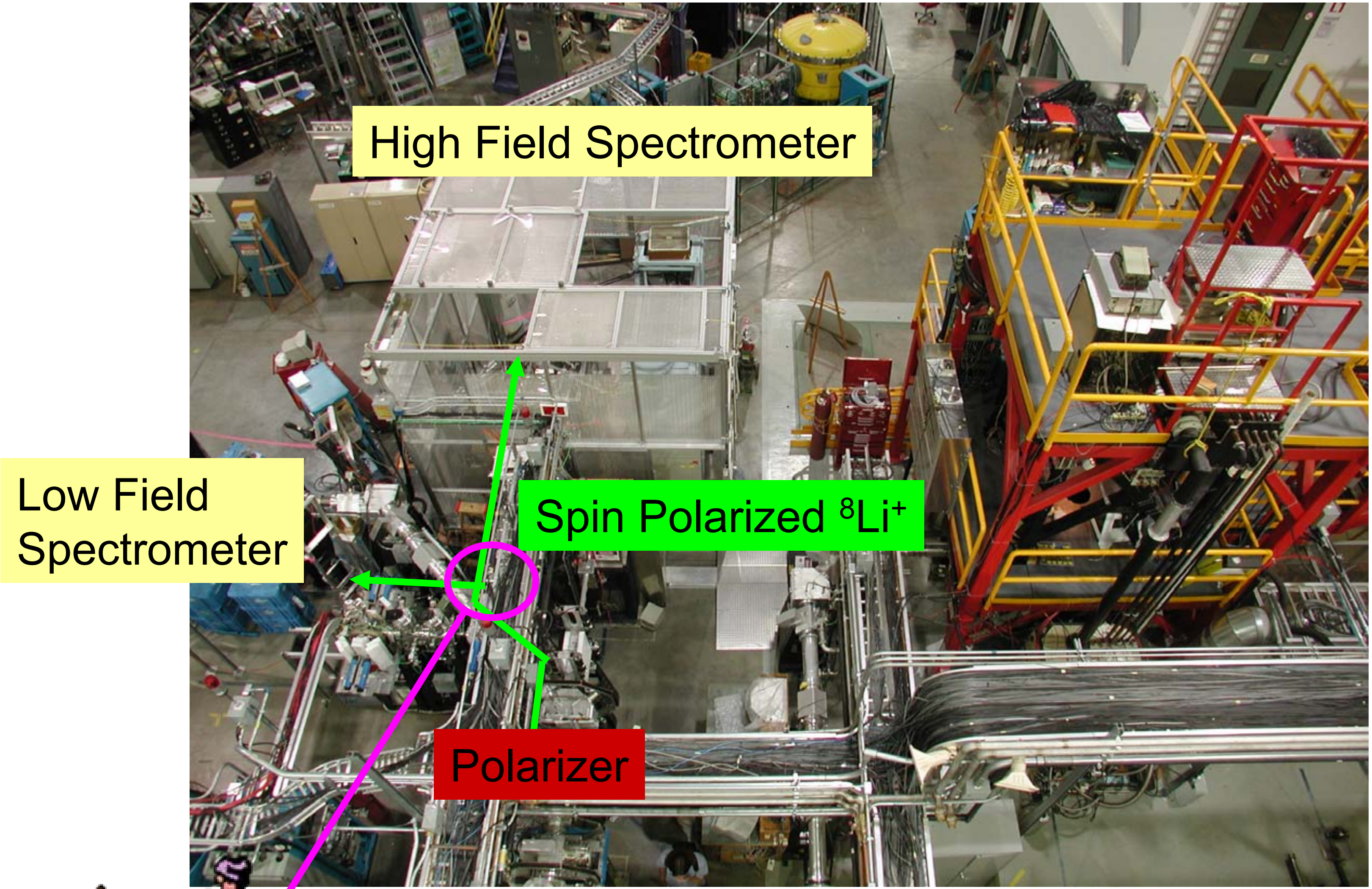


Single-molecule magnets at surface of Si substrate

28 keV implantation: probe senses silicon environment

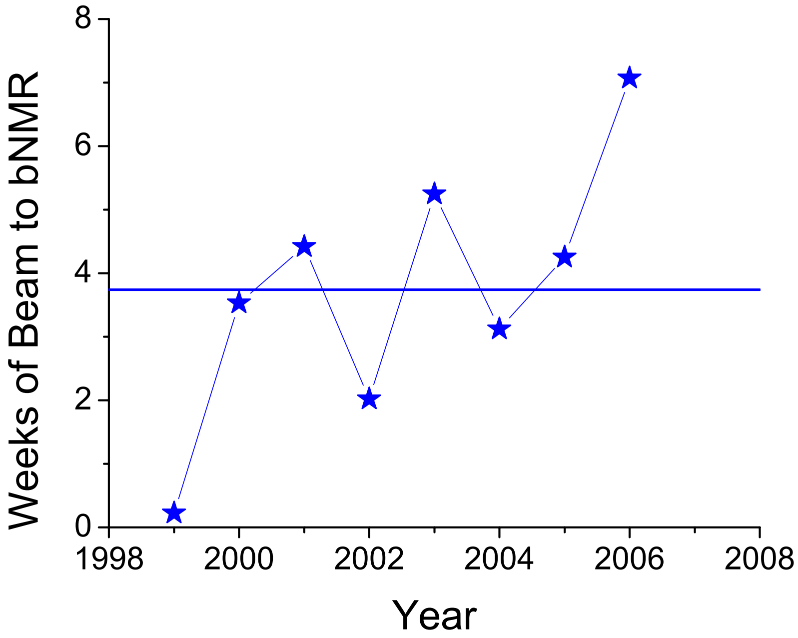
1 keV implantation, probes stops close to SMMs and sense their magnetic fields

β-NMR at TRIUMF ISAC



Fast Kicker (2005) allows semi-simultaneous operation

$^{8}Li^{+}$ Beam Delivered to β-NMR per year



Average:
3.74 weeks
per year

user facility
not feasible

- **To make the leap to user facility, it is essential to implement a parallel source of RIBs such as the proposed photofission source.**
- As β-NMR uses exclusively light isotopes, like ^{8}Li, species may be produced directly by photodisintegration, *e.g.* the ^{9}Be(γ, *p*)^{8}Li reaction,
- With the proposed new e-linac source, we anticipate that the beam time available for β-NMR will quadruple.

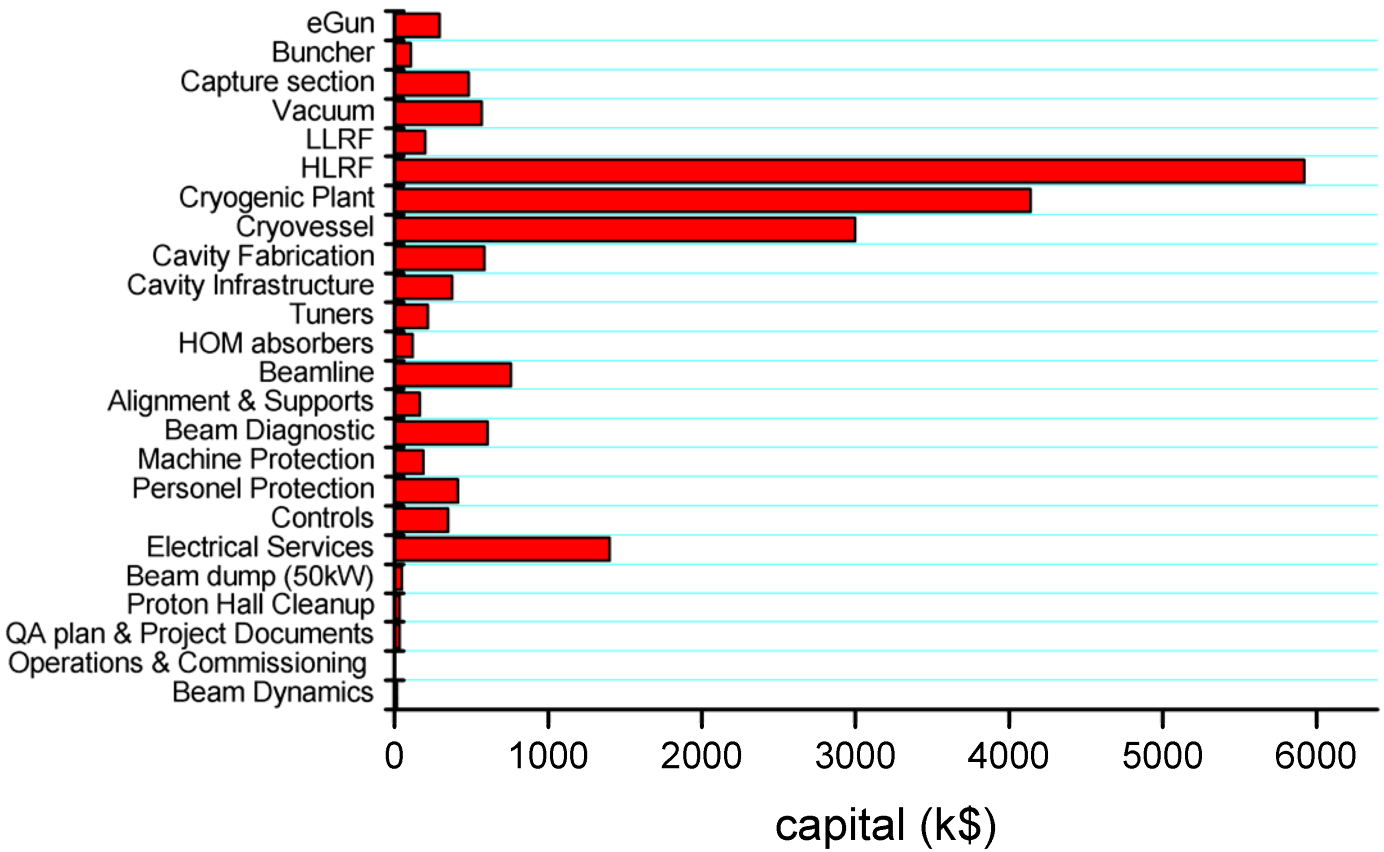
Thanks for your attention

Acknowledgements

F. Ames, P. Bricault, Y. Bylinsky, B. Davids, J. Dilling, M. Dombsky, R. Laxdal, M. Marchetto, A.K. Mitra, I. Sekachev, V. Verzilov (TRIUMF, Vancouver, BC, Canada)
D. Karlen (U.Victoria), W.A. MacFarlane (U.B.C).

Project costs and manpower

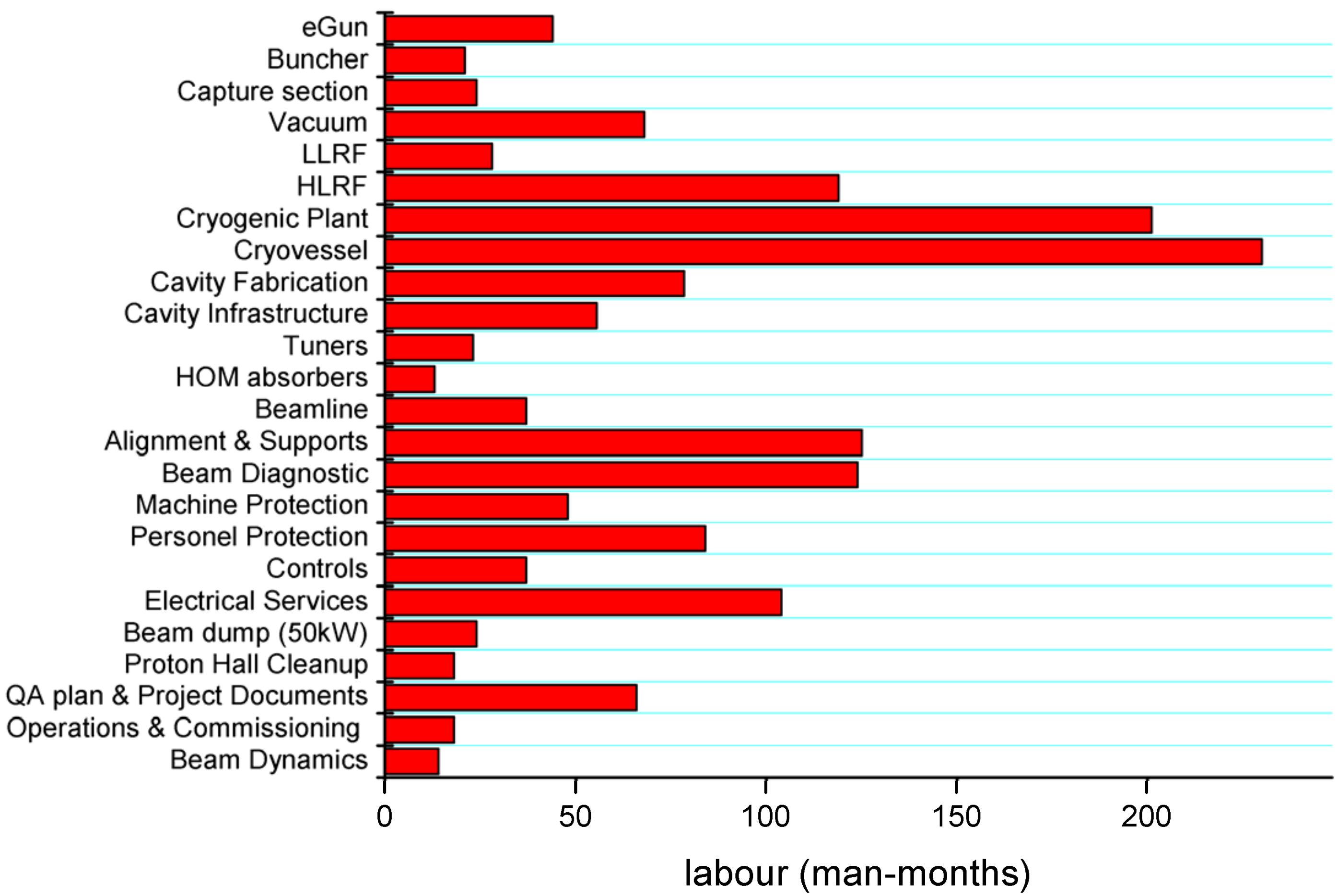
- Much of the capital costs and manpower have been estimated (first pass)
- Does not include buildings / HVAC



Total capital cost: $20M

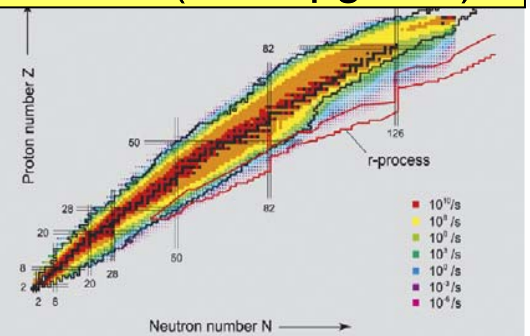
Project costs and manpower

- Total manpower (physicists, engineers, technicians, machinists) = 130 person-years

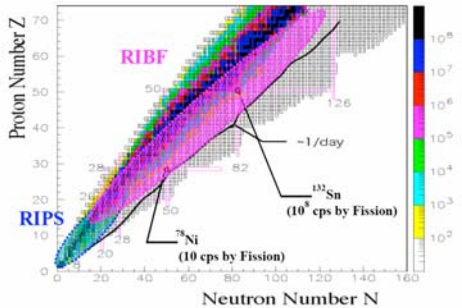


ISAC photo-fission in comparison

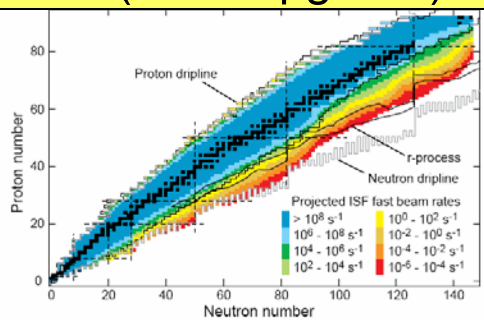
FAIR (GSI upgrade)



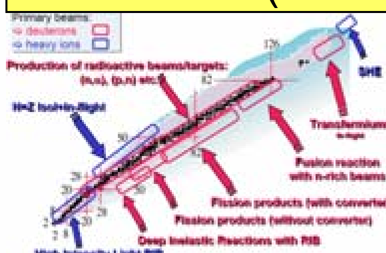
RIBF (RIKEN)



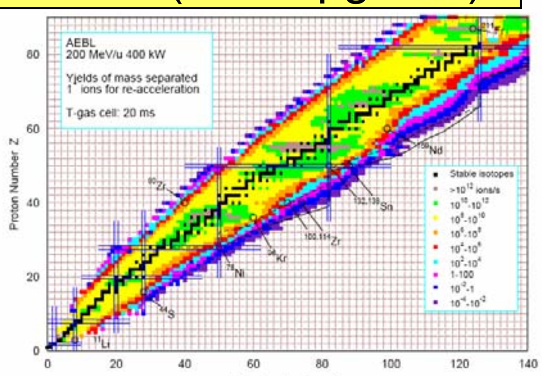
ISF (MSU upgrade)

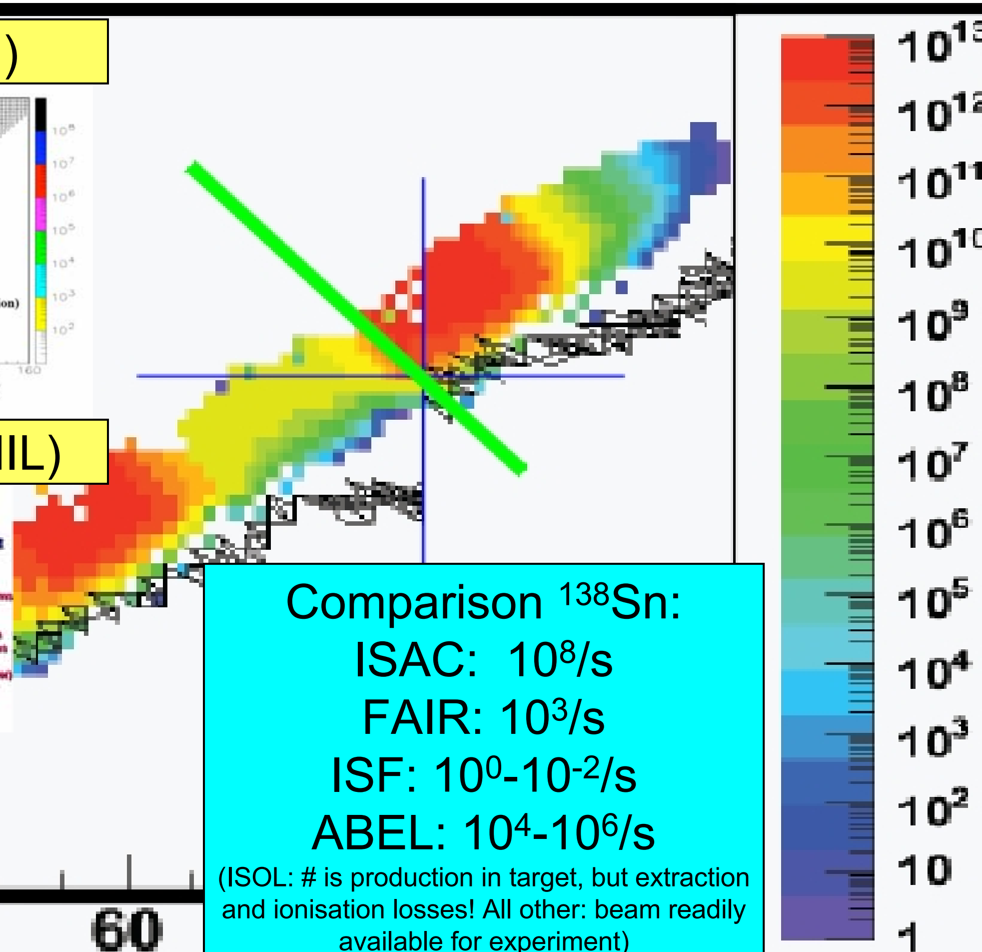


SPIRAL2 (GANIL)



ABEL (ANL upgrade)





Comparison ^{138}Sn:
ISAC: 10^{8}/s
FAIR: 10^{3}/s
ISF: 10^{0}-10^{-2}/s
ABEL: 10^{4}-10^{6}/s
(ISOL: # is production in target, but extraction and ionisation losses! All other: beam readily available for experiment)

- **New facilities have global approach for production, here very localized dedicated effort to boost very neutron rich nuclei.**
- **Operation planned for in ~5 years after funding (before 2015 pending funding).**

Recent Progress in ß-NMR

Project	**Publications**
Molecular Magnets on Surfaces	Nano Letters **7**, 1551 (07)
Superconductivity	Phys Rev Lett, **98**, 167001 (07) Submitted to Phys. Rev. Lett. (08)
Metallic Heterostructures	Phys Rev Lett **98,** 047601 (07) Phys Rev B **75,** 073405 (07) Phys Rev Lett **93**, 157601 (04) J. Magn. Reson. **191**, 47 (08)
Magnetic Multilayers	Phys Rev B **77**, 144429 (08)
Surface Phase Transitions	Phys Rev Lett **96,** 147601 (06)

http://bnmr.triumf.ca

E-linac design summary

L-band SCRF technology provides cost effective approach to MW-class fission driver.

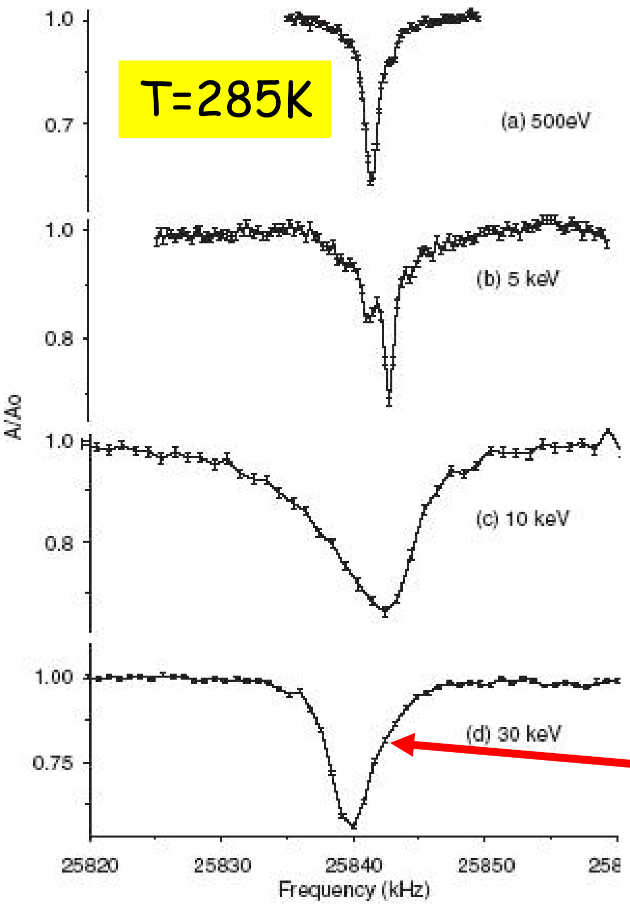
There are cell, cavity, input coupler, HOM damper, tuner, klystron, IOT, cryostat and BPM designs all pre-existing – eliminates substantial R&D & cost.

C.W. operation poses some challenges c.f. TESLA/ILC – but these are being met by ERL light source designs.

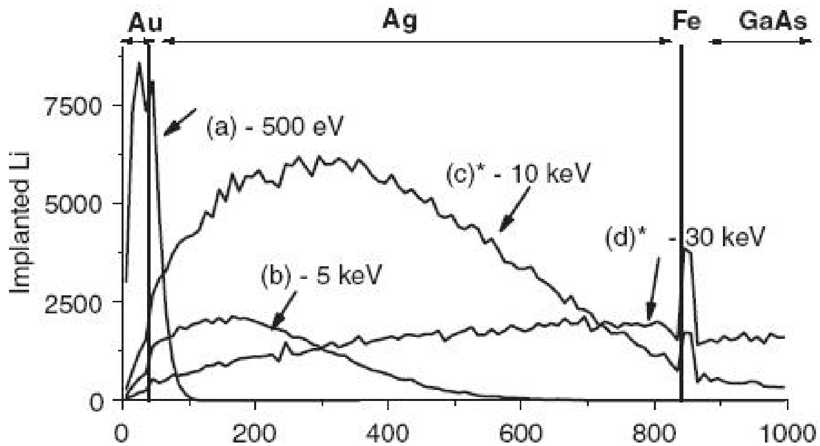
Indeed, some of the fission driver specifications are more relaxed than for ILC and/or ERLs.

β-NMR Preliminary Work

Ag/Fe/GaAs heterostructure, GaAs is semi-insulating (undoped)



- Line width varies with the depth



- Line is broader than GaAs

Physica B ***374***, *79 (2006)*
Phys. Rev. B ***77***, *144429 (2008)*