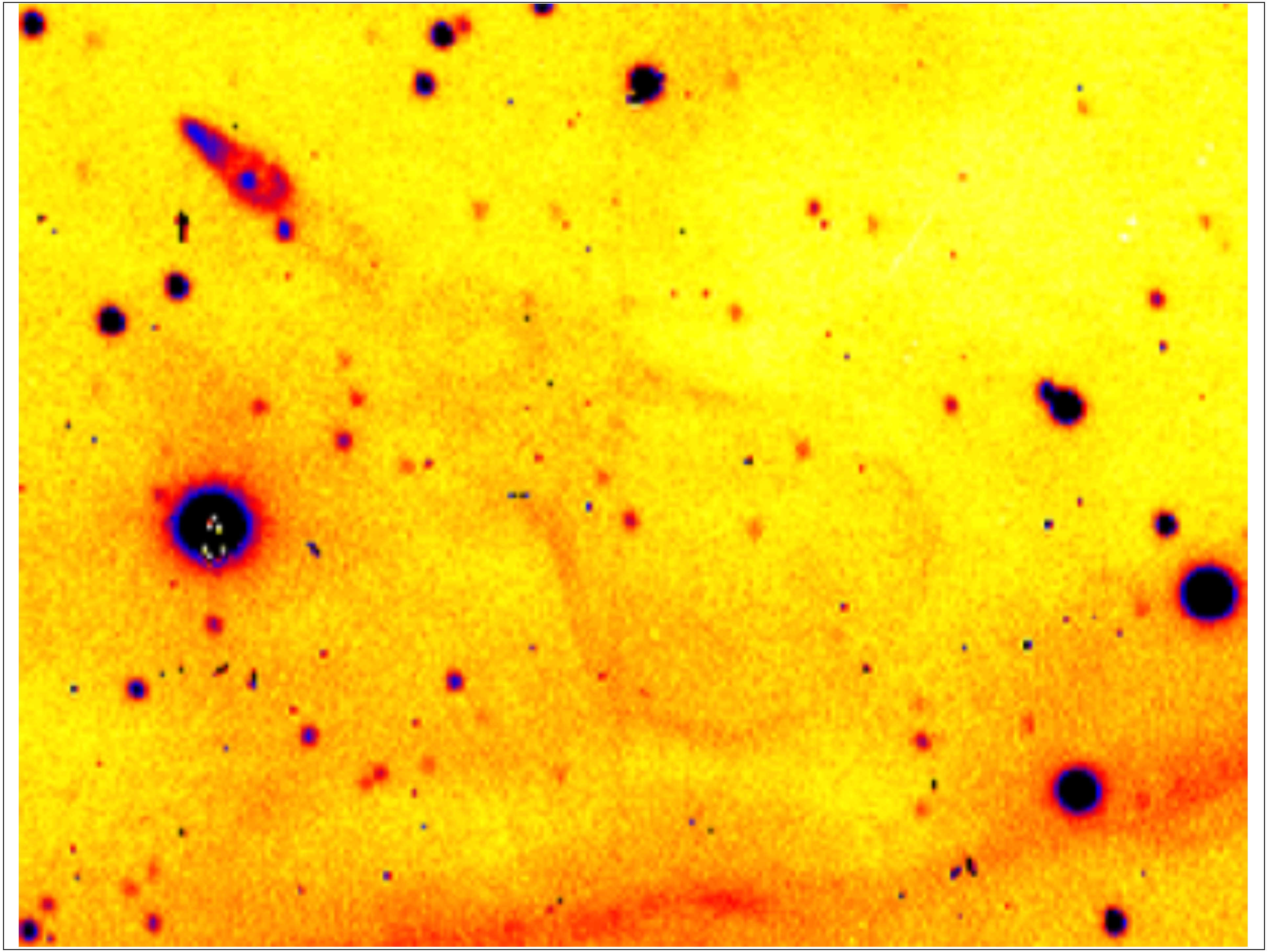
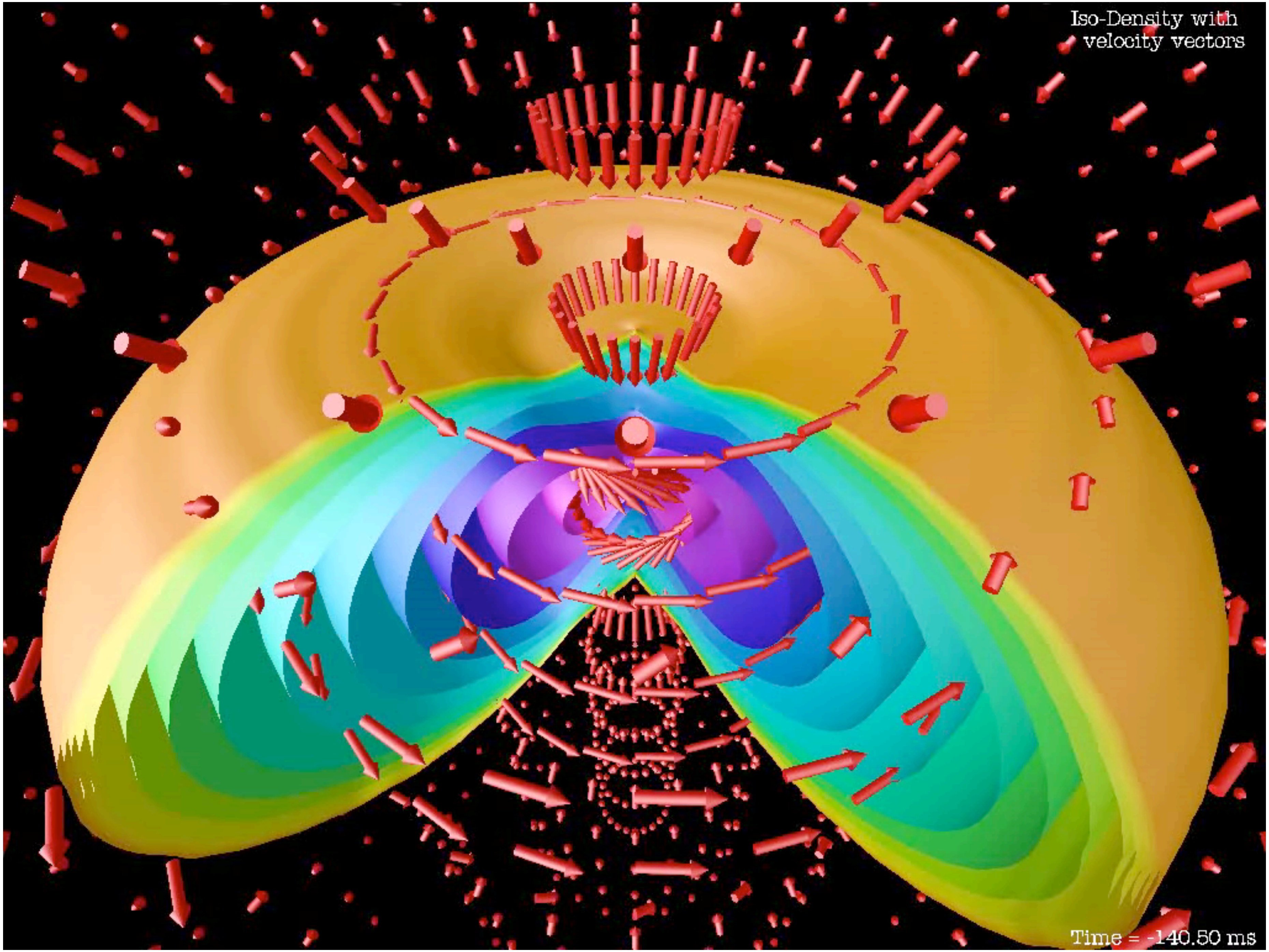
^{44}Ti and Core Collapse Supernovae

Alex Murphy



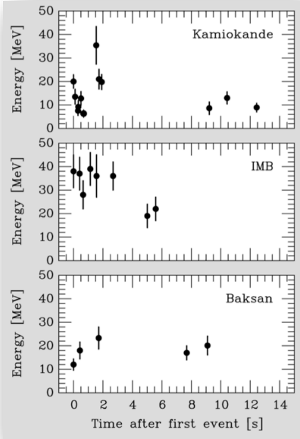

Iso-Density with
velocity vectors
Time = -140.50 ms

Core Collapse Supernovae are...

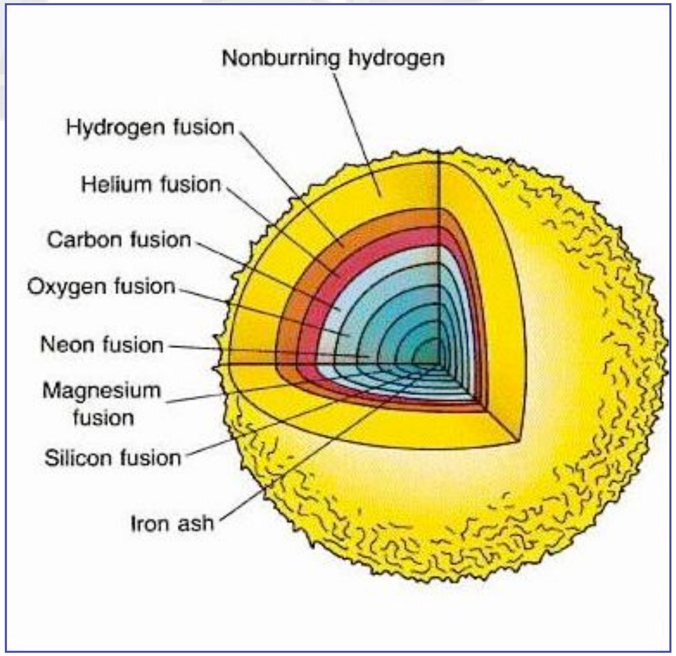
- Some of the most powerful explosions in the Cosmos
- Some of the most scrutinised objects in the Universe
- Responsible for production of many heavy elements
- Responsible for shaping our local distribution of stars
- Until recently there was consensus on the basic mechanism (perhaps there still is...)
- The best simulations still don’t (*) reliably explode
- Extremely complex

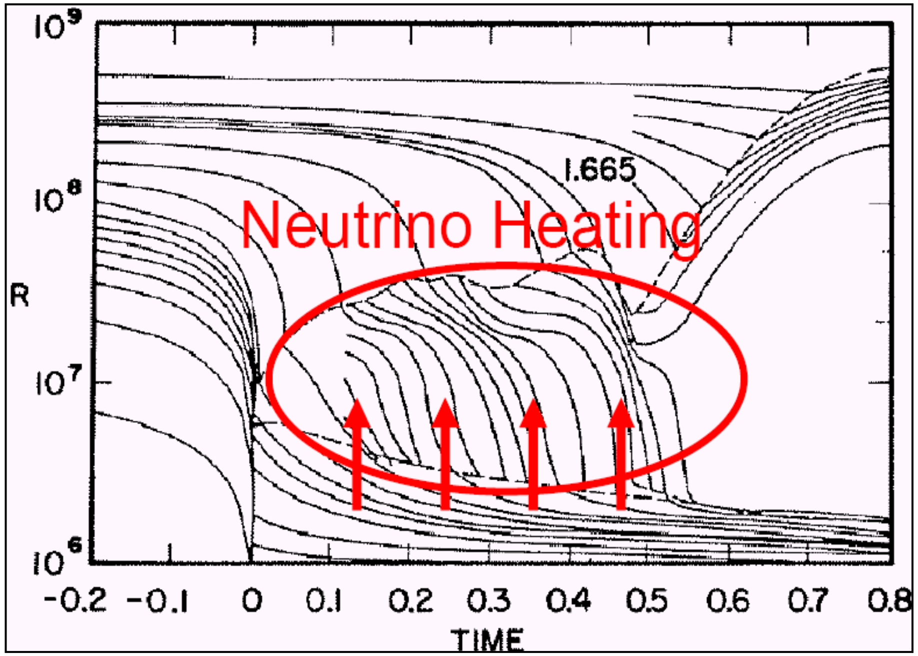
We need a good diagnostic

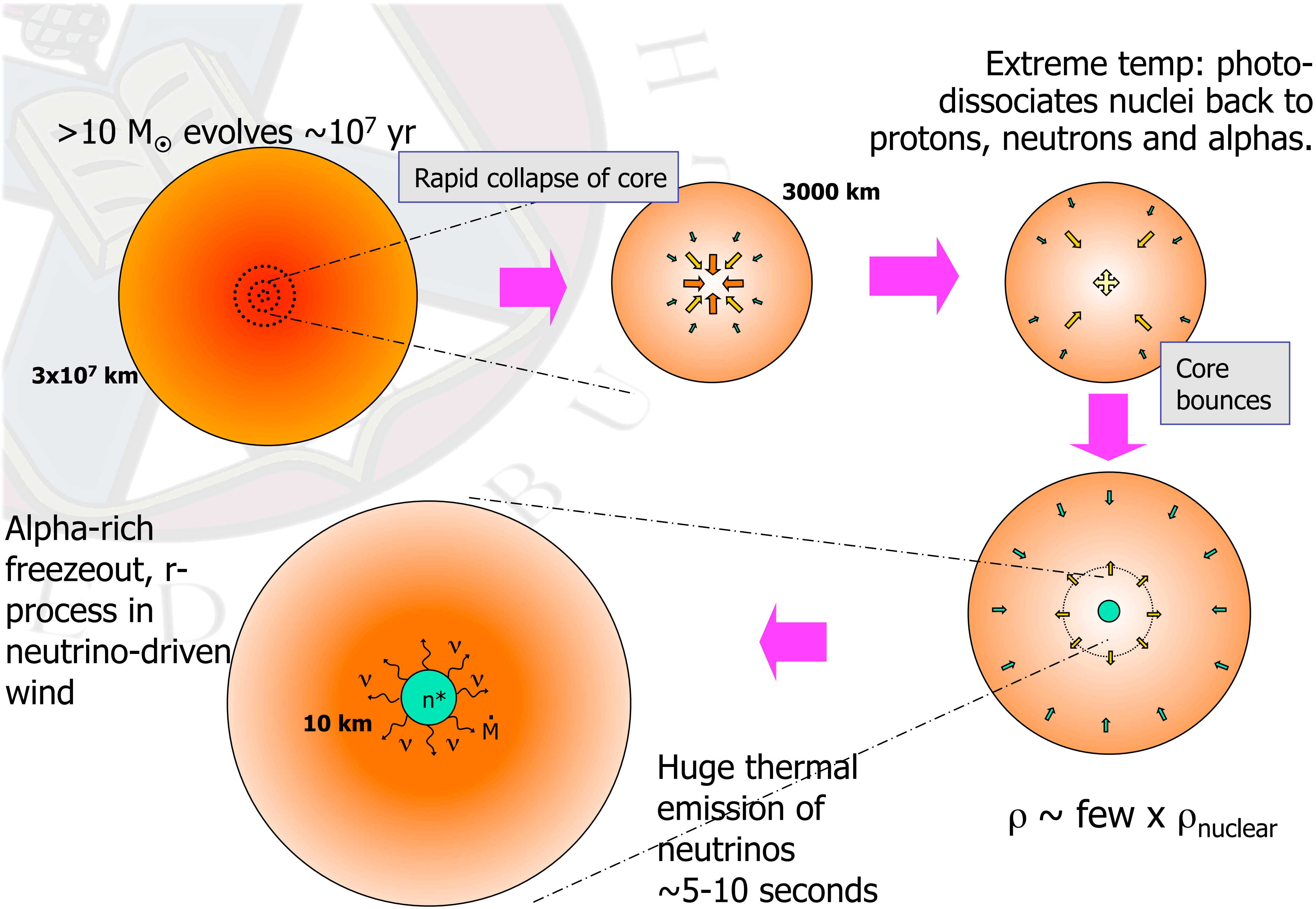
The Neutrino Mechanism



- Massive star (>8–10 $M_\odot$)
- Stellar evolution → onion-skin-like structure
- At maximum of BE/A, thermal support lost → Collapse
- Huge flux of neutrinos "re-energises" explosion
- Neutrino driven wind – an excellent candidate site for the r-process






>10 M$_\odot$ evolves ~10^7 yr
3x10^7 km
Rapid collapse of core
3000 km
Extreme temp: photo-dissociates nuclei back to protons, neutrons and alphas.
Core bounces
$\rho \sim$ few x $\rho_{nuclear}$
Huge thermal emission of neutrinos ~5-10 seconds
Alpha-rich freezeout, r-process in neutrino-driven wind
10 km
n*
ν
Ṁ

CCSN Simulation status
(Adapted from A. Burrows)

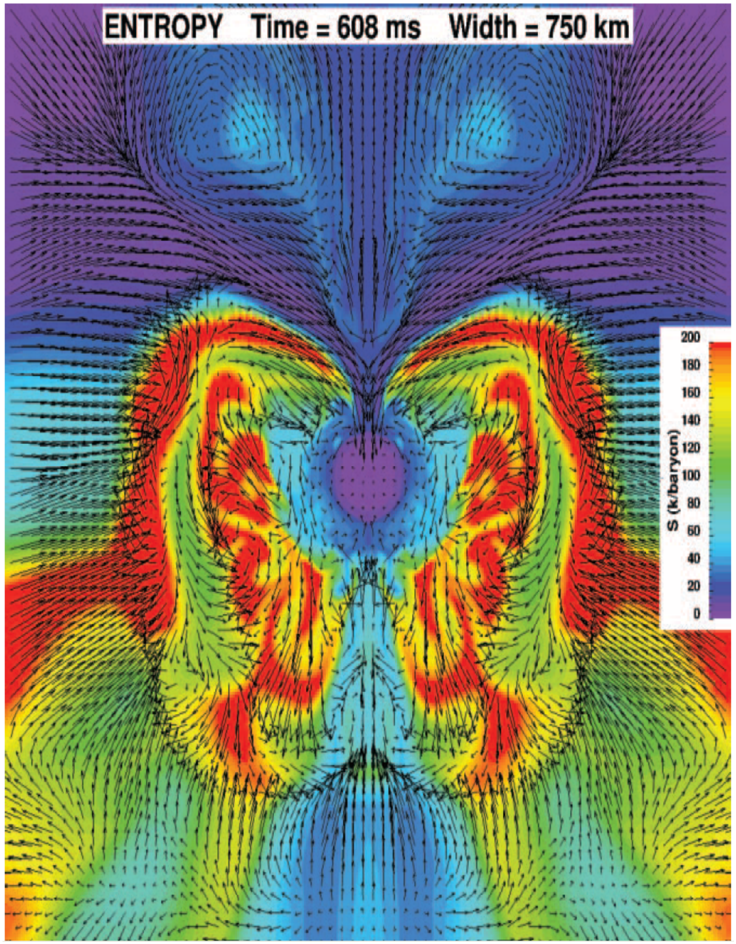
- Rapidly advancing field
- Consensus that the 'true' mechanism should not be 'marginal'
- Prompt shock ALWAYS fizzles
- 1D neutrino-driven model ALWAYS fizzles
- GR... makes no difference
- Improved neutrino physics... makes no difference
- EOS probably has no surprises
- All groups get the same results for all progenitors

CCSN Simulation status
(Adapted from A. Burrows)

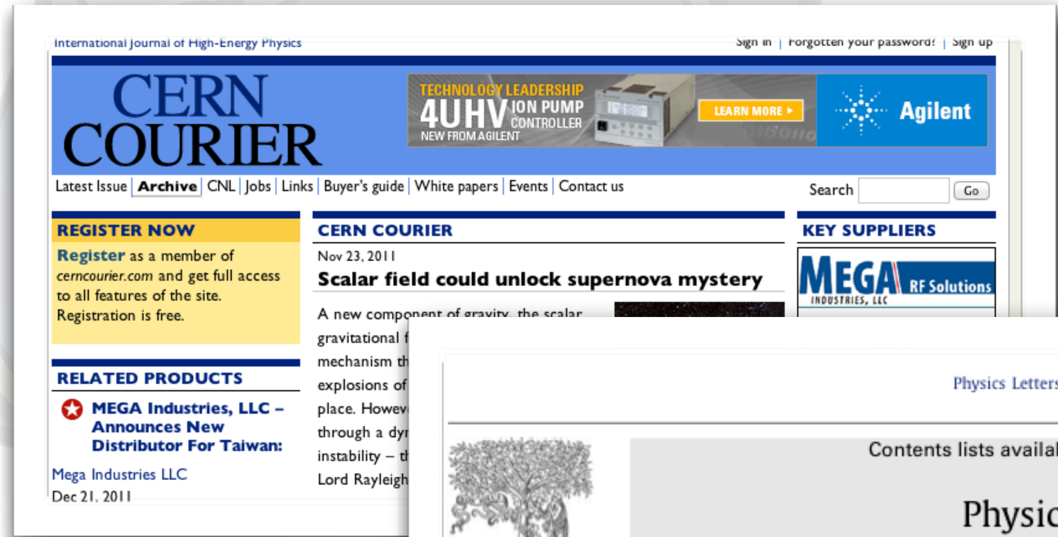
- 2D/3D model are showing more promise
- Asymmetry looks like it is the key
  - Convection
  - 'Fingers'
- The asymmetry probably comes from <u>rotation</u>
  - 'Naturally' produces bi-polar explosions
  - Collapse amplifies rotation
  - Increases gain region
  - Reduces effective gravity
  - Likely explanation of pulsar kicks
  - Likely source of gravitational radiation
  - Possible role of g-wave acoustics

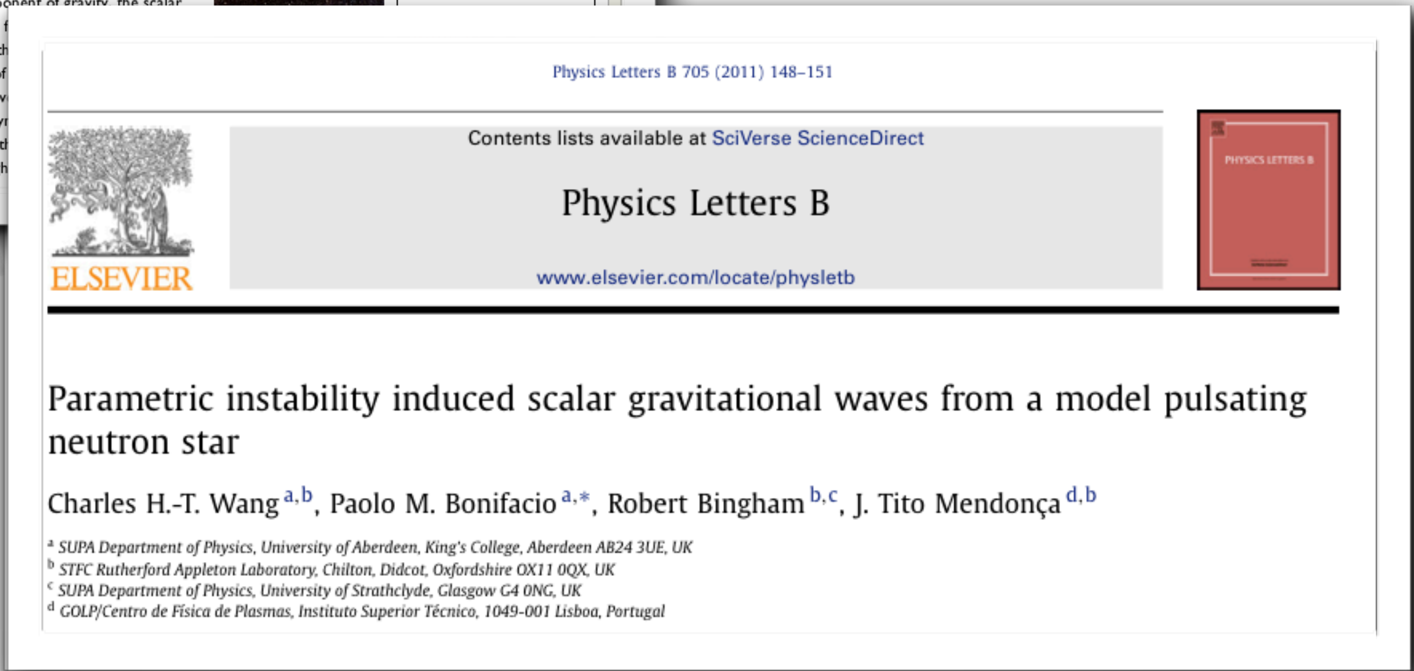
The Acoustic Mechanism

- 'New' mechanism: A. Burrows *et al.* (ApJ 640 (April 2006) 878-890)
  - In-fall of matter on to the core induces strong gravity waves
  - These set up acoustic oscillations a few hundred milliseconds after core collapse.
  - Oscillations couple efficiently with the outer core/overlying material,
  - Intense sound waves radiated.
  - Appears to lead to robust explosion



Parametric instability?





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ELSEVIER

Parametric instability induced scalar gravitational waves from a model pulsating neutron star

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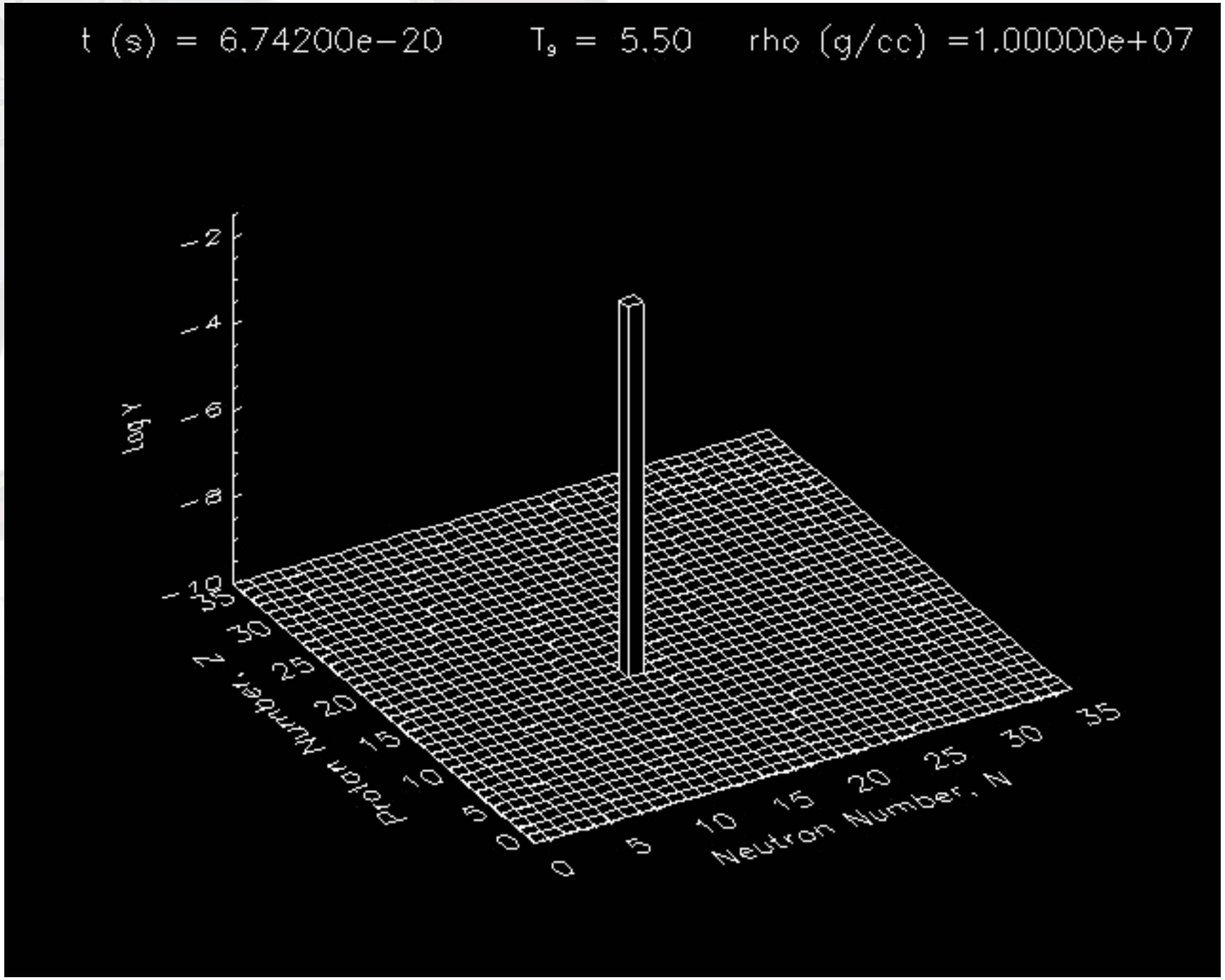
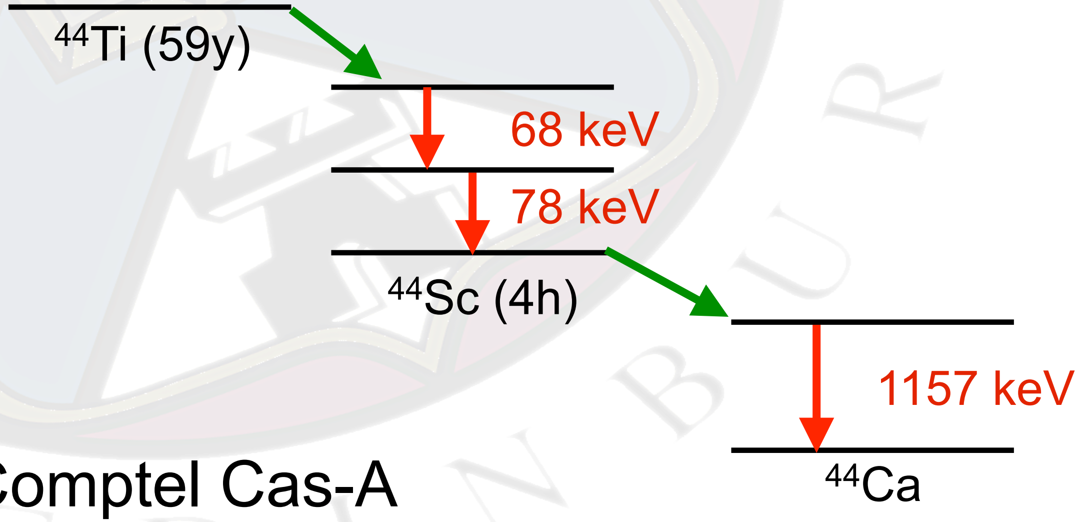
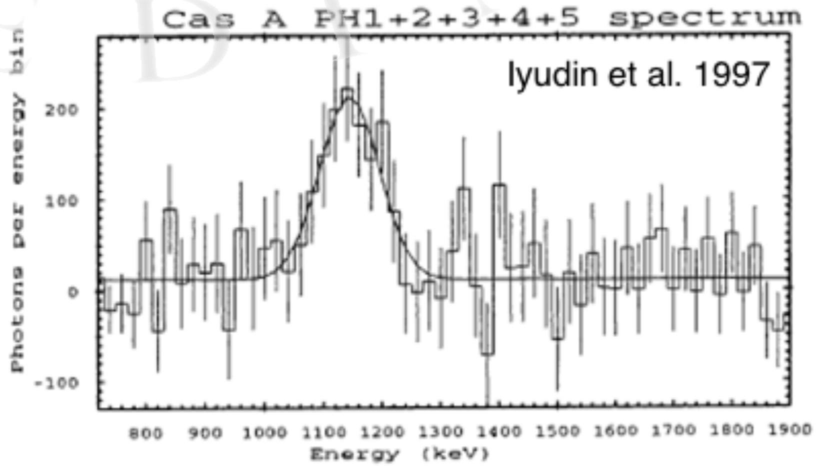
Nucleosynthesis



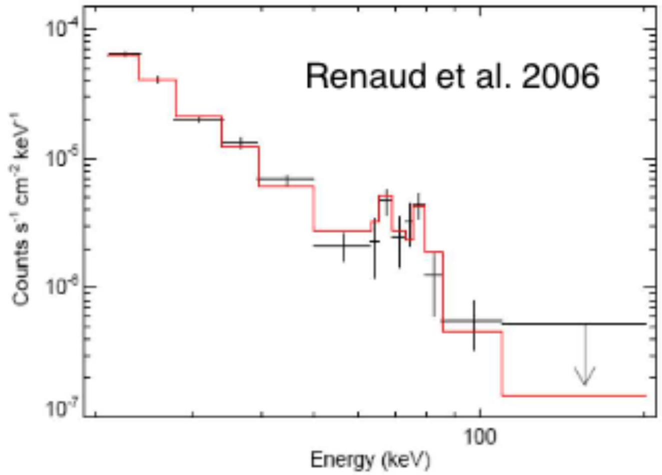
Gamma-ray emission from ^{44}Ti



Comptel Cas-A

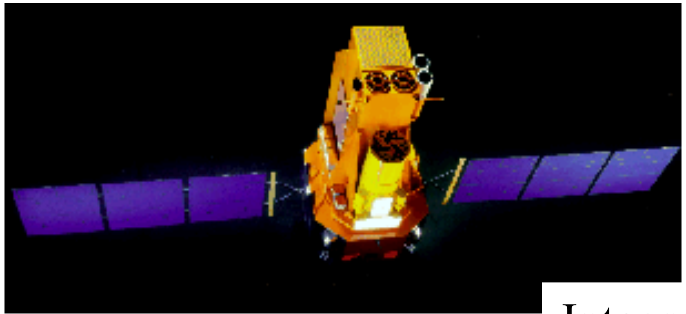


IBIS Cas-A

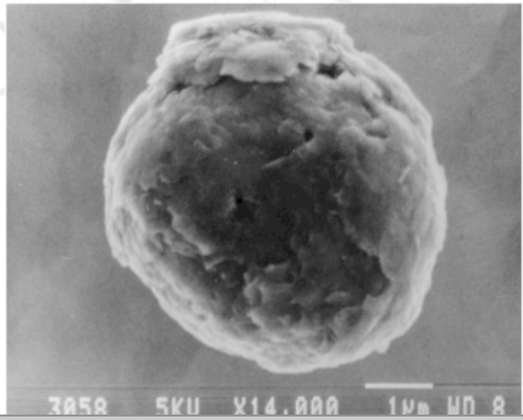


The Importance of ^{44}Ti

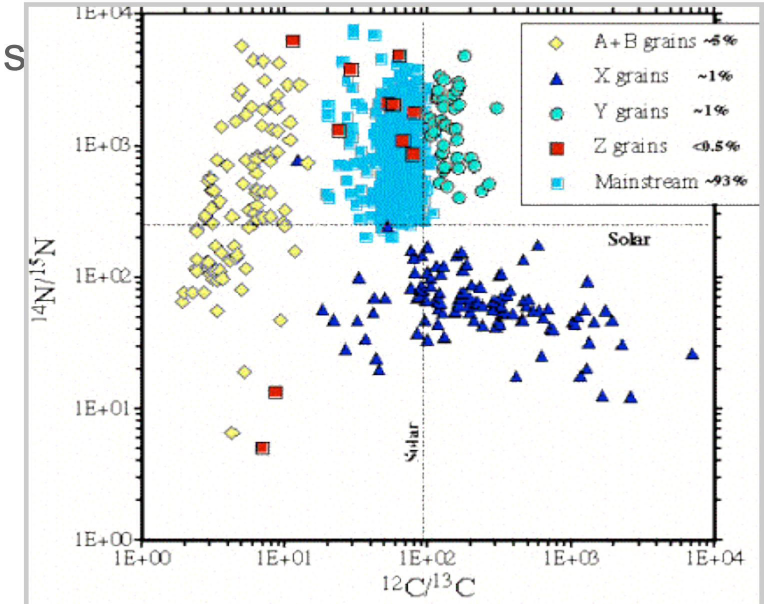
- ^{44}Ti that is ejected will become a γ-ray emitter
- Cassiopeia-A, Vela, not SN1987A
- τ=60 yrs, E_γ =1.157 MeV
- 'Easily' observable
- INTEGRAL & other missions
- Also Meteoritic data
- Enrichment of ^{44}Ca in type X presolar grains



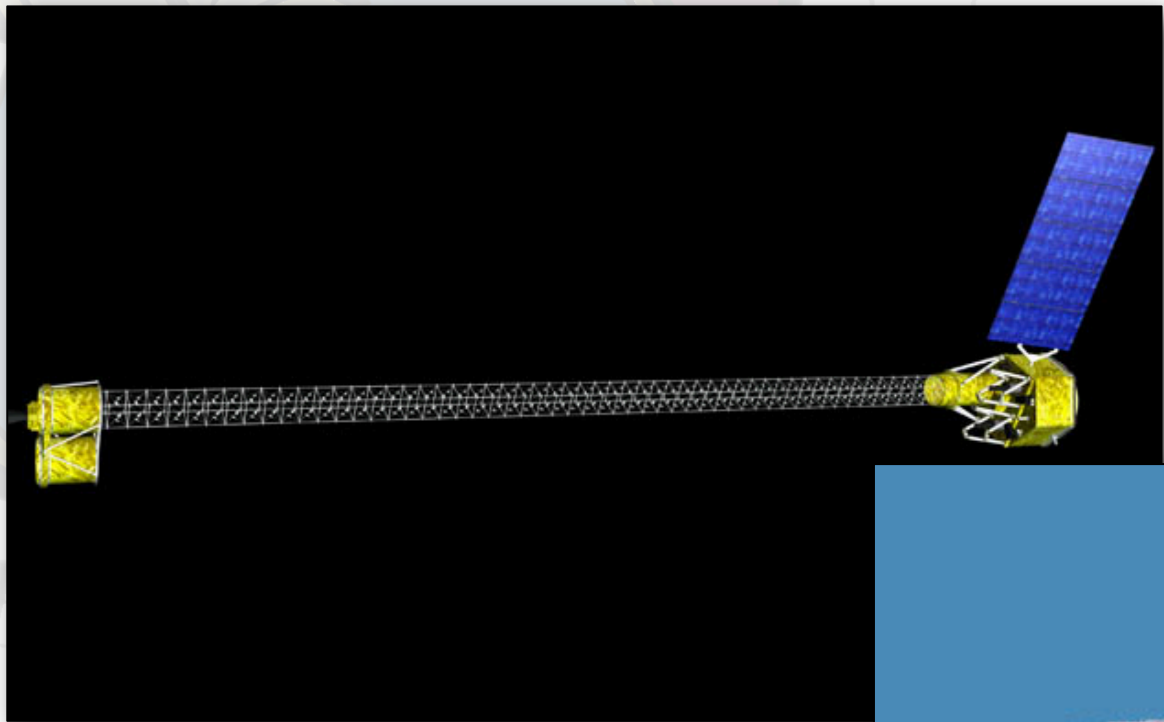
Integral



A grain from the Murchison Meteorite



NuSTAR (the 'other' one)



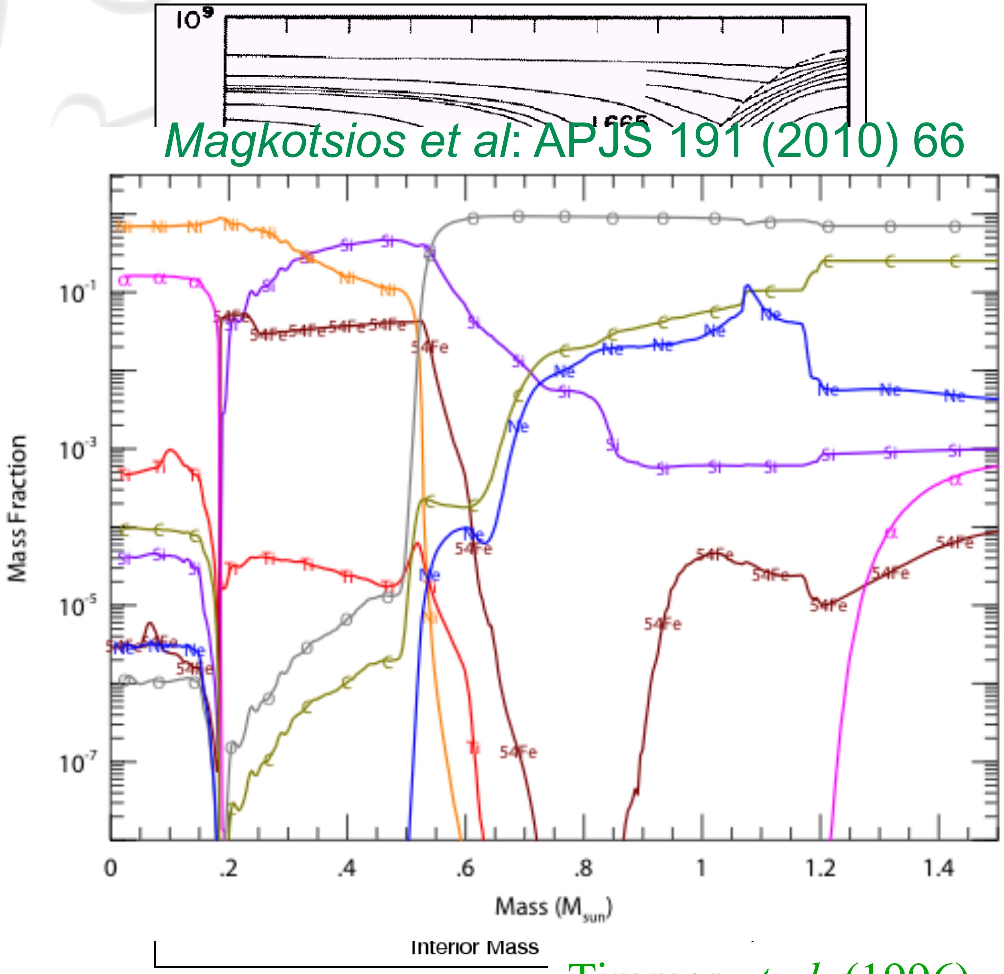
Hard X-ray imager
6-80 keV

~NASA version of ESAs GRI (UK: Tony Bird, Bruce Swinyard, ASM)

LAUNCH:
14th March 2012, 8am

The Importance of ^{44}Ti

- Amount ejected sensitively depends on location of the 'mass cut'
- Material that 'falls back' is not available for detection
- ^{44}Ti yield a sensitive diagnostic of the explosion mechanism
- Thus, very useful for models to make comparisons against



Magkotsios et al: APJS 191 (2010) 66

Timmes *et al.* (1996)

The KEY Question

Could a measurement of ^{44}Ti gamma rays be a diagnostic of the underlying explosion mechanism?

Do the different explosion mechanisms affect the location of the mass cut?

- "there should be some interesting differences on average between the predictions/expectations of the various mechanisms (neutrino, acoustic, magnetic, etc.), we have yet truly to determine these."
  Adam Burrows, Princeton, Jan 2012

- *"By accident we noticed e.g. in simple parametrized explosions with the same explosion energy, that pistons (like used by Woosley and Heger) produce less ^{44}Ti than thermal bombs (like used by Nomoto, myself, Umeda). The point is just that in the innermost ejecta the entropies are higher."*
  Friedel Thielemann, Basel, Jan 2012

Key Reactions

Reaction rate sensitivity studies:

- *The et al*: ApJ 504 (1998) 500
- *Magkotsios et a*l: APJS 191 (2010) 66

- Papers agree, ^{44}Ti(α,p) most important reaction
- Importance stems from it being the bottle neck in reaction flow as material drops out of QSE

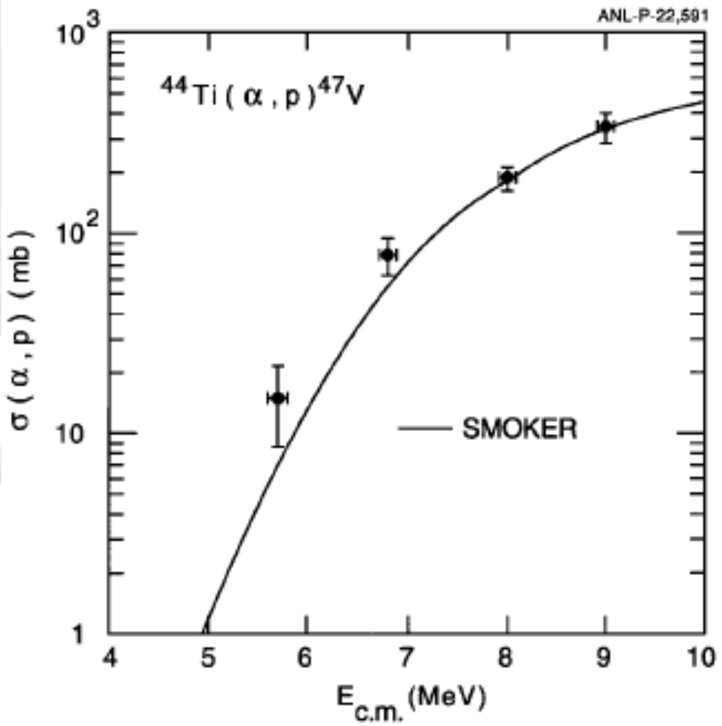
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
^{44}Ti(α, p)^{47}V	−0.394
α(2α, γ)^{12}C	+0.386
^{45}V(p, γ)^{46}Cr	−0.361
^{40}Ca(α, γ)^{44}Ti	+0.137
^{57}Co(p, n)^{57}Ni	+0.102
^{36}Ar(α, p)^{39}K	+0.037
^{44}Ti(α, γ)^{48}Cr	−0.024
^{12}C(α, γ)^{16}O	−0.017
^{57}Ni(p, γ)^{58}Cu	+0.013
^{58}Cu(p, γ)^{59}Zn......	+0.011
^{36}Ar(α, γ)^{40}Ca	+0.008
^{44}Ti(p, γ)^{45}V	−0.005
^{57}Co(p, γ)^{58}Ni	+0.002
^{57}Ni(n, γ)^{58}Cu	+0.002
^{54}Fe(α, n)^{57}Ni	+0.002
^{40}Ca(α, p)^{43}Sc	−0.002

[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\text{Ti})$ near the standard reaction rates.

$^{44}Ti(\alpha,p)$ Present status

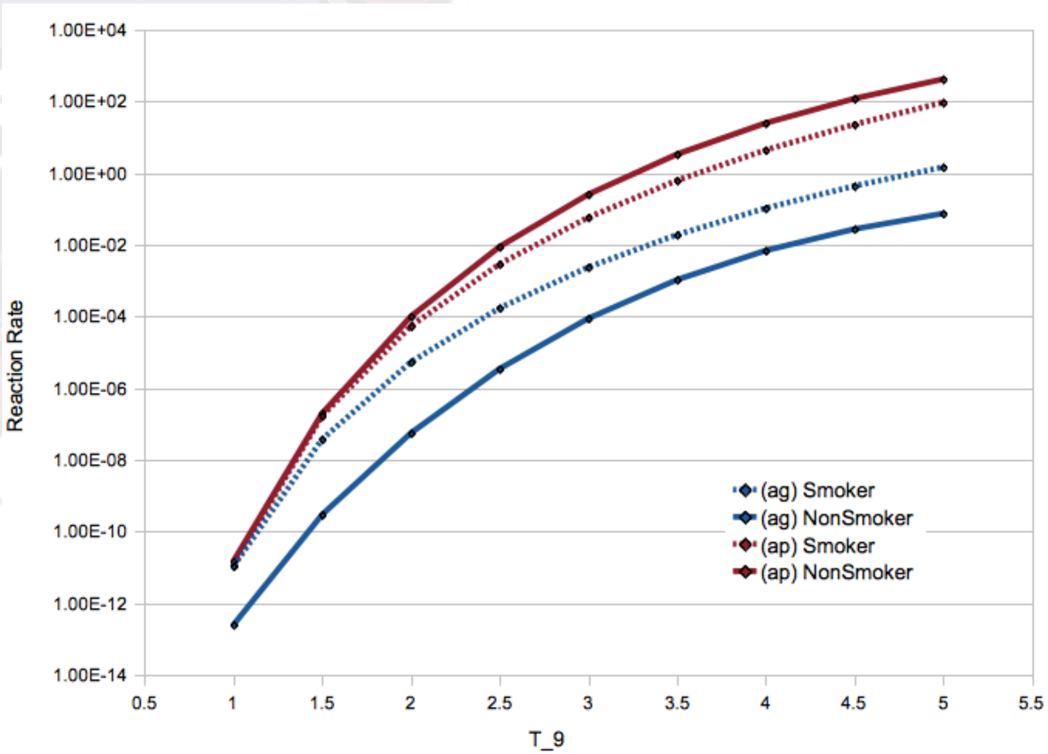
Sonzogni et al. PRL 84 (2000)



- Astrophysical region is 3-6 MeV
- *Hoffman et al.* APJ 715 (2010) 1383
  - New evaluation of $^{44}Ti(\alpha,p)$ reaction rate
  - Conclude that $^{44}Ti(\alpha,p)$ uncertainty has been underestimated (x3)
- Sonzogni compared to SMOKER
- NON-SMOKER provides significant update

Data achieved with ~10^5 pps on target

^{44}Ti(α,p) Reaction Rates



SMOKER → NONSMOKER: ^{44}Ti(α,p) little effect

^{44}Ti(p,γ) major effect

^{44}Ti(α,p) Reaction Rates

- NON-SMOKER includes better treatment of isospin suppression for alpha-capture reactions on N = Z nuclei
- Vockenhuber *et al*. states that ^{44}Ti(α,p) NON-SMOKER rate is 100x smaller than SMOKER rate
  [J. Phys G: Nucl. Part. Phys. 35(2008)]
- Rauscher [priv. comm.] says this is in error. Only a factor of 20.
- Consequences if ^{44}Ti(α,γ) rate > ^{44}Ti(α,p) rate

Proposal

Direct measurement of ^{44}Ti(α,p) at astrophysical energies

- Sonzogni made their own ^{44}Ti via ^{45}Sc(p,2n)^{44}Ti.
  - about 4×10^{15} atoms were used
- Priv. Comm.: Sonzogni approach has limited further capability
- Production of a ^{44}Ti target is viable: Daniel Bemmerer leads; Timescale ‘few years’.
- Production of a ^{44}Ti ISOL beam is viable: beam development at GANIL, TRIUMF. Timescale is ‘few years’
- **Production of offline ^{44}Ti beam... this proposal**

As of yesterday...

Beam request for ISOLDE 2012

April 2 to December 2, 2012

PLEASE COMPLETE ALL INFORMATION REQUESTED AND RETURN BY JANUARY 30, 2012

Experiment IS544

Measurement of the 44Ti(alpha,p)47V reaction cross section, of relevance to gamma-ray observation of core collapse supernovae, using reclaimed 44Ti

Spokesperson: A. Murphy

Total shifts approved: 28

Shifts used in 2011: 0

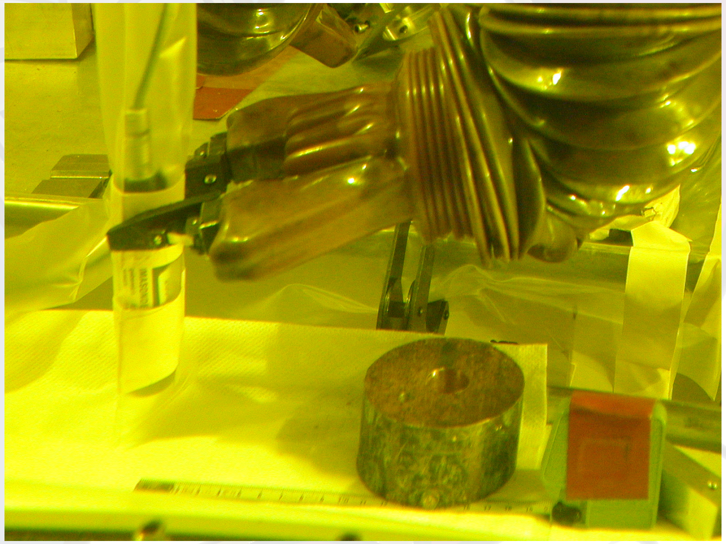
Remaining shifts: **28** (if shifts requested in January 2012 are approved)

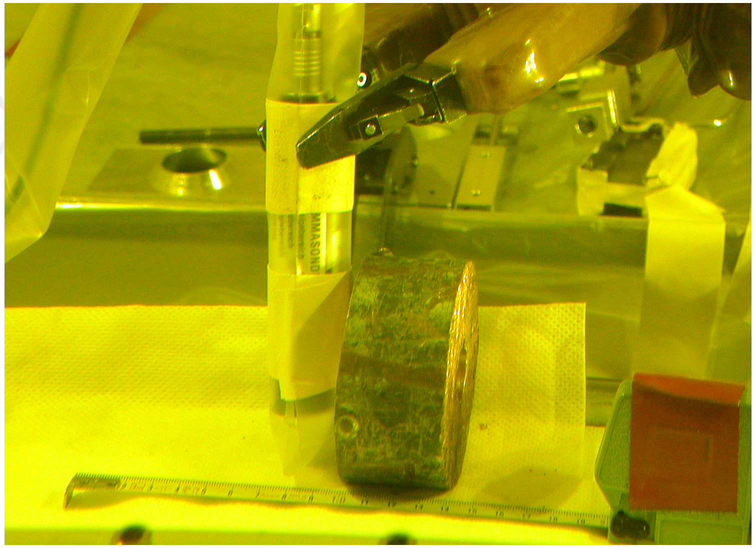
ERAWAST

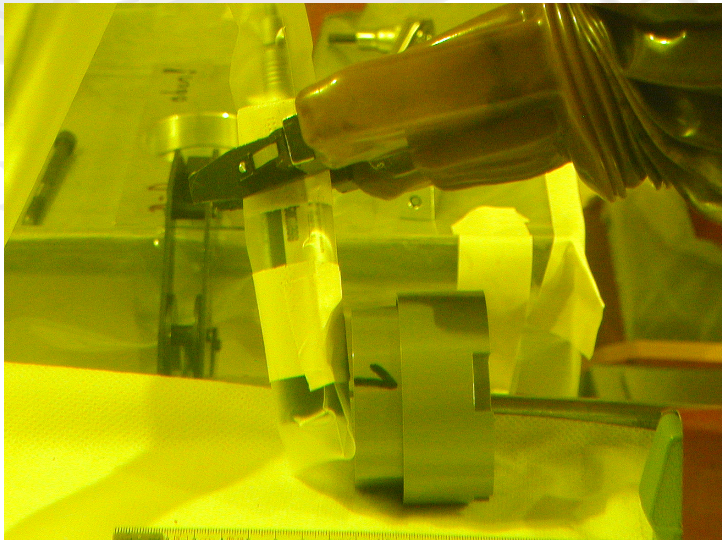
Exotic Radionuclides from Accelerator Waste for Science and Technology

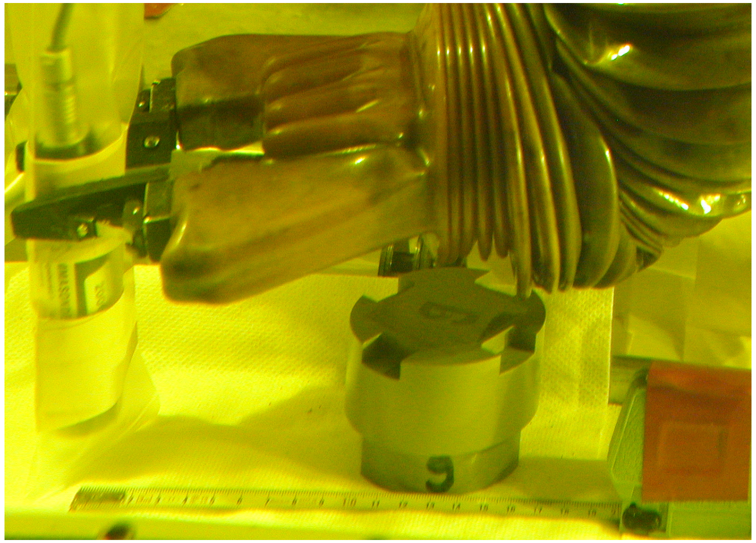
- A project to utilise long lived activity generated in PSI beam dumps
- Copper beam bumps, exposed to 1.5mA protons for ~12 years, dismantled ~15 years ago.
- ^{26}Al, ^{59}Ni, ^{53}Mn, ^{60}Fe or ^{44}Ti have been separated.
- SINQ facility material also available: other isotopes, e.g. ^{182}Hf

Applications: Nuclear physics, nuclear astrophysics, Geophysics, Radio-pharmacy, AMS, RIMS,...









^{44}Ti availability

"The bottom line on the ^{44}Ti is that there is more of it than we are going to know what to do with. They have actually stopped processing the copper beam dump because they have been having a lot more luck with stainless steel test samples that were put in their SINQ facility (spallation neutron source). These samples have the added benefit that no ^{60}Co is produced, so they don't have to wait very long before they can handle the material.

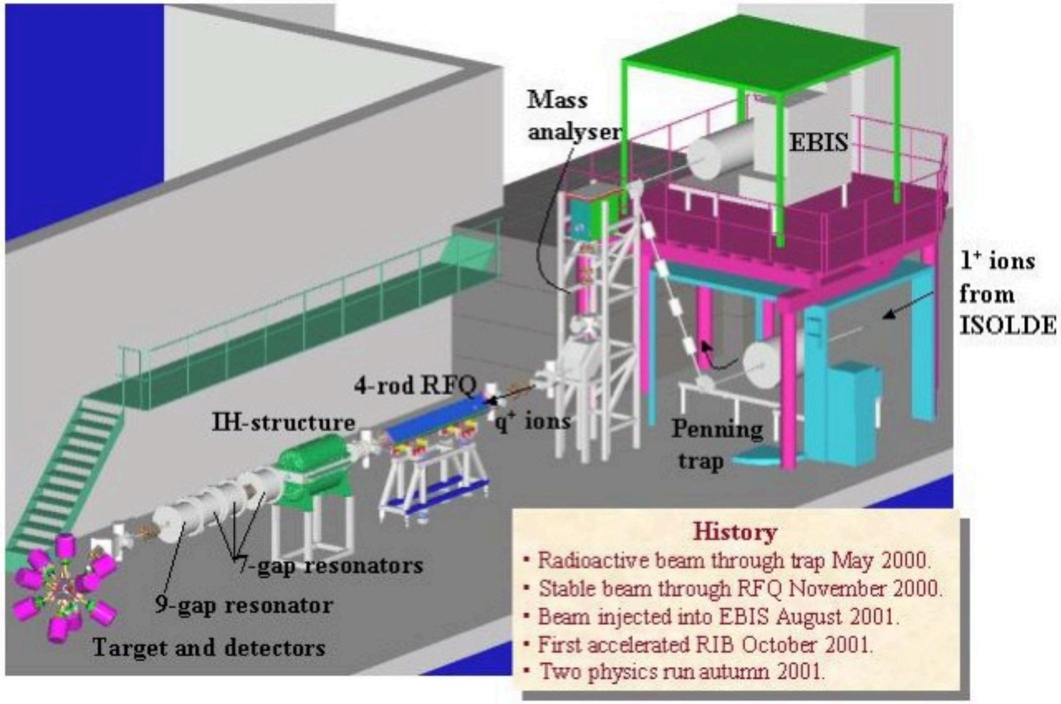
"They have determined that they have ***300MBq*** of ^{44}Ti in the samples produced to-date, and there are more experiments yet to be run. There are also tests on V-metal and V+Ti-metal and each of these samples is expected to contain ***500MBq*** of ^{44}Ti. There is plenty to share with the ^{44}Ti target experiment, and the medical people have moved on and are now producing their own. ***The only limits for how much ^{44}Ti we can use to produce a beam will be set by the safety people."***

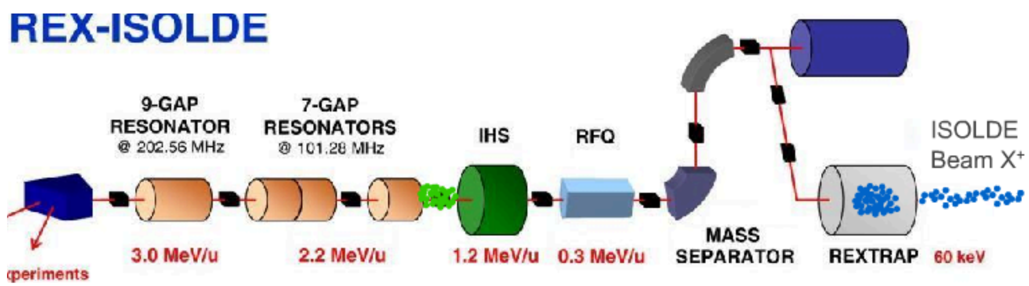
Jennifer Fallis, 6/9/2011

^{44}Ti Beam Production

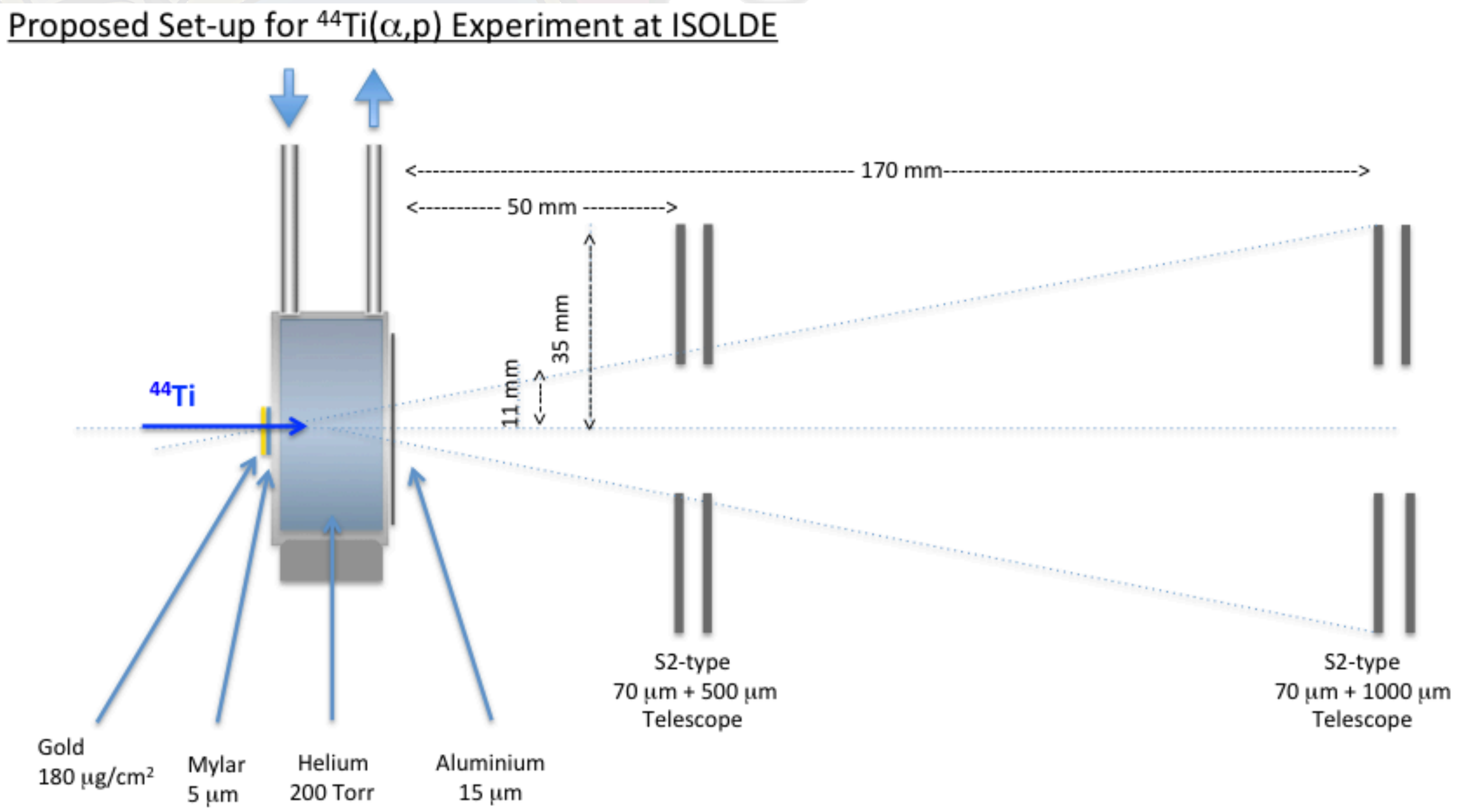
- Development ongoing at ISOLDE, TRIUMF and GANIL
- 1 week at 10^5 pps is about 10^{12} ions
- With 10^{18} ions, 0.0001 total is efficiency required for a significantly improved measurement
- $^{44}TiF_4$ deposited on Ta foil
- FEBIAD ion source; extract TiF_3^+ molecules
- Accelerate, dissociate molecule, accelerate $^{44}Ti^{4+}$ ions
- Expected efficiency... ~0.1 - 1%

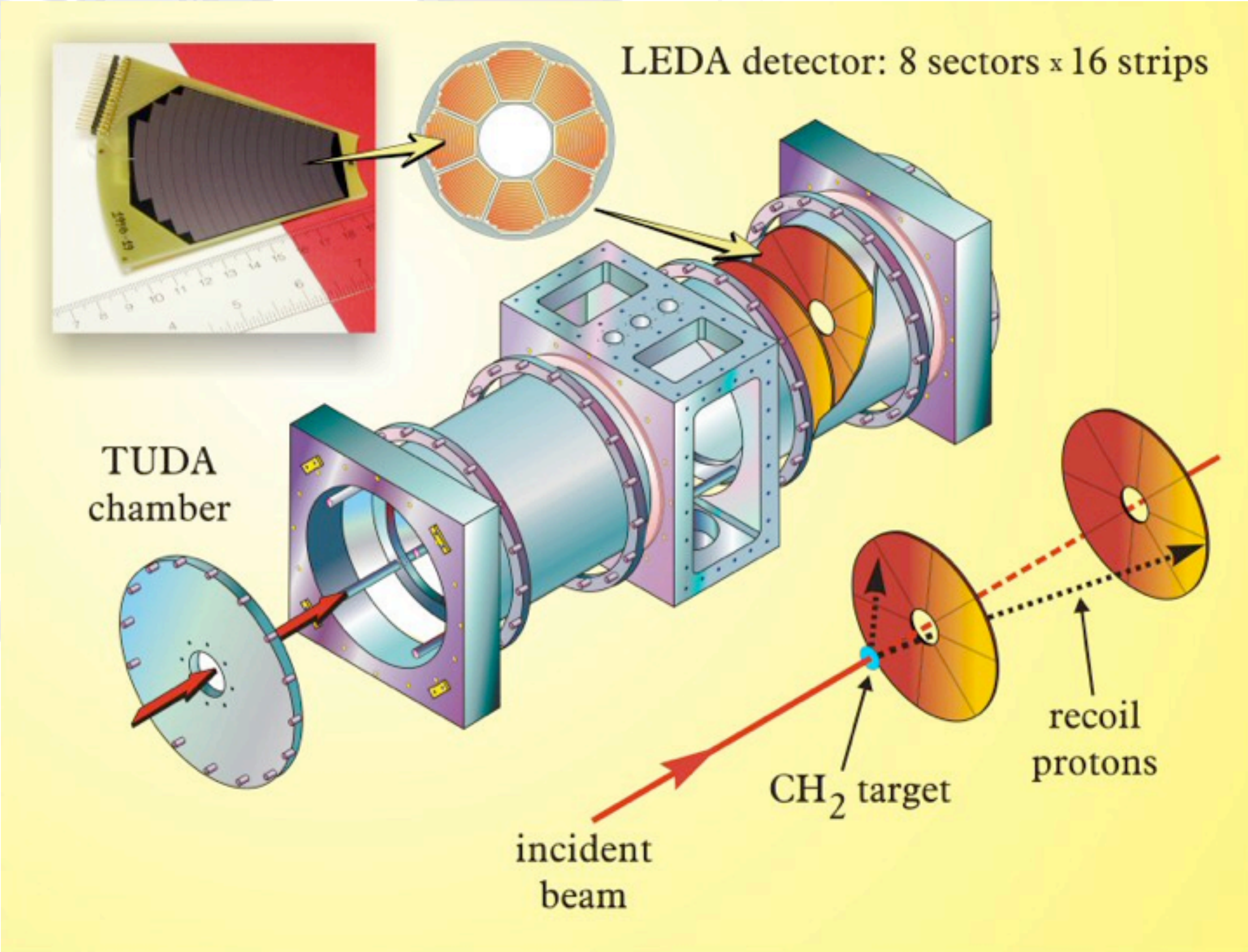
CERN REX - ISOLDE

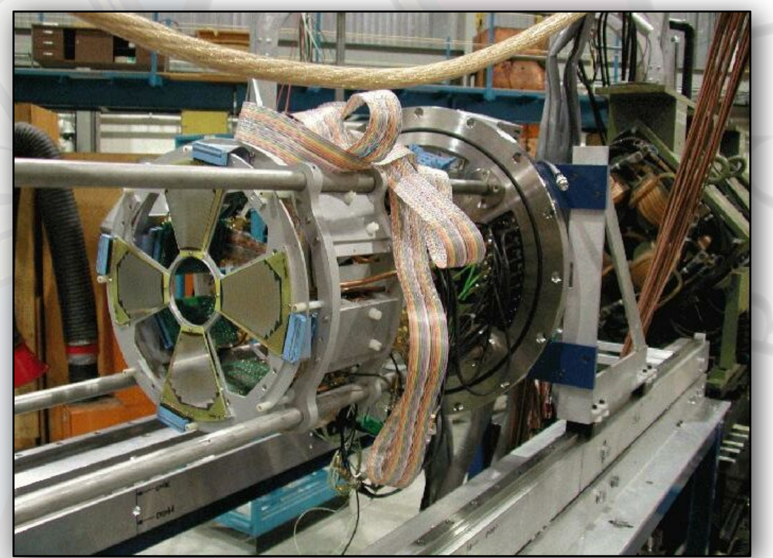


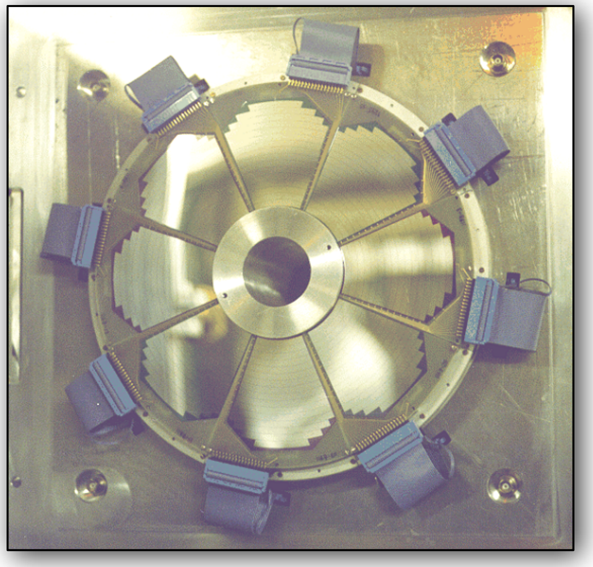


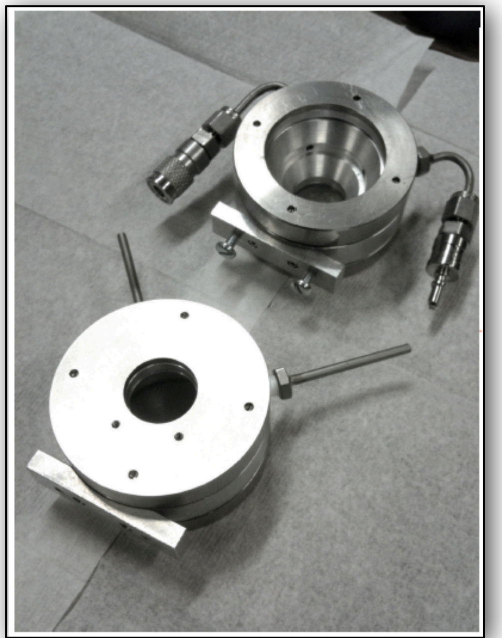
^{44}Ti Experiment configuration




LEDA detector: 8 sectors x 16 strips
TUDA
chamber
incident
beam
CH2 target
recoil
protons

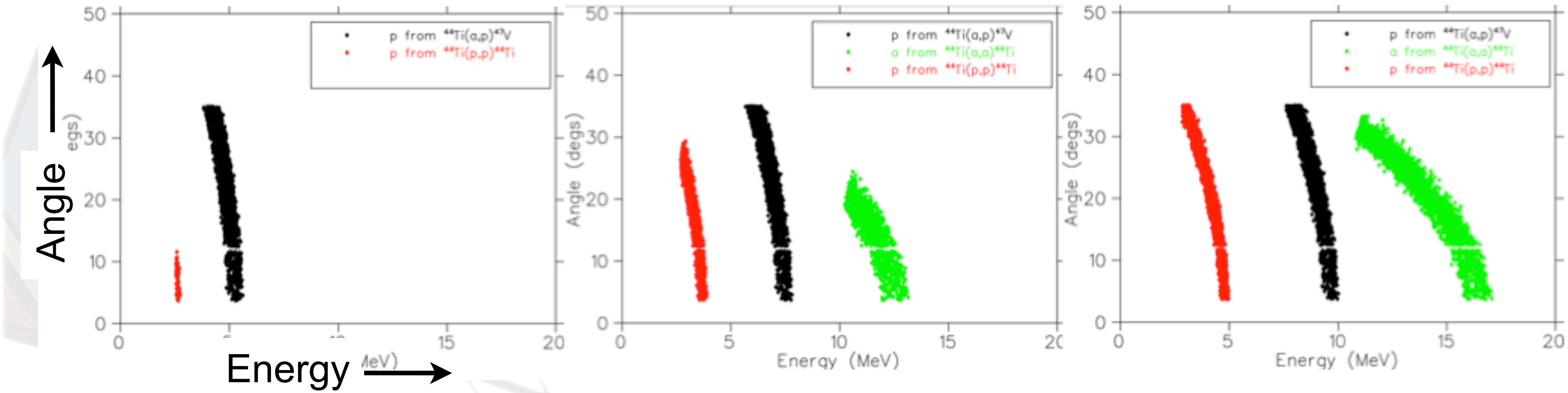






^{44}Ti Experiment Simulations

3 MeV | 4 MeV | 5 MeV



^{44}Ti(a,p)^{47}V

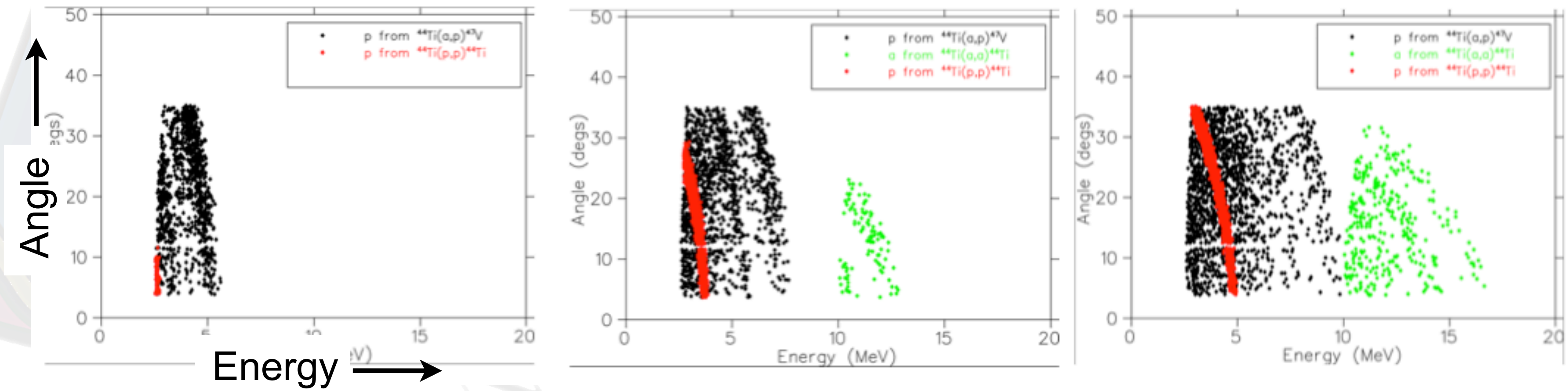
^{44}Ti(p,p)^{44}Ti

^{44}Ti(a,a)^{44}Ti

Clean separation

^{44}Ti Experiment Simulations

3 MeV | 4 MeV | 5 MeV



^{44}Ti(a,p)^{47}V*

^{44}Ti(p,p)^{44}Ti*

^{44}Ti(a,a)^{44}Ti*

Very unrealistic population of excited states! 'Worst case'

^{44}Ti Event rate estimate

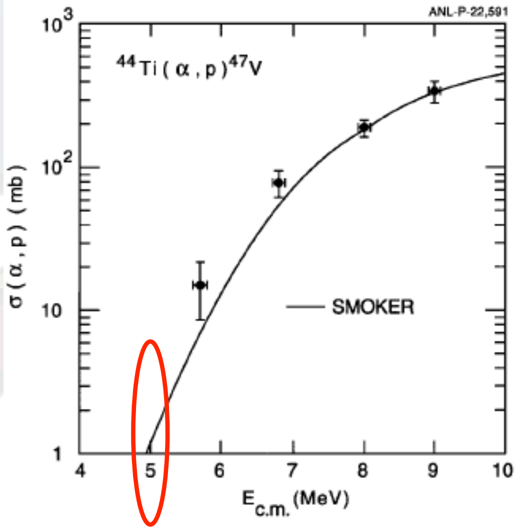


Table 1: Summary of expected rates of events.

Beam energy[1] (MeV/u)	CM Energy[2] (MeV)	Efficiency (%)	Cross section[3] (mb)	Rate (min^{-1})	Rate (hour^{-1})	Rate (day^{-1})
1.41	3.0	19.2	0.004	0.005	0.29	9
1.67	4.0	18.9	0.1	0.16	9.5	229
1.93	5.0	18.6	2.0	3.1	187	4500

[1]Beam energy to be supplied by ISOLDE.
[2]Centre of mass energy for ^{44}Ti(α,p) reactions at the start of the gas cell.
[3]Estimated by extrapolation of Sonzogni *et al.*.

Scheduling

- ^{44}Ti ions are available 'now'
- Experimental apparatus (gas cell, silicon, DAQ) is available now
- Gas cell windows, vacuum chamber need a little work
- Monte Carlo optimisation is ongoing
- Experimental team is already sufficient (additional collaborators welcome)
- Safety situation?
- Assessment of measures required to prevent activation?
- Window of opportunity during CERN 'shutdown year'?
    - We have strong support of ISOLDE team

Thank You