EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

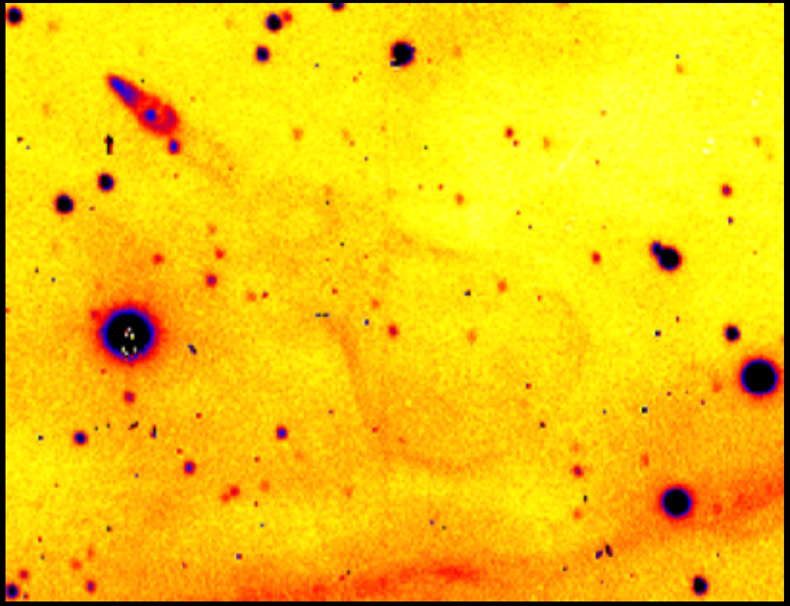
Measurement of the $^{44}Ti(\alpha,p)^{47}V$ reaction cross section, of relevance to gamma-ray observation of core collapse supernovae, using reclaimed ^{44}Ti.

January 6, 2012

Spokesperson: Alex Murphy
Data Analysis: Vincent Margerin

Radioactive waste to probe core collapse supernovae






The case, in a nutshell...

- Core collapse Supernovae are exciting
- There remains fundamental uncertainty in the explosion mechanism
- Gamma-rays from ^{44}Ti decay are one of the few ways in which observational data could improve models
- Major recent space investment is likely to produce new observational data
- The main nuclear uncertainty is the ^{44}Ti(α,p) reaction
- ^{44}Ti reclaimed from irradiated parts at PSI is now available
- A measurement at ISOLDE, dramatically reducing nuclear uncertainties, is now possible
- ...and was performed in Dec 2012!

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

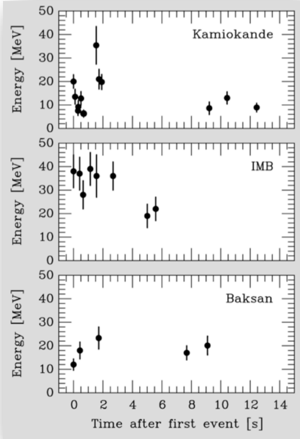
CCSN Simulation status
(Adapted from A. Burrows)

- Rapidly advancing field
- Neutrino driven explosion ‘unsatisfactory’
- Consensus that the ‘true’ mechanism should not be ‘marginal’
- Prompt and 1D models always fizzle
- GR... makes no difference
- Improved neutrino physics... makes no difference
- EOS... probably makes no difference
- All groups get ~the same results for all progenitors

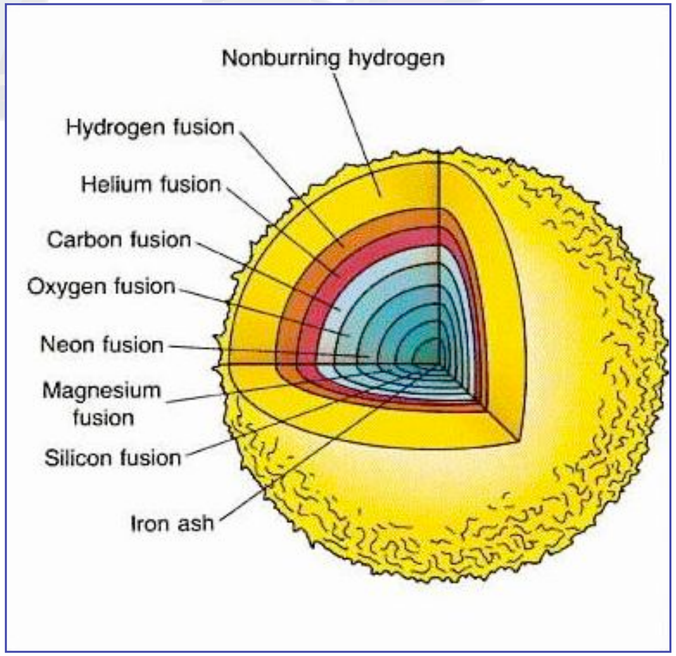
CCSN Simulation status
(Adapted from A. Burrows)

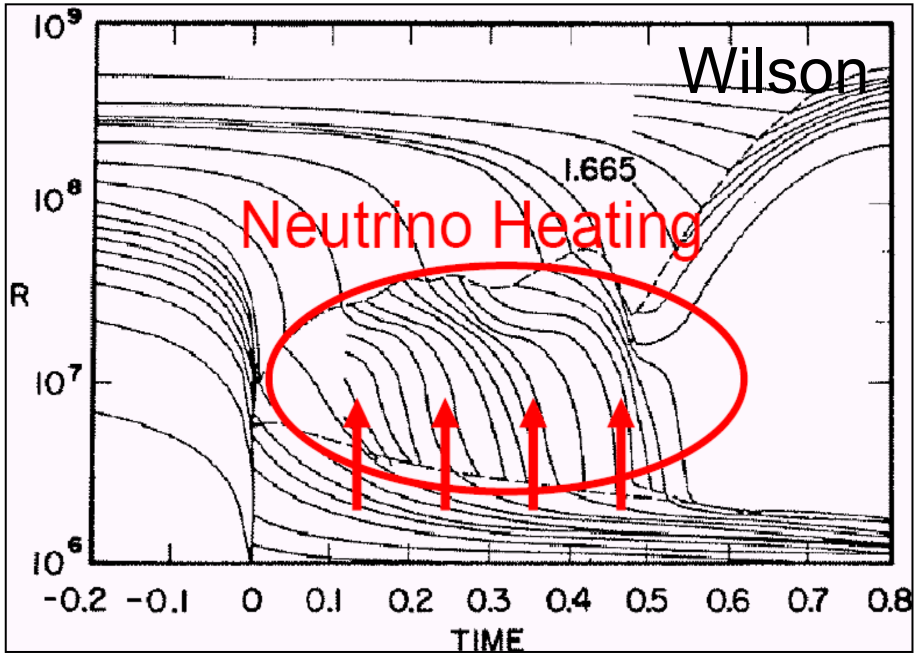
- 2D/3D model are showing more promise
- Asymmetry looks to be the key
  - Enhances convection
  - Induces ‘fingers’
- The asymmetry probably comes from <u>rotation</u>
  - ‘Naturally’ produces bi-polar explosions
  - Collapse amplifies rotation
  - Increases gain region, reduces effective gravity
  - Likely explanation of pulsar kicks
  - Likely source of gravitational radiation
- Possible role of g-wave acoustics, excitation of scalar fields, etc.

The Neutrino Mechanism



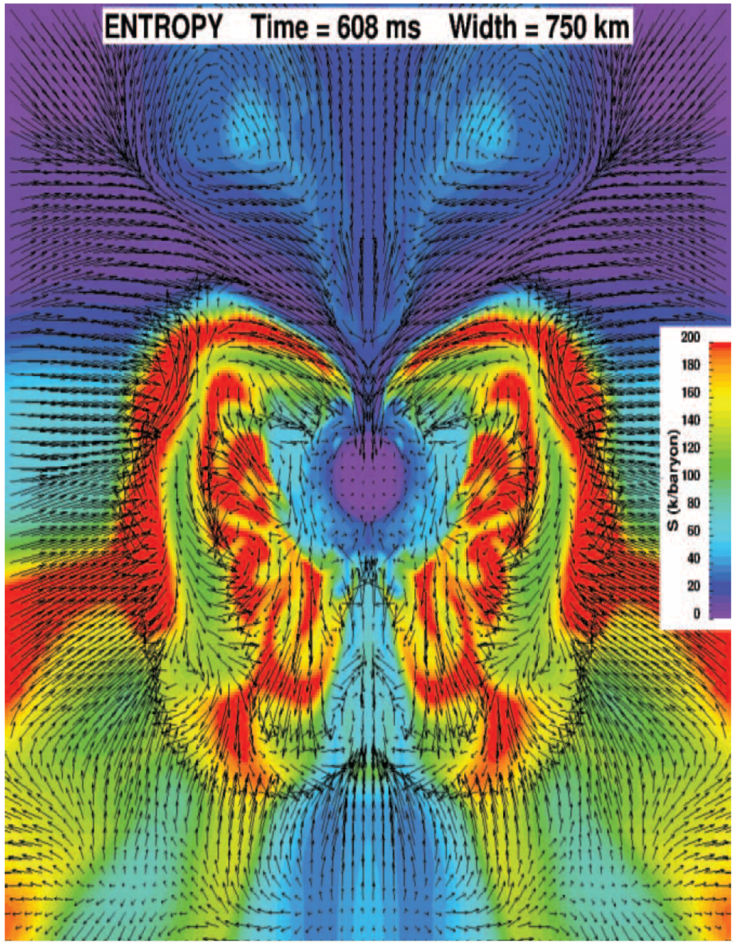
- Massive star (>8–10 $M_\odot$)
- Stellar evolution → onion-skin-like structure
- At maximum of BE/A, thermal support lost → Collapse
- Huge flux of neutrinos "re-energises" explosion
- Neutrino driven wind – an excellent candidate site for the r-process





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



Scalar Gravity

- Scalar fields do exist: Higgs mechanism
  - Also invoked in inflation & dark energy
- Theory here is that extreme nuclear density of a neutron star can excite scalar gravity field.
- Similar to Higgs mechanism, spontaneous symmetry breaking and energy release as ‘matter rolls down a ‘Mexican-hat’ potential’
- Provides required additional energy release for robust SN explosions.
- Could possibly be tested - suppose this mechanism leads to a different ^{44}Ti abundance?
- ***Need nuclear uncertainties removed to allow***

Dynamical trapping and relaxation of scalar gravitational fields

C. H.-T. Wang,[1,2,*] A. O. Hodson,[1] A. St J. Murphy,[3] T. B. Davies,[1] R. Bingham,[2,4] and J. T. Mendoncca[5,2]

[1] *SUPA Department of Physics, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK*
[2] *STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK*
[3] *SUPA School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, UK*
[4] *SUPA Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK*
[5] *GOLP/Centro de F´isica de Plasmas, Instituto Superior Técnico, 1049-001 Lisboa, Portugal*

We present a framework for nonlinearly coupled scalar-tensor theory of gravity to address both inflation and core-collapse supernova problems. The unified approach is based on a novel dynamical trapping and relaxation of scalar gravity in highly energetic regimes. The new model provides a viable alternative mechanism of inflation free from various issues known to affect previous proposals. Furthermore, it could be related to observable violent astronomical events, by specifically releasing a significant amount of additional gravitational energy during core-collapse supernovae. A recent experiment at CERN relevant for testing this new model is then briefly outlined.

"The Wang Particle..."

THE SUNDAY TIMES

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pressdata

Does it all begin with a big Wang?

Jonathan Leake
Science Editor

FRESH from their triumph in tracking down the elusive Higgs boson, physicists at Cern are seeking another exotic subatomic particle — the Wang.

They are designing an experi-

Wang has some uncanny parallels with Higgs, partly because he, too, is based at a Scottish university but also because, if proven, the Wang (as it has not yet been formally named) would be a similar type of particle to the Higgs and

invisible subatomic particles streaming out from the star — rather than a huge visible explosion. It is this explosion that converts the outer layers of the star into new elements and blasts them into space.

At Cern this November, how-

Oh dear...!

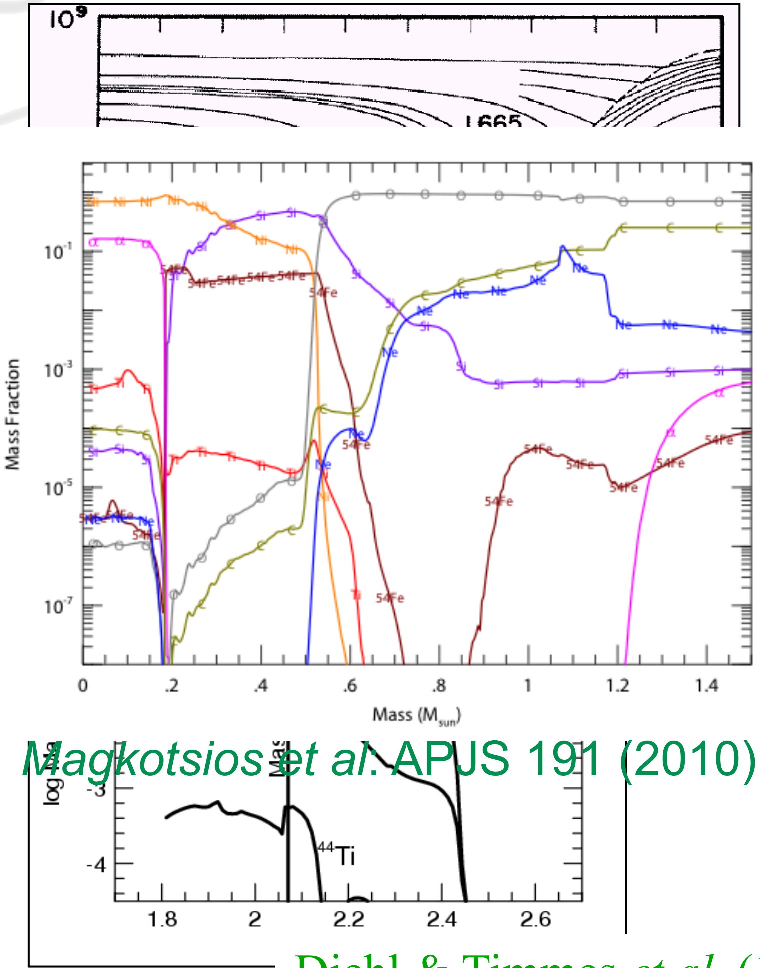
Could ^{44}Ti discriminate between these models?

- "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

The Importance of ^{44}Ti

- Amount ejected sensitively depends on location of the ‘mass cut’
- ^{44}Ti that is ejected will become a γ-ray emitter
- Material that ‘falls back’ is not available for detection
- ^{44}Ti yield is sensitive to the explosion mechanism
- Thus, very useful for models to make compare against



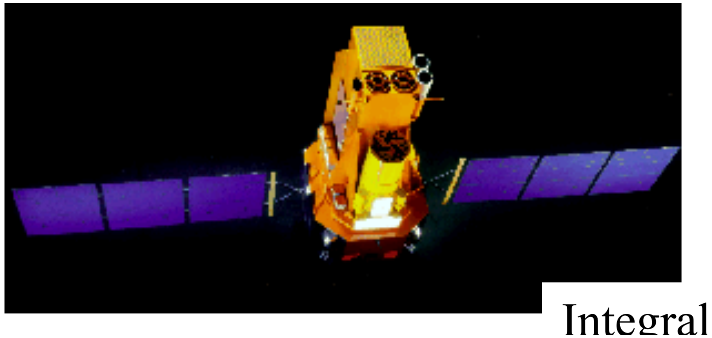
.985)

Magkotsios et al. APJS 191 (2010) 66

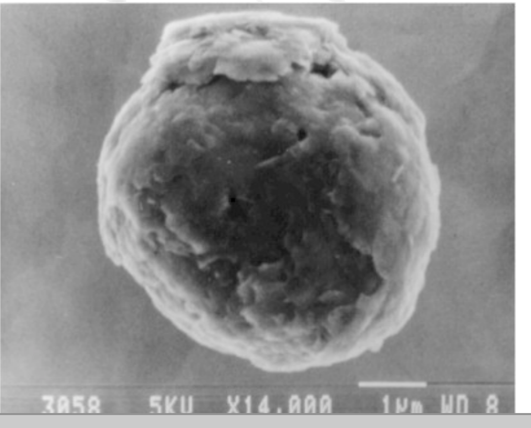
Diehl & Timmes *et al.* (1998)

The Importance of ^{44}Ti

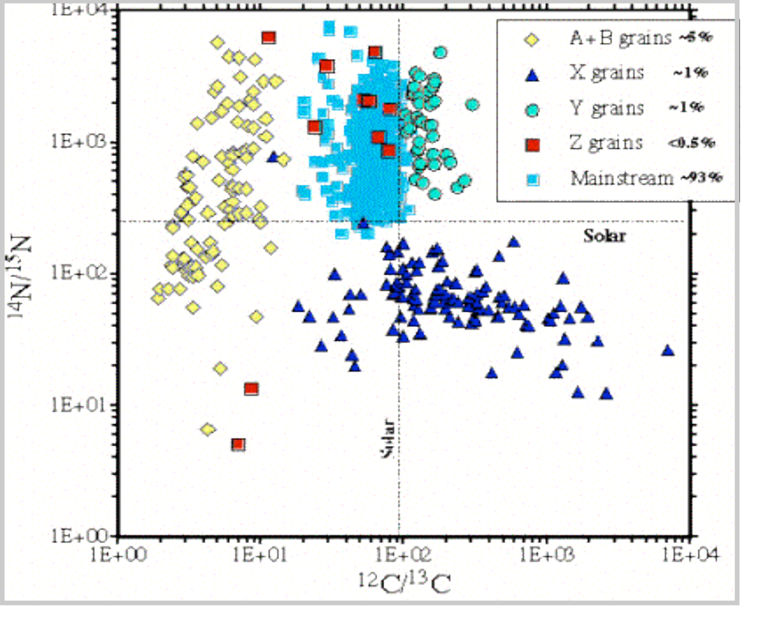
- ^{44}Ti that is ejected will become a γ-ray emitter
- Cassiopeia-A, Vela, SN1987A
- τ=60 yrs, E_γ =1.157 MeV
- 'Easily' observable
- INTEGRAL & other missions
- Also Meteoritic data
- Enrichment of ^{44}Ca in type X presolar grains



Integral



A grain from the Murchison Meteorite



Key Reactions

Reaction rate sensitivity studies:

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

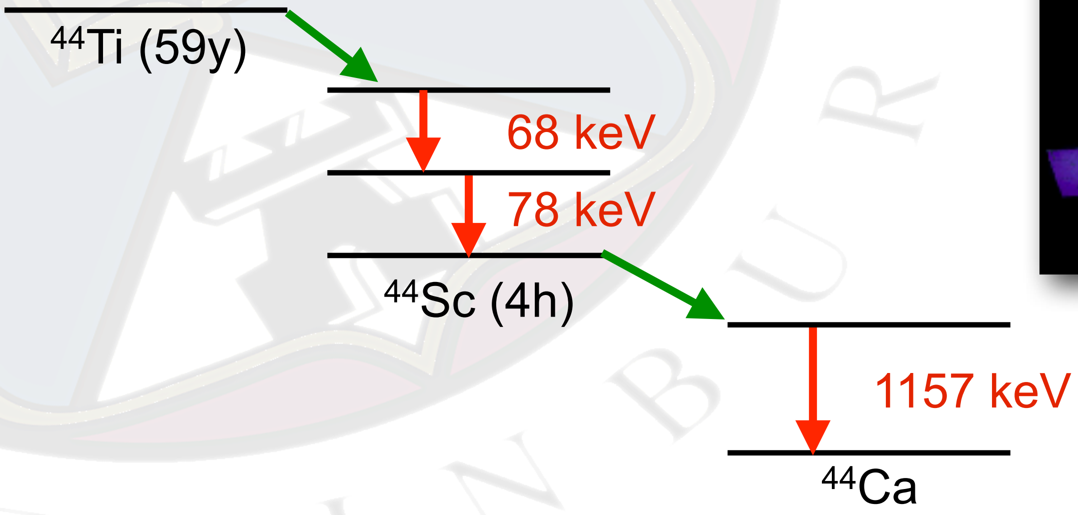
- Papers agree, ^{44}Ti(α,p) most important reaction
- Importance stems from it being the bottle neck in reaction flow as material drops out of QSE

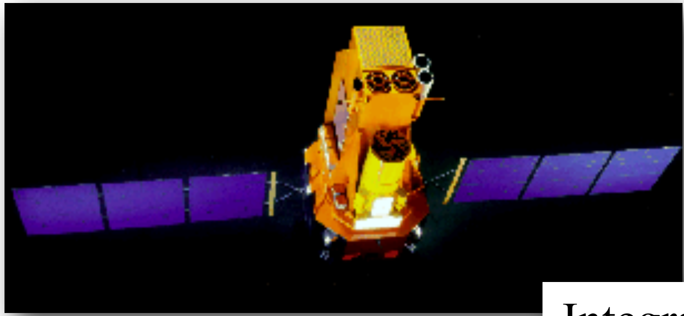
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0^a$

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 $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

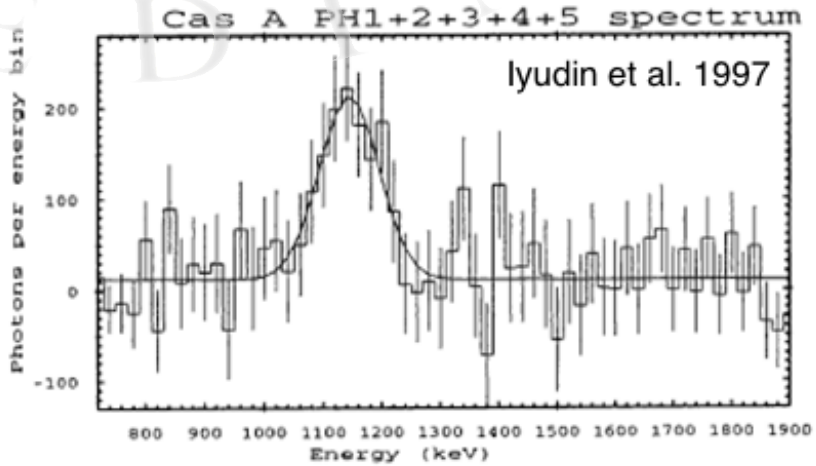
Gamma-ray emission from ^{44}Ti

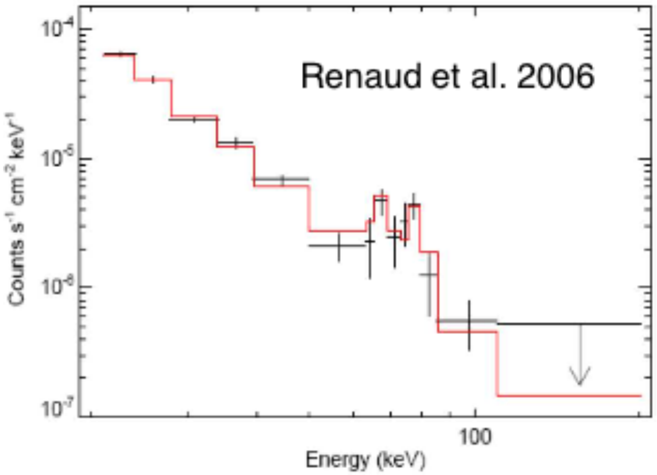


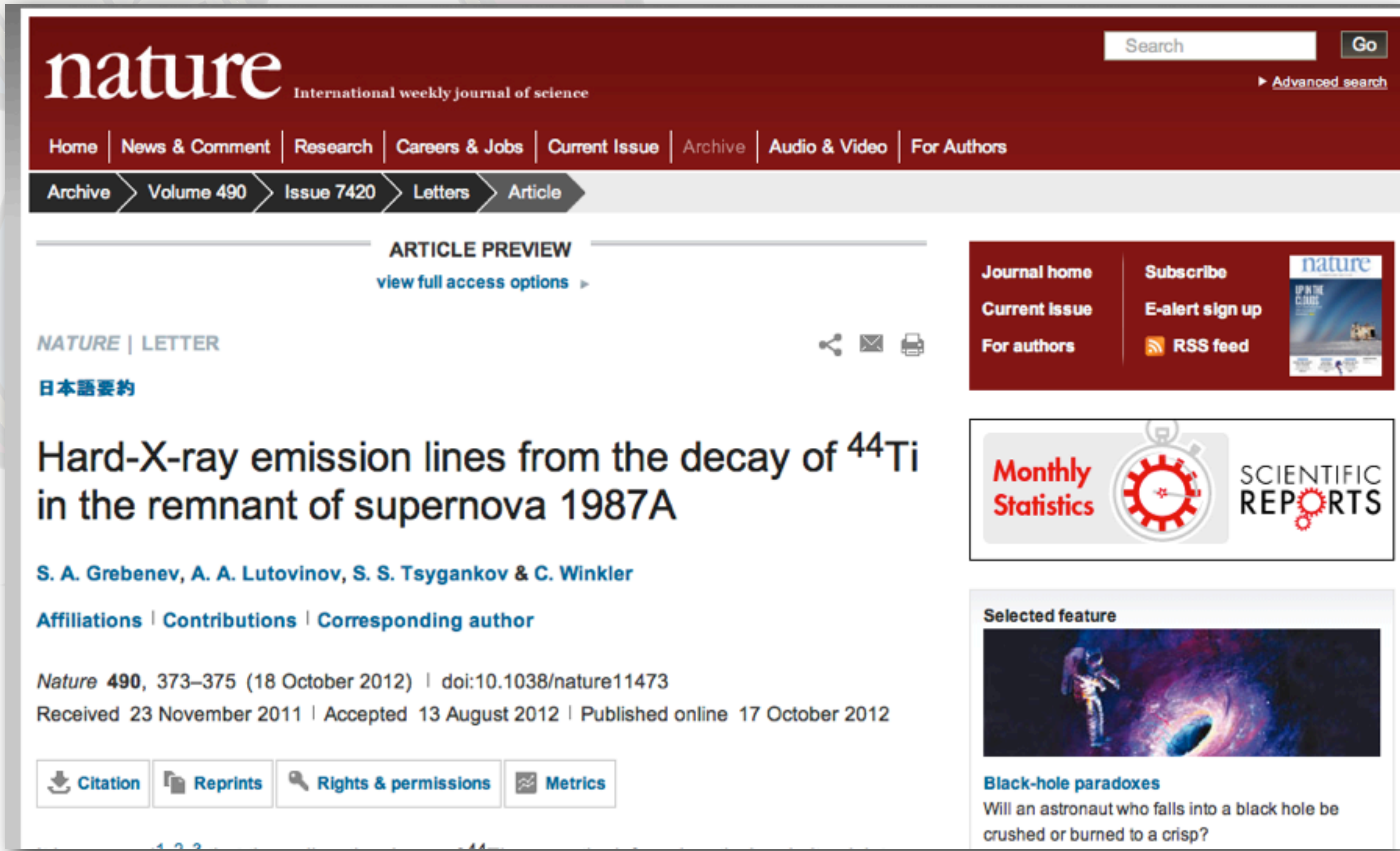


Integral

IBIS Cas-A







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NATURE | LETTER

日本語要約

Hard-X-ray emission lines from the decay of ^{44}Ti in the remnant of supernova 1987A

S. A. Grebenev, A. A. Lutovinov, S. S. Tsygankov & C. Winkler

Affiliations | Contributions | Corresponding author

Nature **490**, 373–375 (18 October 2012) | doi:10.1038/nature11473

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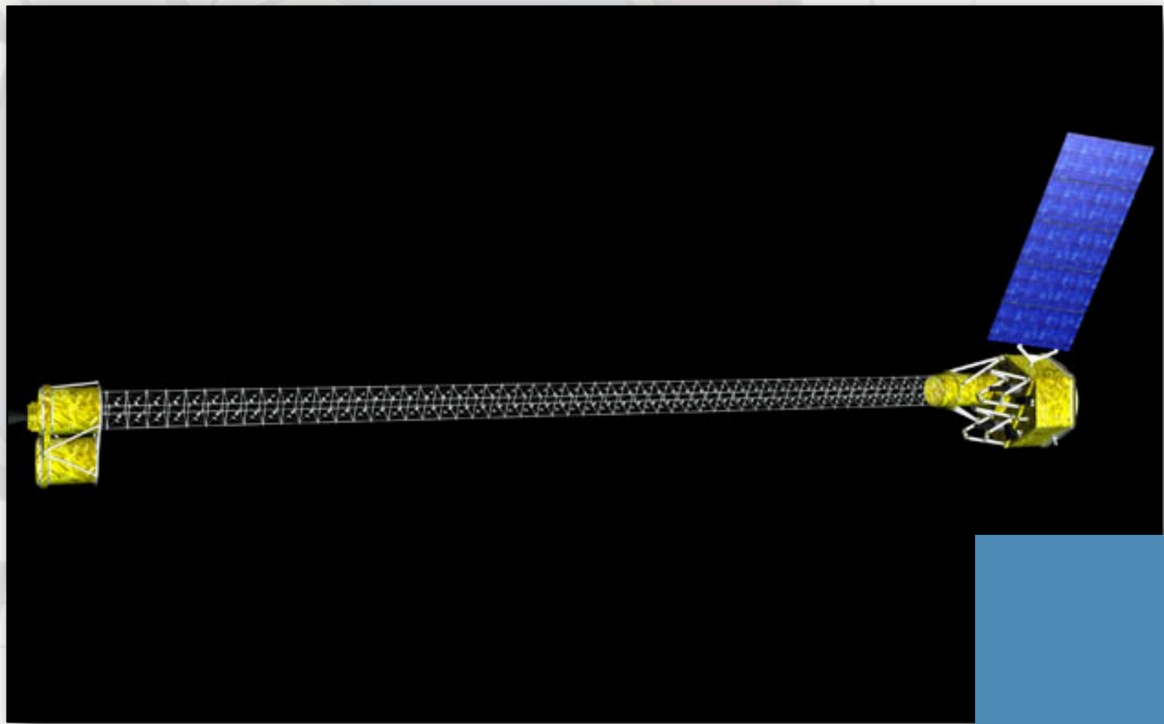
Selected feature

Black-hole paradoxes

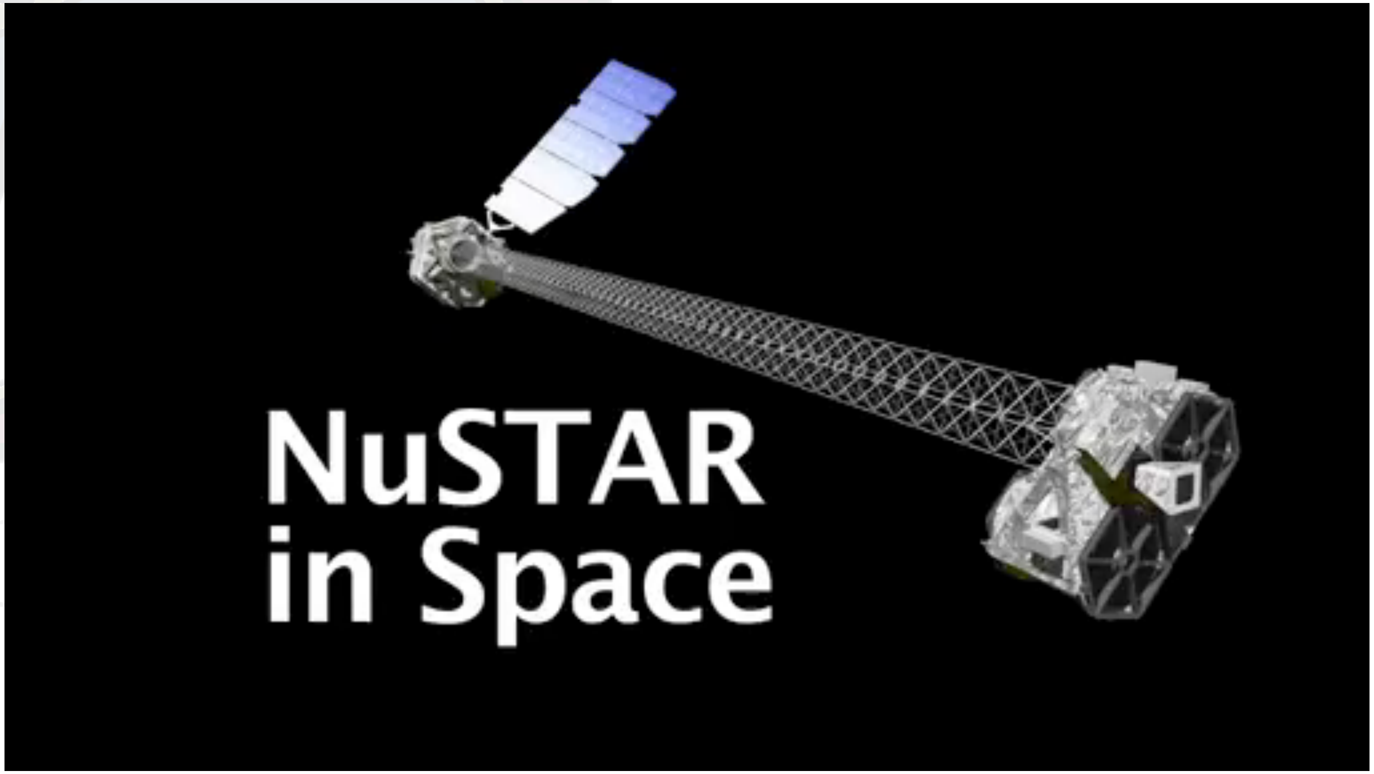
Will an astronaut who falls into a black hole be crushed or burned to a crisp?

NuSTAR (the 'other' one)



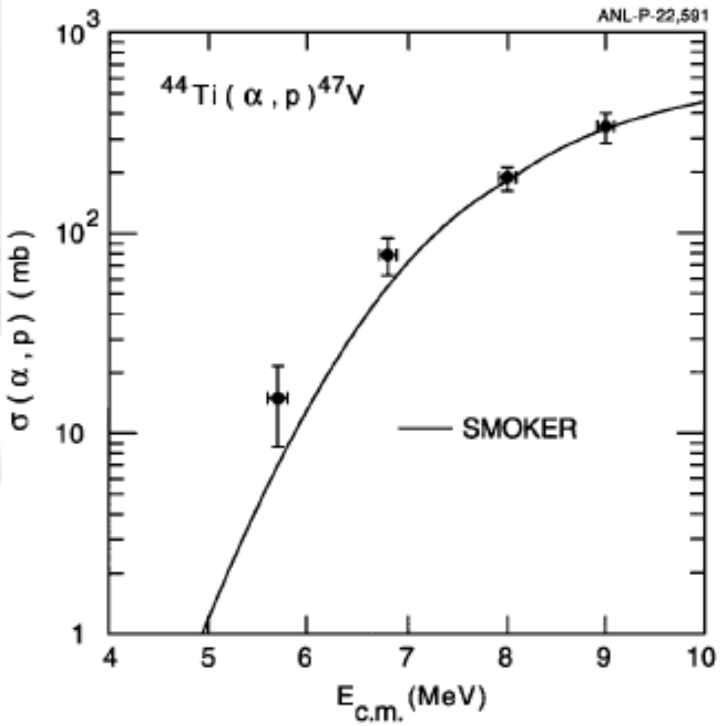
Hard X-ray imager
6-80 keV

LAUNCH:
13th June 2012!


NuSTAR
in Space

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

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)

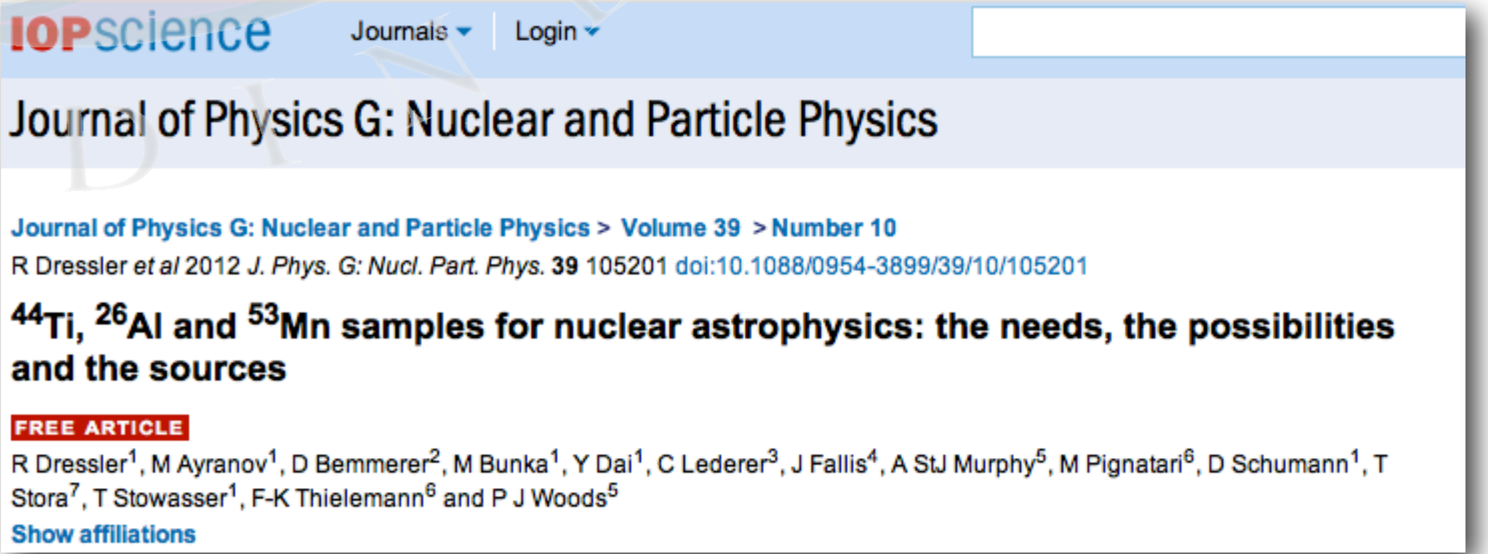
Data achieved with ~10^5 pps on target

A New Proposal

- Direct $^{44}Ti(\alpha,p)^{47}V$, in inverse kinematics
- ^{44}Ti beam
- Helium gas cell
- Silicon strip detectors

^{44}Ti Beam

- Part of the ERAWAST project
- Chemically separate ^{44}Ti from highly irradiated accelerator components of PSI
- SINQ neutron spallation facility:
  - >10 yrs of ~2 mA 590 MeV
  - >10 yrs of cooling



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Journal of Physics G: Nuclear and Particle Physics

Journal of Physics G: Nuclear and Particle Physics > Volume 39 > Number 10

R Dressler *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* **39** 105201 doi:10.1088/0954-3899/39/10/105201

^{44}Ti, ^{26}Al and ^{53}Mn samples for nuclear astrophysics: the needs, the possibilities and the sources

FREE ARTICLE

R Dressler[1], M Ayranov[1], D Bemmerer[2], M Bunka[1], Y Dai[1], C Lederer[3], J Fallis[4], A StJ Murphy[5], M Pignatari[6], D Schumann[1], T Stora[7], T Stowasser[1], F-K Thielemann[6] and P J Woods[5]

Show affiliations

ERAWAST

Exotic Radionuclides from Accelerator Waste for Science and Technology

^{44}Ti Sourcing

- ~100 MBq (~3x10^{17} atoms) has been allocated for this project
- Require 10^{7} pps for 28 shifts: ~10^{13} total
- Required 'Efficiency' is ~10^{-4}

Sample preparation

- Around 50 MBq of ^{44}Ti dissolved in HNO_3.
- Poured and dried on a ***molybdenum*** foil
- Shipped from PSI to CERN

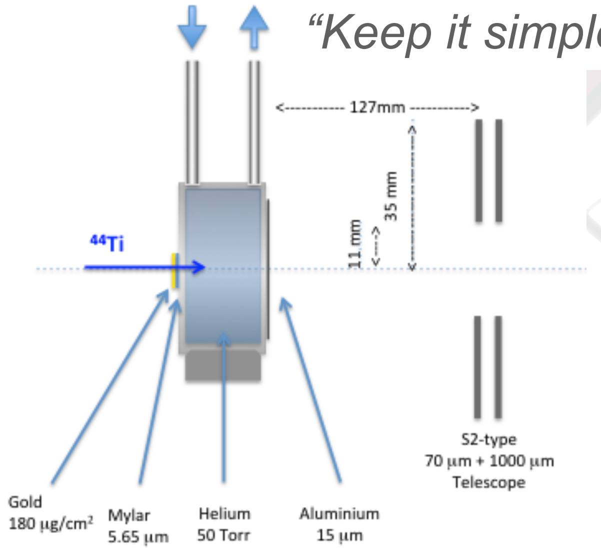
- Would a single source foil provide beam for 2 weeks?

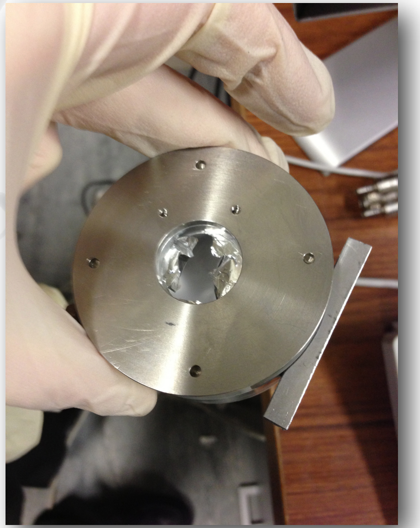
^{44}Ti Delivery from PSI

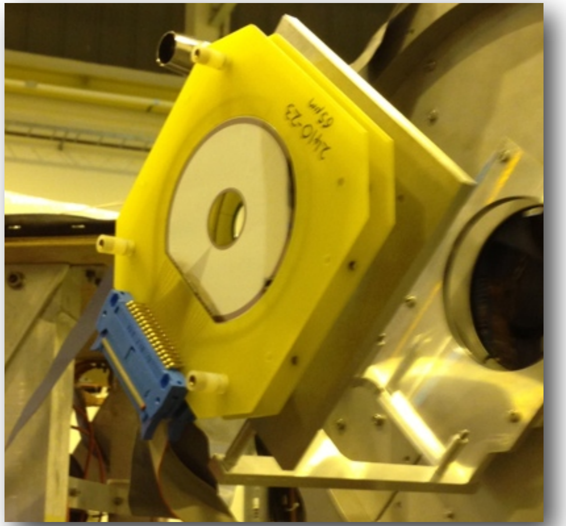
- Foil inserted in a standard target container in the ISOLDE Class A target laboratory,
- Connected to VADIS FEBIAD ion source (VD5 config')
- A large CF_4 gas leak ➔ TiFx molecular ions.
- Installed on GPS Front End
- TiF^{3+} molecular beam extracted.
- Dissociation during charge breeding in REX-ISOLDE
- Accelerated
- ~$5x10^5$ to ~$5x10^6$ pps for ~100 hours.
- No significant apparent isobaric contamination,
- Beams of 3.9 and 4.2 MeV (cm) were provided.

^{44}Ti Experiment configuration

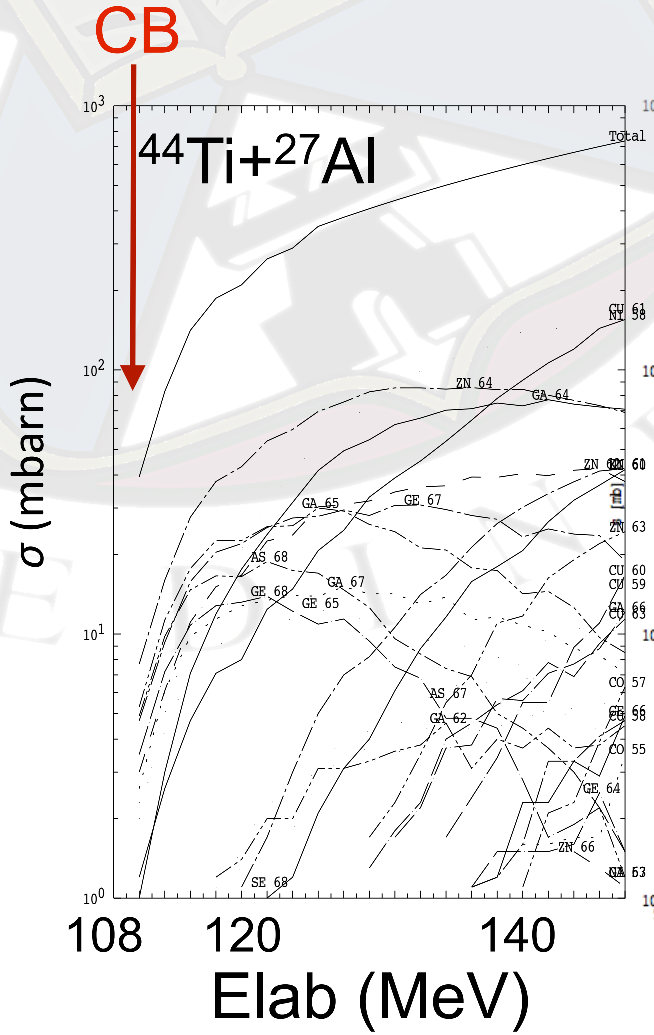
"Keep it simple"

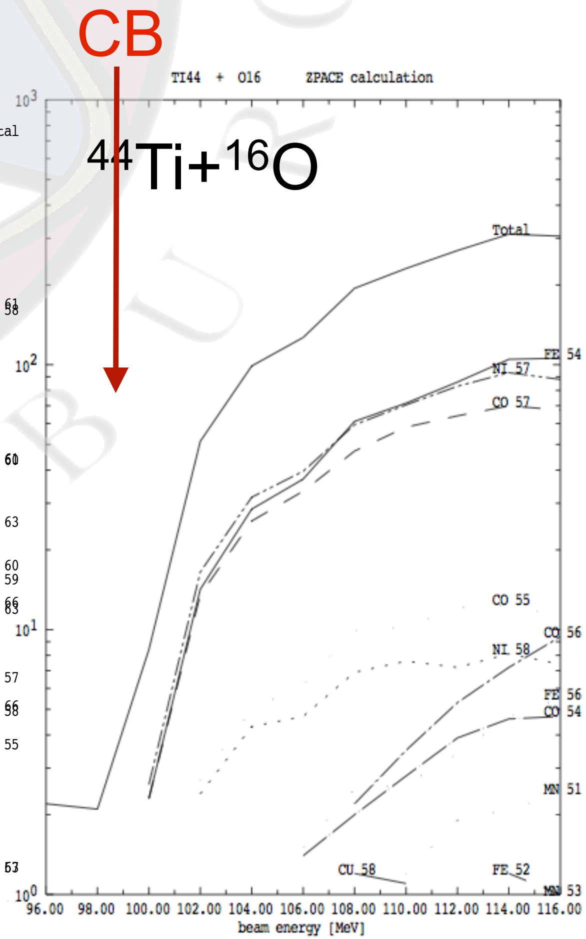






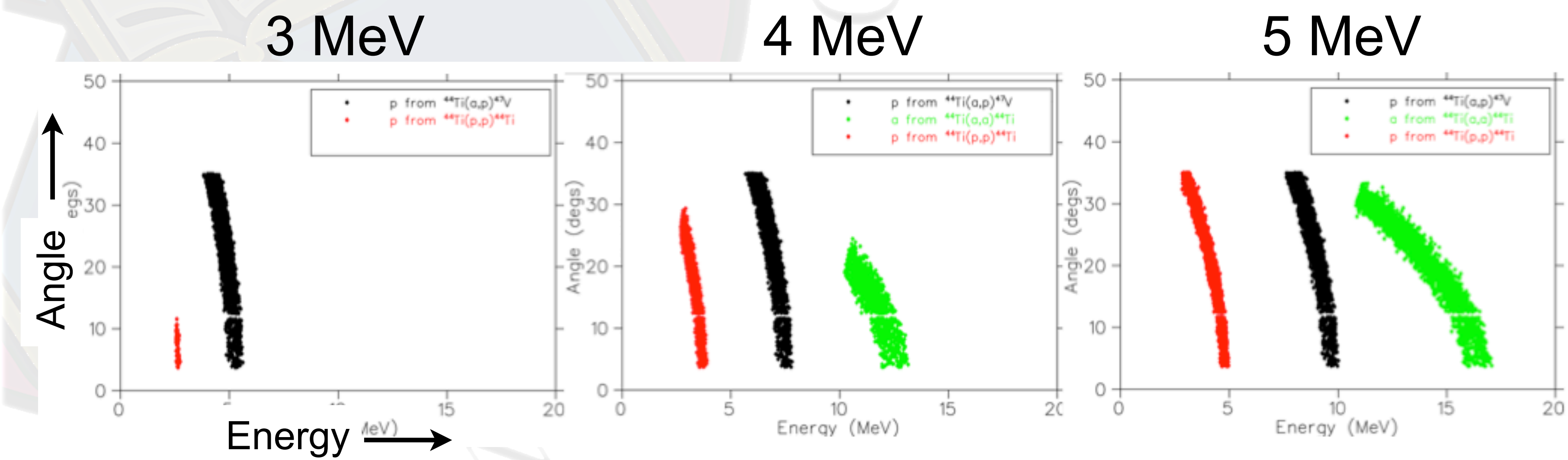
Beware fusion-evaporation





- Entrance window kept thin to keep beam energy low
- Required <9um entrance window
- 6um used.

^{44}Ti Experiment Simulations



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

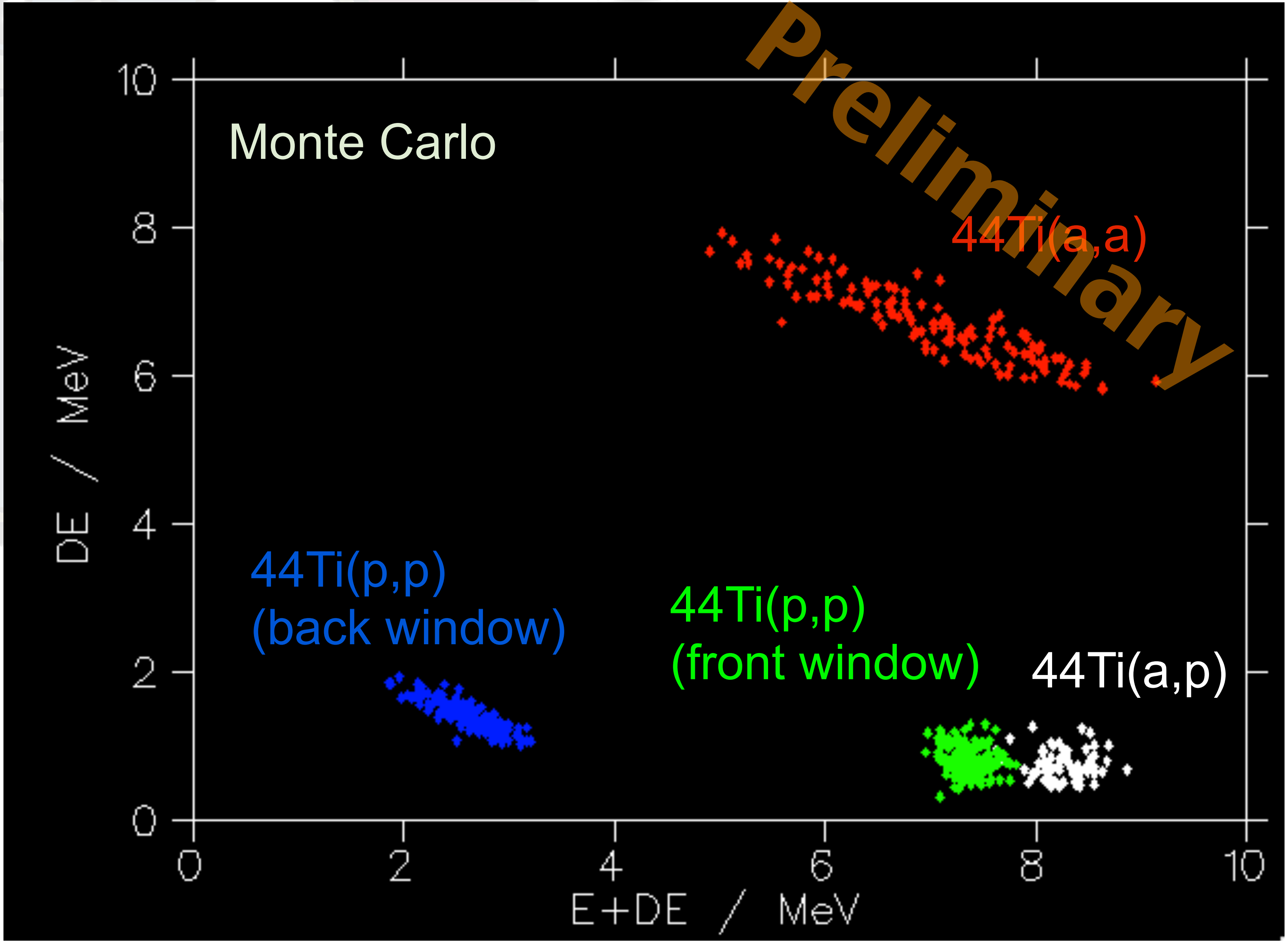
^{44}Ti(p,p)^{44}Ti

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

Clean separation

December 2012

So, what have we seen?


Preliminary
Monte Carlo
44Ti(a,a)
44Ti(p,p)
(back window)
44Ti(p,p)
(front window)
44Ti(a,p)
DE / MeV
E+DE / MeV
0
2
4
6
8
10

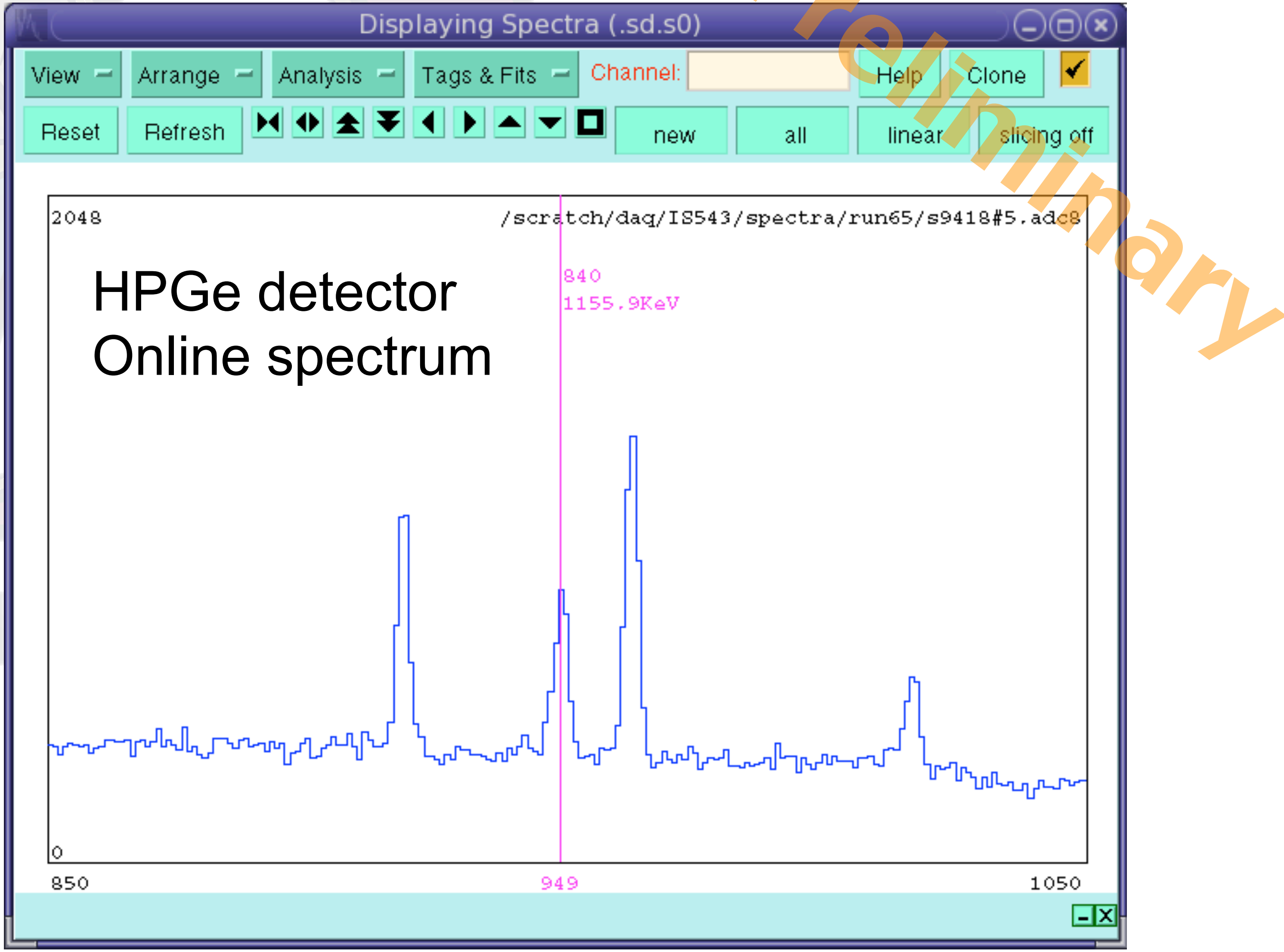
Beam delivery

Preliminary

2.10 & 1.95 MeV/u ^{44}Ti 13^{+}

Started at about 7epA
Ends at about 0.5 epA

Use of photo diodes shows beam to be (almost) pure ^{44}Ti


Displaying Spectra (.sd.s0)
View
Arrange
Analysis
Tags & Fits
Channel:
Help
Clone
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Refresh
new
all
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840
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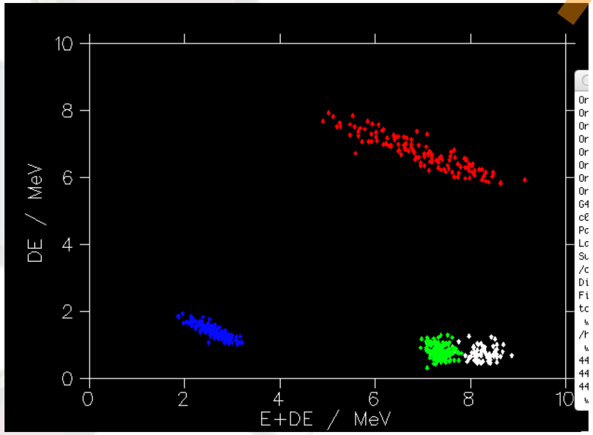
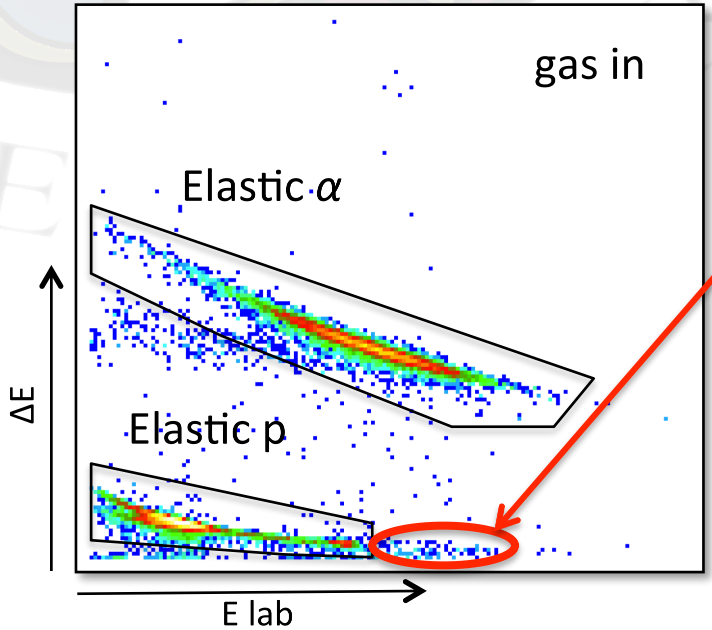
949
1050
Preliminary

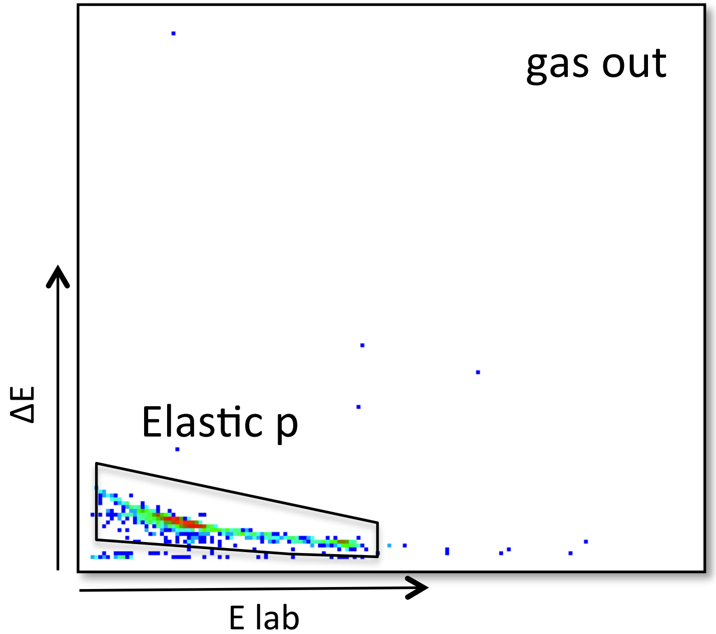
Data!

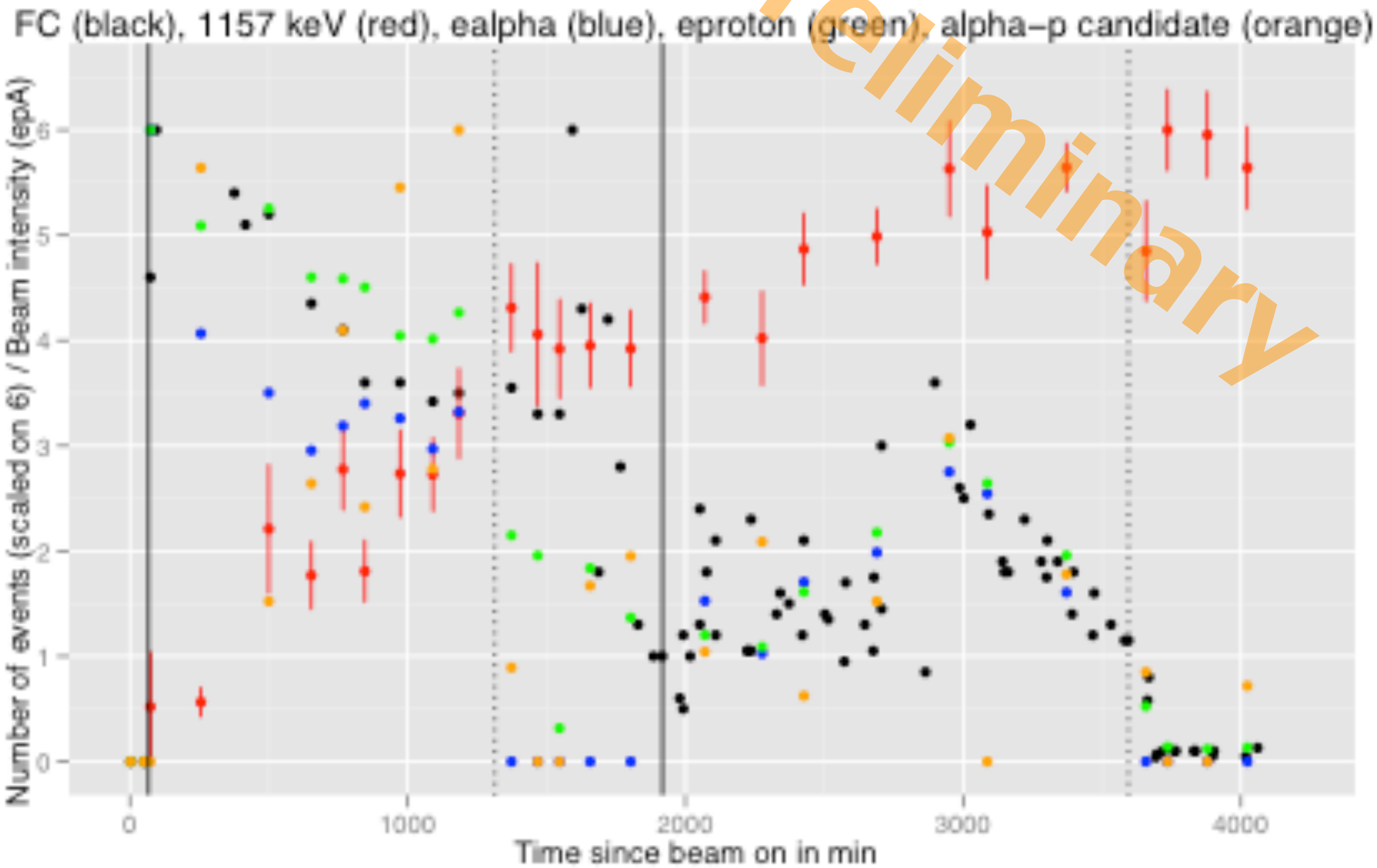


- Elastic α
- Elastic p (back of the front window / front of the back window)
- Elastic p (front of the front window)
- (α,p events)

^{44}Ti(α, p)^{47}V candidates

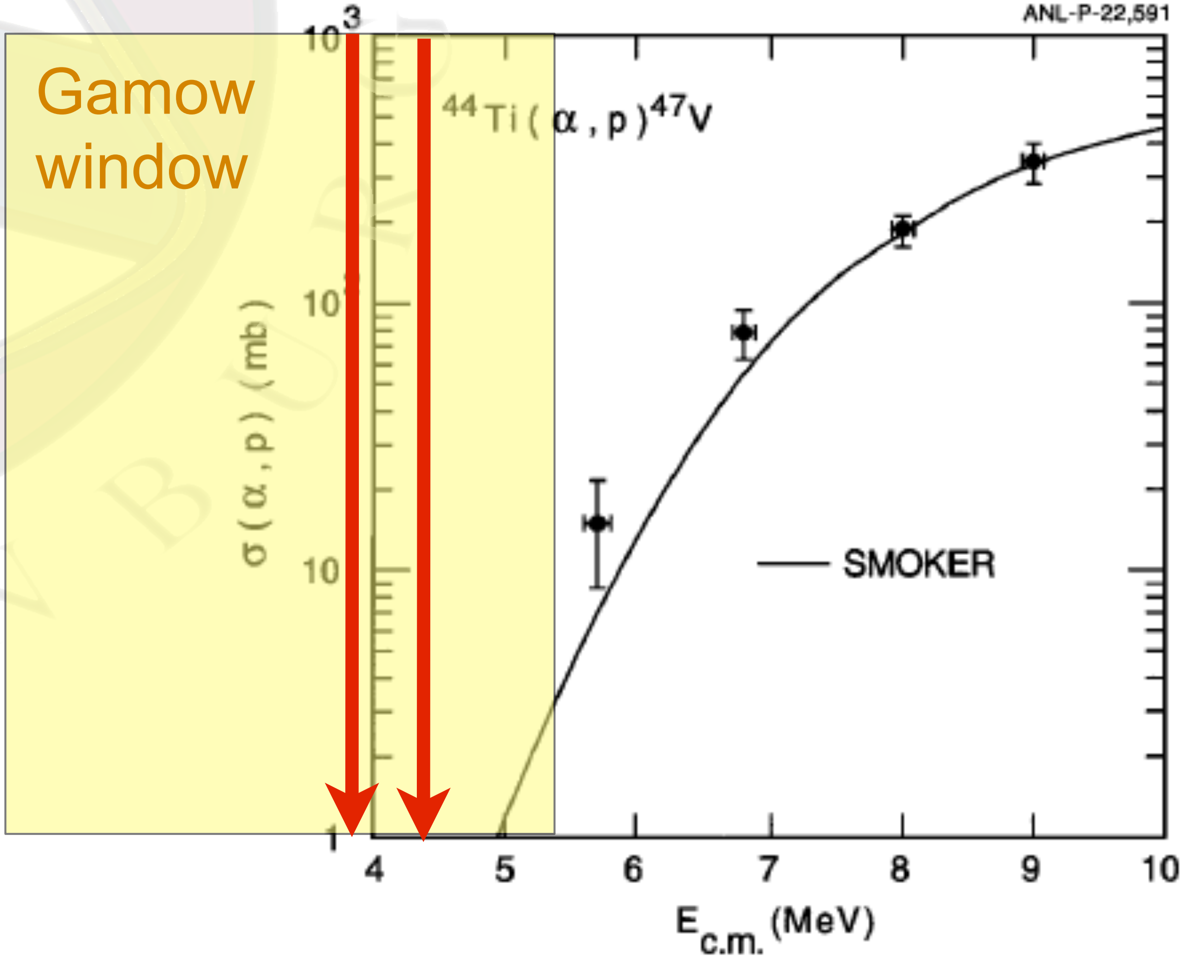






- All numbers are consistent with each other
- σ(Ruth.) ~ 30mbarn
- "Reacting" beam on target: ~$2*10^{11}$ ^{44}Ti

Sonzogni et al. PRL 84 (2000)



2.10 MeV/u → 4.3 MeVcm
1.95 MeV/u → 3.9 MeVcm

Future plans

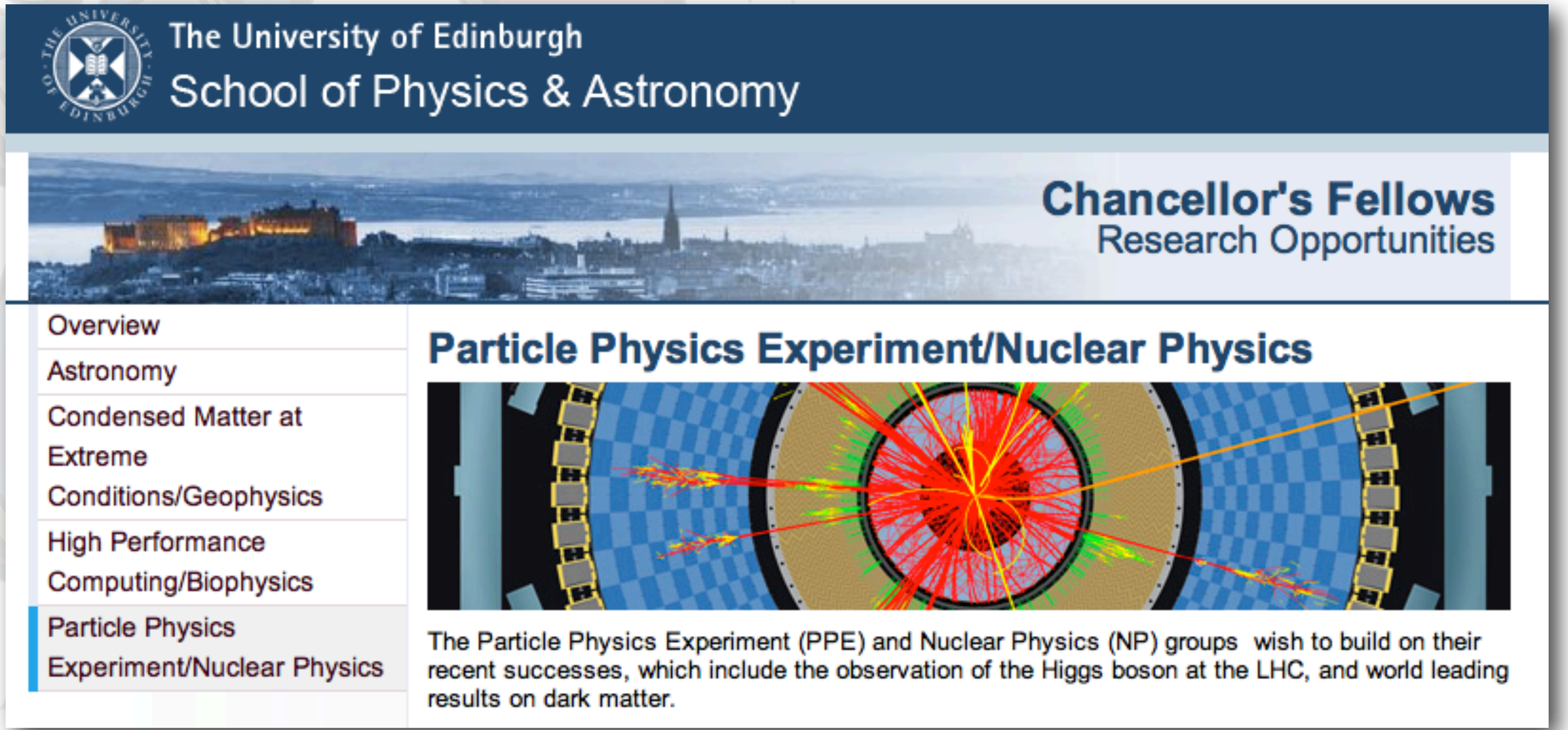
More data!

- *18 shifts still at ISOLDE*
- *TRIUMF?*
- *GANIL?*
- *CRIB RIBF?*

More reactions!

- ^{44}Ti(α, γ); ^{44}Ti(p,γ) @ TRIUMF
- ^{45}V(p, γ) @???

CCSN Simulations...?



http://www.ph.ed.ac.uk/chancellors-fellows

Applications by: 18 April 2013

The team: T. Davinson, J. Fallis, A. Kankainen, A. Laird, G. Lotay, D. Mountford, V. Margerin, ASM, C. Murphy, D. Schumann, T. Stora, C. Wang, P. Woods

Thank you!