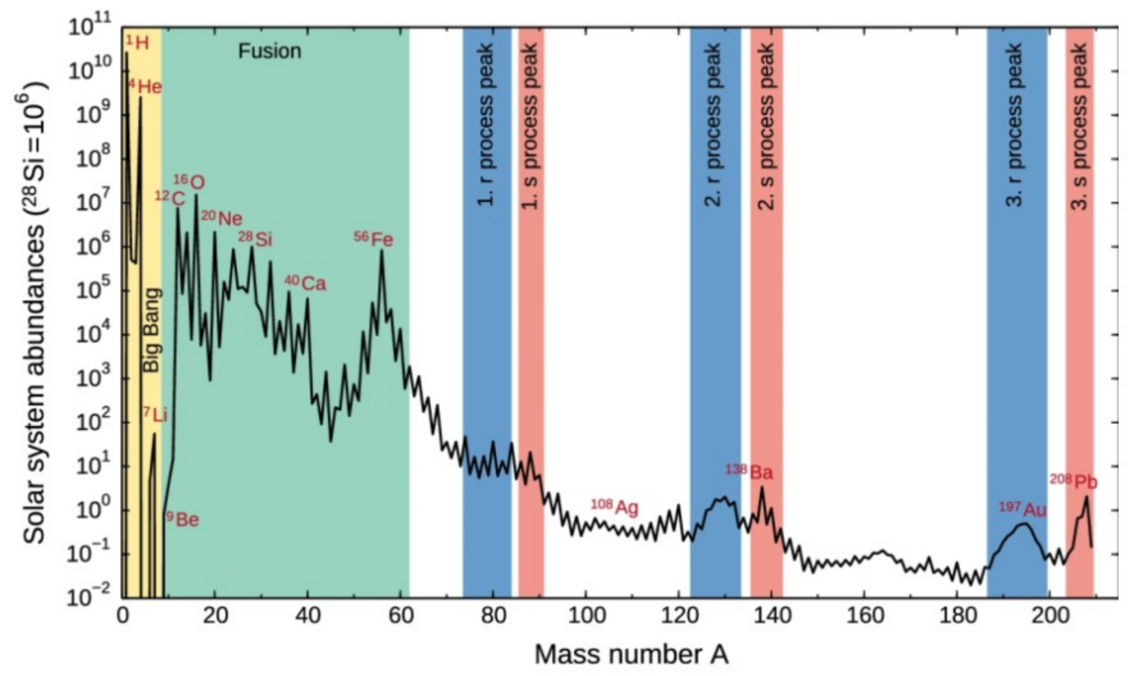
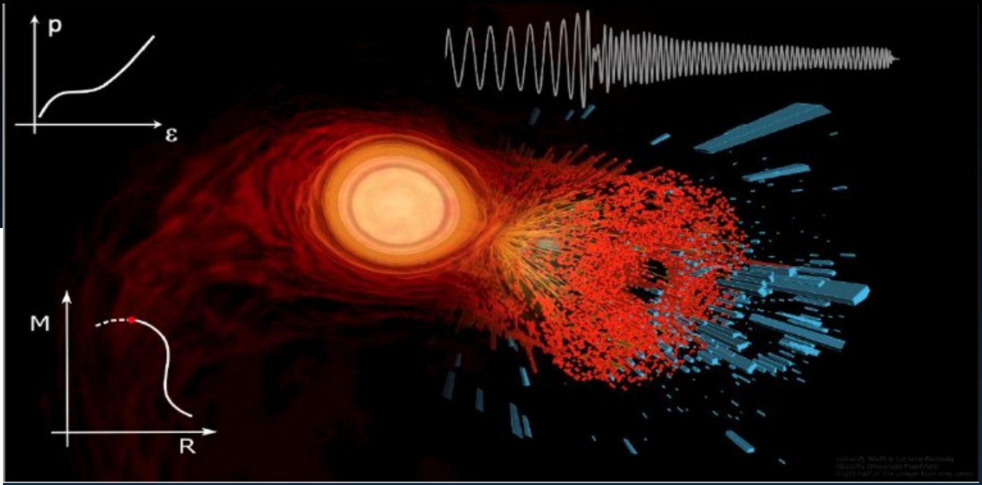
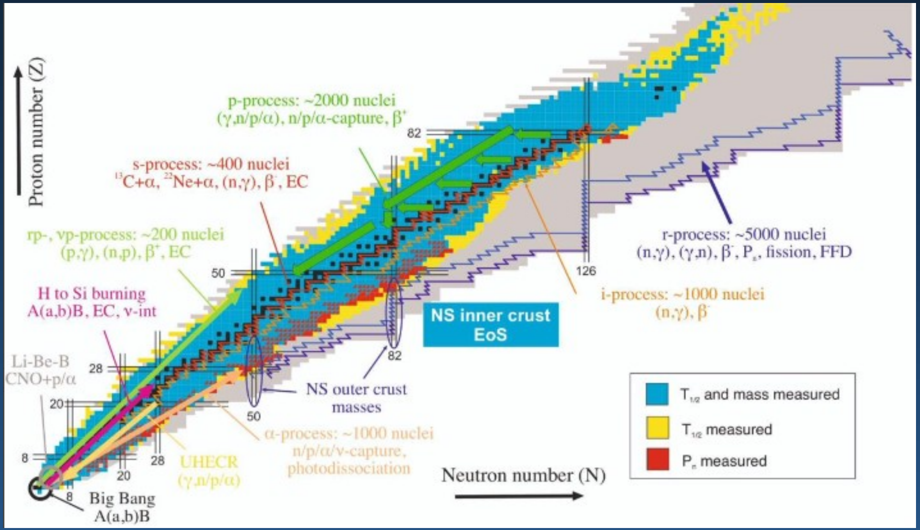
Nuclear Astrophysics







JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Uwe Oberlack (JGU) &
Daniel Bemmerer (HZDR)

Astroparticle Physics in Germany
KIT 2024-Oct-17

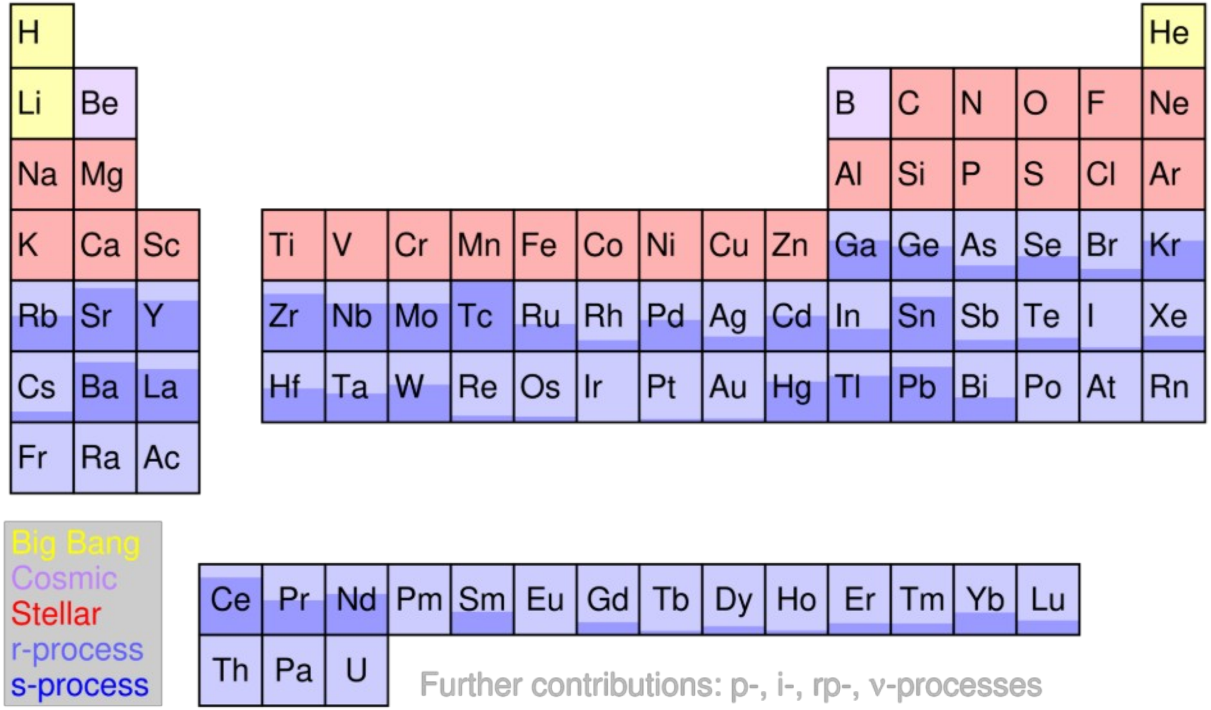
Nuclear Astrophysics

Multidisciplinary research field combining

- experimental and theoretical nuclear data with
- astrophysical modeling of BBN, stellar events, NS mergers to compare and understand
- observations via astronomy or cosmochemistry

→ links to KAT, KHUK, RDS

Cross section measurements for nuclear astrophysics



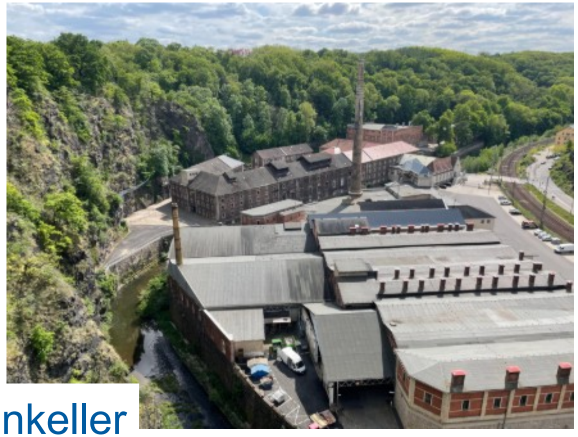
Four topics in the next ten years

- Big Bang nucleosynthesis – back to precision
- Solar hydrogen burning for the solar model
- Helium and carbon burning in stars and supernova precursors
- Neutron capture nucleosynthesis for multi-messenger events

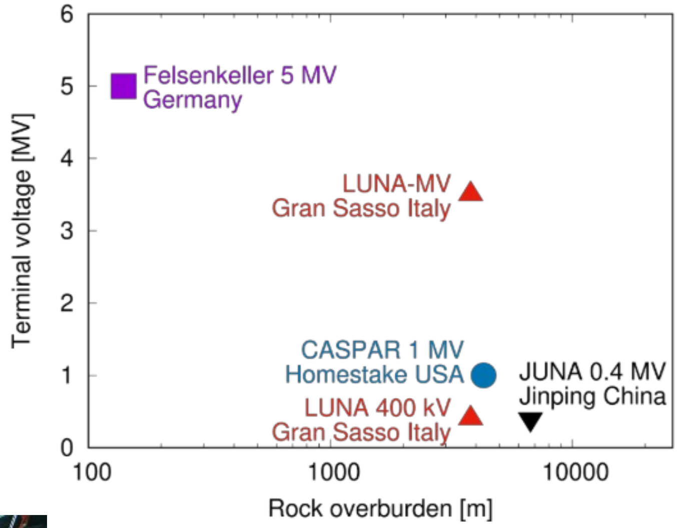
Two tools in the next ten years

- Underground ion accelerators – LUNA-MV, Felsenkeller, DZA?
- Lowest-energy ion storage rings – CRYRING, ring with neutron target?

Underground ion accelerators – new players on three continents



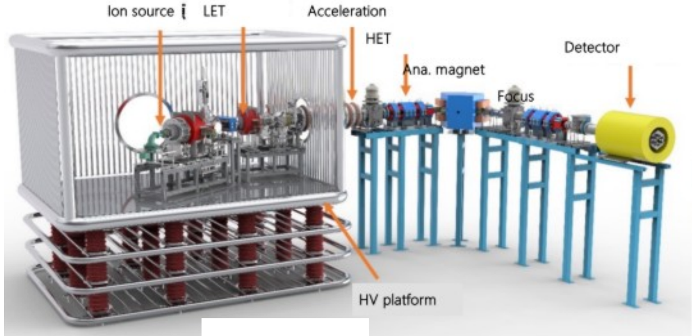
Felsenkeller



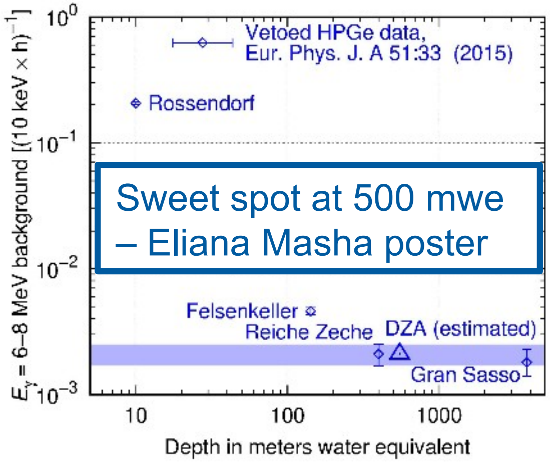
W. P. Liu et al., Sci. China 59(2016)5785.

LUNA-MV

CASPAR



JUNA



Sweet spot at 500 mwe – Eliana Masha poster

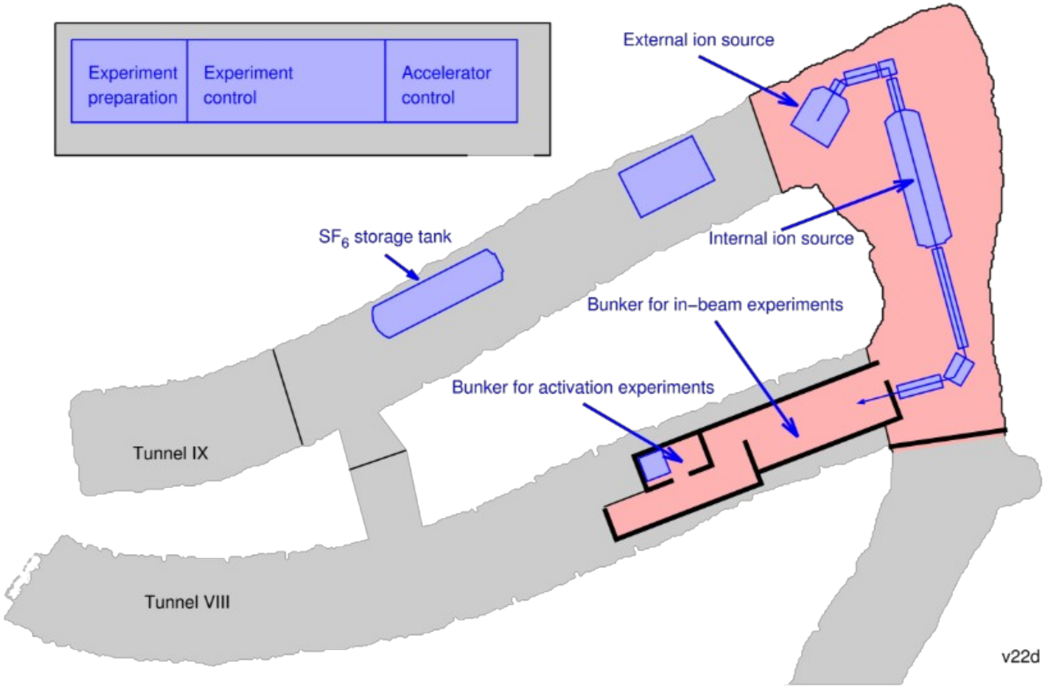
Dresden Felsenkeller underground lab, below 45 m of rock

Joint effort HZDR – TU Dresden

- Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- Day to day operations by HZDR

Two main instruments

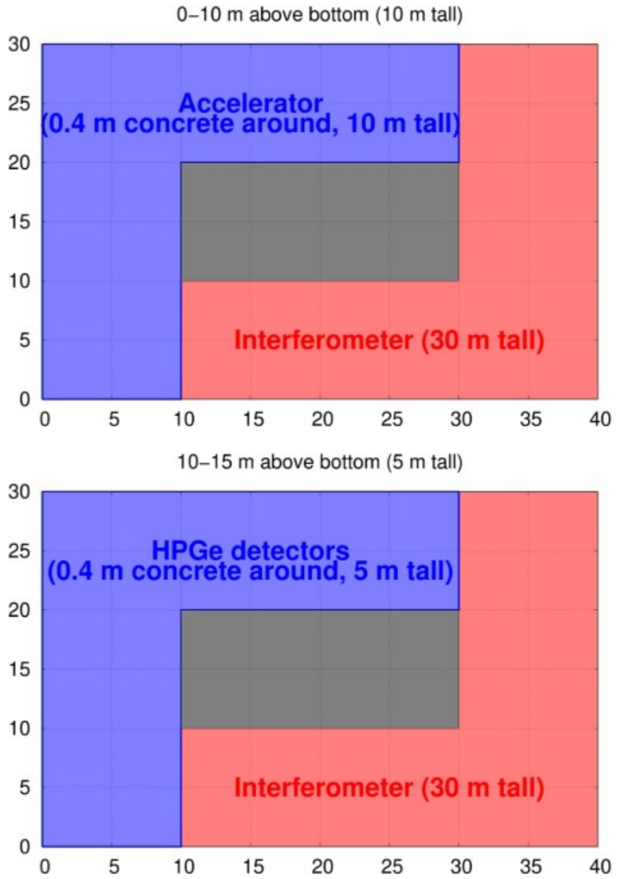
- **HZDR:** 5 MV Pelletron, 30 μA beams of $^{1}H^{+}$, $^{4}He^{+}$, $^{12}C^{+}$, ...
- **TU Dresden:** 163% ultra-low-background HPGe detector for offline radioactivity measurements

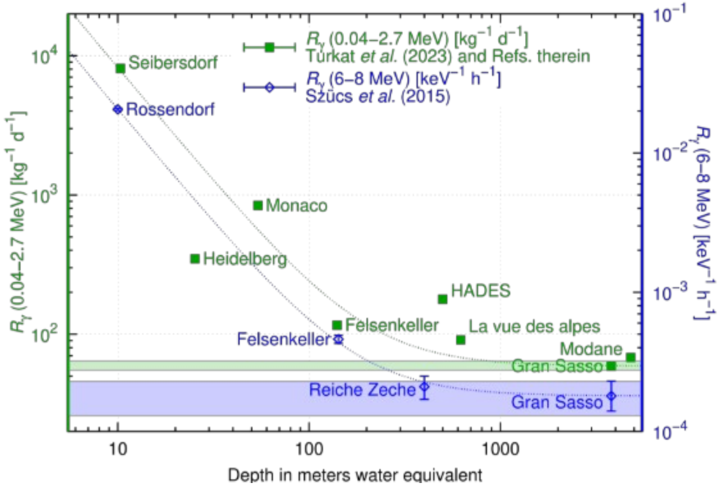


Poster Anup Yadav on new gas target system

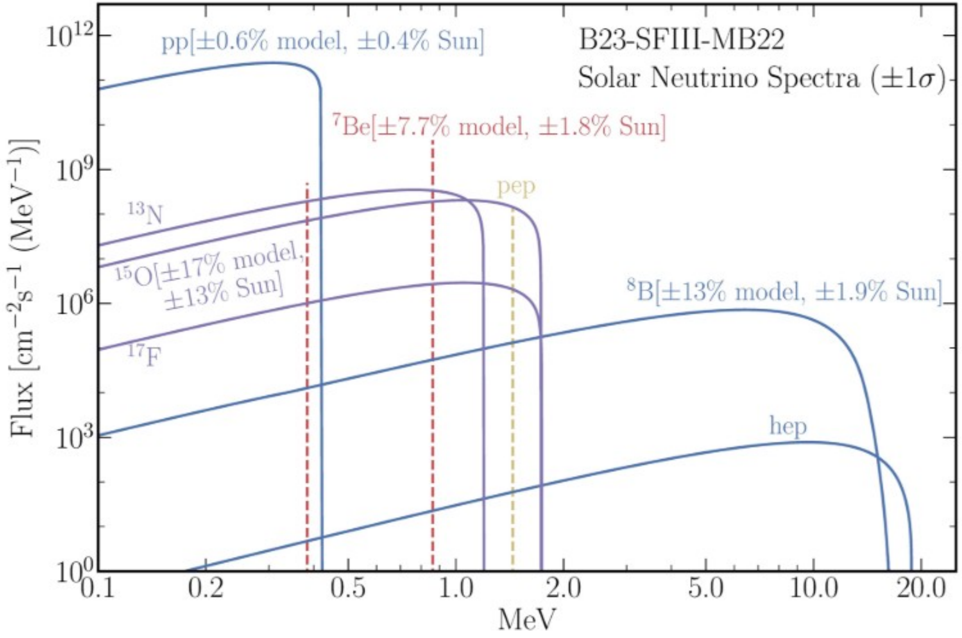
Nuclear astrophysics potential at the DZA Low Seismic Lab

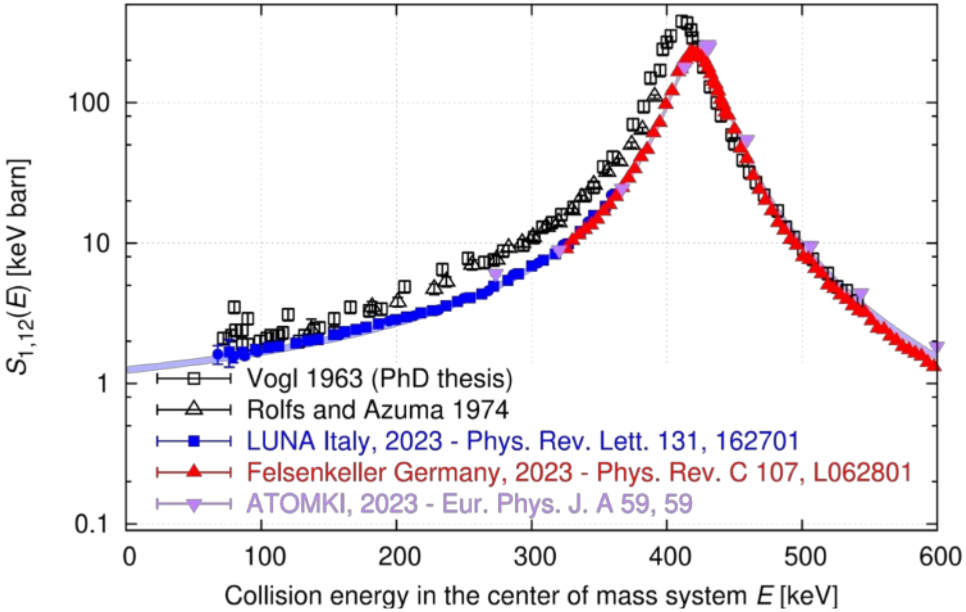
Quick facts
- Low Seismic Lab will be at a depth of at least 200 m granite (550 m.w.e.)
- A sweet spot exists at this depth, for HPGe-based nuclear astrophysics and also for HPGe-based radioactivity measurements with added muon veto.
- L-shaped interferometer and L-shaped accelerator lab may well coexist.





Solar neutrino reactions – still much to do! Here: $^{12}C(p,\gamma)^{13}N$

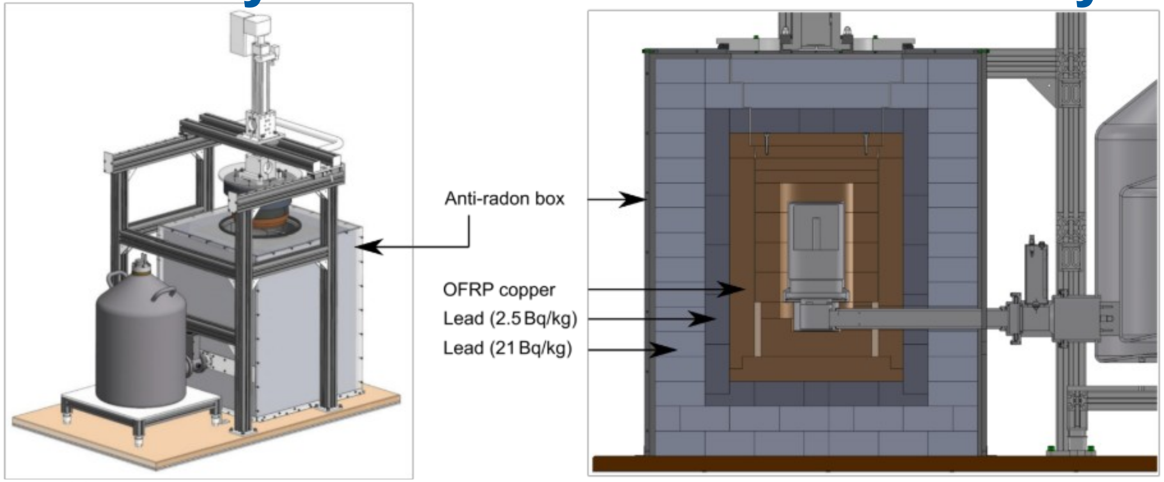


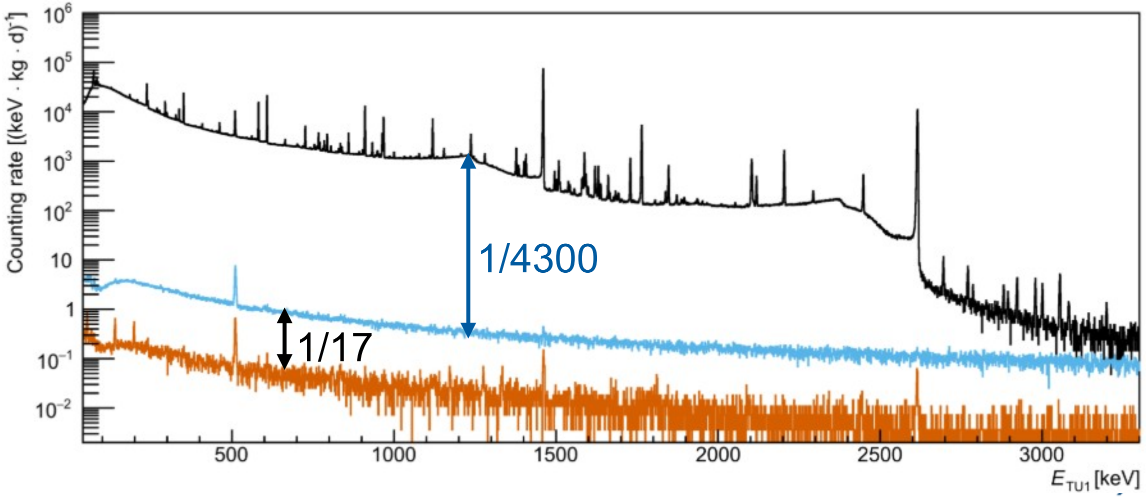


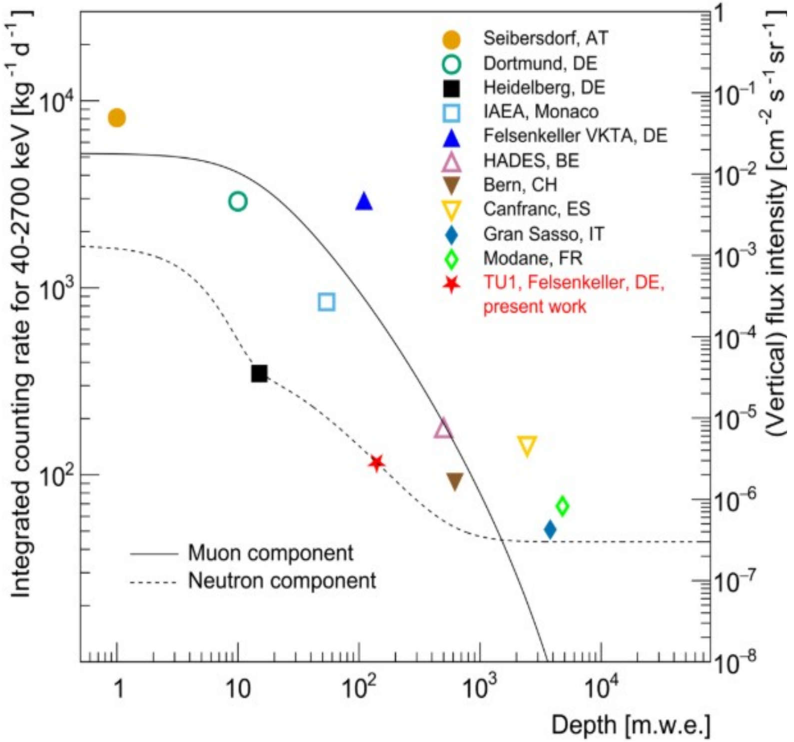
For many important fluxes, the flux uncertainty („Sun") is much lower than the model uncertainty (nuclear physics dominated for many cases, others: opacity, solar composition). Work to do for the models!

Burning-in phase of the CNO cycle in outer core of the sun.

Germany‘s most sensitive radioactivity measurement setup “TU1”







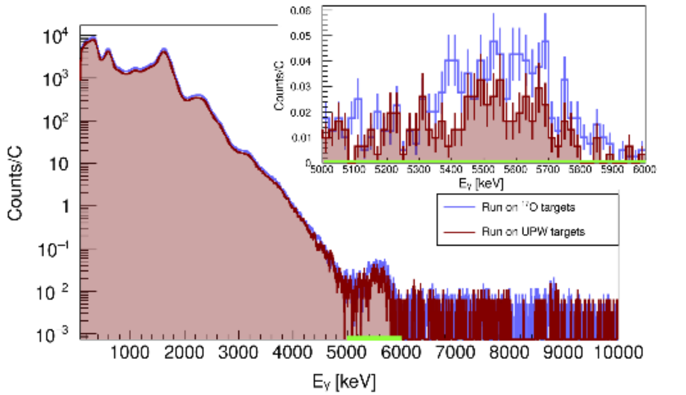
Steffen Turkat, Kai Zuber *et al.*, Astropart. Phys. 148 (2023) 102816

See poster by Björn Lehnert.

CHETEC INFRA TECHNISCHE UNIVERSITÄT DRESDEN DRESDEN concept HZDR

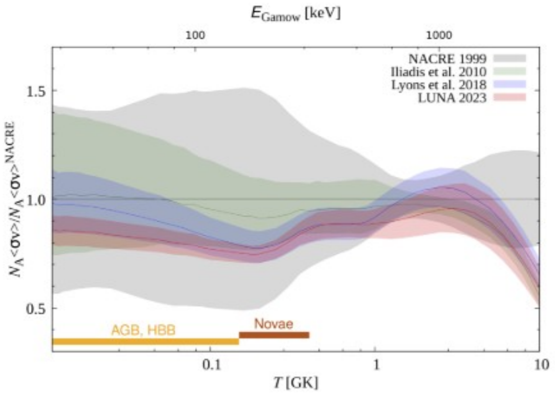
New data from LUNA on higher hydrogen burning…

2× faster $^{17}O(p,\gamma)^{18}F$ rate,
Important for meteoritic analyses



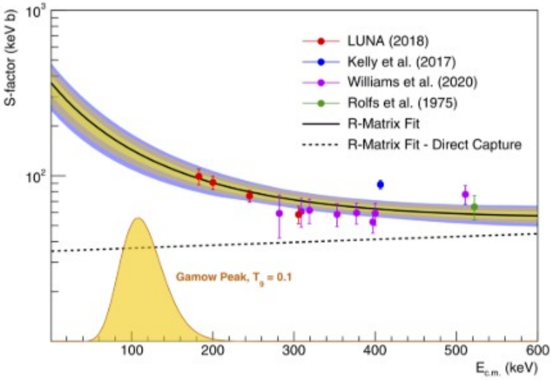
Riccardo Gesuè *et al.* (LUNA), Phys. Rev. Lett. 133, 052701 (2024)

S factor of $^{20}Ne(p,\gamma)^{21}Na$



Eliana Masha *et al.* (LUNA), Phys. Rev. C 108, L052801 (2023)

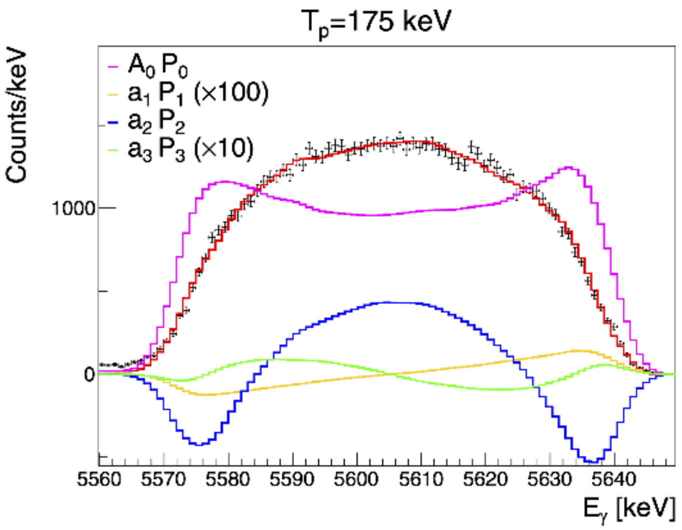
γ-ray branchings and S factor of $^{22}Ne(p,\gamma)^{23}Na$



Marcell Takács *et al.* (LUNA), Phys. Rev. C 109, 064627 (2024)

…and new data from LUNA on Big Bang nucleosynthesis…

γ-ray angular distribution of the $^{2}H(p,\gamma)^{3}He$ reaction obtained from analysis of the Doppler-shifted γ-ray



Klaus Stöckel *et al.* (LUNA),
Phys. Rev. C 110, L032801 (2024)

Outlook for Big Bang nucleosynthesis:

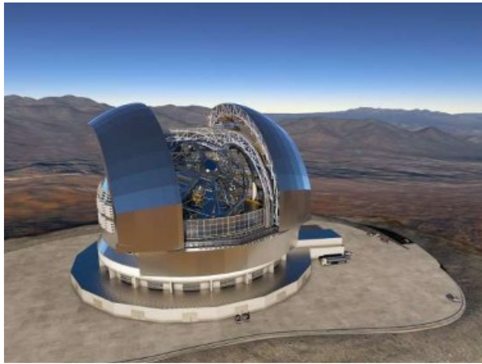
Study of the $^{2}H(d,p)^{3}H$ and $^{2}H(d,n)^{3}He$ reactions, which are now limiting the precision after LUNA greatly improved $^{2}H(p,\gamma)^{3}He$.

- Requires deuterium beam – this is rare nowadays
- In-ring experiment at CRYRING @ FAIR proposed (Carlo Bruno / Edinburgh)
- Direct experiment at TU Dresden deuteron beam (DT generator) proposed (Steffen Turkat / TU Dresden + INFN)

Optical Astronomy for Nuclear Astrophysics

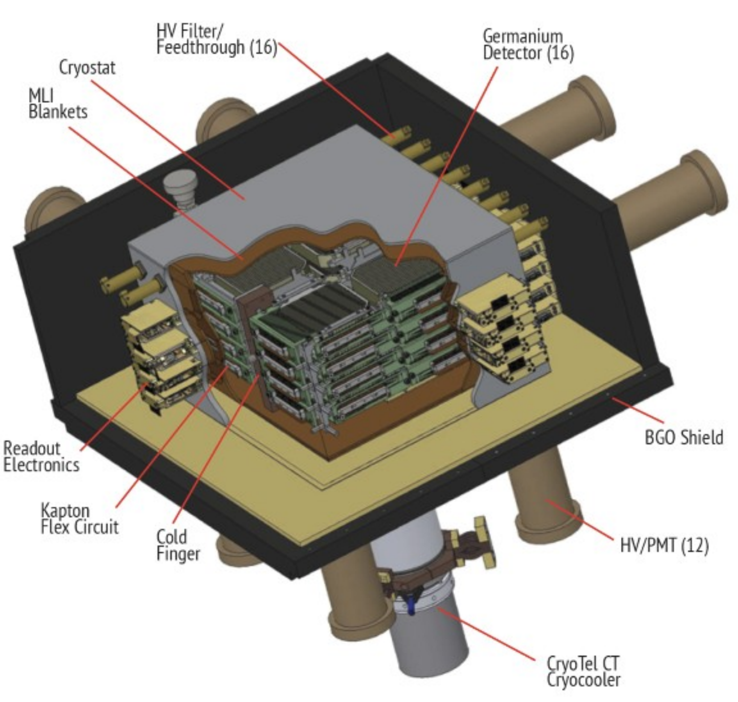
- Initiatives and future plans from Frankfurt:
  - Two surveys targeting heavy element nucleosynthesis (r-process) - using ChETEC-INFRA facilities (EU) and VLT (Chile)
  - Kilonova (KN) line identification & improved atomic physics (for KN and stars)

- Future: Large sky-scanning surveys → 4MOST & 4DWARFS
  - The Extremely large Telescope (ELT/ANDES)



COSI: Compton Spectrometer and Imager

- NASA small explorer (SMEX) mission.
  Launch: 2027, 2 year mission (extensions possible)
  PI: John Tomsick, UC Berkeley / SSL
- Energy: 0.2 – 5 MeV. Ge Compton telescope
- Wide field-of-view. Instantaneous >25% sky, covering the whole sky every day.
- Great energy resolution! But small instrument with limited energy range.
- **All-sky maps** of **511 keV** line and continuum, and ^{26}**Al** and ^{60}**Fe** nuclear lines.
- Search for Galactic SNR in ^{44}**Ti.**



German contribution to analysis software development (Mz, W)

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

Julius-Maximilians-UNIVERSITÄT WÜRZBURG

DLR

COSI science objectives

1. Pinpoint the sources of Galactic positrons
2. Reveal sites of past supernovae and recent element formation (^{44}Ti, ^{26}Al, ^{60}Fe)
3. Probe the physics in extreme environments with polarimetry
4. Find counterparts to merging neutron stars and high-energy neutrino events

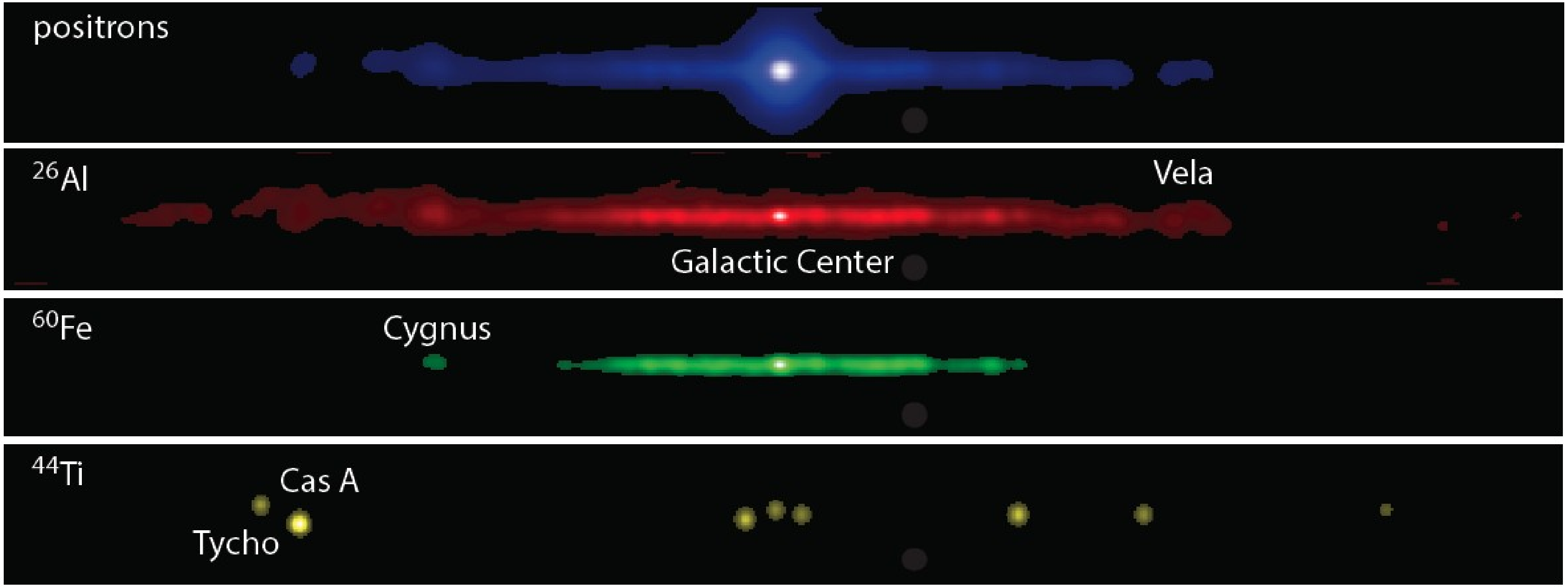
COSI-SMEX simulations (related to objectives 1,2 above)

0.511 MeV + cont.

1.809 MeV

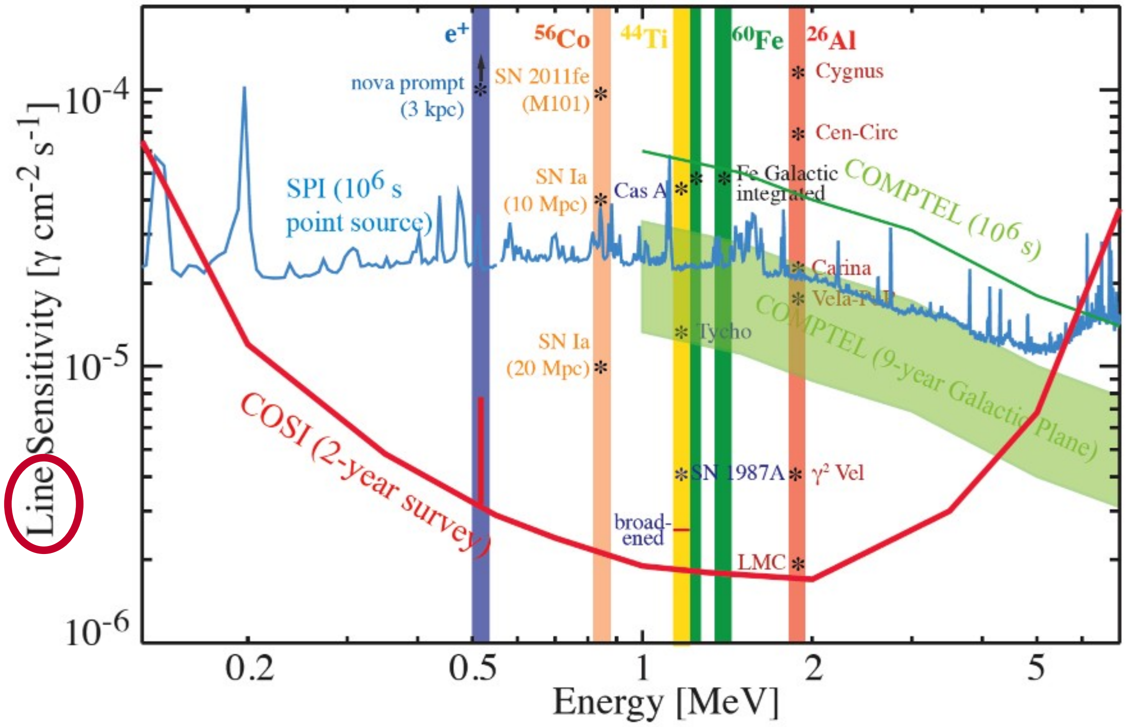
1.173, 1.332 MeV

1.157 MeV + 68, 78 keV



Gamma-ray lines – revealing element formation

- Positron annihilation
  - 511 keV + ortho-pos. continuum
  - bulge, disk, globular clusters
  - dark matter component?
- ^{56}Co study SNIa
- ^{44}Ti SNRs of the last few centuries
- ^{26}Al: galactic diffuse.
  OB associations / superbubbles, spiral arms, individual sources
- ^{60}Fe: only integrated flux measured.
  COSI: first all-sky map.
  Produced only in core-collapse SNe.
  Together w/ ^{26}Al:
  → Galactic star formation rate over the last few million years.



- Nuclear de-excitation lines
  - study low-energy cosmic-ray component
- ...

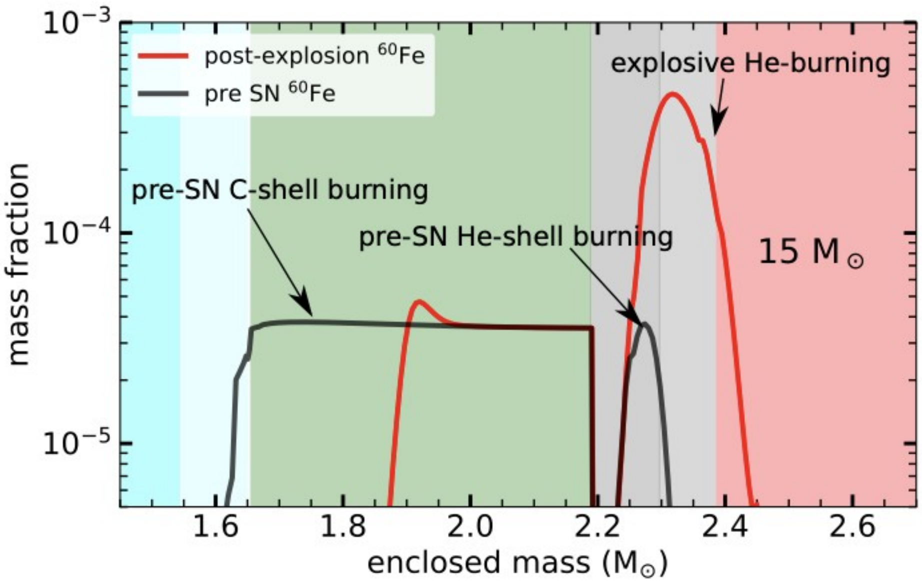
Selection of cosmic gamma-ray lines

- green: observed
- gray: not yet observed

Isotope	Lifetime	Decay Chain	Gamma-ray Energy [keV]	Sources
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478	Novae
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812, 847, 1238	SN Ia
^{57}Ni	390 d	$(^{57}Ni \rightarrow)\ {}^{57}Co^* \rightarrow {}^{57}Fe^*$	122	SN II
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275	Novae
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68, 1157	SN II (mass cut)
^{26}Al	$1.04\ 10^6$ y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809	SN II, massive stars
^{60}Fe	$3.8\ 10^6$ y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332	SN II
e^+	$10^{5\text{-}6}$ y	$e^+ + e^- \rightarrow$ positronium $\rightarrow \gamma\gamma$	511, <511	various

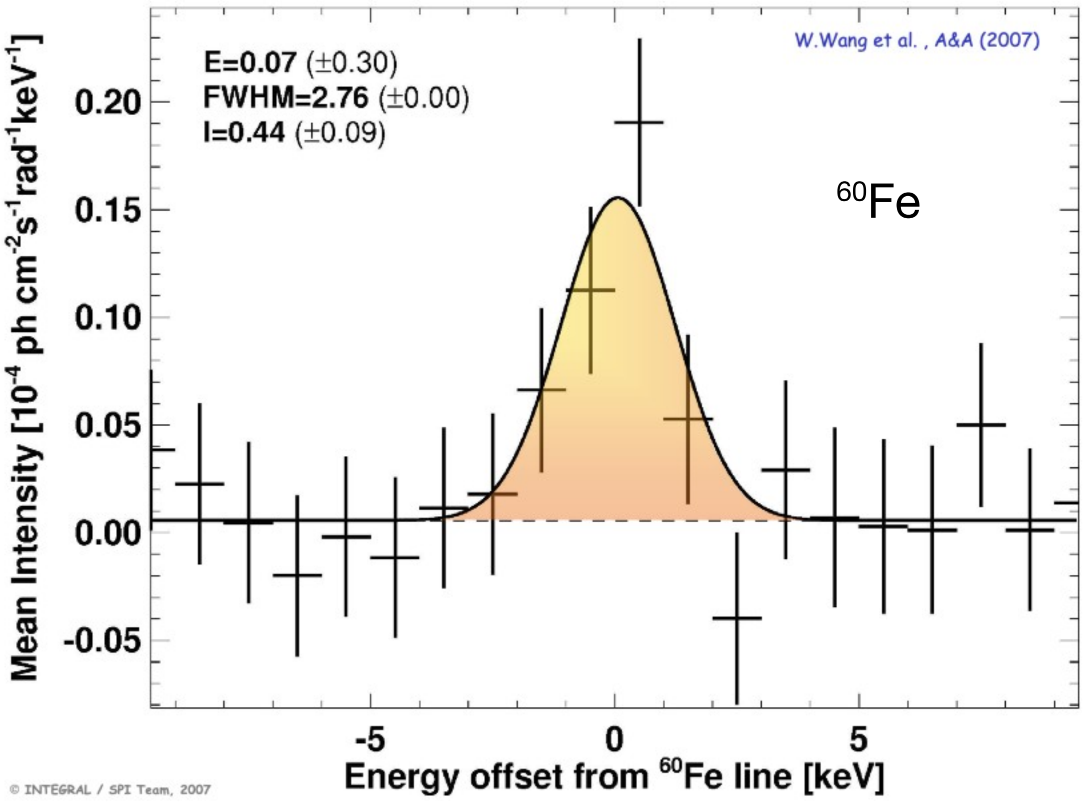
… testing different nuclear burning environments

- p-rich: $^{25}Mg(p,\gamma)^{26}Al$, $^{21}Na(p,\gamma)^{22}Ne$
- n-rich: ^{60}Fe
- alpha-nuclei: ^{44}Ti



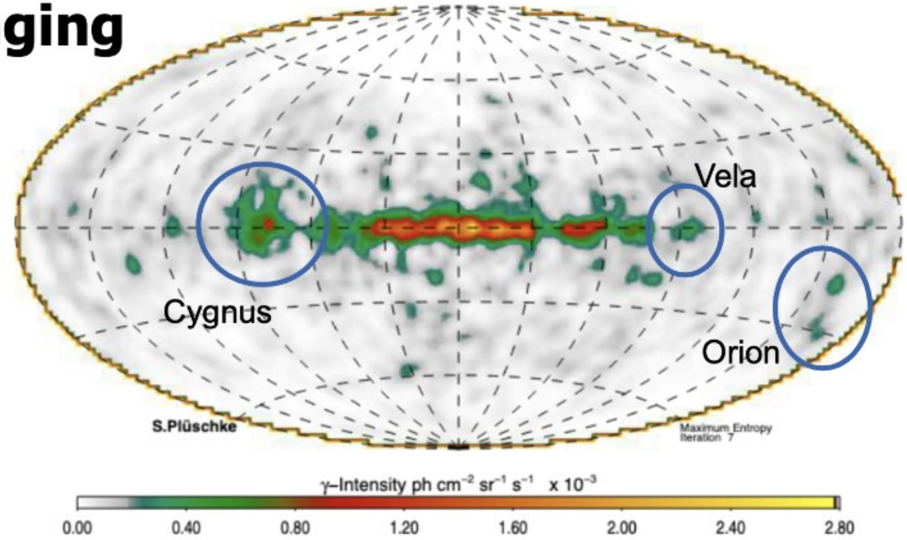
(Diehl *et al.*, 2021)

Combined flux:
$(3.1 \pm 0.6)\times10^{-4}$ ph cm^{-2} s^{-1}

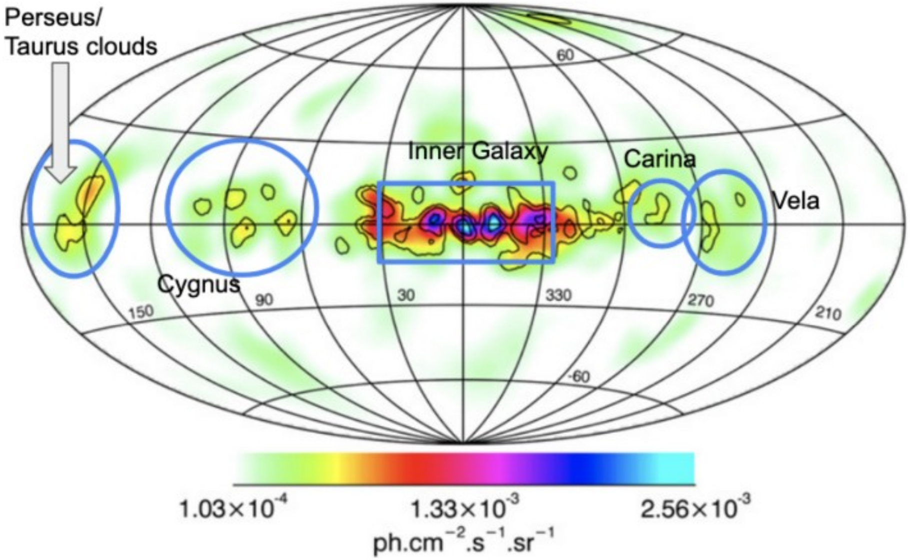


Gamma-ray lines - ^{26}Al

Imaging



COMPTEL
Plüschke et al. 2001
Angular resolution ~ 4° FWHM



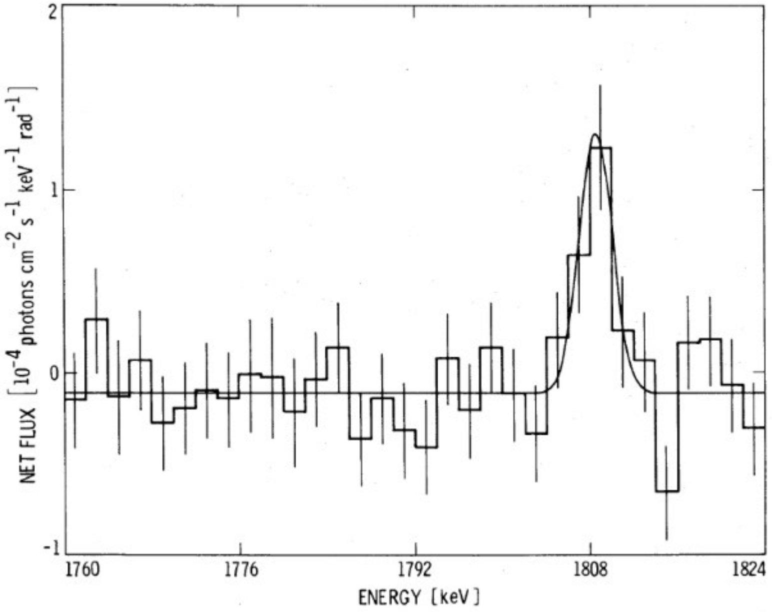
INTEGRAL / SPI
Bouchet et al. 2015
Angular resolution ~ 6° FWHM

Images from COMPTEL and SPI indicate concentrated emission in the **Inner Galaxy** ($|l| \leq 30°$, $|b| \leq 10°$) and enhanced emission in regions of massive star activity (e.g. Cygnus, Carina, and Vela).

Gamma-ray lines - ^{26}Al

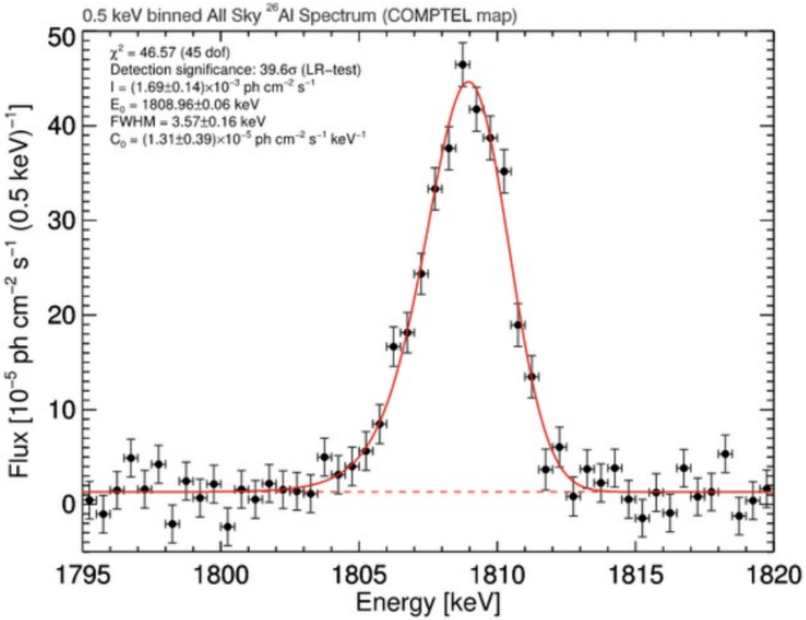
Spectroscopy

- ❑ Discovered by HEAO-3 in the center of the Milky Way
- ❑ Subsequent spectroscopy by INTEGRAL SPI



HEAO-3, Mahoney et al. 1984

E = 1808.49 ± 0.41 keV



INTEGRAL / SPI, Siegert 2017

E = 1808.96 ± 0.06 keV

^{44}Ti from SN1987A

☆ ab-initio models

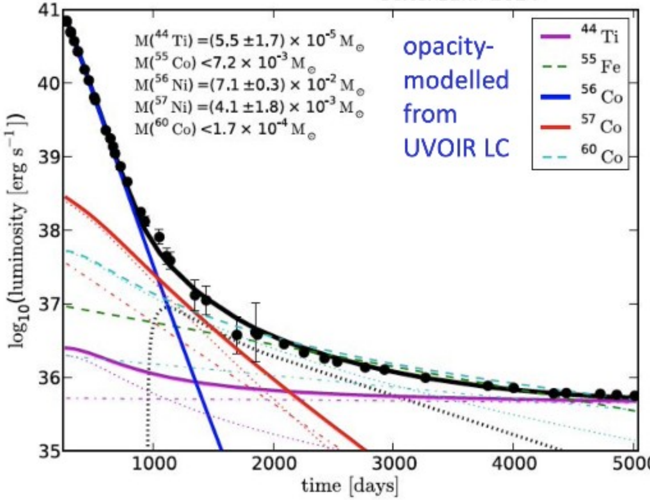
→ $M_{44Ti} \approx 0.x\ 10^{-5}\ M_\odot$ (spherical)

to $0.x\ 10^{-4}\ M_\odot$ (aspherical)

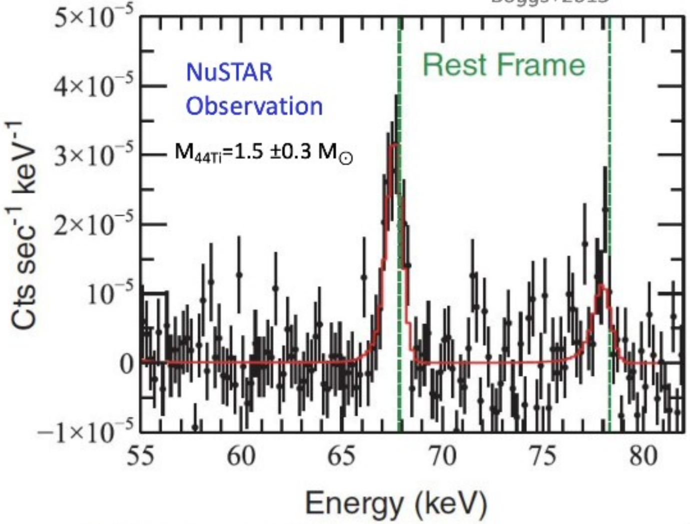
☆ UVOIR LC + energy deposition models

→ $M_{44Ti} \approx 0.5...5\ 10^{-4}\ M_\odot$

Seitenzahl+2014



Boggs+2015



☆ ^{44}Ti X-ray result NuSTAR

→ $M_{44Ti} \approx 1.5\ {\pm 0.3}\ 10^{-4}\ M_\odot$

☆ ^{44}Ti line measurements INTEGRAL

→ $M_{44Ti} < 3.1\ {\pm 0.8}\ 10^{-4}\ M_\odot$ (2σ) (IBIS

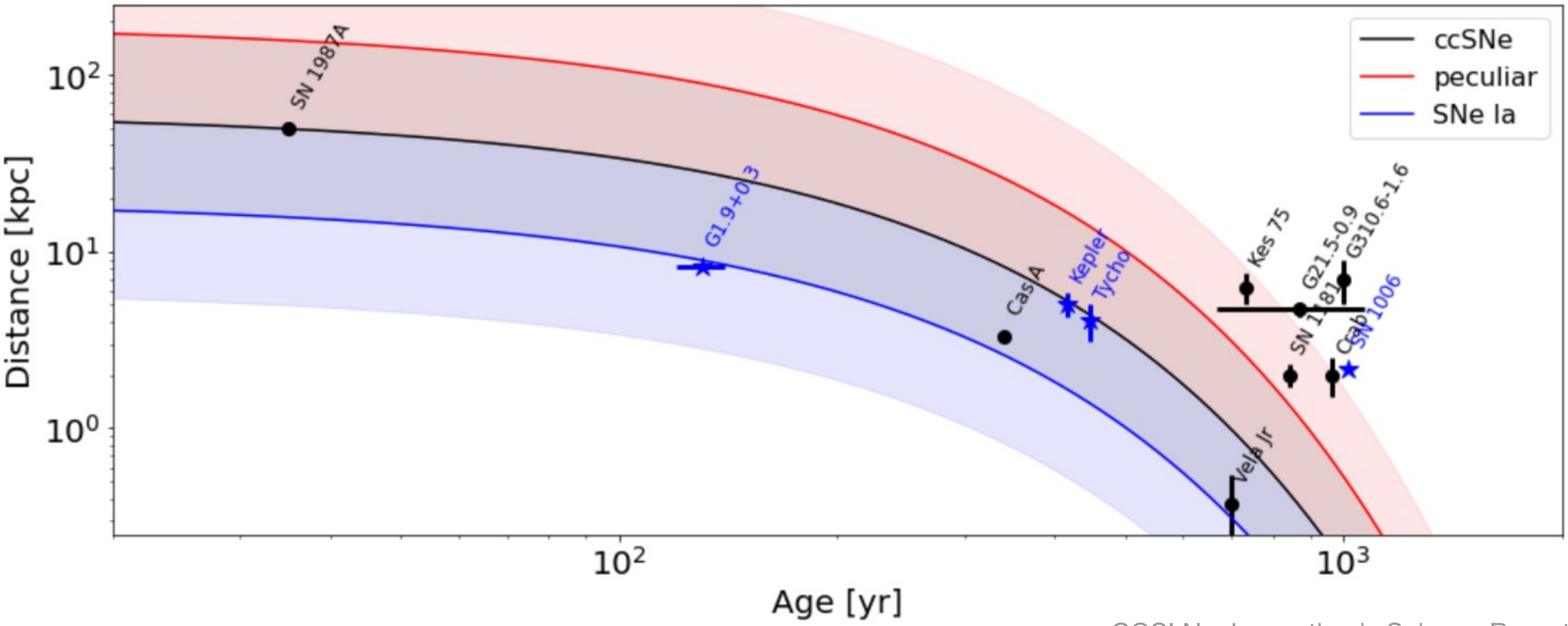
☆ → $M_{44Ti} < 7.5\ 10^{-4}\ M_\odot$ (2σ) (SPI)

see Grebenev+2012; Weinberger+2021

Diehl INTEGRAL '22

Unveiling hidden ^{44}Ti supernova remnants with COSI

COSI 1157 keV line sensitivity = 3.45×10^{-6} ph s^{-1} cm^{-2} for 2 years of observations

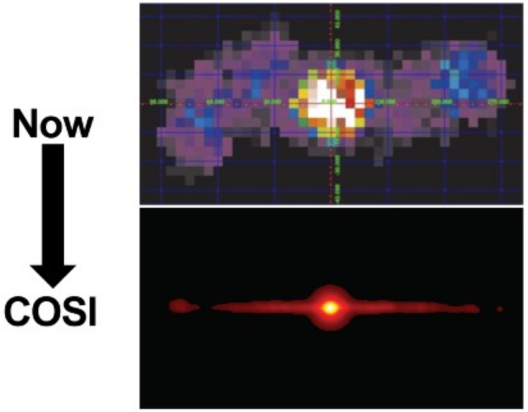


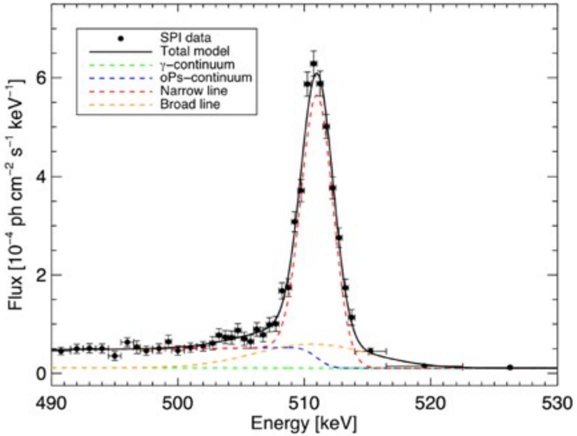
COSI Nucleosynthesis Science Report

Galactic positrons

- Origin of Galactic positrons uncertain despite five decades of study
- INTEGRAL/SPI: bright bulge and a fainter disk
  - ^{26}Al: known contributor (~6%) to disk emission
  - ^{44}Ti: from ccSN, expected ~4%
  - ^{56}Ni: from SNIa, expected bulge emission
- COSI will:
  - Determine if there are point sources or sub-structure
  - Constrain the positron propagation distance by comparing to ^{26}Al distribution
  - Measure the disk scale-height and determine the total Galactic positron production rate

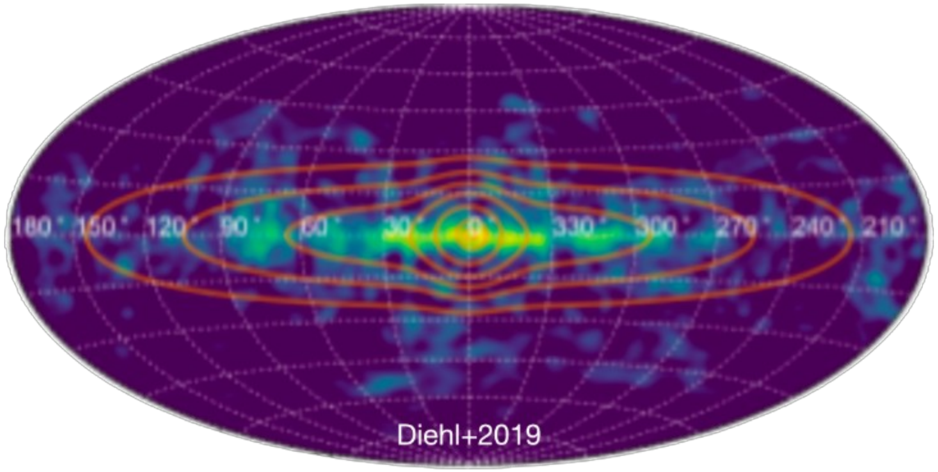
511 keV with INTEGRAL



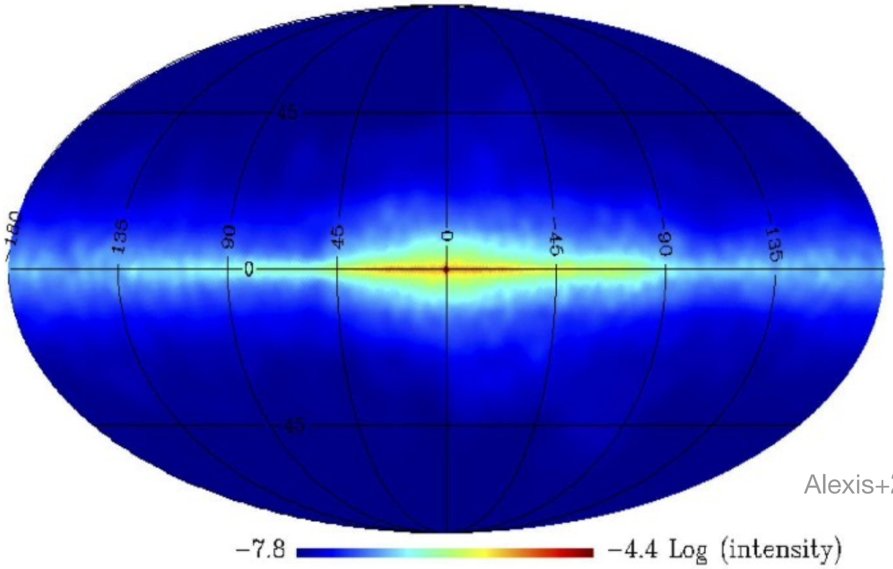


INTEGRAL/SPI: Siegert+2019

Spatial models of galactic positrons



Model from ^{26}Al map

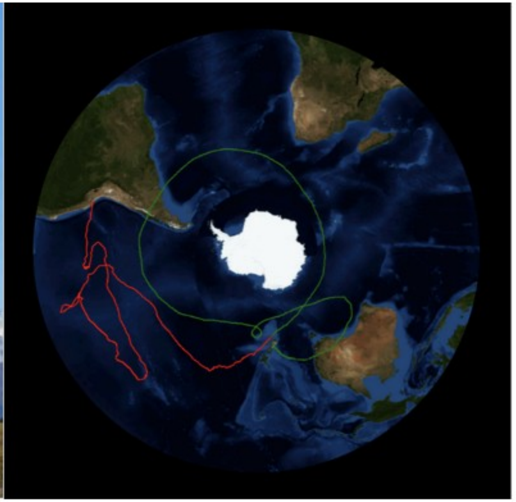


Alexis+2014

Model for ^{56}Ni from SNIa:
bulge + propagation

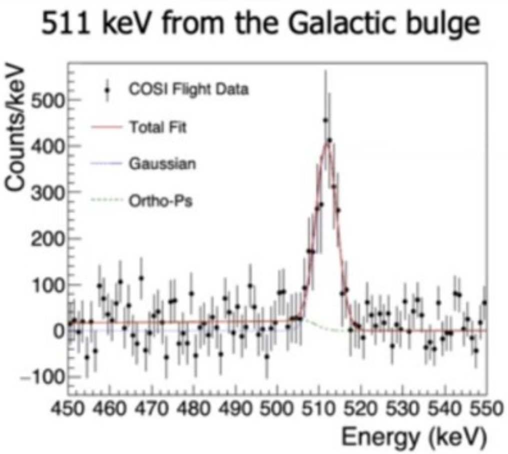
Background Verification and Extragalactic Background with COSI Balloon

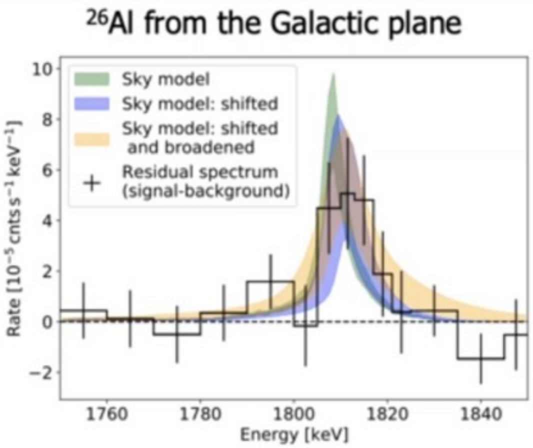
Savitri Gallego+, JGU Mainz



- launched from Wanaka, New Zealand on NASA's Super Pressure Balloon on May 16th, 2016
- 46 days of flight

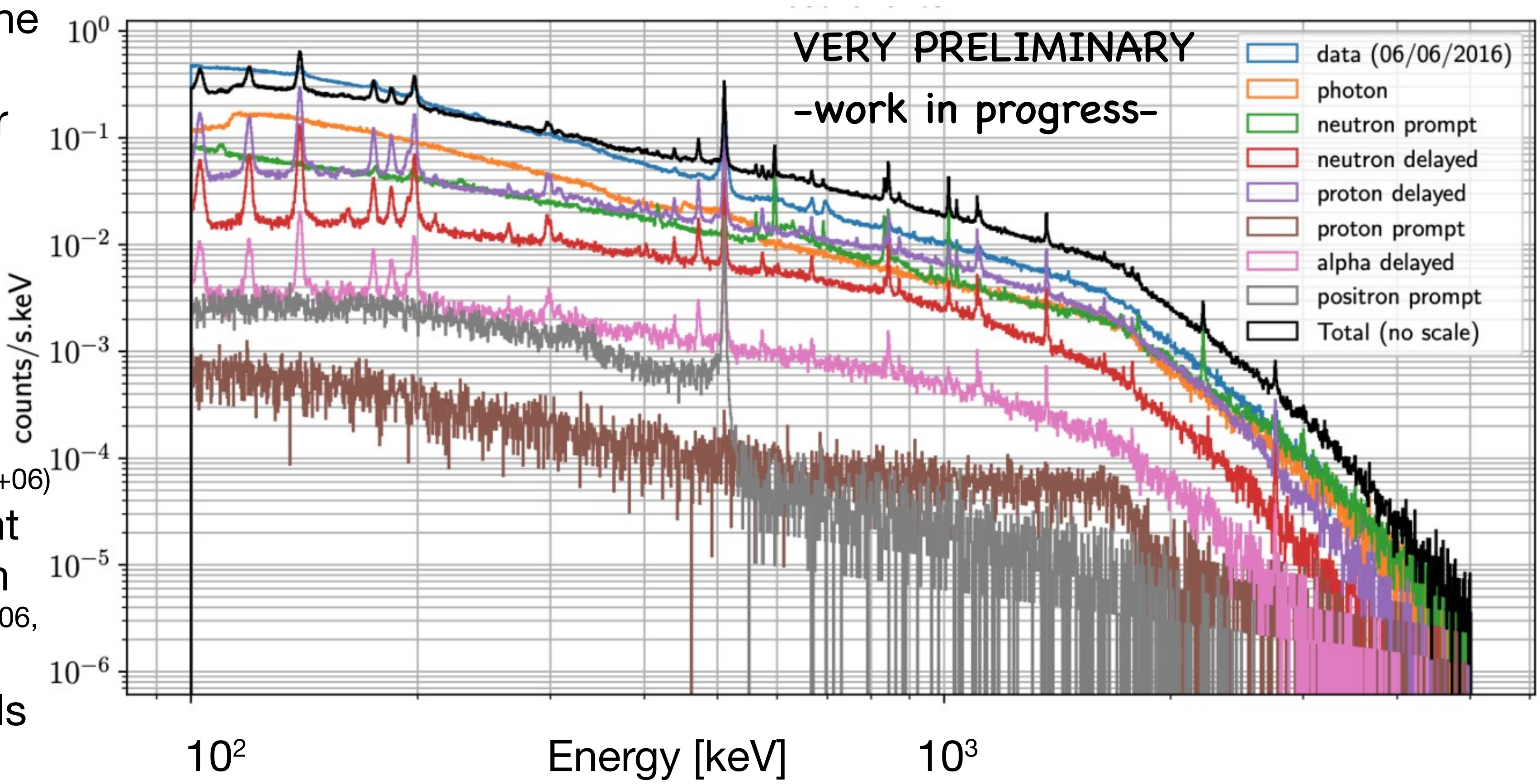
- Results :
  - GRB 160530A (Lowell+17,Sleator+19)
  - 511 KeV (Kierans+18+20,Siegert+20)
  - ^{26}Al (Beechert+22, ApJ)
  - Crab nebula (Zoglauer+21)
  - Cyg X-1, Cen A (Roberts et al., in prep.)
  - Galactic Diffuse (Karwin+23, ApJ)
  - Extra galactic photon background ?





Backgrounds: Example COSI Balloon flight

Simulations of the physical backgrounds for COSI.
Test case: COSI balloon flight.



Setup:
MEGAlib (Zoglauer+06)
based on current GEANT4 version
(Agostinelli+03, Allison+06, Allison+16)
and input models
(Cumani+19 etc.)

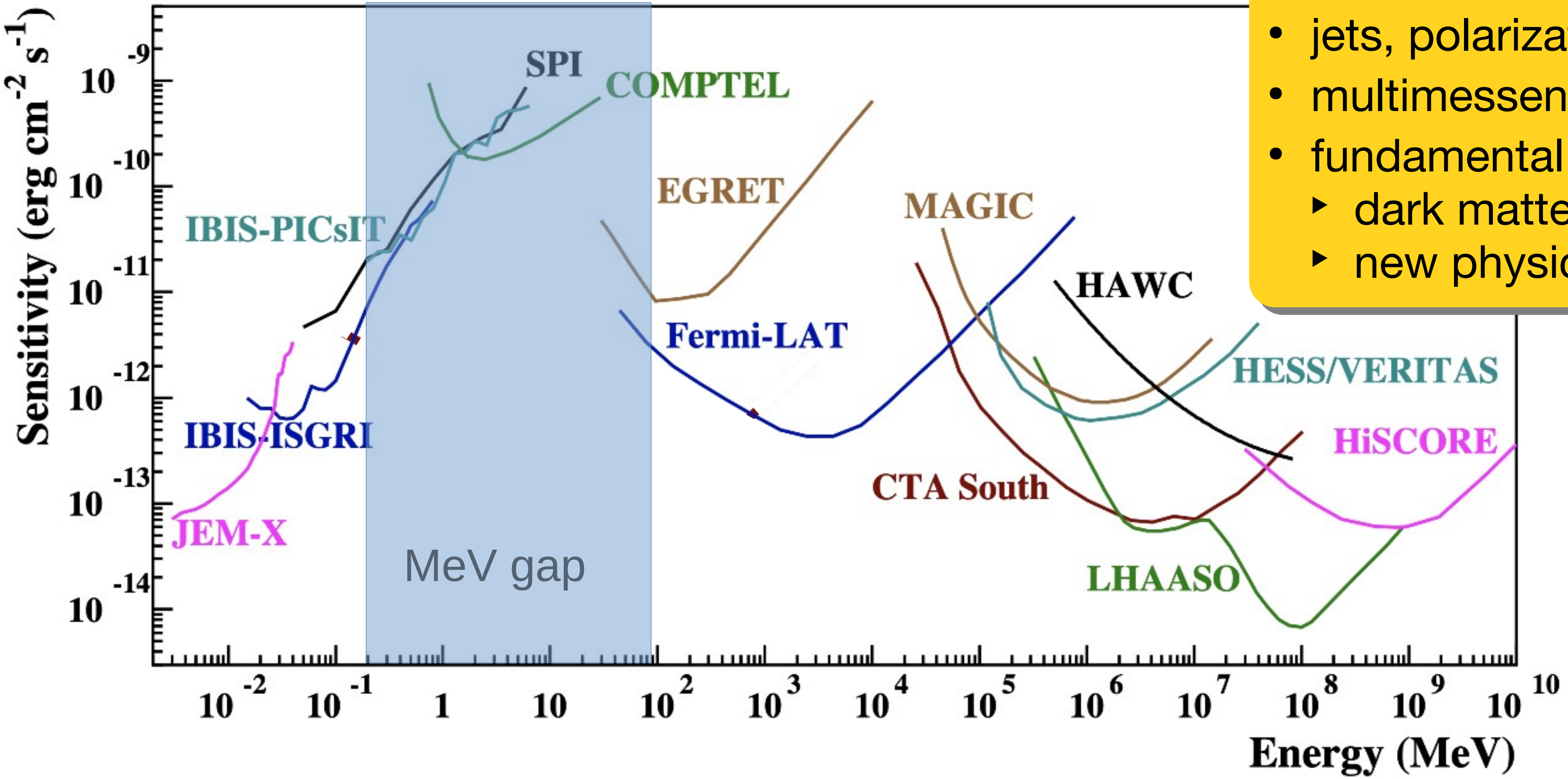
Savitri Gallego+, JGU Mainz

The MeV sensitivity gap

Continuum sensitivity

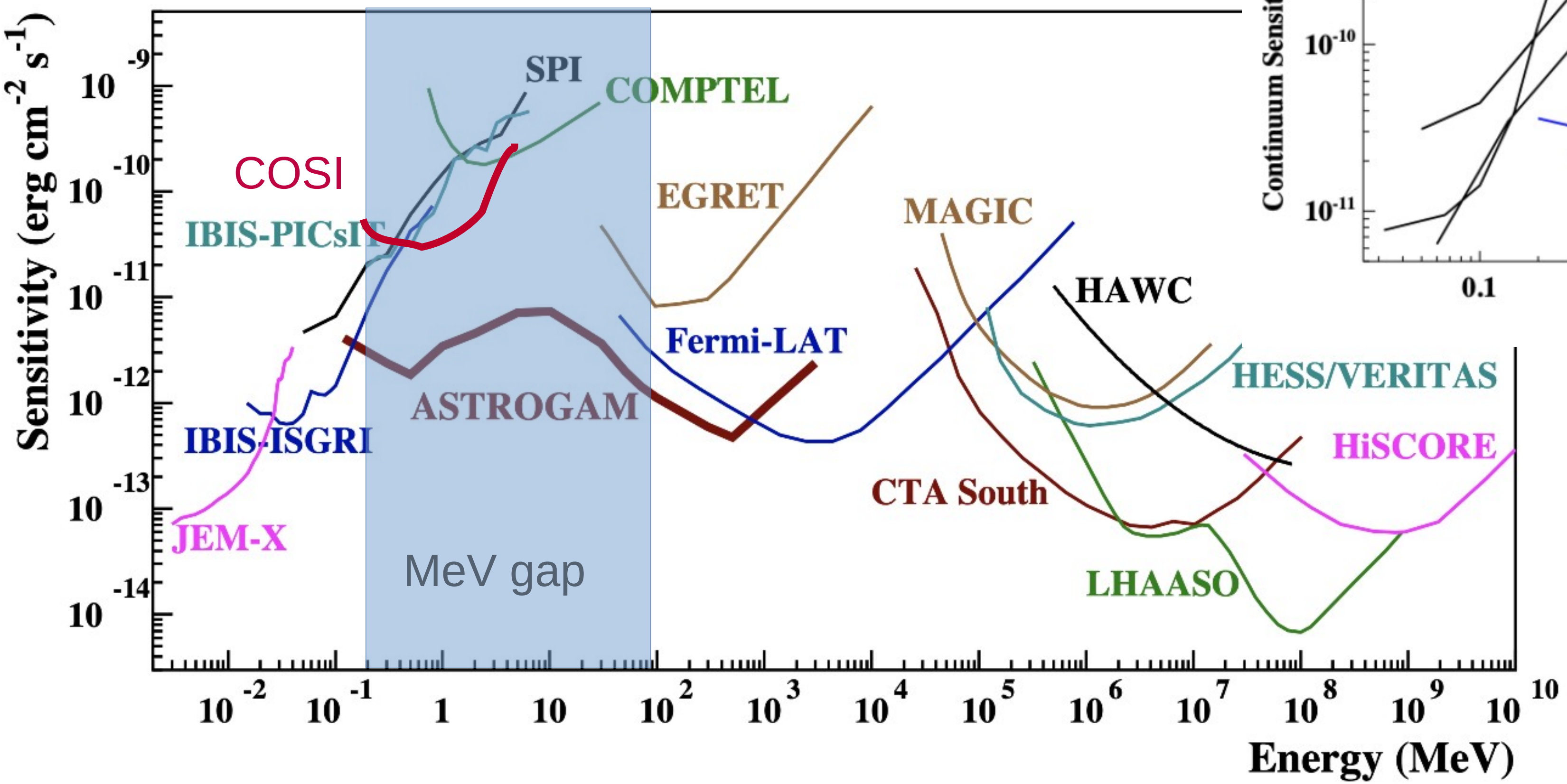
Discovery space where there is known to be exciting and unique physics

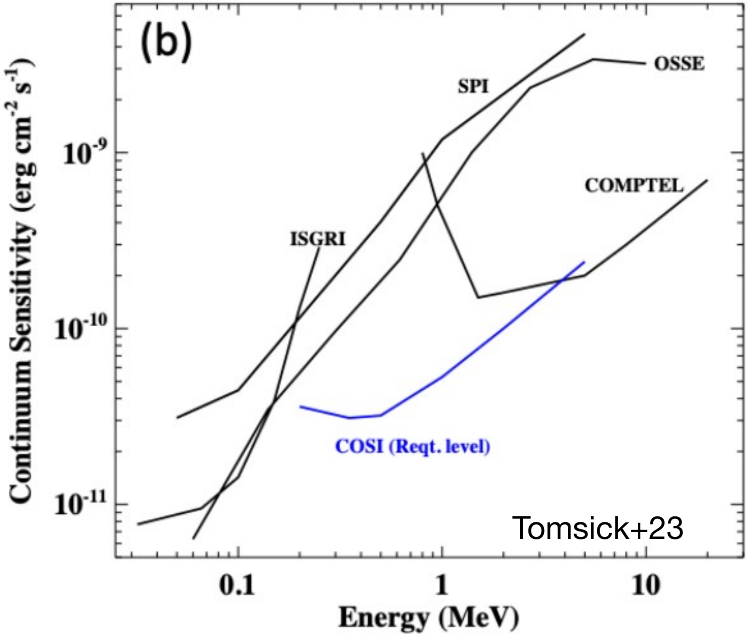
- e^+e^- annihilation line & continuum
- nucleosynthesis & supernovae
- jets, polarization
- multimessenger astrophysics
- fundamental physics
  - dark matter
  - new physics searches



Outlook to COSI and beyond

COSI will provide us new insights in gamma-ray lines
but it will **not** close the MeV gap. → future mission!





Summary Nuclear Astrophysics

- Multidisciplinary field: nuclear physics, astrophysics, astroparticle physics.

Underground cross-section measurements: a central theme in astroparticle physics

- new measurements on higher H-burning and BBN from LUNA (LNGS)
- Felsenkeller:
  - new cross-section measurements
  - ultra-low background gamma-ray screening
- DZA underground lab will provide a great opportunity!

MeV Gamma-ray astronomy: discovery space in little explored em. range.

- Gamma-lines as direct tracers of nucleosynthesis.
- NASA/SMEX mission COSI: German participation in analysis & simulation software (DLR).
  a major step in nuclear lines and positron annihilation radiation
  but only a small step in filling the continuum sensitivity “MeV gap”.
  → a next big mission is needed.
  Physics requires at least a beefy M-sized mission (area, mass) - bigger is better.
- We are missing a tool to fund R&D into new technologies to close the MeV gap, and to perform scientific ballooning to bring new technology to the necessary TRL while training the next generation of (MeV) gamma-ray astronomers.

Thank you!

Discussion

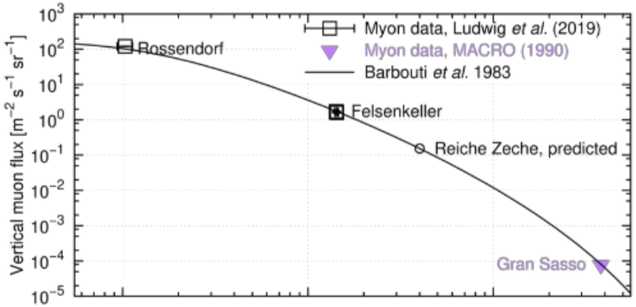
- Funding underground cross-section measurements
- Support for underground use of DZA Low Seismic Lab
- Funding line for R&D on instrumentation in nuclear astrophysics
- Funding line for R&D on instrumentation in MeV gamma-ray astronomy (example NASA/APRA)
- Support for scientific ballooning:
  - space verification
  - laboratory-scale turn-around
  - long-duration flights enable specific sciene
  - perfect tool to train young experimentalists
- Funding to prepare and support science for COSI
- Strategy paper: MeV astronomy in nuclear astrophysics and gamma-ray astronomy
- Suggestions?

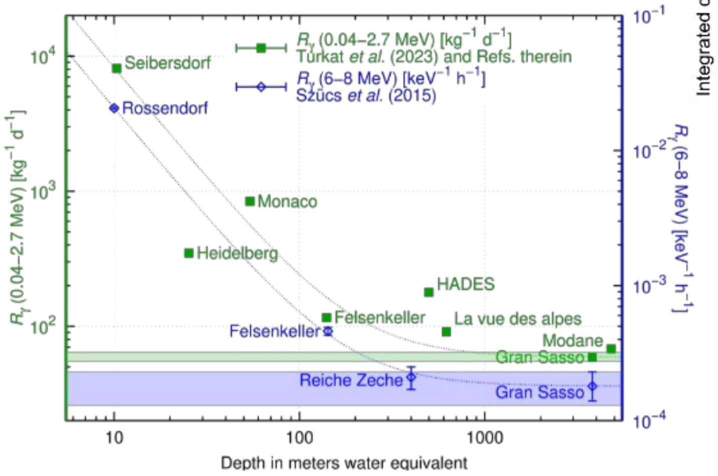
BACKUP

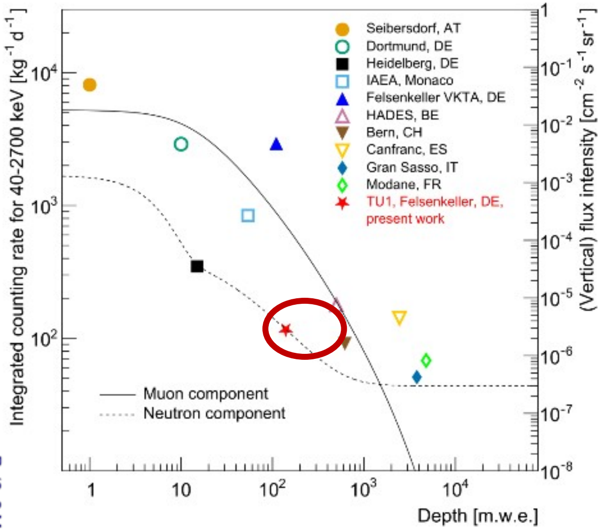
Felsenkeller: Studying low cross sections with low background

40 lower muon background

Astropart. Phys. 112, 24 (2019)

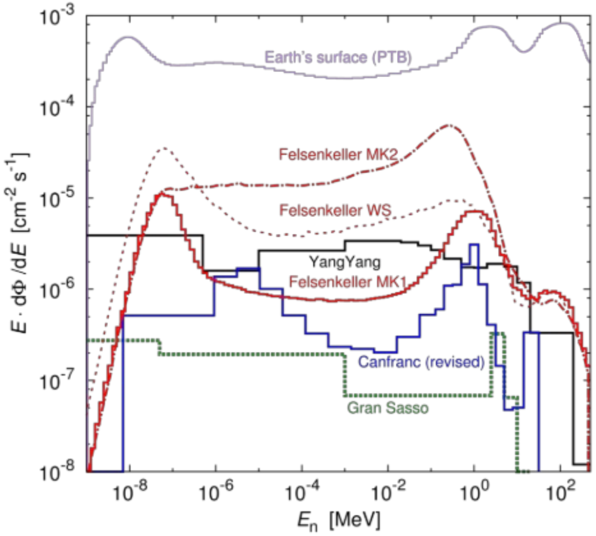






200 lower neutron background

Phys. Rev. D 101, 123027 (2020)



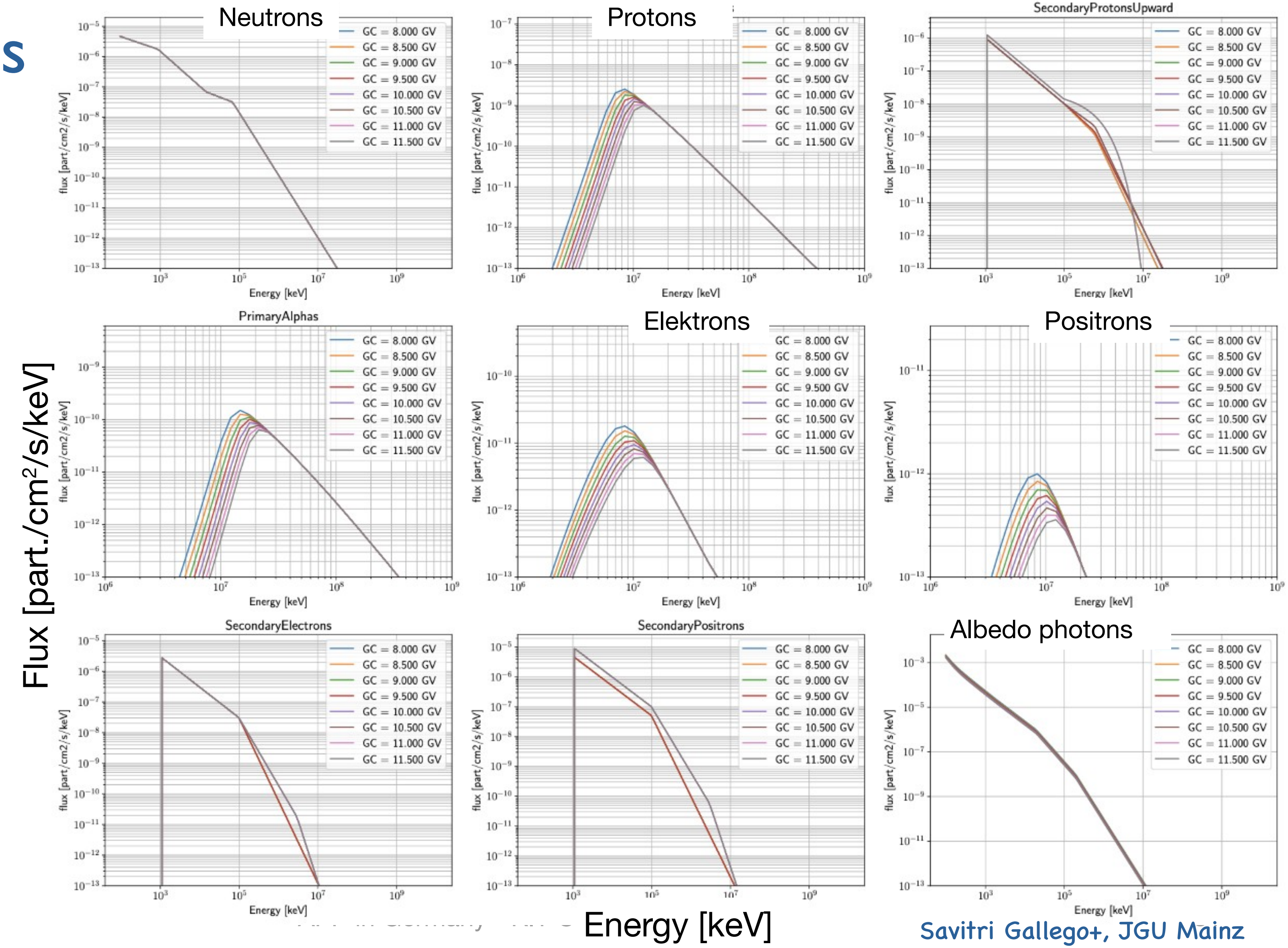
100 lower γ-background

Eur. Phys. J. A 51, 33 (2015)
Astropart. Phys. 148, 102816 (2023)

Backgrounds
input spectra

Simulations of the physical backgrounds for COSI.
Test case: COSI balloon flight.

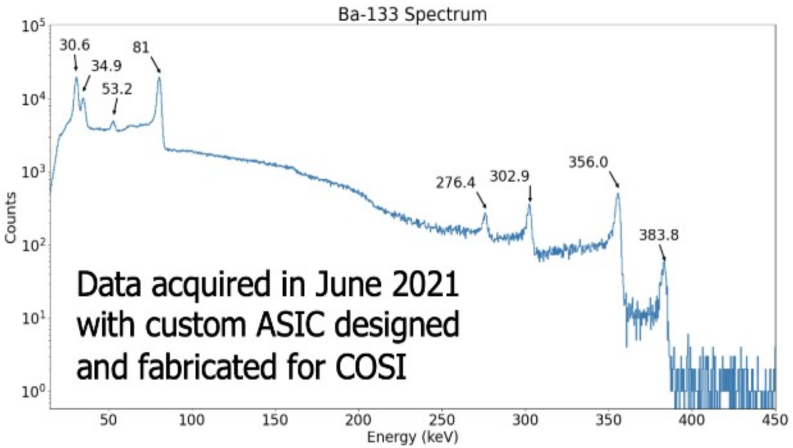
Setup:
MEGAlib (Zoglauer+06) based on current GEANT4 version (Agostinelli+03, Allison+06, Allison+16) and input models (Cumani+19 etc.)

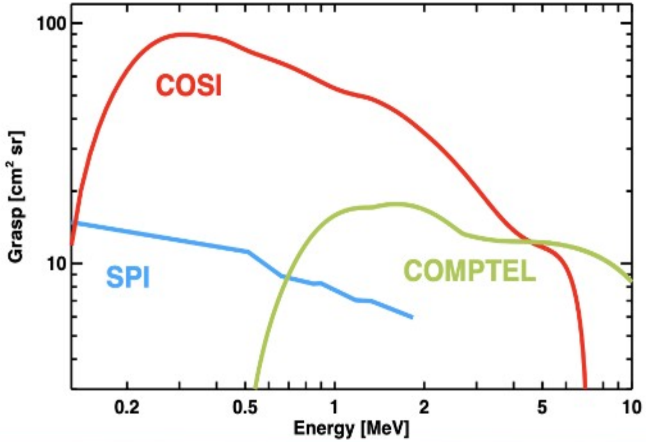


Savitri Gallego+, JGU Mainz

Excellent energy resolution & field of view

- ❑ COSI uses germanium detectors for excellent energy resolution
  - ΔE/E more than an order of magnitude better than the previous Compton telescope (COMPTEL on CGRO)
- ❑ COSI's instantaneous FOV is >25%-sky:
  - Large improvement in grasp (= product of effective area and FOV) over INTEGRAL/SPI and COMPTEL





COSPAR 2022, Athens, Greece – John Tomsick 6

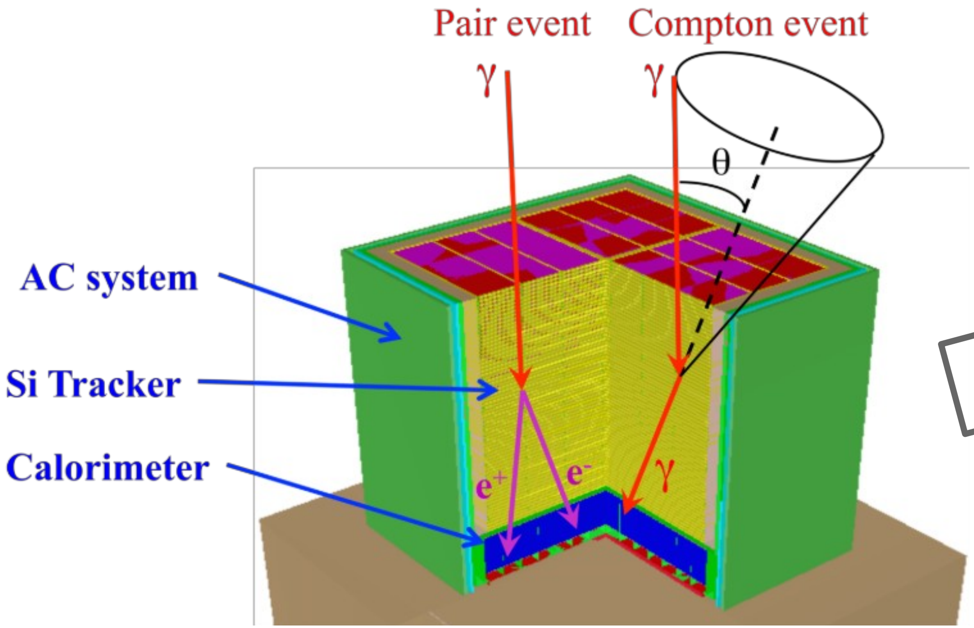
Science Topics (overview)

- Nucleosynthesis & galactic chemical evolution
- Positrons (MW and beyond)
- Supernovae:
  core-collapse, thermonuclear
- Cosmic accelerators
  AGN, galactic X-ray binaries (polarization)
- Low-energy cosmic rays
- "Multi-messenger" science
  - GW + γ (NS merger, kilonovae)
  - ν + γ (AGN, ...)
- Galactic diffuse emission
- Extragalactic background
- Gamma-ray bursts (polarization)
- Dark matter and new physics
- Pulsars
- Expect the unexpected!

medium-size

ASTROGAM Proposal for ESA M7 Mission Opportunity Call

PI: A.De Angelis (INFN, INAF), Co-PI: V.Tatischeff (CNRS), Co-PI: D.Berge (DESY)



Design concept

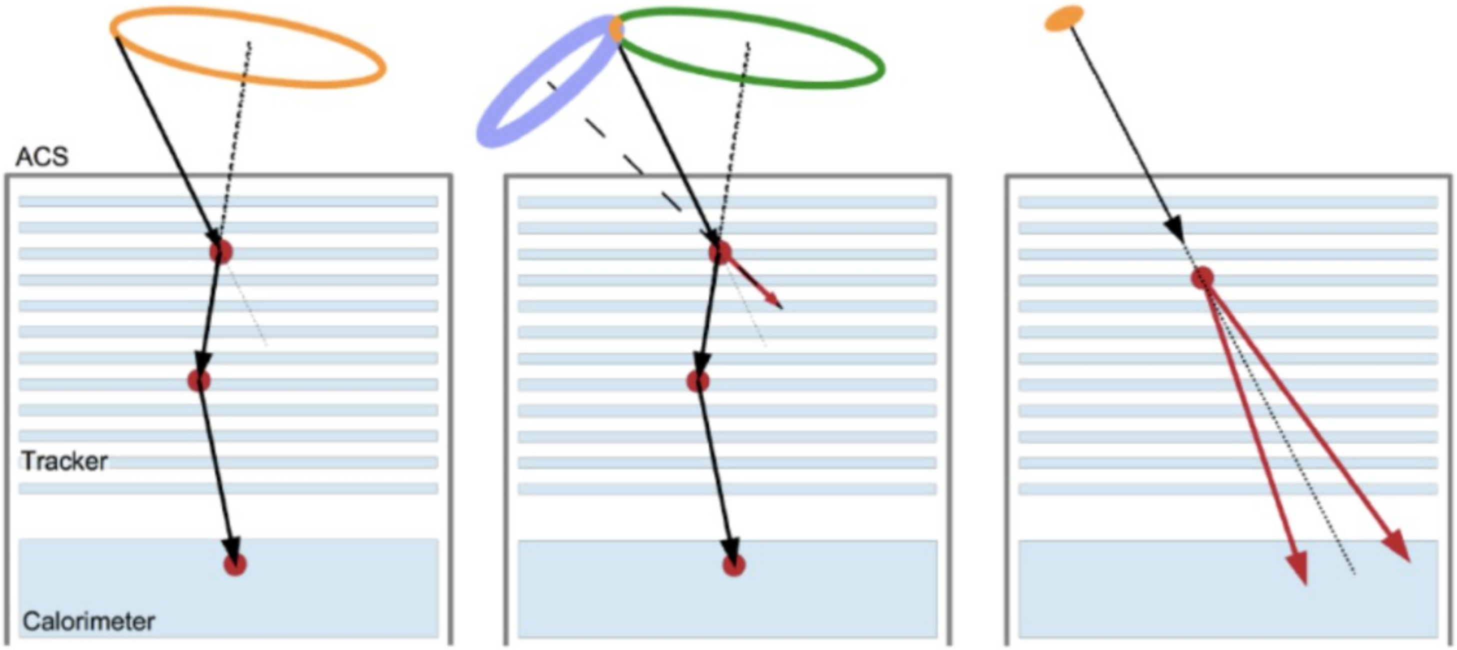
- Gamma-ray satellite concept with unprecedented energy coverage (100 keV – 3 GeV), sensitivity, and angular resolution
- Silicon tracker + pixelated scintillation detector
- Proposal
  - Submitted by scientists from 16 ESA member states: Croatia, Czech Republic, Denmark, Finland, Ireland, Italy, France, Germany, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, UK
  - Launch circa 2037, min. 3 years planned mission time

rejected

- Diverse and unique astrophysics science cases, e.g.
  - Multi-messenger science: Neutrino and GW sources
  - Unique MeV blazar population studies reaching z=6 and beyond
  - Galactic and extragalactic cosmic ray accelerators
  - Explosive nucleosynthesis & chemical evolution
  - Dark matter and new physics
  - See White Paper at https://arxiv.org/abs/2102.02460

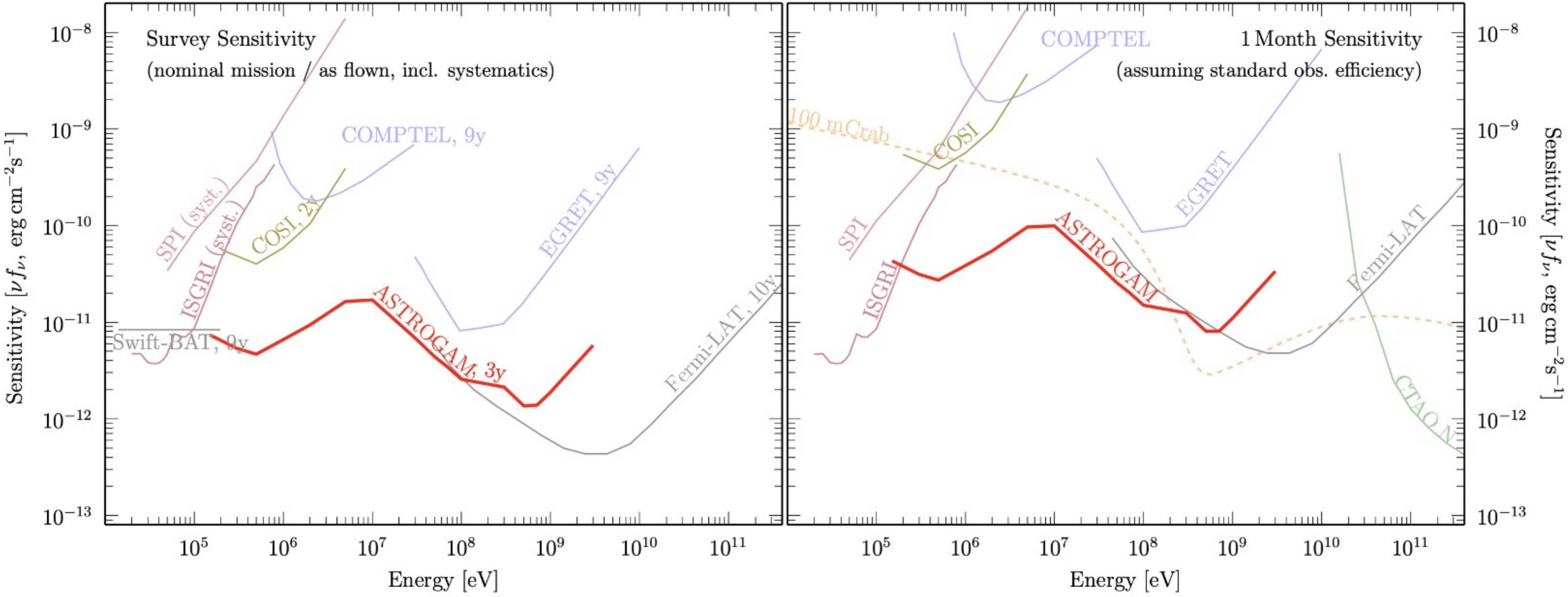
ASTROGAM (ESA M7 Mission)
Exploring the Gamma-Ray Sky from MeV to GeV

- Compton **and** pair telescope
- M7 proposal based on former work (eASTROGAM M5, ...)



ASTROGAM Sensitivity

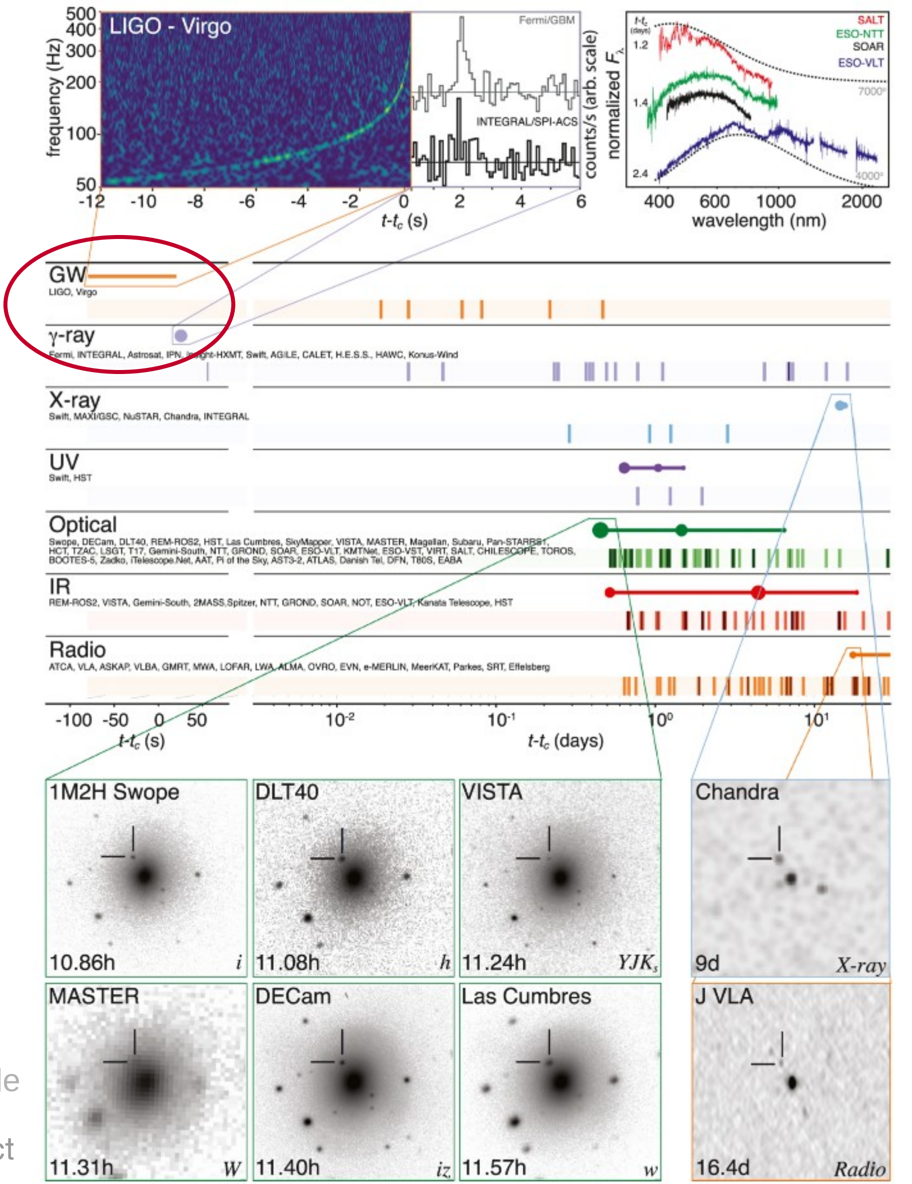
Coverage of MeV-GeV gap in the 2030's



Multimessenger Astronomy

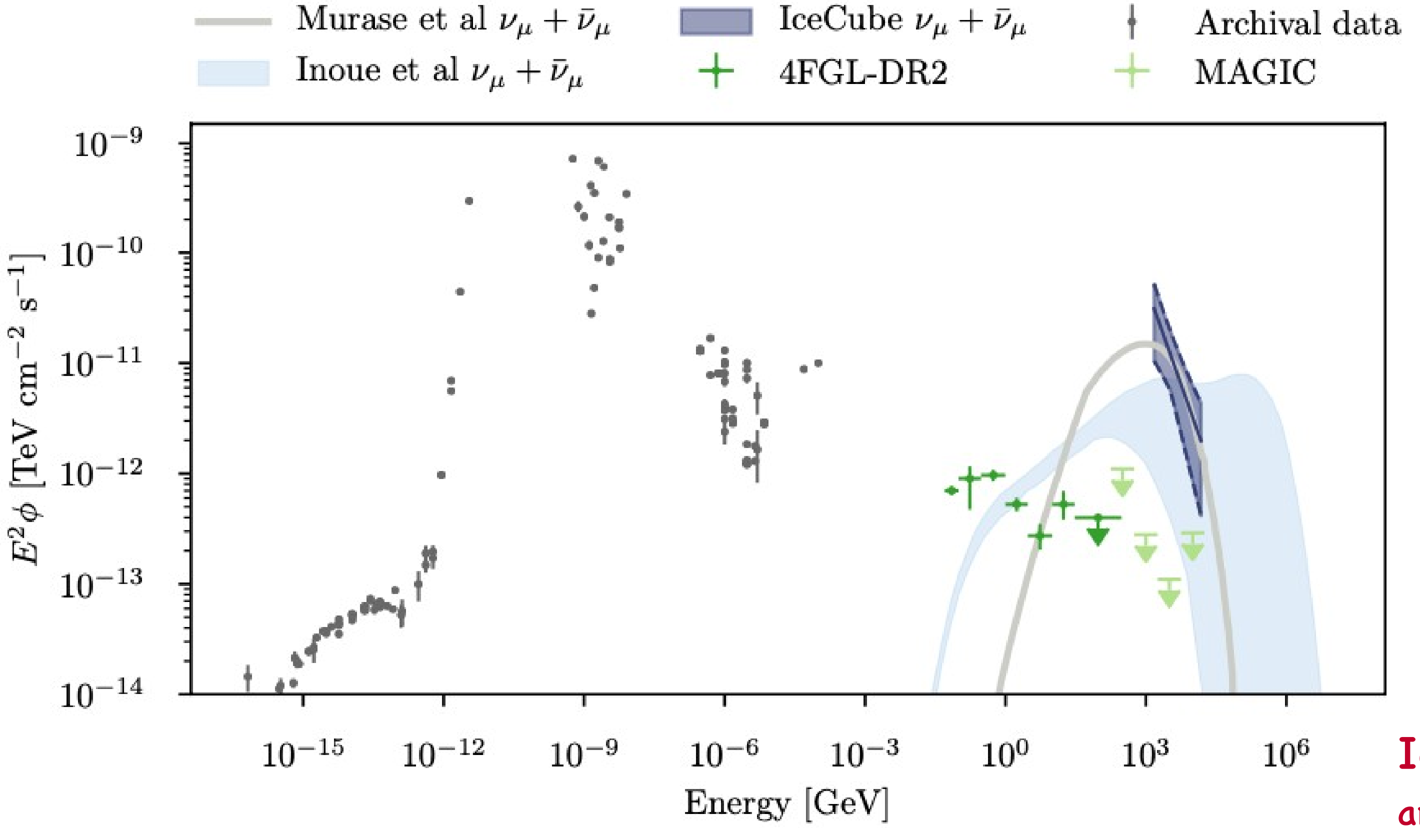
Electromagnetic counterparts to gravitational wave transients

- Detect sGRBs from NS-NS merging (0.2-6 during 2 years) with sensitivity to their likely energy cutoff (~20 MeV)
- and maybe BH-NS
- Particularly interesting energy region to estimate the energetics of these processes
- Use large field of view and imaging to refine localisation for follow-up observations



Stratta & Pannarale

ASTROGAM γ+ν



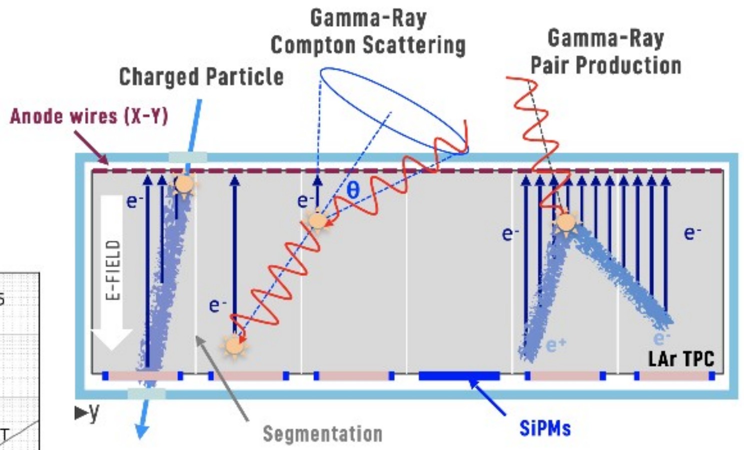
Photon and neutrino emission of active galaxy NGC 1068 and 6-month ASTROGAM sensitivity. MeV band essential to constrain models and identify hadronic accelerators.

Icecube results on NGC 1068

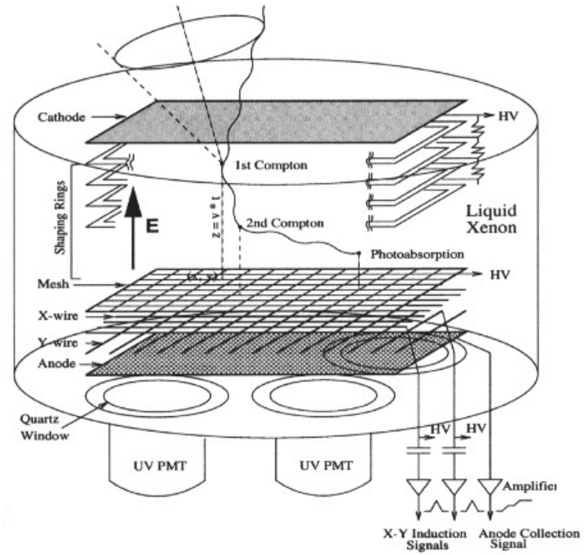
arXiv:2211.09972

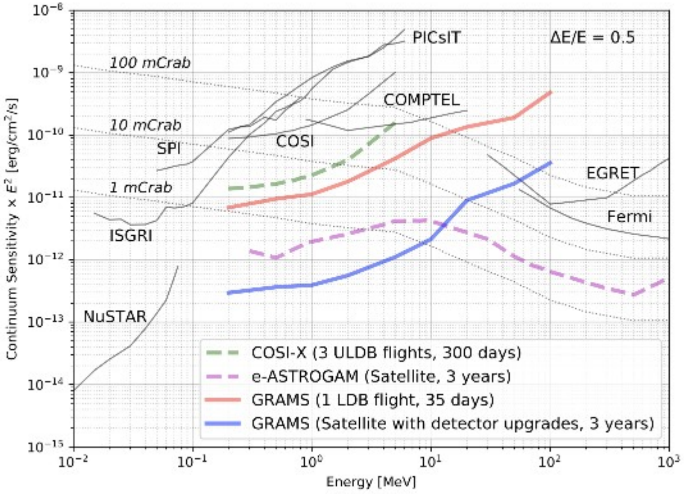
Other technologies

- Liquid noble gas TPC: Liquid Ar: GRAMS, GammaTPC
- Liquid Xe: former LXeGRIT, modern attempt?
- Pixelated Si tracker
- Super-COMPTEL: Scintillator w/ time-of-flight



T. Aramaki et al. 2020 Astropart. Phys., 114, 107-114





E. Aprile et al. 2008, Nucl.Instrum.Meth.A593:414-425