Intersections of QCD and Nuclear Data

Ramona Vogt (LLNL/UC Davis)

Representing the NSAC-ND subcommittee

LLNL-PRES-840137

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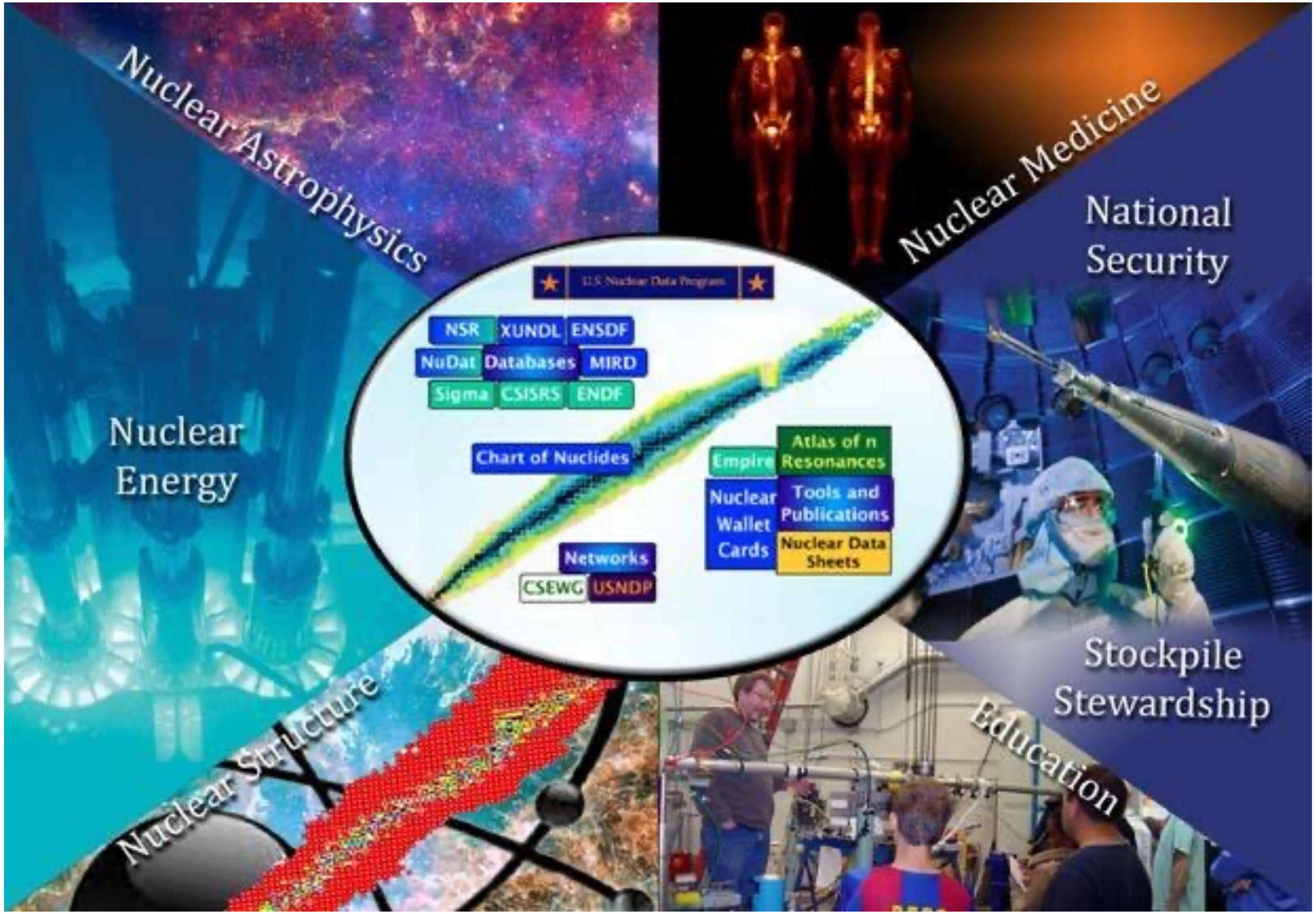
What is Nuclear Data?



From "White Paper on Nuclear Data Needs and Capabilities for Basic Science", arXiv:1705.04637[nucl-ex]

Nuclear data is interwoven throughout all of nuclear physics

Hot and cold QCD related physics touches space and medical applications in particular

Fewer data codes available to deal with the energies and species appropriate for these applications

Note that RHIC is included as a data facility, more on that later

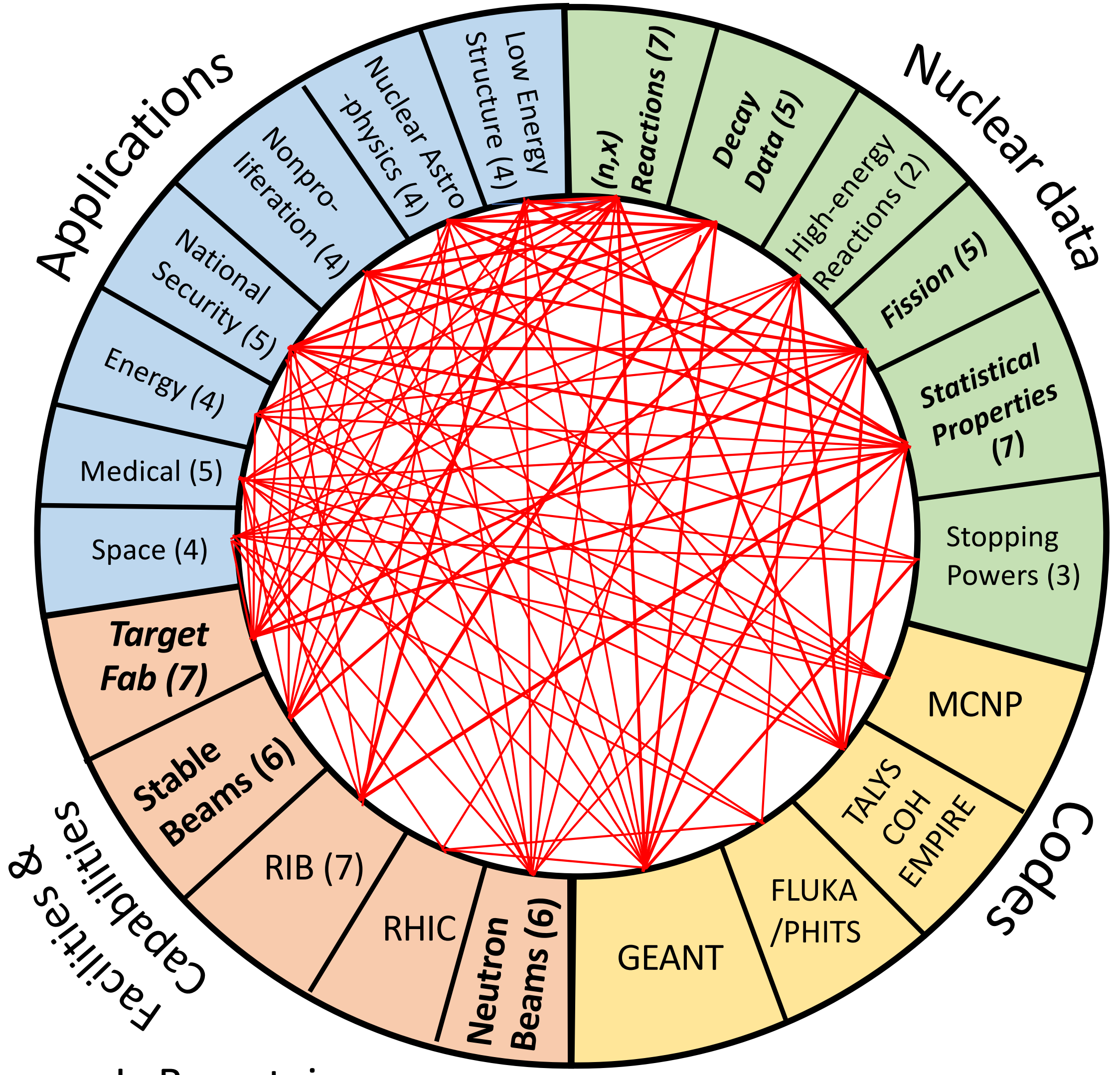


Diagram by A. Spyrou, L. Bernstein

Why are we concerned about nuclear data now?

NSAC charge for nuclear data: April 2022
2 reports expected --
1st at the end of September on USNDP status;
2nd at the end of January including recommendations for future data stewardship; diversifying the workforce; and identifying needs and crosscutting opportunities

U.S. Department of Energy
and the
National Science Foundation

April 13, 2022

Professor Gail Dodge
Chair, DOE/NSF Nuclear Science Advisory Committee
College of Sciences
Old Dominion University
4600 Elkhorn Avenue
Norfolk, Virginia 23529

Dear Professor Dodge:

This letter is to request that the Nuclear Science Advisory Committee (NSAC) establish an NSAC Sub-Committee to assess challenges, opportunities, and priorities for effective stewardship of nuclear data.

"Nuclear data" is data derived from observed properties of nuclei, their decays and decay products, and the interactions of both nuclei and their decay products with other nuclei, subatomic particles or in bulk matter. Data from theoretical models created for comparison with experimental nuclear data may also be considered for inclusion under this definition.

Increasingly, access to accurate, reliable nuclear data plays an essential role in the success of Federal missions such as non-proliferation, nuclear forensics, homeland security, national defense, space exploration, clean energy generation, and scientific research. Data access is also key to innovative commercial developments such as new medicines, automated industrial controls, energy exploration, energy security, nuclear reactor design, and isotope production. The mission of the United States Nuclear Data Program (USNDP) managed by the Department of Energy (DOE) Office of Science Nuclear Physics (NP) program is to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering. This is accomplished primarily through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. USNDP also addresses gaps in nuclear data, through targeted experimental studies and the use of theoretical models. A keystone of USNDP stewardship of nuclear data is the activity of the National Nuclear Data Center (NNDC) hosted at Brookhaven National Laboratory.

NSAC is requested to develop a strategic plan with prioritized recommendations to guide federal investment in the U.S. Nuclear Data Program (USNDP). This will consist of two separate steps and corresponding reports that will serve as a basis to inform the strategic plan:

How important is this?

Between the last long range plan in 2015 and the July 2022 call for the next one, there were 10 charges to NSAC:
1 on double beta decay;
1 on QC and QIS;
2 on the Committee of Visitors;
6 nuclear data related –
5 on ^{99}Mo plus the general nuclear data charge issued in April 2022

Timing of ND and LRP charges not a coincidence!

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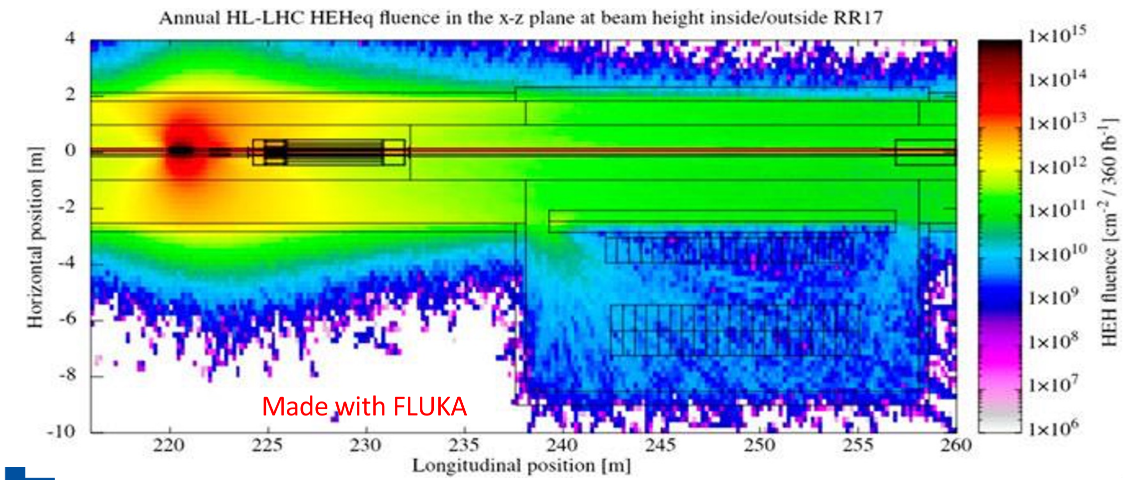
How is nuclear data related to QCD? Detector development

- Transport/interaction of particles in detector material is of paramount importance in all physics experiments and also in accelerators, medical applications
  - Experiment design: material budget, energy loss/stopping power, energy and position resolution, radiation levels, tolerances
  - Monte Carlo corrections to data: material budget, particle tracking (multiple scattering, momentum resolution), energy loss, conversion
- Most commonly used packages: Geant3, Geant4, FLUKA utilize information taken directly from Nuclear Data libraries

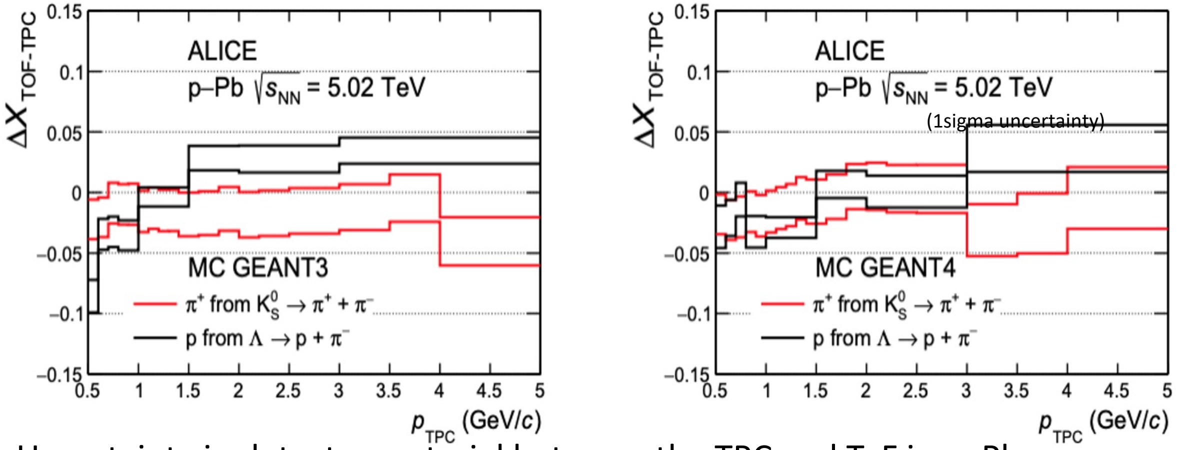
Detector simulations - particle transport through matter

- Examples from GEANT4 (https://geant4.web.cern.ch/support/data_files_citations):
  - Data set of nuclide properties derived from the Evaluated Nuclear Structure Data File (ENSDF @ BNL)
  - Radioactive decay and photon evaporation data from ENSDF
  - ABLA V3 data files (nuclear shell effects): alpha ground state (gs) deformation; gs shell corr. FRLDM for a spherical gs; difference between deformed gs and LDM values; default mass for A, Z nucleus
  - Data evaluated from SAID database for p, n, π inelastic, elastic, and charge exchange cross sections for nucleons < 3 GeV
  - From Livermore data lib: EADL - Evaluated Atomic Data Library

Top view of the annual High Energy Hadron-equivalent fluence at beam height in a portion of the LHC Long Straight Section at Point 1, showing the main tunnel and the nearby RR17 alcove where electronic equipment is hosted.



Understanding the material between sensitive detector volumes - **ALICE**



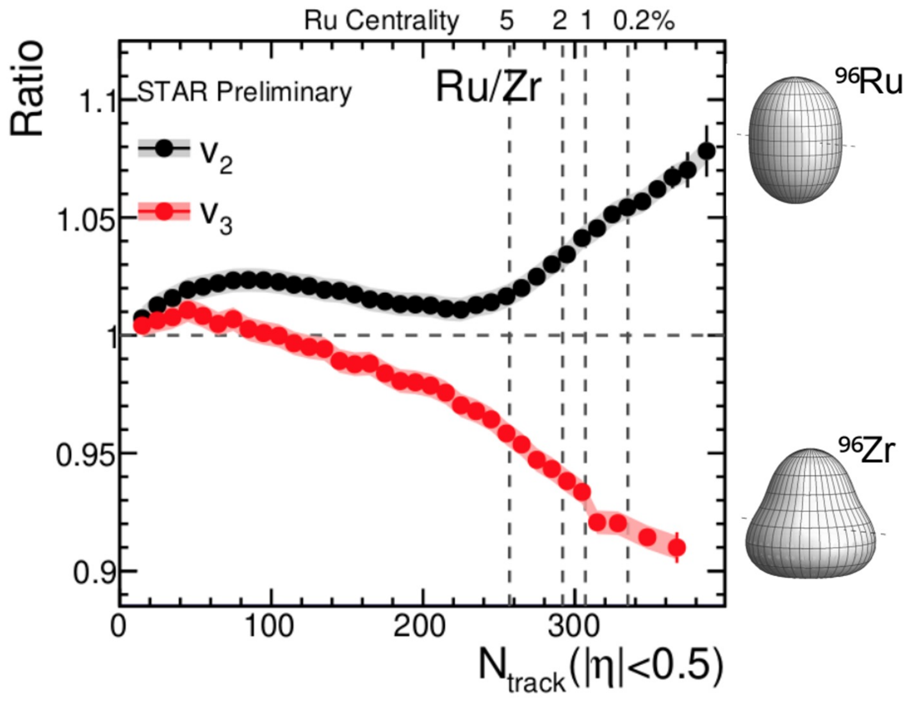
Uncertainty in detector material between the TPC and ToF in p+Pb collisions for Geant3 (left) and Geant4 (right) simulations. The space between the histograms is indicative of the material uncertainties.

M. Ploskon

Nuclear data and heavy-ion collisions

- The shape of the QGP is directly related to the structure/shape of colliding nuclei - knowing the initial conditions of the collisions/QGP is critical
- Distribution of neutrons (skin effect) is important for some physics conclusions (e.g. tidal deformabilities of neutron stars)
- Return value/positive cross talk: angular correlations of particles from heavy-ion collisions retain information about many-body correlations in the colliding nuclei → insight into nuclear structure from heavy-ion collisions
- Interdisciplinary scan of collision species at colliders could complement low energy structure program – see Jia's talk in Hot QCD parallel

FIG. 4. Ratios of flow coefficients, v_n, taken between Ru+Ru and Zr+Zr collisions. The suppression of the v_3 ratio at large multiplicity is due to an enhancement of v_3 in Zr+Zr collisions.



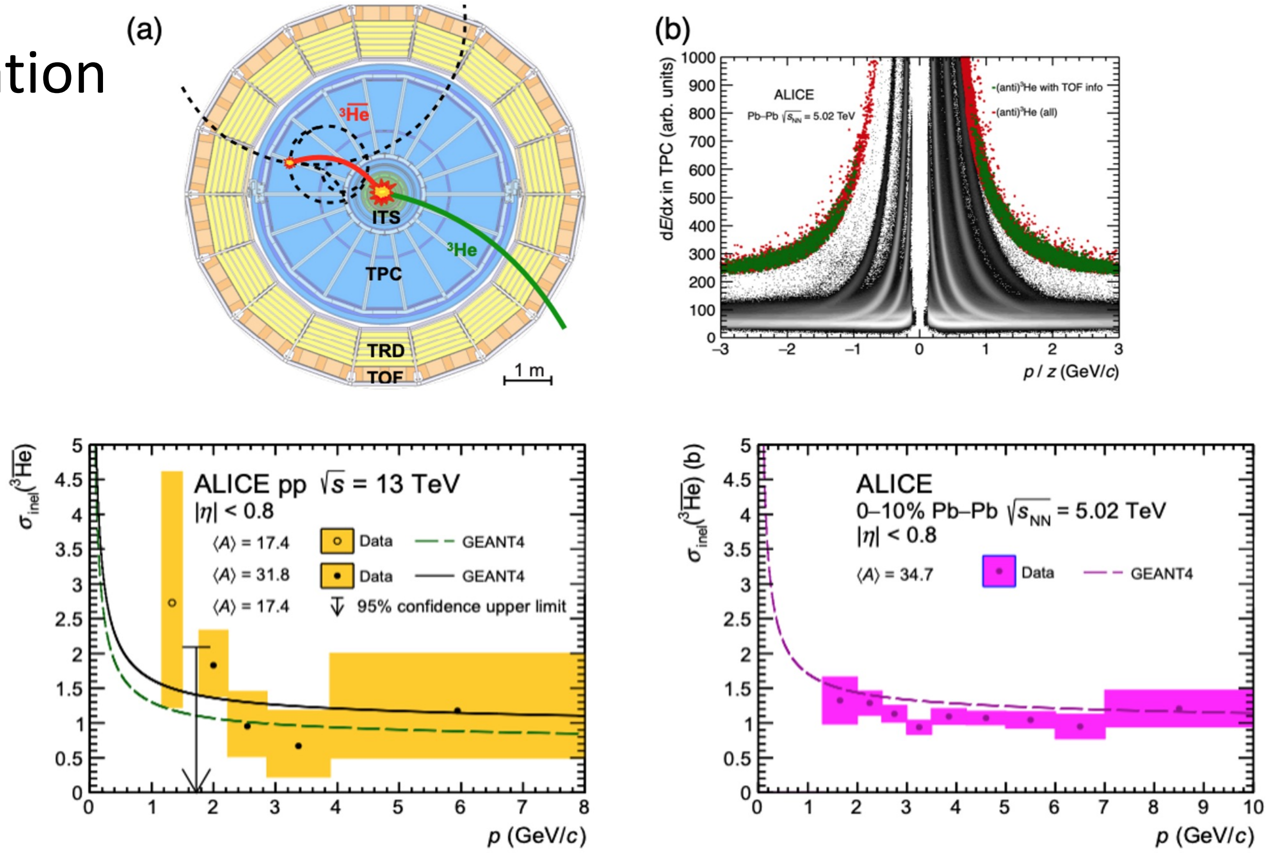
Thanks to M. Ploskon

Nuclei from high energy HIC

Light nuclei are produced in heavy-ion collisions (reconstruction: dE/dx, Time of Flight)

Production mechanisms (statistical hadronization coalescence, hydro+smash - (re)generation in hadronic phase) still not fully understood

First measurement of absorption of anti-nuclei ($^3\overline{He}$) in matter (arXiv:2202.01549 [nucl-ex]): The matter, in this case, is the detector material (!)



Top: (Left) Annihilation of anti-^{3}He in TPC (red) or reaching the ToF (green).
(Right) Identification of antinuclei via dE/dx (red).
Bottom: Anti-^{3}He cross sections in pp (left) and Pb+Pb (right) collisions as a function of energy compared to GEANT4 simulations of the detector material.

Nuclei from high energy HIC

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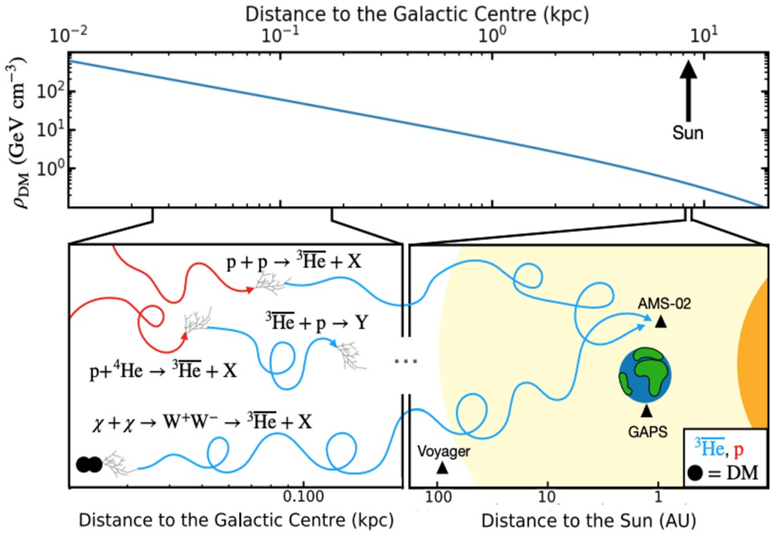
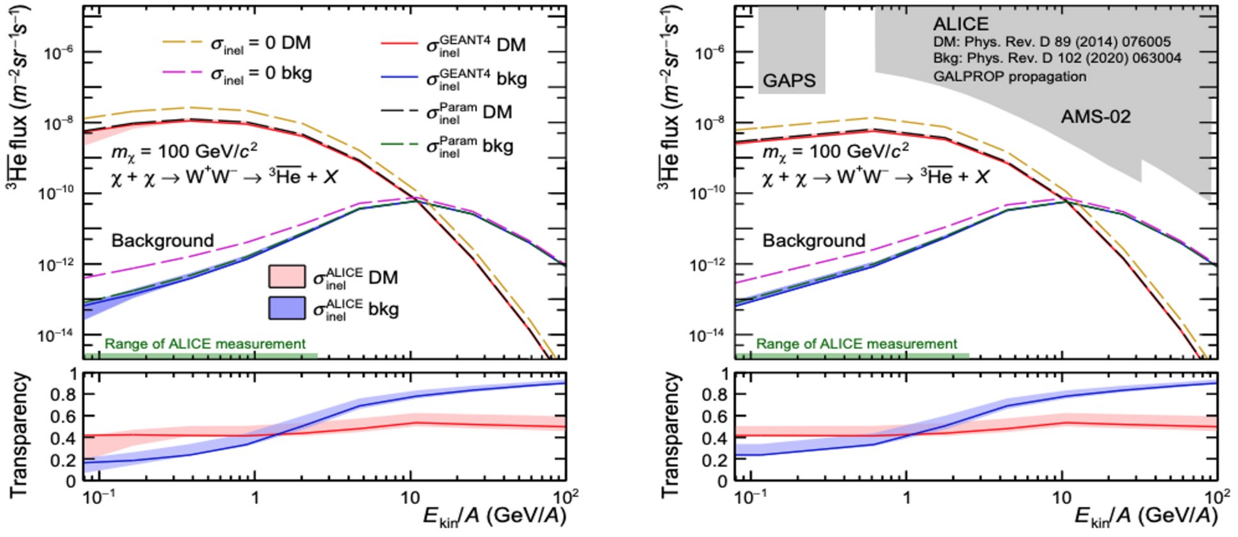
… and the impact on their propagation in the galaxy →studies cosmic-ray interactions and dark matter decays



Top: Dark-matter distribution in the galaxy as a function of the distance R from the galactic center. Bottom: Illustration of anti-^{3}He production from cosmic-ray interactions with interstellar gas or dark-matter (χ) annihilation.



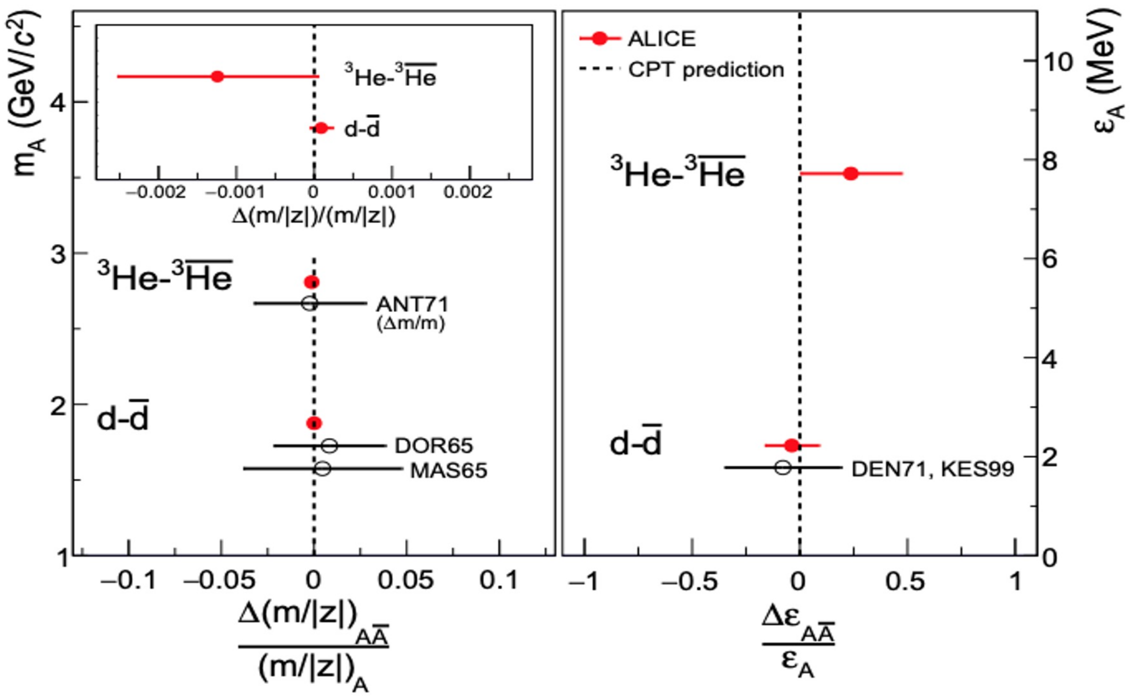
Expected anti-^{3}He flux near Earth before (left and after (right) solar modulation.

(Hyper)nuclei from high energy HIC

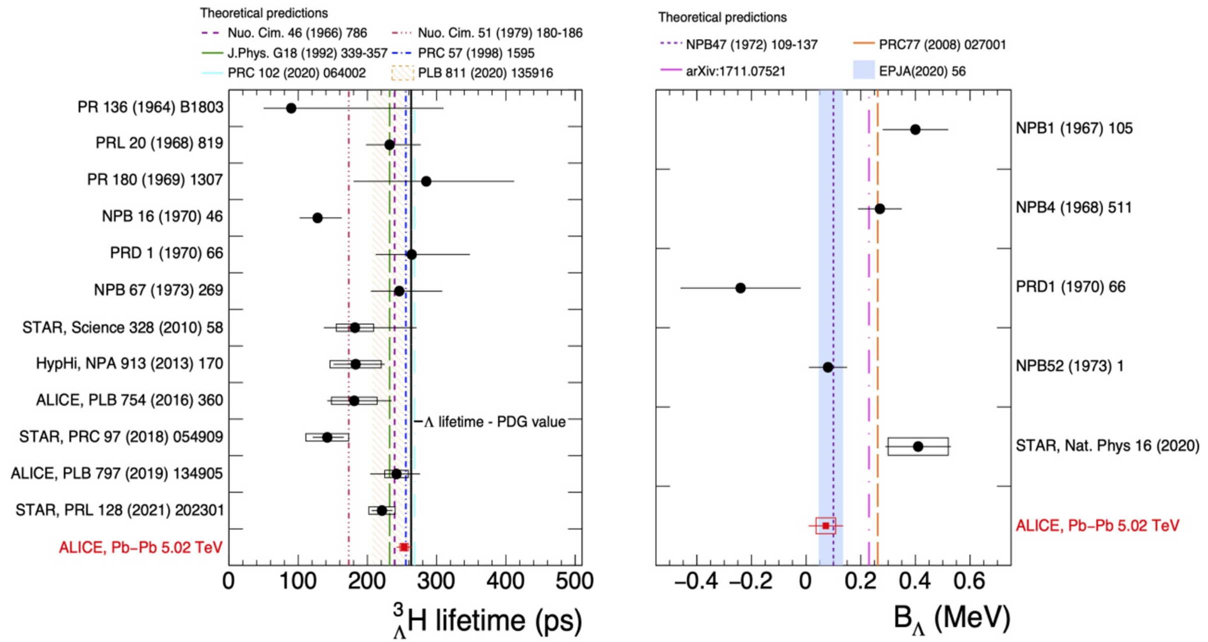
Measurement of lifetime and Λ separation energy of $^{3}_{\Lambda}H$ (arXiv:2209.07360 [nucl-ex])

ALICE 3: A=6 (He, Li and anti-) and search for super-nuclei: c-deuteron, c-triton and c-^{3}He (!)

mass difference between light nuclei and anti-nuclei
Nature Physics volume 11, p. 811–814 (2015)



hypernuclei at the LHC: hypertriton ($^{3}_{\Lambda}$H), composed of a Lambda baryon (Λ), a proton, and a neutron, lifetime (left) and binding energy (right)

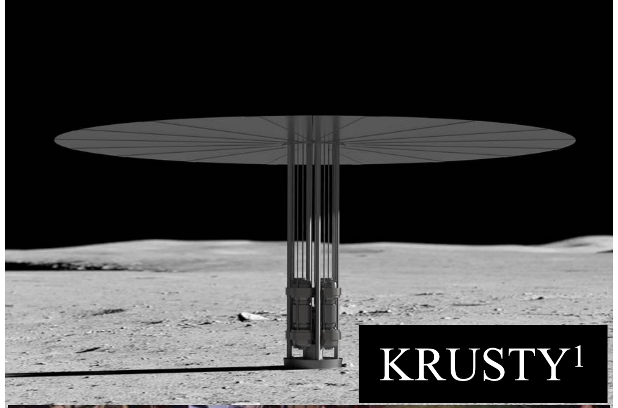


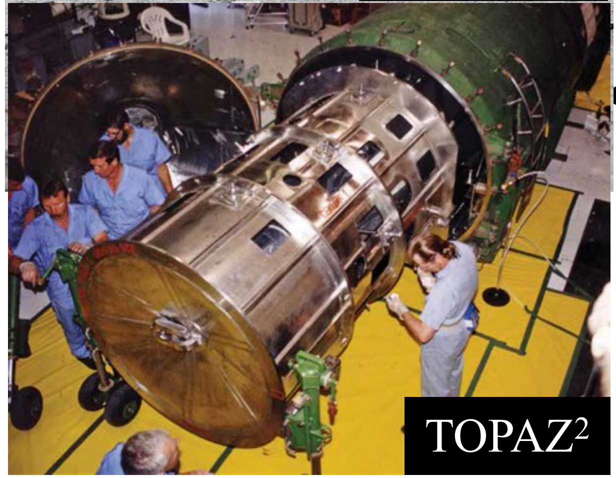
arXiv:2209.07360

Thanks to M. Ploskon

How is Nuclear Data Related to QCD? Space…

Energy Production





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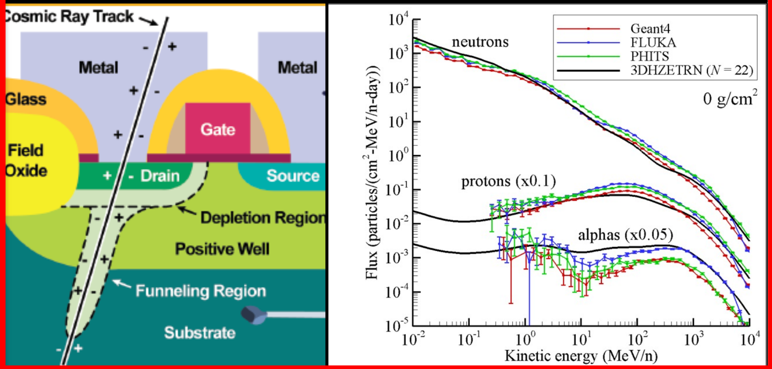
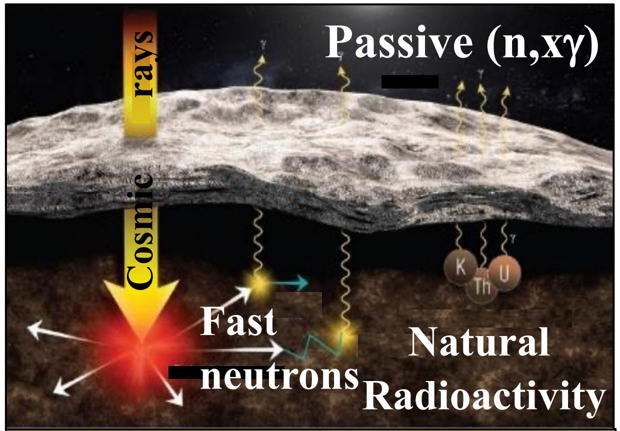
Dose/Shielding Calculations for Electronics and Humans

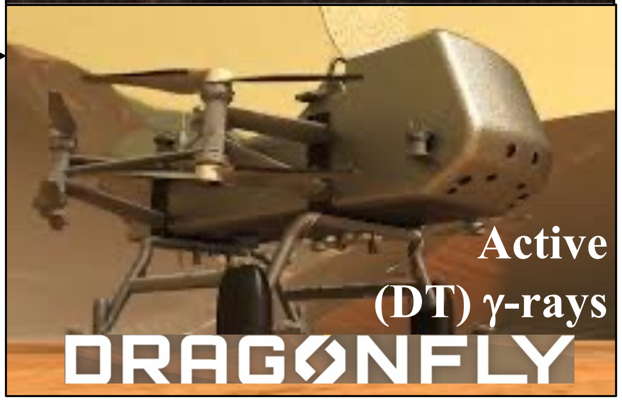


Nuclear Data

Nuclear Propulsion

Planetary Exploration



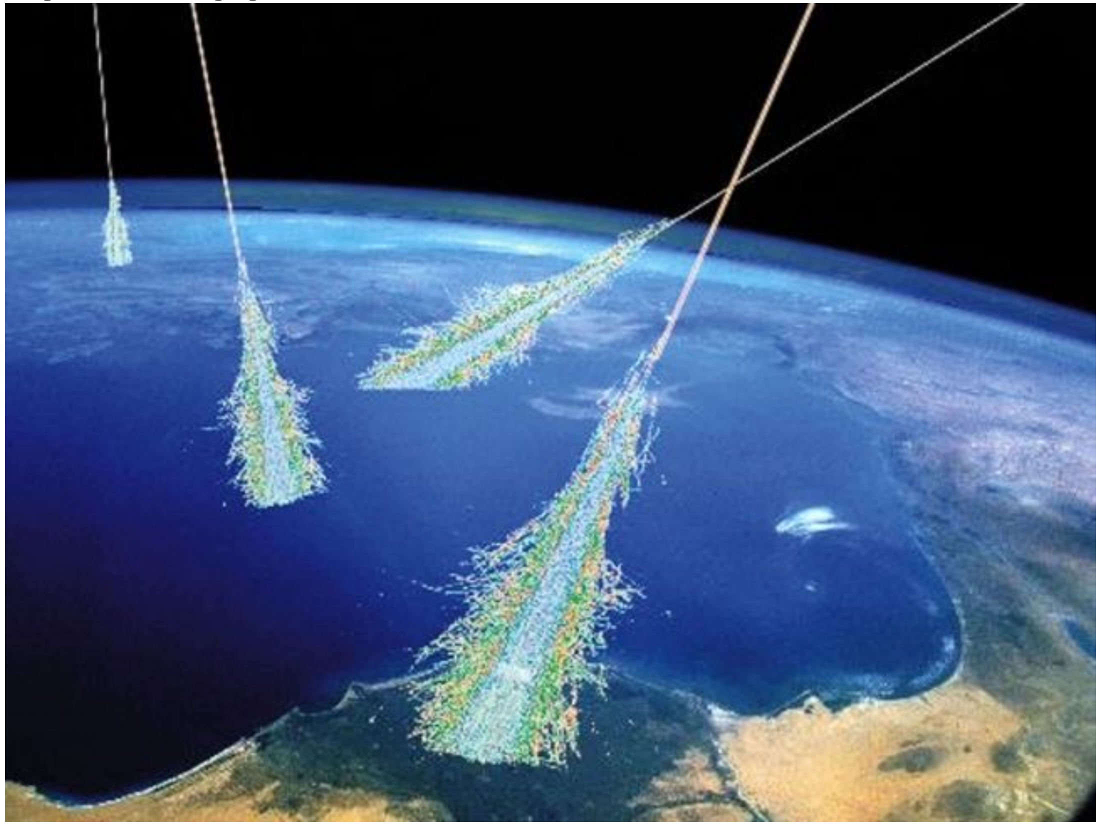


A meeting called WANDA

- Annual assessment of nuclear data needs for applications

- Last meetings have had a major focus on space related applications which also play a role in applications on Earth, especially medical applications like particle therapy

- One focus in 2022 was **high energy data for space applications**



- We are shielded from Galactic cosmic rays on Earth by Earth's magnetic field and our atmosphere

- In space and on planetary missions, shielding is reduced, high energy cosmic rays can penetrate spacecrafts and astronauts, producing high energy secondaries, causing damage

What are the energy ranges of cosmic rays?

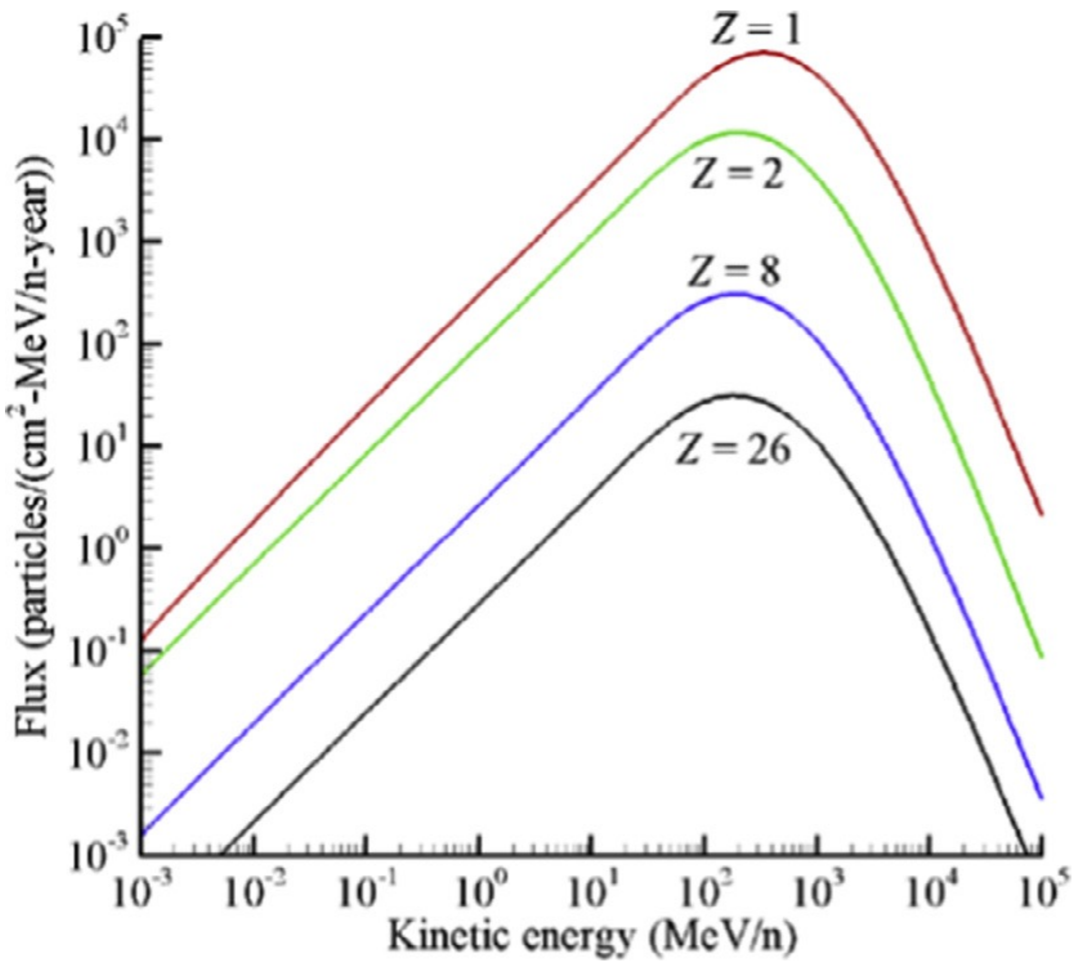
Galactic cosmic rays include everything from protons to heavy nuclei (up to ^{56}Fe) with KE up to 50 GeV/A: peak flux ~ 100 MeV - 1 GeV

The cosmic ray flux is composed of nuclei (90% protons, 9% He, and 1% nuclei up to Fe).

A 1 GeV proton can travel 1 m through Al so shielding spacecraft and satellites is nontrivial

Protons deposit energy more locally while neutrons travel further

The type of shielding contributes to the total multiplicity of secondaries



T.C. Slaba et al., Life Sciences in Space Research 12 (2017) 1–15

What do these secondaries look like?

When a cosmic ray strikes the atmosphere, or rather a nucleus like nitrogen or oxygen in the atmosphere, it triggers a cascade of particles, both hadronic and electromagnetic, similar to those seen in high energy collisions governed by QCD:
fragment nuclei, n, p, π, K, e, μ

Detectors often calibrated by exposure to cosmic rays (ALICE collab, 2010 *JINST* **5** P03003)

When such a cosmic ray strikes a spacecraft or satellite, it can trigger a similar cascade but now through spacecraft shielding, electronics, computers, and astronauts

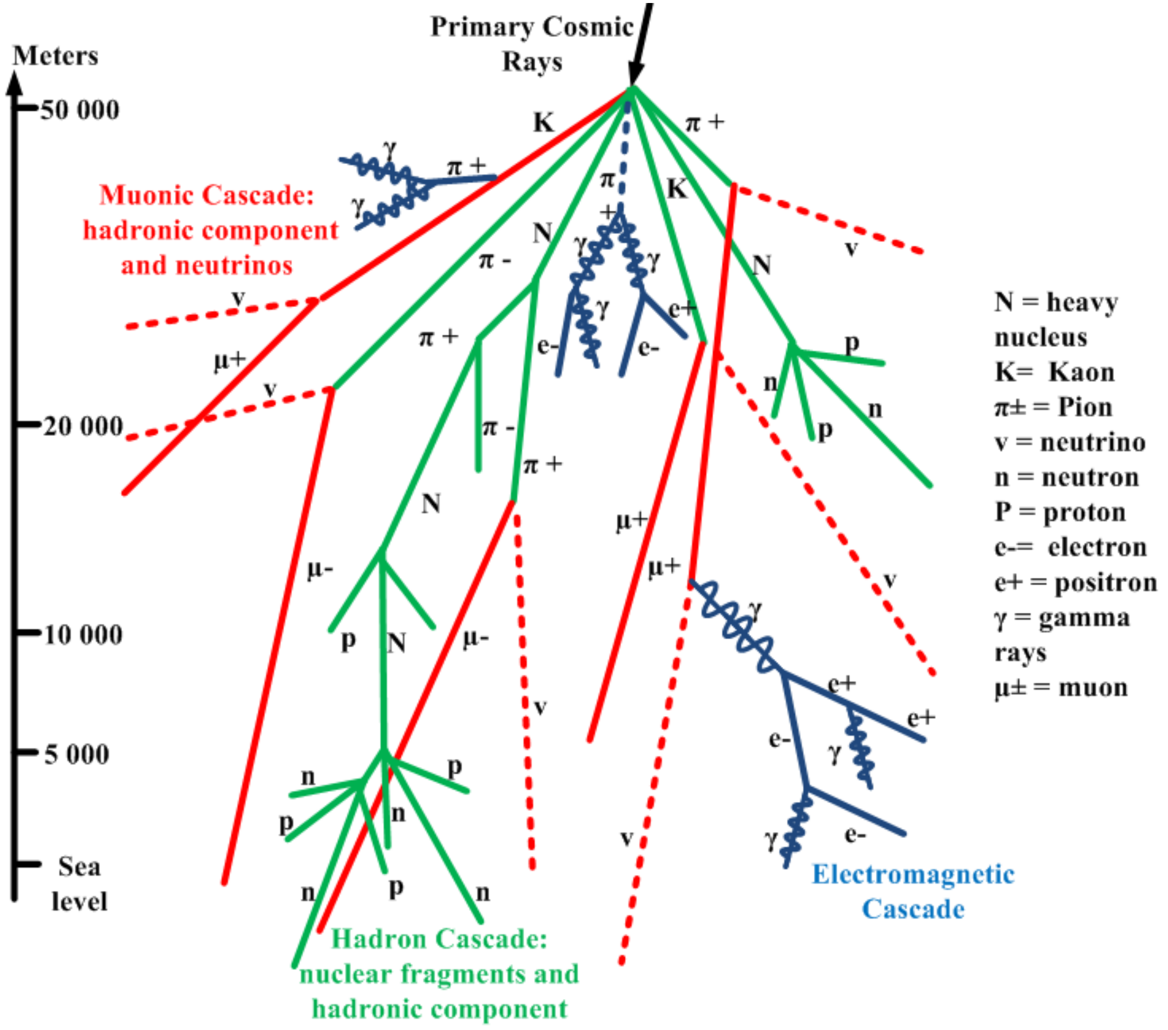
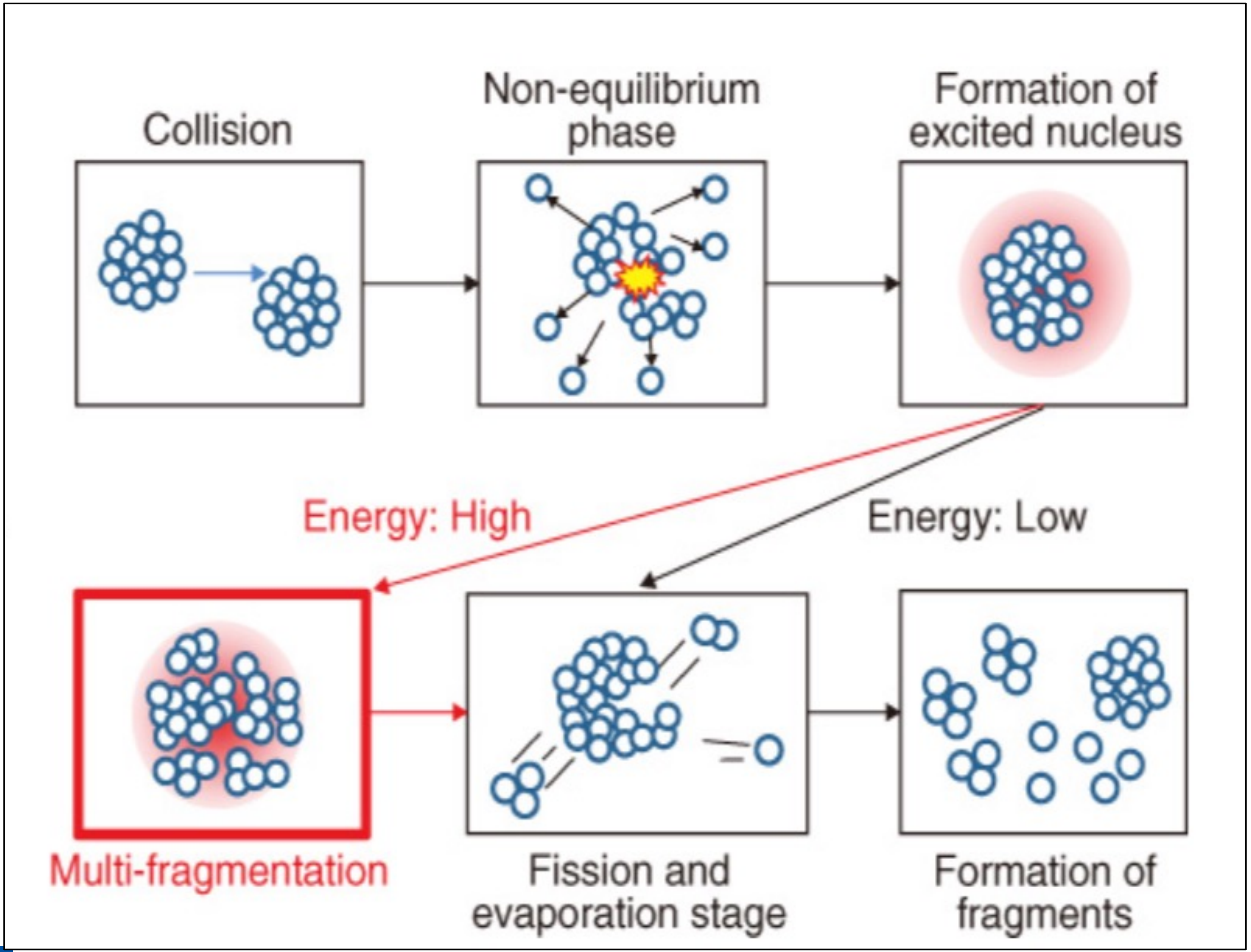
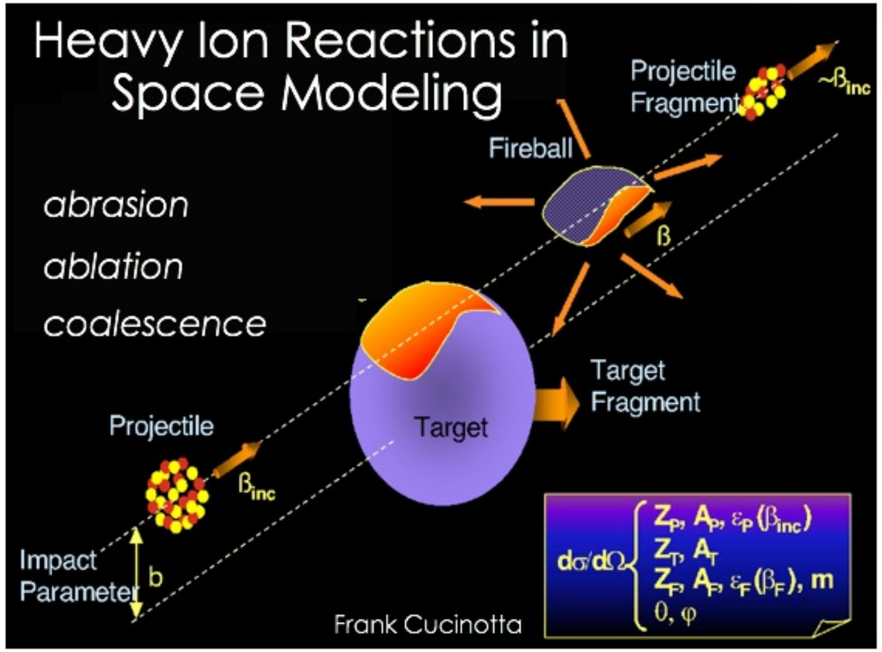


Diagram by Daniel Gomez Toro

How are these energy ranges modeled?





These types of models (abrasion/ablation, etc.)
date back to the 1970s, before more sophisticated codes were available

D. Brown, M. Smith

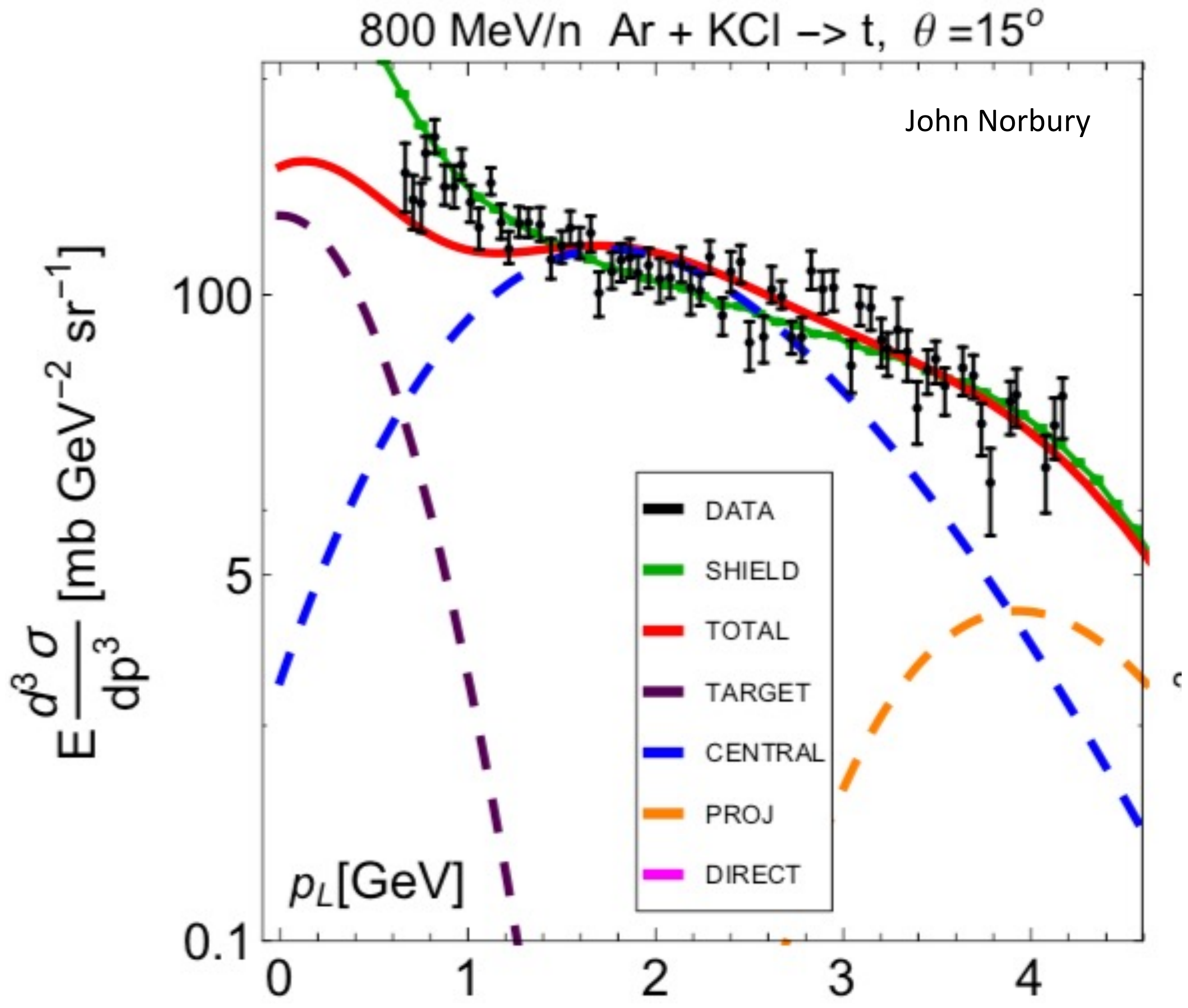
NASA uses very simple phenomenological models

Double differential fragmentation model,
John Norbury, NASA

THERMAL / COALESCENCE MODEL FOR LIGHT ION PRODUCTION

$$\begin{aligned} E_A \frac{d^3\sigma_A}{dp_A^3} = \; & C_A N_4^A \Big\{ w_{\mathcal{P}} \exp[(m_{\rm p} - \gamma_{\mathcal{P}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{P}L}\, \beta_{\mathcal{P}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{P}}] \\ & + w_{\mathcal{C}} \exp[(m_{\rm p} - \gamma_{\mathcal{C}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{C}L}\, \beta_{\mathcal{C}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{C}}] \\ & + w_{\mathcal{T}} \exp[(m_{\rm p} - \gamma_{\mathcal{T}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{T}L}\, \beta_{\mathcal{T}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{T}}] \\ & + w_{\mathcal{D}} w_{\mathcal{D}}^{(\rm p)} \exp[(m_{\rm p} - \gamma_{\mathcal{P}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{P}L}\, \beta_{\mathcal{P}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{D}}] \Big\}^A \end{aligned}$$

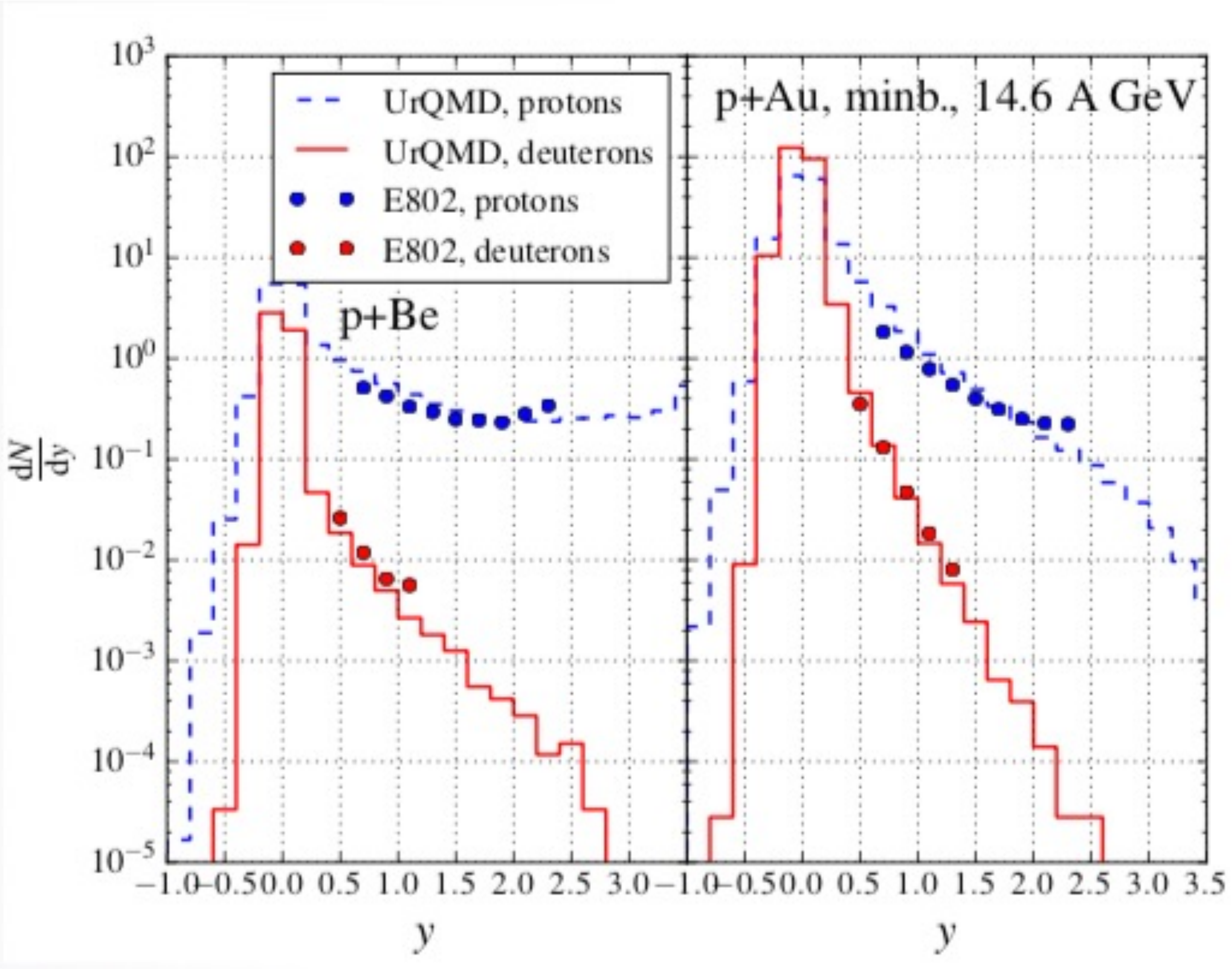
$$\begin{aligned} N_4 = \; & \frac{\sigma_{\rm p}}{4\pi m_{\rm p}} \Big[\Theta_{\mathcal{P}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{P}}}} K_1\Big(\frac{m_{\rm p}}{\Theta_{\mathcal{P}}}\Big) + \Theta_{\mathcal{C}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{C}}}} K_1\Big(\frac{m_{\rm p}}{\Theta_{\mathcal{C}}}\Big) \\ & + \Theta_{\mathcal{T}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{T}}}} K_1\Big(\frac{m_{\rm p}}{\Theta_{\mathcal{T}}}\Big) + w_{\mathcal{D}}^{(\rm p)}\, \Theta_{\mathcal{D}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{D}}}} K_1\Big(\frac{m_{\rm p}}{\Theta_{\mathcal{D}}}\Big) \Big]^{-1} \end{aligned}$$



M. Smith

Hot QCD event generators do much better

Marcus Bleicher, UrQMD



Reaction modeling for space applications could benefit from interactions with heavy-ion physicists

Effects of cosmic rays on electronics

- GCRs can cause *single event upsets* that can cause temporary or permanent failures.
- GCR heavy ions cause a local, dense ionization column
- Secondary p and n can induce reactions that create a recoiling residual nucleus
- The imparted dose depends on the *stopping power* of the recoiling nuclei.
- Stopping powers calculated using Bethe-Bloch equation

Energy deposition (stopping power) in material quantified by linear energy transfer

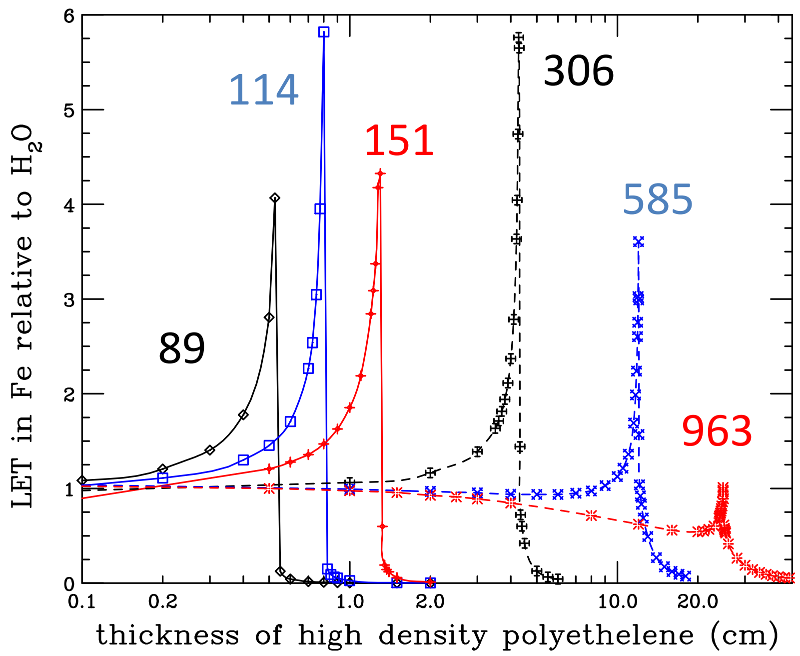
Linear Energy Transfer is the ratio of energy transferred by a charged particle to target atoms along its path, dE/dx.

As E → 0, the stopping power increases, leading to a *Bragg Peak* where the highest dose is deposited

Higher-Z ions have shorter ranges and higher dose in their Bragg Peaks

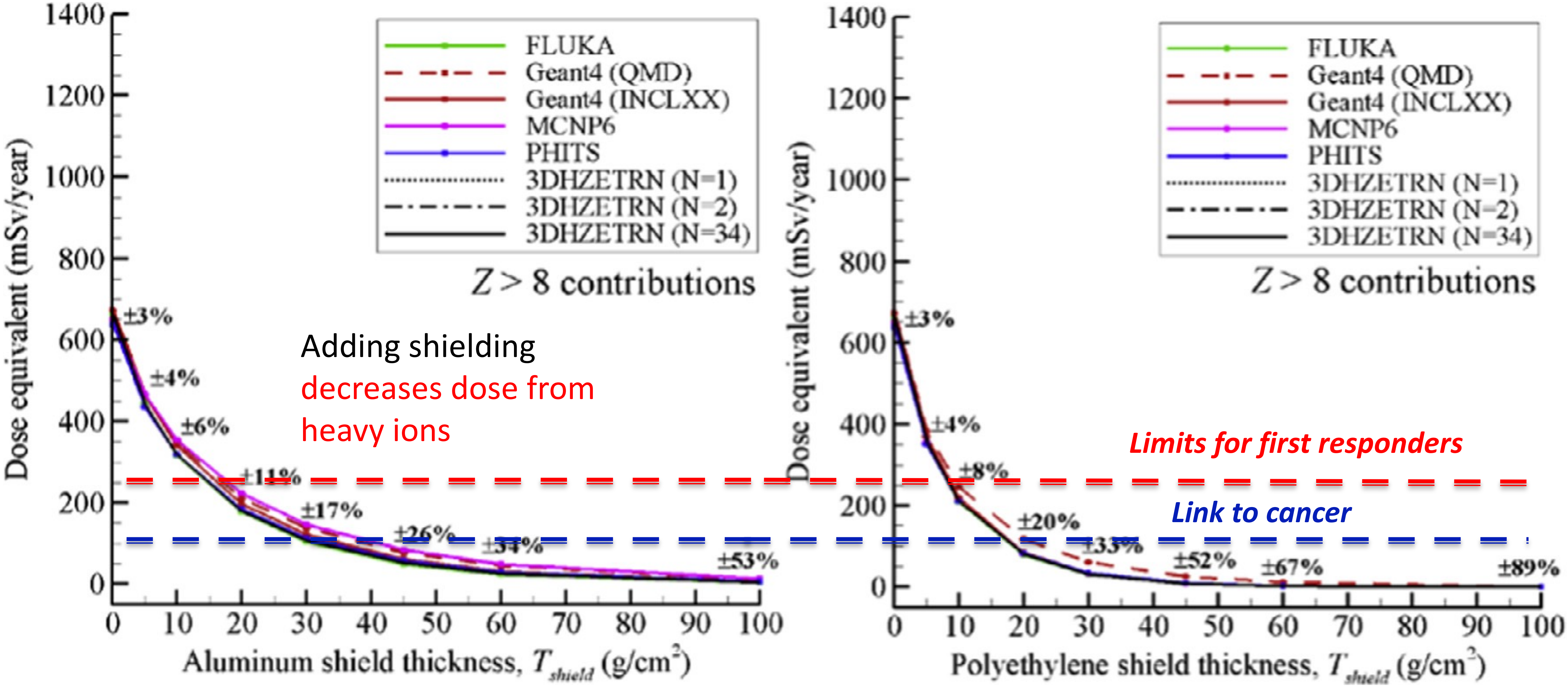
Higher energy ions are of longer range, requiring more material to stop them

Stopping power of Fe in polyethelene for different energies (in MeV), BNL SRL



L. Bernstein

Shielding for ions (Z > 8)



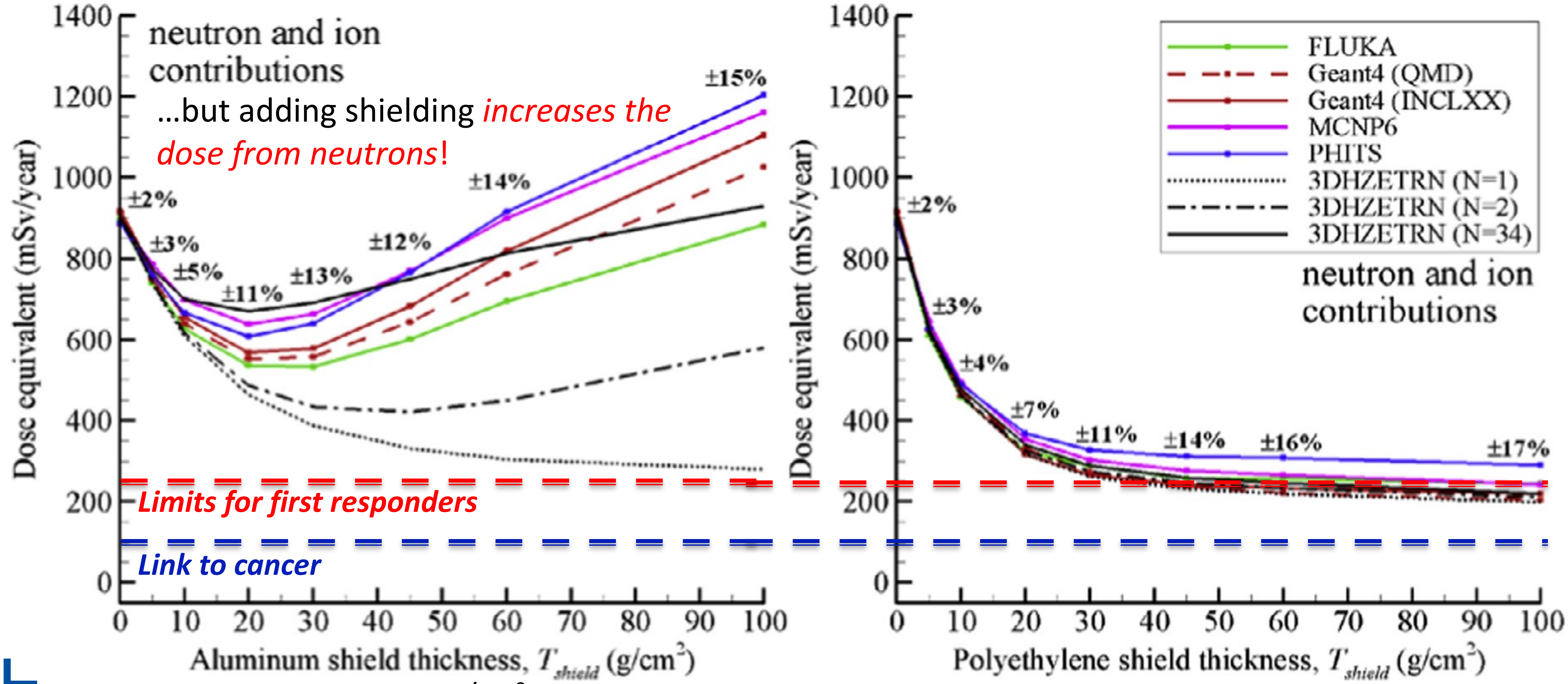
ρ_{Al}=2.7 g/cm^3

ρ_{PE}=0.97 g/cm^3

T.C. Slaba et al. Life Sciences in Space Research 12 (2017) 1–15

Shielding for neutrons and ions

"Variation in model results… is mainly a result of differing nuclear reaction and fragmentation cross sections, affecting both primary and secondary ion transport", Slaba et al, Life Sciences in Space Research 12 (2017) 1-15



ρ_{Al}=2.7 g/cm^3

ρ_{PE}=0.97 g/cm^3

Determining radiation effects on humans (Dose)

$$\text{Dose (D)} = \frac{\text{energy deposited}}{\text{mass of material}}$$

$$\text{Dose Equivalent} = \text{D}\times\text{Q (rem) (1 Sievert (Sv)} = 100\text{ rem)}$$

$$\text{Q}_{\gamma-\text{rays}} = 1, \text{Q}_{\alpha} = 20$$

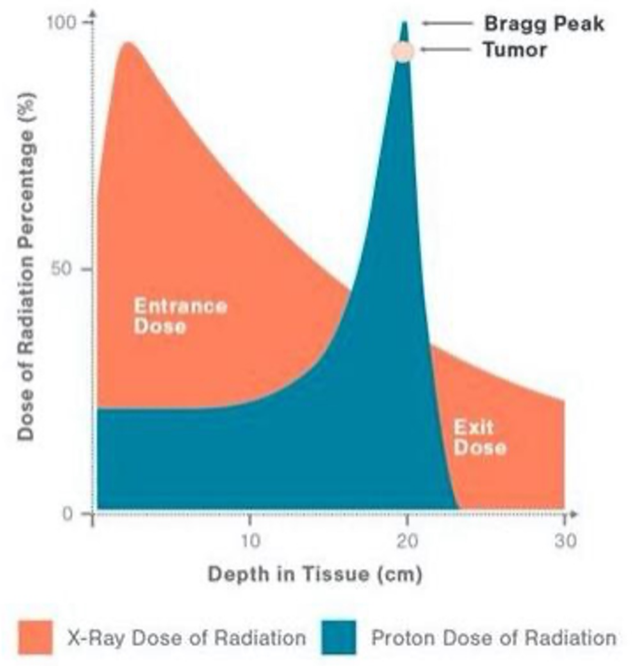
- Normal Background Dose/day on earth: 10 μSv
- **Lowest annual dose linked to cancer: 100 mSv**
- **DOE Limit for first responders: 250 mSv**
- Acute dose causing symptoms: 400 mSv
- **10 minutes next to the Chernobyl core: 50 Sv**

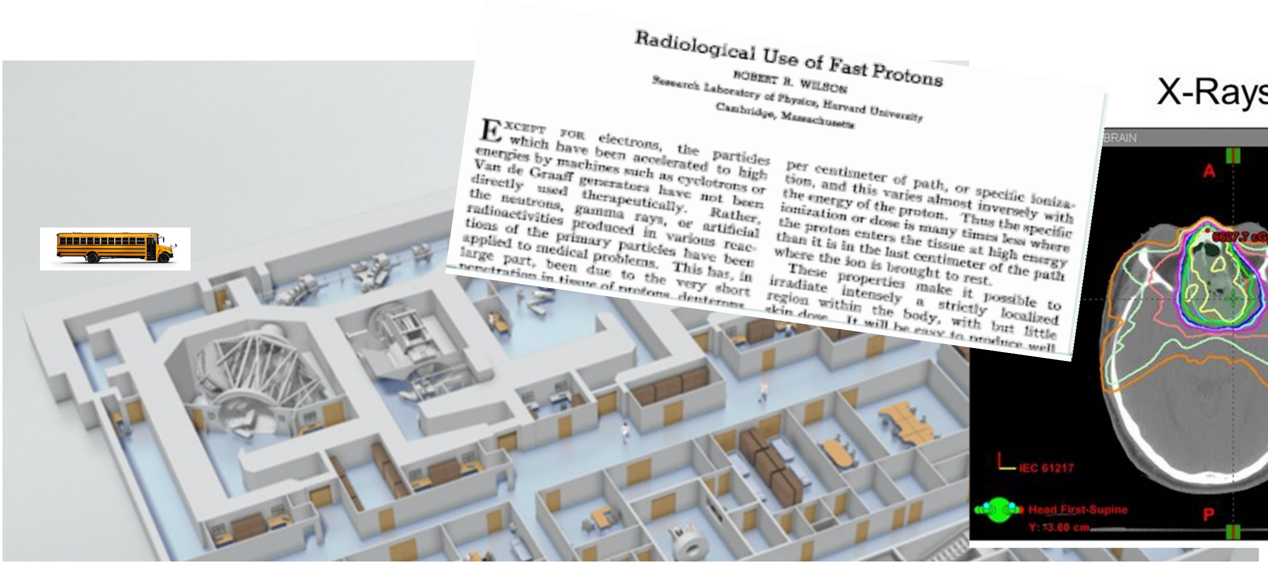
Proton/Ion Therapy for Cancer Treatment

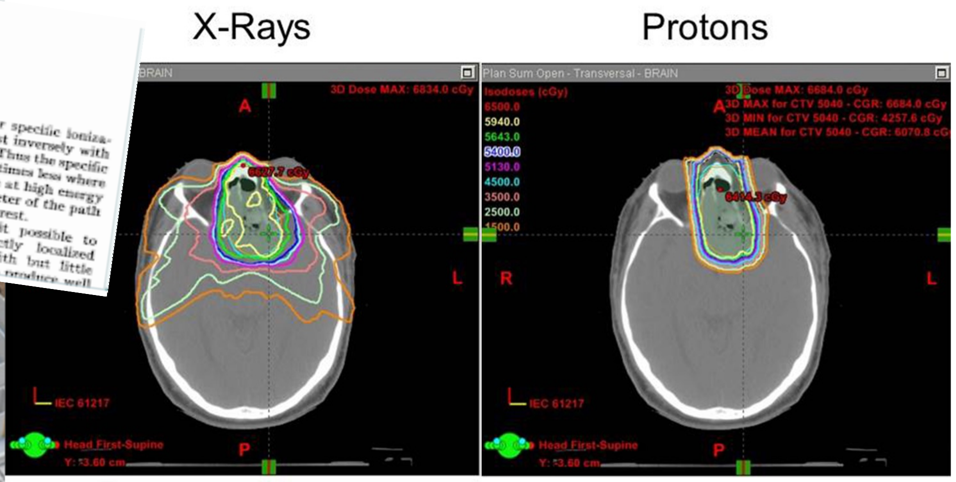
Radiotherapy with a **particle accelerator** allows oncologists to design fine-tuned three-dimensional cancer treatment plans.

Fundamental nuclear physics: *Bragg peak determines proton energy loss = dose to patient*

- Enables higher precision localized treatment
- Associated with fewer side effects due to reduced stray radiation outside the tumor region
- Nuclear physics technology to enable this includes **simulation, beam transport, acceleration, dose monitoring**, *and more….*



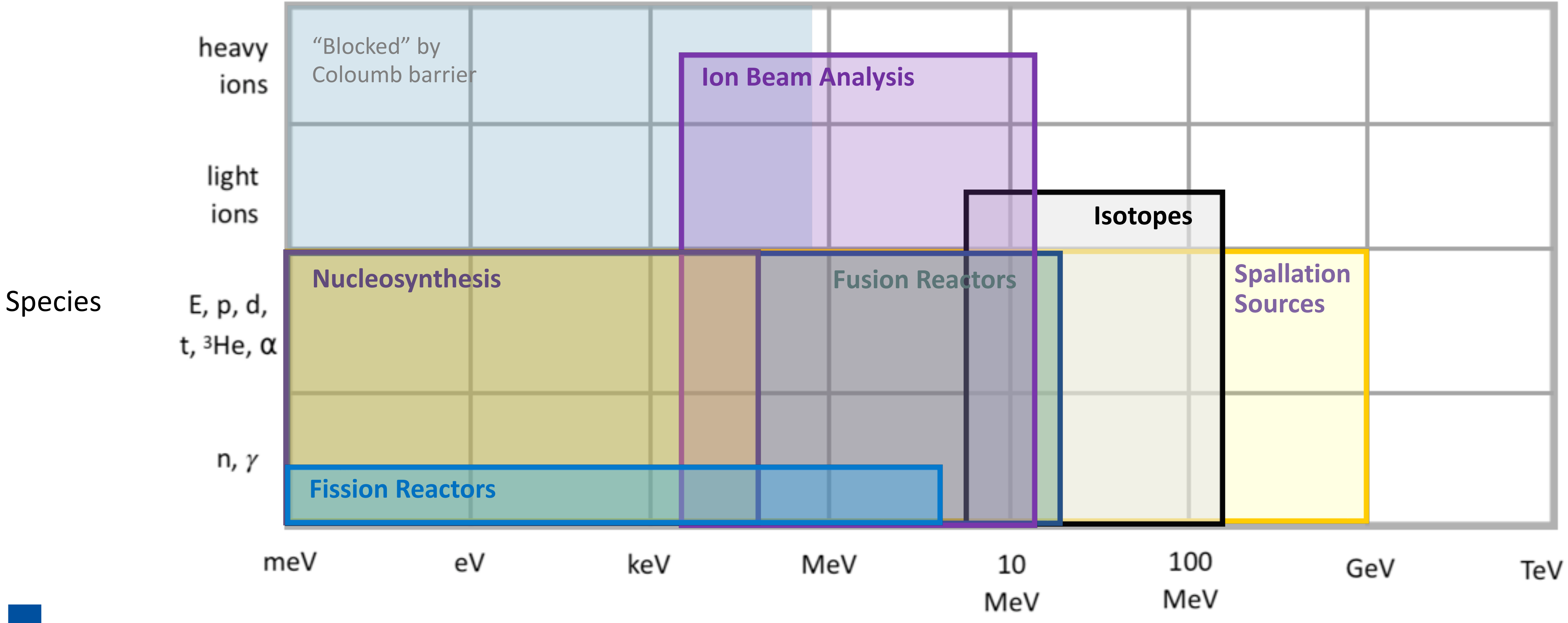




Energy ranges and types of cosmic rays

Standard databases (ENDF, for example) cover mostly neutron-induced reactions (and some charged particles) up to about 20 MeV; need to go beyond that

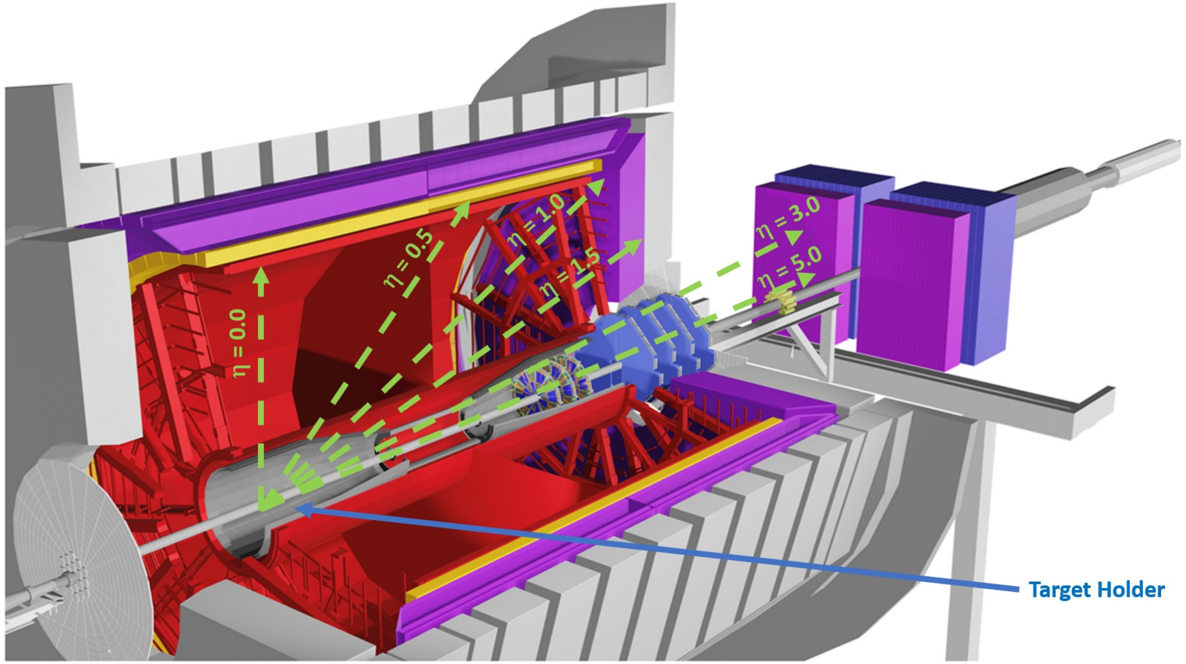
Essentially NO data for E > 3 GeV

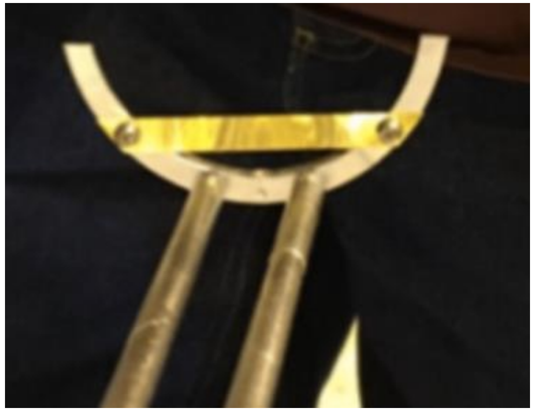


D. Brown

Motivation for STAR measurement to fill gaps

- Radiation damage proportional to Z^2
- Ions are thus very important
- Damage from secondary production of p, d, t, ^{3}He, and ^{4}He is also significant.
- Double differential measurements exist for light fragments production for projectile energies below 3 GeV/n.
- No data exist for projectile energies from 3-50 GeV/n.





STAR as a fixed-target detector

2023-2025 Beam Use Request:
light fragment yields from C, Al, and Fe on C, Al, and Fe targets
with beam energies from 5 to 50 GeV

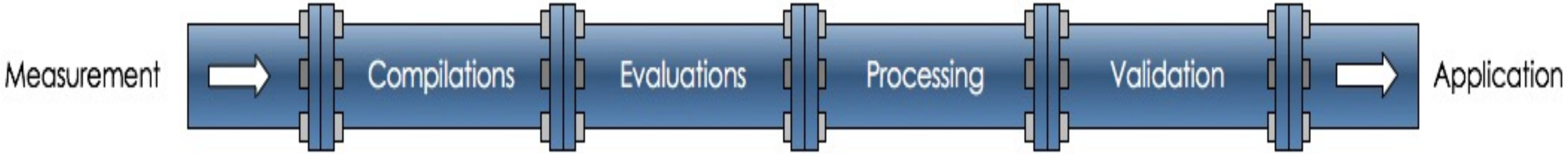
STAR has been run in fixed-target mode from 2018-2021 for Au+Au collisions

Note multiple ways of quantifying the collision energy

Acceptance depends on energy

FXT Energy $\sqrt{s_{NN}}$(GeV)	Single Beam E_T (GeV)	Single beam E_k (A/GeV)	y_{cm}	Chem. Pot. μ_B (MeV)	Year
3.0	3.85	**2.9**	1.05	721	2018
3.2	4.59	**3.6**	1.13	699	2019
3.5	5.75	**4.8**	1.25	666	2020
3.9	7.3	**6.3**	1.37	633	2020
4.5	9.8	**8.9**	1.52	589	2020
5.2	13.5	**12.6**	1.68	541	2020
6.2	19.5	**18.6**	1.87	487	2020
7.2	26.5	**25.6**	2.02	443	2018
7.7	31.2	**30.3**	2.10	420	2020
9.1	44.5	**43.6**	2.28	372	2021
11.5	70	**69.1**	2.51	316	2021
13.7	100	**99.1**	2.69	276	2021

Nuclear data pipeline…



- A sensitivity study is performed to determine what new ***measurements*** are needed.
- Published experimental data (including uncertainties) are ***compiled*** into databases (EXFOR).
- Physics-based models are adjusted to best reproduce measurements (cross section vs. energy, fission yields etc.) and produce an ***evaluation*** that goes into a data library.
- These values are ***processed*** to be used in codes that model benchmarks for ***validation***.
- The data can then be used in applications.

…also requires a human pipeline

Physicists trained in QCD can also work in nuclear data (full or part time). For example --

I am now considered a world expert in nuclear fission, thanks to our FREYA event generator, I've worked with several students, both theory and experiment, have published around 30 papers on the topic, given many invited talks and have a book coming out in November.

Dave Brown (BNL) got his PhD in nuclear theory and is now chair of the USNDP and CSEWG and has been manager of the ENDF library, the US nuclear data library

Nuclear data initiative for the Long Range Plan

Nuclear data play an essential role in all facets of nuclear physics. Access to accurate, reliable nuclear data is crucial to the success of important missions such as nonproliferation and defense, nuclear forensics, homeland security, space exploration, and clean energy generation, in addition to the basic scientific research underpinning the enterprise. These data are also key to innovations leading to new medicines, automated industrial controls, energy exploration, energy security, nuclear reactor design, and isotope production. It is thus crucial to maintain effective US stewardship of nuclear data.

- We recommend identifying and prioritizing opportunities to enhance and advance stewardship of nuclear data and maximize the impact of these opportunities.

- We recommend building and sustaining the nuclear data community by recruiting, training, and retaining a diverse, equitable and inclusive workforce.

- We recommend identifying crosscutting opportunities for nuclear data with other programs, both domestically and internationally, in particular with regard to facilities and instrumentation.

NSAC Subcommittee on Nuclear Data

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