# Solar and Reactor Neutrinos

Joachim Kopp | CERN & JGU Mainz | Lectures at INSS 2019, Fermilab

# Solar Neutrinos

PRISMA

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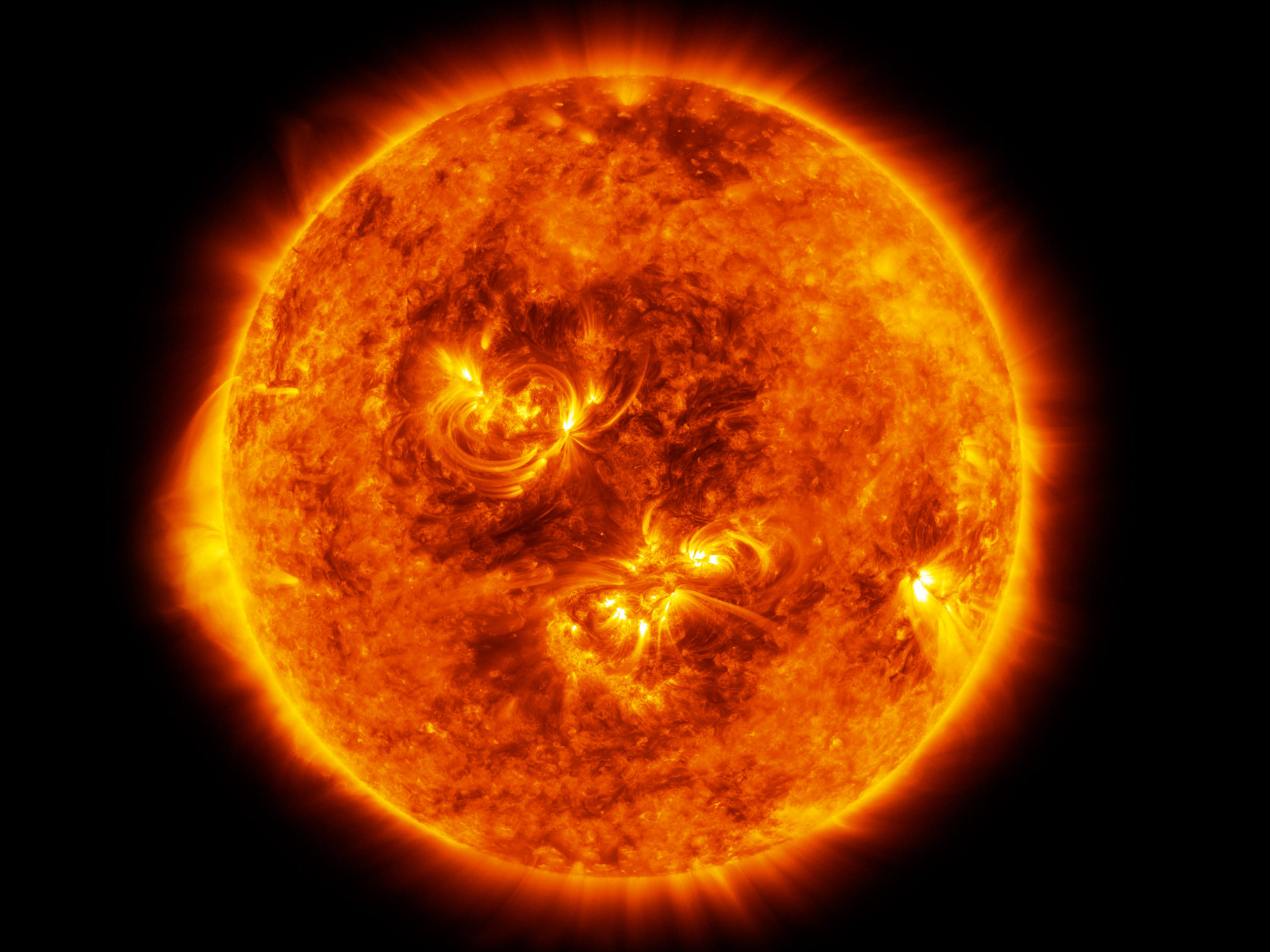

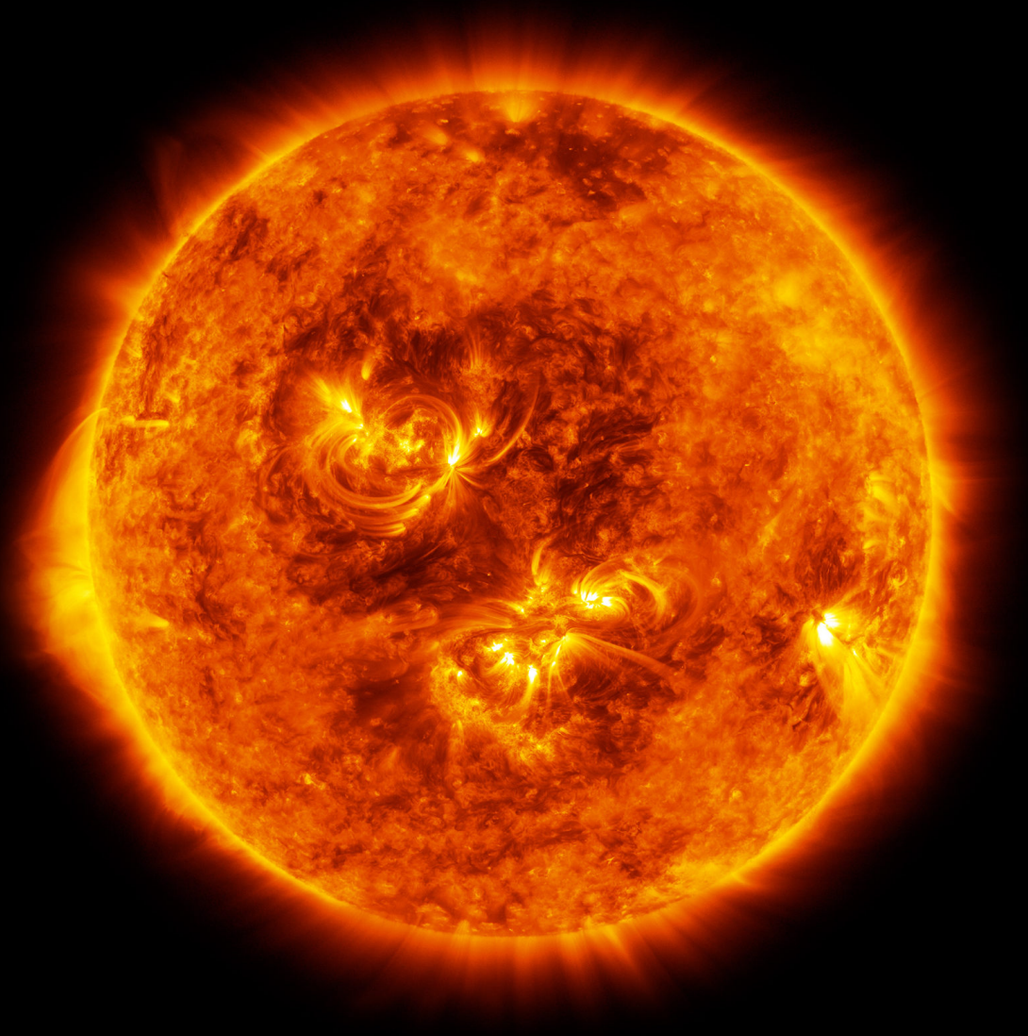

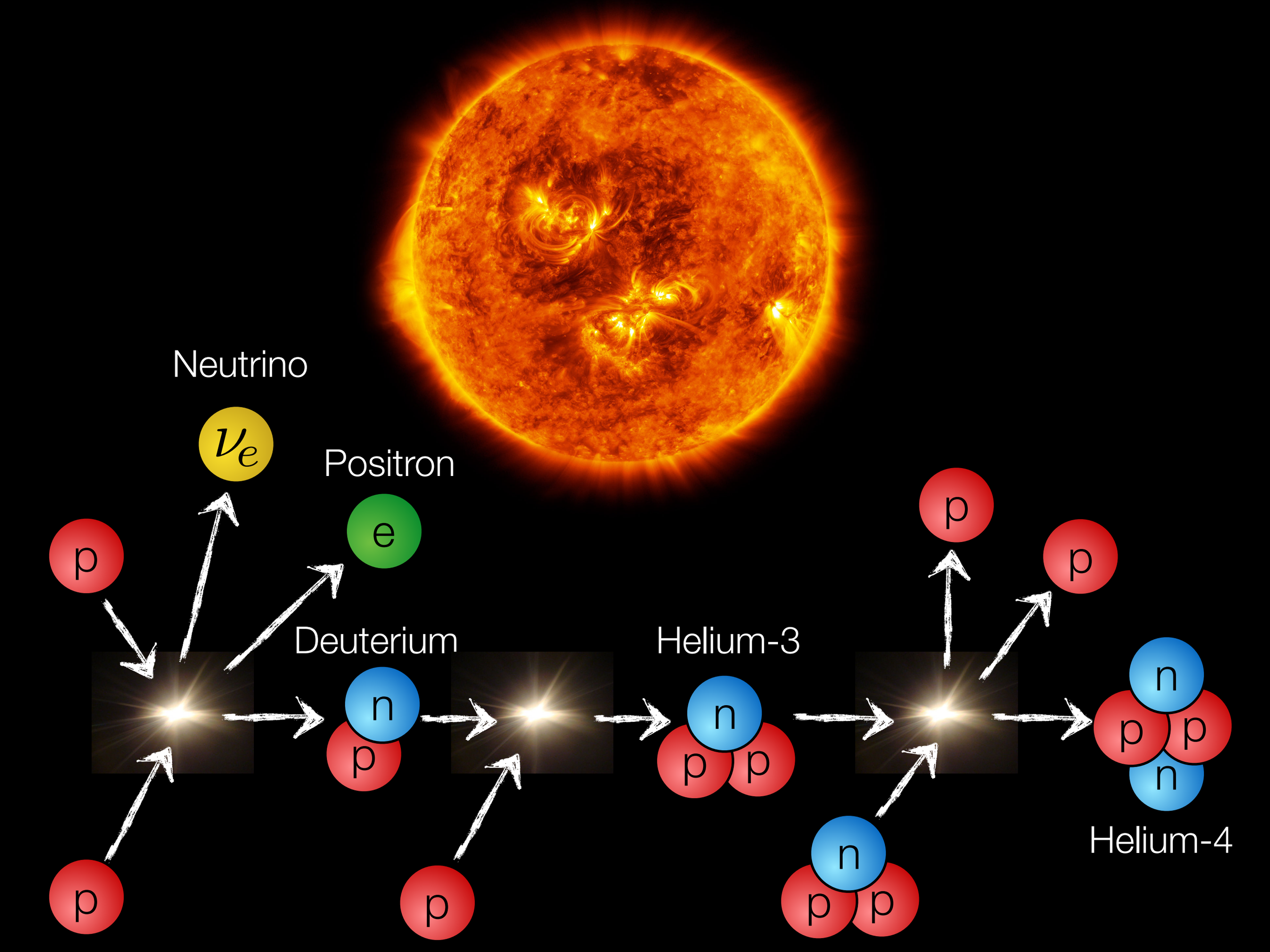
Neutrino
$\nu_e$
Positron
e
p
p
p
Deuterium
n
p
Helium-3
n
p
p
p
p
p
n
p
p
n
Helium-4

## ☑ Stellar Evolution Equations

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \varrho} ,$$

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} ,$$

$$\frac{\partial l}{\partial m} = \varepsilon_{\mathrm{n}} - \varepsilon_{\nu} - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho} \frac{\partial P}{\partial t} ,$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P} \nabla ,$$

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho} \left( \sum_j r_{ji} - \sum_k r_{ik} \right) , \quad i = 1, \ldots, I .$$

from Kippenhahn Weigert Weiss “Stellar Structure and Evolution”

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**Conservation of mass**
(Relation between radius, enclosed mass, and density)

from Kippenhahn Weigert Weiss “Stellar Structure and Evolution”

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**Conservation of momentum**
(Pressure difference across a mass shell is due to mass of the shell)

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$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho}\left(\sum_j r_{ji}\right.$$

**Conservation of energy**
(change in luminosity across a mass shell due to energy generation in nuclear reactions, energy loss due to neutrino emission, and energy production or loss by expansion/contraction)

# Stellar Evolution

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**Thermal Structure**
(change in temperature across a mass shell is related to equation of state $\Delta = d\ln T / d\ln P$)

from Kippenhahn Weigert Weiss "Stellar Structure and Evolution"

# Stellar Evolution

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**Evolution of Mass Fraction of different species**

from Kippenhahn Weigert Weiss “Stellar Structure and Evolution”

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from Kippenhahn Weigert Weiss “Stellar Structure and Evolution”

# Stellar Evolution

- ☑ Stellar Evolution Equations
  - Solve numerically on discretized grid
  - Additional complication: convection
- ☑ Requires input parameters / boundary conditions
  - total mass
  - surface temperature
  - initial chemical composition
- ☑ Most relevant output for neutrino physics
  - Core temperature $T_{\mathrm{core}}$
  - Neutrino flux depends on the $25^{\mathrm{th}}$ power of $T_{\mathrm{core}}$!

# Helioseismology

- ☑ Need to determine the Sun's chemical composition
- ☑ Need tool to verify solar models
- ☑ Helioseismology
  - Study oscillation modes of the Sun
  - Generated in the convective zone
  - Observed via Doppler shift of spectral lines
  - Oscillation modes depend on the Sun's internal structure, so they allow us to learn about the latter

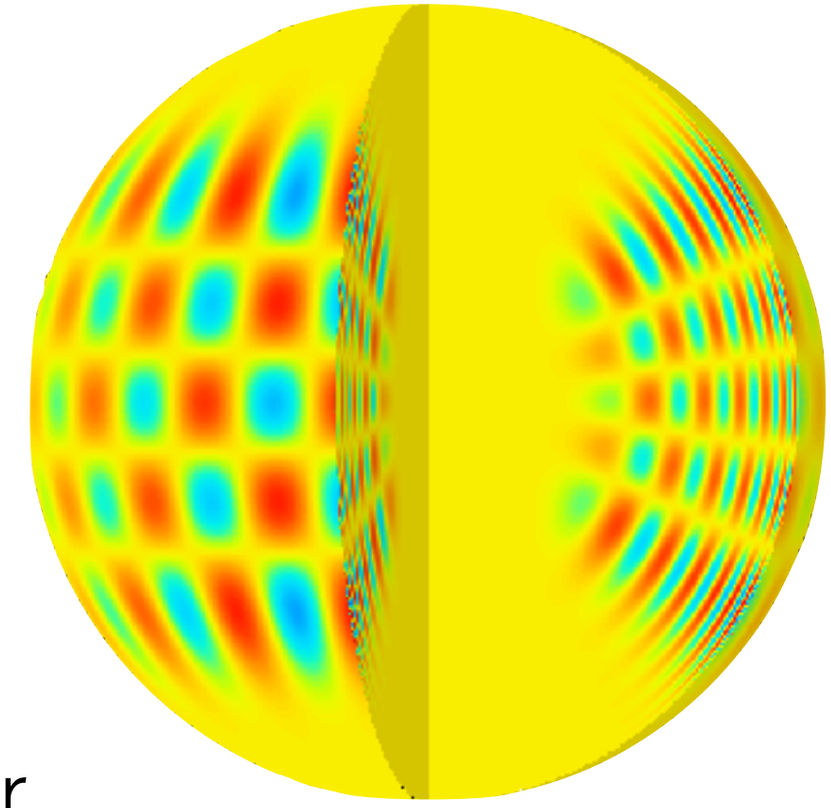
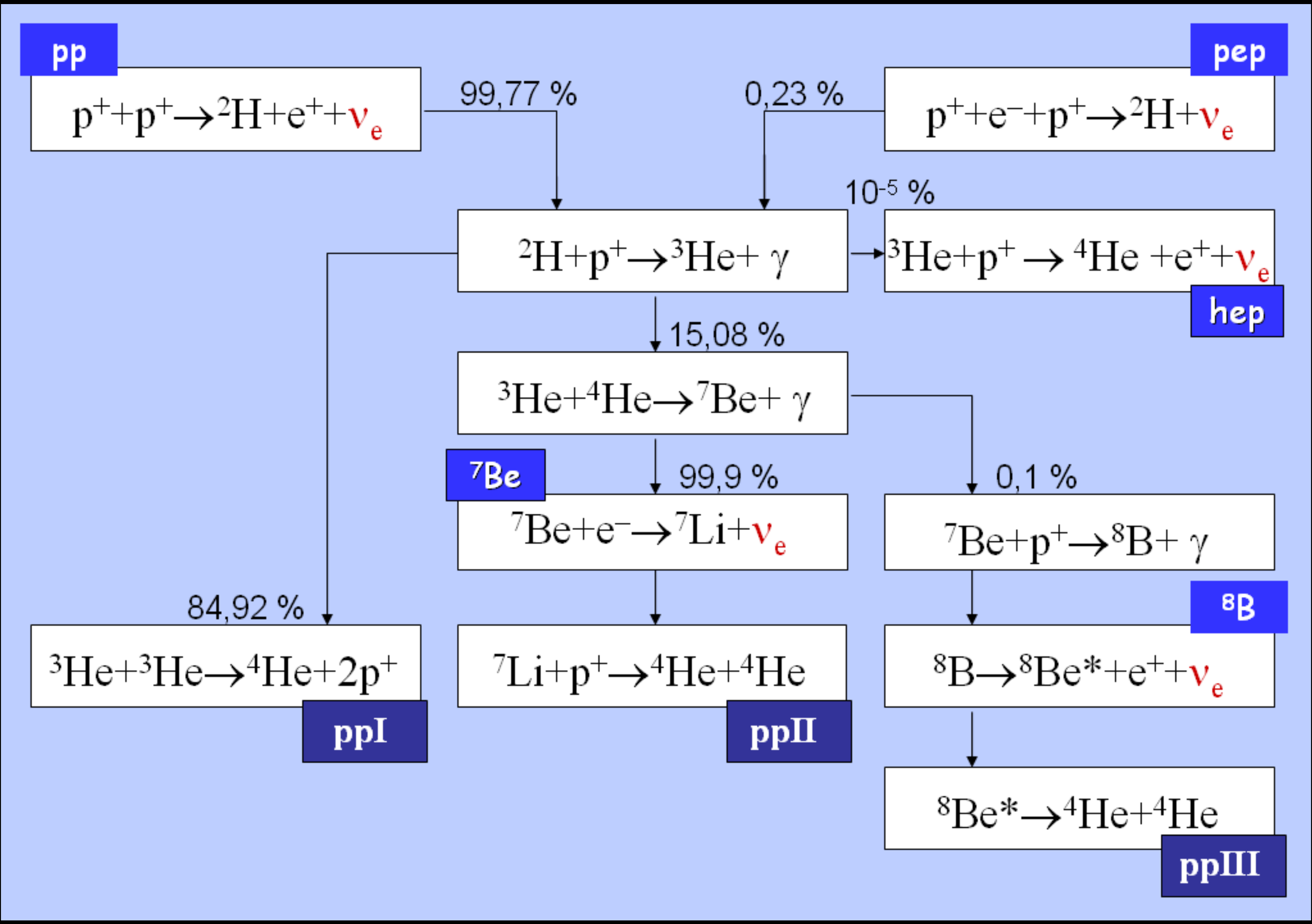


Image from http://soi.stanford.edu/results/heliowhat.html


pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$
99,77 %
0,23 %
pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$
$10^{-5}$ %
${}^2H + p^+ \rightarrow {}^3He + \gamma$
${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep
15,08 %
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
${}^7Be$
99,9 %
0,1 %
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p^+ \rightarrow {}^8B + \gamma$
84,92 %
${}^8B$
${}^3He + {}^3He \rightarrow {}^4He + 2p^+$
ppI
${}^7Li + p^+ \rightarrow {}^4He + {}^4He$
ppII
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
${}^8Be^* \rightarrow {}^4He + {}^4He$
ppIII

# Predicted Solar Neutrino Flux

- ☑ Pure $\nu_e$
- ☑ Flux on Earth: $\sim 10^{11}/cm^2/sec$
- ☑ Energy: $\lesssim 10$ MeV

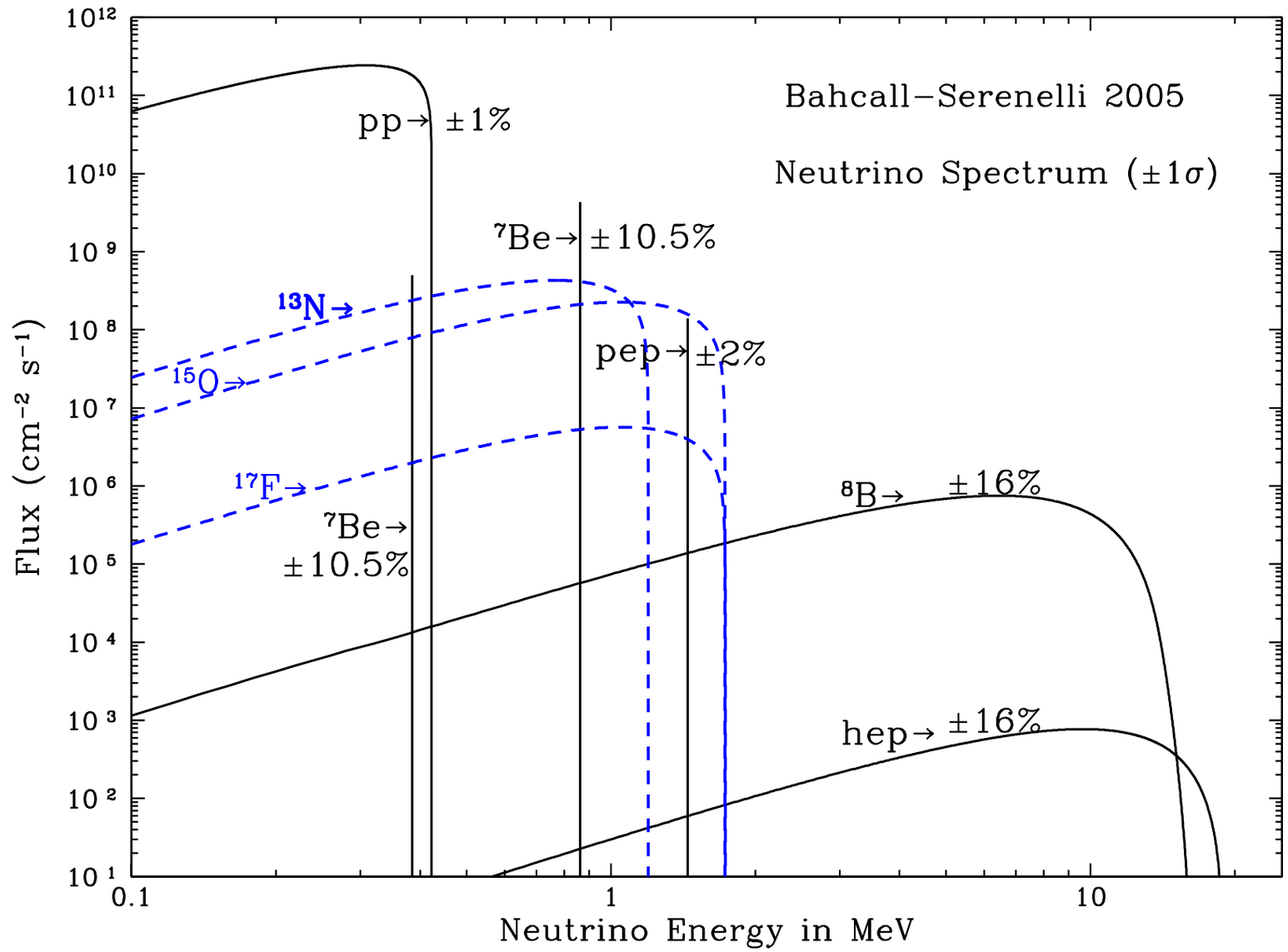



Image by John Bahcall

# Reactor Neutrinos

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# Predicting the Reactor Neutrino Spectrum

## Method:

Mueller *et al.* 1101.2663, Huber 1106.0687

- Use measured β spectra from $^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu fission
- Convert to $\bar{\nu}_e$ spectrum
- For single β decay: $E_\nu = Q - E_e$

$$\frac{dN_\nu(E_\nu)}{dE_\nu} \equiv \frac{dN_e(Q - E_e)}{dE_e}$$

- For energy-independent nuclear matrix elements: simple phase space argument

$$\begin{aligned} dN_\nu &\propto d^3p_e\, d^3p_\nu\, \delta(E_e + E_\nu - Q) \\ &\propto p_e^2 dp_e\, p_\nu^2 dp_\nu\, \delta(E_e + E_\nu - Q) \\ &= p_e E_e\, p_\nu E_\nu dE_\nu \\ &= \sqrt{(Q - E_\nu)^2 - m_e^2}\,(Q - E_\nu)\, E_\nu^2\, dE_\nu\,. \end{aligned}$$

# Corrections to the Reactor ν Spectrum

- ☑ Fermi function $F(A, Z, E_\nu)$
  - describes interactions of final state electron with Coulomb field of the nucleus
- ☑ Screening of the nuclear charge by bound electrons
- ☑ Non-zero nuclear radius
- ☑ Final state radiation: $(A, Z) \rightarrow (AA, Z+1) + e^- + \bar{\nu}_e + \gamma$
- ☑ Approximation of energy-independent nuclear matrix elements valid only for allowed beta decays

# Corrections to the Reactor ν Spectrum (contd.)

- Weak Magnetism: impact of finite nuclear size on weak interactions
  - Weak interaction vertex:

$$\mathcal{L}_{\text{weak}} \supset \frac{g}{\sqrt{2}} J_W^\mu W_\mu + h.c.$$

with the weak current

$$J^\mu_{W,\text{point-like}} = \bar{u}\gamma^\mu \frac{1-\gamma^5}{2} d$$

  - For non-pointlike objects, extra terms and form factors appear

$$J^\mu_{W,\text{extended}} = \bar{u}\left[c_V(q^2)\gamma^\mu + c_A(q^2)\gamma^\mu\gamma^5 + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}\right]d\,,$$

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**weak vector charge**
Fermi form factor

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**weak axial charge**
Gamow-Teller form factor

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**weak magnetism** (analog of magnetic moment in QED)

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# Predicting the Reactor Neutrino Spectrum

- ☑ This was the story for a single beta decay ...
- ☑ Reality: ~6000 decays contribute
  - would need to know Q-value, relative importance, and all correction factors for each of them
  - this information is available only for some decays
  - many isotopes are too short-lived to be studied in the lab
- ☑ Method:
  - Use information from nuclear data tables where available ...
  - ... complemented by a fit to "effective decay branches" (a set of beta decays with parameters fitted in order to match the observed electron spectrum)

Mueller *et al.* 1101.2663, Huber 1106.0687

# Verification

- ☑ Simulate mock electron spectrum
- ☑ Convert to neutrino spectrum using aforementioned method
- ☑ Compare to MC truth

# The Reactor Neutrino Anomaly

Result: predicted flux is ~3.5% (~3σ) higher than observation

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