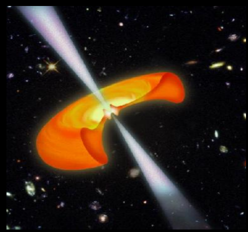

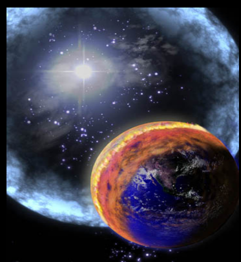

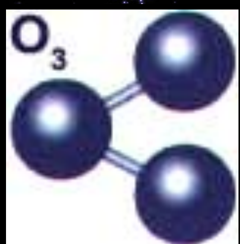


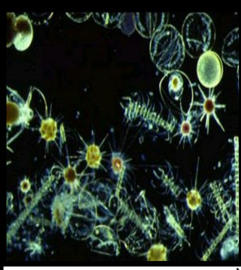

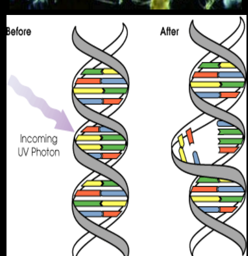


# Astrophysical Events as Episodic Threats to Life on Earth

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Washburn University

KU ASTROBIOPHYSICS WORKING GROUP

Work supported by NASA grant No. NNX09AM85G

# Astrophysical Radiation & Earth

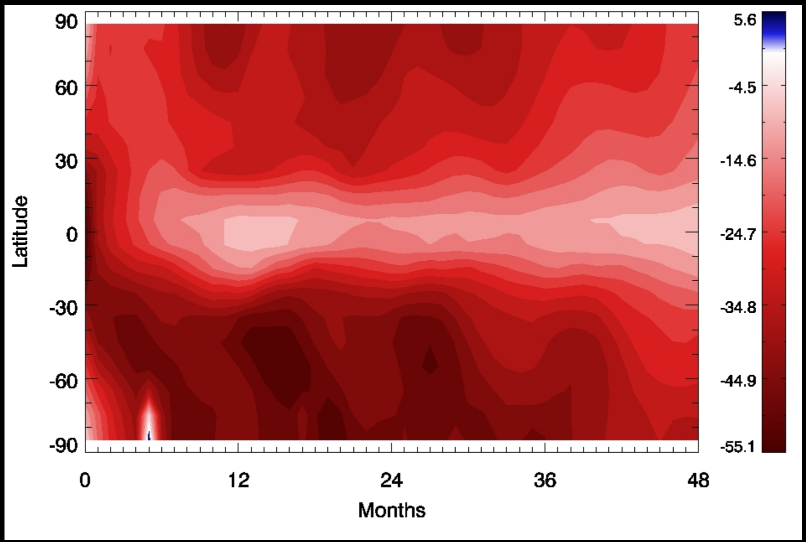
- High energy radiation:
  - X-rays, gamma-rays
  - Cosmic rays – charged particles (protons)

- Effects:
  - Atmospheric chemistry changes
    - Nitrogen dioxide “smog”
    - Stratospheric Ozone depletion
  - High-E CRs => energetic muons
    - Muons are highly penetrating

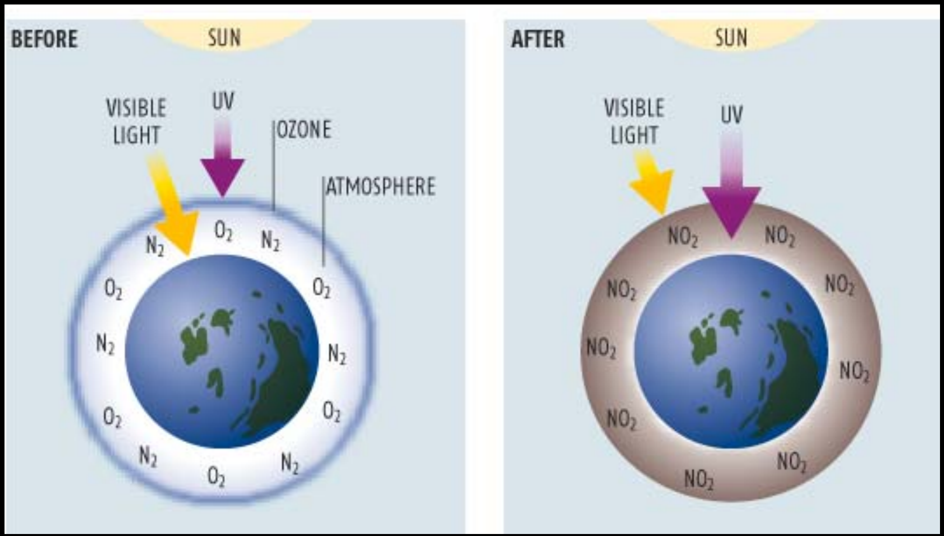
# Long-Term Consequences

- Life at the surface sees enhanced UV for years
  - UV strongly affects DNA, proteins, etc.
  - Phytoplankton and other surface dwellers hit hardest
  - Food-web impact
  - Mass Extinction?

$O_3$ depletion, latitude v. time




Cooling due to opacity of $NO_2$ ?



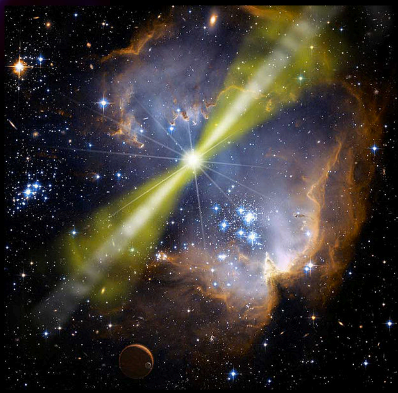

Thomas et al. 2005, ApJ, 634, 509

New Scientist, Sept. 2003

# A Range of Sources

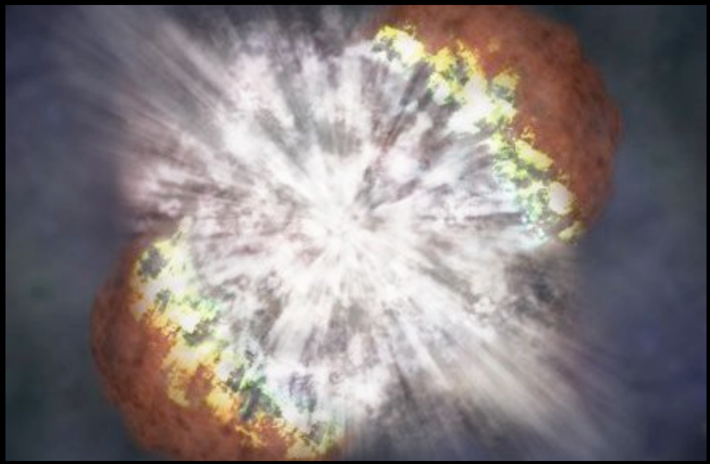
In order of *increasing* energy and *decreasing* frequency:

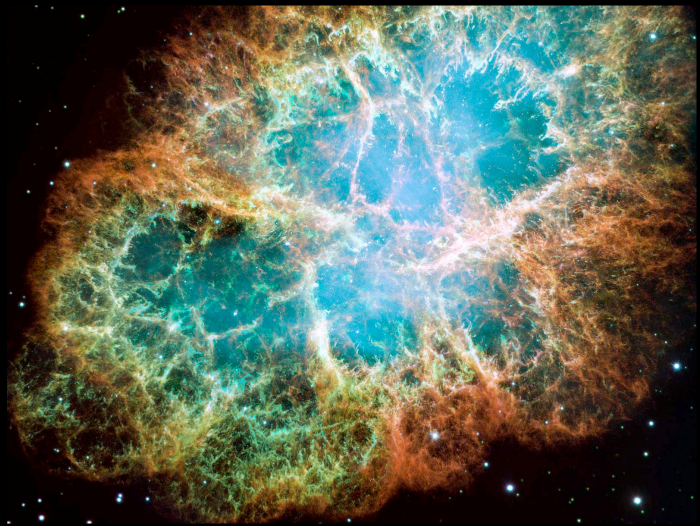
- Solar proton events (CMEs)
  - Primarily protons
  - Up to $10^{25}$ Joules total
- Supernovae (various types)
  - X- and gamma-ray photons
  - CRs (partly location dependent)
  - Up to $10^{46}$ Joules
  - Important at 10's of light years
- Gamma-Ray Bursts (2 types)
  - X- and gamma-ray photons
  - Up to $10^{47}$ Joules
  - Important at 1000's of light years

# Supernova

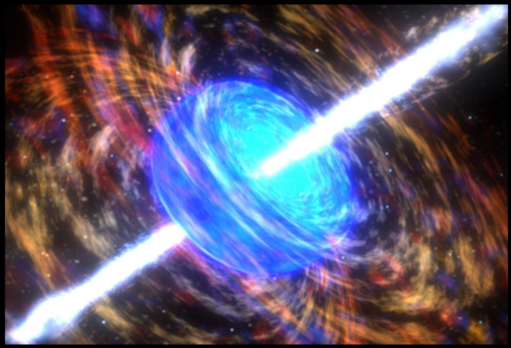
- Photons for ~ 1 year
  - Global average $O_3$ depletion up to 35%, lasting up to a decade (assuming distance of ~ 30 light years)
- Cosmic ray enhancement ~ thousand years
  - Also causes $O_3$ depletion
  - High energy CRs => penetrating muons
- Iron-60 detections around 2.5 Ma strongly indicate a SN at maybe 150 light years.



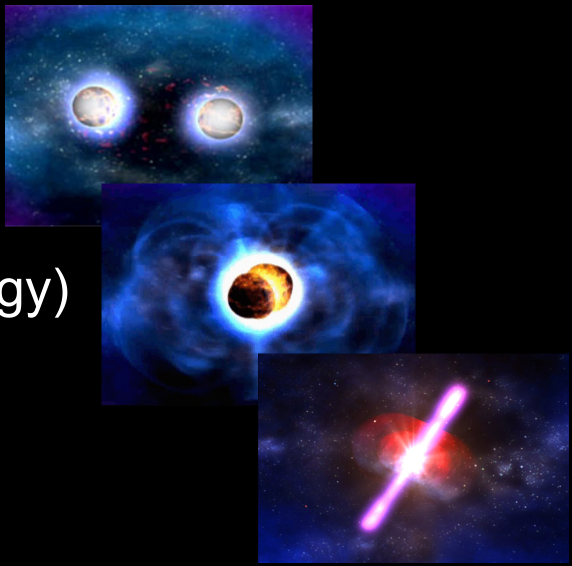


# Gamma-Ray Bursts

- Two main types, both strongly beamed.
  - Long-soft GRB
    - Duration: > 2 s (typical ~ 10 s)
    - Softer spectrum (lower peak photon energy)
    - Special case of core-collapse SN (?)



  - Short-hard GRB
    - Duration: < 2 s (typical ~ 0.1 s)
    - Harder spectrum (higher peak photon energy)
    - Compact-object merger (?)

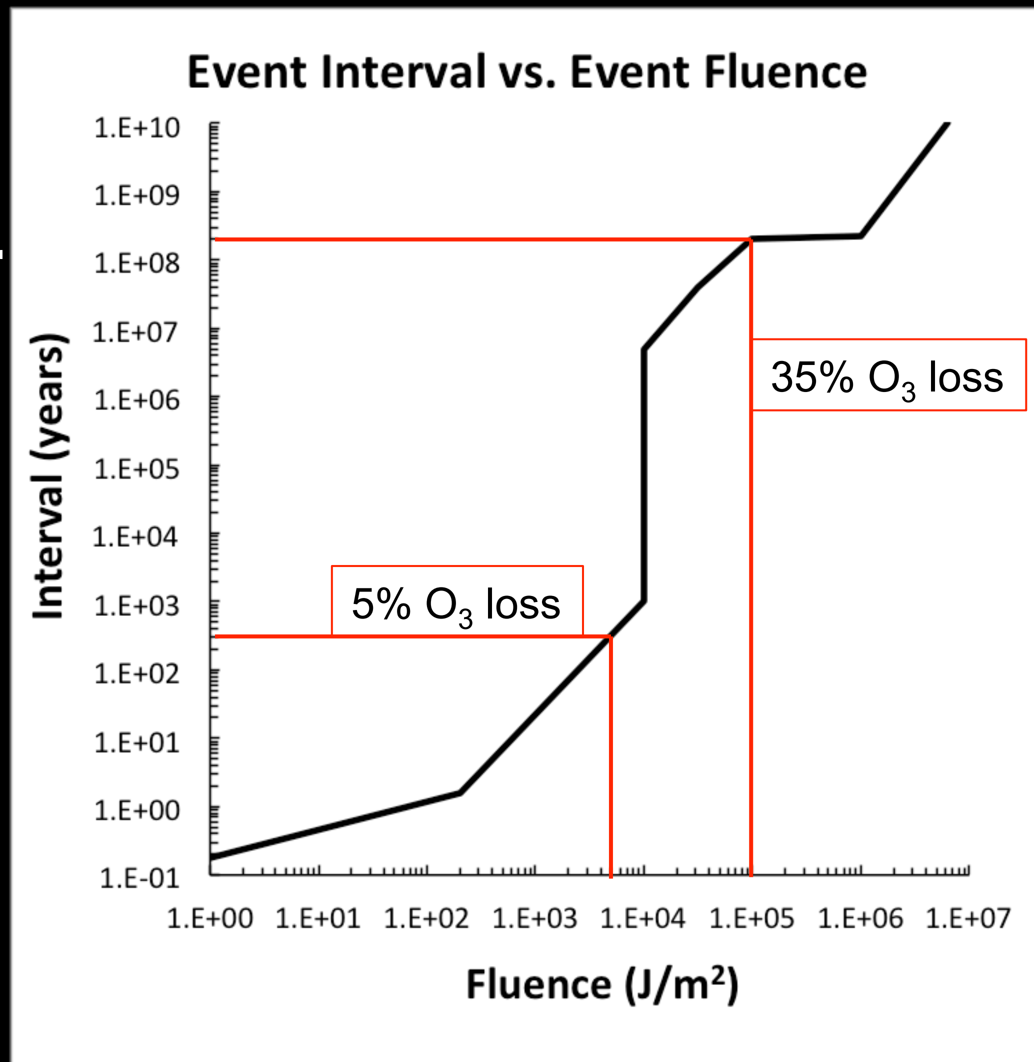


# Rates for "significant" events

- Rate vs. Fluence (energy per unit area)
  - *Fluence convolves total energy and distance*
- Solar, SN, Short-Hard GRBs, Long-Soft GRBs
- $O_3$ global average depletion thresholds:
  - 1) ~5%: current, 1859 SPE
    - noticeable bio effect
  - 2) ~35%: 100 kJ $m^{-2}$ fluence (GRB, SN)
    - major bio impact – mass extinction?

# Event Intervals

- Rates summed over all event types.
- Dominated by:
  - Solar at low fluence
  - Supernova and short-hard gamma-ray burst at high fluence



# Estimated Rates

- For events that yield ~ 35% globally averaged $O_3$ depletion:
  - Short-Hard GRBs: 1 per 300 million years
  - Supernovae: 1 per 500 million years
  - Long-Soft GRBs: 1 per billion years

- For events that yield ~ 5% globally averaged $O_3$ depletion:
  - Solar: 1 per 1000 years?*
    - Uncertain, few data points, extrasolar data support
  - Supernovae: 1 per 1 million years
  - Short-Hard GRBs: 1 per 3 million years
  - Long-Soft GRBs: 1 per 30 million years

* See Melott & Thomas, Nature, 2012; Thomas et al., GRL, 2013

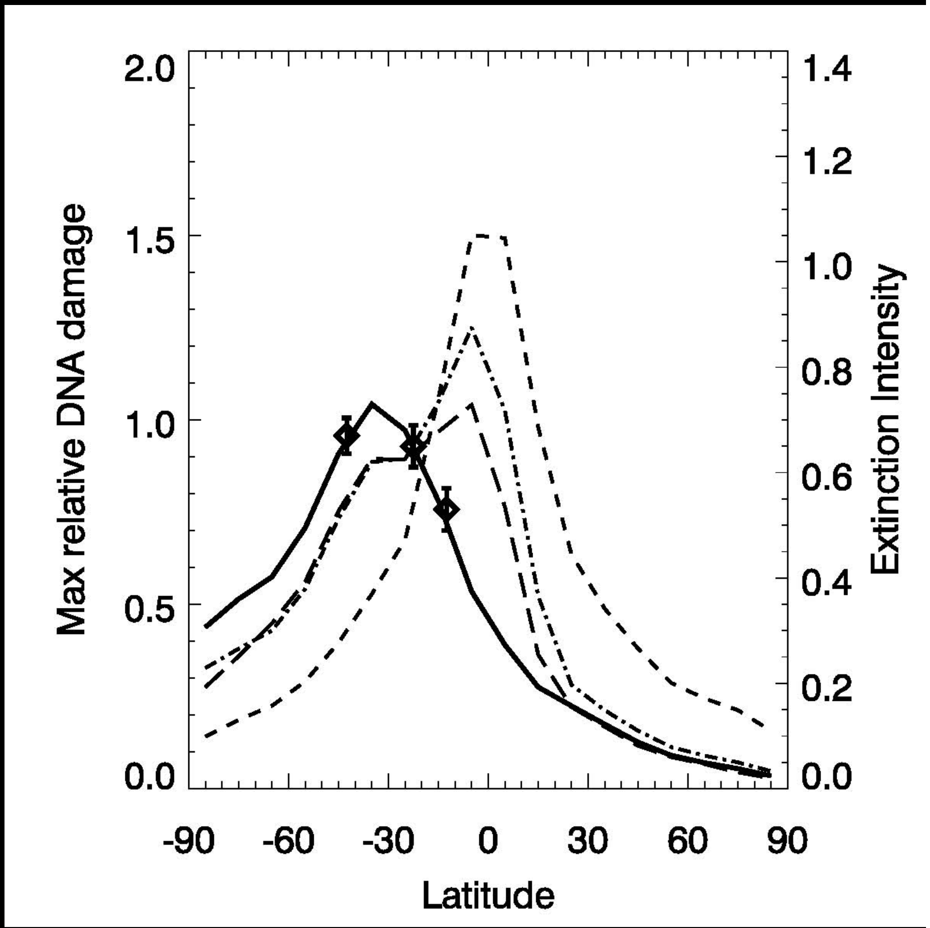
# Extinctions

- 35% global $O_3$ depletion expected to have severe impact for several years.
- We have previously identified correlations in late Ordovician extinction:
  – Depth and latitude dependence (Melott et al. 2004, Thomas et al. 2005, Melott & Thomas 2009)
- Work in progress to better quantify impact on marine primary producers.
- Future work investigating ecological impact?

# End-Ordovician Extinction

- Unexplained short period of glaciation ($NO_2$ cooling?)
- Bias toward extinction of shallow water organisms, surface dwellers…

- Computed DNA damage from a group of simulations for a variety of southern hemisphere GRB cases
- Data points are extinction rates as a function of latitude.
  - Krug & Patzkowsky, 2004, PNAS
- GRB over the (paleo) South Pole fits




From Melott & Thomas, Paleobiology 35, 311 (2009).

# Resources and Acknowledgements

- "Astrophysical Ionizing Radiation and Earth: A Brief Review and Census of Intermittent Intense Sources"
  - Melott & Thomas, *Astrobiology,* v.11 (2011)
- "Late Ordovician geographic patterns of extinction compared with simulations of astrophysical ionizing radiation damage"
  - Melott & Thomas, *Paleobiology*, v.35, p.311 (2009)
- "Gamma-Ray Bursts as a Threat to Life on Earth"
  - Thomas, *Int. J. of Astrobiology*, v.8, p.183 (2009)
- "Causes of an AD 774-775 $^{14}C$ increase"
  - Melott & Thomas, *Nature*, v.491, E1-2 (2013)
- "Terrestrial effects of possible astrophysical sources of an AD 774-775 increase in $^{14}C$ production"
  - Thomas et al., *Geophys. Res. Lett.*, v.40, p.1237 (2013)

Pre-prints available at arXiv.org

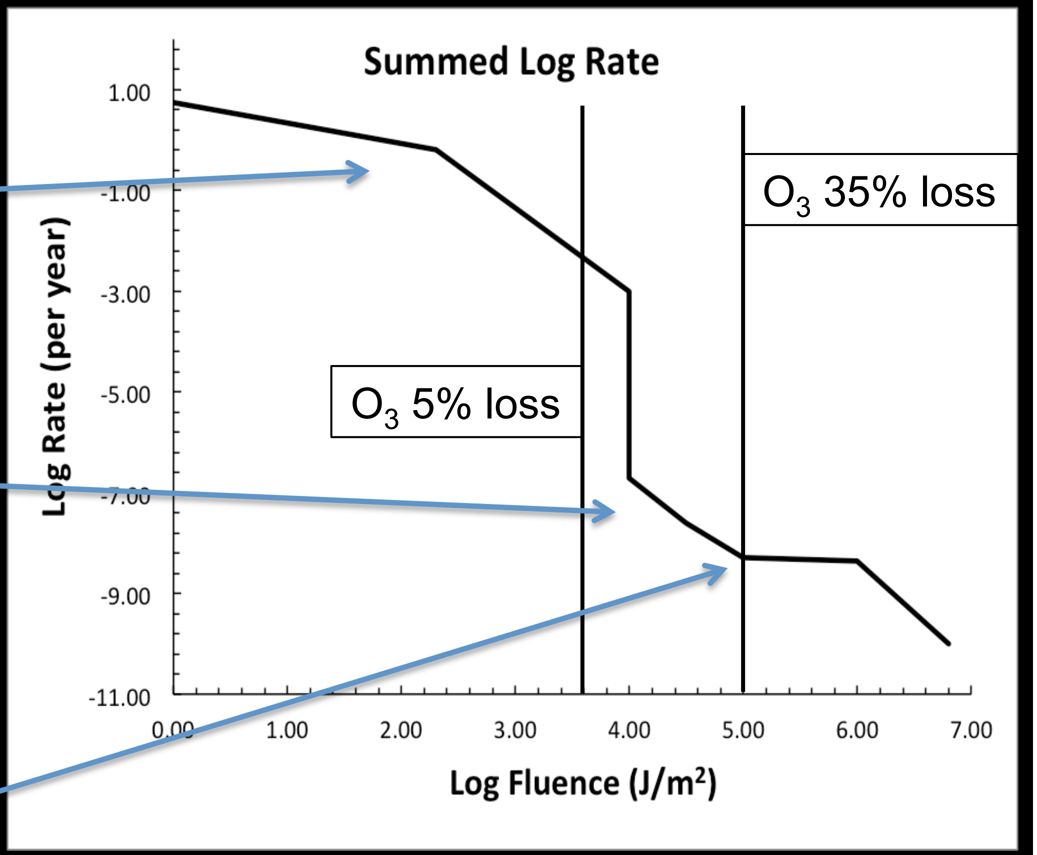
Thanks to various collaborators and students!

Current work supported by NASA grant No. NNX09AM85G

END

# Summed Rate vs. Fluence

- Dominated by:
  - Solar at low fluence
  - Supernova and short-hard gamma-ray burst at high fluence



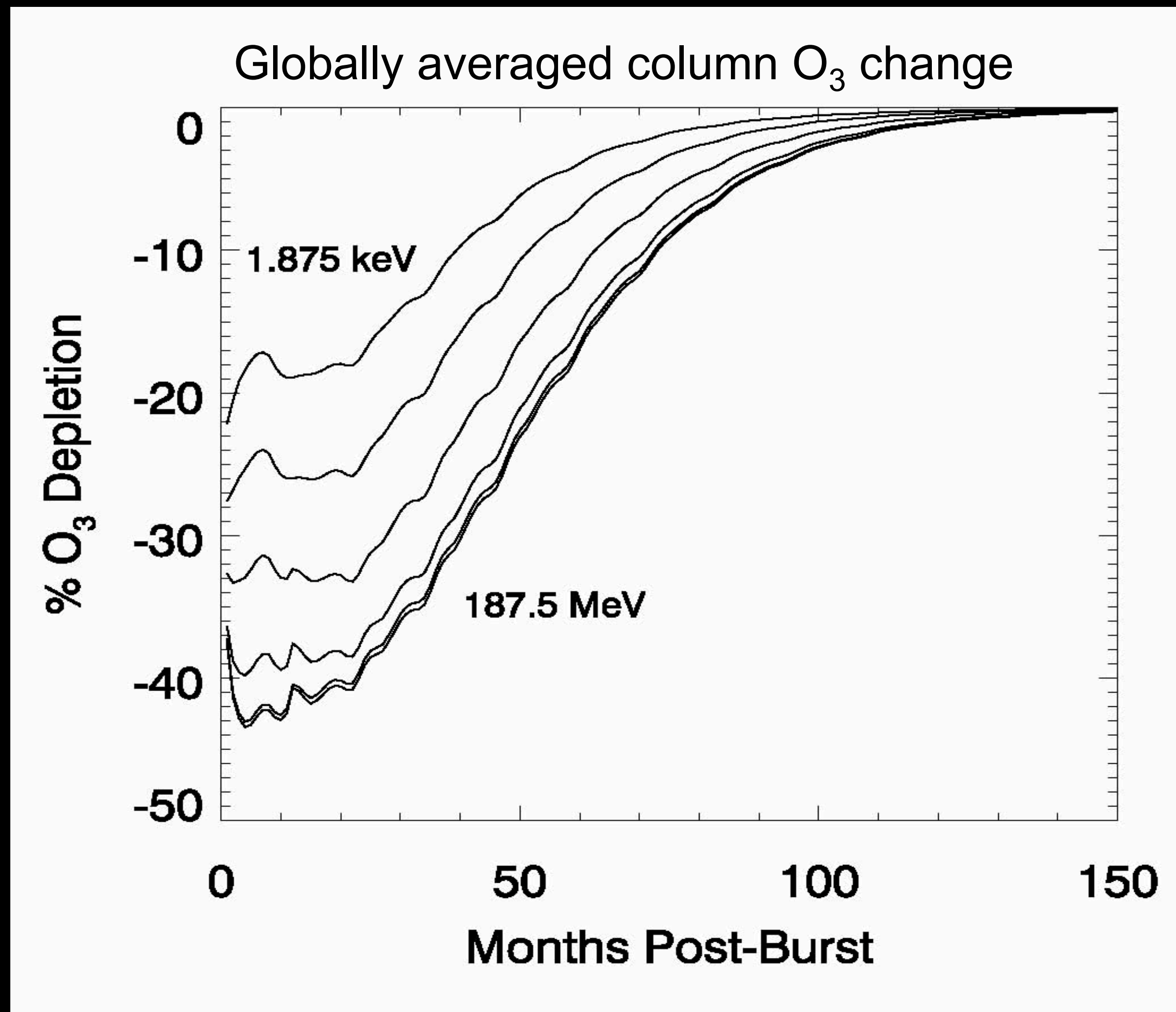

SN:
From $D^{-2}$ to $D^{-3}$
Inside remnant

# Varying Event “Hardness” in Photons

- Same total energy received.
- Vary the relative number of high energy photons

- Broadly,

  Harder = worse

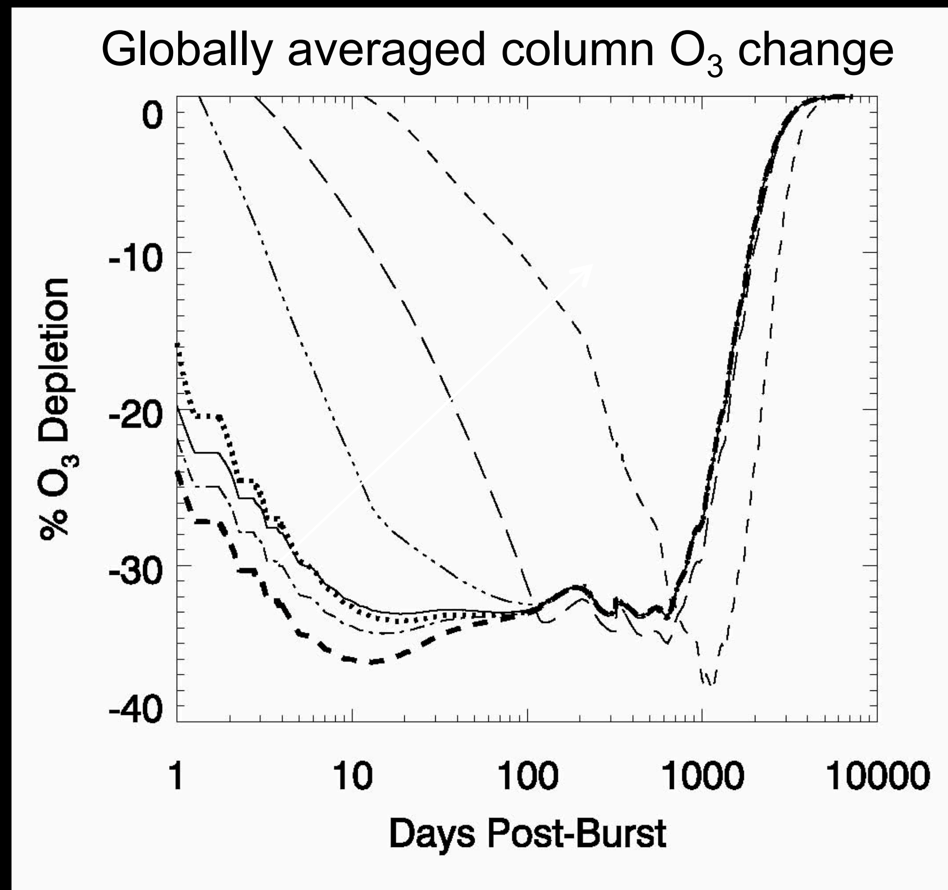



Ejzak et al. 2007, ApJ, 654, 373

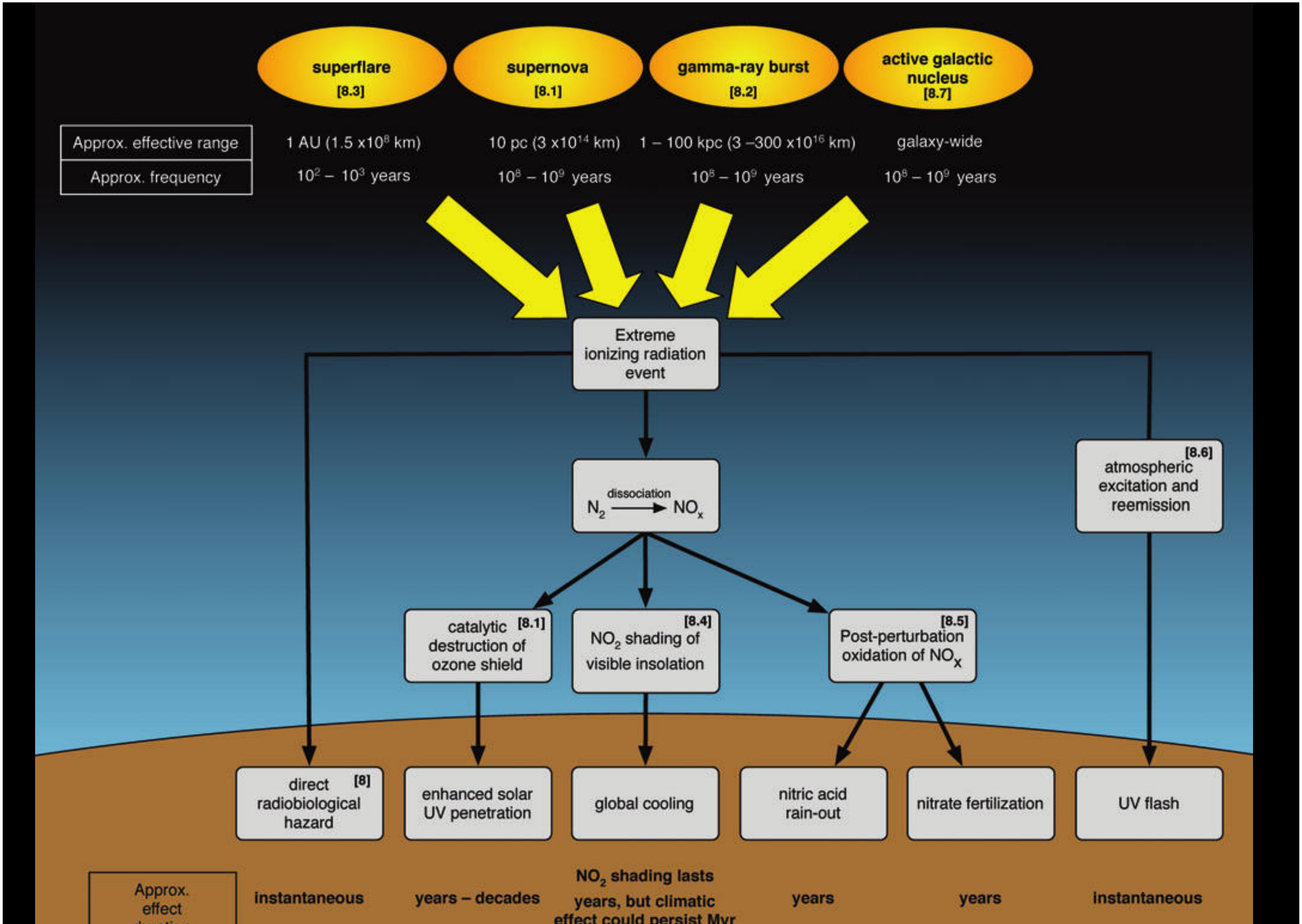
# Varying Event Duration

- Constant spectrum and energy received.
- Duration from 0.1 to $10^8$ s

- Broadly,
  - Variation in timing
  - But, similar total depletion



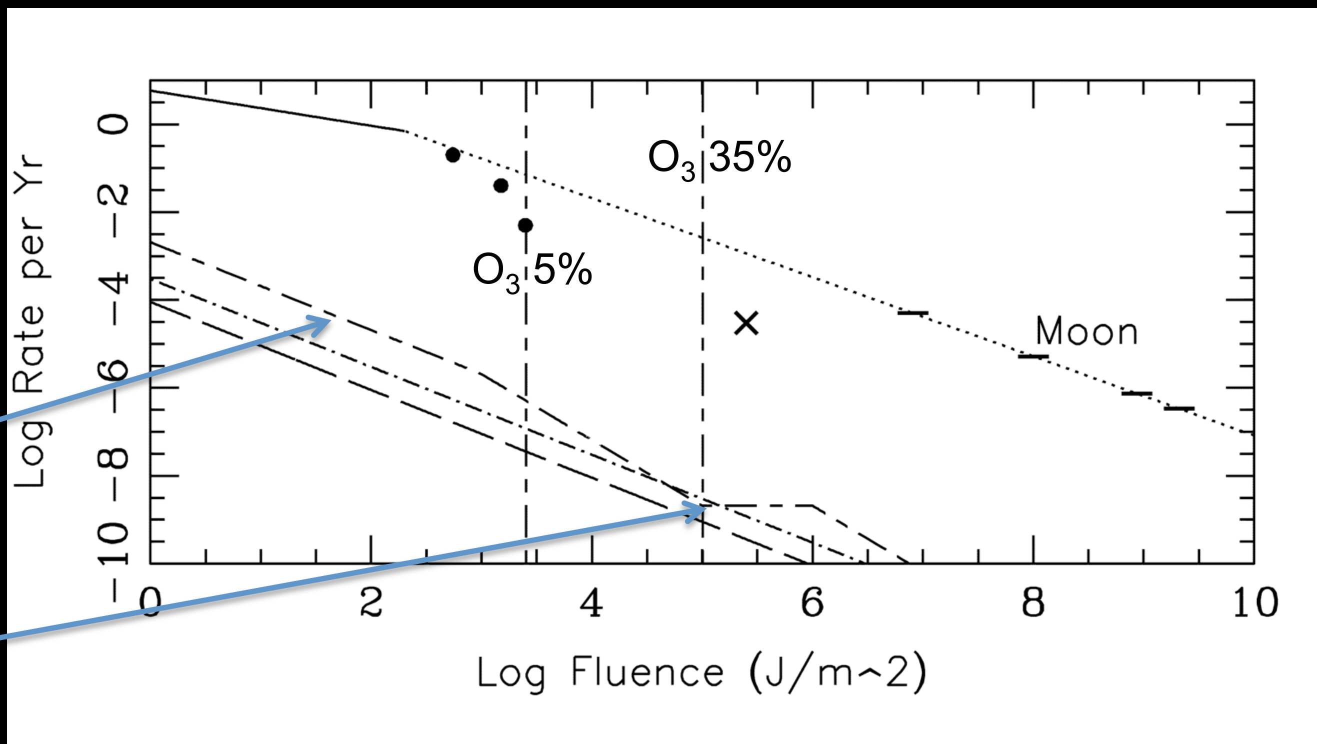

Ejzak et al. 2007, ApJ, 654, 373




From L.R. Dartnell, *Astrobiology*, 11, 2011

# Rate vs. Fluence

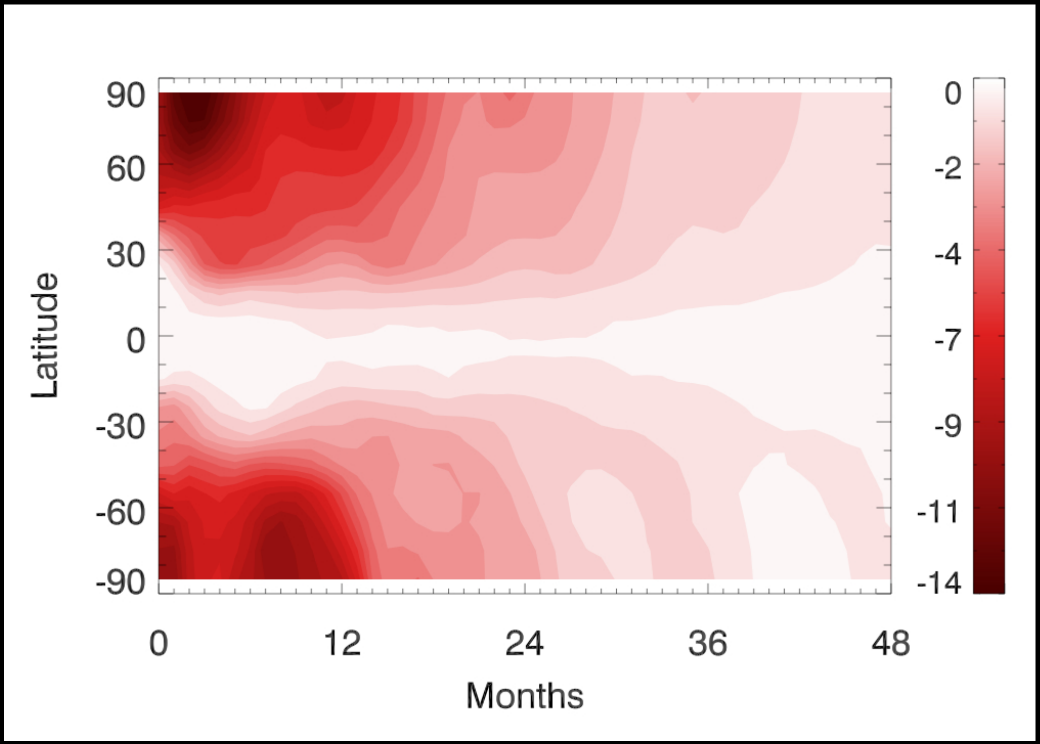
- Solar: Line, Recent SPE; Dots, historical SPE
- "Moon" upper limits on cumulative exposure rates from lunar radionuclides (x=goal; isotopes, ice cores)
- SN
- SHGRB
- LSGRB




SN:
From $D^{-2}$ to $D^{-3}$
Inside remnant

# Atmo Effects: 1859 Flare

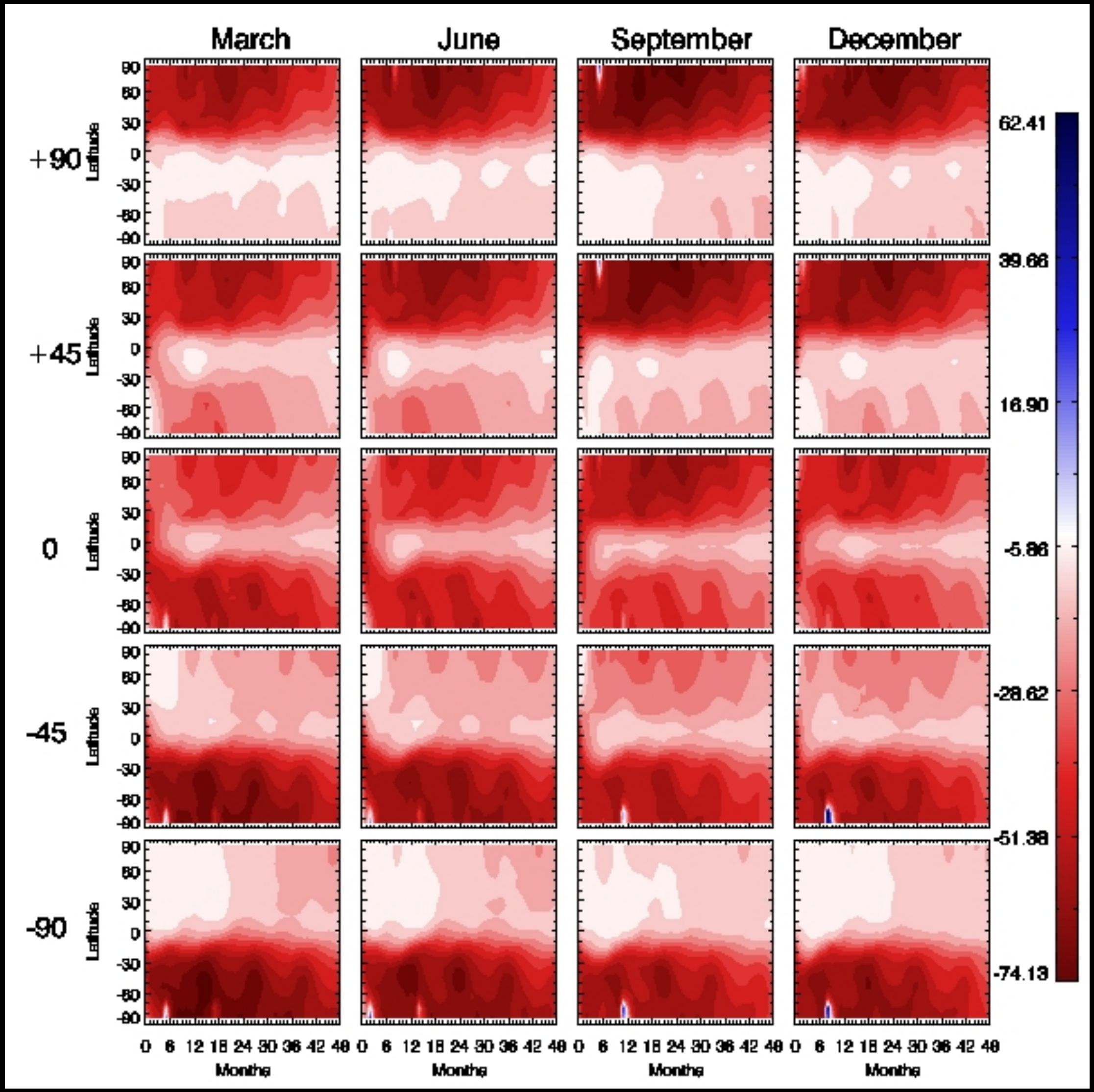
- $O_3$ depletion:
  - Max 5% global avg.
  - Similar to current
  - Recovery ~ 4 yrs




Thomas et al. 2007, GRL, 34, L06810

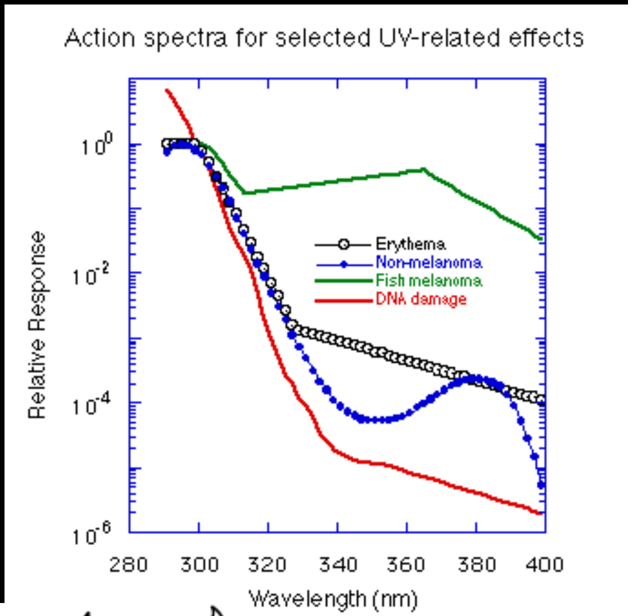
# Atmo Effects: Long GRB

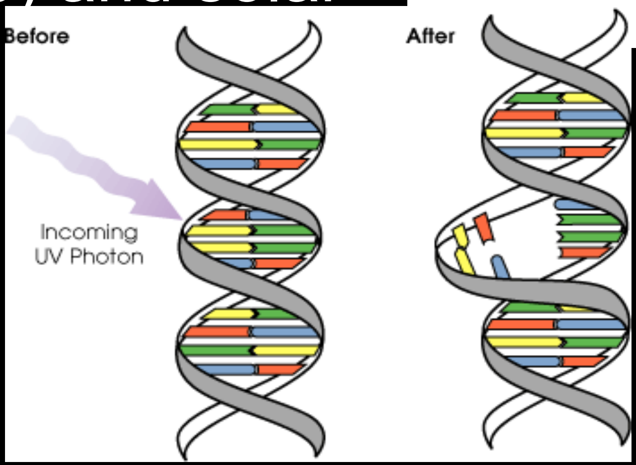
- Location and season of burst affect intensity and geographic distribution of impact.
- Globally averaged depletions up to 35%



# Solar UV and Biological Effects

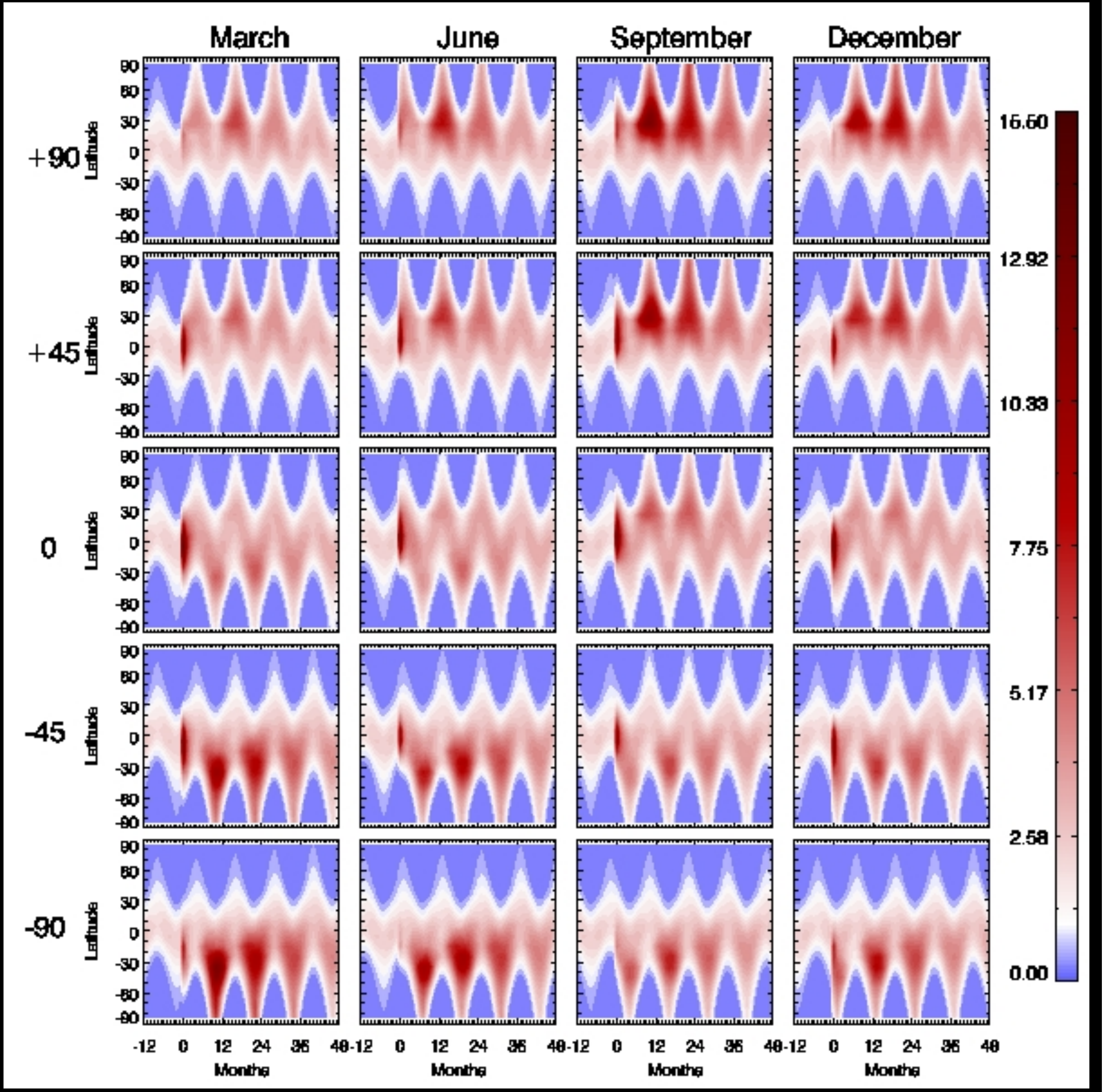
- Surface UVB (280-315 nm)
  – Solar UVB attenuated by $O_3$ column
  – Simple approach (no scattering, etc.)
- DNA damage
  – Computed using a *weighting function* (Setlow 1976) and solar UVB irradiance.



Relative DNA damage (normalized by annual global average pre-burst)

Note primarily mid-low latitudes affected.



# Did a GRB initiate the Late Ordovician Mass Extinction?

| EON | ERA | PERIOD | MILLIONS OF YEARS AGO |
|---|---|---|---|
| Phanerozoic | Cenozoic | Quaternary | 1.6 |
| | | Tertiary | 66 |
| | Mesozoic | Cretaceous | 138 |
| | | Jurassic | 205 |
| | | Triassic | 240 |
| | Paleozoic | Permian | 290 |
| | | Pennsylvanian | 330 |
| | | Mississippian | 360 |
| | | Devonian | 410 |
| | | Silurian | 435 |
| | | Ordovician | 500 |
| | | Cambrian | 570 |
| Proterozoic | Late Proterozoic<br>Middle Proterozoic<br>Early Proterozoic | | 2500 |
| Archean | Late Archean<br>Middle Archean<br>Early Archean | | 3800? |
| Pre-Archean | | | |

http://pubs.usgs.gov/gip/fossils/numeric.html

~ 440 million years ago
2nd largest mass extinction known

Primarily shallow-sea life at this time.
No known land life.

Courtesy W. Berry, UC Museum of Paleontology

We first proposed this connection in 2004 in IJA

| Predicted GRB Effects | Late Ordovician Data |
|---|---|
| Extinction of shallow (not deep) water organisms ! | Yes (correlation) |
| Extinction of free-swimming organisms ! | Yes (correlation) |
| Extinction of surface floaters plankton/ planktonic larval forms ! | Yes (correlation) |
| Nitric acid rain ? | Productivity oscillation in biosphere possibly related to nitrate boost. |
| Reduction of solar radiation – cooling ? | Yes – glaciation needed "kick" |
| Extinctions begin with GRB ! | Extinctions preceeded glaciation and began with plankton |
| No iridium layer due to asteroid, no $^{244}$Pu residue from nearby supernova | Unknown (not yet observed) |

Can we predict any other effects, test the idea in additional ways?

Is this a falsifiable hypothesis?

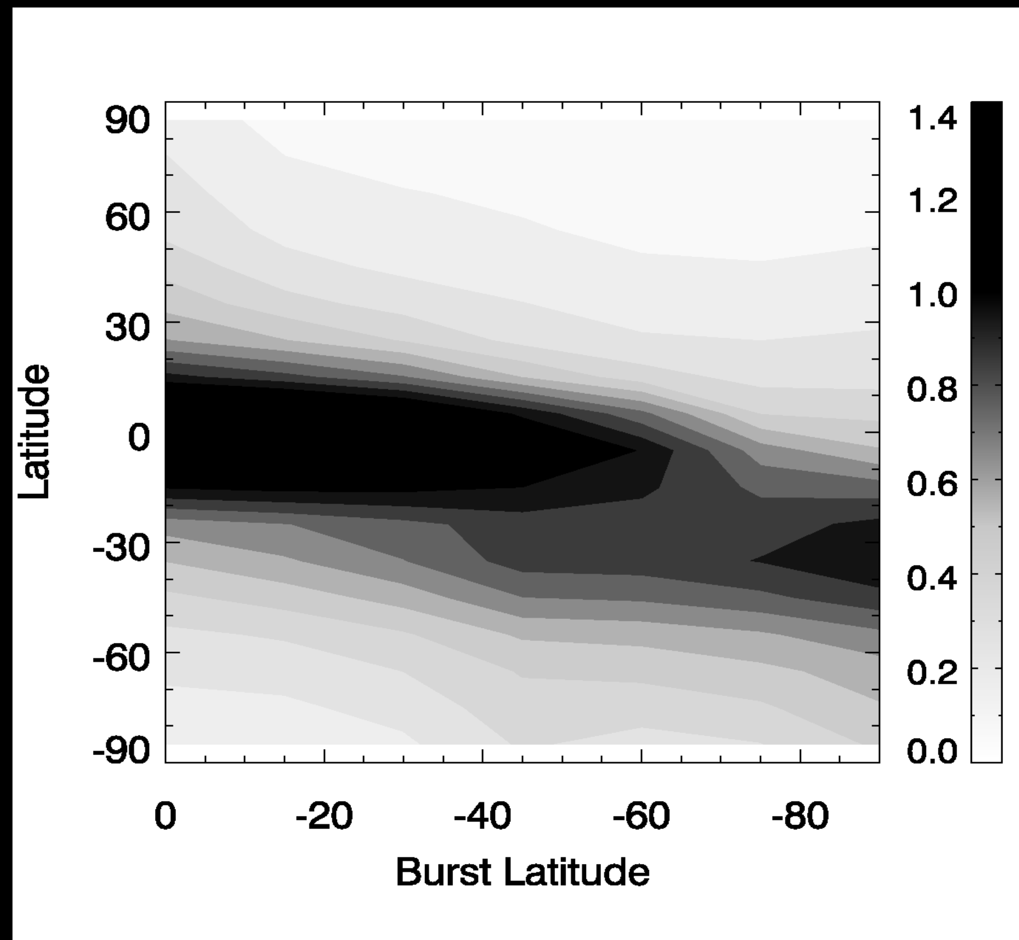
# Latitude dependence of extinction

- Krug and Patzkowsky (2007) analyzed the pattern of extinction in the Ordovician.
  - Presented extinction intensities on three continents, varying in latitude.
- Our simulations show a pattern of damage as a function of latitude. Can now test the hypothesis:
  - If UV effects were a dominant part of the extinction, we should be able to match their pattern.
- Any GRB had to be southern hemisphere
  - Fossil record documents a southern hemisphere extinction
  - Atmospheric effects typically are confined to northern or southern hemisphere.

# Extinction Intensity Patterns

- All cases show a maximum damage intensity at a latitude that depends on burst latitude.
- *Scale shows:* maximum damage intensities for southern hemisphere bursts normalized to average value of maxima at equator for all cases

Effect latitude vs. Burst latitude



# Comparison with Ordovician Data

- Diamonds (with 2σ error bars) represent sampling-standardized extinction intensities from Krug and Patzkowsky (2007)
- Lines correspond to bursts at latitude 0°, -45°, -60°, and over the South Pole -90° (max damage normalized to average value of maxima at equator for all cases)
- Only a burst between -75° and -90° would fit the extinction data.